The 33rd International Symposium on Lattice Field Theory (Lattice 2015)

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Kobe International Conference Center

Book of Abstracts
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent progress on chiral symmetry breaking in QCD</td>
<td>1</td>
</tr>
<tr>
<td>Determining the order of chiral phase transition in QCD from conformal bootstrap</td>
<td>1</td>
</tr>
<tr>
<td>Numerical evaluation of QED contribution to lepton g-2</td>
<td>1</td>
</tr>
<tr>
<td>Lattice QCD moments - ( g - 2 ) and NEDM</td>
<td>2</td>
</tr>
<tr>
<td>Hadronic Light by Light Contributions to the Muon Anomalous Magnetic Moment With Near Physical Pions</td>
<td>2</td>
</tr>
<tr>
<td>The curvature of the chiral phase transition line at small values of the quark chemical potentials</td>
<td>2</td>
</tr>
<tr>
<td>Walking and conformal dynamics in many flavor QCD</td>
<td>3</td>
</tr>
<tr>
<td>Pion-pion interaction from ( N_f = 2 + 1 ) simulations using the stochastic LapH method</td>
<td>3</td>
</tr>
<tr>
<td>A status update on the ALPHA collaboration’s project to determine the Lambda-parameter in 3-flavour QCD</td>
<td>4</td>
</tr>
<tr>
<td>Algorithmic improvements for weak coupling simulations of domain wall fermions</td>
<td>4</td>
</tr>
<tr>
<td>zMobius and other recent developments on Domain Wall Fermions</td>
<td>5</td>
</tr>
<tr>
<td>Prospects and status of quark mass renormalization in three-flavour QCD</td>
<td>5</td>
</tr>
<tr>
<td>Topological observables in many-flavour QCD</td>
<td>5</td>
</tr>
<tr>
<td>On calculating disconnected-type hadronic light-by-light scattering diagrams from lattice QCD</td>
<td>6</td>
</tr>
<tr>
<td>The curvature of the crossover line in the ((T, \mu))-phase diagram of QCD</td>
<td>6</td>
</tr>
<tr>
<td>Large volume calculation of pion-pion scattering phase shifts with the stochastic LapH method on an ( N_f = 2 + 1 ) anisotropic clover lattice</td>
<td>7</td>
</tr>
<tr>
<td>K-pi scattering lengths from physical point ensembles</td>
<td>7</td>
</tr>
<tr>
<td>Fermionic twisted boundary conditions with reweighting method</td>
<td>8</td>
</tr>
<tr>
<td>SU(3) gauge theory with four degenerate fundamental fermions on the lattice</td>
<td>8</td>
</tr>
<tr>
<td>Curvature of the pseudocritical line in ((2+1))-flavor QCD with HISQ fermions</td>
<td>9</td>
</tr>
<tr>
<td>Non-perturbative renormalization of tensor bilinears in Schrodinger Functional schemes</td>
<td>9</td>
</tr>
</tbody>
</table>
Improving the volume-dependence of lattice QCD+QED simulations

The strange contribution to the anomalous magnetic moment of the muon with physical quark masses using Möbius domain wall fermions

K-pi and pi-pi scattering close to the physical pion mass

Optimizing the domain wall fermion Dirac operator using the R-Stream source-to-source compiler

Studying near conformal behavior with four light flavors and eight flavors of variable mass

Curvature of the QCD chiral pseudocritical line from analytic continuation

Scale determination for the CLS 2+1 ensembles

The mass and leptonic decay constant of rho meson at the physical point

Perturbative renormalization of $\Delta S = 2$ four-fermion operators with the chirally rotated Schrödinger functional

Phase structure of Nf=3 QCD at finite temperature and density by Wilson-Clover fermions

Probing near conformal dynamics with 4+8 and 8 flavors: running coupling and the spectrum

Finite volume hadronic vacuum polarisation at arbitrary momenta

A next generation C++ library for data parallel QCD

Resonance Parameters for the rho-meson from Lattice QCD

IR fixed points and conformal window in $SU(3)$ gauge Theories

The chirally rotated Schrödinger functional at work

Lattice calculation of the HVP contribution to the anomalous magnetic moment of muon

Many flavor approach to study the critical point in finite density QCD

A minimal model of the composite Higgs and its Goldstone dynamics

Decay constants and spectroscopy of mesons in lattice QCD using domain-wall fermions

Chiral behavior of light meson form factors in 2+1 flavor QCD with exact chiral symmetry

Direct calculation of hadronic light-by-light scattering

Many flavor approach to study the nature of chiral phase transition of two-flavor QCD

Non-perturbative renormalization of the static quark theory in a large volume

2+1 flavor QCD simulation near the physical point on a $96^4$ lattice
<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Roberge-Weiss Transition in $N_f=2$ QCD with Wilson Fermions on $N_t=6$ lattices</td>
<td>19</td>
</tr>
<tr>
<td>Study of the hadronic contributions to the running of the QED coupling</td>
<td>20</td>
</tr>
<tr>
<td>Implementation of a non-perturbative matching strategy between heavy-light currents in HQET and QCD</td>
<td>21</td>
</tr>
<tr>
<td>Hadron Spectroscopy with a low-mass composite scalar in the sextet model</td>
<td>21</td>
</tr>
<tr>
<td>QED Corrections to Hadronic Processes in Lattice QCD</td>
<td>21</td>
</tr>
<tr>
<td>Latest Results from RQCD using $2+1f$ CLS Simulations with Open Boundaries</td>
<td>22</td>
</tr>
<tr>
<td>Taste symmetry restoration in the sextet model with staggered fermions</td>
<td>22</td>
</tr>
<tr>
<td>The hadronic vacuum polarization function with $O(a)$-improved Wilson fermions - an update</td>
<td>23</td>
</tr>
<tr>
<td>Perturbative versus non-perturbative decoupling of heavy quarks</td>
<td>23</td>
</tr>
<tr>
<td>Neutral Kaon mixing beyond the Standard Model</td>
<td>23</td>
</tr>
<tr>
<td>The $N_f=2$ chiral phase transition from imaginary chemical potential with Wilson Fermions</td>
<td>24</td>
</tr>
<tr>
<td>Improved Hadronic Matrix Element Determination Using the Variational Method</td>
<td>24</td>
</tr>
<tr>
<td>Running coupling of the sextet composite Higgs model</td>
<td>25</td>
</tr>
<tr>
<td>Analytic continuation of finite density QCD with heavy quarks in the strong coupling region</td>
<td>25</td>
</tr>
<tr>
<td>Extracting the eta-prime meson mass from gluonic correlators in lattice QCD</td>
<td>26</td>
</tr>
<tr>
<td>Nonperturbative renormalization in the RI-SMOM scheme and Gribov copies for staggered bilinears</td>
<td>26</td>
</tr>
<tr>
<td>Finite volume effects in hadronic vacuum polarization</td>
<td>27</td>
</tr>
<tr>
<td>Topological feature and phase diagram of QCD at complex chemical potential</td>
<td>27</td>
</tr>
<tr>
<td>Conformal symmetry vs. chiral symmetry breaking in the SU(3) sextet model</td>
<td>27</td>
</tr>
<tr>
<td>A derivative based approach for the leading order hadronic contribution to $g-2$ of the muon</td>
<td>28</td>
</tr>
<tr>
<td>Photon mass term as an IR regularization for QCD+QED on the lattice</td>
<td>28</td>
</tr>
<tr>
<td>Nuclear Parity Violation from Lattice QCD</td>
<td>29</td>
</tr>
<tr>
<td>NPR determination of quark masses from the HISQ action</td>
<td>29</td>
</tr>
<tr>
<td>Finite-temperature phase transition of $N_f=3$ QCD with exact center symmetry</td>
<td>29</td>
</tr>
<tr>
<td>Electromagnetic effects on the light pseudoscalar mesons and determination of $m_u/m_d$</td>
<td>30</td>
</tr>
<tr>
<td>Dashen’s theorem and electromagnetic contributions to pseudoscalar meson masses</td>
<td>30</td>
</tr>
</tbody>
</table>
Leading isospin breaking correction to the hadronic vacuum polarisation

Hadron Structure from Lattice QCD

Light flavours

Kenneth G. Wilson Award for Excellence in Lattice Field Theory

Three-body observables from the lattice

Standard-model prediction for direct CP violation in K→πππ decays

Lattice input on the tau V_{us} puzzle

Magnetic properties of light nuclei and the np!d transition

Lattice study for conformal windows of SU(2) and SU(3) gauge theories with fundamental fermions

Exploring Complex-Langevin Methods for Finite-Density QCD

Renormalizability of the Schrödinger Functional

Parton Distribution Function from Hadronic Tensor

Convergent Perturbation Theory for φ^4 model on lattice

Scalar and vector form factors of D → πℓν decays with N_f = 2 + 1 + 1 Twisted fermions

Light nuclei and nucleon form factors in N_f=2+1 lattice QCD

Approaching the conformal window: systematic study of the particle spectrum in SU(2) field theory with N_f =2,4 and 6

Towards the heavy dense QCD phase diagram using Complex Langevin simulations

Nucleon transverse momentum-dependent parton distributions: Comparing Clover and Domain wall fermion results at ~300 MeV pion mass

Induced YM theory with auxiliary bosons

Nf=2+1+1 renormalisation of four-quark operators

Gradient flow and IR fixed point in SU(2) with Nf=8 flavors

The H-dibaryon in two flavor lattice QCD

Insights into the heavy dense QCD phase diagram using Complex Langevin simulations

Lattice simulations of technicolour theories with adjoint fermions and supersymmetric Yang-Mills theory

Two-nucleon scattering in multiple partial waves

Nucleon generalized form factors from lattice QCD with nearly physical quark masses

Renormalization of two-dimensional XQCD
<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing a generalized cooling procedure in the complex Langevin simulation of chiral Random Matrix Theory</td>
<td>41</td>
</tr>
<tr>
<td>The leading hadronic contribution to γ-Z mixing</td>
<td>42</td>
</tr>
<tr>
<td>Wilson Fermions with Four Fermion Interactions</td>
<td>42</td>
</tr>
<tr>
<td>Understanding the problem with logarithmic singularities in the complex Langevin method</td>
<td>43</td>
</tr>
<tr>
<td>Calculation of the decay width of decuplet baryons</td>
<td>43</td>
</tr>
<tr>
<td>Combining ordinary and topological finite volume effects for fixed topology simulations</td>
<td>43</td>
</tr>
<tr>
<td>Determining the scale in Lattice QCD</td>
<td>44</td>
</tr>
<tr>
<td>Complex Langevin in low-dimensional QCD: the good and the not-so-good</td>
<td>44</td>
</tr>
<tr>
<td>QCD spectroscopy and quark mass renormalisation in external magnetic fields with Wilson fermions</td>
<td>45</td>
</tr>
<tr>
<td>The Roper resonance from spatially large interpolation fields</td>
<td>45</td>
</tr>
<tr>
<td>Three particles in a finite volume</td>
<td>45</td>
</tr>
<tr>
<td>Magnetic properties and deconfinement</td>
<td>46</td>
</tr>
<tr>
<td>First results of baryon interactions from lattice QCD with physical masses (1) – General overview and two-nucleon forces</td>
<td>46</td>
</tr>
<tr>
<td>Effects of higher order operators on the Standard Model Higgs sector</td>
<td>46</td>
</tr>
<tr>
<td>Analysis of short distance current correlators using OPE</td>
<td>47</td>
</tr>
<tr>
<td>Hamiltonian simulation of lattice gauge theories</td>
<td>47</td>
</tr>
<tr>
<td>Pion electromagnetic form factor from full lattice QCD</td>
<td>48</td>
</tr>
<tr>
<td>Lattice study of the Higgs-Yukawa model in and beyond the Standard Model</td>
<td>48</td>
</tr>
<tr>
<td>First results of baryon interaction from lattice QCD with physical masses (2) – S=-3 and S=-4 sectors (XiXi, XiSigma, XiLambda-XiSigma channels)</td>
<td>49</td>
</tr>
<tr>
<td>Towards the continuum limit of the critical endline of finite temperature QCD</td>
<td>49</td>
</tr>
<tr>
<td>SU(3)-breaking effects and induced second-class form factors in hyperon beta decays from 2+1 flavor lattice QCD</td>
<td>49</td>
</tr>
<tr>
<td>Charmonium current-current correlators with Mobius domain-wall fermion</td>
<td>50</td>
</tr>
<tr>
<td>Real-time simulation of dissipation-driven quantum Systems</td>
<td>50</td>
</tr>
<tr>
<td>Chiral phase transition of Nf=3 and 2+1 QCD at vanishing baryon chemical potential</td>
<td>51</td>
</tr>
<tr>
<td>Non-Perturbative Gauge-Higgs Unification in Five Dimensions</td>
<td>51</td>
</tr>
<tr>
<td>Nucleon axial and tensor charges with dynamical overlap quarks</td>
<td>51</td>
</tr>
<tr>
<td>Topic</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Determining the QCD coupling from lattice vacuum polarization</td>
<td>52</td>
</tr>
<tr>
<td>Lefschetz-thimble path integral for solving the mean-field sign problem</td>
<td>52</td>
</tr>
<tr>
<td>First results of baryon interactions from lattice QCD with physical masses (3) – Strangeness S=-2 two-baryon system</td>
<td>53</td>
</tr>
<tr>
<td>Five-dimensional Gauge Theories in a Warped Background</td>
<td>53</td>
</tr>
<tr>
<td>Lattice QCD studies of baryon interactions from HAL QCD method and Luscher’s finite volume method</td>
<td>53</td>
</tr>
<tr>
<td>Thermodynamics and reference scale of SU(3) gauge theory from gradient flow on fine lattices</td>
<td>54</td>
</tr>
<tr>
<td>High statistic analysis of nucleon form factors and charges in lattice QCD</td>
<td>54</td>
</tr>
<tr>
<td>Thermal evolution of the 1-flavour Schwinger model with using Matrix Product States</td>
<td>55</td>
</tr>
<tr>
<td>Light quark masses from infrared fixed point</td>
<td>55</td>
</tr>
<tr>
<td>Nucleon-pion-state contributions in the determination of the nucleon axial charge</td>
<td>55</td>
</tr>
<tr>
<td>Tensor renormalization group analysis of CP(N-1) model in two dimensions</td>
<td>56</td>
</tr>
<tr>
<td>Lambda_c-N interaction from lattice QCD</td>
<td>56</td>
</tr>
<tr>
<td>Gravitational waves from cosmological first order phase transitions</td>
<td>57</td>
</tr>
<tr>
<td>Clover fermions in Numerical Stochastic Perturbation Theory</td>
<td>57</td>
</tr>
<tr>
<td>Polyakov loop renormalization with gradient flow</td>
<td>57</td>
</tr>
<tr>
<td>Some nucleon isovector obsesrvables from 2+1-flavor domain-wall QCD at physical mass</td>
<td>58</td>
</tr>
<tr>
<td>Approaching conformality with the Tensor Renormalization Group method</td>
<td>58</td>
</tr>
<tr>
<td>Pure SU(3) Topological Susceptibility at Finite Temperature with the Wilson Flow</td>
<td>59</td>
</tr>
<tr>
<td>Zc(3900) from coupled-channel HAL QCD approach on the lattice</td>
<td>59</td>
</tr>
<tr>
<td>Lattice QCD code set Bridge++ on arithmetic accelerators</td>
<td>59</td>
</tr>
<tr>
<td>SU(2) gauge theory with domain-wall fermions in fundamental and adjoint representations</td>
<td>60</td>
</tr>
<tr>
<td>Bosonization analysis for artificial ”atomic collapse” in graphene</td>
<td>60</td>
</tr>
<tr>
<td>A novel computation of the thermodynamics of SU(3) Yang-Mills theory</td>
<td>61</td>
</tr>
<tr>
<td>The Rho Resonance from N_f=2+1+1 Twisted Mass Lattice QCD</td>
<td>61</td>
</tr>
<tr>
<td>The Nonlinear O(3) Model with Chemical Potential in a Dual Representation</td>
<td>62</td>
</tr>
<tr>
<td>S-parameter and vector decay constant in QCD with eight fundamental fermions</td>
<td>62</td>
</tr>
<tr>
<td>Beating the sign problem in finite density lattice QCD</td>
<td>62</td>
</tr>
<tr>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Grassmann tensor renormalization group for the lattice Gross-Neveu model with finite chemical potential</td>
<td>63</td>
</tr>
<tr>
<td>Towards the QCD equation of state at the physical point using Wilson fermion</td>
<td>63</td>
</tr>
<tr>
<td>Determination of $\varepsilon_K$ using lattice QCD inputs</td>
<td>64</td>
</tr>
<tr>
<td>Towards string breaking with 2+1 dynamical fermions using the stochastic LapH-method</td>
<td>64</td>
</tr>
<tr>
<td>Study of the conformal phase of the SU(3) gauge theory with domain-wall fermions</td>
<td>65</td>
</tr>
<tr>
<td>Monte Carlo studies of dynamical compactification of extra dimensions in a model of non-perturbative string theory</td>
<td>65</td>
</tr>
<tr>
<td>Adaptive algebraic multigrid on SIMD architectures</td>
<td>65</td>
</tr>
<tr>
<td>Grid: A next generation C++ library for data parallel QCD</td>
<td>66</td>
</tr>
<tr>
<td>Exploring free-form smearing for bottomonium and B meson spectroscopy</td>
<td>67</td>
</tr>
<tr>
<td>Mass anomalous dimension of SU2 with Nf=8 using the spectral density method</td>
<td>67</td>
</tr>
<tr>
<td>Performance of Maxwell GPUs and Optimization of Non-Perturbative Renormalization codes</td>
<td>67</td>
</tr>
<tr>
<td>Update on the Heavy-Meson Spectrum Tests of the Oktay–Kronfeld Action</td>
<td>68</td>
</tr>
<tr>
<td>calculation of strange and light quark condensate using improved staggered fermions and overlap fermions</td>
<td>68</td>
</tr>
<tr>
<td>Non-perturbative Renormalization with RI-MOM scheme for Bilinear Operators on the Fine Lattice</td>
<td>69</td>
</tr>
<tr>
<td>Isospin splitting in Wilson chiral perturbation theory for twisted-mass lattice-QCD with three non-degenerate quark flavours</td>
<td>69</td>
</tr>
<tr>
<td>Investigating some technical improvements to glueball calculations.</td>
<td>69</td>
</tr>
<tr>
<td>Heavy-heavy current improvement for calculating $B^- \rightarrow D^{(*)}(\ell)\nu\overline{\nu}$ semi-leptonic form factors with Oktay-Kronfeld quarks</td>
<td>70</td>
</tr>
<tr>
<td>Instantaneous Stochastic Perturbation Theory and Gradient flow in $\phi^4$ theory</td>
<td>70</td>
</tr>
<tr>
<td>Determination of $f_K/f_{pi}$ from staggered Nf=2+1+1 ensembles</td>
<td>70</td>
</tr>
<tr>
<td>Overlap fermions on GPUs</td>
<td>71</td>
</tr>
<tr>
<td>Proposal for the Quantum Simulation of the CP(2) Model on Optical Lattices</td>
<td>71</td>
</tr>
<tr>
<td>The step scaling function of the SU(3) 2 flavor sextet model with Wilson fermions</td>
<td>71</td>
</tr>
<tr>
<td>Precision study of critical slowing down in lattice simulations of the CP$^\Lambda$[N-1] model</td>
<td>72</td>
</tr>
<tr>
<td>Stochastic calculation of the QCD Dirac operator spectrum with Mobius domain-wall fermion</td>
<td>72</td>
</tr>
<tr>
<td>An application of the hybrid Monte Carlo algorithm for realized stochastic volatility model</td>
<td>72</td>
</tr>
</tbody>
</table>
The static three-quark potential of various quark configurations .............................. 73
Strong coupling expansion of the generalized t-V model in one dimension .................. 73
Lattice QCD study of the I=0 scalar channel using four-quark operators ...................... 74
Mass and Axial current renormalization in the Schroedinger functional scheme for the RG-improved gauge and the stout smeared $O(\alpha)$-improved Wilson quark actions. .......................... 74
The one-loop analysis of the beta-function in the Schroedinger Functional for Moebius Domain Wall Fermions ................................................................. 75
Quark Spin in Proton from Anomalous Ward Identity .................................................. 75
A new method to calculate the Dirac operator spectral density .................................... 76
Multiple right-hand side setup for the DD-\alpha AMG .................................................. 76
Study of high density phase transition in lattice QCD with canonical approach .............. 76
Applications of the Feynman–Hellmann theorem in hadron structure ............................ 77
X(3872) and Y(4140) using diquark-antidiquark operators with lattice QCD .................. 77
Exotic Quantum Critical Points with Staggered Fermions .......................................... 78
Neutral B meson mixings and B meson decay constants in the infinite b quark mass limit with domain-wall light quarks ................................................................. 78
Template Composite Dark Matter : SU(2) gauge theory with Nf=2 ............................... 79
Distribution of the k-th smallest Dirac operator eigenvalue : an update ......................... 79
Exploring finite density QCD phase transition with canonical approach - Power of multiple precision computation - ................................................................. 80
Gluon saturation and gluon densities ........................................................................... 80
Mass spectrum of mesons containing charm quarks - continuum limit results from twisted mass fermions ................................................................. 80
Decay constants $f_B$ and $f_{B_s}$ from HISQ simulations .............................................. 81
Stealth Dark Matter on the lattice .............................................................................. 81
Neutral $B$-meson and $D$-meson mixing bag parameters from $2 + 1$ flavor lattice QCD .................. 82
Nucleon-Sigma-Terms from Lattice QCD ................................................................. 82
Validity range of canonical approach to finite density QCD ....................................... 83
Ground state charmed meson spectra for $N_f = 2 + 1 + 1$ ........................................... 83
The microscopic Twisted Mass Dirac spectrum and the spectral determination of the LECs of Wilson $\chi$-$PT$ ................................................................. 83
Lattice QCD and Axion Cosmology ........................................................................... 84
Exploring possibly existing qq-anti-b-anti-b tetraquark states with qq = ud, ss, cc .................. 84
A lattice study of the nucleon quark content at the physical point ................................. 85
Beyond the Standard model matrix elements with the gradient flow .............................. 85
Chiral Symmetry Breaking for Bosonic Partition Functions ............................................ 85
Calculation of high-order cumulants with canonical ensemble method in lattice QCD .......................... 86
Semileptonic B-meson decay phenomenology with lattice QCD ..................................... 86
Phenomenology with Lattice NRQCD b Quarks ............................................................... 87
Computation of correlation matrices for tetraquark candidates with $J^P = 0^+$ and flavor structure $q_1q_2q_3q_4$ ......................................................... 87
Neutron EDM from quark chromoEDM ........................................................................... 88
Proton spin decomposition with overlap fermion ............................................................. 88
Aspects of topological actions on the lattice ................................................................. 88
Boundary effects on the chiral condensate from Lattice QCD ........................................ 89
Pion spectrum for the 2-flavor staggered Wilson fermion ................................................. 89
NLO and NNLO Low Energy Constants for SU(2) Chiral Perturbation Theory ................ 89
Nucleon charges, form-factors and neutron EDM .......................................................... 90
Charm Physics at the physical point ................................................................................. 90
A Multigrid Based Eigensolver for the Hermitian Wilson Dirac Operator ....................... 90
Diagrammatic Monte Carlo simulations of staggered fermions at finite coupling .............. 91
Flavor Filtered Fermions ................................................................................................. 91
The electric dipole moment of the neutron from N_f=2+1+1 twisted mass fermions ....... 91
Multigrid-accelerated Low-Mode Averaging ................................................................. 92
Neutral D-Meson Mixing near the Charm Mass ............................................................. 93
NLO and NNLO Low Energy Constants for SU(3) Chiral Perturbation Theory .............. 93
Lattice simulation of the SU(2)-chiral model at zero and non-zero pion density ............... 93
Heavy and dense QCD from an effective lattice theory .................................................. 94
Eigenspectrum calculation of the non-Hermitian O(a)-improved Wilson-Dirac operator using the Sakurai-Sugiura method .................................................. 94
Neutron-antineutron oscillation matrix elements with domain wall fermions at the physical point ........................................................................................................... 95
Evidence for a new SU(4) symmetry with J=2 mesons .................................................. 95
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>D meson semileptonic decays from lattice QCD with chiral fermions</td>
<td>95</td>
</tr>
<tr>
<td>Charged particles in QED with C* boundary conditions</td>
<td>96</td>
</tr>
<tr>
<td>Analytic computations of an effective lattice theory for heavy quarks</td>
<td>96</td>
</tr>
<tr>
<td>Accelerating deflation of eigenvalues for fermion matrix inversions on GPUs</td>
<td>97</td>
</tr>
<tr>
<td>D meson semileptonic form factors at zero momentum transfer in 2+1+1 flavor lattice QCD</td>
<td>97</td>
</tr>
<tr>
<td>Testing the Witten-Veneziano Formula on the Lattice</td>
<td>98</td>
</tr>
<tr>
<td>Electromagnetic structure of charmed baryons - extended to spin-3/2</td>
<td>98</td>
</tr>
<tr>
<td>What is QFT? Resurgent trans-series, Lefschetz thimbles, and new exact saddles</td>
<td>99</td>
</tr>
<tr>
<td>Lattice’s Bright, Dark and Safe side</td>
<td>99</td>
</tr>
<tr>
<td>Physics at the Belle II experiment and Lattice QCD</td>
<td>100</td>
</tr>
<tr>
<td>Progress and prospects for heavy flavour physics on the lattice</td>
<td>100</td>
</tr>
<tr>
<td>(Dimensional) twisted reduction in large N gauge theories</td>
<td>101</td>
</tr>
<tr>
<td>Two-Color Lattice QCD with Non-zero Chiral Chemical Potential</td>
<td>101</td>
</tr>
<tr>
<td>Complex Langevin simulation in condensed matter physics</td>
<td>101</td>
</tr>
<tr>
<td>Kaon semileptonic form factors as functions of the momentum transfer with Nf=2+1+1 Twisted Mass fermions</td>
<td>102</td>
</tr>
<tr>
<td>Lattice NRQCD study of quarkonium at non-zero temperature</td>
<td>102</td>
</tr>
<tr>
<td>Chiral symmetry breaking, instantons, and monopoles</td>
<td>102</td>
</tr>
<tr>
<td>Long-distance contributions to the rare kaon decay K+ -&gt; pi+ l+ l-</td>
<td>103</td>
</tr>
<tr>
<td>Charmonia and bottomonia at finite temperature on large quenched lattice</td>
<td>103</td>
</tr>
<tr>
<td>Large N meson propagators from twisted space-time reduced model</td>
<td>104</td>
</tr>
<tr>
<td>Lattice simulation of $QC_2D$ with $N_f = 2$ at non-zero baryon density</td>
<td>104</td>
</tr>
<tr>
<td>Classifying the phases of gauge theories by spectral density of probing chiral quarks</td>
<td>104</td>
</tr>
<tr>
<td>Domain-wall/overlap fermion and topological insulators</td>
<td>105</td>
</tr>
<tr>
<td>Topology and glueballs in $SU(7)$ Yang-Mills with open boundary conditions</td>
<td>105</td>
</tr>
<tr>
<td>Dirac spectrum representation of Polyakov loop fluctuations in lattice QCD</td>
<td>106</td>
</tr>
<tr>
<td>Long-distance contributions to the rare kaon decay K+ -&gt; pi+ nu nu-ba</td>
<td>106</td>
</tr>
<tr>
<td>Transverse and longitudinal spectral functions of charmonia at finite temperature with maximum entropy method</td>
<td>107</td>
</tr>
<tr>
<td>Topic</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Cluster expansions and chiral symmetry at large density in 2-color QCD</td>
<td>107</td>
</tr>
<tr>
<td>Chiral Magnetic Conductivity in an interacting lattice model of a parity-breaking Weyl semimetal</td>
<td>107</td>
</tr>
<tr>
<td>Polyakov loop correlators and cyclic Wilson loop from lattice QCD</td>
<td>108</td>
</tr>
<tr>
<td>SU(4) symmetry of hadrons upon quasi-zero Dirac mode elimination</td>
<td>108</td>
</tr>
<tr>
<td>Thimble regularization at work besides toy models: from Random Matrix Theory to Gauge Theories</td>
<td>109</td>
</tr>
<tr>
<td>Hybrid Monte Carlo simulations of graphene in external magnetic field</td>
<td>109</td>
</tr>
<tr>
<td>Diagrammatic Monte-Carlo algorithms for large-N quantum field theories from Schwinger-Dyson equations</td>
<td>110</td>
</tr>
<tr>
<td>Computing the long-distance contributions to $\epsilon_K$</td>
<td>110</td>
</tr>
<tr>
<td>Thimble regularization at work for Gauge Theories: from toy models onwards</td>
<td>110</td>
</tr>
<tr>
<td>Numerical study of complex instantons in the Gross-Witten $U(N)$ matrix model</td>
<td>111</td>
</tr>
<tr>
<td>Numerical simulations of graphene conductivity with realistic inter-electron potential</td>
<td>111</td>
</tr>
<tr>
<td>Static quark-antiquark pair free energy and screening masses: continuum results at the QCD physical point</td>
<td>112</td>
</tr>
<tr>
<td>Emerging lattice approach to K-Unitarity Triangle</td>
<td>112</td>
</tr>
<tr>
<td>Gauge fixing and the gluon propagator in renormalizable $\xi$-gauge</td>
<td>112</td>
</tr>
<tr>
<td>Confinement/deconfinement transition temperature from the Polyakov loop potential and gauge-invariant gluon mass</td>
<td>113</td>
</tr>
<tr>
<td>Application of the Lefschetz thimble formulation to the (0+1) dimensional Thirring model at finite density</td>
<td>113</td>
</tr>
<tr>
<td>Lattice QCD calculations of nucleon transverse momentum-dependent parton distributions (TMDs) at 170 MeV pion mass</td>
<td>114</td>
</tr>
<tr>
<td>Non-Gaussianity of the topological charge distribution in SU(3) Yang-Mills theory</td>
<td>114</td>
</tr>
<tr>
<td>Matrix Geometry and Coherent States</td>
<td>115</td>
</tr>
<tr>
<td>Lattice gauge theory treatment of strongly correlated Dirac semimetals</td>
<td>115</td>
</tr>
<tr>
<td>A stochastic approach to the reconstruction of spectral functions in lattice QCD</td>
<td>115</td>
</tr>
<tr>
<td>Lattice Conformal Field Theory on the Reimann Sphere</td>
<td>116</td>
</tr>
<tr>
<td>QUDA features, scaling and solvers</td>
<td>116</td>
</tr>
<tr>
<td>Study of non-perturbative contributions to surface operator within lattice gauge theory</td>
<td>117</td>
</tr>
<tr>
<td>Preweighting method in Monte-Carlo sampling with complex action</td>
<td>117</td>
</tr>
<tr>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Improving our determinations of the decay constant $f_B$ and the $B \to \pi\ell\nu$ semi-leptonic form factors using physical light quarks</td>
<td>118</td>
</tr>
<tr>
<td>The density of states approach at finite chemical potential: a numerical study of the Bose gas</td>
<td>118</td>
</tr>
<tr>
<td>Hadronic form factors for rare semi-leptonic $B$ decays</td>
<td>118</td>
</tr>
<tr>
<td>Optimization of Lattice QCD with CG and multi-shift CG on Intel Xeon Phi Coprocessor</td>
<td>119</td>
</tr>
<tr>
<td>Abelian monopole or non-Abelian monopole responsible for quark confinement</td>
<td>119</td>
</tr>
<tr>
<td>Thermal dilepton rates and electrical conductivity of the QGP</td>
<td>120</td>
</tr>
<tr>
<td>Scalar field theory on a 2-sphere using quantum finite element method (QFEM)</td>
<td>120</td>
</tr>
<tr>
<td>Calculation of free baryon spectral densities at finite temperature</td>
<td>121</td>
</tr>
<tr>
<td>Gluon propagators near the phase transition in SU(2) gluodynamics</td>
<td>121</td>
</tr>
<tr>
<td>Accelerating twisted mass LQCD with QPhiX</td>
<td>121</td>
</tr>
<tr>
<td>Spherical Finite Elements for Lattice Radial Quantization</td>
<td>122</td>
</tr>
<tr>
<td>$B - B$ mixing with domain-wall light quarks and relativistic $b$-quarks</td>
<td>122</td>
</tr>
<tr>
<td>Solving the complex action problem of the finite density $Z_3$ spin model with the density of states approach using FFA</td>
<td>123</td>
</tr>
<tr>
<td>Encoding field theories into gravities</td>
<td>123</td>
</tr>
<tr>
<td>Anatomy of SU(3) flux tubes at finite temperature</td>
<td>123</td>
</tr>
<tr>
<td>An implementation of hybrid parallel CUDA code for the hyperonic nuclear forces</td>
<td>124</td>
</tr>
<tr>
<td>Nucleons and parity doubling across the deconfinement transition</td>
<td>124</td>
</tr>
<tr>
<td>Radial distributions of the axial density and the $B^*\rightarrow B \pi$ coupling</td>
<td>125</td>
</tr>
<tr>
<td>Density of states approach with FFA for an effective Polyakov loop model at finite density</td>
<td>125</td>
</tr>
<tr>
<td>The three-quark potential and perfect Abelian dominance in SU(3) lattice QCD</td>
<td>126</td>
</tr>
<tr>
<td>Summary of Super Doubler Approach on Exact Lattice Supersymmetry</td>
<td>126</td>
</tr>
<tr>
<td>Early Performance Evaluation of Lattice QCD on POWER+GPU Cluster</td>
<td>126</td>
</tr>
<tr>
<td>Study of entropy production in Yang-Mills theory with use of Husimi function</td>
<td>127</td>
</tr>
<tr>
<td>Dual representation for massless fermions theory with chemical potential and U(1) gauge fields</td>
<td>127</td>
</tr>
<tr>
<td>Connected contribution to hadron correlation functions</td>
<td>128</td>
</tr>
<tr>
<td>Witten index and phase diagram of compactified N=1 supersymmetric Yang-Mills theory on the lattice</td>
<td>128</td>
</tr>
<tr>
<td>Effective action for the Abelian Higgs model for a gauge-invariant implementation on optical lattices</td>
<td>128</td>
</tr>
</tbody>
</table>
On the axial U(1) symmetry at finite temperature ........................................ 129
Lattice gradient flow with tree-level $O(a^4)$ improvement in pure Yang-Mills theory ........................................ 129
Hagedorn spectrum and equation of state of Yang-Mills theories ................. 130
Disconnected contribution to hadron correlation functions .......................... 130
Renormalization constants of the lattice energy momentum tensor using the gradient flow ........................................ 130
Supermultiplets of the N=1 supersymmetric Yang-Mills theory in the continuum limit ........................................ 131
Schwinger Model Mass Anomalous Dimension .......................................... 131
Study of the U(1)A symmetry restoration in two-flavor QCD at finite temperature with reweighed overlap fermions ........................................ 132
Higher order net baryon number cumulants in the strong coupling lattice QCD ........................................ 132
The $U_A(1)$ anomaly in high temperature QCD with chiral fermions on the lattice ........................................ 133
Canonical simulations of supersymmetric SU(N) Yang-Mills quantum mechanics ........................................ 133
Disconnected quark loop contributions to nucleon observables using $N_f = 2$ twisted clover fermions at a physical value of the light quark mass ........................................ 134
Study of the continuum limit of the Schwinger model using Wilson’s lattice formulation ........................................ 134
(2+1)-flavor QCD Thermodynamics from the Gradient Flow .......................... 134
Polyakov line actions from SU(3) lattice gauge theory with dynamical fermions: first results via relative weights ........................................ 135
Effective Polyakov loop models for QCD-like theories at finite chemical potential ........................................ 135
Background field method in the gradient flow .......................................... 136
New results from lattice N=4 supersymmetric Yang–Mills ........................................ 136
Critical flavour number of the Thirring model in three dimensions ............... 136
Thermal modification of mesons and restoration of broken symmetries from spatial correlation functions with HISQ ........................................ 137
Exploring the effects of open boundary conditions on baryonic observables ........................................ 137
Improving the lattice axial vector current .......................................... 138
Footprint of non-decoupling in chiral phase transition .................................. 138
Generalized Gradient Flow Equation and Its Applications .......................... 138
Large-scale computation of the exponentially expanding universe in a simplified Lorentzian IIB matrix model ........................................ 139
G(2)-QCD at finite temperature and density .......................................... 139
Recent progress on chiral symmetry breaking in QCD

Author: Leonardo Giusti$^1$

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I review recent progress achieved on the lattice in the understanding of chiral symmetry breaking in QCD. Emphasis is given to recent computations of the spectral density of the Dirac operator and of the topological susceptibility.

Determining the order of chiral phase transition in QCD from conformal bootstrap

Author: YU NAKAYAMA$^1$

$^1$ Caltech

There has been a longstanding debate if the chiral phase transition in two-flavor massless QCD is the first order or the second order. The previous arguments based on epsilon expansions, large N expansions, functional renormalization group, and Monte-Carlo simulations had been all inconclusive with shortcomings. If it were the second order phase transition, there should exist a corresponding three-dimensional conformal field theory which describes the critical phenomenon. The recent development in conformal bootstrap enables us to directly study the (non-)existence of conformal fixed points in a non-perturbative manner.

In this talk, I review the conformal bootstrap method and its application to this problem. Our conclusion is that the corresponding conformal fixed point should exist and the phase transition will be the second order if the U(1) chiral anomaly is effectively restored. This means that the original 1-loop prediction by Pisarski and Wilczek would be incorrect. We further provide the most precise prediction of the critical exponent there. We believe future numerical simulations will confirm our prediction.

Numerical evaluation of QED contribution to lepton g-2

Author: Tatsumi Aoyama$^1$

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The anomalous magnetic moment (g-2) of the electron has played the central role in testing the validity of quantum electrodynamics (QED) as well as the standard model of particle physics. The test has been further improved, which was made possible by the complete evaluation of the tenth-order term in the perturbation theory of QED, together with the latest measurement of the electron g-2 by the Harvard group that has reached the precision of 0.24 ppb. In this talk we will present the numerical approach to the evaluation of QED contribution to lepton g-2 up to the recent developments.
Plenary Session / 279

Lattice QCD moments - $g - 2$ and NEDM -

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There has been much progress in studies of the physics of low energy, precision observables in the flavor neutral sector using Lattice QCD, especially on the lepton anomalous magnetic moments ($g - 2$) and nucleon electric dipole moments. The current status of these studies is reviewed, and remaining challenges and new ideas are discussed.

Hadron Structure / 92

Hadronic Light by Light Contributions to the Muon Anomalous Magnetic Moment With Near Physical Pions

Authors: Christoph Lehner; Luchang Jin; Masashi Hayakawa; Norman Christ; Taku Izubuchi; Tom Blum

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The current measurement of muonic $g-2$ disagrees with the theoretical calculation by about 3 standard deviations. Hadronic vacuum polarization (HVP) and hadronic light by light (HLbL) are the two types of processes that contribute most to the theoretical uncertainty. The current value for HLbL is still given by a model. In this talk, I will describe results from a first-principles lattice calculation with a $171 \text{MeV}$ pion in a box of $4.6 \text{ fm}$ extent. Our current numerical strategies, including noise reduction techniques, evaluating the HLbL amplitude at zero external momentum transfer, and important remaining challenges, in particular those associated with finite volume effects, will be discussed.

Nonzero Temperature and Density / 248

The curvature of the chiral phase transition line at small values of the quark chemical potentials

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The QCD chiral phase transition for small values of baryon chemical potentials is expected to be second-order and the dependence of its transition temperature on the chemical potentials is thus controlled by the dependence of $O(N)$ scaling functions on the reduced temperature variables. Though the transition is merely a crossover at physical quark mass, the dependence of the chiral phase transition temperature is nevertheless of interest as it could be related to the freeze-out curve that is obtained from an analysis of hadron multiplicities in heavy-ion collisions.

In this talk we will report on our ongoing work on the leading-order dependence of the chiral phase transition temperature as a function of the light and strange quark chemical potentials i.e. the curvature of the chiral phase transition temperature with respect to the light and the strange chemical potentials. We have performed simulations using the Highly Improved Staggered Quark (HISQ) action on lattices with temporal extent $N_t = 6$ with two degenerate light quarks and a strange quark. The strange quark mass was chosen to be fixed to its physical value and the light quark mass was adjusted in order to have five values of the pseudo-Goldstone pion mass ranging from 160 MeV to about 80 MeV in the continuum limit. The comparison of the resulting curvatures from the current study with those from previous investigations will also be discussed.

This study is on behalf of the BNL-Bielefeld-CCNU collaboration.

**Physics Beyond the Standard Model / 184**

**Walking and conformal dynamics in many flavor QCD**

**Authors:** Akihiro Shibata¹; Ed Bennett²; Enrico Rinaldi³; Hiroshi Ohki³; Kei-ichi Nagai³; Kohtaroh Miura³; Koichi Yamawaki³; Masafumi Kurachi³; Takeshi Yamazaki³; Tatsushi Aoyama³; Toshihide Maskawa³; Yasumichi Aoki³

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In the search for a realistic walking technicolor model, QCD with many flavors is an attractive candidate. From the series of studies by the LatKMI collaboration, we present updated results of the scaling properties of various hadron spectra, including the (pseudo)scalar, vector, and baryon channels, for $N_f=8$ QCD with the HISQ action. By comparing these with $N_f=12$ QCD, which has properties consistent with conformality, possible signals of walking dynamics will be discussed.

**Hadron Spectroscopy and Interactions / 211**

**Pion-pion interaction from $N_f = 2+1$ simulations using the stochastic LapH method**

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We present results on pion-pion scattering in the isovector channel from N_f = 2+1 CLS simulations with open temporal boundary conditions and m_\pi = 280 MeV. The required correlation functions are computed using the stochastic LapH method that facilitates large-volume calculations in order to maintain m_\pi L > 4. Mapping out the \rho resonance structure is a necessary step towards the extraction of the timelike pion form factor.

Standard Model Parameters and Renormalization / 226

A status update on the ALPHA collaboration’s project to determine the Lambda-parameter in 3-flavour QCD

Authors: Alberto Ramos1; Mattia Dalla Brida2; Patrick Fritzsch1; Rainer Sommer2; Stefan Sint1; Tomasz Korzec5

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The ALPHA collaboration has set itself the goal to determine alpha_s(m_Z) with a total error substantially below the percent level. A further step towards this goal can be taken by combining results from the recent simulations of 2+1 flavour QCD by the CLS initiative with a number of tools developed over the years: renormalized couplings in finite volume schemes, recursive finite size techniques, two-loop renormalized perturbation theory and the (improved) gradient flow on the lattice. I will sketch the strategy, which involves both the standard SF coupling in the high energy regime and a gradient flow coupling at low energies. This implies the need for matching both schemes at an intermediate switching scale. Our results for the scale evolution at high energies allow for a well-controlled continuum limit and thus yield the Nf=3 Lambda-parameter in units of this switching scale. Simulations at lower energy scales are underway. I will present first results for the scale evolution of a gradient flow coupling with SF boundary conditions.

Algorithms and Machines / 157

Algorithmic improvements for weak coupling simulations of domain wall fermions

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We discuss algorithmic improvements being used in the evolution of new 2+1+1 flavor lattices by the RBC/UKQCD collaboration. A technique similar to Hasenbusch mass splitting and suggested previously by Brower, Neff, and Orginos allows the light quark action to be split into multiple parts
with different values of $L_s$, the size of the fifth dimension. This allows us to reduce chiral symmetry breaking by making $L_s$ large while most inversions are actually done at a cheaper, smaller value of $L_s$.

**Algorithms and Machines / 192**

**zMobius and other recent developments on Domain Wall Fermions**

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Recent advances in hardware, combined with various deflation techniques has made it crucial to optimize not only for solver performances, but also for memory and disk footprint to keep the overall efficiency high. Here we report on advances in Domain Wall Fermion formalism (DWF), such as zMobius which achieves a good approximation to the scaled Shamir DWF with smaller extent in 5th dimension, and delayed deflation technique which eliminates the need for the source projection by using predetermined approximation for the inverse.

**Standard Model Parameters and Renormalization / 141**

**Prospects and status of quark mass renormalization in three-flavour QCD**

**Authors:** Alberto Ramos$^1$; Carlos Pena$^2$; David Preti$^3$; Isabel Campos$^4$; Patrick Fritzsch$^2$; Tassos Vladikas$^5$

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We present the current status of a revised strategy to compute the running of renormalized quark masses in QCD with three flavours of massless O(a) improved Wilson quarks. The strategy employed uses the standard finite-size scaling method in the Schroedinger functional and accommodates for the non-perturbative scheme-switch which becomes necessary at intermediate renormalized couplings as discussed in [1411.7648].

**Physics Beyond the Standard Model / 243**

**Topological observables in many-flavour QCD**
**Authors:** Akihiro Shibata\(^1\); Ed Bennett\(^2\); Enrico Rinaldi\(^3\); Hiroshi Ohki\(^4\); Kei-ichi Nagai\(^5\); Kohtaroh Miura\(^6\); Koichi Yamawaki\(^7\); Masafumi Kurachi\(^7\); Takeshi Yamazaki\(^8\); Tatsumi Aoyama\(^8\); Toshihide Maskawa\(^5\); Yasumichi Aoki\(^5\)

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SU(3) gauge theory with eight massless flavours is believed to be walking, while the corresponding twelve- and four-flavour appear IR-conformal and confining respectively. Looking at the simulations performed by the LatKMI collaboration of these theories, we use the topological susceptibility as an additional probe of the IR dynamics. By drawing a comparison with SU(3) pure gauge theory, we see a dynamical quenching effect emerge at larger number of flavours, which is suggestive of emerging near-conformal and conformal behaviour.

**Hadron Structure / 178**

**On calculating disconnected-type hadronic light-by-light scattering diagrams from lattice QCD**

**Author:** Masashi Hayakawa\(^1\)

**Co-authors:** Christoph Lehner\(^2\); Luchang Jin\(^3\); Norman Christ\(^3\); Taku Izubuchi\(^4\); Thomas Blum\(^5\)

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The first-principles calculation of the hadronic light-by-light scattering (HLbL) contribution is the most critical issue in the theory of the muon $g - 2$ to confront the standard model prediction with the more accurate experimental result to be provided in the next five years. The feasibility of the lattice QCD computation of the HLbL contribution has been demonstrated for the “connected diagram” where four electromagnetic (EM) vertices appear on a single quark loop. In this talk, we focus on “disconnected diagrams” where the four EM vertices are distributed over more than one quark loop. We note that any method to calculate the disconnected diagrams requires subtraction of unwanted contributions which may affect its feasibility. We present an example of the method with a concrete realization for such a subtraction.

**Nonzero Temperature and Density / 269**

**The curvature of the crossover line in the (T, mu)-phase diagram of QCD**
Author: Jana Guenther¹

Co-authors: Claudia Ratti ²; Kalman K. Szabo ³; Rene Bellwied ²; Sandor D. Katz ⁴; Szabolcs Borsányi ⁵; Zoltan Fodor ⁶

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An efficient way to study the QCD phase diagram at small finite density is to extrapolate thermodynamical observables from imaginary chemical potential. The phase diagram features a crossover line starting from the transition temperature already determined at zero chemical potential. In this talk we focus on the curvature of this line at \( \mu = 0 \). We present the extrapolation of the crossover temperature based on three observables at several lattice spacings. The simulations were performed at zero and at moderate values of the imaginary chemical potential, always in the strangeness neutral point. We used the Symanzik-improved gauge action with four times stout smeared staggered fermions.

Hadron Spectroscopy and Interactions / 304

Large volume calculation of pion-pion scattering phase shifts with the stochastic LapH method on an \( N_f = 2 + 1 \) anisotropic clover lattice

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Results for pion-pion scattering phase shifts using the stochastic LapH method on a single \( N_f = 2 + 1 \) anisotropic clover lattice with \( m_\pi \equiv 240 \text{MeV} \) and \( L \equiv 3.8 \text{fm} \) will be presented. In particular, for \( I = 1 \) this large volume enables good resolution of the \( \rho \) resonance shape. Prospects for the other isospin channels will also be discussed.

Hadron Spectroscopy and Interactions / 109

K-pi scattering lengths from physical point ensembles

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I will present preliminary results on K-pi scattering lengths in both \( I=3/2 \) and \( I=1/2 \) channels obtained by the RBC-UKQCD collaboration. The continuum results are obtained using two of our Moebius
domain wall fermion ensembles - $48^3 \times 96$ and $64^3 \times 128$ - with physical quark masses. I will demonstrate how the large finite time extent effects which are present with such light quark masses can be controlled.

**Algorithms and Machines / 100**

**Fermionic twisted boundary conditions with reweighting method**

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*Co-authors:* Claudio Pica; Martin Hansen

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Imposing twisted boundary conditions on the fermion fields is a procedure extensively used when evaluating, for example, form factors on the lattice. Twisting is usually performed for one flavour and only in the valence, and this causes a breaking of unitarity.

In this work we explore the possibility to restore the unitarity through the reweighting method. We evaluate the change in the fermion determinant with different boundary conditions and include that in the expectation values, avoiding in this way the cost of generating new configurations for each choice of the twisting angle, theta.

As expected the effect of the reweighting is negligible in the case of large volumes but it is important when the volumes are small and the twisting angles are large. In particular we find a measurable effect for the plaquette and the pion correlation function in the case of theta=$\pi/2$ in a volume $16\times8^3$, and we found a systematic upward shift in the pion dispersion relation.

**Physics Beyond the Standard Model / 98**

**SU(3) gauge theory with four degenerate fundamental fermions on the lattice**

*Authors:* Akihiro Shibata; Ed Bennett; Enrico Rinaldi; Hiroshi Ohki; Kohtaroh Miura; Koichi Yamawaki; Masafumi Kurachi; Takeshi Yamazaki; Tatsumi Aoyama; Toshihide Maskawa; Yasumichi Aoki; kei-ichi Nagai

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LatKMI Collaboration has been studying SU(3) gauge theories with 4, 8, 12 and 16 fundamental fermions by using HISQ action on the lattice. This talk is dedicated to show results of $N_f=4$ simulations. We first show the $m_{\rho}/f_{\pi}$ ratio, from which we see $N_f=4$ SU(3) gauge theory is quite similar to the actual QCD. Then, we'll show preliminary results of flavor-singlet scalar bound state and give some discussions.
Nonzero Temperature and Density / 133

Curvature of the pseudocritical line in (2+1)-flavor QCD with HISQ fermions

Authors: Alessandro Papa\(^1\); Leonardo Cosmai\(^2\); Paolo Cea\(^3\)

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We study QCD with (2 + 1) HISQ fermions at nonzero temperature and nonzero imaginary baryon chemical potential. Monte Carlo simulations are performed using the MILC code along the line of constant physics with a light to strange mass ratio of \(m_l/m_s=1/20\) on lattices up to \(48^3\times12\) to check for finite cutoff effects. We determine the curvature of the pseudocritical line extrapolated to the continuum limit.

Standard Model Parameters and Renormalization / 138

Non-perturbative renormalization of tensor bilinears in Schrodinger Functional schemes

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We present preliminary results for the non-perturbative renormalization of the tensor current in QCD for \(N_f = 0, 2\), as well as an ongoing extension to \(N_f = 2 + 1\). The renormalization group running is computed in the continuum limit for a wide range of scales, using various Schrodinger Functional (SF) schemes and finite volume recursive techniques. In all these schemes, we have also computed the matching factor to MSbar and RI-MOM, which allows for a NLO matching to the RGI operator at high energies. An example application of the results is the renormalization and matching of the tensor currents entering the effective Hamiltonian for \(b \rightarrow s\) transitions.

Hadron Structure / 116

Improving the volume-dependence of lattice QCD+QED simulations

Authors: Christoph Lehner\(^1\); Luchang Jin\(^2\); Taku Izubuchi\(^3\)

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We explore methods to improve the volume-dependence of lattice QCD+QED simulations. Applications to QED mass-splittings, QED corrections to decay constants, and the computation of the hadronic light-by-light contribution to the muon anomalous magnetic moment are discussed.

Hadron Structure / 140

The strange contribution to the anomalous magnetic moment of the muon with physical quark masses using Möbius domain wall fermions

Author: Matt Spraggs¹

¹ University of Southampton

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We present preliminary results for the strange leading-order hadronic contribution to the anomalous magnetic moment of the muon using RBC/UKQCD physical point domain wall fermions ensembles. We discuss various analysis strategies in order to constrain the systematic uncertainty in the final result.

Hadron Spectroscopy and Interactions / 131

K-pi and pi-pi scattering close to the physical pion mass

Author: Gordon Donald¹

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Results will be presented for pi-pi and K-pi scattering using lattice configurations on which the pion mass is 150 MeV. In this study the focus is on the kinematic region around the rho (for pi-pi scattering) and K⁺ (for K-pi) resonances. Different lattice volumes and moving frames are used to obtain the spectrum for a range of centre of mass energies, which allows the energy dependence of the scattering phase shift to be extracted.

Algorithms and Machines / 177

Optimizing the domain wall fermion Dirac operator using the R-Stream source-to-source compiler

Author: Meifeng Lin¹

¹ Brookhaven National Laboratory

Co-authors: Chulwoo Jung ¹; Eric Papenhausen ²; M. Harper Langston ³; Richard Lethin ³; Taku Izubuchi ⁴
The application of the Dirac operator on a spinor field, the Dslash operation, is the most computationally intensive part of the lattice QCD simulations. It is often the key kernel to optimize to achieve maximum performance on various platforms. Here we report on a project to optimize the domain wall fermion Dirac operator in Columbia Physics System (CPS) using the R-Stream source-to-source compiler. Our initial target platform is the PC clusters. We discuss the optimization strategies involved before and after the automatic code generation with R-Stream and present some preliminary benchmark results.

**Physics Beyond the Standard Model / 124**

**Studying near conformal behavior with four light flavors and eight flavors of variable mass.**

**Author:** Claudio Rebbi

**Co-authors:** Anna Hasenfratz; Evan Weinberg; Oliver Witzel; Richard Brower

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After a brief review of the motivation for studying an SU(3) theory with four light flavors and eight flavors of variable mass I will discuss the methodologies we have used to investigate the properties of the system. I will then illustrate some recent results. More detailed results will be given in another talk. We will also illustrate some results of a study of the SU(3) theory with eight staggered flavors carried out by the LSD collaboration.

**Nonzero Temperature and Density / 264**

**Curvature of the QCD chiral pseudocritical line from analytic continuation**

**Authors:** Claudio Bonati; Francesco Negro; Francesco Sanfilippo; Marco Mariti; Massimo D’Elia; Michele Mesiti

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We present our latest results on the determination of the curvature of the pseudo-critical line of the QCD phase diagram at the physical point, using the method of analytic continuation from an imaginary chemical potential. We also assess the impact of including a non-zero strange quark
chemical potential. Our results are obtained with stout improved staggered fermions and the tree level Symanzik improvement for the gauge action.

Standard Model Parameters and Renormalization / 153

Scale determination for the CLS 2+1 ensembles

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During the last two years, the CLS effort has generated ensembles with 2+1 dynamical flavors of non-perturbatively improved Wilson fermions at lattice spacings between 0.05fm and 0.09fm. Most of these ensembles are along lines of constant sum of bare sea quark masses tr(M). We give an overview of these simulations and describe our scale setting procedure using the pseudoscalar decay constants. Since this action is relatively new, particular attention will be given to the size of the discretization effects and the impact of the mistuning of tr(M).

Hadron Spectroscopy and Interactions / 87

The mass and leptonic decay constant of rho meson at the physical point

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Co-authors: Andrei Alexandru ²; Keh-Fei Liu ³; Terrence Draper ³; Zhaofeng Liu ⁴; yibo Yang ⁵

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We use overlap valence quarks on the \( L^3 \times T = 48^3 \times 96 \) \( N_f = 2 + 1 \) domain-wall fermion configurations generated by the RBC\&UKQCD Collaboration. The light sea quark mass is at the physical point and the spatial extension is 5.5 fm. The \( \rho \) mass is precisely determined to be \( m_{\rho} = 778(9) \) MeV at the physical pion mass. We also propose a strategy to reduce the noise of the wall-wall correlation functions of hadrons, through which the leptonic decay constant of \( \rho, f_{\rho} \), is determined to be 209(4) MeV at the physical \( m_\pi \). This value is in excellent agreement with the experimental value \( f_\rho = 208 \) MeV derived from the process \( \tau \rightarrow \rho\nu_\tau \).

Standard Model Parameters and Renormalization / 320

Perturbative renormalization of \( \Delta S = 2 \) four-fermion operators with the chirally rotated Schrödinger functional

Author: Pol Vilaseca Mainar¹
The chirally rotated Schrödinger functional (χSF) is a renormalization scheme which renders the mechanism of automatic O(a) improvement compatible with the Schrödinger functional (SF) formulation. Here we define a family of renormalization schemes based on the χSF for a complete basis of ∆S = 2 parity-odd four-fermion operators. We compute the scale-dependant renormalization constants of such operators to one-loop in perturbation theory and obtain their NLO anomalous dimensions. After this is done, we compute the cutoff effects in the corresponding step-scaling functions at one-loop. Due to automatic O(a) improvement, once the χSF action is renormalized and O(a) improved, renormalization constants are affected directly by O(a^2) effects without the need of operator improvement.

Nonzero Temperature and Density / 318

Phase structure of Nf=3 QCD at finite temperature and density by Wilson-Clover fermions

Author: Shinji TAKEDA

Co-authors: Akira Ukawa 2; Xiao-Yong Jin 3; Yoshifumi Nakamura 2; Yoshinobu Kuramashi 4

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We investigate the phase structure of finite temperature and density QCD with three-flavor by using Wilson-Clover fermions. We focus on locating the critical end point that characterizes the phase structure and extracting the curvature of critical line on the plane of quark chemical potential and pseudo-scalar meson mass.

Physics Beyond the Standard Model / 156

Probing near conformal dynamics with 4+8 and 8 flavors: running coupling and the spectrum

Author: Evan Weinberg

Co-authors: Anna Hasenfratz 2; Claudio Rebbi 3; Oliver Witzel 4

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We investigate an SU(3) gauge theory with four light flavors and eight heavy flavors of variable mass as a model of near conformal dynamics. By continuously varying the mass of the eight heavy flavors we can tune between chirally broken and conformal behavior. We report on recent progress with probing this model deeper in the light flavor chiral regime, including updated measurements of a light 0++ isosinglet meson. This will be presented alongside a study of an SU(3) theory with eight light flavors by the LSD collaboration.

Hadron Structure / 159

Finite volume hadronic vacuum polarisation at arbitrary momenta

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The muon anomalous magnetic moment constitute one of the most important tension between experimental measurements and the Standard Model predictions. The dominant theoretical uncertainties is coming from hadronic contributions, therefore it is crucial to aim at determining precisely and reliably this quantity from lattice QCD. Most of the contributions to the leading hadronic contribution comes from the low q^2 sector of the hadronic vacuum polarization (HVP). Because of momentum quantization in finite volume, it is hard to compute the HVP at low momentum and generally one has to use models to describe this region which can introduce significant systematic errors. Here we propose a model-independent method to reconstruct the HVP at continuous momenta. Using sampling theory, we show that this reconstruction is exact up to corrections that decay exponentially fast with the pion mass times the lattice extent. We conclude by presenting preliminary numerical results and we compare them to model-dependent approaches.

Algorithms and Machines / 5

A next generation C++ library for data parallel QCD

Author: Peter Boyle¹

Co-author: Azusa Yamaguchi ¹

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We discuss progress and performance from the development of a data parallel interface for cartesian fields of tensor data types. The library is suitable for the simulation of QCD including multiple grids. Wherever appropriate the interface is quite similar to that of QDP++, but the library makes use of C++11 features to reduce the volume of code, compared to QDP++ while bringing greater generality and greater performance. While the library simultaneously targets MPI, OpenMP and SIMD parallelism, the SIMD optimisation is notably flexible. Performance is substantially improved through the use of a data layout transformation and benchmark results are presented for simple Lattice QCD operations and the Wilson operator under AVX, AVX2 and AVX512 instruction set targets.
Resonance Parameters for the rho-meson from Lattice QCD

Author: Dehua Guo
Co-author: Andrei Alexandru

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We present a lattice calculation of the mass and width for the rho meson by determining the energy dependent phaseshift for pi-pi scattering in isospin-1, spin-1 channel in the elastic region. We compute the energy spectrum from spatially asymmetric boxes. We use Nf=2 nHYP fermions and generate two sets of ensembles with pion masses of 300MeV and 220MeV. To determine the energy spectrum we perform a variational analysis with interpolating fields including several q-$\bar{q}$ and pi-pi interpolating fields.

IR fixed points and conformal window in $SU(3)$ gauge Theories

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We propose a novel RG method to specify the location of the IR fixed point in lattice gauge theories and apply it to the $SU(3)$ gauge theories with $N_f$ fundamental fermions. It is based on the scaling behavior of the propagator through the RG analysis with a finite IR cutoff, which we cannot remove in the conformal field theories in sharp contrast with the confining theories. The method also enables us to estimate the anomalous mass dimension in the continuum limit at the IR fixed point. We perform the program for $N_f = 16, 12, 8$ and $N_f = 7$ and indeed identify the location of the IR fixed points in all cases. Our results are consistent with that the conformal window is $7 \le N_f \le 16$.

The chirally rotated Schrödinger functional at work

Author: Mattia Dalla Brida
Co-authors: Mauro Papinutto; Pol Vilaseca; Thomas Korzec

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The chirally rotated Schrödinger functional has proven to be a powerful tool in addressing non-perturbative renormalization problems in lattice QCD with Wilson-type fermions. In this contribution we consider two novel applications of the method. Firstly, we investigate the renormalization of a complete basis of $\Delta S=2$ four-quark operators relevant for searches of Beyond the Standard Model physics. Preliminary results are presented for the theory with $N_f=2$ dynamical flavours. Secondly, we discuss the renormalization of several quark-bilinears in the $N_f=2+1$ theory.

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**Hadron Structure / 284**

**Lattice calculation of the HVP contribution to the anomalous magnetic moment of muon**

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We report our (HPQCD) progress with the lattice QCD calculations of both the connected and disconnected hadronic Vacuum Polarisation (HVP) contributions to the anomalous magnetic moment of the muon ($g-2$). Our method uses Padé approximants to reconstruct the Adler function from its derivatives at $q^2=0$. These are obtained simply and accurately from time-moments of the vector current-current correlator at zero spatial momentum. We give a full flavor estimate of the total HVP contribution calculated on MILC Collaboration’s $n_f=2+1+1$ HISQ ensembles at multiple values of the lattice spacing, multiple volumes and multiple light sea quark masses (including physical pion mass configurations) and corrected for finite volume effects.

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**Nonzero Temperature and Density / 111**

**Many flavor approach to study the critical point in finite density QCD**

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We discuss the QCD critical point at finite density through the study of many-flavor QCD, in which two light flavors and $N_f$ massive flavors exist. Performing simulations of QCD with 2 flavors of improved Wilson fermions, we calculate probability distribution functions in many-flavor QCD at finite temperature and density, where the reweighting technique is used to add the dynamical effect of massive flavors and the chemical potential. From the shape of the distribution functions, we determine the critical surface separating the first order transition and crossover regions in the space spanned by the light and massive quark masses and the chemical potentials. It is found that the critical massive quark mass becomes larger as the chemical potential increases in $(2+N_f)$-flavor QCD. The indication to the $(2+1)$-flavor QCD is then discussed.
**A minimal model of the composite Higgs and its Goldstone dynamics**

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A low mass scalar state has been observed by the Lattice Higgs Collaboration as a viable candidate for the minimal realization of the composite Higgs from a fermion doublet in the two-index symmetric representation of the SU(3) color gauge group. The difficulty of decoupling Goldstone dynamics from the low mass scalar state in realistic simulations requires the extension of the low energy effective theory for chiral symmetry breaking.

**Decay constants and spectroscopy of mesons in lattice QCD using domain-wall fermions**

**Author:** Brendan Fahy

**Co-authors:** Guido Cossu; Jun Noaki; Masaaki Tomii; Shoji Hashimoto; Takashi Kaneko

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We report results of masses and decay constants of light and charmed pseudoscalar mesons using lattice QCD with Moebius domain-wall fermions. Using this formulation we are able to compute pseudoscalar decay constants through the pseudo-scalar density operator as well as with the axial-vector current. Results are shown from several lattice spacings and pion masses between 240 MeV and 500 MeV. We present an analysis of these results at different quark masses to show the chiral properties of the light mesons masses and decay constants.

**Chiral behavior of light meson form factors in 2+1 flavor QCD with exact chiral symmetry**

**Author:** Takashi Kaneko

**Co-authors:** Guido Cossu; Hidenori Fukaya; Jun Noaki; Shoji Hashimoto; Sinya Aoki; Tetsuya Onogi; Xu Feng

1 KEK
We present a study of the chiral behavior of light meson form factors in QCD with three flavors of overlap quarks. Gauge ensembles are generated at single lattice spacing 0.12fm with pion masses down to 300 MeV. The pion and kaon electro-magnetic form factors and the kaon semileptonic form factors are precisely calculated using the all-to-all quark propagator. We discuss their chiral behavior using the NNLO chiral perturbation theory.

**Hadron Structure / 66**

**Direct calculation of hadronic light-by-light scattering**

**Author:** Jeremy Green  
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Calculations of hadronic light-by-light scattering amplitudes via lattice QCD evaluation of Euclidean four-point functions of vector currents will be reported. These initial results include only the fully quark-connected contribution. Particular attention will be given to the case of forward scattering, which can be related via dispersion relations to the gamma gamma -> hadrons cross section, and thus allows lattice data to be compared with phenomenology. A strategy for computing the hadronic light-by-light contribution to the muon anomalous magnetic moment will also be briefly outlined.

**Nonzero Temperature and Density / 280**

**Many flavor approach to study the nature of chiral phase transition of two-flavor QCD**

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We perform lattice numerical simulations to study the phase transition of QCD at finite temperature and the vanishing chemical potential with intent to clarify the nature of the transition of massless two flavor QCD. We investigate QCD with two light and N_f heavy quarks instead of two-flavor QCD, and focus on
the light quark mass dependence of the critical heavy mass below which
the transition is of first order.
The nature of the transition is identified by the shape of the
constraint effective potential, constructed from the histogram of the
generalized plaquette, at the critical temperature.
The heavy quark effects are incorporated in the form of the hopping parameter
expansion through the re-weighting technique.
Our result indicates that the critical heavy mass remains finite in
the chiral limit of the two flavors of light quarks, suggesting
the phase transition of massless two-flavor QCD is of second order.

Standard Model Parameters and Renormalization / 53

Non-perturbative renormalization of the static quark theory in a
large volume

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Co-authors: Christoph Lehner 1; Tomomi Ishikawa 2

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We report on progress to renormalize non-perturbatively the static heavy quark theory on the lattice.
In particular, we present first results for position-space renormalization scheme for heavy-light bilin-
ears. We test our approach on RBC’s 16^3 x 32 lattice ensemble with pion mass of 420 MeV, Iwasaki
gauge action and domain wall light fermions.

Hadron Spectroscopy and Interactions / 194

2+1 flavor QCD simulation near the physical point on a 96^4 lat-
tice

Author: Naoya Ukita

Co-authors: Ken-Ichi Ishikawa 2; Naruhiro Ishizuka 1; Takeshi Yamazaki 1; Yoshifumi Nakamura 3; Yoshinobu
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We present our preliminary results on 2+1 flavor QCD with the stout smeared O(a)-improved Wilson
quark action and the Iwasaki gauge action. Simulations are carried out at a lattice spacing 0.085fm
on a 96^4 lattice with the quark masses near the physical point. The reweighing technique and ChPT
are employed for the extrapolation to the physical point. We will show the preliminary results of
the light quark masses, the decay constants and the light hadron spectrum.

Nonzero Temperature and Density / 234
The nature of the Roberge-Weiss Transition in N_f=2 QCD with Wilson Fermions on N_t=6 lattices

Authors: Alessandro Sciarra; Christopher Czaban; Christopher Pinke; Francesca Cuteri; Owe Philipsen

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The chiral and deconfinement phase transitions at zero density for light and heavy quarks, respectively, have analytic continuations to imaginary chemical potential. At some critical imaginary chemical potential, they meet the high temperature Roberge-Weiss transition between adjacent Z3 sectors. For light and heavy quarks, where the chiral and deconfinement transitions are first order, the transition lines meet in a triple point. For intermediate masses chiral or deconfinement transitions are crossover and the Roberge-Weiss transition ends in a second order point. At the boundary between these regimes the junction is a tricritical point, as shown in studies with N_f=2,3 flavors of staggered and Wilson quarks on Nt=4 lattices. Employing finite size scaling we investigate the nature of this point as a function of quark mass for N_f=2 flavors of Wilson fermions with a temporal lattice extent of Nt=6. In particular we are interested in the change of the location of tricritical points compared to our earlier study on Nt=4.

Hadron Structure / 281

Study of the hadronic contributions to the running of the QED coupling

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Co-authors: Benjamin Jaeger; Hanno Horch; Hartmut Wittig

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The electromagnetic coupling receives significant contributions to its running from non-perturbative QCD effects. We present an update of our study of the Adler function and of its application to the determination of leading order hadronic contribution to the running of the QED coupling. We use a high-statistics lattice QCD computation with two flavours of O(a) improved Wilson fermions in a broad range of the momentum transfer Q^2. The running of the QED coupling, including valence contributions from u, d, s and c quarks, is compared to phenomenological results at intermediate Q^2 values.
Implementation of a non-perturbative matching strategy between heavy-light currents in HQET and QCD

**Author:** Christian Wittemeier

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We outline our strategy to non-perturbatively match all components of the heavy-light axial and vector currents in Heavy Quark Effective Theory (HQET) at O(1/m) to finite-volume lattice QCD. Based on a tree-level study, we propose a set of matching conditions between suitable observables defined in QCD and HQET to fix the parameters of the effective theory, which are required to absorb the power divergences of lattice HQET. These conditions can be evaluated through numerical simulations, and we report on the status of our implementation in two-flavour QCD. The results of this finite-volume matching strategy will enter a HQET computation of the form factors of semi-leptonic B→π decays as a first application.

Hadron Spectroscopy with a low-mass composite scalar in the sextet model

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The SU(3) gauge theory with two flavors of two-index symmetric (sextet) fermions has been of great interest recently since a low-mass scalar meson that may serve as a composite Higgs candidate was observed in our previous studies. The hadron spectrum analysis on a more extended dataset will be presented as a followup investigation.

QED Corrections to Hadronic Processes in Lattice QCD

**Author:** Christopher Sachrajda

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We review the method proposed in [1] to compute electromagnetic effects in hadronic processes, such as decays, using lattice simulations. The method can be applied, for example, to the leptonic and semileptonic decays of light
of heavy pseudoscalar mesons. For these quantities the presence of infrared divergences in intermediate stages of the calculation makes the procedure much more complicated than is the case for the hadronic spectrum, for which calculations already exist. In order to compute the physical widths, diagrams with virtual photons must be combined with those corresponding to the emission of real photons. Only in this way do the infrared divergences cancel as rst understood by Bloch and Nordsieck in 1937. We present a detailed analysis of the method for the leptonic decays of a pseudoscalar meson and also review the status of exploratory numerical studies.


**Hadron Spectroscopy and Interactions / 198**

**Latest Results from RQCD using 2+1f CLS Simulations with Open Boundaries**

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We will report on latest results of the RQCD group obtained from 2+1f gauge field configurations with non-perturbatively improved Wilson action and open boundaries generated within the CLS effort. We have extended our simulations to include two chiral trajectories, one keeping the average quark mass fixed and an additional one where the strange quark mass is kept at its physical value. For the latter, we present details of our tuning strategy which enables us to fix the strange quark mass at the percent level (or possibly below). We will focus on spectroscopy, scale setting, and improvement coefficients.

**Physics Beyond the Standard Model / 230**

**Taste symmetry restoration in the sextet model with staggered fermions**

**Author:** santanu Mondal

**Co-authors:** Daniel Nogradi 2; Julius Kuti 3; Kieran Holland 4; Zoltan Fodor 5; chik him wong 5

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We show the cutoff dependence of taste symmetry breaking on the full staggered Goldstone spectrum in the sextet model. Taste symmetry in the Goldstone valence spectrum is restored using a mixed action setup on the gauge field gradient flow.
Hadron Structure / 121

The hadronic vacuum polarization function with O(a)-improved Wilson fermions - an update

Author: Hanno Horch¹

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We present an update of the analysis of the leading order hadronic contribution to the muon g-2 using a high statistics evaluation of the vacuum polarization function (VPF) with O(a)-improved $N_f = 2$ Wilson fermions. Partially twisted boundary conditions are used to increase the number of available $Q^2$ points. We employ an extended frequentist’s method to study the systematic errors arising from the $Q^2$ dependence of the VPF as well as various ansätze for the continuum and chiral extrapolation. We present preliminary results for $a^{\text{HLO}}_\mu$ including the valence contributions of u,d,s and c quarks.

Standard Model Parameters and Renormalization / 212

Perturbative versus non-perturbative decoupling of heavy quarks

Author: Francesco Knechtli¹

Co-authors: Björn Leder ²; Jacob Finkenrath ¹; Mattia Bruno ³; Rainer Sommer ⁴

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We simulate a theory with $N_f=2$ heavy quarks of mass $M$. At energies much smaller than $M$ the heavy quarks decouple and the theory can be described by an effective theory which is a pure gauge theory to leading order in $1/M$. We present results for the mass dependence of ratios such as $t_{00}(M)/t_{00}(0)$. We compute these ratios from simulations and compare them to the perturbative prediction. The latter relies on a factorization formula for the ratios which is valid to leading order in $1/M$ in the low energy effective theory.

Weak Decays and Matrix Elements / 286

Neutral Kaon mixing beyond the Standard Model

Author: Renwick Hudspith¹

Co-authors: Andrew Lytle ²; Christopher Sachrajda ³; Julien Frison ⁴; Nicolas Garron ³; Peter Boyle ⁴
We compute the hadronic matrix elements of the four-quark operators needed for the study of $K^0 - \bar{K}^0$ mixing beyond the Standard Model (SM). We have used $n_f = 2 + 1$ flavours of domain wall fermion (DWF) at two values of the lattice spacing ($a \approx 0.08$ and $a \approx 0.11$fm) and with lightest unitary Pion mass of $\approx 300$ MeV. Renormalisation is performed non-perturbatively and the impact of several different intermediate momentum schemes is investigated.

Nonzero Temperature and Density / 42

The $N_f = 2$ chiral phase transition from imaginary chemical potential with Wilson Fermions

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The clarification of the order of the thermal transition in the chiral limit of QCD with two dynamical flavours of quarks is a long-standing issue. Still, it is not definitely known if the transition is of first or second order. Which of the two scenarios is realized has important implications for the physical QCD phase diagram, and in particular it is important regarding the existence of a critical endpoint at finite densities. Settling this issue by simulating at successively decreased pion mass was not conclusive yet, primarily because of the increasing demands of the simulations as the pion mass is lowered.

Recently, an alternative approach was proposed, which relies on the nontrivial phase structure of QCD at purely imaginary chemical potential $\mu_I$ induced by the Roberge-Weiss symmetry. At critical values of $\mu_I$, the endpoint of the Roberge-Weiss transition is mass-dependent and changes from a triple point at low and high masses to a second order endpoint for intermediate masses. These regions are separated by tricritical points. Leaving the critical $\mu_I$-values, it is known that lines of second order transitions depart from the tricritical points, separating regions of first order transitions from crossover regions. Furthermore, at $\mu_I$ the sign problem is absent and standard simulation algorithms can be applied.

Hence, determining the second order line for lower quark masses is possible. The line is governed by tricritical scaling laws, which then allow an extrapolation to the chiral limit. In this way one can clarify the order of the chiral limit at zero chemical potential.

Using staggered fermions on $N_t = 4$ lattices, it was indeed found that the transition is of first order in the chiral limit. These findings have to be contrasted with other fermion discretizations. In this talk, we report on the status of our simulations with Wilson fermions following the same approach.
Improved Hadronic Matrix Element Determination Using the Variational Method

Authors: Jack Dragos¹; James Zanotti¹; Ross Young¹; Waseem Kamleh¹

Co-authors: Gerrit Schierholz ²; Paul Rakow ³; Roger Horsley ⁴; Yoshifumi Nakamura ⁵

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Calculating hadronic matrix elements in Lattice QCD that are relevant for e.g. Form Factors and Parton Distribution Functions, provides important insights into the structure of hadrons. However standard 3-point function methods have their limitations. One of the most commonly studied sources of systematic error is excited state contamination, which occurs when correlators are contaminated with results from higher energy excitations. This investigation uses configurations generated by the QCDSF/UKQCD/CSSM collaborations at the SU(3)-symmetric point (pion mass of 460 MeV) a lattice spacing of 0.074 fm with a volume of 32³ x 64. We apply the variational method to calculate a range of quantities and compare the results to the more commonly used summation and two-state fit methods. The results of this analysis demonstrate that the variational approach offers a more efficient and robust method for the determination of nucleon matrix elements.

Physics Beyond the Standard Model / 322

Running coupling of the sextet composite Higgs model

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The renormalized running coupling of SU(3) gauge theory coupled to Nf = 2 flavors of massless Dirac fermions in the 2-index-symmetric (sextet) representation is calculated. This model is of particular interest as a minimal realization of the strongly interacting composite Higgs scenario. A recently proposed finite volume gradient flow scheme is used. The calculations are performed at several lattice spacings and two discretizations allowing for a controlled continuum extrapolation and particular attention is paid to estimating the systematic uncertainties.

Nonzero Temperature and Density / 27

Analytic continuation of finite density QCD with heavy quarks in the strong coupling region

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Finite density and temperature QCD with heavy quarks is studied in the complex chemical potential ($\mu$) plane by use of a mean field method and Monte Carlo simulations, where the former applies to the strong coupling region. We calculate the effective potential as a function of Polyakov line, and study thermodynamic singularities and their associated Stokes lines in the complex $\mu$ plane. We also perform an explicit analytic continuation of the first order transition and crossover lines appearing on the real $\mu$ axis in the strong coupling region.

Hadron Spectroscopy and Interactions / 214

Extracting the eta-prime meson mass from gluonic correlators in lattice QCD

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Calculation of the eta-prime mass is a notoriously difficult problem, as it requires evaluation of the disconnected diagram which is costly and noisy. In this work, we use a glujonic operator to extract the eta-prime state after smearing the link variables through the Wilson flow. With this choice, one can avoid a large cancellation of pion contribution between the connected and disconnected diagrams. We obtain the eta-prime meson mass on lattices with three different lattice spacings and two physical volumes, which allow us to estimate its continuum and large volume limits.

Standard Model Parameters and Renormalization / 225

Nonperturbative renormalization in the RI-SMOM scheme and Gribov copies for staggered bilinears

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We present renormalization factors for the bilinear operators obtained using the nonperturbative renormalization method (NPR) in RI-SMOM scheme for improved staggered fermions on the MILC asqtad lattice (Nf=2+1). We compare the RI-SMOM result to the RI-MOM scheme result and the one-loop perturbative result. Since the NPR requires Landau gauge fixing, we study related Gribov copy problem in staggered NPR analysis.
Hadron Structure / 49

Finite volume effects in hadronic vacuum polarization

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We investigate finite volume effects in the hadronic vacuum polarization, with an eye toward the corresponding systematic error in the muon anomalous magnetic moment. While it is well known that leading-order chiral perturbation theory does not provide a good description of the hadronic vacuum polarization, it turns out that it gives a much better representation of finite volume effects. Indications are that finite volume effects cannot be ignored when the aim is a few percent level accuracy for the hadronic contribution to the muon anomalous magnetic moment, even when $m_{\pi} L \sim 4$ and $m_{\pi} \sim 200$ MeV.

Nonzero Temperature and Density / 26

Topological feature and phase diagram of QCD at complex chemical potential

Author: Kouji Kashiwa 1

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One of the important subjects in QCD is understanding properties of deconfinement transition at finite temperature and density. We investigate the pseudo-critical temperature of the deconfinement transition by considering the complex chemical potential. The imaginary chemical potential can be interpreted as the Aharonov-Bohm phase induced by U(1) flux insertions to the fictitious hole of the imaginary-time direction, then the analogy of topological order suggests that we can determine the deconfinement transition temperature by the Roberge-Weiss endpoint. We also present the expected QCD phase diagram based on the perturbative calculation at finite complex chemical potential.

Physics Beyond the Standard Model / 21

Conformal symmetry vs. chiral symmetry breaking in the SU(3) sextet model

Author: Martin Hansen 1

Co-authors: Ari Hietanen 1; Claudio Pica 1; Francesco Sannino 1; Vincent Drach 2
We present new results from our simulations of the SU(3) "sextet model" with two flavors in the 2-index symmetric representation of the gauge group. The simulations use unimproved Wilson fermions and we measure the meson and baryon spectrum of the theory for multiple bare quark masses at two different lattice spacings. To address the ongoing issue of whether the model is inside or outside the conformal window, we compare the spectrum to the expectations for a theory with spontaneous chiral symmetry breaking and to those of an IR conformal theory.

Hadron Structure / 329

A derivative based approach for the leading order hadronic contribution to g-2 of the muon

Author: Eric Gregory

We describe a lattice approach to calculate the leading-order anomalous magnetic moment of the muon. We employ lattice momentum derivatives to determine the hadronic vacuum polarization scalar at low momenta and construct a smooth, integrable function in this momentum region. We present preliminary results for hex-smear Wilson-quark lattice ensembles.

Hadron Spectroscopy and Interactions / 251

Photon mass term as an IR regularization for QCD+QED on the lattice

Authors: Andre Walker-Loud; Andrea Shindler; Brian C. Tiburzi; Michael Endres

The commonly adopted approach for including QED in lattice QCD simulations introduces power-law finite volume corrections to physical quantities. These effects, which are due to the long-range nature of the electromagnetic interaction, must be removed by performing simulations at multiple lattice volumes, followed by an extrapolation to the infinite volume limit. In this work, we explore the advantages and disadvantages of introducing a photon mass term as an alternative means for gaining control over the finite volume effects associated with the inclusion of QED. We present exploratory findings for hadron mass shifts due to electromagnetic interactions (i.e., for the proton, neutron, charged and neutral kaon) and corresponding mass splittings, and compare them with standard QCD+QED calculations. Preliminary results are reported for numerical studies of three flavor electroquenched QCD using ensembles corresponding to 800 MeV pions and three lattice volumes ranging from 3.4 fm to 6.7 fm.
Nuclear Parity Violation from Lattice QCD

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The electroweak interaction on the level of quarks and gluons are well understood from precision measurements in high energy collider experiments. Relating these fundamental parameters to Hadronic Parity Violation in nuclei however remains an outstanding theoretical challenge. One of the most interesting observables in this respect is the parity violating hadronic neutral current: it is hard to measure in collider experiments and is thus the least constrained observable of the Standard Model. Precision measurements of parity violating transitions in nuclei can help to improve these constraints.

In these systems however, the weak interaction is masked by effects of the ~7 orders of magnitude stronger non-perturbative strong interaction. Therefore, in order to relate experimental measurements of the parity violating pion-nucleon couplings to the fundamental Lagrangian of the SM, these non-perturbative effects have to be well understood. In this talk, I am going to present a Lattice QCD approach for computing the $\Delta I = 2$ parity violating matrix element in proton proton scattering. This process does not involve disconnected diagrams in the isospin symmetric limit and is thus a perfect testbed for studying the feasibility of the more involved calculation of the parity violating pion-nucleon coupling. In this talk, I am going to present our technology for computing this quantity and some preliminary results.

NPR determination of quark masses from the HISQ action

Author: Andrew Lytle

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I will report on a calculation of quark bilinear Z-factors for the HISQ action using non-perturbative renormalization techniques. One of the main outputs is the mass renormalization factor $Z_m$ relating bare quark masses to the MSbar scheme. This will provide an independent determination of quark masses in addition to other methods being used by the HPQCD collaboration.

Finite-temperature phase transition of Nf=3 QCD with exact center symmetry

Author: Tatsuhiro Misumi

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Page 29
By imposing flavor-dependent boundary conditions on quarks, we construct three-flavour SU(3) gauge theory reconciling fundamental fermion representation and exact Z3 center symmetry. In this talk, we show the first result of lattice simulation on this QCD-like theory, which we call Z3-QCD, with emphasis on the finite-temperature phase transition with respect to center and chiral symmetries. On the lattice, we formulate Z3-symmetric SU(3) gauge theory with three fundamental Wilson quarks by twisting quark boundary conditions in a compact dimension. We calculate the finite-temperature vacuum expectation value of Polyakov loop and the chiral condensate. We find out the first-order center phase transition where the hysteresis of temperature dependence exists depending on cold and hot starts. We also discuss the chiral crossover transition, and its relation to the center phase transition.

Standard Model Parameters and Renormalization / 317

Electromagnetic effects on the light pseudoscalar mesons and determination of $m_u/m_d$

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The MILC Collaboration has completed production running of electromagnetic effects on light mesons using asqtad improved staggered quarks. In these calculations, the photons are quenched using the non-compact formalism. Four lattice spacings from 0.12 fm to 0.045 fm have been used. Finite volume effects with $\alpha = 0.12$ fm have been studied with spatial sizes $L_s = 12$, 16, 20, 28, 40, and 48. The chiral-continuum fit of the meson masses allows calculation of corrections to Dashen’s theorem and determination of the ratio of up to down quark masses.
Dashen’s theorem and electromagnetic contributions to pseudoscalar meson masses

Author: Paul Rakow

Co-authors: Arwed Schiller; Dirk Pleiter; Gerrit Schierholz; Hinnerk Stueben; Holger Perlt; James Zanotti; Roger Horsley; Ross Young; Yoshifumi Nakamura

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We present results on the pseudoscalar meson masses from a fully dynamical simulation of QCD plus QED. We concentrate particularly on the question of how to divide the measured masses into a QED contribution and a QCD contribution. This decomposition is not unique, it depends on the renormalisation scheme and scale. We suggest a renormalisation scheme in which Dashen’s theorem holds, so that the electromagnetic self-energies of the neutral mesons are zero, and discuss how the self-energies change when we transform to a scheme such as MS-bar, in which Dashen’s theorem is violated.

Hadron Structure / 265

Leading isospin breaking correction to the hadronic vacuum polarisation

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Several leading lattice collaborations are investing significant effort to reduce the uncertainty in the lattice computation of the HVP to a sub-percent level. In order to achieve this goal, giving an estimate of the size of the isospin breaking effects becomes relevant. Recently, the RM123 developed a method for separating QCD from QED isospin breaking effects based on expansion of the path–integral in powers of the up and down quark mass difference and the fine structure constant. We discuss how to apply this method to the connected part of the hadronic vacuum polarisation from the lattice.

Plenary Session / 346

Hadron Structure from Lattice QCD

Author: James Zanotti
Here we review the progress made in understanding the internal structure of hadrons in terms of the gluonic and quark constituents. Recent results for standard observables such as the nucleon axial charge, electromagnetic form factors and quark momentum fraction will be summarised, before turning our attention to more challenging quantities, including quark disconnected contributions and so-called parton quasi-distribution functions. With many new experiments whose primary goal is to understand the internal dynamics of hadrons now underway, particular emphasis will be given to lattice calculations that promise to assist and guide these experimental efforts.

**Light flavours**

**Author:** Andreas Juettner

For quite some time now simulations of lattice QCD have allowed for predicting a basic set of light flavour quantities reliably and with increasingly high precision. The field has started to move on: Advances in field theory, algorithms and computing for the first time allow to address more complicated problems like for example hadronic and rare kaon decays, the kaon mass-difference or the conceptually clean inclusion of electromagnetic and isospin effects. This talk aims at providing an overview over the state-of-the-art.

**Three-body observables from the lattice**

**Author:** Maxwell Hansen

Scattering and transition amplitudes with three-hadron final states play an important role in nuclear and particle physics. In order to predict such quantities using Lattice QCD, formalism is required to overcome the limitations of Euclidean time and finite volume. In this talk I will focus on extensions of Luescher’s work relating the finite-volume energy spectrum to physical scattering amplitudes. I will highlight the challenges that arise in extending the formalism from two- to three-particle states, and will describe how these have been addressed. Finally, I will outline outstanding problems and discuss the prospects of applying the formalism in a numerical Lattice QCD calculation.
Standard-model prediction for direct CP violation in K->pi pi decays

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We discuss our recent publication [arXiv:1505.07863] of the first lattice QCD calculation of the complex kaon decay amplitude A_0 with physical kinematics, using a single 32^3 x 64 domain wall ensemble with G-parity spatial boundary conditions. We obtain approximate agreement with the experimental value for Re(A_0), which serves as a test of our method. Our prediction of Im(A_0) can be used to compute the direct CP violating ratio Re(ε′/ε), which we find to be ~2 sigma lower than the experimental value. This result provides a new test of the Standard Model theory of CP violation, one which can be made more accurate with increasing computer capability.

Lattice input on the tau V_us puzzle

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Existing versions of the standard determinations of V_us from flavor-breaking finite energy sum rules with hadronic tau decay data as input yield V_us values 3 sigma or more below the expectations of 3-family unitarity. Slow convergence of the D=2 OPE series employed in these sum rules, however, makes it hard to assess the reliability of the use of the OPE representation. In this paper we use Euclidean Q^2 lattice data for the relevant flavor-breaking polarization function difference to assess the use and reliability of the OPE for this quantity. We then revisit the sum rule determination of V_us with the lessons learned from this study in mind. We show that previously encountered self-consistency problems are solved by the new analysis, and note that, with the strange spectral distribution modified to account for the somewhat larger preliminary BaBar result for the K-> pi^0 branching fraction, the resulting output V_us is in good agreement with the result obtained from K_{ell 3} using lattice input for f_+(0).

Magnetic properties of light nuclei and the np -> dγ transition

Author: William Detmold

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I will discuss the NPLQCD collaboration’s recent calculations of the magnetic moments and polarisabilities of light nuclei up to $A=4$ using background field methods. I will also describe an a calculation of the magnetic transition amplitude that determines the $np \rightarrow d\gamma$ cross section that is of central importance in Big Bang Nucleosynthesis.

**Physics Beyond the Standard Model / 183**

**Lattice study for conformal windows of SU(2) and SU(3) gauge theories with fundamental fermions**

**Authors:** Alberto Ramos\(^1\); C.-J. David Lin\(^2\); Cynthia Y.-H. Huang\(^3\); Eigo Shintani\(^4\); Enrico Rinaldi\(^5\); Hiroshi Ohki\(^5\); Issaku Kanamori\(^2\); Kenji Ogawa\(^6\)

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We present results from our study of SU(2) gauge theory with eight flavours, and SU(3) gauge theory with twelve flavours. These two theories may be very close to the lower ends of the conformal windows for the SU(2) and SU(3) gauge groups, respectively, when only the fundamental-representation fermions are present. For the SU(2) theory with eight flavours, we report our investigation for the distribution of the lowest-lying eigenvalues of the Dirac operator. In particular, we compare our numerical results with predictions from Random Matrix Theory and extract the chiral condensate. As for the SU(3) theory with twelve flavours, we show our final analysis for the Gradient-Flow running coupling constant using the step-scaling method. In this presentation, we demonstrate our detailed study of the continuum extrapolation in the step-scaling approach, and comment on the challenges in such computations.

**Nonzero Temperature and Density / 18**

**Exploring Complex-Langevin Methods for Finite-Density QCD**

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Recent advances in applying complex-Langevin simulations to gauge theories with complex actions, in particular gauge-cooling, have revived interest in using these methods for QCD at finite baryon-number density. QCD at a finite chemical potential $\mu$ for quark number has a complex fermion determinant which prevents use of standard simulation techniques. Complex-Langevin simulations show promise for simulating this theory. We describe our preliminary investigations in applying complex-Langevin simulations to lattice QCD at finite $\mu$. We use a complex extension of the partial second-order approach to Langevin simulations of Fukugita, Ukawa and others, using staggered
fermions. Our current studies are of 2-flavour lattice QCD at finite \( \mu \) at zero temperature on a \( 12^4 \) lattice. Of special interest is if we can observe the expected transition at \( \mu \approx m_N/3 \), and whether there is a spurious transition at \( \mu \approx m_\pi/2 \). Finite-temperature simulations at finite \( \mu \) are also planned.

**Theoretical Developments / 77**

**Renormalizability of the Schrödinger Functional.**

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Symanzik showed that quantum field theory can be formulated on a space with boundaries by including suitable surface interactions in the action to implement boundary conditions. We show that to all orders in perturbation theory all the divergences induced by these surface interactions can be absorbed by a renormalization of their coefficients.

**Hadron Structure / 83**

**Parton Distribution Function from Hadronic Tensor**

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Parton Distribution function can be obtained from calculating the hadronic tensor on the lattice. It involves a 4-point function evaluation with two vector or axial-vector currents. We propose to use the source method for one of the currents and effectively reduce the numerical complexity to that of a 3-point function. The method can be generalized to evaluate other 4-point functions.

**Theoretical Developments / 340**

**Convergent Perturbation Theory for \( \phi^4 \) model on lattice**

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The small coupling expansions in the lattice field theory are asymptotic and do not converge. It was shown in previous studies, that an appropriate regularization of the integrals or shifting of the initial approximation allows one to construct convergent series. In this work we study the convergent series in application to the lattice $\phi^4$-model and compare the observables calculated using the series with the results of the Monte Carlo simulations. In addition, we consider the Borel resummation of the weak coupling lattice $\phi^4$-perturbation theory.

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**Standard Model Parameters and Renormalization / 134**

**Scalar and vector form factors of $D \rightarrow \pi\ell\nu$ decays with $N_f = 2 + 1 + 1$ Twisted fermions**

**Author:** Paolo Lami

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We present lattice results for the form factors relevant for $D \rightarrow \pi\ell\nu$ decays, obtained from simulations performed by the European Twisted Mass Collaboration with $N_f = 2 + 1 + 1$ flavors of dynamical quarks, at three values of the lattice spacing and pion masses as low as 210 MeV. We computed both the vector and the scalar form factors, studied their dependence on the momentum transfer and compared our results with the experimental ones. Specifically, by combining our determination of $f_+(0)$ with the experimental result for $|f_+(0)V_{cd}|$ we are able to determine the CKM matrix element.

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**Hadron Spectroscopy and Interactions / 89**

**Light nuclei and nucleon form factors in $N_f=2+1$ lattice QCD**

**Author:** Takeshi Yamazaki

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We present our result of binding energy of light nuclei with the nuclear mass number less than or equal to four at the pion mass $m_\pi = 0.3$ GeV. The simulations are performed in $N_f=2+1$ QCD with Iwasaki gauge and non-perturbative improved Wilson fermion actions at the lattice spacing of $a = 0.09$ fm. We discuss the quark mass dependence of the binding energies using our previous results and also a preliminary result at almost physical pion mass $m_\pi \sim 0.145$ GeV with $a \sim 0.085$ fm. Furthermore, we show a preliminary result of the axial charge and the radii obtained from isovector nucleon form factors at the almost physical pion mass.
Physics Beyond the Standard Model / 242

Approaching the conformal window: systematic study of the particle spectrum in SU(2) field theory with N_f = 2, 4 and 6.

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Co-authors: Alessandro Amato ²; Kari Rummukainen ²; Kimmo Tuominen ²; Teemu Rantalaiho ²

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It is expected that SU(2) gauge theory with N_f fundamental fermions has an infrared fixed point when N_f is between ~6 and 11. We study the hadron spectrum and scale setting in SU(2) gauge field theory with N_f = 2, 4, 6 using hypercubic stout smeared Wilson-clover (HEX) action. The case N_f = 2 is QCD-like, whereas N_f = 6 is close to the lower edge of the conformal window. In our study length scales are determined by using gradient flow approach.

Nonzero Temperature and Density / 129

Towards the heavy dense QCD phase diagram using Complex Langevin simulations

Author: Felipe Attanasio¹
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Monte Carlo methods cannot probe far into the QCD phase diagram with a real chemical potential, due to the famous sign problem. Complex Langevin simulations, using adaptive step-size scaling and gauge cooling, are suited for sampling path integrals with complex weights. We report here tests on the deconfinement transition in pure Yang-Mills SU(3) simulations and present an update on the QCD phase diagram in the limit of heavy and dense quarks.

Hadron Structure / 48

Nucleon transverse momentum-dependent parton distributions: Comparing Clover and Domain wall fermion results at ~300 MeV pion mass

Author: Boram Yoon¹

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We present a lattice QCD calculation of transverse momentum dependent parton distributions (TMDs) in the proton using staple-shaped gauge links. We calculate both naively time-reversal odd (T-odd) observables, namely, the generalized Sivers and Boer-Mulders transverse momentum shifts in SIDIS and DY processes, as well as T-even observables, namely, the transversity related to the tensor charge and the generalized worm-gear shift. The calculation is done on a $n_f=2+1$ clover ensemble with lattice spacing 0.114 fm and pion mass 317 MeV. The results are compared with a previous calculation on a domain-wall ensemble at 0.084 fm lattice spacing with 297 MeV pion mass.

**Theoretical Developments / 23**

**Induced YM theory with auxiliary bosons**

**Authors:** Bastian Brandt$^1$; Robert Lohmayer$^1$; Tilo Wettig$^1$

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We study pure SU(N) lattice gauge theory with a plaquette weight factor given by an inverse determinant which can be written as an integral over auxiliary bosonic fields (modifying a proposal of Budczies and Zirnbauer). We derive conditions for the existence of a continuum limit and its equivalence to Yang-Mills theory. Furthermore, we perturbatively compute the relation between the coupling constants of the 'induced' gauge action and the familiar Wilson gauge action using the background-field technique. The perturbative relation agrees well with numerical results for $N=2$ in three dimensions.

**Standard Model Parameters and Renormalization / 240**

**Nf=2+1+1 renormalisation of four-quark operators**

**Author:** Julien Frison$^1$

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The phenomenology of several problems of flavour physics require the renormalisation of four-quark effective operators at the electroweak scale. While some part of the running can be done perturbatively, it is important to perform the non-perturbative renormalisation at a scale as high as possible. We will present results at an energy range where four flavours of quarks are present, and show how it improves our control of the perturbative matching.

**Physics Beyond the Standard Model / 249**

**Gradient flow and IR fixed point in SU(2) with Nf=8 flavors**

**Author:** Viljami Leino$^1$

**Co-authors:** Jarno Rantaharju$^2$; Joni Suorsa$^3$; Kari Rummukainen$^1$; Kimmo Tuominen$^1$; Teemu Rantalaicho$^1$; Tuomas Karavirta$^2$
SU(2) with Nf=8 flavors of fundamental fermions is expected to feature an infrared fixed point (IRFP). We measure the evolution of the coupling constant with Schrödinger functional boundary conditions and gradient flow, using HEX-smeared Wilson-clover action. We observe clear evidence for a fixed point, qualitatively compatible with perturbative results.

HADRON SPECTROSCOPY AND INTERACTIONS / 171

THE H-DIBARYON IN TWO FLAVOR LATTICE QCD

Author: Parikshit Junnarkar

Co-authors: Anthony Francis; Chuan Miao; Hartmut Wittig; Jeremy Green; Thomas Rae

We present preliminary results from a lattice QCD calculation of the H-dibaryon using two flavours of O(a) improved Wilson fermions. We employ six-quark interpolating operators with the appropriate quantum numbers of the H-dibaryon and also explore its couplings to two-baryon channels. To improve the overlap to the ground state two smearings are employed and a generalised eigenvalue problem is solved in the aforementioned operator basis. With the application of Lüscher’s finite volume formalism, we explore the nature of the infinite volume interaction of the two baryons. The relevant correlators are projected to three moving frames further enabling the isolation of the infinite volume bound/scattering state. Preliminary results on pion mass of 1 GeV indicate the H-dibaryon is bound in the infinite volume. Results at a lower pion mass of 451 MeV will also be presented.

NONZERO TEMPERATURE AND DENSITY / 165

INSIGHTS INTO THE HEAVY DENSE QCD PHASE DIAGRAM USING COMPLEX LANGEVIN SIMULATIONS

Author: Benjamin Jaeger

Co-authors: Aarts Gert; Denes Sexty; Felipe Attanasio; Ion-Olimpiu Stamatescu; Seiler Erhard

Complex Langevin simulations provide an alternative to sample path integrals with complex weights and therefore are suited to determine the phase diagram of QCD from first principles. Adaptive step-size scaling and gauge cooling are used to make correct convergence possible. We present results for
the phase diagram of QCD in the limit of heavy quarks and discuss the order of the phase transitions, which are studied by varying the spatial simulation volume.

**Physics Beyond the Standard Model / 272**

**Lattice simulations of technicolour theories with adjoint fermions and supersymmetric Yang-Mills theory**

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In this talk I will present our newest results from the lattice simulation of SU(2) adjoint QCD with two Dirac flavours, also known as minimal walking technicolour. These results include the mass spectrum of the theory, in particular mesonic states with disconnected contributions and a specific spin half fermion-gluon state of the theory. I will discuss the results in comparison with SU(2) adjoint QCD with one Dirac flavour and supersymmetric Yang-Mills theory.

**Hadron Spectroscopy and Interactions / 334**

**Two-nucleon scattering in multiple partial waves**

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We determine scattering phase shifts for s,p,d, and f partial wave channels in two-nucleon systems using lattice QCD methods. We use a generalization of Luscher’s finite volume method to determine infinite volume phase shifts from a set of finite volume ground- and excited-state energy levels on two volumes, \( V=(3.4 \text{ fm})^3 \) and \( V=(4.5 \text{ fm})^3 \). The calculations are performed in the SU(3)-flavor limit, corresponding to a pion mass of approximately 800 MeV. From the energy dependence of the phase shifts we are able to extract scattering parameters corresponding to an effective range expansion.
Hadron Structure / 130

Nucleon generalized form factors from lattice QCD with nearly physical quark masses

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We show results of generalized form factors of the nucleon from lattice simulations with $N_f = 2$ mass-degenerate non-perturbatively improved Wilson-Sheikholeslami-Wohlert fermions down to a pion mass of 150 MeV. We also present the resulting isovector quark angular momentum. Possible excited state contaminations are treated with correlated simultaneous fits to all 3pt functions of a given ensemble with fixed momentum transfer squared.

Theoretical Developments / 175

Renormalization of two-dimensional XQCD

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Recently, Kaplan proposed an interesting extension of QCD : XQCD (=extended QCD) with bosonic auxiliary fields. While its partition function is kept exactly the same as that of QCD, XQCD naturally contains properties of low-energy hadrons.

We apply this extension to the two-dimensional QCD in the large $N_c$ limit (’t Hooft model). In this solvable model, it is possible to directly examine the hadronic picture of the 2d XQCD and analyze its renormalization group flow to understand how the auxiliary degrees of freedom behave in the low energy region. We confirm that the additional scalar fields can become dynamical acquiring the kinetic term, and its parity-odd part becomes dominant in the low energy region.

This renormalization of XQCD provides an “extension” of the renormalization scheme of QCD, inserting different field variables from those in the original theory, without any changes in physical observables.

Nonzero Temperature and Density / 60

Testing a generalized cooling procedure in the complex Langevin simulation of chiral Random Matrix Theory

Author: Keitaro Nagata

Co-authors: Jun Nishimura; Shinji Shimasaki

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The complex Langevin (CL) method has been attracting much attention as a solution to the sign problem since the method was shown to work in finite density QCD in the deconfined phase by using the so-called gauge cooling procedure. Whether it works also in the confined phase with light quarks is still an open question, though. In order to shed light on this question, we apply the method to the chiral Random Matrix Theory (RMT), which describes the epsilon regime of finite density QCD. Earlier works reported that a naive implementation of the method fails to reproduce the known exact results and that the problem can be solved by choosing a suitable coordinate. In this work we stick to the naive implementation, and show that a generalized gauge cooling procedure can be used to avoid the problem.

The leading hadronic contribution to $\gamma$-$Z$ mixing

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We study the hadronic contribution to the $\gamma$-$Z$ mixing, which determines the leading order hadronic contribution to the running of the electroweak mixing angle $\theta_W$. The required vacuum polarization function $\Pi^{\gamma Z}$ is calculated from the appropriate vector correlation functions in a mixed time-momentum representation. We explicitly calculate the connected and the disconnected contributions to such vector correlators using $N_f = 2$ dynamical flavors of non-perturbatively $O(a)$-improved Wilson fermions.

Wilson Fermions with Four Fermion Interactions

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We present a study of a chirally symmetric model of four fermion interactions, the Nambu Jona-Lasinio model, on the lattice with Wilson fermions. Four fermion interactions are a necessary part of many models of beyond Standard Model physics. In particular, they can couple the Standard Model fermions to a strongly interacting Higgs sector. In technicolor models they may cause spontaneous chiral symmetry breaking and modify the running coupling. As a first step, we study the restoration and spontaneous breaking of chiral symmetry in the lattice NJL model before adding a gauge interactions.
Nonzero Temperature and Density / 200

Understanding the problem with logarithmic singularities in the complex Langevin method

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In recent years, there has been remarkable progress in theoretical justification of the complex Langevin method, which is a promising method for evading the sign problem in the path integral with a complex weight. There still remains, however, an issue concerning occasional failure of this method in the case where the action involves logarithmic singularities such as the one appearing from the fermion determinant in finite density QCD.

In this talk, we point out that this failure is due to the breakdown of the relation between the complex weight which satisfies the Fokker-Planck equation and the probability distribution generated by the stochastic process. In fact, this kind of failure can occur in general when the stochastic process involves a singular drift term. We show, however, in simple examples, that there exists a parameter region in which the method works although the standard reweighting method is hardly applicable.

Hadron Spectroscopy and Interactions / 216

Calculation of the decay width of decuplet baryons

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We present an update of our investigation of hadronic decays of decuplet baryons using the transfer matrix method. In addition to the benchmark decay Delta -> pi N we look at other channels, like Sigma -> pi Sigma and Sigma -> pi Lambda, to further test the reach of the method. Lattice calculations are done using a hybrid setup with domain wall fermions on a staggered sea at pion mass 350 MeV and using a unitary setup with domain wall fermions at pion mass 180 MeV.

Theoretical Developments / 218

Combining ordinary and topological finite volume effects for fixed topology simulations

Authors: Arthur Dromard; Marc Wagner

Co-authors: Hector Mejia-Diaz; Urs Gerber; Wolfgang Bietenholz
In lattice simulations at fine lattice spacings typical algorithms tend to freeze topologically. In such cases specific topological finite size effects have to be taken into account, to obtain physical results corresponding to infinite volume or unfixed topology. Moreover, in QCD simulations, where the volume is not that large, it is often also necessary to get rid of ordinary finite volume effects not related to topology freezing. To extract physical results from simulations affected by both types of finite volume effects, we extend a known relation from the literature between hadron masses at fixed and at unfixed topology by incorporating additionally also ordinary finite volume effects. Numerical results for SU(2) Yang-Mills theory are presented.

**Standard Model Parameters and Renormalization / 224**

**Determining the scale in Lattice QCD**

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Numerical lattice QCD simulations determine mass (or other) ratios but not the scale itself, which has to be determined from experiment. A hadron mass such as the proton mass or decay constant such as the pion decay constant are often used for this purpose. We discuss here the advantages of setting the scale using a flavour-singlet quantity, which in conjunction with simulations keeping the average quark mass constant allow SU(3) flavour breaking expansions to be used. This is illustrated using 2+1 clover fermions, and a determination of the Wilson flow scales $t_0$ and $w_0$ is given.

**Nonzero Temperature and Density / 341**

**Complex Langevin in low-dimensional QCD: the good and the not-so-good**

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We present our latest results on the application of the Complex Langevin method in one- and two-dimensional QCD. Although the method is stable, it unfortunately converges to an incorrect result when applied as such. After applying additional gauge cooling steps, the results agree with the known analytical results in the one-dimensional case. However, in the two-dimensional case the disagreement subsists, even with gauge cooling, when the sign problem is sufficiently large.
QCD spectroscopy and quark mass renormalisation in external magnetic fields with Wilson fermions

Authors: Bastian Brandt\textsuperscript{1}; Benjamin Glaessle\textsuperscript{1}; Gergely Endrodi\textsuperscript{1}; Gunnar Bali\textsuperscript{1}

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We study the change of the QCD spectrum of low-lying mesons in the presence of an external magnetic field using Wilson fermions in the quenched approximation. Motivated by qualitative differences observed in the spectra of overlap and Wilson fermions for large magnetic fields, we investigate the dependence of the additive quark mass renormalisation on the magnetic field. To this purpose we derive Ward identities for lattice and continuum QCD+QED from which we can extract the current quark masses. We then compare different strategies of tuning for the quark masses.

The Roper resonance from spatially large interpolation fields

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We present our calculations of the Roper state obtained from a combination of spatially large interpolation fields. The calculation is carried out with overlap valence fermion on 2+1-flavor domain-wall fermion configurations on the $24^3 \times 64$ lattice with $a^{-1} = 1.73$ GeV. Our result is consistent with that from the Sequential Bayesian method (SBM) on the same lattice, and with the experimental value at 1440 MeV. We utilize the same method on the anisotropic Clover lattice, and compare with the overlap results. In the end we give an explanation on the nature of the difference.

Three particles in a finite volume

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The spectrum of a bound state of three identical particles with a mass $m$ in a finite cubic box is studied within the effective field theory approach. It is shown that in the limit of a large two-body scattering length, the energy shift of a shallow bound state is given by $\Delta E = c(n^2/m) (\kappa L)^{-3/2} |A|^2 \exp(-2\kappa L/\sqrt{3})$, where $\kappa$ is the bound-state momentum, $L$ is the box size,
\[ |A|^2 \] denotes the three-body analog of the asymptotic normalization coefficient of the bound state wave function and \( c \) is a numerical constant. The formula is valid for \( \kappa L \gg 1 \). We further compare these predictions to the results of numerical calculations of the three-body spectrum in a finite volume. Using this approach to study the nature of the three-body bound states on the lattice is discussed.

Nonzero Temperature and Density / 276

**Magnetic properties and deconfinement**

**Authors:** Claudio Bonati\(^1\); Francesco Negro\(^1\); Francesco Sanfilippo\(^2\); Marco Mariti\(^3\); Massimo D’Elia\(^3\); Michele Mesiti\(^4\)

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We report on our recent results regarding the properties of strongly interacting matter in the presence of strong magnetic background fields below and above the deconfinement transition.

Hadron Spectroscopy and Interactions / 232

**First results of baryon interactions from lattice QCD with physical masses (1) – General overview and two-nucleon forces**

**Author:** Takumi Doi\(^1\)

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One of the most important frontier in lattice QCD is the first-principles determination of baryon-baryon interactions. Our novel method, the HAL QCD method, has been shown to be effective for this objective, while the calculations so far employed unphysically heavy quark masses. Under these circumstances, we have launched the new project to calculate baryon interactions in lattice QCD, employing quark masses around the physical point on a huge lattice volume of \((8\text{fm})^4\). Resources such as K computer at AICS, Kobe, Japan are used for this computations. In this talk, we first give the overview of this on-going project, such as the theoretical formalism in HAL QCD method and numerical aspects of the baryon-force computations. We then turn to the numerical results, where first preliminary results for two-nucleon forces will be shown.

Physics Beyond the Standard Model / 323

**Effects of higher order operators on the Standard Model Higgs sector**

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We study generic effects of Beyond the Standard Model physics on the Standard Model Higgs sector. Specifically we investigate the effects of higher order operators in the Higgs potential in the Higgs-Yukawa and gauge-Higgs sectors separately. Our main result is the dependence of the critical endpoint of the Electroweak finite temperature phase transition on the scale of new physics.

Standard Model Parameters and Renormalization / 245

Analysis of short distance current correlators using OPE

Author: Masaaki Tomii

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We investigate correlation functions of light quark flavor non-singlet bilinear operators at short distances, where non-perturbative effects are encoded in the form of Operator Product Expansion (OPE). Comparing lattice results and continuum perturbation theory, we determine renormalization constants and vacuum expectation values appearing in OPE. We use the lattice data obtained with the Mobius domain-wall fermion at three lattice spacings.

Theoretical Developments / 10

Hamiltonian simulation of lattice gauge theories

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We consider the matrix product state formalism for the simulation of Hamiltonian lattice gauge theories. To this end, we define matrix product states which are manifestly gauge invariant. As an application, we study 1+1 dimensional one flavor quantum electrodynamics, also known as the massive Schwinger model. First, we discuss our results on full quantum non-equilibrium dynamics induced by a quench in the form of a uniform background electric field (i.e. the Schwinger pair creation mechanism). Furthermore we study the effects of charge screening and confinement in the vacuum for integer and non-integer external charges. Finally, we present some results on finite temperature simulations.
Hadron Structure / 126

Pion electromagnetic form factor from full lattice QCD

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We present the first calculation of the pion electromagnetic form factor at physical light quark masses. This form factor parameterizes the deviations from the behaviour of a point-like particle when a photon hits the pion. These deviations result from the internal structure of the pion and can thus be calculated in QCD. We use three sets (different lattice spacings) of $n_f = 2+1+1$ lattice configurations generated by the MILC collaboration. The Highly Improved Staggered Quark formalism (HISQ) is used for all of the sea and valence quarks. Using lattice configurations with u/d quark masses very close to the physical value is a big advantage, as we avoid the chiral extrapolation. We study the shape of the vector ($f_+$) form factor in the $q^2$ range from 0 to $-0.15 \text{GeV}^2$ and extract the mean square radius, $\langle r_v^2 \rangle$. The shape of the vector form factor and the resulting radius is compared with experiment. We also discuss the scalar form factor and the resulting radius compared with experiment.

Physics Beyond the Standard Model / 122

Lattice study of the Higgs-Yukawa model in and beyond the Standard Model

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We consider a chirally-invariant Higgs-Yukawa model as a limiting case of the Standard Model (SM) and investigate the model using lattice simulation. We present result of the study of the model near the mean-field using Renormalisation Group (RG) improved finite-size scaling. We derived formulae for such scaling behaviour by including the contributions of the leading logarithms. Results for the magnetisation, susceptibility and Binder’s cumulant are tested against the lattice simulation data performed with small bare scalar-quartic and Yukawa couplings. In these tests we found the predicted logarithmic volume dependence of those observables. The technique we establish in this work can be applied to an extensive investigation of the phase structure of the Higgs-Yukawa models. In particular, it can be used to study the possibility of having non-trivial fixed points in such models.
In a different aspect of our work, we have also included a $(\phi^4 \phi)^3$ term to investigate effects of a higher dimensional operator in this model. Such a higher-dimensional operator can originate from physics beyond the SM. With the zero temperature phase structure established in our previous work, it is worthwhile to study the finite temperature properties of such a model.

**Hadron Spectroscopy and Interactions / 315**

**First results of baryon interaction from lattice QCD with physical masses (2) – S=-3 and S=-4 sectors (XiXi, XiSigma, XiLambda-XiSigma channels) –**

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Nucleaon-Nucleon interaction plays an essential role in nuclear physics. In the same way, hyperon-hyperon interactions should play an important role in hyper nuclear physics. However, unlike the nucleons who are quite stable, hyperons decay quickly so that the direct scattering experiments are difficult. As a result, phenomenological determination of hyperon potentials involves large uncertainty. In this talk, we present our preliminary lattice QCD results on the determination of hyperon potentials in XiXi, XiSigma, and XiLambda-XiSigma channels based on the HAL QCD method by using a 2+1 flavor gauge configuration near the physical point generated by K computer.

**Nonzero Temperature and Density / 314**

**Towards the continuum limit of the critical endline of finite temperature QCD**

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We report on preliminary results for the critical endpoint of finite temperature phase transition of $N_f = 3$ QCD at $N_t = 10, 12$ and the critical endline of $N_f = 2 + 1$ QCD at $N_t = 6$ around the SU(3)-flavour symmetric point.

We employ the renormalization-group improved Iwasaki gauge action and non-perturbatively $O(\alpha)$-improved Wilson-clover fermion action.
SU(3)-breaking effects and induced second-class form factors in hyperon beta decays from 2+1 flavor lattice QCD

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We discuss the effects of SU(3) symmetry breaking measured in hyperon semileptonic decays from fully dynamical lattice QCD. Our calculations are carried out with gauge configurations generated by the RBC and UKQCD collaborations with (2+1)-flavors of dynamical domain-wall fermions and the Iwasaki gauge action at two couplings, $\beta = 2.13$ and $2.25$. We have estimated the value of the hyperon vector coupling $f_1(0)$ with an accuracy of less than one percent. We then find that lattice results of $f_1(0)$ combined with the best estimate of $|V_{us}|$ with imposing CKM unitarity are slightly deviated from the experimental result of $|V_{us} f_1(0)|$ for $\Sigma \rightarrow N$ decay. This discrepancy can be attributed to an assumption made in the experimental analysis on $V_{us}$; where the induced second-class form factor $g_2$ is set to be zero. We will therefore report on this matter and show the preliminary results of $g_2(0)$ evaluated in both indirect and direct ways.

Standard Model Parameters and Renormalization / 228

Charmonium current-current correlators with Mobius domain-wall fermion

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We calculate the moments of charmonium current-current correlators with the Mobius domain-wall fermion. Following the method adopted by the HPQCD collaboration, we extract the charm quark mass by matching the results with the corresponding perturbative QCD calculations. We use the recently generated domain-wall fermion ensembles by the JLQCD collaboration at lattice spacings $a = 0.083$ fm, $0.055$ fm and $0.044$ fm.

Theoretical Developments / 220

Real-time simulation of dissipation-driven quantum Systems

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We set up a real-time path integral to study the evolution of quantum systems driven in real-time completely through the coupling of the system with the environment. This can also be interpreted as measurements being performed on the system. For a spin-1/2 system, in particular, when the measurement results are averaged over, the resulting sign problem completely disappears, and the system can be simulated with an efficient cluster algorithm.
Nonzero Temperature and Density / 275

Chiral phase transition of $N_f=3$ and 2+1 QCD at vanishing baryon chemical potential

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We present updated studies of chiral phase transition in $N_f=2+1$ and 3 QCD based on the simulations using Highly Improved Staggered Quarks on lattices with temporal extent $N_T=6$ at vanishing baryon chemical potential. In $N_f=2+1$ QCD we have performed simulations with a strange quark fixed to its physical value and two degenerate light quarks whose values are adjusted to have 5 values of Goldstone pion masses in the region of 160 - 80 MeV in the continuum limit. Datasets with more values of temperature near chiral phase transition temperature are produced compared to our previous study (1312.0119). The universal scaling behavior of chiral condensates as well as chiral susceptibilities and uncertainties of the determination of non-universal parameters, e.g. chiral phase transition temperature $T_c$, are discussed. Simulations with 3 degenerate quarks have also been performed with more temperature values and with almost doubled statistics compared to our previous investigation (1302.5740). Signatures of first order phase transition and the estimate of the value of critical quark mass where the second order phase transition ends are discussed.

Physics Beyond the Standard Model / 105

Non-Perturbative Gauge-Higgs Unification in Five Dimensions

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We study the phase diagram and mass spectrum of an $SU(2)$ Gauge-Higgs Unification scenario on a five-dimensional orbifold. This theory exhibits spontaneous symmetry breaking, and we observe that a newly discovered phase transition plays an important role in the ability of the theory to produce a standard model-like spectrum. We comment on dimensional reduction and take first steps towards constructing renormalised trajectories along the phase diagram such that physical quantities remain constant.

Hadron Structure / 326

Nucleon axial and tensor charges with dynamical overlap quarks

**Author:** Nodoka Yamanaka
We report on our calculation of the nucleon axial and tensor charges in 2+1-flavor QCD with dynamical overlap quarks. Numerical simulations are carried out at single lattice spacing 0.12 fm with pion masses below 500 MeV. We calculate both of the connected and disconnected contributions by using the all-to-all quark propagator. We present our preliminary results for the isoscalar and isovector charges.

Standard Model Parameters and Renormalization / 75

Determining the QCD coupling from lattice vacuum polarization

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The QCD coupling appears in the perturbative expansion of the current-current two-point (vacuum polarization) function. Any lattice calculation of vacuum polarization is plagued by several competing non-perturbative effects at small momenta and by discretization errors at large momenta. We work in an intermediate region and compute vacuum polarization for many off-axis momentum directions on the lattice. Having many momentum directions provides a way to monitor and account for lattice artifacts. Our results are competitive with, and have certain systematic advantages over, the alternate phenomenological determination of the strong coupling from the same light quark vacuum polarization produced by sum rule analyses of hadronic tau decay data.

Theoretical Developments / 258

Lefschetz-thimble path integral for solving the mean-field sign problem

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Lefschetz-thimble method is a recently developing tool for solving the sign problem. We showed that the sign problem appearing in the mean-field approximation can be completely solved by applying this technique. The manifest reality of the physical observables is shown to be ensured in spite of the
complexification of the field variables. The result is demonstrated through the heavy-quark model, and we also discuss some implications to the lattice QCD.

Hadron Spectroscopy and Interactions / 302

First results of baryon interactions from lattice QCD with physical masses (3) – Strangeness S=-2 two-baryon system

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The determination of baryon-baryon interactions directly from QCD is highly awaited. Especially for the strangeness S=-2 two-baryon system, we can investigate the SU(3) structure and its breaking effect of baryon-baryon interactions because the flavor singlet combination is allowed only in this system.

Our approach is deriving a potential from coupled channel Schroedinger equation using Nambu-Bethe-Salpeter wave function measured on the lattice.

We will report our latest results of the S=-2 baryon-baryon interactions and the fate of H-dibaryon by lattice QCD simulation employing quark masses around the physical point on a huge lattice volume of L=8fm generated by K computer at AICS.

Physics Beyond the Standard Model / 36

Five-dimensional Gauge Theories in a Warped Background

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The anisotropic five-dimensional SU(2) lattice gauge theory in a flat space-time background has a rich phase diagram that has been investigated extensively using various techniques. The objective is to understand whether a layered phase exists that could support a four-dimensional brane in the continuum limit, but the results to date provide no evidence for this. We present new results, obtained in mean-field theory, for the phase diagram of this theory when the extra dimension is warped.

Hadron Spectroscopy and Interactions / 231

Lattice QCD studies of baryon interactions from HAL QCD method and Luscher’s finite volume method

Author: Takumi Iritani

1 Yukawa Institute for Theoretical Physics
Both HAL QCD and Luscher’s finite volume methods are used to calculate the hadron interactions from lattice QCD. However, there are some systematic deviations between these methods.

In this talk, we investigate baryon interactions from both HAL QCD and Luscher’s finite volume methods using the same lattice setups. From systematic comparison of these two techniques, we discuss the origin of the deviations between them and possibilities of the improvements of both methods.

We study thermodynamics of SU(3) gauge theory on the basis of the Yang-Mills gradient flow on fine lattices. For this purpose, the lattice spacing of the Wilson gauge action is determined over a wide range of \( \beta \) with high accuracy. We then measure the flow time and lattice spacing dependences of the expectation values of the energy-momentum tensor. The extrapolation to the continuum limit of these results is performed.

I present our recent analysis of isovector nucleon electromagnetic form factors, as well as the axial, scalar and tensor charges with high statistics in lattice QCD. By applying the all-mode-averaging technique to two flavors of Wilson-Clover fermions, we obtain precise lattice results of form factors at various lattice spacings and pion masses in the range 200–500 MeV for \( m_{\pi}L>4 \). An extensive numerical study of excited state contamination suggests that large effects persist for source-sink
separations of less than 1.3 fm when the standard plateau method is used. In order to reduce it to less than a few percent uncertainty, separations of more than 1.5 fm are required. I present the results from several analyses including the first excited state and perform a consistency check with the region where the ground state dominates. I also discuss the chiral behaviour and systematic uncertainties arising from finite size effects and lattice artifacts.

Theoretical Developments / 219

Thermal evolution of the 1-flavour Schwinger model with using Matrix Product States

Author: Hana Saito

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The Schwinger model, or 1+1 dimensional QED, offers an interesting object of study, both at zero and non-zero temperature, because of its similarities to QCD. In this talk we present the first full calculation of the temperature dependent chiral condensate of this model in the continuum limit using Matrix Product States (MPS). MPS methods, in general tensor networks, constitute a very promising technique for the non-perturbative study of Hamiltonian quantum systems. In the last few years, they have shown their suitability as ansatzes for ground states and low-lying excitations of lattice gauge theories. We show the feasibility of the approach also for finite temperature.

Standard Model Parameters and Renormalization / 227

Light quark masses from infrared fixed point

Author: Gerrit Schierholz

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It is argued that low energy parameters, such as the light quark masses, are related by infrared fixed points of the underlying theory. Implications for the u and d quark masses are discussed.

Hadron Structure / 102

Nucleon-pion-state contributions in the determination of the nucleon axial charge

Author: Oliver Baer

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The nucleon-pion-state contributions to QCD two- and three-point functions used in the calculation of the nucleon axial charge are studied in chiral perturbation theory. For sufficiently small quark masses and large volumes the nucleon-pion states are expected to have smaller total energy than the single-particle excited states. To leading order in chiral perturbation theory the results do not depend on low-energy constants associated with the interpolating nucleon fields and apply to local as well as smeared interpolators. The nucleon-pion-state contribution is found to be at the few percent level and non-negligible for precise determinations of the axial charge.

Theoretical Developments / 99

Tensor renormalization group analysis of CP(N-1) model in two dimensions

Author: Hikaru Kawauchi
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We apply the tensor renormalization group (TRG) method to the lattice CP(N-1) model in two dimensions. A tensor network representation of this model is derived for arbitrary N. For N=2, we compute the average energy by using the higher-order TRG. We compare it with the result of the O(3) nonlinear sigma model in two dimensions which is analyzed by the same method. Finally, we discuss the tensor network representation in the presence of the theta term.

Hadron Spectroscopy and Interactions / 246

Lambda_c-N interaction from lattice QCD

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Lambda_c (2286), the lightest baryon that contains one charm quark, has been found at some experiments, but its detailed properties such as the strength of the interaction with the nucleon, including a possibility of forming a deuteron-like bound state, are not known.

Due to the heavy quark symmetry, heavy baryons such as Lambda_c (2286) sometimes show quite different behavior from light baryons, so the direct study of heavy baryons in QCD is important to reveal their properties.

Recently, a new approach to investigate hadron interactions in lattice QCD has been proposed and developed extensively by the HAL QCD Collaboration. Employing this method, we have investigated the interaction between Lambda_c and nucleon (N). We first calculate the (single channel) potential between Lambda_c-N, with which we investigate an existence of the bound state in this system. We then consider
the coupled channel potentials between Lambda_c-N and Sigma_c-N, in order to see effects from inelastic states to Lambda_c-N interactions.

In this talk, we present the current status of our research project on Lambda_c-N interactions as well as future prospects.

**Physics Beyond the Standard Model / 255**

**Gravitational waves from cosmological first order phase transitions**

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Future space-based gravitational wave detectors, e.g. the eLISA satellite constellation scheduled for launch in 2034, can potentially observe primordial gravitational radiation, opening a new window to the early Universe. Gravitational radiation can be generated in first order phase transitions, for example the electroweak transition in some extensions of the Standard Model. In order to obtain detailed understanding of the generation of gravitational radiation, we have initiated a research program using large-scale simulations of an effective order parameter field + fluid systems. We find that the dominant source of radiation are the acoustic waves of the fluid, the sound of the transition. This hitherto unappreciated mechanism gives significantly stronger gravitational radiation background than the earlier estimates have indicated.

**Standard Model Parameters and Renormalization / 217**

**Clover fermions in Numerical Stochastic Perturbation Theory**

**Author:** Michele Brambilla

**Co-authors:** Barbara De Palma, Francesco Di Renzo, Marco Guagnelli

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We present an implementation of clover fermions in Numerical Stochastic Perturbation Theory. Two loop computations are already possible, e.g. we already computed critical mass. We stress that any two loop computation only relies on the known value of c_SW to one loop.

A two loop determination of c_SW would be of great interest: we report on the status of our computation of the latter.
Polyakov loop renormalization with gradient flow

Authors: Hans-Peter Schadler\(^1\); Peter Petreczky\(^2\)

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We propose to use gradient flow for the renormalization of Polyakov loops in various representations. We study Polyakov loops in 2+1 flavor QCD using HISQ action and lattices with temporal extents \(N_t=6,8,10\) and 12 in various representations, including fundamental, sextet, adjoint, decuplet, 15-plet and 27-plet. This alternative renormalization procedure allows the renormalization over a large temperature range from \(T=100\) up to \(T=1000\) MeV, with small errors not only for the fundamental but also for higher representations of the Polyakov loop. We discuss the Casimir scaling of the Polyakov loops and also compare with weak coupling results.

Some nucleon isovector observables from 2+1-flavor domain-wall QCD at physical mass

Author: Shigemi Ohta\(^1\)

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Current status will be reported of the nucleon isovector form factors and low moments of structure functions calculated by RBC and LHP Collaborations using a physical mass 2+1-flavor dynamical domain-wall fermion (DWF) lattice-QCD ensemble generated by UKQCD and RBC Collaborations at momentum cutoff of 1.730(4) GeV and lattice spatial extent of 5.476(12) fm.

Approaching conformality with the Tensor Renormalization Group method

Author: Yannick Meurice\(^1\)

Co-authors: Haiyuan Zou\(^2\); James Osborn\(^3\); Judah Unmuth-Yockey\(^4\); Li-Ping Yang\(^5\); Yuzhi Liu\(^6\)

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We discuss the Tensor Renormalization Group (TRG) method for various spin and gauge lattice models in 1+1 dimensions with emphasis.
on near gapless/conformal situations. We present recent progress on optimized truncation methods. We describe the entanglement entropy in the superfluid phase of the O(2) model with a chemical potential.

Nonzero Temperature and Density / 254

**Pure SU(3) Topological Susceptibility at Finite Temperature with the Wilson Flow**

**Authors:** Kálmán Szabó; Simon Mages; Szabolcs Borsányi; Zoltán Fodor

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We give a summary of our preliminary results on the finite temperature topological susceptibility $\chi$ from pure SU(3) theory. The simulations use a Symanzik improved action and a gluonic definition of the topological charge with cutoff effects at the $a^2$ level. We use the Wilson flow to calculate a properly renormalized topological charge and its susceptibility. Our results suggest a very strong decay of the topological susceptibility above $T_c$ in line with the results in literature.

Hadron Spectroscopy and Interactions / 287

**Zc(3900) from coupled-channel HAL QCD approach on the lattice**

**Author:** Yoichi Ikeda

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We study the candidate of charmed tetraquark Zc(3900) from full QCD simulation. The Zc(3900) was first reported by both BESIII and Belle Collaborations in $\pi J/\psi$ invariant mass spectrum. After that, structure of the Zc(3900) is actively discussed using many phenomenological models. However, due to lack of information of the interactions of the $\pi J/\psi$ and its coupled systems, the predicted structures of the Zc(3900) are highly dependent on model parameters so that the information on the coupled-channel interactions are necessary to conclude the structure.

We perform the coupled-channel analysis for the Zc(3900) through the HAL QCD method. We measure wave functions (NBS wave functions) on the lattice, and extract the potential matrix. Using the interactions obtained from LQCD, we investigate the $\pi J/\psi$ and $D\bar{D}^{*}$ invariant mass spectra of 2-body scatterings, the pole position of the scattering amplitudes on the complex energy plane, and production reaction of the Zc(3900) from Y(4260) decay. I will report those results for the Zc(3900).

Poster Session - Board: 26 / 296

**Lattice QCD code set Bridge++ on arithmetic accelerators**

**Author:** Shinji Motoki
We are developing a code set “Bridge++” for simulations of lattice gauge theories that aims at an extensible, readable, and portable workbench, while achieving high performance. This work concerns the design of Bridge++ to incorporate the accelerator devices, such as GPUs. As generic frameworks for heterogeneous programming using CPU and accelerator devices, we apply OpenCL and OpenACC to Bridge++. OpenCL and OpenACC are based on different policies. The former explicitly controls the devices through API functions, while the latter is a directive-based extension of a programming language. The inversion of a fermion matrix is offloaded to the accelerator devices. From a viewpoint of constructing reusable components based on the object-oriented programming, as well as tuning the code to achieve high performance, we evaluate feasibility of these frameworks.

**SU(2) gauge theory with domain-wall fermions in fundamental and adjoint representations**

**Author:** Hideo Matsufuru¹

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We study the SU(2) gauge theory with dynamical domain-wall fermions in fundamental and adjoint representations. Dynamical simulations with fundamental fermions are performed with numbers of flavors $N_f=2,4,6$, and 8. $N_f$ dependence of the meson masses and decay constants are investigated. The same analyses are applied also to the adjoint fermions, based on the investigation of the Aoki phase structure of the Wilson fermion operator.

**Bosonization analysis for artificial ”atomic collapse” in graphene**

**Authors:** Aya Kagimura¹; Tetsuya Onogi²
Around a large charge with atomic number $Z > 137$, the QED vacuum is expected to collapse due to the strong Coulombic force. While the relativistic quantum mechanics fails to make reliable predictions for the fate of the vacuum, the heavy ion collision experiment also does not give clear understanding of this system.

Recently, the "atomic collapse" resonances were observed on graphene where an artificial nuclei can be made.

In this poster, I will present our non-perturbative study of the vacuum structure which contains multi-body effect using bosonization method.

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**Poster Session** - Board: 38 / 199

**A novel computation of the thermodynamics of SU(3) Yang-Mills theory**

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We present an accurate computation of the Equation of State of SU(3) Yang-Mills theory using shifted boundary conditions in the temporal direction. In this framework, the entropy density $s(T)$ can be obtained in a simple way from the v.e.v. of the space-time components $T_{0k}$ of the energy-momentum tensor. Furthermore, contrary to the standard approach, the Equation of State $s(T)/T^3$ can be measured in an independent way at any value of the temperature. The extrapolation to the continuum limit shows almost no dependence on the lattice artifacts.

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**Poster Session** - Board: 7 / 108

**The Rho Resonance from N_f=2+1+1 Twisted Mass Lattice QCD**

**Author:** Markus Werner

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We present first results for I=1 p\pi scattering with N_f=2+1+1 twisted mass fermions utilizing the sLapH method. The rho mass and decay width are computed for various pion masses and lattice spacings. Special care was taken in the analysis of systematic uncertainties.
The 33rd International Symposium on Lattice Field Theory (Lattice 2015) / Book of Abstracts

**Poster Session** - Board: 40 / 106

**The Nonlinear O(3) Model with Chemical Potential in a Dual Representation**

**Author:** Thomas Kloiber

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We study the two dimensional nonlinear O(3) model with a chemical potential coupled to the conserved charge. The complex action problem occurring at nonzero chemical potential is solved by means of a duality transform, which yields real and positive weights and makes Monte Carlo simulations feasible. We find a phase transition at the end of a Silver Blaze region, where a net number of particles appears in the system. We show various results for bulk observables and correlators at finite chemical potential and discuss their finite size behavior. Furthermore, an approximate method to obtain the two particle potential is discussed.

**Poster Session** - Board: 22 / 104

**S-parameter and vector decay constant in QCD with eight fundamental fermions**

**Authors:** Akihiro Shibata \(^1\); Ed Bennett \(^2\); Enrico Rinaldi \(^3\); Hiroshi Ohki \(^4\); Kei-ichi Nagai \(^5\); Kohtaroh Miura \(^6\); Koichi Yamawaki \(^5\); Masafumi Kurachi \(^7\); Takeshi Yamazaki \(^7\); Tatsumi Aoyama \(^7\); Toshihide Maskawa \(^5\); Yasumichi Aoki \(^5\)

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SU(3) gauge theory with eight massless fundamental fermions seems to be near the conformal boundary, and is a candidate of walking technicolor. Along the series of study by LatKMI collaboration using HISQ fermions, S-parameter and vector decay constant, which provide important constraints in the model building, are calculated for this theory. Use of various volumes allows a systematic investigation of finite volume effect, where a strong sensitivity on the S-parameter is found.

**Poster Session** - Board: 39 / 38

**Beating the sign problem in finite density lattice QCD**

**Author:** Atsushi Nakamura

Page 62
Co-authors: Asobu Suzuki; Keitaro Nagata; Ryutaro Fukuda; Shotaro Oka; Shuntaro Sakai; Yusuke Taniguchi

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At finite density lattice QCD, the famous sign problem has prevented us from studying the QCD phase diagram based on the first-principle calculation. In order to circumvent the problem, we propose a method where we put new wine into old wineskins: i.e., we use an old idea, “canonical approach”, but put into it a new ingredient, multi-precision calculations. This is free from the usual limitation due to Taylor expansion.

We briefly present the history of the canonical partition function method, describe our formulation, and show outcomes of the first test, which are very promising and encourages us to go to the final stage, i.e., the study of the QCD under extreme conditions by realistic simulations at small quark masses and on large lattices.

Poster Session - Board: 42 / 338

Grassmann tensor renormalization group for the lattice Gross-Neveu model with finite chemical potential

Author: Yusuke Yoshimura

Co-author: Shinji TAKEDA

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In numerical calculation of the lattice QCD, the sign problem of Monte Carlo methods has been a major issue. A numerical renormalization group called tensor renormalization group (TRG) is one of the candidates for the solution of this problem. Grassmann tensor renormalization group (GTRG) is a generalization of the TRG to fermion systems. In this study, We apply the GTRG to the lattice Gross-Neveu model in the presence of a chemical potential as a benchmark for future works in finite density systems.

Poster Session - Board: 37 / 93

Towards the QCD equation of state at the physical point using Wilson fermion

Author: Takashi Umeda

Co-authors: Kazuyuki Kanaya; Ryo Iwami; Shinji Ejiri

1 Hiroshima University
We study the \(N_f = 2 + 1\) QCD at nonzero temperatures using nonpertubatively improved Wilson quarks of the physical masses by the fixed scale approach. We perform physical point simulations at finite temperatures with the coupling parameters which were adopted by the PACS-CS collaboration in their studies using the reweighting technique. Zero temperature values are obtained on the PACS-CS configurations which are open to the public on the ILDG. Finite temperature configurations are generated with the RHMC algorithm. The lattice sizes are \(32^3 \times N_t\), that \(N_t = 14, 13, \cdots, 4\) correspond to \(T \approx 140 - 500\,\text{MeV}\). We present some basic observables at these temperatures and the status of our calculation of the equation of state.

**Poster Session - Board: 5 / 94**

**Determination of \(\varepsilon_K\) using lattice QCD inputs**

**Author:** Weonjong Lee

**Co-authors:** Jon Bailey \(^1\); Yong-Chull Jang \(^1\)

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We present the Standard Model evaluation of the indirect CP violation parameter \(\varepsilon_K\) determined using lattice QCD inputs: \(B_K, \zeta_0, V_{us}, \text{ and } V_{cb}\).

We find that the Standard Model prediction of \(\varepsilon_K\) with exclusive \(V_{cb}\) (lattice QCD results) is lower than the experimental value by 3.6\(\sigma\).

However, this tension disappears with inclusive \(V_{cb}\) (results of heavy quark expansion).

**Poster Session - Board: 10 / 235**

**Towards string breaking with 2+1 dynamical fermions using the stochastic LapH-method**

**Author:** Vanessa Koch

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We investigate the use of stochastically estimated light quark propagators in correlation functions involving a static color source. To this end we compute the static-light meson correlation function in the stochastic LapH framework, using \(N_f = 2 + 1\) gauge configurations generated through the CLS effort. Together with the static potential, we obtain an estimate for the expected string breaking distance.
Study of the conformal phase of the SU(3) gauge theory with domain-wall fermions

Author: Jun Noaki

Co-authors: Guido Cossu; Ken-Ichi Ishikawa; Tomoteru Yoshie; Yoichi iwasaki

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We study the vacuum structure of the SU(3) gauge theory with the flavor number within the conformal region. We perform numerical simulation employing the massless Domain-Wall fermions with the one-step stout smearing.

We investigate a conjecture based on the idea of “the conformal field theories with an IR cutoff”, which was recently studied using the Wilson fermions. Dealing with the Polyakov loops, the pseudo-scalar correlators and the anomalous mass-dimension, we collect further supporting evidence of this conjecture.

Monte Carlo studies of dynamical compactification of extra dimensions in a model of nonperturbative string theory

Author: Takehiro Azuma

Co-authors: Jun Nishimura; Konstantinos N. Anagnostopoulos

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The IIB matrix model has been proposed as a nonperturbative definition of superstring theory. In this work, we study the Euclidean version of this model in which extra dimensions can be dynamically compactified if a scenario of the spontaneous breakdown of the SO(10) rotational symmetry is realized. Monte Carlo calculations of the Euclidean IIB matrix model suffer from a very strong complex action problem due to the large fluctuations of the complex phase of the Pfaffian after integrating out the fermion. We employ the factorization method to achieve the effective sampling. We report on preliminary results that can be compared with previous studies of the rotational symmetry breakdown using the Gaussian expansion method.

Adaptive algebraic multigrid on SIMD architectures

Author: Simon Heybrock

Co-authors: Matthias Rottmann; Peter Georg; Tilo Wettig
We present details of our implementation of the Wuppertal adaptive algebraic multigrid code on SIMD architectures, with particular emphasis on the Intel Xeon Phi processor (KNC) used in QPACE 2. As a smoother, the algorithm uses a domain-decomposition-based solver code previously developed for the KNC in Regensburg. We optimized the remaining parts of the multigrid code and conclude that it is a very good target for SIMD architectures. Some of the remaining bottlenecks can be eliminated by a multiple-right-hand-sides setup, which is discussed in the contribution of Daniel Richtmann.

**Poster Session** - Board: 25 / 24

**Grid: A next generation C++ library for data parallel QCD**

*Author:* Azusa Yamaguchi

*Co-author:* Peter Boyle

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We discuss progress and performance from the development of the Grid data parallel interface for cartesian fields of tensor data types. The library is suitable for the simulation of QCD including multiple grids. Wherever appropriate the interface is quite similar to that of QDP++, but the library makes use of C++11 features to reduce the volume of code, compared to QDP++ while bringing greater generality and greater performance.

While the library simultaneously targets MPI, OpenMP and SIMD parallelism, the SIMD optimisation is notably flexible. Performance is substantially improved through the use of a data layout transformation and benchmark results are presented for simple Lattice QCD operations and the Wilson operator under AVX, AVX2 and AVX512 instruction set targets.

This work is performed as part of the Intel Parallel Computing Centre in the Higgs Centre for Theoretical Physics at Edinburgh.

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Content

We discuss progress and performance from the development of a data parallel interface for cartesian fields of tensor data types. The library is suitable for the simulation of QCD including multiple grids. Wherever appropriate the interface is quite similar to that of QDP++, but the library makes use of C++11 features to reduce the volume of code, compared to QDP++ while bringing greater generality and greater performance.

While the library simultaneously targets MPI, OpenMP and SIMD parallelism, the SIMD optimisation is notably flexible. Performance is substantially improved through the use of a data layout transformation and benchmark results are presented for simple Lattice QCD operations and the Wilson operator under AVX, AVX2 and AVX512 instruction set targets.
Exploring free-form smearing for bottomonium and B meson spectroscopy

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Co-authors: Mark Wurtz; Randy Lewis

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Free-form smearing was designed as a way to implement source operators of any desired shape. A variation of the method is introduced that reduces the computational cost by reducing the number of link multiplications to its absolute minimum. Practical utility is demonstrated through calculations of bottomonium and B meson masses.

Mass anomalous dimension of SU2 with Nf=8 using the spectral density method

Author: Joni Suorsa
Co-authors: Jarno Rantaharju; Kari Rummukainen; Kimmo Tuominen; Teemu Rantalaiho; Viljami Leino

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SU2 with Nf=8 is believed to have an infrared conformal fixed point. We use the spectral density method to evaluate the coupling constant dependence of the mass anomalous dimension. We use massless theory with Schrödinger functional boundary conditions and HEX smeared Wilson clover fermions.

Performance of Maxwell GPUs and Optimization of Non-Perturbative Renormalization codes.

Authors: Jeonghwan Pak; Weonjong Lee
Co-authors: Hwancheol Jeong; Jangho Kim; Sangbaek Lee

1 Seoul National University
2 Seoul National university
Matching factors for the four-fermion operators relevant to $B_K$ are obtained using the Non-Perturbative Renormalization (NPR) method in the RI-MOM scheme. Our NPR codes are calculated in Double Precision (DP) and optimized on Fermi GPU. NVIDIA released The GTX Titan X based on the Maxwell architecture. The Single Precision (SP) calculation performance of the GTX Titan X is improved, but the ratio of DP performance to SP performance is low. Hence, We optimize NPR codes on GTX Titan X and measure its scalability on Multi GPUs. And, we measure the performance of GTX Titan X using our conjugate gradient (CG) solver.

**Poster Session** - Board: 9 / 185

**Update on the Heavy-Meson Spectrum Tests of the Oktay–Kronfeld Action**

**Author:** Yong-Chull Jang

**Co-authors:** Andreas Kronfeld; Carleton DeTar; Jon Bailey; Mehmet Oktay; Weonjong Lee

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We present updated results of the heavy-meson spectrum obtained using the Oktay–Kronfeld (OK) action on MILC asqtad lattices. The OK action was designed to improve the heavy-quark action of the Fermilab formulation by including complete dimension six and part of dimension seven bilinear improvement terms. Improvement terms are truncated by power counting of order $\Lambda^3/m^3$ for heavy-light system and $v^6$ for quarkonium. They suffice for tree-level matching to QCD of the given order from the power counting. To assess the improvement, we update previous numerical tests with heavy meson masses by generating new data that covers both charm and bottom quark mass regions on an ensemble of lattice spacing $a = 0.12$ fm. We update the analyses of the inconsistency parameter and the hyperfine splittings for the rest and kinetic masses.

**Poster Session** - Board: 2 / 188

**calculation of strange and light quark condensate using improved staggered fermions and overlap fermions**

**Authors:** Hwancheol Jeong; Weonjong Lee

**Co-authors:** Nigel Cundy; Seung-Yeob Jwa

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We calculate the strange quark condensate and the light quark condensate by using improved staggered fermions and overlap fermions, respectively. Then we report the mass dependence of the quark condensate. We use $N_f = 2+1+1$ MILC HISQ (highly improved staggered quark) gauge ensembles. We use a normal CG inverter to calculate the quark condensates for higher quark masses, and the Lanczos and the eigCG algorithms for lower quark masses. We also study the multi-mass algorithm.
Non-perturbative Renormalization with RI-MOM scheme for Bilinear Operators on the Fine Lattice

Authors: Hwancheol Jeong\(^1\); Jeonghwan Pak\(^1\); Sungwoo Park\(^1\); Weonjong Lee\(^1\); Jangho Kim\(^2\)

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We present the preliminary results of the wave function renormalization factor \(Z_q\) and mass renormalization factor \(Z_m\) from the bilinear operators obtained using non-perturbative renormalization method (NPR) in the RI-MOM scheme with improved staggered fermions.

We use fine ensembles of MILC asqtad lattices \((N_f=2+1)\) with \(28^3 \times 96\) geometry and \(am_\ell/ am_s = 0.0062 / 0.031\).

We also present the dependence of lattice spacing for \(Z_q\) and \(Z_m\) by comparing the results of coarse and fine lattices.

Isospin splitting in Wilson chiral perturbation theory for twisted-mass lattice-QCD with three non-degenerate quark flavours

Author: Gernot Münster\(^1\)

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We present the expansions of the masses of the pseudoscalar mesons in chiral perturbation theory at next-to-leading order for twisted mass lattice QCD with three light quark flavours, taking the mass difference between the up and down quarks into account.

Investigating some technical improvements to glueball calculations.

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Preliminary results for the effect of open boundary conditions on the masses of glueballs and the probability distributions of glueball correlators, in quenched QCD, are presented. Initial results from glueball correlators computed on unquenched ensembles downloaded from the ILDG data grid are reported.
**Poster Session** - Board: 6 / 207

**Heavy-heavy current improvement for calculating B^− → D^+(*) lv^− semi-leptonic form factors with Oktay-Kronfeld quarks.**

**Authors:** JAEHOON LEEM¹; Jon Bailey¹; WEONJONG LEE¹; Yong-Chull Jang¹

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We improve heavy-heavy currents for calculating B^− → D^+(*) lv^− semi-leptonic form factors with Oktay-Kronfeld (OK) heavy quarks. The OK action, which has dimension 6 and 7 interaction terms, can control the discretization errors of heavy quarks (b and c quarks). The OK action is improved through third order in HQET power counting. We report work on heavy-heavy currents to get the systematic improvement of the hadronic matrix elements for B^− → D^+(*) lv^− processes with the OK action.

**Poster Session** - Board: 33 / 76

**Instantaneous Stochastic Perturbation Theory and Gradient flow in φ⁴ theory**

**Authors:** Anthony D. Kennedy¹; Marco garofalo²; Mattia Dalla Brida³

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Lüscher recently introduced Instantaneous Stochastic Perturbation Theory (ISPT) as a method for the stochastic evaluation of lattice perturbation theory. We present an exploratory study of its properties in φ⁴ theory, and we compare it with both analytical computations and Numerical Stochastic Perturbation Theory. In addition, we propose a automated method based on ISPT for solution of the Gradient flow equations.

**Poster Session** - Board: 4 / 70

**Determination of f_K/f_π from staggered Nf=2+1+1 ensembles**

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Preliminary results are presented from a new determination of f_K/f_π which is based on a series of staggered Nf=2+1+1 simulations in the vicinity of the physical point. Special emphasis is put on the interpolation to the physical point, the finite-volume corrections, the continuum extrapolation and the breaking of the isospin symmetry.
**Overlap fermions on GPUs**

*Author:* Nigel Cundy¹  
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We report on our efforts to implement overlap fermions on NVIDIA GPUs using CUDA, commenting on the algorithms used, implementation details, and the performance of our code.

**Proposal for the Quantum Simulation of the CP(2) Model on Optical Lattices**

*Authors:* Catherine Laflamme¹; Hector Mejia-Diaz²; Marcello Dalmonte³; Peter Zoller¹; Urs Gerber³; Uwe-Jens Wiese³; Wolfgang Bietenholz²; Wynne Evans³

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The 2d CP(N-1) models share a number of features with QCD, like asymptotic freedom, a dynamically generated mass gap, and topological sectors. They have been formulated and analysed successfully in the formalism of the so-called D-theory. In that framework, we propose an experimental set-up for the quantum simulation of the CP(2) model. It is based on ultracold alkaline-earth-atoms located on the sites of an optical lattice, where the nuclear spins represent the relevant fields. We present results for the correlation length and for tunnelling transitions, to be compared with such a future experiment. The latter would also enable the exploration of theta vacua and the phase diagram at finite chemical potential, since it does not suffer from the sign problem.

**The step scaling function of the SU(3) 2 flavor sextet model with Wilson fermions**

*Author:* Anna Hasenfratz¹  
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We investigate the discrete $\beta$ function of the 2-flavor SU(3) sextet model using the gradient flow scheme. Staggered fermion investigations suggest that the system is chirally broken, contradicting earlier Schroedinger functional Wilson fermion studies that were consistent with conformality. Our results, using improved Wilson fermions and the gradient flow RG scheme, suggests a step scaling function that differs significantly from the perturbative 2-loop prediction and in tension with the staggered results. Considering the potential phenomenological impact of this model, it is important to resolve this disagreement.

**Poster Session** - Board: 34 / 163

**Precision study of critical slowing down in lattice simulations of the CP^{N-1} model**

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With the aim of studying the relevance and properties of critical slowing down in Monte Carlo simulations of lattice quantum field theories we carried out a high precision numerical study of the discretised two-dimensional CP^{N-1} model at N=10 using an over-heat bath algorithm. We identify critical slowing down in terms of slowly-evolving topological modes and present evidence that other observables couple to these slow modes. This coupling is found to reduce however as we increase the physical volume in which we simulate.

**Poster Session** - Board: 3 / 215

**Stochastic calculation of the QCD Dirac operator spectrum with Mobius domain-wall fermion**

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We calculate the spectral function of the QCD Dirac operator using the four-dimensional effective operator constructed from the Mobius domain-wall implementation. We utilize the eigenvalue filtering technique combined with the stochastic estimate of the mode number. The spectrum in the entire eigenvalue range is obtained with a single set of measurements. Results on 2+1-flavor ensembles with Mobius domain-wall sea quarks at lattice spacing ~0.08 fm are shown.
An application of the hybrid Monte Carlo algorithm for realized stochastic volatility model

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The hybrid Monte Carlo (HMC) algorithm has been widely used for dynamical lattice QCD simulations. One of the advantages of using the HMC algorithm is that it is a global algorithm that can update all link variables simultaneously. In this way we can greatly reduce computational cost concerning the fermionic part. We utilize this advantage for parameter estimations of the realized stochastic volatility model which has been used for modelling time series data. The realized stochastic volatility model includes a number of volatility variables to be updated. We update those variables by the HMC algorithm. It is found that the HMC algorithm de-correlates effectively Monte Carlo samples of volatility variables. We also show that the algorithm can be accelerated by the GPU computing.

Poster Session - Board: 15 / 210

The static three-quark potential of various quark configurations

**Author:** Miho Koma

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We study the static three-quark potential in SU(3) lattice gauge theory at zero temperature with the Polyakov loop correlation function consisting of three Polyakov loops. By employing the multi-level algorithm we overcome the smallness of the signal to noise ratio and obtain remarkably clean signals.

We extend our previous investigation of the three-quark potential and compute the potential for some eccentric cases such that the three quarks are located at the vertices of obtuse triangles, and are located in line.

We compare these results with the cases that the three quarks are located at the vertices of the equilateral, the isosceles, and the right triangles.

Poster Session - Board: 35 / 288

Strong coupling expansion of the generalized t-V model in one dimension

**Author:** Marcin Szymiszewski

**Co-author:** Evgeni Burovski

1 Lancaster University
We employ a strong coupling expansion - similar to the one used in the lattice field theory studies [1] - to solve the one-dimensional extended t-V model of fermions on a lattice [2]. This model is solved for a range of filling factors, including both commensurate - where a charge density wave is present - and incommensurate densities. The first set consists not only of a trivial case of half filling. The method allows us to trace the transition from a Luttinger liquid phase to a Mott insulating phase and calculate the critical parameter K. This simple yet powerful method is not based on Bethe ansatz and it works for both integrable and non-integrable systems. Furthermore, we investigate how tailoring the interaction can introduce other ordered phases of the system [3].


Poster Session - Board: 11 / 267

**Lattice QCD study of the I=0 scalar channel using four-quark operators**

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We study the possible significance of four-quark states in the isosinglet scalar mesons ($J^{PC} = 0^{++}$, $I=0$) by performing two-flavor full lattice QCD simulations on an $8^3 \times 16$ lattice using the improved gauge action and the clover-improved Wilson quark action. In particular, we evaluate the propagators of molecular and tetraquark operators together with singly disconnected diagrams. In the computation of the singly disconnected diagrams we employ the $Z_2$-noise method with the truncated eigenmode approach. We show that the quark loops given by the disconnected diagrams play an essential role in propagators of tetraquark and molecular operators.

Poster Session - Board: 16 / 58

**Mass and Axial current renormalization in the Schrödinger functional scheme for the RG-improved gauge and the stout smeared $O(a)$-improved Wilson quark actions.**

**Author:** Ken-Ichi Ishikawa

**Co-authors:** Naoya Ukita; Naruhiito Ishizuka; Takeshi Yamazaki; Tomoteru Yoshie; Yoshifumi Nakamura; Yoshinobu Kuramashi; Yusuke Namekawa; Yusuke Taniguchi
We present the quark mass and axial current renormalization factors for the RG-improved gauge and the stout smeared $O(a)$-improved Wilson quark actions. The $O(a)$ improvement coefficient for the three-flavors of dynamical quarks has been determined previously with the stout-link smearing parameter $\alpha = 0.1, n = 6$. We employ the Schrödinger functional scheme and obtain the renormalization factors at $\beta = 1.82$ with three-flavors of quarks where a large scale simulation is being carried out.

Poster Session - Board: 13 / 56

The one-loop analysis of the beta-function in the Schroedinger Functional for Moebius Domain Wall Fermions

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Last year we reported the property of the Moebius Domain Wall Fermions (MDWF) in the Schroedinger Functional (SF) scheme with the palindromic fifth dimensional parameters and the appropriate boundary operator at the tree-level, and the non-universal behavior for a small fifth direction extent $N_5$. We find that this behavior comes from the residual mass at the tree-level and the universality of the MDWF in the SF setup is confirmed after removal of the residual mass even if the value of $N_5$ is small. Moreover we discuss the scaling property of the one-loop contribution to the beta function based on this set up.

Poster Session - Board: 14 / 253

Quark Spin in Proton from Anomalous Ward Indentity

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We report a quark spin calculation from the anomalous Ward identity with overlap fermions on 2+1 flavor dynamical fermion configurations. Such a formulation decomposes the divergence of the flavor-singlet axial-vector current into a quark pseudoscalar term and a triangle anomaly term, flavor
by flavor. We use the overlap fermion for the valence and the quark loop so that the renormalization constants $Z_m$ and $Z_P$ cancel in the pseudoscalar operator $2mP$. In addition, the overlap Dirac operator is used to calculate the local topological charge in the anomaly so that there is no renormalization for the anomaly term either.

**Poster Session** - Board: 23 / 154

**A new method to calculate the Dirac operator spectral density**

**Author:** Kieran Holland

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We describe a new method to determine in a stochastic fashion the Dirac operator spectral density over the entire range of eigenvalues. This allows for example studies of the chiral limit of the fermion condensate, the mode number and the anomalous mass dimension. We apply this technique to the 2-flavor sextet SU(3) gauge theory, to investigate this theory’s viability as a minimal realization of the composite Higgs scenario.

**Poster Session** - Board: 29 / 112

**Multiple right-hand side setup for the DD-\(\alpha\)AMG**

**Author:** Daniel Richtmann

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The setup cost of a modern solver such as the DD-\(\alpha\)AMG (Wuppertal Multigrid) is a significant contribution to the total time spent on solving the Dirac equation, and in HMC it can even be dominant. We present an improved implementation of this algorithm with modified computation order in the setup procedure. By processing multiple right-hand sides simultaneously we can alleviate many of the performance issues of the default single right-hand side setup. The main improvements are as follows:

- Many matrix-vector products are replaced by matrix-matrix products, leading to better cache reuse.
- The synchronization overhead inflicted by on-chip parallelization (threading), which is becoming crucial on many-core architectures such as the Intel Xeon Phi, is effectively reduced. By combining multiple right-hand sides the message size for off-chip communication is larger, which leads to better utilization of the network bandwidth.
- In the parts implemented so far, we observe a speedup of roughly 2x compared to the optimized version of the single right-hand side setup on realistic lattices.

**Nonzero Temperature and Density / 195**

**Study of high density phase transition in lattice QCD with canonical approach**

**Author:** Yusuke Taniguchi

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The canonical partition function is related to the grand canonical one through the fugacity expansion.
In this talk we perform the fugacity expansion by a method of the hopping parameter expansion in temporal direction.
The canonical partition function is evaluated for $N_f=2$ QCD up to baryon numbers of $n_B=30$ in a wide range of temperature.
After derivation of the canonical partition function we study the chemical potential dependences of hadronic observables like chiral condensate, quark number density and its susceptibility.
In this talk we report a phase transition found at real chemical potential and its dependence on the quark mass and the volume.

Hadron Structure / 103

Applications of the Feynman–Hellmann theorem in hadron structure

Author: Ross Young

Co-authors: Alexander Chambers ¹; Arwed Schiller ²; Dirk Pleiter ³; Gerrit Schierholz ⁴; Hinnerk Stüben ⁵; Holger Perlt ⁶; James Zanotti ⁷; Kim Somfleth ¹; Paul Rakow ⁷; Roger Horsley ⁸; Yoshifumi Nakamura ⁹

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By considering an appropriate modification of the action, the Feynman–Hellman (FH) theorem provides an alternative technique for studying hadron matrix elements. We report on new developments in the extension of the FH technique to the study of non-forward matrix elements, where preliminary results demonstrate the feasibility of accessing relatively large momentum transfers. In the near future, these methods offer the potential to address physics topics such as the transition to the perturbative regime in the pion form factor and the possible zero crossing in the proton’s electric form factor. We also present updated results on the extraction of the quark spin fractions in a range of hadrons, including contributions from disconnected operator insertions. At the quark masses studied, the results suggest a negative contribution to the total quark spin of the nucleon from disconnected insertions.

Hadron Spectroscopy and Interactions / 29
X(3872) and Y(4140) using diquark-antidiquark operators with lattice QCD

Author: Padmanath Madanagopalan 1
Co-authors: C. B. Lang 1; Sasa Prelovsek 2

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I will discuss recent lattice study of charmonium-like mesons with $J^{PC} = 1^{++}$ and three quark contents $c\bar{c}d\bar{u}$, $c\bar{c}(u\bar{u} + d\bar{d})$, and $c\bar{c}ss$, where the latter two can mix with $c\bar{c}$. In this quantum channel, the long known exotic candidate, X(3872), resides. This simulation employs $N_f = 2$, $m_u = 266$ MeV and a large basis of $c\bar{c}$, two-meson and diquark-antidiquark interpolating fields, with diquarks in both anti-triplet and sextet color representations. It aims at the possible signatures of four-quark exotic states. Along the way, I will discuss the relations between the diquark-antidiquark operators and the two-meson operators via the Fierz transformations.

Chiral Symmetry / 3

Exotic Quantum Critical Points with Staggered Fermions

Author: Venkit Ayyar 1

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We study two flavors of massless staggered fermions interacting via an on-site four-fermion interaction and argue that the model contains an exotic quantum critical point separating the perturbative massless phase from a massive fermion phase at strong couplings where the fermion bilinear condensate remains zero. We believe that no spontaneous symmetry breaking occurs at the transition. We have extensive calculations in three Euclidean dimensions that are consistent with the existence of a single second order phase transition separating the two phases. Although mean field theory suggests that this transition will turn first order at sufficiently large number of dimensions, preliminary results suggest that the transition remains second order in four-dimensions.

Weak Decays and Matrix Elements / 250

Neutral B meson mixings and B meson decay constants in the infinite b quark mass limit with domain-wall light quarks

Author: Tomomi Ishikawa 1
Co-authors: AMARJIT SONI 2; Christoph Lehner 3; Chulwoo Jung 4; Taku Izubuchi 5; Yasumichi Aoki 6

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Neutral B meson mixing matrix elements and B meson decay constants are calculated in the infinite \(b\) quark mass limit. For the light quarks, domain-wall fermion (DWF) formalism is employed. The calculations are carried out using all-mode-averaging (AMA) technique on \(N_f=2+1\) dynamical DWF ensembles with lattice spacings of nearly 0.08fm and 0.11fm, where pion masses are relatively heavy (>280MeV). We show statistical improvements from our previous results. We also present preliminary results at physical pion mass using \(48^3\) dynamical Mobius DWF ensemble mainly for B\(_s\) quantities.

**Template Composite Dark Matter : SU(2) gauge theory with Nf=2**

**Author:** Vincent Drach

**Co-authors:** Ari Hietanen \(^2\); Claudio Pica \(^2\); Francesco Sannino \(^2\); Jarno Rantaharju \(^2\); Martin Hansen \(^2\)

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We present a non perturbative study of SU(2) gauge theory with two fundamental Dirac flavours. We discuss how the model can be used as a template for composite Dark Matter (DM). We estimate two types of interactions of the DM candidate with the Standard Model: the interaction through Higgs exchange and the interaction through photon exchange computing the electric polarizability of the DM candidate. Finally, we briefly discuss the viability of the model given the present experimental constraints.

**Distribution of the k-th smallest Dirac operator eigenvalue : an update**

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Based on the exact relationship to random matrix theory, we present alternative methods of evaluating the probability distribution of the k-th smallest Dirac eigenvalue in the epsilon regime of QCD and related gauge theories. By employing (1) the Nystrom-type evaluation of Fredholm determinants and Pfaffians and/or (2) the interrelationship between tau functions for random matrix ensembles at beta=2,1,4 sharing the weight function, practical troubles and a technical restriction in our previous work [PRD63, 045012 (2001)] are resolved. Especially, this update enables the computation of individual Dirac eigenvalue distributions for a lattice gauge theory with \(4n\) staggered flavors in the pseudo-real representation.
Nonzero Temperature and Density / 30

Exploring finite density QCD phase transition with canonical approach - Power of multiple precision computation -

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The canonical approach is one of the methods that have been pursued to solve the sign problem. However, this approach has the numerical instability, and most people have thought that this approach does not work for a long time.

We found that this instability can be solved by using the multiple precision computation. In this talk, we will study effects of the multiple precision computation and report some physical quantities in the finite density.

Hadron Structure / 0

Gluon saturation and gluon densities

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In the talk I will overview status of QCD at region of phase space when the partons form a dense system leading eventually to parton saturation i.e. situation when the partons are not growing any more due to nonlinear dynamics.

I will overview recent developments leading to construction of gluon densities which take into account saturation effects. Finally I will present predictions for observables which eventually will test saturation phenomenon in p-Pb collisions at LHC.

Hadron Spectroscopy and Interactions / 61

Mass spectrum of mesons containing charm quarks - continuum limit results from twisted mass fermions

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We present results from an on-going computation of masses of D mesons, D_s mesons and charmonium, including both ground states and several parity and angular momentum excitations. We employ 2+1+1 flavours of dynamical maximally twisted mass fermions at three lattice spacings and...
three u/d quark masses at each lattice spacing. We consider different combinations of valence quarks, with either identical or opposite signs in front of the twisted mass terms. In the end, our setup allows for a good control of different kinds of systematic effects, in particular the quark mass dependence of the resulting meson masses and cut-off effects. We obtain very good agreement with experiment for the well-established states and some of our results are predictions.

Weak Decays and Matrix Elements / 289

Decay constants $f_B$ and $f_{B_s}$ from HISQ simulations

Author: Javad Komijani

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We present preliminary, high-precision results for the decay constants $f_B$ and $f_{B_s}$ from simulations with HISQ heavy and light valence and sea quarks. Calculations are carried out with several heavy valence-quark masses on ensembles with 2+1+1 flavors of HISQ sea quarks at five lattice spacings and three light sea quark mass ratios $m_{ud}/m_s$, including approximately physical sea quark masses. This range of parameters provides excellent control of the continuum limit and of heavy-quark discretization errors.

Physics Beyond the Standard Model / 150

Stealth Dark Matter on the lattice

Author: Enrico Rinaldi

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The Stealth Dark Matter model contains a candidate composite dark matter particle which appears as a bosonic neutral baryon of a new strongly coupled sector. The elementary constituents of this composite state carry electroweak charges. This construction provides a mechanism to naturally reduce the strength of dark matter interactions with standard model particles. However such interactions exist and can allow direct detection, and collider experiments to put constraints on the model. In order to get predictions from this strongly-coupled model, lattice simulations are employed and give definite predictions for the cross-section of the dark matter candidate with standard nuclei in detectors for example. Lattice simulations are shown to be of utmost relevance for some dark matter models and they are increasingly important to obtain phenomenological predictions of experimental interest.

Weak Decays and Matrix Elements / 277

Neutral $B$-meson and $D$-meson mixing bag parameters from 2 + 1 flavor lattice QCD

Author: James Simone$^1$

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We compute hadronic matrix elements for neutral $B$-meson mixing in the Standard Model and beyond as well as the corresponding operators for the the short-distance contribution to $D$-meson mixing. On the same sets of gauge ensembles, we calculate the leptonic decay constants for the $B$- and $D$-meson systems. The matrix elements are computed with asqtad light quarks and clover heavy quarks in the Fermilab interpretation. We use the MILC asqtad gauge ensembles at four lattice spacings between 0.11 fm and 0.043 fm. We review the the matrix element calculations and report on the determination of the bag parameters. The bag parameters are computed by combining the mixing matrix elements and the decay constant results in a bootstrap process which accounts for correlations from both statistics and the dominant systematic errors. Some systematic effects, such as discretization errors, and quark mass tunings, tend to cancel in ratios.

Hadron Structure / 330

Nucleon-Sigma-Terms from Lattice QCD

Author: Lukas Varnhorst$^1$

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The nucleon-sigma-terms are measures of the light-quark- and strange-quark-content of the nucleon. Especially the strangeness-content is of significant interest for dark-matter searches, as it determines the coupling of several dark matter candidates to hadronic matter. While the sigma-terms can not be measured directly they can be determined via lattice QCD from first principles.

The sigma-terms are related to the light- and strange-quark mass dependence of the nucleon mass by the Feynman-Hellmann-theorem. To measure this dependence we used \( N_f = 1+1+1+1 \) ensembles generated with tree-level improved Symanzik gauge action and tree-level improved clover Wilson fermions with three levels of HEX smearing at four values of the lattice spacing.

Nonzero Temperature and Density / 14

Validity range of canonical approach to finite density QCD

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We calculate the baryon chemical potential (\(\mu\)) dependence of thermodynamic observables, i.e., pressure, baryon number density and susceptibility by lattice QCD using the canonical approach with winding number expansion. We compare the results with those obtained by the multi parameter reweighting (MPR) method; Both methods give very consistent values in the regions where errors of the MPR are under control. The canonical method gives reliable results up to \(\mu/T=3\).

Hadron Spectroscopy and Interactions / 73

Ground state charmed meson spectra for \( N_f = 2 + 1 + 1 \)

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We present a preliminary study of the charmed meson spectra using the electrically neutral subset of the new Budapest-Marseille-Wuppertal \( N_f = 2 + 1 + 1 \) gauge configurations that utilise the 3-HEX smeared clover action. The analysis is performed with a focus on the hyperfine splitting.

Chiral Symmetry / 310

The microscopic Twisted Mass Dirac spectrum and the spectral determination of the LECs of Wilson \( \chi \)-PT
**Authors:** Elena Garcia-Ramos\(^1\); Karl Jansen\(^2\); Kim Splittorff\(^3\); Krzysztof Cichy\(^4\); Savvas Zafeiropoulos\(^4\)

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We present the comparison of the analytical microscopic spectral density for lattice QCD with \(N_f = 2\) twisted mass fermions with the one obtained on the lattice utilizing configurations produced by the ETM collaboration.

We extract estimates for the chiral condensate as well as the low-energy constant \(W_8\) of Wilson \(\chi\)-PT by employing spectral information of the Wilson Dirac operator with fixed index at finite volume.

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**Physics Beyond the Standard Model / 167**

**Lattice QCD and Axion Cosmology**

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The Strong CP Problem can be resolved by introducing an additional global symmetry known as Peccei-Quinn symmetry.

Once PQ symmetry is broken the associated particle, the QCD axion, is a plausible dark matter candidate.

Calculating the cosmological energy density of the axion requires nonperturbative QCD input—the high-temperature topological susceptibility.

I will show results from a pure-glue calculation and examine the implications for the axion mass and coupling.

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**Hadron Spectroscopy and Interactions / 101**

**Exploring possibly existing \(\text{qq-anti-b-anti-b}\) tetraquark states with \(\text{qq = ud, ss, cc}\)**

**Author:** Antje Peters\(^1\)

**Co-authors:** Björn Wagenbach \(^2\); Krzysztof Cichy \(^3\); Marc Wagner \(^2\); Pedro Bicudo \(^4\)

\(^1\) **Goethe-Universität Frankfurt am Main**
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We explore the possible existence of \(\text{qq-anti-b-anti-b}\) tetraquark states, where \(\text{qq}\) denotes two up/down, strange or charm quarks. To this end we compute potentials of two static antiquarks in the presence of the two quarks \(\text{qq}\) of finite mass using lattice QCD. Then
we check, whether these potentials are sufficiently attractive to host bound states. We find strong indication for a bound four-quark state for \( q\bar{q} = (ud-du)/\sqrt{2} \), i.e. isospin \( I=0 \). At the same time there is clear evidence against the existence of \( q\bar{q}-\bar{b}b \) tetraquarks with strange or charm flavor or isospin \( I=1 \).

**Hadron Structure / 339**

**A lattice study of the nucleon quark content at the physical point**

**Author:** Christian Torrero

\(^{1}\) on behalf of the Budapest-Marseille-Wuppertal Collaboration (Centre de Physique Théorique and CNRS, Aix-Marseille Université, France)

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After a detailed analysis of possible sources of systematic uncertainty, ab-initio \( N_f = 2 + 1 \) results for the up-down and strange quark content - with pion masses all the way down to the physical point - will be presented and discussed.

**Physics Beyond the Standard Model / 328**

**Beyond the Standard model matrix elements with the gradient flow**

**Author:** Andrea Shindler

**Co-authors:** Jordy de Vries \(^{1}\); Tom Luu \(^{1}\)

\(^{1}\) Forschungszentrum Jülich

The nucleon EDM receives potential contributions from fermionic and gluonic local operators representing the effective interactions from BSM physics. We have recently proposed to use the gradient flow to calculate the QCD component of these key BSM matrix elements. I present an update of the results we have obtained.

**Chiral Symmetry / 120**

**Chiral Symmetry Breaking for Bosonic Partition Functions.**

**Author:** Jacobus Verbaarschot

**Co-author:** Moshe Kellerstein

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The behavior of quenched Dirac spectra of two-dimensional lattice QCD is consistent with spontaneous chiral symmetry breaking which is forbidden according to the Coleman-Mermin-Wagner theorem. One possible resolution of this paradox is that because of the bosonic determinant that enters in the
partially quenched partition function the conditions of this theorem are violated allowing for spontaneous symmetry breaking in two dimensions or less. This goes back to work by Niedermaier and Seiler on nonamenable symmetries of the hyperbolic spin chain and work with Splittorf on bosonic partition functions at nonzero chemical potential. In this talk we discuss chiral symmetry breaking for a bosonic random matrix theory at imaginary chemical potential for which the chiral symmetry group is noncompact and compare with results from the corresponding fermionic theory with the usual compact symmetries.

Nonzero Temperature and Density / 57

Calculation of high-order cumulants with canonical ensemble method in lattice QCD

Author: Asobu Suzuki

Co-authors: Atsushi Nakamura; Shotaro Oka; Yusuke Taniguchi

High-order cumulants are numbers characterizing the probability distribution and have a lot of physical information. However, sign problem makes it difficult to numerical calculation of high-order cumulants in finite density lattice QCD. In this study we realize the calculation of high-order cumulants with “canonical ensemble method” in heavy quark region. Also, we study a finite density phase transition from the specific behavior of high-order cumulants.

Weak Decays and Matrix Elements / 260

Semileptonic $B$-meson decay phenomenology with lattice QCD

Authors: Aida El-Khadra; Daping Du

Co-authors: Andreas Kronfeld; Enrico Lunghi; John Laiho; Ran Zhou; Ruth Van de Water; Steven Gottlieb; Yannick Meurice; Yuzhi Liu

We present Standard Model predictions for phenomenologically interesting observables for the rare decays $B \to K \ell^+\ell^-$, $B \to \pi \ell^+\ell^-$, $B \to K\nu\bar{\nu}$, and $B \to \pi\nu\bar{\nu}$, as well as for $B \to \pi\tau\nu$. All of these processes are sensitive to new physics effects, and there are a number of tensions between experimental measurements and Standard Model expectations of these and similar processes. We
recently completed lattice calculations of the form factors for the semileptonic $B \to \pi$ and $B \to K$ transitions. Here we use these form factors to explore the phenomenology of these decays with quantitative control over the theoretical uncertainties.

Weak Decays and Matrix Elements / 271

Phenomenology with Lattice NRQCD b Quarks.

Author: Brian Colquhoun

Co-authors: Andrew Lytle, Christine Davies, Jonna Koponen, Rachel Dowdall

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Lattice NRQCD is a relatively inexpensive formalism that can be used to simulate b quarks on the lattice at their physical mass. The HPQCD collaboration has used radiatively-improved NRQCD for b quarks in bottomonium to determine the decay rate to leptons of the ground-state Upsilon and its first radial excitation in lattice QCD. Using time moments of vector bottomonium current-current correlators, we present our determination of the b quark mass in the MS-bar scheme.

We use NRQCD b quarks and HISQ light quarks – with masses down to their physical values – in the semileptonic B to pi decay at zero recoil to calculate $f_B^0(q^2_{\text{max}})$. Our results are consistent with the soft pion theorem for this decay, which relates the meson decay constants to the form factor by $f_B^0(q^2_{\text{max}})=f_B/f_\pi$ in the massless pion limit.

Hadron Spectroscopy and Interactions / 333

Computation of correlation matrices for tetraquark candidates with $J^P = 0^+$ and flavor structure $q_1\bar{q}_2q_3\bar{q}_3$

Author: Joshua Berlin

Co-authors: Abdou Abdel-Rehim, Constantia Alexandrou, Marc Wagner, Mario Gravina, Mattia Dalla Brida

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The conjecture that several recently observed mesons have a structure, which is not dominated by an ordinary quark antiquark pair, but by a four-quark structure, is being actively investigated both theoretically and experimentally. Such a state may be characterised as molecular state or as a diquark-antidiquark pair. Lattice QCD provides a theoretically sound framework to study such states. In order to quantitatively investigate the internal structure of such mesons one needs the precise computation of correlation matrices with several different interpolating fields that include two- and four-quarks. This talk presents our study of such correlation matrices paying particular attention to the technical aspects involved in the computation of diagrams that include closed quark loops and disconnected parts. We study tetraquark candidates with $J^P = 0^+$ and flavor structure $q_1\bar{q}_2q_3\bar{q}_3$ including e.g. the $a_0(980)$ meson, the $D_{s0}^*$ meson and some of the the charged $c\bar{c}X$ states. Numerical results on the $a_0(980)$ meson are discussed in detail.
Neutron EDM from quark chromoEDM

Author: Tanmoy Bhattacharya

Co-authors: Boram Yoon; Rajan Gupta; Vincenzo Cirigliano

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The presentation will discuss the connection between RI-SMOM and MSbar schemes for the quark chromo EDM operators. A preliminary study of the signal in the matrix element of neutron EDM using clover quarks on an HISQ ensemble will also be described.

Proton spin decomposition with overlap fermion

Author: yibo Yang

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We calculate glue spin with the overlap fermion on 2+1 flavor domain wall fermion configurations as a function of the nucleon momentum. The calculation is carried out on 24^3 x 64 and 32^3 x 64 lattice at two lattice spacings and the light sea quarks correspond to pion mass at 330 MeV and 290 MeV on these two lattices. Other issues related to the proton spin will be discussed.

Aspects of topological actions on the lattice

Author: Philippe de Forcrand

Co-author: Oscar Akerlund

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We discuss properties of actions which are invariant under smooth deformations of the lattice fields, which are restricted to a subspace of phase space. In particular we comment on the continuum limit of such actions and show how to directly measure the free energy. We also investigate possible applications to finite density systems.
Boundary effects on the chiral condensate from Lattice QCD

Author: Andrei Alexandru

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In the presence of a constant electric field the vacuum becomes unstable due to Schwinger pair creation. One way to avoid this instability is to use Dirichlet boundary conditions. In this case the chiral condensate vanishes on the walls and it is important to know how quickly it gets restored to its bulk value. A sigma-model calculation predicts that the region where the condensate differs significantly from its bulk value is rather thick. We show by direct calculation that this region is much thinner than estimated.

Pion spectrum for the 2-flavor staggered Wilson fermion

Authors: Christian Zielinski; David Adams

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The 4 flavors of the usual staggered fermion give rise to 16 pions (pseudoscalar mesons). We study the effect on the pion spectrum of turning on the 2-flavor staggered Wilson term in the staggered fermion action. 8 of the pions become heavy while 8 remain light. 6 of the light pions are identified as two copies of the 2-flavor pion triplet. They have the same light quark content but different heavy (doubler) quark content. The pions within each triplet are degenerate. The remaining two light mesons are identified as two copies of the flavor-singlet eta meson, which remains light in our study since the disconnected piece of its propagator is omitted. This verifies that the 2-flavor staggered Wilson formulation works as intended as far as the pion spectrum is concerned.

NLO and NNLO Low Energy Constants for SU(2) Chiral Perturbation Theory

Author: David Murphy

Co-author: Robert Mawhinney

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We have performed global fits of \( f_\pi \) and \( m_\pi \), from a variety of RBC-UKQCD domain wall fermion ensembles, to \( SU(2) \) partially quenched chiral perturbation theory at NNLO. We report values for 9 NLO and 8 linearly independent combinations of NNLO partially quenched low energy constants,
which we compare to other lattice and phenomenological determinations. We discuss the convergence of the expansion and use our large set of low energy constants to make predictions for the pion mass splitting due to QCD isospin breaking effects and the S-wave $\pi\pi$ scattering lengths. Finally, we discuss the effects of including lattice results for the $I = 2$ $\pi\pi$ scattering length in our chiral fits.

**Hadron Structure / 15**

**Nucleon charges, form-factors and neutron EDM**

*Author:* Rajan Gupta

*Co-authors:* Boram Yoon; Huey-Wen Lin; Tanmoy Bhattacharya

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Results for the matrix elements of quark bilinear operators within a nucleon state will be presented using nine ensembles of gauge configurations generated by the MILC collaboration using the HISQ action with 2+1+1 dynamical flavors. Excited state contamination and extrapolation to the physical point will be discussed for the charges $g_A$, $g_S$, and $g_T$, the vector and axial form factors, and the quark EDM operator. The impact of these results in constraining scalar and tensor interactions at the TeV scale and on new sources of CP violation will be discussed.

**Weak Decays and Matrix Elements / 125**

**Charm Physics at the physical point**

*Author:* Justus Tobias Tsang

1. *University of Southampton, UK*

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This talk will provide an overview of RBC/UKQCD’s charm project on their 2+1 flavour physical point ensembles using Moebius Domain Wall Fermions for the light as well as for the charm quark. I will discuss the analysis strategy and present first preliminary results for $D$ and $D_s$ decay constants.

**Algorithms and Machines / 312**

**A Multigrid Based Eigensolver for the Hermitian Wilson Dirac Operator**

*Author:* Matthias Rottmann

*Co-authors:* Andreas Frommer; Karsten Kahl

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In this talk, we present a multigrid based eigensolver for computing low modes of the hermitian Wilson Dirac operator. For the non-hermitian case, multigrid methods have already replaced conventional Krylov subspace solvers in many lattice QCD computations. Since the gamma5 preserving aggregation based interpolation is valid for both, the hermitian and the non-hermitian case, inversions of very ill-conditioned shifted systems with the non-hermitian operator become feasible. This enables the use of multigrid within shift-and-invert type eigensolvers. We show numerical results from our MPI-C implementation of a Rayleigh quotient iteration with multigrid. For state-of-the-art lattice sizes and moderate numbers of desired low modes we achieve speed ups of an order of magnitude and more over PARPACK.

Nonzero Temperature and Density / 283

Diagrammatic Monte Carlo simulations of staggered fermions at finite coupling

Author: Helvio Vairinhos

Co-author: Philippe de Forcrand

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The diagrammatic Monte Carlo method has been a very fruitful tool for taming, and in some cases even solving, the sign problem in several lattice models. We have recently proposed a diagrammatic model for simulating lattice gauge theories with staggered fermions at arbitrary coupling, which extends earlier successful efforts to simulate lattice QCD at finite baryon density in the strong-coupling regime. Here we present the first numerical simulations of our model, using a worm algorithm.

Theoretical Developments / 197

Flavor Filtered Fermions

Author: James Osborn

Co-author: Xiao-Yong Jin

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We present a new discretization of the lattice Dirac operator that preserves chiral symmetry while suppressing the effects of doubler states. The new operator is constructed from the naive Dirac operator by filtering out doubler states while preserving one physical quark state. In the simplest version the filtering is only approximate and the filter would require fine tuning to produce a single flavor in the continuum limit. We will present results from quenched simulations for the doubler suppression, locality and topology of the operator. We also discuss prospects for improving the filter to reduce and possibly eliminate the need for fine tuning.
The 33rd International Symposium on Lattice Field Theory (Lattice 2015) / Book of Abstracts

Hadron Structure / 34

The electric dipole moment of the neutron from N_f=2+1+1 twisted mass fermions

Author: Andreas Athenodorou

Co-authors: Constantia Alexandrou 1; Giannis Koutsou 2; Karl Jansen 3; Konstantin Ottnad 4; Kyriakos Hadjiyan-nakou 1; Marcus Petschlies 1; Martha Constantinou 1

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We extract the neutron electric dipole moment (nEDM) |d_n| on configurations produced with N_f=2+1+1 twisted mass fermions with lattice spacing of a=0.082fm and a light quark mass that corresponds to M_{\pi}=370 MeV. We do so by evaluating the CP-odd form factor F_3 for small values of the vacuum angle \theta at the limit of zero momentum transfer. This limit is taken using a parametrization of the momentum dependence and performing a fit as well as using the position space methods we refer to as “continuum derivative” and “direct computation”. The extraction of the CP-odd form factor F_3 requires the evaluation of the field theoretical topological charge. We measure the topological charge via cooling and gradient flow using the ordinary Wilson, Symanzik tree-level improved and Iwasaki actions for smoothing. We obtain consistent results for all choices of smoothing actions, smoothing procedures and momentum dependence treating techniques. We report an nEDM of |d_n|/\theta = -0.036(11)(7) e fm.

Algorithms and Machines / 97

Multigrid-accelerated Low-Mode Averaging

Author: Jakob Simeth

Co-authors: Andreas Frommer 2; Gunnar Bali 1; Issaku Kanamori 3; Karsten Kahl 5; Matthias Rottmann 5; Sara Collins 1

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Disconnected contributions to hadronic quantities are noisy and still computationally challenging. Here, we explore the possibilities of Multigrid-based eigensolvers for Low-mode averaging and related methods.

Using only the few lowest approximate eigenmodes of the Hermitian Dirac operator \gamma_5 M allows us to avoid expensive exact solves and improve the signal efficiently.

In this first test we apply the method to pion and eta correlators for N_f = 2 Wilson-Clover fermions at several quark masses, down to m_{\pi} = 150 MeV and volumes of up to 64^4 sites.
Neutral D-Meson Mixing near the Charm Mass

Author: Ava Khamesh

Co-authors: Andreas Juettner; Francesco Sanfilippo; Justus Tobias Tsang; Luigi Del Debbio; Peter Boyle

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We will report on the RBC/UKQCD charm project with (2+1)-flavor Domain Wall fermions at the physical point, and present progress on the determination of the matrix element of the VV+AA operator, and the Bag and Xi-parameters in the region of the physical charm quark mass. We will address the region of practical use of the domain wall action for heavy quark simulation and outline a strategy for the renormalization, continuum extrapolation and possibly extrapolation in heavy quark mass.

NLO and NNLO Low Energy Constants for SU(3) Chiral Perturbation Theory

Author: Robert Mawhinney

Co-author: David Murphy

1 Columbia University

Corresponding Author: rdm10@columbia.edu

We have performed global fits of pseudoscalar masses and decay constants, from a variety of RBC-UKQCD domain wall fermion ensembles, to SU(3) partially quenched chiral perturbation theory at NNLO. We report values for 9 NLO and 10 linearly independent combinations of NNLO partially quenched low energy constants, which we compare to other lattice and phenomenological determinations. We discuss the convergence of the expansion and use our large set of low energy constants to make predictions for mass and decay constant splittings due to QCD isospin breaking effects. We also discuss S-wave $K\pi$ scattering lengths.

Lattice simulation of the SU(2)-chiral model at zero and non-zero pion density

Author: Tobias Rindlisbacher

Co-author: Philippe de Forcrand
Corresponding Author: rindlisbacher@itp.phys.ethz.ch

We present a flux representation based lattice formulation of the partition function corresponding to the SU(2)-chiral Lagrangian, including a chemical potential and scalar/pseudo-scalar source terms. Lattice simulations are then used to obtain non-perturbative properties of the theory, in particular its mass spectrum at zero and non-zero pion density.

Nonzero Temperature and Density / 342

Heavy and dense QCD from an effective lattice theory

Author: Owe Philipsen

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A three-dimensional effective lattice theory of Polyakov loops can be constructed by integrating over the spatial links in combined strong coupling and hopping parameter expansions. The effective theory is valid for sufficiently heavy quarks and coarse to intermediate lattice spacings. In its domain of validity, the sign problem is weak enough to enable simulations at finite baryon chemical potential and allows for a description of the onset transition as well as cold nuclear matter directly from QCD. We summarize recent results and test the analytic effective couplings against improved numerically determined versions. We also compare complex Langevin and Monte Carlo simulations of the effective theory.

Algorithms and Machines / 33

Eigenspectrum calculation of the non-Hermitian O(a)-improved Wilson-Dirac operator using the Sakurai-Sugiura method

Author: Hiroya Suno

Co-authors: Akira Imakura; Ken-Ichi Ishikawa; Tetsuya Sakurai; Yasunori Futamura; Yoshifumi Nakamura; Yoshinobu Kuramashi

Corresponding Author: suno@riken.jp

We are developing a computer code for calculating eigenvalues of the non-Hermitian O(a)-improved Wilson-Dirac operator. We introduce here the Sakurai-Sugiura method, which is an eigensolver algorithm based on a contour integral, allowing us to calculate desired eigenvalues located inside a
given contour. We report the test results for low-lying eigenvalues obtained with free-case, quenched and full QCD configurations up to a lattice size of $96^4$.

**Hadron Structure / 247**

**Neutron-antineutron oscillation matrix elements with domain wall fermions at the physical point**

**Author:** Sergey Syritsyn

**Co-author:** Michael Buchoff

1. RIKEN BNL Research Center
2. University of Washington, USA

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Neutron-antineutron oscillations are hypothetical processes changing the baryon number by 2 units. Compared to proton decay, they present another scenario of baryon number violation and, if found, they would have different implications for phenomenology of baryogenesis. If such baryon number violation exists at higher scales beyond the Standard model, it will manifest itself at the hadron scale as effective six-(anti)quark operators turning neutrons into antineutrons and vice versa. Nucleon matrix elements of these operators are important for experiments looking for evidence of such processes. I will present preliminary results for these matrix elements computed with physical $N_f=2+1$ domain wall quarks. Results are non-perturbatively renormalized and converted to MSbar.

**Chiral Symmetry / 17**

**Evidence for a new SU(4) symmetry with $J=2$ mesons**

**Author:** Markus Pak

**Co-authors:** Leonid Glozman; Mikhail Denissenya

1. University of Graz

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Recently, a new $SU(4)$ symmetry has been established, which appears after removing the quasi-zero modes from the Overlap Dirac operator. Namely, the $\rho, \rho', \omega, \omega', a_1, b_1$ and possibly $f_1$, $J = 1$ mesons become mass degenerate after the quasi-zero mode removal. The $SU(4)$ symmetry contains $SU(2)_L \times SU(2)_R \times U(1)_A$ as a subgroup and predicts, among other things, that all isovector states of given spin $J$ become mass degenerate. Here we study isovector $J = 2$ mesons and observe the degeneracy of all states after removing the quasi-zero modes. This result gives evidence that the $SU(4)$ symmetry is present for mesons of total spin $J \geq 1$.

**Weak Decays and Matrix Elements / 204**

**D meson semileptonic decays from lattice QCD with chiral fermions**

**Author:** Takashi Suzuki

**Co-authors:** Hidenori Fukaya; Jun Noaki; Shoji Hashimoto; Takashi Kaneko; Yong-Gwi Cho
We report on our study of D meson semileptonic decays in QCD with 2+1 flavors of the Moebius domain-wall fermions. Gauge ensembles are generated at lattice cut-off around 2.4 GeV and pion masses as low as 300 MeV. Relevant form factors are calculated by using the Moebius action also for charm quarks.

Theoretical Developments / 257

Charged particles in QED with C* boundary conditions I

Authors: Agostino Patella1; Alberto Ramos2; Biagio Lucini3; Nazario Tantalo4

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In order to calculate QED corrections to hadronic quantities by means of lattice simulations, a coherent description of electrically-charged states in finite volume is needed. In the usual periodic setup, Gauss’ law and large gauge transformations forbid the propagation of electrically-charged states. A possible solution to this problem, which does not violate the axioms of local quantum field theory, has been proposed by Wiese and Polley, and is based on the use of C* boundary conditions.

We discuss the properties and symmetries of QED in isolation and QED coupled to QCD, with C* boundary conditions. We show that a certain class of electrically-charged states can be constructed in this setup in a fully consistent fashion, without relying on gauge fixing. This class of states covers most of the interesting phenomenological applications. We also calculate finite-volume corrections to the mass of stable charged particles and show that these are much smaller than in non-local formulations of QED.

This is the first of two consecutive talks on the subject.

Nonzero Temperature and Density / 62

Analytic computations of an effective lattice theory for heavy quarks

Author: Jonas Rylund Glesaaen1

Co-authors: Mathias Neuman 1; Owe Philipsen 2

1 Goethe University Frankfurt
2 Goethe-University Frankfurt
We discuss the fermionic contribution to a three dimensional effective lattice theory for heavy quarks. We first study the mathematical structure of higher order contributions of the hopping parameter expansion to the effective action. We then examine how to apply a graphical linked cluster expansion to retrieve analytical results for various lattice quantities such as nucleon number and nucleon binding energy. The free parameters of the analytic results are temperature, chemical potential and the hopping parameter. The results are compared to Monte Carlo simulations of the dimensionally reduced theory.

**Algorithms and Machines / 72**

**Accelerating deflation of eigenvalues for fermion matrix inversions on GPUs**

**Author:** Alexei Strelchenko

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We present a brief overview of deflation algorithms recently implemented in the SciDAC QUDA library for solving the lattice-Dirac equation with multiple right-hand sides on NVIDIA accelerators. In particular, we discuss implementation aspects of the mixed precision technique for the eigenvalue deflation which helps to considerably relax GPU memory requirements while allowing for an appropriate deflation quality in fermion matrix inverters. We analyze the efficiency of mixed precision deflation on the examples of HISQ and Wilson twisted mass ensembles.

**Weak Decays and Matrix Elements / 311**

**D meson semileptonic form factors at zero momentum transfer in 2+1+1 flavor lattice QCD**

**Author:** Thomas Primer

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We present a calculation of the $D \to K, l, \nu$ and $D \to \pi, l, \nu$ semileptonic form factors at $q^2 = 0$. These form factors are needed for the determination of the CKM matrix elements $\text{Re} V_{cs}$ and $\text{Re} V_{cd}$ respectively.

This work uses the HISQ action for both valence quarks and sea quarks on MILC $N_f = 2 + 1 + 1$ configurations, with ensembles including several at the physical pion mass and lattice spacings ranging from 0.12 fm to 0.042 fm. The calculation employs twisted boundary conditions to calculate the form factors at zero momentum transfer directly.

We use HMxPT to obtain preliminary results at the physical point and in the continuum limit.
Testing the Witten-Veneziano Formula on the Lattice

**Author:** Konstantin Ottnad

**Co-authors:** Carsten Urbach, Elena Garcia-Ramos, Karl Jansen, Krzysztof Cichy

We employ lattice techniques to compute both sides of the Witten-Veneziano formula. For the one side we perform dedicated quenched simulations and use the spectral projector method to determine the topological susceptibility in pure Yang-Mills theory. The other side we determine in lattice QCD with $N_f = 2 + 1 + 1$ dynamical Wilson twisted mass fermions including for the first time also the flavour singlet decay constant. Taking the continuum and the SU(2) chiral limits we compare both sides and find good agreement within uncertainties.

Charged particles in QED with C* boundary conditions II

**Authors:** Agostino Patella, Alberto Ramos, Biagio Lucini, Nazario Tantalo

**Corresponding Author:** nazario.tantalo@roma2.infn.it

In order to calculate QED corrections to hadronic quantities by means of lattice simulations, a coherent description of electrically-charged states in finite volume is needed. In the usual periodic setup, Gauss' law and large gauge transformations forbid the propagation of electrically-charged states. A possible solution to this problem, which does not violate the axioms of local quantum field theory, has been proposed by Wiese and Polley, and is based on the use of C* boundary conditions.

We discuss the properties and symmetries of QED in isolation and QED coupled to QCD, with C* boundary conditions. We show that a certain class of electrically-charged states can be constructed in this setup in a fully consistent fashion, without relying on gauge fixing. This class of states covers most of the interesting phenomenological applications. We also calculate finite-volume corrections to the mass of stable charged particles and show that these are much smaller than in non-local formulations of QED.

This is the second of two consecutive talks on the subject.
Electromagnetic structure of charmed baryons - extended to spin-3/2

Author: Utku Can

Co-authors: Guray Erkol 2; Makoto Oka 1; Toru T. Takahashi 3

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The electromagnetic form factors of the spin-3/2 \( \Omega \) baryons, namely the \( \Omega_c, \Omega_{cc} ^*, \Omega_{ccc} ^* \) and \( \Omega_{ccc} \), are calculated in full QCD on \( 32^3 \times 64 \) PACS-CS lattices with a pion mass of 156(9) MeV. The electric charge radii and magnetic moments from the E0 and M1 multipole form factors are extracted. Results for the electric quadrupole form factor, E2, are also provided. Quark sector contributions are computed individually for each observable and then combined to obtain the baryon properties. Charm quark contributions are observed to be systematically smaller compared to the strange quark contributions in case of the charge radii and magnetic moments. E2 moments of the \( \Omega_{cc} ^* \) and \( \Omega_{ccc} ^* \) are estimated significantly enough to show that their electric charge distributions are deformed. Properties of the spin-1/2 counterparts of the \( \Omega_c \) and \( \Omega_{cc} ^* \) baryons are also computed and a comparison is presented.

Plenary Session / 350

What is QFT? Resurgent trans-series, Lefschetz thimbles, and new exact saddles

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Resurgent trans-series provide a novel mathematical formalism to unify perturbative and non-perturbative physics, leading to new insights into the general structure of quantum theories. I will review the main ideas with some illustrative examples.

In many quantum mechanical systems, all orders non-perturbative data is encoded into perturbation theory, and it can be decoded. In QFTs, there are cases in which resurgence provides a new interpretation of IR-renormalon puzzle, reveals the existence of many new saddles (such as magnetic and neutral bions), and potentially provide a non-perturbative continuum definition of QFT in a semi-classical domain. I will also describe a new perspective on path integration, which is intimately tied with resurgence theory and employs some tools of Picard-Lefschetz theory. This perspective leads to many dramatic and surprising results, and implies that the proper framework to study semi-classics in path integral formulation is yet to be developed.

Plenary Session / 351

Lattice’s Bright, Dark and Safe side

Author: Francesco Sannino

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Circa 95% of the universe is made of unknown forms of matter and energy, while to describe the remaining 5% one needs at least three fundamental forces, i.e. Quantum Electrodynamics, Weak Interactions and Quantum Chromo Dynamics (QCD). Furthermore strong interactions are responsible for creating the bulk of the bright mass, i.e. the 5%. It is therefore natural to expect that to correctly describe the rest of our universe while providing a sensible link to the visible component new forces will soon emerge. For example the standard model sector responsible for breaking the electroweak symmetry spontaneously could be replaced by a new and more natural strongly coupled sector. Another interesting avenue is the possibility that dark matter itself, as the ordinary proton and neutron, is not an elementary particle but rather a state composed by new strongly coupled matter. I will argue that models of composite dynamics are indeed primary candidates for a better understanding of the origin of bright and dark matter in Nature. I will also show by reviewing recent results that Lattice field methods can provide clear and falsifiable predictions for the Large Hadron Collider experiment as well as dark matter direct experiments searches.

I will then switch gear and exhibit the first proof of existence of nonsupersymmetric and non-asymptotically free 4D Gauge-Yukawa theories (structurally similar to the standard model) that are UV finite thanks to the existence of an exact interacting quantum UV fixed point in the gauge, Yukawa and scalar self-couplings. These theories are therefore asymptotically safe. Theories with this behaviour have been searched for on the lattice for the past several decades. The results show the critical ingredients needed to construct these new classes of theories and offer a strategy for future lattice studies. I will then comment on the wide phenomenological impact of this discovery.

Understanding strong dynamics is therefore crucial to construct phenomenologically relevant extensions of the standard model of particle interactions, and ultimately being able to describe our Universe.

**Plenary Session / 352**

**Physics at the Belle II experiment and Lattice QCD**

**Author:** Toru Iijima

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In this talk, we discuss the status and future prospect in B physics, focusing on the SuperKEKB/Belle II experiment at KEK, with the target peak luminosity of $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$. This enables us to study decays of heavy flavor particles, B and D mesons as well as tau leptons, at the order of O(10$^{11}$) per year, and to search for New Physics through processes sensitive to presence of virtual heavy particles. We present physics reach, status and plan of the experiment. We also discuss the inputs necessary from lattice QCD calculations, in order to identify effects of New Physics.

**Plenary Session / 353**

**Progress and prospects for heavy flavour physics on the lattice**

**Author:** Carlos Pena

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I will review recent progress in lattice computations relevant for B- and charm physics. Emphasis will be put on the interplay with the upcoming new generation of experimental results.
Theoretical Developments / 297

**(Dimensional) twisted reduction in large N gauge theories**

**Authors:** Alberto Ramos\(^1\); Liam Keegan\(^1\)

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We will use the idea of twisted reduction and volume independence to numerically investigate the large N limit of Yang-Mills theories by reducing two of the directions to a single point. We will show that this framework might be convenient to analyze some properties of these theories.

Nonzero Temperature and Density / 31

**Two-Color Lattice QCD with Non-zero Chiral Chemical Potential**

**Authors:** Alexander Molochkov\(^1\); Andrey Kotov\(^2\); Bengt Petersson\(^3\); Ernst-Michael Ilgenfritz\(^4\); Michael Müller-Preussker\(^5\); Victor Braguta\(^2\); Vladimir Goy\(^1\)

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The phase diagram of two-color QCD with non-zero chiral chemical potential is studied by means of lattice simulation. We focus on the influence of a chiral chemical potential on the confinement/deconfinement phase transition and the breaking/restoration of chiral symmetry. The simulation is carried out with dynamical staggered fermions without rooting. The dependences of the Polyakov loop, the chiral condensate and the corresponding susceptibilities on the chiral chemical potential and the temperature are presented. The critical temperature is observed to increase with increasing chiral chemical potential.

Applications Beyond QCD / 7

**Complex Langevin simulation in condensed matter physics**

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The complex Langevin method is one hopeful candidate to tackle the sign problem. This method is applicable not only to QCD but also to nonrelativistic field theory. We present the simulation results of nonrelativistic condensed matter systems.
Weak Decays and Matrix Elements / 202

Kaon semileptonic form factors as functions of the momentum transfer with Nf=2+1+1 Twisted Mass fermions

Author: Lorenzo Riggio

Co-authors: Nuria Carrasco 1; Paolo Lami 2; Silvano Simula 1; Vittorio Lubicz 2

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We present lattice results for the form factors relevant for K \to p\pi l nu decays, obtained from simulations performed by the European Twisted Mass Collaboration with Nf=2+1+1 flavors of dynamical quarks, at three values of the lattice spacing and pion masses as low as 250 MeV. Our determination of f_+(0), which in combination with the experimental result for (f_+(0)*V_us) can be used to determine the CKM matrix element, will be presented along with a study of both the vector and the scalar form factors as functions of the momentum transfer comparing our results with the experimental ones.

Nonzero Temperature and Density / 176

Lattice NRQCD study of quarkonium at non-zero temperature

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To study the in-medium modification of quarkonium properties, charmonium correlators at 140.4(\beta = 6.664) \leq T \leq 221(\beta = 7.280) (MeV) are calculated using the NRQCD formalism on 48^3 \times 12 gauge configurations with dynamical N_f = 2 + 1 flavors of Highly Improved Staggered Quarks (HISQ). To determine the "zero energy shift" for these lattices, we perform a fine zero temperature scan (\beta = 6.664, 6.740, 6.800, 6.880, 6.950, 7.030, 7.150 and 7.280). In addition, we investigate the influence of statistical errors on the reconstruction of spectral functions by varying the number of correlators in the study. We find that the temperature dependence of charmonium correlators is stronger than the temperature dependence of bottomonium correlators in a given channel. This fits into the expected pattern of sequential quarkonium melting.

Vacuum Structure and Confinement / 8

Chiral symmetry breaking, instantons, and monopoles

Author: Masayasu Hasegawa

Co-author: Adriano Di Giacomo

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The purpose of this study is to show that monopoles are related to chiral symmetry breaking and to instantons, using the Overlap fermions as an analytical tool.

In order to study these relations, we add one pair of monopoles with different magnetic charges to the quenched SU(3) configurations by a monopole creation operator. We then count the number of zero modes, and compute the average square of the topological charges as the number of instantons. We have shown that one pair of monopoles makes one instanton, and that the chiral condensate which is computed from the eigenvalues and eigenvectors of the Overlap Dirac operator decreases by increasing the charges of the monopoles.

We have also found that the fermion spectral density of the eigenvalues increases by increasing the charges of the monopoles. Moreover, we compare the low-lying eigenvalues with the prediction of the random matrix theory.

By now these studies have been done using one small lattice ($V = 14^4, \beta = 6.00$). Our program is to investigate this subject more precisely using larger lattices and different lattice spacings. In this study, we present results on the chiral condensate, the pseudo scalar mass, and pion decay constants on larger lattice.

Weak Decays and Matrix Elements / 107

Long-distance contributions to the rare kaon decay K$^+ \to \pi^+ l^+ l^-$

Author: Andrew Lawson$^1$

Co-authors: Andreas Juettner $^1$; Antonin Portelli $^1$; Christopher Sachrajda $^1$; Norman Christ $^2$; Xu Feng $^2$

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The rare decays of a kaon into a pion and a charged lepton/antilepton pair proceed via a flavour changing neutral current and therefore may only be induced beyond tree level in the Standard Model. This natural suppression makes these decays sensitive to the effects of potential New Physics. To discern such New Physics one must be able to control the errors on the Standard Model prediction of the decay amplitude. These particular decay channels however are dominated by a single photon exchange; this involves a sizeable long-distance hadronic contribution which represents the current major source of theoretical uncertainty. In this talk I will outline our methodology for the computation of the long distance contributions to these rare decay amplitudes using lattice QCD, and present the numerical results of some exploratory studies using the Domain Wall Fermion ensembles of the RBC and UKQCD collaborations.

Nonzero Temperature and Density / 321

Charmonia and bottomonia at finite temperature on large quenched lattice

Author: Hiroshi Ohno$^1$

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We present our updated study on charmonia and bottomonia at finite temperature with quenched ensembles on large and fine isotropic lattices. Simulations have been performed by using the standard plaquette gauge and the $O(a)$-improved Wilson fermion actions in a region of quark mass for charmonia to bottomonia in order to investigate difference of in-medium behavior between them. We show spectral functions of quarkonia at temperatures in a range between about $0.73T_c$ and $2.2T_c$ at both vanishing and finite momenta and discuss about their temperature, quark mass and momentum dependence.

**Theoretical Developments / 168**

**Large N meson propagators from twisted space-time reduced model**

**Author:** Masanori Okawa

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We propose a new method to calculate meson propagators in the large N limit from twisted space-time reduced model. Preliminary results of meson spectra and decay constants are presented.

**Nonzero Temperature and Density / 113**

**Lattice simulation of QC$_2$D with $N_f = 2$ at non-zero baryon density**

**Authors:** Alexander Nikolaev; Andrey Kotov; Victor Braguta

**Co-author:** Semen Valgushev

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2 ITEP
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4 University of Regensburg

We present the results of lattice simulation of QC$_2$D with two flavors of staggered fermions and non-zero chemical potential ($\mu_q$). Dependencies of the Polyakov loop, chiral condensate and baryon number density on $\mu_q$ were studied. We found, that raising of the baryon chemical potential leads to the chiral symmetry restoration. At small $\mu_q$ our results for the baryon density agree with ChPT predictions.

**Vacuum Structure and Confinement / 301**

**Classifying the phases of gauge theories by spectral density of probing chiral quarks**

**Author:** Ivan Horvath

**Co-author:** Andrei Alexandru
We describe our recent proposal that distinct phases of vector-like gauge theories with fundamental quarks translate into specific types of low-energy behavior in Dirac spectral density. The resulting scenario is built around new evidence substantiating the existence of a phase characterized by bimodal (anomalous) density, and corresponding to deconfined dynamics with broken valence chiral symmetry. We argue that such anomalous phase occurs quite generically in these theories, including in "real world" QCD above the crossover temperature, and in zero-temperature systems with many light flavors.

Applications Beyond QCD / 47

Domain-wall/overlap fermion and topological insulators

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Topological insulators are a new class of materials which have gapped spectra in the bulk, but are accompanied by topologically protected gapless excitations at the surface (edge) of the system. These phenomena have a close relationship with symmetry and dimensionality of the system through quantum anomalies. We point out that such a surface state is a physical realization of the domain-wall/overlap fermion. From this point of view, we discuss its implications for experiments of topological insulators. We also discuss an unconventional overlap fermion, which is suggested by the "periodic table" of topological insulators and superconductors.

Theoretical Developments / 299

Topology and glueballs in $SU(7)$ Yang-Mills with open boundary conditions

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It is well known that the topology of gauge configurations generated in a Markov Monte-Carlo chain freezes as the continuum limit is approached. The corresponding autocorrelation time increases exponentially with the inverse lattice spacing, affecting the ergodicity of the simulation. In $SU(N)$ gauge theories for large $N$ this problem sets in at much coarser lattice spacings than for $N=3$. This means that its systematics can be studied on lattices that are smaller in terms of the number of lattice sites. It has been shown that using open
boundary conditions in time allows instantons to be created and
destroyed, restoring topological mobility and ergodicity.
However, with open boundary conditions translational invariance is lost
and the influence of spurious states propagating from the boundary into
the bulk on physical correlators needs to be carefully evaluated.
Moreover, while the total topological charge can be changed, the mobility
of instantons across the lattice is still reduced. We consider SU(7)
Yang-Mills theory and analyse its topological content in
the periodic and open boundary condition cases. We also investigate
scalar and pseudoscalar glueball correlation functions.

Vacuum Structure and Confinement / 335

Dirac spectrum representation of Polyakov loop fluctuations in
lattice QCD

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We investigate contribution to the Polyakov loop fluctuations from each Dirac mode. The Polyakov
loop fluctuations are sensitive probes for the quark deconfinement even if considering dynamical
quarks. We derive analytical relations between the Polyakov loop fluctuations and Dirac modes
on the temporally odd-number lattice, where the temporal lattice size is odd, with the normal non-
twisted periodic boundary condition for link-variables. These relations indicate that low-lying Dirac
modes have little contribution to the Polyakov loop fluctuations. We numerically confirmed that
at the quenched level in both confinement and deconfinement phases. Our results suggest that
there is no direct one-to-one correspondence between confinement and chiral symmetry breaking
in QCD.

Weak Decays and Matrix Elements / 238

Long-distance contributions to the rare kaon decay K+ -> pi+ nu nu-bar

Author: Xu Feng¹
Co-authors: Andreas Juettner ²; Andrew Lawson ²; Antonin Portelli ²; Christopher Sachrajda ²; Norman Christ ¹

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As flavor changing neutral current processes, rare kaon decays K -> pi nu nu-bar are highly sup-
pressed in the standard model and thus provide ideal probes for the observation of new physics
effects.

Given the importance of rare kaon decays, the CERN NA62 experiment aims at an observation of
O(100) events of K+ -> pi+ nu nu-bar decay and a 10%-precision measurement of the branching ratio
in two years. Another experiment, J-PARC KOTO, is dedicated to search for the CP-violating KL -> pi0 nu nu-bar decay.

Recognizing that the standard model predictions will soon be confronted with new experimental results, it is important to determine the long-distance contributions to K+ -> pi+ nu nu-bar with a controlled error.

In this talk I will present an exploratory calculation of the long-distance contributions to the K+ -> pi+ nu nu-bar decay amplitude from first principles using lattice QCD.

Nonzero Temperature and Density / 203

Transverse and longitudinal spectral functions of charmonia at finite temperature with maximum entropy method

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We study the charmonium spectral functions with finite momentum from lattice Euclidean correlators using the maximum entropy method. In medium, the spectral function of vector channel with finite momentum is decomposed into transverse and longitudinal components because of the lack of Lorentz invariance.

We investigate these spectral functions, their residues and the dispersion relations on the quenched lattice below and above the critical temperature.

Nonzero Temperature and Density / 172

Cluster expansions and chiral symmetry at large density in 2-color QCD

Author: Terry E. Tomboulis

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We study lattice SU(Nc) gauge theories with massless staggered fermions at finite quark chemical potential \( \mu \). At strong coupling such theories have been studied with a variety of techniques such as mean field, monomer-dimer representations and MC simulations. Here we employ a new cluster expansion which has recently been shown to converge for large \( \mu \) and small \( \beta \). Extension to weaker coupling, however, does not appear feasible in the presence of complex fermion determinant.

For theories with real determinant, however, such as 2-color QCD, we show how such large \( \mu \) cluster expansions can be used to obtain information on the behavior of lattice observables in the weak coupling regime. We discuss the intertwined questions of presence of chiral symmetry and quarkyonic vs. superfluidity/superconductivity phases at large \( \mu \), and the problem of saturation, a lattice artifact, and means to circumvent it.
Chiral Magnetic Conductivity in an interacting lattice model of a parity-breaking Weyl semimetal

Authors: Matthias Puhr¹; Pavel Buividovich¹; Semen Valgushev²

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With the recent experimental realization of Dirac and Weyl semimetals it has become possible to study the Chiral Magnetic Effect (CME) in clean table-top experiments. We present results of a mean-field study of the static Chiral Magnetic Conductivity (sCMC) in a simple lattice model of a parity-breaking Weyl semimetal. Our model is given by the lattice Wilson-Dirac Hamiltonian with on-site repulsive interaction and a constant chiral chemical potential term. The value of the sCMC for free Dirac fermions is well known and possible corrections due to fermion-interactions are often neglected. We study the model in the parameter space of bare Wilson-Dirac mass, inter-fermion interaction strength and bare chiral chemical potential and find that on-site repulsive interactions affect the sCMC almost exclusively through the enhancement of the renormalized chiral chemical potential. Non-trivial corrections to the sCMC due to inter-fermion interactions seem to be irrelevant in practice, since they become important only in a phase where the CME response is strongly suppressed by a large gap in the energy spectrum.

Nonzero Temperature and Density / 273

Polyakov loop correlators and cyclic Wilson loop from lattice QCD

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We calculate the correlation function of Polyakov loops and the cyclic Wilson loops in 2+1 flavor QCD at non-zero temperature. We also study the correlation function of Wilson lines in Coulomb gauge. In our investigations we use the highly improved staggered quark (HISQ) action and lattices with temporal extent Nt=4,6,8,10 and 12. At high temperatures we compare our numerical results with perturbation theory.

Vacuum Structure and Confinement / 39

SU(4) symmetry of hadrons upon quasi-zero Dirac mode elimination.

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A large degeneracy of mesons of given spin has been discovered upon reduction of the quasi-zero modes of the Dirac operator in a dynamical simulation. One expects a priori, that upon elimination of the quasi-zero modes of the Dirac operator, the chiral symmetry should be restored, since the quark condensate of the vacuum is connected with the density of the quasi-zero modes. However, it has turned out that not only degeneracy patterns from the SU(2)_R * SU(2)_L and U(1)_A symmetries are observed, but a larger degeneracy that includes all possible chiral multiplets for given spin. This symmetry has been established to be SU(4) that includes both the isospin rotations of quarks of given chirality as well as the rotations chirality itself.

This symmetry is higher than the symmetry of the QCD Lagrangian and should be consequently considered as an emergent symmetry that reflects the QCD dynamics without the quasi-zero modes of the Dirac operator. This symmetry implies the absence of the color-magnetic field in the system and might be interpreted as a manifestation of the dynamical QCD string.

Nonzero Temperature and Density / 143

Thimble regularization at work besides toy models: from Random Matrix Theory to Gauge Theories.

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Thimble regularization as a solution of the sign problem has been successfully put at work for a few toy models. Given the non trivial nature of the method (also from the algorithmic point of view) it is compelling to provide evidences that it works for realistic models.

A chiral random matrix theory has been studied in detail. The known analytical solution shows that the model is non-trivial as for the sign problem (in particular, phase quenched results can be very far away from the exact solution). This study gave us the chance to address a couple of key issues: how many thimbles contribute to the solution of a realistic problem? can one devise algorithms which are robust as for staying on the correct manifold?

The obvious step forward we are interested in are applications to gauge theories.

Applications Beyond QCD / 64

Hybrid Monte Carlo simulations of graphene in external magnetic field

Author: Maksim Ulybyshev

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Recent experimental results [Nature Physics, 8 (2012) 550 and Nature 505 (2014) 528] indicate that graphene turns into insulator in sufficiently strong magnetic field. However, the exact nature of this state is still elusive and there are large discrepancies between theoretical predictions and experimental results.

To resolve this discrepancies extensive simulations of graphene in external magnetic field were performed using Hybrid Monte Carlo algorithm. Insulating state was observed in agreement with experiment. Mass gap and various order parameters were measured.
Diagrammatic Monte-Carlo algorithms for large-N quantum field theories from Schwinger-Dyson equations

Author: Pavel Buividovich

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I present a general framework for constructing Diagrammatic Monte-Carlo algorithms for large-N quantum field theories, which is based on the stochastic solution of the full untruncated hierarchy of Schwinger-Dyson equations and is an extension of the approach proposed in arXiv:1104.3459, arXiv:1009.4033. The algorithms are capable of constructing both weak- or strong-coupling expansions which are convergent at large N and asymptotic 1/N expansions. We illustrate the application of the algorithm on the examples of the planar phi^4 theory, U(N) sigma model and strong-coupling QCD in the Veneziano limit at finite density. In the latter cases of lattice field theories with U(N) degrees of freedom, simulations in the weak-coupling regime are hindered by a sign problem. We discuss possible ways to overcome these problems, e.g. using the “bold” diagrammatic Monte-Carlo.

Computing the long-distance contributions to $\epsilon_K$

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We will discuss the theoretical framework and initial results for the lattice QCD calculation of the long-distance contributions to $\epsilon_K$, the measure of indirect CP violation in $K_L$ decay. A proof-of-principle calculation has been carried out on a $24^3 \times 64$ lattice volume with an inverse lattice spacing of 1.73 GeV and pion mass of 329 MeV. A complete calculation will be described which shows how the logarithmically divergent lattice contribution can be combined with continuum perturbation theory to obtain a physical result.

Thimble regularization at work for Gauge Theories: from toy models onwards.

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A final goal for thimble regularization of lattice field theories is the application to lattice QCD and the study of the phase diagram.
Gauge theories pose a number of conceptual and algorithmic problems, some of which can be addressed even in the framework of toy models. We report on our progresses in this field, starting in particular from first successes in the study of one link models.

**Theoretical Developments / 139**

**Numerical study of complex instantons in the Gross-Witten U(N) matrix model**

**Authors:** Buividovich Pavel\(^1\); Semen Valgushev\(^2\)

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It is known that the 1/N expansion in the Gross-Witten U(N) matrix model is divergent and leading divergence in the weak coupling regime is governed by instanton which is associated with eigenvalue tunneling. However, it was not known what triggers divergences in the strong coupling phase where instantons disappear. To address this problem, we numerically study structure of saddle points in the Gross-Witten model with complexified degrees of freedom. These complex saddle points can be considered as complex instantons. In the strong coupling phase we identify complex instanton which governs leading divergence in the 1/N expansion. Also we find, that in the limit of large N in the strong coupling regime action of the perturbative vacuum has one flat direction. We present an evidence that in the vicinity of the transition point all complex instantons might give a significant contribution to the partition function, which might be important observation for Hybrid Monte-Carlo simulations based on integration on a Lefschetz thimbles.

**Applications Beyond QCD / 78**

**Numerical simulations of graphene conductivity with realistic inter-electron potential**

**Author:** Denis Boyda\(^1\)

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There was a long time disagreement in literature between theoretical calculations and experimental data about conductor-insulator phase transition in graphene. This contradiction was resolved in the papers [Phys. Rev. Lett. 111, 56801 (2013)] and [Phys. Rev. B 89, 195429 (2014)] where chiral condensate was studied taking into account screening of Coulomb potential by \(\sigma\)-electrons of carbon atoms. Unfortunately there was no explicit evidence that conductivity drops down simultaneously with appearance of chiral condensate. Therefore it is required to perform direct calculations of graphene conductivity in tight-binding model.

We performed Monte-Carlo simulations of graphene tight-biding model with realistic electron-electron interaction and calculated the dependence of conductivity on dielectric permittivity of substrate.

According to our calculations suspended graphene has conductivity \(\sigma = 0.325 \pm 0.003e2/\hbar\) which is very close to experimental value \(\sigma = (1.01 \pm 0.04)e2/4\hbar\). The phase transition in
conductivity is also shifted to unphysical region $\epsilon < 1$ due to influence of $\sigma$-electrons.

Nonzero Temperature and Density / 65

Static quark-antiquark pair free energy and screening masses: continuum results at the QCD physical point

Authors: Attila Pasztor¹; Csaba Torok²; K. Kalman Szabo¹; Sandor Katz²; Szabolcs Borsanyi¹; Zoltan Fodor²

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We study the correlators of Polyakov loops, and the corresponding gauge invariant free energy of a static quark-antiquark pair in 2+1 flavor QCD at finite temperature. Our simulations were carried out on $N_t = 6, 8, 10, 12, 16$ lattices using a Symanzik improved gauge action and a stout improved staggered action with physical quark masses. The free energies calculated from the Polyakov loop correlators are extrapolated to the continuum limit. For the free energies we use a two step renormalization procedure that only uses data at finite temperature. We also measure correlators with definite Euclidean time reversal and charge conjugation symmetry to extract two different screening masses, one in the magnetic, and one in the electric sector, to distinguish two different correlation lengths in the full Polyakov loop correlator. This conference contribution is based on the paper: JHEP 1504 (2015) 138

Weak Decays and Matrix Elements / 263

Emerging lattice approach to K-Unitarity Triangle

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It has been been clear for past many years that in low energy observables new physics can only appear as a perturbation. Therefore precise theoretical predictions and precise experimental measurements have become rather mandatory. Here we draw attention to the significant advances that have been made on the lattice in recent years in $K \rightarrow \pi \pi$, $\Delta M_K$, long- distance part of $\epsilon_K$ and rare $K$-decays. Thus, in conjunction with experiments, the construction of a unitarity triangle purely from Kaon physics should soon become feasible. In comparison with the B-unitarity triangle, this should allow for more stringent tests of the Standard Model and tighter constraints on new physics.

Vacuum Structure and Confinement / 43

Gauge fixing and the gluon propagator in renormalizable xi gauges
Covariant $R_\xi$ gauge fixing is notoriously difficult for large lattice volumes, large $\xi$ and small $N_c$. We thoroughly test different convergence techniques, which allows the gauge fixing of lattice configurations with a total volume of $(3.25 \text{ fm})^4$, up to $\xi = 0.5$. We are able to study the gluon propagator in the infrared region and its dependence on the gauge fixing parameter $\xi$. As expected, the longitudinal gluon dressing functions stay constant at their tree-level value. Similar to the Landau gauge, the transverse $R_\xi$ gauge gluon propagators saturate at a non-vanishing value in the deep infrared for all values of $\xi$ studied. We compare with very recent continuum studies and perform a simple analysis of the found saturation with a dynamically generated effective gluon mass.

### Nonzero Temperature and Density / 22

**Confinement/deconfinement transition temperature from the Polyakov loop potential and gauge-invariant gluon mass**

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In this talk we give an analytical derivation for the existence of the confinement/deconfinement phase transition at finite temperature in Yang-Mills theory. Moreover, we give a numerical estimate on the transition temperature $T_d$ in the form of the ratio to a gauge-invariant gluon mass $M(T)$ measured on the lattice. For this purpose, we use the functional renormalization-group equation of the Wetterich type to obtain the effective potential of the Polyakov loop average in the Yang-Mills theory. This result enables us to understand the reason why the phase transition from deconfinement to confinement occurs at a certain temperature and what is the mechanism for confinement at finite temperature.

### Nonzero Temperature and Density / 86

**Application of the Lefschetz thimble formulation to the (0+1) dimensional Thirring model at finite density**

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**Co-authors:** Hirotsugu Fujii¹; Yoshio Kikukawa²

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We investigate the (0+1) dimensional Thirring model at finite chemical potential by HMC simulations based on the Lefschetz thimble formulation of path-integration. We adopt the lattice model defined with staggered fermion and a compact link field for the auxiliary vector field. We firstly find the critical points (saddle points) under the assumption that the complexified link field is space-time independent, and investigate gradient flows and the Stokes phenomenon to identify the thimbles which contribute to the path-integral. Then, we perform lattice simulations using HMC algorithm with taking one particular thimble and the results are compared to the exact solution. The numerical results are in agreement with the exact ones in small and large chemical potential regions, while we observe a discrepancy between the numerical and exact results around the intermediate transition region in the chemical potential. We also discuss the result in relation to the contributions of the other thimbles.

Weak Decays and Matrix Elements / 74

Lattice QCD calculations of nucleon transverse momentum-dependent parton distributions (TMDs) at 170 MeV pion mass

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An exploration of nucleon TMD observables at a substantially lower pion mass, 170 MeV, than used in previous lattice TMD calculations is presented. On a corresponding RBC/UKQCD DWF ensemble, TMDs are extracted from nucleon matrix elements of a bilocal quark operator containing a staple-shaped gauge link. Appropriate TMD ratios are constructed to cancel divergences associated with the gauge link. In particular, time-reversal odd observables associated with the Sivers and Boer-Mulders effects are considered. The results are compared with previous DWF calculations at 297 MeV pion mass with a view to exploring whether these observables vary strongly as a function of pion mass in the chiral regime.

Vacuum Structure and Confinement / 128

Non-Gaussianity of the topological charge distribution in SU(3) Yang–Mills theory

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We report the results of a study of the distribution of the topological charge of the SU(3) Yang–Mills theory: we estimate the second and fourth cumulant with high precision in order to measure the deviation from the normal distribution. The computation is done on the lattice implementing a naïve discretization of the topological charge evolved with the Yang–Mills gradient flow. A range of high
statistics Monte Carlo simulations with different lattice volumes and spacings is used to extrapolate
the results to the continuum limit with confidence by keeping finite volume effects negligible with
respect to the statistical errors.

Theoretical Developments / 4

Matrix Geometry and Coherent States

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Some matrix models have been proposed as a non-perturbative formulation of string theories. In the
matrix model formulation of string theories, configurations of strings or D-branes are described by
a set of Hermitian matrices. Here, we propose a new class of observables in matrix models, which
are made of the Hermitian matrices and encode geometric information of the strings or D-branes.
By performing a Monte Carlo simulation and computing those observables for a simple toy model
of a bosonic matrix model, we demonstrate how we can see the geometric properties of the strings
from the matrix configurations.

Applications Beyond QCD / 229

Lattice gauge theory treatment of strongly correlated Dirac semimetals

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We study the strong correlation effect from Coulomb interaction in two- and three-dimensional Dirac
semimetals. Effective field theory for the interacting Dirac semimetals can be constructed in terms
of quantum electrodynamics (QED). We propose a U(1) lattice gauge theory formulation with the
internal degrees of freedom, such as spin and orbitals (pseudospin), explicitly. In the strong coupling
limit, the coupling to the U(1) gauge field leads to local charge neutrality, which can be expressed as
a sufficiently strong Hubbard (on-site) repulsion as well, rendering the system into a Mott insulator.
We discuss the evolution of charge and spin orders by strong coupling expansion and mean-field
analysis, and examine the effect of dimensionality and number of flavors.

Nonzero Temperature and Density / 292

A stochastic approach to the reconstruction of spectral functions in lattice QCD

Author: Hai-Tao Shu

Co-author: Heng-Tong Ding
All the information of quantum states are encoded in their spectral functions. The reconstruction of the spectral function from the corresponding Euclidean correlation function is, however, a typical ill-posed problem as an analytic continuation from imaginary time to real time is required. The commonly used Maximum Entropy Method (MEM) is based on the Bayesian interference and its output thus may have bias on the prior information provided in the default models.

We present results using a stochastic approach for the reconstruction of the spectral functions from the Euclidean correlation functions. In this approach the spectral function is parameterized as a sum of randomly distributed boxes. By varying the width, location and the height of the box stochastically an optimal spectral function can be obtained. Using this approach we can reproduce fairly well the mock spectral functions which contain very sharp resonance peaks, transport peaks and continuum spectra. Application to real lattice QCD charmonium correlator data with $N_{\text{tau}}=96$, 48, 32 and 24 has also been performed and the same conclusion on the dissociation temperature of ground charmonium states as obtained from MEM is obtained.

Theoretical Developments / 191

**Lattice Conformal Field Theory on the Reimann Sphere**

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Viable non-perturbative methods for quantum field theories on curved manifold are difficult. By adapting features from both the traditional finite element methods (FEM) and simplicial Regge calculus we are developing a Quantum Finite Element Method (QFEM). To test the QFEM approach, we study the $\phi^4$ on the simplicial lattice for the Riemann Sphere. To reach the Wilson-Fisher fixed point in the continuum requires modifying the lattice Lagrangian by a counter terms which cancels the ultraviolet distortions of classical FEIM simplicial lattice. In addition Fermions are formulated on the Riemann sphere. Both are compared with the exact solutions to Ising $c=1/2$ 2D CFT field theory. Future directions and application are entertained.

Algorithms and Machines / 208

**QUDA features, scaling and solvers**

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We describe recent developments to the QUDA software framework, a library aimed at deploying lattice QCD computations on GPUs. The library has ever broadening support for various LQCD actions and algorithms, as well as being integrated into many LQCD applications. Recent focus has been on improving strong scaling for multi-GPU calculations and developing an adaptive multigrid
solver. We give updates on both of these efforts, and compare performance against other platforms. Lastly, we look to the future and discuss how upcoming technologies such as stacked memory and nvlink, a fast GPU interconnect, will bring disruptive changes to lattice QCD calculations.

Vacuum Structure and Confinement / 313

Study of non-perturbative contributions to surface operator within lattice gauge theory

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The most important probes for the phase states of a four-dimensional gauge field theory are the Wilson and t’Hooft line operators that are defined on one-dimensional curves in the space-time. However, for more detail understanding of four-dimensional gauge field theory dynamics and vacuum topology we need additional probes expressed by operators defined on the subspaces with higher dimensions. Possible candidates are operators that are defined on the two-dimensional surface in the four-dimensional space-time. The corresponding spatial surface operators are sensitive to the magnetic flux through a closed surface, what provides a tool for monopole condensate study. The area and volume dependence of the surface operator can provide a probe for the correlated and uncorrelated monopoles and antimonopoles condensation. In the present work the surface operator dependence on the surface area and volume are studied in the confinement and deconfinement phases within the SU(2) gauge field theory on the lattice. It is shown that spatial and temporal surface operators cannot be defined by the perturbation theory expansion only. The leading non-perturbative correction is obtained. Its dependence on inverse lattice coupling constants and temperature is studied. It is shown that the non-perturbative correction has dimension two and does not depend on temperature.

Nonzero Temperature and Density / 222

Preweighting method in Monte-Carlo sampling with complex action

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Understanding the QCD phase diagram from first principles is one of the ultimate goals in nuclear and particle physics. The largest obstacle towards this goal is the sign problem in lattice QCD at finite chemical potential. The statistical weight is reduced by the average phase factor and it becomes difficult to obtain precise results in the phase reweighting method. If we know the amount of cancellation beforehand, it would be possible to take account of the reduction during the sampling of configurations. In the case where the phase distribution is Gaussian, the average phase factor is \( \exp(-D^2/2) \) [1], where \( D^2 \) is the variance of the phase. We can approximately include this reduction in the Monte-Carlo sampling by adding “penalty” terms to the action.
We examine the usefulness of this “preweighting” method in the auxiliary field Monte-Carlo configurations in the strong coupling limit of lattice QCD [2]. We will also apply the preweighting to the strong coupling lattice QCD with $1/g^2$ corrections [3], where the sign problem is more serious.


Weak Decays and Matrix Elements / 155

**Improving our determinations of the decay constant $f_B$ and the $B \to \pi \ell \nu$ semi-leptonic form factors using physical light quarks**

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We report on updates of our $B$-physics program using domain-wall light quarks and nonperturbatively tuned, relativistic $b$-quarks by adding measurements obtained with dynamical and physical light quarks. We present progress towards improved determinations of the $B$-meson decay constant $f_B$, the ratio $f_{B_s}/f_B$, and the $B \to \pi \ell \nu$ semi-leptonic form factor. Our results are based on the RBC/UKQCD 2+1 flavor gauge field configurations with (M"obius) domain-wall fermions and the Iwasaki gauge action at two lattice spacing of 0.086 fm and 0.11 fm.

Nonzero Temperature and Density / 145

**The density of states approach at finite chemical potential: a numerical study of the Bose gas.**

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Recently, a novel algorithm for computing the density of states in statistical systems and quantum field theories has been proposed. The same method can be applied to theories at finite density affected by the notorious sign problem, reducing a high-dimensional oscillating integral to a more tractable one-dimensional one. As an example we applied the method to the relativistic Bose gas.
Hadronic form factors for rare semi-leptonic $B$ decays

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We show first results for the computation of semi-leptonic form factors for rare $B$ decays focusing in particular on $B \to K(\pi)\ell^+\ell^-$ and $B_s \to \phi\ell^+\ell^-$. Our setup uses domain-wall light quarks, relativistic $b$ quarks, and the RBC/UKQCD 2+1 flavor gauge field configurations with domain-wall fermions and the Iwasaki gauge action.

Optimization of Lattice QCD with CG and multi-shift CG on Intel Xeon Phi Coprocessor

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We implemented lattice QCD on Xeon Phi coprocessor using intrinsics as vectorization method, and OpenMP and MPI as parallelization method. Our implementation uses double precision conjugate gradient (CG) solver which also supports multi-shift CG.

We present our optimization methodology and performance for key steps in CG algorithms.

Abelian monopole or non-Abelian monopole responsible for quark confinement

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We have pointed out that the SU(3) Yang-Mills theory has a new way of reformulation using new field variables (minimal option), in addition to the conventional option adopted by Cho, Faddeev and Niemi (maximal option). The reformulation enables us to change the original non-Abelian gauge field into the new field variables such that one of them called the restricted field gives the dominant contribution to quark confinement in the gauge-independent way.

In the minimal option, especially, the restricted field is non-Abelian U(2) and involves the non-Abelian magnetic monopole. In the preceding lattice conferences, we have accumulated the numerical evidences for the non-Abelian magnetic-monopole dominance in addition to the restricted non-Abelian field dominance for quark confinement supporting the non-Abelian dual superconductivity using the minimal option for the SU(3) Yang-Mills theory.

This should be compared with the maximal option which is a gauge invariant version of the Abelian projection in the maximal Abelian gauge: the restricted field is Abelian U(1) x U(1) and involves only the Abelian magnetic monopole, just like the Abelian projection.

In this talk, we focus on discriminating between two reformulations, i.e., maximal and minimal options of SU(3) Yang-Mills theory for quark confinement from the viewpoint of dual superconductivity. For this purpose, we measure the distribution of the chromoelectric flux connecting a quark and an antiquark and the induced magnetic-monopole current around the flux tube.

**Nonzero Temperature and Density / 268**

### Thermal dilepton rates and electrical conductivity of the QGP

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We present new results on the reconstruction of mesonic continuum spectral functions for three temperatures between 1.1Tc and 1.5Tc in quenched QCD. Making use of non-perturbatively improved clover Wilson valence quarks allows for a clean extrapolation of measured correlator data to the continuum. We found that the vector correlation function is almost temperature independent in the current temperature window. For the case of vanishing momentum the vector spectral function is obtained by fitting the data to a well motivated ansatz. The electrical conductivity of the hot medium, related to the slope of the vector spectral function, is computed from the resulting parameters leading to a temperature independent estimate for all three temperatures. The dilepton rates resulting from the obtained spectral functions are compared to a perturbative expression, obtained by combining the results of different computations in different frequency regimes. Our results qualitatively yield a larger rate in the intermediate frequency regime, and also show no significant temperature dependence. The continuum extrapolated transversally and longitudinally polarized correlation functions at different momenta are compared to the corresponding perturbative expressions.
Scalar field theory on a 2-sphere using quantum finite element method (QFEM)

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We demonstrate the quantum finite element method (QFEM) by computing known properties of the 2-D Wilson-Fisher fixed point using scalar field theory on 2-sphere.

Nonzero Temperature and Density / 236

Calculation of free baryon spectral densities at finite temperature

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Following a recent study of nucleon parity doubling at finite temperature from the computation of the two-point nucleon correlators, we study the spectral functions of free baryons at finite temperature. A full analytic review of the spectral densities in the continuum is presented along with a comparison with numerical results. Particular attention will be given to lattice artifacts at higher energies.

Vacuum Structure and Confinement / 85

Gluon propagators near the phase transition in SU(2) gluodynamics

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We study Landau gauge transverse and longitudinal gluon propagators at non-zero temperature in close vicinity of the phase transition in SU(2) gluodynamics. We compute the screening mass and the electric-magnetic asymmetry of the $A^0$ condensate. Our goal is to provide results free of finite volume and Gribov copies systematic effects and with small scaling violations.

Algorithms and Machines / 319
Accelerating twisted mass LQCD with QPhiX

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We present the implementation of twisted mass fermions within the QPhiX code package along with an interface to tmLQCD. We analyze the performance on Intel Xeon Phis and Intel Xeon Haswell CPUs. On the latter we find a speedup of larger than 4x for the mixed precision conjugate gradient inverter.

Theoretical Developments / 261

**Spherical Finite Elements for Lattice Radial Quantization**

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Recent efforts have been made to study conformal field theories in radial quantization on the lattice. The lattice necessarily breaks spherical symmetry down to icosahedral symmetry, so efforts must be made to restore spherical symmetry — even at the classical level — by clever construction of the action. Linear finite elements have been shown to improve the spectrum of the Laplacian. In this work, we introduce spherical finite elements, which are bounded not by chords but by great circle arcs. We compare the spectra of the linear finite element Laplacian to the spherical finite element Laplacian.

Weak Decays and Matrix Elements / 152

**B \(-\bar{B}\) mixing with domain-wall light quarks and relativistic b-quarks**

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Using our well established setup of domain-wall light quarks and nonperturbatively tuned, relativistic b-quarks we extend our B-physics program to the computation of B-meson bag parameters and their ratio $\xi$. We present first results based on the RBC/UKQCD 2+1 flavor gauge field configurations.
with domain-wall fermions and the Iwasaki gauge action at two lattice spacing of 0.086 fm and 0.11 fm.

Nonzero Temperature and Density / 41

Solving the complex action problem of the finite density Z3 spin model with the density of states approach using FFA

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In this contribution we apply a variant of the density of states method to the Z3 spin model with a chemical potential. We use a restricted Monte Carlo strategy to compute restricted expectation values and study their dependence on a free parameter \( \lambda \) which enters in the Boltzmann weight. When expressed in terms of the density, the expectation values are well known functions of \( \lambda \) which we fit to the Monte Carlo data and in this way determine the density of states (functional fit approach (FFA)). We calculate observables related to the particle number and the particle number susceptibility and compare the results to a reference simulation in the dual formulation of the Z3 spin model. We find a good agreement of the methods for a wide range of parameters.

Theoretical Developments / 16

Encoding field theories into gravities

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We propose a method, which encodes the information of a \( d \) dimensional quantum field theory into a \( d + 1 \) dimensional gravity in the \( 1/N \) expansion. We first construct a \( d + 1 \) dimensional field theory from the \( d \) dimensional one via the gradient flow equation, whose flow time \( t \) represents the energy scale of the system such that \( t \rightarrow 0 \) corresponds to the ultra-violet (UV) while \( t \rightarrow \infty \) to the infra-red (IR). We then define the induced metric from \( d + 1 \) dimensional field operators. We show that the metric defined in this way becomes classical in the large \( N \) limit, in a sense that quantum fluctuations of the metric are suppressed as \( 1/N \) due to the large \( N \) factorization property. As a concrete example, we apply our method to the O(N) non-linear \( \Sigma \) model in two dimensions. We calculate the induced metric in three dimensions, which is shown to describe asymptotically De Sitter (DS) or Anti De Sitter (AdS) space in the UV limit. We finally discuss several open issues in future studies.
Anatomy of SU(3) flux tubes at finite temperature

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An attempt to adapt the study of color flux tubes to the case of finite temperature has been made. The field is measured through a connected correlator of Wilson loop and plaquette in the spatial sub-lattice. Still the profile of the flux tube resembles the transverse field distribution around an isolated vortex in an ordinary superconductor. The temperature dependence of all the parameters characterizing the flux tube is investigated.

Algorithms and Machines / 160

An implementation of hybrid parallel CUDA code for the hyperonic nuclear forces

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².

We present our recent effort to develop the CUDA code to measure the Nambu-Bethe-Salpeter (NBS) wave function of various baryon-baryon systems on the lattice, which is a primary quantity to make a first-principle calculation of nuclear force and hyperonic-nuclear forces from lattice QCD. Not only the nucleon-nucleon (NN) but also the hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions are fundamental inputs to study the properties of (hyper-)nuclei and the (hyperonic-)matter inside the neutron stars while the present phenomenological YN and YY potentials are not well constrained from experimental data. In the HAL QCD method, which is recently developed to study various interhadron interactions from lattice QCD, the NN, YN and YY potentials can be obtained at the same time by defining the set of interpolating field of baryons. The purpose of this contribution is to present a fast algorithm to calculate a large set of NBS wave functions and its implementation to the heterogeneous system involving GPUs. This is a branched work from the hybrid parallel programming reported in LATTICE 2013 [PoS LATTICE2013 (2014) 426]. A hybrid parallel CUDA code is implemented with utilizing the MPI and OpenMP. The present code works on HA-PACS at University of Tsukuba which comprises 16 CPUs (Intel E5-2670) and 4 GPUs (NVIDIA M2090) per node. We would also like to present preliminary results of YN potentials which is obtained from the 2+1 flavor lattice QCD at almost physical point.

Nonzero Temperature and Density / 303

Nucleons and parity doubling across the deconfinement transition

Author: Chris Allton¹

Co-authors: Benjamin Jaeger ¹; Chrisanthi Praki ¹; Gert Aarts ¹; Jon-Ivar Skullerud ²; Simon Hands ¹
The spectrum of nucleons and their parity partners is studied as a function of temperature across the deconfinement transition. We analyse our results using the correlation functions directly, and the Maximum Entropy Method. Both techniques show that there is degeneracy (i.e. parity restoration) in the parity partners’ ground states above $T_c$. This is in accordance with the expectation that parity and chiral symmetry are restored in the deconfined phase. We also find that the nucleon ground state is largely independent of the temperature, whereas there are substantial temperature effects in the negative parity ($N^*$) channel, already in the confined phase. All results are obtained using our FASTSUM $N_f=2+1$ ensembles.

Weak Decays and Matrix Elements / 223

Radial distributions of the axial density and the $B^{\ast\ast}B\pi$ coupling

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We will present our results for the radial distributions of the axial density in the heavy-light B meson in the static limit of HQET: $\langle B(p)A_\mu(\mathbf{r})B^{\ast\ast}(p',\lambda)\rangle$. Here, $r$ is the distance between the static heavy quark and the insertion of the axial current acting like a probe. Using the Generalized Eigenvalue Problem, we are able to isolate the first radial excitation of the vector $B^{\ast}$ meson and the associated density. After discussing the results, we will show how these distributions allow us to determine the $B^{\ast\ast}B\pi$ coupling at the kinematical point $q^2 = 0 \neq m_{B^{\ast\ast}} - m_B$. The simulations are performed using CLS gauge configurations with $N_f=2$ non-perturbatively $O(a)$-improved Wilson-Clover fermions and Heavy Quark Effective Theory in the static limit.

Nonzero Temperature and Density / 40

Density of states approach with FFA for an effective Polyakov loop model at finite density

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We study an effective theory for Polyakov loops at finite density (SU(3) spin model) using the density of states (DoS) method. We generalize a recently developed variant of DoS, the so-called functional fit approach (FFA) for systems with continuous degrees of freedom (compare also the related talk by P. Törek). We show that the density of states can be computed with sufficiently high accuracy and we compare our physical observables to the results of a reference simulation of the model in a dual simulation.
The three-quark potential and perfect Abelian dominance in SU(3) lattice QCD

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We study the static three-quark (3Q) potential with high statistics in SU(3) lattice QCD at the quenched level. For all the distances, the 3Q potential is found to be well described by the Y-Ansatz, i.e., one-gluon-exchange Coulomb plus Y-type linear potential.

As a remarkable fact, we find that the quark confinement force in the 3Q system can be perfectly described only with Abelian variables in the maximally Abelian gauge, which we call “perfect Abelian dominance” of the quark confinement.


Summary of Super Doubler Approach on Exact Lattice Supersymmetry

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Recently we have proposed a lattice SUSY formulation which we may call super doubler approach, where chiral fermion species doublers are identified as super partners of extended supersymmetry. We claim that the super symmetry is exactly kept on the lattice. However the formulation is nonlocal and breaks lattice translational invariance. We argue that these features cause no fundamental difficulties in the continuum limit. Furthermore a naive formulation breaks associativity of the product of fields and thus cannot be applicable to super Yang-Mills theory. We propose a modified super doubler approach to recover the associativity, which is essentially equivalent to the continuum formulation even for a finite lattice constant. We discuss fundamental meanings of the formulation.

Early Performance Evaluation of Lattice QCD on POWER+GPU Cluster

Author: Jun Doi

Page 126
As supercomputers are shifting from peta-scale to exa-scale, computers with accelerators such as GPUs, MICs and FPGAs have become one of the big trends of supercomputer because of their low energy consumption and high density. Now IBM’s POWER processor has quite new power. Nvidia’s Tesla GPU brings huge computational capability. It is important for us to understand how this new POWER+GPU environment brings power to the actual applications in the early stage. We implemented Wilson-Dirac kernel and BiCGStab solver using CUDA7.0 on the POWER+GPU cluster and evaluated the performance. We will show the performance results of serial and parallel executions.

Nonzero Temperature and Density / 68

Study of entropy production in Yang-Mills theory with use of Husimi function

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Understanding the thermalization process in a pure quantum system is a challenge in theoretical physics. In this work, we explore possible thermalization mechanism in Yang-Mills(Y-M) theory by using a positive semi-definite quantum distribution function called Husimi function which is given by a coarse graining of Wigner function within the minimal uncertainty. Then entropy is defined in terms of the Husimi function, which is called the Husimi-Wehrl(H-W) entropy. We propose two numerical methods to calculate the H-W entropy. We find that it is feasible to apply the semi-classical approximation with the use of classical Y-M equation. It should be noted that the semi-classical approximation is valid in the systems of physical interest including the early stage of heavy-ion collisions. Using a product ansatz for the Husimi function, which is checked to give only some 10 % over estimate, we succeed in a numerical evaluation of H-W entropy of Y-M theory and show that it surely has a finite value and increases in time.

Nonzero Temperature and Density / 118

Dual representation for massless fermions with chemical potential and U(1) gauge fields

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We show that the massless Schwinger model with staggered fermions can be represented with dual variables which are loops for the fermions and surfaces for the gauge fields. In the dual form the complex action problem of the conventional representation at finite chemical potential or non-vanishing theta-angle is absent, and dual Monte Carlo simulations are possible at arbitrary values.
of these parameters. We show that the dualization can be generalized to 1+1 dimensional fermions interacting with 4 dimensional U(1) gauge fields, i.e., to a system of wires with relativistic charged fermions.

**Hadron Structure / 278**

**Connected contribution to hadron correlation functions**

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We present an update of our lattice QCD calculation of the connected contribution to the hadronic vacuum polarization. We discuss different evaluations procedures (including the moment base approach and Pade fits) and the corresponding systematic errors.

**Physics Beyond the Standard Model / 337**

**Witten index and phase diagram of compactified N=1 supersymmetric Yang-Mills theory on the lattice**

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Owing to confinement, the fundamental particles of N=1 Supersymmetric Yang-Mills (SYM) theory, gluons and gluinos, appear only in colourless bound states at zero temperature. Compactifying one space-time dimension with periodic boundary conditions for fermions preserves supersymmetry, and confinement is predicted to persist independently of the length of the compactified dimension. This scenario can be tested non-perturbatively with Monte-Carlo simulations on a lattice. SUSY is, however, broken on the lattice and can be recovered only in the continuum limit. The partition function of compactified N=1 SYM with periodic fermion boundary conditions corresponds to the Witten index. Therefore it can be used to test whether supersymmetry is realized on the lattice. Results of our recent numerical simulations will be presented, supporting the disappearance of the deconfinement transition in the supersymmetric limit and the restoration of SUSY at low energies.

**Applications Beyond QCD / 90**

**Effective action for the Abelian Higgs model for a gauge-invariant implementation on optical lattices**

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We present a gauge-invariant effective action for the Abelian Higgs model in 1+1 dimensions. It is constructed by integrating out the gauge field and then using the hopping parameter expansion. The latter is tested with Monte Carlo simulations for small values of the scalar self-coupling. In the opposite limit, at infinitely large self-coupling, the Higgs mode is frozen and the partition function can be written in terms of local tensors and the tensor renormalization group blocking can be applied. The numerical implementation requires truncations and the time continuum limit of the blocked transfer matrix can be obtained numerically. At zero gauge coupling and with a spin-1 truncation, the small volume energy spectrum is identical to the low energy spectrum of a two-species Bose-Hubbard model in the limit of large onsite repulsion. The procedure is extended to finite gauge coupling and we derive a spin-1 approximation of the Hamiltonian which involves terms corresponding to transitions among the two species in the Bose-Hubbard model. An optical lattice implementation involving a ladder structure is proposed.

Nonzero Temperature and Density / 182

On the axial U(1) symmetry at finite temperature

Author: Guido Cossu

Co-authors: Akio Tomiya 2; Hidenori Fukaya 3; Jun Noaki 4; Shoji Hashimoto 4; Takashi Kaneko 4

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We report the results of our finite temperature investigation of the axial symmetry restoration at finite temperature. We simulated two flavors of domain-wall fermions at several volumes and lattice spacings. After taking into account the systematic errors from the violation of the Ginsparg-Wilson relation, our results show that in the chiral limit there is a strong suppression of the axial U(1) symmetry breaking measured using meson susceptibilities. This suppression is compatible with a no-breaking scenario at zero quark mass in the chirally symmetric phase. We observed that the contribution of the violations of the GW relation to the meson susceptibilities are much larger that what the residual mass measurement would suggest. We also show some insights on the sources of the violations related to the lowest eigenmodes of the Dirac operator.

Theoretical Developments / 252

Lattice gradient flow with tree-level $O(a^4)$ improvement in pure Yang-Mills theory
Recently, the Yang-Mills gradient flow method has continued to develop remarkably. The most successful application is demonstrated in an accurate determination of a reference scale. However, there is still room for improvement with respect to the lattice gradient flow, where some lattice artifacts are found to be non-negligible. Following a recent paper by Fodor et al. (arXiv:1406.0827), we examine several types of tree-level improvements on the flow action with various gauge actions in order to reduce the lattice discretization error.

In this talk, we will present our numerical results for reference scale $t_0$ using tree-level, $O(a^4)$ improved lattice gradient flow including the rectangle term in the flow action, and discuss effects of the discretization error in the lattice gradient flow.

Nonzero Temperature and Density / 45

Hagedorn spectrum and equation of state of Yang-Mills theories

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We present a novel lattice calculation of the equation of state of SU(2) Yang-Mills theory in the confining phase.

We show that a gas of massive, non-interacting glueballs describes remarkably well the results, provided that a bosonic closed-string model is used to derive an exponentially growing Hagedorn spectrum for the heavy glueball states with no free parameters.

This effective model can be applied to SU(3) Yang-Mills theory and the theoretical prediction agrees nicely with the lattice results reported by Borsányi et al. in JHEP 07 (2012) 056.

Hadron Structure / 266

Disconnected contribution to hadron correlation functions

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We report on our lattice QCD calculation of the disconnected contribution to various hadron correlation functions. We discuss different evaluation strategies, optimization of algorithmic parameters and we show first results at a coarse lattice spacing.

Theoretical Developments / 147
Renormalization constants of the lattice energy momentum tensor using the gradient flow

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We implement two different strategies for the non perturbative determination of the renormalized energy momentum tensor in SU(3) Yang-Mills on the lattice. Both strategies employ observables built with gauge fields that evolve according to the Yang Mills gradient flow.

In the first case, we use observables computed along the flow in order to define suitable lattice Ward Identities from which the renormalization constants of the energy momentum tensor can be measured.

In the second one, we show how to compute the renormalized energy momentum tensor using the small flow time expansion of properly chosen flowed observables.

We show and discuss the numerical results coming from the application of the first method, as well as some preliminary data from the second one.

Supermultiplets of the N=1 supersymmetric Yang-Mills theory in the continuum limit

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The spectrum of N=1 supersymmetric Yang-Mills theory, calculated on the lattice, is presented. The masses have been determined on three different lattice spacings and extrapolated towards vanishing gluino mass. We present the extrapolation to the continuum limit which is consistent with the formation of degenerate supermultiplets.

Schwinger Model Mass Anomalous Dimension

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The mass anomalous dimension for several gauge theories with an infrared fixed point has recently been determined using the mode number of the Dirac operator. In order to better understand the sources of systematic error in this method, we apply it to a simpler model, the massive Schwinger model with two flavours of fermions, where analytical results are available for comparison with the lattice data.

Nonzero Temperature and Density / 162

Study of the U(1)A symmetry restoration in two-flavor QCD at finite temperature with reweighed overlap fermions

Author: Akio Tomiya

Co-authors: Guido Cossu; Hidenori Fukaya; Jun Noaki; Shoji Hashimoto; Sinya Aoki; Takashi Kaneko

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We study the U(1)A anomaly in two-flavor lattice QCD at finite temperature using the Ginsparg-Wilson fermions. The gauge configurations are generated with the Mobius domain-wall fermion at and above the critical temperature on $32^3 \times 8$ and $32^3 \times 12$ lattices. We apply the reweighting of the fermion determinant to that of domain-wall fermion satisfying the GW relation exactly. The results for low-lying eigenmodes are significantly different, indicating that even a small violation of the GW relation may strongly affect the low-modes. We find a strong suppression of the low-modes after the reweighting, which suggests vanishing U(1)A in the chiral limit.

Nonzero Temperature and Density / 55

Higher order net baryon number cumulants in the strong coupling lattice QCD

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In the Beam Energy Scan Phase-1 (BES-1), net proton number fluctuations have been measured in search for the QCD critical point [1]. Finding the critical point is one of the most challenging subjects also in lattice QCD due to the sign problem. In the strong coupling limit
of QCD, one can investigate the finite density region by employing the Auxiliary Field Monte-Carlo (AFMC) method [2] or monomer-dimer-polymer simulation [3] in which the sign problem becomes milder. We will report results on the baryon number fluctuations in the chiral limit with AFMC and discuss the influence of the mesonic fluctuations on the critical behavior of the cumulants.


Nonzero Temperature and Density / 291

The $U_A(1)$ anomaly in high temperature QCD with chiral fermions on the lattice

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The magnitude of the $U_A(1)$ symmetry breaking is expected to affect the nature of the $N_f = 2$ QCD chiral phase transition. The explicit breaking of chiral symmetry due to realistic light quark mass is small, hence it is important to use chiral fermions on the lattice to understand the effect of $U_A(1)$ near the chiral crossover temperature, $T_c$. I present our latest results for the eigenvalue spectrum of 2+1 flavour QCD with dynamical M"{o}bius domain wall fermions at finite temperature probed using the overlap fermion operator on a $32^3 	imes 8$ lattice. We observe that the $U_A(1)$ is broken near $T_c$ and the low-lying eigenvalues primarily contributing to it. We check how sensitive the low-lying eigenvalues are on the sea-light quark mass and the lattice volume. We also present comparison with the earlier independent results with domain wall fermions.

Physics Beyond the Standard Model / 274

Canonical simulations of supersymmetric SU(N) Yang-Mills quantum mechanics

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The fermion loop formulation naturally separates partition functions into their canonical sectors. Here we discuss various strategies to make use of this for supersymmetric SU(N) Yang-Mills quantum mechanics obtained from dimensional reduction in various dimensions and present numerical results for the separate canonical sectors with fixed fermion numbers. We comment on potential problems due to the sign of the contributions from the fermions and due to flat directions. Finally, we discuss the possibility to extend the simulation strategies to higher dimensional gauge field theories, such as QCD.
Hadron Structure / 35

Disconnected quark loop contributions to nucleon observables using $N_f = 2$ twisted clover fermions at a physical value of the light quark mass

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We compute the disconnected quark loop contributions entering the determination of nucleon observables, by using an $N_f = 2$ ensemble of twisted mass fermions with a clover term at a pion mass $m_{\pi} \approx 130$ MeV. We employ exact deflation and implement all calculations in QUDA, enabling us to achieve large statistics and a good signal.

Applications Beyond QCD / 336

Study of the continuum limit of the Schwinger model using Wilson’s lattice formulation

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We estimate the critical point of the Schwinger model in the theta vacuum by taking the continuum limit of Wilson’s lattice formulation. The decorated tensor renormalization group which has been recently proposed by Dittrich et al. is employed for numerical investigation. We compare our numerical results with those of Byrnes et al., which were derived from Kogut-Susskind’s lattice formulation employing the density matrix renormalization group.

Theoretical Developments / 84

(2+1)-flavor QCD Thermodynamics from the Gradient Flow

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Recently, we proposed a novel method to define and calculate the energy-momentum tensor (EMT) in lattice gauge theory on the basis of the Yang-Mills gradient flow. In this talk, we show the bulk thermodynamic quantities in lattice gauge theory using this method for (2+1)-flavor QCD. The entropy density of (2+1)-flavor QCD at fixed temperature are calculated. We also show the flow time dependence of the EMT including the dynamical fermion contributions. This work is based on a joint-collaboration between FlowQCD and WHOT QCD.

Nonzero Temperature and Density / 54

Polyakov line actions from SU(3) lattice gauge theory with dynamical fermions: first results via relative weights

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We apply the relative weights method to extract an effective Polyakov line action, at finite chemical potential, from an underlying SU(3) lattice gauge theory with dynamical fermions. The center-symmetry breaking terms in the effective theory are fit to a form suggested by the hopping-parameter expansion, and the effective action is solved at finite chemical potential by a mean field approach. We present preliminary results for staggered fermions at $m_a=0.3$.

Nonzero Temperature and Density / 142

Effective Polyakov loop models for QCD-like theories at finite chemical potential

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We study QCD-like theories at finite density with three-dimensional Polyakov theories for heavy quarks. These effective theories are derived by combined strong coupling and hopping expansion techniques as previously been used for QCD. In particular we investigate the cold and dense regimes of the phase diagrams where one either expects Bose-Einstein condensation of bosonic or a liquid-gas transition of fermionic baryons, depending on the theory. We explicitly verify that there is no Silver Blaze problem, i.e. that the density tends to zero in the zero temperature limit for all quark chemical potentials below half the diquark mass in two-color and G2-QCD. As the quark number density increases with larger chemical potentials we generally also observe that the Polyakov loop rises indicating the creation of deconfined quark matter.
Background field method in the gradient flow

Author: Hiroshi Suzuki

Kyushu University

We develop a background field method and associated gauge fixing prescription in gradient flow equations. By using this formulation, we carry out non-diagramatic one-loop computations of the small flow time expansion of gauge invariant composite operators, aiming for the application to the energy-momentum tensor and the flavor-singlet axial-vector current on the lattice.

New results from lattice N=4 supersymmetric Yang–Mills

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I will present results from numerical studies of maximally supersymmetric Yang–Mills theory, using a new improved lattice action. I will also summarize the improvement procedure, which modifies the moduli equations in order to lift U(1) flat directions without violating the exact supersymmetry preserved at non-zero lattice spacing by the lattice formulation. The resulting improved action leads to dramatically reduced lattice artifacts and much more rapid approach to the continuum limit, allowing us to investigate stronger couplings on accessible lattice volumes.

Critical flavour number of the Thirring model in three dimensions

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The Thirring model is a four fermion theory with vector interaction. We study it in three dimensions, where it is closely related to QED and other models used to describe properties of graphene. In addition it is a good toy model to study chiral symmetry breaking, since a phase with broken chiral symmetry is present for the model with one fermion flavour. On the other hand, there is no such phase in the limit of infinitely many fermion flavours. Thus, a transition at some critical flavour number Nfc is expected, where the broken phase vanishes.

The model was already studied with different methods, including Schwinger-Dyson, functional renormalization group and lattice approaches. Most studies agree that there is indeed a phase transition from a chirally symmetric phase to a spontaneously broken phase for a small number of fermion flavours. But there is no agreement on the critical flavour number and further details of the critical behaviour. Values of Nfc found in the literature usually range between 2 and 7.
All earlier lattice studies were performed with staggered fermions, where it is questionable if the lattice model has the same chiral symmetry as the continuum version. We present new results from simulations of the Thirring model with SLAC fermions. With this choice, we can be sure to implement the same chiral symmetry of the continuum model. First estimates for the critical flavour number are given in this talk.

**Nonzero Temperature and Density / 50**

**Thermal modification of mesons and restoration of broken symmetries from spatial correlation functions with HISQ**

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By using spatial correlation functions we study thermal modifications of meson states and the restoration of broken symmetries at finite temperature in 2+1 flavor QCD with the Highly Improved Staggered Quarks (HISQ) action.

The spatial correlation functions provide a direct signal for the thermal modification of meson spectral functions and indicate the restoration of chiral and $U_A(1)$ symmetries at finite temperature. We calculate spatial correlation functions for several meson states on lattices with aspect ratio $N_s/N_t=4$ in a wide temperature range of 110–170 MeV on $N_t=8$ and 150–400 MeV on $N_t=12$ with a physical strange quark mass ($m_s$) and light quark masses ($m_l$) set to $m_l=m_s/20$.

In pion and kaon sectors we find that the thermal modifications become obvious even below the critical temperature ($T_c$) and the modification of positive parity states is more significant than those of the negative parity states. We also find that the spatial correlation functions of the vector parity partners degenerate at $T_c$, whereas those of the scalar parity partners show clear differences at $T_c$ and degenerate only above 1.6$T_c$.

This means that the breaking of the $U_A(1)$ symmetry is still significant at $T_c$. This fact is also confirmed through simulations at the physical point ($m_l=m_s/27$). We also discuss several properties of open-strange and open-charm mesons.

This is study on behalf of the BNL-Bielefeld Collaboration.

**Hadron Structure / 158**

**Exploring the effects of open boundary conditions on baryonic observables**

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We explore the effects of open boundary conditions, as used in the CLS $N_f = 2 + 1$ ensembles, on nucleon two- and three-point functions, with a view towards studying nucleon form factors on these
ensembles. Particular emphasis is put on controlling systematic effects due to the boundaries and excited states, and to the approach to the physical point.

Hadron Structure / 196

Improving the lattice axial vector current

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For Wilson and clover fermions traditional formulations of the axial vector current do not respect the continuum Ward identity which relates the divergence of that current to the pseudoscalar density. Here we propose to use an one-link axial vector current whose divergence exactly satisfies a lattice Ward identity, involving the pseudoscalar density and a number of irrelevant operators. We check in one-loop lattice perturbation theory with SLiNC fermion and gauge plaquette action that this is indeed the case including order O(a) effects. With those operators that axial Ward identity remains renormalisation invariant. First preliminary results of a nonperturbative check of the Ward identity are presented.

Nonzero Temperature and Density / 96

Footprint of non-decoupling in chiral phase transition

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We study chiral phase transition of two flavor massless QCD in the presence of a finite breaking of U(1) axial symmetry using the corresponding linear sigma model (LSM), in which half of eight scalar fields acquire the mass proportional to the U(1) breaking. Naively, the model is expected to reduce to ordinary O(4) LSM in the infrared limit if the massive degrees of freedom decouple sufficiently fast. We examine this expectation through the analysis of the renormalization group flows of the model, and discuss possible non-decoupling effects in chiral phase transition.

Theoretical Developments / 12

Generalized Gradient Flow Equation and Its Applications
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We generalize the gradient flow equation for field theories with nonlinearly realized symmetry. We apply the method to two theories, the super Yang-Mills theory in four dimensions and the O(N) nonlinear sigma model in two dimensions. Firstly, applying the formalism to super Yang-Mills theory, we construct the supersymmetric gradient flow equation. Furthermore, choosing an appropriate modification term to damp the gauge degrees of freedom, we obtain the gradient flow equation which is closed within the Wess-Zumino gauge. Secondly, applying the formalism to the O(N) nonlinear sigma model in two dimensions, we construct the gradient flow equation in the 1/N expansion. Solving this equation in the large N limit, we show non-perturbatively that the two point function at finite flow time is free from UV divergence. We also discuss the solution for four point function in the next-to-leading order of the 1/N expansion.

Physics Beyond the Standard Model / 201

Large-scale computation of the exponentially expanding universe in a simplified Lorentzian IIB matrix model

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The type IIB matrix model is conjectured to be a nonperturbative formulation of superstring theory. In 2011, the Lorentzian version of the model was studied for the first time by Monte Carlo simulation, and it was shown that (3+1)D expanding universe emerges from (9+1)D space-time predicted by superstring theory. Recently, a simplified model that describes the early time behaviors of the original model was studied with matrix size up to N=64, and it was suggested that the expansion of the (3+1)D universe is actually exponential, which is reminiscent of the inflation. In this work, we confirm this exponential expansion by simulating the simplified model with much larger matrix size up to N=512 using a large-scale parallel computer.

Nonzero Temperature and Density / 209

G(2)-QCD at finite temperature and density

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G(2)-QCD is a QCD-like theory that can be simulated with standard Monte-Carlo methods at finite baryon density. It shares many properties with QCD, especially fermionic baryons. In addition also bosonic baryons are present in the theory. In the talk we review the effect of bosonic and fermionic baryons on the phase diagram at zero temperature and show evidence for a first order nuclear matter transition. Furthermore we present our latest results on the phase diagram at finite temperature and density.

**Applications Beyond QCD / 305**

**Asymptotically free lattice gauge theory in five dimensions**

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The first lattice formulation of Lifshitz-type gauge theories is presented. While the Lorentz-invariant Yang-Mills theory is not renormalizable in five dimensions, non-Abelian Lifshitz-type gauge theories are renormalizable and asymptotically free. We construct a lattice gauge action and numerically examine the continuum limit and the bulk phase structure.

**Theoretical Developments / 237**

**The Wilson flow in scalar field theory**

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A nonperturbative renormalization prescription for the energy-momentum tensor, based on space-time symmetries along the Wilson flow, has been proposed recently in the context of four-dimensional gauge theories. We extend this construction to the case of a scalar field theory, and investigate its numerical feasibility by studying Ward identities in 3-dimensional phi^4 theory. In this talk, we introduce the Wilson flow for the scalar theory, discuss its renormalization properties, and present some preliminary results about the determination of the renormalization constants for the energy-momentum tensor.

**Physics Beyond the Standard Model / 332**

**Lattice and string worldsheets in AdS/CFT: a numerical study**

**Author:** Valentina Forini

**Co-authors:** Bjoern Leder; Edoardo Vescovi; Lorenzo Bianchi; Marco Bianchi; Mattia Bruno
A possible discretization of the Green-Schwarz string in AdS5xS5 background is discussed and applied to the numerical study of the so-called cusp anomaly f(g). The latter, a pure function of the coupling g, when studied assuming the integrability of the underlying model, is an example of non-trivial interpolation smoothly connecting weak and strong coupling regimes and testing the AdS/CFT correspondence at a very deep level.

**Hadron Structure / 146**

**A systematic study of excited-state effects on nucleon axial form factors**

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We extend our study of excited-state effects on nucleon form factors to the case of the axial vector and pseudoscalar form factors. Combining information from a variety of different ratios of two- and three-point functions, we are able to extract the form factors $G_A$ and $G_P$ over a range of momentum transfers $Q^2$; together with the use of different methods to suppress excited-state contaminations this allows us to systematically study the effect of excited states.

**Nonzero Temperature and Density / 325**

**Phase diagram of the U(2)xU(2) scalar model in three dimensions**

**Author:** Kazuhiko Kamikado

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If the chiral anomaly is effectively restored at finite temperature, the chiral phase transition of 2-flavor QCD with massless quarks is characterised by the symmetry breaking pattern $U_L(2) \times U_R(2) \rightarrow U_V(2)$. Therefore, the order of the phase transition of the $U(2) \times U(2)$ scalar model in three dimensions has been extensively studied.

The results of the perturbative renormalization group (RG) analyses are controversial. Up to 4th order of the perturbative expansion, there was no stable IR fixed point of the beta functions, therefore, the phase transition had been believed to be of first order. However there are reports that an infrared fixed point emerges at 5th order. Then the existence of the IR fixed point (or second order phase transition) is still under debate.
In this talk, we present results of a Monte Carlo simulation of the U(2) x U(2) scalar model on three dimensional lattice. We will make clear that the system undergoes both second and first order phase transition depending on the choice of the model parameters. We represent a phase diagram in the model parameter space from the view point of the order of the phase transition. We make a comparison the phase diagram with the RG flow of the 5th order RG analyses. We will show both results are consistent and the IR fixed point of the RG flow likely to exist.

Nonzero Temperature and Density / 164

**Determination of U_A (1) restoration from meson screening masses by using the entanglement PNJL model: Toward chiral regime**

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We determine temperature (T) dependence of U_A (1) restoration from meson screening masses calculated with 2+1 flavor lattice QCD, using PNJL model with entanglement vertex. The entanglement PNJL (EPNJL) model exhibits the U_A (1) anomaly through the Kobayashi- Maskawa- ‘t Hooft (KMT) interaction. T dependence of KMT interaction strength is then determined from the difference between pion and a0 meson screening masses. The strength is strongly suppressed around the pseudocritical temperature of chiral transition. This suppression is much stronger than that predicted by instanton liquid model.

Using this T-dependent KMT interaction, we draw the Columbia plot near the physical point. In the light-quark chiral-limit with the strange quark mass (m_s) fixed at the physical value, the chiral transition becomes the second order. A tricritical point appears when m_s is slightly below the physical value. Finally, we calculate T dependence of other meson screening masses with the EPNJL model and compare the model results with lattice QCD ones to check the validity of the present model.

Applications Beyond QCD / 307

**The gradient flow in simple field theories**

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The gradient flow has proved a valuable tool to the lattice community, with a range of applications to a variety of lattice calculations, from scale-setting to renormalisation. In this talk, I will focus on the gradient flow as a tool to suppress power-divergent mixing, a consequence of the hypercubic symmetry of the lattice regulator that is a particular difficulty for calculations of high moments of parton distribution functions. Provided the flow time is kept fixed in physical units, the gradient flow removes power-divergent mixing at the expense of introducing a new physical scale in the continuum. The smeared operator product expansion is a formalism that systematically accounts for this additional scale and connects nonperturbative calculations of flowed operators to continuum physics. Here I investigate the role of the gradient flow in suppressing power-divergent mixing and discuss the smeared operator product expansion for simple field theories.
QCD at non-zero temperature from the lattice

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I will review the status of calculations of thermodynamics quantities, spatial correlation lengths and real-time properties of strongly interacting matter at non-zero temperature. An attempt at a synthesis will be made. Quark number susceptibilities will not be covered here.

Fluctuations of conserved charges at finite temperature and density

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Fluctuations of conserved charges in a grand canonical ensemble can be calculated as derivatives of the free energy with respect to the respective chemical potential. They are directly related to experimentally available observables that describe the hadronization in heavy ion collisions. The same derivatives can be used to extrapolate zero density results to finite chemical potential. We review the recent lattice calculations in the staggered formalism and discuss its implications to phenomenology and resummed perturbation theory.

The Lefschetz thimble and the sign problem

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In this talk I will review the proposal to formulate quantum field theories (QFTs) on a Lefschetz thimble, which was put forward to enable Monte Carlo simulations of lattice QFTs affected by a sign problem. First I will review the theoretical justification of the approach, and comment on some open issues. Then, I will review the algorithms that have been proposed and are being tested to represent and simulate a lattice QFT on a Lefschetz thimble. In particular, I will review the lessons from the very first models of QFTs that have been studied with this approach.

Recent progress in lattice supersymmetry – from lattice gauge theory to black hole
Non-perturbative investigations of supersymmetry and superstring theory through lattice simulations are promising research directions. In this talk, I will review the recent progress in lattice supersymmetry, in particular, the numerical verification of the gauge/gravity duality.

**Beyond the Standard Model: lattice calculations at the energy frontier**

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The discovery of the Higgs boson in 2012 completed the Standard Model but many puzzles remain. Composite systems where the Higgs boson is a bound state of some new fermion species are viable models to describe beyond-SM phenomenology, but are most likely strongly coupled and require non-perturbative investigations.

In this talk I will review recent lattice calculations that investigate general properties of near-conformal systems and might describe the Higgs boson.