

# THE HIDDEN-CHARM PENTAQUARK AND TETRAQUARK STATES

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# Experimental status of Pc(4380) and Pc(4450)

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 PHYSICAL REVIEW LETTERS

week ending  
 14 AUGUST 2015



## Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays

R. Aaij *et al.*\*  
 (LHCb Collaboration)

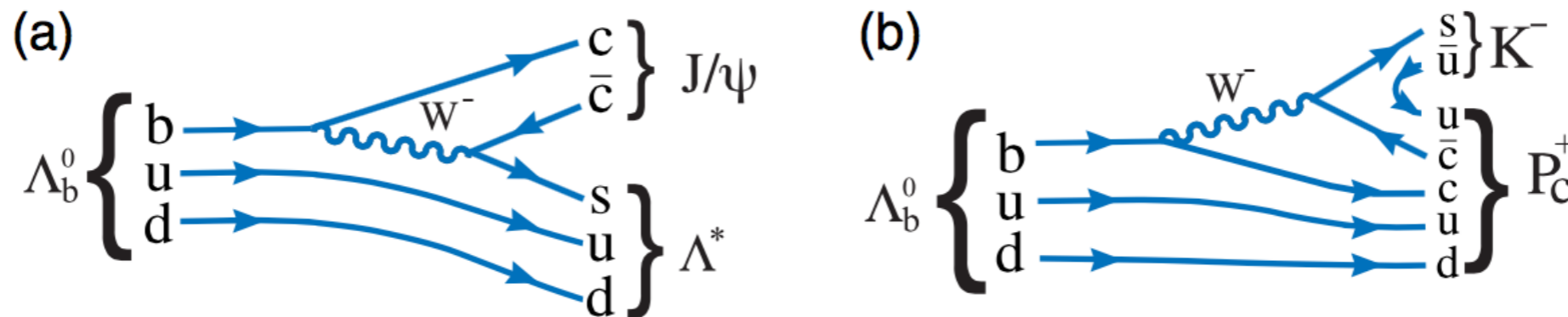


FIG. 1 (color online). Feynman diagrams for (a)  $\Lambda_b^0 \rightarrow J/\psi \Lambda^*$  and (b)  $\Lambda_b^0 \rightarrow P_c^+ K^-$  decay.

# The measured invariant mass spectra

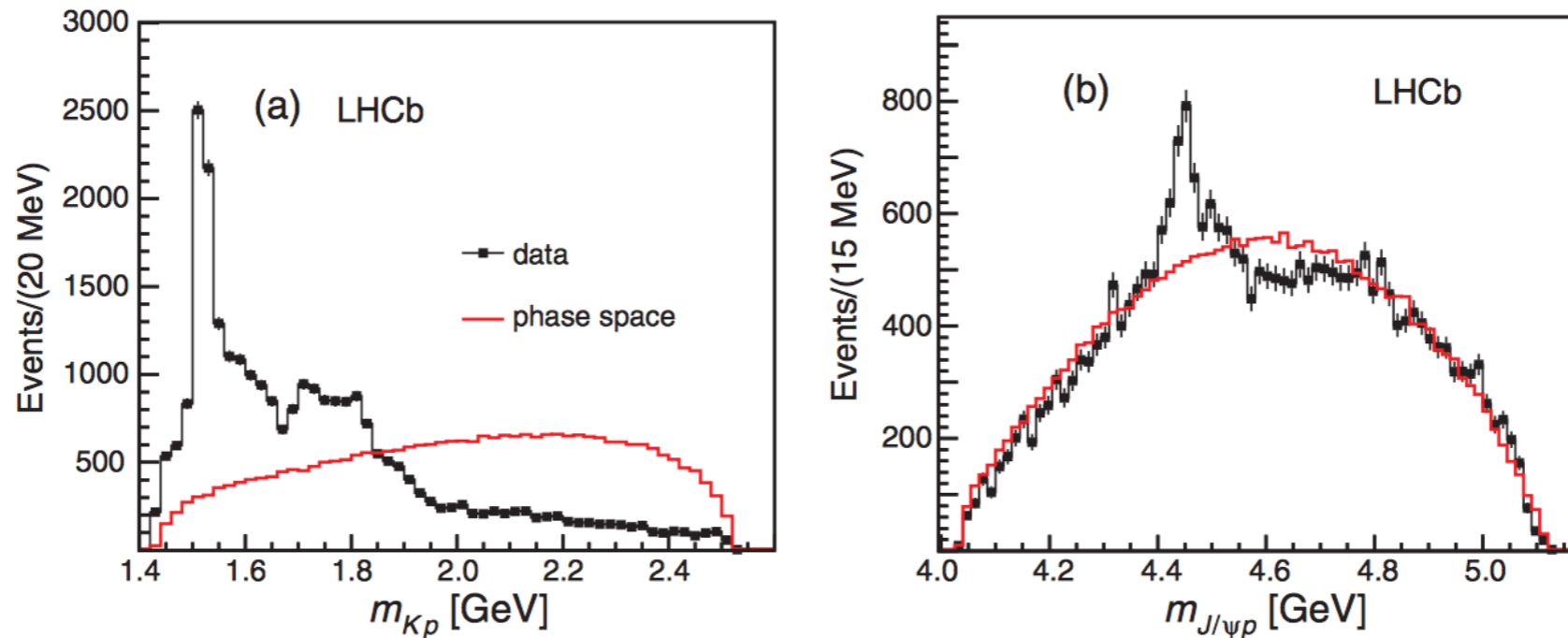
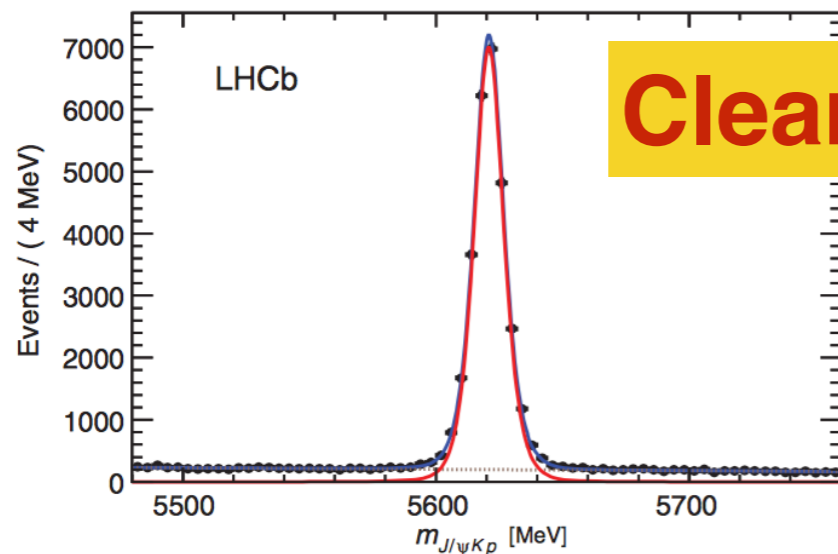


FIG. 2 (color online). Invariant mass of (a)  $K^- p$  and (b)  $J/\psi p$  combinations from  $\Lambda_b^0 \rightarrow J/\psi K^- p$  decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.



**Clear signal of  $\Lambda_b$**

**LHCb performed the analysis of the above experimental data**

FIG. 4 (color online). Invariant mass spectrum of  $J/\psi K^- p$  combinations, with the total fit, signal, and background components shown as solid (blue), solid (red), and dashed lines, respectively.

# With two Pc states to fit the data

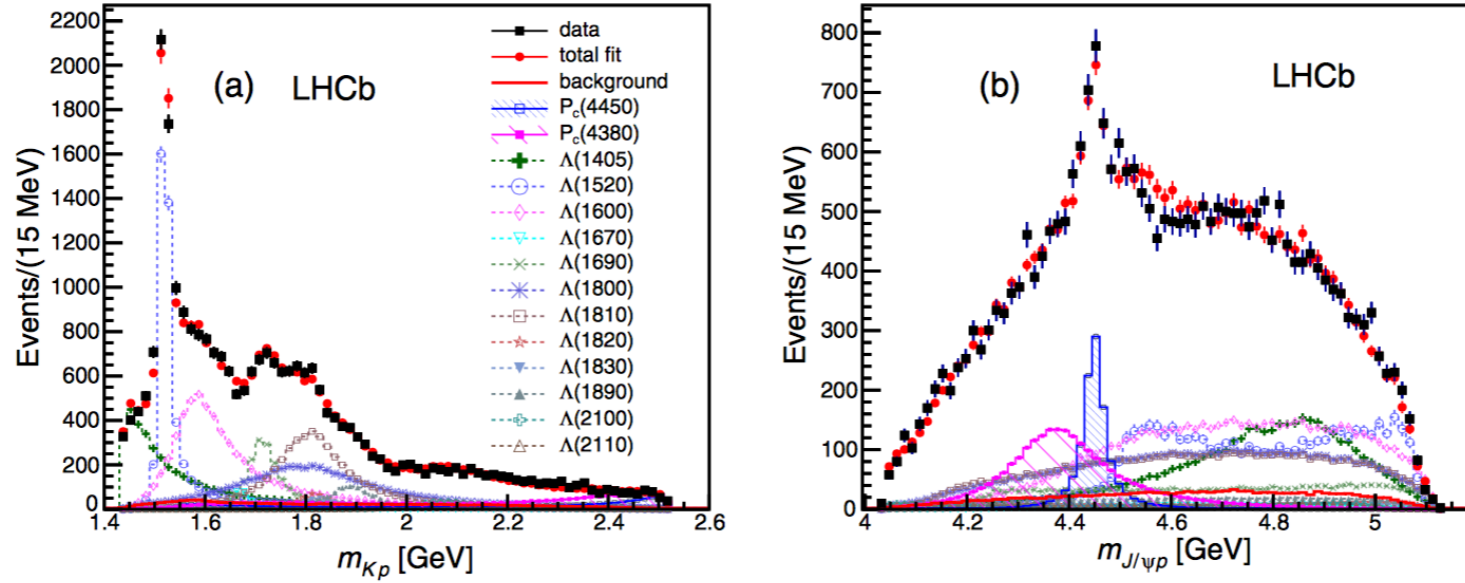


FIG. 5 (color online). Fit projections for (a)  $m_{Kp}$  and (b)  $m_{J/\psi p}$  for the reduced  $\Lambda^*$  model with two  $P_c^+$  states (see Table I). The data are shown as solid (black) squares, while the solid (red) points show the results of the fit. The solid (red) histogram shows the background contribution. The (blue) open squares with the shaded histogram represent the  $P_c(4450)^+$  state, and the shaded histogram topped with (purple) filled squares represents the  $P_c(4380)^+$  state. Each  $\Lambda^*$  component is also shown. The error bars on the points showing the fit results are due to simulation statistics.

# Without two Pc states to fit the data

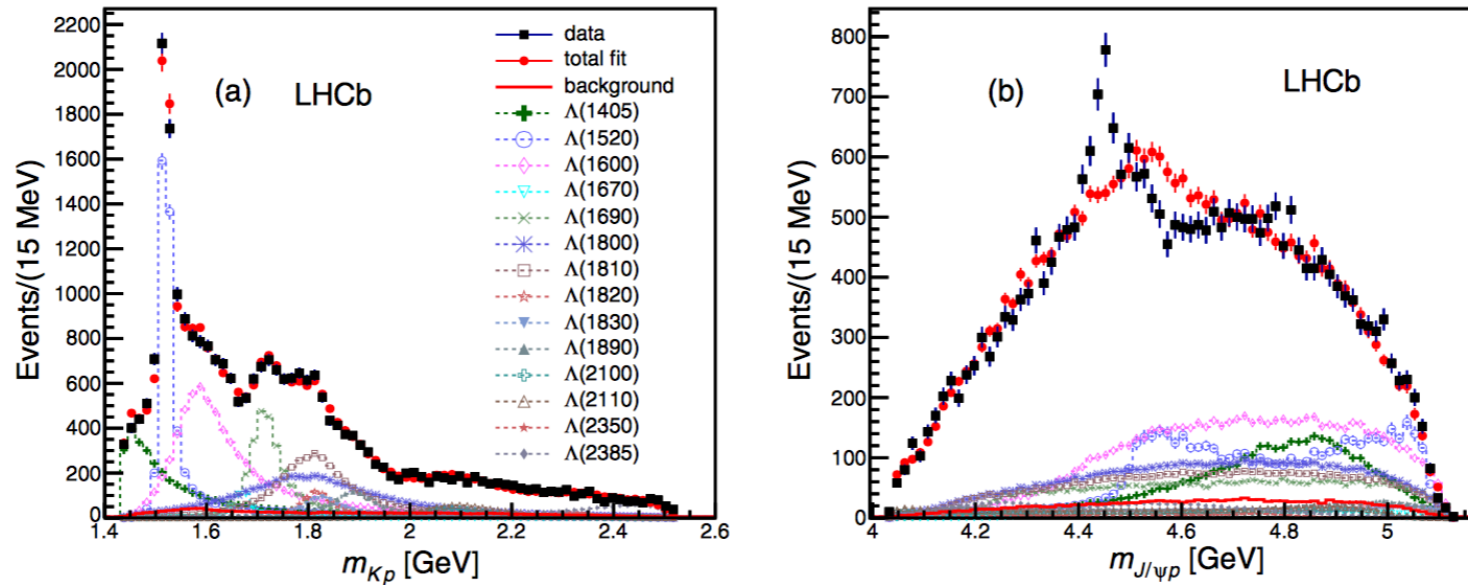


FIG. 6 (color online). Results for (a)  $m_{Kp}$  and (b)  $m_{J/\psi p}$  for the extended  $\Lambda^*$  model fit without  $P_c^+$  states. The data are shown as (black) squares with error bars, while the (red) circles show the results of the fit. The error bars on the points showing the fit results are due to simulation statistics.

# The $\Lambda^*$ resonances included in the data analysis

TABLE I. The  $\Lambda^*$  resonances used in the different fits. Parameters are taken from the PDG [12]. We take  $5/2^-$  for the  $J^P$  of the  $\Lambda(2585)$ . The number of  $LS$  couplings is also listed for both the reduced and extended models. To fix overall phase and magnitude conventions, which otherwise are arbitrary, we set  $B_{0,\frac{1}{2}} = (1, 0)$  for  $\Lambda(1520)$ . A zero entry means the state is excluded from the fit.

State	$J^P$	$M_0$ (MeV)	$\Gamma_0$ (MeV)	Number Reduced	Number Extended
$\Lambda(1405)$	$1/2^-$	$1405.1_{-1.0}^{+1.3}$	$50.5 \pm 2.0$	3	4
$\Lambda(1520)$	$3/2^-$	$1519.5 \pm 1.0$	$15.6 \pm 1.0$	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx 2585$	200	0	6

**If describing the experimental data, **two Pc states are introduced**. Otherwise, the mass distribution of  $J/\psi p$  cannot be understood**

# Resonance parameters of two $P_c$ states

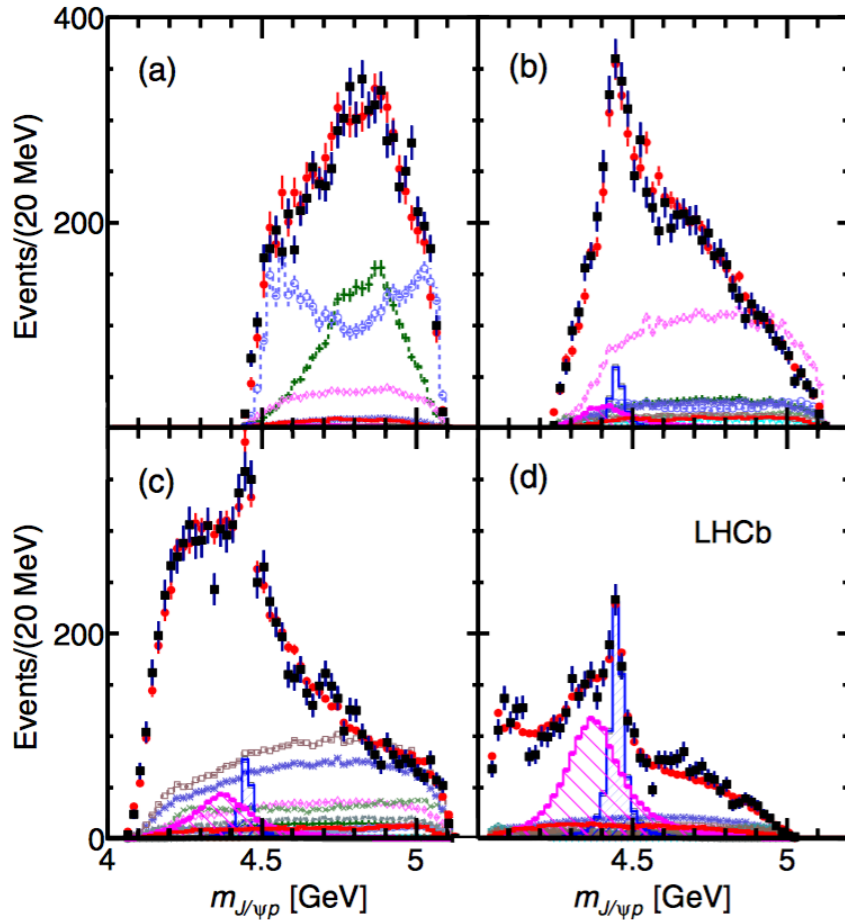
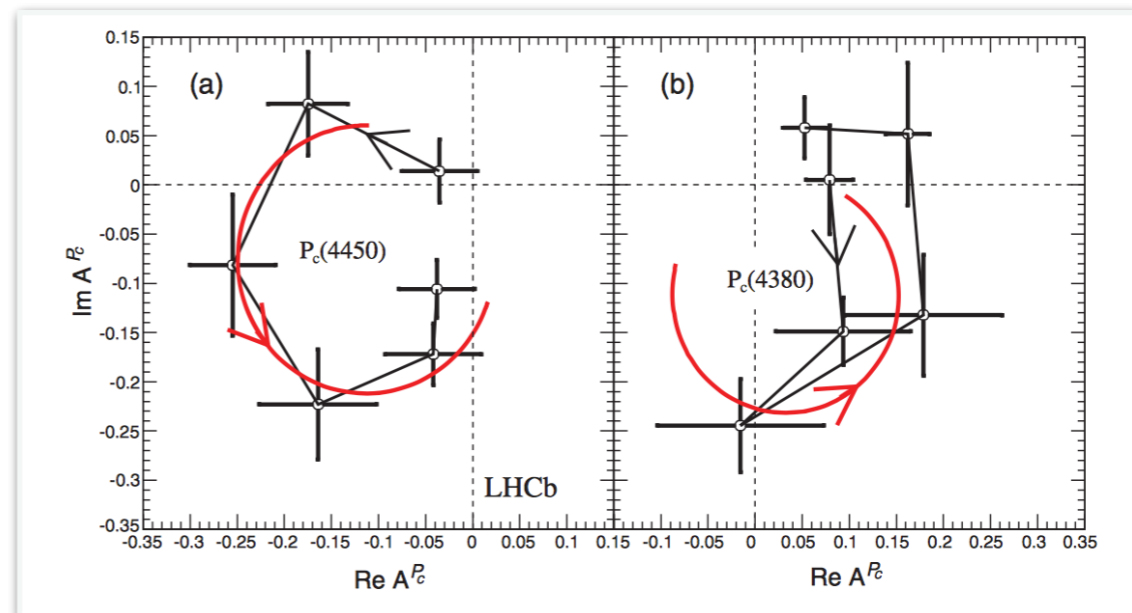


FIG. 8 (color online).  $m_{J/\psi p}$  in various intervals of  $m_{Kp}$  for the fit with two  $P_c^+$  states: (a)  $m_{Kp} < 1.55$  GeV, (b)  $1.55 < m_{Kp} < 1.70$  GeV, (c)  $1.70 < m_{Kp} < 2.00$  GeV, and (d)  $m_{Kp} > 2.00$  GeV. The data are shown as (black) squares with error bars, while the (red) circles show the results of the fit. The blue and purple histograms show the two  $P_c^+$  states. See Fig. 7 for the legend.

	$P_c(4380)^+$	$P_c(4450)^+$
Significance	$9\sigma$	$12\sigma$
Mass (MeV)	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width (MeV)	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction(%)	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$
$\mathcal{B}(\Lambda_b^0 \rightarrow P_c^+ K^-;$ $P_c^+ \rightarrow J/\psi p)$	$(2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5}$	$(1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5}$

Branching ratio results are submitted to Chin. Phys. C (arXiv:1509.00292)  
 Ref:  $\mathcal{B}(B^0 \rightarrow Z^-(4430)K^+; Z^- \rightarrow J/\psi\pi^-) = (3.4 \pm 0.5^{+0.9}_{-1.9} \pm 0.2) \times 10^{-5}$

Argand diagrams show the resonance behavior of two  $P_c$  states



# Decay angular distributions

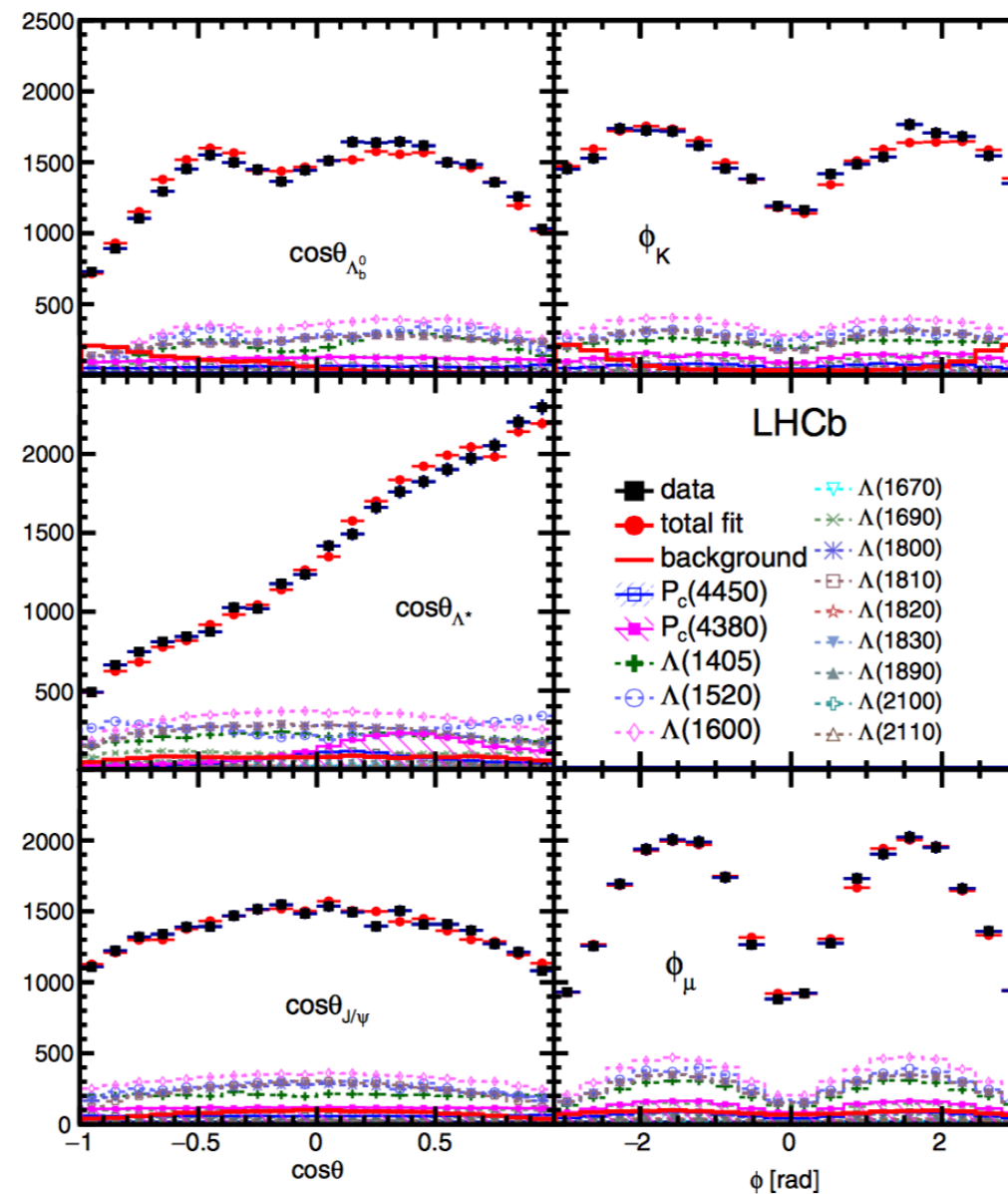


FIG. 7 (color online). Various decay angular distributions for the fit with two  $P_c^+$  states. The data are shown as (black) squares, while the (red) circles show the results of the fit. Each fit component is also shown. The angles are defined in the text.

The preferred  $J^P$  are of opposite parity, with one state having  $J=3/2$  and the other  $5/2$



- The LHCb experiment at CERN's Large Hadron Collider has reported **the discovery of a class of particles** known as **pentaquarks**.

Posted by Corinne Pralavorio on 14 Jul 2015. Last updated 14 Jul 2015, 10:19.

[Voir en français](#)



Possible layout of the quarks in a pentaquark particle. The five quarks might be tightly bound (left). They might also be assembled into a meson (one quark and one antiquark) and a baryon (three quarks), weakly bound together (Image: Daniel Dominguez)



# A summary of the observed XYZ states

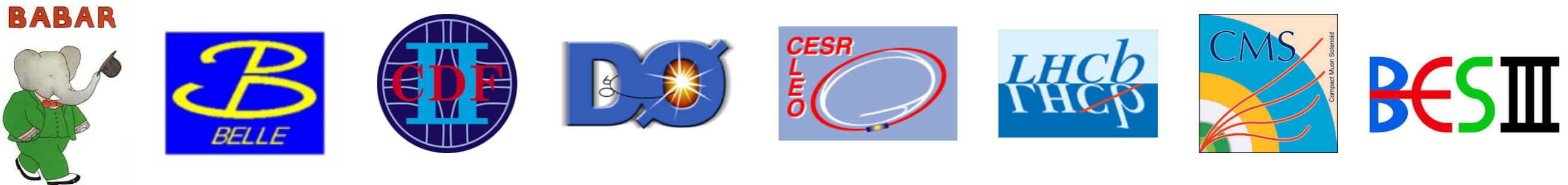
截屏发图

$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_b(10610)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_b(10650)$
$Z^+(4430)$	$Y(4360)$	–	$Z(3930)$	$Z_c(3900)$
$Z^+(4051)$	$Y(4660)$	–	–	$Z_c(4025)$
$Z^+(4248)$	$Y(4630)$	–	–	$Z_c(4020)$
$Y(4140)$	–	–	–	$Z_c(3885)$
$Y(4274)$	–	–	–	–

X. Liu, Chin. Sci. Bull., 59: 3815–3830 (2014)

In past decade, more and more XYZ states have been reported by experiments

BaBar, Belle, CDF, D0, CLEOc, LHCb, CMS, BESIII



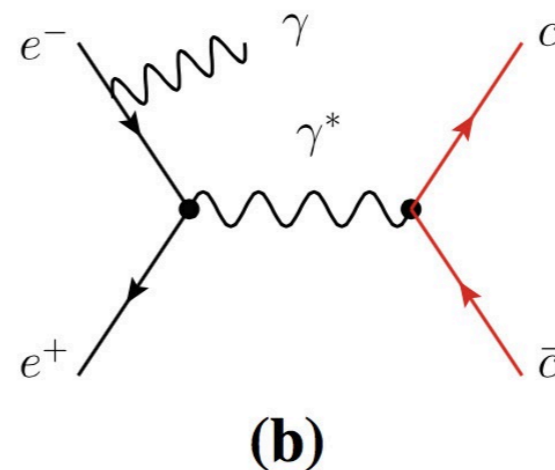
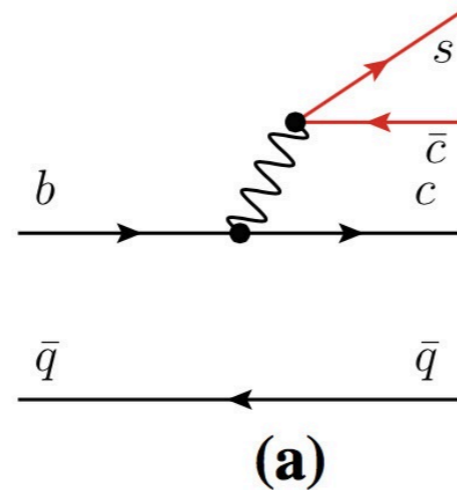
In general, the observed XYZ states can be categorized into **five groups**

X. Liu, Chin. Sci. Bull., 59: 3815–3830 (2014)

**B meson decay**

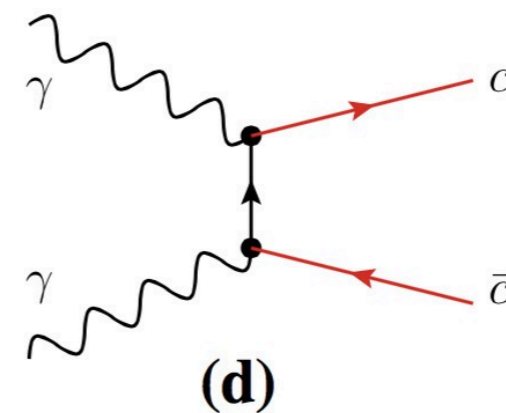
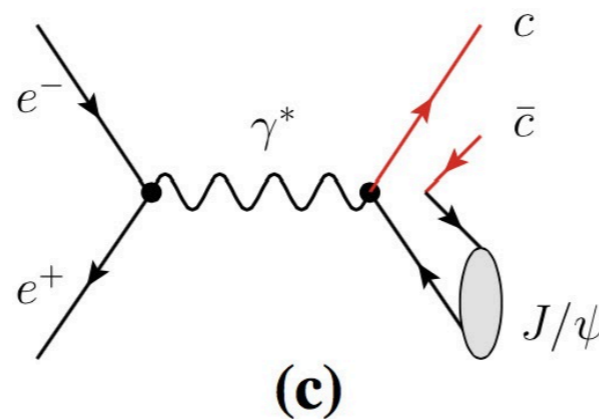
**$e^+e^-$  annihilation**

X(3872)  
Y(3940)  
Z<sup>+</sup>(4430)  
Z<sup>+</sup>(4051)  
Z<sup>+</sup>(4248)  
Y(4140)  
Y(4274)



Y(4260)  
Y(4008)  
Y(4360)  
Y(4660)  
Y(4630)

X(3940)  
X(4160)



X(3915)  
X(4350)  
Z(3930)

**the double charm production**

**$\gamma\gamma$  fusion process**

**These observations provide good chance to study exotic states**

19. **Observation of a Charged Charmoniumlike Structure in  $e^+e^- \rightarrow \pi^+\pi^- J/\psi$  at  $\sqrt{s}=4.26$  GeV**

BESIII Collaboration (M. Ablikim (Beijing, Inst. High Energy Phys.) *et al.*). Mar 24, 2013. 7 pp.

Published in **Phys.Rev.Lett.** **110** (2013) 252001

DOI: [10.1103/PhysRevLett.110.252001](https://doi.org/10.1103/PhysRevLett.110.252001)

e-Print: [arXiv:1303.5949](https://arxiv.org/abs/1303.5949) [hep-ex] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#); [Interactions.org article](#); [Link to WIRED](#); [physicsworld.com article](#)

详细记录 - Cited by 421 records 250+

$Z_c(3900)$

18. **Observation of a charged charmoniumlike structure in  $e^+e^- \rightarrow (D^*\bar{D}^*)^\pm\pi^\mp$  at  $\sqrt{s}=4.26$  GeV**

BESIII Collaboration (M. Ablikim (Beijing, Inst. High Energy Phys.) *et al.*). Aug 13, 2013. 7 pp.

Published in **Phys.Rev.Lett.** **112** (2014) no.13, 132001

DOI: [10.1103/PhysRevLett.112.132001](https://doi.org/10.1103/PhysRevLett.112.132001)

e-Print: [arXiv:1308.2760](https://arxiv.org/abs/1308.2760) [hep-ex] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#); [Interactions.org article](#)

详细记录 - Cited by 191 records 100+

$Z_c(4025)$

17. **Observation of a Charged Charmoniumlike Structure  $Z_c(4020)$  and Search for the  $Z_c(3900)$  in  $e^+e^- \rightarrow \pi^+\pi^- h_c$**

BESIII Collaboration (M. Ablikim (Beijing, Inst. High Energy Phys.) *et al.*). Sep 7, 2013. 7 pp.

Published in **Phys.Rev.Lett.** **111** (2013) no.24, 242001

DOI: [10.1103/PhysRevLett.111.242001](https://doi.org/10.1103/PhysRevLett.111.242001)

e-Print: [arXiv:1309.1896](https://arxiv.org/abs/1309.1896) [hep-ex] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#); [Interactions.org article](#)

详细记录 - Cited by 201 records 100+

$Z_c(4020)$

16. **Observation of a charged  $(D\bar{D}^*)^\pm$  mass peak in  $e^+e^- \rightarrow \pi D\bar{D}^*$  at  $\sqrt{s}=4.26$  GeV**

BESIII Collaboration (M. Ablikim (Beijing, Inst. High Energy Phys.) *et al.*). Oct 4, 2013. 7 pp.

Published in **Phys.Rev.Lett.** **112** (2014) no.2, 022001

DOI: [10.1103/PhysRevLett.112.022001](https://doi.org/10.1103/PhysRevLett.112.022001)

e-Print: [arXiv:1310.1163](https://arxiv.org/abs/1310.1163) [hep-ex] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#); [Interactions.org article](#); [Link to PHYSICS](#)

详细记录 - Cited by 155 records 100+

$Z_c(3885)$

- **Below 1 GeV**, the multiquark exotic states do not exist individually but mix with regular structures. Moreover, in a pentaquark component might exist in the total wave function of a nucleon.

C. Amsler and F. E. Close, Phys. Lett. B **353**, 385 (1995)

K. T. Chao, X. G. He and J. P. Ma, Phys. Rev. Lett. **98**, 149103 (2007)

B. S. Zou and D. O. Riska, Phys. Rev. Lett. **95**, 072001 (2005)

- **States that decay into charmonium** may have particularly distinctive signatures.

X.-Q. Li and X. Liu, Eur. Phys. J. C **74** (2014) 3198

## • Light sector

- Exotic in structure

light scalar mesons  $\sigma(600)$ ,  $\kappa(800)$ , etc.

- Exotic in quantum numbers

$\pi_1(1400)$ ,  $\pi_1(1600)$  with  $I^G J^{PC} = 1^- 1^- +$

- Six-quark state  $d^*(2380)$

## • Heavy sector

- Exotic in structure

charmonium-like resonances  $X(3872)$ , etc.

- **Meson:** Exotic in quantum numbers

charged charmonium-like resonances  $Z_c(3900)$ ,  $Z(4430)$ , etc.

- **Baryon:** Exotic in quantum numbers

hidden-charm pentaquarks  $P_c(4380)$  and  $P_c(4450)$

# Theoretical studies

- Some earlier studies
- Studies at the **hadron level**
  - one-boson exchange model
- Studies at the **quark-gluon level**
  - QCD sum rules

# The history of multiquark states



Phys.Lett. 8 (1964) 214-215

Volume 8, number 3

PHYSICS LETTERS

1 February 1964

## A SCHEMATIC MODEL OF BARYONS AND MESONS \*

M. GELL-MANN

*California Institute of Technology, Pasadena, California*

Received 4 January 1964

...

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon  $b$  if we assign to the triplet  $t$  the following properties: spin  $\frac{1}{2}$ ,  $z = -\frac{1}{3}$ , and baryon number  $\frac{1}{3}$ . We then refer to the members  $u^{\frac{2}{3}}$ ,  $d^{-\frac{1}{3}}$ , and  $s^{-\frac{1}{3}}$  of the triplet as "quarks"  $q$  and the members of the anti-triplet as anti-quarks  $\bar{q}$ . Baryons can now be constructed from quarks by using the combinations  $(qqq)$ ,  $(qqq\bar{q})$ , etc., while mesons are made out of  $(q\bar{q})$ ,  $(qq\bar{q}\bar{q})$ , etc. It is assumed that the lowest baryon configuration  $(qqq)$  gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412  
21 February 1964

AN  $SU_3$  MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II \*)

G. Zweig

CERN---Geneva

\*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

- 6) In general, we would expect that baryons are built not only from the product of three aces,  $AAA$ , but also from  $\bar{A}AAAA$ ,  $\bar{A}AAAAA$ , etc., where  $\bar{A}$  denotes an anti-ace. Similarly, mesons could be formed from  $\bar{A}A$ ,  $\bar{A}AAA$  etc. For the low mass mesons and baryons we will assume the simplest possibilities,  $\bar{A}A$  and  $AAA$ , that is, "deuces and treys".

The multiquark states were predicted at the birth of Quark Model

# Quark Model

LIGHT UNFLAVORED (S = C = B = 0)		STRANGE (S = ±1, C = B = 0)		CHARMED, STRANGE (C = S = ±1)		c $\bar{c}$ f $\bar{f}$ (J <sup>PC</sup> )			
f $\bar{f}$ (J <sup>PC</sup> )		f $\bar{f}$ (J <sup>PC</sup> )		f (J <sup>P</sup> )		f $\bar{f}$ (J <sup>PC</sup> )			
• $\pi^\pm$	1 <sup>-</sup> (0 <sup>-</sup> )	• $\pi_2(1670)$	1 <sup>-</sup> (2 <sup>-+</sup> )	• $K^\pm$	1/2(0 <sup>-</sup> )	• $D_s^\pm$	0(0 <sup>-</sup> )	• $\eta_c(1S)$	0 <sup>+</sup> (0 <sup>-+</sup> )
• $\pi^0$	1 <sup>-</sup> (0 <sup>-+</sup> )	• $\phi(1680)$	0 <sup>-</sup> (1 <sup>-</sup> )	• $K^0$	1/2(0 <sup>-</sup> )	• $D_s^{*\pm}$	0(? <sup>?</sup> )	• $J/\psi(1S)$	0 <sup>-</sup> (1 <sup>-</sup> )
• $\eta$	0 <sup>+</sup> (0 <sup>-+</sup> )	• $\rho_3(1690)$	1 <sup>+</sup> (3 <sup>-</sup> )	• $K_S^0$	1/2(0 <sup>-</sup> )	• $D_{s0}^*(2317)^\pm$	0(0 <sup>+</sup> )	• $\chi_{c0}(1P)$	0 <sup>+</sup> (0 <sup>++</sup> )
• $f_0(600)$	0 <sup>+</sup> (0 <sup>++</sup> )	• $\rho(1700)$	1 <sup>+</sup> (1 <sup>-</sup> )	• $K_L^0$	1/2(0 <sup>-</sup> )	• $D_{s1}(2460)^\pm$	0(1 <sup>+</sup> )	• $\chi_{c1}(1P)$	0 <sup>+</sup> (1 <sup>++</sup> )
• $\rho(770)$	1 <sup>+</sup> (1 <sup>-</sup> )	• $a_2(1700)$	1 <sup>-</sup> (2 <sup>++</sup> )	• $K_0^0(800)$	1/2(0 <sup>+</sup> )	• $D_{s1}(2536)^\pm$	0(1 <sup>+</sup> )	• $h_c(1P)$	? <sup>?</sup> (1 <sup>+-</sup> )
• $\omega(782)$	0 <sup>-</sup> (1 <sup>-</sup> )	• $f_0(1710)$	0 <sup>+</sup> (0 <sup>++</sup> )	• $K^*(892)$	1/2(1 <sup>-</sup> )	• $D_{s2}(2573)^\pm$	0(? <sup>?</sup> )	• $\chi_{c2}(1P)$	0 <sup>+</sup> (2 <sup>++</sup> )
• $\eta'(958)$	0 <sup>+</sup> (0 <sup>-+</sup> )	• $\eta(1760)$	0 <sup>+</sup> (0 <sup>-+</sup> )	• $K_1(1270)$	1/2(1 <sup>+</sup> )	• $D_{s1}(2700)^\pm$	0(1 <sup>-</sup> )	• $\eta_c(2S)$	0 <sup>+</sup> (0 <sup>-</sup> )
• $f_0(980)$	0 <sup>+</sup> (0 <sup>++</sup> )	• $\pi(1800)$	1 <sup>-</sup> (0 <sup>-+</sup> )	• $K_1(1400)$	1/2(1 <sup>+</sup> )	BOTTOM (B = ±1)		• $\psi(2S)$	0 <sup>-</sup> (1 <sup>-</sup> )
• $a_0(980)$	1 <sup>-</sup> (0 <sup>++</sup> )	• $f_2(1810)$	0 <sup>+</sup> (2 <sup>++</sup> )	• $K^*(1410)$	1/2(1 <sup>-</sup> )			• $B^\pm$	1/2(0 <sup>-</sup> )
• $\phi(1020)$	0 <sup>-</sup> (1 <sup>-</sup> )	• $X(1835)$	? <sup>?</sup> (? <sup>-+</sup> )	• $K_0^*(1430)$	1/2(0 <sup>+</sup> )	• $B^0$	1/2(0 <sup>-</sup> )	• $X(3872)$	0 <sup>?</sup> (? <sup>++</sup> )
• $h_1(1170)$	0 <sup>-</sup> (1 <sup>+-</sup> )	• $\phi_3(1850)$	0 <sup>-</sup> (3 <sup>-</sup> )	• $K_2^*(1430)$	1/2(2 <sup>+</sup> )	• $B^\pm/B^0$ ADMIXTURE		• $\chi_{c2}(2P)$	0 <sup>+</sup> (2 <sup>++</sup> )
• $b_1(1235)$	1 <sup>+</sup> (1 <sup>+-</sup> )	• $\eta_2(1870)$	0 <sup>+</sup> (2 <sup>-+</sup> )	• $K(1460)$	1/2(0 <sup>-</sup> )	• $B^\pm/B^0/B_S^0/b$ -baryon ADMIXTURE		• $X(3940)$	? <sup>?</sup> (? <sup>??</sup> )
• $a_1(1260)$	1 <sup>-</sup> (1 <sup>++</sup> )	• $\pi_2(1880)$	1 <sup>-</sup> (2 <sup>-+</sup> )	• $K_2(1580)$	1/2(2 <sup>-</sup> )	• $V_{cb}$ and $V_{ub}$ CKM Ma- trix Elements		• $X(3945)$	? <sup>?</sup> (? <sup>??</sup> )
• $f_2(1270)$	0 <sup>+</sup> (2 <sup>++</sup> )	• $\rho(1900)$	1 <sup>+</sup> (1 <sup>-</sup> )	• $K(1630)$	1/2(? <sup>?</sup> )	• $B^*$	1/2(1 <sup>-</sup> )	• $\psi(4040)$	0 <sup>-</sup> (1 <sup>-</sup> )
• $f_1(1285)$	0 <sup>+</sup> (1 <sup>++</sup> )	• $f_2(1910)$	0 <sup>+</sup> (2 <sup>++</sup> )	• $K_1(1650)$	1/2(1 <sup>+</sup> )	• $B_J^*(5732)$	?(? <sup>?</sup> )	• $\psi(4160)$	0 <sup>-</sup> (1 <sup>-</sup> )
• $\eta(1295)$	0 <sup>+</sup> (0 <sup>-+</sup> )	• $f_2(1950)$	0 <sup>+</sup> (2 <sup>++</sup> )	• $K^*(1680)$	1/2(1 <sup>-</sup> )	• $B_1(5721)^0$	1/2(1 <sup>+</sup> )	• $X(4260)$	? <sup>?</sup> (1 <sup>-</sup> )
• $\pi(1300)$	1 <sup>-</sup> (0 <sup>-+</sup> )	• $\rho_3(1990)$	1 <sup>+</sup> (3 <sup>-</sup> )	• $K_2(1770)$	1/2(2 <sup>-</sup> )	• $B_2^*(5747)^0$	1/2(2 <sup>+</sup> )	• $X(4360)$	? <sup>?</sup> (1 <sup>-</sup> )
• $a_2(1320)$	1 <sup>-</sup> (2 <sup>++</sup> )	• $f_2(2010)$	0 <sup>+</sup> (2 <sup>++</sup> )	• $K_3^*(1780)$	1/2(3 <sup>-</sup> )	BOTTOM, STRANGE (B = ±1, S = ∓1)		• $\psi(4415)$	0 <sup>-</sup> (1 <sup>-</sup> )
• $f_0(1370)$	0 <sup>+</sup> (0 <sup>++</sup> )	• $f_0(2020)$	0 <sup>+</sup> (0 <sup>++</sup> )	• $K_2(1820)$	1/2(2 <sup>-</sup> )			• $B_S^0$	0(0 <sup>-</sup> )
• $h_1(1380)$	? <sup>-</sup> (1 <sup>+-</sup> )	• $a_4(2040)$	1 <sup>-</sup> (4 <sup>++</sup> )	• $K(1830)$	1/2(0 <sup>-</sup> )	• $B_S^*$	0(1 <sup>-</sup> )	• $\eta_b(1S)$	0 <sup>+</sup> (0 <sup>-+</sup> )
• $\pi_1(1400)$	1 <sup>-</sup> (1 <sup>+-</sup> )	• $f_4(2050)$	0 <sup>+</sup> (4 <sup>++</sup> )	• $K_0^*(1950)$	1/2(0 <sup>+</sup> )	• $B_{s1}(5830)^0$	1/2(1 <sup>+</sup> )	• $\mathcal{T}(1S)$	0 <sup>-</sup> (1 <sup>-</sup> )
• $\eta(1405)$	0 <sup>+</sup> (0 <sup>-+</sup> )	• $\pi_2(2100)$	1 <sup>-</sup> (2 <sup>-+</sup> )	• $K_2^*(1980)$	1/2(2 <sup>+</sup> )	• $B_{s2}(5840)^0$	1/2(2 <sup>+</sup> )	• $\chi_{b0}(1P)$	0 <sup>+</sup> (0 <sup>++</sup> )
• $f_1(1420)$	0 <sup>+</sup> (1 <sup>++</sup> )	• $f_0(2100)$	0 <sup>+</sup> (0 <sup>++</sup> )	• $K_4^*(2045)$	1/2(4 <sup>+</sup> )	• $B_{sJ}^*(5850)$	?(? <sup>?</sup> )	• $\chi_{b1}(1P)$	0 <sup>+</sup> (1 <sup>++</sup> )
• $\omega(1420)$	0 <sup>-</sup> (1 <sup>-</sup> )	• $f_2(2150)$	0 <sup>+</sup> (2 <sup>++</sup> )	• $K_2(2250)$	1/2(2 <sup>-</sup> )	BOTTOM, CHARMED		• $\chi_{b2}(1P)$	0 <sup>+</sup> (2 <sup>++</sup> )
• $f_2(1430)$	0 <sup>+</sup> (2 <sup>++</sup> )	• $\rho(2150)$	1 <sup>+</sup> (1 <sup>-</sup> )	• $K_3(2320)$	1/2(3 <sup>+</sup> )			• $\mathcal{T}(2S)$	0 <sup>-</sup> (1 <sup>-</sup> )
• $a_0(1450)$	1 <sup>-</sup> (0 <sup>++</sup> )	• $\phi(2170)$	0 <sup>-</sup> (1 <sup>-</sup> )	• $K_5^*(2380)$	1/2(5 <sup>-</sup> )	• $\chi_{b0}(2P)$	0 <sup>+</sup> (0 <sup>++</sup> )	• $\chi_{b1}(2P)$	0 <sup>+</sup> (1 <sup>++</sup> )
• $\rho(1450)$	1 <sup>+</sup> (1 <sup>-</sup> )	• $f_0(2200)$	0 <sup>+</sup> (0 <sup>++</sup> )	• $K_4(2500)$	1/2(4 <sup>-</sup> )	• $\chi_{b2}(2P)$	0 <sup>+</sup> (2 <sup>++</sup> )	• $\mathcal{T}(3S)$	0 <sup>-</sup> (1 <sup>-</sup> )
• $\eta(1475)$	0 <sup>+</sup> (0 <sup>-+</sup> )	• $f_J(2220)$	0 <sup>+</sup> (2 <sup>++</sup> )	• $K(3100)$	? <sup>?</sup> (? <sup>??</sup> )				
• $f_0(1500)$	0 <sup>+</sup> (0 <sup>++</sup> )	• $\eta(2225)$	0 <sup>+</sup> (0 <sup>-+</sup> )						
• $f_1(1510)$	0 <sup>+</sup> (1 <sup>++</sup> )	• $\rho_3(2250)$	1 <sup>+</sup> (3 <sup>-</sup> )						
				CHARMED					

**Multiquark hadrons. I. Phenomenology of  $Q^2\bar{Q}^2$  mesons\***R. J. Jaffe<sup>†</sup>*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305**and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

(Received 15 July 1976)

The spectra and dominant decay couplings of  $Q^2\bar{Q}^2$  mesons are presented as calculated in the quark-bag model. Certain known  $0^+$  mesons [ $\epsilon(700), S^*, \delta, \kappa$ ] are assigned to the lightest cryptoexotic  $Q^2\bar{Q}^2$  nonet. The usual quark-model  $0^+$  nonet ( $Q\bar{Q} L=1$ ) must lie higher in mass. All other  $Q^2\bar{Q}^2$  mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other  $Q^2\bar{Q}^2$  states which may be experimentally prominent are discussed.

The hadron with four quarks plus one antiquark was developed by Strottman in 1979

**Multiquark baryons and the MIT bag model**

D. Strottman

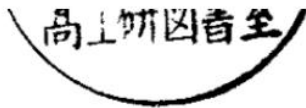
*Theoretical Division, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545*

(Received 4 December 1978)

The calculation of masses of  $q^4\bar{q}$  and  $q^5\bar{q}^2$  baryons is carried out within the framework of Jaffe's approximation to the MIT bag model. A general method for calculating the necessary  $SU(6) \supset SU(3) \otimes SU(2)$  coupling coefficients is outlined and tables of the coefficients necessary for  $q^4\bar{q}$  and  $q^5\bar{q}^2$  calculations are given. An expression giving the decay amplitude of an arbitrary multiquark state to arbitrary two-body final states is given in terms of  $SU(3)$  Racah and  $9-\lambda\mu$  recoupling coefficients. The decay probabilities for low-lying  $1/2^-$   $q^4\bar{q}$  baryons are given and compared with experiment. All low-lying  $1/2^-$  baryons are found to belong to the same  $SU(6)$  representation and all known  $1/2^-$  resonances below 1900 MeV may be accounted for without the necessity of introducing  $P$ -wave states. The masses of many exotic states are predicted including a  $1/2^-$   $Z_0^*$  at 1650 MeV and  $1/2^-$  hypercharge  $-2$  and  $+3$  states at 2.25 and 2.80 GeV, respectively. The agreement with experiment for the  $3/2^-$  and  $5/2^-$  baryons is less good. The lowest  $q^5\bar{q}^2$  state is predicted to be a  $1/2^+$   $\Lambda^*$  at 1900 MeV.



# The name **pentaquark** was first proposed by Lipkin in 1987



WIS-87/32/May-PH

New Possibilities for Exotic Hadrons - Anticharmed Strange Baryons\*

Harry J. Lipkin  
Department of Nuclear Physics  
Weizmann Institute of Science  
76100 Rehovot, Israel  
Submitted to Physics Letters

**PLB 195 (1987) 484**

May 20, 1987

**ABSTRACT**

## **$Y = 2$ STATES IN SU(6) THEORY\***

Freeman J. Dyson† and Nguyen-Huu Xuong

Department of Physics, University of California, San Diego, La Jolla, California

(Received 30 November 1964)

Two-baryon states. – The SU(6) theory of strongly interacting particles<sup>1,2</sup> predicts a classification of two-baryon states into multiplets according to the scheme

$$\underline{56} \otimes \underline{56} = \underline{462} \oplus \underline{1050} \oplus \underline{1134} \oplus \underline{490}. \quad (1)$$

We now propose the hypothesis that all low-lying resonant states of the two-baryon system belong to the 490 multiplet.<sup>3</sup> This means that six zero-strangeness states shown in Table I should be observed. In all these states odd  $T$  goes with even  $J$  and vice versa.

# Prediction of narrow $N^*$ and $\Lambda^*$ resonances with hidden charm above 4 GeV

Jia-Jun Wu<sup>1,2</sup>, R. Molina<sup>2,3</sup>, E. Oset<sup>2,3</sup> and B. S. Zou<sup>1,3</sup>

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3. Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China

(Dated: June 25, 2010) [arXiv:1007.0573](https://arxiv.org/abs/1007.0573)

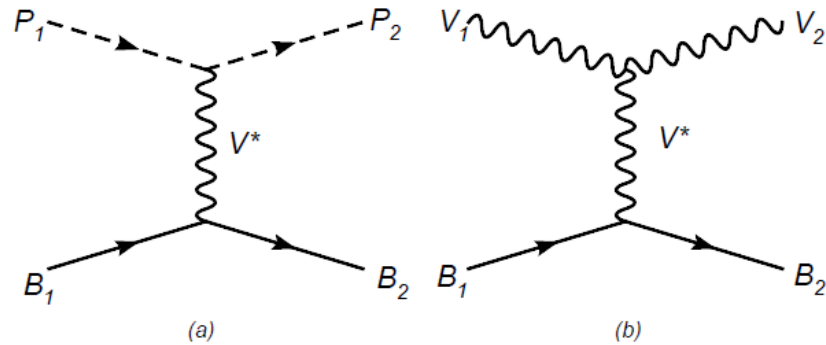


FIG. 1: The Feynman diagrams of pseudoscalar-baryon (a) or vector-baryon (b) interaction via the exchange of a vector meson.  $P_1, P_2$  is  $D^-, \bar{D}^0$  or  $D_s^-, \bar{D}_s^0$ , and  $V_1, V_2$  is  $D^{*-}, \bar{D}^{*0}, D_s^{*-}, \bar{D}_s^{*0}$ , and  $B_1, B_2$  is  $\Sigma_c, \Lambda_c^+, \Xi_c, \Xi_c', \Omega_c$ , and  $V^*$  is  $\rho, K^*, \omega$ .

$\bar{D}_s \Lambda_c^+$	0	$-\sqrt{2}$	0	1	0	$\sqrt{\frac{1}{3}}$	$\sqrt{\frac{2}{3}}$	$-\sqrt{\frac{1}{3}}$
$\bar{D} \Xi_c$		-1	0	$\sqrt{\frac{1}{2}}$	$-\frac{3}{2}$	$\sqrt{\frac{1}{6}}$	$-\sqrt{\frac{1}{12}}$	0
$\bar{D} \Xi_c'$			-1	$-\sqrt{\frac{3}{2}}$	$\sqrt{\frac{3}{4}}$	$-\sqrt{\frac{1}{2}}$	$\frac{1}{2}$	0
$\eta_c \Lambda$				0	0	0	0	0

$$\mathcal{L}_{VVV} = ig \langle V^\mu [V^\nu, \partial_\mu V_\nu] \rangle$$

$$\mathcal{L}_{PPV} = -ig \langle V^\mu [P, \partial_\mu P] \rangle$$

$$\mathcal{L}_{BBV} = g (\langle \bar{B} \gamma_\mu [V^\mu, B] \rangle + \langle \bar{B} \gamma_\mu B \rangle \langle V^\mu \rangle)$$

(0, -1)		$D_s \Lambda_c^+$	$D \Xi_c$	$D \Xi_c'$
	4213	1.37	3.25	0
	4403	0	0	2.64

TABLE III: Pole positions  $z_R$  and coupling constants  $g_a$  for the states from  $PB \rightarrow PB$ .

(I, S)	$z_R$ (MeV)	$g_a$		
(1/2, 0)		$\bar{D}^* \Sigma_c$	$\bar{D}^* \Lambda_c^+$	
	4418	2.75	0	
(0, -1)		$\bar{D}_s^* \Lambda_c^+$	$\bar{D}^* \Xi_c$	$\bar{D}^* \Xi_c'$
	4370	1.23	3.14	0
	4550	0	0	2.53

TABLE IV: Pole position and coupling constants for the bound states from  $VB \rightarrow VB$ .

# Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon\*

 $\mathcal{L}_{\mathcal{B}_6}$ YANG Zhong-Cheng(杨忠诚)<sup>1</sup> SUN Zhi-Feng(孙志峰)<sup>2,4</sup> HE Jun(何军)<sup>1,3;1)</sup> $\mathcal{L}_{\mathcal{B}_6}$ LIU Xiang(刘翔)<sup>2,4;2)</sup> ZHU Shi-Lin(朱世琳)<sup>1;3)</sup>

$$-\frac{i\lambda_S g_V}{3\sqrt{2}} \langle \bar{\mathcal{B}}_6 \gamma_\mu \gamma_\nu (\partial^\mu \nabla^\nu$$

$$\mathcal{L}_{\mathcal{B}_6 \mathcal{B}_6 \sigma} = -l_S \langle \bar{\mathcal{B}}_6 \sigma \mathcal{B}_6 \rangle.$$

$$\mathcal{B}_3 = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix},$$

$$\mathcal{B}_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}} \Sigma_c^+ & \frac{1}{\sqrt{2}} \Xi_c'^+ \\ \frac{1}{\sqrt{2}} \Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}} \Xi_c'^0 \\ \frac{1}{\sqrt{2}} \Xi_c'^+ & \frac{1}{\sqrt{2}} \Xi_c'^0 & \Omega_c^0 \end{pmatrix}.$$

In this work, we have employed the OBE model to study whether there exist the loosely bound hidden-charm molecular states composed of an S-wave anti-charmed meson and an S-wave charmed baryon. Our numerical results indicate that there do not exist  $\Lambda_c \bar{D}$  and  $\Lambda_c \bar{D}^*$  molecular states due to the absence of bound state solution, which is an interesting observation in this work. Additionally, we notice the bound state solutions only for five hidden-charm states, i.e.,  $\Sigma_c \bar{D}^*$  states with  $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ ,  $\frac{1}{2}(\frac{3}{2}^-)$ ,  $\frac{3}{2}(\frac{1}{2}^-)$ ,  $\frac{3}{2}(\frac{3}{2}^-)$  and  $\Sigma_c \bar{D}$  state with  $\frac{3}{2}(\frac{1}{2}^-)$ . We also extend the same

## A possible global group structure for exotic states

Xue-Qian Li<sup>1,a</sup>, Xiang Liu<sup>3,2,b</sup>

**Abstract** Based on the fact that the long expected pentaquark which possesses the exotic quantum numbers of  $B = 1$  and  $S = 1$  was not experimentally found, although exotic states of  $XYZ$  have been observed recently, we conjecture that the heavy flavors may play an important role in stabilizing the hadronic structures beyond the traditional  $q\bar{q}$  and  $qqq$  composites.

$$G = SU_c(3) \times SU_H(2) \times SU_L(3),$$

where the subscripts  $c$ ,  $H$ , and  $L$  refer to color, heavy, and light, respectively. The  $SU_L(3)$  corresponds to the regular quark model for the light quarks  $u$ ,  $d$ ,  $s$  and the newly introduced  $SU_H(2)$  involves  $c$  and  $b$  quarks (antiquarks). This idea is inspired by the heavy quark effective theory (HQET) [27,28].

## Prediction:

Therefore, we would predict that the pentaquarks should be  $c\bar{c}qqq$  and  $b\bar{b}qqq$ . However, such baryons would have the same quantum numbers as the regular baryons, unlike their mass spectra, and it is hard to identify them as an exotic state. By contrast, the pentaquark  $b\bar{c}qqq$  [38] would have

- There **hidden-charm pentaquarks** are studied in the chiral unitary approach:

J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010)

T. Uchino, W. H. Liang and E. Oset, arXiv:1504.05726

- Especially, the **hidden-charm molecular baryons** of  $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$  were first investigated and predicted to exist within the one boson exchange model in

Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, Chin. Phys. C 36, 6 (2012)

- More references:

chiral quark model

W.L. Wang, F. Huang, Z.Y. Zhang, and B.S. Zou, Phys.Rev. C84 (2011) 015203

hyperfine interaction

S. G. Yuan, K. W. Wei, J. He, H. S. Xu, B. S. Zou, Eur.Phys.J. A48 (2012) 61

photoproduction

Yin Huang, Jun He, Hong-Fei Zhang, Xu-Rong Chen, J.Phys. G41 (2014) 11, 115004

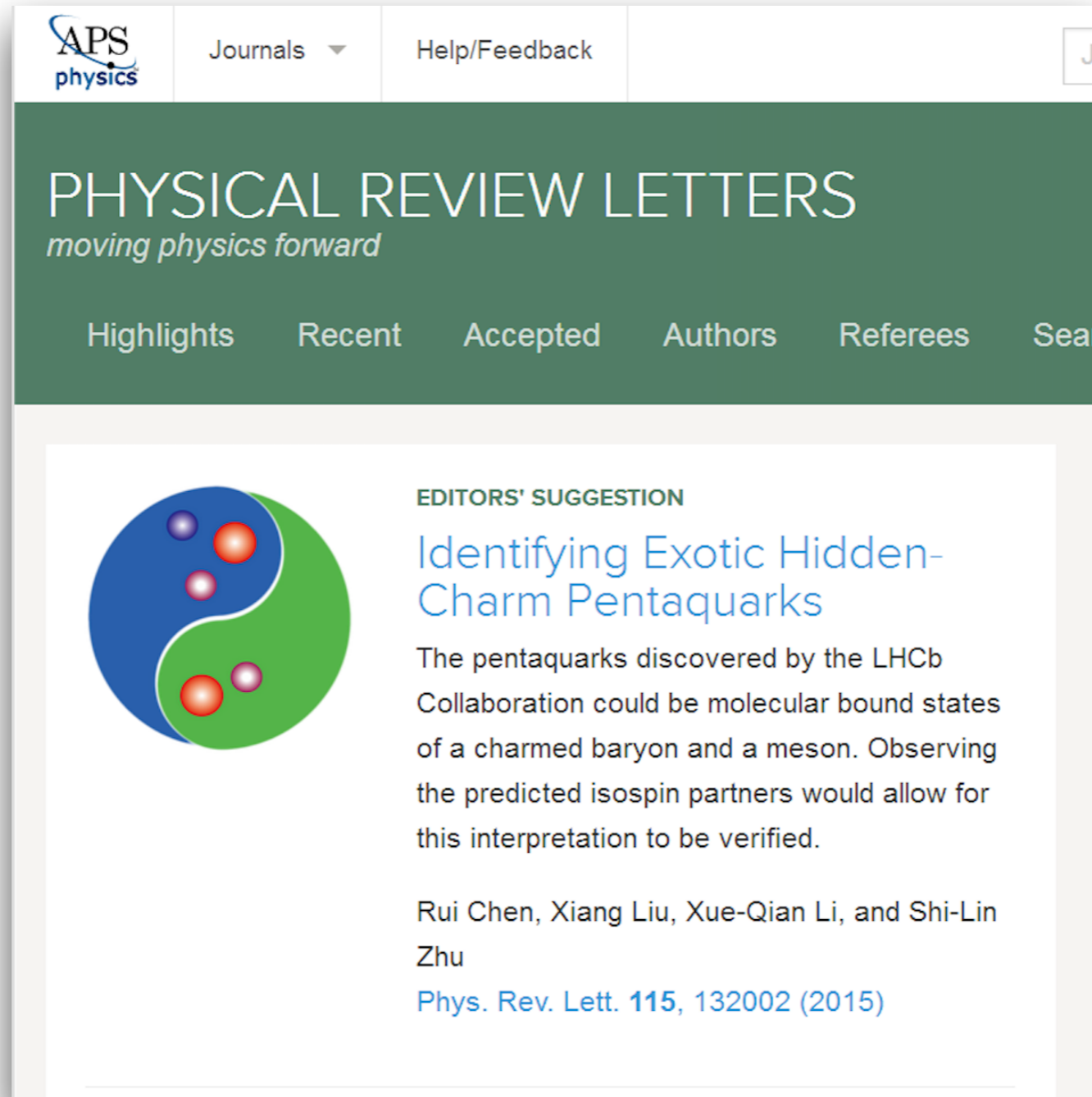
kaon-induced reaction

Xiao-Yun Wang, Xu-Rong Chen, Eur.Phys.J. A51 (2015) 7, 85

isospin-exchange attraction

M. Karliner and J. L. Rosner, arXiv:1506.06386

# Identify exotic hidden-charm pentaquarks




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**EDITORS' SUGGESTION**

## Identifying Exotic Hidden-Charm Pentaquarks

The pentaquarks discovered by the LHCb Collaboration could be molecular bound states of a charmed baryon and a meson. Observing the predicted isospin partners would allow for this interpretation to be verified.

Rui Chen, Xiang Liu, Xue-Qian Li, and Shi-Lin Zhu  
[Phys. Rev. Lett. 115, 132002 \(2015\)](#)



## The peculiarity of two $P_c$ states:

- The masses of  $P_c(4380)$  and  $P_c(4450)$  are **close to the  $\Sigma_c(2455)D^*$  and  $\Sigma_c^*(2520)D^*$  thresholds**, respectively.
- According to their final state  $J/\psi+p$ , we conclude that the **two observed  $P_c$  must not be an isosinglet state**, and the two  $P_c$  states **contain hidden-charm quantum numbers**.
- The discovery of  $P_c(4380)$  and  $P_c(4450)$  inspires us interest in revealing their underlying structures under molecular state assignment

# The corresponding flavor wave functions



**l l<sub>3</sub>**

$$\left| \frac{1}{2}, \frac{1}{2} \right\rangle = \sqrt{\frac{2}{3}} |\Sigma_c^{(*)++} D^{*-}\rangle - \frac{1}{\sqrt{3}} |\Sigma_c^{(*)+} \bar{D}^{*0}\rangle,$$

$$\left| \frac{1}{2}, -\frac{1}{2} \right\rangle = \frac{1}{\sqrt{3}} |\Sigma_c^{(*)+} D^{*-}\rangle - \sqrt{\frac{2}{3}} |\Sigma_c^{(*)0} \bar{D}^{*0}\rangle,$$

$$\left| \frac{3}{2}, \frac{3}{2} \right\rangle = |\Sigma_c^{(*)++} \bar{D}^{*0}\rangle,$$

$$\left| \frac{3}{2}, \frac{1}{2} \right\rangle = \frac{1}{\sqrt{3}} |\Sigma_c^{(*)++} D^{*-}\rangle + \sqrt{\frac{2}{3}} |\Sigma_c^{(*)+} \bar{D}^{*0}\rangle,$$

$$\left| \frac{3}{2}, -\frac{1}{2} \right\rangle = \sqrt{\frac{2}{3}} |\Sigma_c^{(*)+} D^{*-}\rangle + \frac{1}{\sqrt{3}} |\Sigma_c^{(*)0} \bar{D}^{*0}\rangle,$$

$$\left| \frac{3}{2}, -\frac{3}{2} \right\rangle = |\Sigma_c^{(*)0} D^{*-}\rangle,$$

**These flavor wave functions with  $l=1/2$  match the discussed  $P_c(4380)$  and  $P_c(4450)$**

**We need to perform a dynamical calculation of the structures of  $\Sigma_c(2455)D^*$  and  $\Sigma_c^*(2520)D^*$**



# One pion exchange (OPE) model

**Deuteron: loosely bound state of proton and neutron**

**Nucleon force: short-range, mid-range, long-range**

$\rho$  and  $\omega$  exchanges

Scalar  $\sigma$  with mass  
around 600 MeV

Pion exchange

The coupling of  $\pi$  with nucleons reads

$$\mathcal{L} = g_{NN\pi} \bar{\psi} i \gamma_5 \boldsymbol{\tau} \psi \cdot \boldsymbol{\pi},$$

the non-relativistic nucleon-nucleon potential via  $\pi$  meson exchange can be obtained as

$$V_{\pi} = \frac{g_{NN\pi}^2}{4\pi} \frac{m_{\pi}^2}{12m_N^2} (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) \left\{ \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \left[ \frac{3(\boldsymbol{\sigma}_1 \cdot \mathbf{r})(\boldsymbol{\sigma}_2 \cdot \mathbf{r})}{r^2} - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \right] \left[ 1 + \frac{3}{m_{\pi}r} + \frac{3}{m_{\pi}^2 r^2} \right] \right\} \frac{e^{-m_{\pi}r}}{r}$$

# In the past decade, one boson exchange was extensively applied to the studies of newly observed hadron states

## Long list:

LIU X, ZENG X Q, DING Y B, LI X Q, SHEN H, SHEN H. arXiv:hep-ph/0406118  
HE X G, LI X Q, LIU X, ZENG X Q. Eur. Phys. J. C, 2007, **51**: 883–889  
LIU X. Eur. Phys. J. C, 2008, **54**: 471–474  
LIU X, LIU Y R, DENG W Z, ZHU S L. Phys. Rev. D, 2008, **77**: 034003  
LIU X, ZHANG B. Eur. Phys. J. C, 2008, **54**: 253–258  
Tornqvist N A. arXiv:hep-ph/0308277  
Swanson E S. Phys. Lett. B, 2004, **598**: 197  
LIU Y R, LIU X, DENG W Z, ZHU S L. Eur. Phys. J. C, 2008, **56**: 63–73  
Close F, Downum C. Phys. Rev. Lett., 2009, **102**: 242003  
Close F, Downum C, Thomas C E. Phys. Rev. D, 2010, **81**: 074033  
Lee I W, Faessler A, Gutsche T, Lyubovitskij V E. Phys. Rev. D, 2009, **80**: 094005  
XU Q, LIU G, JIN H. arXiv:1012.5949

LIU X, LIU Y R, DENG W Z. arXiv:0802.3157  
LIU X, LIU Y R, DENG W Z, ZHU S L. Phys. Rev. D, 2008, **77**: 094015  
LIU X, LUO Z G, LIU Y R, ZHU S L. Eur. Phys. J. C, 2009, **61**: 411–428  
LIU X, ZHU S L. Phys. Rev. D, 2009, **80**: 017502  
HU B, CHEN X L, LUO Z G, HUANG P Z, ZHU S L, YU P F, LIU X. Chin. Phys. C (HEP & NP), 2011, **35**: 113–125  
SHEN L L, CHEN X L, LUO Z G, HUANG P Z, ZHU S L, YU P F, LIU X. Eur. Phys. J. C, 2010, **70**: 183–217  
HE J, LIU X. Phys. Rev. D, **82**: 114029  
LIU X, LUO Z G, ZHU S L. Phys. Lett. B, 2011, **699**: 341–344  
LIU Y R, ZHANG Z Y. Phys. Rev. C, 2009, **80**: 015208  
LIU Y R, ZHANG Z Y. Phys. Rev. C, **79**: 035206  
LIU Y R, ZHANG Z Y. arXiv:0908.1734  
DING G J. arXiv:0711.1485  
DING G J, HUANG W, LIU J F, YAN M L. Phys. Rev. D, 2009, **79**: 034026  
DING G J. Phys. Rev. D, 2009, **79**: 014001  
DING G J. Phys. Rev. D, 2009, **80**: 034005  
Lee N, LUO Z G, CHEN X L, ZHU S L. arXiv:1104.4257  
CHEN Y D, QIAO C F. arXiv:1102.3487

...

## One conclusion:

**Pion exchange** play **crucial role** to form heavy flavor molecular states

**It is the reason why we adopt one pion exchange model to study two  $P_c$  states**

# The effective Lagrangian relevant to the deduction of OPE potential:

$$\mathcal{L}_{\bar{D}^* \bar{D}^* \mathbb{P}} = i \frac{2g}{f_\pi} v^\alpha \varepsilon_{\alpha\mu\nu\lambda} \bar{D}_a^{*\mu\dagger} \bar{D}_b^{*\lambda} \partial_\nu \mathbb{P}_{ab},$$

$$\mathcal{L}_{\mathcal{B}_6 \mathcal{B}_6 \mathbb{P}} = i \frac{g_1}{2f_\pi} \varepsilon^{\mu\nu\lambda\kappa} v_\kappa \text{Tr}[\bar{\mathcal{B}}_6 \gamma_\mu \gamma_\lambda \partial_\nu \mathbb{P} \mathcal{B}_6],$$

$$\mathcal{L}_{\mathcal{B}_6^* \mathcal{B}_6^* \mathbb{P}} = -i \frac{3g_1}{2f_\pi} \varepsilon^{\mu\nu\lambda\kappa} v_\kappa \text{Tr}[\bar{\mathcal{B}}_{6\mu}^* \partial_\nu \mathbb{P} \mathcal{B}_{6\nu}^*],$$

where  $g = 0.59 \pm 0.07 \pm 0.01$  is extracted from the width of  $D^*$  [25] as is done in Ref. [26], and  $g_1 = 0.94$  was fixed in Refs. [12,24].

[12] Z. C. Yang, Z. F. Sun, J. He, X. Liu, and S. L. Zhu, Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon, *Chin. Phys. C* **36**, 6 (2012).

[24] Y. R. Liu and M. Oka,  $\Lambda_c N$  bound states revisited, *Phys. Rev. D* **85**, 014015 (2012).

[25] C. Isola, M. Ladisa, G. Nardulli, and P. Santorelli, Charming penguin contributions in  $B \rightarrow K^* \pi, K(\rho, \omega, \phi)$  decays, *Phys. Rev. D* **68**, 114001 (2003).

[26] X. Liu, Y.-R. Liu, W.-Z. Deng, and S.-L. Zhu,  $Z^+(4430)$  as a  $D_1' D^*(D_1 D^*)$  molecular state, *Phys. Rev. D* **77**, 094015 (2008).

The effective potential in momentum space

Scattering amplitude

$$V(\mathbf{Q}) \approx - \frac{\mathcal{M}}{\sqrt{2E_A} \sqrt{2E_B} \sqrt{2E_C} \sqrt{2E_D}}.$$

Fourier transformation

$V(\mathbf{r})$  → The effective potential in coordinate space

# The effective potentials of $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$ systems

$$V_{\Sigma_c \bar{D}^*}(r) = \frac{1}{3} \frac{gg_1}{f_\pi^2} \nabla^2 Y(\Lambda, m_\pi, r) \mathcal{J}_0 \mathcal{G}_0,$$

$$V_{\Sigma_c^* \bar{D}^*}(r) = \frac{1}{2} \frac{gg_1}{f_\pi^2} \nabla^2 Y(\Lambda, m_\pi, r) \mathcal{J}_1 \mathcal{G}_1,$$

$$Y(\Lambda, m, r) = \frac{1}{4\pi r} (e^{-mr} - e^{-\Lambda r}) - \frac{\Lambda^2 - m^2}{8\pi\Lambda} e^{-\Lambda r}.$$

TABLE I. The values of the  $\mathcal{J}_i$  and  $\mathcal{G}_i$  coefficients. Here,  $S$ ,  $L$ , and  $J$  denote the spin, orbital, and total angular quantum numbers, respectively.  $\mathbb{S}$  denotes  $L = 1$  since we are interested in the  $S$ -wave interaction of the  $\Sigma_c(2455)\bar{D}^*$  and  $\Sigma_c^*(2520)\bar{D}^*$  systems.

$I$	$\mathcal{G}_0$	$\mathcal{G}_1$	$ ^{2S+1}L_J\rangle$	$\mathcal{J}_0$	$\mathcal{J}_1$
1/2	1	-1	$ ^2\mathbb{S}_{(1/2)}\rangle$	-2	5/3
3/2	-1/2	1/2	$ ^4\mathbb{S}_{(3/2)}\rangle$	1	2/3
...	...	...	$ ^6\mathbb{S}_{(5/2)}\rangle$	...	-1

**By solving Shrourding equation, we try to find bound state solutions**

# Numerical results

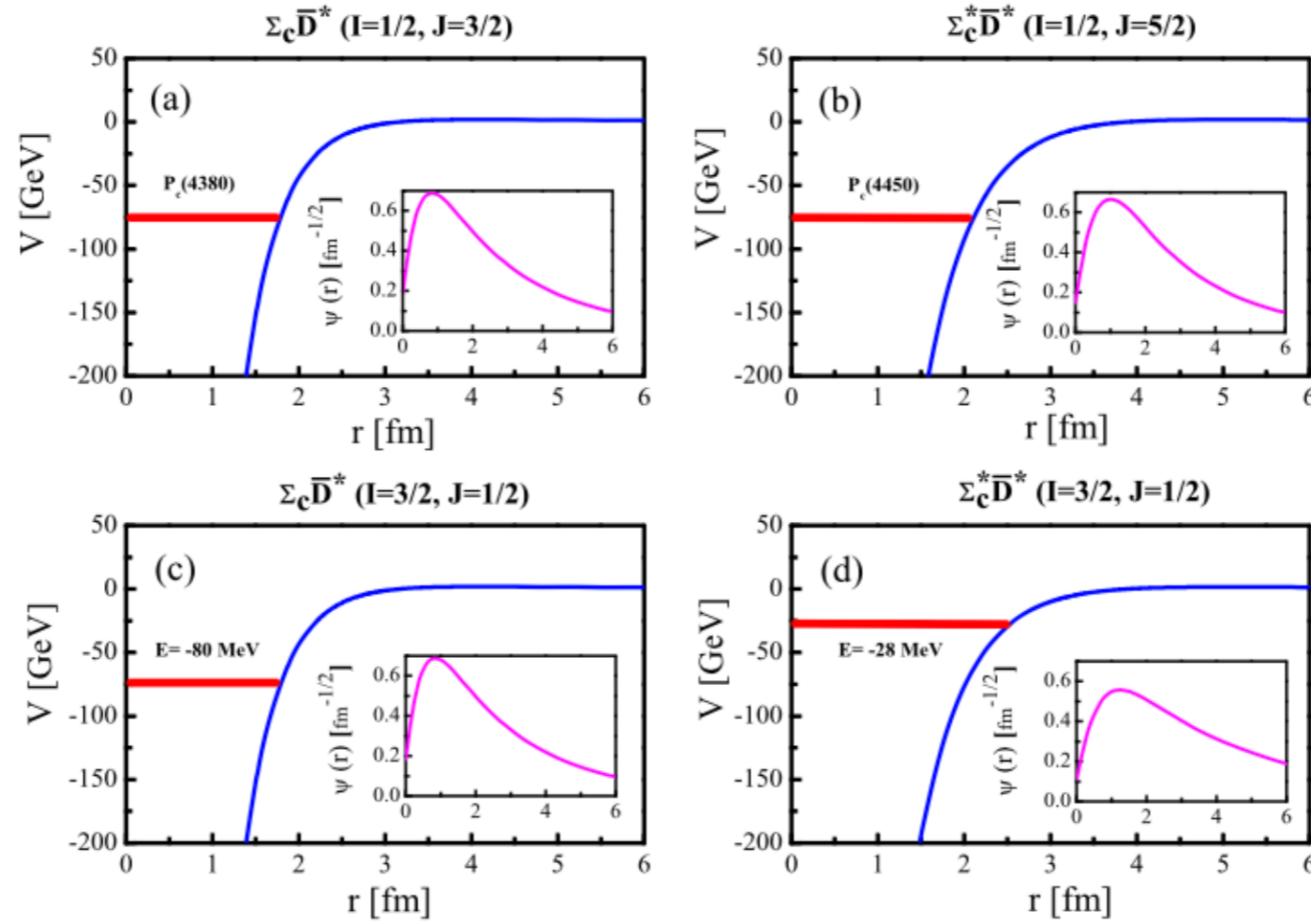


FIG. 1 (color online). The variations of the obtained OPE effective potentials for the  $\Sigma_c^{(*)} \bar{D}^*$  systems to  $r$ , and obtained bound state solutions. Here, the masses of  $P_c(4380)$  and  $P_c(4450)$  can be reproduced well under the  $\Sigma_c \bar{D}^*$  with ( $I = 1/2, J = 3/2$ ) and  $\Sigma_c^* \bar{D}^*$  with ( $I = 1/2, J = 5/2$ ) molecular assignments, respectively.  $\Lambda = 2.35$  GeV and  $\Lambda = 1.77$  GeV are taken for the  $\Sigma_c \bar{D}^*$  and  $\Sigma_c^* \bar{D}^*$  systems, respectively. The blue curves are the effective potentials, and the red line stands for the corresponding energy levels. Additionally, the obtained spatial wave functions are given here.



# Conclusions

- The masses of Pc(4380) and Pc(4450) can be reproduced
  - **Pc(4380) and Pc(4450) as  $\Sigma_c(2455)D^*$  and  $\Sigma_c^*(2520)D^*$  molecular states with  $(l=1/2, J=1/2)$  and  $(l=1/2, J=3/2)$ , respectively.**
  - Qualitatively explain why the width of Pc(4450) is much narrower than that of Pc(4380)
    - S-wave: Pc(4380)  $\rightarrow$  J/ $\psi$ +p**
    - D-wave: Pc(4450)  $\rightarrow$  J/ $\psi$ +p**
  - **Predict two isospin partners** of Pc(4380) and Pc(4450)
    - $\Sigma_c(2455)D^*$  with  $(l=3/2, J=1/2)$  and binding energy **-80** MeV
    - $\Sigma_c^*(2520)D^*$  with  $(l=3/2, J=1/2)$  and binding energy **-28** MeV
- Decay modes:  $\Delta(1232)J/\psi$  and  $\Delta(1232)\eta_c$

# Our Study through QCD Sum Rules

## Towards exotic hidden-charm pentaquarks in QCD

Hua-Xing Chen<sup>1</sup>, Wei Chen<sup>2,\*</sup>, Xiang Liu<sup>3,4,†</sup>, T. G. Steele<sup>2,‡</sup> and Shi-Lin Zhu<sup>5,6,7§</sup>

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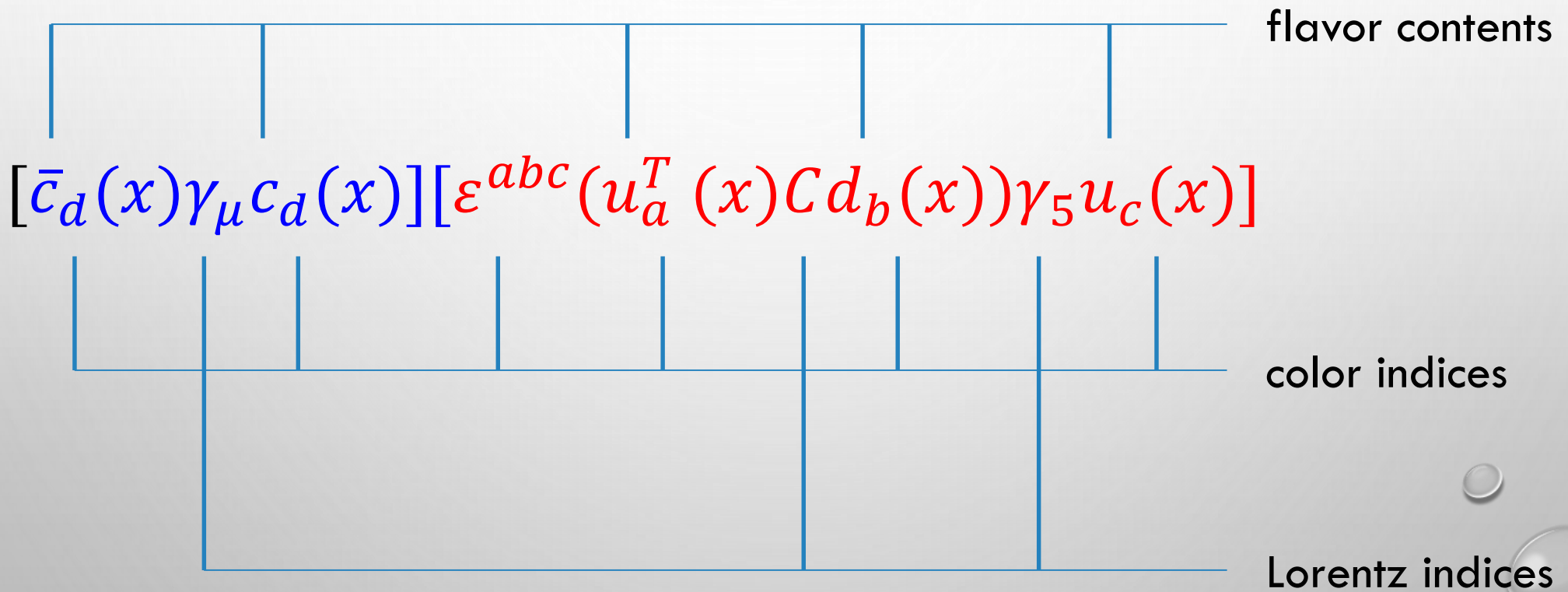
Inspired by the  $P_c(4380)$  and  $P_c(4450)$  recently observed by LHCb, a QCD sum rule investigation is performed, by which  $P_c(4380)$  and  $P_c(4450)$  can be identified as exotic hidden-charm pentaquarks composed of an anti-charmed meson and a charmed baryon. Our results suggest that the  $P_c(4380)$  and  $P_c(4450)$  states have quantum numbers  $J^P = 3/2^-$  and  $5/2^+$ , respectively. As an important extension, the mass predictions of hidden-bottom pentaquarks are given. Searches for these partners of  $P_c(4380)$  and  $P_c(4450)$  is especially accessible at future experiments like LHCb.

# Internal structure of hadrons

- The internal structure of hadrons is of interest, but we do not know much.
- An example: There are many excited heavy mesons well observed in experiments, such as  $\Lambda_c(2595)$  of  $J^P = 1/2^-$  and  $\Lambda_c(2625)$  of  $J^P = 3/2^-$ .
- They both contain **one orbital excitation**, but we do not know whether this orbital excitation is between the two light quarks or between the light quarks and the heavy quark.
- We can construct different interpolating currents to study this subject using the method of QCD sum rule.



• **A  $[J/\psi p]$  current**



## Two Configurations:

$$[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c] \text{ and } [\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$$

These two configurations, **as if they are local**, can be related to each other through

- **The Fierz transformation**

$$\begin{aligned} (\bar{s}_a u_b)(\bar{s}_b d_a) = & -\frac{1}{4} \{ (\bar{s}_a u_a)(\bar{s}_b d_b) + (\bar{s}_a \gamma_\mu u_a)(\bar{s}_b \gamma^\mu d_b) + \frac{1}{2} (\bar{s}_a \sigma_{\mu\nu} u_a)(\bar{s}_b \sigma^{\mu\nu} d_b) \\ & - (\bar{s}_a \gamma_\mu \gamma_5 u_a)(\bar{s}_b \gamma^\mu \gamma_5 d_b) + (\bar{s}_a \gamma_5 u_a)(\bar{s}_b \gamma_5 d_b) \}. \end{aligned}$$

- **The color rearrangement**

$$\delta^{de} \epsilon^{abc} = \delta^{da} \epsilon^{ebc} + \delta^{db} \epsilon^{aec} + \delta^{dc} \epsilon^{abe}$$

# Configuration $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$

- There are three independent local light baryon fields of flavor-octet and having a positive parity:

H. X. Chen, V. Dmitrasinovic, A. Hosaka, K. Nagata and S. L. Zhu, Phys. Rev. D 78, 054021 (2008)

$$\begin{aligned} N_1^N &= \epsilon_{abc} \epsilon^{ABD} \lambda_{DC}^N (q_A^{aT} C q_B^b) \gamma_5 q_C^c, \\ N_2^N &= \epsilon_{abc} \epsilon^{ABD} \lambda_{DC}^N (q_A^{aT} C \gamma_5 q_B^b) q_C^c, \\ N_{3\mu}^N &= \epsilon_{abc} \epsilon^{ABD} \lambda_{DC}^N (q_A^{aT} C \gamma_\mu \gamma_5 q_B^b) \gamma_5 q_C^c, \end{aligned}$$

- Together with light baryon fields having negative parity and the charmonium fields:

$$\begin{aligned} &\bar{c}_d c_d [0^+], \bar{c}_d \gamma_5 c_d [0^-], \\ &\bar{c}_d \gamma_\mu c_d [1^-], \bar{c}_d \gamma_\mu \gamma_5 c_d [1^+], \bar{c}_d \sigma_{\mu\nu} c_d [1^\pm], \end{aligned}$$

- We can construct the currents of the configuration  $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$ .
- Those containing  $J=3/2$  components are

$$\begin{aligned} &[\bar{c}_d c_d][N_{3\mu}^N], [\bar{c}_d \gamma_5 c_d][N_{3\mu}^N], [\bar{c}_d \gamma_\mu c_d][N_{1,2}^N], \\ &[\bar{c}_d \gamma_\mu \gamma_5 c_d][N_{1,2}^N], [\bar{c}_d \gamma_\mu c_d][N_{3\nu}^N], [\bar{c}_d \gamma_\mu \gamma_5 c_d][N_{3\nu}^N], \\ &[\bar{c}_d \sigma_{\mu\nu} c_d][N_{1,2}^N], [\bar{c}_d \sigma_{\mu\nu} c_d][N_{3\rho}^N], \end{aligned}$$

- Three of them of  $J=3/2$  &  $5/2$  couple well to the combination of  $J/\psi$  and **proton**

$$\begin{aligned} \eta_{1\mu}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc} (u_a^T C d_b) \gamma_5 u_c], \\ \eta_{2\mu}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc} (u_a^T C \gamma_5 d_b) u_c], \\ \eta_{3\{\mu\nu\}}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc} (u_a^T C \gamma_\nu \gamma_5 d_b) u_c] + \{\mu \leftrightarrow \nu\}. \end{aligned}$$



# Configuration $[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$

- The currents of this type can not be systematically constructed so easily, so we just transform the previous currents to this configuration, and select those related to  $D/D^*$  and  $\Lambda_c/\Sigma_c/\Sigma_c^*$ .

- We shall investigate the following currents of  $J=3/2$

$$J_{\mu}^{\bar{D}^* \Sigma_c} = [\bar{c}_d \gamma_{\mu} d_d][\epsilon_{abc}(u_a^T C \gamma_{\nu} u_b) \gamma^{\nu} \gamma_5 c_c],$$

$$J_{\mu}^{\bar{D} \Sigma_c^*} = [\bar{c}_d \gamma_5 d_d][\epsilon_{abc}(u_a^T C \gamma_{\mu} u_b) c_c],$$

- We shall investigate the following currents of  $J=5/2$

$$J_{\{\mu\nu\}}^{\bar{D}^* \Sigma_c^*} = [\bar{c}_d \gamma_{\mu} d_d][\epsilon_{abc}(u_a^T C \gamma_{\nu} u_b) \gamma_5 c_c] + \{\mu \leftrightarrow \nu\},$$

$$J_{\{\mu\nu\}}^{\bar{D} \Sigma_c^*} = [\bar{c}_d \gamma_{\mu} \gamma_5 d_d][\epsilon_{abc}(u_a^T C \gamma_{\nu} u_b) c_c] + \{\mu \leftrightarrow \nu\},$$

$$J_{\{\mu\nu\}}^{\bar{D}^* \Lambda_c} = [\bar{c}_d \gamma_{\mu} u_d][\epsilon_{abc}(u_a^T C \gamma_{\nu} \gamma_5 d_b) c_c] + \{\mu \leftrightarrow \nu\},$$

# QCD SUM RULES

- In sum rule analyses, we consider **two-point correlation functions**:

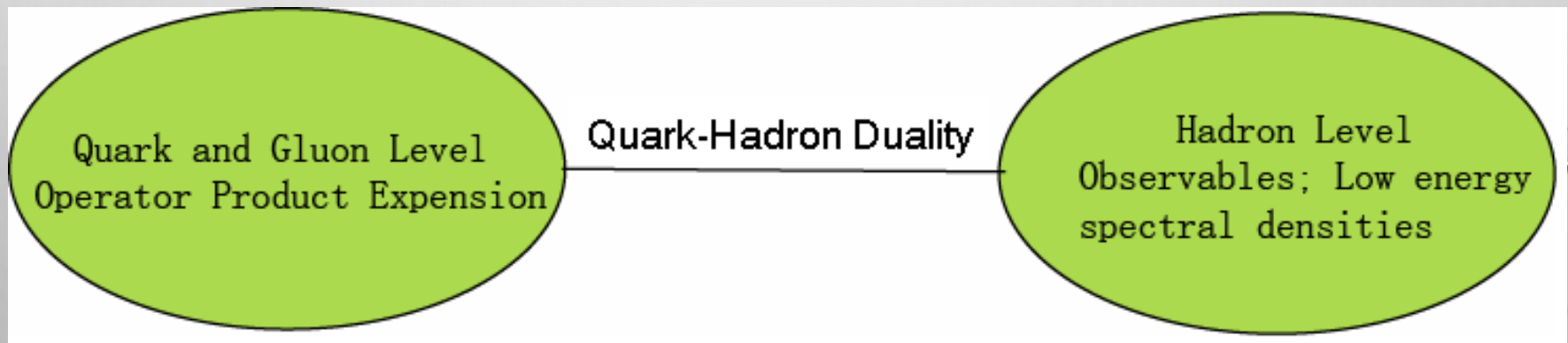
$$\begin{aligned}\Pi(q^2) &\stackrel{\text{def}}{=} i \int d^4x e^{iqx} \langle 0 | T \eta(x) \eta^\dagger(0) | 0 \rangle \\ &\approx \sum_n \langle 0 | \eta | n \rangle \langle n | \eta^\dagger | 0 \rangle\end{aligned}$$

where  $\eta$  is the current which can couple to **hadronic states**.

- By using the **dispersion relation**, we can obtain the **spectral density**

$$\Pi(q^2) = \int_{s_<}^{\infty} \frac{\rho(s)}{s - q^2 - i\epsilon} ds$$

- In QCD sum rules, we can calculate these matrix elements from QCD (**OPE**) and relate them to observables by using **dispersion relation**.



# Quark and Gluon Level

(Convergence of OPE)

$$\Pi_{OPE}(q^2) \xrightarrow[\substack{\text{dispersion relation} \\ s = -q^2}]{\hspace{10em}} \rho_{OPE}(s) = a_n s^n + a_{n-1} s^{n-1}$$

Quark-Hadron Duality

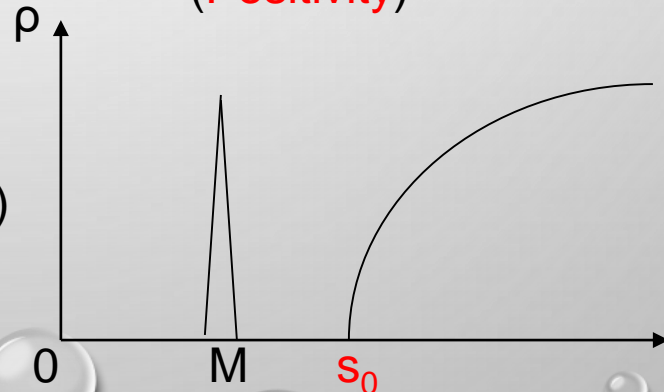
# Hadron Level

$$\Pi_{phys}(q^2) = f_P^2 \frac{\not{q} + M}{q^2 - M^2} \longleftrightarrow \rho_{phys}(s) = \lambda_x^2 \delta(s - M_x^2) + \dots$$

(Positivity)

(for baryon case)

(Sufficient amount of Pole contribution)



# QCD Sum Rules

- **Borel transformation** to suppress the higher order terms:

$$\Pi(M_B^2) \equiv f^2 e^{-M^2/M_B^2} = \int_{s_0}^{s_0} e^{-s/M_B^2} \rho(s) ds$$

- **Two** parameters

$$M_B, s_0$$

We need to choose certain region of  $(M_B, s_0)$ .

- **Criteria**

1. Stability
2. Convergence of OPE
3. Positivity of spectral density
4. Sufficient amount of pole contribution



Y. Chung, H. G. Dosch, M. Kremer and D. Schall, Nucl. Phys. B 197, 55 (1982)

D. Jido, N. Kodama and M. Oka, Phys. Rev. D 54, 4532 (1996)

Y. Kondo, O. Morimatsu and T. Nishikawa, Nucl. Phys. A 764, 303 (2006)

K. Ohtani, P. Gubler and M. Oka, Phys. Rev. D 87, no. 3, 034027 (2013)

## Parity of Pentaquark

- Assuming  $J$  is a pentaquark current,  $\gamma_5 J$  is its partner having the opposite parity.
- They can couple to the same physical state through

$$\langle 0 | J | P(q) \rangle = f_P u(q),$$

$$\langle 0 | \gamma_5 J | P(q) \rangle = f_P \gamma_5 u(q).$$

- The same pentaquark current  $J$  can couple to states of both positive and negative parities through

$$\langle 0 | J | P(q) \rangle = f_P u(q),$$

$$\langle 0 | J | P'(q) \rangle = f_{P'} \gamma_5 u'(q).$$

where  $|P(q)\rangle$  has the same parity as  $J$ , while  $|P'(q)\rangle$  has the opposite parity.

$$f_P^2 \frac{\not{q} + M}{q^2 - M^2}$$

$$f_{P'}^2 \frac{-\not{q} + M}{q^2 - M^2}$$

# Numerical Results

- Technically, in the following analyses we use the terms proportional to  $\mathbf{1}$  to evaluate the mass of  $P_c(4380)$  and  $P_c(4450)$ , which are then compared with those proportional to  $\not{q}$  to determine its parity.
- We perform QCD sum rule analyses using  $\eta_{12\mu}^{\bar{c}cuud} = \eta_{1\mu}^{\bar{c}cuud} - \eta_{2\mu}^{\bar{c}cuud}$  and  $\eta_{3\{\mu\nu\}}^{\bar{c}cuud}$  of the  $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$  configuration, but the results are not useful.
- We also perform QCD sum rule analyses using  $J_{\mu}^{\bar{D}^* \Sigma_c}, J_{\mu}^{\bar{D} \Sigma_c^*}, J_{\{\mu\nu\}}^{\bar{D}^* \Sigma_c^*}, J_{\{\mu\nu\}}^{\bar{D} \Sigma_c^*}$ , and  $J_{\{\mu\nu\}}^{\bar{D}^* \Lambda_c}$  of the  $[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$  configuration.

The sum rule results obtained using  $J_{\mu}^{\bar{D}^* \Sigma_c} (J=3/2)$  are

$$M_{[\bar{D}^* \Sigma_c], 3/2^-} = 4.37^{+0.18}_{-0.12} \text{ GeV} .$$

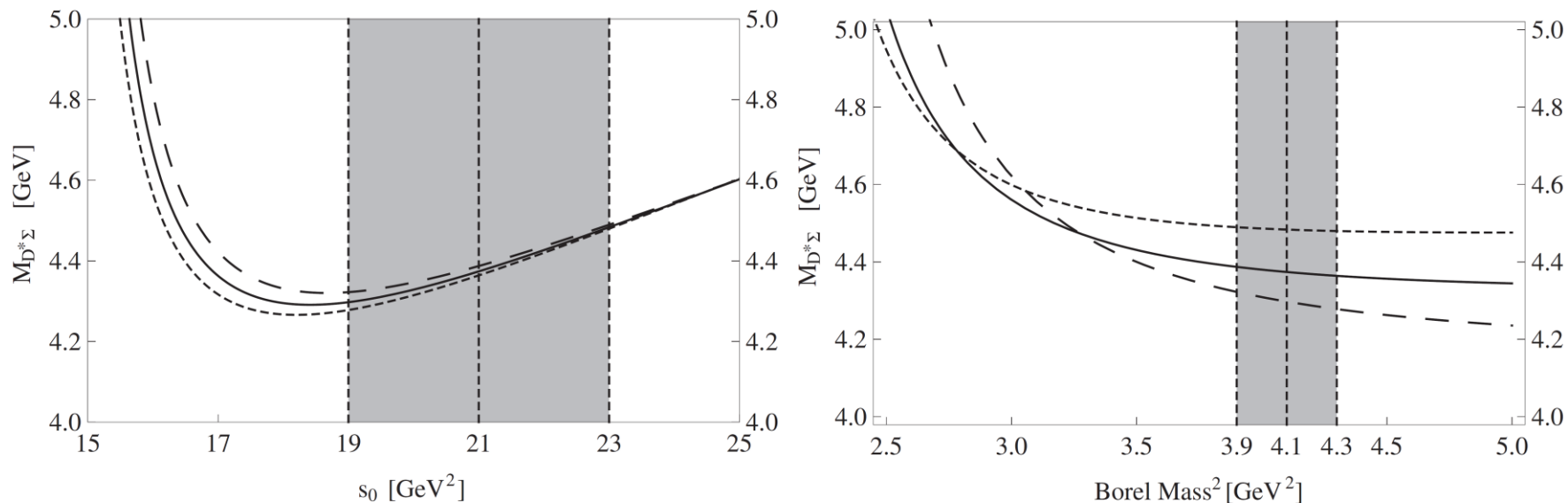


FIG. 1: The variation of  $M_{[\bar{D}^* \Sigma_c], 3/2^-}$  with respect to the threshold value  $s_0$  (left) and the Borel mass  $M_B$  (right). In the left figure, the

The sum rule results obtained using  $J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^*}$  and  $J_{\{\mu\nu\}}^{\bar{D}^*\Lambda_c}$  are not useful.  
 However, their mixing gives reliable mass sum rules ( $J=5/2$ )

$$J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^* \& \bar{D}^*\Lambda_c} = \sin \theta \times J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^*} + \cos \theta \times J_{\{\mu\nu\}}^{\bar{D}^*\Lambda_c}$$

$$\tan \theta = -1.25$$

$$M_{[\bar{D}\Sigma_c^* \& \bar{D}^*\Lambda_c], 5/2^+} = 4.47^{+0.19}_{-0.12} \text{ GeV}.$$

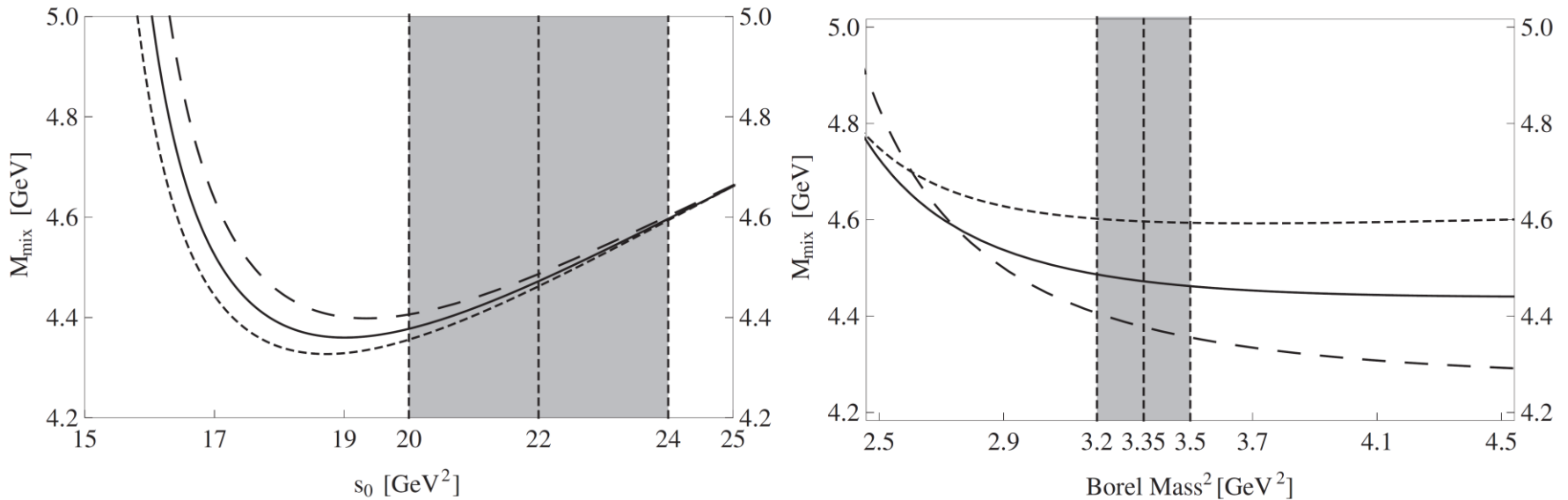


FIG. 2: The variation of  $M_{[\bar{D}\Sigma_c^* \& \bar{D}^*\Lambda_c], 5/2^+}$  with respect to the threshold value  $s_0$  (left) and the Borel mass  $M_B$  (right).

# Summary

- We have performed a QCD sum rule investigation, by which the  $P_c(4380)$  and  $P_c(4450)$  states recently observed by LHCb are identified as **hidden-charm pentaquark states** composed of **anti-charmed meson** and **charmed baryon**.
- We use the interpolating current  $J_\mu^{\bar{D}^*\Sigma_c}$  to perform QCD sum rule analysis. The result is consistent with the experimental mass of the  $P_c(4380)$  state, which supports the  $P_c(4380)$  state as a  $[\bar{D}^*\Sigma_c]$  hidden-charm pentaquark, and of quantum numbers  $J^P = 3/2^-$ .
- We use a mixed current  $J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^* \& \bar{D}^*\Lambda_c}$  to perform QCD sum rule analysis. The result is consistent with the experimental mass of the  $P_c(4450)$  state, which implies a possible mixed hidden-charm pentaquark structure of the  $P_c(4450)$  state, as admixture of  $[\bar{D}\Sigma_c^*]$  and  $[\bar{D}^*\Lambda_c]$ , and of quantum numbers  $J^P = 5/2^+$ .

# More: doubly hidden-charm/bottom tetraquark states

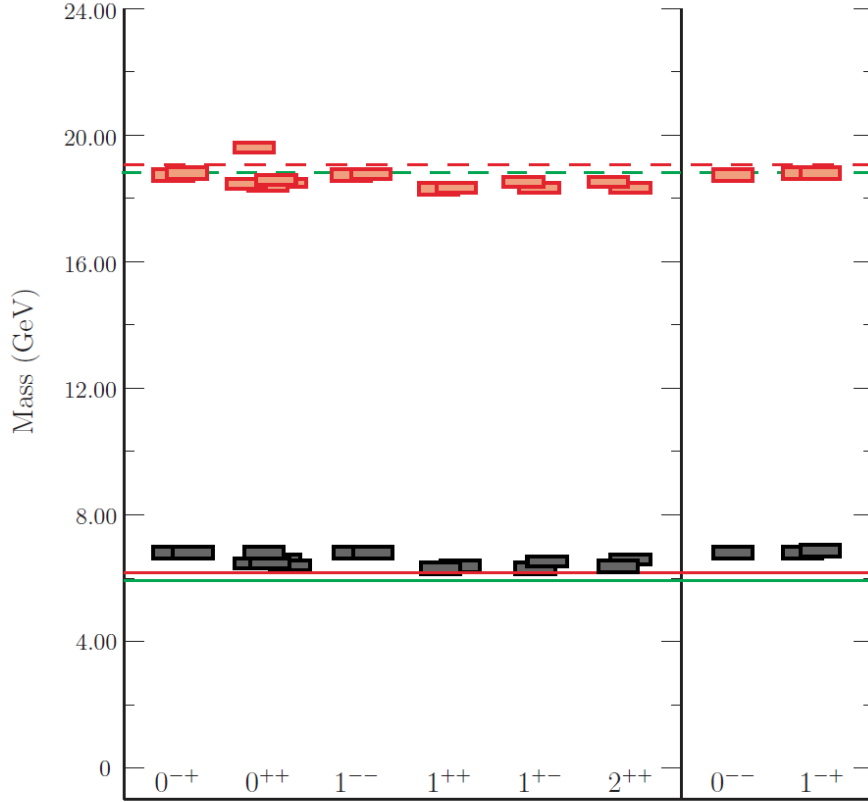


FIG. 3: Summary of the doubly hidden-charm/bottom tetraquark spectra labelled by  $J^{PC}$ . The red and black rectangles are the masses of the  $cc\bar{c}\bar{c}$  and  $bb\bar{b}\bar{b}$  states, respectively. The vertical size of the rectangle represents the uncertainty of our calculation. The green and red solid (dashed) lines indicate the two-charmonium (bottomonium) thresholds  $\eta_c(1S)\eta_c(1S)$  ( $\eta_b(1S)\eta_b(1S)$ ) and  $J/\psi J/\psi$  ( $\Upsilon(1S)\Upsilon(1S)$ ), respectively.

$J^{PC}$	S-wave	P-wave
$0^{++}$	$\eta_c(1S)\eta_c(1S), J/\psi J/\psi$	$\eta_c(1S)\chi_{c1}(1P), J/\psi h_c(1P)$
$0^{-+}$	$\eta_c(1S)\chi_{c0}(1P), J/\psi h_c(1P)$	$J/\psi J/\psi$
$0^{--}$	$J/\psi\chi_{c1}(1P)$	$J/\psi\eta_c(1S)$
$1^{++}$	–	$J/\psi h_c(1P), \eta_c(1S)\chi_{c1}(1P), \eta_c(1S)\chi_{c0}(1P)$
$1^{+-}$	$J/\psi\eta_c(1S)$	$J/\psi\chi_{c0}(1P), J/\psi\chi_{c1}(1P), \eta_c(1S)h_c(1P)$
$1^{-+}$	$J/\psi h_c(1P), \eta_c(1S)\chi_{c1}(1P)$	–
$1^{--}$	$J/\psi\chi_{c0}(1P), J/\psi\chi_{c1}(1P), \eta_c(1S)h_c(1P)$	$J/\psi\eta_c(1S)$

TABLE II: Possible decay modes of the  $cc\bar{c}\bar{c}$  states by spontaneous dissociation into two charmonium mesons.

# Summary

**We still need more theoretical and experimental joint efforts**

**Thank you for your  
attention**



# More: hidden-charm baryonium states

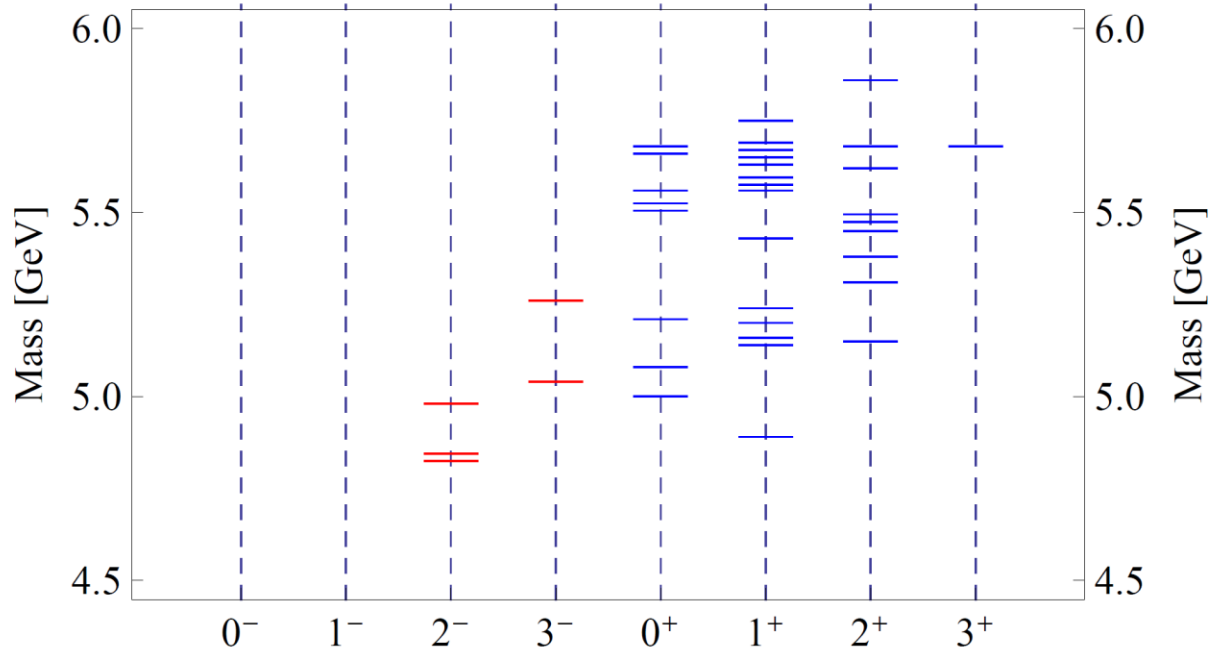


FIG. 5: Spectrum of hidden-charm baryonium states obtained using the method of QCD sum rules. The blue lines are obtained using the currents of Type D, and the red lines are obtained using the currents of Type F.