Phase Transitions and Gluodynamics in 2-Colour Matter at High Density

T. Boz, S. Cotter, LF, D. Mehta, J.-I. Skullerud, Eur. Phys. J. A49 (2013) 87.

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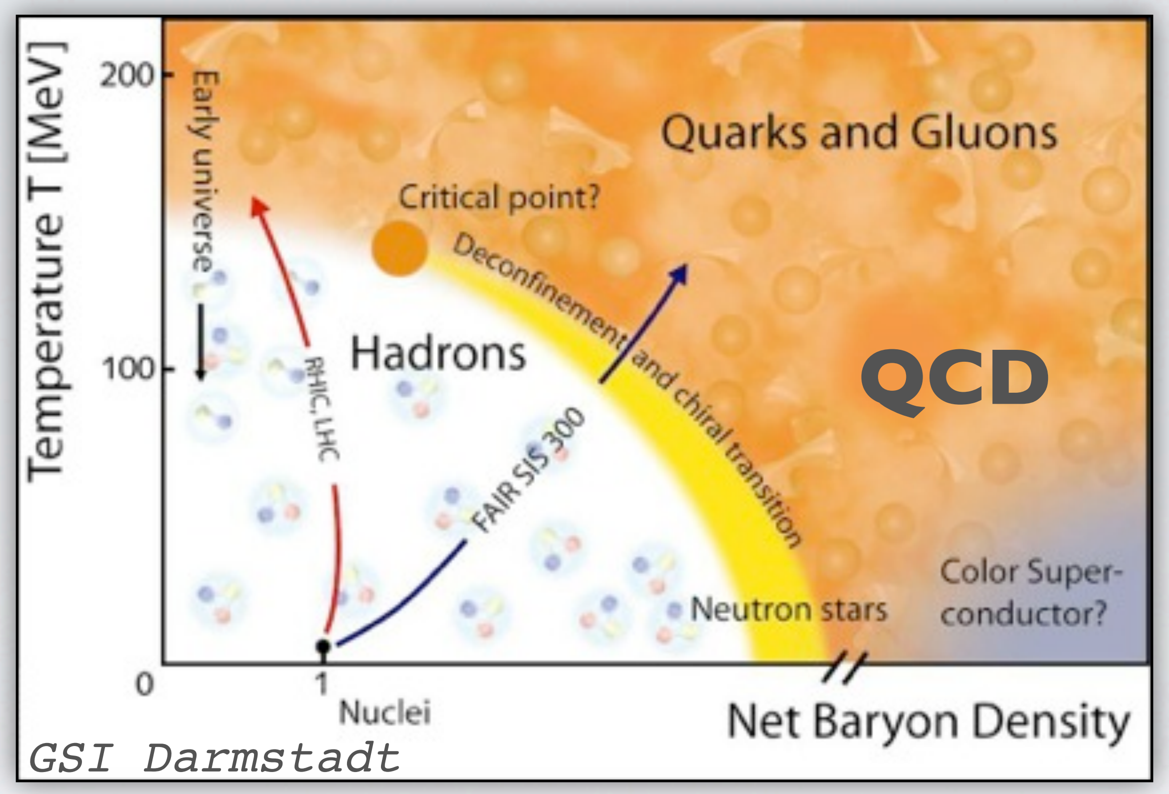
motivation



- sign problem in Monte Carlo simulations in QCD
- 2-colour matter (QC_2D): QCD-like theory
- QC_2D has chiral symmetry breaking and confinement/deconfinement
- (bosonic) diquarks are theory's lightest baryons, ⇝ can condense
- first principle lattice computations in QC_2D at all μ/T
- benchmark lattice computations and continuum approaches

  ↳ cf. talk Yuji Sakai

outline

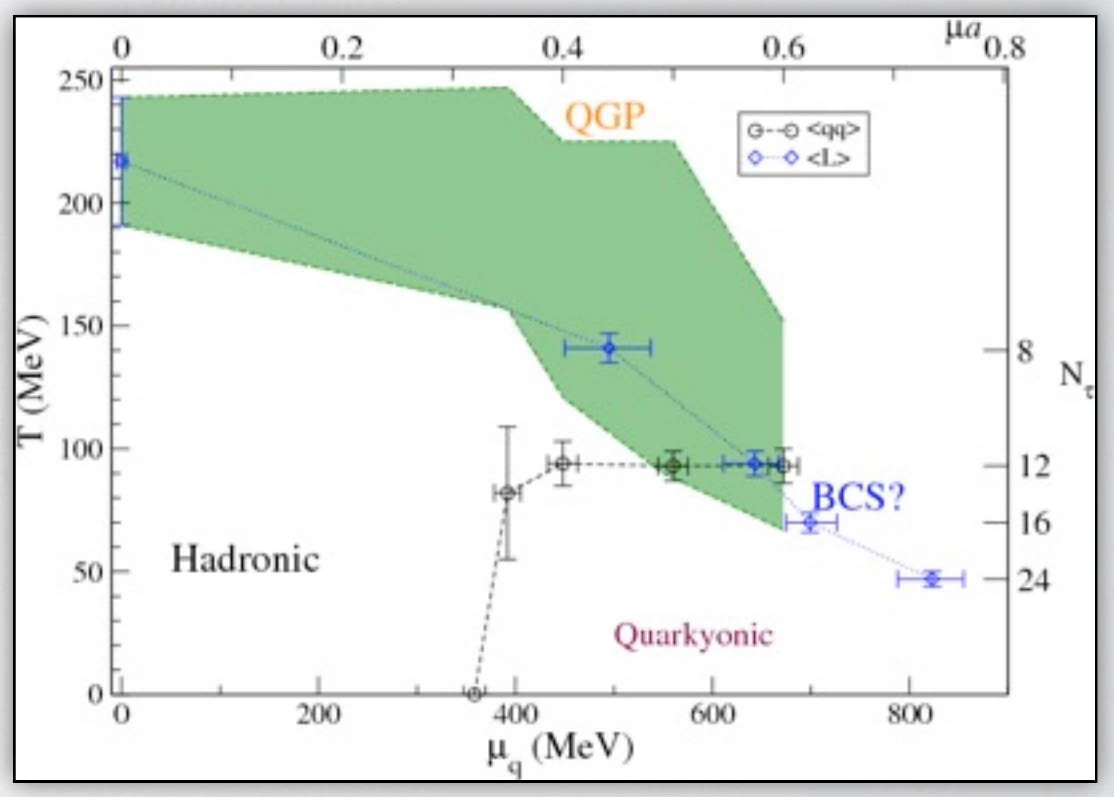
- motivation and introduction
- simulational details
- phase transitions (superfluid to normal, deconfinement)
- static quark potential
- gluodynamics (μ & T effects in gluon propagator)
- phase diagram
- summary

introduction to QC_2D

for lattice results see

- Cotter, Giudice, Hands, Skullerud, Phys. Rev. D87, 034507 (2013).
- XQCD-poster of Pietro Giudice, ‘Thermodynamics of Dense 2-Color Matter‘.
- Boz, Cotter, LF, Mehta, Skullerud, Eur. Phys. J. A49 (2013) 87.
- Skullerud, PoS QCD-TNT09 (2009) 043; Nucl. Phys. A820 (2009) 175C-178C.

- phase transitions
  - superfluidity (diquark condensate <qq>)
  - deconfinement (Polyakov loop L)
  - (dynamical chiral symmetry breaking)
- at least 3 phases
  - hadronic (low T, low μ): <qq>=0, <L>≈0
  - quarkyonic (low T, intermediate μ): <qq>≠0, <L>≈0
  - deconfined quark-gluon plasma (high T): <qq>=0, <L>≠0
  - (?) deconfined, superfluid (high μ, low T):<qq>≠0≠<L>
  - (?) BEC (for smaller m_π/m_ρ)
- Silver Blaze property for $\mu_o \leq m_{baryon}/N_c$
- bulk thermodynamics:
  quark number density/susceptibility, pressure, energy density
- gluon propagator antiscreened/screened at intermediate/high μ



simulational details

- Wilson gauge action with 2 flavours of unimproved Wilson fermion
- diquark source j to lift low-lying eigenmodes, 'physical' limit $j \to 0$
- $\beta = 1.9$, $\kappa = 0.168$, $a = 0.178(6)$ fm, $m_\pi = 717(25)$ MeV, $m_\pi / m_\rho \approx 0.8$
- $ja = 0.02$–0.05
- most simulations on $12^3 \times 24$
- $\mu a = 0.25$–1.1
- for thermal aspects: $16^3 \times N_\tau$, with $N_\tau = 4$–20, $\mu a = 0.35$–$.6$
- for details see

Cotter, Giudice, Hands, Skullerud, Phys. Rev. D87, 034507 (2013).
Boz, Cotter, LF, Mehta, Skullerud, Eur. Phys. J. A49 (2013) 87.

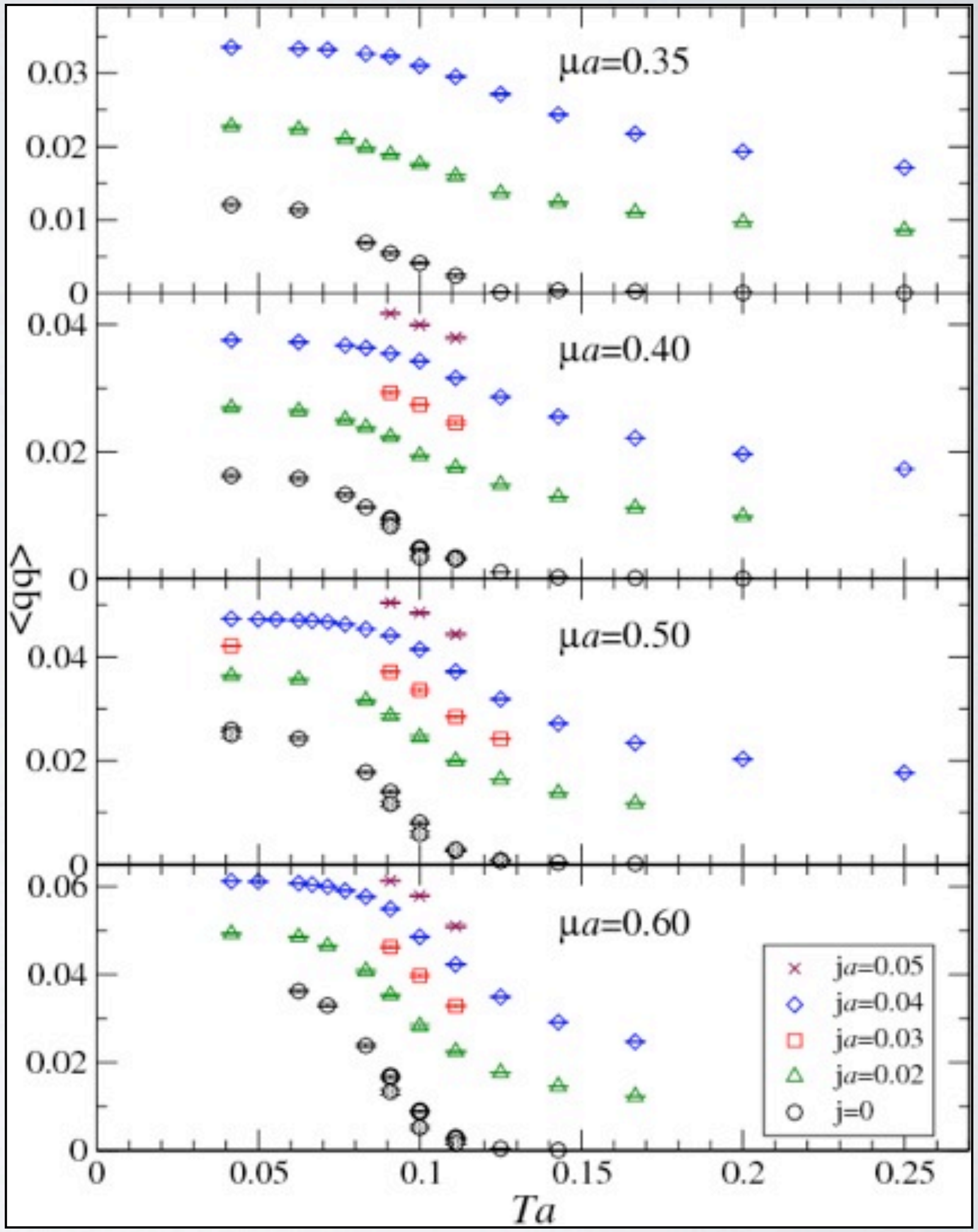
phase transitions: superfluid to normal transition

- order parameter for superfluidity:
  diquark condensate

$$\langle qq\rangle = \langle \psi^{2tr} C\gamma_5\tau_2\psi^1 - \bar{\psi}^1 C\gamma_5\tau_2\bar{\psi}^{2tr}\rangle$$

- linear extrapolation to $j \to 0$ has large uncertainties
- clear transition from superfluid phase <qq> ≠ 0 to normal phase <qq> = 0
- expected 2nd order phase transition (3d XY-model) but not enough data to determine order properly
- phase transition temperature T_s from inflection point of <qq>, linear extrapolation to $j \to 0$

$a\mu$	0.35	0.40	0.50	0.60
$aT_s(0.04)$	0.121(6)	0.108(2)	0.111(5)	0.102(6)
$aT_s(0.02)$	0.097(16)	0.096(5)	0.097(2)	0.093(5)
aT_s	0.073(24)	0.084(8)	0.083(5)	0.083(6)
T_s (MeV)	82(27)	94(9)	93(6)	93(7)



$16^3 \times N_\tau$

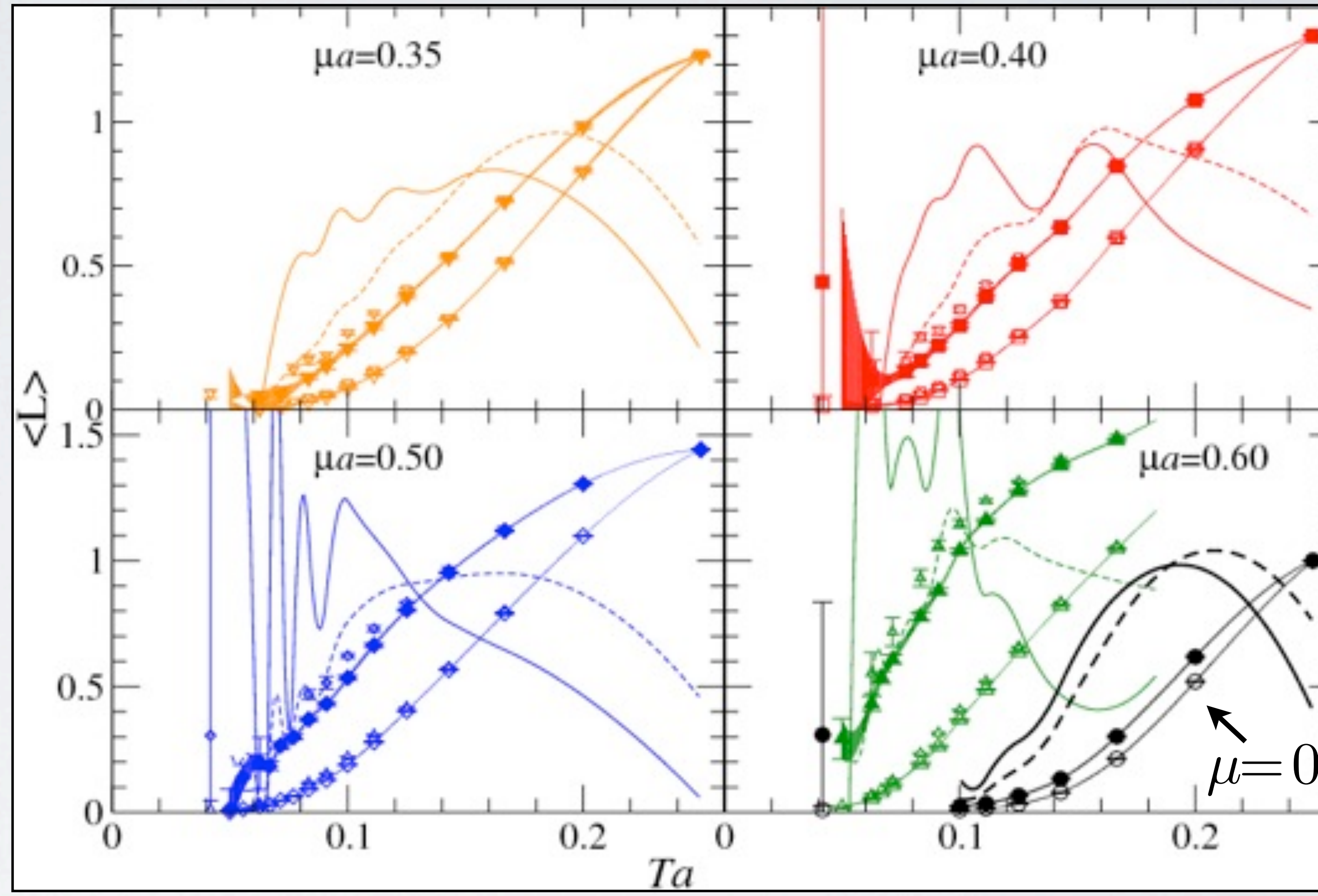
phase transitions: deconfinement transition

- 'order parameter' for deconfinement:
  exp. value of Polyakov loop <L>

$$L(\vec{x}) = \frac{1}{N_c} \mathrm{tr}\, \mathcal{P} e^{ig \int_0^{1/T} dx_0\, A_0(x)}$$

- crossover at all μ
- renormalisation of <L> is T-dependent
- crossover temperature T_d
  from inflection point (in scheme B)
- T_d decreases as μ increases

μa	$T_d a$	T_d (MeV)
0.0	0.193(20)	217(23)
0.35	0.140–0.220	157–247
0.40	0.108–0.200	121–225
0.50	0.080–0.200	90–225
0.60	0.060–0.135	67–152



$16^3 \times N_\tau$, ja=0.04(, 0.02)

renormalisation:

$$L_R(T,\mu) = Z_L^{N_\tau} L_0\left(\frac{1}{aN_\tau}, \mu\right)$$

$$L_R\left(T = \frac{1}{4a}, \mu=0\right) = \begin{cases} 1 & \text{solid symbols} \leftarrow \textbf{scheme A} \\ 0.5 & \text{open symbols} \leftarrow \textbf{scheme B} \end{cases}$$

... are multiplied by 2
to facilitate comparison

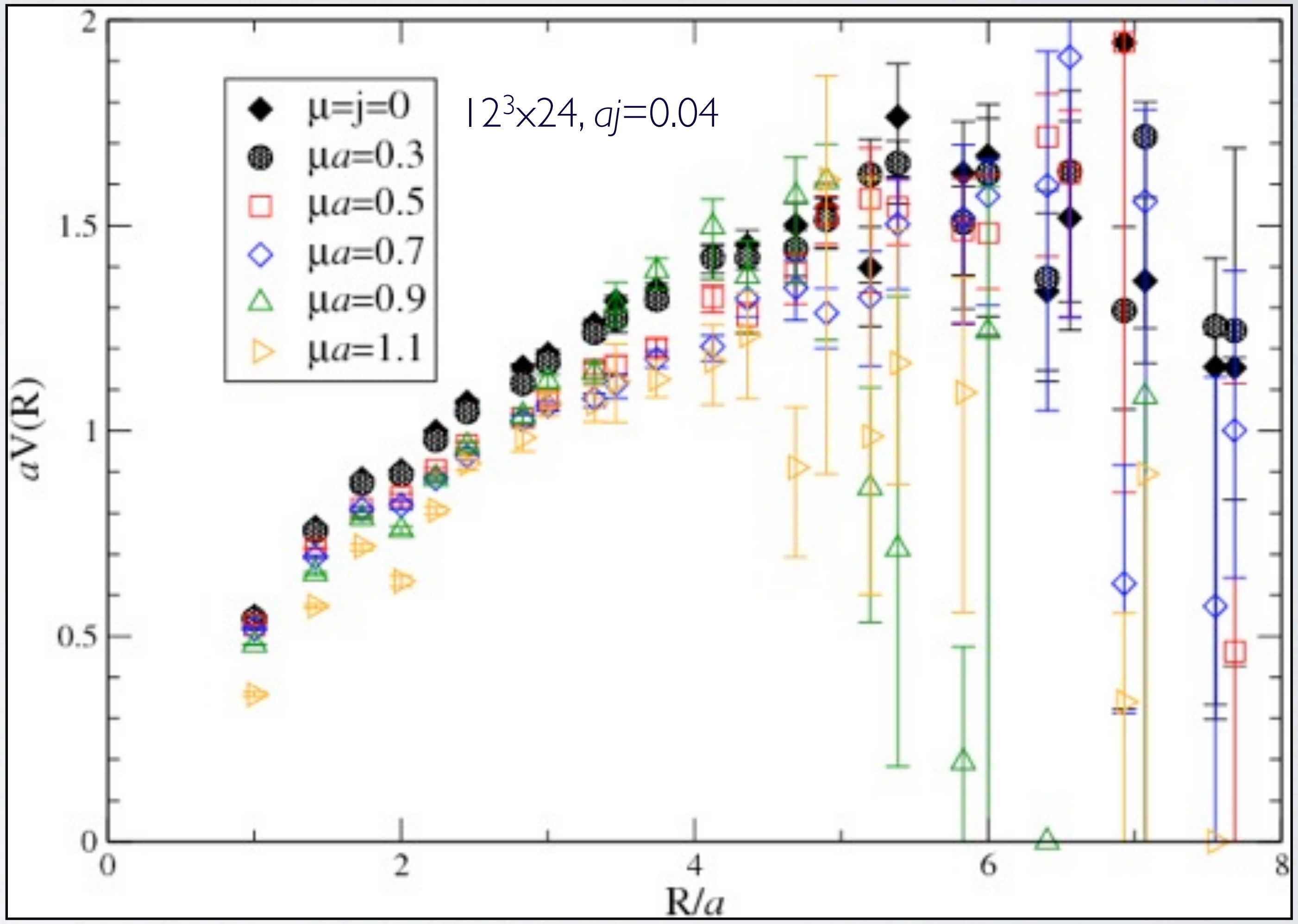
static quark potential

- linear rising potential indicates confinement
- string breaking if quarks dynamical,
  but intermediate region with linear rise
- high T: Debye screening expected
- data obtained from fitted Wilson loop

$$W(r,\tau) \sim \exp\left(-V(r)\tau\right)$$

- superfluid region ($a\mu\approx0.5$):
  potential flatter than $\mu=0=j$
- deconfinement region ($a\mu=0.9$)
  potential consistent with $\mu=0$
- pattern consistent with previous findings

`Hands, Kim, Skullerud, Eur. Phys. J. C48, 193 (2006).`



static quark potential

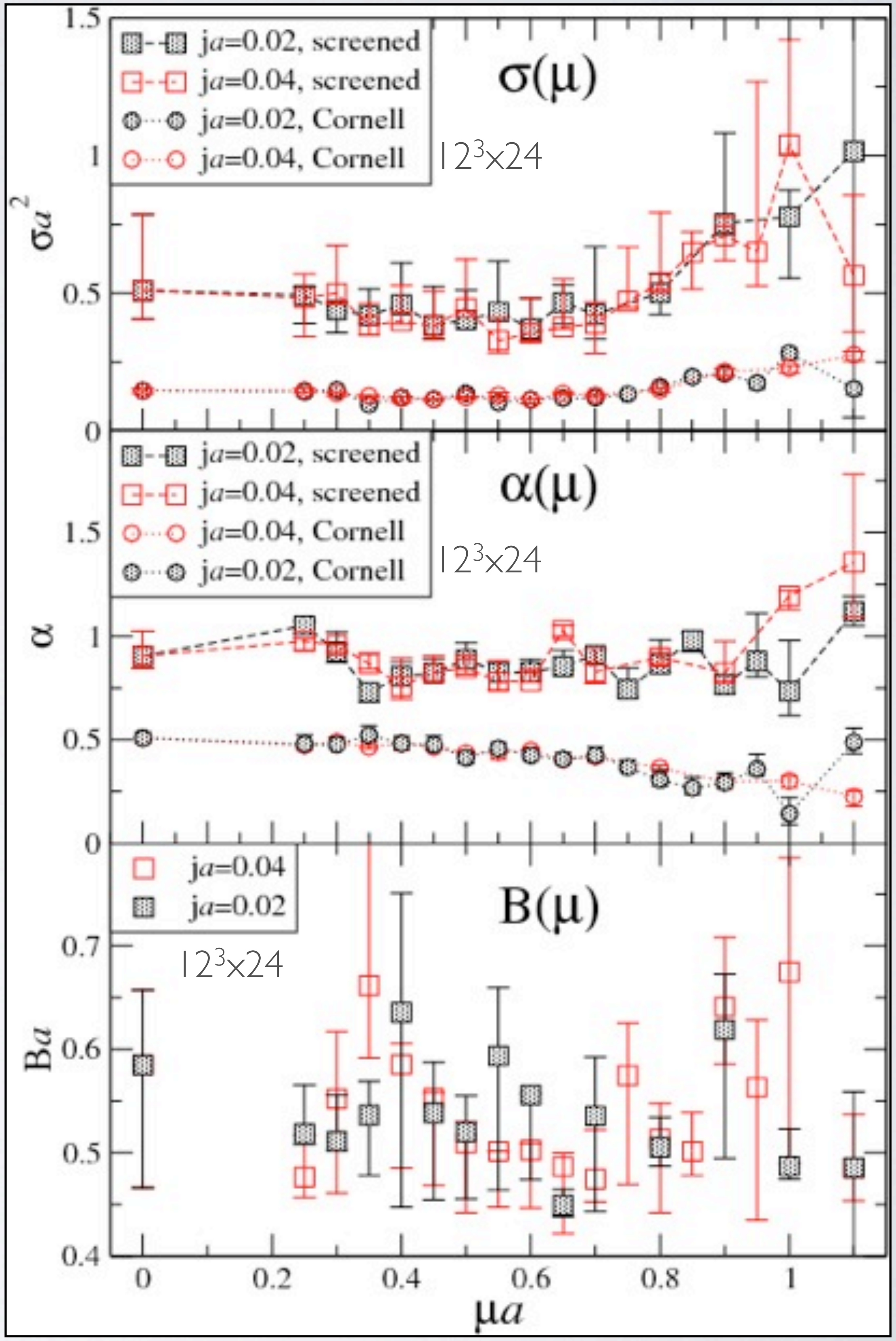
- quantify variation with μ via fits
  - (standard) Cornell potential

$$V(r) = C(\mu, j) + \sigma(\mu, j) r + \frac{\alpha(\mu, j)}{r}$$

  - add exponential term (allow for screening)

$$V(r) = C(\mu, j) + \frac{\sigma(\mu, j) r}{B(\mu, j)} e^{-Br} + \frac{\alpha(\mu, j)}{r}$$

- σ const for low μ, increases for high μ
- exponential term insensitive to μ but non-zero, no interpretation as screening mass
- possible explanations
  - medium with long-range interactions
  - screening not seen in Wilson loop
  - large lattice artefacts for large μ

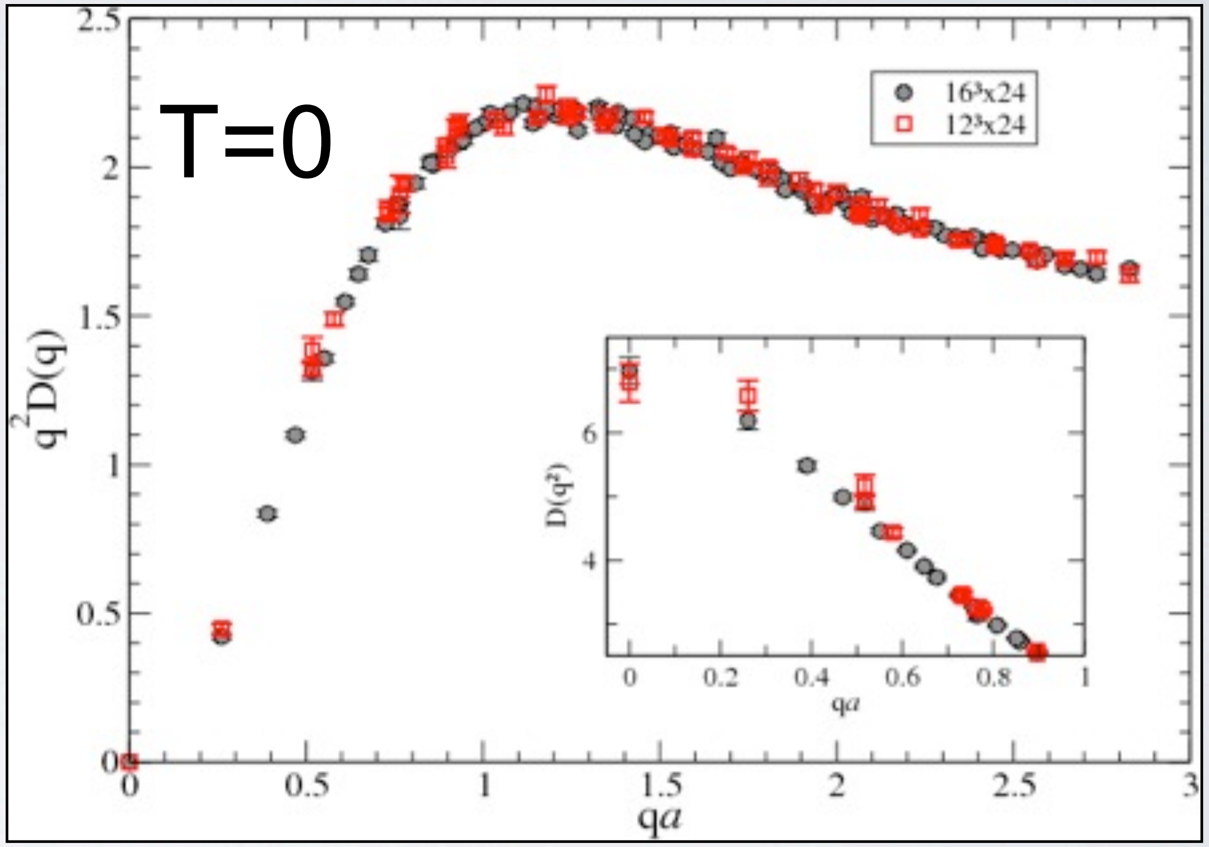


gluon propagator

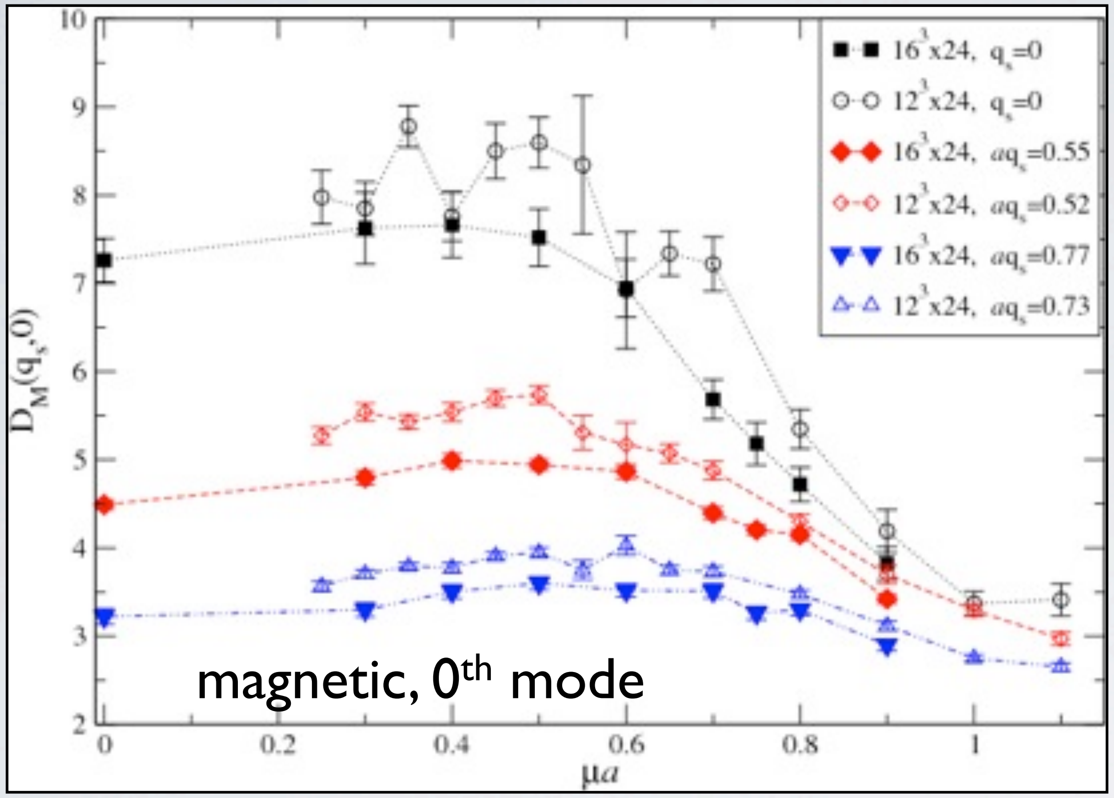
- study effects of T and *μ:* guideline for full QCD (?)
- (minimal) Landau gauge: only transverse mode(s), chromomagnetic D_M and -electric D_E modes

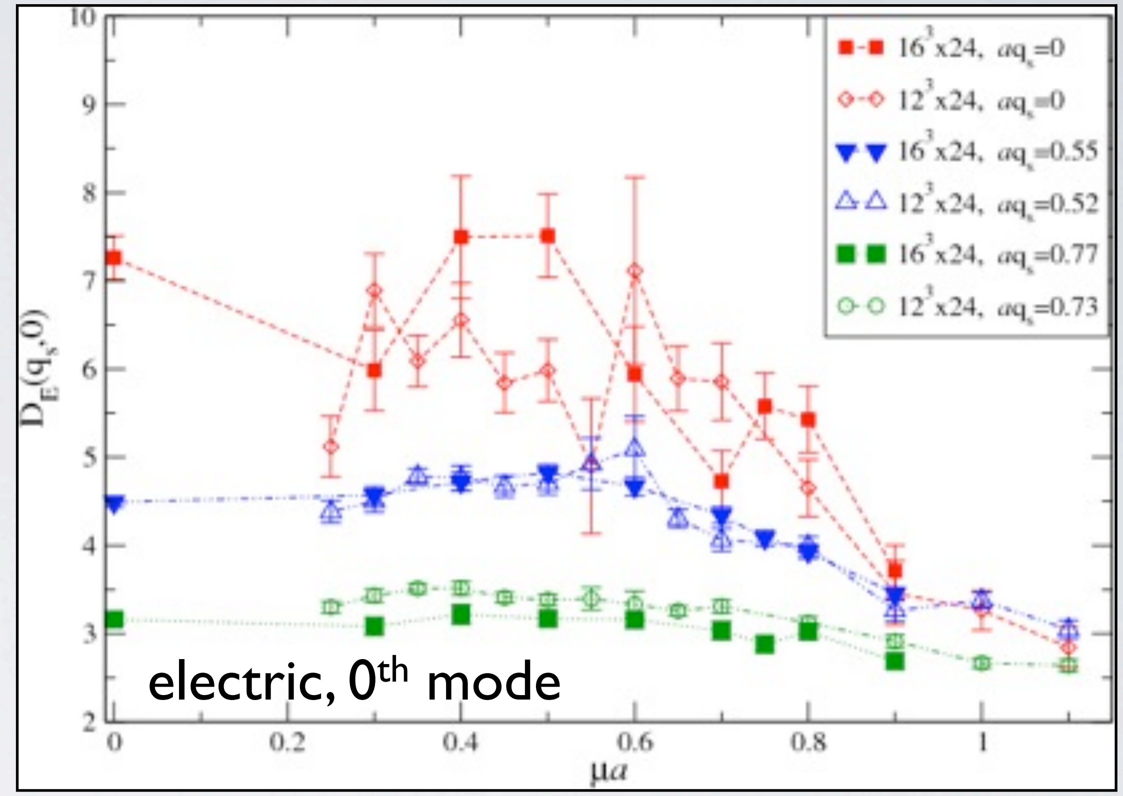
$$D_{\mu\nu} = P^M_{\mu\nu}\, D_M(q_s, q_0) \,+\, P^E_{\mu\nu}\, D_E(q_s, q_0)$$

- seperately depends on spatial momentum q_s and Matsubara modes q_0
- small volume dependence on lattices used

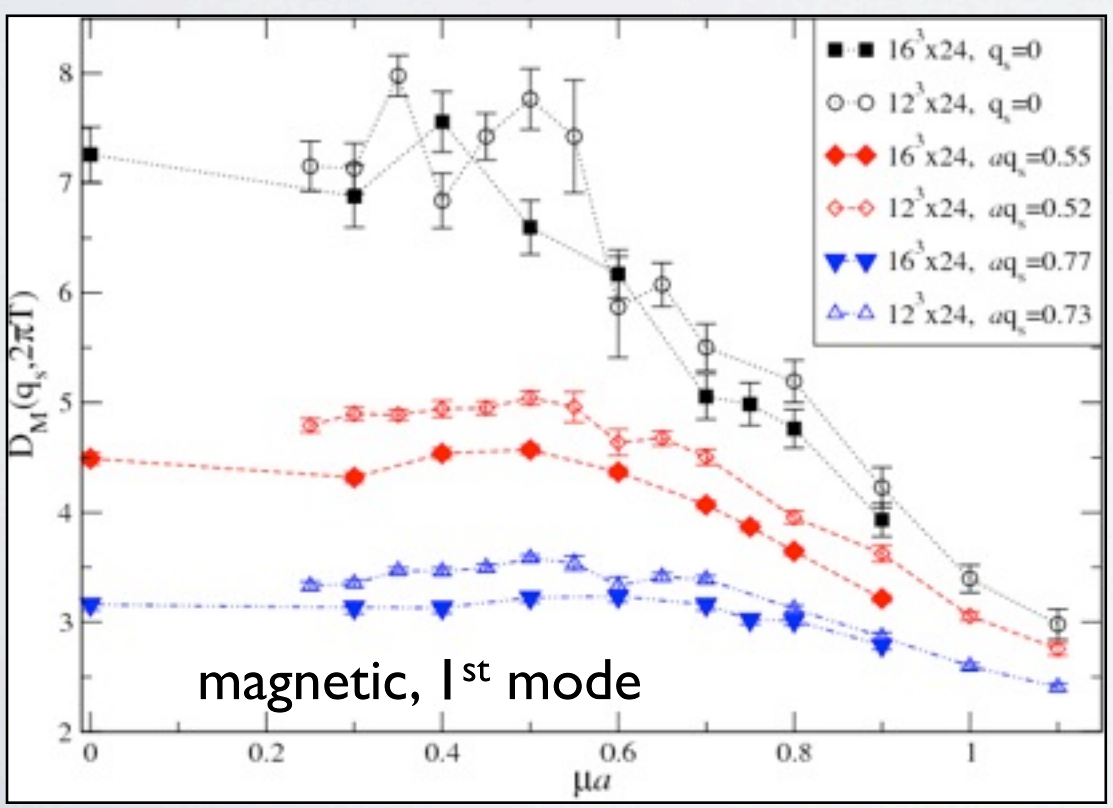


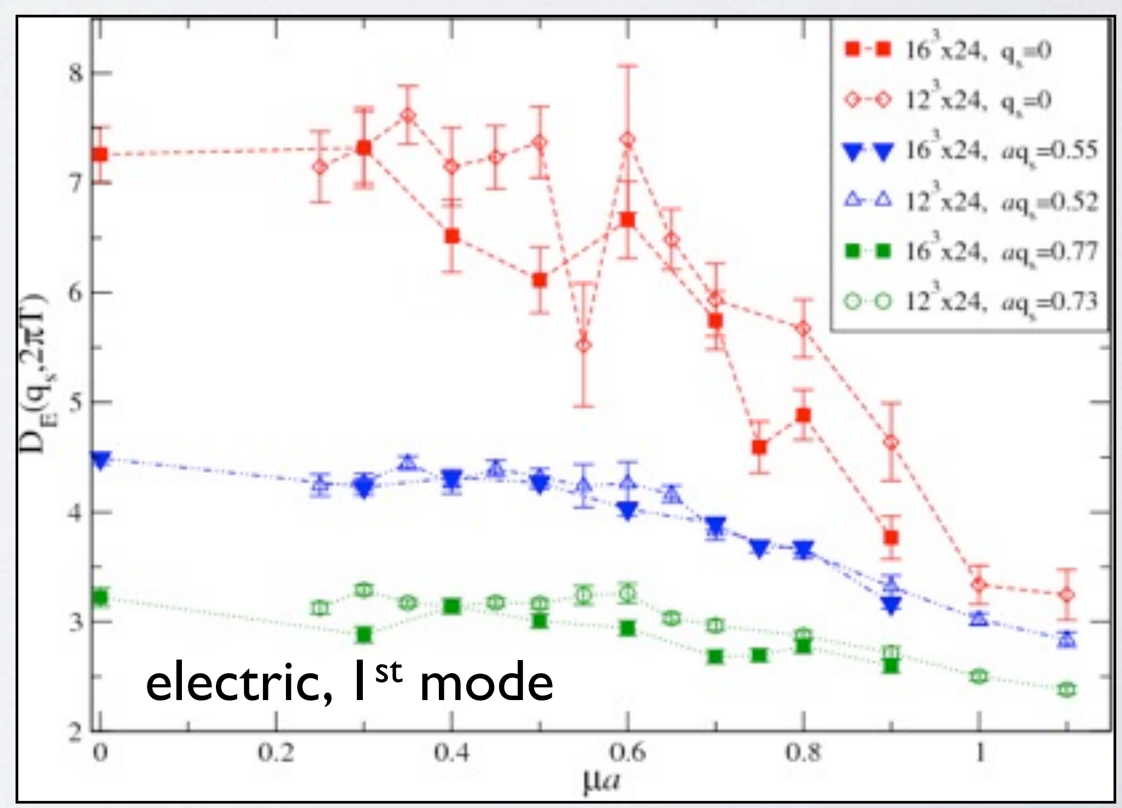
gluon propagator – μ-dependence



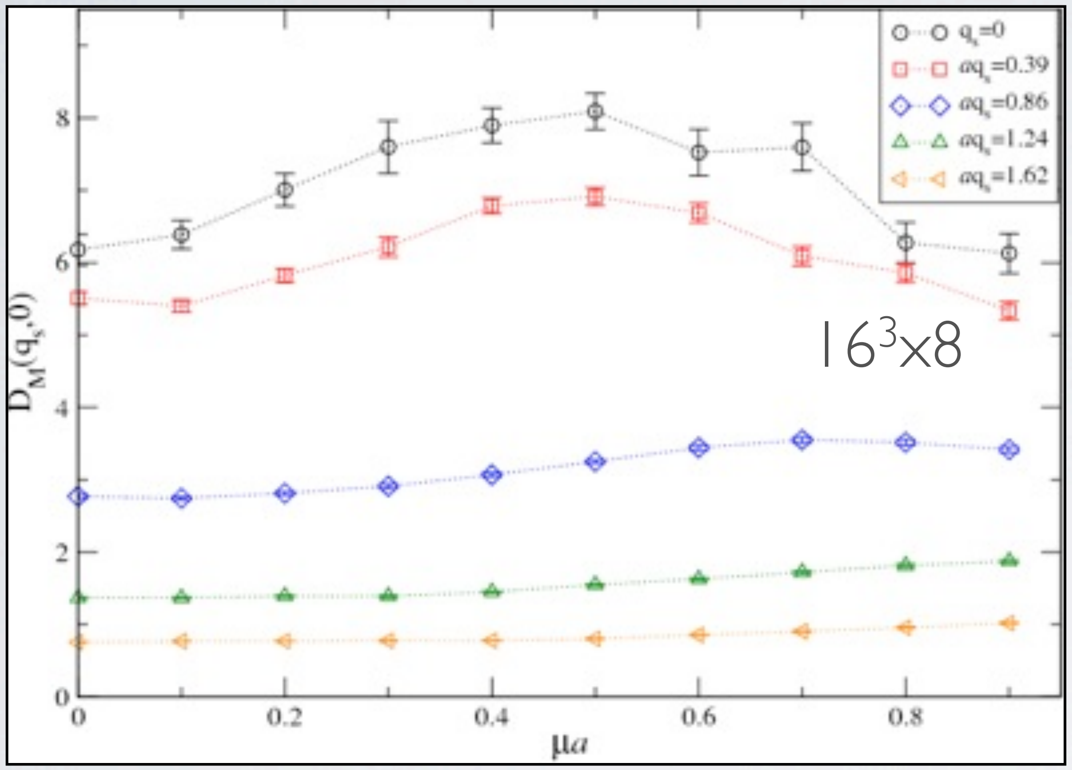


- mild enhancement at intermediate μ, ← in superfluid, confined phase
- suppression at high μ, ← in deconfined phase

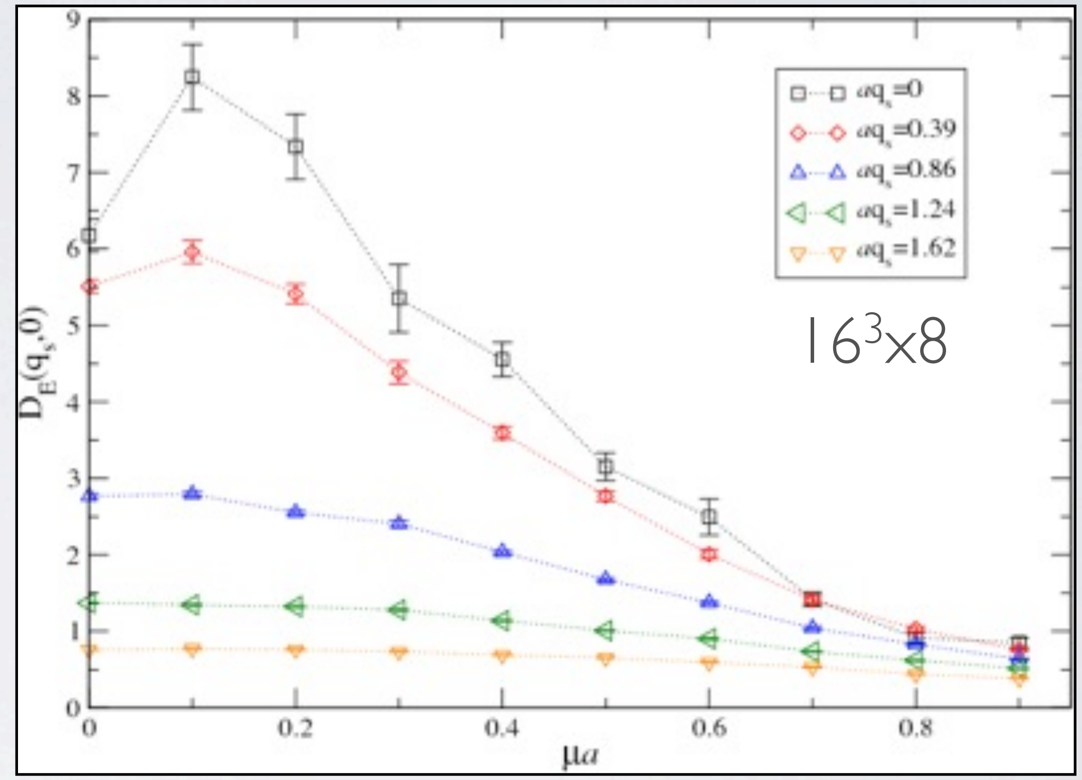




gluon propagator – μ-dep. at high temperature



magnetic, 0^{th} mode



electric, 0^{th} mode

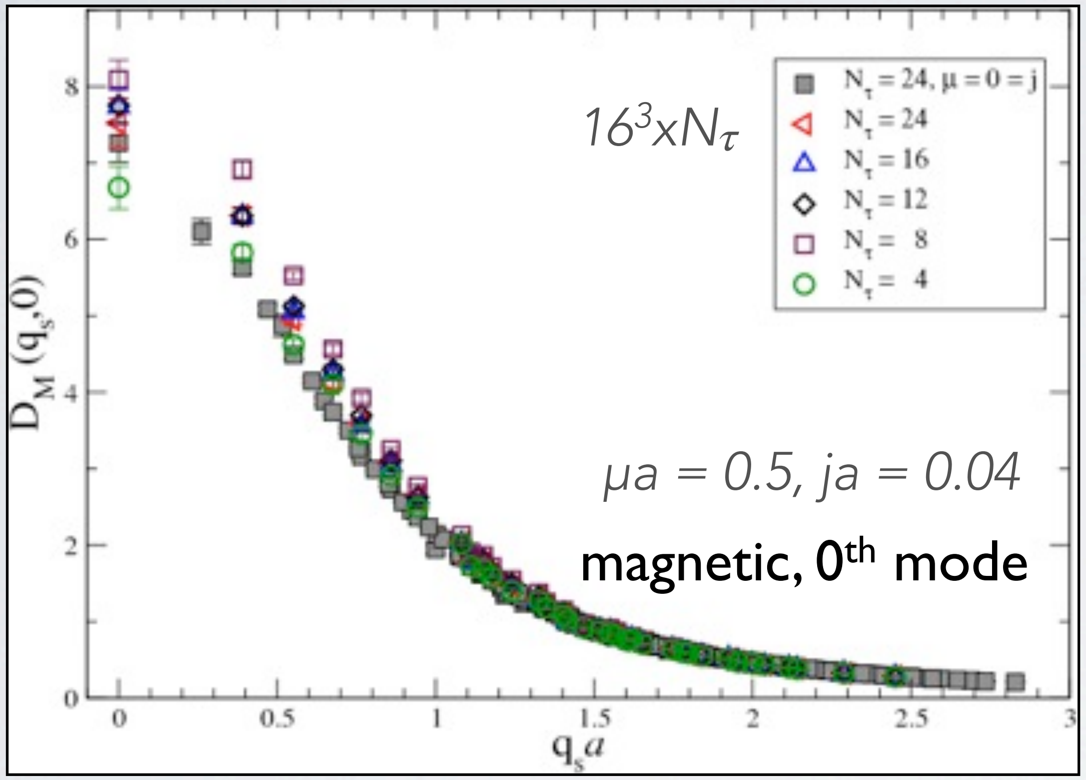
at high temperatures ($16^3 \times 8$ lattice)

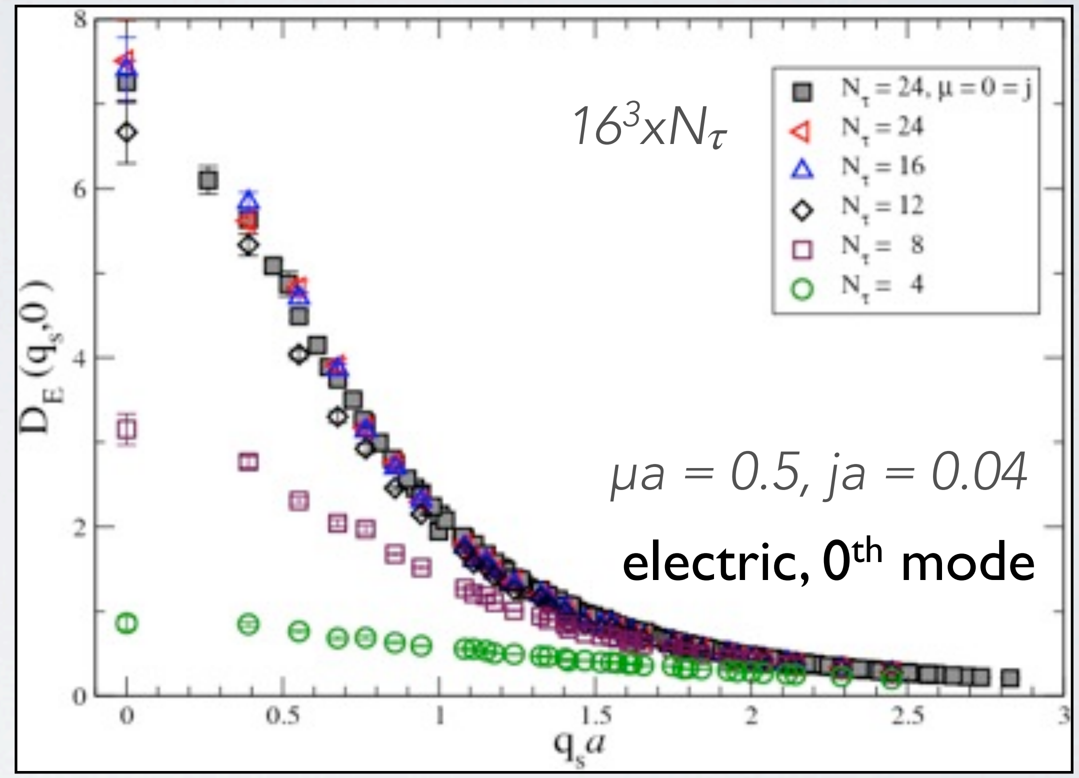
- D_M has enhancement for intermediate/large μ for small/large momenta
- D_E suppressed

gluon propagator – thermal dependence

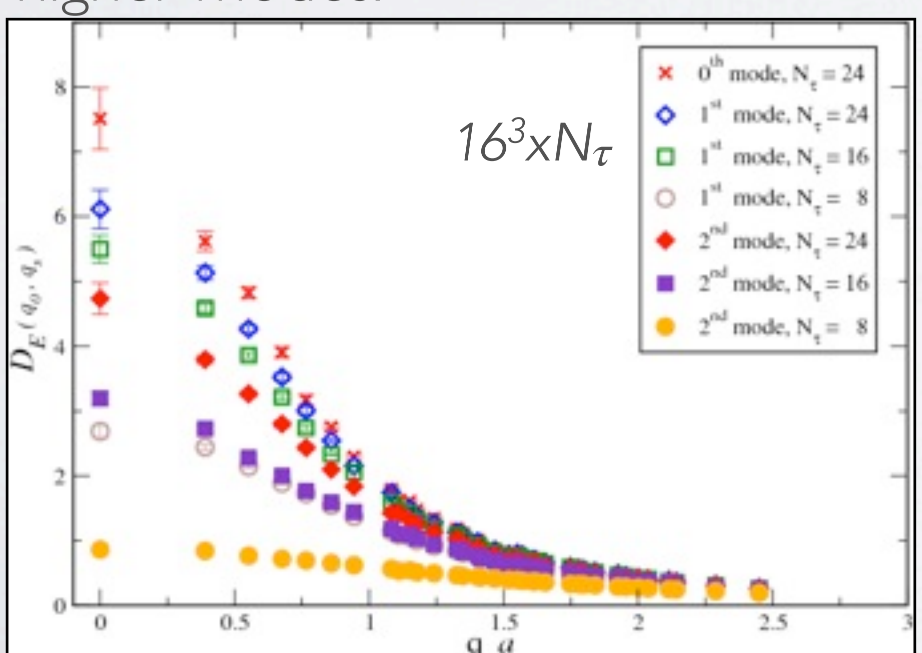
zero modes:

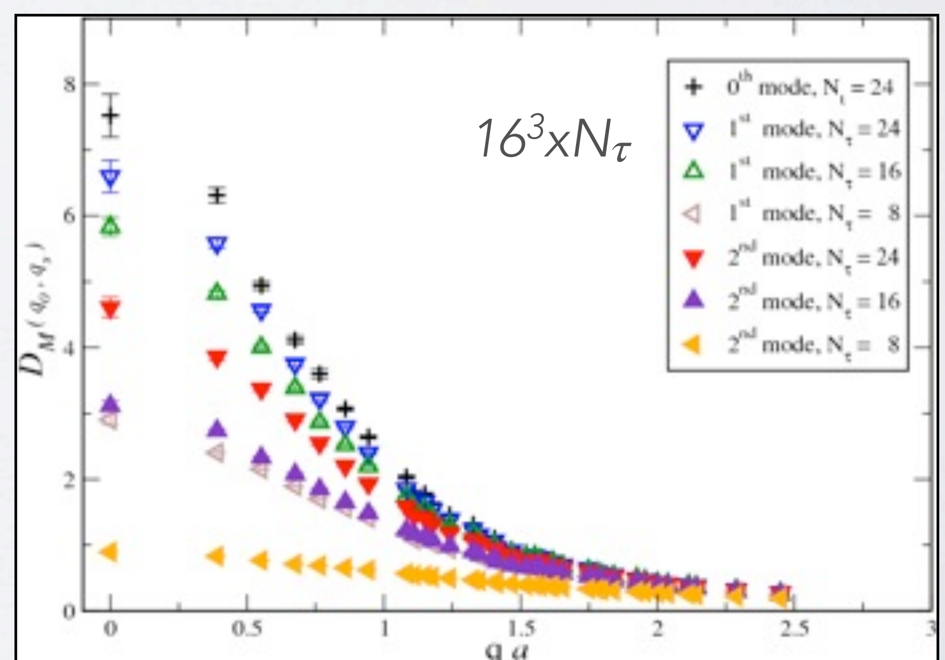
- D_M hardly feels temperature for low and intermediate T
- D_E suppressed with temperature





higher modes:



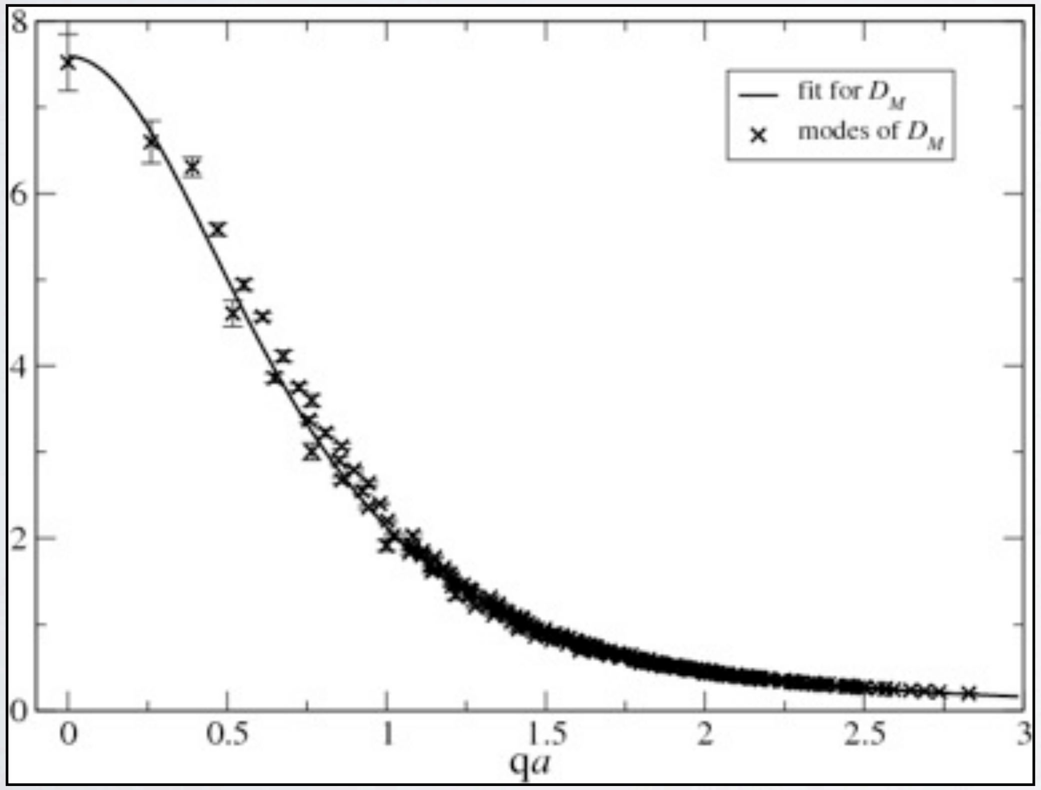


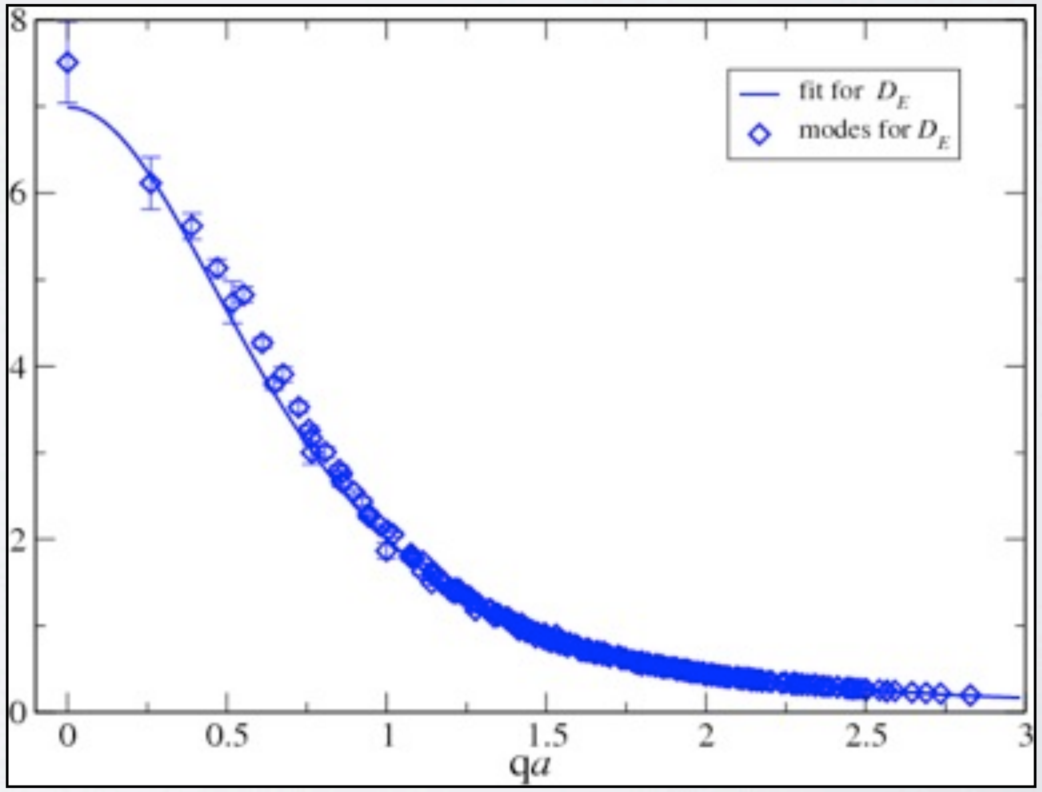
gluon propagator – fits

- 3 parameter (multi-mode) fit for the propagator

$$D^{\text{fit}}_{M/E}(q^2) \;=\; \frac{\Lambda^2}{(q^2+\Lambda^2)^2}\left(q^2+\Lambda^2 a_{M/E}\right)^{-b_{M/E}}$$

- Λ fixed in the vacuum: *$a\Lambda$=0.999(3)*
- $a_{M/E}$ and $b_{M/E}$ are T- & μ-dependent
- χ^2/d.o.f. ≲10
- no significant *j*-dependence

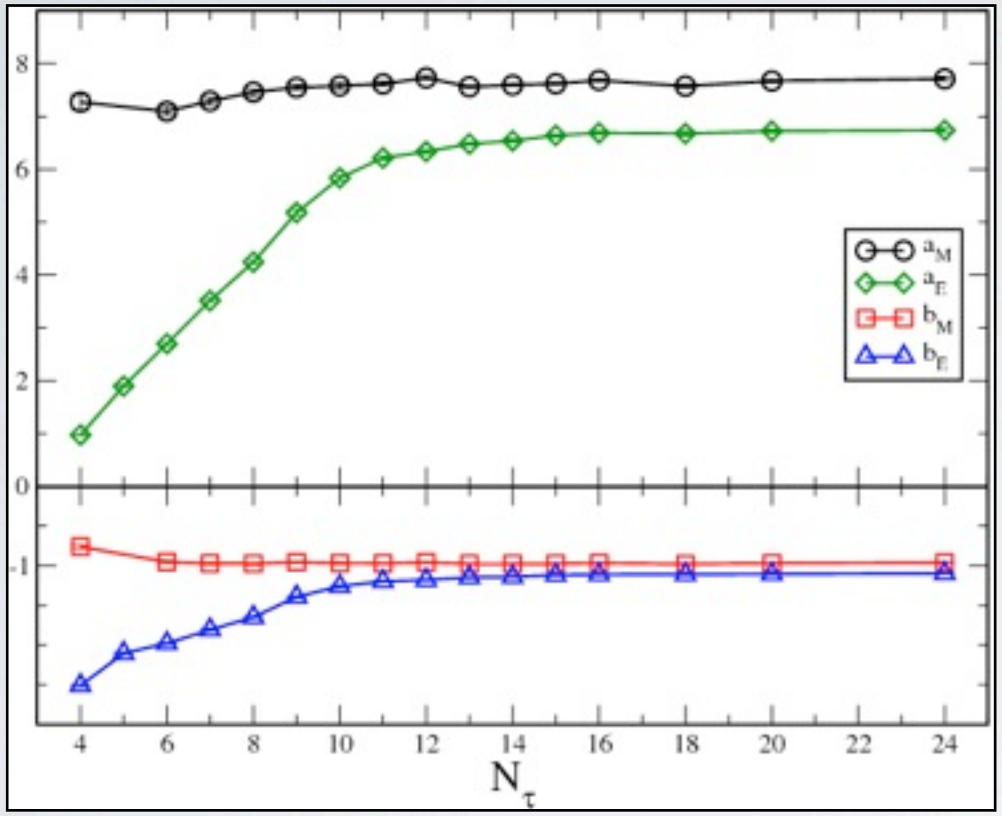




16^3x24, μa = 0.5, ja = 0.04

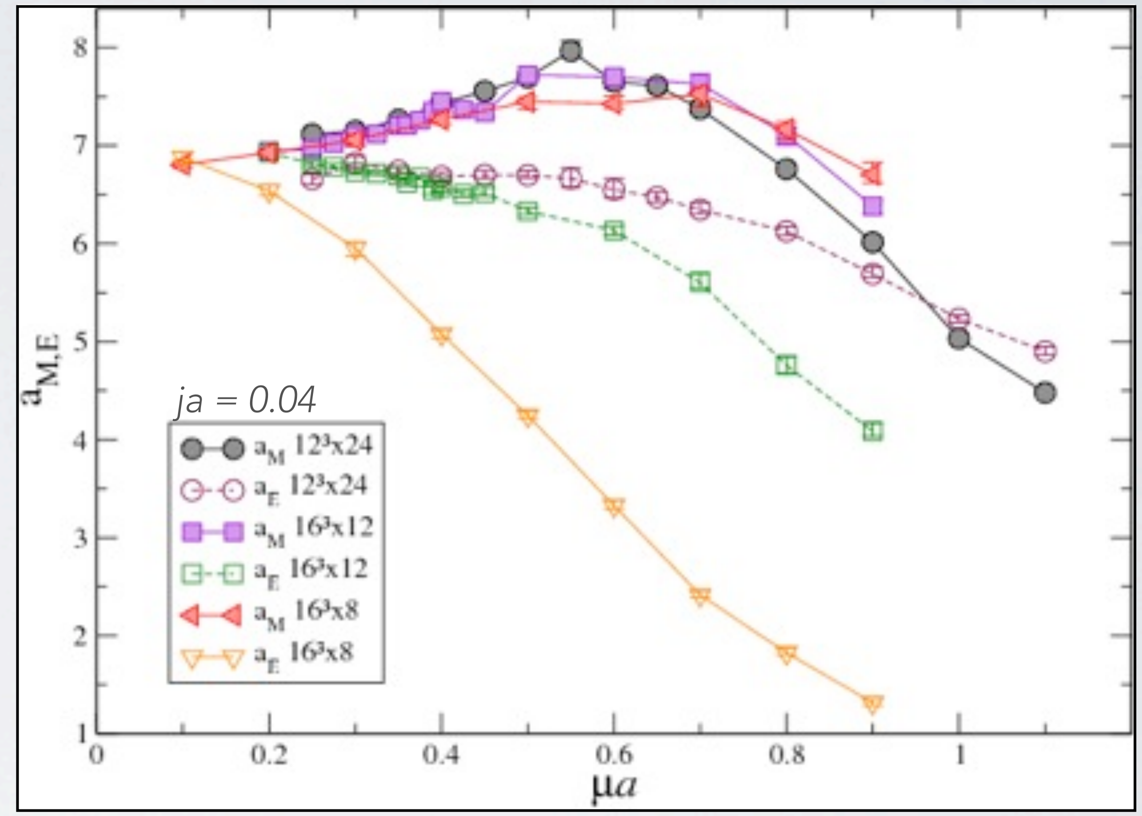
gluon propagator – fits

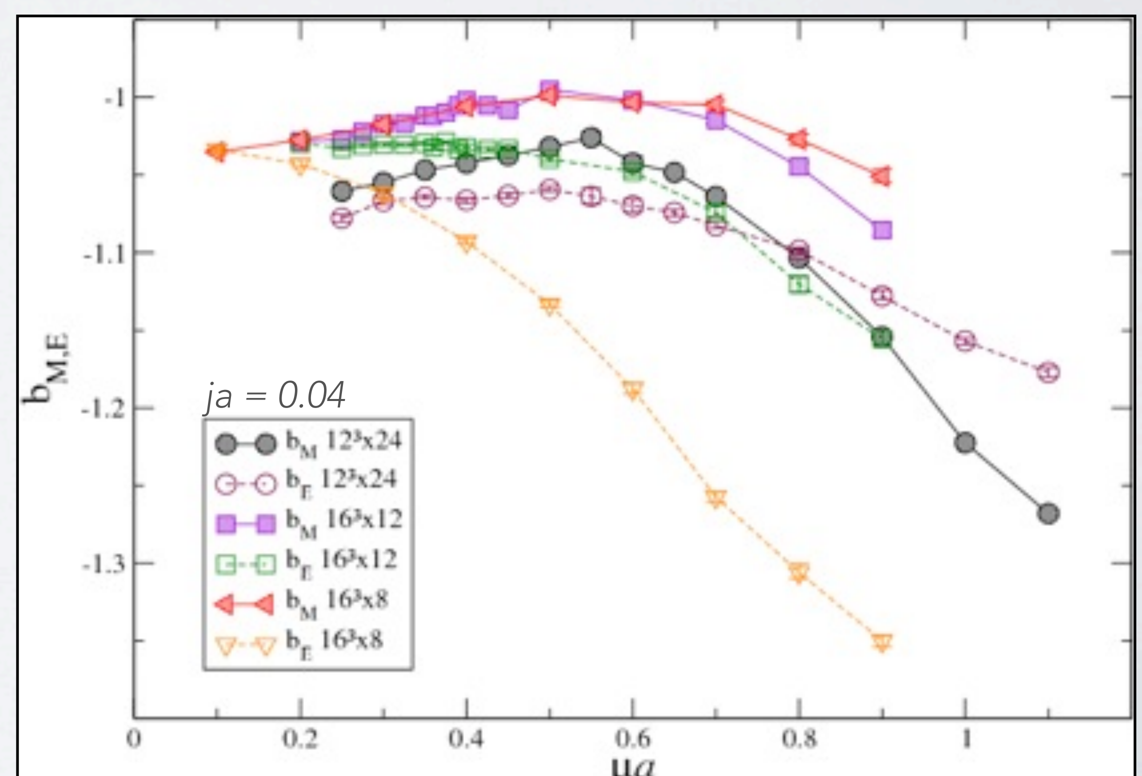
T-dependence



$16^3 x N_\tau$, $\mu a = 0.5$, $ja = 0.04$

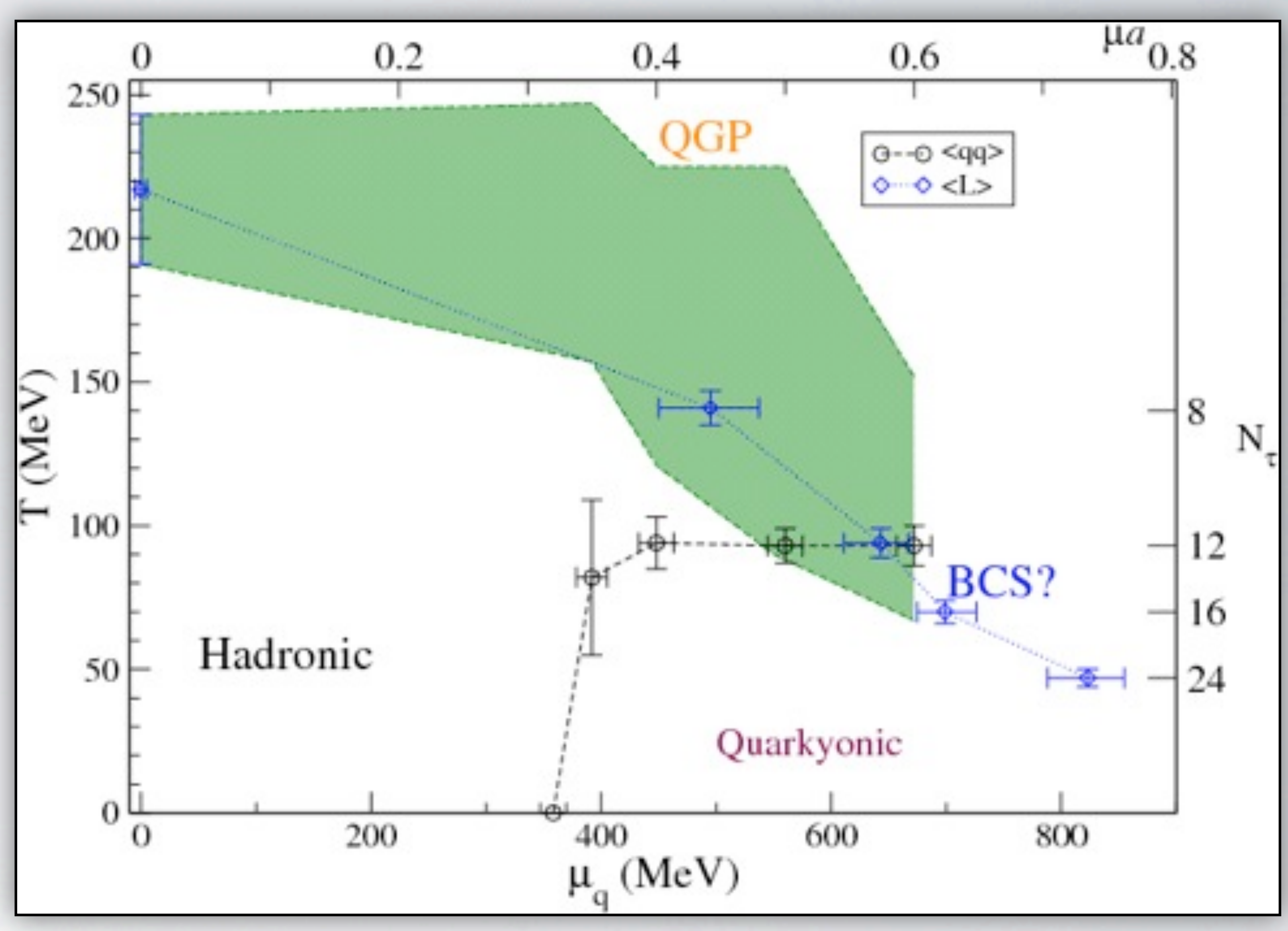
μ-dependence





summary

- 2-colour, 2-flavour QCD at T & mu
- superfluid to normal transition
  - at 0.35 ≲ aμ ≲ 0.6 (μ =385-665MeV),
  - T_s constant in μ
  - second order (?)
- deconfinement transition
  - (broad) crossover
  - T_d decreases, crossover broadens when μ increases
- static quark potential
  - at most weakly screened at intermediate μ
  - dense but deconfined medium not (ordinary) QGP (?)
- chromomagnetic and chromoelectric gluon propagators
  - electric: strongly screened at increasing μ and T
  - magnetic: mildly enhanced/suppressed for intermediate/large μ, little sensitivity to T
- phase diagram
  - at least three phases: hadronic, quarkyonic, QGP
  - possible deconfined and superfluid phase



outlook

- smaller lattice spacings, controlled extrapolation to cont. limit, identify lattice artefacts
- lack of screening (or even antiscreening) in static quark potential $\rightsquigarrow$ exotic phase ?
- gluon and quark propagators
- compare lattice results with functional methods