Study of deconfined quark matter at zero temperature and high density

N.Yu. Astrakhantsev, V.G. Bornyakov, V.V. Braguta, E.-M. Ilgenfritz, A.Yu. Kotov, A.A. Nikolaev, A. Rothkopf

IHEP, Protvino, Russia

ITEP, Moscow, Russia

FEFU, Vladivostok, Russia

JINR, Dubna, Russia

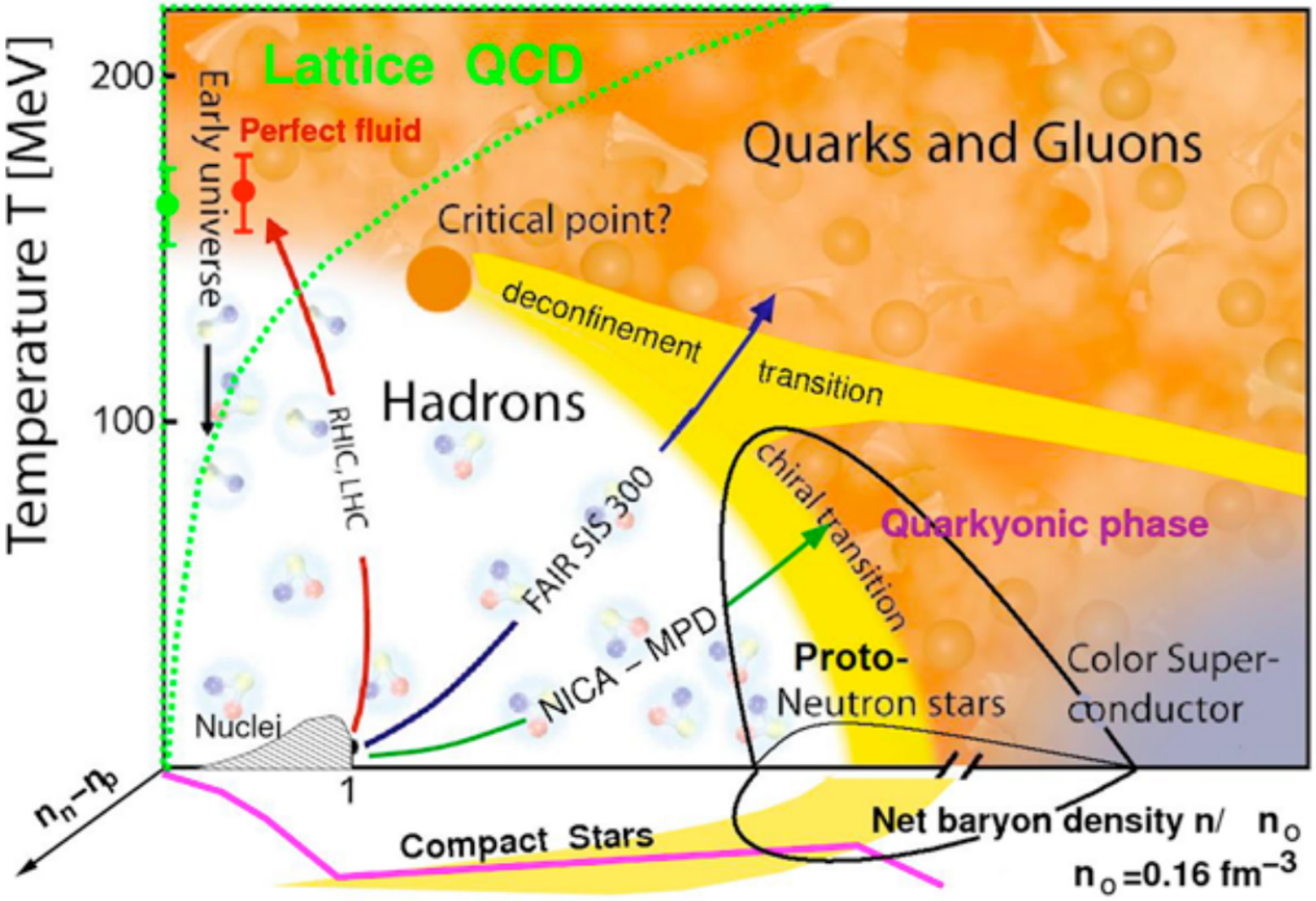
University of Stavanger, Norway

Confinement XIII, 05.08.2018

Outline

- Introduction
- Features of QC_2D
- Static quark-antiquark potential zero T
- Quarkonia dissociation
- Debye screening
- Conclusions

QCD phase diagram



The Phases of Dense Matter, INT, July 11 - August 12, 2016

No sign problem in QC_2D

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

- $$det\Big[M(\mu_q)\Big] = det\Big[(\tau_2 C\gamma_5)^{-1} M(\mu_q)(\tau_2 C\gamma_5)\Big] = \\ = det\Big[M(\mu_q^*)\Big]^*, \text{ where } C = \gamma_2\gamma_4$$
- In LQC_2D with fundamental quarks $det\Big[M(\mu_q)\Big]$ 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 QC_2D

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

QC_2D 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]:
  $\chi^{1/4}/\sqrt{\sigma} = 0.3928(40)\ (SU(2)), \quad \chi^{1/4}/\sqrt{\sigma} = 0.4001(35)\ (SU(3))$

  Critical temperature [B. Lucini *et. al.*, Phys. Lett. B712 (2012) 279]:
  $T_c/\sqrt{\sigma} = 0.7092(36)\ (SU(2)), \quad T_c/\sqrt{\sigma} = 0.6462(30)\ (SU(3))$

  Shear viscosity:
  $\eta/s = 0.134(57)\ (SU(2))$ [N.Yu. Astrakhantsev *et. al.*, JHEP 1509 (2015) 082]
  $\eta/s = 0.102(56)\ (SU(3))$ [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)

QC_2D compared to usual QCD

Differences

- The Lagrangian of the QC_2D has the symmetry $SU(2N_f)$ instead of $SU_R(N_f) \times SU_L(N_f)$ for $SU(3)$ QCD
- Goldstone bosons ($N_f = 2$): $\pi^+, \pi^-, \pi^0, d, \bar{d}$

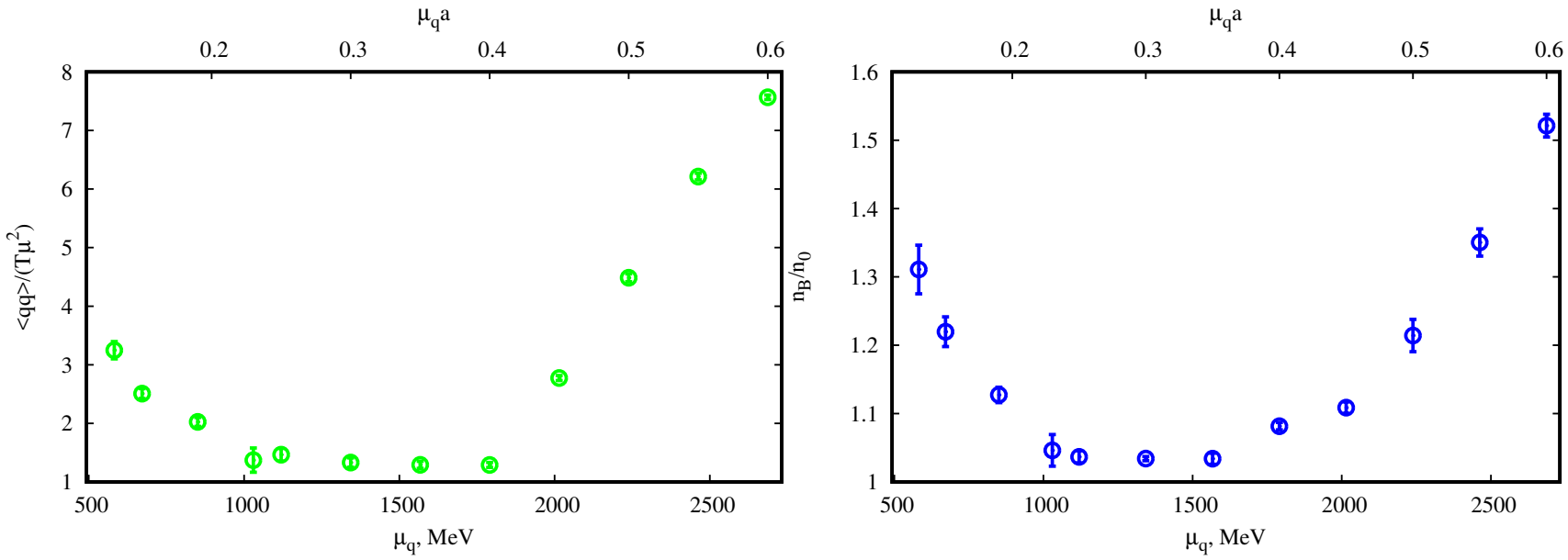
However, in dense medium

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

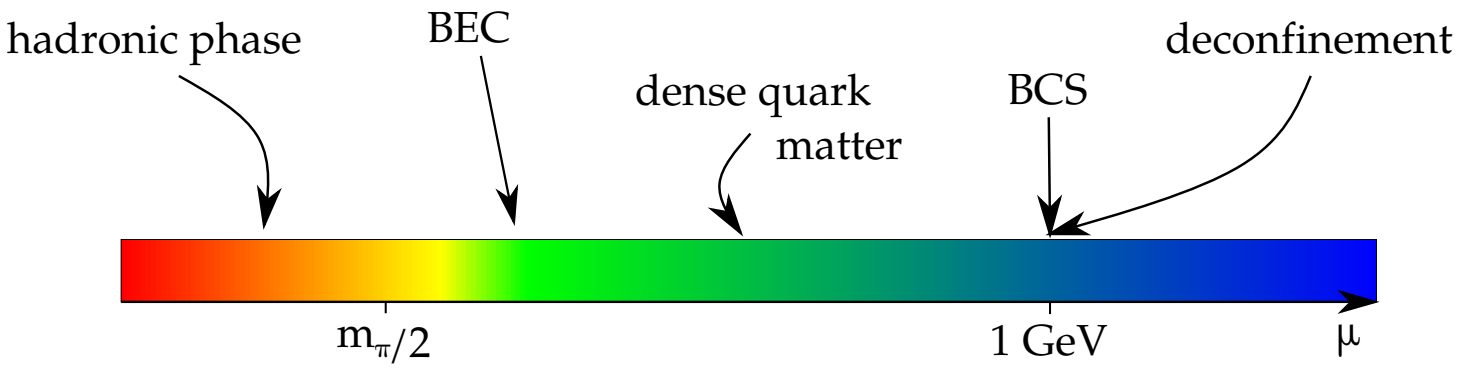
Our current study

- $N_f = 2$ of rooted staggered quarks
- $M_\pi = 740(40)$ MeV, $M_\pi L_s \approx 5$

Tentative phase diagram of QC_2D at low T

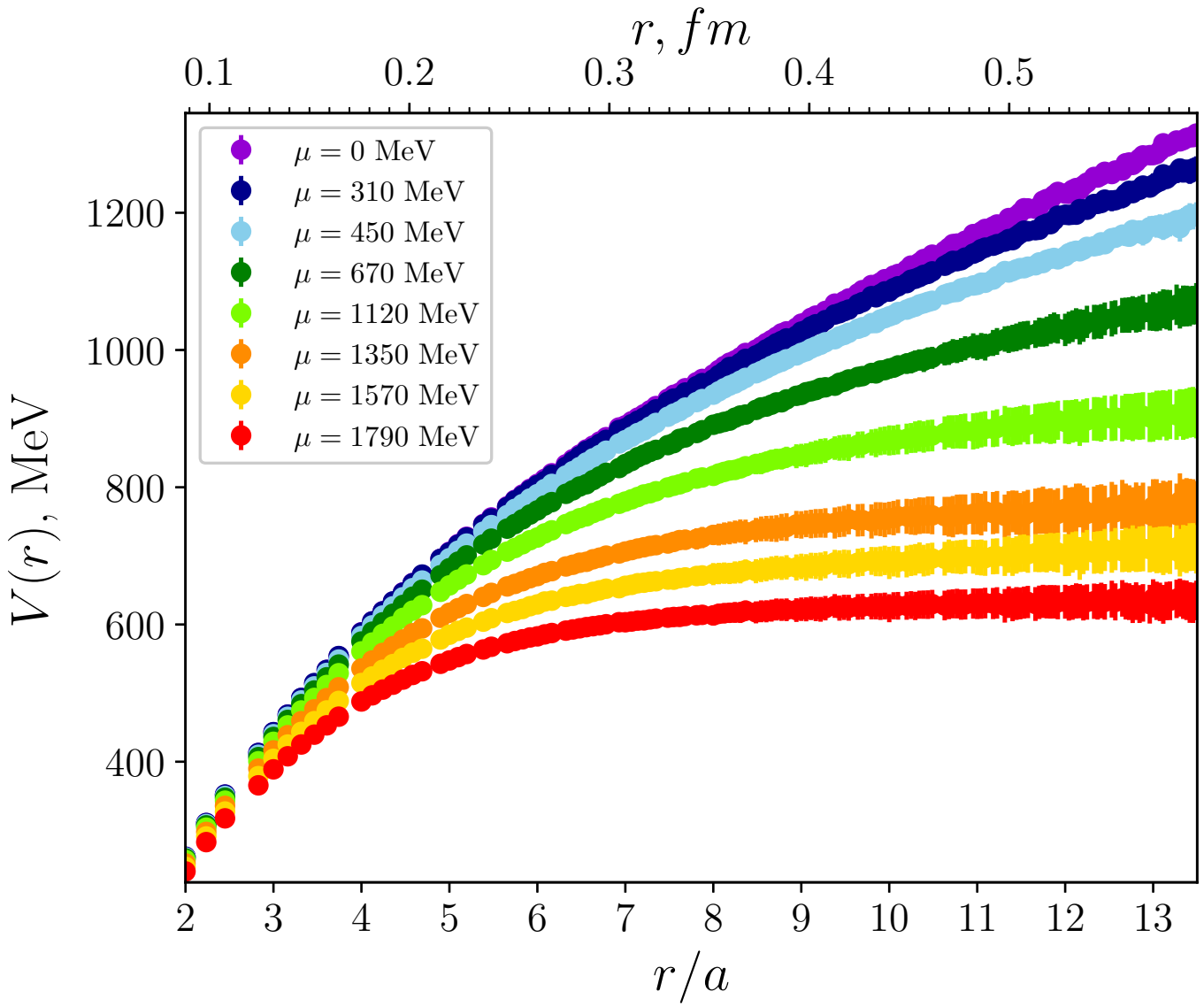


Zero temperature profile:



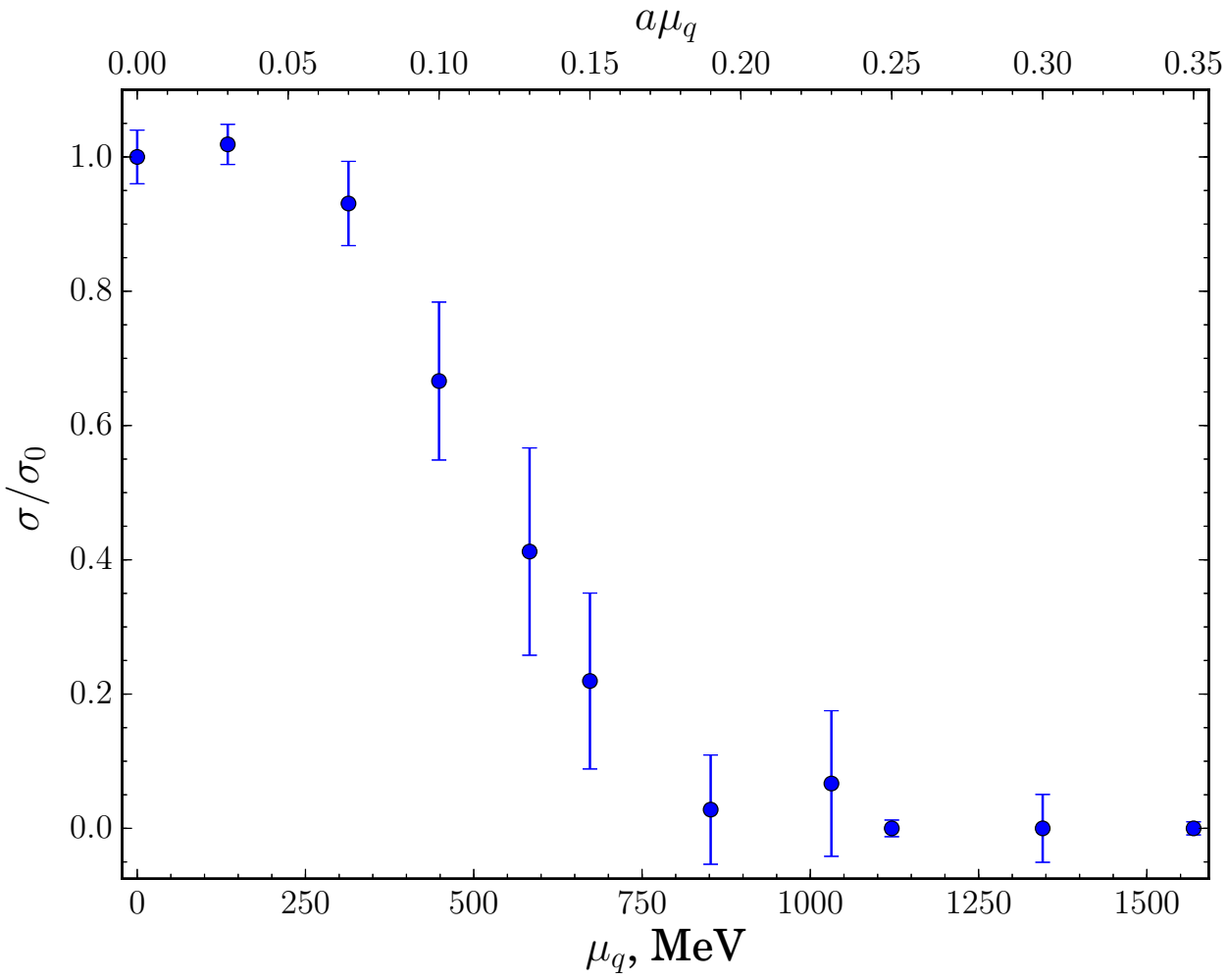
[For details see JHEP03(2018)161; PRD 94, 114510(2016)]

Quark-antiquark potential in dense medium



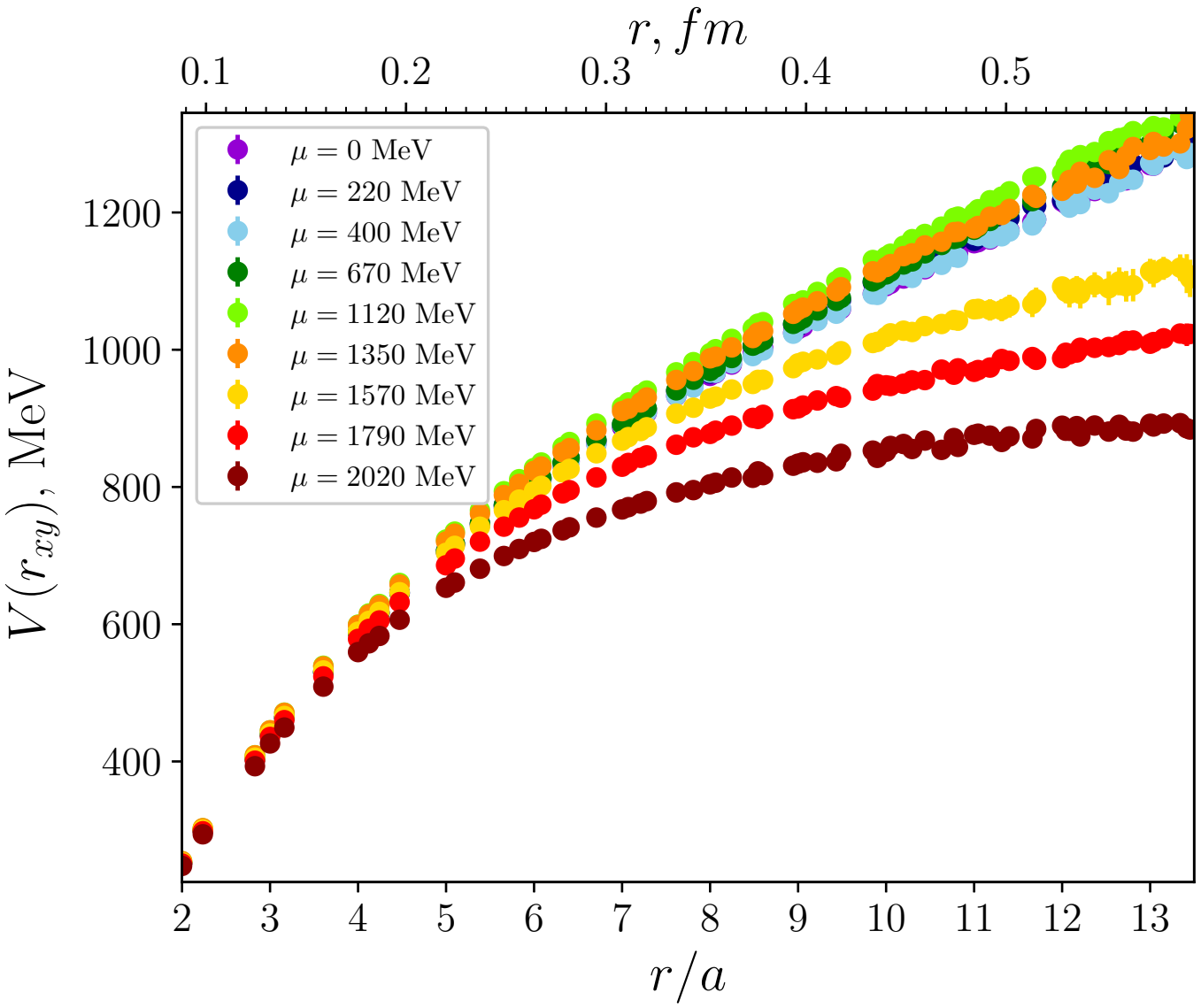
We observe deconfinement in dense medium

String tension



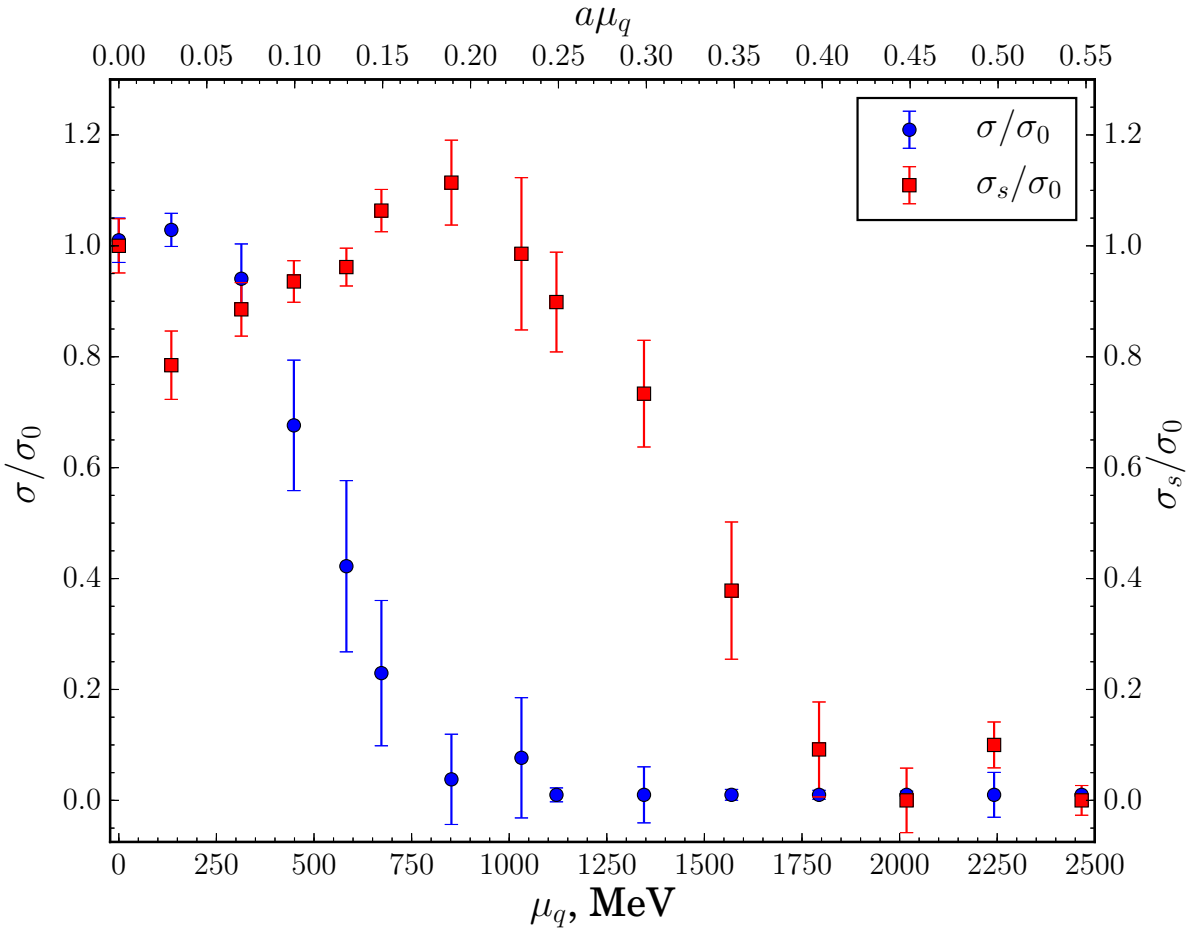
- Deconfinement at $\mu_q > 900 - 1100$ MeV
- Good fit of V(r) by the Cornell potential at $\mu_q \leqslant 1100$ MeV

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

Grand potential of a static quark-antiquark pair

In Coulomb gauge:

$$\begin{aligned}\Omega_{\bar{q}q}(r,\mu)/T &= -(1/4)\log\left\langle \mathrm{Tr}L(\vec{r})\mathrm{Tr}L^{\dagger}(0)\right\rangle + c(\mu)\\ \Omega_1(r,\mu)/T &= -(1/2)\log\left\langle \mathrm{Tr}\Big[L(\vec{r})L^{\dagger}(0)\Big]\right\rangle + c_1(\mu)\end{aligned}$$

Color-averaged grand potential may be decomposed into the singlet and triplet components (we study $N_c = 2$):

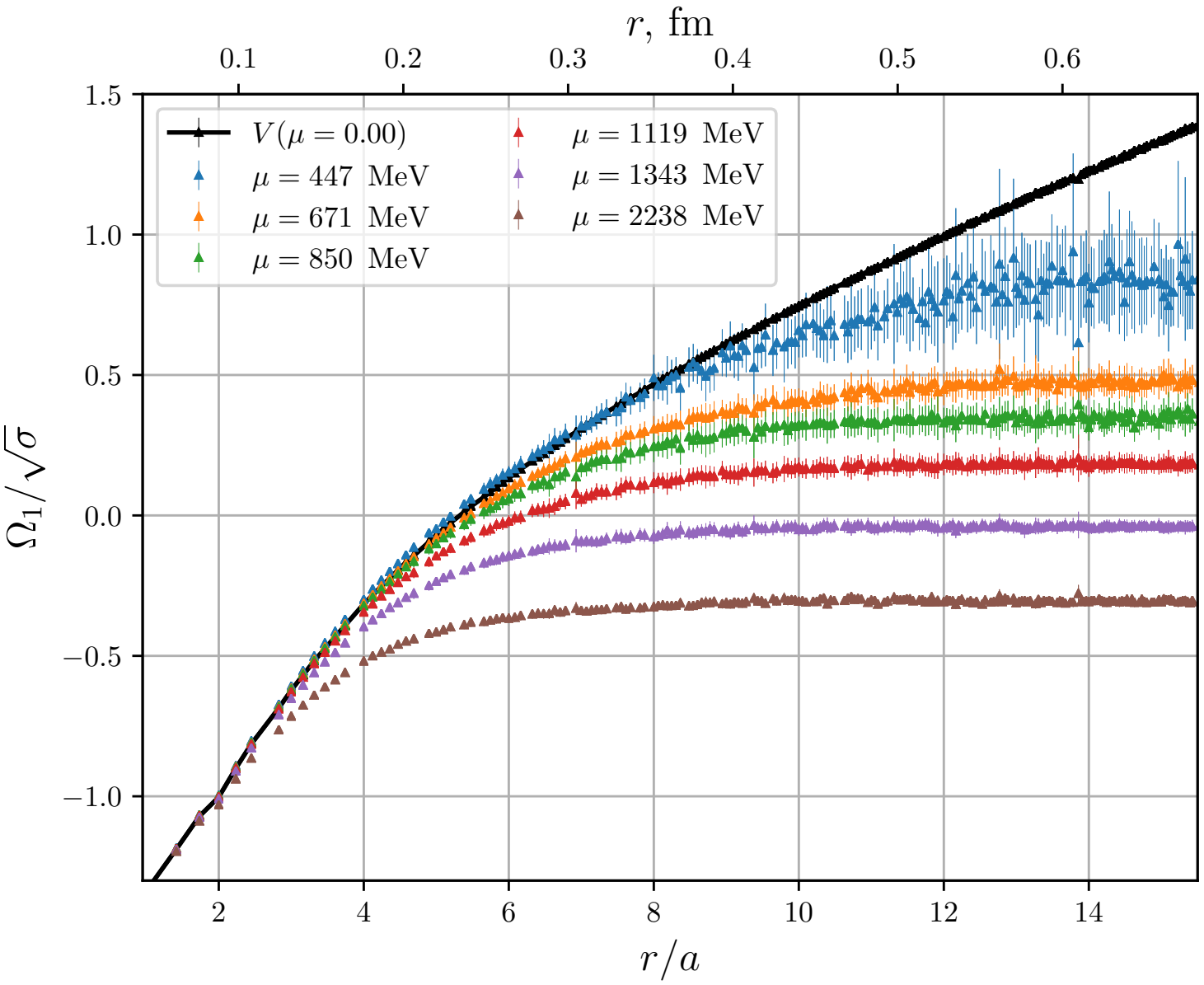
$$exp\Big(-\Omega_{\bar{q}q}/T\Big) = \frac{1}{4}exp\Big(-\Omega_1/T\Big) + \frac{3}{4}exp\Big(-\Omega_3/T\Big)$$

Renormalization:

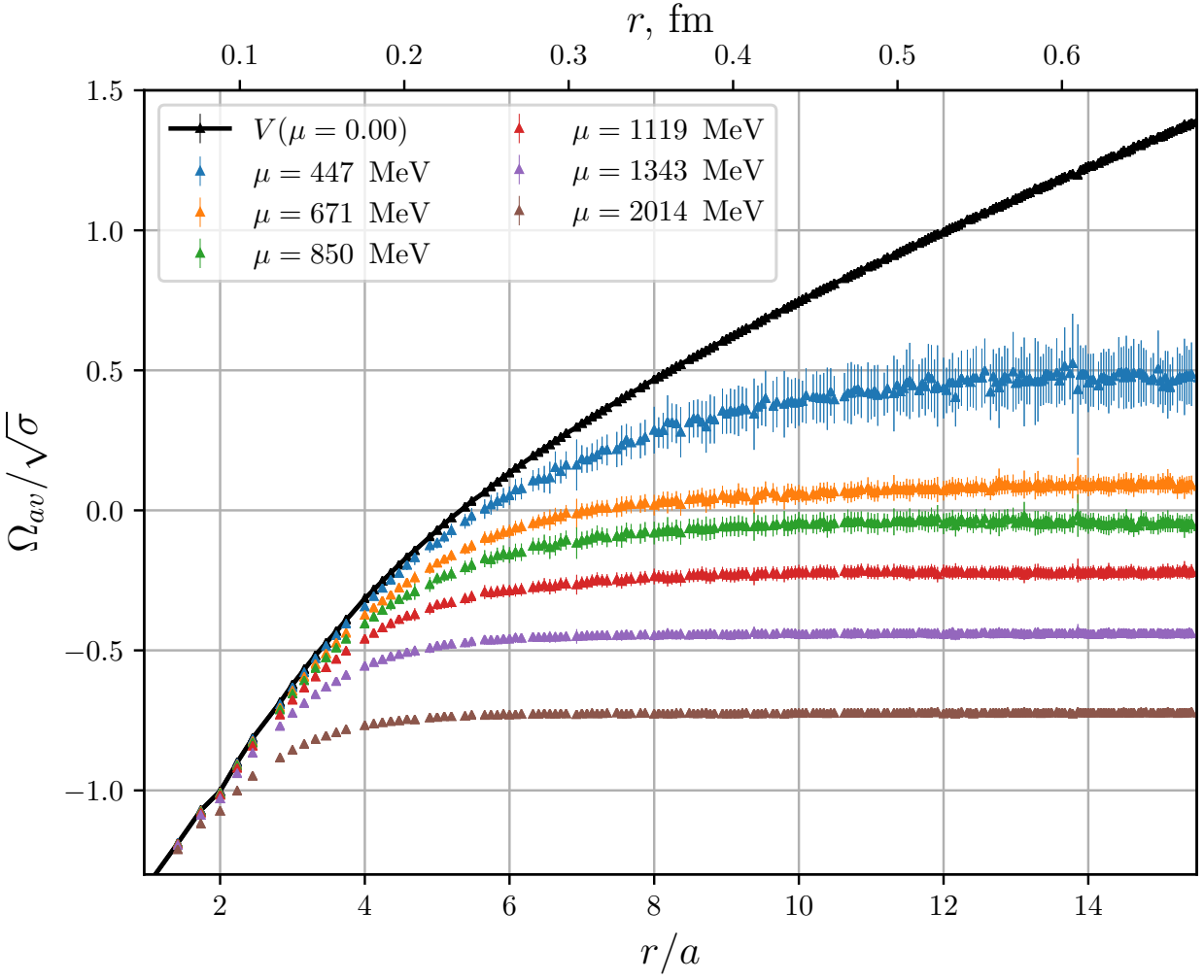
$$\begin{aligned}\Omega_1(r\to 0) &= V^{ren.}(r\to 0)\\ \Omega_{\bar{q}q}(r\to\infty) &= \Omega_1(r\to\infty)\end{aligned}$$

[for details see O. Kaczmarek *et al.*, Phys. Lett. **B543**, 41 (2002)]

Color singlet grand potential

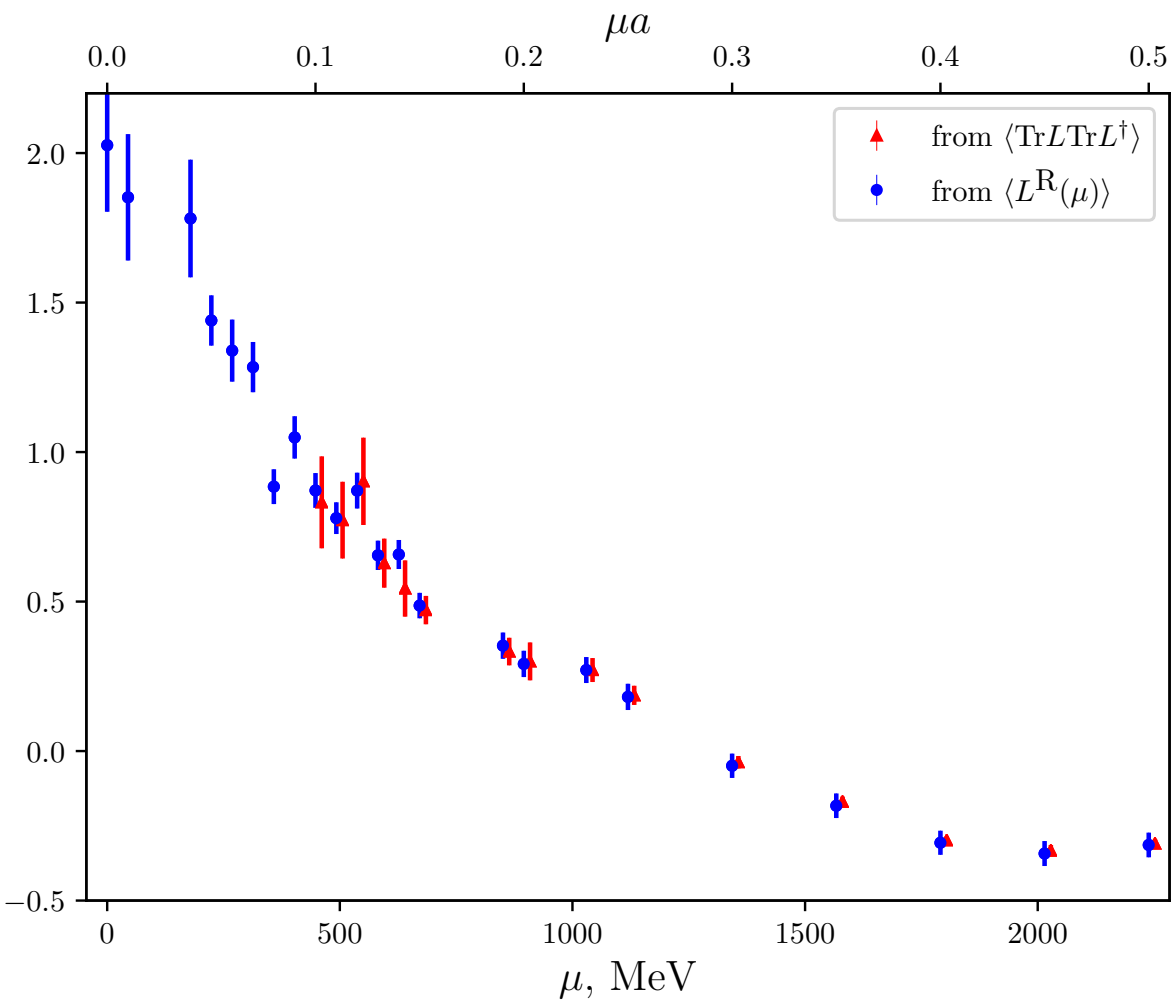


Color averaged grand potential



Screening radius definition: $V_{\mu=0}(R_{scr.}) = \Omega_{\bar{q}q}(\infty, \mu)$

$\Omega_{\bar{q}q}(\infty, \mu)$ in dense medium

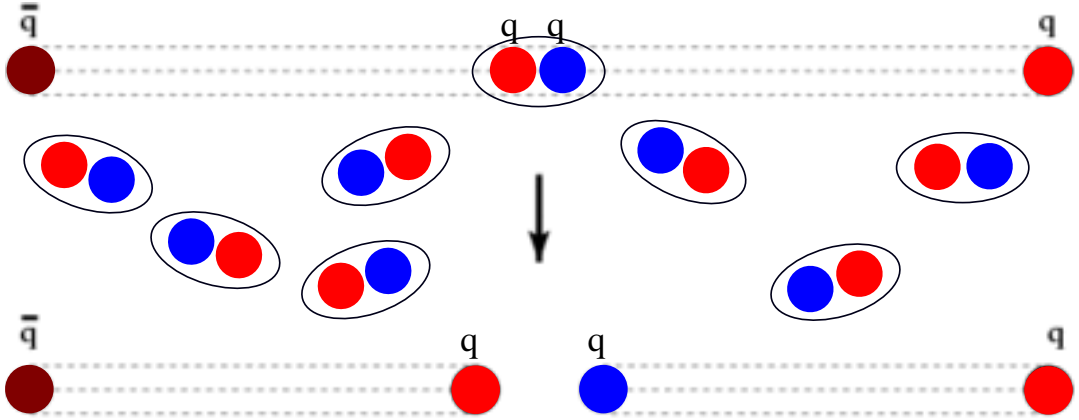


Blue circles are obtained from renormalized Polyakov loop:

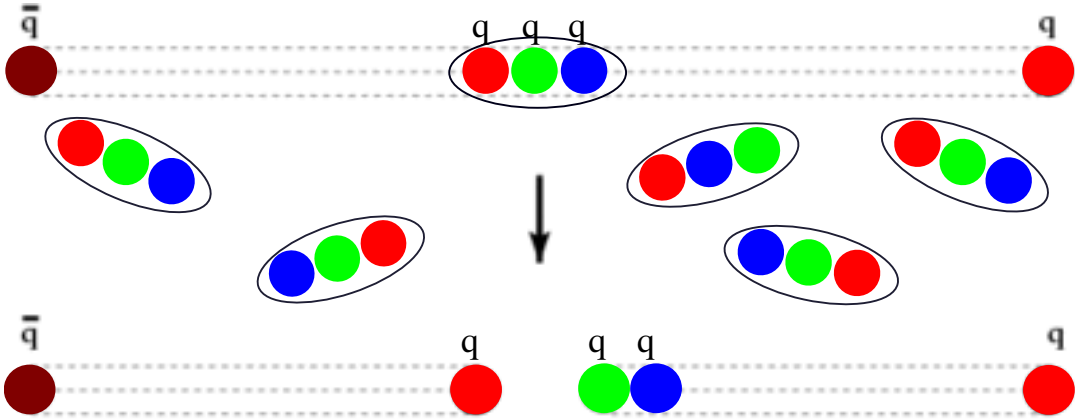
$$\Omega_{\bar{q}q}(\infty, \mu) = -2\,T \log \left\langle L^R(\mu) \right\rangle$$

String breaking in dense medium

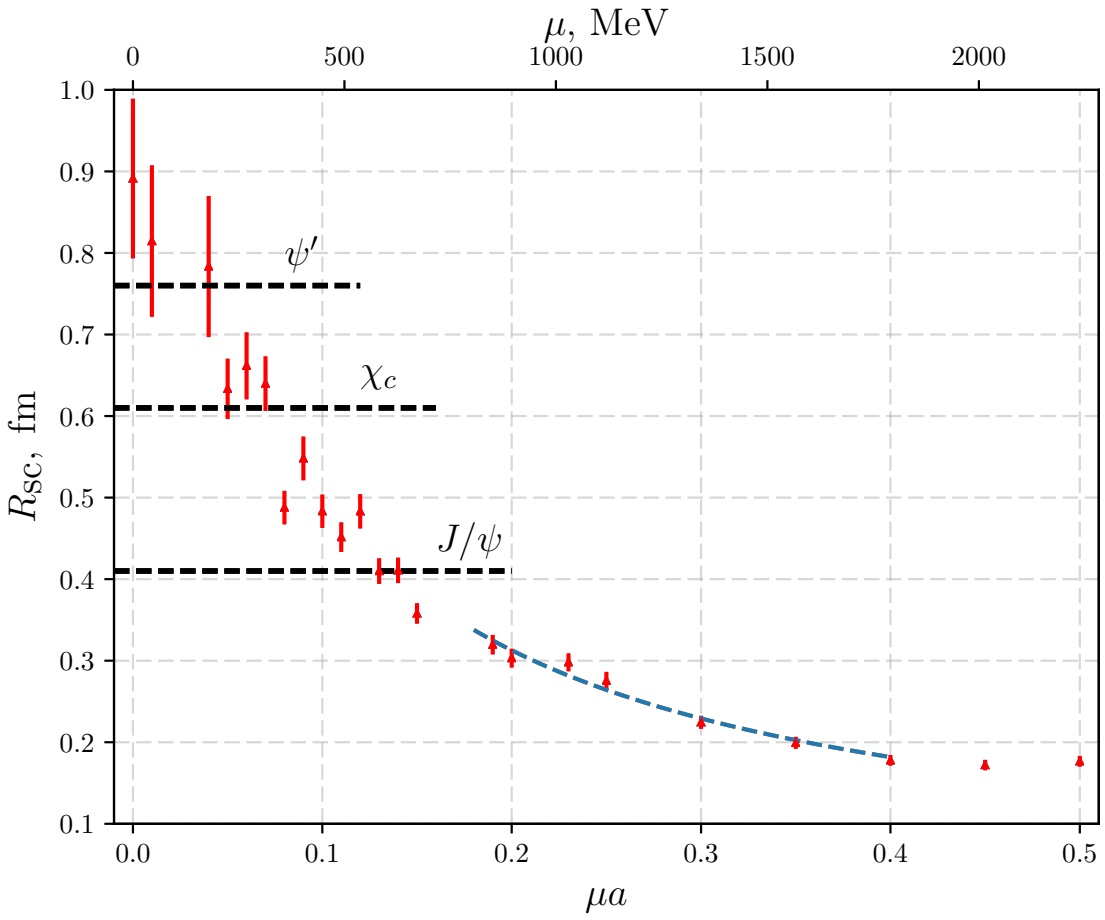
In QC_2D:



Analogous mechanism may be introduced in QCD:

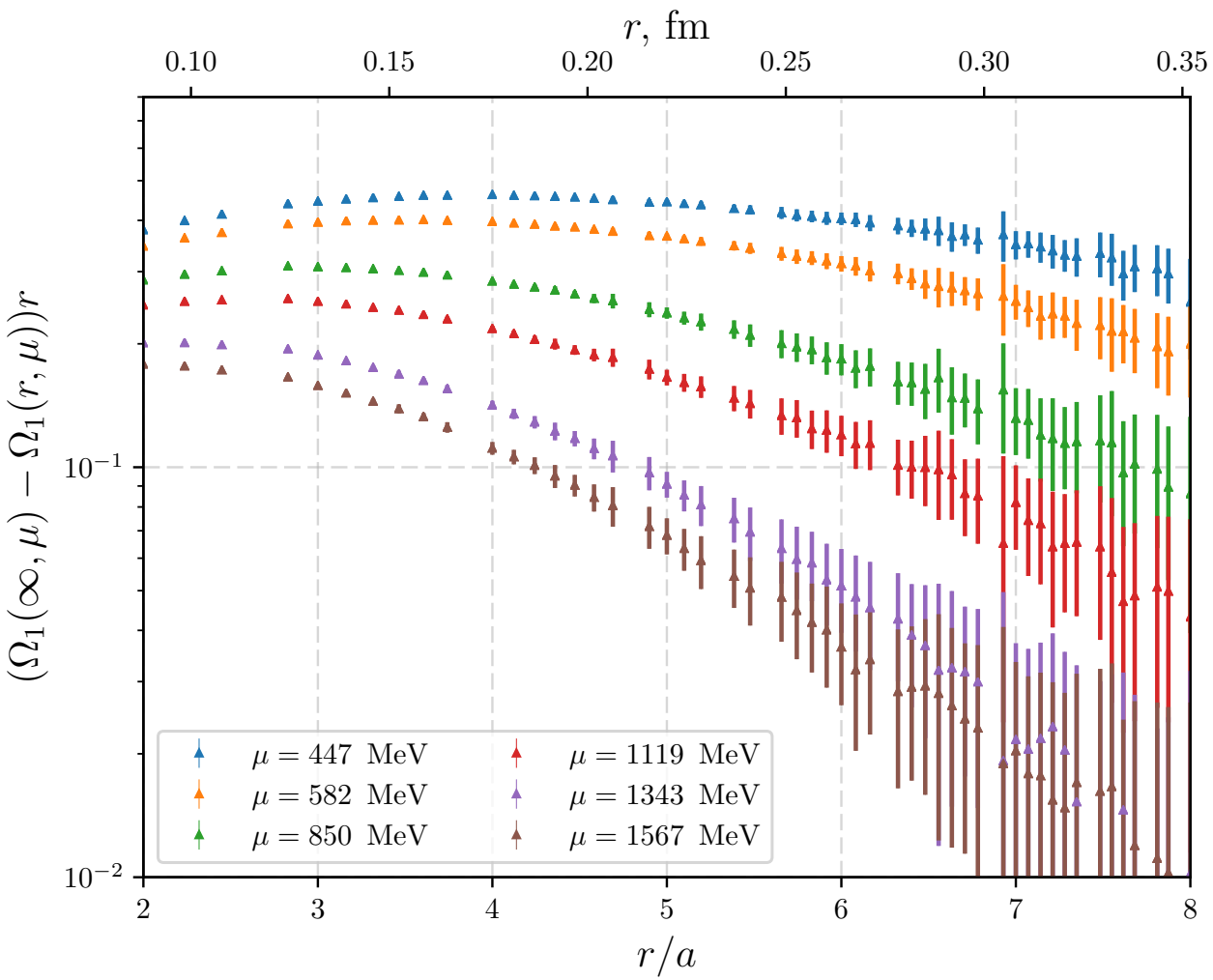


Screening radius and quarkonia dissociation



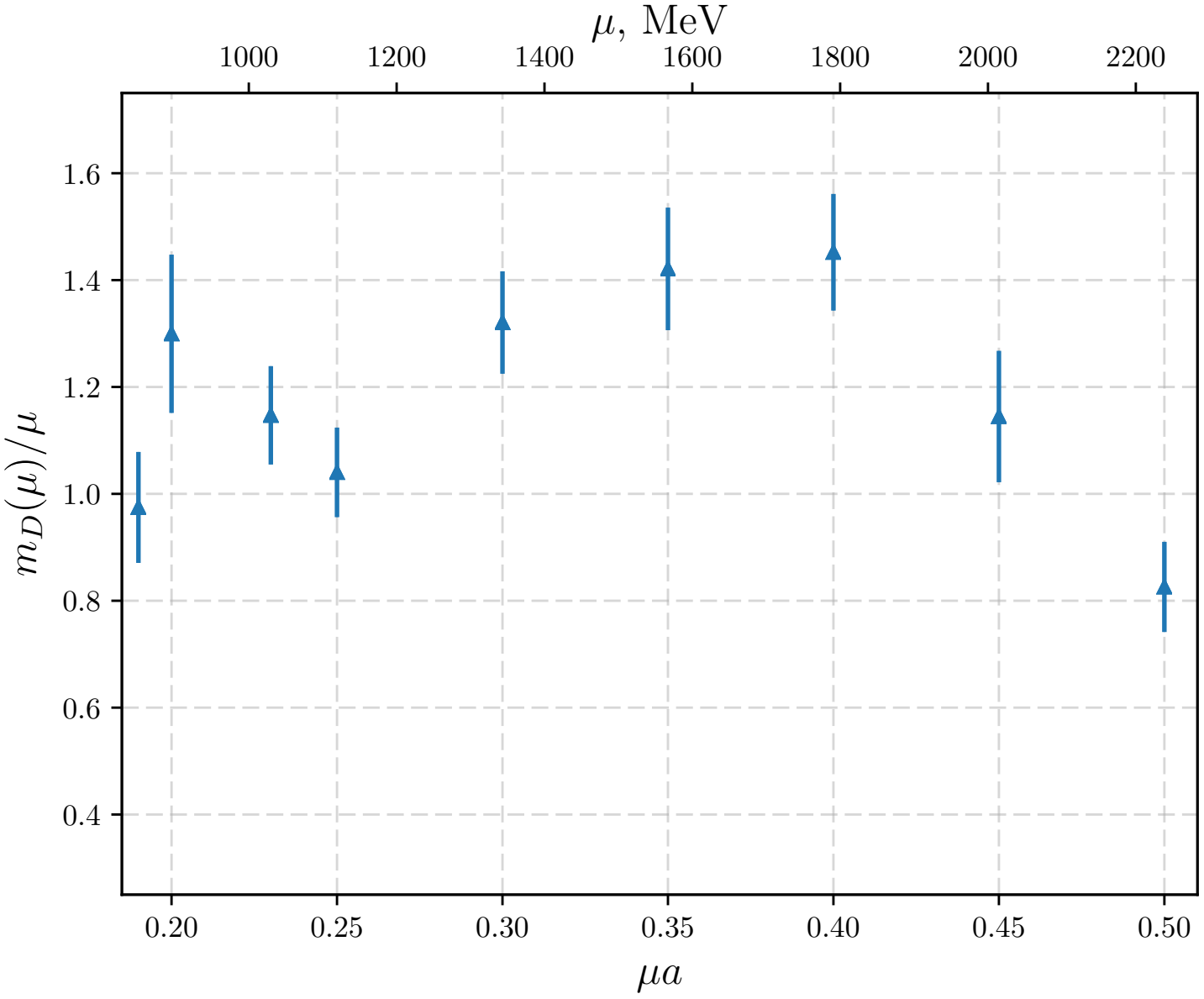
- $\sqrt{\langle r^2 \rangle}$ are estimated from NR Schodinger eq. with Cornell potential
- **Onset of quarkonia dissociation (?)**
- Blue curve: $R_{SC} = 1/[A m_D(\mu)]$, where $m_D^2(\mu) = (4/\pi)\alpha_s(\mu)\mu^2$

Debye screening in dense medium

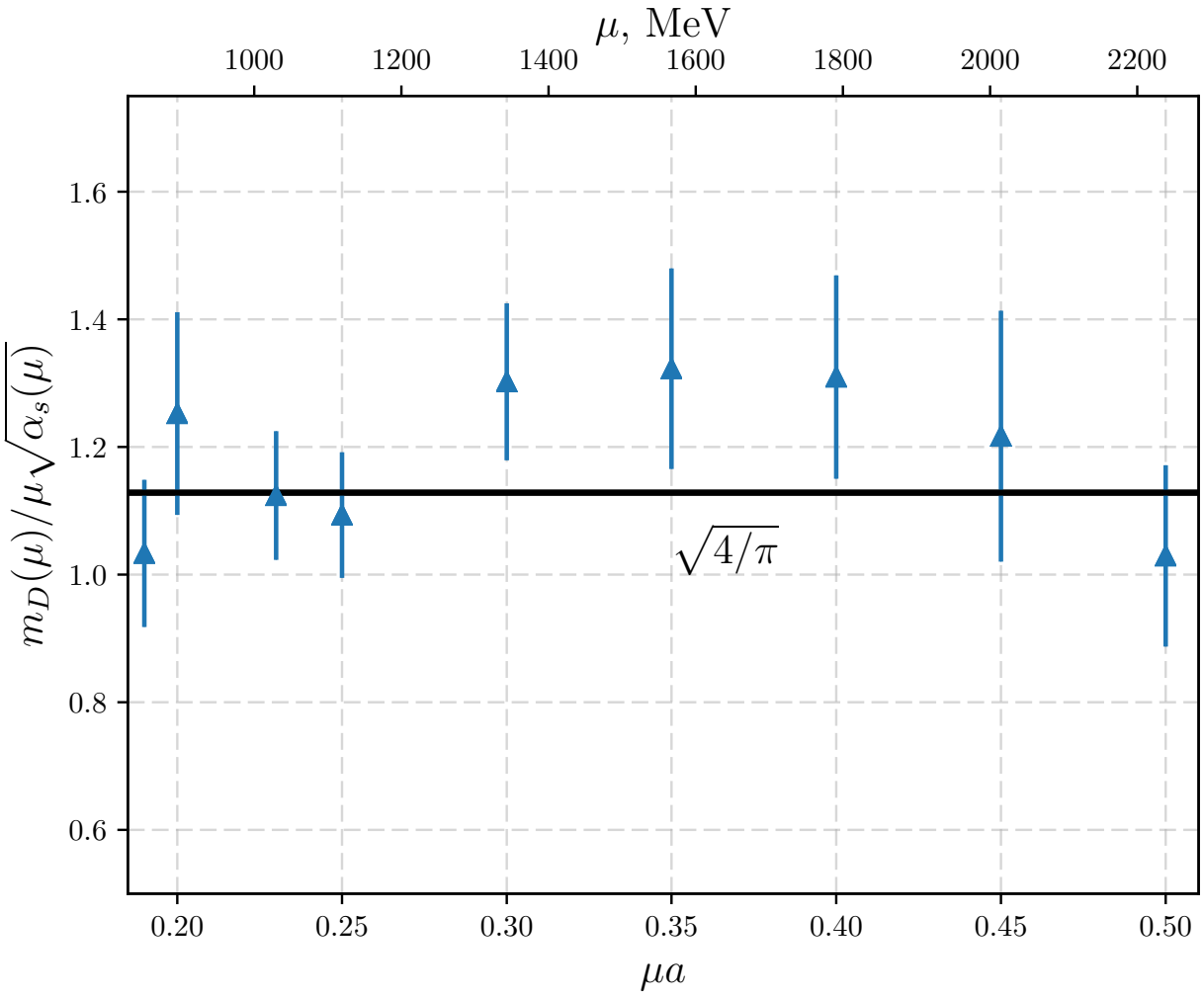


$$\Omega_1(r,\mu) = \Omega_1(\infty,\mu) - \frac{3}{4}\frac{\alpha_s(\mu)}{r} exp(-m_D r)$$

Debye mass


μ, MeV
1000
1200
1400
1600
1800
2000
2200
1.6
1.4
1.2
1.0
0.8
0.6
0.4
$m_D(\mu)/\mu$
0.20
0.25
0.30
0.35
0.40
0.45
0.50
μa

Debye mass



In one-loop: $m_D^2(\mu) = (4/\pi)\alpha_s(\mu)\mu^2$

Conclusions

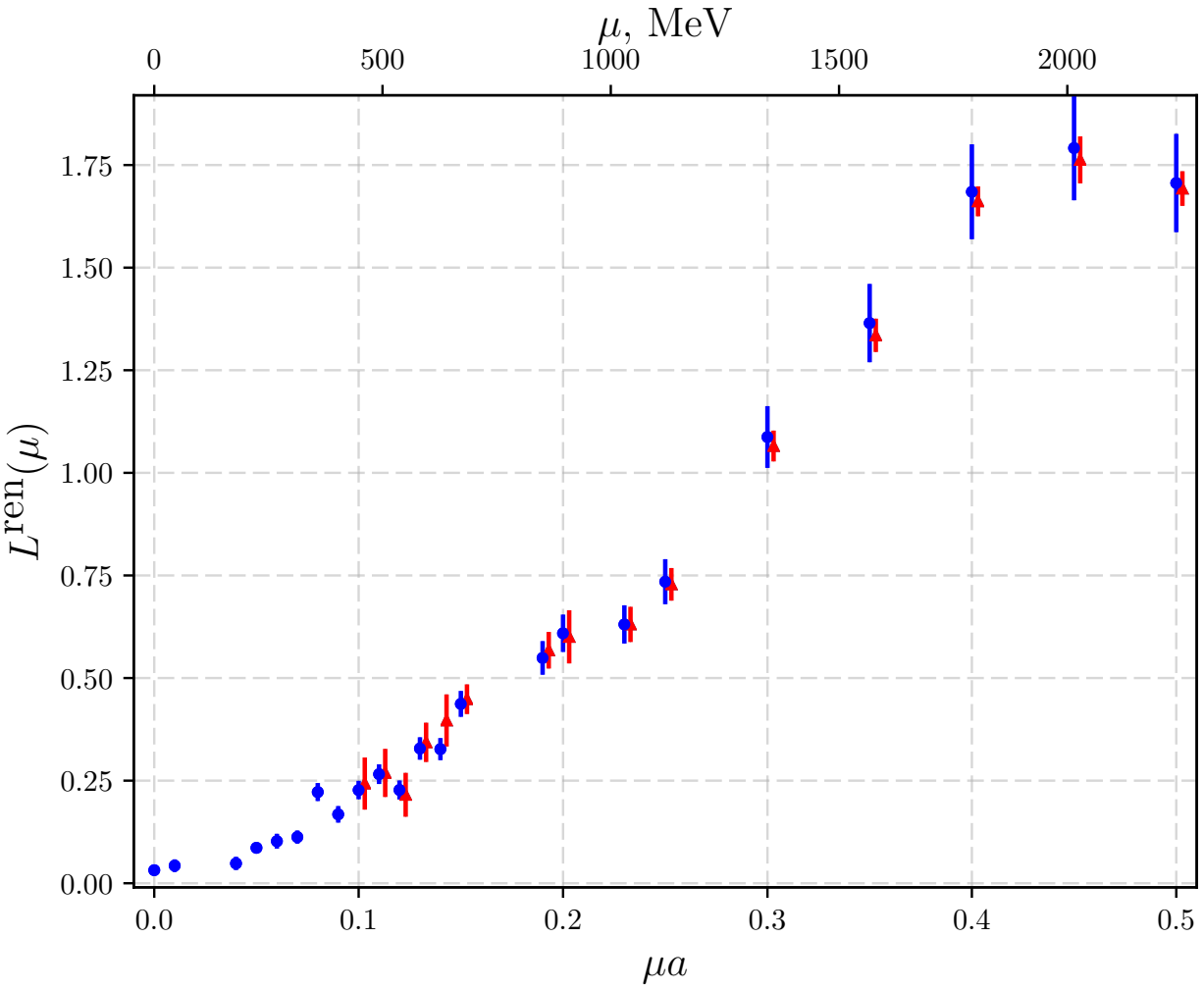
- We observe deconfinement in dense medium at $\mu_q^{(c)} \approx 1$ GeV for the first time
- Spatial string tension disappears at $\mu_q \geqslant 2$ GeV
- Onset of quakonia dissociation (?)
- Quark-gluon plasma at large density is probably perturbative

Backup slides

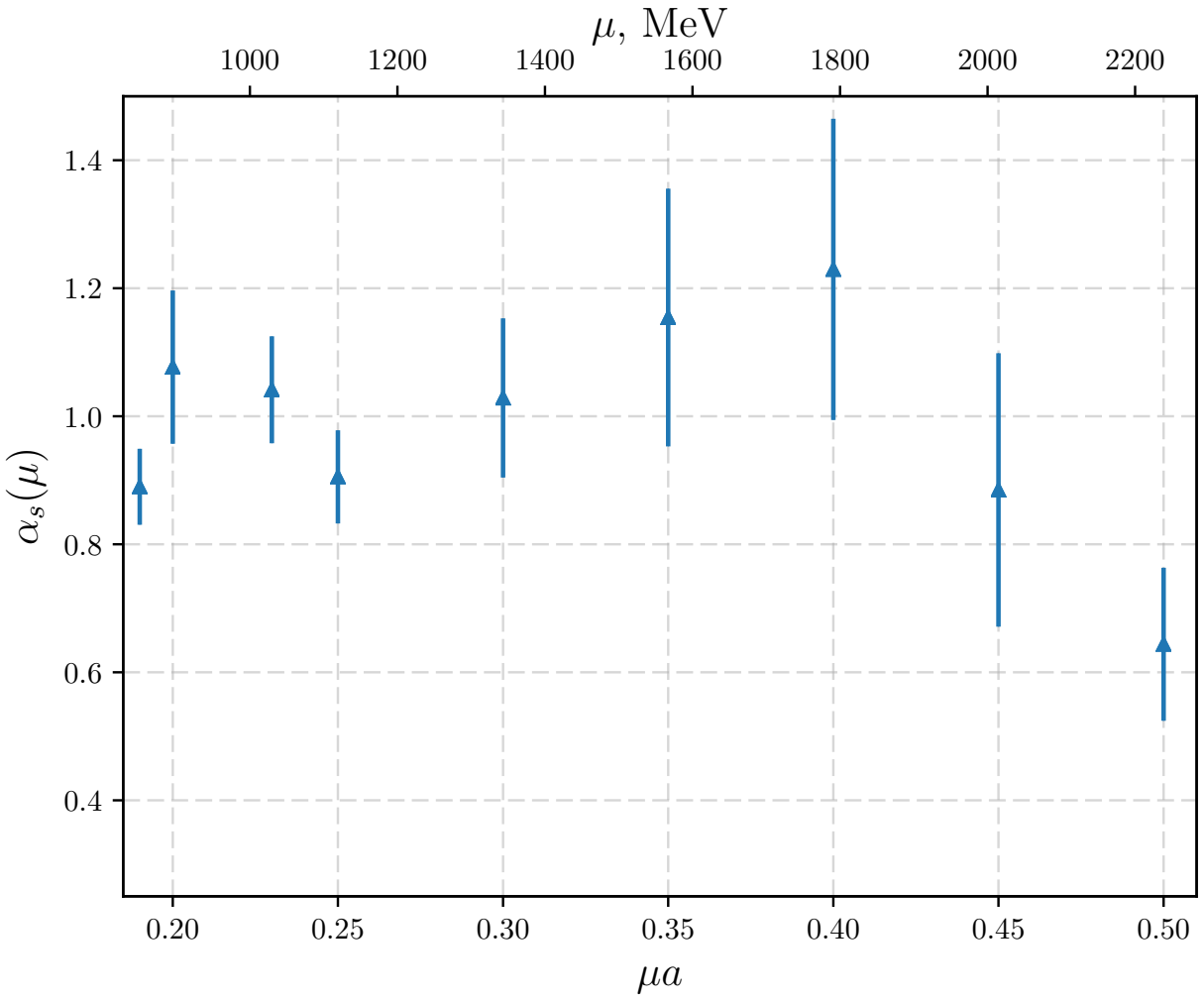
Simulation parameters

- $N_f = 2$ of rooted staggered quarks
- 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 $\lambda = 0.00075$, $\lambda^2 << (ma)^2$

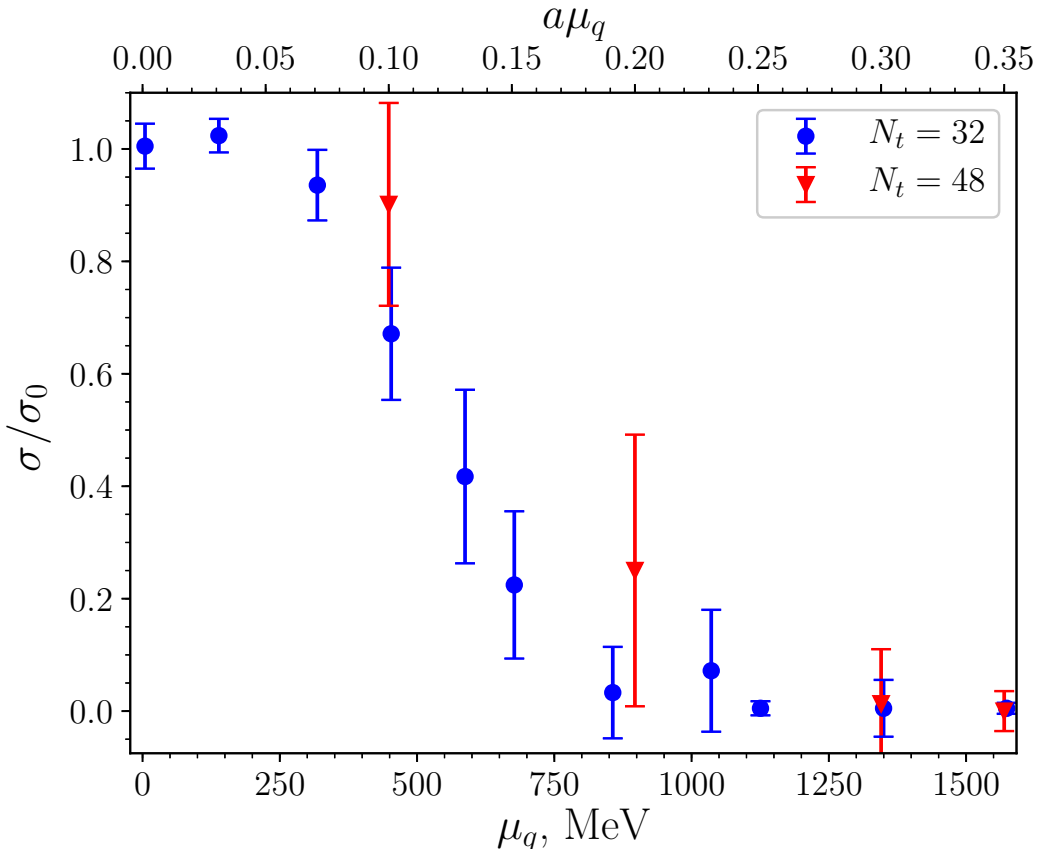
Renormalized Polyakov loop



$\alpha_s(\mu)$


μ, MeV
1000
1200
1400
1600
1800
2000
2200
1.4
1.2
1.0
0.8
0.6
0.4
$\alpha_s(\mu)$
0.20
0.25
0.30
0.35
0.40
0.45
0.50
μa

String tension with $N_t = 48$



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

Chiral condensate