Phase diagram of dense two-color QCD within lattice simulations

(based on arXiv:1605.04090)

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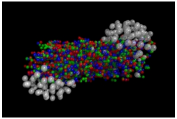
XIIth Confinement and the Hadron Spectrum

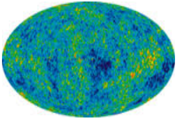
2 September, 2016

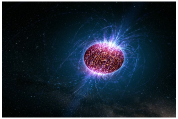
What happens if we compress matter as much as possible?

Introduction

- Baryon density $n_B - n_{\bar{B}}$
- Excess of baryons over antibaryons
- Excess of quarks over antiquarks
- Applications
  - Heavy ion collisions
  - Neutron stars
  - Early Universe

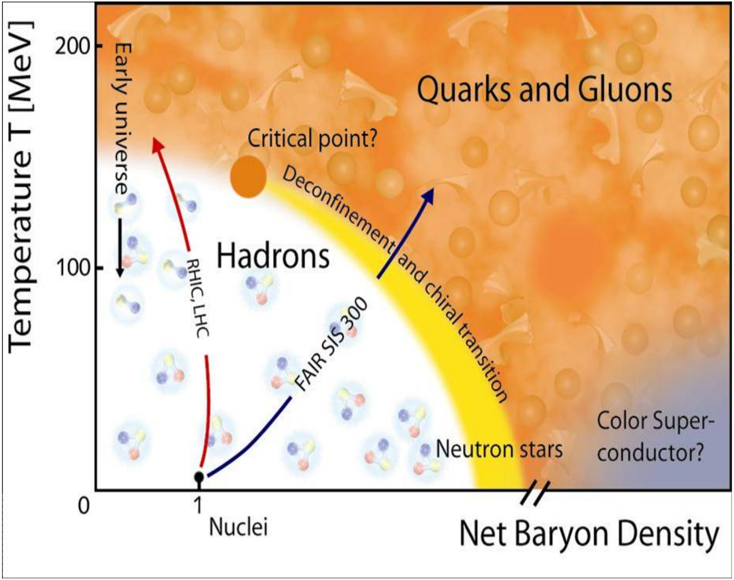






- Baryon chemical potential $\mu_B = N_c \mu_q$

QCD Phase diagram



Can theory provide some information?

In some limits:

- Small or large μ
- Large N_c
- ...

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Generally:

- QCD is strongly coupled
- Lattice: sign problem

Sign problem

- SU(3) QCD
  - $Z = \int DUD\bar{\psi}D\psi \ \exp\left(-S_G - \int d^4x\bar{\psi}(\hat{D}+m)\psi\right) =$
    $= \int DU \exp\left(-S_G\right) \times \det\left(\hat{D}+m\right)$

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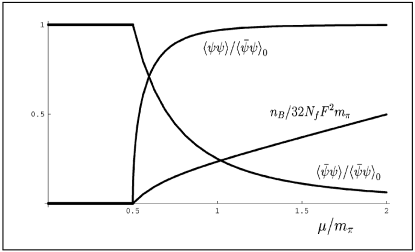
- SU(2) QCD: $\det\left(\hat{D}-\mu\gamma_4+m\right) > 0$ ✓
- QCD-like theories without sign problem [von Smekal, Thu]
- QCD with chiral chemical potential [Braguta, Thu]

χPT

- Low energy QCD: pions
- QC_2D: pions + baryons
- $\mu < m_\pi/2$: Vacuum
  $\mu = m_\pi/2$: BEC
  $\mu > m_\pi/2$: dilute baryonic gas

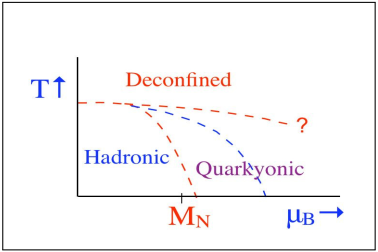


- Order parameter: diquark condensate $\psi\psi$

J. B. Kogut et al., Nucl. Phys. B582 (2000) 477-513

Phase diagram for $N_c \to \infty$

- Hadronic phase $\mu < M_N/N_c$
- Dilute baryonic gas $\mu > M_N/N_c$
  (Width $\delta\mu \sim \frac{\Lambda}{N_c^2}$)
- Quarkyonic phase $\mu > \Lambda$
  - No chiral symmetry breaking
  - Confinement
  - Fermi sphere (inside are quarks, on the surface - baryons)
- Deconfinement



Larry McLerran, Robert D. Pisarski. Nucl.Phys. A796 (2007) 83-100

$SU(2)$ QCD in lattice simulations

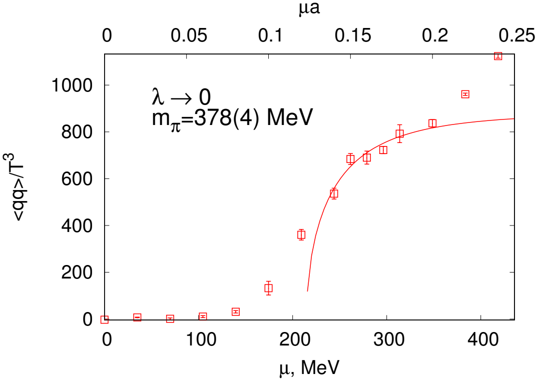
Low temperature scan

Lattice setup

- Dynamical staggered $N_f = 2$ fermions
- $a = 0.112$ fm
- Lattice size $16^3 \times 32$
- Low temperature scan
- $m_\pi = 378(4)$ MeV
- Diquark source $\lambda \to 0$

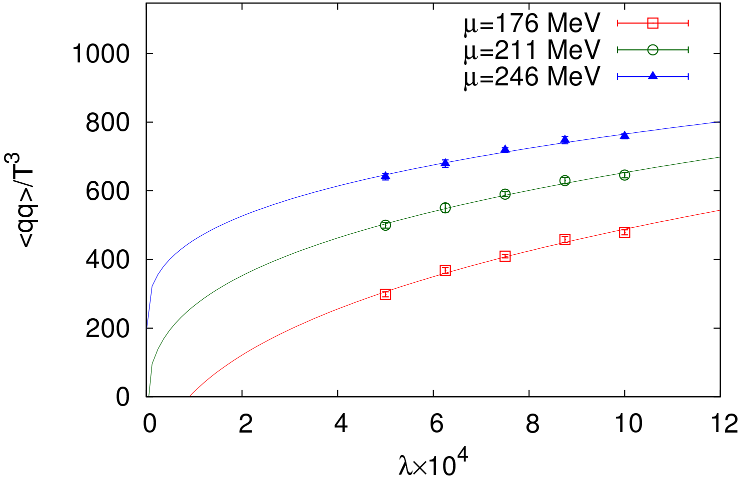
Bose-Einstein condensation

Diquark condensate



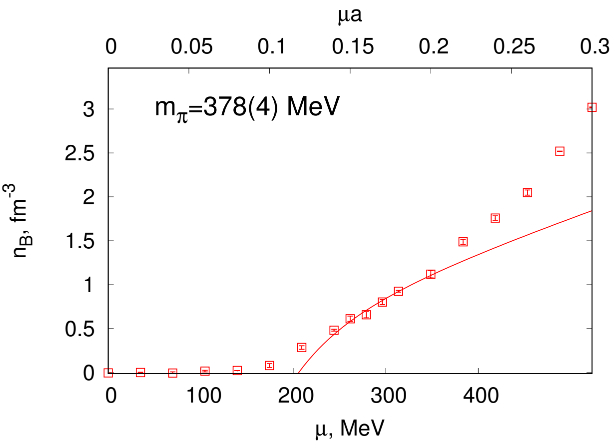
- χPT: $\langle\psi\psi\rangle/\langle\bar{\psi}\psi\rangle_0 = \sqrt{1 - m_\pi^4/(2\mu)^4}$
- Phase transition at $\mu = 215(10)$ MeV $\sim m_\pi/2$
- BEC phase $\mu \in (200, 350)$ MeV

Diquark condensate: critical index



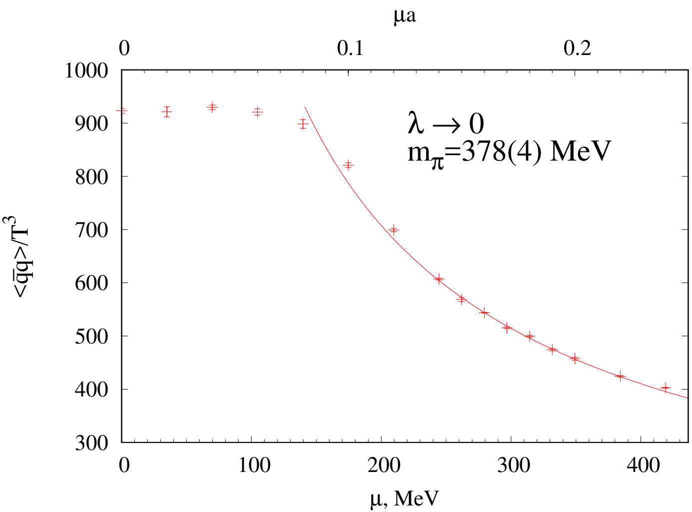
Fit motivated by χPT: $\langle qq \rangle = A + B\lambda^{1/3}$

Baryonic density



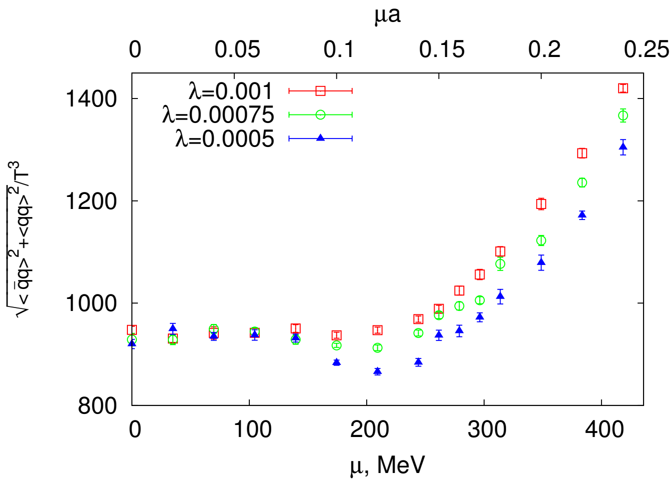
- χPT prediction: $n \sim \mu - \frac{m_\pi^4}{\mu^3}$
- $\mu_c = 207(7)$ MeV $\sim m_\pi/2$

Chiral condensate



- Fit: $\langle \bar{q}q \rangle = A/\mu^{\alpha}$, $\alpha = 0.78(2)$
- χPT: $\alpha = 2$

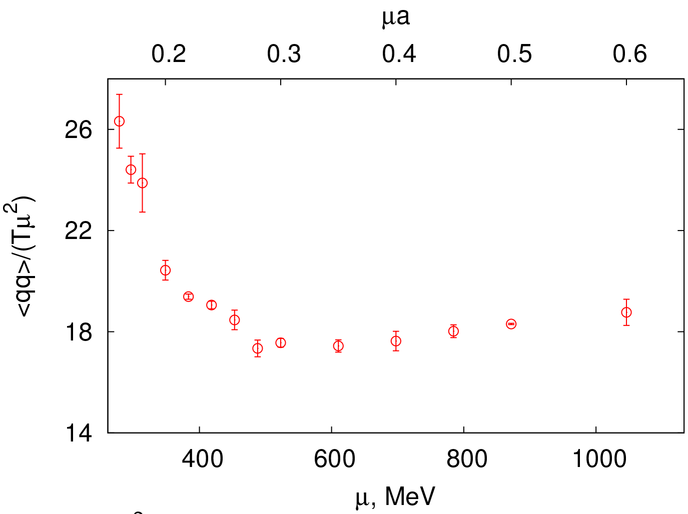
Chiral and diquark condensates



Leading order χPT: $\langle\bar{\psi}\psi\rangle^2 + \langle\psi\psi\rangle^2 = const$

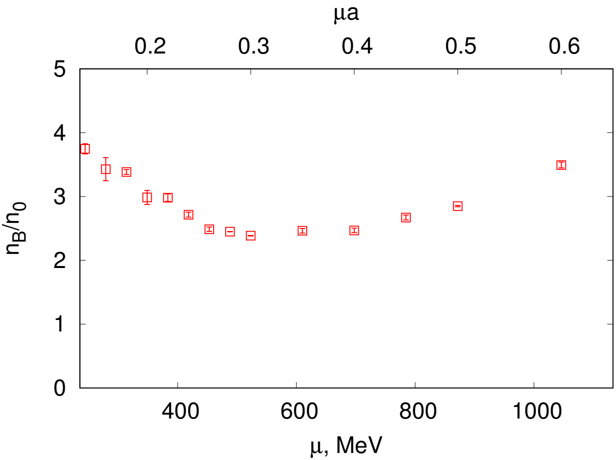
Large baryon chemical potential

Diquark condensate



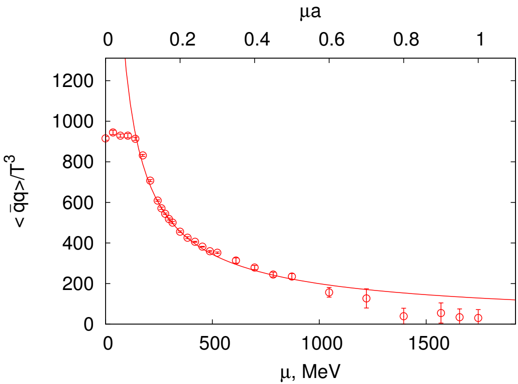
- $\langle\psi\psi\rangle \sim \mu^2$
- BCS phase $\mu > 500$ MeV

Baryonic density



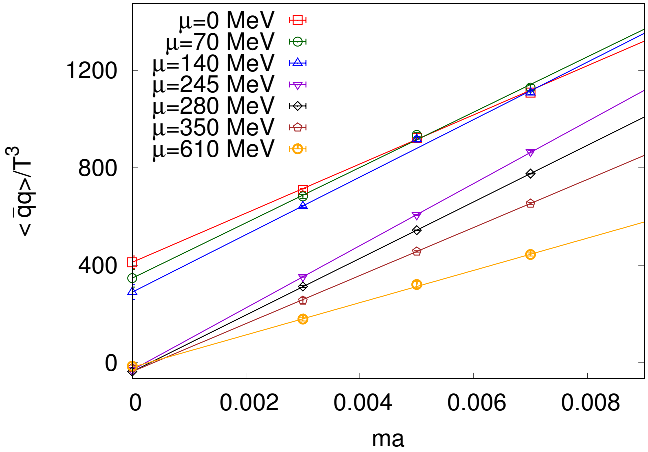
- $n_B \sim n_0 \sim \mu^3$, n_0 - free fermion density
- BCS phase $\mu > 500$ MeV

Chiral condensate



- χPT prediction $\langle\bar{\psi}\psi\rangle \sim \frac{m_\pi^2}{\mu^2}$
- Our results $\langle\bar{\psi}\psi\rangle \sim \frac{1}{\mu^\alpha}, \alpha = 0.78(2)$

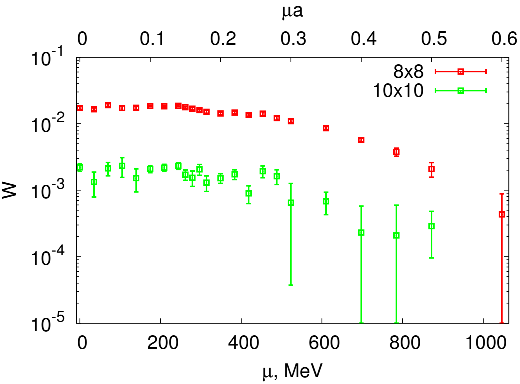
Chiral condensate (chiral limit $m \to 0$)



At $\mu > m_\pi/2$ no chiral symmetry breaking

Gluonic observables

- Wilson loops



- Polyakov loop is zero (Confinement)

Conclusions

Hadronic phase

- $\mu < m_\pi/2$

BEC phase

- Diquark condensate at $\mu \gtrsim m_\pi/2$
- At $m_\pi/2 < \mu < m_\pi/2 + 150$ MeV dilute baryonic gas

BCS phase

- $\mu \sim 600$ MeV, transition BEC$\rightarrow$BCS is smooth
- Similar to the quarkyonic phase

- BEC&BCS: Chiral symmetry restoration
- No transition to the deconfinement

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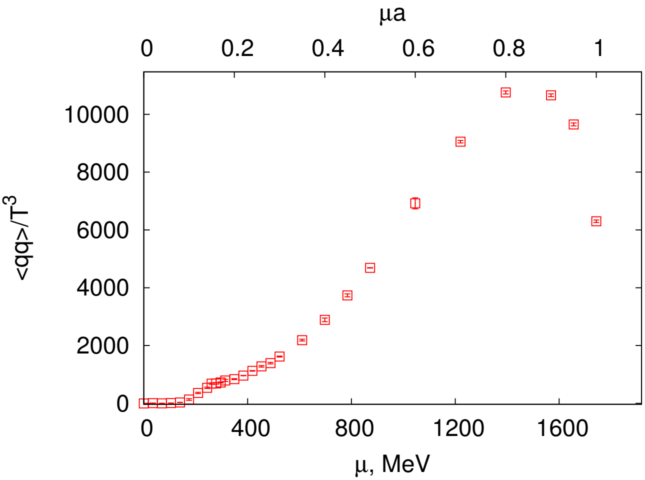
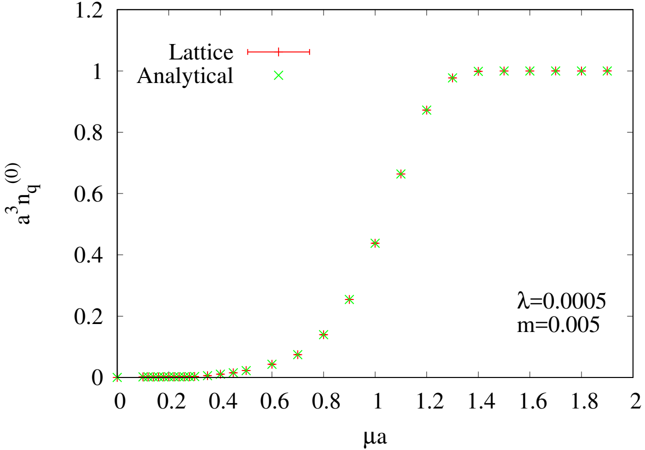
Thank you!

Backup

Diquark condensate, saturation



Free baryon density, saturation



Scale setting