Lattice simulation of QC_2D with $N_f = 2$ at non-zero baryon density

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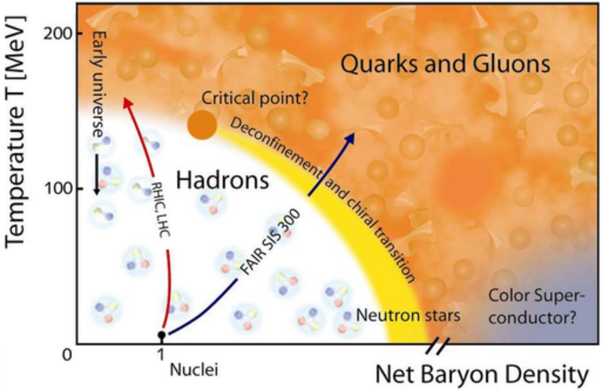
Outline

- Introduction
- Two-color QCD formulation
- Results
- Conclusions

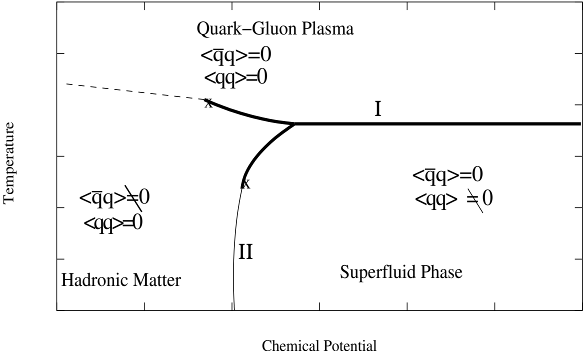
Why do we need to study the QCD phase diagram?

QCD phase diagram is important for HEP, particle physics and astrophysics. But at the moment we can not directly study it in LQCD at finite density due to the sign problem.



Why do we need to study the QC_2D phase diagram?

Two-color QCD has no sign problem and its phase diagram resembles the QCD phase diagram. We can study this simpler theory in order to understand qualitative features of QCD phase diagram.



Picture from J. B. Kogut, D. Toublan, and D. K. Sinclair, Nucl. Phys. B 642, 181—209 (2002)

Sign problem in QC_2D

In LQCD we have the following relation for the Dirac operator:

$$det\Big[M(\mu_q)\Big]^* = det\Big[M(-\mu_q^*)\Big],$$

but the case of $SU(2)$ is special:

$$\begin{aligned} det\Big[M(\mu_q)\Big] &= det\Big[(\tau_2 C\gamma_5)^{-1} M(\mu_q)(\tau_2 C\gamma_5)\Big] = \\ &= det\Big[M(\mu_q^*)\Big]^*, \end{aligned}$$

where $C = \gamma_2\gamma_4$.

In QC_2D at real μ_q:
$det\Big[M(\mu_q)\Big]$ is real, $det\Big[M^\dagger(\mu_q)M(\mu_q)\Big] > 0$ at $m_q \neq 0$.

Previous and ongoing lattice studies of QC_2D at $\mu_q \neq 0$

- $N_f = 8$, staggered fermions, no rooting:
  S. Hands, J. B. Kogut, M. P. Lombardo, S. E. Morrison, Nucl. Phys. B **558**, 327—346 (1999);
- $N_f = 4$, staggered fermions with rooting:
  J. B. Kogut, D. Toublan, and D. K. Sinclair, Phys.Lett. **B514**, 77—87 (2001);
  J. B. Kogut, D. Toublan, and D. K. Sinclair, Nucl. Phys. B **642**, 181—209 (2002);
- $N_f = 2$, Wilson fermions:
  S. Cotter, P. Giudice, S. Hands, and J. I. Skullerud, Phys. Rev. D **87**, 034507 (2013);
  T. Makiyama, *et al.*, arXiv:hep-lat/1502.06191 (2015);
- our study: $N_f = 2$, staggered fermions with rooting.

Action

We consider $N_f = 2$ of staggered fermions by using rooting:

$$Z = \int DU\, det\left[M^\dagger(\mu_q)M(\mu_q)\right]^{\frac{1}{4}} e^{-S_G[U]},$$

where

$$M_{xy}(\mu_q) = m_q a\delta_{xy} + \frac{1}{2}\sum_{\mu=1}^{4}\eta_\mu(x)\Big[U_{x,\mu}\delta_{x+\hat{\mu},y}e^{\mu_q a\delta_{\mu,4}} - \\ - U^\dagger_{x-\hat{\mu},\mu}\delta_{x-\hat{\mu},y}e^{-\mu_q a\delta_{\mu,4}}\Big].$$

Φ-algorithm and RHMC are being used in simulations.

Diquark source

In QC_2D we can add diquark source to the action to study spontaneous breakdown of $U(1)_V$:

$$S_F = \sum_{x,y}\left[\overline{\chi}_x M(\mu_q)_{xy}\chi_y + \frac{\lambda}{2}\delta_{xy}\left(\chi^T\tau_2\chi + \overline{\chi}\tau_2\overline{\chi}^T\right)\right],$$

which modifies partition function as follows:

$$Z = \int DU\, det\left[M^\dagger(\mu_q)M(\mu_q) + \lambda^2\right]^{\frac{1}{4}} e^{-S_G[U]}.$$

Diquark condensate is colorless and may be measured:

$$\langle qq\rangle = \frac{1}{N_\tau N_s^3}\frac{\partial\,(logZ)}{\partial\lambda} = \frac{2\lambda}{N_\tau N_s^3}\left\langle \mathrm{Tr}\left(M^\dagger M + \lambda^2\right)^{-1}\right\rangle$$

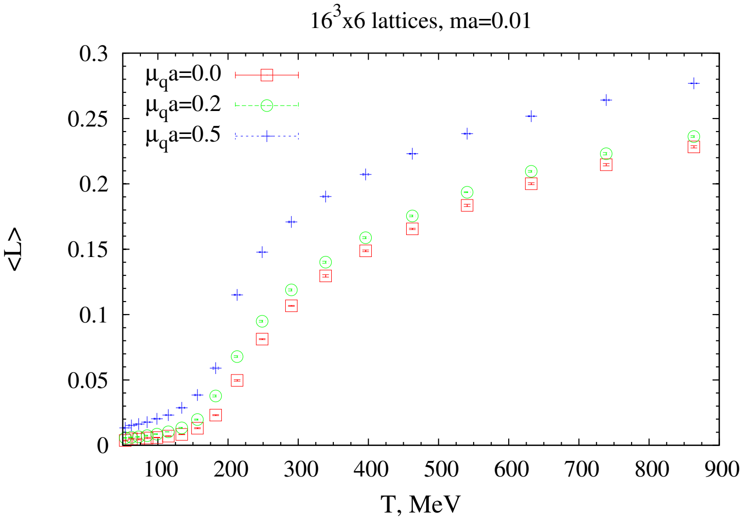
Simulation details

- Unimproved action were used (we do not need improvements to scan the phase diagram)
- Preliminary simulations at non-zero temperature: $16^3 \times 6$ lattices, $m_q a = 0.01$, $\mu_q a = 0.0 \dots 0.6$, $\beta = 1.6 \dots 2.5$, $\lambda = 0$
- Scale setting and m_π determination:
  - $16^3 \times 32$ lattices, $m_q a = 0.01$, $\mu_q a = 0.0$, $\beta = 2.0, 2.1, 2.2$
  - $r_0 = 0.468(4)$ fm (A. Bazavov, *et al.*, PRD 85, 054503 (2012))

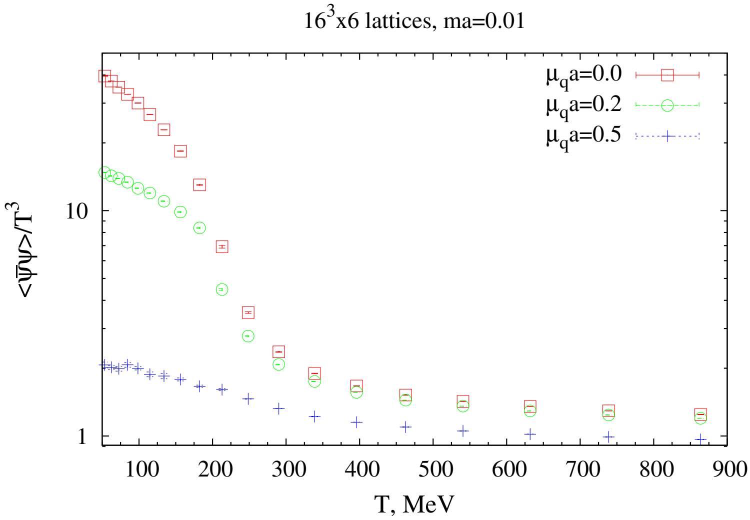
β	a, fm	M_π, MeV
2.0	0.171(4)	310(6)
2.1	0.135(2)	431(8)
2.2	0.097(1)	558(11)

- Ongoing simulations:
  scans in μ_q at fixed T, $16^3 \times 16 \dots 32$ lattices, $N_\sigma a \approx 1.8$ fm
  $m_q \approx 9$ MeV (fixed), $\mu_q = 0.0 \dots 1.0$ GeV
  3 values of λ, extrapolation to $\lambda \to 0$

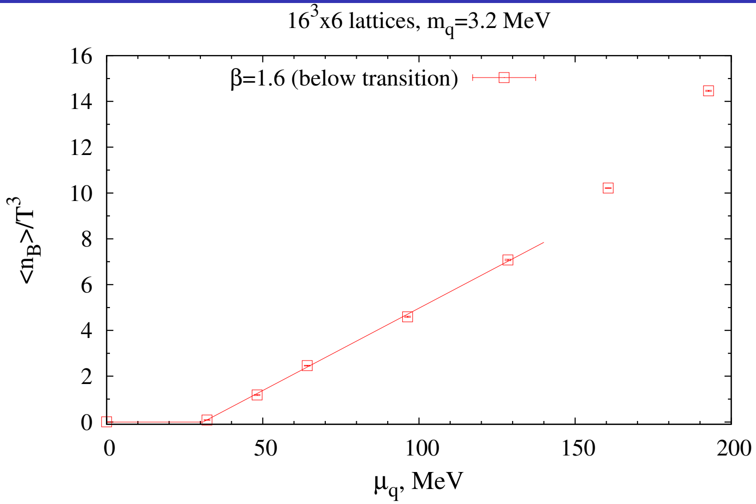
Polyakov loop



Chiral condensate



Baryon number density



At $\beta = 1.7$ pion mass is 110(3) MeV.

Conclusions

Preliminary results:

- Increasing of the baryonic chemical potential leads to the decreasing of $\langle\bar{\psi}\psi\rangle$ and T_c;
- In the confinement phase the dependence of n_B on μ_q is linear at $\mu_q > m_\pi/2$.

Plans for the nearest future:

- calculation of the QC_2D phase diagram (m_q is fixed, $\lambda \to 0$);
- investigation of the diquark condensation phase at large μ_q;
- checking of the influence of μ_q on χ_T.

Thank you for attention

The end