

Heavy Exotics and RHIC

Su Houn Lee



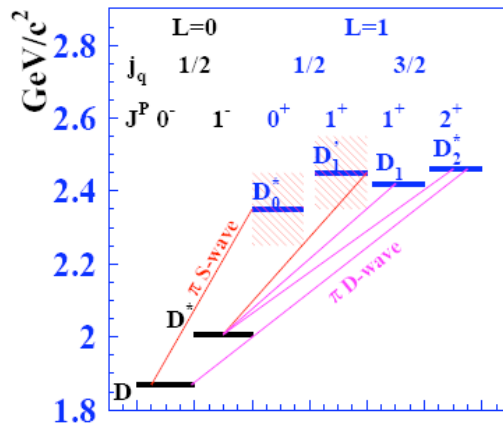
YONSEI
UNIVERSITY

Based on

SHL, S. Yasui, W.Liu, C.M.Ko:
SHL, S. Yasui :

EPJ 08, arXiv:0707.1747
arXiv:0901.2977

Recent Highlights in Hadron Physics



Babar: $D_{SJ}(2317) 0^+$

Puzzle in Constituent Quark Model(2400)

1. DK threshold effect
2. Chiral partner of $(0^- 1^-)$
3. Tetraquark

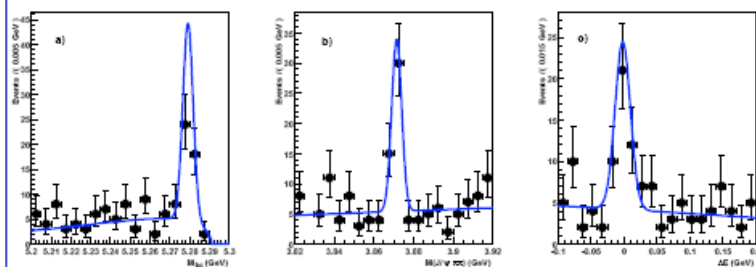


FIG. 17: X(3872) in the $J/\psi\pi^+\pi^-$ channel from Ref. [150].

molecule ?

D0	D*	D1
1864	2007	2420
D0+D*	D*+D*	D1+D*
3871	4014	4427

X(3872), Y(4260),

Z(4430) $\rightarrow \psi'\pi$ (Belle PRL08) (BaBar ?)

Z(4051), Z(4248) $\rightarrow \chi_{c1}\pi$ (arXiv:0806.4098)

Must contain $c\bar{c}$?

Z(4248) ?

Tetraquark ?

observation of scalar nonet

VOLUME 86, NUMBER 5

PHYSICAL REVIEW LETTERS

29 JANUARY 2001

Experimental Evidence for a Light and Broad Scalar Resonance in $D^+ \rightarrow \pi^- \pi^+ \pi^+$ Decay

(Fermilab E791 Collaboration)

σ

From a sample of 1172 ± 61 $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decays, we find $\Gamma(D^+ \rightarrow \pi^- \pi^+ \pi^+)/\Gamma(D^+ \rightarrow K^- \pi^+ \pi^+) = 0.0311 \pm 0.0018^{+0.0016}_{-0.0026}$. Using a coherent amplitude analysis to fit the Dalitz plot of these decays, we find strong evidence that a scalar resonance of mass $478^{+24}_{-23} \pm 17$ MeV/ c^2 and width $324^{+42}_{-40} \pm 21$ MeV/ c^2 accounts for approximately half of all decays.

VOLUME 89, NUMBER 12

PHYSICAL REVIEW LETTERS

16 SEPTEMBER 2002

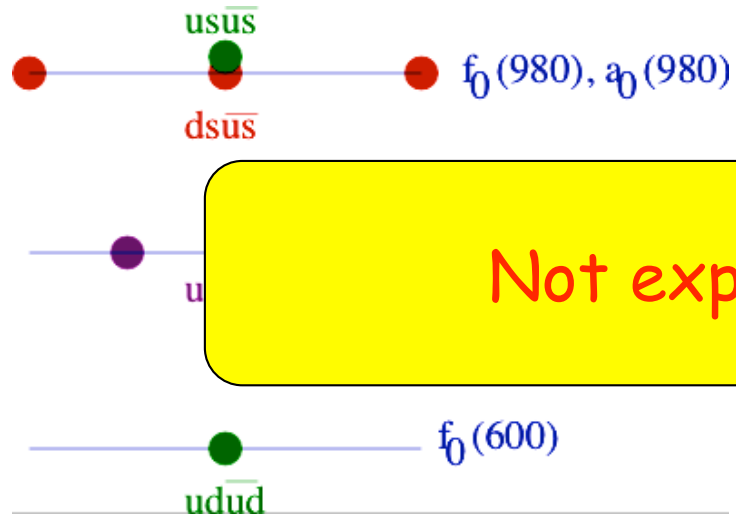
Dalitz Plot Analysis of the Decay $D^+ \rightarrow K^- \pi^+ \pi^+$ and Indication of a Low-Mass Scalar $K\pi$ Resonance

(Fermilab E791 Collaboration)

κ

We study the Dalitz plot of the decay $D^+ \rightarrow K^- \pi^+ \pi^+$ with a sample of 15090 events from Fermilab experiment E791. Modeling the decay amplitude as the coherent sum of known $K\pi$ resonances and a uniform nonresonant term, we do not obtain an acceptable fit. If we allow the mass and width of the $K_0^*(1430)$ to float, we obtain values consistent with those from PDG but the χ^2 per degree of freedom of the fit is still unsatisfactory. A good fit is found when we allow for the presence of an additional scalar resonance, with mass $797 \pm 19 \pm 43$ MeV/ c^2 and width $410 \pm 43 \pm 87$ MeV/ c^2 . The mass and width of the $K_0^*(1430)$ become $1459 \pm 7 \pm 5$ MeV/ c^2 and $175 \pm 12 \pm 12$ MeV/ c^2 , respectively. Our results provide new information on the scalar sector in hadron spectroscopy.

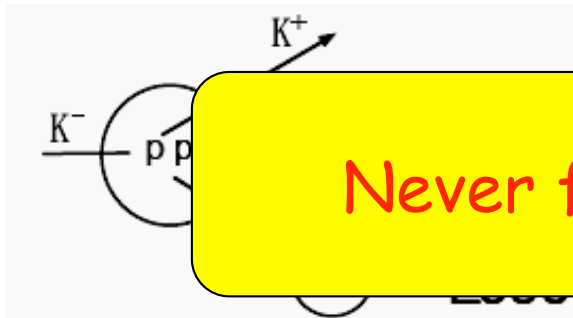
Previous work on Multiquark configuration



Scalar tetraquark (Jaffe 76)

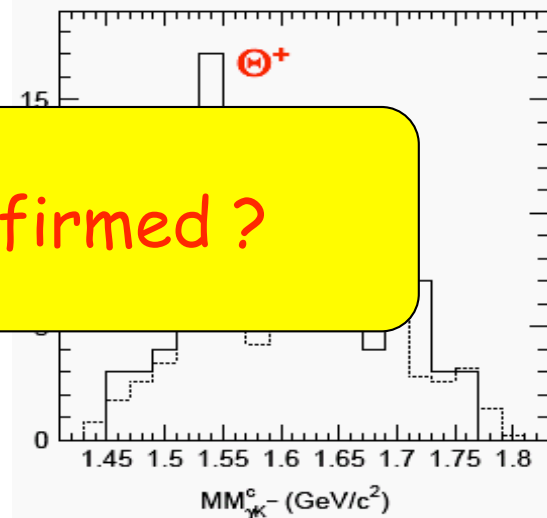
Not explicitly exotic

Search for H dibaryon



Never found nor confirmed ?

Search for Θ^+ pentaquark

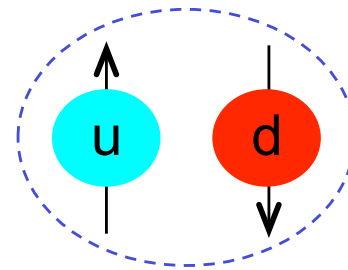


Many theoretical approaches

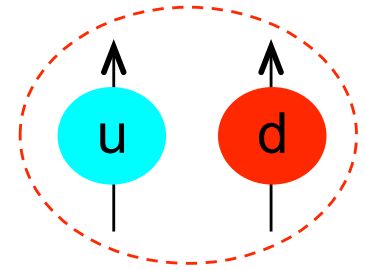
- Soliton models
- QCD sum rules
- Bag models
- Constituent quark models
- ADS/QCD

Scalar Diquark $\langle \epsilon^{abc} u_a C \gamma^5 d_b \rangle$: A common feature in Quark model

Important diquark	qq (scalar)	qq (A-Vector)
Color	Antisym	Antisym
Flavor	Antisym (I=0)	Sym (I=1)
Spin	Antisym (S=0)	Sym (S=1)
Total force	attractive	repulsive



Scalar diquark



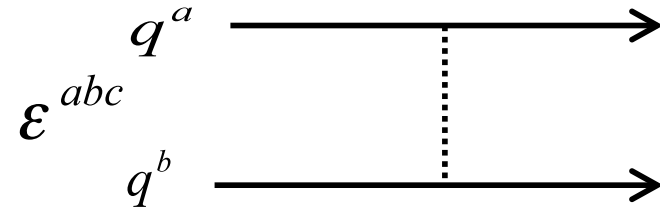
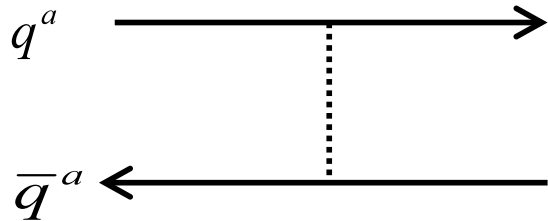
A-Vector diquark

Jaffe, Wilczek PRL03

Attraction between quarks in the color $\bar{3}_c$ channel has profound roots in microscopic QCD. Indeed, by bringing quarks together in this channel one halves the magnitude of their effective charge, and thus largely cancels the associated field energy. This idea is the basis color superconductivity in dense quark matter, a context in which it can be made quite rigorous [17].

1. Special feature of QCD: comes from one gluon exchange, Instanton
2. Long history in Baryon spectrum : example $\Lambda \Sigma$,,,,
3. Responsible for Exotics (Multiquark configuration)♪
4. Color superconductivity: 2SC,CFL, BEC♪
5. sQGP: Shuryak, Zahed (04)

$q\bar{q}$ vs qq attraction



$$-\frac{4\alpha}{3} \frac{1}{r}$$

One gluon exchange

$$-\frac{1}{2} \frac{4\alpha}{3} \frac{1}{r}$$

$$\sigma \times r$$

Lattice calculation
(Nakamura, Saito 05)

$$\frac{1}{2} \sigma \times r$$

$$\frac{C}{m_i m_k} \sum S_i \cdot S_k$$

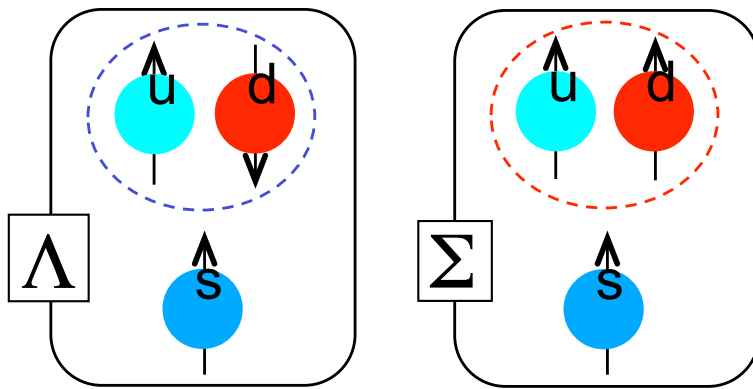
Phenomenological fit of
color spin interaction
to hadron spectrum

$$\frac{1}{3} \frac{C}{m_i m_k} \sum S_i \cdot S_k$$

Baryon Mass difference

$$\text{Mass} = \text{Kinetic} + \text{confining..} + \sum_{i,j} \frac{C_B}{m_i m_j} [s_i \cdot s_j]$$

Example



$$\Lambda_c \text{ Mass} = \text{Kinetic} + \dots - \frac{3}{4} \frac{C_B}{m_u m_d}$$

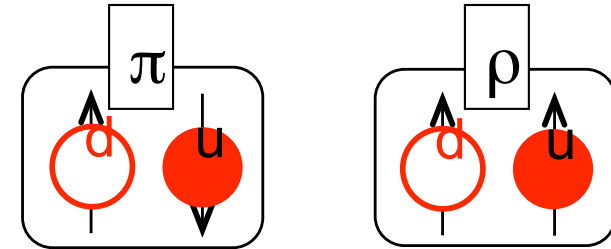
$$\Sigma_c \text{ Mass} = \text{Kinetic} + \dots + \frac{1}{4} \frac{C_B}{m_u m_d} - \frac{C_B}{m_u m_s}$$

$$m_u = m_d = 300 \text{ MeV}, \quad m_s = 500 \text{ MeV}, \quad m_c = 1500 \text{ MeV}, \quad m_b = 4700 \text{ MeV}$$

Mass diff	$M_\Delta - M_N$	$M_\Sigma - M_\Lambda$	$M_{\Sigma_c} - M_{\Lambda_c}$	$M_{\Sigma_b} - M_{\Lambda_b}$
Formula	290 MeV	77 MeV	154 MeV	180 MeV
Experiment	290 MeV	75 MeV	170 MeV	192 MeV

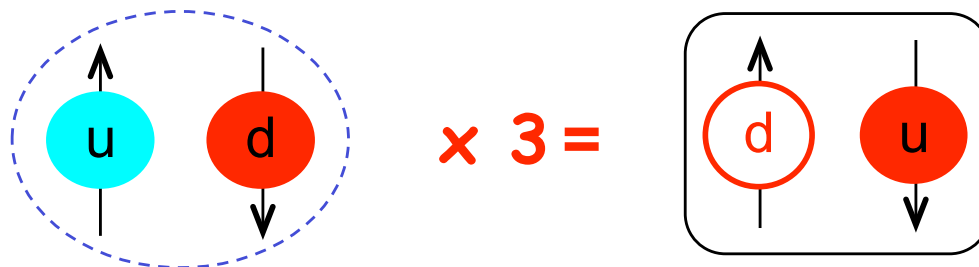
Meson Mass difference

$$\text{Mass} = \text{Kinetic} + \text{confining..} + \sum_{i,j} \frac{C_M}{m_i m_j} [s_i \cdot s_j]$$



Mass diff	$M_\rho - M_\pi$	$M_{K^*} - M_K$	$M_{D^*} - M_D$	$M_{B^*} - M_B$
Formula	635 MeV	381 MeV	127 MeV	41 MeV
Experiment	635 MeV	397 MeV	137 MeV	46 MeV

Works very well with $3 \times C_B = C_M = 635 m_u^2$



Stable Multiquark configurations in a schematic diquark model

$$\text{Mass} = \text{Kinetic} + \text{confining..} + \sum_{i,j} \frac{C_H}{m_i m_j} [s_i \cdot s_j]$$

Diquarks with different flavors

	Type of diquark and its q-q binding		
S=C=0	(ud) $\rightarrow$ A		
S=-1, $m_s=5/3m_u$	(us) $\rightarrow$ 3/5 A	(ds) $\rightarrow$ 3/5 A	
C=1, $m_c=5m_u$	(uc) $\rightarrow$ 1/5 A	(dc) $\rightarrow$ 1/5 A	(sc) $\rightarrow$ 3/25 A

$$A = \frac{3}{4} \frac{C_B}{m_u^2} = 145 \text{ MeV}$$

Multiquark hadrons

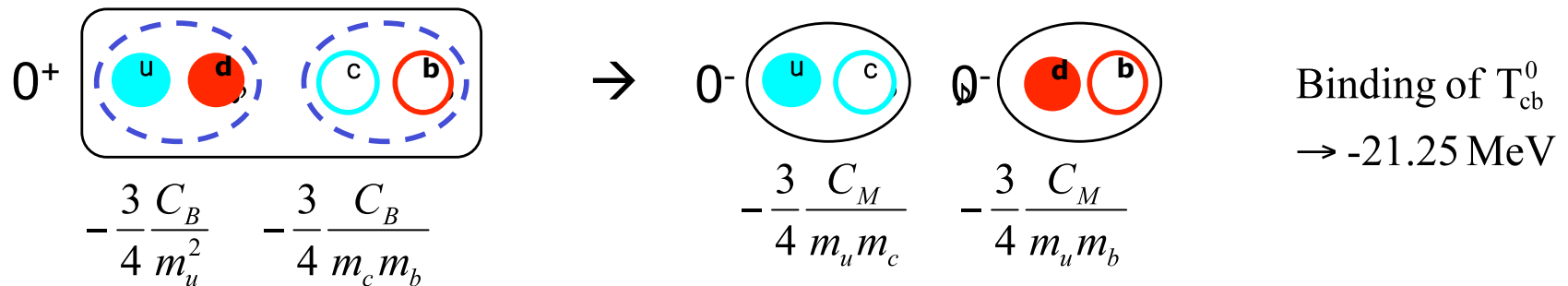
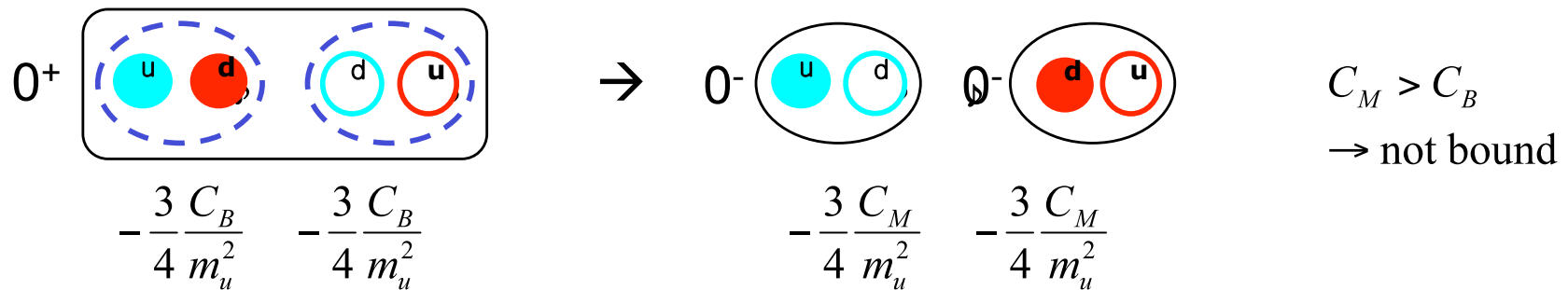
(ud) + $\overline{(us)}$ $\rightarrow$ Tetraquark

(ud) (us) (ds) $\rightarrow$ dibaryon

(ud) (us) + $\overline{q}$ $\rightarrow$ Pentaquark

Tetra-quark - configurations

Binding against decay = (Mass of 2 Mesons) – (Mass of Tetraquark)



Tetra-quark - hadronic weak decay modes

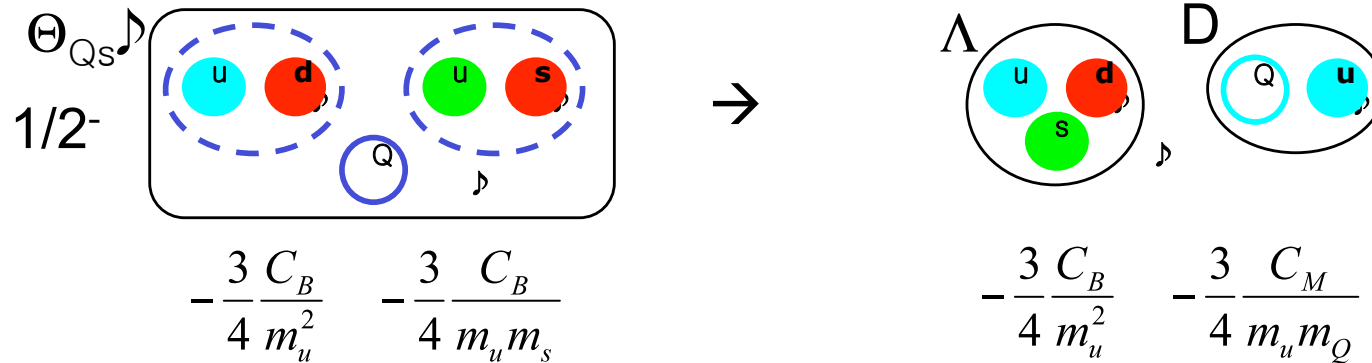
$$T_{cb}^0(ud\bar{c}\bar{b}) \rightarrow (\bar{D}^0 + B^0) \rightarrow K^+\pi^- + K^+\pi^-$$

$$T_{cc}^1(ud\bar{c}\bar{c}) \quad 1^+ \quad \left[\begin{array}{c} \text{u} \quad \text{d} \\ \text{c} \quad \text{c} \end{array} \right] \rightarrow \quad 0^- \quad \left[\begin{array}{c} \text{u} \quad \text{c} \\ \text{d} \quad \text{c} \end{array} \right] \quad 1^-$$

$$-\frac{3}{4} \frac{C_B}{m_u^2} + \frac{1}{4} \frac{C_B}{m_c^2} \quad -\frac{3}{4} \frac{C_M}{m_u m_c} + \frac{1}{4} \frac{C_M}{m_u m_c}$$

T_{cc}^1	$ud\bar{c}\bar{c}$	$us\bar{c}\bar{c}$	$ds\bar{c}\bar{c}$
	-79.3 $\bar{D}^0 + D^{*-}, \bar{D}^{*0} + D^-$	-8.7 $\bar{D}^0 + D_s^{*-}$	-8.7 $D^- + D_s^{*-}$
T_{bb}^1	$ud\bar{b}\bar{b}$	$us\bar{b}\bar{b}$	$ds\bar{b}\bar{b}$
	-124.3 $B^+ + B^{*0}, B^{*+} + B^0$	-62.3 $B^+ + B_s^{*0}$	-62.3 $B^0 + B_s^{*0}$
T_{cb}^1	$ud\bar{c}\bar{b}$	$us\bar{c}\bar{b}$	$ds\bar{c}\bar{b}$
	-59.0 $B^{*+} + D^-, B^{*0} + \bar{D}^0$	+2.9 $B_s^{*0} + D^0$	+2.9 $B_s^{*0} + D^-$

Pentaquarks (states with two diquarks)



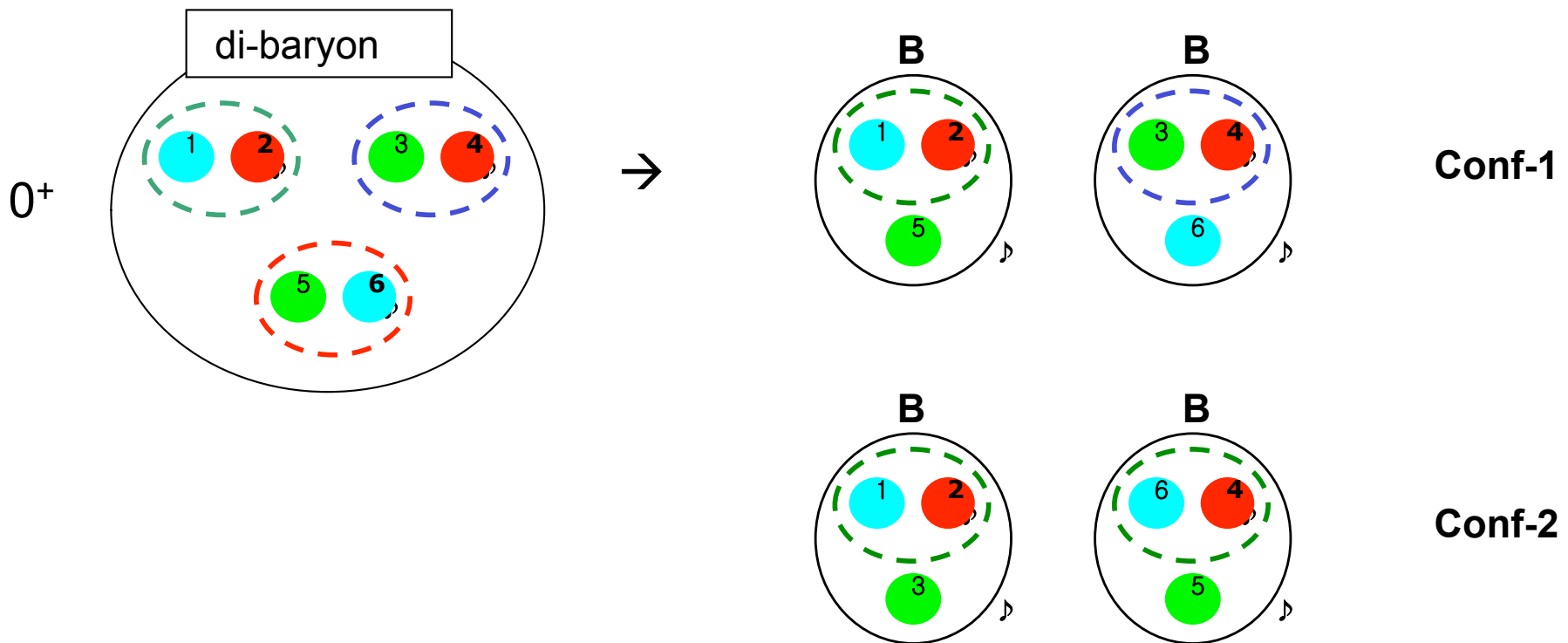
Θ	$M+B$	$\bar{u}$	$\bar{s}$	$\bar{c}$	b
$ud\,us\,\bar{q}$	$ud\,s+u\bar{q}$	389.4	198.9	8.4	-56.4
$us\,ds\,\bar{q}$	$ds\,s+u\bar{q}$	389.4	198.9	8.4	-56.4
	$ud\,s+s\bar{q}$	256.8	142.5	28.4	-10.7

$$\Theta_{cs}(udus\bar{c}) \rightarrow (\Lambda + \bar{D}^0) \rightarrow \Lambda + K^+ \pi^-$$

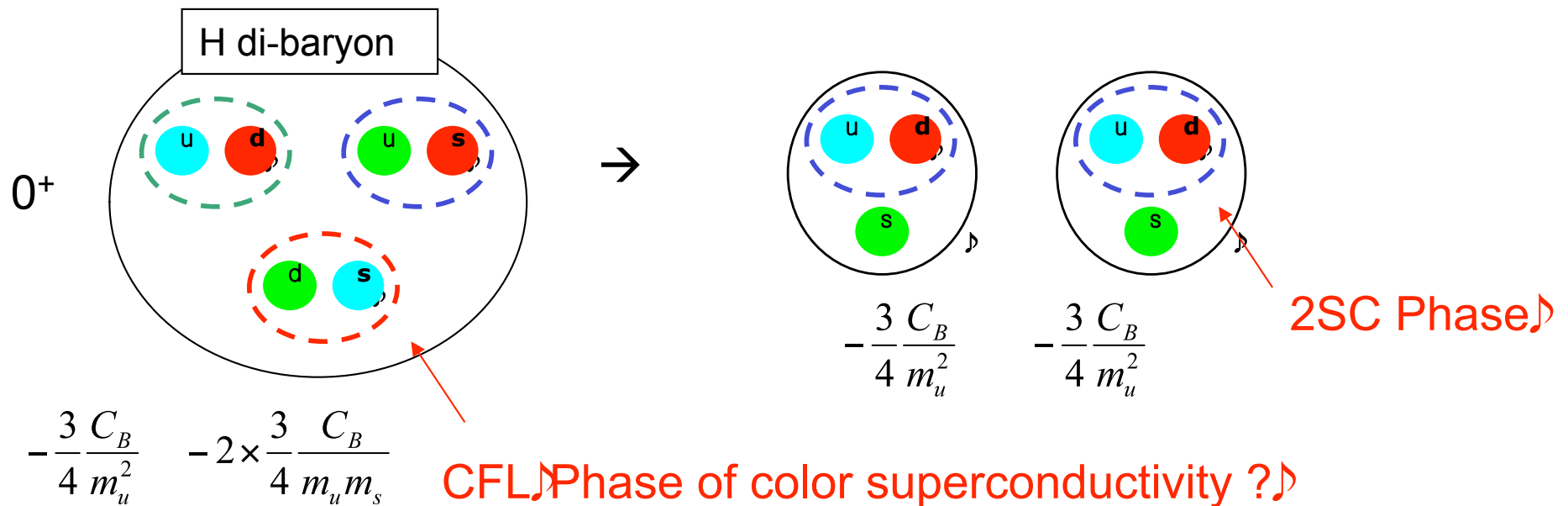
Di-baryon - general considerations

$S=C=0$	$(ud) \rightarrow -A$		
$S=-1, m_s=5/3m_u$	$(us) \rightarrow -3/5 A$	$(ds) \rightarrow -3/5 A$	
$C=1, m_c=5m_u$	$(uc) \rightarrow -1/5 A$	$(dc) \rightarrow -1/5 A$	$(sc) \rightarrow -3/25 A$

$$A = \frac{3}{4} \frac{C_B}{m_u^2} = 145 \text{ MeV}$$



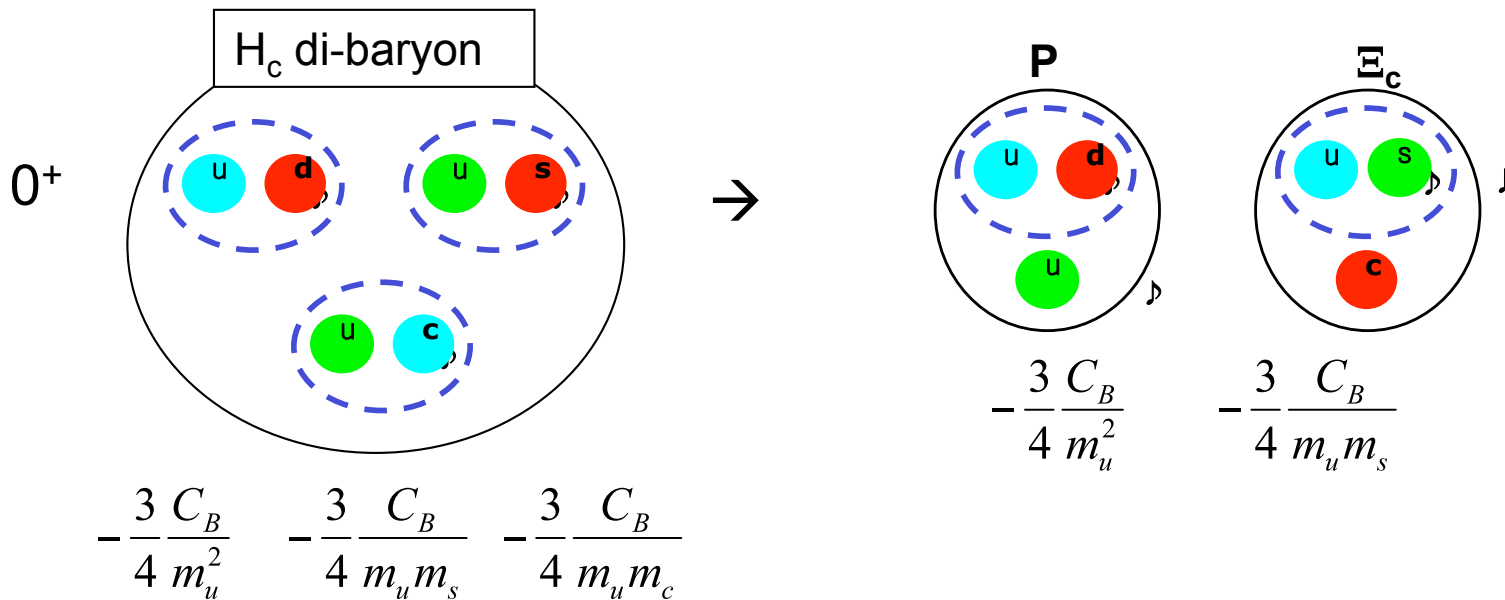
Di-bayron (Conf 1) - (qq) (qq) (qq)



H Binding = -29 MeV

H di-baryon → could be bound
→ unfortunately not found in elementary processes

Di-baryon (Conf 2) - (qq) (qq) (qQ)



H_c Binding = -29 MeV

H_c di-baryon $\rightarrow$ new prediction

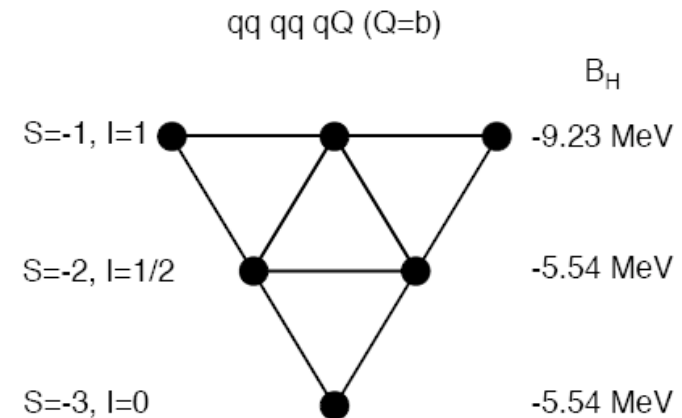
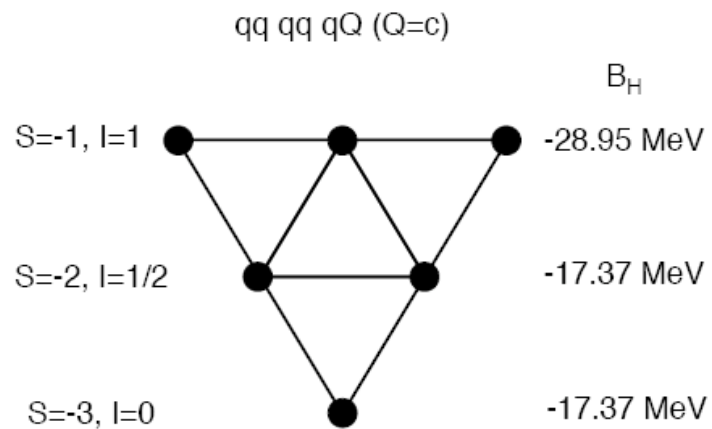
$\rightarrow$ could be found in heavy ion collision

$$H_c(udusuc) \rightarrow (\Lambda_c^+ + \Sigma^+) \rightarrow pK^- \pi^+ + p\pi^0$$

$$\rightarrow (p + \Xi_c^+) \rightarrow p + \Lambda K^- \pi^+ \pi^+$$

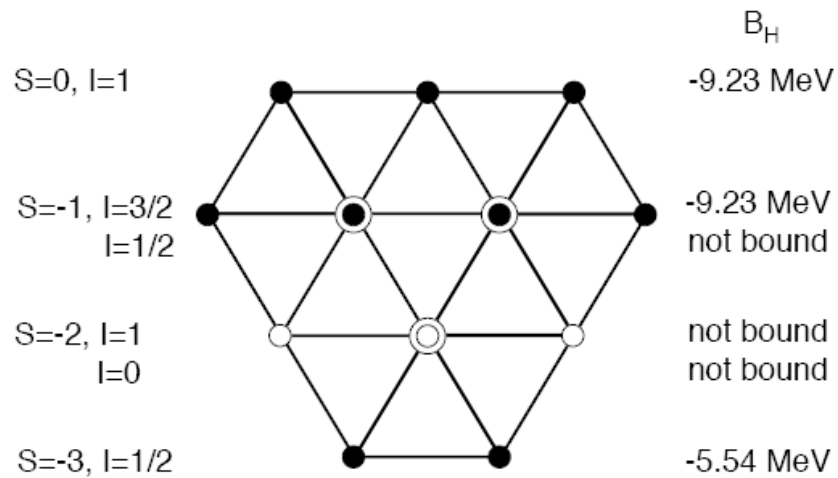
Representation of H_c Di-baryon $(qq)(qq)(qQ)$

$$\bar{\mathbf{3}}_f \times \bar{\mathbf{3}}_f \times \mathbf{3}_f = (\mathbf{3}_f^a + \bar{\mathbf{6}}_f^s) \times \mathbf{3}_f = \boxed{\bar{\mathbf{3}}_f^a + \mathbf{6}_f} + \bar{\mathbf{3}}_f^s + \bar{\mathbf{15}}_f$$

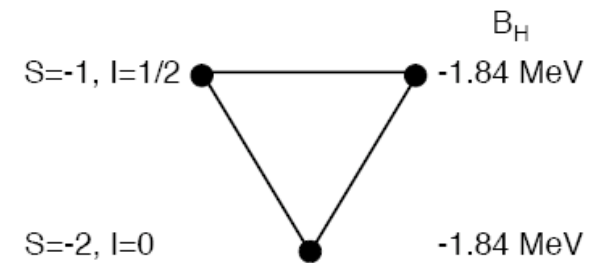


Other Possibly Stable Di-baryons

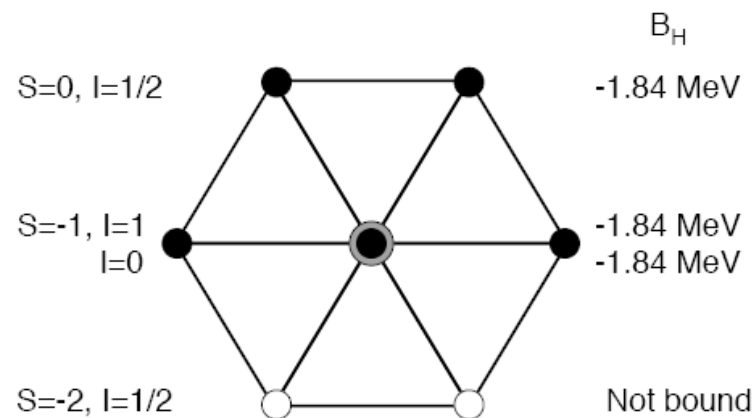
qq qQ qQ' (Q=c, Q'=b)



qq qq QQ' (Q=c, Q'=b)



qq qQ QQ' (Q=c, Q'=b)



Searching for Exotics at RHIC (STAR, FAIR, LHC)

1. Large number of c and b quark produced
2. Vertex detector
3. Example: FAIR 10^4 / Month $D^0 \rightarrow k^- \pi^+$

Lee, Yasui, Liu, Ko EPJ 08

$n_u n_d n_q = \exp(-\Delta m/T)$	Coalescence model	Statistical model
Θ_{cs} / D^0	0.74×10^{-3}	1.4×10^{-3}
Θ_{cs} / D_{s1}	2.3×10^{-3}	4.0×10^{-3}

Summary

1. Diquark are unique in QCD
2. Multiquark states will exist in Heavy sector, due to diquark structure $T_{cc} (ud \bar{c}\bar{c})$, $\Theta_{cs} (udus\bar{c})$, $H_c(udusuc)$...
RHIC, LHC can be a very useful heavy exotic factory
 - ☒ If found, it will be the first exotic ever,
 - ☒ will tell us about QCD, q-q interaction and dense matter
 - ☒ great step forward in QCD
3. If diquarks exist near T_c , additional production of T_{cc} and Θ_{cs} . Λ_c / D enhancement can be a signature of sQGP
 - ☒ LHC plans to measure Λ_c and D
4. Multiquark states are doorway to dense QCD.

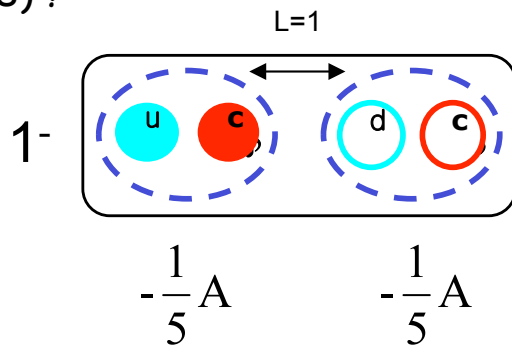
Back ups

diquark - anti-diquark (Tetra-quark) - II

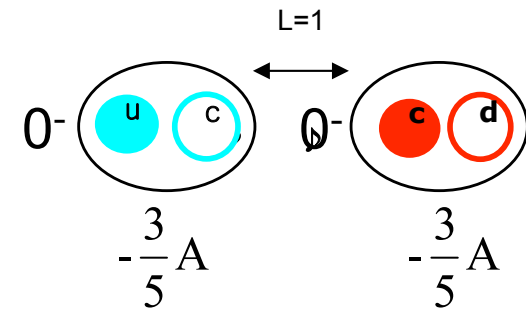
$S=C=0$	$(ud) \rightarrow A$		
$S=-1, m_s=5/3m_u$	$(us) \rightarrow 3/5 A$	$(ds) \rightarrow 3/5 A$	
$C=1, m_c=5m_u$	$(uc) \rightarrow 1/5 A$	$(dc) \rightarrow 1/5 A$	$(sc) \rightarrow 3/25 A$

$$A = \frac{3}{4} \frac{C_B}{m_u^2} = 145 \text{ MeV}$$

Z(4248) ?



→



$$\text{Tetraquark Mass} = \text{Kinetic} + \dots + \left(-\frac{2}{5} A + \frac{L^2}{2I} \right)$$

$$2 \text{ Meson mass} = \text{Kinetic} + \dots + \left(-\frac{6}{5} A \right) = 3740 \text{ MeV}$$

$$\frac{L^2}{2I} = \frac{2\Lambda_{c[3/2]}^* (2625) + \Lambda_{c[1/2]}^* (2593)}{3} - \Lambda_c = 330.74 \text{ MeV}$$

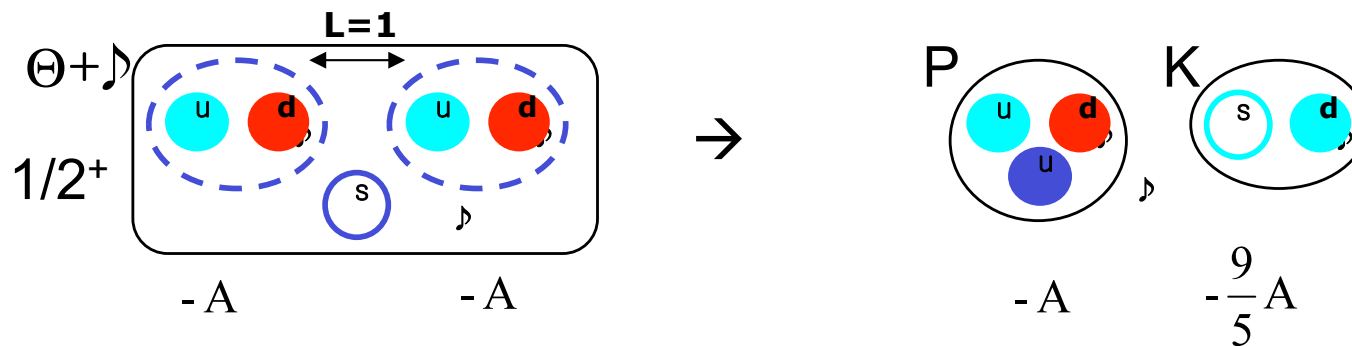
$$\text{Binding} = -\frac{6}{5} A - \left(-\frac{2}{5} A + \frac{L^2}{\mu^{0.23}} \right) = -447 \text{ MeV}$$

$$\rightarrow \text{Tetraquark Mass} \approx 3740 \text{ MeV} + 447 \text{ MeV} = 4187 \text{ MeV}$$

Pentaquark - general considerations

$S=C=0$	$(ud) \rightarrow -A$		
$S=-1, m_s=5/3m_u$	$(us) \rightarrow -3/5 A$	$(ds) \rightarrow -3/5 A$	
$C=1, m_c=5m_u$	$(uc) \rightarrow -1/5 A$	$(dc) \rightarrow -1/5 A$	$(sc) \rightarrow -3/25 A$

$$A = \frac{3}{4} \frac{C_B}{m_u^2} = 145 \text{ MeV}$$



$$L^2 \text{ contribution} \quad \frac{2\Lambda_{[3/2]}^*(1520) + \Lambda_{[1/2]}^*(1405)}{3} - \Lambda = \frac{L^2}{2I} = 366.15 \text{ MeV}$$

$$\Theta + \text{Binding} \approx -\frac{4}{5}A - 366 \text{ MeV} = -480 \text{ MeV} \rightarrow -500 \text{ MeV}$$

in Full quark model by Hiyama, Hosaka et al

$\Theta^+ 1540$ can not be a pentaquark state, if it exists ?