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

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Motivation

Today's lattice QCD simulations

- more computing power and better algorithms → better precision of lattice QCD results
- more and more important → good control of systematics

⇒ obviously, very important: good control of continuum limit

Problem when lattice spacing $a \to 0$

⇒ freezing of topology

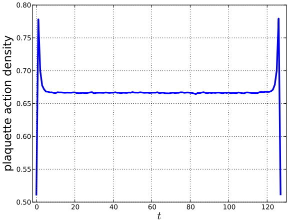
- lattice simulations get stuck in topological sectors
- problems begin at $a \approx 0.05\ \mathrm{fm}$

⇒ elegant solution: lattice simulations with open boundary conditions

[Lüscher and Schaefer 2011]

→ topology can flow in and out through the boundary

Lattice QCD with Open Boundaries



Open Boundaries

- $F_{0k}(x)|_{x_0=0} = F_{0k}(x)|_{x_0=T} = 0$
- $P_+\psi(x)|_{x_0=0} = P_-\psi(x)|_{x_0=T} = 0,$
- $\bar{\psi}(x)P_-|_{x_0=0} = \bar{\psi}(x)P_+|_{x_0=T} = 0$
- $P_\pm = \frac{1}{2}(1 \pm \gamma_0)$

Major CLS effort

CLS: CERN, DESY/NIC, Dublin, Berlin HU, Mainz, Madrid, Milan, Münster, Odense/CP3-Origins, Regensburg, Roma-La Sapienza, Roma-Tor Vergata, Valencia, Wuppertal

See also talks by

- Stefan SCHAEFER, Tue at 15:00h
- Tim HARRIS, Sat at 10:00h

Simulation Overview

Lattice Action

- Two degenerate light quarks and one strange quark (2+1f)
- Non-perturbatively improved Wilson Clover action
- Tree-level improved Symmanzik gauge action

Three Different Chiral Trajectories

Chiral Trajectory $\mathrm{Tr}M = const.$ (CLS)

$\mathrm{Tr}M = 2m_{(l)ight} + m_{(s)trange} = const. \leftrightarrow \sum_i \frac{1}{\kappa_i} = \frac{2}{\kappa_{light}} + \frac{1}{\kappa_{strange}} = const.$ (up to $\mathcal{O}(a)$)

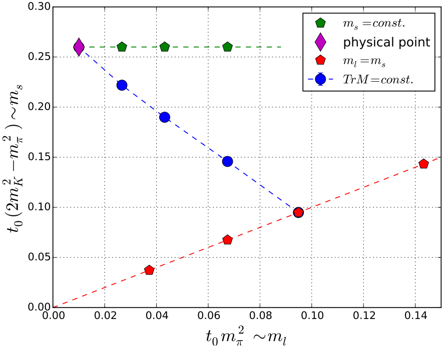
Chiral Trajectory $m_s = const.$ (CLS)

Keeping the strange PCAC mass constant at its physical value

Chiral Trajectory $m_l = m_s$ (Mainz/Regensburg)

Joint non-perturbative renormalization program
$\rightarrow$ simulations with anti-periodic boundary conditions (for $a > 0.05$fm)

General Simulation Strategy



1. simulate $\mathrm{Tr}M = const.$ trajectory: start from symmetric line
2. simulate symmetric trajectory ($m_l = m_s$)
3. fit PCAC masses (with $\mathrm{O}(a)$-improvement) using both $m_l = m_s$ and $\mathrm{Tr}M = const.$ trajectory
4. using this fit we determine physical point along $\mathrm{Tr}M = const.$ through $m_s^{PCAC}/m_l^{PCAC} = 27.46(44)$ [FLAG]
   $\rightarrow$ obtain $m_{s,physical}^{PCAC}$
5. using this fit we can predict κ_l, κ_s at which $m_s^{PCAC} = m_{s,physical}^{PCAC}$ $\rightarrow$ simulate $m_s = const.$ trajectory

CLS Ensemble Overview → JHEP 1502 (2015) 043 [hep-lat 1411.3982]

$\mathrm{Tr}M = const.$ trajectory

id	β	N_s	N_t	κ_u	κ_s	m_π [MeV]	m_K [MeV]	$m_\pi L$
B105	3.40	32	64	0.136970	0.13634079	280	460	3.9
H101	3.40	32	96	0.13675962	0.13675962	420	420	5.8
H102	3.40	32	96	0.136865	0.136549339	350	440	4.9
H105	3.40	32	96	0.136970	0.13634079	280	460	3.9
C101	3.40	48	96	0.137030	0.136222041	220	470	4.7
D100	3.40	64	128	0.137090	0.136103607	130	480	3.7
H200	3.55	32	96	0.137000	0.137000	420	420	4.4
N200	3.55	48	128	0.137140	0.13672086	280	460	4.4
D200	3.55	64	128	0.137200	0.136601748	200	480	4.2
N300	3.70	48	128	0.137000	0.137000	420	420	5.1
N301	3.70	48	128	0.137005	0.137005	410	410	4.9
J303	3.70	64	192	0.137123	0.1367546608	260	470	4.1

$m_s = const.$ trajectory

id	β	N_s	N_t	κ_u	κ_s	m_π [MeV]	$\eta_{s\bar{s}}$ [MeV]	$m_\pi L$
H107	3.40	32	96	0.13694566590798	0.136203165143476	360	680	5.1
H106	3.40	32	96	0.137015570024	0.136148704478	270	670	3.8
C102	3.40	48	96	0.13705084580022	0.13612906255557	220	670	4.7
N201	3.55	48	128	0.137160	0.136560678	280	670	4.4
D201	3.55	64	128	0.1372067	0.136546844	200	670	4.2

Ensemble Overview and Outlook

Mainz/Regensburg ensembles: symmetric line $m_l = m_s$

id	β	N_s	N_t	κ	m_π [MeV]	$m_\pi L$
rqcd19	3.40	32	32	0.13660000	610	8.5
rqcd16	3.40	32	32	0.13675962	420	5.9
rqcd21	3.40	32	32	0.13681300	340	4.8
rqcd17	3.40	32	32	0.13686500	260	3.6
B201	3.55	32	64	0.136700	710	7.4
rqcd25	3.55	32	64	0.137000	420	4.4
B200	3.55	48	64	0.137050	350	5.5
B202	3.55	48	64	0.137100	260	4.1

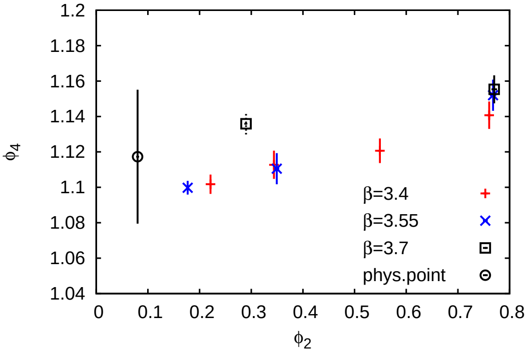
$\rightarrow$ with anti-periodic boundary condition in time!

Outlook

- $\beta = 3.55$ (in production), $\beta = 3.46$ (in preparation)
- finite volume study at $\beta = 3.4$
- extend $\beta = 3.7$, start new $\beta = 3.85$

- Tuning Details and Results for $\mathrm{Tr}M = const.$ Trajectory

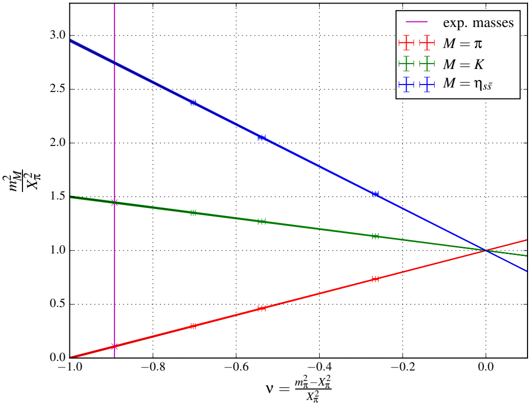
Tuning Strategy: $\mathrm{Tr}M = const.$



- $\phi_2 = t_0 m_\pi^2 \sim m_l, \quad \phi_4 = 8t_0(m_K^2 + m_\pi^2/2) \sim \mathrm{Tr}M$
- At fixed β match lattices with different lattice spacings at flavor symmetric point (i.e. $m_{ud} = m_s \rightarrow m_\pi = m_\mathrm{K} \approx 420\ \mathrm{MeV}$)
- We have determining the slope of ϕ_4 as a function of ϕ_2 at $\beta = 3.4$ from a set of preliminary runs: $\phi_4\big|_{m_{ud}=m_s} = 1.15$

Chiral Fits: Mesons

preliminary

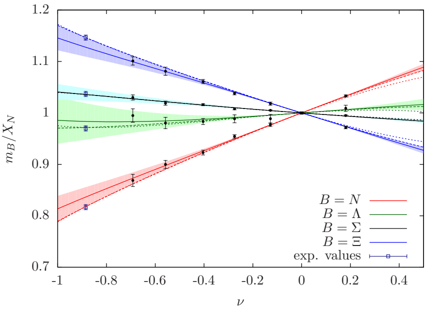


Average pion mass $X_\pi^2 = \frac{1}{3}\left(2m_K^2 + m_\pi^2\right) \sim \mathrm{Tr}M$

$\nu = \frac{m_\pi^2 - X_\pi^2}{X_\pi^2} \sim \frac{\delta m}{\mathrm{Tr}M} = \frac{m_s - m_l}{\mathrm{Tr}M}$

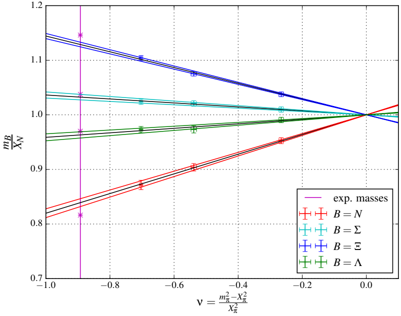
Chiral Fits: Baryon Spectrum

preliminary



[Bruns, Greil, Schaefer 2013]

based on QCDSF data



preliminary RQCD(CLS) data

⇒ consistency with other studies (QCDSF, RQCD)

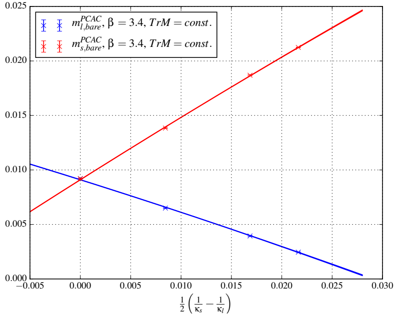
Average nucleon mass $X_N = \frac{1}{3}(m_N + m_\Sigma + m_\Xi) \sim \mathrm{Tr}M$

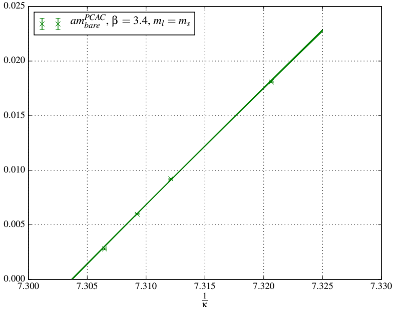
$\nu = \frac{m_\pi^2 - X_\pi^2}{X_\pi^2} \sim \frac{\delta m}{\mathrm{Tr}M} = \frac{m_s - m_l}{\mathrm{Tr}M}$

- Tuning Details for $m_s = const.$ Trajectory

PCAC masses and O(a)-Improvement

preliminary



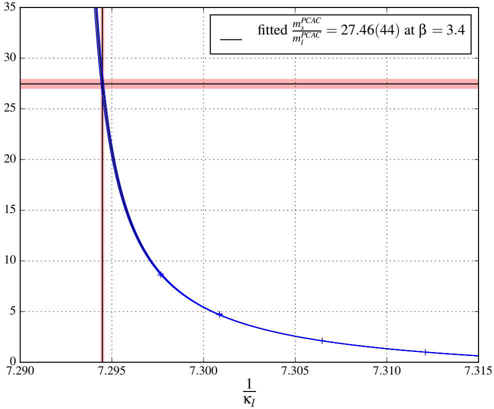


Simultanous fit of light and strange improved PCAC masses $m^{PCAC}_{(l,s),bare}(\kappa_l, \kappa_s)$ from $\mathrm{Tr}M = const.$ and $m_l = m_s$ trajectory

- fit parameters: $Z \equiv \frac{Z_P Z_m}{Z_A}$, r_m, κ_{crit}, $\mathcal{A}_0$, $\mathcal{B}_0$, $\mathcal{C}_0$, $\mathcal{D}_0$ ($\rightarrow$ fit dominated by C_0)
- $\mathcal{A}_0, \ldots, \mathcal{D}_0$ are combinations of r_m, b_P, b_A, b_m, d_m, $\bar{b}_P$, $\bar{b}_A$, $\bar{b}_m$, $\bar{d}_m$

Physical Point

preliminary

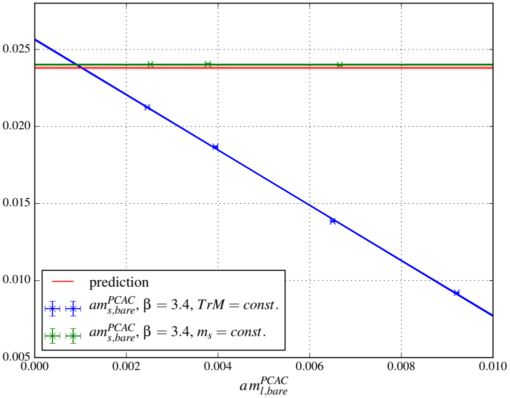


$\frac{m^{PCAC}_{s,bare}}{m^{PCAC}_{l,bare}}$ determined from fit and evaluated along $\mathrm{Tr}M = const.$

- physical value = 27.46(44) taken from [FLAG] $\rightarrow$ obtain physical $m^{PCAC}_{s,bare}$

Chiral Trajectory $m_s = const.$: prediction vs. simulation

Predicted and simulated value of physical $m_{s,bare}^{PCAC}$

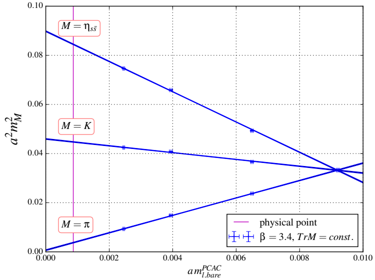


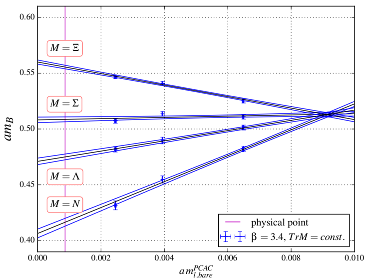
preliminary

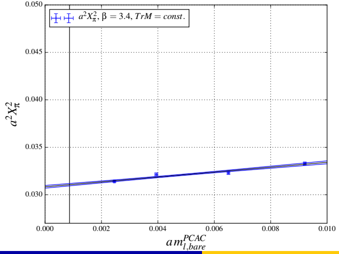
- Comparing Chiral Trajectory $\mathrm{Tr}M = const.$ to $m_s = const.$

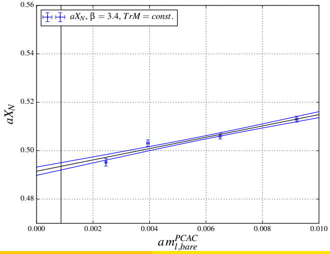
Chiral Fits $\mathrm{Tr}M = const.$: masses vs. m_l

preliminary



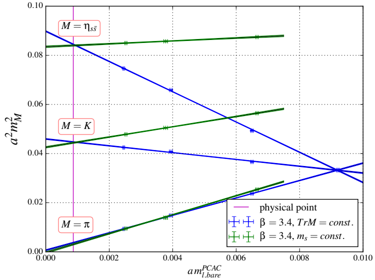


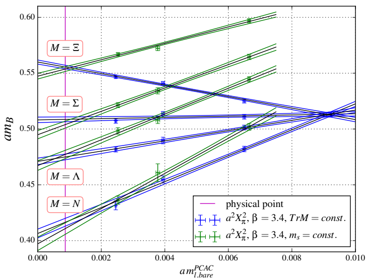


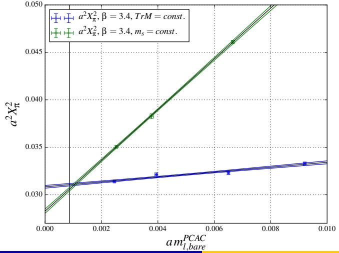


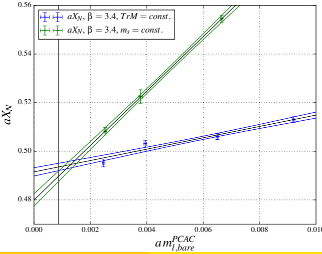
Chiral Fits: Comparing $\mathrm{Tr}M = const.$ to $m_s = const.$

preliminary

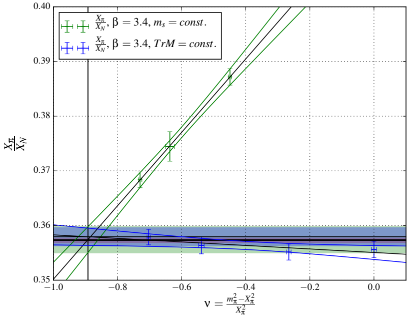


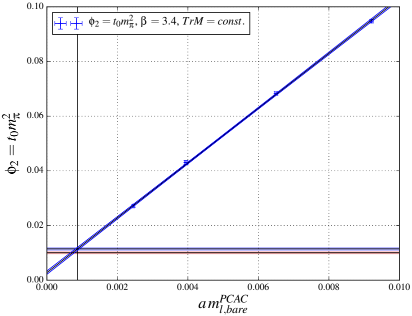






Consistency Checks (preliminary)





TrM chosen correctly?

consistency between different observables?

$$\phi_4, \phi_2 \longleftrightarrow \frac{X_\pi}{X_N}, \nu = \frac{m_\pi^2 - X_\pi^2}{X_\pi^2}$$

$\rightarrow$ very good agreement!

Definition of physical point consistent?

$$\phi_2 = t_0 m_\pi^2 \longleftrightarrow \frac{m_s}{m_l} = 27.46(44)$$

$\rightarrow$ only very little deviation!

Compare scale setting

relative error on a from $m_N \approx 1.3\%$, from $m_\Xi \approx 0.4\%$ $\longleftrightarrow$ from $t_0 \approx 1.7$ (t_0 from BMW)

Summary

Lattice Simulations with Open Boundaries

- avoid topological freezing as $a \to 0$
- long term effort within CLS

$\mathrm{Tr}M = const.$ trajectory: Meson/Baryon Spectrum

- chiral fitting: work in progress

$m_s = const.$ trajectory: Meson/Baryon Spectrum

- achieved simulations with very constant strange PCAC mass along $m_s = const.$ trajectory
- good overall agreement of masses at the physical point with $\mathrm{Tr}M$ trajectory

Strategy allows us

- to determine $\mathrm{SU}(2)$ as well as $\mathrm{SU}(3)$ low energy constants
- to safely extrapolate to the physical quark mass point

Outlook

- extend present study: continuum estimate containing 3 lattice spacing within next year
- more ensembles with smaller lattice spacing planned/in generation