Phases and facets of 2-colour matter

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New Directions in Subatomic Physics, CSSM, 10 March 2016

Outline

Tony and lattice QCD

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1. **Chiral symmetry breaking in strongly coupled quenched QED in four-dimensions using the Dyson-Schwinger equation formalism**
   Anthony G. Williams (Adelaide U.), F.T. Hawes (Florida State U. & Florida State U., SCRI). Jul 1995. 4 pp.
   Published in **Nucl.Phys.Proc.Suppl. 47 (1996) 691-694**
   ADP-95-48-T-195, C95-07-11
   DOI: 10.1016/0920-5632(96)00152-1
   Presented at Conference: C95-07-11 (Lattice 1995:0691-694) Proceedings
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   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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2. **Optimization of Monte Carlo calculations of the effective potential**
   A. Ardekani, Anthony G. Williams (Adelaide U.). May 1997. 26 pp.
   Published in **Phys.Rev. E57 (1998) 6140-6151**
   ADP-97-13-T-250
   DOI: 10.1103/PhysRevE.57.6140
   e-Print: **hep-lat/9705021** | **PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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3. **The Infrared behavior of the gluon propagator from lattice QCD**
   UKQCD Collaboration (D.B. Leinweber *et al.*). Feb 1998. 7 pp.
   Published in **In *Adelaide 1998, Nonperturbative methods in quantum field theory* 97-103**
   ADP-98-31-T304
   Talk given at Conference: C98-02-02 Proceedings
   e-Print: hep-lat/9808033 | **PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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4. **Gluon propagator in the infrared region**
   UKQCD Collaboration (Derek B. Leinweber *et al.*). Mar 1998. 13 pp.
   Published in **Phys.Rev. D58 (1998) 031501**
   ADP-98-4-T284, LTH-421
   DOI: 10.1103/PhysRevD.58.031501
   e-Print: **hep-lat/9803015** | **PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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5. **Lattice gauge theory studies of the gluon propagator**
   UKQCD Collaboration (D.B. Leinweber *et al.*). Jun 1998. 8 pp.
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   Talk given at Conference: C98-10-14.1, Talk given at Conference: C98-10-12.4, Talk given at Conference: C98-06-01.4 Proceedings
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PHYSICAL REVIEW D, VOLUME 58, 074504

Lattice calculation of the strangeness magnetic moment of the nucleon

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(Received 22 December 1997; published 2 September 1998)

We report on a lattice QCD calculation of the strangeness magnetic moment of the nucleon. Our result is $G_M^s(0) = -0.36 \pm 0.20$. The sea contributions from the u and d quarks are about 80% larger. However, they cancel to a large extent due to their electric charges, resulting in a smaller net sea contribution of $-0.097 \pm 0.037 \mu_N$ to the nucleon magnetic moment. As far as the neutron to proton magnetic moment ratio is concerned, this sea contribution tends to cancel out the cloud-quark effect from the Z graphs and results in a ratio of -0.68 ± 0.04 which is close to the SU(6) relation and the experiment. The strangeness Sachs electric mean-square radius $\langle r_s^2 \rangle_E$ is found to be small and negative. [S0556-2821(98)01817-7]

PACS number(s): 13.40.Em, 12.38.Gc, 14.20.Dh

PHYSICAL REVIEW D, VOLUME 58, 031501

Gluon propagator in the infrared region

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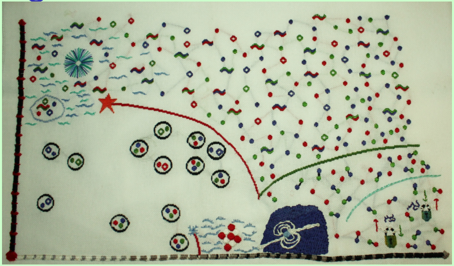
(Received 23 March 1998; published 9 July 1998)

The gluon propagator is calculated in quenched QCD for two different lattice sizes ($16^3 \times 48$ and $32^3 \times 64$) at $\beta = 6.0$. The volume dependence of the propagator in the Landau gauge is studied. The smaller lattice is instrumental in revealing finite volume and anisotropic lattice artifacts. Methods for minimizing these artifacts are developed and applied to the larger lattice data. New structure seen in the infrared region survives these conservative cuts to the lattice data. This structure serves to rule out a number of models that have appeared in the literature. A fit to a simple analytical form capturing the momentum dependence of the nonperturbative gluon propagator is also reported. [S0556-2821(98)50215-9]

Background



- A plethora of phases at high μ, low T
- Based on models and perturbation theory

Indirect approach

Study QCD-like theories without a sign problem

- Generic features of strongly interacting systems at $\mu \neq 0$
- Check on model calculations, functional methods

QC_2D vs QCD

- Baryons are bosons (diquarks); superfluid ‘nuclear matter’
- Scalar diquark is pseudo-Goldstone (degenerate with pion)
- Onset transition at $\mu_q = m_\pi/2$, not $m_N/3$

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Phase diagram

- Superfluid phase for $\mu > m_\pi/2$: BEC $\longrightarrow$ BCS?
- Exotic phases: quarkyonic, spatially varying?
- Deconfinement at high density, shape of deconfinement line?

Two-colour quarks and gluons

Gluodynamics — SU(2) and SU(3) very similar?

- Effects of deconfinement on gluon propagation?
- Gap equation with effective or one-gluon interaction used to determine superconducting gap $\rightarrow$ more realistic input?

Quark propagator

- Details of phase diagram depend critically on the effective quark mass in the medium.
- Dynamical quark masses $\rightarrow$ effective strange quark mass?
- Location of Fermi surface?
- Direct determination of diquark gap, size of Cooper pairs?

Lattice formulation

We use Wilson fermions:

- Correct symmetry breaking pattern, Goldstone spectrum
- $N_f < 4$ needed to guarantee continuum limit
- No problems with locality, fourth root trick
- Chiral symmetry buried at bottom of Fermi sea

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$$S = \bar{\psi}_1 M(\mu)\psi_1 + \bar{\psi}_2 M(\mu)\psi_2 - J\bar{\psi}_1(C\gamma_5)\tau_2\bar{\psi}_2^T + \bar{J}\psi_2^T(C\gamma_5)\tau_2\psi_1$$

$$\gamma_5 M(\mu)\gamma_5 = M^\dagger(-\mu), \quad C\gamma_5\tau_2 M(\mu) C\gamma_5\tau_2 = -M^*(\mu)$$

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Diquark source $J \equiv \kappa j$ introduced to

- lift low-lying eigenmodes in the superfluid phase
- study diquark condensation without uncontrolled approximations

Simulation parameters

Name	β	κ	a	am_π	m_π/m_ρ
Coarse	1.9	0.1680	0.18fm	0.65	0.80
Light	1.7	0.1810	0.19fm	0.42	0.61
Fine	2.1	0.1577	0.12fm	0.45	0.81

μ-scans, fixed T

Ensemble	N_s	N_τ	T (MeV)	μa	ja
Coarse	12	24	47	0.25–1.10	0.02, 0.04 (0.03)
	16	24	47	0.30–0.90	0.04
	12	16	70	0.30–0.90	0.04
	16	12	94	0.20–0.90	0.02, 0.04
	16	8	141	0.10–0.90	0.02, 0.04
Fine	16	32	54	0.15–0.80	0.02, 0.03 (0.01)
	16	20	86	0.20–0.60	0.02, 0.03
	16	16	107	0.20–0.60	0.02, 0.03
	16	12	143	0.20–0.60	0.03
Light	12	24	43	0.15–0.90	0.02, 0.04 (0.03)

Simulation parameters

T-scans, fixed μ (coarse lattice)

All simulations done on $16^3 \times N_\tau$ lattices

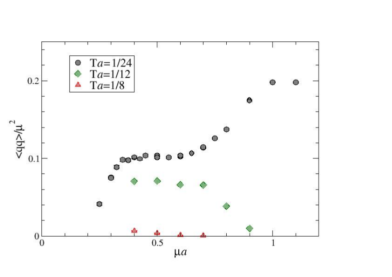
μa	ja	N_τ
0.0	0.0	4–10
0.35	0.02	4–13, 16
	0.04	4–12, 14, 16
0.40	0.02	5–13, 16
	0.04	4–13
0.50	0.02	6–12, 16
	0.04	4–16, 18, 20
0.60	0.02	6–12, 14, 16
	0.04	6–16, 20

In addition, 300 trajectories were generated at $ja = 0.03, 0.05$ for $N_\tau = 9, 10, 11$ at all $\mu > 0$.

Diquark condensate — μ-scan

Coarse lattice

Results shown are for linear extrapolation
Power law $\langle qq\rangle = Aj^{\alpha}$ works for $\mu a \lesssim 0.4$, with $\alpha = 0.85 - 0.5$.
[Effective field theory predicts $\alpha = \frac{1}{3}$ near onset]



- BCS scaling $\langle qq\rangle \sim \mu^2$ for $0.35 \lesssim \mu a \lesssim 0.7$
- Melted at $T = 141\text{MeV}$ ($N_\tau = 8$)

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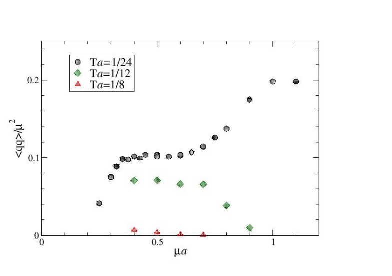
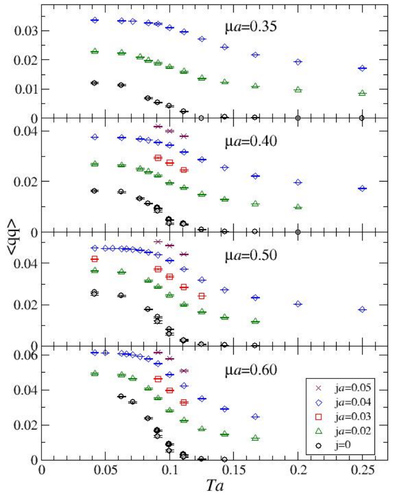


- BCS scaling $\langle qq \rangle \sim \mu^2$ for $0.35 \lesssim \mu a \lesssim 0.7$
- Melted at $T = 141\text{MeV}$ ($N_\tau = 8$)
- New transition for $\mu a \gtrsim 0.7$?
- Melting for $N_\tau = 12, \mu a \gtrsim 0.7$?

$N_\tau = 16$ results are very close to $N_\tau = 24$ results.

Superfluid to normal transition



$j \to 0$ extrapolation not fully under control
Linear form used here

Transition temperatures from inflection points (and $j \to 0$)

$a\mu$	T_s (MeV)
0.35	82(27)
0.40	94(9)
0.50	93(6)
0.60	93(7)

Remarkably constant!

Deconfinement transition

Polyakov loop L requires renormalisation,

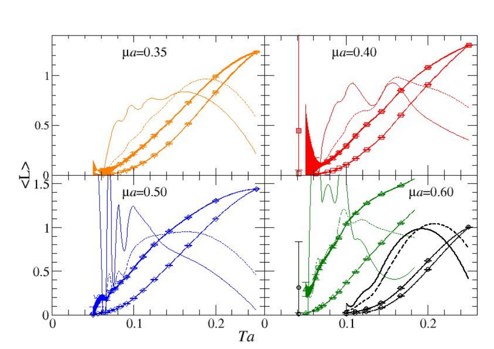
$$L_R = e^{-F_q/T} = e^{-(F_0+\Delta F)/T} = Z_L^{N_\tau} L_0$$

We use two schemes to determine $Z_L = \exp(-a\Delta F)$,

Scheme A	$L_R(T = \frac{1}{4a}, \mu = 0) = 1\,,$
Scheme B	$L_R(T = \frac{1}{4a}, \mu = 0) = 0.5\,.$

We determine the deconfinement temperature (crossover region) from the inflection point (linear region) of L_R

Deconfinement transition

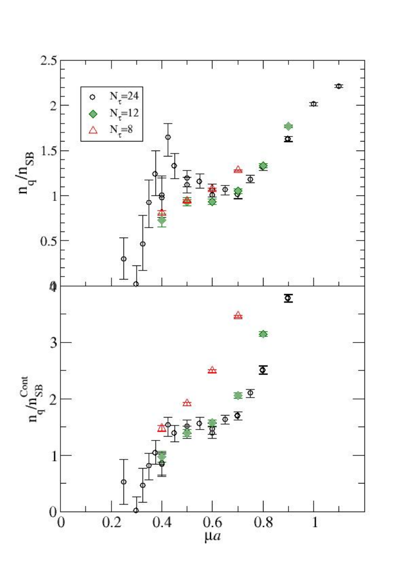


Estimates from Scheme B, encompassing Scheme A

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

Scheme dependence $\longleftrightarrow$ broad crossover?

Number density

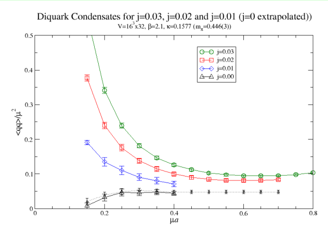


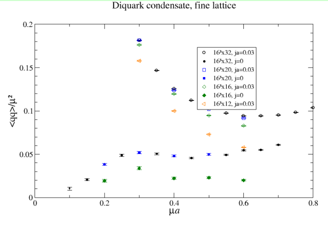
- Normalised to lattice SB or

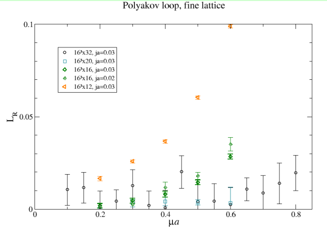
$$n_{SB}^{\text{Cont}} = \frac{4\mu T^2}{3} + \frac{4\mu^3}{3\pi^2}$$

- Close to SB scaling for $0.4 \lesssim \mu a \lesssim 0.7$, $N_\tau = 24, 12$.
- Little T-dependence for $T \lesssim 100\text{MeV}$.
- Strong thermal effects for $N_\tau = 8$
- $N_\tau = 16, 24$ almost identical

Results from fine ensemble

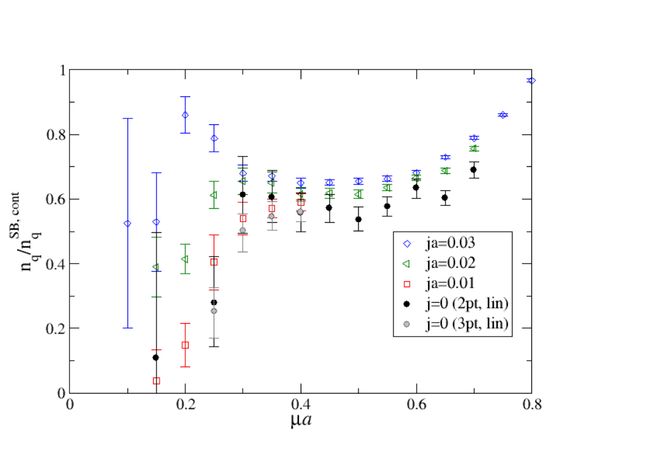






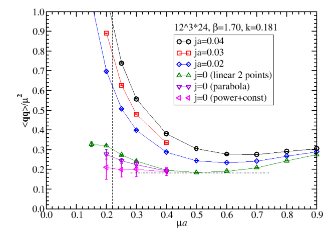
- BCS scaling of diquark condensate confirmed
- Similar melting temperature
- Second transition at high μ a lattice artefact?
- No deconfinement at low T?

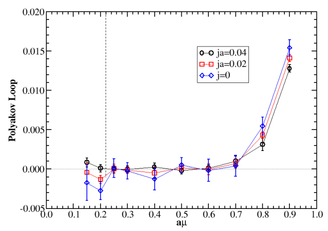
Number density on fine ensemble

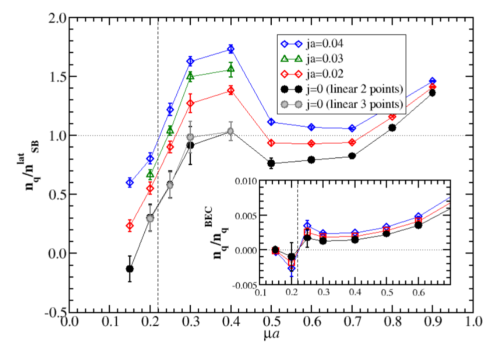


The same qualitative features as on coarse ensemble!

Results from light ensemble







Deviation from BCS scaling:
BEC window?

Gluon propagator

- Essential ingredient in gap equation

$$S^{-1}(p) = S_0^{-1}(p) + Z_2 \int d^4q \Gamma_\mu(p,q) D_{\mu\nu}(q) S(p-q)\gamma_\nu$$

  used to determine dynamical fermion mass and superfluid/superconducting gap
- Link to functional methods (DSE, FRG)
- Electric gluon may signal deconfinement transition

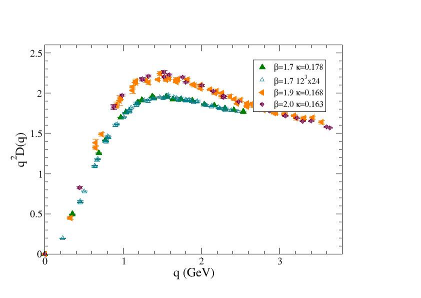
Tensor structure in medium

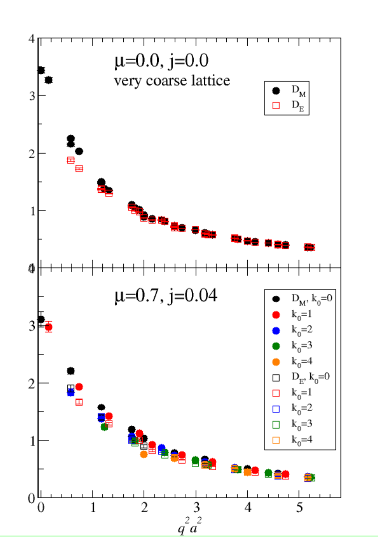
$$D_{\mu\nu}(\vec{q}, q_0) = P^T_{\mu\nu} D_M(\vec{q}^{\,2}, q_0^2) + P^E_{\mu\nu} D_E(\vec{q}^{\,2}, q_0^2) + \xi \frac{q_\mu q_\nu}{(q^2)^2}$$

$$P^M_{\mu\nu}(\vec{q}, q_0) = (1 - \delta_{0\mu})(1 - \delta_{0\nu})(\delta_{\mu\nu} - \frac{q_\mu q_\nu}{\vec{q}^{\,2}}),$$

$$P^E_{\mu\nu}(q_0, \vec{q}) = (\delta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}) - P^M_{\mu\nu}(q_0, \vec{q}).$$

Gluon propagator results

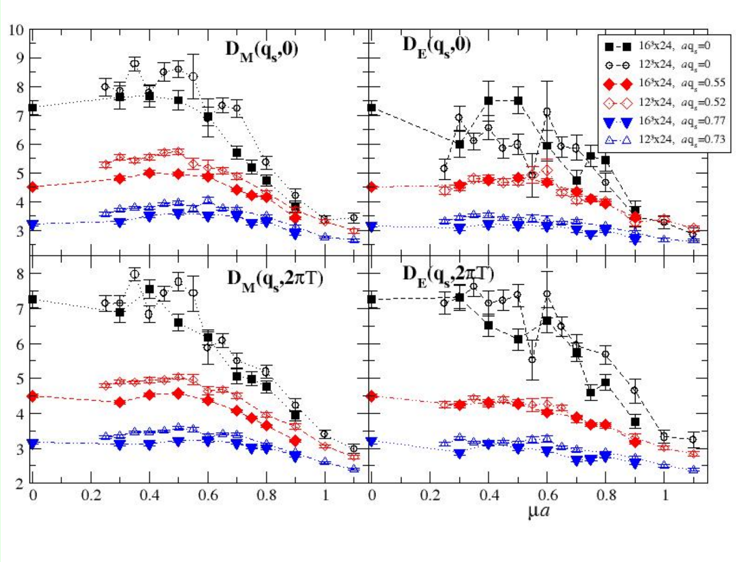




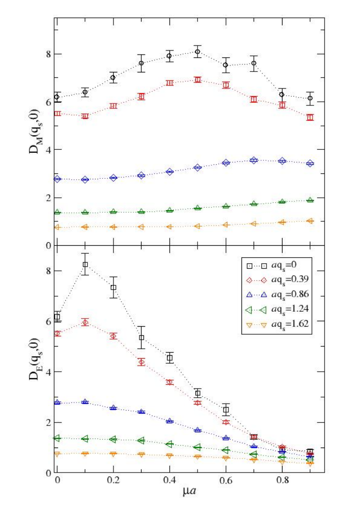
Some finite volume and lattice spacing effects at $\mu = 0$

In-medium modifications, incl. violations of Lorentz symmetry, visible in magnetic gluon at high density

Gluon propagator: μ-scans, $N_\tau = 24$

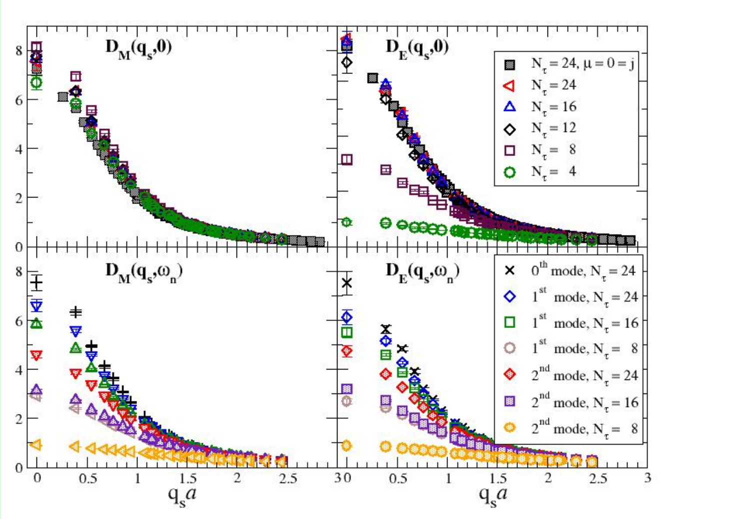


Gluon propagator: μ-scans, $N_\tau = 8$



- Very little volume dependence
- No j-dependence observed
- All modes screened at high μ, low T:
  Weak-coupling theory says static D_M is unscreened
- Static magnetic gluon not screened at high T

Gluon propagator: T-scan, $\mu a = 0.5$



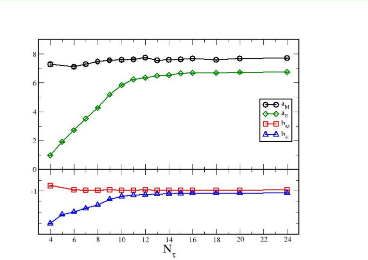
Gluon propagator fits

2-parameter fit:

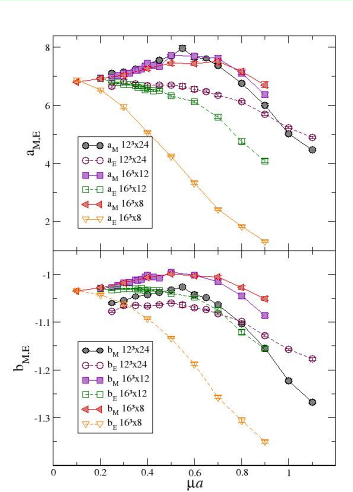
$$D_k^{\text{fit}}(q^2) \;=\; \frac{\Lambda^2(q^2+\Lambda^2 a_k)^{-b_k}}{(q^2+\Lambda^2)^2}$$

with $k = M, E$ and
$\Lambda a = 0.999(3)$ from $\mu = j = 0$ fit

T-scan



μ-scans



Quark propagator — tensor structure

$$
\begin{aligned}
S^{-1}(\vec{p},\tilde{\omega}) &= i\vec{\not{p}}\,A(\vec{p}^{\,2},\tilde{\omega}^2) + i\gamma_4\tilde{\omega}\,C(\vec{p}^{\,2},\tilde{\omega}^2) + B(\vec{p}^{\,2},\tilde{\omega}^2) \\
&\quad + i\gamma_4\vec{\not{p}}\,D(\vec{p}^{\,2},\tilde{\omega}^2) \\
S(\vec{p},\tilde{\omega}) &= i\vec{\not{p}}\,S_a + i\gamma_4\tilde{\omega}S_c + S_b + i\gamma_4\vec{\not{p}}\,S_d
\end{aligned}
$$

where $\tilde{\omega} \equiv p_4 - i\mu$.

In general the form factors are complex!

Quark propagator — tensor structure

$$S^{-1}(\vec{p},\tilde{\omega}) = i\vec{\not p}A(\vec{p}^{\,2},\tilde{\omega}^2) + i\gamma_4\tilde{\omega}C(\vec{p}^{\,2},\tilde{\omega}^2) + B(\vec{p}^{\,2},\tilde{\omega}^2) + i\gamma_4\vec{\not p}D(\vec{p}^{\,2},\tilde{\omega}^2)$$

$$S(\vec{p},\tilde{\omega}) = i\vec{\not p}S_a + i\gamma_4\tilde{\omega}S_c + S_b + i\gamma_4\vec{\not p}S_d$$

where $\tilde{\omega} \equiv p_4 - i\mu$.

In general the form factors are complex!

The D form factors can be shown to vanish [Rusnak&Furnstahl 1995]

Gor'kov formalism

Quarks and antiquarks are in the same representation.

Construct Gor'kov spinor

$$\Psi = \begin{pmatrix} \psi \\ \overline{\psi}^T \end{pmatrix} \quad \Longrightarrow \quad \langle \Psi(x)\bar{\Psi}(y)\rangle \equiv \mathcal{G}(x,y) = \begin{pmatrix} S_N & -S_A \\ \bar{S}_A & \bar{S}_N \end{pmatrix}$$

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S_A contains information about anomalous propagation

Self-energies are diquark gaps Δ (superfluid/superconducting)

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S_A contains information about anomalous propagation
Self-energies are diquark gaps Δ (superfluid/superconducting)
General tensor structure is the same as for normal components,
scalar diquark gap is Δ_b.

From isospin and charge conjugation symmetry it follows that

$$\bar{S}_N(x,y) = -S_N(y,x)^T\,, \qquad S_A(x,y) = S_A(y,x)^T$$

Fermi surface and Cooper pairs

Fermi surface

In a Fermi liquid the Fermi surface is given by

$$\det S^{-1}(\overrightarrow{p_F}, p_4 = 0) = 0 \quad \Longleftrightarrow \quad \overrightarrow{p}^2 A^2 + \tilde{\omega}^2 C^2 + B^2 = 0$$

Pole in propagator

Fermi surface and Cooper pairs

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Pole in propagator

In gapped phase: zero crossing!

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Pole in propagator

In gapped phase: zero crossing!

Size of Cooper pair

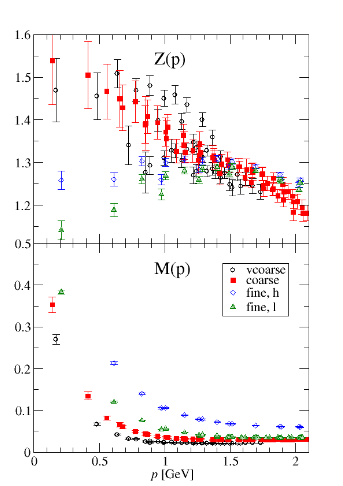
If we know the anomalous propagator $S_A(x)$ we can compute the size of the Cooper pairs:

$$\xi^2 = \frac{\int d^3x \, \overrightarrow{x}^2 |\frac{1}{2} \operatorname{Tr}(S_A(x)\Lambda^+)|^2}{\int d^3x \, |\frac{1}{2} \operatorname{Tr}(S_A(x)\Lambda^+)|^2}$$

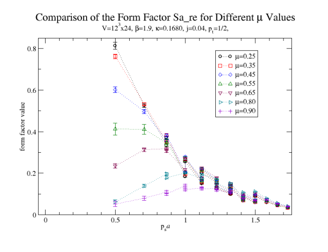
Quark propagator results

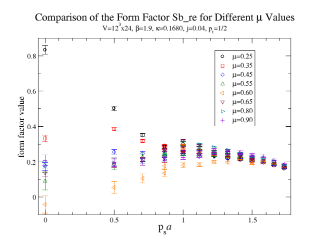
Quark propagator in vacuum

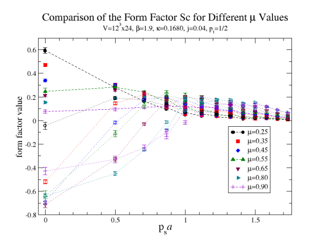
- Large lattice spacing dependence
- Substantial quark mass dependence for $Z(p)$
- Unusual p-dependence in $Z(p)$
- infrared suppression recovered in low-mass and continuum limit?
- M(p) not yet properly corrected!



Normal form factors – PRELIMINARY

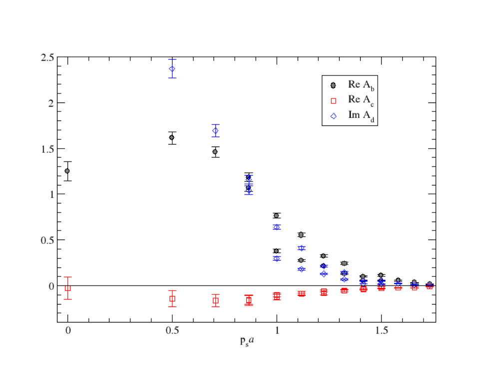






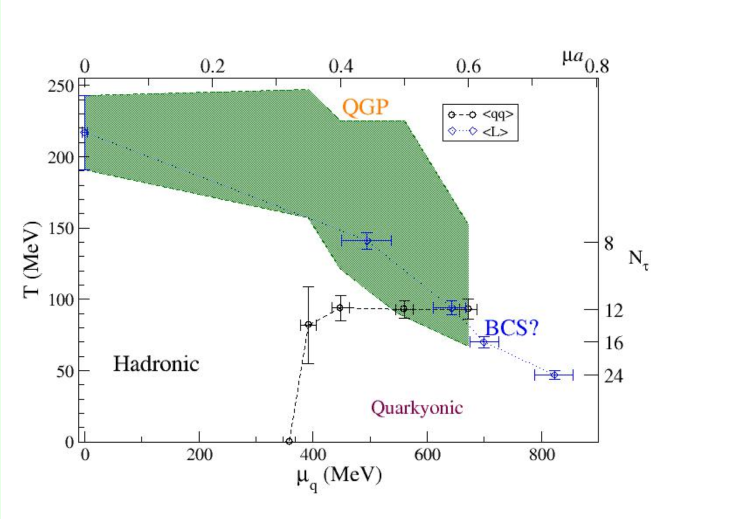
- Dramatic changes in superfluid phase
- Vanishing M(0) at $\mu a = 0.65$?
- Zero crossing in S_c

Anomalous form factors $[\mu a = 0.7, ja = 0.02, n_t = \frac{1}{2}]$



- Diquark gap is evident
- Nonzero tensor form factor A_d
- Evidence of vector form factor A_c

Summary


0
0.2
0.4
0.6
μa 0.8
250
200
150
100
50
0
QGP
<qq>
<L>
T (MeV)
8
12
16
24
N_τ
BCS?
Hadronic
Quarkyonic
0
200
400
600
800
μ_q (MeV)

Summary

Evidence for three phases/regions

- Vacuum/hadronic phase below $\mu_o = m_\pi/2$, low T
- BCS/quarkyonic for intermediate μ, low T
- Deconfined/QGP matter at high T

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- Both electric and magnetic gluon screened at high μ, low T
- Static magnetic gluon not screened at high T
- Dramatic modification of quarks in superfluid region

Outlook

- Attempt O(2) scaling fit for superfluid to normal transition?
  - $\rightarrow$ Requires several larger lattice volumes
- Full analysis of quark propagator in progress
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Happy 60th birthday Tony!