Searching for evidence of diquark states using lattice QCD simulations

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Brief summary of diquark : Why are diquarks **important** ?

It is considered that diquarks play an important role
in variety of phenomena in hadronic physics.

For example,

① Diquark picture is a hopeful candidate to explain exotic hadrons (tetra-, penta-quarks etc.) which cannot be explained naturally by quark model.

② Diquarks are considered as the central ingredient of cold, dense matter where they condense to form a color superconductor.

Our motivation for this work

To check if diquark states are **for real** using lattice QCD simulation.

Classification of diquarks

Spin color effective interaction predicts that there is a **good diquark**.

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^-	$\bar{3}$	$\bar{3}$	$\bar{q}_C\vec{\gamma}\gamma_5 q, \bar{q}_C\sigma_{ij} q$

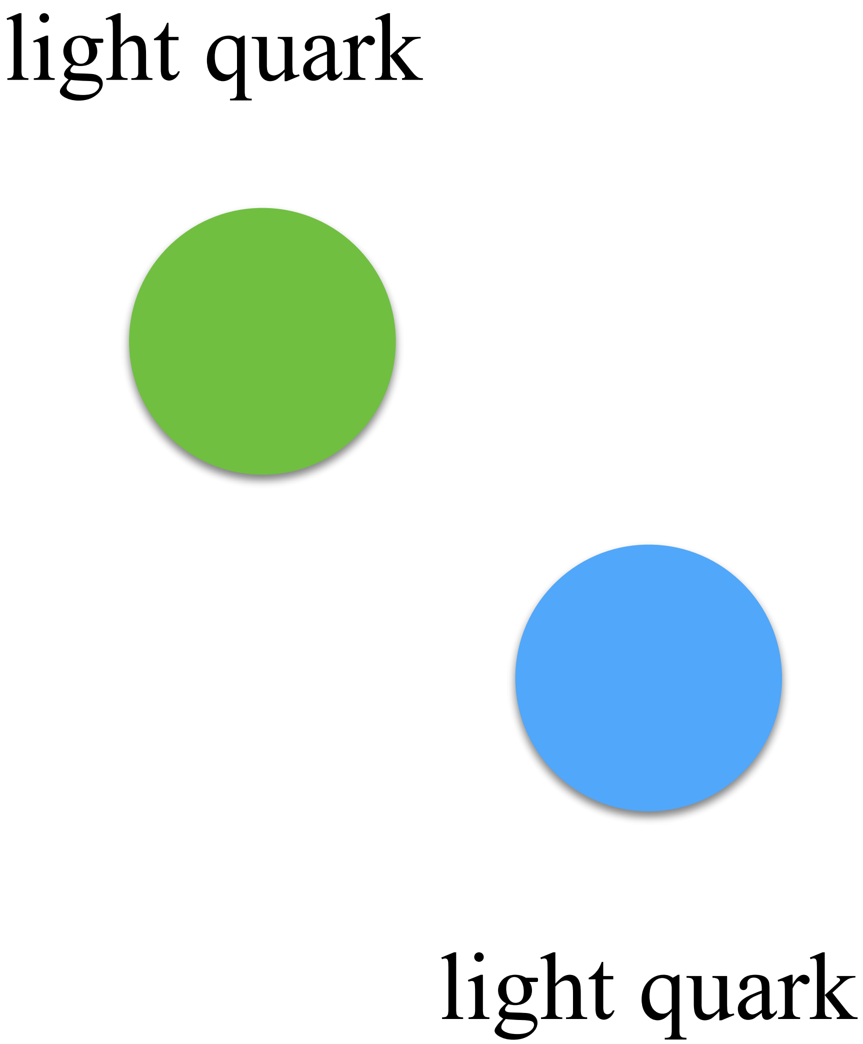
From R. Jaffe, hep-ph/0409065

Diquark correlation is **enhanced in a good diquark channel**.

- Parity-odd states are heavier than parity-even states.
- $M(0^+) < M(1^+)$.

We should check this prediction using the first principle calculation.

How to investigate diquark state using lattice QCD?



Diquark states are colored.

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< Possible choices >

1. Gauge fixing
2. Other gauge invariant formula

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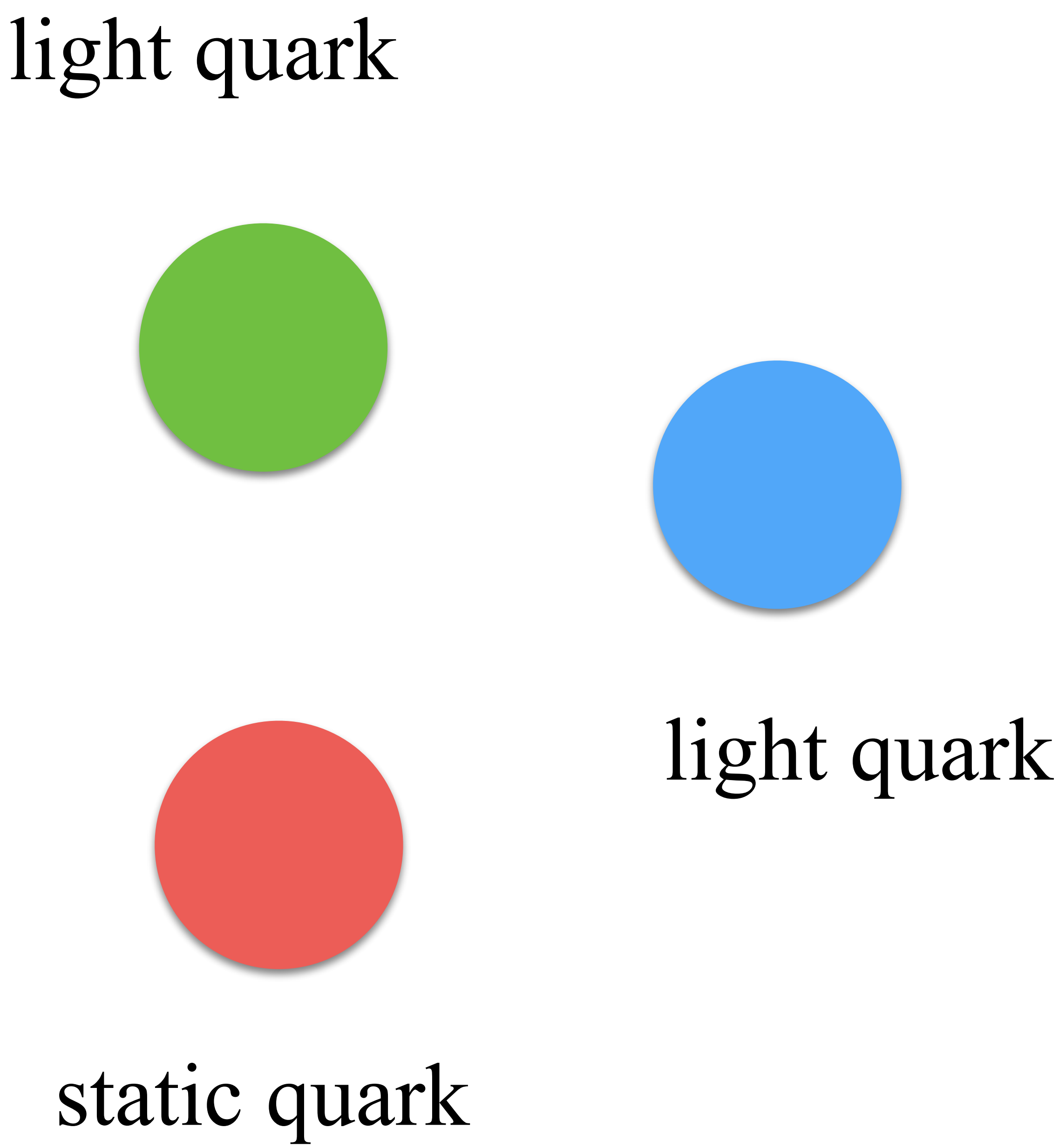
Gauge invariant strategy is adopted in this work.

How to investigate diquark state using lattice QCD?



Combine diquark + static quark
into color singlet

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Static-light-light baryon

We are looking at a diquark in the background field of a static quark.

→ relevant limit: static quark far from light quarks

I. Calculation of diquark mass

Using a static-light-light baryon, we can calculate **diquark mass difference** in gauge invariant manner.

First, calculate a static-light-light baryon correlator in standard manner.

$$\sum_{\vec{x}} \left\langle O_\Gamma(\vec{x},t) O_\Gamma^\dagger(\vec{0},0) \right\rangle \propto e^{-\{M(\mathrm{diquark})+M(\mathrm{heavy\ quark})\}t}$$

From the correlator at large *t*,

we can extract the sum of diquark mass and static quark mass.

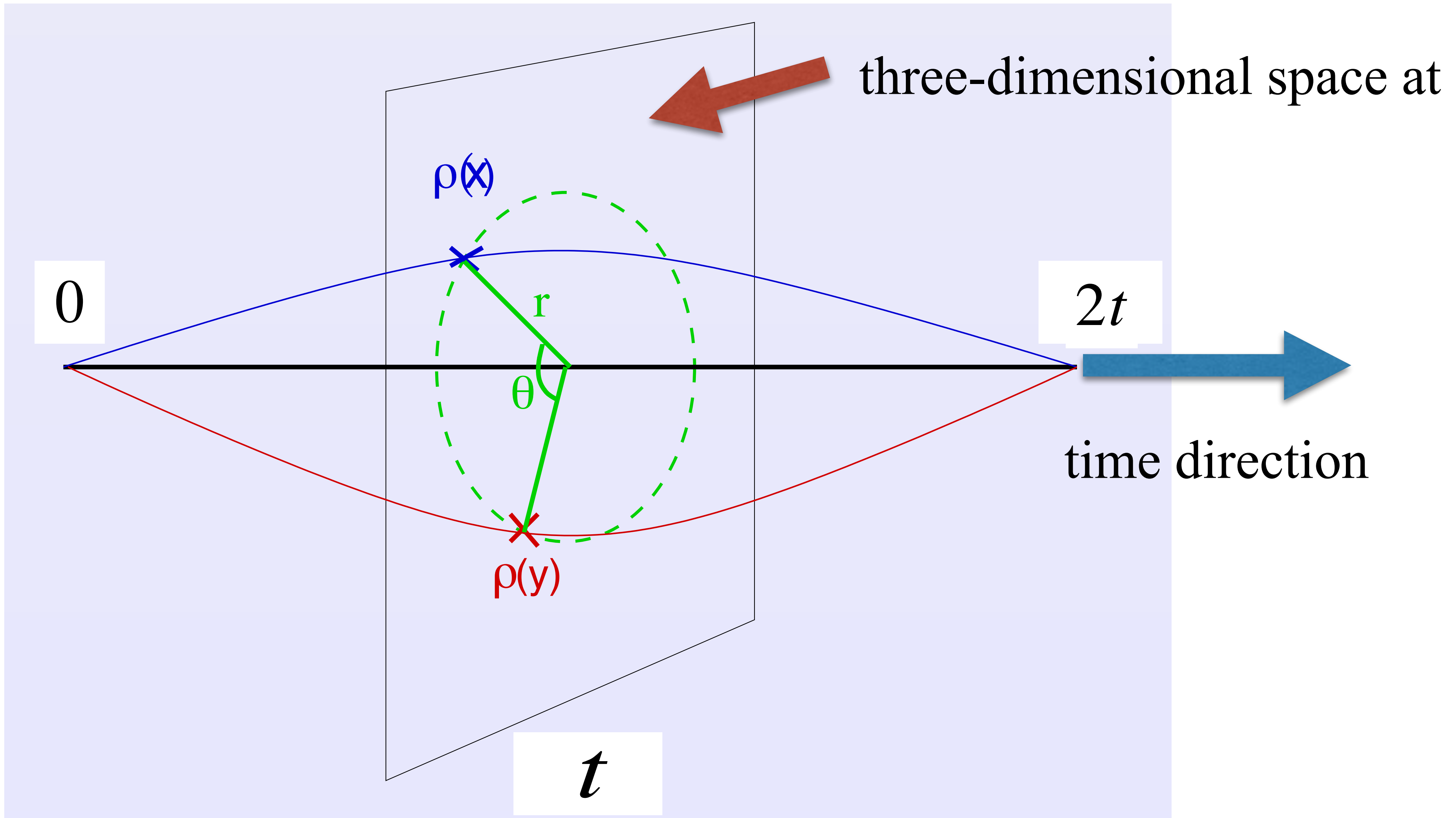
(Static quark → mass UV divergent)

↓

Finally, we can obtain mass difference between two diquarks.

$$\Delta M = M(\Gamma_1) - M(\Gamma_2) = \text{diquark mass difference}$$

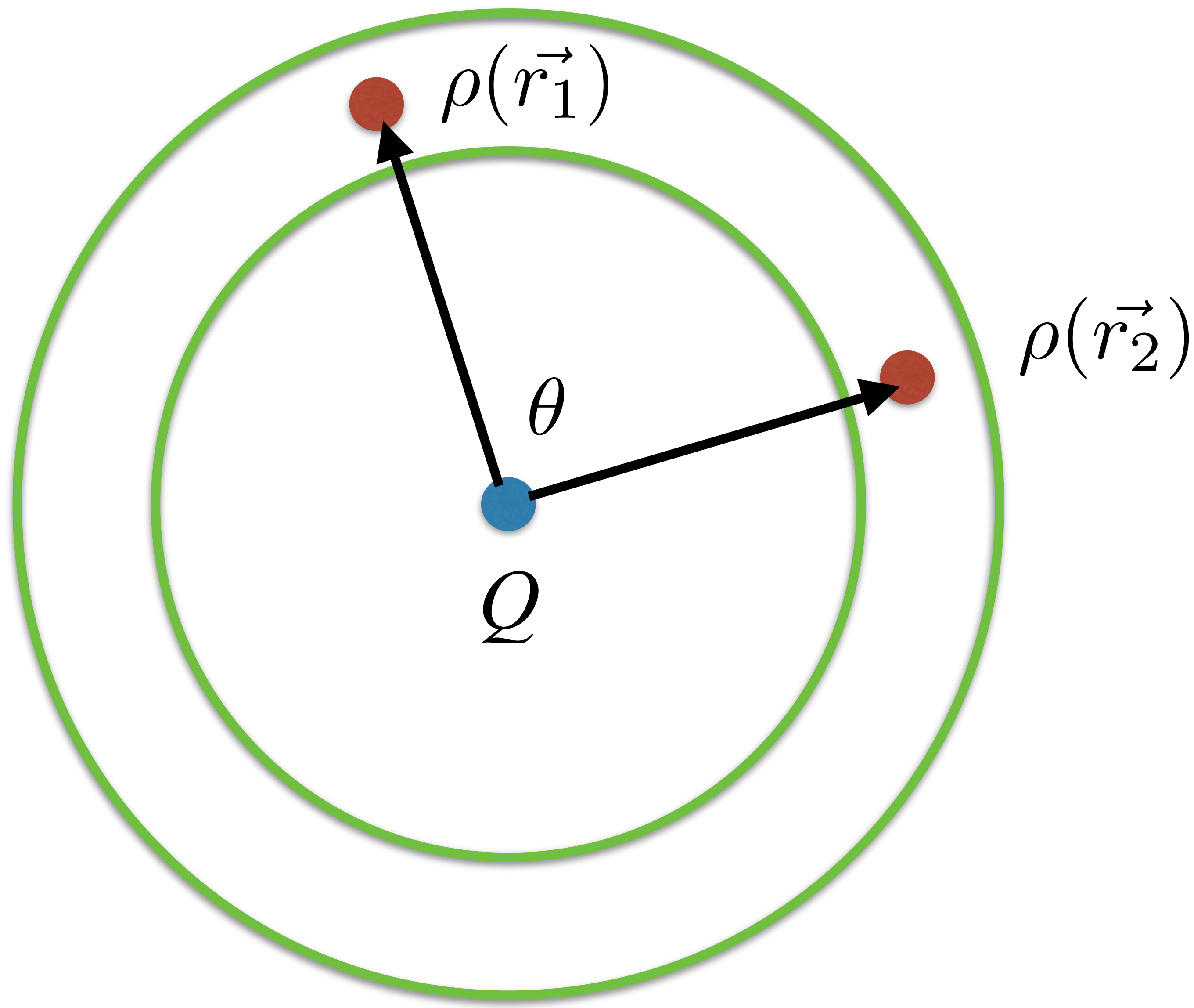
II. Search for diquark interaction: Density-density correlator



$$C_\Gamma(\vec{r}_1, \vec{r}_2, t) = \left\langle O_\Gamma(\vec{0}, 2t)\rho(\vec{r}_1, t)\rho(\vec{r}_2, t)O_\Gamma^\dagger(\vec{0}, 0)\right\rangle$$

$$\rho(\vec{r}, t) = \bar{q}(\vec{r}, t)\gamma_0 q(\vec{r}, t)$$ (density operator)

Calculation of density-density correlator



In the middle of t-direction, we calculate density-density correlators as a function of θ in the spherical shell.

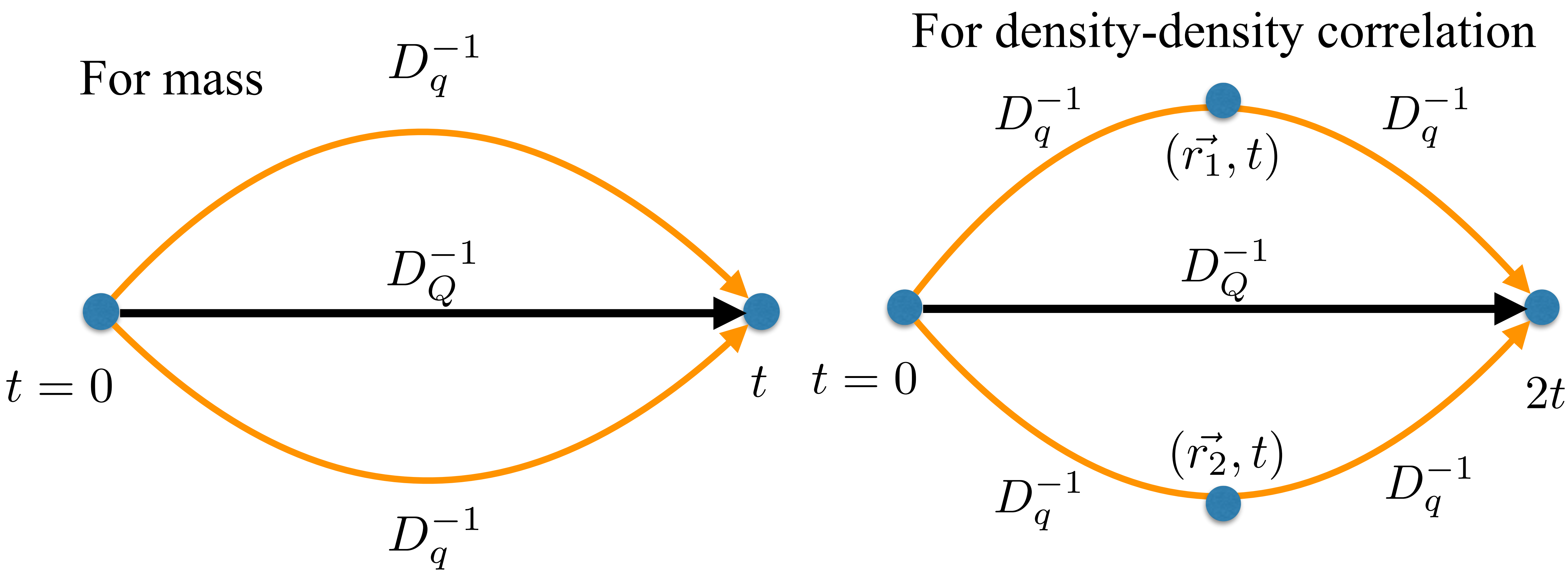
If the density-density correlator is enhanced when two light quarks approach each other, this can be interpreted as diquark attraction.

Numerical setup

- O(a)-improved 2-flavor Wilson fermions
- Wilson gauge action (thanks to CLS ensemble)

$$32^3 \times 64 \qquad m_\pi = 380 \text{ MeV}$$

(Alexandrou *et al*, hep-lat/0609004, 2005: $16^3 \times 32$, $m_\pi = 600 - 900$ MeV)



light quark propagator: source and sink smeared with HYP smeared gauge links

static quark propagator: calculated with HYP smeared gauge links

Numerical calculation

J^P	Color	Flavor	Operator
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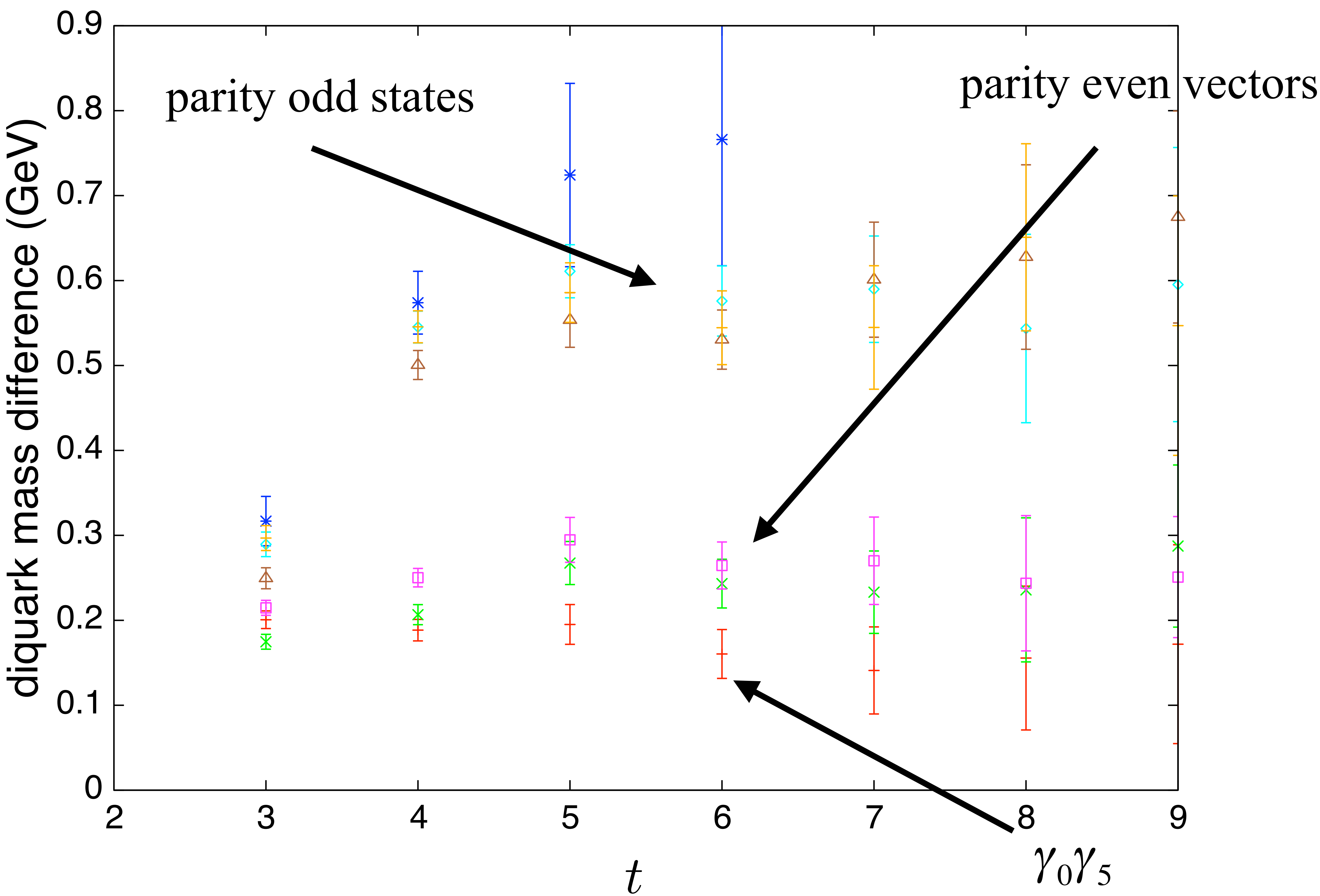
From R. Jaffe, hep-ph/0409065

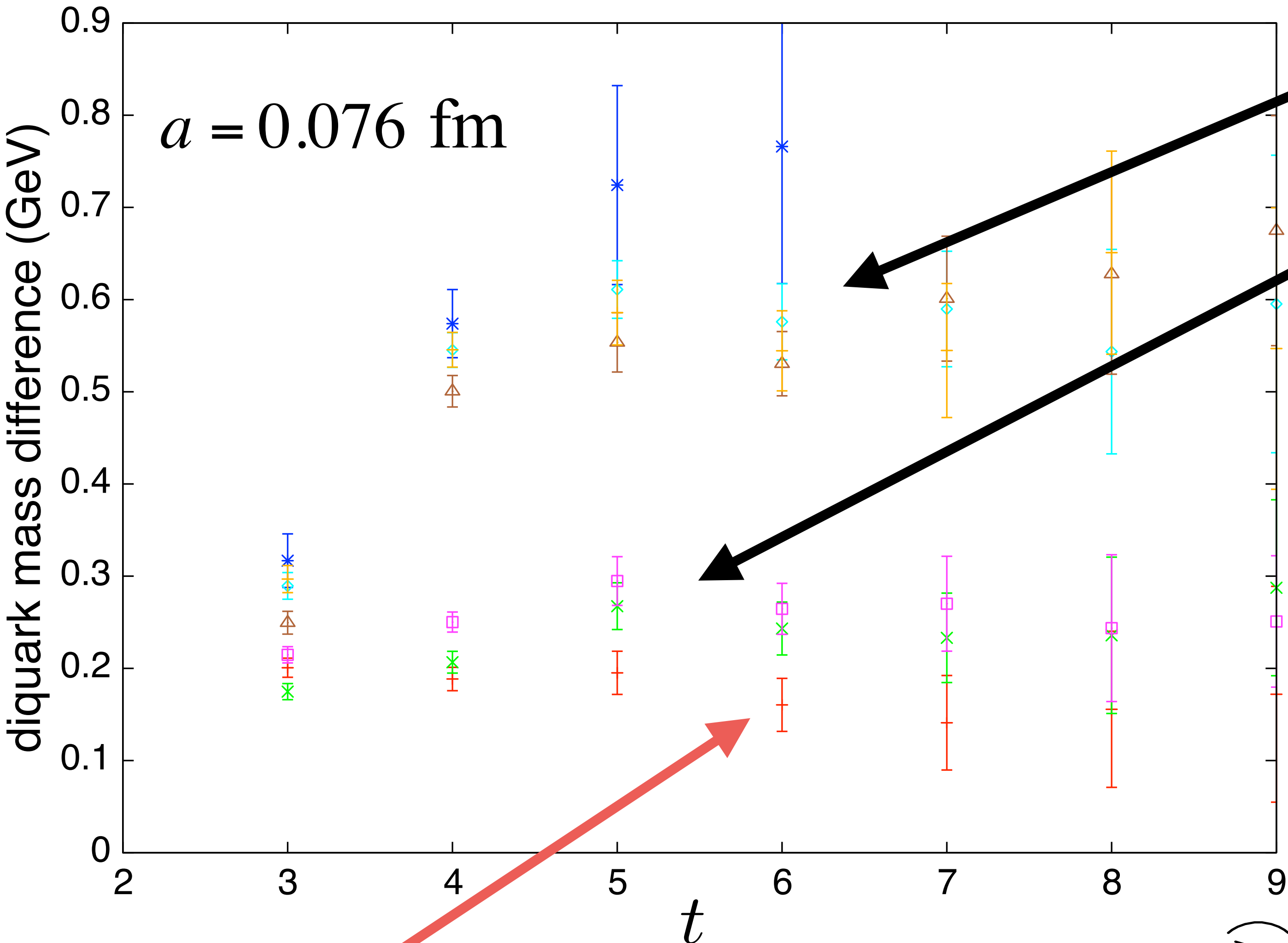
We calculate

1. mass differences between γ_5 diquark and other diquarks
2. density-density correlators for all diquark channels.

Mass differences between γ_5 diquark and other diquarks



Comparison with previous lattice result

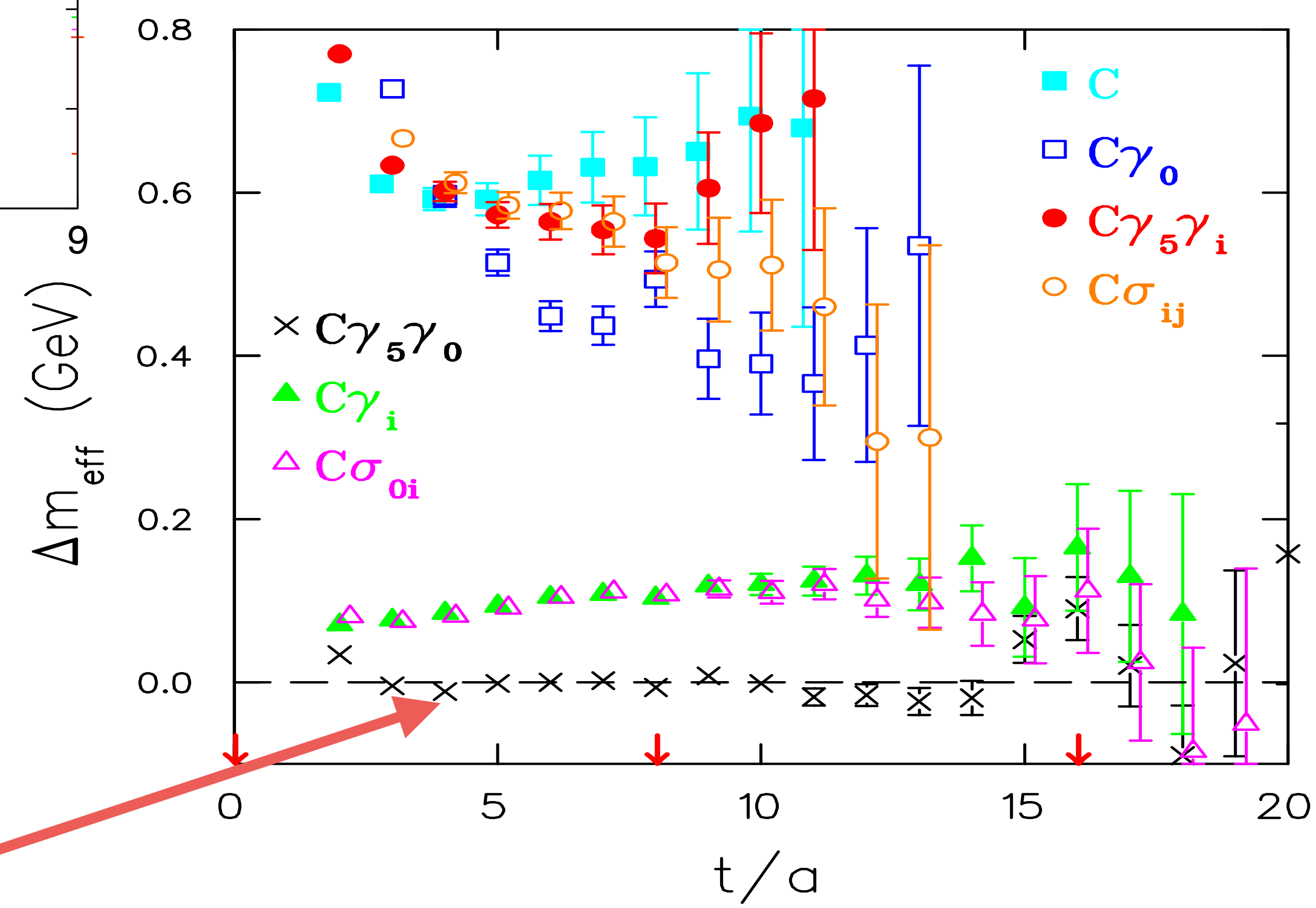


parity odd states

parity even vectors

$\gamma_0\gamma_5$

From Alexandrou *et al,* hep-lat/0609004, 2005

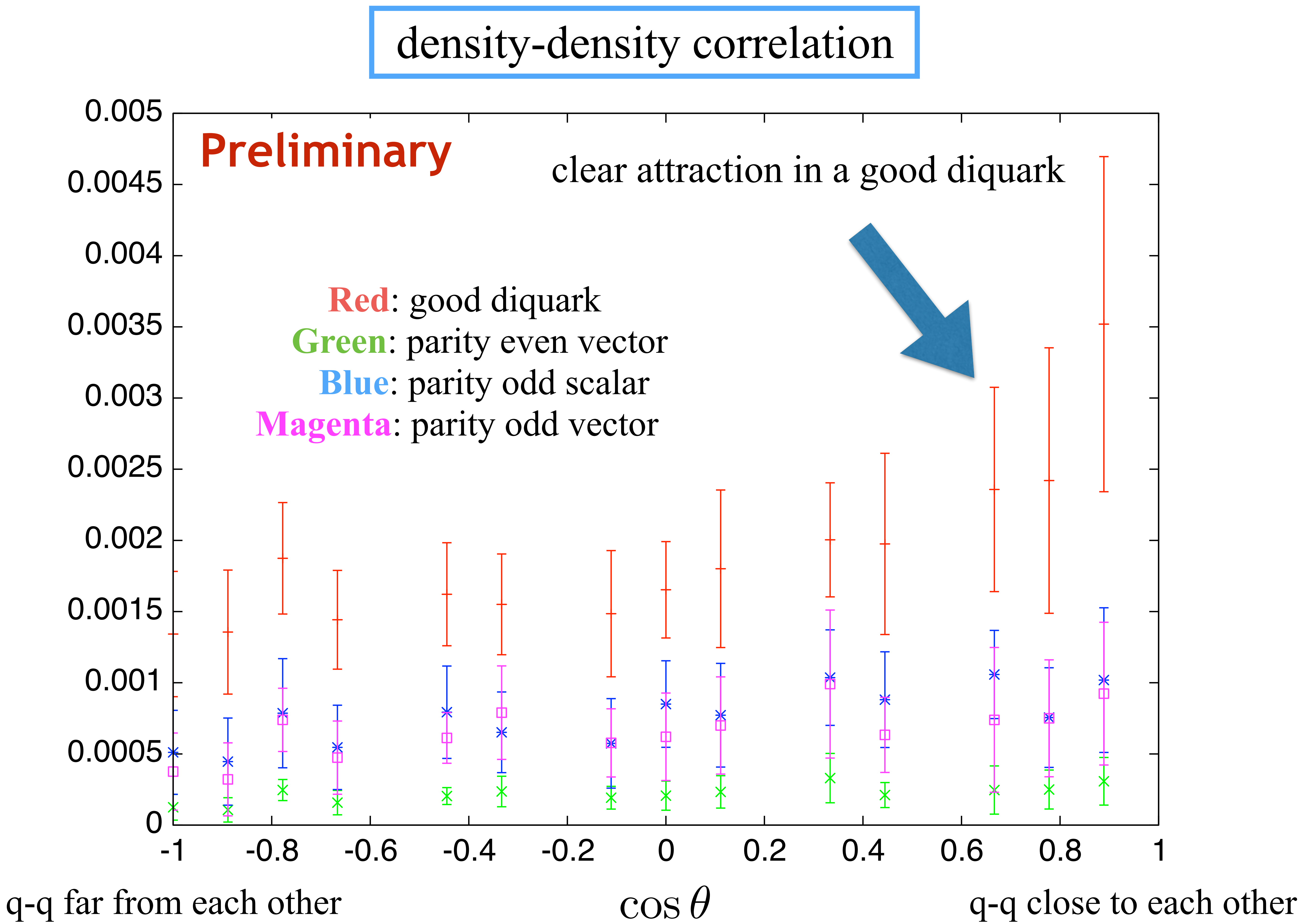


$a = 0.092$ fm

This behavior is different from
Jaffe's prediction
and previous lattice result.

discretization effect?

Good diquark states have degenerated mass.


density-density correlation
Preliminary
clear attraction in a good diquark
Red: good diquark
Green: parity even vector
Blue: parity odd scalar
Magenta: parity odd vector
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
q-q far from each other
cos θ
q-q close to each other

Summary of my talk

The good diquark is the lightest among all possible states.

Clear attraction between two quarks is visible in a good diquark .

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This statement is consistent with the prediction obtained by phenomenological calculation.

Lattice QCD supports the possibility of existence of diquark states.