# Searching for Diquarks on the Lattice

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with C. Alexandrou and B. Lucini

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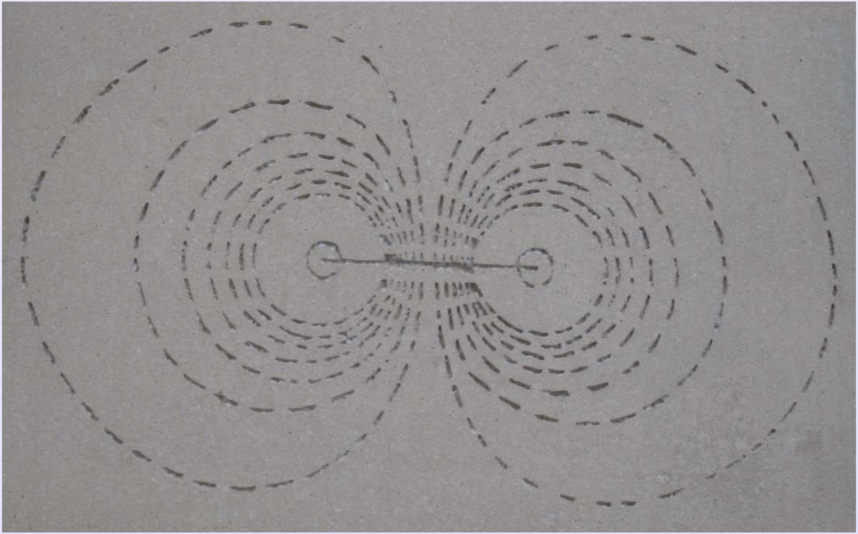
hep-lat/0509113 and in progress

# Subtitle

”Exploration of Hadron Structure...”

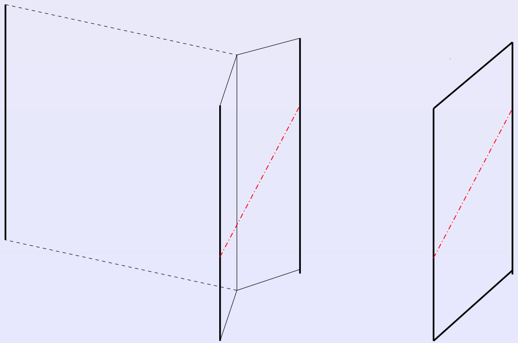
$\Downarrow$

Are diquarks for real ?



# First encounter with diquarks

Baryonic static potential $V_{qqq}$:



- $qq$ (antisymmetrized in color) behaves like $\bar{q}$
- one-gluon exchange: $V_{qq} = \frac{1}{2} V_{q\bar{q}}$ attractive

# Diquark advocacy

Diquarks

- are Cooper pairs of color superconductivity
- can explain the $\Delta I = 1/2$ rule in weak non-leptonic decays
- can explain some features of excited baryon spectrum
- can explain stability of exotics
  ($\Theta^+ \rightarrow$ pentaquark, $X$ and $Y \rightarrow$ tetraquarks)
- can explain hadronic parity violation

# Diquarks

Diquarks are a combination of quarks in the color antitriplet

$$3 \otimes 3 = \bar{3} \oplus 6$$

In particular the parity even flavor antisymmetric spinless combination is the most attractive channel in this sector

# Diquark operators: complete classification

| $J^P$ | Color | Flavor | Operator |
|---|---|---|---|
| $0^+$ | $\bar{3}$ | $\bar{3}$ | $\bar{q}_C\gamma_5 q\ ,\bar{q}_C\gamma_0\gamma_5 q$ |
| $1^+$ | $\bar{3}$ | 6 | $\bar{q}_C\vec{\gamma}q\ ,\bar{q}_C\sigma_{0i}q$ |
| $0^-$ | $\bar{3}$ | 6 | $\bar{q}_C q, \bar{q}_C\gamma_0 q$ |
| $1^-$ | $\bar{3}$ | $\bar{3}$ | $\bar{q}_C\vec{\gamma}\gamma_5 q, \bar{q}_C\sigma_{ij}q$ |

From R. Jaffe, hep-ph/0409065

Spin-color effective interaction $\rightarrow$ wealth of predictions:

- parity-odd states heavier (suppressed in non-relat. limit)
- $M(0^+) < M(1^+)$: $0^+$ is "good" diquark, while $1^+$ is "bad"
- in the real world $\Delta M \equiv M(1^+) - M(0^+) \simeq 200$ MeV
- $\Delta M$ from spin-spin interaction $\propto \frac{1}{m_1 m_2}$ for heavy quarks

# Lattice setup

Problem: diquarks are colored

$\hookrightarrow$ combine (diquark+static quark) into color singlet:
static-light-light baryon

i.e. diquark in the background color field of static quark
$\longrightarrow$ robustness of results vs distance from static quark ?

# Summary of the calculations

Wilson fermions, quenched: $3 \times \beta$, $3 \times \kappa$ (heavy,medium,light)
unquenched (thanks to Th. Lippert & co.)

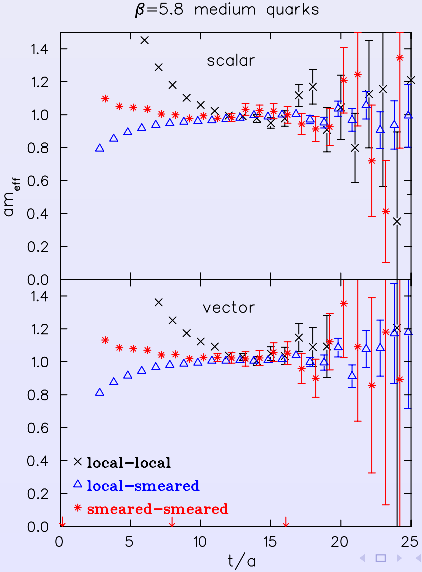
| $\beta$ | $N_f$ | size | #conf | $a(r_0)$(fm) | $\kappa$ | $m_\pi$ (MeV) |
|---|---|---|---|---|---|---|
| 5.8 | 0 | $16^3 32$ | 2-500 | 0.136 | 0.156-0.159 | 690-910 |
| 6.0 | 0 | $16^3 32$ | 2-500 | 0.093 | 0.153-0.155 | 620-900 |
| 6.2 | 0 | $20^3 40$ | 200 | 0.068 | 0.151-0.1523 | 570-870 |
| 5.6 | 2 | $24^3 40$ | 100 | $\sim 0.1(m_N)$ | 0.1575 | 530 |

Technical difficulty:

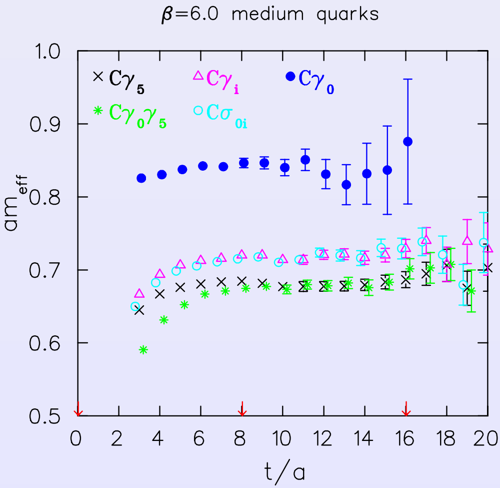
static quark propagator very noisy $\Rightarrow$ HYP-smearing

- I. Masses
- II. Wavefunctions

# I. Masses: the [unbearable] lightness of smearing



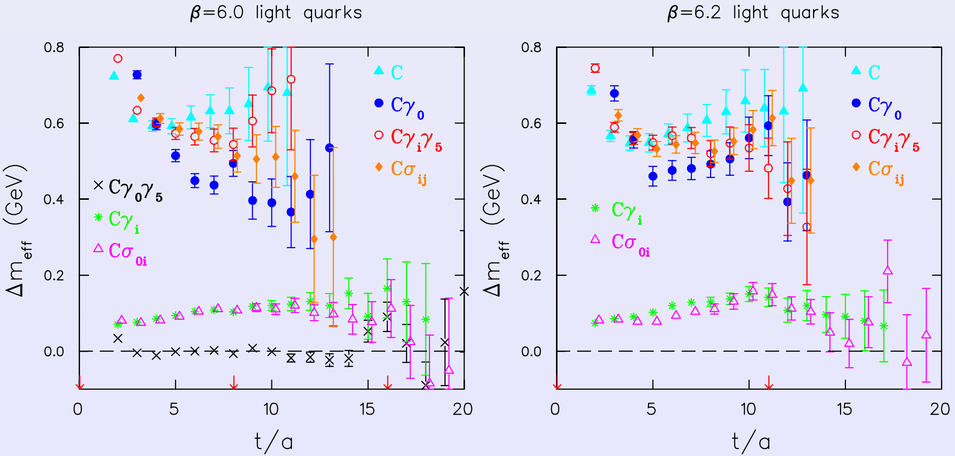
# Effective masses: 3 groups




Static quark → mass UV divergent

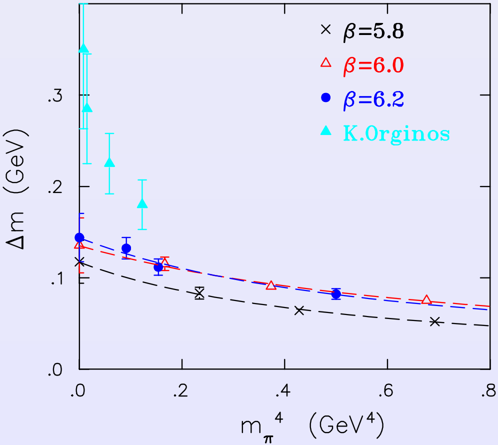
Look at mass differences

# The good, the bad and the ugly




$m(\text{scalar}) < m(\text{vector}) \ll m(\text{others})$ as predicted

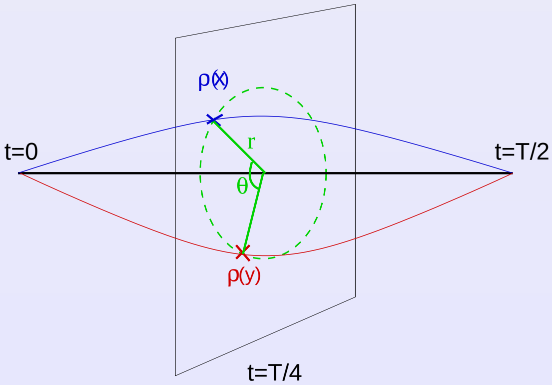
# $m$(vector) - $m$(scalar) versus pion mass




Ansatz $\Delta m = \frac{c_1}{c_2 + m_\pi^4} \rightarrow$ extrapolation $\sim$ 150 MeV (200 MeV expected)

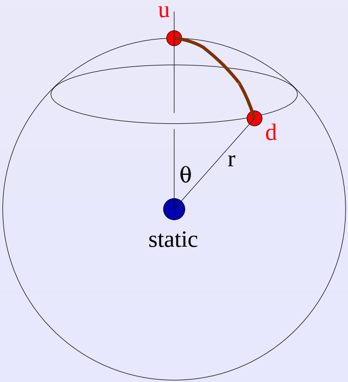
Larger in full QCD (Orginos) ?

# II. Wavefunction: density-density correlator




Fix distance from static quark → fixed background field
Look at angular distribution

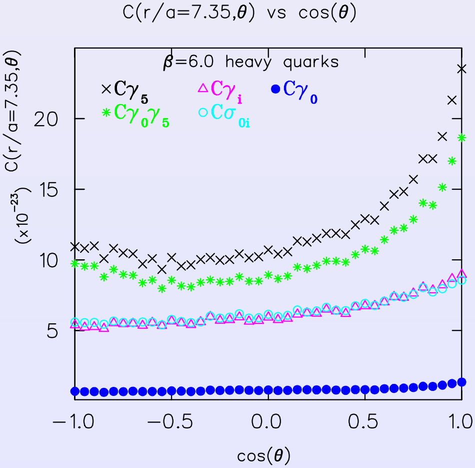
# II. Wavefunction: density-density correlator

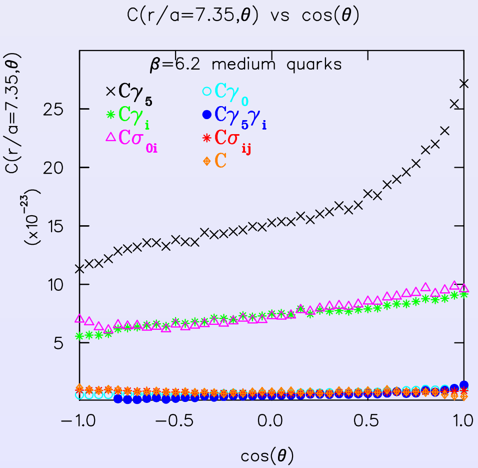



$$C_{\rm tot}(r) = \int \langle N|\rho^u \rho^d|N\rangle \ \sin\theta d\theta d\phi \ \equiv \int d(\cos\theta) C(\theta, r), \quad \rho^q =: \bar{q}\gamma_0 q :$$

No correlation $\Leftrightarrow$ flat in $\cos\theta$

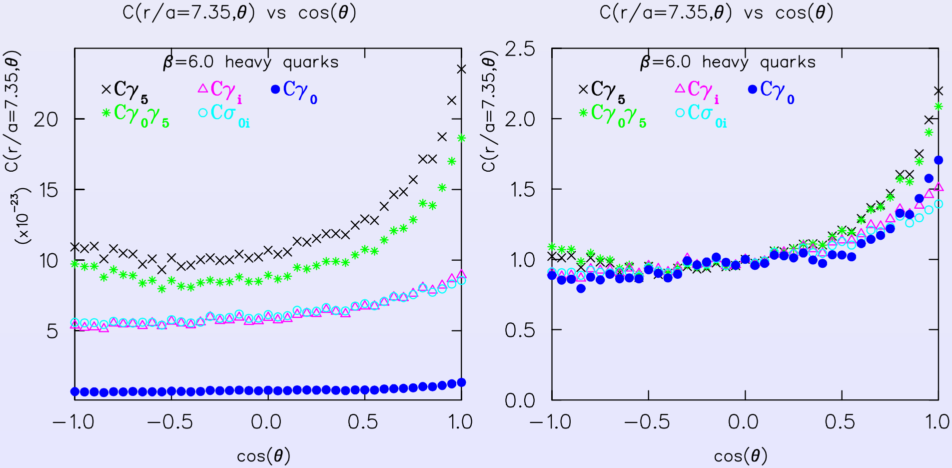
# Spatial correlations?




Attraction in scalar channel > vector channel as predicted

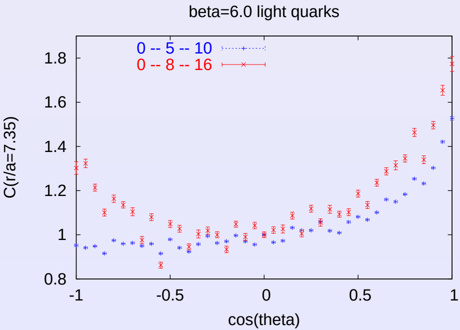
# Smaller mass ↔ stronger correlation?



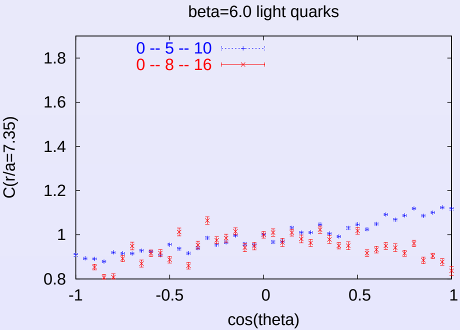

- Excited states contamination?
- Concentrate on light channels (scalar and vector)

# Excited states contamination?

Vary separations between source – measurement – sink:



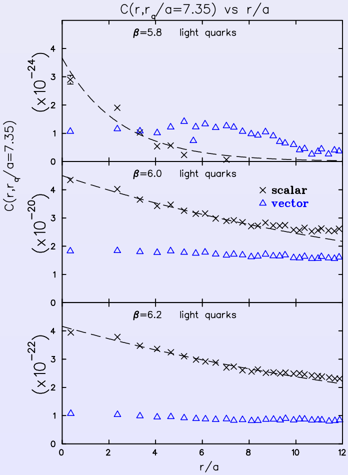

Scalar




Vector

Better groundstate
$\longrightarrow$ more correlation in scalar diquark, less in vector diquark

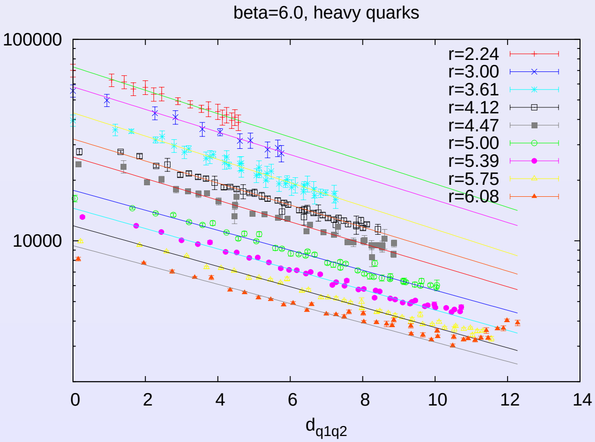
# Diquark size?




Very large size for vector; $\mathcal{O}(1)$fm for scalar

box size $\sim$ 1.5 fm $\longrightarrow$ wrap-around effects

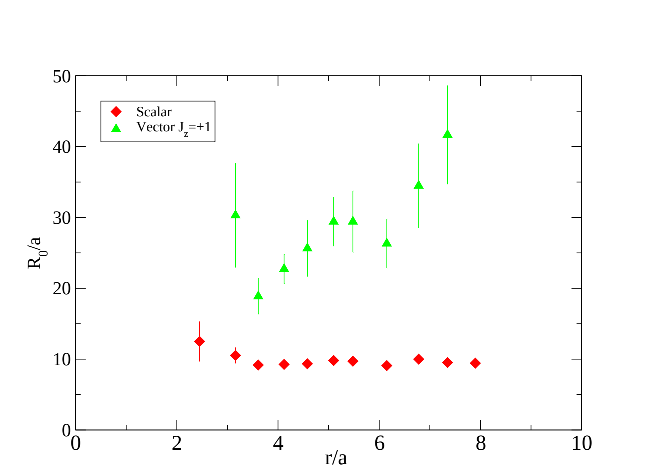
# Size vs distance from static quark




Very stable (slowly increasing?)

Lighter quarks seem to give larger size – systematics when size $\gtrsim L_s/2$?

# Size summary




From hep-lat/0509113

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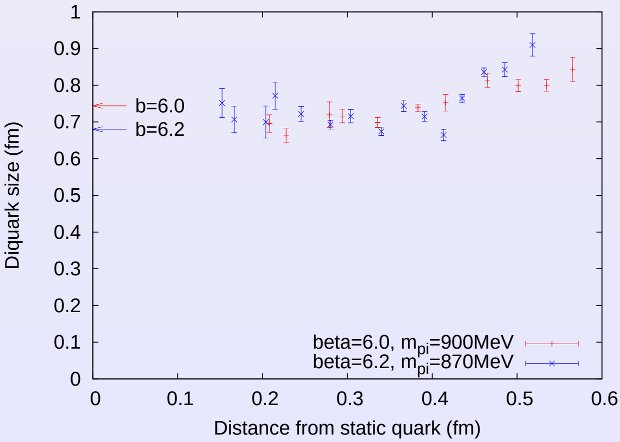


- Scalar: size $\lesssim$ 1 fm robust vs background field
- Vector: size $\gtrsim$ 2 fm
- Light quarks? Full QCD ?

# Conclusions

- "Good" diquark more than phenomenological construct:
  diquarks are for real!
- Surprise: all measurements consistent with predictions.
- Scalar diquark $\sim$ robust versus background field
  $\longrightarrow$ unchanged in color superconductivity?
- Tighter binding, smaller size for lighter quarks?
  $\longrightarrow$ fit diquark inside nucleon?
- Outlook:
  static $\bar{q}$ + diquark + diquark $\rightarrow$ diquark-diquark interactions
- Density-density correlators: powerful gauge-invariant tool for investigating hadron structure (J. Negele)

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