TOWARDS EXOTIC HIDDEN-CHARM PENTAQUARKS IN QCD SUM RULE

陈华星

北京航空航天大学

合作者：陈伟　刘翔　T. G. STEELE　朱世琳

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5. Summary

三体衰变$\Lambda_b^0 \longrightarrow J/\psi\ p\ K^-$

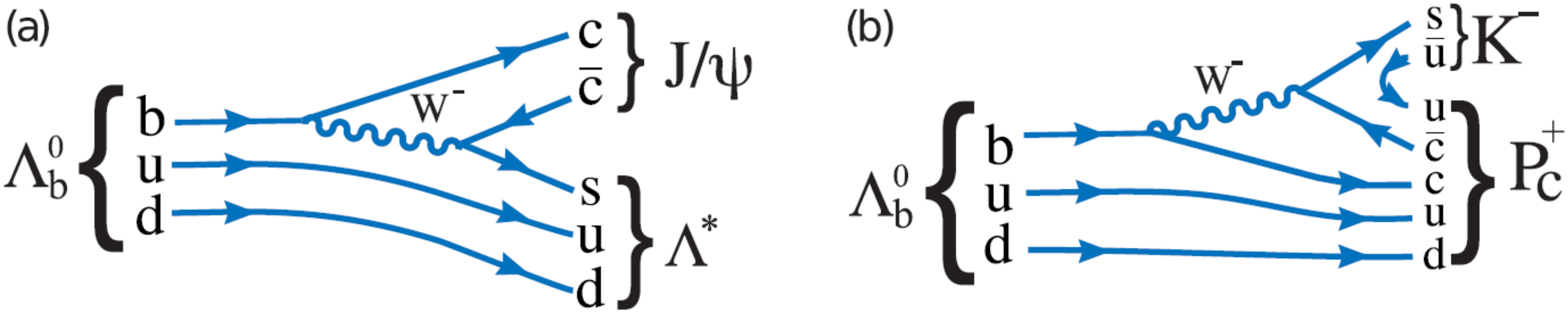
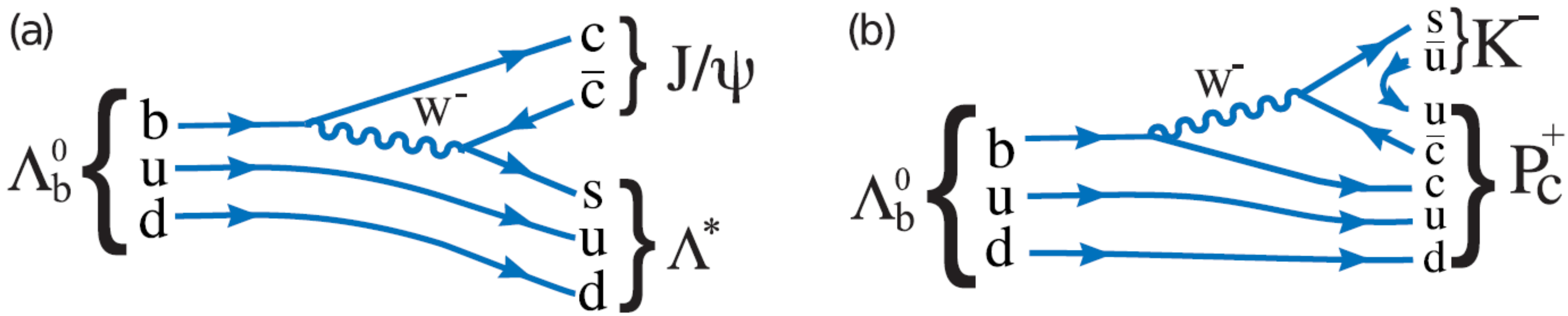


Figure 1: Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi\,\Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

三体衰变$\Lambda_b^0 \rightarrow J/\psi\ p\ K^-$



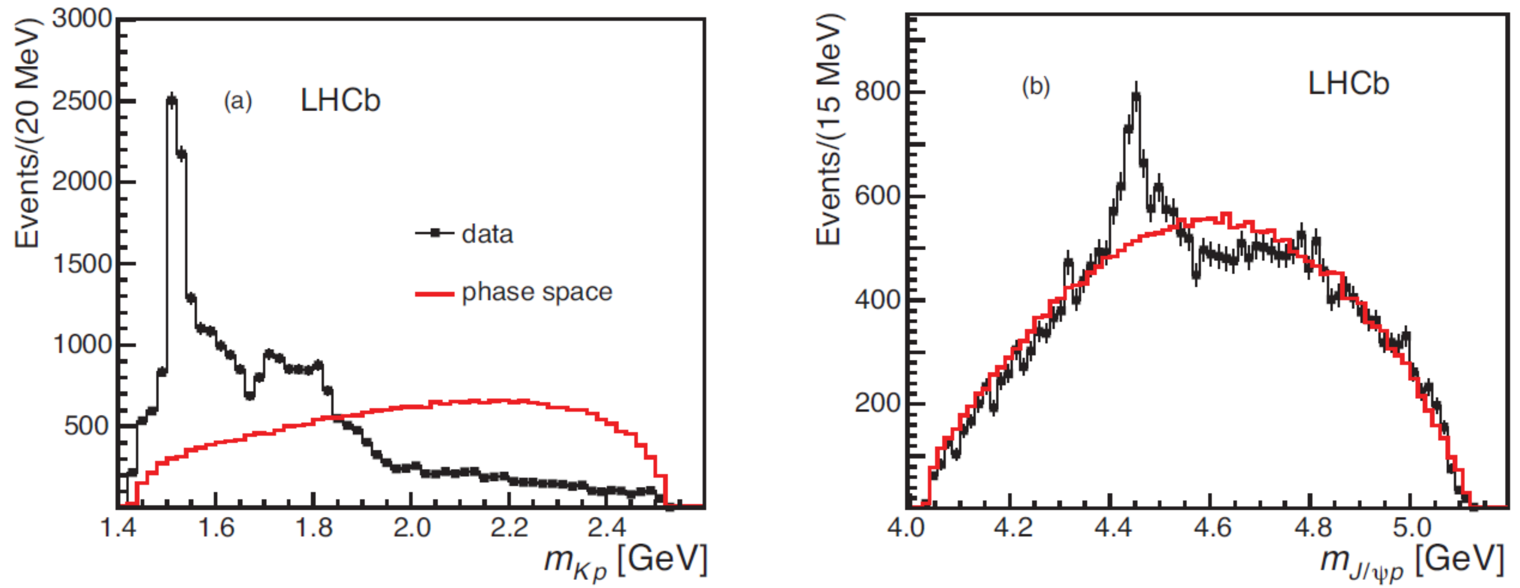
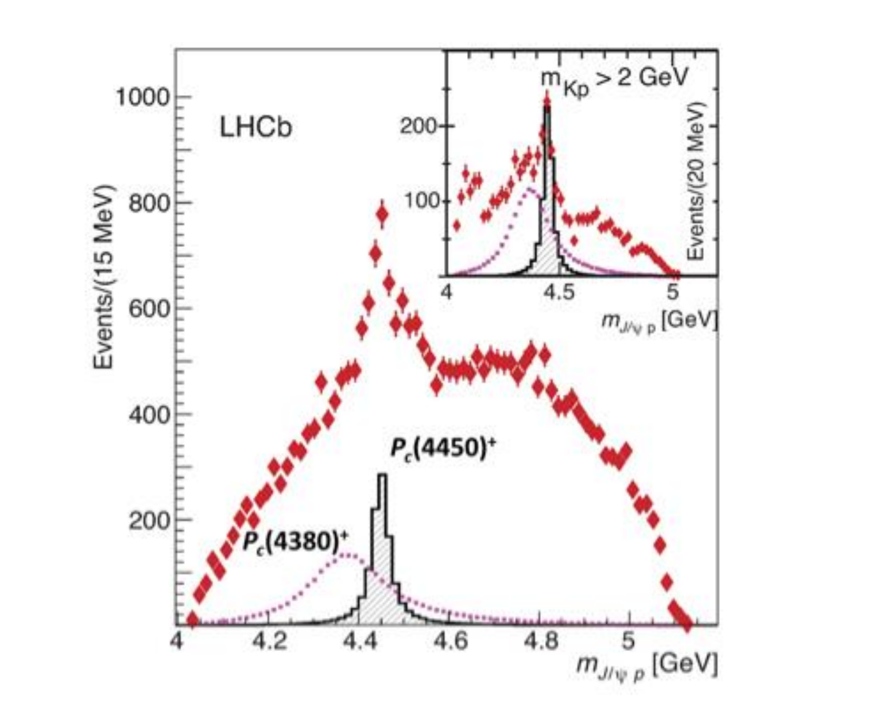
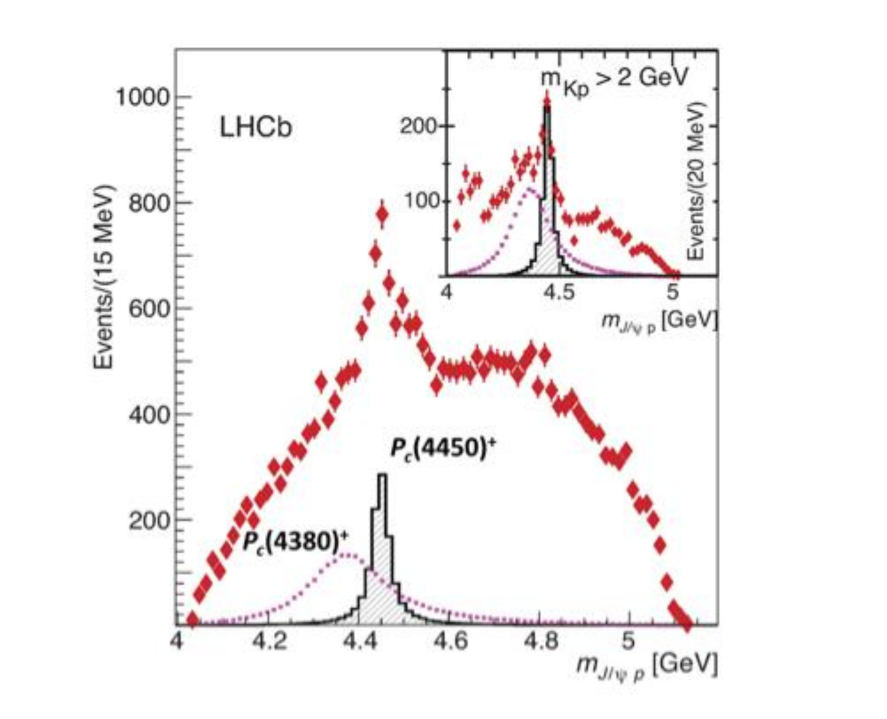
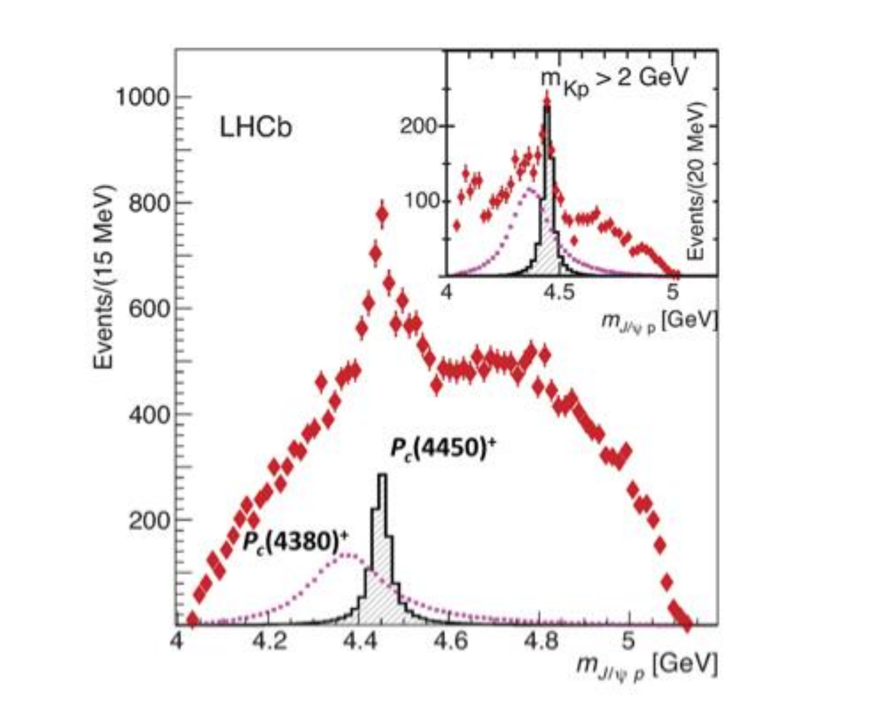


Figure 2: Invariant mass of (a) K^-p and (b) $J/\psi p$ combinations from $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.


LHCb
Events/(15 MeV)
$m_{J/\psi\, p}$ [GeV]
$P_c(4450)^+$
$P_c(4380)^+$
$m_{Kp} > 2$ GeV
Events/(20 MeV)
$m_{J/\psi\, p}$ [GeV]



- The **fractions** of the total sample due to the lower mass and higher mass states are $(8.4 \pm 0.7 \pm 4.2)\%$ and $(4.1 \pm 0.5 \pm 1.1)\%$, respectively.
- The **significances** of the lower mass and higher mass states are 9 and 12 standard deviations, respectively.



- The two P_c^+ states are found to have **masses and widths** of

$$M_{P_c\,(4380)} = 4380 \pm 8 \pm 29 \text{ MeV}$$
$$\Gamma_{P_c\,(4380)} = 205 \pm 18 \pm 86 \text{ MeV}$$
$$M_{P_c\,(4450)} = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$$
$$\Gamma_{P_c\,(4450)} = 39 \pm 5 \pm 19 \text{ MeV}$$

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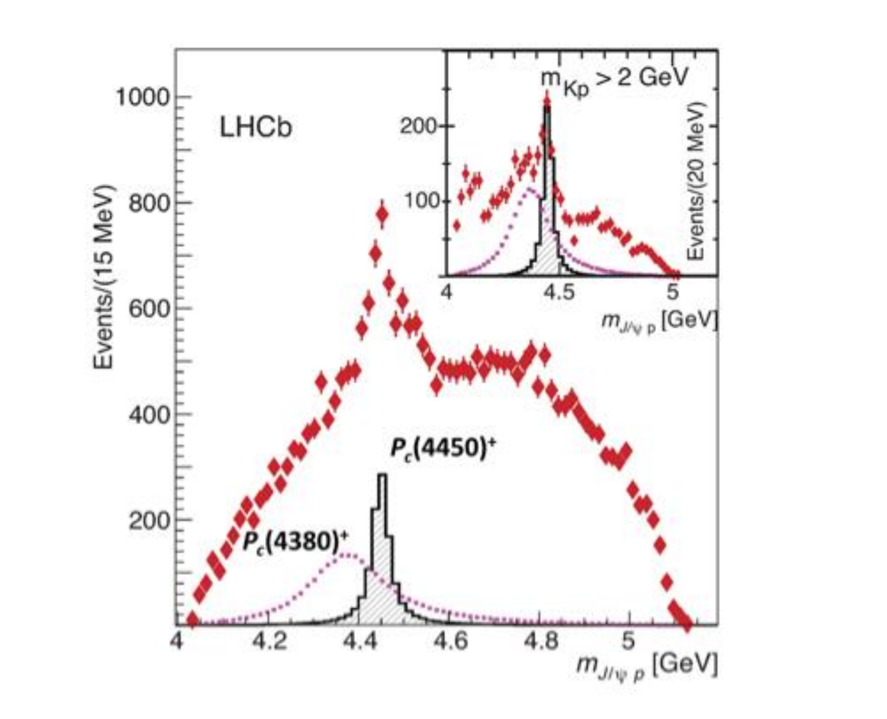

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- The best fit solution has **spin-parity J^P values** of $(3/2^-, 5/2^+)$.
- Acceptable solutions are also found for additional cases with opposite parity, either $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$.

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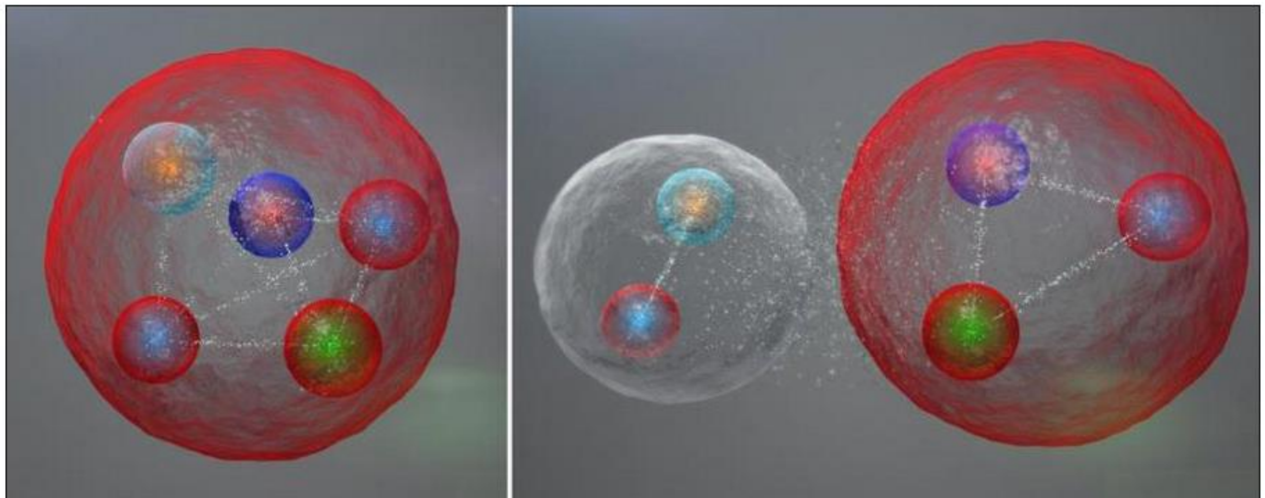
- The LHCb experiment at CERN's Large Hadron Collider has reported **the discovery of a class of particles** known as **pentaquarks**.

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)

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Large Hadron Collider discovers new pentaquark particle

By Paul Rincon
Science editor, BBC News website

14 July 2015 | Science & Environment

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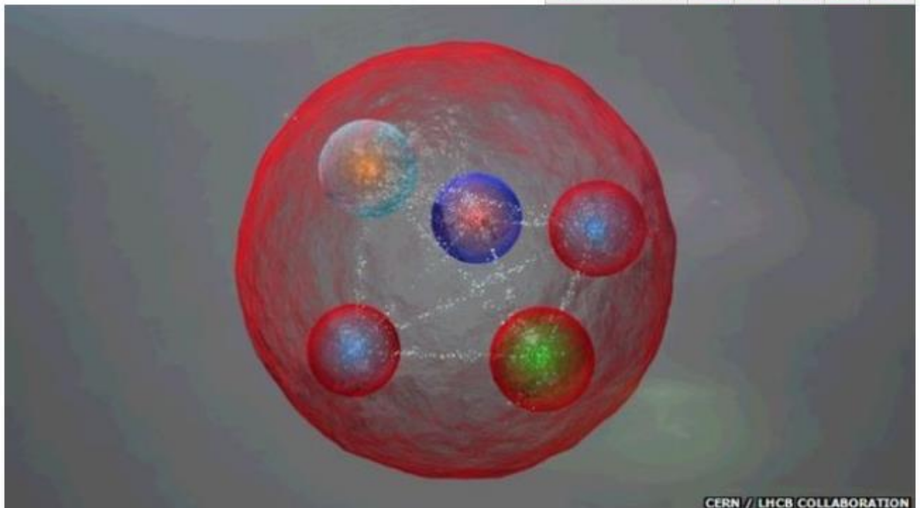

An illustration of one possible layout of quarks in a pentaquark particle such as those seen at LHCb (showing five tightly-bonded quarks)

Scientists at the Large Hadron Collider have announced the discovery of a new particle called the pentaquark.

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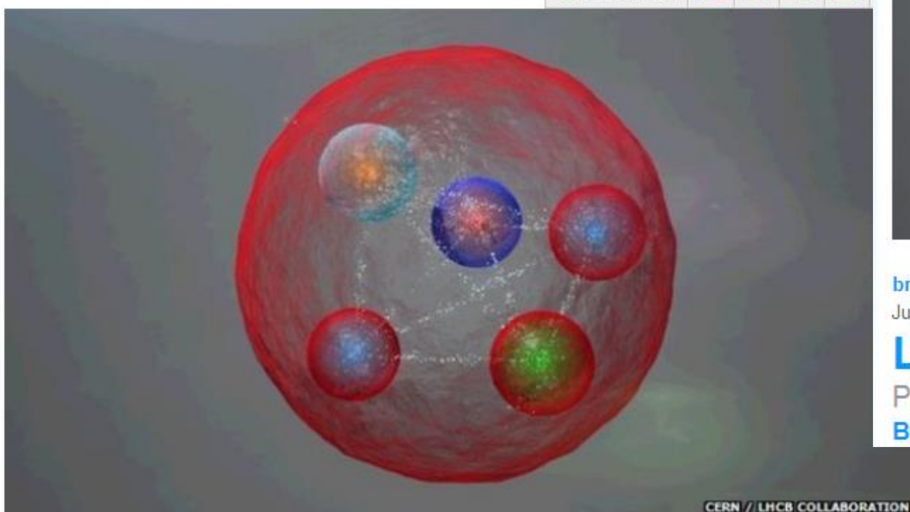

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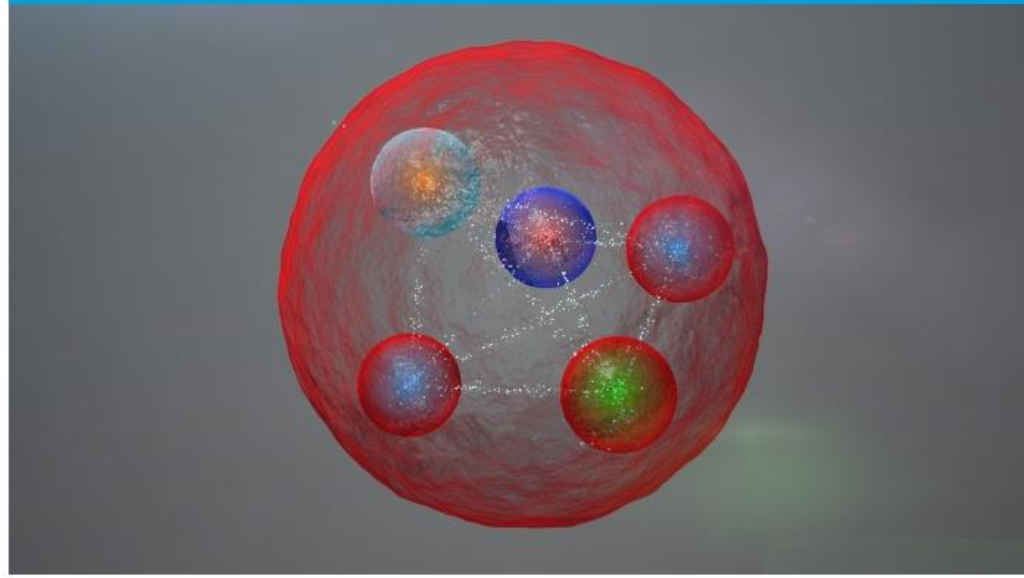


Artwork by CERN

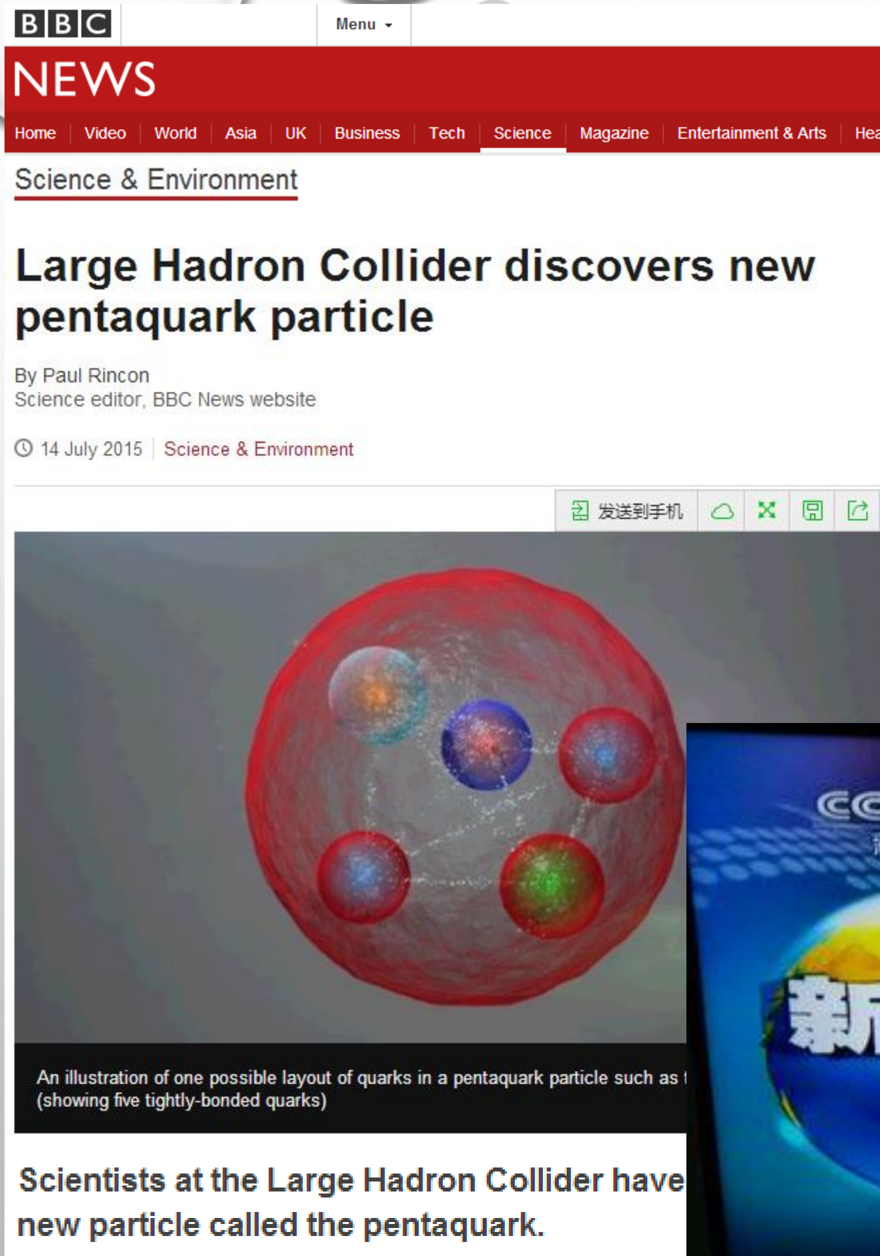
breaking

July 14, 2015

LHC physicists discover five-quark particle

Pentaquarks are no longer just a theory.

By Sarah Charley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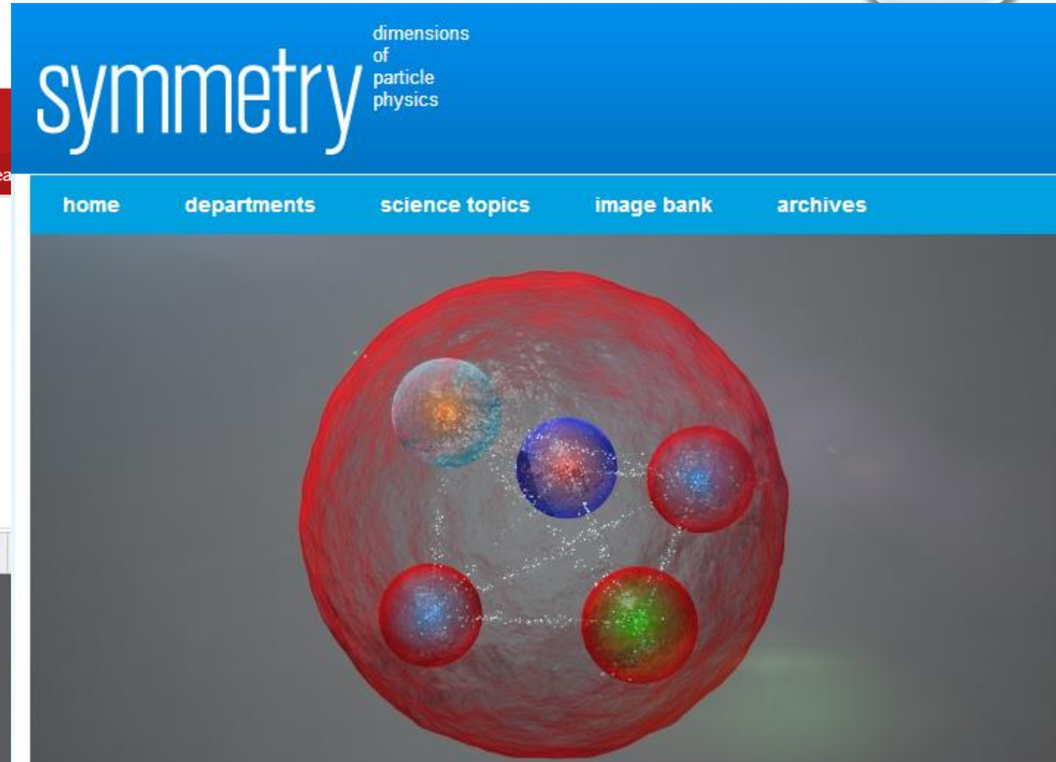

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- **Unfortunately**, the early proposed pentaquark $uudd\bar{s}$ was not observed in all available experiments.

- **Fortunately**, several years later, many **mesonic X, Y, Z particles** have been observed at **Belle, BaBar, BESIII and LHCb**.

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- 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)

Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV

Jia-Jun Wu[1,2], R. Molina[2,3], E. Oset[2,3] and B. S. Zou[1,3]
1. Institute of High Energy Physics, CAS, Beijing 100049, China
2. Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain
3. Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China

(Dated: June 25, 2010) arXiv:1007.0573

The interaction between various charmed mesons and charmed baryons are studied within the framework of the coupled channel unitary approach with the local hidden gauge formalism. Several meson-baryon dynamically generated narrow N^* and Λ^* resonances with hidden charm are predicted with mass above 4 GeV and width smaller than 100 MeV. The predicted new resonances definitely cannot be accommodated by quark models with three constituent quarks and can be looked for at the forthcoming PANDA/FAIR experiments.

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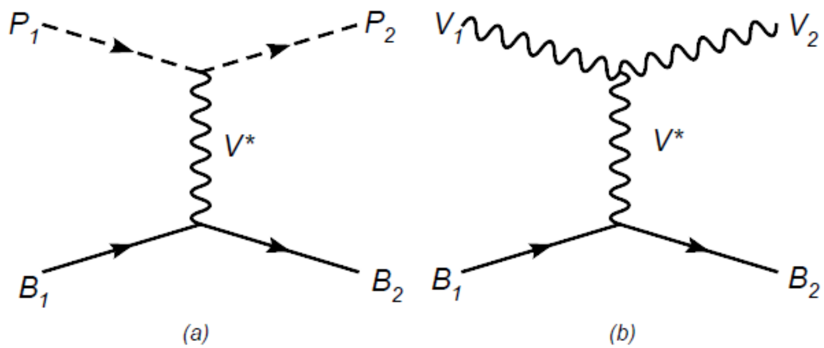

$$
\begin{aligned}
\mathcal{L}_{VVV} &= ig\langle V^\mu[V^\nu,\partial_\mu V_\nu]\rangle \\
\mathcal{L}_{PPV} &= -ig\langle V^\mu[P,\partial_\mu P]\rangle \\
\mathcal{L}_{BBV} &= g(\langle \bar{B}\gamma_\mu[V^\mu,B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle)
\end{aligned}
$$

TABLE I: Coefficients C_{ab} in Eq. (2) for $(I,S) = (1$

	$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	$\eta_c N$	πN	ηN	$\eta' N$	$K\Sigma$
$\bar{D}\Sigma_c$	-1	0	$-\sqrt{3/2}$	$-1/2$	$-1/\sqrt{2}$	$1/2$	1
$\bar{D}\Lambda_c^+$		1	$\sqrt{3/2}$	$-3/2$	$1/\sqrt{2}$	$-1/2$	0

TABLE II: Coefficients C_{ab} in Eq. (2) for $(I,S) = ($

	$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$	$\eta_c\Lambda$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$\bar{K}N$
$\bar{D}_s\Lambda_c^+$	0	$-\sqrt{2}$	0	1	0	$\sqrt{\frac{1}{3}}$	$\sqrt{\frac{2}{3}}$	$-\sqrt{}$
$\bar{D}\Xi_c$		-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

$J = 1/2$

(I,S)	z_R (MeV)	g_a		
$(1/2,0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
	4269	2.85	0	
$(0,-1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
	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 $PB \to PB$.

(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 $VB \to VB$.

Baryon states with hidden charm in the extended local hidden gauge approach

T. Uchino,[1,*] Wei-Hong Liang,[2] and E. Oset[1]

[1]*Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apartado 22085, 46071 Valencia, Spain*

[2]*Department of Physics, Guangxi Normal University, Guilin, 541004, People's Republic of China*

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main channel	J	(E, Γ) [MeV]	main decay channels
$\frac{1}{\sqrt{2}}(\bar{D}^*\Sigma_c + \bar{D}\Sigma_c)$	1/2	4228, 21(51)	$\bar{D}\Lambda_c$
$\frac{1}{\sqrt{2}}(\bar{D}^*\Sigma_c - \bar{D}\Sigma_c)$	1/2	4295, 11(41)	$\bar{D}\Lambda_c$
$\bar{D}^*\Sigma_c$	3/2	4218, 103	$\bar{D}\Lambda_c$
$\bar{D}^*\Sigma_c^*$	1/2, 5/2	4344, 0	–
$\frac{1}{\sqrt{2}}(\bar{D}^*\Sigma_c^* + \bar{D}\Sigma_c^*)$	3/2	4325, 0	–
$\frac{1}{\sqrt{2}}(\bar{D}^*\Sigma_c^* - \bar{D}\Sigma_c^*)$	3/2	4378, 0	–

TABLE VIII. Energies and widths of the obtained states with the dominant component and main decay channels of each state. All the states are nucleon resonances with negative parity and have an estimated uncertainty of ±20 MeV. The numbers in brackets for the first two states correspond to the estimated width, adding the 30 MeV width obtained in Refs. [3, 4] from coupling to the light PB or VB sectors.

New Exotic Meson and Baryon Resonances from Doubly-Heavy Hadronic Molecules

Marek Karliner[a†] and Jonathan L. Rosner[b‡]

[a] *School of Physics and Astronomy*
Raymond and Beverly Sackler Faculty of Exact Sciences
Tel Aviv University, Tel Aviv 69978, Israel

[b] *Enrico Fermi Institute and Department of Physics*
University of Chicago, 5620 S. Ellis Avenue, Chicago, IL 60637, USA

arXiv:1506.06386

ABSTRACT

We predict several new exotic doubly-heavy hadronic resonances, inferring from the observed exotic bottomonium-like and charmonium-like narrow states $X(3872)$, $Z_b(10610)$, $Z_b(10650)$, $Z_c(3900)$, and $Z_c(4020/4025)$. We interpret the binding mechanism as mostly molecular-like isospin-exchange attraction between two heavy-light mesons in a relative S-wave state. We then generalize it to other systems containing two heavy hadrons which can couple through isospin exchange. The new predicted states include resonances in meson-meson, meson-baryon, baryon-baryon, and baryon-antibaryon channels. These include those giving rise to final states involving a heavy quark $Q = c, b$ and antiquark $\bar{Q}' = \bar{c}, \bar{b}$, namely $D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, $\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$, as well as corresponding S-wave states giving rise to QQ' or $\bar{Q}\bar{Q}'$.

New Exotic Meson and Baryon Resonances from Doubly-Hea

Marek Karliner[a†]

[a] School of P
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[b] Enrico Fermi Institute and Departmen
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$\bar{Q}' = \bar{c}, \bar{b}$, namely $D\bar{D}$
$\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}$
giving rise to QQ' or Q

For pion exchange between states 1 and 2 with isospins $I_{1,2}$ and spins $S_{1,2}$, the effective potential is proportional to [21]

$$V \sim \pm(I_1 \cdot I_2)(S_1 \cdot S_2) \text{ for } (qq, q\bar{q}) \text{ interactions} , \quad (1)$$

where q or $\bar{q}$ stands for the light quark(s) or antiquark(s) in hadrons 1 and 2, as long as the total spins S_i are correlated with the direction of the light-quark spins. (This is true for D^*, B^*, Σ_c, and Σ_b.)

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	S-wave J^P	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	1^+	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$0^+, 1^+, 2^+$	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$0^+, 1^+, 2^+$	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	1^+	$\Upsilon(nS)\pi\pi$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$0^+, 1^+, 2^+$	$\Upsilon(nS)\pi\pi$
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$1/2^-, 3/2^-$	$J/\psi\,p$
Σ_cB^*	1/2	$c\bar{b}qqq'$	7779.5	$1/2^-, 3/2^-$	B_c^+p
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	$1/2^-, 3/2^-$	B_c^-p
Σ_bB^*	1/2	$b\bar{b}qqq'$	11139.6	$1/2^-, 3/2^-$	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$0^-, 1^-$	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$0^-, 1^-$	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$0^-, 1^-$	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$0^-, 1^-$	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$0^-, 1^-$	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$0^-, 1^-$	$\Upsilon(nS)\pi\pi$

Notes added: We thank X. Liu for informing us of an earlier calculation [35] of binding between a charmed baryon and anticharmed meson, obtaining — as we do — no binding between Λ_c and $\bar{D}^{(*)}$ but binding between Σ_c and $\bar{D}^*$ in all four spin–isospin channels, as well as — unlike us — between Σ_c and $\bar{D}$ with $I = 3/2$ and $J = 1/2$.

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arXiv:1105.2901

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

YANG Zhong-Cheng(杨忠诚)[1] SUN Zhi-Feng(孙志峰)[2,4] HE Jun(何军)[1,3;1)]
LIU Xiang(刘翔)[2,4;2)] ZHU Shi-Lin(朱世琳)[1;3)]

[1] Department of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
[2] Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of Chinese Academy of Sciences, Lanzhou 730000, China
[3] Nuclear Theory Group, Institute of Modern Physics of Chinese Academy of Sciences, Lanzhou 730000, China
[4] School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China

Abstract: Using the one-boson-exchange model, we studied the possible existence of very loosely bound hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon. Our numerical results indicate that the $\Sigma_c\bar{D}^*$ and $\Sigma_c\bar{D}$ states exist, but that the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not.

CPC(HEP & NP), 2012, **36**(1): 6–13 Chinese Physics C Vol. 36, No. 1, Jan., 2012

arXiv:1105.2901

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}\mathcal{B}_{\bar{3}}\mathbb{V}} = \frac{\beta_B g_V}{\sqrt{2}} \langle \bar{\mathcal{B}}_{\bar{3}}\ v\cdot\mathbb{V}\ \mathcal{B}_{\bar{3}}\rangle, \quad (24)$$

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}\mathcal{B}_{\bar{3}}\sigma} = \ell_B \langle \bar{\mathcal{B}}_{\bar{3}}\ \sigma\ \mathcal{B}_{\bar{3}}\rangle, \quad (25)$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{P}} = \frac{ig_1}{2f_\pi} \epsilon^{\mu\nu\lambda\kappa} v_\kappa \langle \bar{\mathcal{B}}_6\ \gamma_\mu\gamma_\lambda\partial_\nu\mathbb{P}\ \mathcal{B}_6\rangle, \quad (26)$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{V}} = -\frac{\beta_S g_V}{\sqrt{2}} \langle \bar{\mathcal{B}}_6\ v\cdot\mathbb{V}\ \mathcal{B}_6\rangle - \frac{i\lambda_S g_V}{3\sqrt{2}} \langle \bar{\mathcal{B}}_6\gamma_\mu\gamma_\nu(\partial^\mu\mathbb{V}^\nu$$

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

$$\mathcal{B}_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix},$$

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

cular baryons composed and a charmed baryon*

eng(孙志峰)[2,4] HE Jun(何军)[1,3;1)]
J Shi-Lin(朱世琳)[1;3)]

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

Hadronic molecules for charmed and bottom baryons near thresholds

Yasuhiro Yamaguchi[1], Shunsuke Ohkoda[1], Shigehiro Yasui[2], and Atsushi Hosaka[1]

[1] *Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka, 567-0047, Japan* and

[2] *KEK Theory Center, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization, 1-1, Oho, Ibaraki, 305-0801, Japan*

(Dated: January 31, 2013)

Abstract

We study hadronic molecules formed by a heavy meson and a nucleon, DN and D^*N ($\bar{B}N$ and $\bar{B}^*N$) systems. Respecting the heavy quark symmetry and chiral symmetry, we consider the DN-D^*N ($\bar{B}N$-$\bar{B}^*N$) mixing induced by the one boson exchange potential including the tensor force. We find many bound and resonant states with $J^P = 1/2^{\pm}$, $3/2^{\pm}$, $5/2^{\pm}$ and $7/2^-$ in isospin singlet channels, while only a few resonant states with $J^P = 1/2^-$ in isospin triplet channels. The analysis of DN and D^*N ($\bar{B}N$ and $\bar{B}^*N$) molecules will be useful to study mass spectra of excited charmed (bottom) baryons with large angular momenta, when their masses are close to the DN and D^*N ($\bar{B}N$ and $\bar{B}^*N$) thresholds.

Hadronic molecules for charmed and bottom baryons near thresholds

Yasuhiro Yamaguchi[1], Shunsuke O

[1]Research Center

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[2]KEK Theory Center, Ins

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We study hadronic molecules formed b

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charmed (bottom) baryons with large ang

and D^*N ($\bar{B}N$ and $\bar{B}^*N$) thresholds.

Dynamically generated $J^P = 1/2^-$ singly charmed and bottom heavy baryons

Jun-Xu Lu,[1] Yu Zhou,[1] Hua-Xing Chen,[1] Ju-Jun Xie,[2] and Li-Sheng Geng[1,*]

[1]*School of Physics and Nuclear Energy Engineering and International Research Center for Nuclei and Particles in the Cosmos, Beihang University, Beijing 100191, China*

[2]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

(Dated: September 11, 2014)

Abstract

Approximate heavy-quark spin and flavor symmetry and chiral symmetry plays an important role in our understanding of the nonperturbative regime of the strong interactions. In this work, using the unitarized chiral perturbation theory, we explore the consequences of these symmetries in the description of the interactions between the ground-state singly charmed (bottom) baryons and the pseudo Nambu-Goldstone bosons. In particular, by fixing the only parameter in the theory to reproduce the $\Lambda_b(5912)$ or the $\Lambda_c(2595)$, we predict a number of dynamically generated states, which are contrasted with those of other approaches and available experimental data. In anticipation of future lattice chromodynamics simulations, we calculate the corresponding scattering lengths and compare them with the existing predictions from a $\mathcal{O}(p^3)$ chiral perturbation theory study.

$\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ states in a chiral quark model

W.L. Wang,[1,2] F. Huang,[3] Z.Y. Zhang,[1,2] and B.S. Zou[1,2]

[1] *Institute of High Energy Physics, CAS, P.O. Box 918-4, Beijing 100049, China*
[2] *Theoretical Physics Center for Science Facilities (TPCSF), CAS, Beijing 100049, China*
[3] *Department of Physics and Astronomy, The University of Georgia, Athens, GA 30602, USA*

The S-wave $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ states with isospin $I = 1/2$ and spin $S = 1/2$ are dynamically investigated within the framework of a chiral constituent quark model by solving a resonating group method (RGM) equation. The results show that the interaction between Σ_c and $\bar{D}$ is attractive, which consequently results in a $\Sigma_c \bar{D}$ bound state with the binding energy of about $5 - 42$ MeV, unlike the case of $\Lambda_c \bar{D}$ state, which has a repulsive interaction and thus is unbound. The channel coupling effect of $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ is found to be negligible due to the fact that the gap between the $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ thresholds is relatively large and the $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ transition interaction is weak.

$\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states in a chiral quark model

W.L. Wang,[1, 2] F. Huang,[3] Z.Y. Zhang,[1, 2] and B.S. Zou[1, 2]

Study of $qqqc\bar{c}$ five quark system with three kinds of quark-quark hyperfine interaction

S. G. Yuan[1,2,4], K. W. Wei[3], J. He[1,5], H. S. Xu[1,2], B. S. Zou[2,3]
1. *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
2. *Theoretical Physics Center for Science Facilities, Chinese Academy of Sciences, Beijing 100049, China*
3. *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
4. *Graduate University of Chinese Academy of Sciences, Beijing 100049, China*
5. *Research Center for Hadron and CSR Physics, Institute of Modern Physics of CAS and Lanzhou University, Lanzhou 730000, China*

(Dated: January 5, 2012)

The low-lying energy spectra of five quark systems $uudc\bar{c}$ (I=1/2, S=0) and $udsc\bar{c}$ (I=0, S=−1) are investigated with three kinds of schematic interactions: the chromomagnetic interaction, the flavor-spin dependent interaction and the instanton-induced interaction. In all the three models, the lowest five quark state ($uudc\bar{c}$ or $udsc\bar{c}$) has an orbital angular momentum L = 0 and the spin-parity J^P = $1/2^-$; the mass of the lowest $udsc\bar{c}$ state is heavier than the lowest $uudc\bar{c}$ state.

$\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states in a chiral quark model

W.L. Wang,[1,2] F. Huang,[3] Z.Y. Zhang,[1,2] and B.S. Zou[1,2]

Study of $qqqc\bar{c}$ five quark system with three kinds of quark-quark hyperfine interaction

S. G. Yuan[1,2,4], K. W. Wei[3], J. He[1,5], H. S. Xu[1,2], B. S. Zou[2,3]

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Discovery potential of hidden charm baryon resonances *via* photoproduction

Yin Huang[1,2,3], and Jun He[1,2,4]‡, Hong-Fei Zhang[3] and Xu-Rong Chen[1]

[1]Institute of modern physics,Chinese Academy of Sciences, Lanzhou 730000, China
[2]Research Center for Hadron and CSR Physics, Institute of Modern Physics of CAS and Lanzhou University, Lanzhou 730000, China.
[3]School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China
[4]State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences

Abstract. In this work, we study the possibility to find $N^*_{c\bar{c}}$ and $\Lambda^*_{c\bar{c}}$ resonances with hidden charm with mass above 4 GeV in the photon-induced production. The cross sections for the photoproductions of hidden charmed baryons are predicted in the effective Lagrangian approach with the vector meson dominance mechanism. The

$\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ states in a chiral quark model

W.L. Wang,[1,2] F. Huang,[3] Z.Y. Zhang,[1,2] and B.S. Zou[1,2]

Study of $qqqc\bar{c}$ five quark system with three kinds of quark-quark hyperfine interaction

S. G. Yuan[1,2,4], K. W. Wei[3], J. He[1,5], H. S. Xu[1,2], B. S. Zou[2,3]

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Discovery potential of hidden charm baryon resonances *via* photoproduction

Yin Huang[1,2,3], and Jun He[1,2,4]‡, Hong-Fei Zhang[3] and Xu-Rong Chen[1]

Production of the superheavy baryon $\Lambda^*_{c\bar{c}}(4209)$ in kaon-induced reaction

Xiao-Yun Wang[1,2,3,*] and Xu-Rong Chen[1,3]

[1] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2] *University of Chinese Academy of Sciences, Beijing 100049, China*
[3] *Research Center for Hadron and CSR Physics, Institute of Modern Physics of CAS and Lanzhou University, Lanzhou 730000, China*

The production of superheavy $\Lambda^*_{c\bar{c}}(4209)$ baryon in the $K^- p \to \eta_c \Lambda$ process via s-channel is investigated with an effective Lagrangian approach and the isobar model. Moreover, the t-channel with K^* and u-channel with nucleon exchange are also considered, which are regarded as the background for the $\Lambda^*_{c\bar{c}}(4209)$ production in the $K^- p \to \eta_c \Lambda$ reaction. The numerical results indicate it is feasible to searching for the superheavy $\Lambda^*_{c\bar{c}}(4209)$ via $K^- p$ scattering. These theoretical results not only provide valuable informations to future experimental exploration of $\Lambda^*_{c\bar{c}}(4209)$ resonance but enable us to have a better understanding of the exotic baryons.

Following Studies

A new page for hadron physics: Identifying exotic hidden-charm pentaquarks

Rui Chen[1,2] and Xiang Liu[1,2*]
[1]Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China
[2]School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China

Xue-Qian Li[†]
School of Physics, Nankai University, Tianjin 300071, China

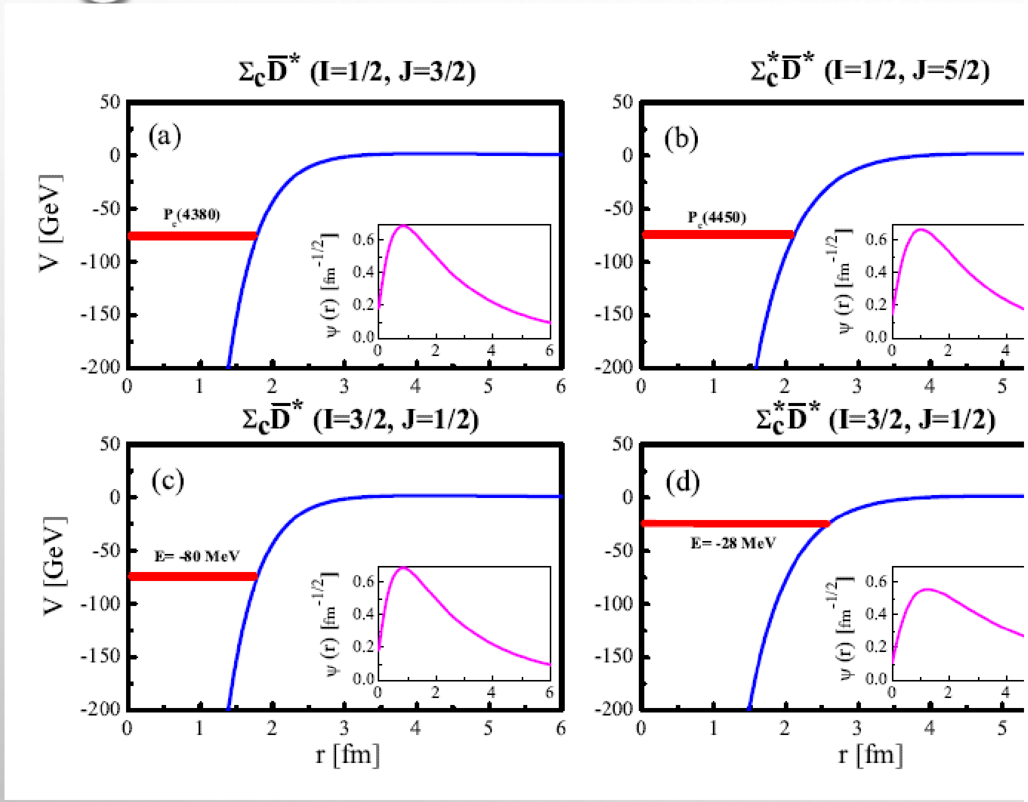
Shi-Lin Zhu[1,2,3‡]
[1]School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
[2]Collaborative Innovation Center of Quantum Matter, Beijing 100871, China
[3]Center of High Energy Physics, Peking University, Beijing 100871, China

The authors investigated the **one-pion-exchange-based potentials** for the $\Sigma_c\bar{D}^*$ and $\Sigma_c^*\bar{D}^*$ systems:

$$\mathcal{L}_{\bar{D}^*\bar{D}^*\mathbb{P}} = i\frac{2g}{f_\pi}v^\alpha\varepsilon_{\alpha\mu\nu\lambda}\bar{D}_a^{*\mu\dagger}\bar{D}_b^{*\lambda}\partial^\nu\mathbb{P}_{ab}, \qquad \mathbb{P} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} & \pi^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} \end{pmatrix},$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{P}} = i\frac{g_1}{2f_\pi}\varepsilon^{\mu\nu\lambda\kappa}v_\kappa\mathrm{Tr}\left[\bar{\mathcal{B}}_6\gamma_\mu\gamma_\lambda\partial_\nu\mathbb{P}\mathcal{B}_6\right], \qquad \mathcal{B}_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{\Sigma_c^+}{\sqrt{2}} \\ \frac{\Sigma_c^+}{\sqrt{2}} & \Sigma_c^0 \end{pmatrix},$$

$$\mathcal{L}_{\mathcal{B}_6^*\mathcal{B}_6^*\mathbb{P}} = -i\frac{3g_1}{2f_\pi}\varepsilon^{\mu\nu\lambda\kappa}v_\kappa\mathrm{Tr}\left[\bar{\mathcal{B}}_{6\mu}^*\partial_\nu\mathbb{P}\mathcal{B}_{6\nu}^*\right], \qquad \mathcal{B}_6^* = \begin{pmatrix} \Sigma_c^{*++} & \frac{\Sigma_c^{*+}}{\sqrt{2}} \\ \frac{\Sigma_c^{*+}}{\sqrt{2}} & \Sigma_c^{*0} \end{pmatrix}.$$



- $\boldsymbol{P_c(4380)}$ and $\boldsymbol{P_c(4450)}$ are first identified as the hidden-charm molecular pentaquarks $\Sigma_c\bar{D}^*$ with (I=1/2, J=3/2), and $\Sigma_c^*\bar{D}^*$ with (I=1/2, J=3/2), respectively.
- Their study indicates that there should exist a $\Sigma_c\bar{D}^*$ state with (I=3/2, J=1/2) and a $\Sigma_c^*\bar{D}^*$ state with (I=3/2, J=1/2).
- Besides the above predictions, they also investigated the **hidden-bottom** $\Sigma_b^{(*)}\bar{B}^*$ pentaquark and the **Bc-like** $\Sigma_c^{(*)}\bar{B}^*$ and $\Sigma_b^{(*)}\bar{D}^*$ molecular pentaquark systems which possess open charm and bottom quantum numbers.

The LHCb pentaquark as a $\bar{D}^*\Sigma_c - \bar{D}^*\Sigma_c^*$ molecular state

L. Roca
Departamento de Física, Universidad de Murcia, E-30100 Murcia, Spain

J. Nieves
IFIC, Centro Mixto Universidad de Valencia-CSIC,
Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain

E. Oset
Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC
Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain
(Dated: July 16, 2015)

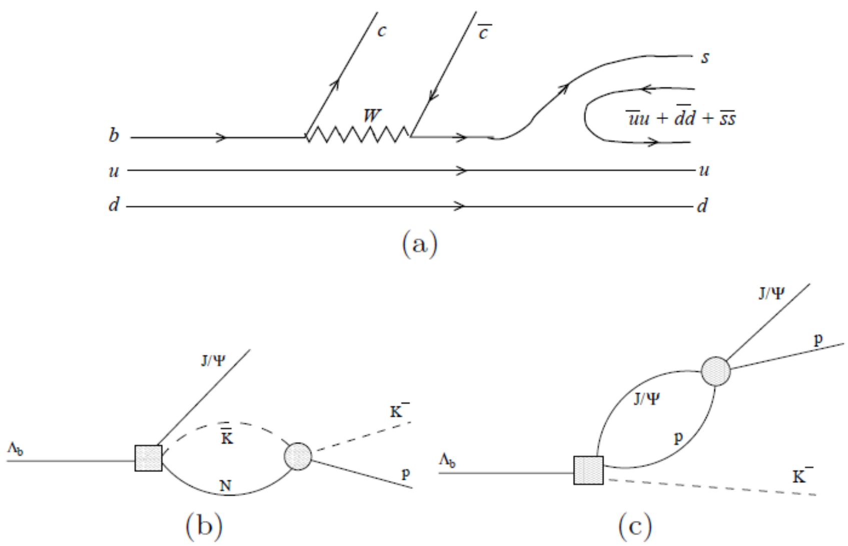


FIG. 1: Mechanisms for the $\Lambda_b \to J/\psi K^- p$ reaction implementing the final state interaction

- The authors investigated the hidden charm state around 4450 MeV, called pentaquark $P_c(4450)$, which shows up as a clear peak, with a width of about 39 ± 5 ± 19 MeV.
- They combined the information obtained from the experiment on the K-p invariant mass distribution close to threshold and the strength of the peak in the J/Ψ-p spectrum.

The contribution of the J/Ψ-p final state interaction to the amplitude is

$$T^{(J/\psi p)}(M_{J/\psi p}) = V_p h_{K^- p} G_{J/\psi p}(M_{J/\psi p}) \times t_{J/\psi p \to J/\psi p}(M_{J/\psi p}) \, ,$$

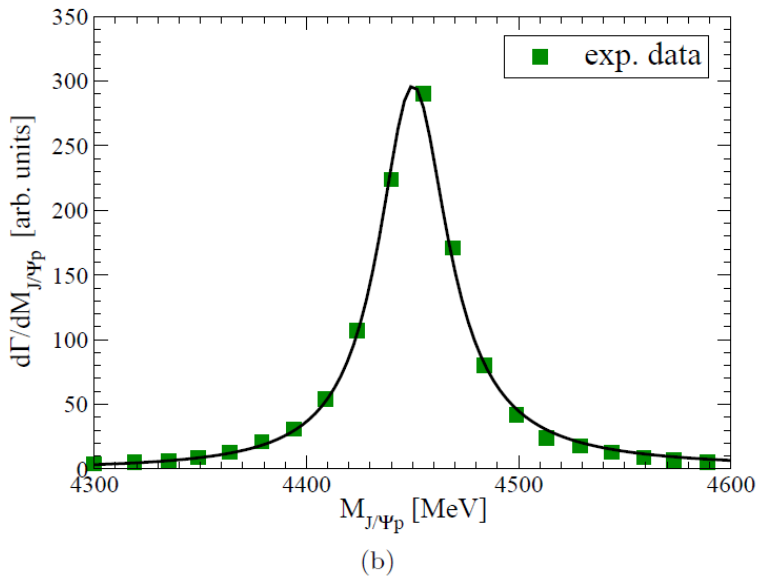


FIG. 2: Results for the K^-p and $J/\psi\, p$ invariant mass distributions compared to the data of ref. [24].

- "The non-trivial matching of so many pieces in this puzzle gives a strong support to our interpretation of the $P_c(4450)$ state found as a molecular state of mostly $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ nature with isospin I = 1/2 and spin parity 3/2−."

Is pentaquark doublet a hadronic molecule?

A. Mironov[a,b,c,d] and **A. Morozov**[b,c,d]

[a] *Lebedev Physics Institute, Moscow 119991, Russia*
[b] *ITEP, Moscow 117218, Russia*
[c] *National Research Nuclear University MEPhI, Moscow 115409, Russia*
[d] *Institute for Information Transmission Problems, Moscow 127994, Russia*

Abstract

A recently announced discovery by LHCb of a doublet of overlapping pentaquark resonances poses a question of what can be the origin of this doublet structure. We attract attention to the fact that such degeneracy could naturally arise if constituent "baryon" and "meson" were in the colored, rather than colorless states. This is an appealing possibility, also because in such a case the pentaquark state would be no less "elementary" than the other hadrons, and would provide a chance for essentially new non-Abelian chemistry.

Is pentaquark doublet a hadronic molecule?

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…es poses a … that such … ather than … e would be … on-Abelian

How to reveal the exotic nature of the $P_c(4450)$

Feng-Kun Guo[1,*], Ulf-G. Meißner[1,2,†], Wei Wang[3,4,‡] and Zhi Yang[1,§]

[1] *Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*

[2] *Institute for Advanced Simulation, Institut für Kernphysik and Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany*

[3] *INPAC, Shanghai Key Laboratory for Particle Physics and Cosmology, Department of Physics and Astronomy, Shanghai Jiao-Tong University, Shanghai 200240, China*

[4] *State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Science, Beijing 100190, China*

July 20, 2015

Abstract

The LHCb Collaboration announced two pentaquark-like structures in the $J/\psi\, p$ invariant mass distribution. We show that the current information on the narrow structure at 4.45 GeV is compatible with kinematical effects of the rescattering from $\chi_{c1}\, p$ to $J/\psi\, p$: First, it is located exactly at the $\chi_{c1}\, p$ threshold. Second, the mass of the four-star well-established $\Lambda(1890)$ is such that a leading Landau singularity from a triangle diagram can coincidentally appear at the $\chi_{c1}\, p$ threshold, and third, there is a narrow structure at the $\chi_{c1}\, p$ threshold but not at the $\chi_{c0}\, p$ and $\chi_{c2}\, p$ thresholds. In order to check whether that structure corresponds to a real exotic resonance, one can measure the process $\Lambda_b^0 \to K^- \chi_{c1}\, p$. If the $P_c(4450)$ structure exists in the $\chi_{c1}\, p$ invariant mass distribution as well, then the structure cannot be just a kinematical effect but is a real resonance, otherwise, one cannot conclude the $P_c(4450)$ to be another exotic hadron. In addition, it is also worthwhile to measure the decay $\Upsilon(1S) \to J/\psi\, p\bar{p}$: a narrow structure at 4.45 GeV but not at the $\chi_{c0}\, p$ and $\chi_{c2}\, p$ thresholds would exclude the possibility of a pure kinematical effect.

Is pentaquark doublet a hadronic molecule?

The New Pentaquarks in the Diquark Model

L. Maiani,[1] A.D. Polosa,[1] and V. Riquer[1]

[1] *Dipartimento di Fisica and INFN, 'Sapienza' Università di Roma P.le Aldo Moro 5, I-00185 Roma, Italy*

Pentaquark baryons are a natural expectation of an extended picture of hadrons where quarks and diquarks are the fundamental units. The parity/mass pattern observed, when compared to that of exotic mesons, appears as the footprint of a compact five-quark structure. What has been learned from the X, Y, Z phenomenology informs about the newly found pentaquark structure and suggests further experimental tests and directions to be explored.

How to reveal the exotic nature of the $P_c(4450)$

Feng-Kun Guo[1,*], Ulf-G. Meißner[1,2,†], Wei Wang[3,4,‡] and Zhi Yang[1,§]

Abstract

The LHCb Collaboration announced two pentaquark-like structures in the $J/\psi\, p$ invariant mass distribution. We show that the current information on the narrow structure at 4.45 GeV is compatible with kinematical effects of the rescattering from $\chi_{c1}\, p$ to $J/\psi\, p$: First, it is located exactly at the $\chi_{c1}\, p$ threshold. Second, the mass of the four-star well-established $\Lambda(1890)$ is such that a leading Landau singularity from a triangle diagram can coincidentally appear at the $\chi_{c1}\, p$ threshold, and third, there is a narrow structure at the $\chi_{c1}\, p$ threshold but not at the $\chi_{c0}\, p$ and $\chi_{c2}\, p$ thresholds. In order to check whether that structure corresponds to a real exotic resonance, one can measure the process $\Lambda_b^0 \to K^- \chi_{c1}\, p$. If the $P_c(4450)$ structure exists in the $\chi_{c1}\, p$ invariant mass distribution as well, then the structure cannot be just a kinematical effect but is a real resonance, otherwise, one cannot conclude the $P_c(4450)$ to be another exotic hadron. In addition, it is also worthwhile to measure the decay $\Upsilon(1S) \to J/\psi\, p\bar{p}$: a narrow structure at 4.45 GeV but not at the $\chi_{c0}\, p$ and $\chi_{c2}\, p$ thresholds would exclude the possibility of a pure kinematical effect.

Is pentaquark doublet a hadronic molecule?

How to reveal the exotic nature of the $P_c(4450)$

Feng-Kun Guo[1,*], Ulf-G. Meißner[1,2,†], Wei Wang[3,4,‡] and Zhi Yang[1,§]

The New Pentaquarks in the Diquark Model

L. Maiani,[1] A.D. Polosa,[1] and V. Riquer[1]

The $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks

Jun He[a,b,c]

[a] Theoretical Physics Division, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[b] Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China
[c] State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China

Abstract

Very recently, two hidden-charmed resonances $P_c(4380)$ and $P_c(4450)$ consistent with pentaquark states were observed at the LHCb detector. The two P_c states locate just below the $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ thresholds with mass gaps about 5 and 15 MeV, respectively. Inspired by this fact we perform a dynamical investigation about the $\bar{D}\Sigma_c^*(2520)$ and $\bar{D}^*\Sigma_c(2455)$ interactions which are described by the meson exchanges. A bound state that carries spin-parity $J^P = 3/2^-$ is produced from the $\bar{D}\Sigma_c^*(2520)$ interaction, which is consistent with the $P_c(4380)$ observed at LHCb detector. From the $\bar{D}^*\Sigma_c(2455)$ interaction, a bound state with $5/2^+$ is produced, which can be related to the $P_c(4450)$. The results suggest that the $P_c(4380)$ and $P_c(4450)$ are good candidates of $\bar{D}\Sigma_c^*(2520)$ and $\bar{D}^*\Sigma_c(2455)$ molecular states, respectively.

to be another exotic hadron. In addition, it is also worthwhile to measure the decay $\Upsilon(1S) \to J/\psi\, p\bar{p}$: a narrow structure at 4.45 GeV but not at the $\chi_{c0}\,p$ and $\chi_{c2}\,p$ thresholds would exclude the possibility of a pure kinematical effect.

Is pentaquark doublet a hadronic molecule?

How to reveal the exotic nature of the $P_c(4450)$

Feng-Kun Guo[1,*], Ulf-G. Meißner[1,2,†], Wei Wang[3,4,‡] and Zhi Yang[1,§]

The New Pentaquarks in the Diquark Model

L. Maiani,[1] A.D. Polosa,[1] and V. Riquer[1]

The $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks

Jun He[a,b,c]

Abstract

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Understanding the newly observed heavy pentaquark candidates

Xiao-Hai Liu[1*], Qian Wang[2†], and Qiang Zhao[3‡]
[1] Department of Physics, H-27, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan
[2] Institut für Kernphysik, Institute for Advanced Simulation, and Jülich Center for Hadron Physics, D-52425 Jülich, Germany and
[3] Institute of High Energy Physics and Theoretical Physics Center for Science Facilities, Chinese Academy of Sciences, Beijing 100049, China
(Dated: July 21, 2015)

We find that several thresholds can contribute to the enhancements of the newly observed heavy pentaquark candidates $P_c^+(4380)$ and $P_c^+(4450)$ via the anomalous triangle singularity (ATS) transitions in the specific kinematics of $\Lambda_b \to J/\psi K^- p$. Apart from the observed two peaks we find that another peaks around 4.5 GeV can also be produced by the ATS. We also show that the $\Sigma_c^{(*)}$ can be produced at leading order in Λ_b decay. We find that this process is different from the triangle diagram and the threshold enhancement only appear as CUSP effects if there is no pole structure or the ATS involved. The threshold interaction associated by the presence of the ATS turns out to be a general phenomenon and plays a crucial role in the understanding of candidates for exotic states.

Our Study through QCD Sum Rule

Towards exotic hidden-charm pentaquarks in QCD

Hua-Xing Chen[1], Wei Chen[2,*] Xiang Liu[3,4,†] T. G. Steele[2,‡] and Shi-Lin Zhu[5,6,7§]
[1]*School of Physics and Nuclear Energy Engineering and International Research Center for Nuclei and Particles in the Cosmos, Beihang University, Beijing 100191, China*
[2]*Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, SK, S7N 5E2, Canada*
[3]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[4]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
[5]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[6]*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*
[7]*Center of High Energy Physics, Peking University, Beijing 100871, China*

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.

Motivation

- **Conventional** mesons $q\bar{q}$ and baryons qqq
- QCD allows much richer hadron spectrum
- **Exotic** hadrons:

glueballs	GG, GGG
multiquark states	$qq\bar{q}\bar{q}$, $qqqq\bar{q}$
hybrids	$q\bar{q}G$, $qq\bar{q}\bar{q}G$
hadron molecules	$[D\bar{D}^*]$, $[\bar{D}^*\Sigma_c]$

Quark Model

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $a_0(1450)$	$1^-(0^{++})$	$\phi(2170)$	$0^-(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $f_0(1500)$	$0^+(0^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$f_1(1510)$	$0^+(1^{++})$	$\rho_3(2250)$	$1^+(3^{--})$

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED

CHARMED, STRANGE ($C = S = \pm1$)

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)^\pm$	$0(?^?)$
$D_{s1}(2700)^\pm$	$0(1^-)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B^0_s	$0(0^-)$
• B^*_s	$0(1^-)$
• $B_{s1}(5830)^0$	$1/2(1^+)$
• $B_{s2}^*(5840)^0$	$1/2(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED

$c\bar{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
$\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
$X(3945)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
• $X(4260)$	$?^?(1^{--})$
$X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$

$b\bar{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
$\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$

Motivation

- **Light sector**
  - Exotic in structure

    light scalar mesons $\sigma(600)$, $\kappa(800)$, etc.
  - Exotic in quantum numbers

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

- **Heavy sector**
  - Exotic in structure

    charmonium-like resonances $\mathrm{X}(3872)$, etc.
  - Meson: Exotic in quantum numbers

    charged charmonium-like resonances $Z_c(3900)$, $\mathrm{Z}(4430)$, etc.
  - Baryon: Exotic in quantum numbers

    hidden-charm pentaquarks $\boldsymbol{P_c(4380)}$ and $\boldsymbol{P_c(4450)}$

Hidden-Charm Pentaquarks $P_c(4380)$&$P_c(4450)$

- 衰变末态 $J/\psi\, p$

  同位旋 $I=1/2$, $SU(3)_F$味道八重态

- **Spin-parity J^P values** $3/2^-$&$5/2^+$, $3/2^+$&$5/2^-$, or $5/2^+$&$3/2^-$.

- **Masses and widths**

$$M_{P_c\,(4380)} = 4380 \pm 8 \pm 29 \text{ MeV} \qquad \Gamma_{P_c\,(4380)} = 205 \pm 18 \pm 86 \text{ MeV}$$

$$M_{P_c\,(4450)} = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV} \qquad \Gamma_{P_c\,(4450)} = 39 \pm 5 \pm 19 \text{ MeV}$$

A $[J/\psi\, p]$ current

flavor contents

$$[\bar{c}_d(x)\gamma_\mu c_d(x)][\varepsilon^{abc}({u_a}^T(x)Cd_b(x))\gamma_5 u_c(x)]$$

color indices

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**

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

$$
\begin{aligned}
S_6 &= (\bar{s}_a \gamma_5 C \bar{s}_b^T)(u_a^T C \gamma_5 d_b)\,,\\
V_6 &= (\bar{s}_a \gamma_\mu \gamma_5 C \bar{s}_b^T)(u_a^T C \gamma^\mu \gamma_5 d_b)\,,\\
T_3 &= (\bar{s}_a \sigma_{\mu\nu} C \bar{s}_b^T)(u_a^T C \sigma^{\mu\nu} d_b)\,,\\
A_3 &= (\bar{s}_a \gamma_\mu C \bar{s}_b^T)(u_a^T C \gamma^\mu d_b)\,,\\
P_6 &= (\bar{s}_a C \bar{s}_b^T)(u_a^T C d_b)\,.
\end{aligned}
$$

$(qq)(\overline{q}\overline{q})$

Fierz Transformations

$$
\begin{aligned}
S_6 &= -\frac{1}{4}S_1 - \frac{1}{4}V_1 + \frac{1}{8}T_1 - \frac{1}{4}A_1 - \frac{1}{4}P_1\,,\\
V_6 &= S_1 - \frac{1}{2}V_1 + \frac{1}{2}A_1 - P_1\,,\\
T_3 &= 3S_1 + \frac{1}{2}T_1 + 3P_1\,,\\
A_3 &= S_1 + \frac{1}{2}V_1 - \frac{1}{2}A_1 - P_1\,,\\
P_6 &= -\frac{1}{4}S_1 + \frac{1}{4}V_1 + \frac{1}{8}T_1 + \frac{1}{4}A_1 - \frac{1}{4}P_1\,.
\end{aligned}
$$

$(q\overline{q})(q\overline{q})$

$$
\begin{aligned}
S_1 &= (\bar{s}_a u_a)(\bar{s}_b d_b)\,,\\
V_1 &= (\bar{s}_a \gamma_\mu u_a)(\bar{s}_b \gamma^\mu d_b)\,,\\
T_1 &= (\bar{s}_a \sigma_{\mu\nu} u_a)(\bar{s}_b \sigma^{\mu\nu} d_b)\,,\\
A_1 &= (\bar{s}_a \gamma_\mu \gamma_5 u_a)(\bar{s}_b \gamma^\mu \gamma_5 d_b)\,,\\
P_1 &= (\bar{s}_a \gamma_5 u_a)(\bar{s}_b \gamma_5 d_b)\,,
\end{aligned}
$$

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)

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

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

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

- 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

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

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

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

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

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

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

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

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

$$< 0|\, J\, |P(q) > = f_P u(q)\,, \qquad < 0|\, \gamma_5 J\, |P(q) > = f_P \gamma_5 u(q).$$

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

$$< 0|\, J\, |P(q) > = f_P u(q)\,, \qquad < 0|\, J\, |P'(q) > = f_{P'} \gamma_5 u'(q).$$

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

Y. Chung, H. G. Dosch, M. Kremer and D. Schall, Nucl. Phys. B 197, 55 (1982)
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$$< 0|\, J\, |P(q) > = f_P u(q)\,, \qquad < 0|\, J\, |P'(q) > = f_{P'} \gamma_5 u'(q).$$

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

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

QCD SUM RULE

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

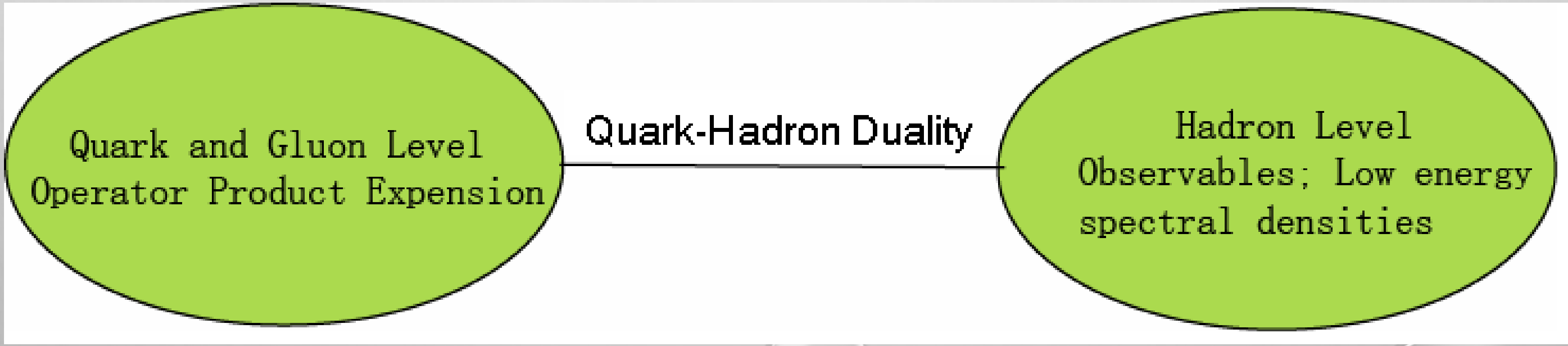
$$\Pi(q^2) \stackrel{\text{def}}{=} i\int d^4x e^{iqx}\langle 0|T\eta(x)\eta^+(0)\,|0\rangle$$
$$\approx \Sigma_n\langle 0|\eta|n\rangle\langle n|\eta^+|0\rangle$$

  where η is the current which can couple to hadronic states.

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

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

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



SVZ sum rule (Shifman 1979)

Quark and Gluon Level

(Convergence of OPE)

dispersion relation

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

Quark-Hadron Duality

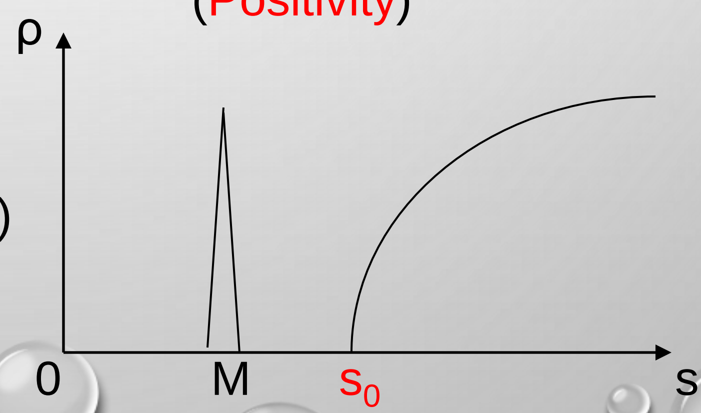
Hadron Level

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

(for baryon case)

(Positivity)

(Sufficient amount of Pole contribution)



QCD Sum Rule

- Borel transformation to suppress the higher order terms:

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

- 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

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.

Sum rule analyses using $J_\mu^{\bar{D}^*\Sigma_c}$

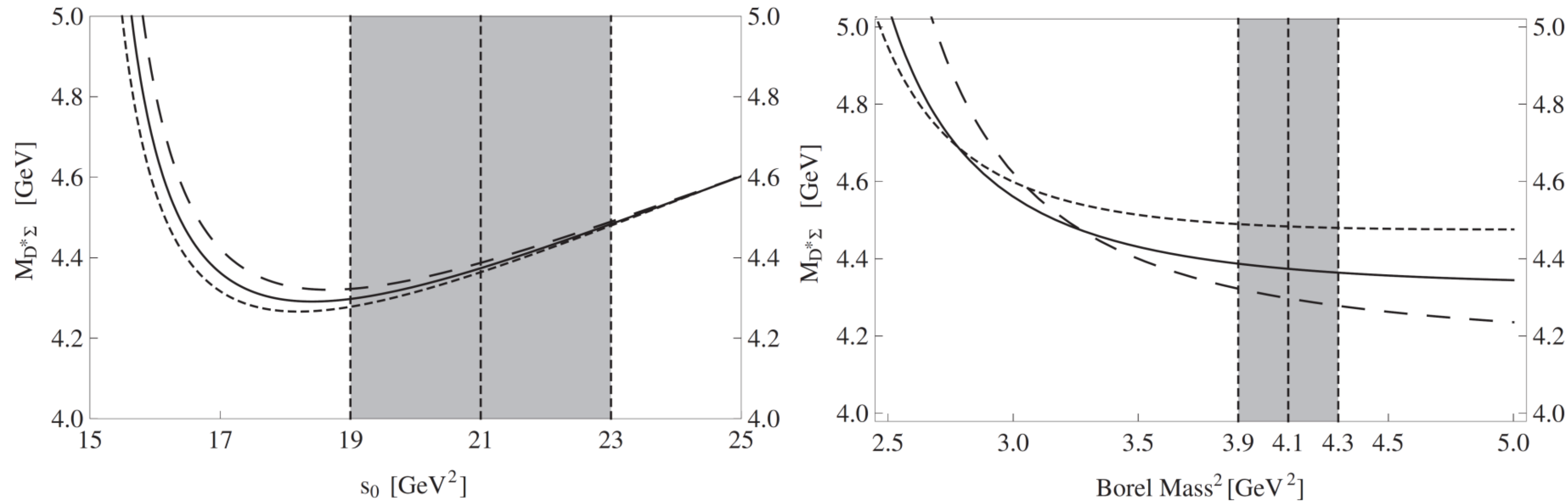


FIG. 1: The variation of $M_{[\bar{D}^*\Sigma_c],3/2^-}$ with respect to the threshold value s_0 (left) and the Borel mass M_B (right). In the left figure, the

The sum rule results results obtained using $J_{\mu}^{\bar{D}^*\Sigma_c}$, $J_{\mu}^{\bar{D}\Sigma_c^*}$, and $J_{\{\mu\nu\}}^{\bar{D}^*\Sigma_c^*}$ are

$$M_{[\bar{D}^*\Sigma_c],3/2^-} = 4.37^{+0.18}_{-0.12}\ \text{GeV}\,.$$
$$M_{[\bar{D}\Sigma_c^*],3/2^-} = 4.45^{+0.17}_{-0.13}\ \text{GeV}\,,$$
$$M_{[\bar{D}^*\Sigma_c^*],5/2^+} = 4.59^{+0.17}_{-0.12}\ \text{GeV}\,.$$

The sum rules obtained using $J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^*}$, and $J_{\{\mu\nu\}}^{\bar{D}^*\Lambda_c}$ are not useful. However, their mixing gives a reliable mass sum rule

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

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

Sum rule analyses using $J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^*\&\bar{D}^*\Lambda_c}$

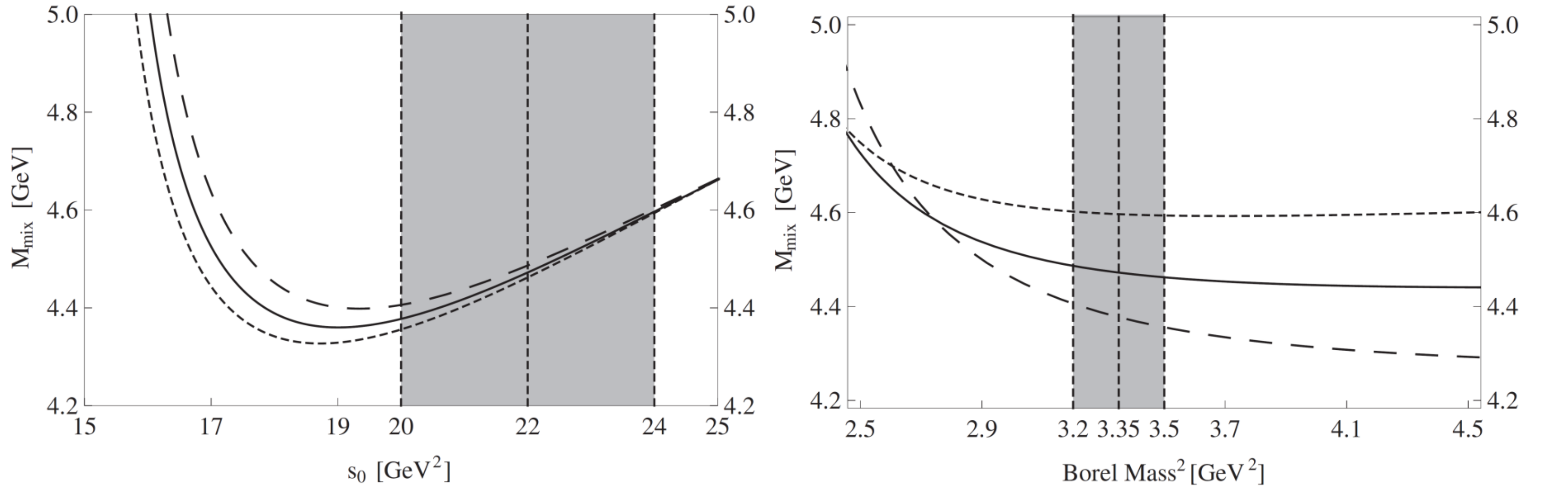


FIG. 2: The variation of $M_{[\bar{D}\Sigma_c^*\&\bar{D}^*\Lambda_c],5/2^+}$ with respect to the threshold value s_0 (left) and the Borel mass M_B (right).

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 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 $J^P = 5/2^+$.

Thank you very much!