Two-color QCD with chiral chemical potential

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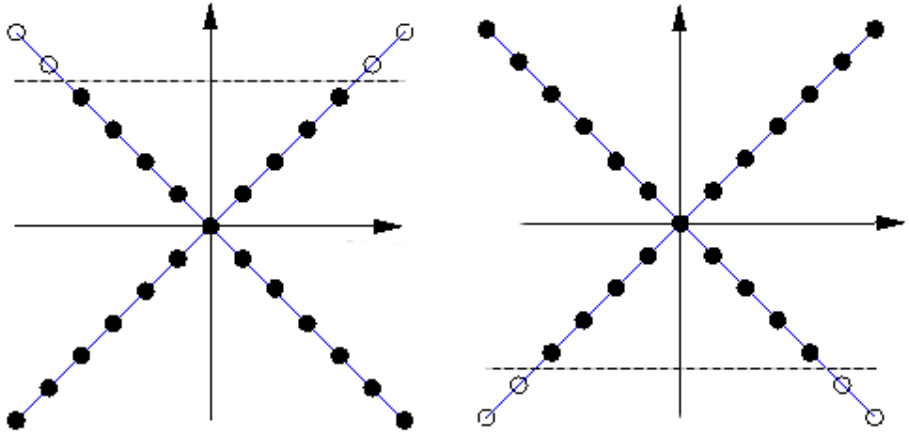
Outline

- Introduction. Motivation.
- Previous phenomenological studies.
- Lattice setup.
- Results and conclusion.

Chiral chemical potential

$$S_f = \int \bar{\psi}(\partial_\mu \gamma_\mu + igA_\mu \gamma_\mu + m + \mu_5 \gamma_0 \gamma_5)\psi$$

$$\langle \bar{\psi}\gamma_0\gamma_5\psi \rangle = \langle \psi_R^\dagger \psi_R - \psi_L^\dagger \psi_L \rangle > 0$$



Right-handed Fermi sea

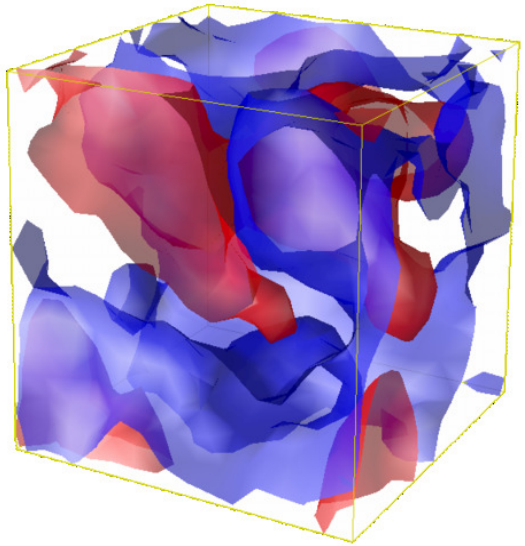
Left-handed Fermi sea

"chirally imbalanced matter"

Chiral chemical potential

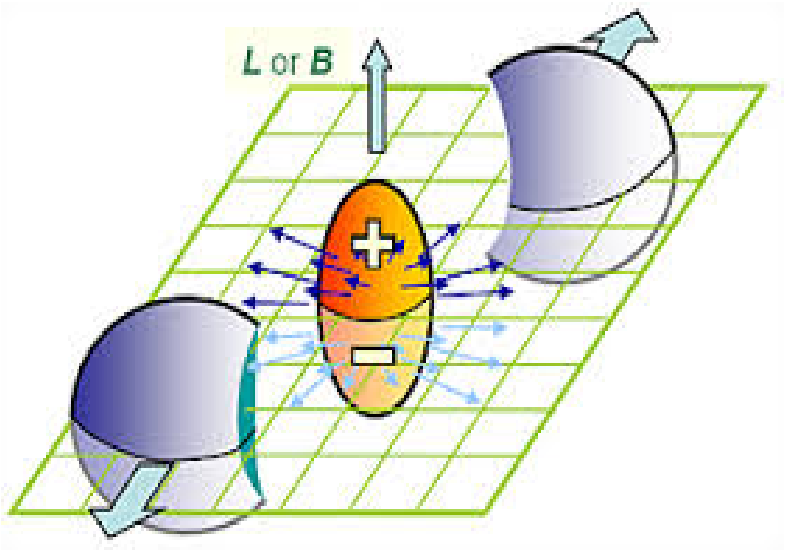
In QCD fluctuations of topological charge may lead to creation of difference between left and right-handed quarks density (chirally imbalanced matter).

$$\partial_\mu j_5^\mu \sim F_a^{\mu\nu} \tilde{F}_{\mu\nu}^a \tag{1}$$



P. V. Buividovich, T. Kalaydzhyan, M. I. Polikarpov, arXiv:1111.6733[hep-lat]

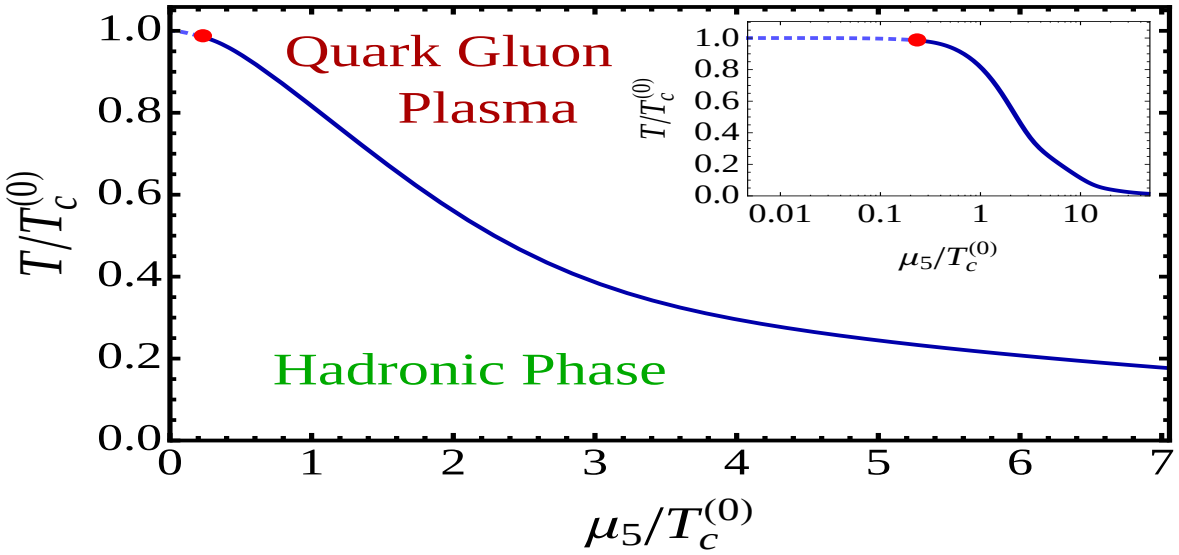
Chiral chemical potential



- Chiral magnetic effect and other non-dissipative phenomena. Occur in deconfinement.
- Interesting to study phase diagram.
- No sign problem contrary to chemical potential μ - lattice simulations.

Phenomenological studies

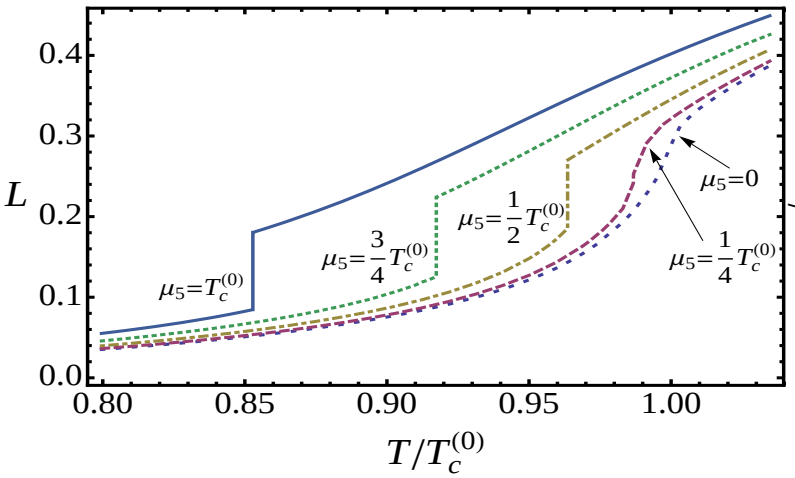
- M. N. Chernodub and A. S. Nedelin, Phase diagram of chirally imbalanced QCD matter, Phys. Rev. D**83**, 105008 (2011), arXiv: 1102.0188(hep-ph).
- K. Fukushima, M. Ruggieri, and R. Gatto, Chiral magnetic effect in the PNJL model, Phys. Rev. D**81**, 114031 (2010), arXiv: 1003.0047 (hep-ph).



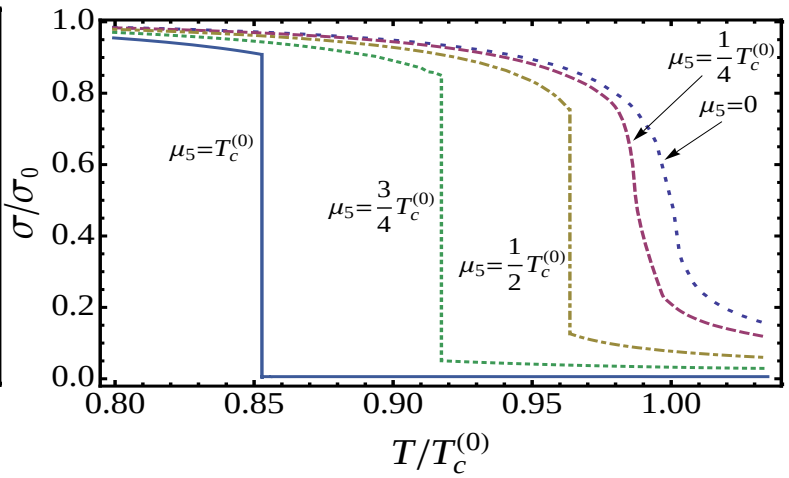
At large μ_5 crossover transforms to the first order phase transition (details differ in different papers).

Phenomenological studies

M. N. Chernodub and A. S. Nedelin, Phase diagram of chirally imbalanced QCD matter, Phys. Rev. D**83**, 105008 (2011), arXiv: 1102.0188(hep-ph).



Polyakov loop



Chiral condensate

Aim (optimistic)

The aim of our study: phase diagram of QCD in the plane of the chiral chemical potential and temperature: $\mu_5 - T$.

Chiral chemical potential on the lattice

For staggered fermions:

$$S_f = \frac{1}{2}\sum_{x\mu}\eta_\mu(x)(\bar\psi_{x+\mu}U_\mu(x)\psi_x - \bar\psi_x U^\dagger_\mu(x)\psi_{x+\mu}) + ma\sum_x \bar\psi_x\psi_x +$$

$$+\frac{1}{2}\mu_5 a\sum_x s(x)(\psi_{x+\delta}\bar U_{x+\delta,x}\psi_x - \psi_{x+\delta}\bar U^+_{x+\delta,x}\psi_x)$$

Here
$\delta = (1,1,1,0)$
$s(x) = (-1)^{x_2}$ corresponds $\gamma_0\gamma_5$
$\bar U_{x+\delta,x}$ is a product of gauge fields along the ways $x \to x+\delta$ (averaged over 6 different ways)

Lattice setup

- The code is developed on the basis of the code of A. Schreiber, Humboldt University, Berlin.
- Parameters(lattice steps etc) are taken from E.-M. Ilgenfritz et al., Two-color QCD with staggered fermions at finite temperature under the influence of a magnetic field, Phys.Rev. D**85** (2012) 114504, arXiv: 1203.3360[hep-lat]
- Simulations were performed at GPUs of supercomputer K100 and computers of Berlin group.
- We present first preliminary results.

Lattice setup

- $SU(2)$ gauge group for simplicity
- For gauge fields we adopted Wilson action

$$S_g = \frac{\beta}{4} \sum_{x,\mu\neq\nu} \mathrm{tr}\left(1 - U_\mu(x) U_\nu(x+\mu) U_\mu^\dagger(x+\nu) U_\nu^\dagger(x)\right)$$

- Lattice size $N_\sigma^3 \times N_\tau = 16^3 \times 6$

Lattice setup

- 4 tastes of dynamical staggered fermions (without rooting)
- 2 values of μ_5: $460 MeV$, $920 MeV$
- Small $ma = 0.01$
- For each point N configurations $\sim O(1000)$

Observables

- Polyakov loop $\langle L \rangle$:

$$L = \frac{1}{N_\sigma^3} \sum_{n_1,n_2,n_3} \frac{1}{2} \mathrm{tr} \left(\prod_{n_4=1}^{N_\tau} U_4(n_1, n_2, n_3, n_4) \right)$$

- Chiral condensate $a^3 \langle \bar{\psi}\psi \rangle$:

$$a^3 \langle \bar{\psi}\psi \rangle = -\frac{1}{N_\tau N_\sigma^3} \frac{1}{4} \frac{\partial}{\partial(ma)} \log(Z) = \frac{1}{N_\tau N_\sigma^3} \frac{1}{4} \langle \mathrm{tr}(D + ma)^{-1} \rangle$$

Observables. Susceptibilities

- Polyakov loop susceptiblity:

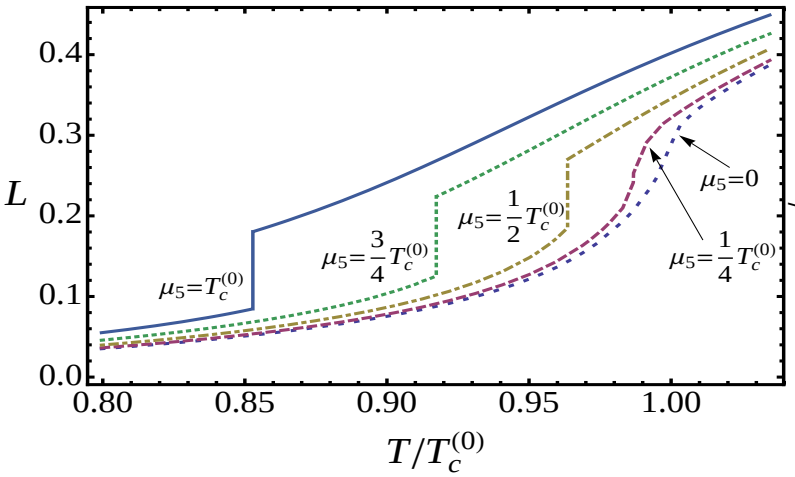
$$\chi_L = N_\sigma^3(\langle L^2\rangle - \langle L\rangle^2)$$

- Chiral susceptibility:

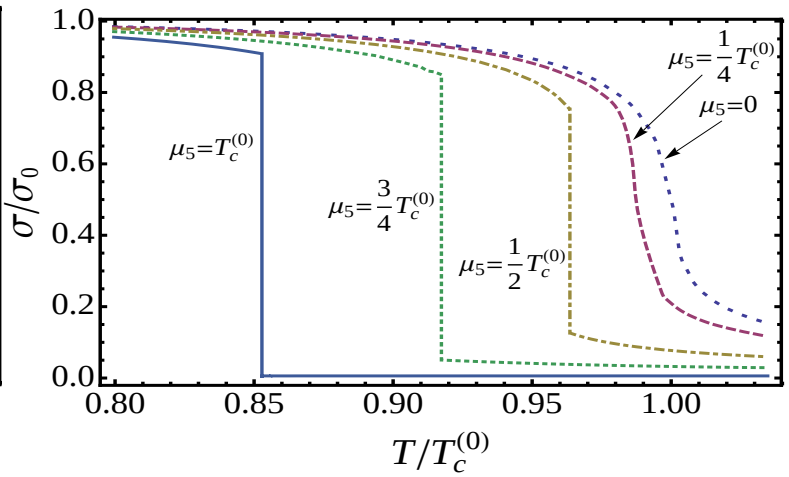
$$\chi = \frac{1}{N_\tau N_\sigma^3}\frac{1}{16}(\langle(\mathrm{tr}(D+ma)^{-1})^2\rangle - \langle \mathrm{tr}(D+ma)^{-1}\rangle^2)$$

Results. Polyakov loop and chiral condensate

M. N. Chernodub and A. S. Nedelin, arXiv: 1102.0188(hep-ph)

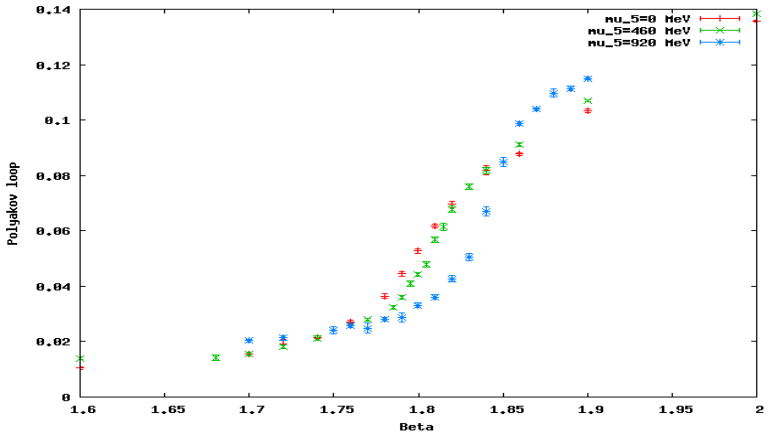


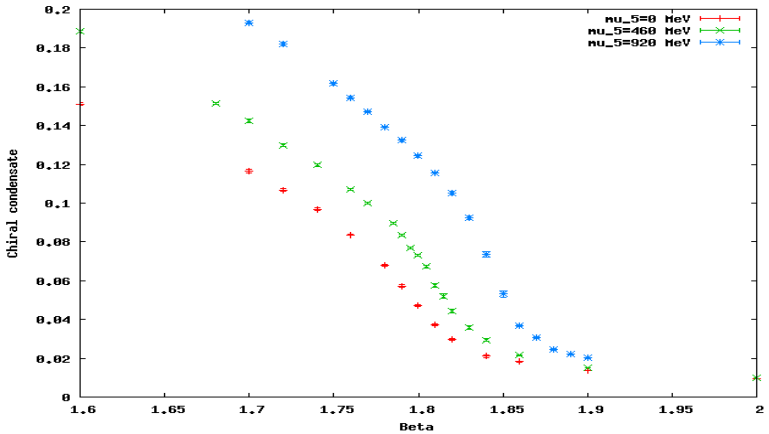
Polyakov loop



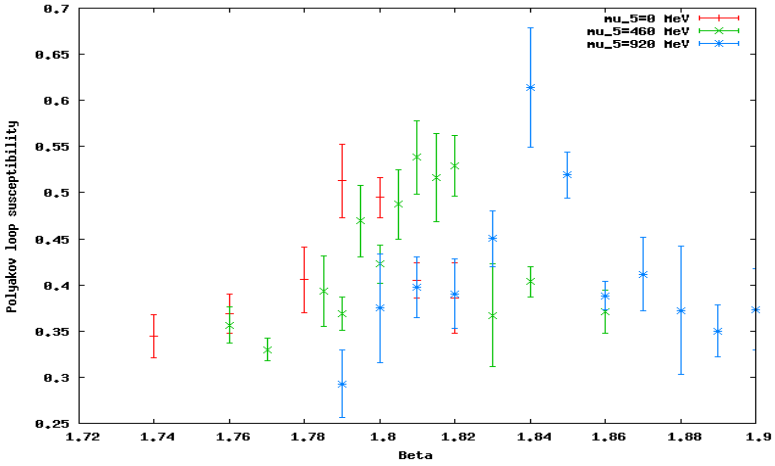
Chiral condensate

Results

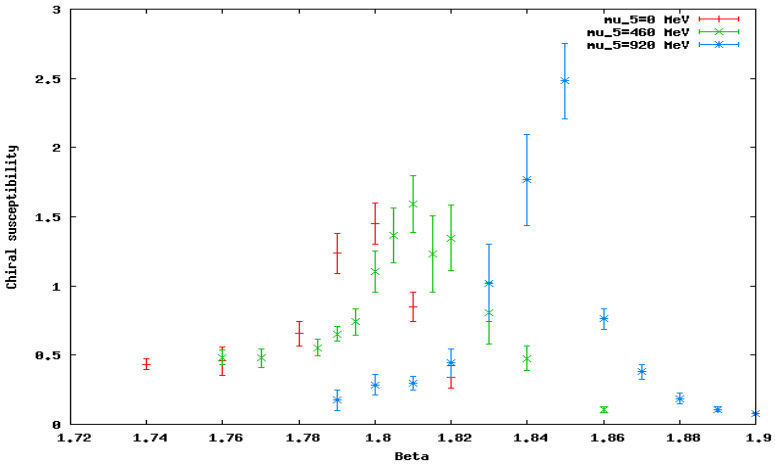




Results. Susceptibilities



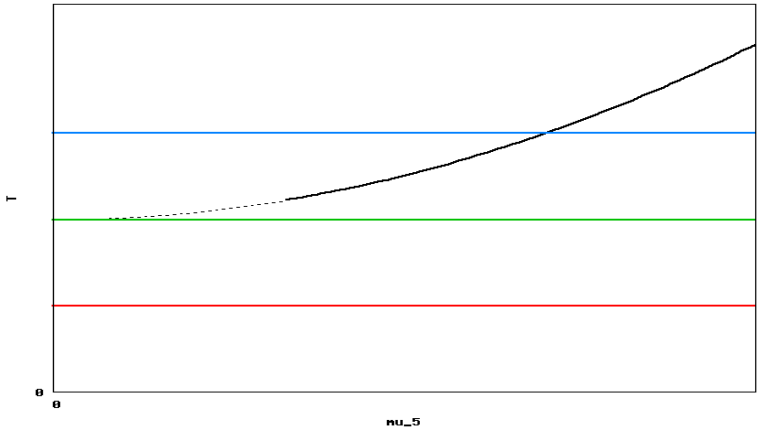
Polyakov loop susceptibility



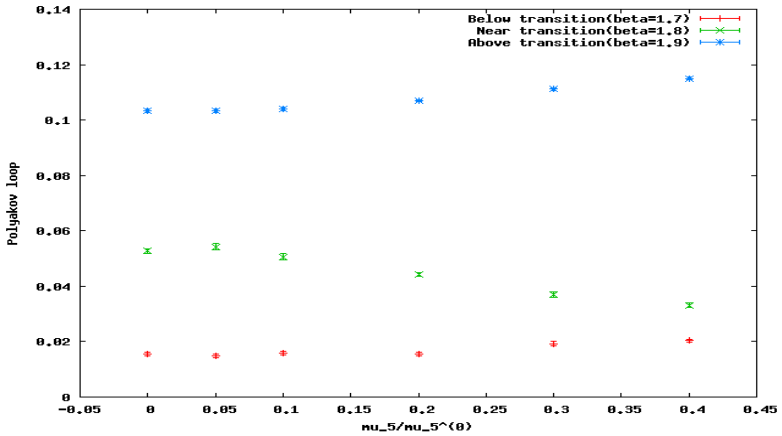
Chiral susceptibility

Results. Varying μ_5

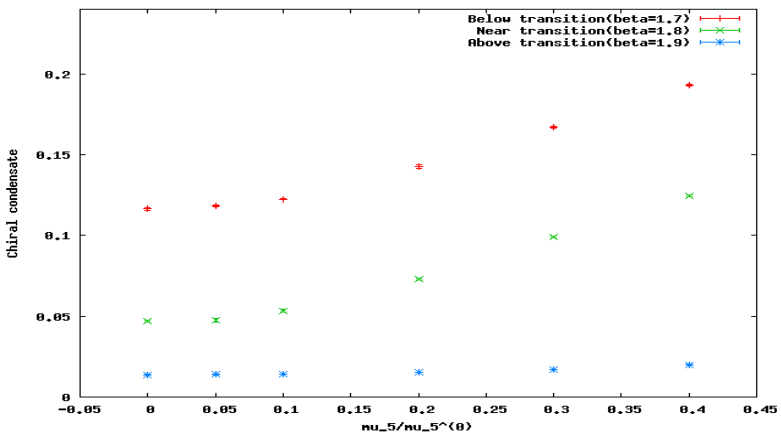
Observables with respect to μ_5(β, lattice size are fixed) in different phases.



Phase diagram



Polyakov loop



Chiral condensate

Conclusions

Conclusions:

- T_c slightly increases when μ_5 grows - contrary to predictions of phenomenological studies.
- The transition seems to become sharper.

Possible issues (plans for future work):

- Discretization errors (ongoing study)
- SU(3) instead of SU(2)
- Rooting - 4 identical tastes of staggered fermions
- Renormalization

Thank you!