

Observation of deconfinement in a cold dense quark medium

V.G. Bornyakov, V.V. Braguta, E.-M. Ilgenfritz, A.Yu. Kotov,
A.V. Molochkov, A.A. Nikolaev

IHEP, Protvino, Russia

ITEP, Moscow, Russia

FEFU, Vladivostok, Russia

JINR, Dubna, Russia

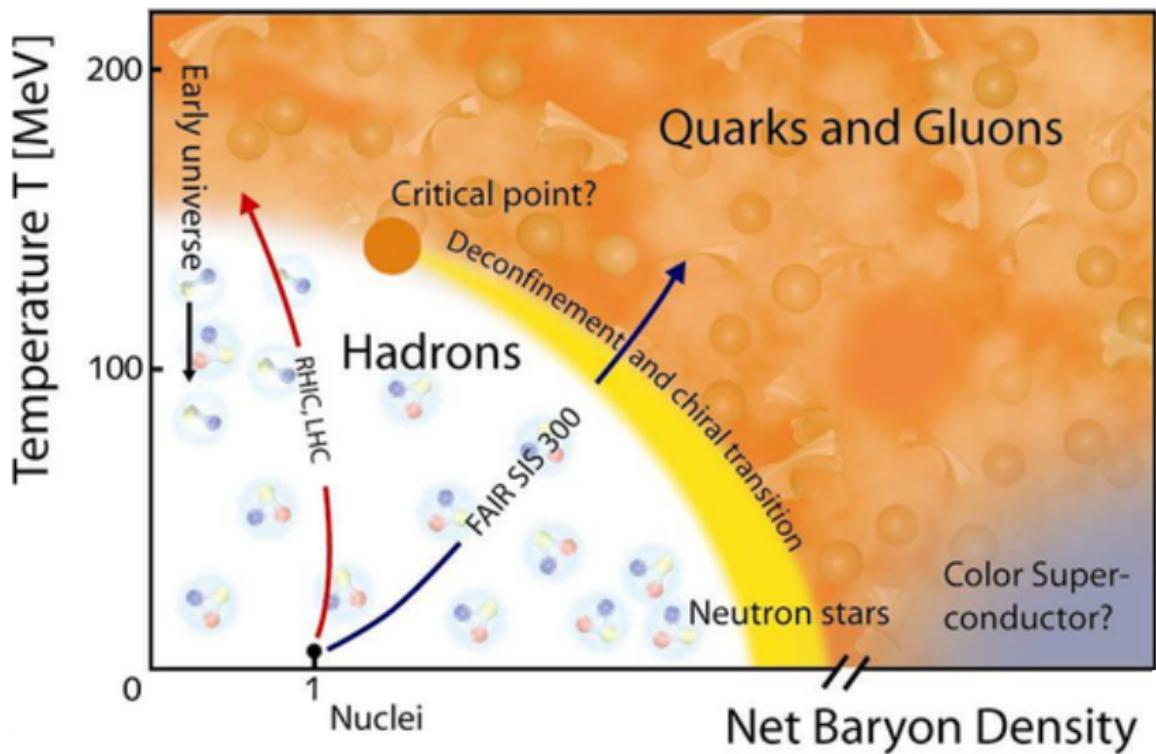
xQCD 2018, 21.05.2018

Outline

- Introduction
- Features of QC₂D
- Results at zero T and finite density
- Conclusions

The talk is mainly based on JHEP03 (2018) 161
[arXiv:1711.01869].

Tentative QCD phase diagram



No sign problem in QC₂D

SU(3) QCD

- Eigenvalues of \hat{D} : $\pm i\lambda$, $\det(\hat{D} + m) = \prod_{\lambda} (\lambda^2 + m^2) > 0$
- But $\det(\hat{D} - \mu\gamma_4 + m)$ is complex

SU(2) QCD

- $\det[M(\mu_q)] = \det[(\tau_2 C \gamma_5)^{-1} M(\mu_q) (\tau_2 C \gamma_5)] = \det[M(\mu_q^*)]^*$, where $C = \gamma_2 \gamma_4$
- In LQC₂D with fundamental quarks $\det[M(\mu_q)]$ is positive definite at real μ_q [see S. Hands, I. Montvay, S. Morrison, M. Oevers, L. Scorzato, J.-I. Skullerud, EPJ **C17**, 285 (2000)]

At real μ_q in QC₂D

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

QC₂D compared to usual QCD

Similarities

- Phase transitions: confinement/deconfinement, chiral symmetry restoration
- Some observables (normalized) are nearly equal in both theories:

Topological susceptibility [B. Lucini et. al., Nucl. Phys. B715 (2005) 461]:

$$\chi^{1/4}/\sqrt{\sigma} = 0.3928(40) \text{ (SU}(2)\text{)}, \quad \chi^{1/4}/\sqrt{\sigma} = 0.4001(35) \text{ (SU}(3)\text{)}$$

Critical temperature [B. Lucini et. al., Phys. Lett. B712 (2012) 279]:

$$T_c/\sqrt{\sigma} = 0.7092(36) \text{ (SU}(2)\text{)}, \quad T_c/\sqrt{\sigma} = 0.6462(30) \text{ (SU}(3)\text{)}$$

Shear viscosity:

$$\eta/s = 0.134(57) \text{ (SU}(2)\text{)} \quad [\text{N.Yu. Astrakhantsev et. al., JHEP 1509 (2015) 082}]$$

$$\eta/s = 0.102(56) \text{ (SU}(3)\text{)} \quad [\text{H.B. Meyer, PRD 76 (2007) 101701}]$$

- Mass spectrum (T. DeGrand, Y. Liu, PRD 94, 034506 (2016))
- Thermodynamical properties (M. Caselle et. al. JHEP 1205 (2012) 135)

QC₂D compared to usual QCD

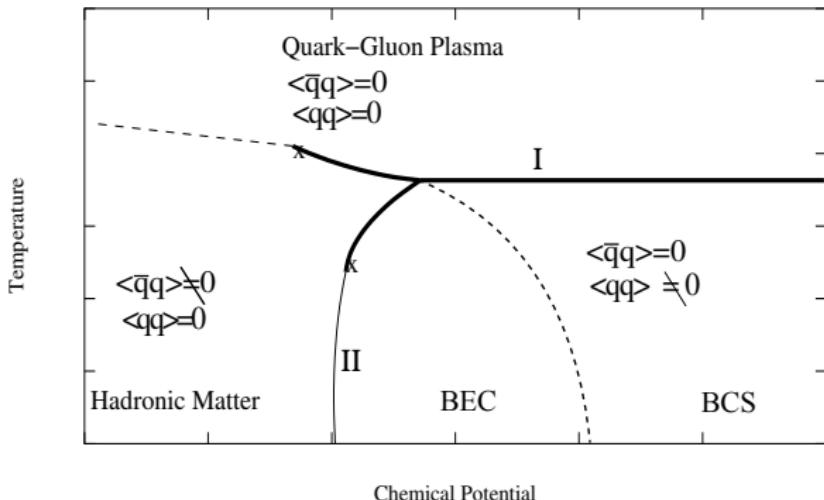
Differences

- The Lagrangian of the QC₂D has the symmetry $SU(2N_f)$ instead of $SU_R(N_f) \times SU_L(N_f)$ for $SU(3)$ QCD
- Goldstone bosons ($N_f = 2$): $\pi^+, \pi^-, \pi^0, d, \bar{d}$

However, in dense medium

- **Chiral symmetry is restored**
thus symmetry breaking pattern is not important
- **Relevant degrees of freedom are quarks and gluons**
rather than Goldstone bosons

Tentative phase diagram of QC₂D



- J.B. Kogut *et. al.*, Nucl. Phys. **B582** (2000) 477–513
- J.B. Kogut, D. Toublan, D.K. Sinclair, Nucl. Phys. **B642** (2002) 181–209
- S. Cotter, P. Giudice, S. Hands, J.-I. Skullderud, PRD **87**, 034507 (2013)
- T. Boz, S. Cotter, L. Fister, D. Mehta ,J.-I. Skullderud, EPJ **A49** (2013)
- V.V. Braguta *et. al.*, PRD **94**, 114510 (2016) (our previous study)

Diquark source

In QC₂D there is a possibility to add diquark source to the action to study spontaneous breakdown of $U(1)_V$:

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

which modifies partition function as follows:

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

instead of

$$Z = \int DU \det M(\mu_q) e^{-S_G[U]}.$$

$\langle qq \rangle$ is colorless, gauge invariant and thus may be measured.

Action and lattice set-up

We study $N_f = 2$ of rooted staggered fermions:

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

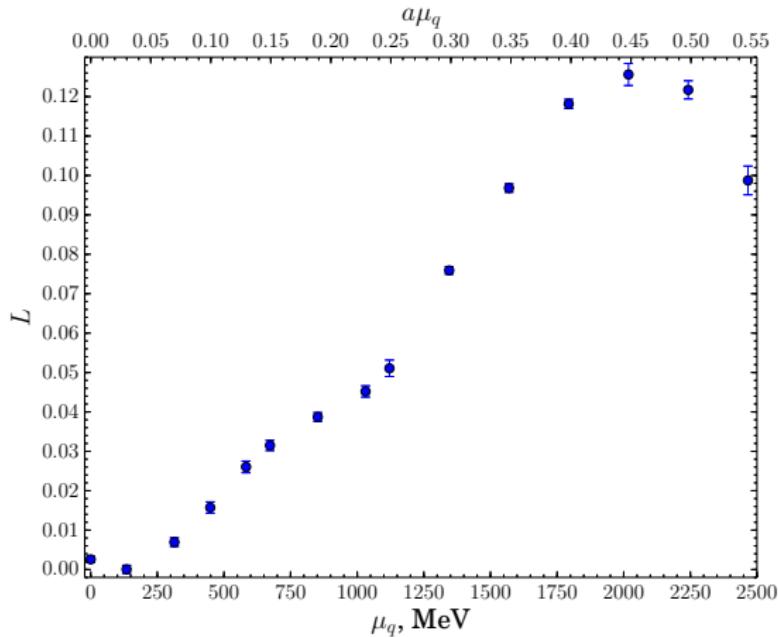
where $S_G^{impr.}[U]$ is the tree-level improved gauge action and

$$\begin{aligned} M_{xy}(\mu_q) = m_q a \delta_{xy} + \frac{1}{2} \sum_{\mu=1}^4 \eta_\mu(x) & \left[U_{x,\mu} \delta_{x+\hat{\mu},y} e^{\mu_q a \delta_{\mu,4}} - \right. \\ & \left. - U_{x-\hat{\mu},\mu}^\dagger \delta_{x-\hat{\mu},y} e^{-\mu_q a \delta_{\mu,4}} \right]. \end{aligned}$$

Simulation parameters

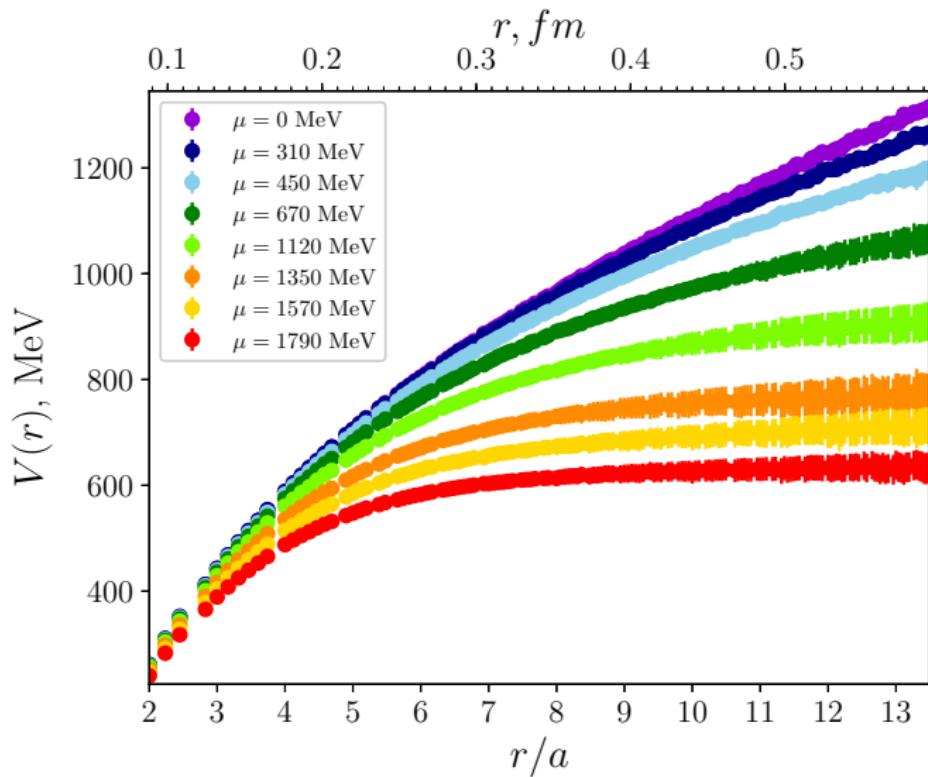
- Lattice: 32^4 ($T=0$)
- $\beta = 1.8$, $a = 0.044(1)$ fm (Sommer parameter), $L_s \approx 1.4$ fm
- $ma = 0.0075$, $M_\pi = 740(40)$ MeV; $M_\pi L_s \approx 5$, $M_\pi/M_\rho \approx 0.55$
- Fixed $\lambda = 0.00075$, $\lambda^2 \ll (ma)^2$

Polyakov loop



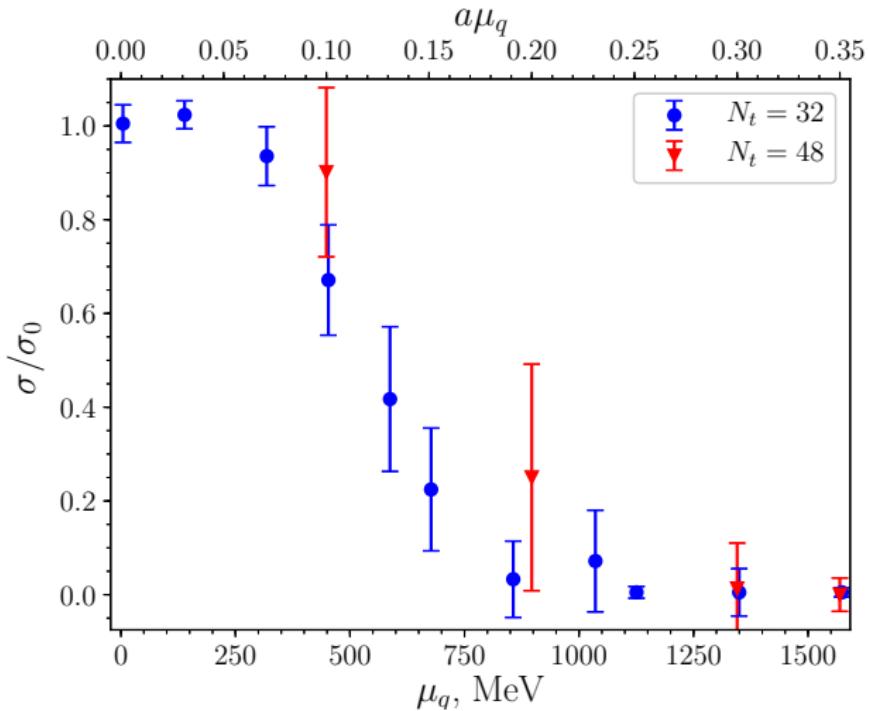
- Qualitatively the same behavior as at finite temperature transition
- Critical chemical potential $\mu_q^{(c)} \approx 900 - 1100$ MeV

Quark-antiquark potential in dense medium



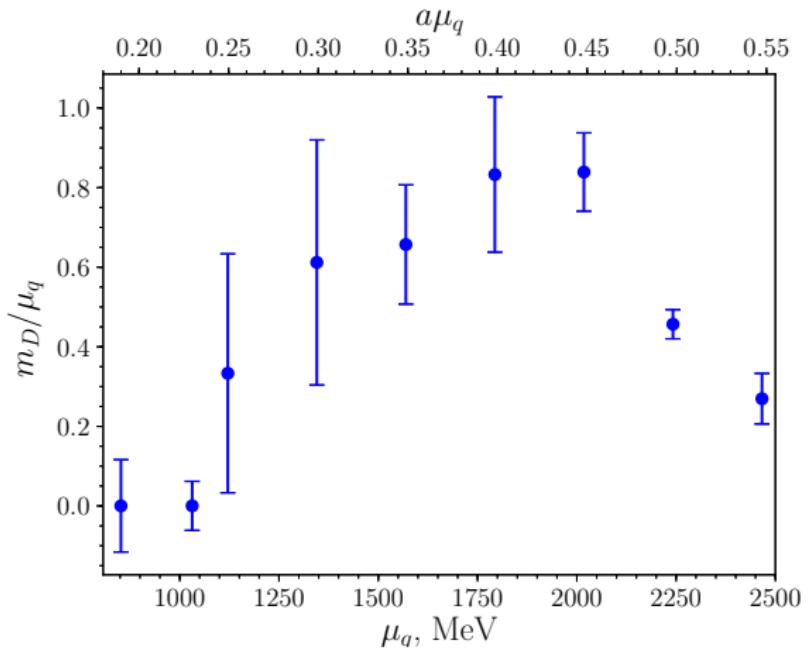
We observe deconfinement in dense medium

String tension



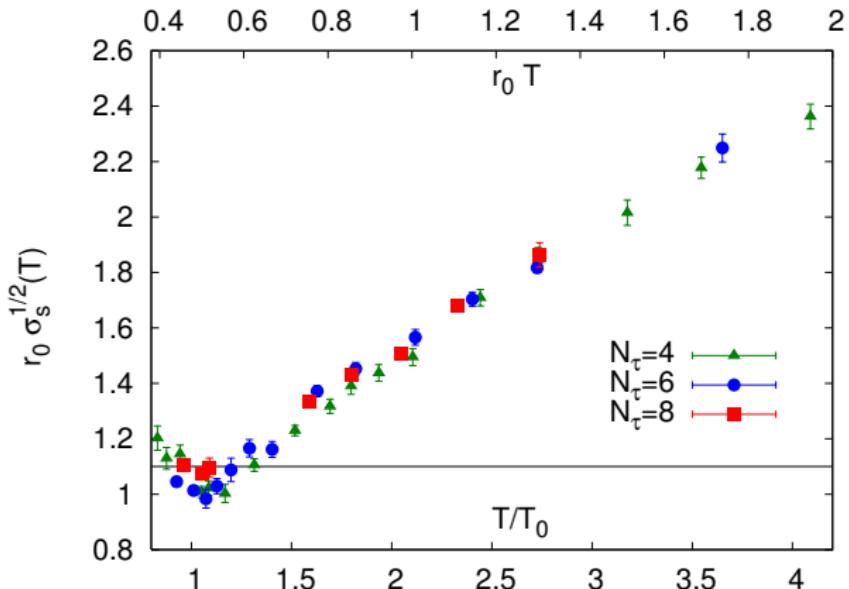
- Deconfinement at $\mu_q > 900 - 1100$ MeV
- Good fit of $V(r)$ by the Cornell potential at $\mu_q \leq 1100$ MeV

Debye mass



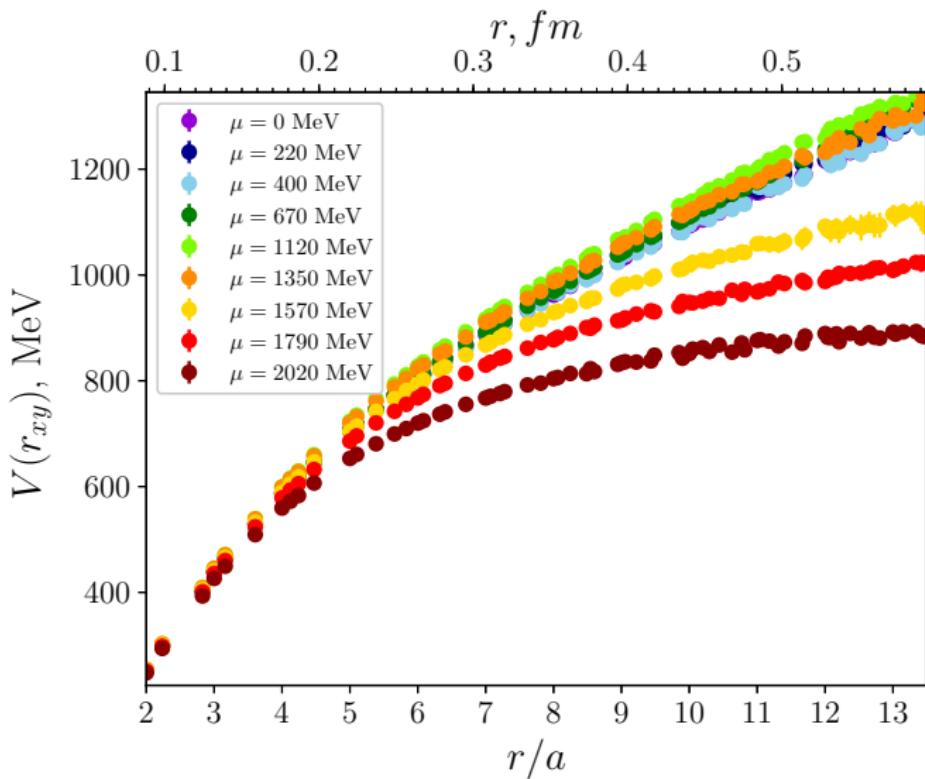
- $V(r) = A - B e^{-m_D r}/r$, good fit at $\mu_q \geq 850$ MeV
- Debye mass rises with chemical potential

Spatial string tension at finite T



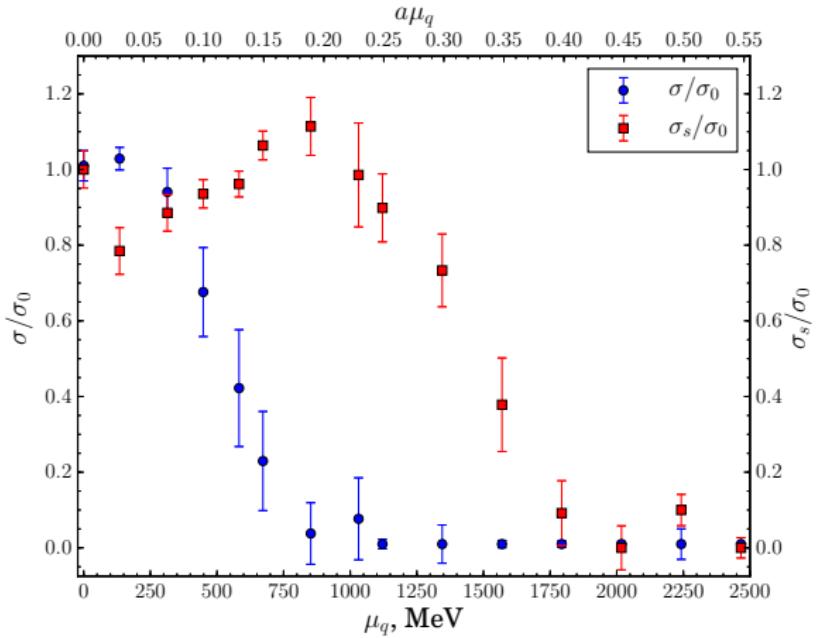
*The Spatial String Tension and Dimensional Reduction in QCD,
M. Cheng et al., PRD 78 (2008) 034506*

Spatial quark-antiquark potential in dense medium



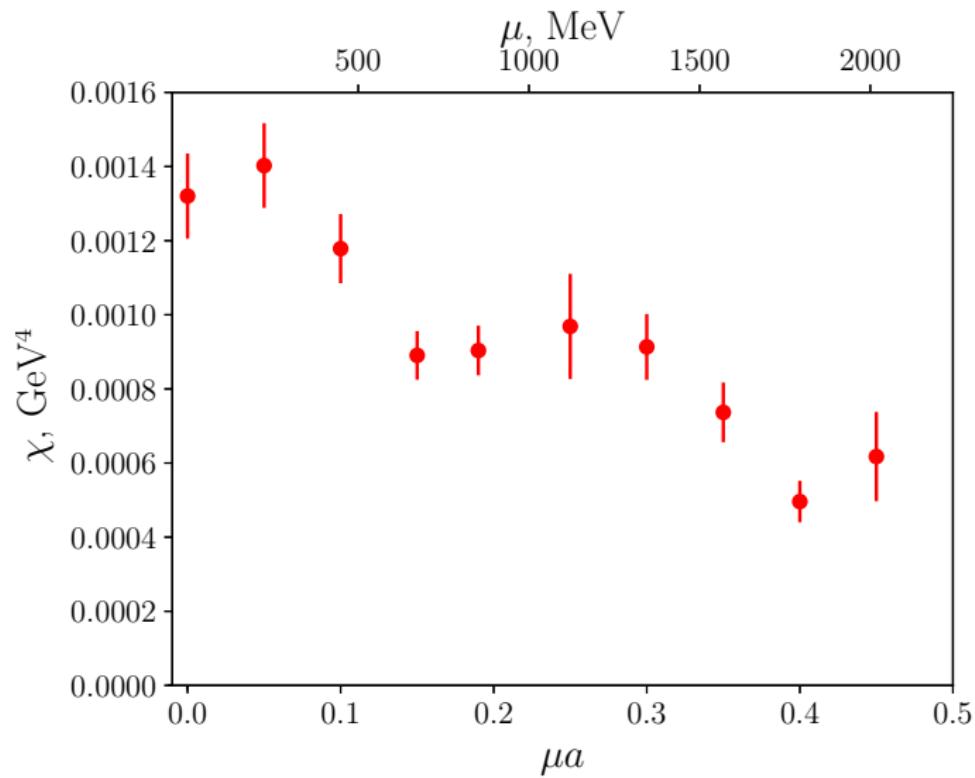
Different behavior compared to zero μ_q and finite T case

String tensions



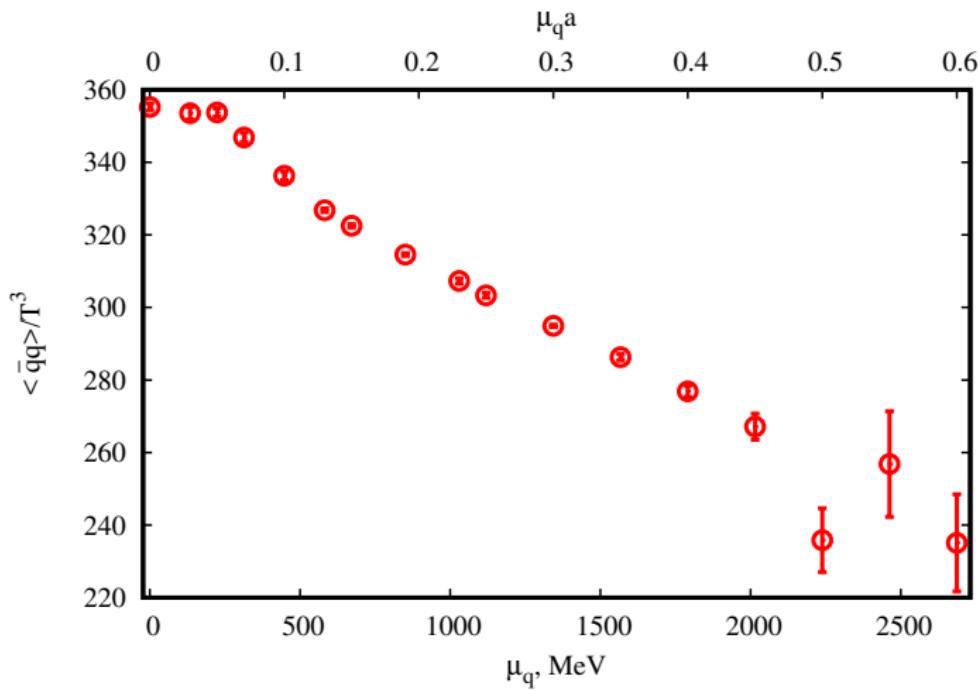
- σ goes to zero around $\mu_q = 1000$ MeV
- σ_s goes to zero around $\mu_q = 2000$ MeV

Topological susceptibility



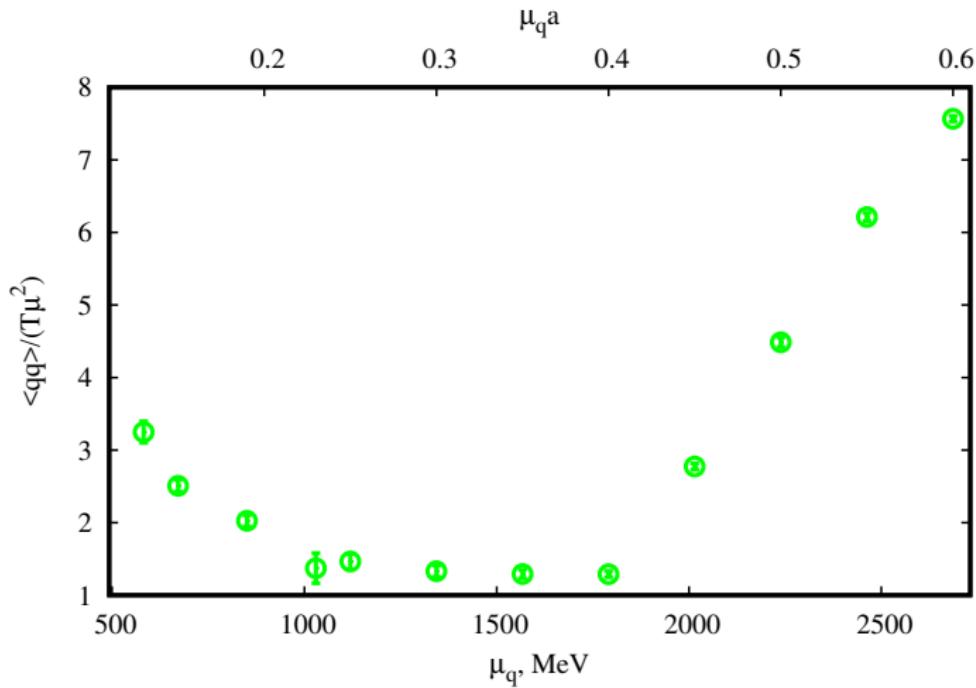
Signs of partial restoration of $U_A(1)$

Chiral condensate



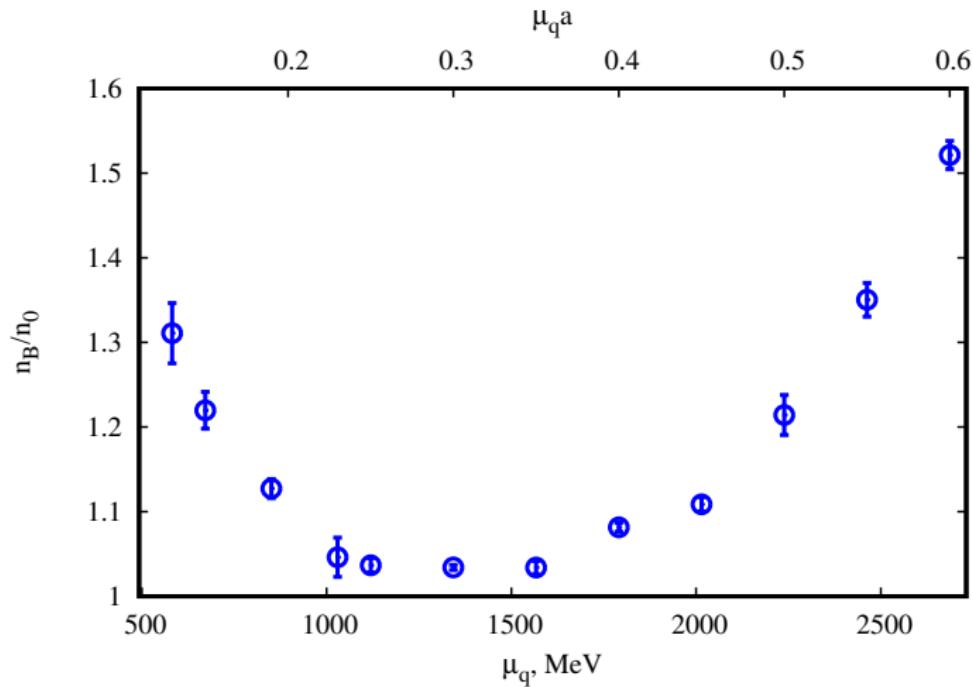
Chiral condensate drops slowly, probably due to large pion mass

Diquark condensate



- BCS phase for $\mu_q \geq 1000$ MeV
- Diquark condensate rises for $\mu_q > 1800$ MeV

Baryon number density



- $n_0 = N_f(2s+1) \int \frac{d^3k}{(2\pi)^3} \theta(|k| - \mu) = 2\mu^3/(3\pi^2)$
- Fermi sphere dominates over the surface for $\mu_q \geq 1000$ MeV

Conclusions

- We observe deconfinement in dense medium at $\mu_q^{(c)} \approx 1$ GeV for the first time
- Difficult to determine critical chemical potential $\mu_q^{(c)} \in (850, 1100)$ MeV
- Spatial string tension disappears at $\mu_q \geq 2$ GeV
- Deconfinement at large density is different from the finite temperature deconfinement
- Quark-gluon plasma at large density is perturbative (gas of quarks and gluons)

We are currently studying the properties of deconfined matter at high baryon density