# Lattice QCD searches for tetraquarks and mesonic molecules

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1005.0948 hep-lat (PRD)

1004.3636 hep-lat

# Motivation

Hadrons: $qqq, \quad \bar{q}q$

Exotic states - none confirmed beyond doubt:

$[\bar{q}\bar{q}][qq], (\bar{q}q)(\bar{q}q),$

$\bar{q}qqqq, (\bar{q}q)(qqq),$

$glueball, \bar{q}qG$

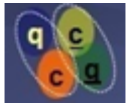
physical states can have several Fock components

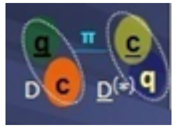

diquark [qq]:

$\bar{3}$ in color

$\bar{3}$ in flavor

Presented lattice criteria do no distinguish between tetraquarks / molecules: when saying "tetraquarks" I have in mind both types.

# Tetraquarks 

and mesonic molecules 

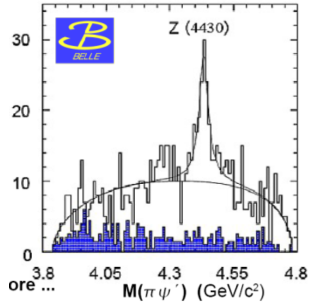

Candidates:

- **hidden charm states X,Y,Z**

$$Z^+(4430) \to \pi^+ \psi'$$

$\bar{d} u \bar{c} c$ quark content

Belle, not Babar




- **observed scalars** [Jaffe, 1977]

| $\sigma(600)$ | $\kappa(800)$ | $a_0(980)$ | $f_0(980)$ |
|---|---|---|---|
| $\bar{u}\bar{d}du$ | $\bar{u}\bar{d}ds$ | $\bar{u}\bar{s}sd$ | $\bar{u}\bar{s}su$ |

Some reasons in favor of large tetraquark Fock component (possibly in addition to $\bar{q}q$ component):

| | $m(I=1)$ | | $m(I=\frac{1}{2})$ |
|---|---|---|---|
| $\bar{q}q$ : | $\bar{u}d$ | $<$ | $\bar{u}s$ |
| $\bar{q}\bar{q}qq$ : | $\bar{u}\bar{s}sd$ | $>$ | $\bar{u}\bar{d}ds$ |
| observed : | $a_0(980)$ | $>$ | $\kappa(800)$ |

experiment : $a_0(980)$ has large coupling to $K\bar{K}$

natural if $\bar{u}\bar{s}sd$

not natural if $\bar{u}d$

# Correlator and physical states *n*

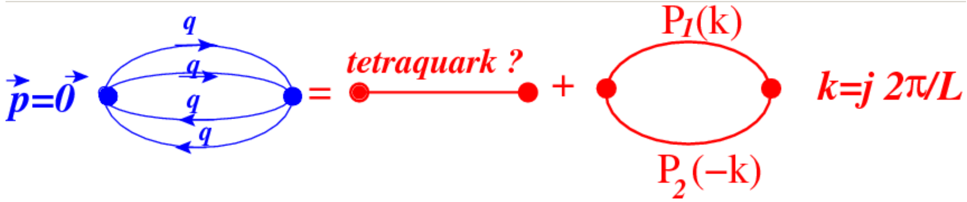
- Compute correlation function in lattice QCD using interpolators with desired $J^{PC}$ and flavor

$$O \approx (\bar{q}q)(\bar{q}q) \quad \text{or} \quad [\bar{q}\bar{q}][qq]$$

$$C_{ij}(t) = \langle O_i(t) | O_j^+(0) \rangle = \sum_{n=1,2,..} \langle O_i | n \rangle \langle n | O_j \rangle \; e^{-E_n t} \rightarrow w\, e^{-E_1 t}$$

$$E_n \,, \quad \langle O_i | n \rangle$$

- Which physical states $\boldsymbol{n}$ contribute?




examples: σ, Z+ (4430) | ππ, ψ'π

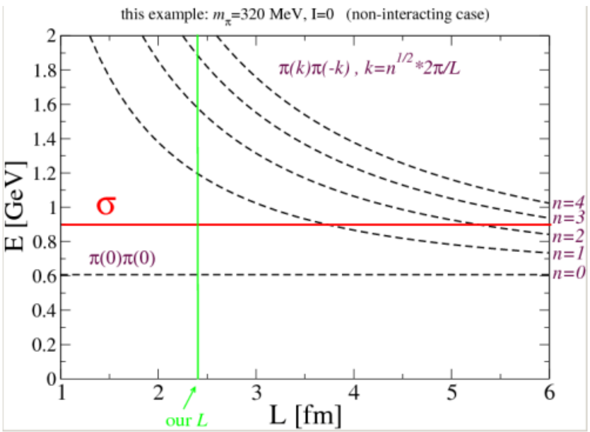
- Two-particle scattering states have discrete spectrum (for periodic BC in space)

$$P_1(\vec{k})P_2(-\vec{k}), \quad \vec{k} = \tfrac{2\pi}{L}\vec{j} \quad \text{for} \quad \vec{p} = \vec{0}$$

$$E_{P_1P_2} \approx E_{P_1} + E_{P_2} = \sqrt{m_{P_1}^2 + \vec{k}^2} + \sqrt{m_{P_2}^2 + \vec{k}^2}$$

# Looking for a state in addition to scattering states

Schematic spectrum ignoring interactions




**Non-interacting** two-pion states:

$$\pi(\vec{k})\pi(-\vec{k}), \quad \vec{k} = \tfrac{2\pi}{L}\vec{j} \qquad E_{\pi\pi} \approx 2\sqrt{m_\pi^2 + \vec{k}^2}$$

**Interacting** two-pion states:

energy shifted: information on interaction:

Luscher

Rusetski, Maissner, Bernard, Lage

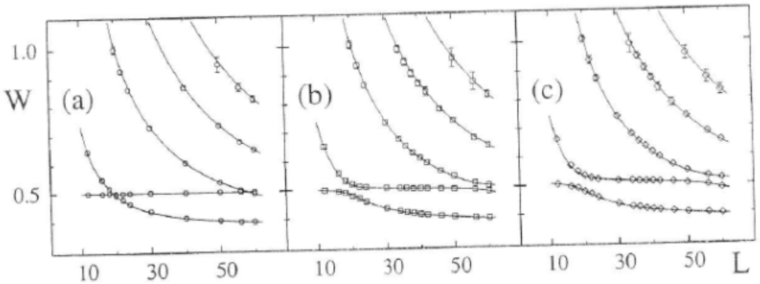
Rummukainen & Gottlieb

Resonances plus scattering states have been Extracted in simulations of **toy models**:

lines: Luscher formula

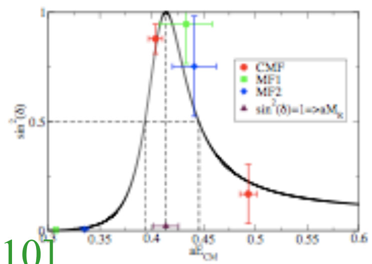
Simulation points: Lang & Gattringer (1993)

$$m_R\, ,\Gamma_R :\ E^{\text{lat.}}(L) - E^{\text{no int.}}_{P_1P_2}$$



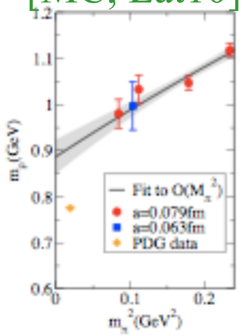

Dyn. QCD simulations to extract rho meson width in pioneering stage!

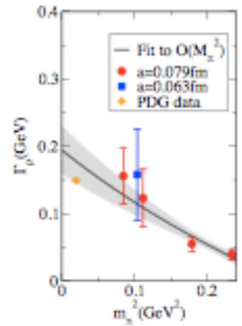
$$m_\rho\, ,\Gamma_\rho :\ E^{\text{lat.}}_{\text{gr.st}}(L) - E^{\text{no i}}_{\pi\pi}$$




PACS-CS, QCDSF, BMW, ETMC

Feng, ET [MC, Lat10]



# Light scalars

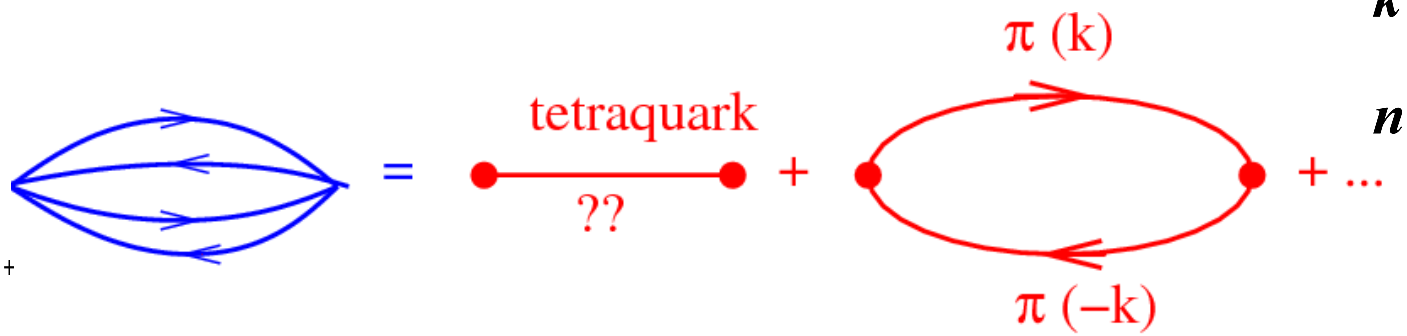
# Investigated channels

S.P., Draper, Lang, Limmer, Liu, Mathur, Mohler, 1005.0949[hep-lat]

$$\vec{k} = \vec{n}\,\frac{2\pi}{L} \qquad n = 0,1,2,..$$

$$\vec{p} = \vec{0}$$

$$C_{I=0} = \qquad J^{PC} = 0^{++}$$




| | | | tetraquark | scattering states |
|---|---|---|---|---|
| attractive (non-exotic) channels | I=0 | | $\sigma = \overline{u}d\overline{u}d$ ? | $\pi\pi$ |
| | I=1/2 | | $\kappa = \overline{u}d\overline{d}s$ ? | K $\pi$ |
| | I=1 | | a0 = $\overline{u}s\overline{d}s$ ? | K K, $\pi\eta$ (not considered: challenge due to two scattering towers) |
| repulsive exotic channels | I=2 | | no experimental | $\pi\pi$ |
| | I=3/2 | | resonance | K $\pi$ |

# Tetraquark interpolators O with $J^{PC}=0^{++}$

$$C_{ij}(t) = \langle O_i(t) | O_j^+(0) \rangle = \sum_{n=1,2,..} \langle O_i | n \rangle \langle n | O_j \rangle \ e^{-E_n t} \to e^{-E_1 t} \qquad E_n, \ Z_i^n = \langle O_i | n \rangle$$

## Present simulation:

S.P., Draper, Lang, Limmer, Liu, Mathur, Mohler, 1005.0949 hep-lat (PRD)

Interp. with different color and Dirac st.
same spatial structure

$P_1(\frac{2\pi}{L})P_2(-\frac{2\pi}{L})$ found

$I = 0, \frac{1}{2}$: $5x5$ correlation matrices

$$PP, \ \sum_{i=1,2,3} V_i V_i, \ \sum_{i=1,2,3} A_i A_i,$$

$$[\bar{q} C\gamma_5 \bar{q}][q C\gamma_5 q], \ [\bar{q} C\bar{q}][qCq]$$

$P = \bar{q}\gamma_5 q, \ V_i = \bar{q}\gamma_i q, \ A_i = \bar{q}\gamma_i\gamma_5 q$

$I = 2, \frac{3}{2}$: $3x3$ correlation matrices

$$PP, \ \sum_{i=1,2,3} V_i V_i, \ \sum_{i=1,2,3} A_i A_i$$

## Previous simulation:

S.P., Mohler, PRD79(2009)

Interp. with same color and Dirac st.
different spatial structure

$P_1(\frac{2\pi}{L})P_2(-\frac{2\pi}{L})$ not found

# Details of simulation

## Present simulation:

S.P., Draper, Lang, Limmer, Liu, Mathur, Mohler, 1005.0949[hep-lat]

- Nf=2 **dyn. Chirally Improved quarks** [BGR col.]

  first dyn. simulation intended to look for tetraq.

  *a=0.15 fm,* $V=16^3x32$,

  $m\pi$= 318, 469, 526 MeV

  200 configurations

- **quenched overlap quarks** [Kentucky, XQCD col.]

  *a=0.2 fm,* $V=16^3x28$, $12^3x28$,

  $m\pi$= 230, 342, 478 MeV

  300 configurations

## Previous simulation:

S.P., Draper, Mohler, PRD79 (2009)

- **Quenched Chirally Improved quarks** [BGR Col.]

# Finding physical states $n$

$$E_n,\ Z_i^n = \langle O_i | n \rangle$$

$$C_{ij}(t) = \langle O_i(t) | O_j^+(0) \rangle = \sum_{n=1,2,..} \langle O_i | n \rangle \langle n | O_j \rangle \ e^{-E_n t} = \sum_{n=1,2,..} Z_i^n Z_j^{n*} \ e^{-E_n t} \xrightarrow{\text{large t}} Z_i^1 Z_j^{1*} \ e^{-E_1 t}$$

$C(t):\quad N \times N$ matrix

[Luscher , Wolf]

$$C(t)\vec{u}^n = \lambda_n(t)\, C(t_0)\vec{u}^n$$

$$\lambda_n = e^{-E_n(t-t_0)}; \quad Z_i^n = \frac{C_{ik}(t) u_k^n}{\sqrt{u_l^{n*} C_{lm}(t) u_m^n}} e^{E_n t/2}$$

[Blossier, Sommer, Morte,… 2009]

for $t_0 \geq \frac{t}{2}$ controlled rel. error on $E, Z$: $\quad O(e^{-(E_{N+1} - E_n)t})$

# Spectrum for I=0,2

**Conclusions:**

- I=0: Two light states. One of them could be possibly related to σ.

Roy equations:

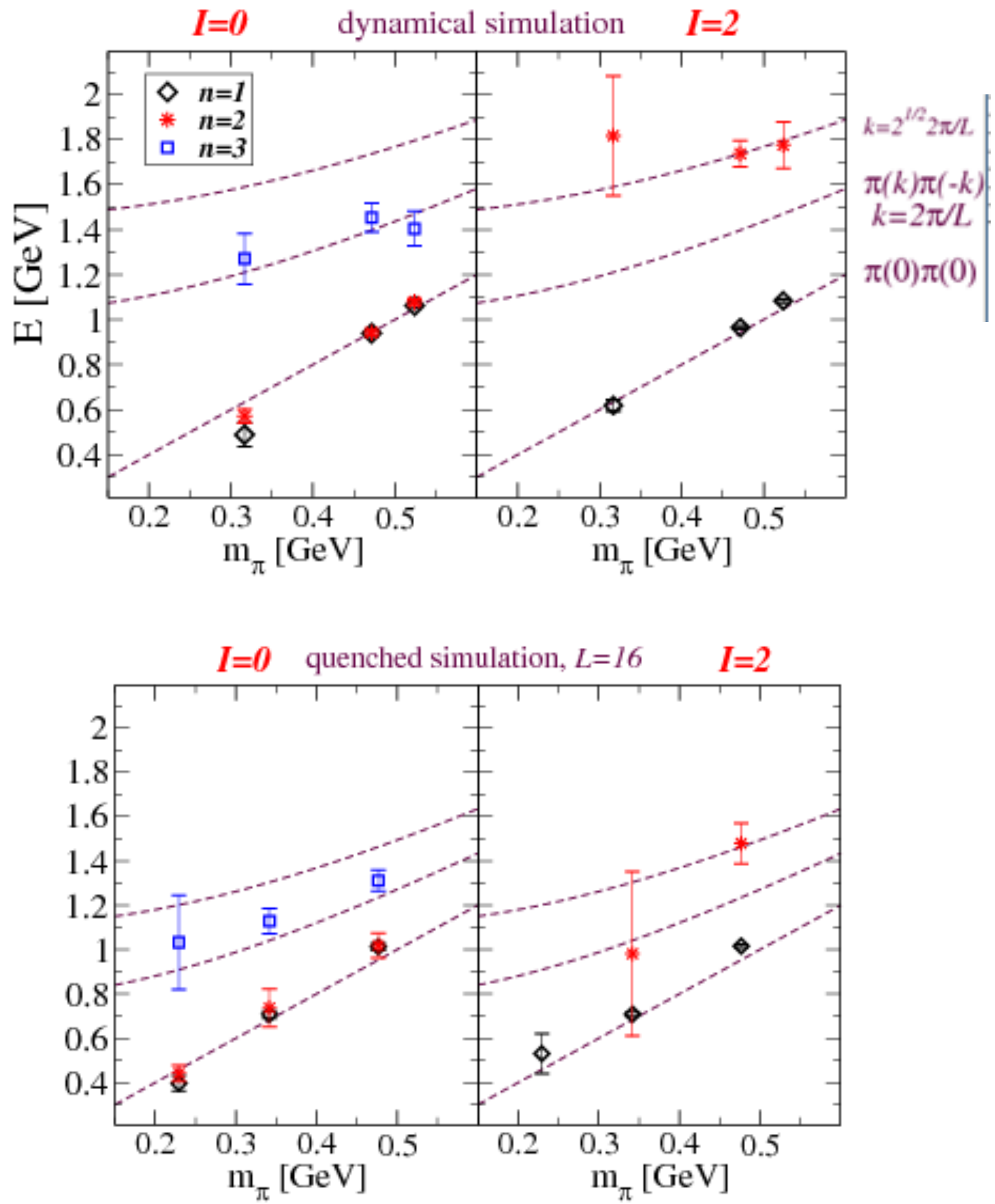
Leutwler, Colangelo, Caprini [PRL06]

$$m_\sigma = 441 \pm 16\ MeV$$

$$\Gamma_\sigma = 544 \pm 25\ MeV$$

σ is narrower at simulated mπ

- I=2: Just one light state π(0)π(0), as expected (since no resonance was experimentally observed in this repulsive channel)



# Spectrum for I=1/2, 3/2

**Conclusion** (analogous to I=0,2 case):

- I=1/2: Two light states. One of them could be possibly related to κ.

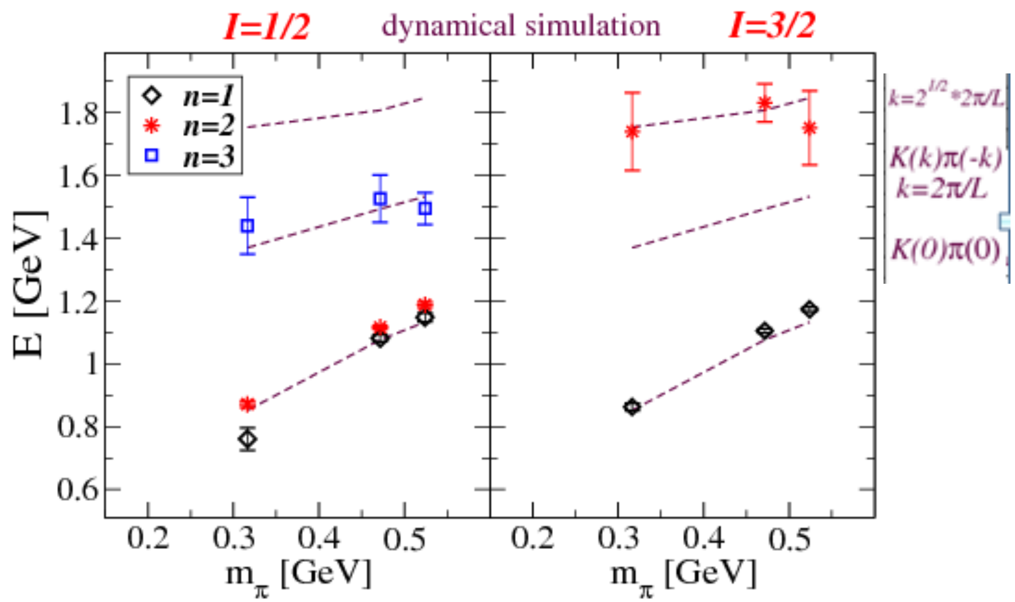
Roy equations:

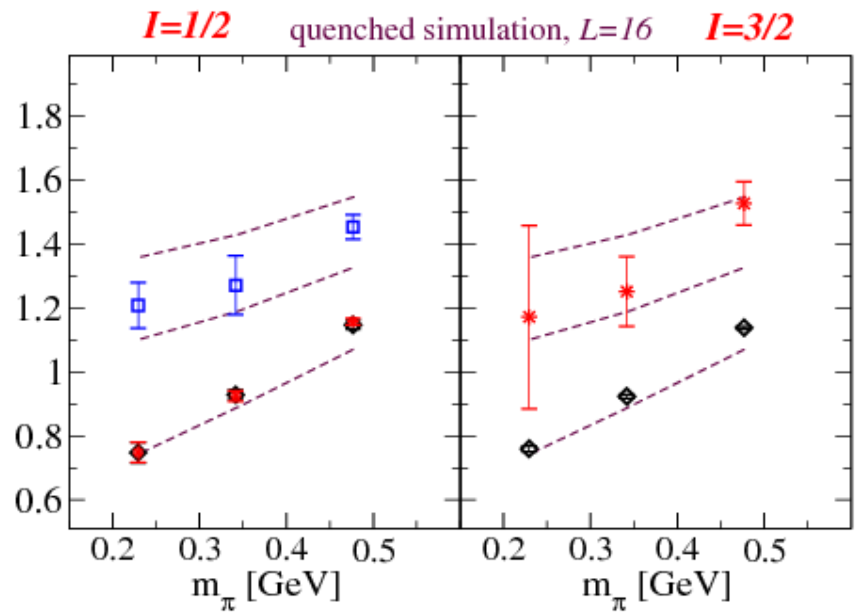
Descotes-Genon, Moussalam 2006

$$m_\kappa = 658 \pm 13\ MeV$$
$$\Gamma_\kappa = 557 \pm 24\ MeV$$

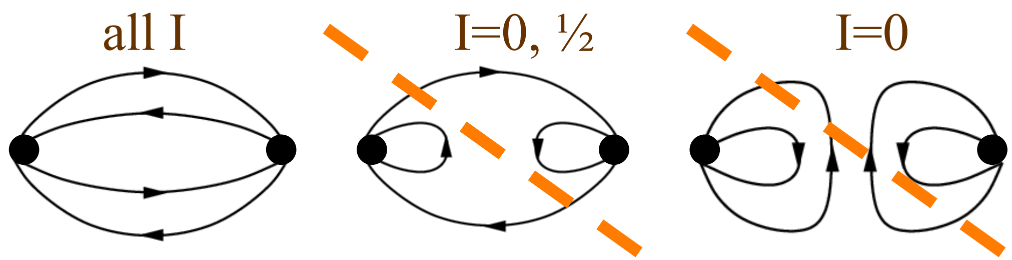
κ is narrower at simulated mπ

- I=3/2: Just one light state π(0)K(0), as expected (since no resonance was experimentally observed in this repulsive channel)



# physics motivated approximation




- we discard single and double annihilation contr. (as in all previous tetraquark studies)
- excuse: we are interested in tetraquark state with 4 valence quarks
- We do find a state in addition to scattering states:
  corresponding physical state can not be pure qq
- We verified that this approximation can not lead to
  additional unphysical eigenstate (for example with wrong isospin).
- Verification of our result with disconnected contractions is needed

# Methods to distinguish one/two particle states

- one-particle (tetraquark) states
- two-particle (scattering) states

A) time -dependence of C(t) (finite T effect)

B) L-dependence of $<O_i|n>$ (finite L effect)

C) spectrum dependence on boundary conditions (finite L effect)

new proposal to determine nature of scalar mesons:

Bernard, Lage, Meissner, Rusetsky: 1010.6018 [hep-lat]

D) Behavior of energy shifts (finite L effect)

# Methods to distinguish one/two particle states

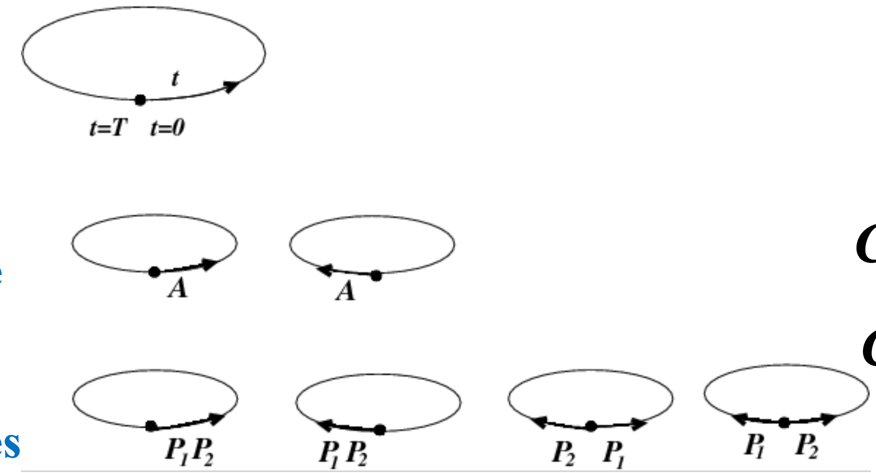
- one-particle (tetraquark) states
- two-particle (scattering) states

## A) Time -dependence of C(t) at finite T

Detmold, Savage, 2008
S.P. & Mohler, PRD 79 (2009)

**One-particle**

**Two-particles**




$$C_{ii}(t) \propto e^{-Et} + e^{-E(T-t)}$$

$$C_{ii}(t) \propto e^{-Et} + e^{-E(T-t)} + R[e^{-m_{P1}t}e^{-m_{P2}(T-t)} + e^{-m_{P2}t}e^{-m_{P1}(T-t)}]$$

Effect on $\lambda_n(t)$ explored in S.P. & al., 1005.0949

Conclusion: n=1 is scattering state for all I
n>1: the method does not indicate the nature

# Methods to distinguish one/two particle states (cont')

## B) L-dependence of $Z=\langle O_i|n\rangle$

[Niu, Liu, Shen, Gong, PRD80 (2009)
Mathur et al., PRD76( 2007)
S.P. & Mohler, PRD 79 (2009)]

$$Z_i^n = const. \quad \Rightarrow \quad \frac{Z_i^n(12)}{Z_i^n(16)} = 1 \qquad \text{for one-particle st. } n$$

$$Z_i^n \propto \frac{1}{L^{3/2}} \quad \Rightarrow \quad \frac{Z_i^n(12)}{Z_i^n(16)} = \frac{16^{3/2}}{12^{3/2}} \qquad \text{for two-particle st. } n$$

Limitations pointed out in Niu & at. PRD80 (2009), 1005.5571

Our case: quenched sim: *a=0.2 fm,* $V=16^3x28,\ 12^3x28$

Our conclusions:

- n=1 & I=2, 3/2: roughly consistent with scattering state
- other states: errors to large for clear distinction

# Comparison to analytical expectations

- Pelaez, Hanhart, Rios [PRL 2008] , Nebreda & Pelaez [PRD 2010]

m(σ) ~2 m(π) for m(π)=300-450 MeV σ becomes bound at m(π)~350 MeV

$\sigma$ pole : $\sqrt{s_{pole}} \simeq M - i\Gamma/2$

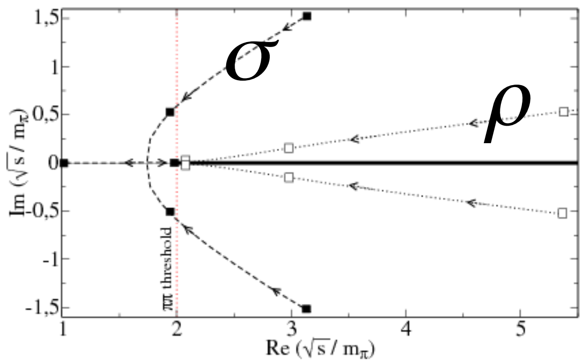



FIG. 1: Movement of the $\sigma$ (dashed lines) and $\rho$ (dotted lines) poles for increasing pion masses (direction indicated by the arrows) on the second sheet. The filled (open) boxes denote the pole positions for the $\sigma$ ($\rho$) at pion masses $m_\pi = 1$, 2, and $3 \times m_\pi^{\rm phys}$, respectively. Note, for $m_\pi = 3m_\pi^{\rm phys}$ three poles accumulate in the plot very near the $\pi\pi$ threshold.

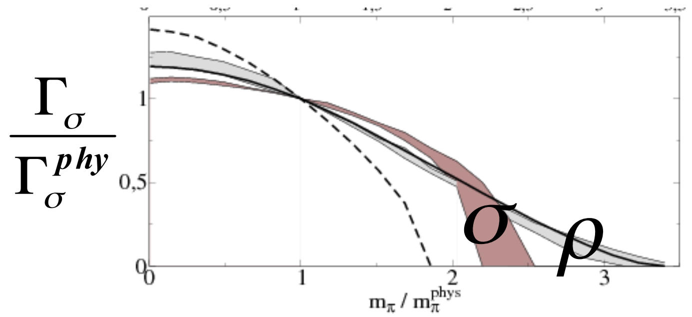



FIG. 2: $m_\pi$ dependence of resonance masses (upper panel) and widths (lower panel) in units of the physical values. In both panels the dark (light) band shows the results for the $\sigma$ ($\rho$). The width of the bands reflects the uncertainties induced from the uncertainties in the LEC. The dotted line shows the $\sigma$ mass dependence estimated in Ref. [8]. The dashed (continuous) line shows the $m_\pi$ dependence of the $\sigma$ ($\rho$) width from the change of phase space only, assuming a constant coupling of the resonance to $\pi\pi$.

- Lattice simulation of toy model with loosely bound and scattering states:

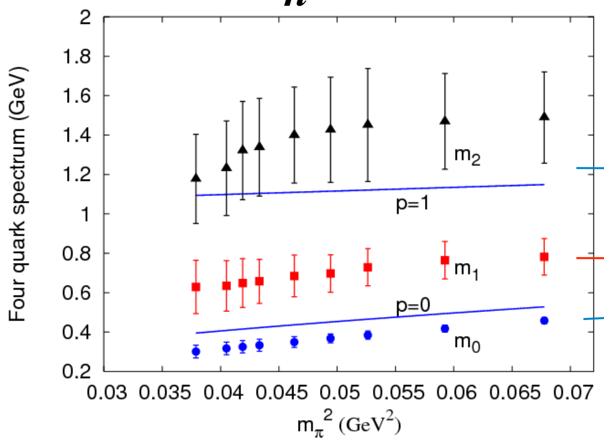
  loosely bound state is close to threshold [Sasaki, Terasaki, 2006]

# Previous lattice indication for tetraquark σ

[Mathur et al, PRD76 (2007)]

- quenched , overlap fermions, exactly same props
- Single I=0 interpolator $O = (\bar{q}\gamma_5 q)(\bar{q}\gamma_5 q)$
- three states with sequential Bayes method;

$E_n$

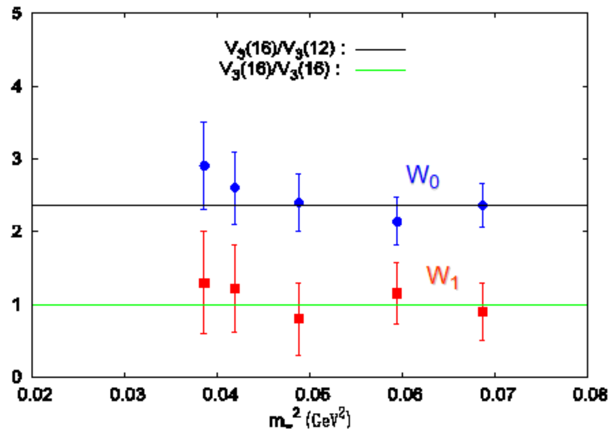



π(1)π(-1)

σ ?

π(0)π(0)

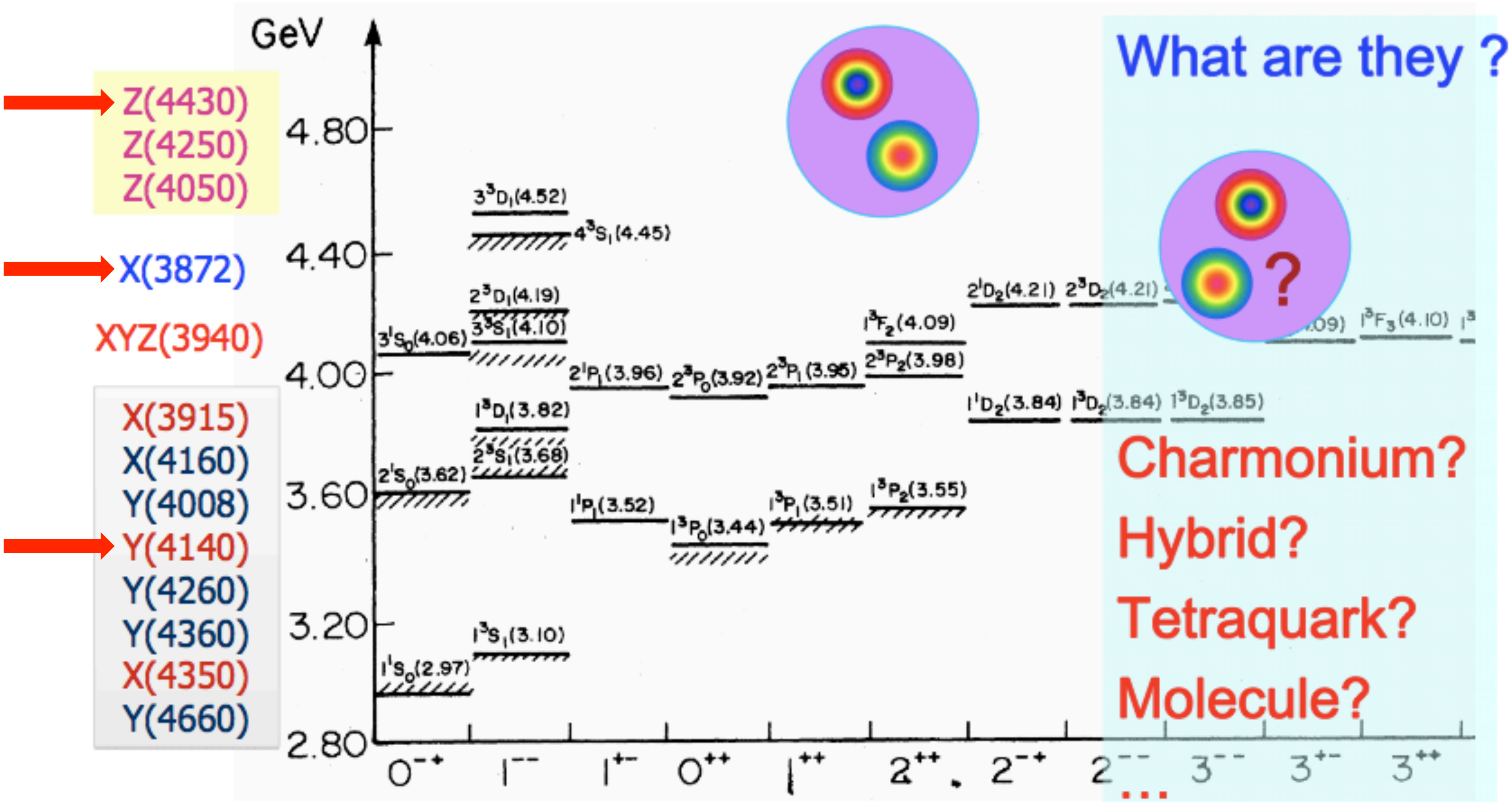
$$\frac{\langle O|n\rangle^2 (L=12)}{\langle O|n\rangle^2 (L=16)}$$



# Charmonium (like) XYZ states

# Charmonium (like) states

[Yuan, plenary @ ICHEP 2010]




Godfrey & Isgur,
PRD32, 189 (1985)

Not all XYZ states are charmonia!

# Charmonium (like) states

[Brodzicka, plenary @ Lepton-Photon 2009]

## neutral X and Y

| Name | $J^{PC}$ | $\Gamma$ (MeV) | Decay modes | Experiments | interpretation |
|---|---|---|---|---|---|
| X(3872) | $1^{++}$ | <2.3 | $\pi\pi J/\psi$; $\gamma J/\psi$; $DD^*$ | Belle/CDF/D0/BaBar | $DD^*$ molecule? |
| X(3940) | $0^{?+}$ | ~37 | $DD^*$ (not $DD$, $\omega J/\psi$) | Belle | $\eta_c''$(?) |
| Y(3940) | $?^{?+}$ | ~30 | $\omega J/\psi$ (not $DD^*$) | Belle/BaBar | |
| X(4160) | $0^{?+}$ | ~140 | $D^*D^*$ (not $DD$, $DD^*$) | Belle | $\eta_c''$(?) |
| Y(4008) | $1^{--}$ | ~220 | $\pi\pi J/\psi$ | Belle (not Babar) | |
| Y(4260) | $1^{--}$ | ~80 | $\pi\pi J/\psi$ (not $\pi\pi\psi'$) | BaBar/CLEO/Belle | $c\underline{c}g$ hybrid? |
| Y(4360) | $1^{--}$ | ~75 | $\pi\pi\psi'$ (not $\pi\pi J/\psi$) | BaBar/Belle | |
| Y(4660) | $1^{--}$ | ~50 | $\pi\pi\psi'$;$\Lambda_c\Lambda_c$ (?) | Belle | |

## charged Z

| | | | | | |
|---|---|---|---|---|---|
| $Z^{\pm}$(4430) | $?^{??}$ | ~100 | $\psi(2S)\pi^{\pm}$ | Belle (not Babar) | 4quark? |
| $Z^{\pm}$(4050) | $?^{??}$ | ~80 | $\chi_{c1}\pi^{\pm}$ | Belle | 4quark? |
| $Z^{\pm}$(4250) | $?^{??}$ | ~180 | $\chi_{c1}\pi^{\pm}$ | Belle | 4quark? |

# Looking for a state $\overline{c}\overline{q}cq$

- General challenge:
  Scattering states are close for typical L (splitting ~ 100 MeV)

$$D(\vec{k})\overline{D}(-\vec{k}), \quad \vec{k} = \tfrac{2\pi}{L}\vec{j} \qquad E_{D\overline{D}} \approx \sqrt{m_D^2 + j(\tfrac{2\pi}{L})^2} + \sqrt{m_{\overline{D}}^2 + j(\tfrac{2\pi}{L})^2}$$

- All simulations so far:
  Extract **only the ground state**
  Study only channels with **no disconnected contractions** or ignore them
  [except Ehmann, Bali]

# Is X(3872) tetraquark/molecule ?

$$O = (\bar{c}\Gamma q)(\bar{q}'\Gamma' c)$$
$$O = [\bar{c}\bar{q}][q'c]$$

[Chiu & Hsieh, PLB (2006), PRD (2006)]

**$J^{PC}=1^{++}$**

Quenched, overlap fermions

Neglect disconnected contr.

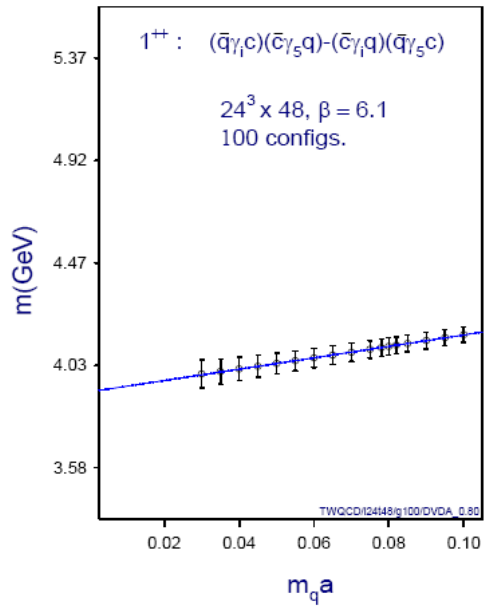
| | | |
|---|---|---|
| $\bar{c}\bar{u}cu$ | $X(3872)$ | $1^+$ or $2^-$ |

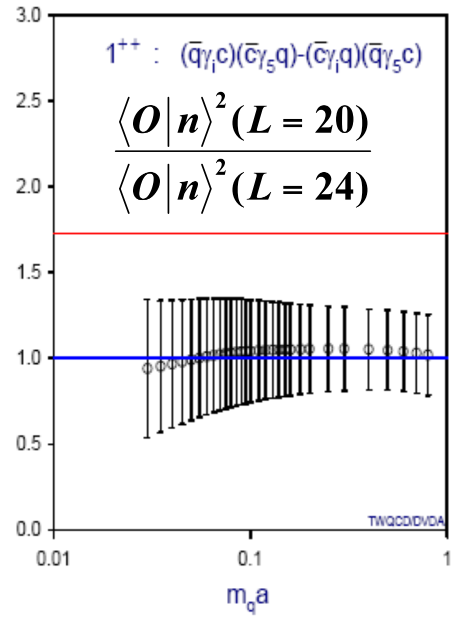
Belle, Babar, CDF, D0

$X(3872) \to \rho\, J/\psi$

$X(3872) \to \omega\, J/\psi$

almost at $\bar{D}^0 D^{0*}$ threshold




possible issue: scattering should be found at the same energies, before tetraquarks can be trusted

indication for tetraquarks with masses:

$\bar{c}\bar{u}cu:\quad m = 3890 \pm 30\ MeV \quad X(3872) \qquad DD^*, \quad m(D)+m(D^*) = 3874\ MeV$

predictions:

$\bar{c}\bar{s}cs:\quad m = 4100 \pm 50\ MeV \quad Y(4140) \qquad J/\psi\ \phi, \quad m(J/\psi)+m(\phi) = 4120\ MeV$

$\bar{c}\bar{u}cs:\quad m = 4010 \pm 50\ MeV \qquad \downarrow \qquad D^*\phi, \quad m(D^*)+m(\phi) = 3980\ MeV$

Discovered by CDF in 2009

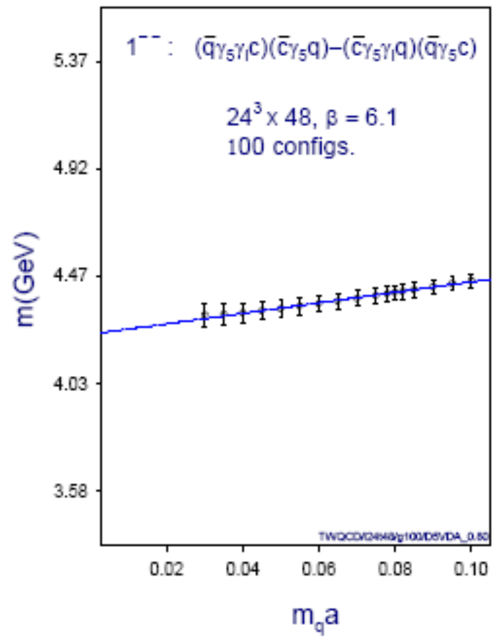
# Is Y(4260) tetraquark/molecule ?

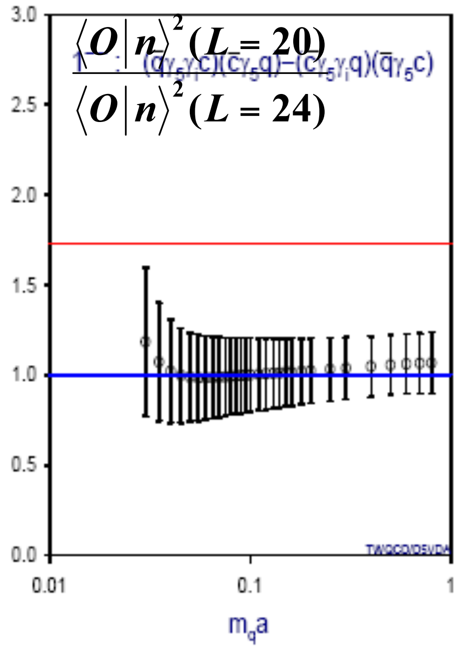
$$O=(\bar{c}\Gamma q)(\bar{q}'\Gamma' c)$$
$$O=[\bar{c}\bar{q}][q'c]$$

[Chiu & Hsieh, PRD73 (2006) 094510]

**$J^{PC}=1^{--}$**
Quenched, overlap fermions
Neglect disconnected contr.

| | | |
|---|---|---|
| $\bar{c}\bar{u}cu$ | $Y(4260)$ | $1^{--}$ |
| Belle, Babar, CDF, D0 | | |
| $Y(4260)\to\rho\, J/\psi$ | | |




indication for tetraquarks with mas

$\bar{c}\bar{u}cu:\quad m=4238\pm 31\ MeV\quad Y(4260)$

predictions :

$\bar{c}\bar{s}cs:\quad m=4450\pm 100\ MeV$

$\bar{c}\bar{c}cc:\quad m=6400\pm 50\ MeV$

possible issue: nearby scattering states should be found, before tetraquarks can be trusted

# Methods to distinguish one/two particle states (again):

## D) Energy shifts

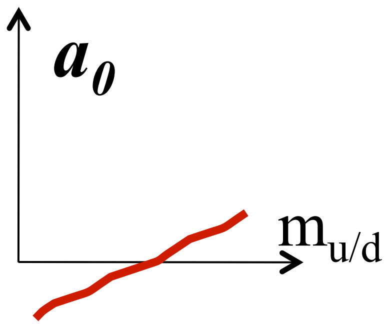
Only precise simulations can determine them

[Luscher 1986, 1991,
Sasaki, Yamazaki :PRD74, 114507]
Liuming Liu, PoS(lat09) 099]

$$O = P_1 P_2$$

$$\Delta E = E^{lat}(L) - m_{P1} - m_{P2} \quad \rightarrow \quad \text{phase shifts}$$

scattering lenght $a_0$




Bound state

Scattering state (attractive)

indication for a bound state: $\cot(\delta) = i$

$a_0$ changes sign

# Is X(3872) tetraquark/molecule ?

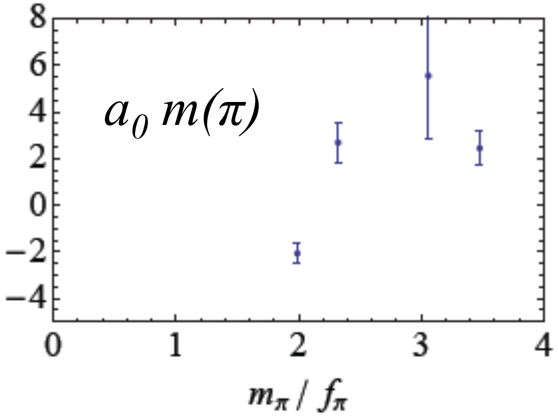
[Liuming Liu, PoS(lat09)099 ]

- dynamical , staggered sea
- extract ground state from single correlator

$$O = (\bar{c}\gamma_5 q)(\bar{q}\gamma_i c) = DD^*$$

$$I = 1, \quad J^{PC} = 1^{++}$$

$\Delta E = E - m_D - m_{D^*} \quad \rightarrow \quad$ scattering lenght $a_0$




Change of sign in a: possible indication for bound state related to X(3872)

Many scattering lenghts determined by Liu (not with purpose of looking for tetraquarks) [see also Yokokawa et al, PRD74 (2006)034504]

$$\mathcal{O}_{\eta_c-\pi}(t) = \eta_c(t)\pi^+(t) \quad \mathcal{O}_{J/\Psi-\pi}(t) = J/\Psi(t)\pi^+(t) \quad \mathcal{O}_{\eta_c-N}(t) = \eta_c(t)N(t)$$

$$\mathcal{O}_{J/\Psi-N} = J/\Psi(t)N(t) \quad \mathcal{O}_{D_s-\pi} = D_s\pi^+ \quad \mathcal{O}^{I=1}_{D-\pi} = D^+\pi^+$$

$$\mathcal{O}^{I=1}_{D-\bar{K}} = D^+\bar{K}^0 \quad \mathcal{O}^{I=0}_{D-\bar{K}} = D^+K^- - D^0\bar{K}^0 \quad \mathcal{O}^{I=1}_{D-K} = D^+K^+$$

$$\mathcal{O}_{D_s-K} = D_s^+K^+ \quad \mathcal{O}^{I=1}_{D-\bar{D}^*} = D^+\bar{D}^{0^*}$$

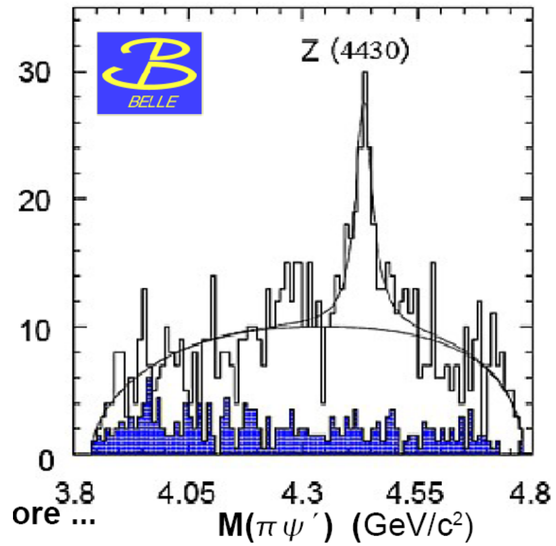
# Is Z+(4430) tetraquark/molecule ?

[Meng et al., PRD80 (2009) 034503]

$\bar{c}c\bar{d}u \quad Z^+(4430)\,, \quad J^{PC}$ unknown

Belle, not Babar

$Z^+(4430) \to \psi' \, \pi^+$




- near to D* $D_1$ threshold: m(D*) + m(D1)= 4430 MeV
- suspected to be D* $D_1$ molecule
  1- 1+
- ground state energy determined from correlator

$$O = (\bar{c}\gamma_i q)(\bar{q}\gamma_5\gamma_i c) = D^* D_1, \quad J^P = 0^-$$

$$\Delta E = E - m_D - m_{D*} \quad \rightarrow \quad \text{scattering lenght } a > 0$$

- attractive interaction , but no change in sign of scattering length
- authors suspect that interaction is no strong enough for bound state

# Methods to distinguish one/two particle states (again):

## C) Dependence of spectrum on boundary cond. in space (finite L eff.)

**1. recent proposal to determine nature of light scalar mesons by**

[Bernard, Lage, Meissner, Rusetsky: 1010.6018 hep-lat] (not applied yet on lattice)

$$u(x+L)=u(x) \quad d(x+L)=d(x) \quad s(x+L)=e^{i\theta}s(x)$$

**2. Comparing spectrum for ordinary and hybrid BC** [Suganuma et al.]

$$\text{ordinary BC}: \; q(x+L)=q(x) \quad \bar{q}(x+L)=\bar{q}(x) \quad \bar{q}q(x+L)=\bar{q}q(x) \quad \bar{q}\bar{q}qq(x+L)=\bar{q}\bar{q}qq(x)$$

$$\text{hybrid BC}: \; q(x+L)=q(x) \quad \bar{q}(x+L)=-\bar{q}(x) \quad \bar{q}q(x+L)=-\bar{q}q(x) \quad \bar{q}\bar{q}qq(x+L)=\bar{q}\bar{q}qq(x)$$

lowest momenta meson is (1,1,1)*2π/L

Tetraquarks: E(hybrid BC)=E(ordinary BC)

Meson-Meson: E(hybrid BC)>E(ordinary BC)

# Ds*(2317): cs or cusu ? Probably cs

$J^P = 0^+$

**Tetraquark interpolator** $O = K\ D = (\bar{s}\gamma_5 u)(\bar{u}\gamma_5 c)$

[ Ming Gong @ Lattice 2010, chiQCD coll, Kentucky]

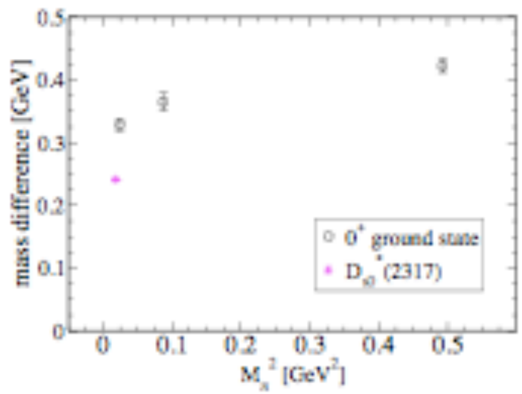
- Dynamical u,d,s, quarks (domain wall quark: RBC/UKQCD)
- Valence u,d,s,c quarks (overlap quarks: exact chiral sym. at mq=0)

- is the ground state tetraquark/molecule or scattering state DK, $D_s\pi$ ?

- two indications showing that ground st. is a scattering state:
  - E with ordinary and hybrid BC differ, just like expected for two meson states
  - C(t) behaves as expected as two-meson state

**Quark-antiquark interpolators** $O = \bar{s}c$

[Mohler Lat2010,
chiQCD,
Ohta … ]




Mohler, Lat2010

# Mixing of charmonia and DD states

[Ehmann & Bali, Lat2009, 0911.1238]

- 2+1 flavor simulation
- Disconnected contractions are taken into account !
- Several eigenstates are extracted, not only ground state!

$\bar{c}q$ and $(\bar{c}q)(\bar{q}c)$ interpolators in the same variational basis

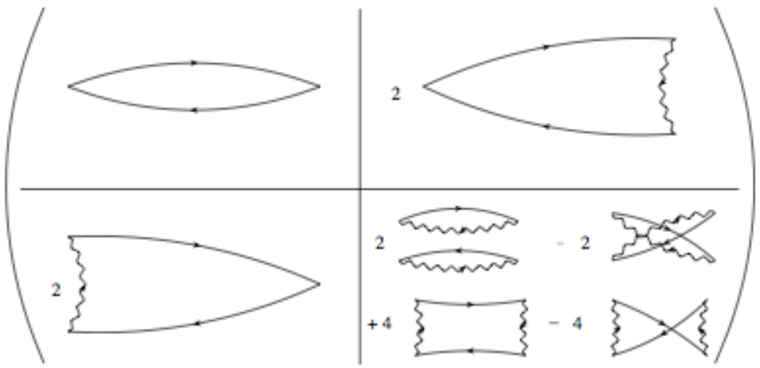



**Figure 1:** The mixing matrix. Solid lines represent charm quarks, wiggled lines light quarks.

# Conclusions

- Do light scalar mesons σ and κ have tetraquark component?

We find two light states in I=0 and I=1/2 channels. One is the scattering state, while the other state may be candidate for σ or κ with strong tetraquark component. Confirmation is needed before firm conclusion!

Ultimate study would need to take into account mixing $\bar{q}\bar{q}qq \leftrightarrow \bar{q}q \leftrightarrow vac. \leftrightarrow glue$ and the interpolators have to cover all these Fock components. Then one could determine the fraction of physical states in terms of various Fock components.

- Are some of hidden charm states XYZ tetraquarks/molecules?

There is some indication for tetraquark/molecular structure of X(3872), Y(4260), Y(4140) from the lattice, but much more work is needed. Few excited states would have to be extracted in addition to the ground state to make reliable identification for tetraquark/molecular states.

# Backup slides

# E and Z independent of interpolator set and t0

for all isospins, pion masses, both simulations

$E_n,\ Z_i^n = \langle O_i | n \rangle$

from C(t):

**5x5, 4x4, 3x3**