Theoretical review on XYZ states

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兰州大学

6th workshop on the XYZ particles 复旦大学

2020年1月11-13日

Outline

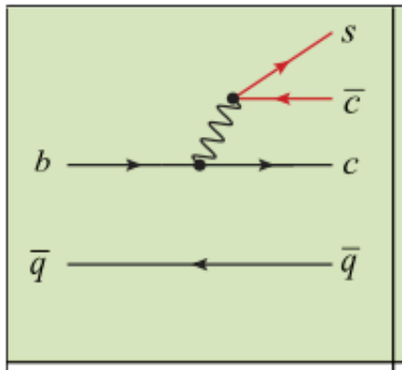
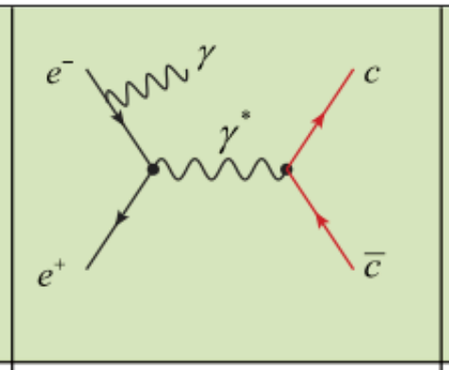
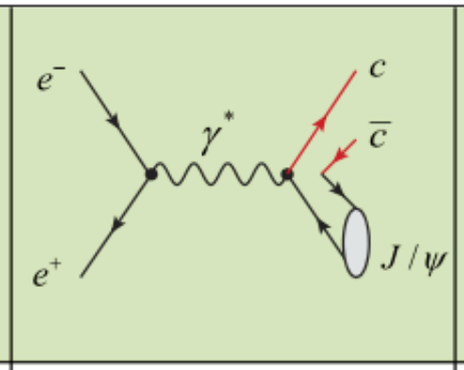
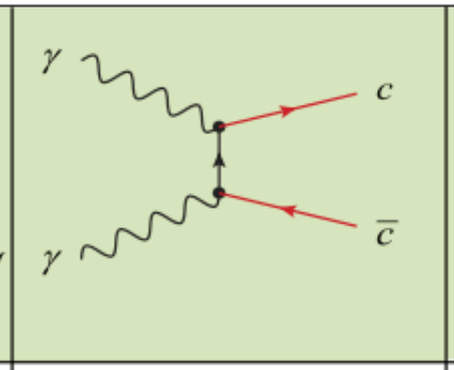
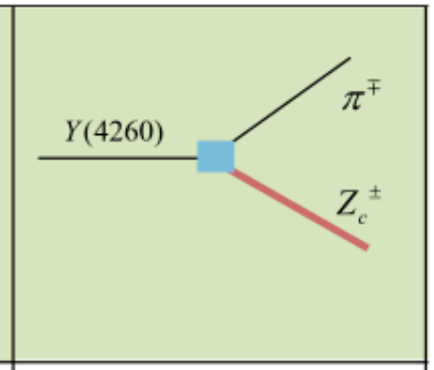
1. The status of XYZ charmoniumlike states
2. The Y problems
3. The hadronic molecular picture for XYZ
4. ISPE mechanism and charged Zc
5. Summary

1

The status of XYZ charmoniumlike states

The observed XYZ states

According to the production mechanisms, we can categorize them into five groups

				
$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_c(3900)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_c(4025)$
$Z^+(4430)$	$Y(4360)$		$Z(3930)$	$Z_c(4020)$
$Z^+(4051)$	$Y(4630)$			$Z_c(3885)$
$Z^+(4248)$	$Y(4660)$			
$Y(4140)$				
$Y(4274)$				
$Z_c^+(4200)$				
$Z^+(4240)$				
$X(3823)$				

see review

Physics Reports 639 (2016) 1–121

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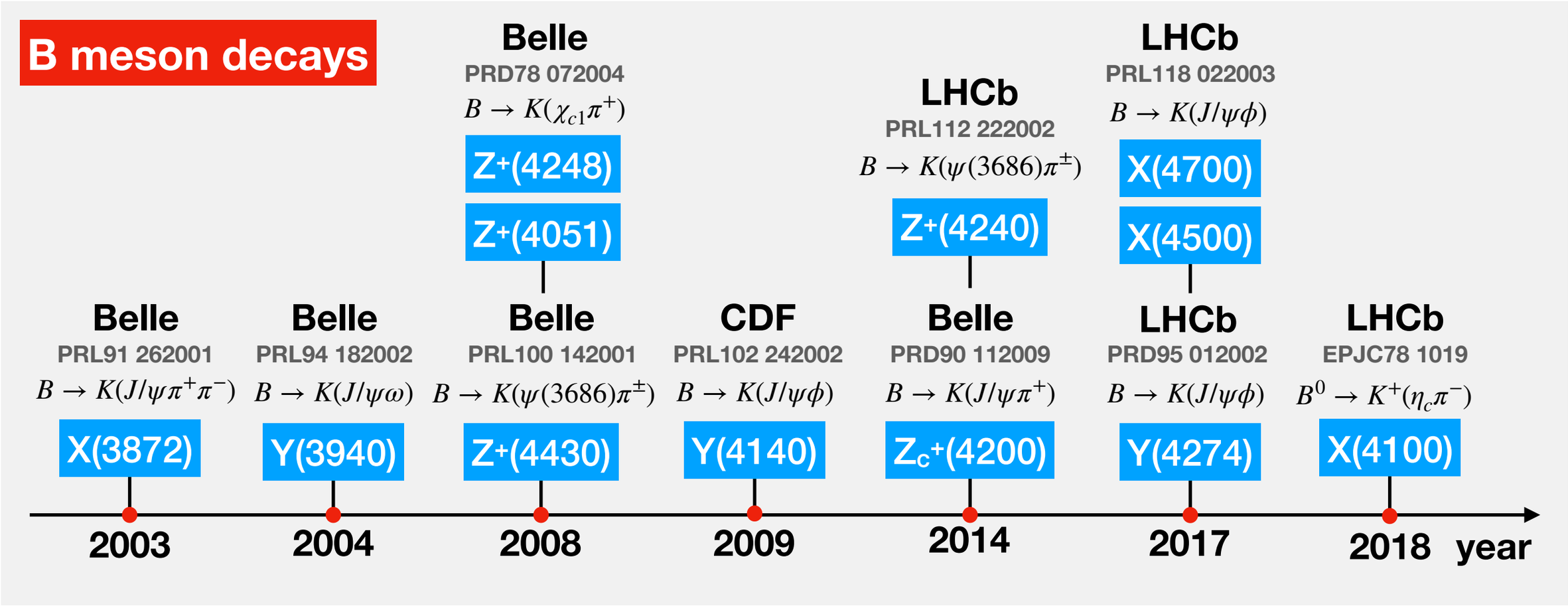
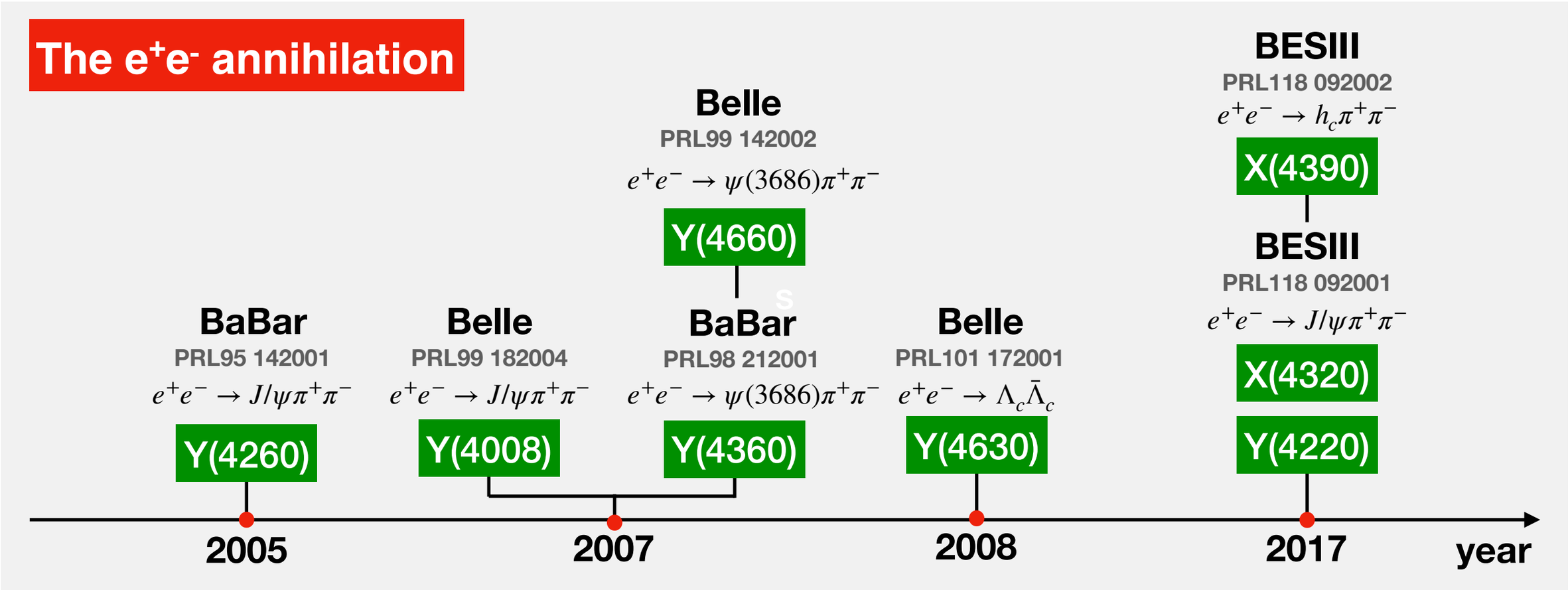
journal homepage: www.elsevier.com/locate/physrep

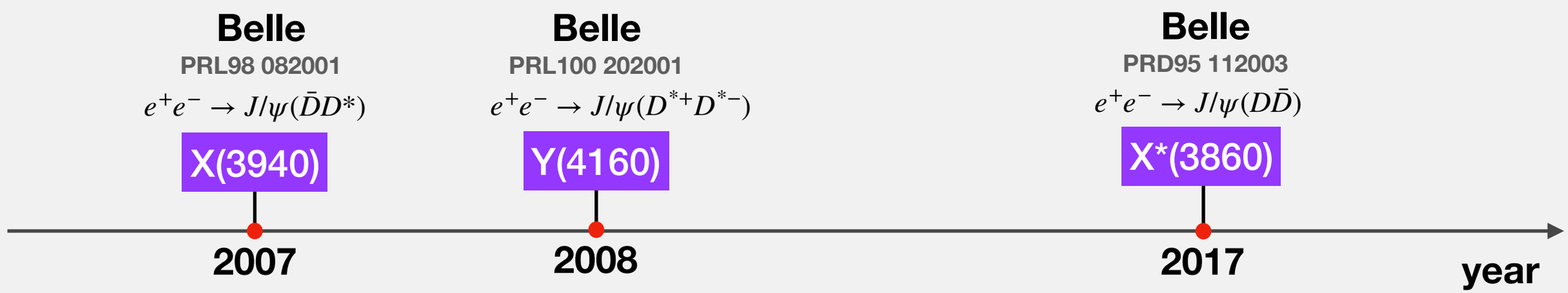
The hidden-charm pentaquark and tetraquark states

Hua-Xing Chen [a,b,1], Wei Chen [c,1], Xiang Liu [d,e,*], Shi-Lin Zhu [a,f,g,**]

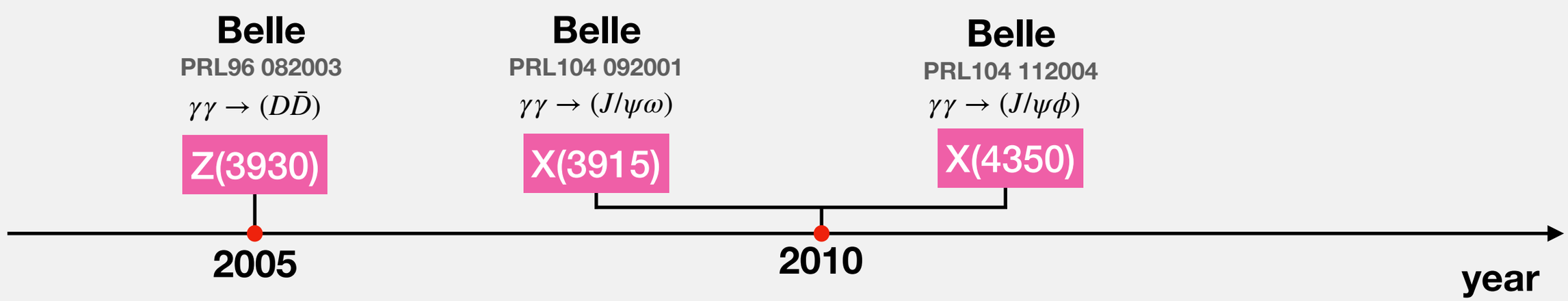

B meson decays
Belle
PRD78 072004
$B \to K(\chi_{c1}\pi^+)$
Z+(4248)
Z+(4051)
LHCb
PRL112 222002
$B \to K(\psi(3686)\pi^\pm)$
Z+(4240)
LHCb
PRL118 022003
$B \to K(J/\psi\phi)$
X(4700)
X(4500)
Belle
PRL91 262001
$B \to K(J/\psi\pi^+\pi^-)$
X(3872)
Belle
PRL94 182002
$B \to K(J/\psi\omega)$
Y(3940)
Belle
PRL100 142001
$B \to K(\psi(3686)\pi^\pm)$
Z+(4430)
CDF
PRL102 242002
$B \to K(J/\psi\phi)$
Y(4140)
Belle
PRD90 112009
$B \to K(J/\psi\pi^+)$
Zc+(4200)
LHCb
PRD95 012002
$B \to K(J/\psi\phi)$
Y(4274)
LHCb
EPJC78 1019
$B^0 \to K^+(\eta_c\pi^-)$
X(4100)
2003
2004
2008
2009
2014
2017
2018
year


The e+e- annihilation
Belle
PRL99 142002
$e^+e^- \to \psi(3686)\pi^+\pi^-$
Y(4660)
BESIII
PRL118 092002
$e^+e^- \to h_c\pi^+\pi^-$
X(4390)
BESIII
PRL118 092001
$e^+e^- \to J/\psi\pi^+\pi^-$
X(4320)
Y(4220)
BaBar
PRL95 142001
$e^+e^- \to J/\psi\pi^+\pi^-$
Y(4260)
Belle
PRL99 182004
$e^+e^- \to J/\psi\pi^+\pi^-$
Y(4008)
BaBar
PRL98 212001
$e^+e^- \to \psi(3686)\pi^+\pi^-$
Y(4360)
Belle
PRL101 172001
$e^+e^- \to \Lambda_c\bar{\Lambda}_c$
Y(4630)
2005
2007
2008
2017
year

The double charmonium production process



The γγ fusion process



The hadronic decays of Y(4260)

BESIII/Belle
PRL110 252001
PRL110 252002
$e^+e^- \to Y(4260) \to (J/\psi\pi^+)\pi^-$
$Z_c(3900)$

BESIII
PRL111 242001
$e^+e^- \to Y(4260) \to (h_c\pi^+)\pi^-$
$Z_c(4020)$

BESIII
PRL112 132001
$e^+e^- \to Y(4260) \to (D^*\bar{D}^*)^+\pi^-$
$Z_c(4025)$

BESIII
PRL112 022001
$e^+e^- \to Y(4260) \to (D\bar{D}^*)^+\pi^-$
$Z_c(3885)$

BESIII
PRD96 032004
$e^+e^- \to Y(4260) \to (\psi(3686)\pi^+)\pi^-$
$Z_c(4032)$

2013 — 2014 — 2017 — year

Other processes

Belle
PRL108 122001
$e^+e^- \to \Upsilon(10860) \to (h_b(mS)\pi^+)\pi^-$
$e^+e^- \to \Upsilon(10860) \to (\Upsilon(nS)\pi^+)\pi^-$
$Z_b(10650)$
$Z_b(10610)$

LHCb
PRL115 072001
$\Lambda_b^0 \to (J/\psi p)K^-$
$P_c(4450)$
$P_c(4380)$

BESIII
PRL115 011803
$e^+e^- \to \pi^+\pi^-(\gamma\chi_{c1})$
$X(3823)$

2011 — 2015 — year

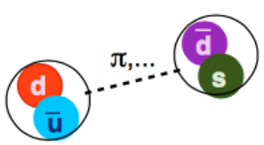
Theoretical explanations

Resonant *vs* Non-resonant

Conventional hadrons

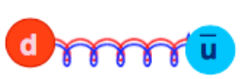
charmonium

Exotic states



- **Molecular states:** loosely bound states composed of a pair of mesons, probably bound by the pion exchange

- **Tetraquarks:** bound states of four quarks, bound by colored-force between quarks, some are charged or carry strangeness, there are many states within the same multiplet



- **Hybrid charmonium:** bound states composed of a pair of quarks and one excited gluon

Many XYZ states lie very close to open-charm threshold

It's quite possible some threshold enhancements are not ***real*** resonances.

- Kinematical effect
- Opening of new threshold
- Cusp effect
- Final state interaction
- Interference between continuum and well-known charmonium states
- Triangle singularity due to the special kinematics

2

The Y problem

White Paper on the Future Physics Programme of BESIII

IHEP-Physics-Report-BESIII-2019-12-13
To be submitted to Chin. Phys. C

3.3.2 Broad Problems in XYZ Physics

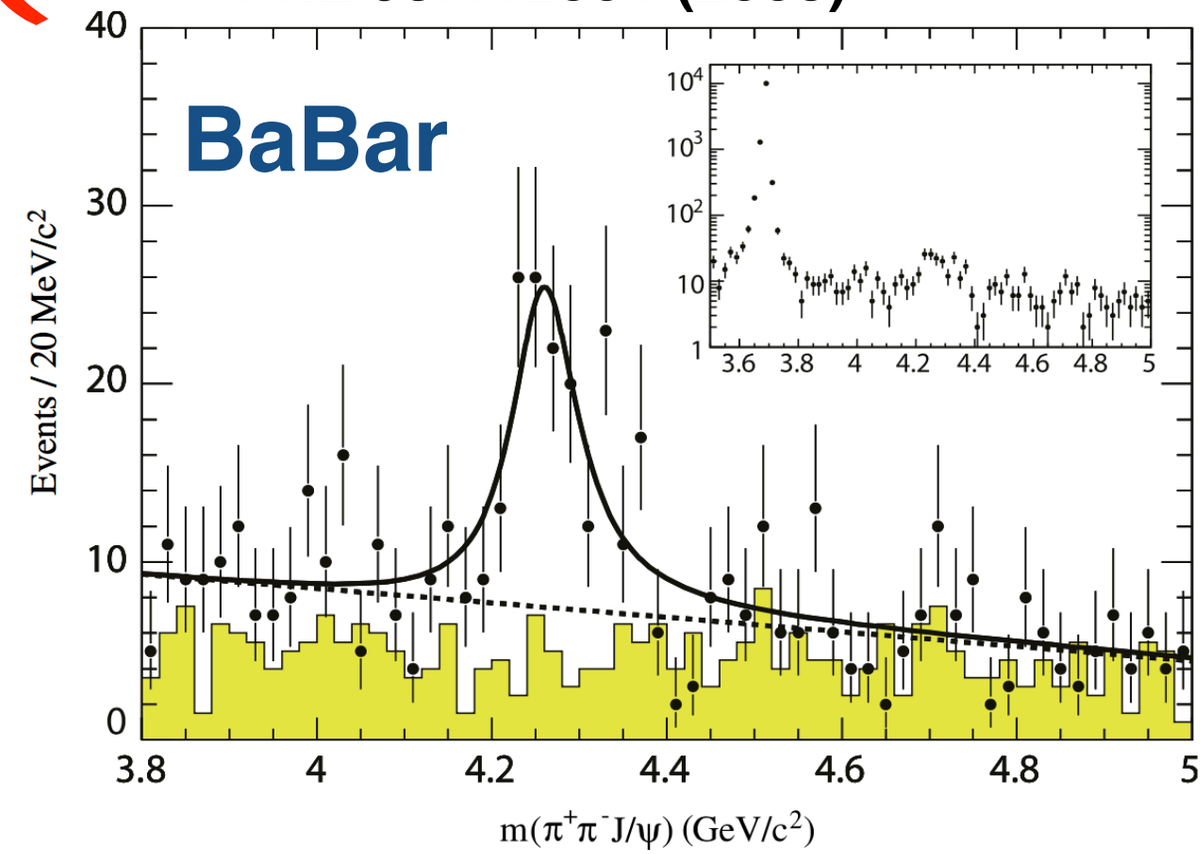
The XYZ results from BESIII have helped uncover several broad problems in the field, and these are the subjects of intense studies at BESIII. Below, these are labeled the "Y problem," the "Z problem," and the "X problem." With more data, BESIII is in the unique position to definitively address all three. This section includes descriptions of these problems and indicates a variety of the ways they can be addressed at BESIII.

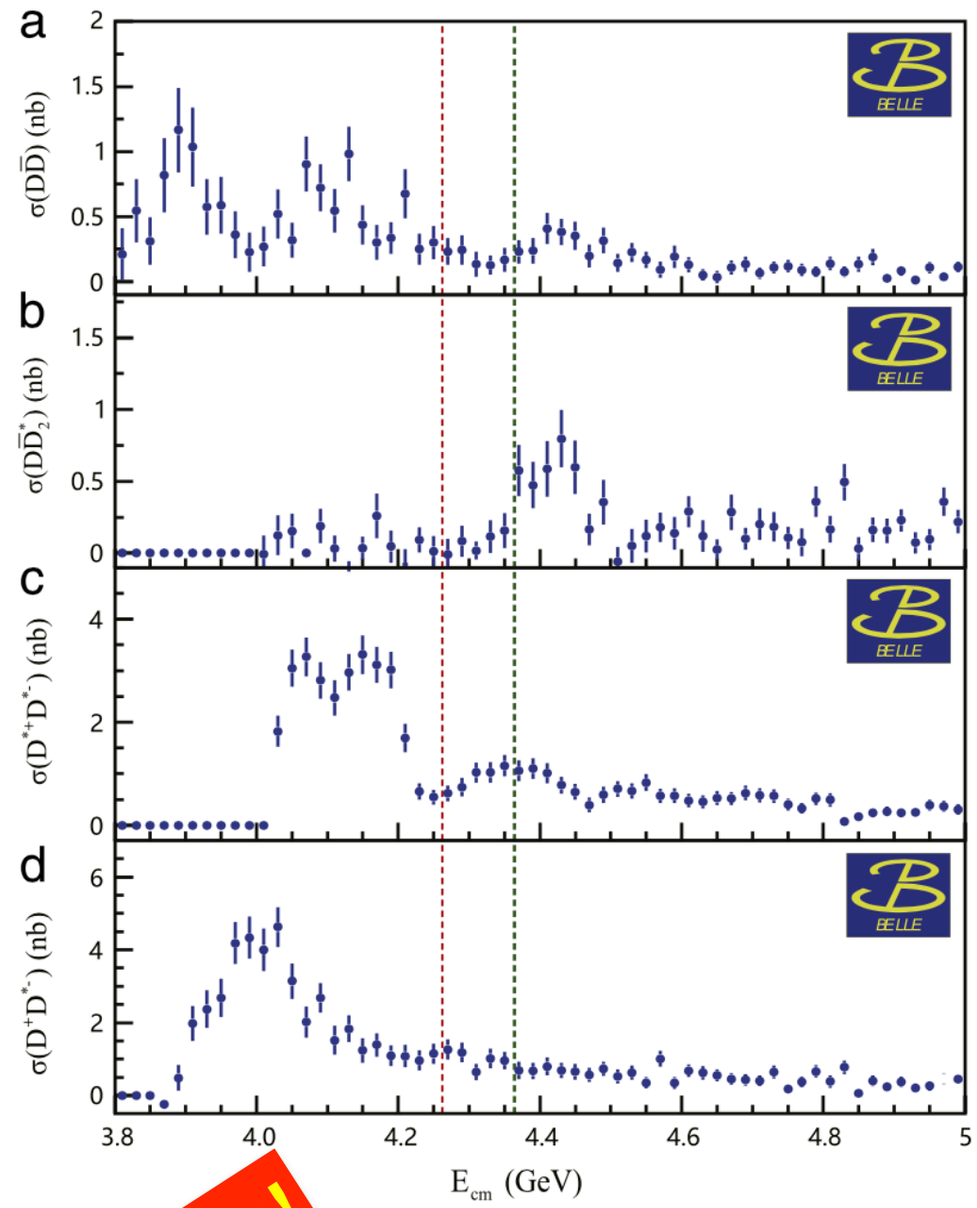
The Y Problem

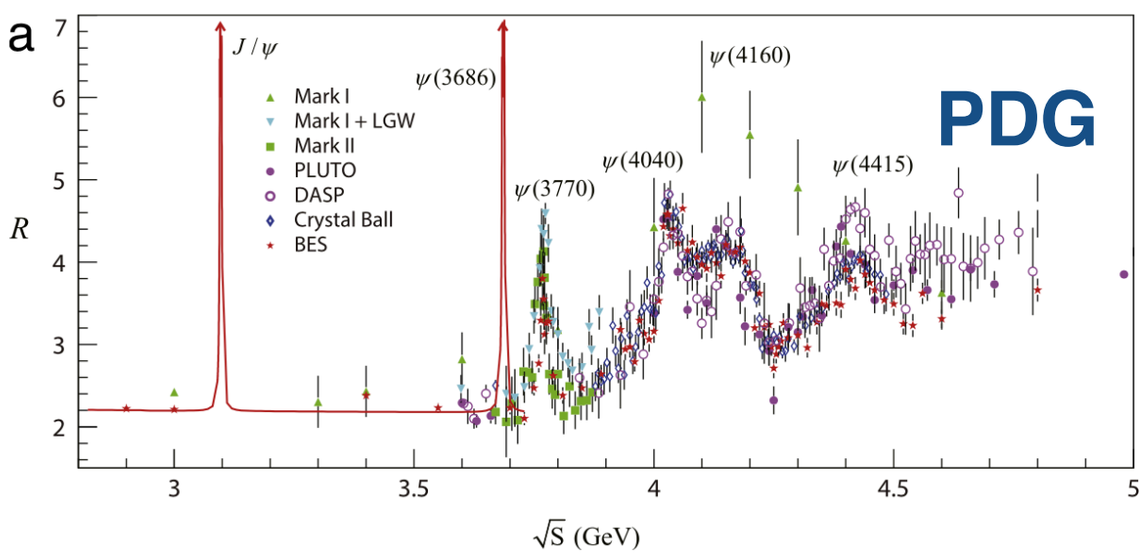
Exclusive e^+e^- cross sections have shown surprisingly complex behavior as a function of cms energy. The $Y(4260)$ is more complex than a single ordinary resonance, as shown by the complicated lineshape in the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section in Fig. 3.10(e); the $Y(4360)$ and $Y(4660)$ are seen in $e^+e^- \to \pi^+\pi^-\psi(3686)$; two other peaks are seen in $e^+e^- \to \pi^+\pi^- h_c$ in Fig. 3.10(f); the $Y(4220)$ is seen in $e^+e^- \to \omega\chi_{c0}$ in Fig. 3.10(g) and so on. A summary of the masses and widths of resonances extracted from recent BESIII results is shown in Fig. 3.11. There is currently very little consistency between different reactions. Furthermore, none of these complicated features are apparently present in the inclusive e^+e^- cross section, which only shows evidence for the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ [59]. This is the "Y" problem. Are the many peaks seen in e^+e^- cross sections really new states? Or are they the results of more subtle effects? With new data, will new patterns emerge? With our limited number of data points (cms energies), there is little hope in resolving the issue. We require (1) more data spread over a variety of cms energies, and (2) a global and simultaneous analysis of many final states. This latter effort will likely require close collaboration with the theory community, in particular with the view on amplitude analysis.

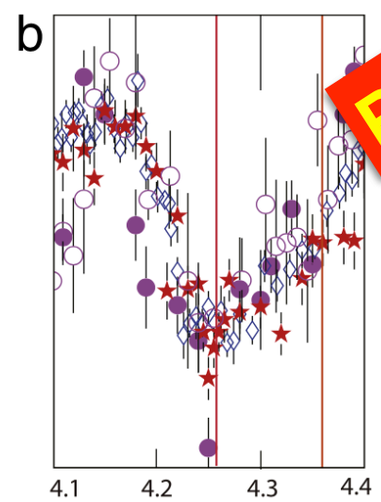
Y(4260)

PRL 95:142001 (2005)









Puzzle!

No evidence of Y(4260) in R scan data and open-charm decay channels

Theoretical explanations

Exotic state

Charmonium hybrid

Zhu, Kou&Pene, Close&Page

Diquark-antidiquark state

Maiani&Riquer&Piccinini&Polosa

Ebert&Faustov&Galkin

Molecular state

Liu&Zeng&Li, Yuan&Wang&Mo, Qiao,Ding,Torres&Khemchandani&Gamermann&Oset, Close&Downum&Thomas

Charmonium hybrid state with strong coupling with DD1 and DD0

Kalashnikova &Nefediev

Conventional charmonium

4S-3D vector charmonium

Lanes-Estrada

2^3D_1 state decay behavior

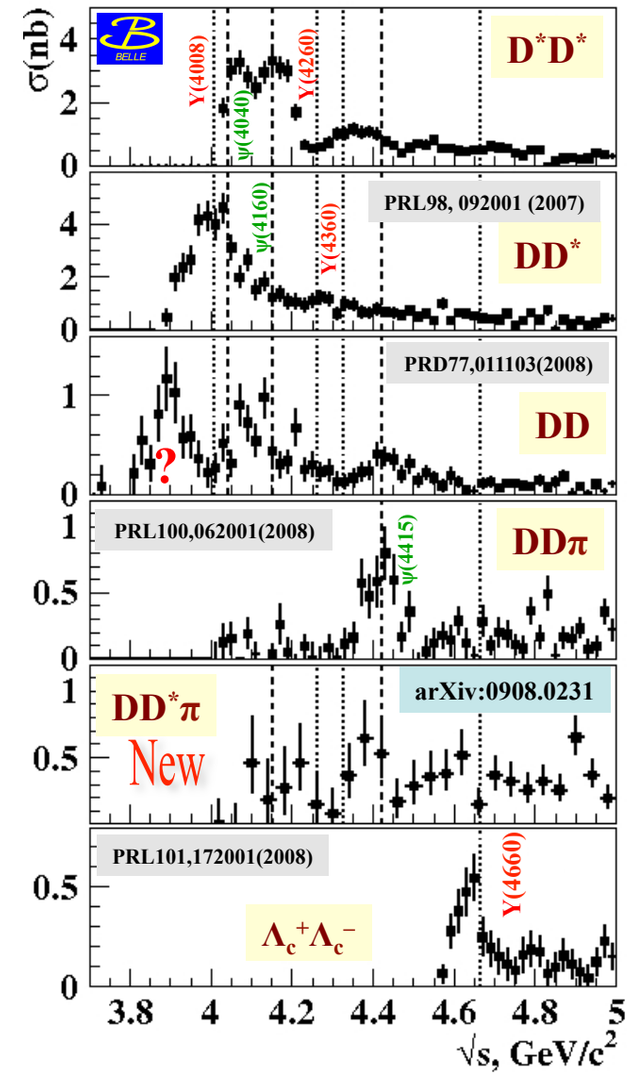
Eichten&Lane&Quigg

Mass spectrum Y(4260) ≠charmonium

Segovia&Yasser&Entem&Fernandez

Screened potential Y(4260) =Ψ(4S)

Li&Chao

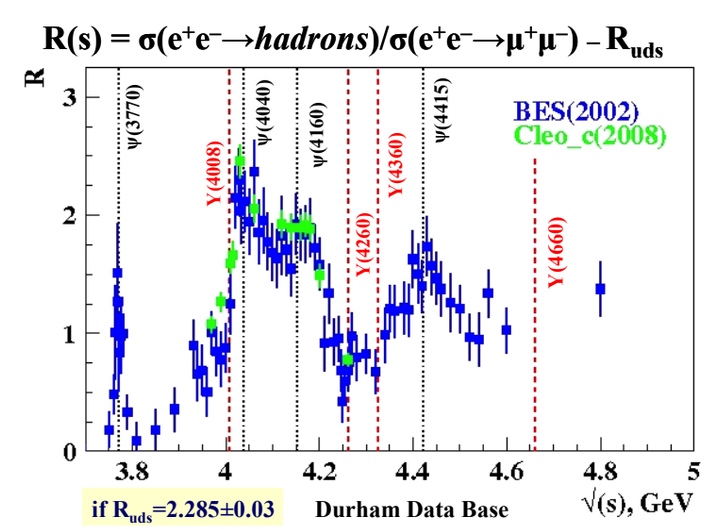


Difficulty

The **lack of signal in certain channels** also poses **a serious challenge** to a number of the explanations proposed in the framework of an exotic state

Difficulty

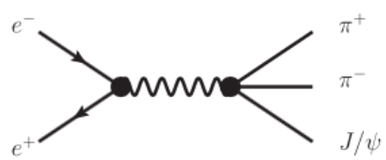
No evidence of Y(4260) in R scan data and open-charm decay channels



Non-resonant picture of Y(4260)

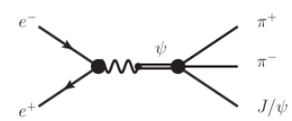
- **Asymmetric Y(4260) structure can be reproduced by Fano-like interference picture**

Continuum



$\widehat{=} g\, u^2 e^{-au^2}$

Charmonium

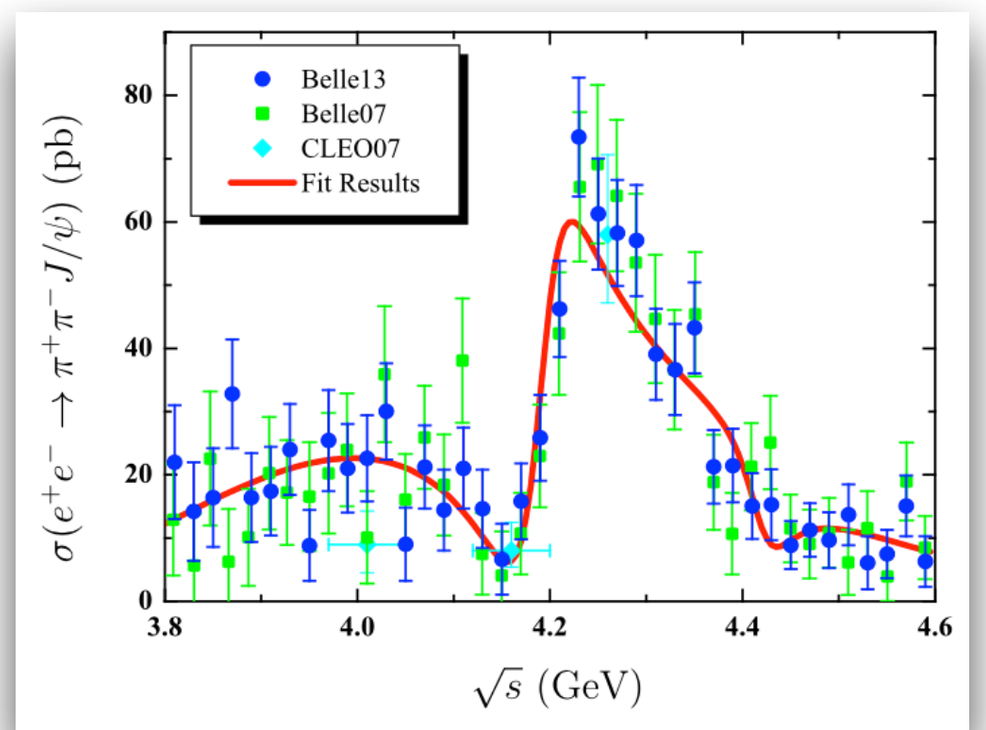


$$\widehat{=} \frac{\sqrt{12\pi\Gamma_\psi^{e^+e^-}\times\mathcal{B}(\psi\to\pi^+\pi^- J/\psi)\Gamma_\psi}}{s-m_\psi^2+im_\psi\Gamma_\psi}\sqrt{\frac{\Phi_{2\to3}(s)}{\Phi_{2\to3}(m_\psi^2)}}$$

Interference

$$\mathcal{A}^{\rm Total} = \mathcal{A}_{\rm Continuum} + e^{i\phi_1}\mathcal{A}_{\psi(4160)} + e^{i\phi_2}\mathcal{A}_{\psi(4415)},$$

Chen, He, Liu, PRD83 (2011) 05402
Chen, He, Liu, PRD83 (2011) 074012
Chen, Liu, Matsuki, PRD93 (2016) 014011

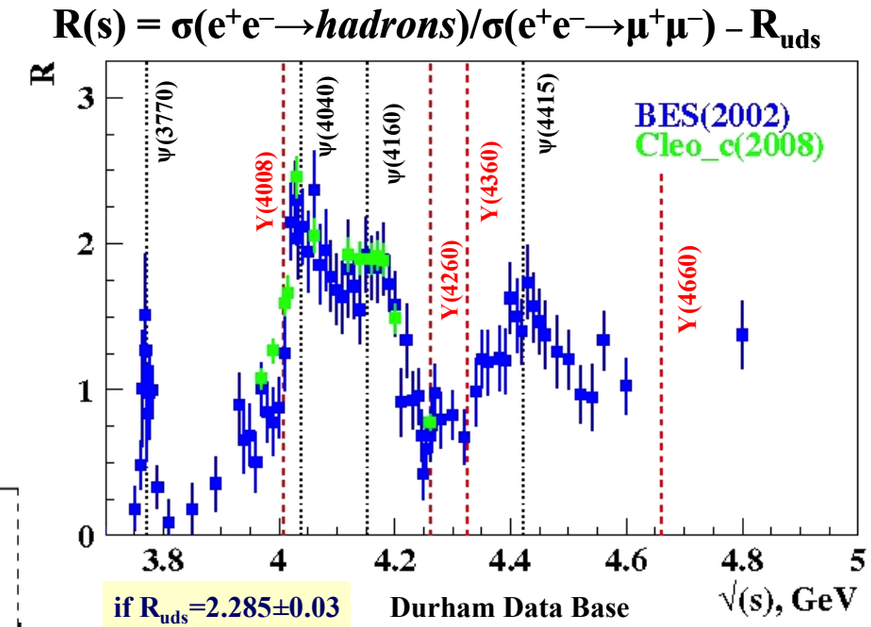


Success:

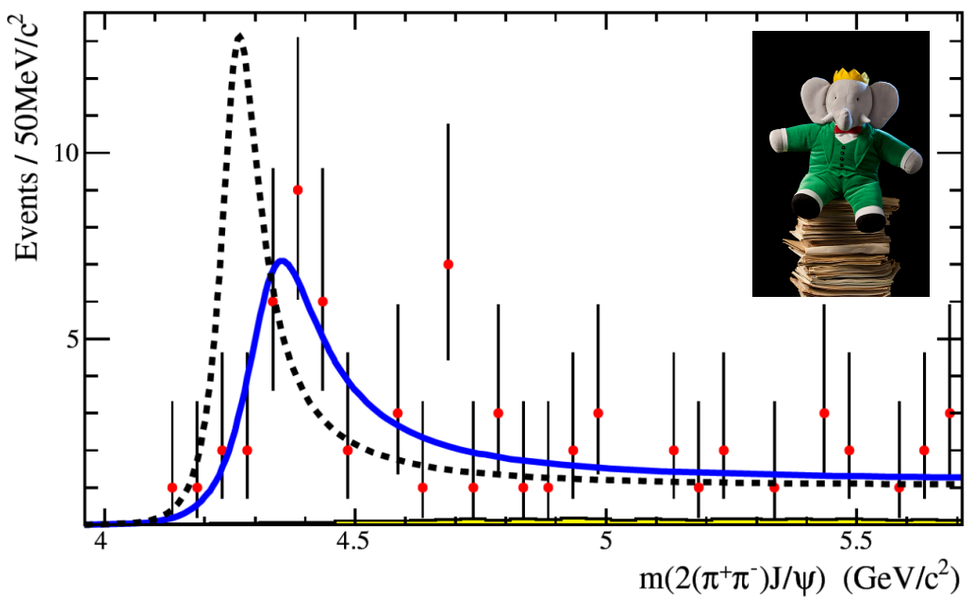
- **Explain why ψ(4160) and ψ(4415) signals are missing in data**
- **Naturally understand why no evidence of Y(4260) in R scan data and the open-charm decay channels**

Y(4360)

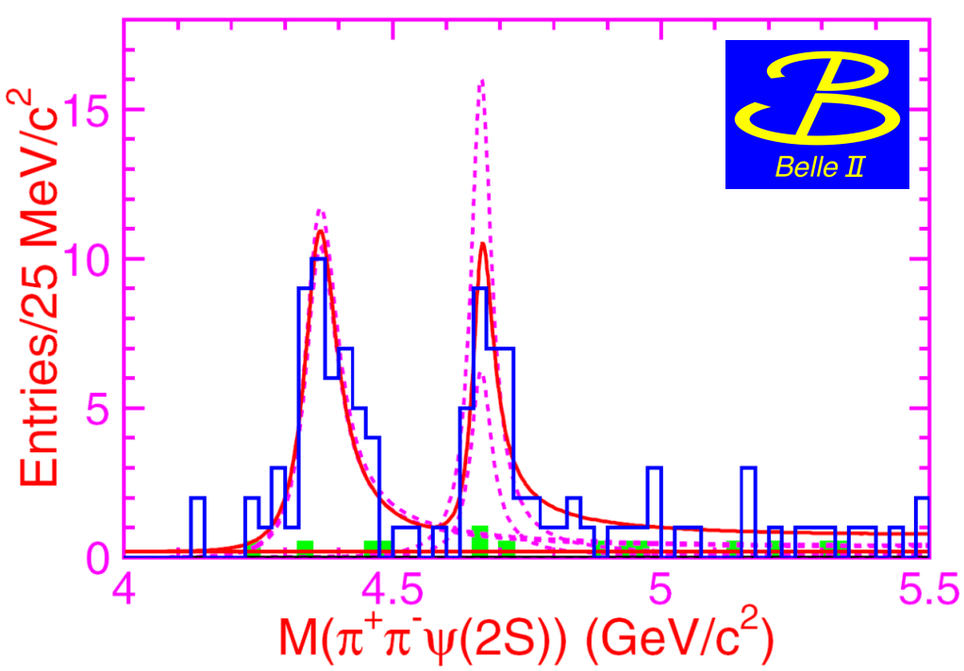
No evidence of *Y*(4260)/Y(4360) in the obtained open-charm process and *R*-value scan

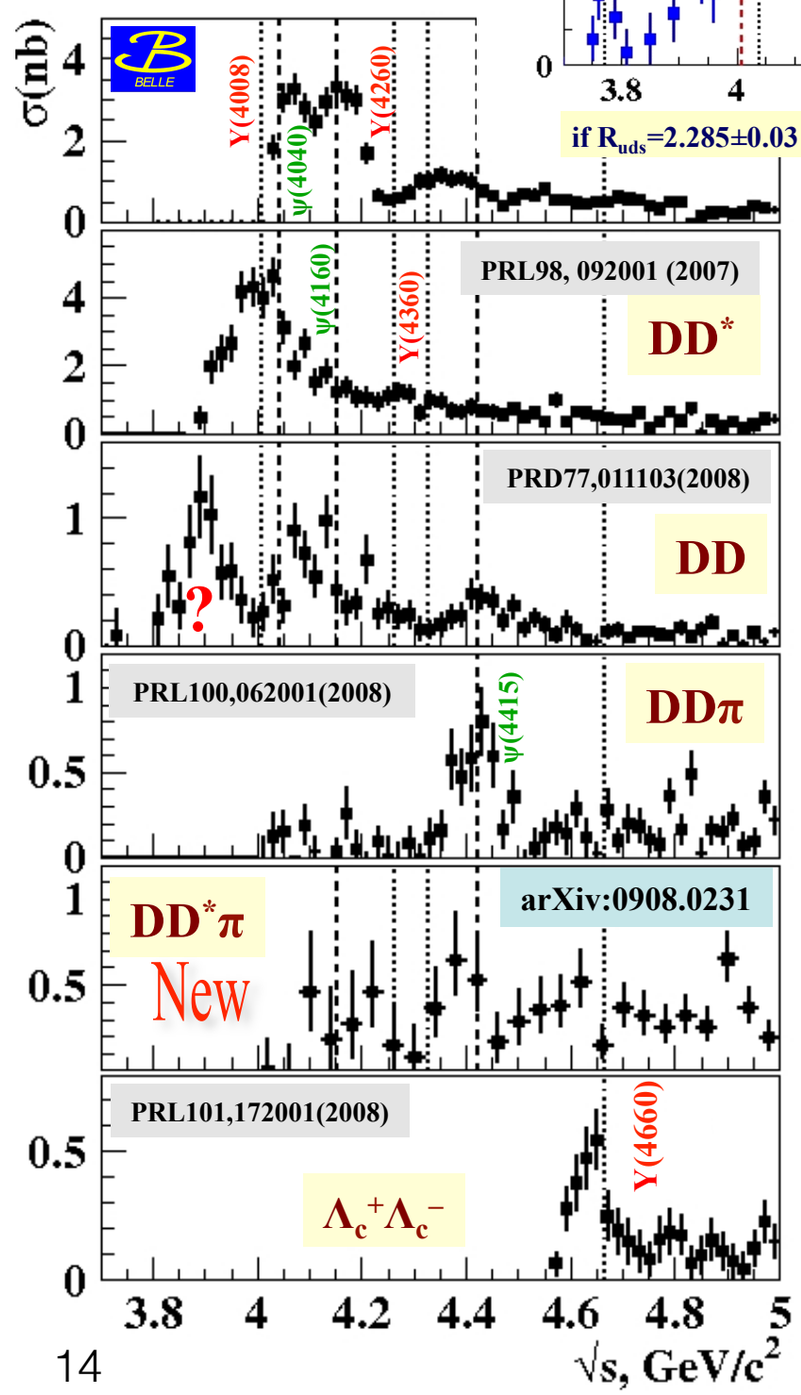


PRL 98:212001 (2007)



PRL 99:142002 (2007)

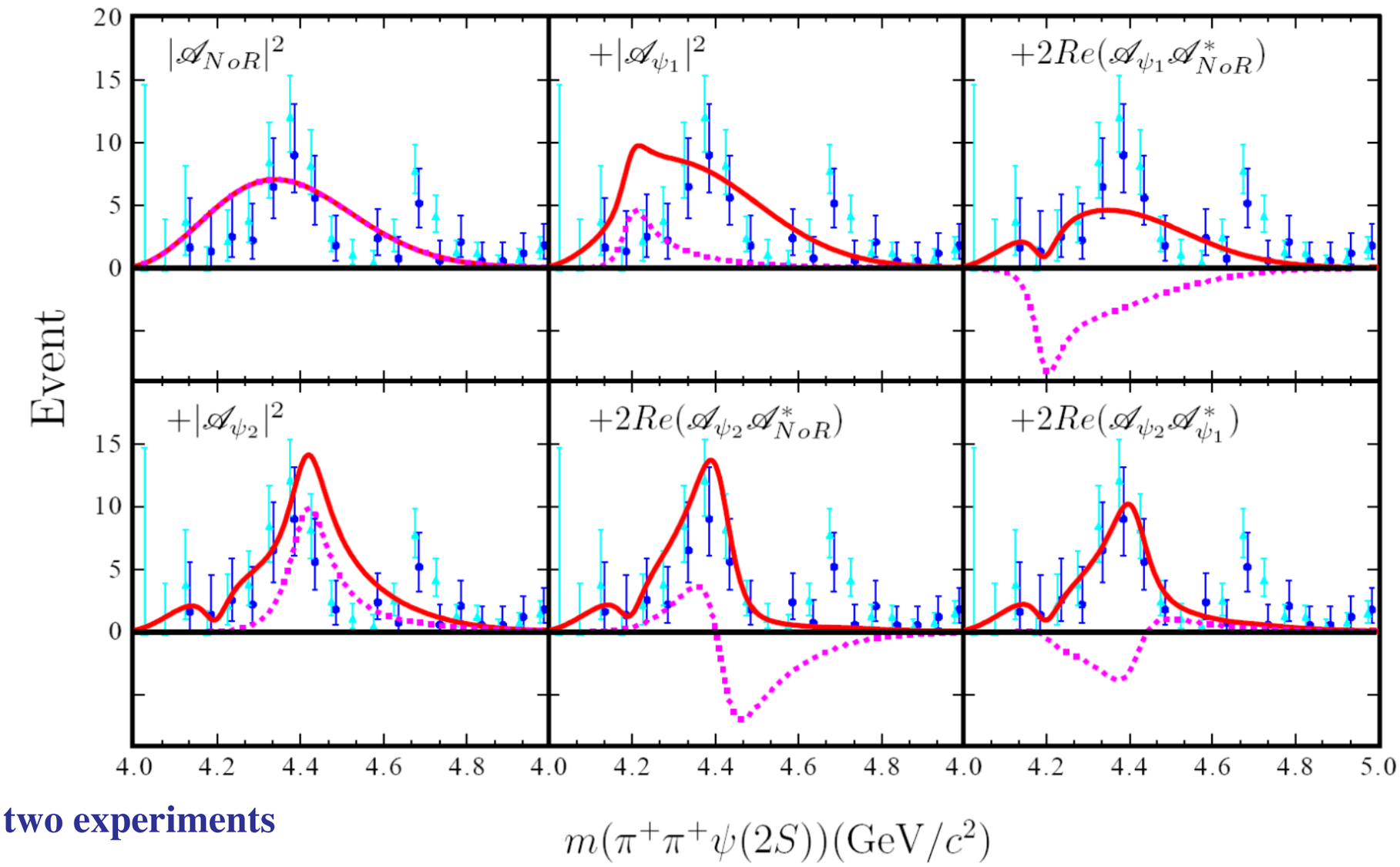




The situation of Y(4360) is similar to that of Y(4260)

Fano interference effect also plays resonance killer to Y(4360)

Chen, He and Liu, PRD 83:074012 (2011)



Data from two experiments

- **BaBar: PRL 98, 212001 (2007)**
- **Belle: PRL 99:142002 (2007)**

In 2017, BESIII gave more precise data of $e^+e^- \to J/\psi\pi^+\pi^-$

PRL **118,** 092001 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

Precise Measurement of the $e^+e^- \to \pi^+\pi^- J/\psi$ Cross Section at Center-of-Mass Energies from 3.77 to 4.60 GeV

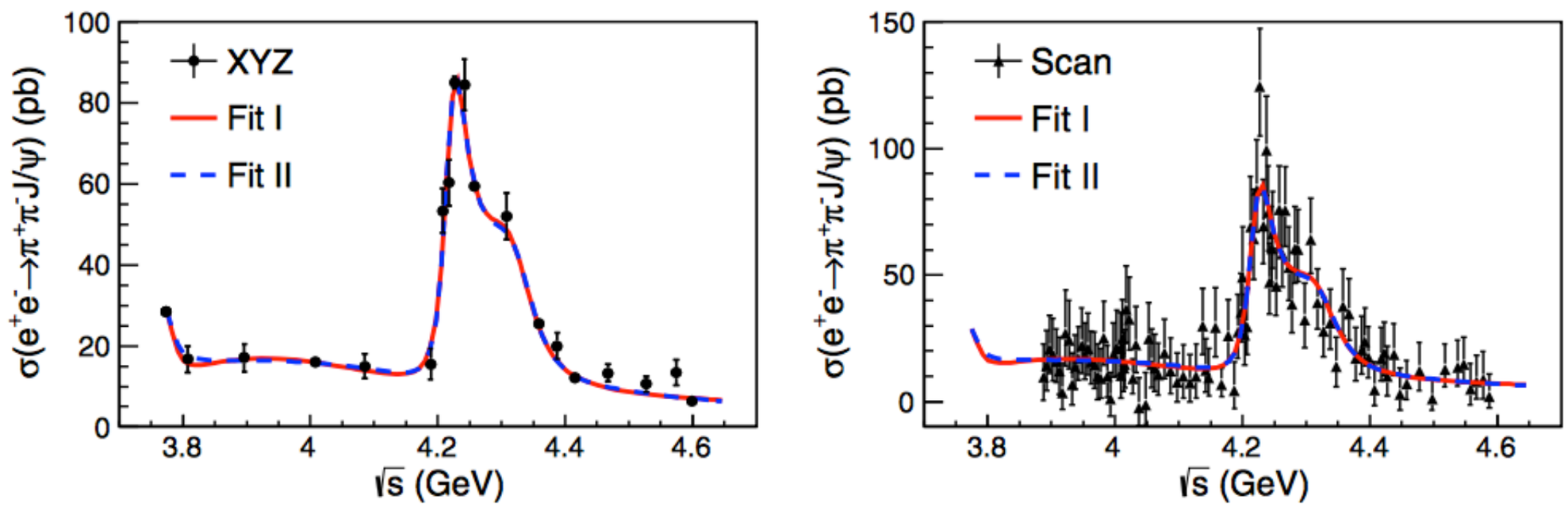


FIG. 1. Measured cross section $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ and simultaneous fit to the XYZ data (left) and scan data (right) with the coherent sum of three Breit-Wigner functions (red solid curves) and the coherent sum of an exponential continuum and two Breit-Wigner functions (blue dashed curves). Dots with error bars are data.

Y(4260) ⟶ Y(4220) + Y(4330)

Introducing a narrow structure Y(4220) and considering Fano-like interference picture can reproduce the data well!

Chen, Liu, Matsuki, EPJC 78:136 (2018)

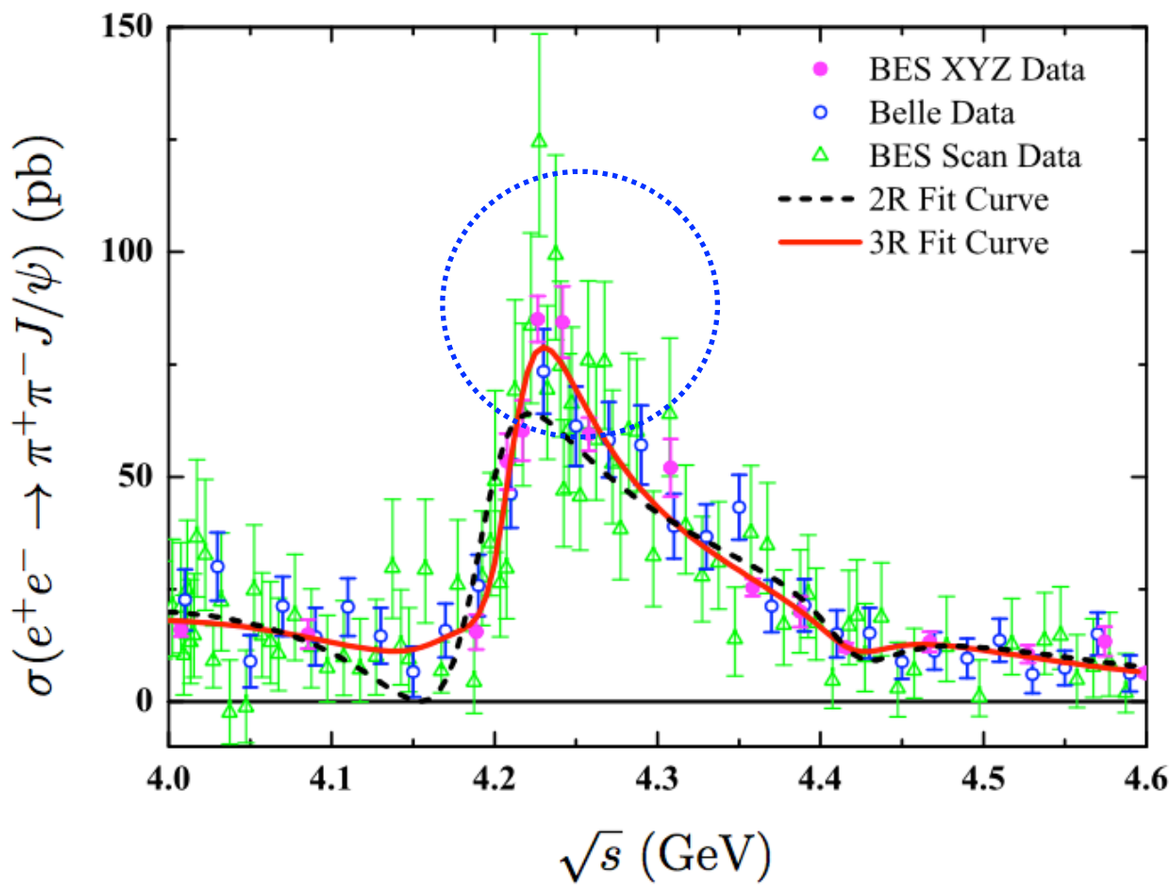


FIG. 2: (color online). Our fit to the cross sections for the $e^+e^- \to \pi^+\pi^- J/\psi$ process measured by the Belle [8] and BESIII collaborations [11] under the 2R and 3R fit schemes. Here, the BES scan data [11] are also listed for comparison.

	$e^+e^- \to \pi^+\pi^- J/\psi$	
Parameters	2R Fit	3R Fit
g (GeV^{-1})	49.93 ± 6.51	49.86 ± 5.89
a (GeV^{-2})	2.00 ± 0.17	2.11 ± 0.16
$\mathcal{R}_{\psi(4160)}$ (eV)	5.59 ± 0.25	2.38 ± 1.37
ϕ_1 (rad)	5.70 ± 0.23	1.59 ± 0.76
$\mathcal{R}_{\psi(4415)}$ (eV)	5.14 ± 1.82	5.05 ± 2.54
ϕ_2 (rad)	4.41 ± 0.21	4.62 ± 0.46
$m_{Y(4220)}$	–	4207 ± 12
$\Gamma_{Y(4220)}$	–	58 ± 38
$R_{Y(4220)}$	–	6.59 ± 4.88
ϕ_3	–	5.75 ± 0.93
χ^2/n.d.f	205/157	118/153

Fano-like interference picture plays resonance killer to Y(4330)

Resonance parameter

$$M = (4207 \pm 12) \quad \text{MeV}$$
$$\Gamma = (58 \pm 38) \quad \text{MeV}$$

What is Y(4220)?

Evidence of Two Resonant Structures in $e^+e^- \to \pi^+\pi^- h_c$

Y(4220)+Y(4390)

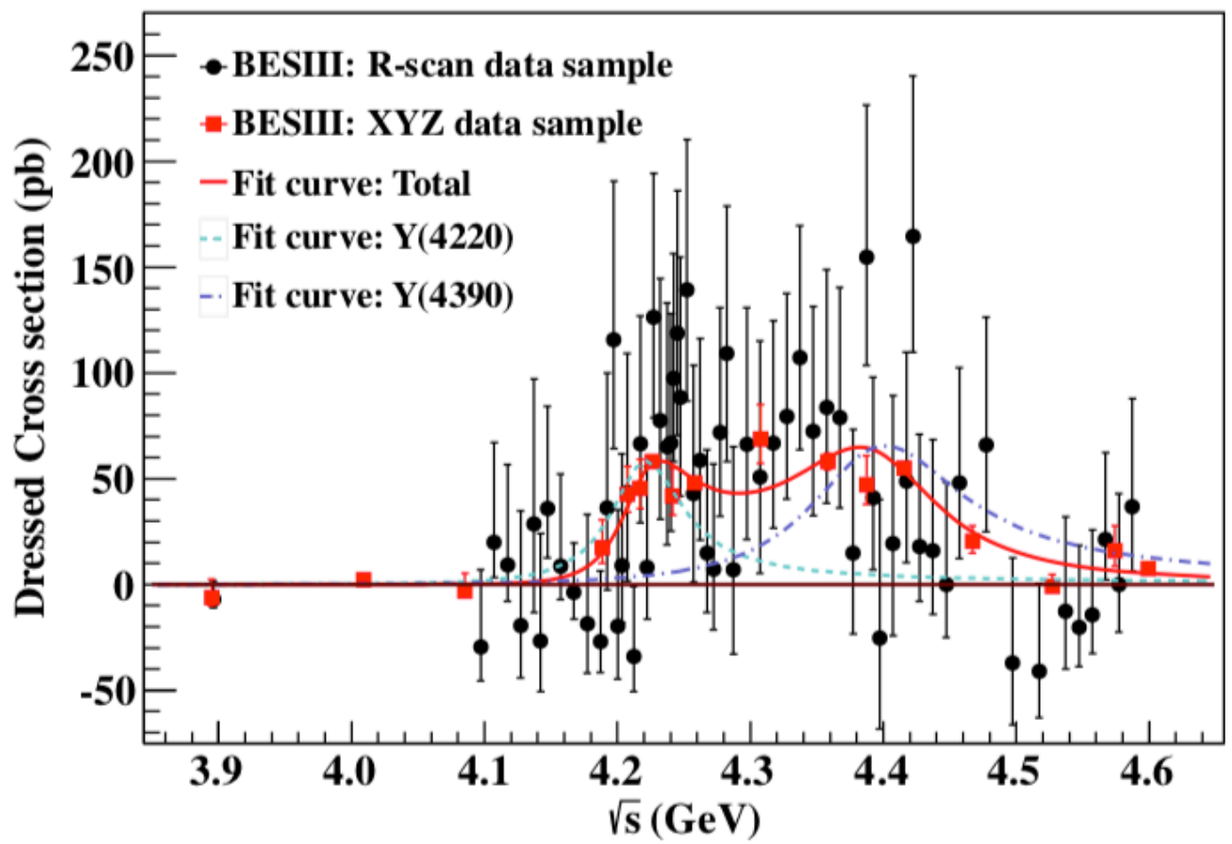


FIG. 2. Fit to the dressed cross section of $e^+e^- \to \pi^+\pi^- h_c$ with the coherent sum of two Breit-Wigner functions (solid curve). The dash (dash-dot) curve shows the contribution from the two structures $Y(4220)$ [$Y(4390)$]. The dots with error bars are the cross sections for the R-scan data sample, the squares with error bars are the cross sections for the XYZ data sample. Here the error bars are statistical uncertainty only.

More Y structures are reported!

How to explain them?

Eur. Phys. J. C (2018) 78:136
https://doi.org/10.1140/epjc/s10052-018-5635-1

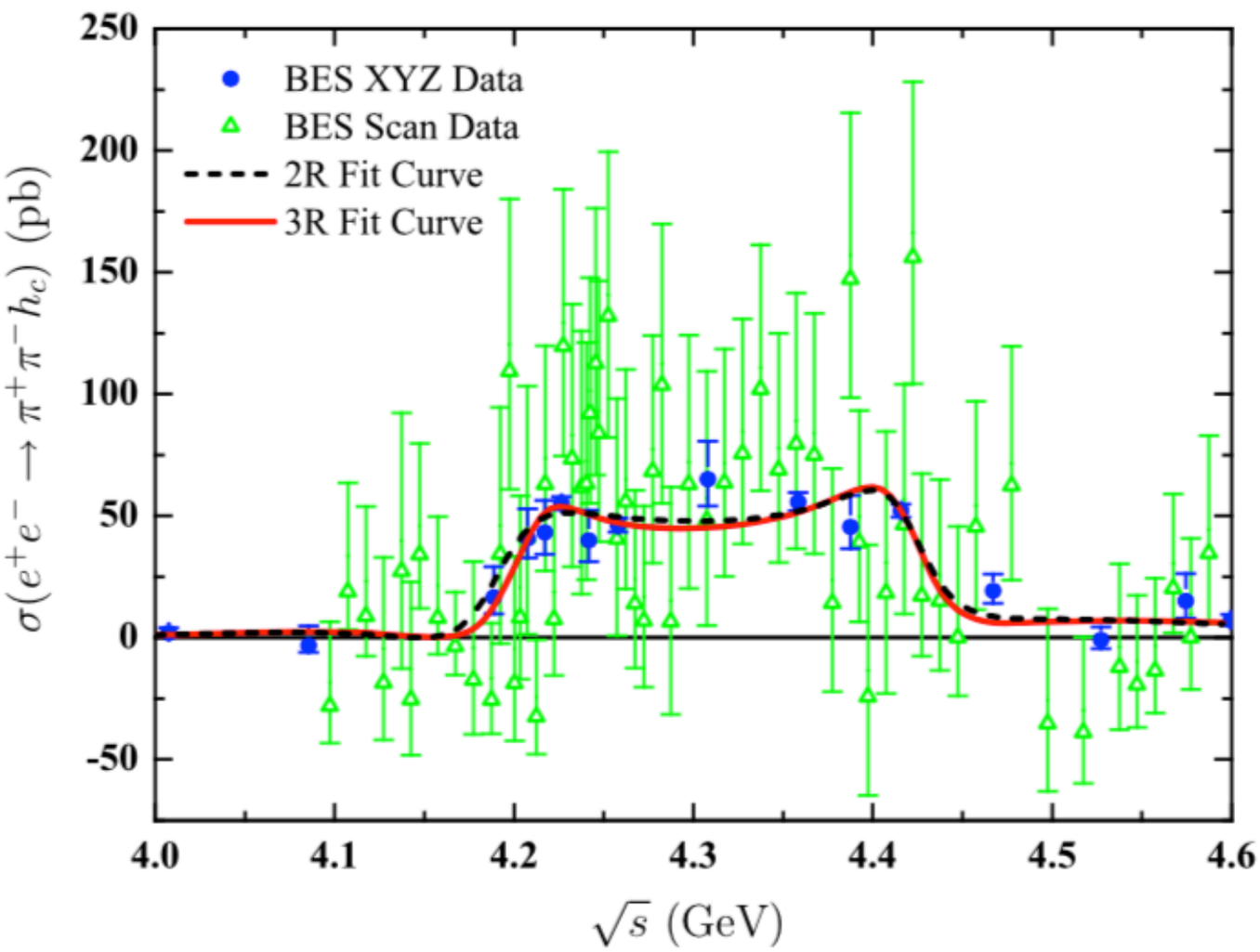
THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Theoretical Physics

Interference effect as resonance killer of newly observed charmoniumlike states $Y(4320)$ and $Y(4390)$

Dian-Yong Chen[1,a], Xiang Liu[2,3,b], Takayuki Matsuki[4,5,c]



Only Y(4220) is left

$$m = (4211 \pm 6)\, MeV$$

$$\Gamma = (47 \pm 13)\, MeV$$

from our fit

Summary of Y states from electron and positron annihilations

Belle PRL99:182004

Y(4008)

BaBar PRD86:051102

Y(4008)

$e^+e^- \to J/\psi\pi^+\pi^-$

Y(4260)

Y(4220)

Y(4320)

Inference effect

Y(4390)

Y(4360)

$e^+e^- \to \psi(2S)\pi^+\pi^-$

Y(4660)

Y(4630)

Y(4660)

Y(4630)

$e^+e^- \to \Lambda_c^+\Lambda_c^-$

Summary of Y states from electron and positron annihilations

Belle PRL99:182004

Y(4008)

BaBar PRD86:051102

Y(4008)

$e^+e^- \to J/\psi\pi^+\pi^-$

Y(4260)

Y(4220)

Y(4320)

Inference effect

Y(4390)

Y(4360)

$e^+e^- \to \psi(2S)\pi^+\pi^-$

Y(4660)

Y(4630)

Y(4660)

Y(4630)

$e^+e^- \to \Lambda_c^+\Lambda_c^-$

Summary of Y states from electron and positron annihilations

Y(4220)

Y(4660)
Y(4630)

1980

PHYSICAL REVIEW D VOLUME 21, NUMBER 1 1 JANUARY 1980

Charmonium: Comparison with experiment

E. Eichten,* K. Gottfried, T. Kinoshita, K. D. Lane,* and T. M. Yan
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 25 June 1979)

TABLE II. $c\bar{c}$ bound states in naive model, and their properties. Parameters used are $m_c = 1.84$ GeV, $a = 2.34$ GeV^{-1}, and $\kappa = 0.52$.

State	Mass (GeV)	Γ_{ee} (keV) [b]	$\left\langle \frac{v^2}{c^2} \right\rangle$	$\langle r^2 \rangle^{1/2}$ (fm)	Candidate
$1S$	3.095 [a]	4.8	0.20	0.47	$\psi(3095)$
$1P$	3.522 [a]		0.20	0.74	$\chi_{0,1,2}(3522 \pm 5)$
$2S$	3.684 [a]	2.1	0.24	0.96	$\psi'(3684)$
$1D$	3.81		0.23	1.0	$\psi'(3772)$ [c]
$3S$	4.11	1.5	0.30	1.3	$\psi(4028)$
$2D$	4.19		0.29	1.35	$\psi(4160)$ [d]
$4S$	4.46	1.1	0.35	1.7	$\psi(4414)$
$5S$	4.79	0.8	0.40	2.0	

psi(4415) as 4S state was proposed here

Is it a correct assignment?

PHYSICAL REVIEW D VOLUME 51, NUMBER 9

1995

Possible effects of color screening and large string tension in heavy quarkonium spectra

Yi-Bing Ding
China Center of Advanced Science and Technology (World Laboratory), Beijing 100080, China and Department of Physics, Graduate School, Academia Sinica, Beijing 100039, China

Kuang-Ta Chao
China Center of Advanced Science and Technology (World Laboratory), Beijing 100080, China and Department of Physics, Peking University, Beijing 100871, China

Dan-Hua Qin
Department of Physics, Peking University, Beijing 100871, China
(Received 8 July 1994)

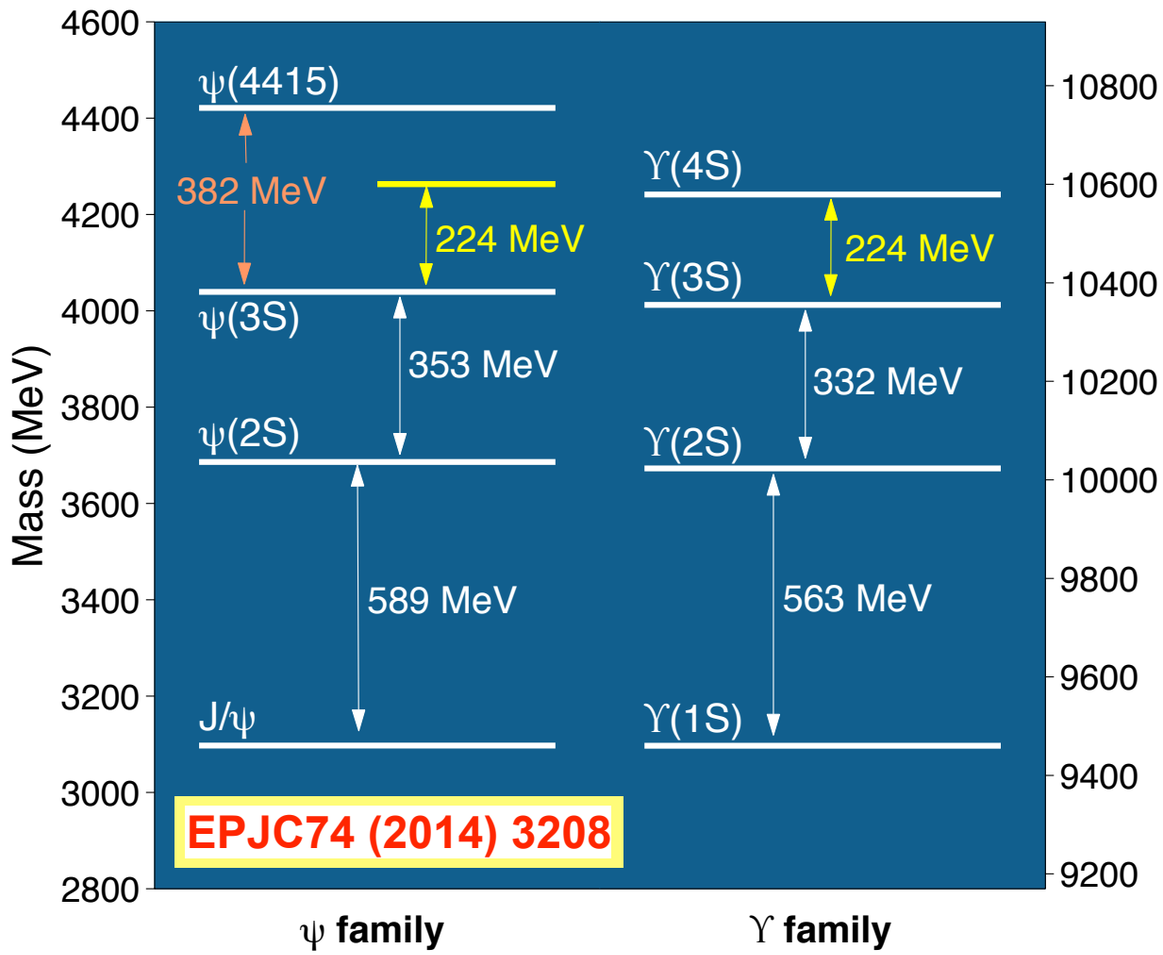
TABLE I. Calculated masses and leptonic widths for charmonium states with the screened potential (5) and parameters (8), where $\Gamma_{ee} = \Gamma^0_{ee}[1 - \frac{16}{3\pi}\alpha_s(m_c)]$ with $\alpha_s(m_c) = 0.28$ [16].

States	Mass (MeV)	Γ^0_{ee} (keV)	Γ_{ee} (keV)	$\Gamma^{\rm expt}_{ee}$ (keV)	Candidate
$1S$	3097	10.18	5.34	5.26 ± 0.37	$\psi(3097)$
$2S$	3686	4.13	2.17	2.14 ± 0.21	$\psi(3686)$
$3S$	4033	2.35	1.23	0.75 ± 0.15	$\psi(4040)$
$4S$	4262	1.46	0.77	0.77 ± 0.23	$\psi(4160)$
$5S$	4415	0.91	0.48	0.47 ± 0.10	$\psi(4415)$
$1P$	3526				$\chi(3526)_{\rm c.o.g.}$
$1D$	3805				$\psi(3770)$
$2D$	4105				

The predicted ψ(4S) and its property

2014

The similarity between J/ψ and Υ families



The predicted mass of ψ(4S) should be located at 4263 MeV

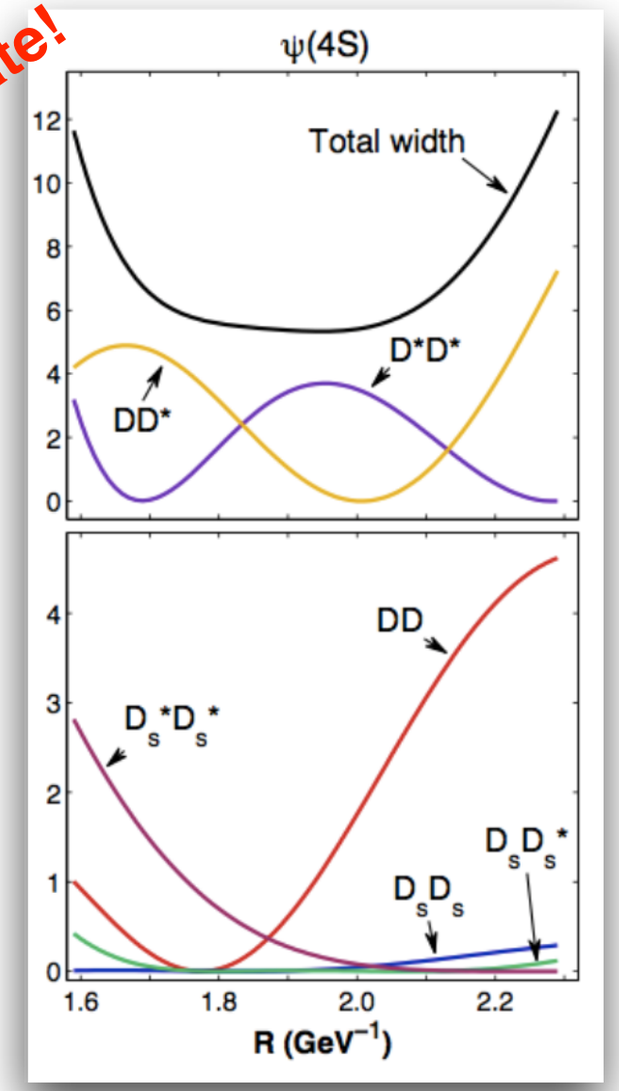
Consistent

The screening potential prediction of ψ(4*S*) mass:

- **4273 MeV Li&Chao PRD79, 094004 (2009)**
- **4247 MeV Dong et al., PRD49, 1642**

Open-charm decay behavior

A narrow state!



Due to node effect!

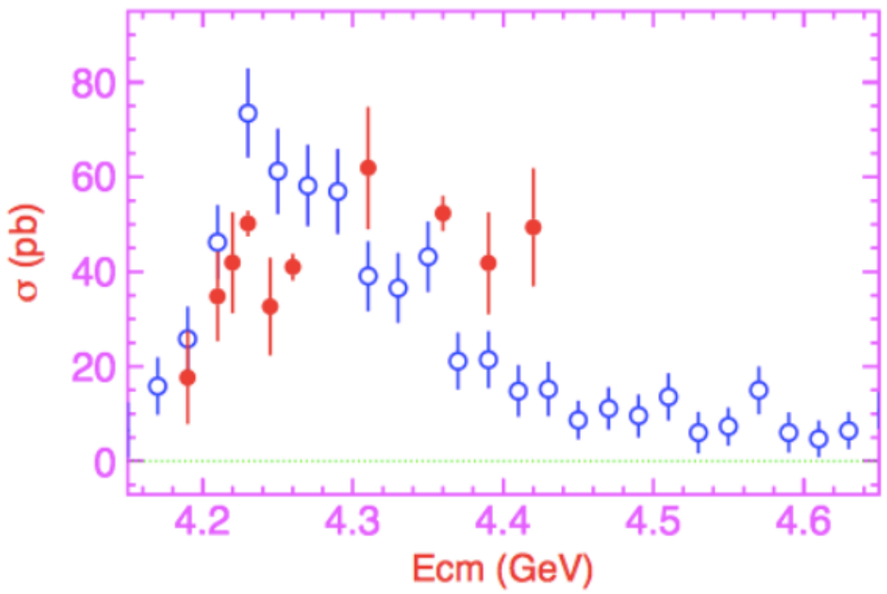
The predicted charmonium ψ(4*S*) has very narrow width around 6 MeV

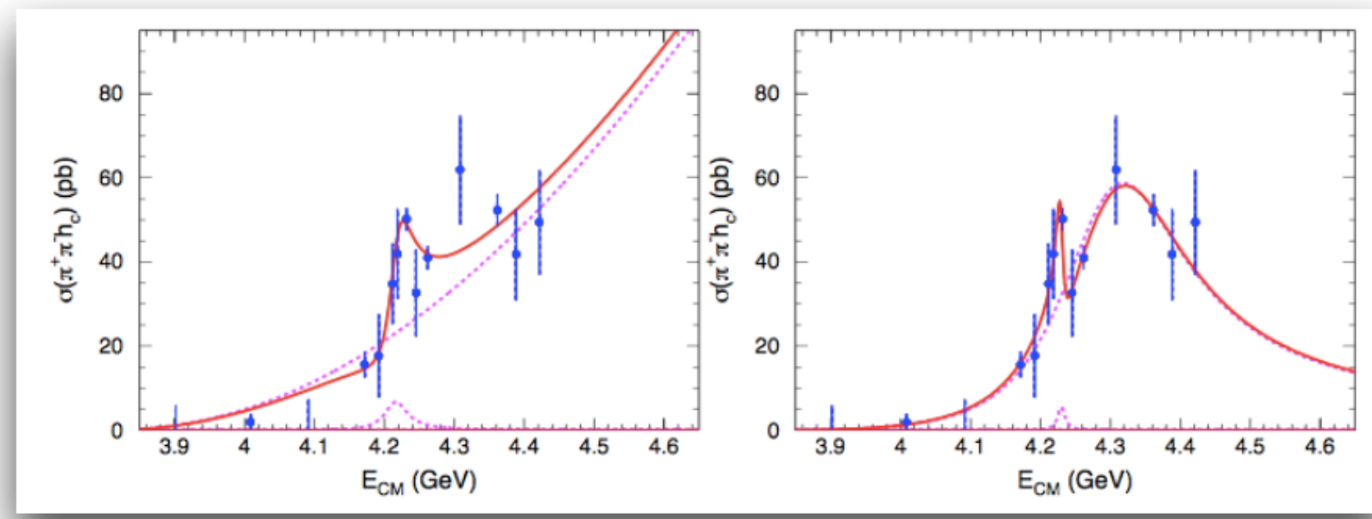
Y(4220)= ψ(4S)?

Experimental evidence

Experimental data

C.Z. Yuan, Chinese Physics C 38, 043001 (2014)





Red points: e+e—>hc\pi\pi
BESIII PRL 111, 242001 (2013)
Blue points: e+e—>J/\psi\pi\pi
Belle PRL 110, 252002 (2013)

"we conclude that very likely there is a narrow structure at around 4.22 GeV"

$$M(Y(4220)) = (4216 \pm 18)\ \mathrm{MeV}/c^2,$$
$$\Gamma_{\mathrm{tot}}(Y(4220)) = (39 \pm 32)\ \mathrm{MeV},$$

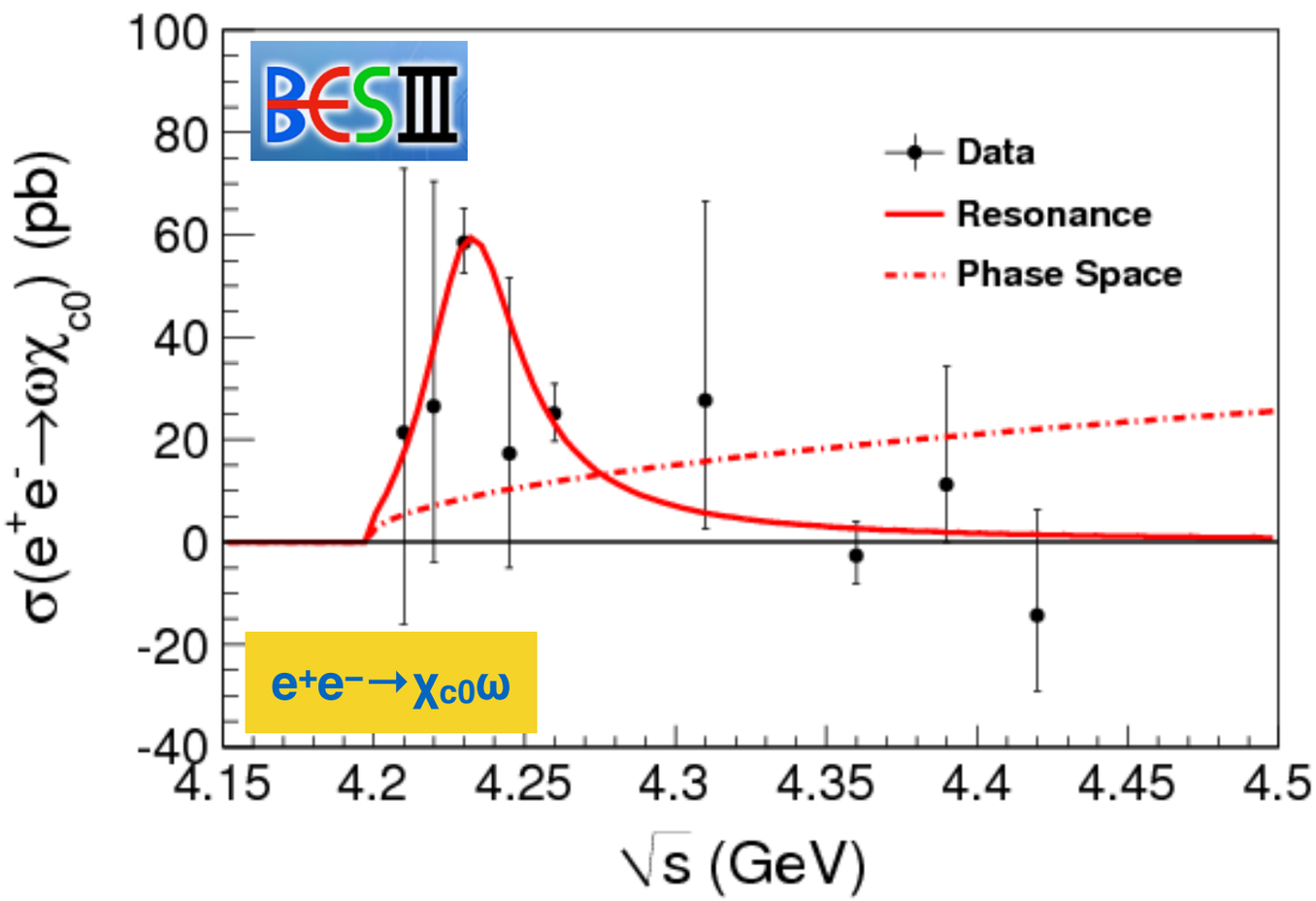
Is it the prediced higher charmonium with the mass around 4.26 GeV?

Need further experimental and theoretical efforts!

Experimental results of the open-charm decays and more precise study of the *R* value scan, especially from BESIII, Belle and forthcoming BelleII

The observation of $e^+e^- \to \chi_{c0}\omega$ from BESIII

BESIII, Phys. Rev. Lett. 114, 092003 (2015)



$$M = 4230 \pm 8 \text{ MeV} \quad \Gamma = 38 \pm 12 \text{ MeV}$$

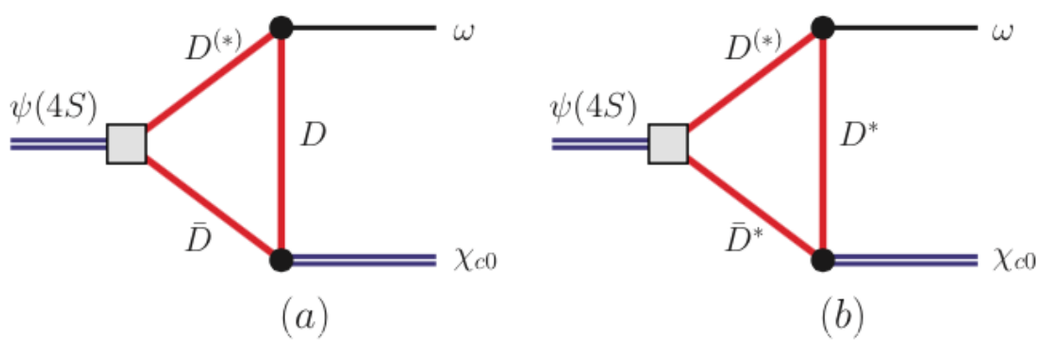
$e^+e^- \to \chi_{c1}\omega$ and $e^+e^- \to \chi_{c2}\omega$ are not significant

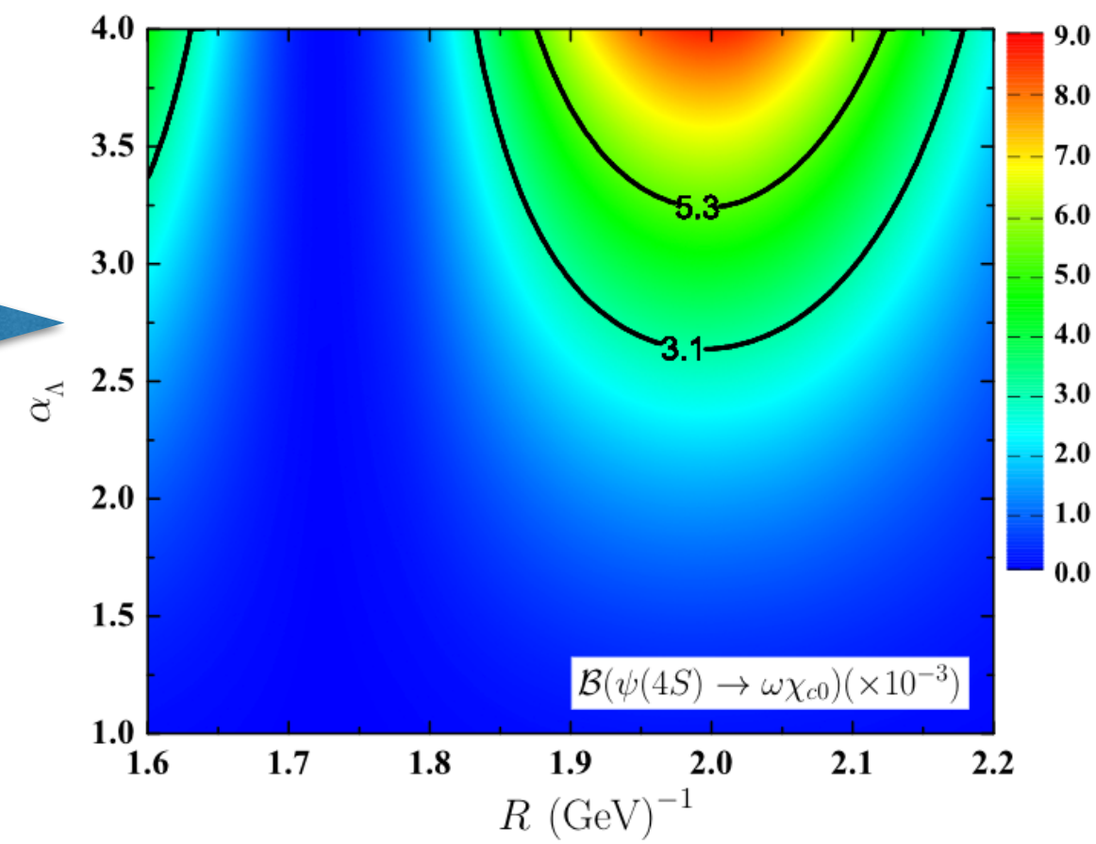
If taking the mass of $\psi(4S)$ to be 4230 MeV (Expt.), we find:

- $\psi(4S) \to \chi_{c0}\omega$ is allowed
- $\psi(4S) \to \chi_{c1}\omega$ and $\psi(4S) \to \chi_{c2}\omega$ are forbidden kinematically

Explain why only $e^+e^- \to \chi_{c0}\omega$ was reported by BESIII

- Our theoretical result **overlaps** with the experimental data in a reasonable parameter range of $2.6 < \alpha_\Lambda < 4.0$ and $1.83 < R < 2.17$
- $e^+e^- \to \omega\chi_{c0}$ observation can be **understood** through introducing the predicted $\psi(4S)$ contribution





- **Coupled-channel effect**
- **Non-perturbative properties of QCD**
- **Hadronic loop is an effective description for this effect**

Chen, X. Liu, Matsuki, **PRD91 (2015) 094023**

2016

PHYSICAL REVIEW D **93**, 034028 (2016)

Search for missing $\psi(4S)$ in the $e^+e^- \to \pi^+\pi^-\psi(2S)$ process

Dian-Yong Chen,[1,2,*] Xiang Liu,[2,3,†] and Takayuki Matsuki[4,5,‡]

Experimental data

X. L. Wang *et al.* (Belle Collaboration), Measurement of $e^+e^- \to \pi^+\pi^-\psi(2S)$ via initial state radiation at Belle, Phys. Rev. D **91**, 112007 (2015).

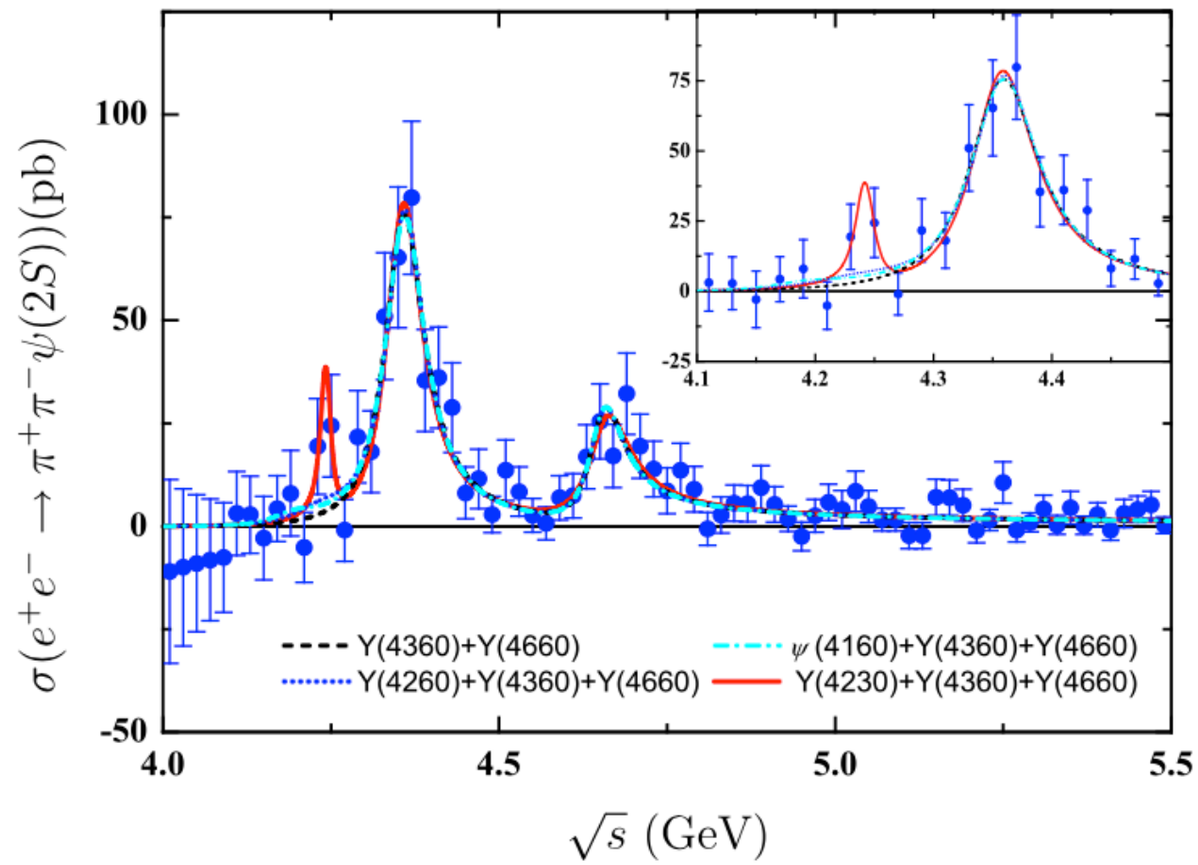


FIG. 2. A comparison of the fits to the cross sections for $e^+e^- \to \pi^+\pi^-\psi(2S)$ with different schemes.

The total cross section can be described by

$$\sigma(m) = \left| \sum_{i=0}^{2} e^{i\phi_i} \mathrm{BW}_i(m) \sqrt{\frac{\mathrm{PS}_{2\to3}(m)}{\mathrm{PS}_{2\to3}(m_i)}} \right|^2, \qquad (1)$$

where ϕ_i is the phase angle between different resonances with $\phi_0 = 0$, and $\mathrm{PS}_{2\to3}$ indicates the phase space of the $2 \to 3$ body process. The indices $i = 0, 1, 2$ are assigned to the resonances $Y(4230)$, $Y(4360)$, and $Y(4660)$, respectively. The concrete form of the Breit-Wigner function of a resonance with mass m_R and width Γ_R is

$$\mathrm{BW}(m) = \frac{\sqrt{12\pi\Gamma_R^{e^+e^-}\mathcal{B}(R \to f)\Gamma_R}}{m^2 - m_R^2 + i m_R \Gamma_R}. \qquad (2)$$

Resonance parameter:

$$m_{Y(4230)} = 4243 \pm 7 \text{ MeV},$$

$$\Gamma_{Y(4230)} = 16 \pm 31 \text{ MeV}.$$

By introducing ψ(4S), the branching ratio B(ψ(4S) →ψ(2S)π⁺π⁻) resulting from meson-loop contributions overlaps with the upper limit, 3×10^{-3}, obtaining by fitting the cross section for $e^+e^-\to\psi(2S)\pi^+\pi^-$

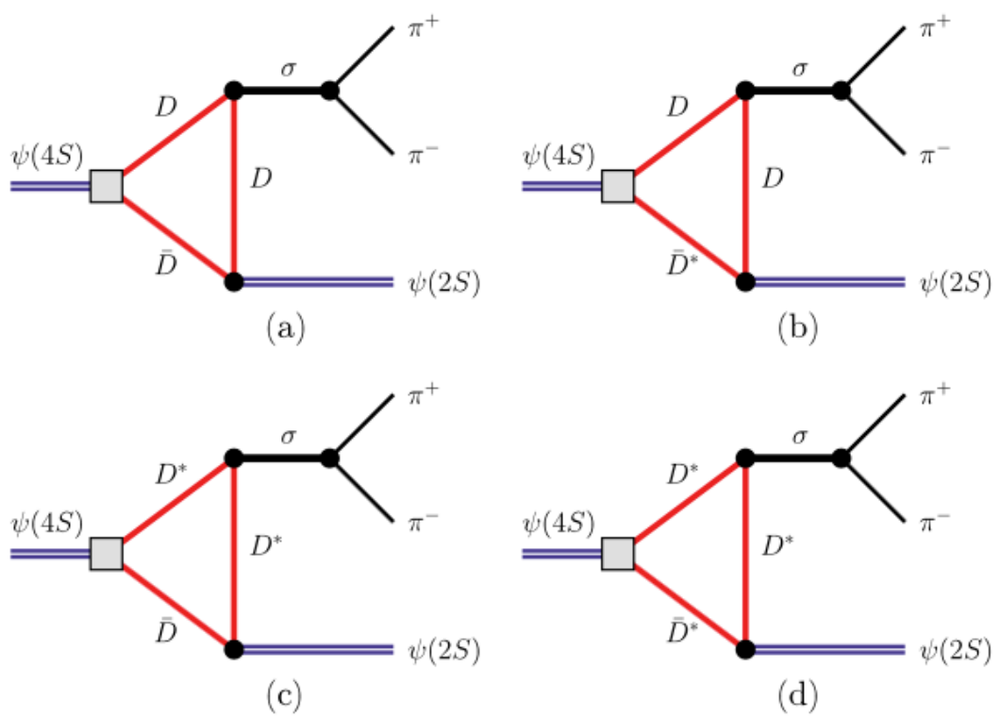


FIG. 3. Typical meson-loop contributions to $\psi(4S)\to\psi(2S)\pi^+\pi^-$, where the dipion comes from a σ meson.

Chen, X. Liu, Matsuki, PRD93, 034028 (2016)

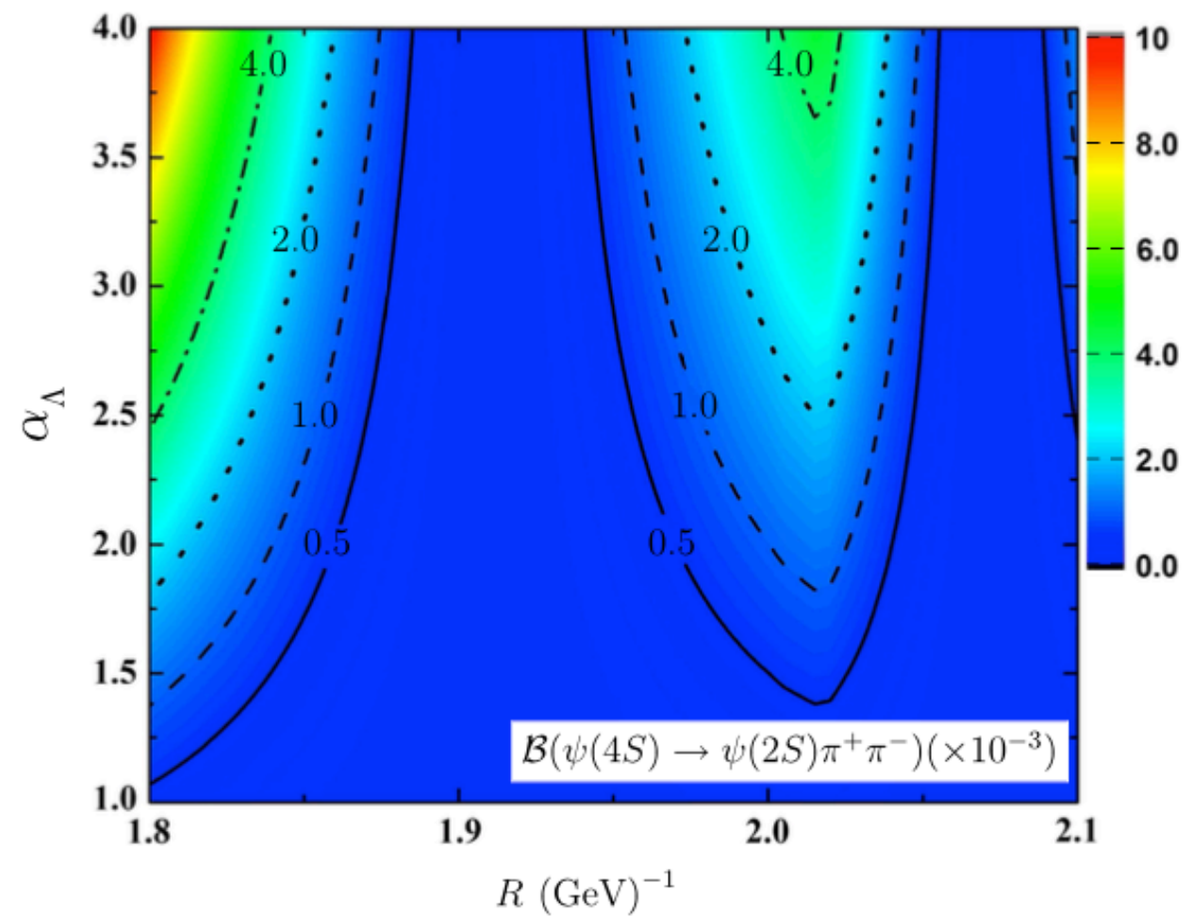


FIG. 4. The R and α_Λ dependence of the branching ratio for $\psi(4S)\to\psi(2S)\pi^+\pi^-$.

Combined fit to $e^+e^- \to \psi(2S)\pi^+\pi^-, h_c\pi^+\pi^-, \chi_{c0}\omega$

Chen, X. Liu, Matsuki
PRD93, 034028 (2016)

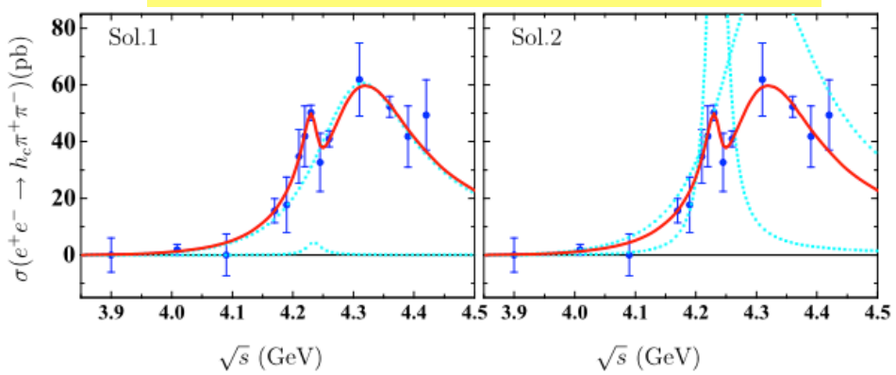


FIG. 6. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to h_c\pi^+\pi^-$ in scheme I. The cyan dashed and red solid curves are the resonance contributions and the fitting results, respectively.

TABLE II. The parameters determined by fitting the experimental data of $e^+e^- \to \psi(2S)\pi^+\pi^-, h_c\pi^+\pi^-, \chi_{c0}\omega$ simultaneously, where the experimental data of $e^+e^- \to h_c\pi^+\pi^-$ are depicted by two Breit-Wigner structures. The masses and the total decay widths are in units of MeV, while the product of the branching ratios is in units of eV.

Final State	$\psi(2S)\pi^+\pi^-$				$h_c\pi^+\pi^-$		$\chi_{c0}\omega$
	Sol. A	Sol. B	Sol. C	Sol. D	Sol. 1	Sol. 2	
$m_{Y(4230)}$				4234 ± 5			
$\Gamma_{Y(4230)}$				29 ± 14			
$\Gamma^{e^+e^-}_{Y(4230)}\mathcal{B}(\psi(4S) \to f)$	1.3 ± 0.5	0.3 ± 0.2	1.3 ± 0.5	0.3 ± 0.3	0.2 ± 0.1	7.1 ± 2.9	2.2 ± 0.6
$m_{Y(4300)}$	...	...	...	...	4294 ± 11		...
$\Gamma_{Y(4300)}$	...	...	...	...	201 ± 55		...
$\Gamma^{e^+e^-}_{Y(4300)}\mathcal{B}(Y(4300) \to f)$	...	...	...	...	14.7 ± 2.0	23.9 ± 2.4	...
ϕ_1	...	...	...	...	5.7 ± 0.8	3.7 ± 0.1	...
$m_{Y(4360)}$		4359 ± 7			...	...	...
$\Gamma_{Y(4360)}$		64 ± 11			...	...	...
$\Gamma^{e^+e^-}_{Y(4360)}\mathcal{B}(Y(4360) \to f)$	7.4 ± 1.4	5.5 ± 1.9	8.9 ± 1.0	6.6 ± 1.0	...	...	...
ϕ_2	4.2 ± 0.4	1.5 ± 0.9	4.4 ± 0.4	1.7 ± 0.6	...	...	...
$m_{Y(4660)}$		4666 ± 28			...	...	...
$\Gamma_{Y(4660)}$		90 ± 20			...	...	...
$\Gamma^{e^+e^-}_{Y(4660)}\mathcal{B}(Y(4660) \to f)$	1.9 ± 0.8	1.8 ± 0.7	6.0 ± 3.2	5.8 ± 2.3	...	...	...
ϕ_3	5.2 ± 0.7	2.2 ± 1.0	3.1 ± 0.5	0.1 ± 2.1	...	...	...
χ^2/ndf				52.2/81			

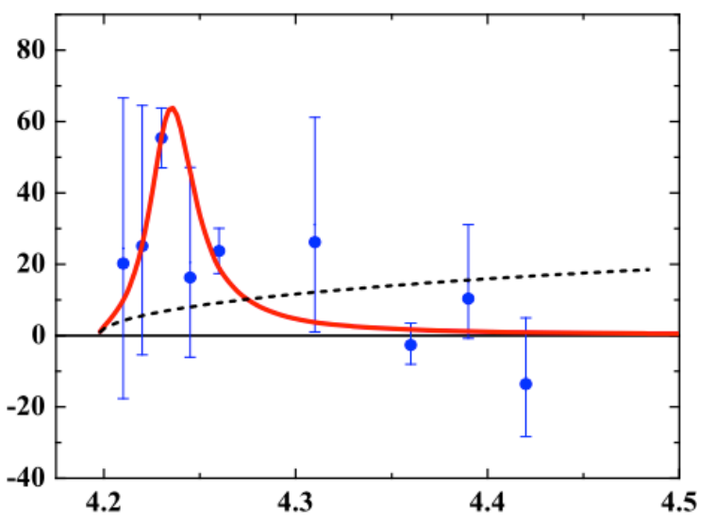


FIG. 7. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to \chi_{c0}\omega$ (solid curve) in scheme I. The dashed curve is the phase space of $e^+e^- \to \chi_{c0}\omega$.

Resonance parameter:

$$m_{Y(4230)} = 4234 \pm 5 \text{ MeV},$$
$$\Gamma_{Y(4230)} = 29 \pm 14 \text{ MeV}.$$

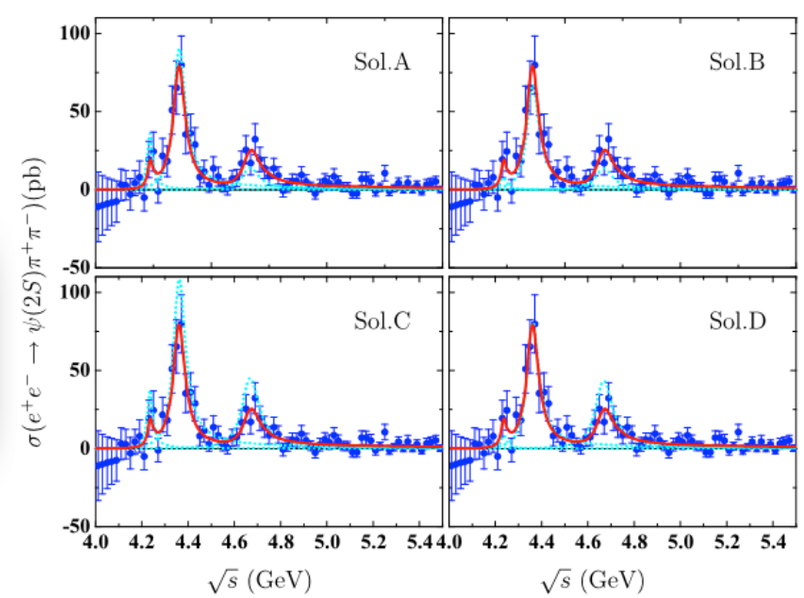
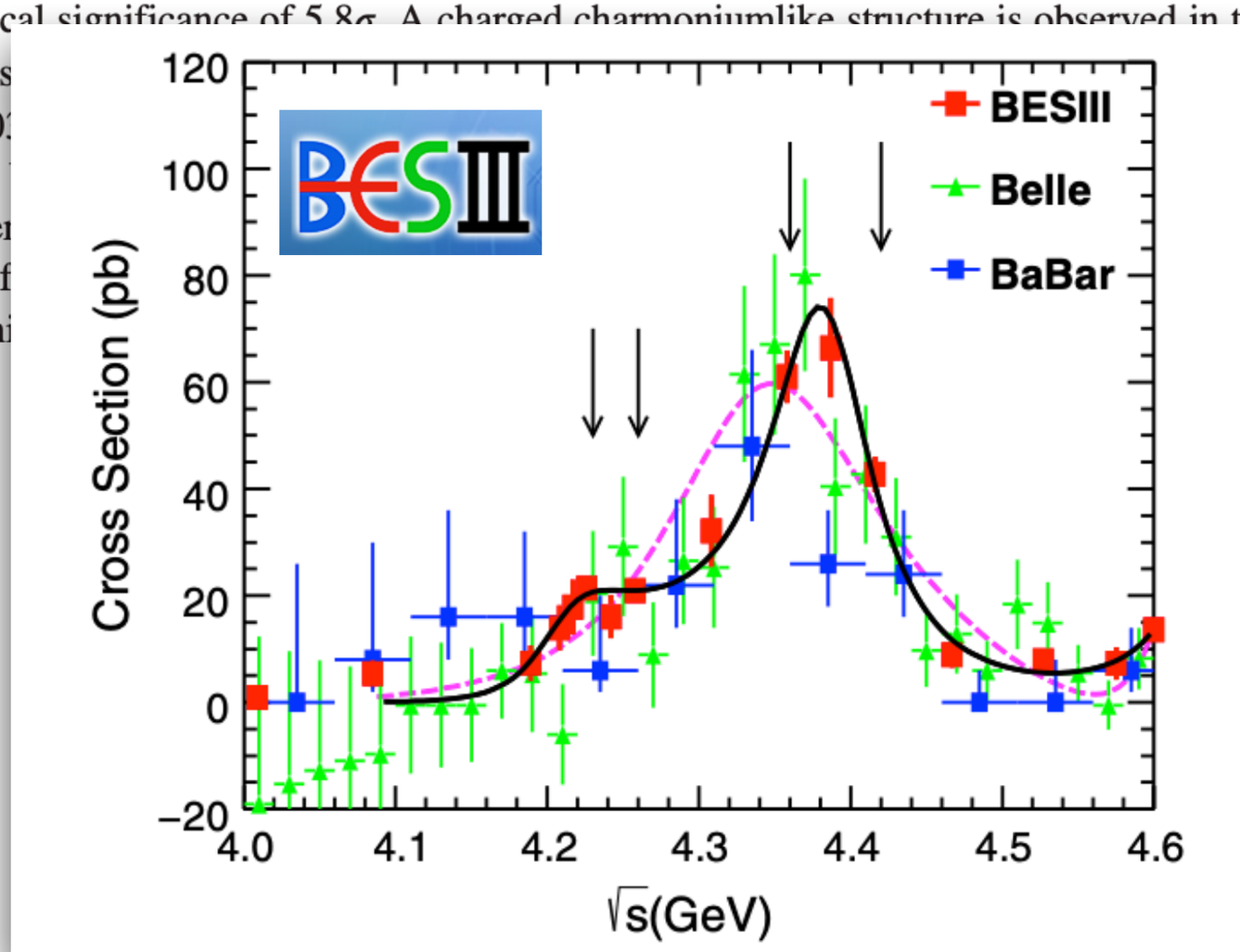


FIG. 5. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to \psi(2S)\pi^+\pi^-$ in scheme I. The cyan dashed and red solid curves are the resonance contributions and the fitting results, respectively.

PHYSICAL REVIEW D **96,** 032004 (2017)

Measurement of $e^+e^- \to \pi^+\pi^-\psi(3686)$ from 4.008 to 4.600 GeV and observation of a charged structure in the $\pi^\pm\psi(3686)$ mass spectrum

We study the process $e^+e^- \to \pi^+\pi^-\psi(3686)$ using 5.1 fb^{-1} of data collected at 16 center-of-mass energy ($\sqrt{s}$) points from 4.008 to 4.600 GeV by the BESIII detector operating at the BEPCII collider. The measured Born cross sections for $e^+e^- \to \pi^+\pi^-\psi(3686)$ are consistent with previous results, but with much improved precision. A fit to the cross section shows contributions from two structures: the first has $M = 4209.5 \pm 7.4 \pm 1.4\ \mathrm{MeV}/c^2$ and $\Gamma = 80.1 \pm 24.6 \pm 2.9$ MeV, and the second has $M = 4383.8 \pm 4.2 \pm 0.8\ \mathrm{MeV}/c^2$ and $\Gamma = 84.2 \pm 12.5 \pm 2.1$ MeV, where the first errors are statistical and the second systematic. The lower-mass resonance is observed in the process $e^+e^- \to \pi^+\pi^-\psi(3686)$ for the first time with a statistical significance of 5.8σ. A charged charmoniumlike structure is observed in the $\pi^\pm\psi(3686)$ invariant mass nction yields a mass $M = 40$ till unresolved discrepancies wide range for different kiner data has been found, and a f uired to better understand thi

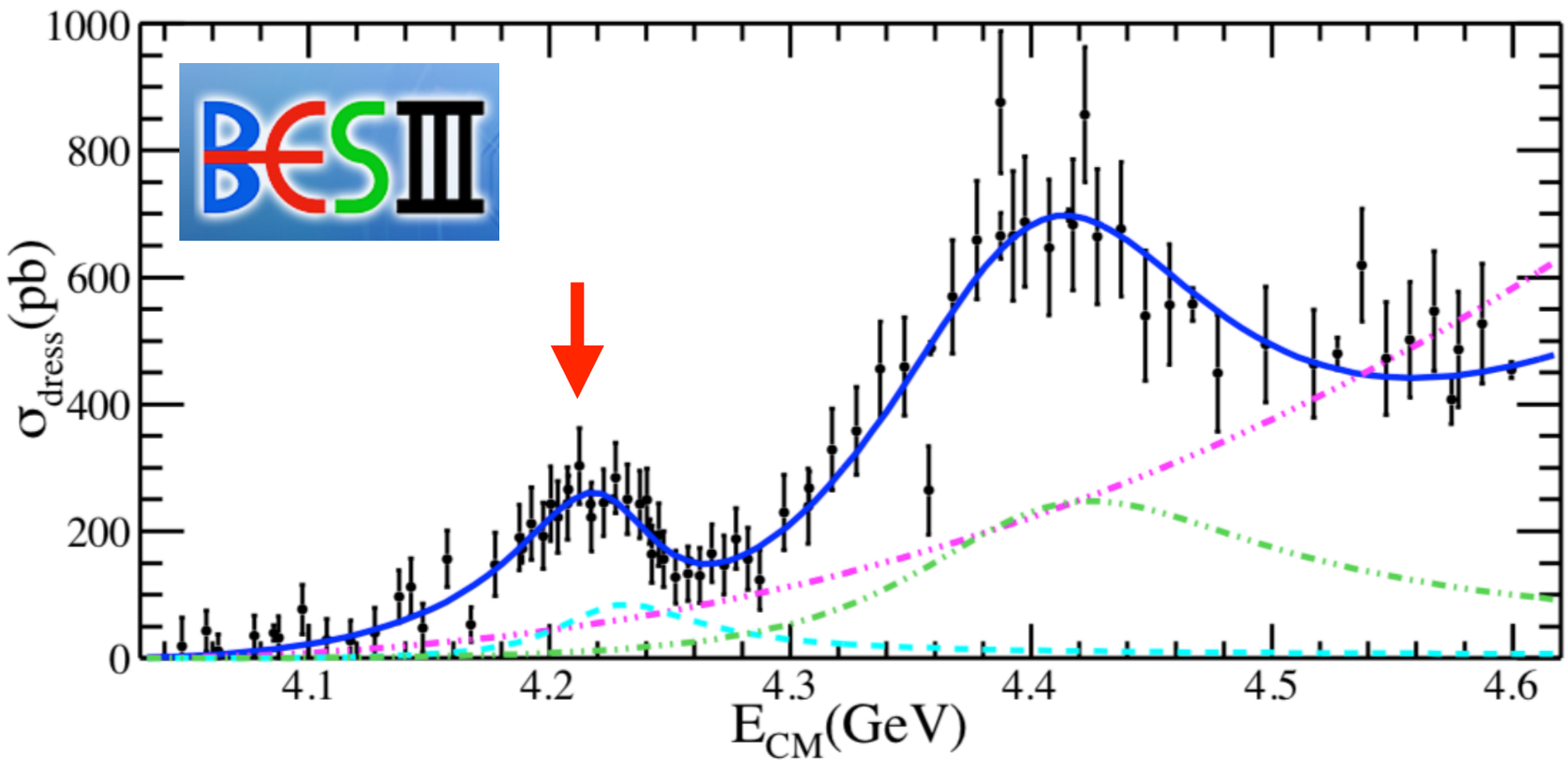


If Y(4220) narrow is ψ(4S), Y(4220) should be observed in open-charm decay channel!

Evidence of a resonant structure in the $e^+e^- \to \pi^+ D^0 D^{*-}$ cross section between 4.05 and 4.60 GeV

PRL 122 (2019)102002

$$M = 4228.6 \pm 4.1 \pm 5.9 MeV$$
$$\Gamma = 77.1 \pm 6.8 \pm 6.9 MeV$$



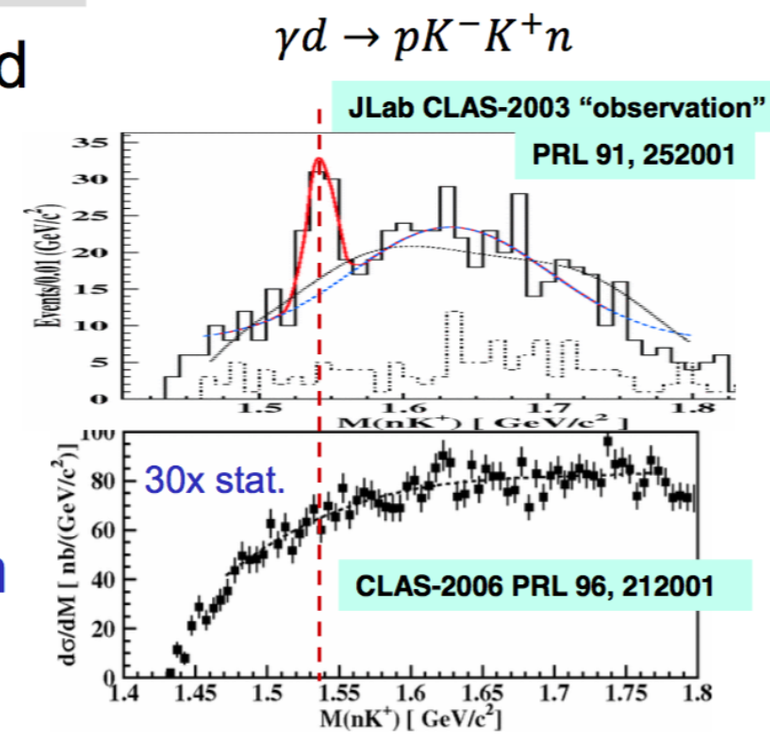
维尔切克的感叹（2005年目睹五夸克态的兴衰）：

对于五夸克态事件折射出我们对 QCD的了解还是多么的贫乏

Curious history of pentaquark Θ^+ search

See summary by [K. H. Hicks, Eur. Phys. J. H37 (2012) 1]

- No convincing states 50 years after Gell-mann paper proposing $qqqq\bar{q}$ states
- Prediction: $\Theta^+(uudd\bar{s})$ could exist with m ≈1530 MeV
- In 2003,10 experiments reported seeing narrow peaks of K^0p or K^+n, all >4 σ
- High statistics repeats from JLab showed the original claims were fluctuation
- It was merely a case of "bump hunting"



Borrowed from Li-Ming Zhang's talk at PhiPsi2015

The observation of pentaquark Pc(4380) and Pc(4450)

Selected for a Viewpoint in *Physics*

PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

R. Aaij *et al.*[*]
(LHCb Collaboration)

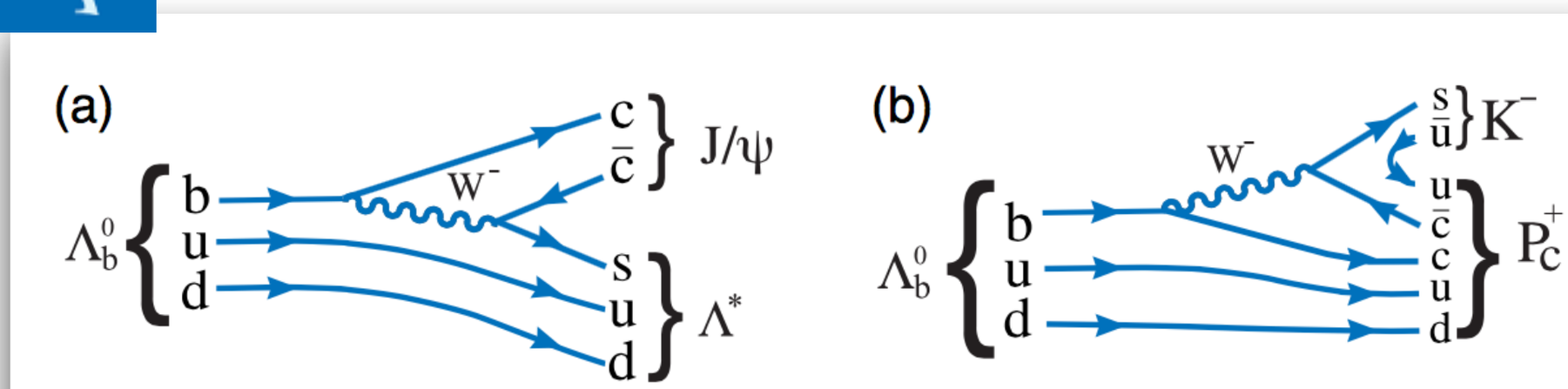
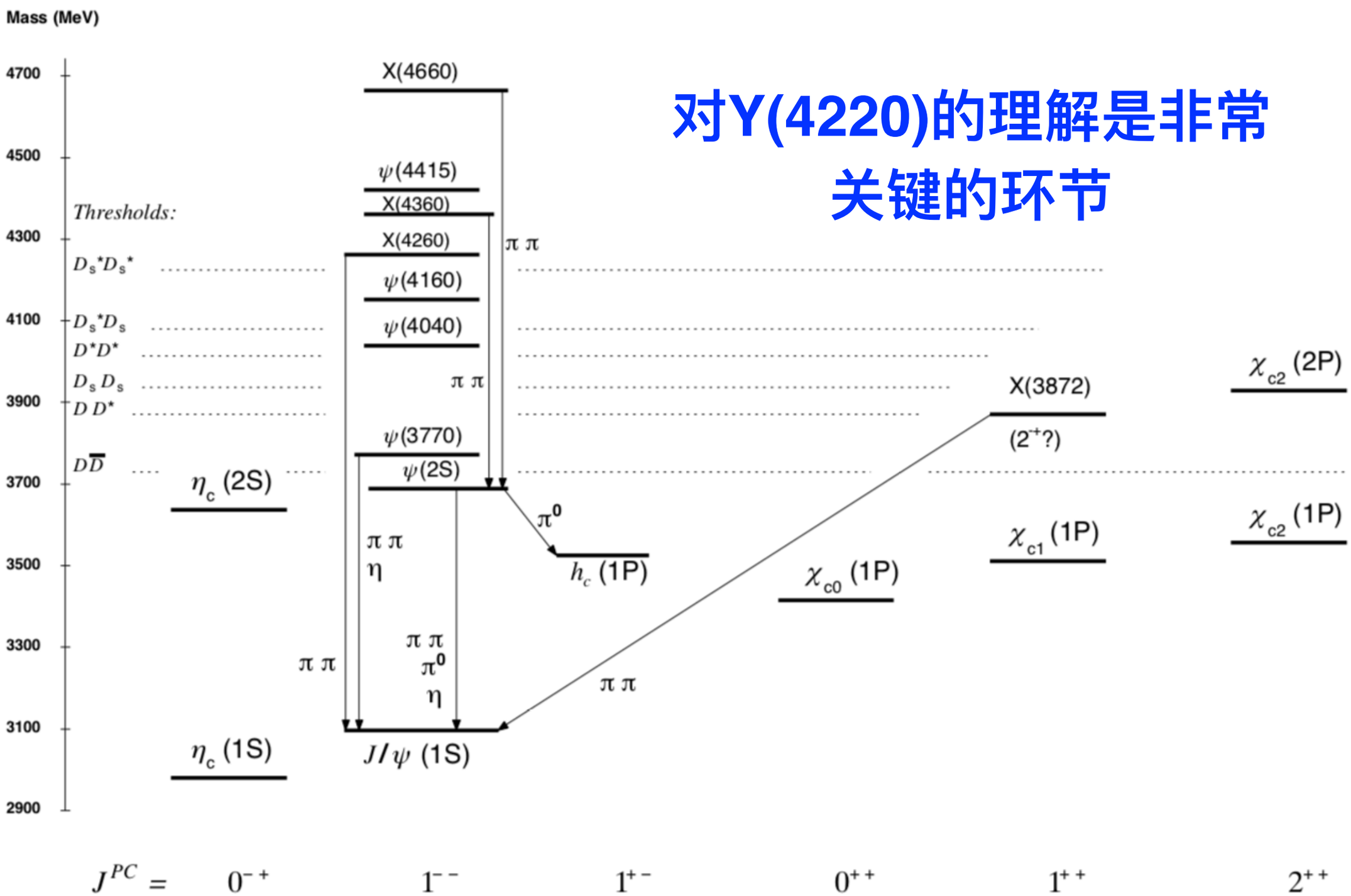


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

对于粲偶素的理解也折射出我们对 QCD的了解还是多么的贫乏



对Y(4220)的理解是非常关键的环节

Constructing J/ψ family with updated data of charmoniumlike Y states

Jun-Zhang Wang,[1,2,*] Dian-Yong Chen,[3,†] Xiang Liu,[1,2,‡] and Takayuki Matsuki[4,5,§]

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[2]*Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China*
[3]*School of Physics, Southeast University, Nanjing 211189, China*
[4]*Tokyo Kasei University, 1-18-1 Kaga, Itabashi, Tokyo 173-8602, Japan*
[5]*Theoretical Research Division, Nishina Center, RIKEN, Wako, Saitama 351-0198, Japan*

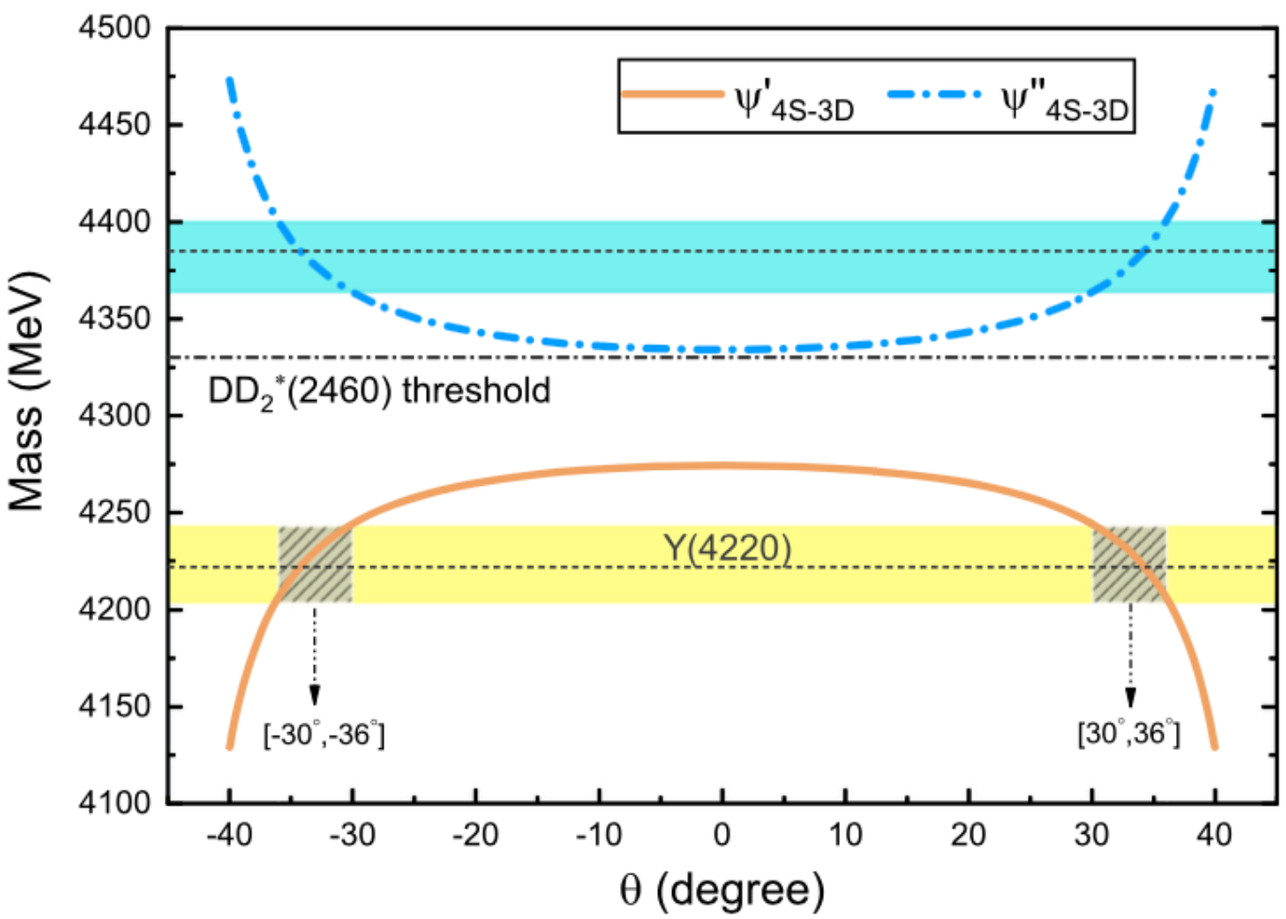
(Received 20 March 2019; published 5 June 2019)

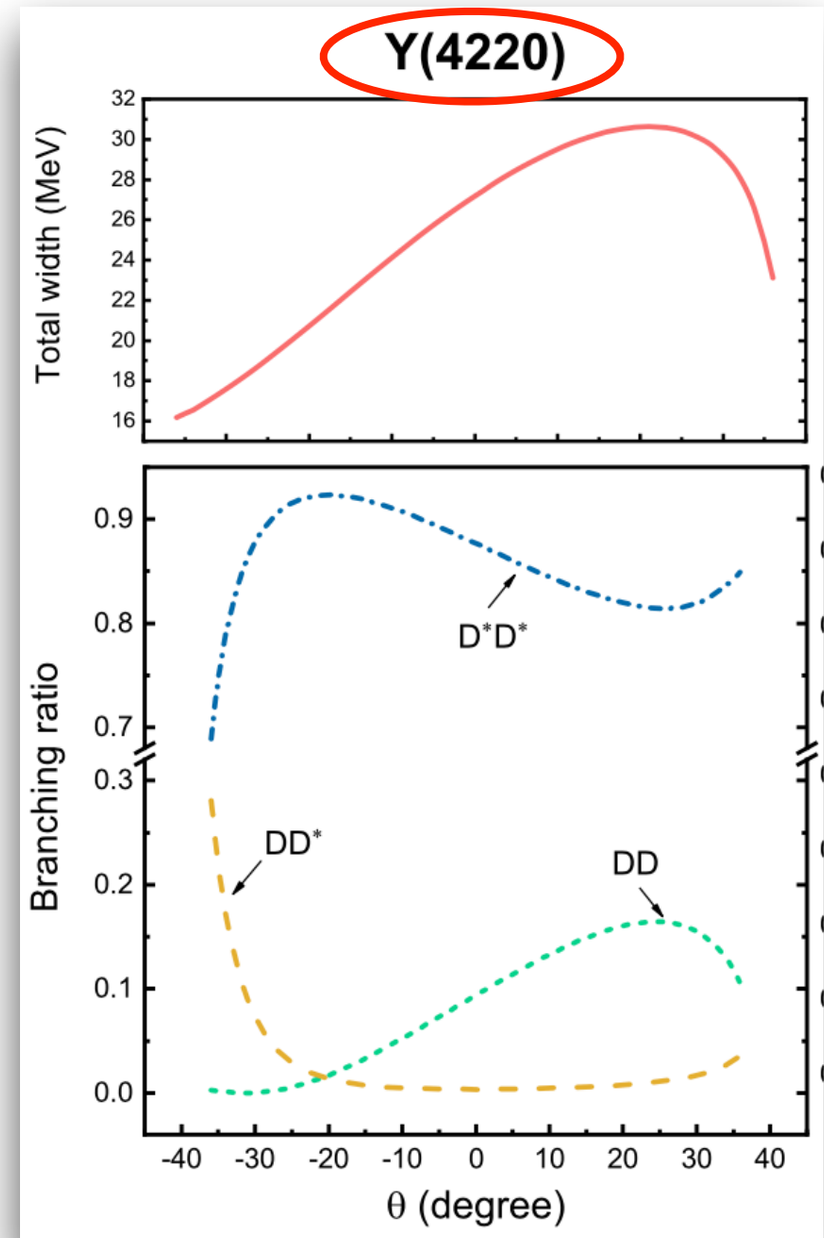
Based on the updated data of charmoniumlike state $Y(4220)$ reported in the hidden-charm channels of the e^+e^- annihilation, we propose a $4S$-$3D$ mixing scheme to categorize $Y(4220)$ into the J/ψ family. We find that the present experimental data can support this charmonium assignment to $Y(4220)$. Thus, $Y(4220)$ plays a role of a scaling point in constructing higher charmonia above 4 GeV. To further test this scenario, we provide more abundant information on the decay properties of $Y(4220)$, and predict its charmonium partner $\psi(4380)$, whose evidence is found by analyzing the $e^+e^- \to \psi(3686)\pi^+\pi^-$ data from BESIII. If $Y(4220)$ is indeed a charmonium, we must face how to settle the established charmonium $\psi(4415)$ in the J/ψ family. In this work, we may introduce a $5S$-$4D$ mixing scheme, and obtain the information of the resonance parameters and partial open-charm decay widths of $\psi(4415)$, which do not contradict the present experimental data. Additionally, we predict a charmonium partner $\psi(4500)$ of $\psi(4415)$, which can be accessible at future experiments, especially, BESIII and BelleII. The studies presented in this work provide new insights to establish the higher charmonium spectrum.

DOI: 10.1103/PhysRevD.99.114003

Introducing 4S-3D mixing scheme

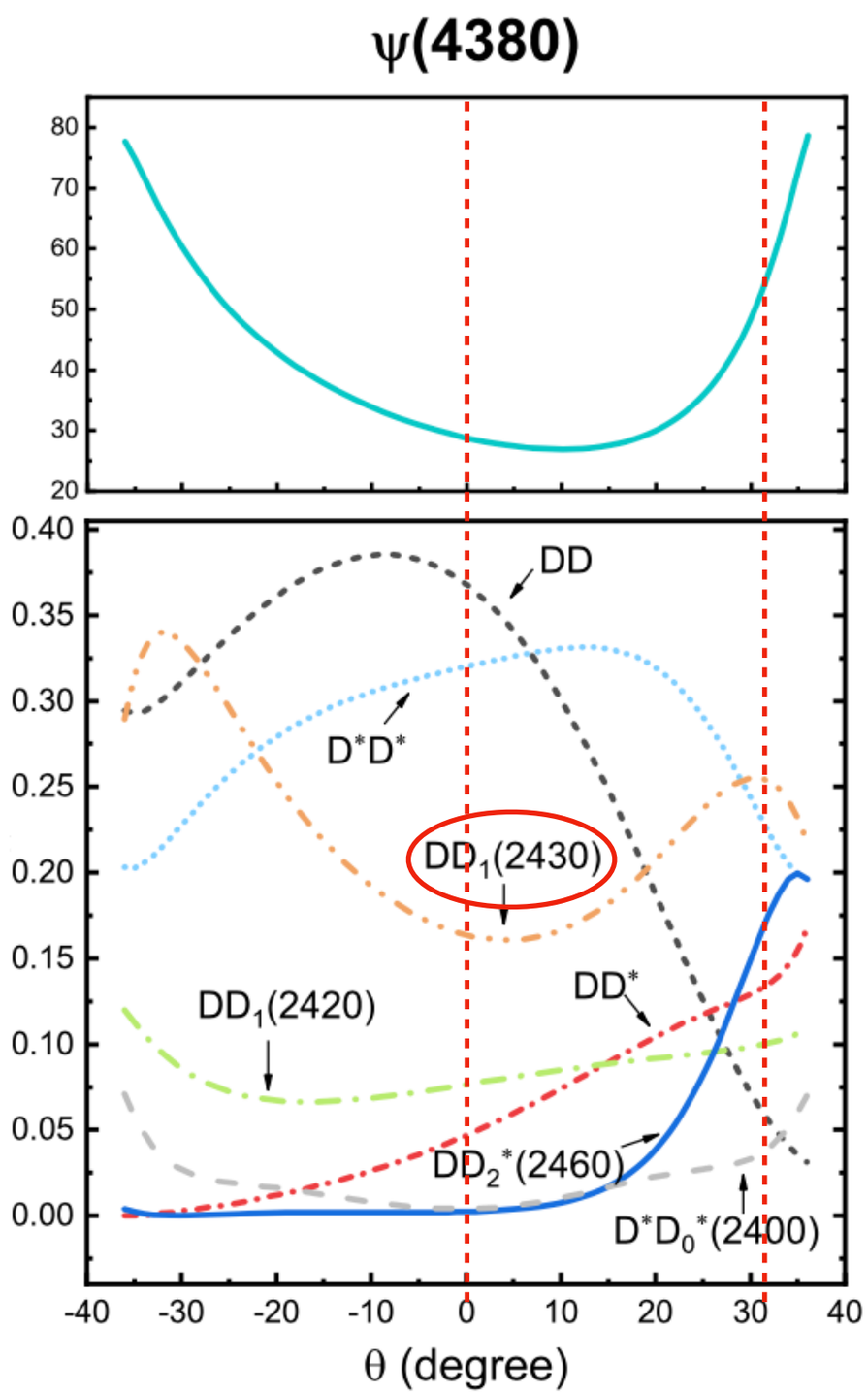
$$\begin{pmatrix} |\psi'_{4S-3D}\rangle \\ |\psi''_{4S-3D}\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |4^3S_1\rangle \\ |3^3D_1\rangle \end{pmatrix}$$



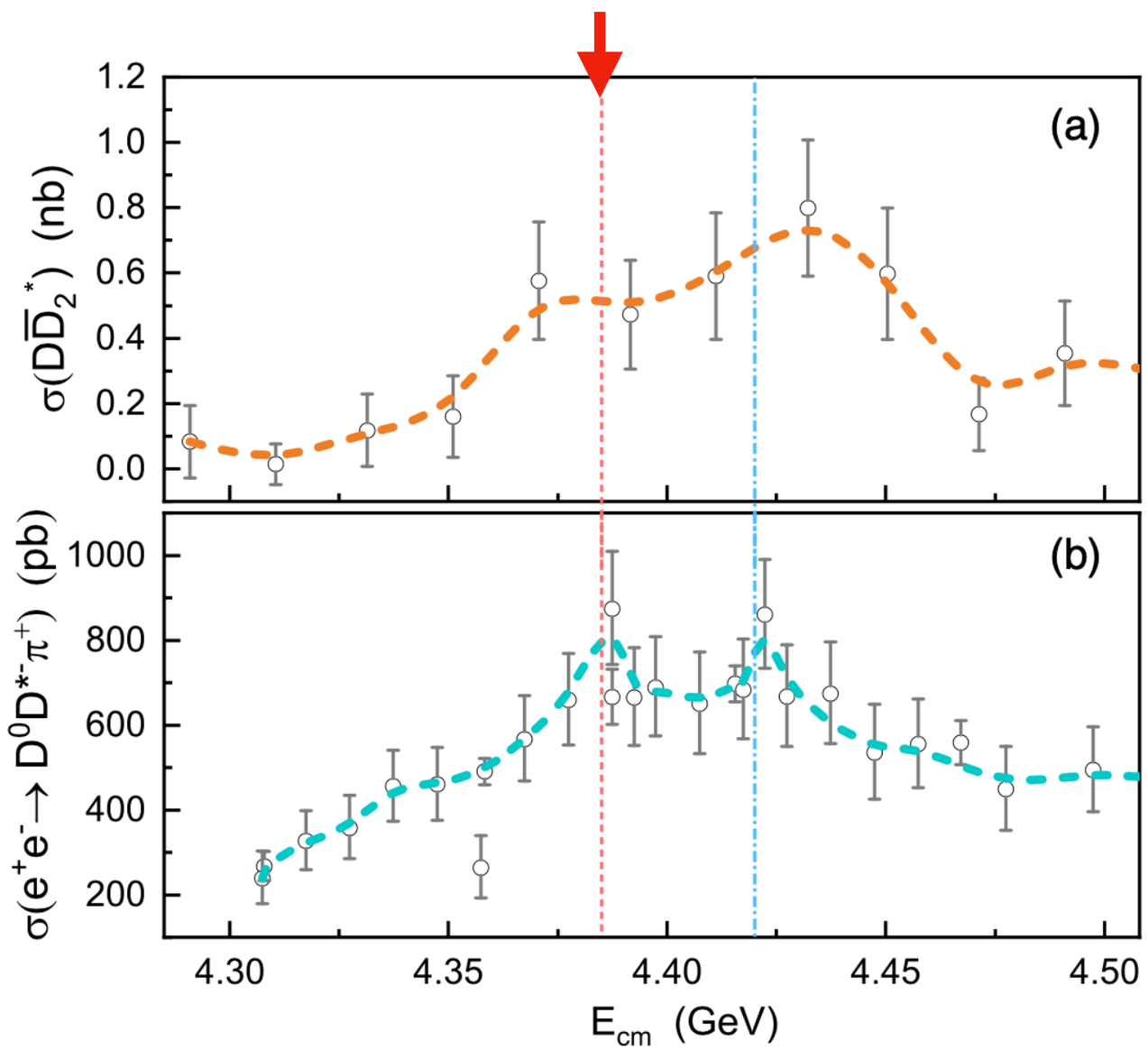


Our calculation supports this scenario

Predicting ψ(4380) the partner of Y(4220)

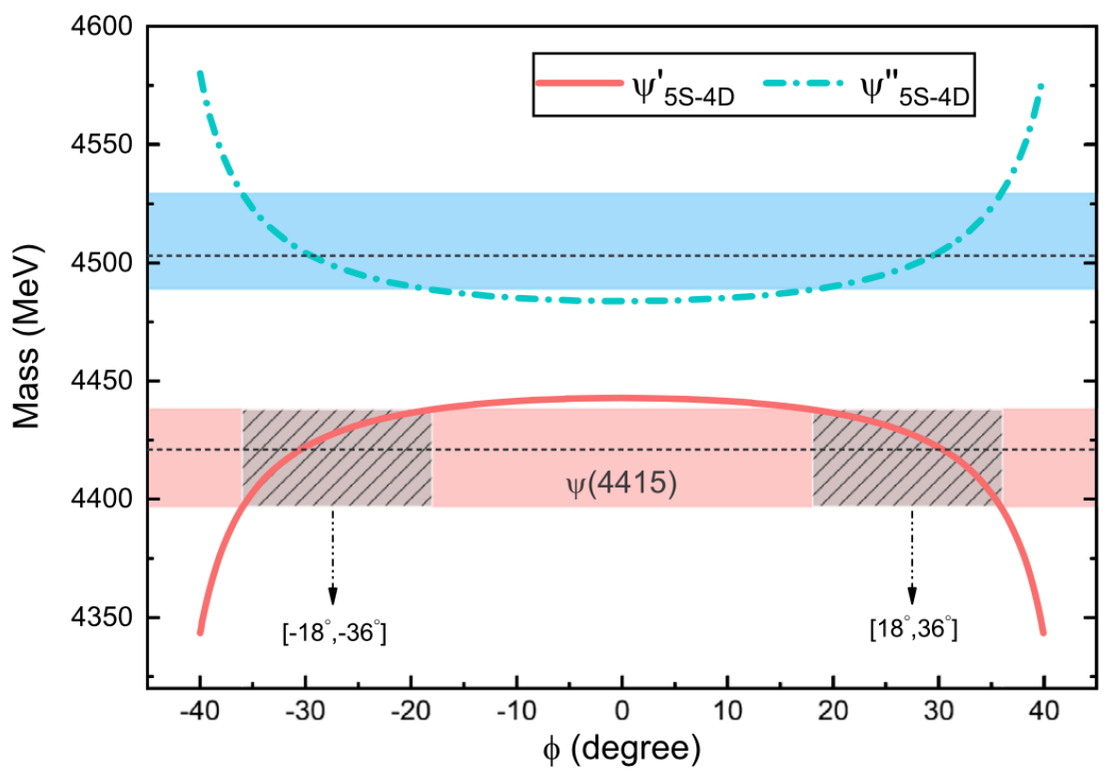


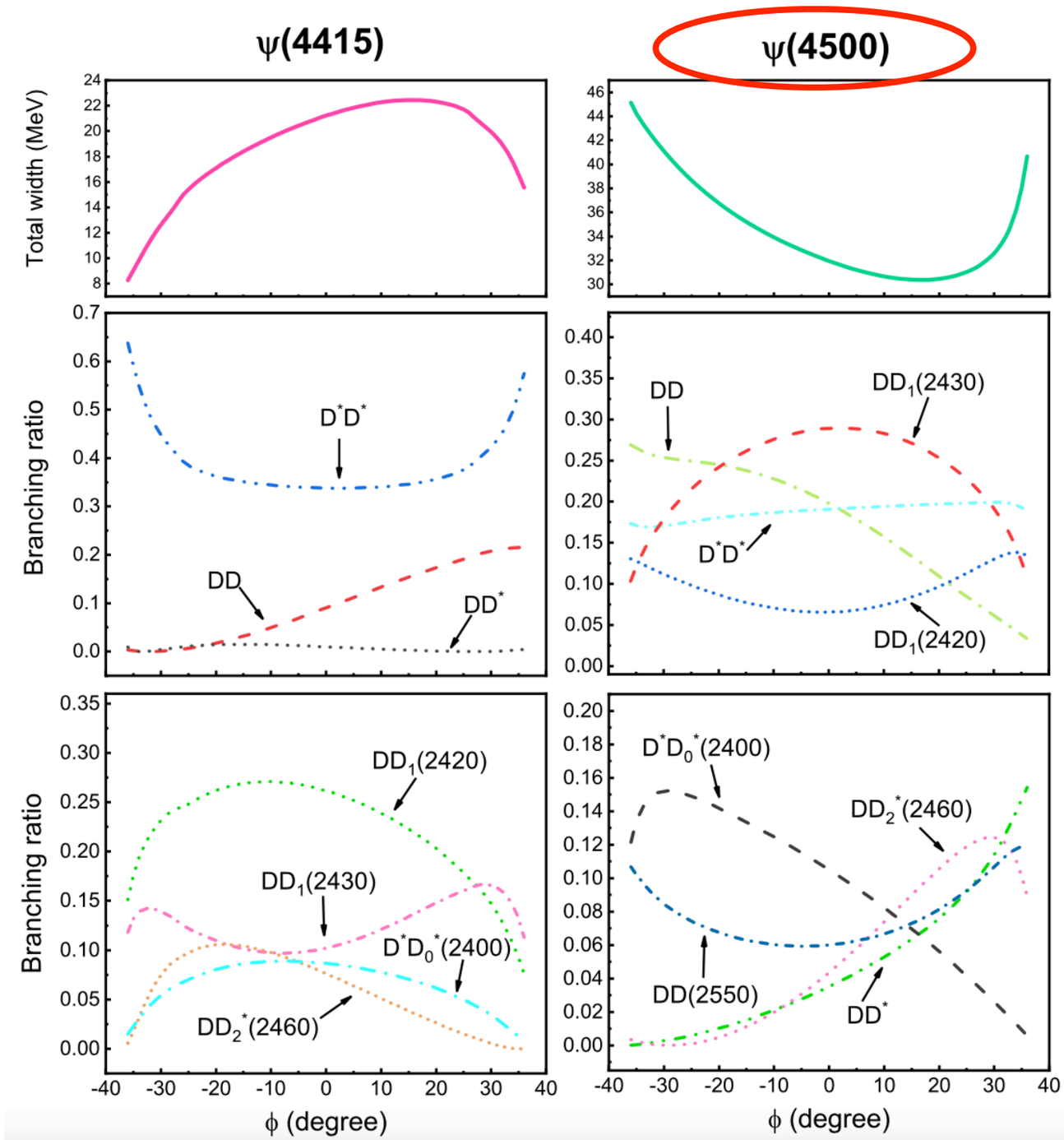
- The total width of ψ(4380) has a significant enhancement
- There exists sizable enhancement of ψ(4380)→DD_2(2460)



Proposing 5S-4D mixing scheme

$$\begin{pmatrix} |\psi'_{5S-4D}\rangle \\ |\psi''_{5S-4D}\rangle \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} |5^3S_1\rangle \\ |4^3D_1\rangle \end{pmatrix},$$





arXiv:2001.00175

Are the Y states around 4.6 GeV from e^+e^- annihilation higher charmonia?

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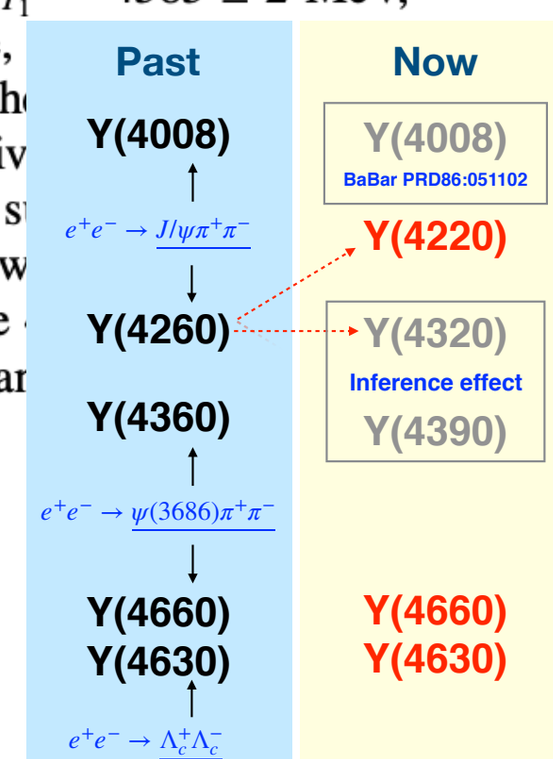
(Dated: January 3, 2020)

In this work, we present the mass spectrum of higher charomona around and above 4.6 GeV by adopting the unquenched potential model. We perform a combined fit to the updated experimental data of $e^+e^- \to \psi(2S)\pi^+\pi^-$ and $e^+e^- \to \Lambda_c\bar{\Lambda}_c$. To understand the "platform" structure observed in the range of 4.57 ~ 4.60 GeV existing in the $\Lambda_c\bar{\Lambda}_c$ invariant mass spectrum of $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ of BESIII, we introduce two resonances in this combined fit to the $e^+e^- \to \psi(2S)\pi^+\pi^-$ and $e^+e^- \to \Lambda_c\bar{\Lambda}_c$, which have resonance parameters, $m_{Y_1} = 4585 \pm 2$ MeV, $\Gamma_{Y_1} = 29.8 \pm 8.0$ MeV, $m_{Y_2} = 4676 \pm 7$ MeV, and $\Gamma_{Y_2} = 85.7 \pm 15.0$ MeV. Furthermore, theoretical results, we indicate that the two charmonium-like Y states can be due to two high are mixtures of $6S$ and $5D$ $c\bar{c}$ states. Their two-body open-charm decay behaviors are giv framework, our analysis of the data of $e^+e^- \to D_s^+ D_{s1}(2536)^-$ recently released by Belle s these two higher charmonia around 4.6 GeV. Additionally, we predict the masses and tw decays of six higher charmonia $\psi(nS)$ and $\psi(mD)$ with $n = 7, 8, 9$ and $m = 6, 7, 8$ above these higher charmonia will be an interesting issue for the running BESIII and BelleII, ar Super Tau-Charm Factory discussed in China.



An unquenched calculation of mass spectrum of charmonium

TABLE I: The charmonium mass spectrum with different μ values. Here, we take $\mu = 0.11, 0.12, 0.13, 0.14, 0.15$ to show our results. The results in Ref. [15] are also presented for comparison. All results are in units of MeV.

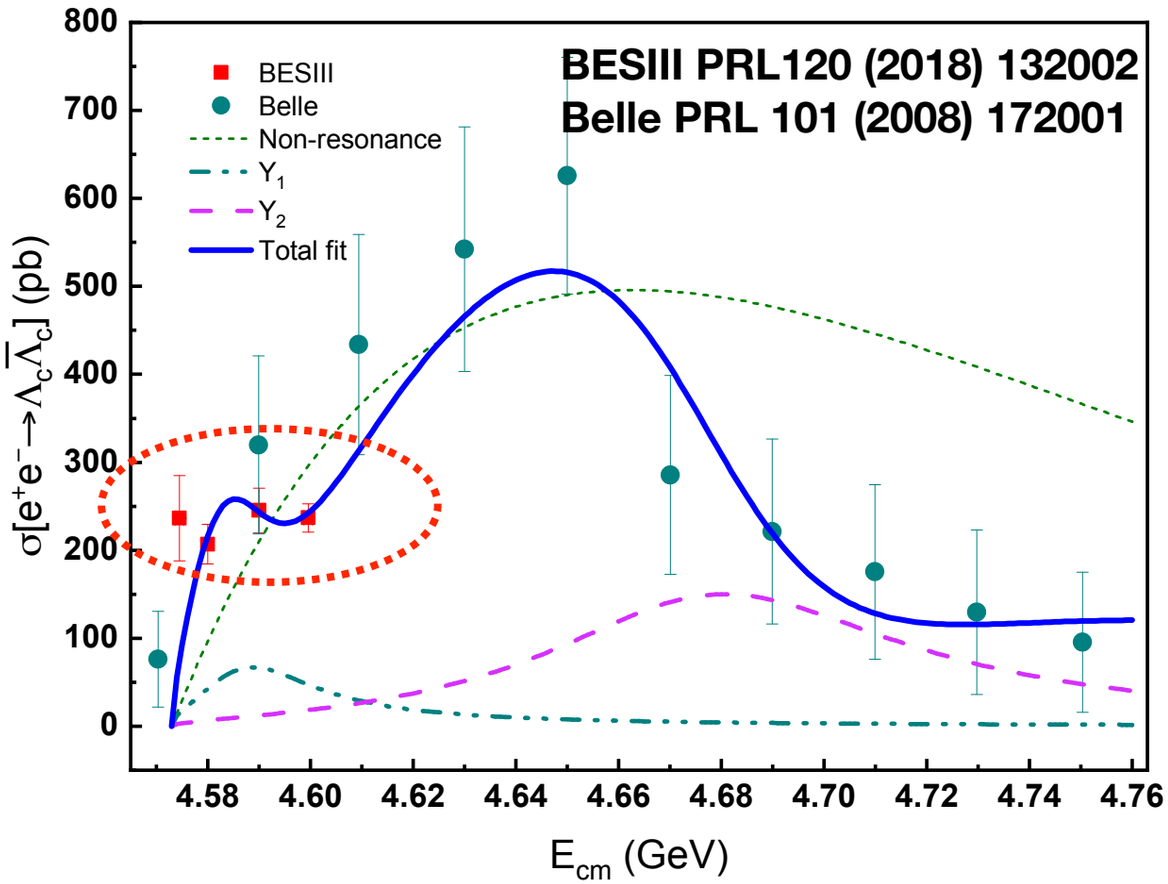
	μ=0.11	μ=0.12	μ=0.13	μ=0.14	μ=0.15	Ref. [15]	Expt. [32]
$\eta_c(1^1S_0)$	2984	2984	2984	2984	2984	2981	2983.9 ± 0.5
$\psi(1^3S_1)$	3096	3096	3096	3097	3098	3096	3096.9 ± 0.5
$\chi_{c0}(1^3P_0)$	3449	3452	3455	3457	3462	3464	3414.71 ± 0.30
$\chi_{c1}(1^3P_1)$	3515	3517	3520	3523	3528	3530	3510.67 ± 0.05
$h_{c1}(1^1P_1)$	3523	3526	3528	3531	3536	3538	3525.38 ± 0.11
$\chi_{c2}(1^3P_2)$	3555	3557	3560	3563	3568	3571	3556.17 ± 0.07
$\eta_c(2^1S_0)$	3626	3669	3631	3634	3638	3642	3637.6 ± 1.2
$\psi(2^3S_1)$	3667	3669	3672	3674	3679	3683	3686.097 ± 0.006
$\psi(1^3D_1)$	3808	3811	3818	3818	3824	3830	3778.1 ± 1.2
$\psi_2(1^3D_2)$	3827	3830	3833	3836	3842	3848	3822.2 ± 1.2
$\psi_3(1^3D_3)$	3838	3841	3844	3847	3853	3859	3842.71 ± 0.16 ± 0.12 [33]
$\chi_{c2}(1^3P_2)$	3937	3938	3939	3940	3944	3952	3927.2 ± 2.6
$\psi(3^3S_1)$	4026	4025	4025	4024	4027	4035	4039 ± 1
$\psi(2^3D_1)$	4115	4114	4113	4112	4115	4125	4159 ± 20
$\psi(4^3S_1)$	4286	4279	4272	4264	4262	4274	4230 ± 8
$\psi(3^3D_1)$	4348	4340	4333	4324	4321	4334	···
$\psi(5^3S_1)$	4484	4470	4454	4437	4428	4443	4421 ± 4
$\psi(4^3D_1)$	4530	4514	4497	4479	4468	4484	···
$\psi(6^3S_1)$	4640	4615	4589	4562	4542	···	···
$\psi(5^3D_1)$	4674	4648	4620	4591	4570	···	···
$\psi(7^3S_1)$	4762	4726	4688	4649	4618		
$\psi(6^3D_1)$	4788	4750	4711	4669	4636		
χ^2/n	30.1	25.2	21.8	24.4	22.0		

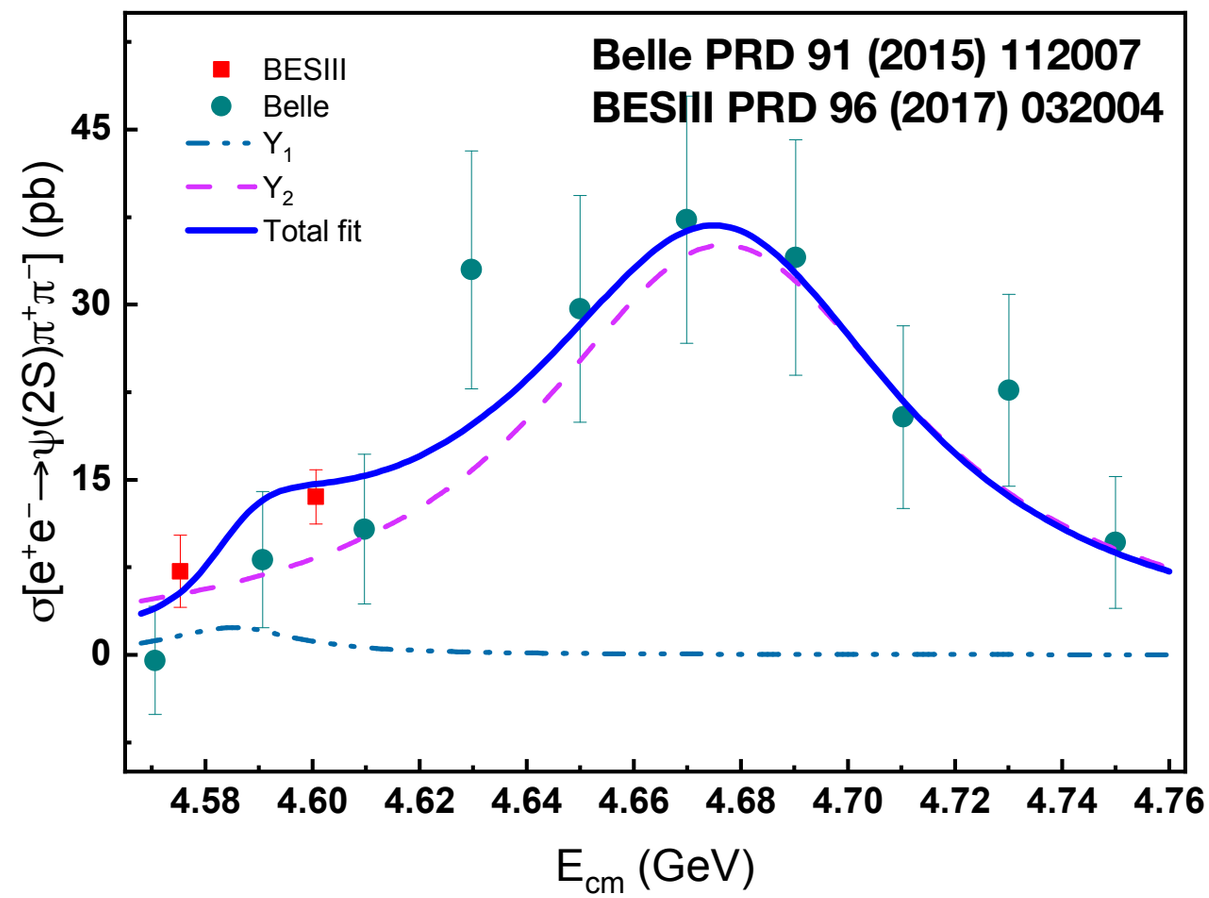
The screened confining potential

$$S(r) = \frac{b(1 - e^{-\mu r})}{\mu} + c$$

Hints from experimental data

Wang, Qian, X. Liu, Matsuki, arXiv:2001.00175





Two structures?

$$\mathcal{M}^{\rm Total}_{\psi(2S)\pi^+\pi^-} = \mathcal{M}_R(Y_1) + e^{i\theta}\mathcal{M}_R(Y_2),$$
$$\mathcal{M}^{\rm Total}_{\Lambda_c\bar{\Lambda}_c} = \mathcal{M}_{NoR} + e^{i\phi_1}\mathcal{M}'_R(Y_1) + e^{i\phi_2}\mathcal{M}'_R(Y_2),$$

In our scheme, the resonance parameters of two charmonium-like structures Y_1 and Y_2 are fitted to be

$$m_{Y_1} = 4585 \pm 2\,\text{MeV}, \qquad \Gamma_{Y_1} = 29.8 \pm 8.0\,\text{MeV},$$
$$m_{Y_2} = 4676 \pm 7\,\text{MeV}, \qquad \Gamma_{Y_2} = 85.7 \pm 15.0\,\text{MeV}, \quad (18)$$

6S and 5D mixing scheme for these Y states around 4.6 GeV

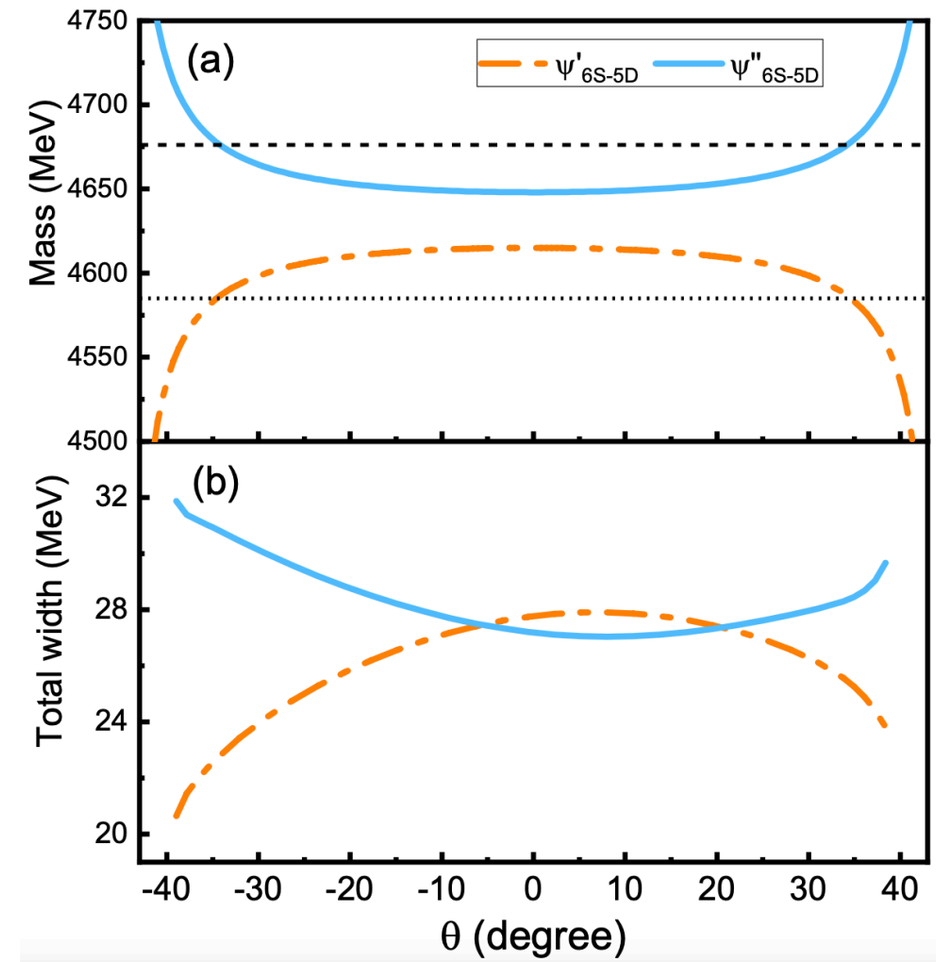
we introduce

$$\begin{pmatrix} |\psi'_{6S-5D}\rangle \\ |\psi''_{6S-5D}\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |6^3S_1\rangle \\ |5^3D_1\rangle \end{pmatrix}. \quad (19)$$

Here, θ denotes the mixing angle, and the mass eigenvalues of ψ'_{6S-5D} and ψ''_{6S-5D} are determined by the masses of two basis vectors m_{6S}, m_{5D}, and the mixing angle θ, i.e.,

$$m^2_{\psi'_{6S-5D}} = \frac{1}{2}\left(m^2_{6S} + m^2_{5D} - \sqrt{(m^2_{5D} - m^2_{6S})^2 \sec^2 2\theta}\right), \quad (20)$$

$$m^2_{\psi''_{6S-5D}} = \frac{1}{2}\left(m^2_{6S} + m^2_{5D} + \sqrt{(m^2_{5D} - m^2_{6S})^2 \sec^2 2\theta}\right), \quad (21)$$

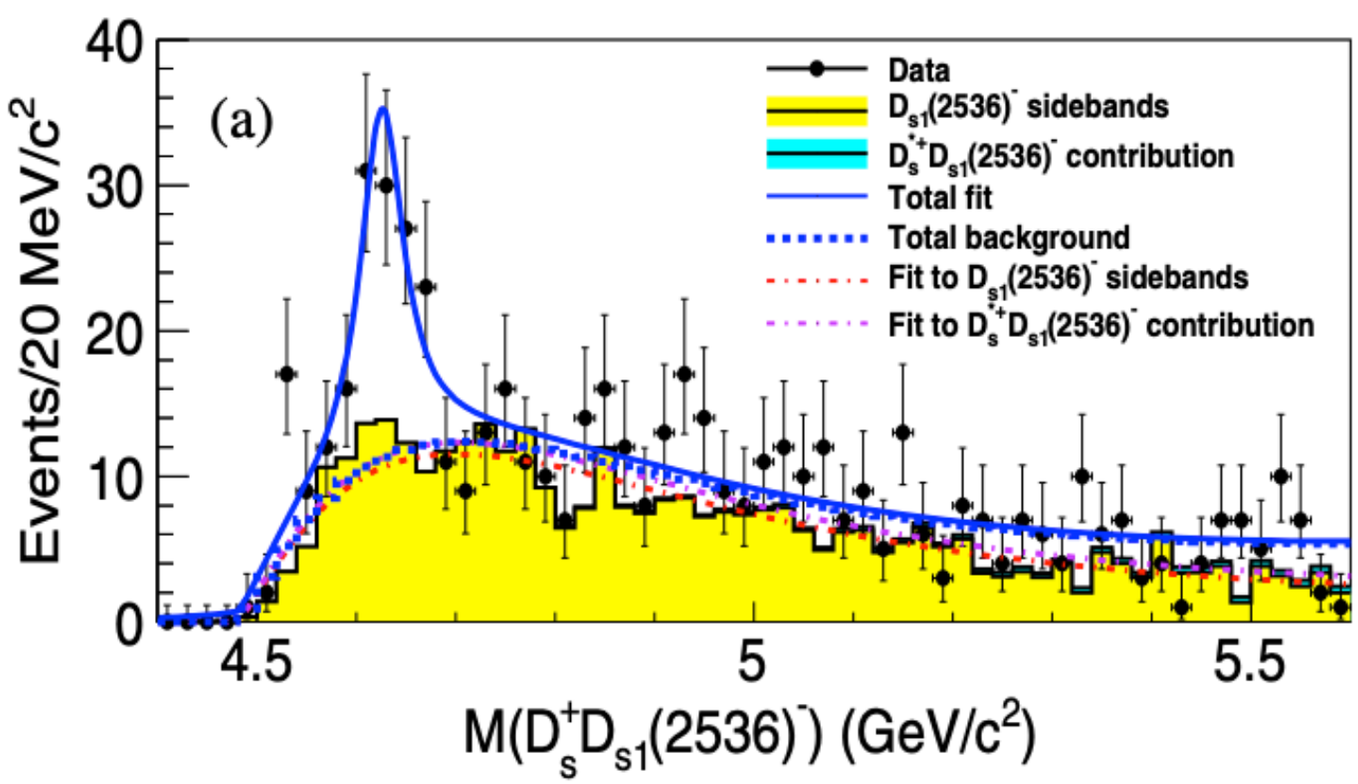


	$\theta = -34°(34°)$		Fit	
	M(MeV)	Γ(MeV)	M(MeV)	Γ(MeV)
ψ'_{6S-5D}	4587(4587)	23(25)	4585±2	29.8±8
ψ''_{6S-5D}	4675(4675)	31(28)	4676±7	85.7±15

Rapid Communications

Observation of a vector charmoniumlike state in $e^+e^- \to D_s^+ D_{s1}(2536)^- + \text{c.c.}$

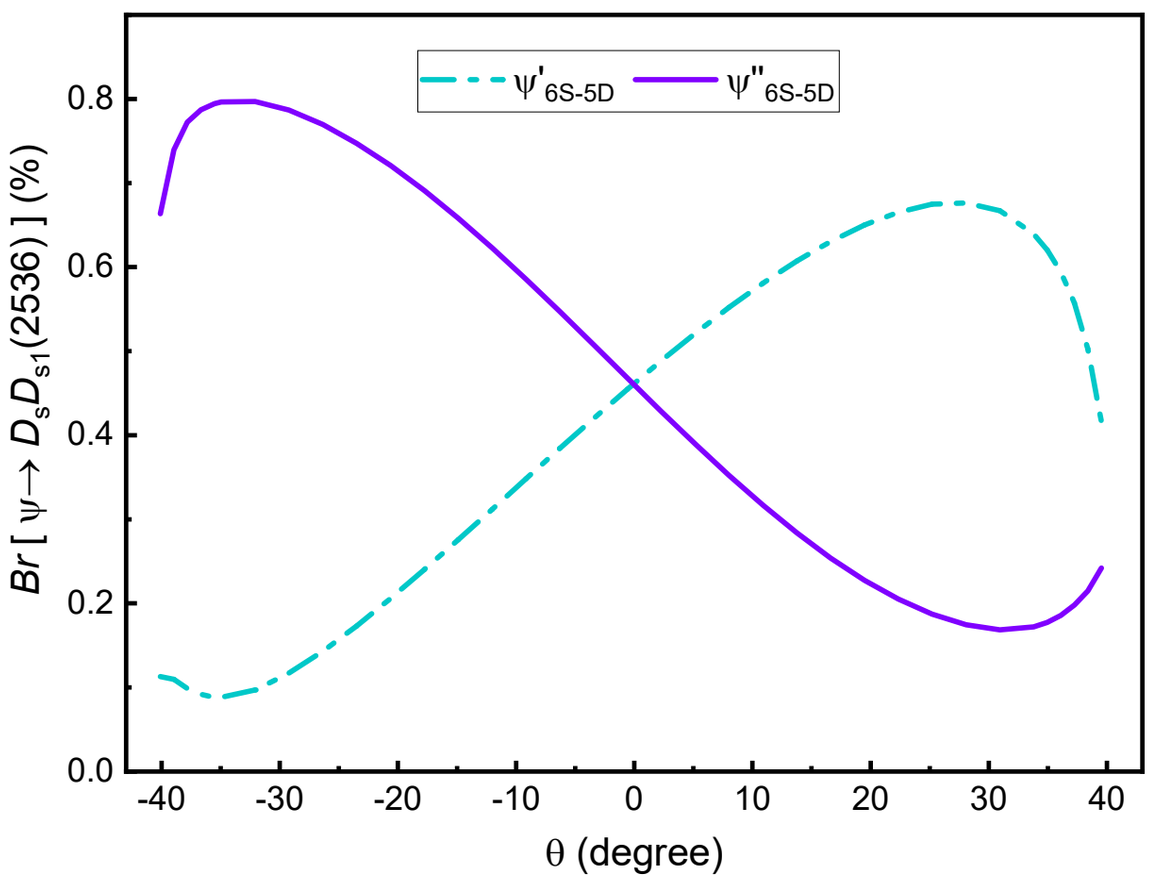
Using a data sample of 921.9 fb^{-1} collected with the Belle detector, we study the process of $e^+e^- \to D_s^+ D_{s1}(2536)^- + \text{c.c.}$ via initial-state radiation. We report the first observation of a vector charmoniumlike state decaying to $D_s^+ D_{s1}(2536)^- + \text{c.c.}$ with a significance of 5.9σ, including systematic uncertainties. The measured mass and width are $(4625.9^{+6.2}_{-6.0}(\text{stat}) \pm 0.4(\text{syst}))\,\text{MeV}/c^2$ and $(49.8^{+13.9}_{-11.5}(\text{stat}) \pm 4.0(\text{syst}))\,\text{MeV}$, respectively. The product of the $e^+e^- \to D_s^+ D_{s1}(2536)^- + \text{c.c.}$ cross section and the branching fraction of $D_{s1}(2536)^- \to \bar{D}^{*0} K^-$ is measured from the $D_s \bar{D}_{s1}(2536)$ threshold to 5.59 GeV.

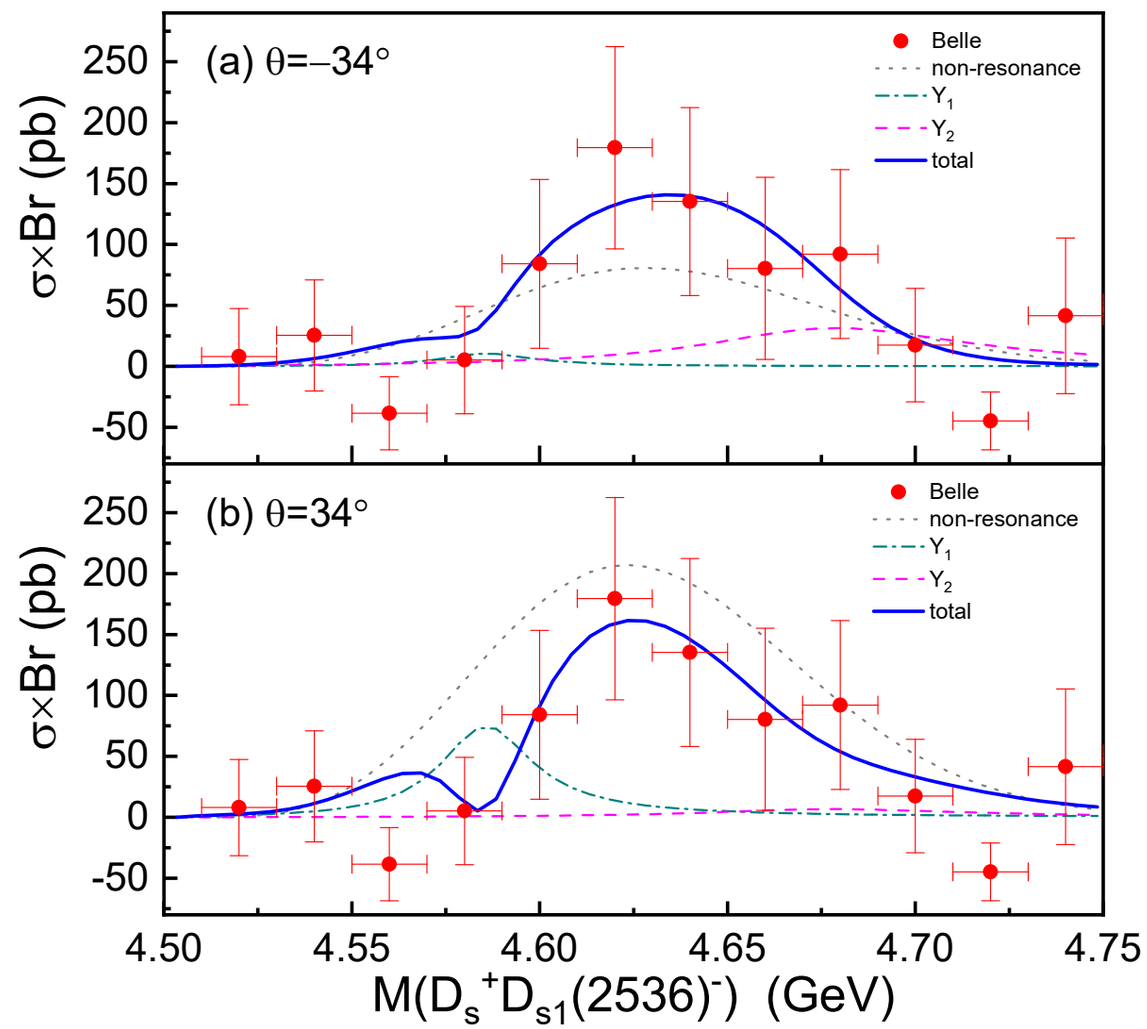


We can depict the Belle data in our framework

Wang, Qian, X. Liu, Matsuki, arXiv:2001.00175

$$e^+e^- \to D_s^+ D_{s1}(2536)^-$$





Predicting the open-charm decays of vector charmonia around and above 4.6 GeV

Wang, Qian, X. Liu, Matsuki, arXiv:2001.00175

	$\psi(6S)$	$\psi(7S)$	$\psi(8S)$	$\psi(9S)$	$\psi(5D)$	$\psi(6D)$	$\psi(7D)$	$\psi(8D)$
Mass	4615	4726	4808	4867	4648	4750	4826	4880
Total width	28.50	27.60	23.11	17.07	27.35	19.77	14.71	10.19
Channel								
DD	1.49	1.13	0.81	0.55	4.33	2.98	2.04	1.31
DD^*	0.40	0.49	0.45	0.35	0.76	0.58	0.44	0.28
D^*D^*	3.06	1.29	0.60	0.29	4.22	3.17	2.32	1.52
$DD_0^*(2400)$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$DD_1(2420)$	7.09	5.41	3.80	2.51	2.04	1.09	0.62	0.36
$DD_1(2430)$	1.85	0.92	0.53	0.32	2.76	1.04	0.50	0.29
$DD_2^*(2460)$	2.23	1.10	0.51	0.23	0.53	0.14	0.03	0.01
$D^*D_0^*(2400)$	5.89	5.27	3.94	2.69	1.66	1.01	0.63	0.38
$DD(2550)$	1.33	0.42	0.10	0.02	1.18	0.11	10^{-3}	0.02
$DD^*(2600)$	1.44	2.05	1.29	0.69	1.75	1.03	0.49	0.23
$D^*D_1(2420)$	1.14	3.34	3.60	2.92	1.72	2.01	1.66	1.18
$D^*D_1(2430)$	1.09	2.19	1.90	1.32	3.82	3.33	2.19	1.31
$D^*D_2^*(2460)$	0.02	2.01	2.70	2.23	1.50	1.35	0.86	0.50
$D^*D(2550)$	0.05	0.58	0.89	0.70	0.22	0.78	0.62	0.38
$D^*D^*(2600)$	$\cdots$	0.02	0.44	0.95	0.08	0.36	0.88	0.74
$DD(^3D_1)$	$\cdots$	10^{-5}	0.02	0.03	10^{-4}	0.02	0.06	0.06
$DD(^1D_2)$	$\cdots$	10^{-3}	0.03	0.07	0.01	0.04	0.34	0.38
$DD(^3D_2)$	$\cdots$	10^{-3}	0.02	0.06	10^{-3}	0.01	0.09	0.11
$DD^*(2760)$	$\cdots$	10^{-3}	0.05	0.08	10^{-3}	0.02	0.06	0.05
$D_0^*(2400)D_0^*(2400)$	$\cdots$	10^{-6}	0.01	0.02	10^{-3}	0.03	0.11	0.13
$DD(2^3P_0)$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$DD(2^1P_1)$	$\cdots$	10^{-4}	0.02	0.09	$\cdots$	0.03	0.22	0.45
$DD(2^3P_1)$	$\cdots$	$\cdots$	0.04	0.11	$\cdots$	0.01	0.06	0.14
$DD(2^3P_2)$	$\cdots$	$\cdots$	10^{-4}	10^{-3}	$\cdots$	$\cdots$	10^{-3}	0.02
D_sD_s	10^{-3}	10^{-3}	10^{-3}	10^{-3}	0.01	0.01	0.01	0.01
$D_sD_s^*$	0.12	0.06	0.03	0.01	0.07	0.04	0.02	0.01
$D_s^*D_s^*$	0.31	0.22	0.14	0.09	0.09	0.05	0.03	0.02
$D_sD_{s0}^*(2317)$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$D_s^*D_{s0}^*(2317)$	0.8	0.77	0.84	0.41	0.23	0.15	0.09	0.06
$D_sD_{s1}(2460)$	0.01	0.03	0.03	0.02	0.21	0.18	0.13	0.08
$D_s^*D_{s1}(2460)$	0.01	0.01	0.01	0.05	10^{-3}	0.01	0.02	0.02
$D_sD_{s2}^*(2573)$	10^{-4}	10^{-3}	0.01	0.01	10^{-3}	0.01	0.01	0.01
$D_s^*D_{s2}^*(2573)$	$\cdots$	10^{-5}	10^{-4}	10^{-6}	$\cdots$	10^{-4}	10^{-4}	10^{-3}
$D_sD_{s1}(2536)$	0.17	0.23	0.21	0.16	0.16	0.13	0.10	0.06
$D_s^*D_{s1}(2536)$	$\cdots$	0.06	0.08	0.07	10^{-4}	0.01	0.02	0.02

3

The hadronic molecular pictures for XYZ

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" 6) 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), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming 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 $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ 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 muliquark states were predicted at the birth of Quark Model

Types of hadrons in nature

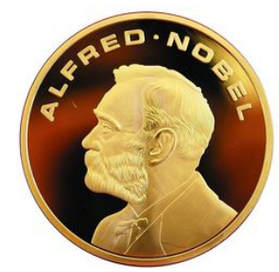
$$\text{Hadron}\begin{cases}\text{Conventional QM states}\begin{cases}\text{Meson}: & q\bar{q}, \quad Q\bar{q}, \quad Q\bar{Q} \\ \text{Baryon}: & qqq, \quad Qqq, \quad QQq, \quad \ldots\end{cases} \\ \text{Exotic states}\begin{cases}\text{Molecular state} \\ \text{Hybrid meson} \\ \text{Glueball} \\ \text{Tetraquark} \\ \text{Pentaquark} \\ \ldots\end{cases}\end{cases}$$

- **Identifying exotic states is one of the most important research issues of particle physics**
- **The observed XYZ states provide us good platform to identify exotic state**

The Nobel Prize in Physics 1949

The Nobel Prize in Physics 1949 was awarded to Hideki Yukawa "for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces."

Hideki Yukawa



I. The nuclear forces are described by a scalar field U, which satisfies the wave equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\varkappa^2\right)U=0 \qquad (1)$$

in vacuum, where x is a constant with the dimension of reciprocal length. Thus, the static potential between two nucleons at a distance r is proportional to $\exp(-\varkappa r)/r$, the range of forces being given by $1/\varkappa$.

II. According to the general principle of quantum theory, the field U is inevitably accompanied by new particles or quanta, which have the mass

$$\mu=\frac{\varkappa\hbar}{c} \qquad (2)$$

and the spin 0, obeying Bose-Einstein statistics. The mass of these particles can be inferred from the range of nuclear forces. If we assume, for instance, $\varkappa = 5 \times 10^{12}$ cm^{-1}, we obtain $\mu \cong 200\ m_e$, where m_e is the mass of the electron.

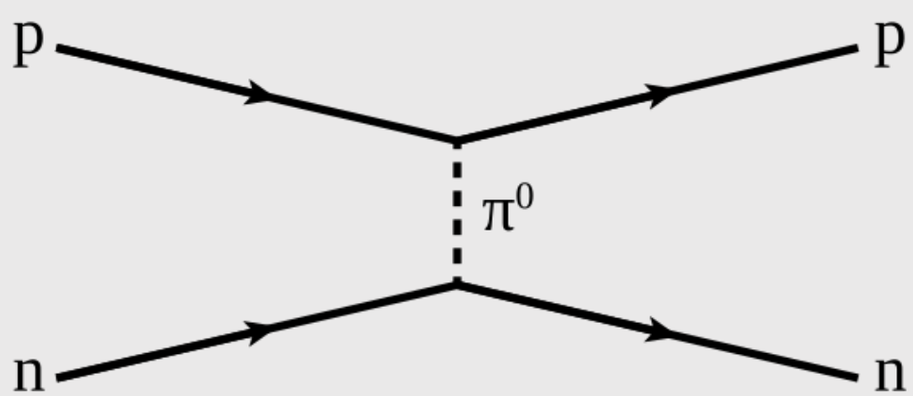
HIDEKI YUKAWA

Meson theory in its developments

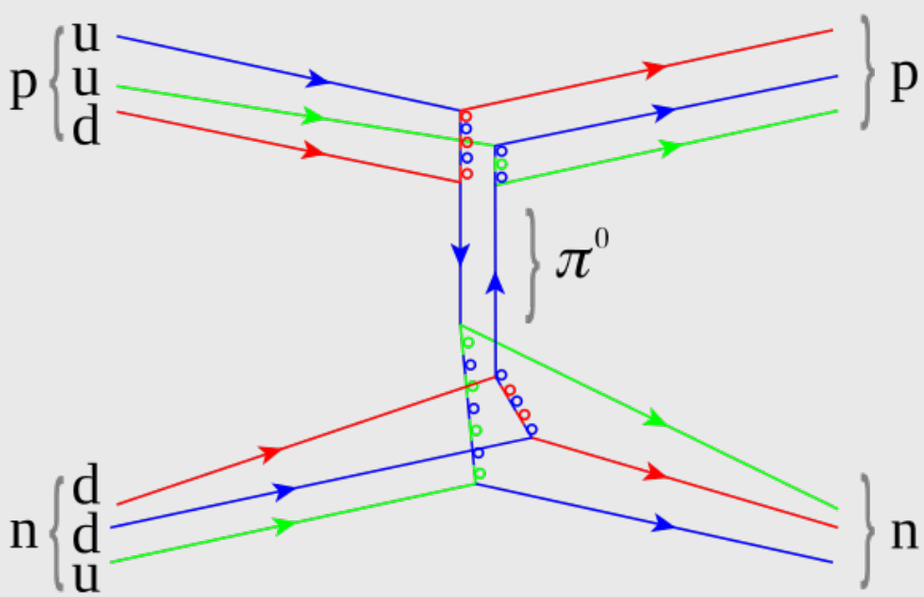
Nobel Lecture, December 12, 1949

https://www.nobelprize.org/uploads/2018/06/yukawa-lecture.pdf

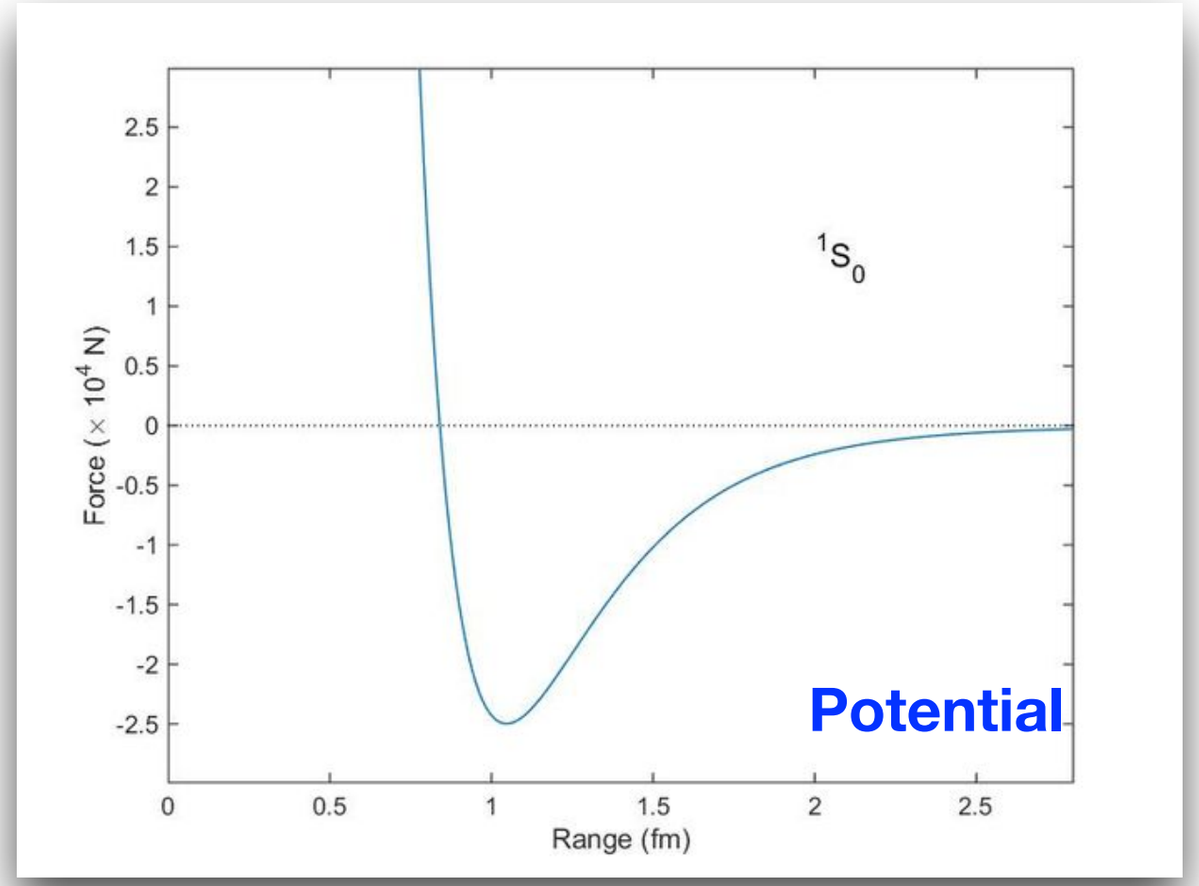
Nuclear force



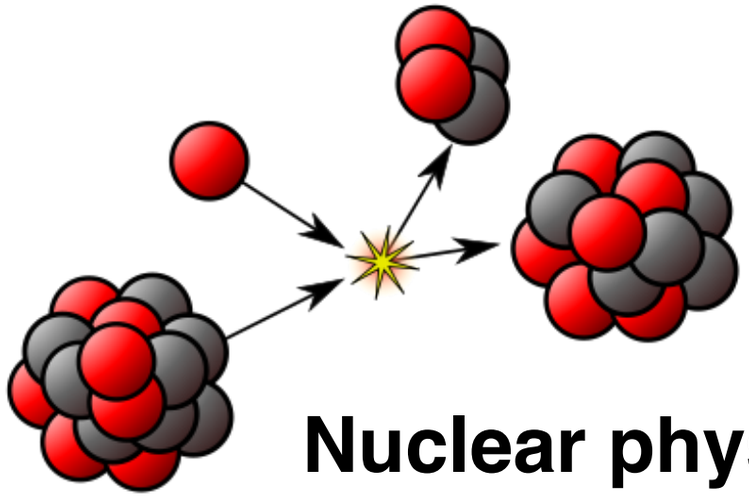
Hadronic level



Quark level



Potential



Nuclear physics

One pion exchange (OPE) model

Deuteron: loosely bound state of proton and neutron

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

ϱ and ω exchanges	Scalar σ with mass around 600 MeV	Pion exchange

The coupling of π with nucleons reads

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

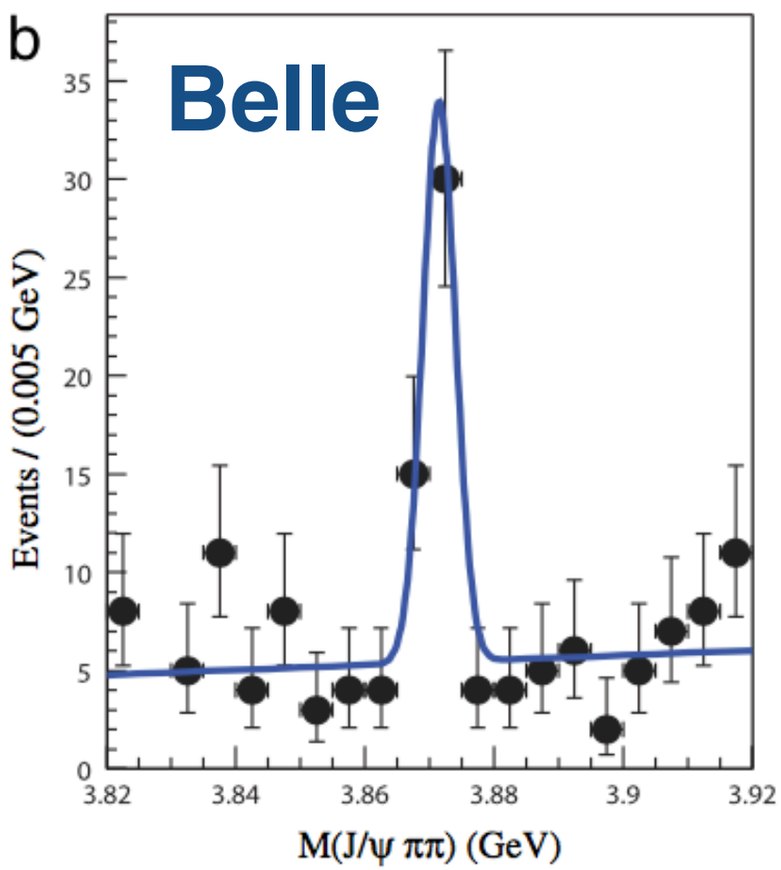
the non-relativistic nucleon-nucleon potential via π meson exchange can be obtained as

$$V_\pi = \frac{g_{NN\pi}^2}{4\pi}\frac{m_\pi^2}{12m_N^2}(\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2})\left\{\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2} + \left[\frac{3(\boldsymbol{\sigma_1}\cdot\boldsymbol{r})(\boldsymbol{\sigma_2}\cdot\boldsymbol{r})}{r^2} - \boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}\right]\left[1 + \frac{3}{m_\pi r} + \frac{3}{m_\pi^2 r^2}\right]\right\}\frac{e^{-m_\pi r}}{r}$$

X(3872)

Abundant experimental information

PRL 91 (2003) 262001



	Decay modes							Mass (MeV)	J^{PC}
	$J/\psi\pi^+\pi^-$	$J/\psi\pi^+\pi^-\pi^0$ $(J/\psi\omega)$	$J/\psi\eta$	$D^0\bar{D}^0\pi^0$	$D^{*0}\bar{D}^0$	$\gamma J/\psi$	$\gamma\psi'$		
Belle-1	■							$3872.0 \pm 0.6 \pm 0.5$	
Belle-2		■				■		–	
Belle-3				■				$3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$	
Belle-4	■							$3871.46 \pm 0.37 \pm 0.07$	
Belle-5					■			$3872.9^{+0.3+0.5}_{-0.6-0.5}$	
Belle-6						■	■	–	
BaBar-1	■							3873.4 ± 1.4	
BaBar-2			□					–	
BaBar-3	■							–	
BaBar-4	■							$3871.3 \pm 0.6 \pm 0.1$ (B^-)	
								$3868.6 \pm 1.2 \pm 0.2$ (B^0)	
BaBar-5				■				–	
BaBar-6						■		–	
BaBar-7					■			$3875.1^{+0.5}_{-0.7} \pm 0.5$	
BaBar-8	■							$3871.4 \pm 0.6 \pm 0.1$ (B^+)	
								$3868.7 \pm 1.5 \pm 0.4$ (B^0)	
BaBar-9						■	■	–	
BaBar-10		■						$3873.0^{+1.8}_{-1.6} \pm 1.3$	2^{-+}
CDF-1	■							$3871.3 \pm 0.7 \pm 0.4$	
CDF-2	■							–	
CDF-3	■							–	$1^{++}/2^{-+}$
CDF-4	■							$3871.61 \pm 0.16 \pm 0.19$	
D0	■							$3871.8 \pm 3.1 \pm 3.0$	
LHCb-1	■							–	1^{++}
LHCb-2	■							$3871.95 \pm 0.48 \pm 0.12$	
CMS	■							–	
BESIII						■		$3891.9 \pm 0.7 \pm 0.2$	

$m(D^0D^{*0}) = (3871.81 \pm 0.36)$ MeV — PDG average mass of $X(3872)$: (3871.68 ± 0.17) MeV

Low mass puzzle: The mass of X(3872) is 50-200 MeV lower than the prediction from potential model

X(3872)=molecular state?

$D\bar{D}^*$ **interaction**

Different effects were considered

N. Li, S.L. Zhu, PRD86(2012)

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Y. Liu, X. Liu, Deng, Zhu, EPJC56, 63 (2008)

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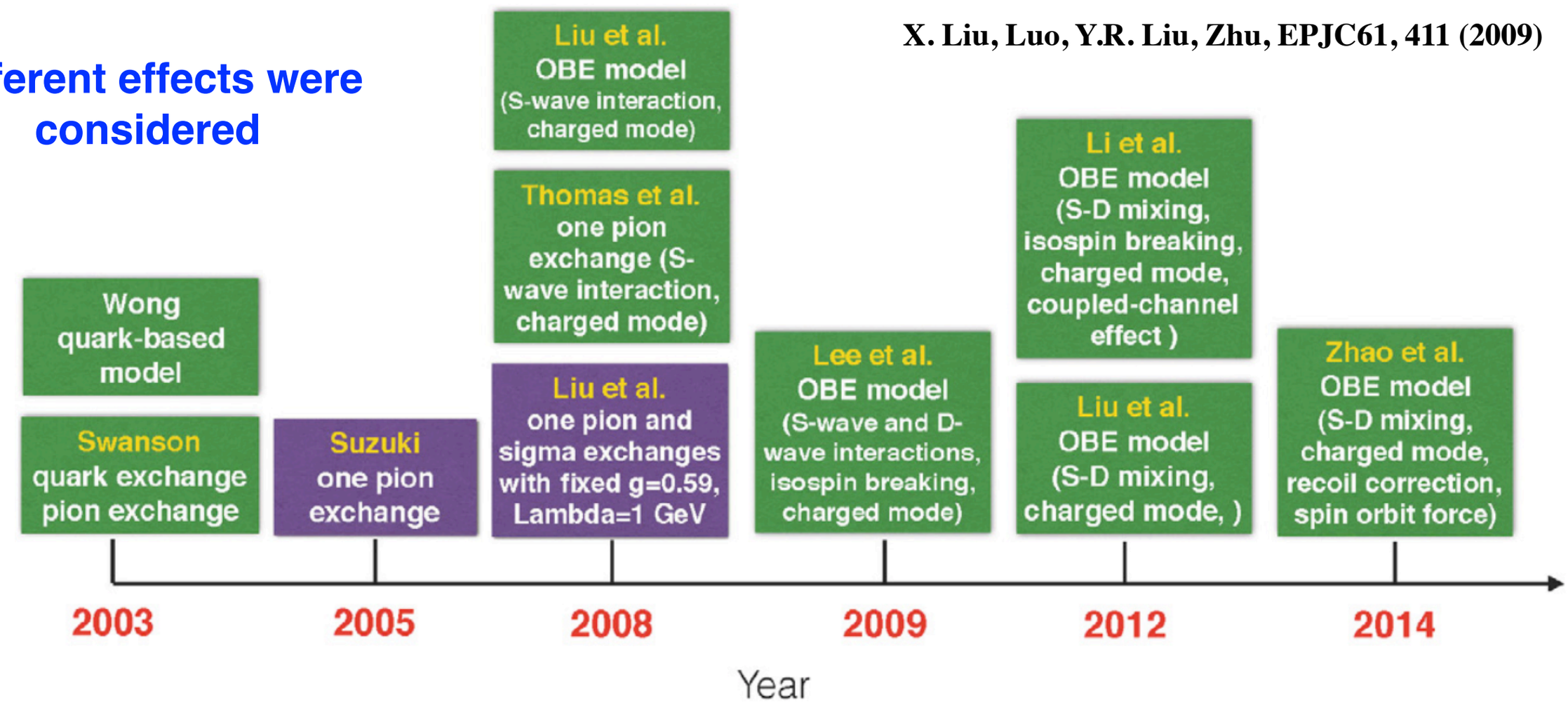

- **Reproduce the mass of X(3872)**
- **Explain isospin violating $J/\psi\rho$ decay mode of X(3872)**

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

Long list:

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CHEN Y D, QIAO C F. arXiv:1102.3487

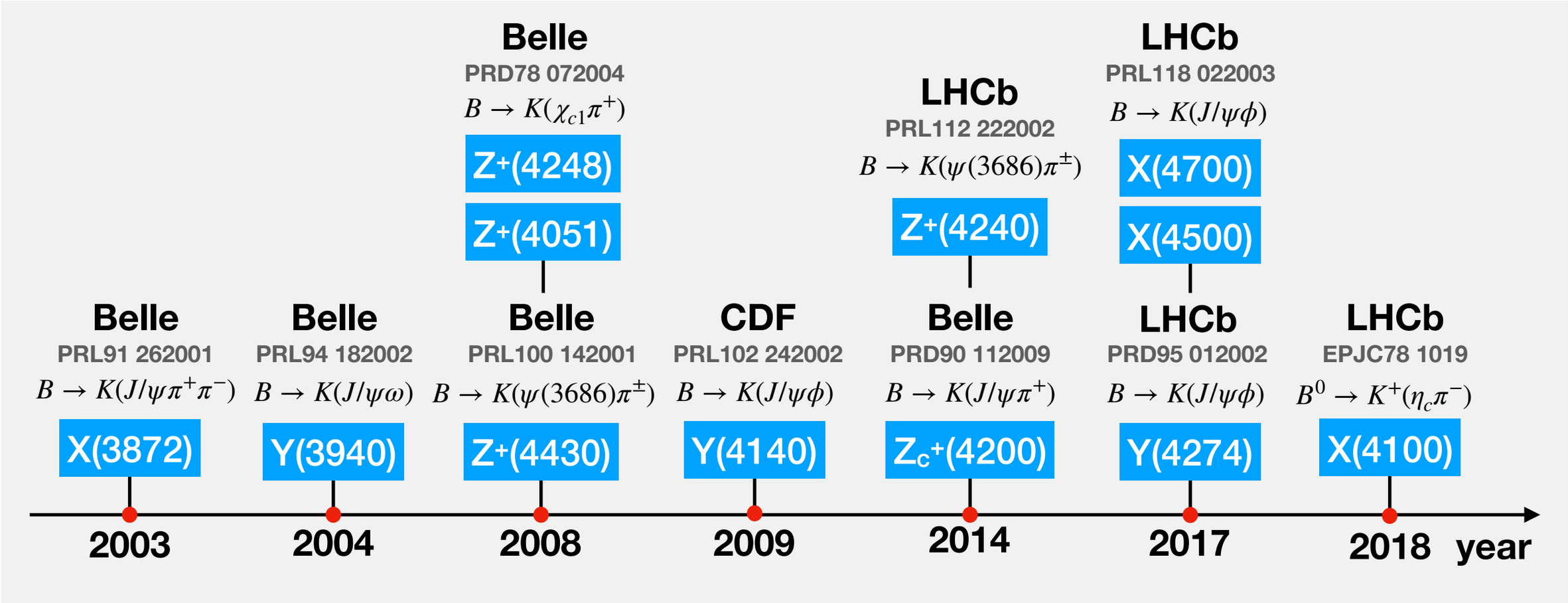
...

One conclusion:

Pion exchange plays crucial role to form heavy flavor molecular states

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

XYZ from B meson decays



The prediction of hidden-charm pentaquarks

PRL **105,** 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

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]

- **Hidden-charm pentaquarks are predicted in the chiral unitary model**

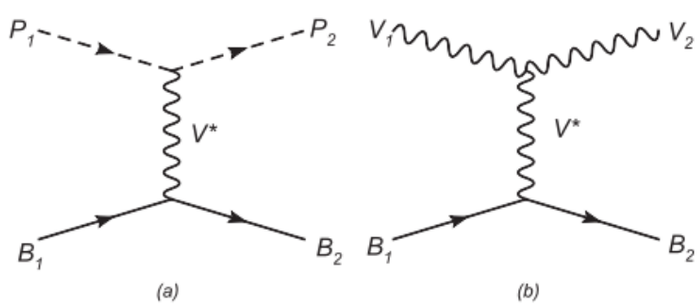


FIG. 1. Feynman diagrams of pseudoscalar-baryon (a) or vector-baryon (b) interaction via exchange of a vector meson. P_1, P_2 is D^-, $\bar{D}^0$, or D_s^-, V_1, V_2 is D^{*-}, $\bar{D}^{*0}$, or D_s^{*-}, B_1, B_2 is Σ_c, Λ_c^+, Ξ_c, Ξ_c', or Ω_c, and V^* is ρ, K^*, ϕ, or ω.

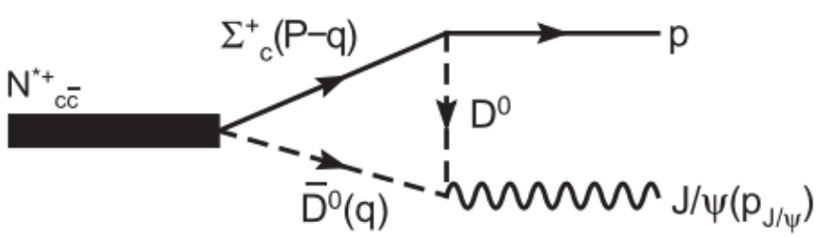


FIG. 2. Feynman diagram for $N^{*+}_{c\bar{c}}(4265) \to J/\psi p$.

TABLE II. Pole positions z_R and coupling constants g_a for the states from $PB \to PB$.

(I, S)	z_R (MeV)		g_a	
$(1/2, 0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
	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 position and coupling constants for the bound states from $VB \to VB$.

(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

arXiv:1105.2901

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

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)]

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[2] Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of Chinese Academy of Sciences, Lanzhou 730000, China
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[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.

and an S-wave charmed baryon do exist. Our numerical results indicate that $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not exist, due to the absence of bound state solution, which is an interesting observation in this work. Additionally, we only notice the bound state solutions for five hidden-charm states, i.e. $\Sigma_c\bar{D}^*$ states with $I(J^P) = \frac{1}{2}\left(\frac{1}{2}^-\right), \boxed{\frac{1}{2}\left(\frac{3}{2}^-\right)}, \frac{3}{2}\left(\frac{1}{2}^-\right), \frac{3}{2}\left(\frac{3}{2}^-\right)$ and $\Sigma_c\bar{D}$ states with $\frac{3}{2}\left(\frac{1}{2}^-\right)$. We also ex-

- **Explicitly Indicate the existence of hidden-charm pentaquark with J=3/2**
- **Such prediction is consistent with the LHCb measurement**

Eur. Phys. J. C (2014) 74:3198
DOI 10.1140/epjc/s10052-014-3198-3

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

A possible global group structure for exotic states

Xue-Qian Li[1,a], Xiang Liu[3,2,b]

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.

$$c\bar{b},\ (c\bar{c}+b\bar{b})/\sqrt{2},\ b\bar{c},\quad \text{(triplet)},$$

$$(c\bar{c}-b\bar{b})/\sqrt{2},\quad \text{(singlet)}.$$

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

where the subscripts c, H, and L refer to color, heavy, and light, respectively. The $\mathrm{SU_L}(3)$ corresponds to the regular quark model for the light quarks u, d, s and the newly introduced $\mathrm{SU_H}(2)$ 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

PRL 115, 122001 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]

Thus the conditions for existence of the resonance are as follows: (a) The state contains two heavy hadrons. They have to be heavy, as the repulsive kinetic energy is inversely proportional to the reduced mass (see, e.g., Ref. [26]) (For a more recent discussion see Ref. [27].) (b) The two hadrons carry isospin, so that they can couple to pions. Channels like $\Sigma_c\bar{\Lambda}_c$, in which one of the particles has zero isospin, can exchange a pion to become the equal-mass channel $\Lambda_c\bar{\Sigma}_c$. (c) The spin and parity of the two hadrons have to be such that they can bind through single pion exchange. (d) The hadrons making up the molecule have to

Consistent with our conclusion

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

Notes added.—We thank X. Liu for informing us of an earlier calculation [37] 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 $J = 1/2$. We also

The consistency between their result and our former work published in CPC 36 (2012) 6-13

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

Experimental observation of Pc(4380) and Pc(4450)

PRL 115, 072001 (2015)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
14 AUGUST 2015

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

R. Aaij *et al.*[*]
(LHCb Collaboration)

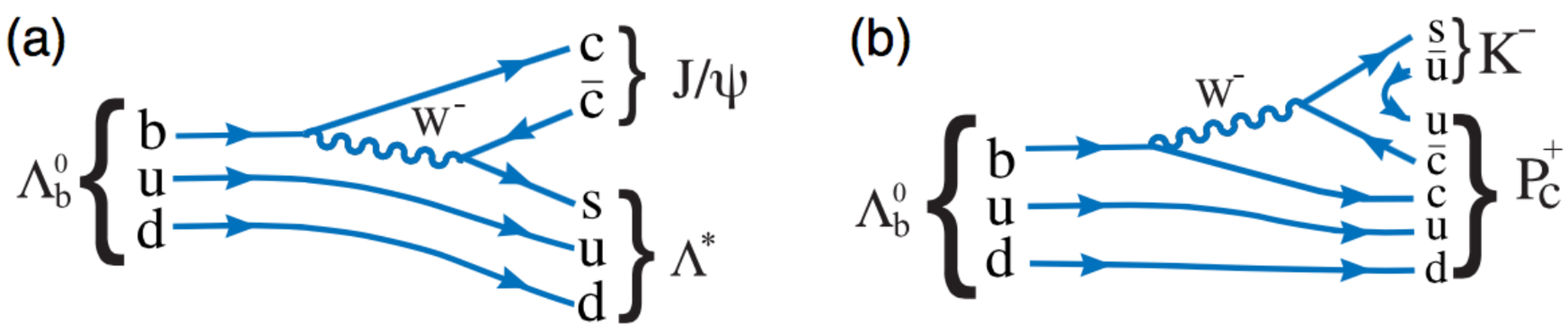


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

The measured invariant mass spectra

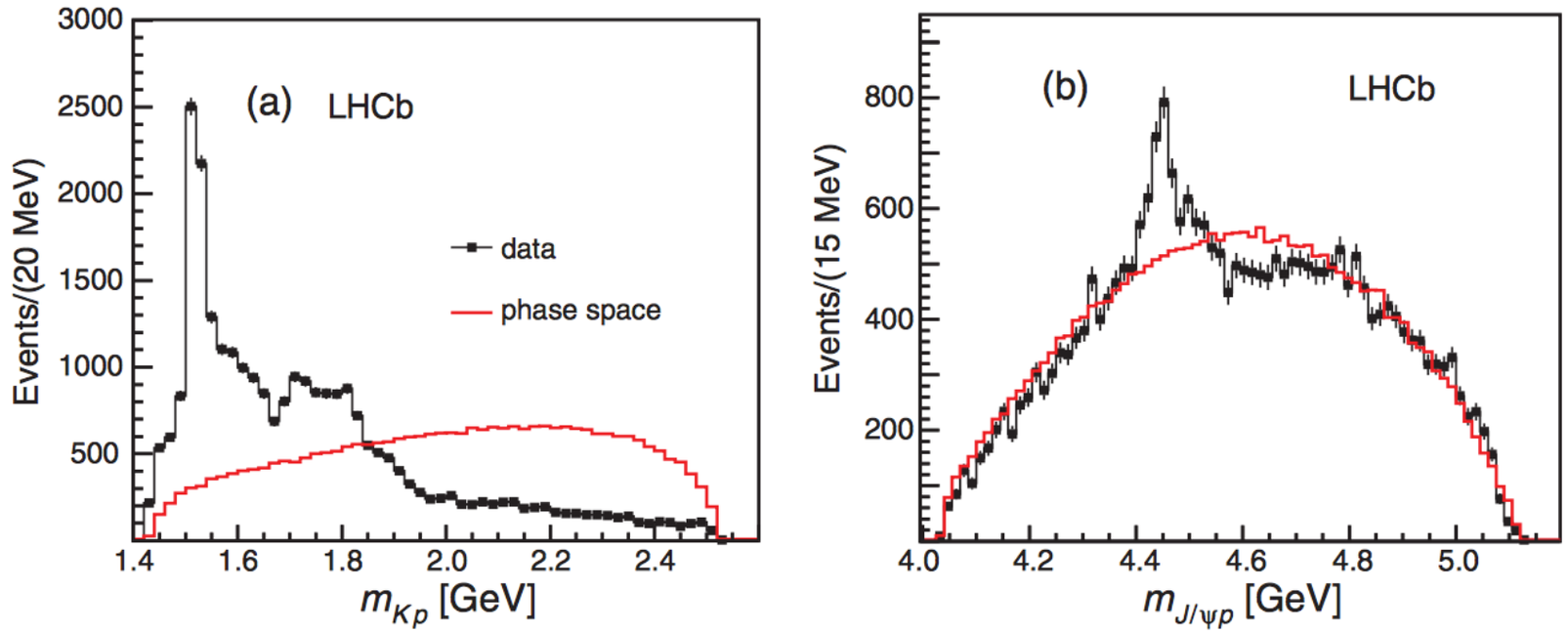


FIG. 2 (color online). Invariant mass of (a) K^-p and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.

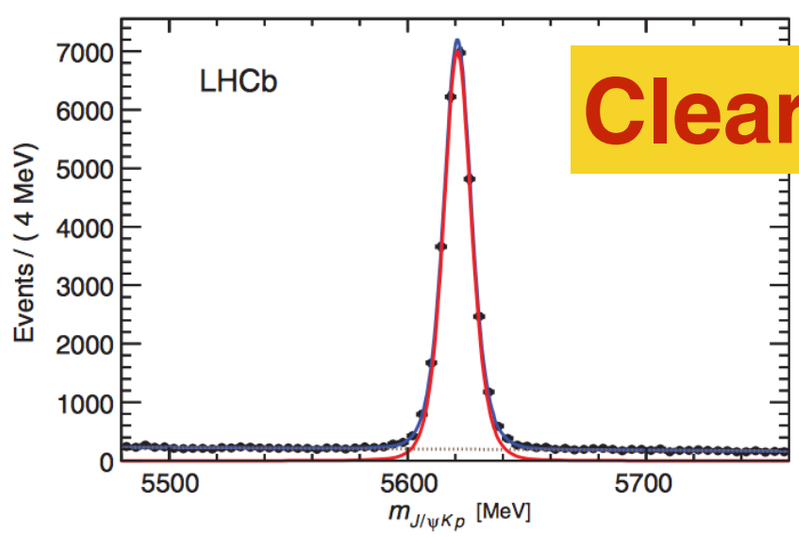
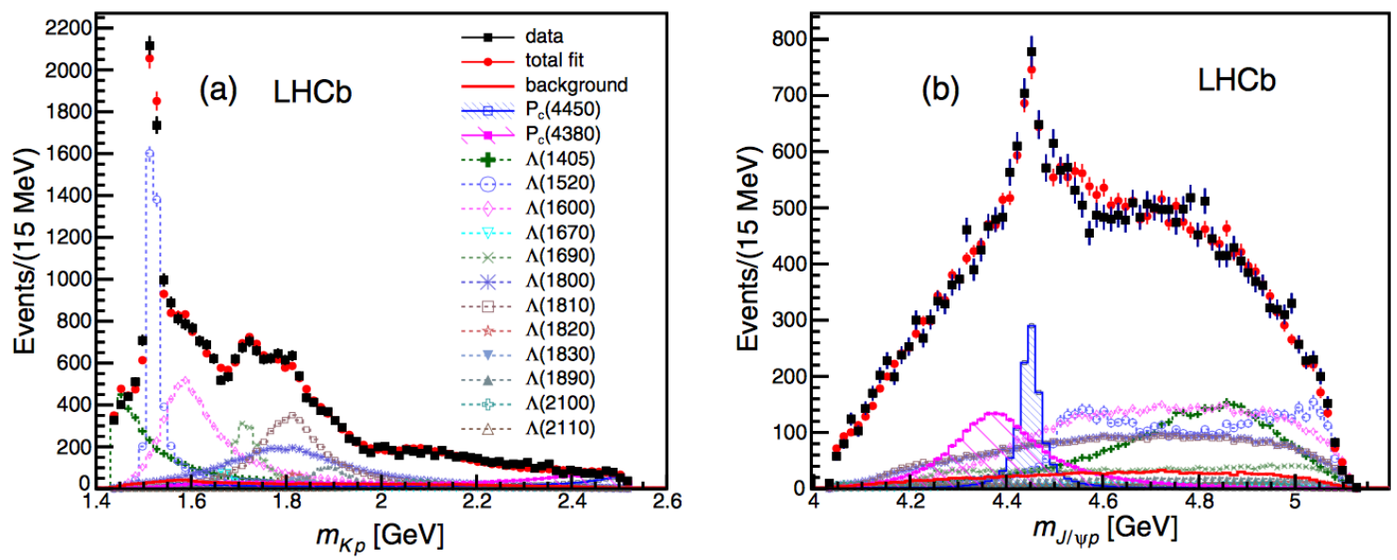


FIG. 4 (color online). Invariant mass spectrum of $J/\psi K^- p$ combinations, with the total fit, signal, and background components shown as solid (blue), solid (red), and dashed lines, respectively.

Clear signal of Λb

LHCb performed the analysis of the above experimental data

With two Pc states to fit the data



ɜ. 3 (color online). Fit projections for (a) m_{Kp} and (b) $m_{J/\psi p}$ for the reduced Λ^* model with two P_c^+ states (see Table I). The data are ›wn as solid (black) squares, while the solid (red) points show the results of the fit. The solid (red) histogram shows the background tribution. The (blue) open squares with the shaded histogram represent the $P_c(4450)^+$ state, and the shaded histogram topped with rple) filled squares represents the $P_c(4380)^+$ state. Each Λ^* component is also shown. The error bars on the points showing the fit ılts are due to simulation statistics.

Without two Pc states to fit the data

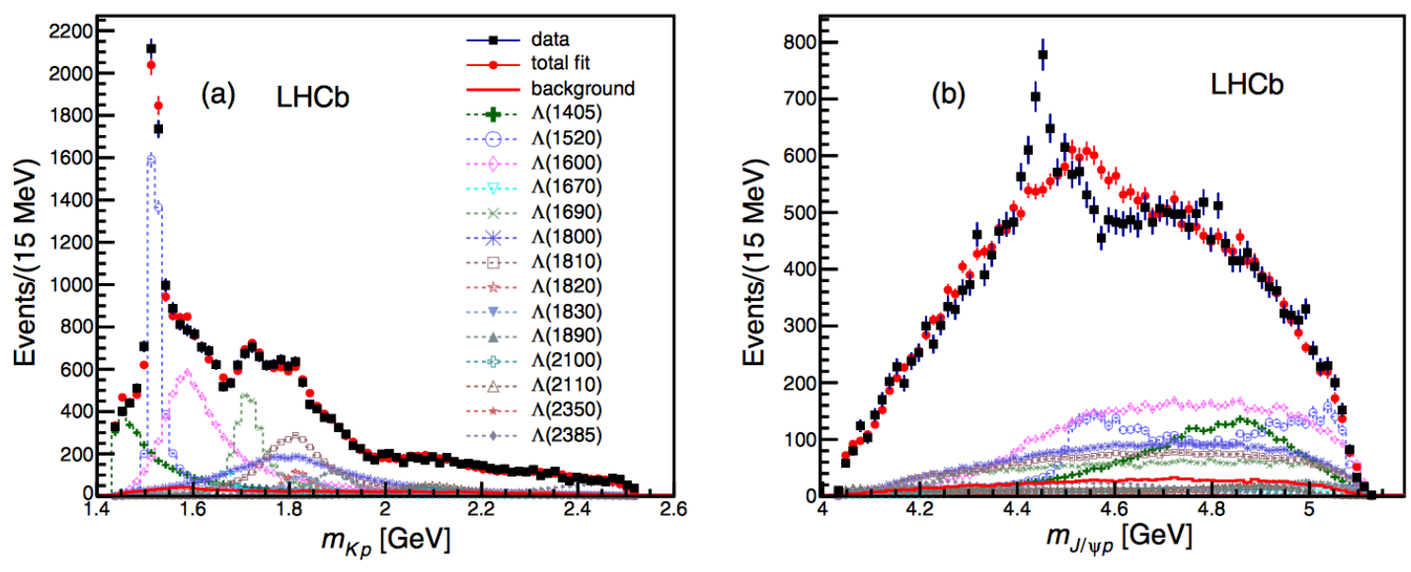


FIG. 6 (color online). Results for (a) m_{Kp} and (b) $m_{J/\psi p}$ for the extended Λ^* model fit without P_c^+ states. The data are shown as (black) squares with error bars, while the (red) circles show the results of the fit. The error bars on the points showing the fit results are due to simulation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

The Λ* resonances included in the data analysis

TABLE I. The Λ^* 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)	Γ_0 (MeV)	Number Reduced	Number Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 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
$\Lambda(2585)$	?	≈ 2585	200	0	6

If describing the experimental data, two Pc states are introduced. Otherwise, the mass distribution of J/ψp cannot be understood

Resonance parameters of two Pc states

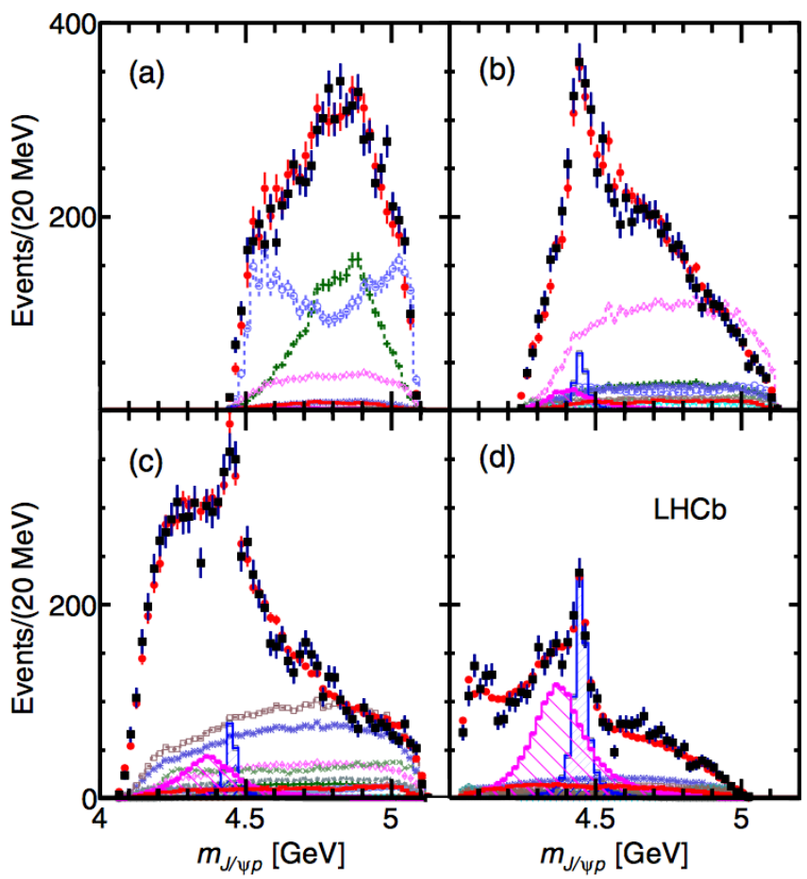


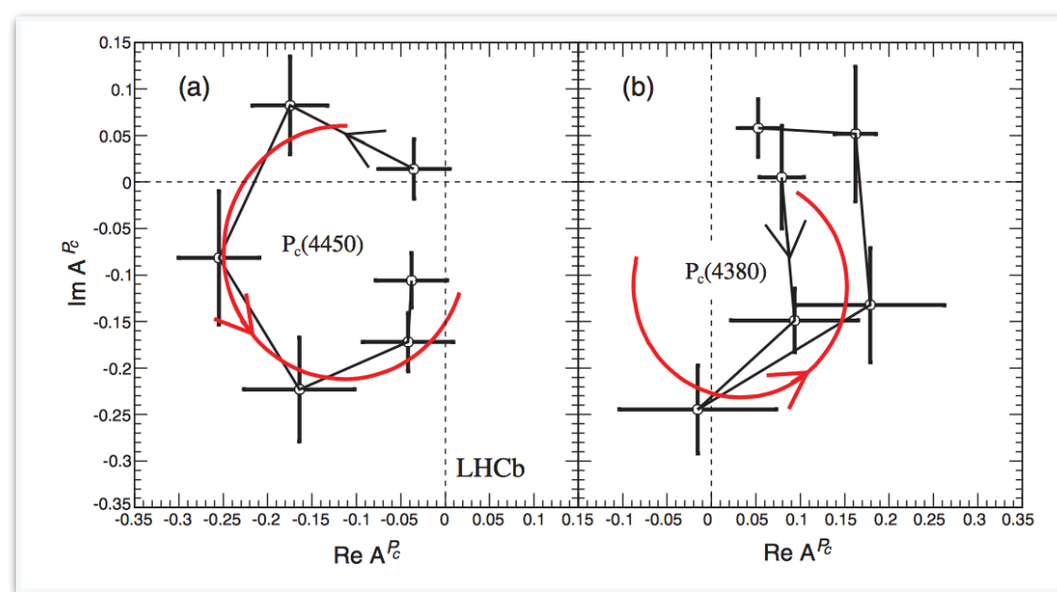
FIG. 8 (color online). $m_{J/\psi p}$ in various intervals of m_{Kp} for the fit with two P_c^+ states: (a) $m_{Kp} < 1.55$ GeV, (b) $1.55 < m_{Kp} < 1.70$ GeV, (c) $1.70 < m_{Kp} < 2.00$ GeV, and (d) $m_{Kp} > 2.00$ GeV. The data are shown as (black) squares with error bars, while the (red) circles 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	9σ	12σ
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit fraction(%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1
$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-; P_c^+ \to J/\psi p)$	$(2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5}$	$(1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5}$

Branching ratio results are submitted to Chin. Phys. C (arXiv:1509.00292)

Ref: $\mathcal{B}(B^0 \to Z^-(4430)K^+; Z^- \to J/\psi\pi^-) = (3.4 \pm 0.5^{+0.9}_{-1.9} \pm 0.2) \times 10^{-5}$

Argand diagrams show the resonance behavior of two Pc states



Decay angular distributions

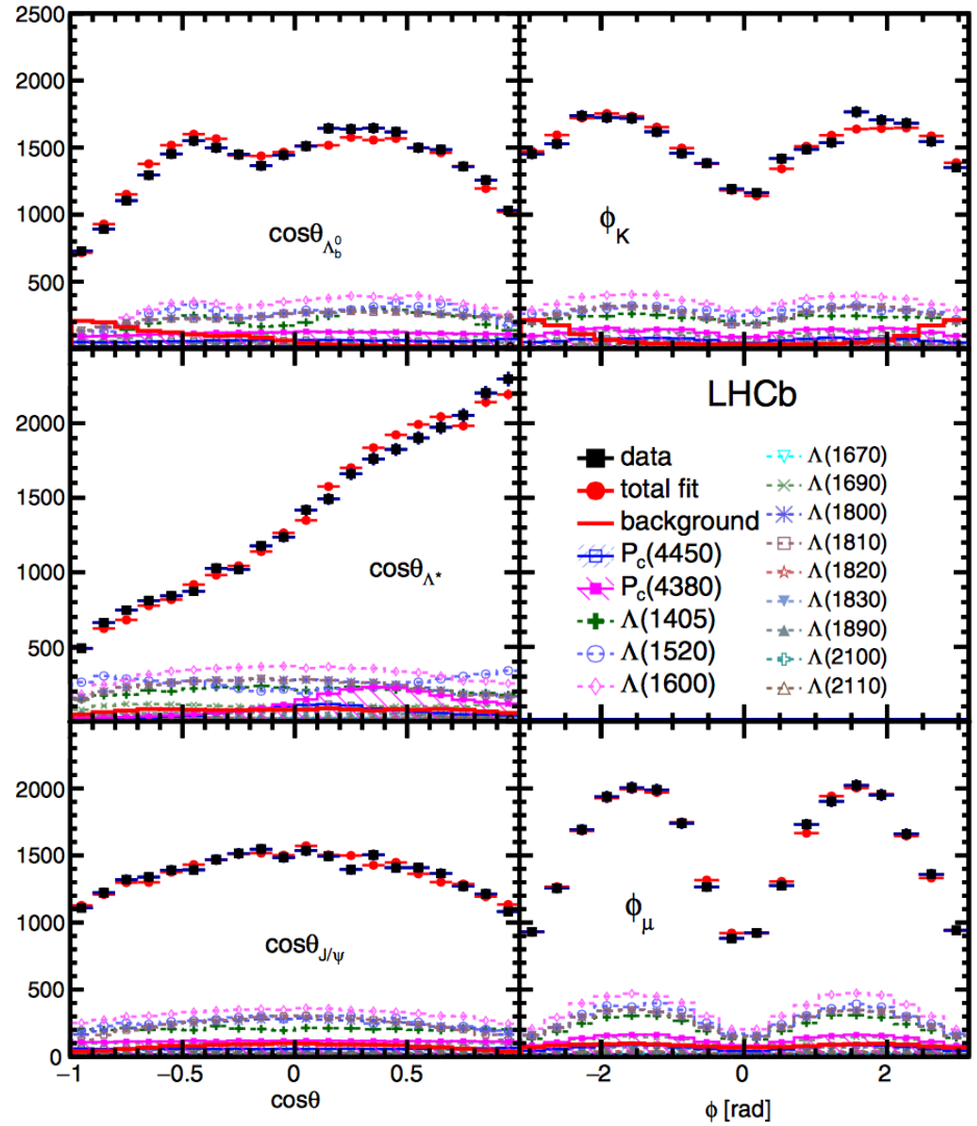


FIG. 7 (color online). Various decay angular distributions for the fit with two P_c^+ states. The data are shown as (black) squares, while the (red) circles show the results of the fit. Each fit component is also shown. The angles are defined in the text.

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

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PHYSICAL REVIEW LETTERS

moving physics forward

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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)

Identify exotic hidden-charm pentaquarks

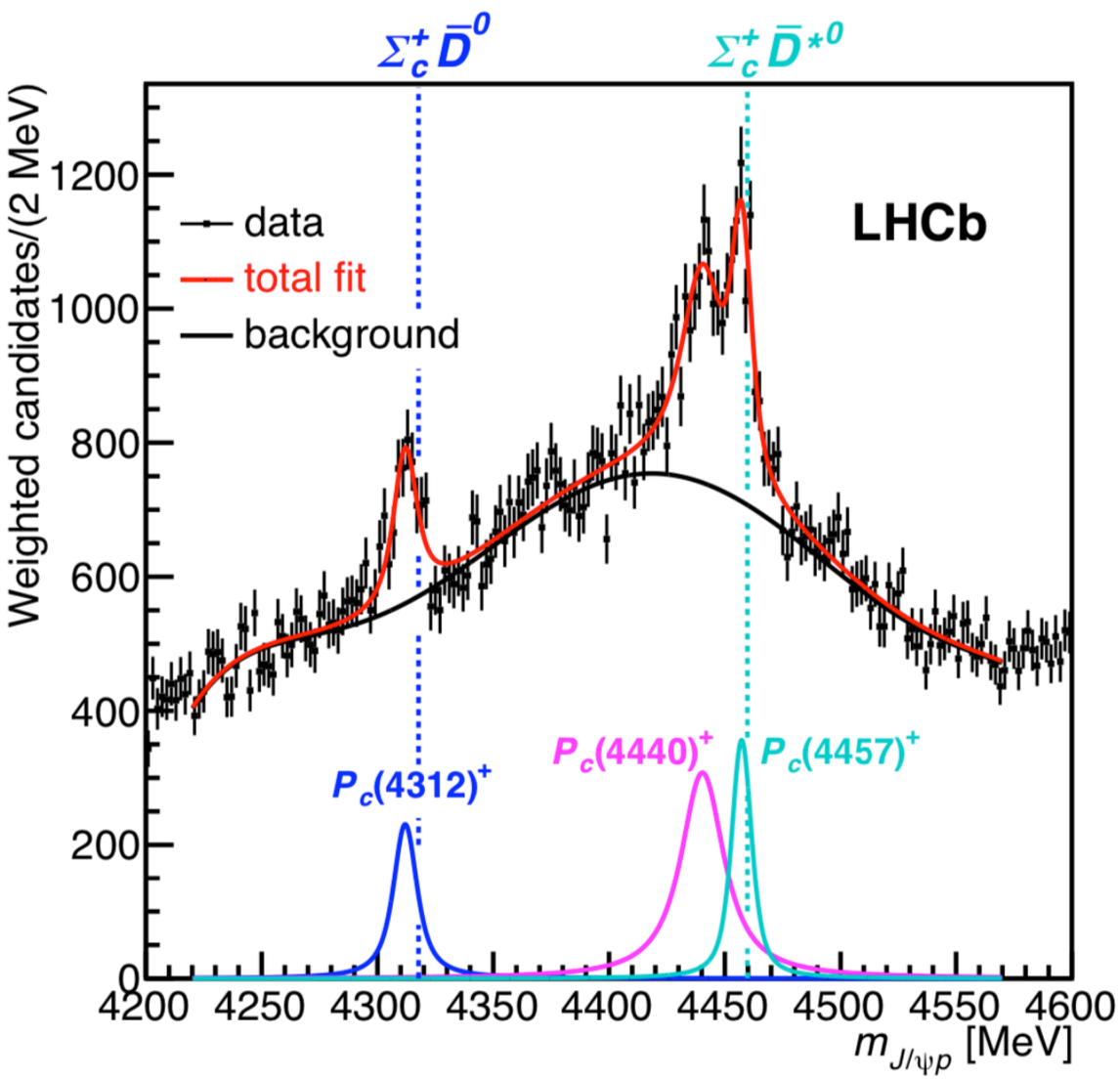
PHYSICAL REVIEW LETTERS **122,** 222001 (2019)

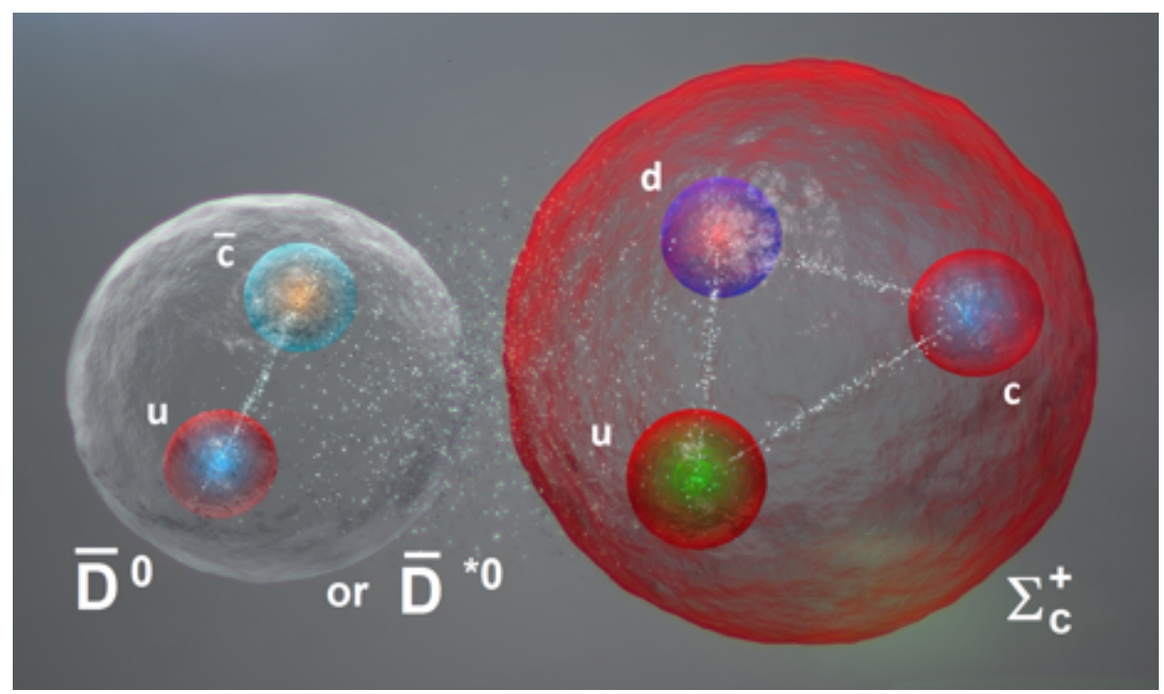
Editors' Suggestion | Featured in Physics

Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 6 April 2019; published 5 June 2019)





arXiv:1105.2901

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

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)]

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[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.

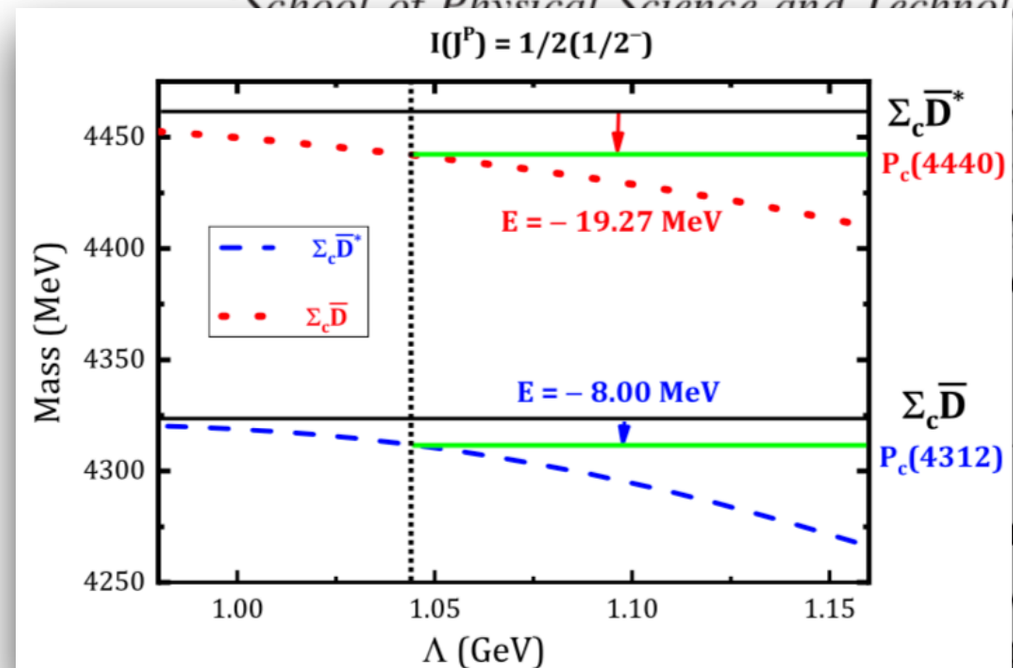
PHYSICAL REVIEW D **100,** 011502(R) (2019)

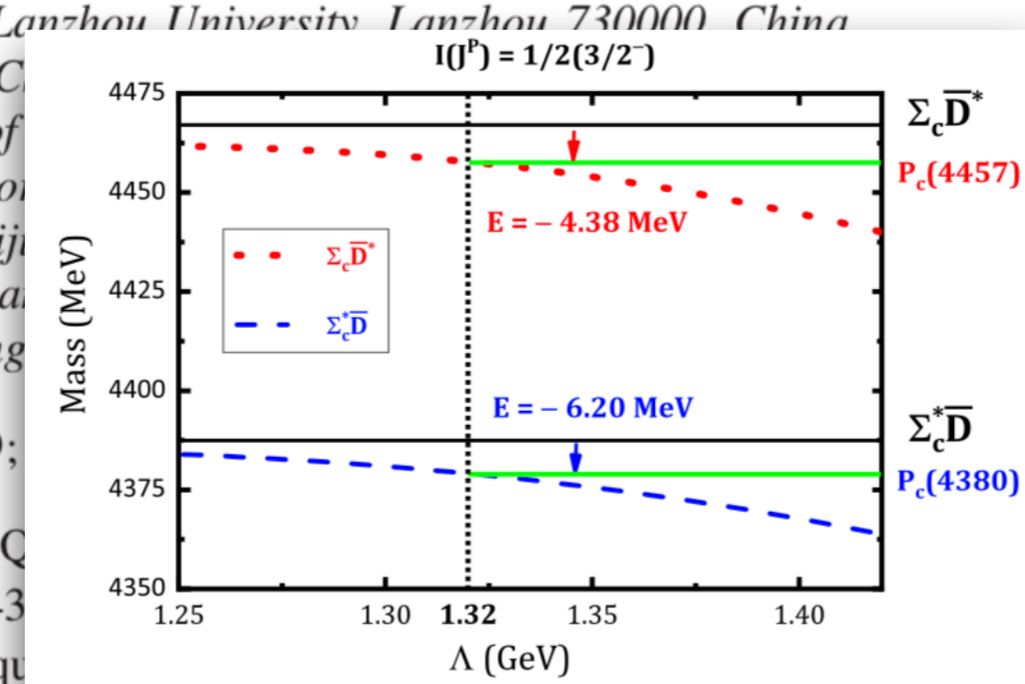
Rapid Communications

Strong LHCb evidence supporting the existence of the hidden-charm molecular pentaquarks

Rui Chen,[1,2,3] Zhi-Feng Sun,[1,2] Xiang Liu,[1,2,*] and Shi-Lin Zhu[3,4,5,†]

[1]School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China





Σ_c and an S-wave anticharmed meson ($\bar{D}$, $\bar{D}^*$). In this work, we present a direct calculation by the one-boson-exchange model and demonstrate explicitly that the $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ do correspond to the loosely bound $\Sigma_c\bar{D}$ with ($I = 1/2$, $J^P = 1/2^-$), $\Sigma_c\bar{D}^*$ with ($I = 1/2$, $J^P = 1/2^-$), and $\Sigma_c\bar{D}^*$ with ($I = 1/2$, $J^P = 3/2^-$), respectively.

Selected for a Viewpoint in *Physics*

PRL **119,** 112001 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

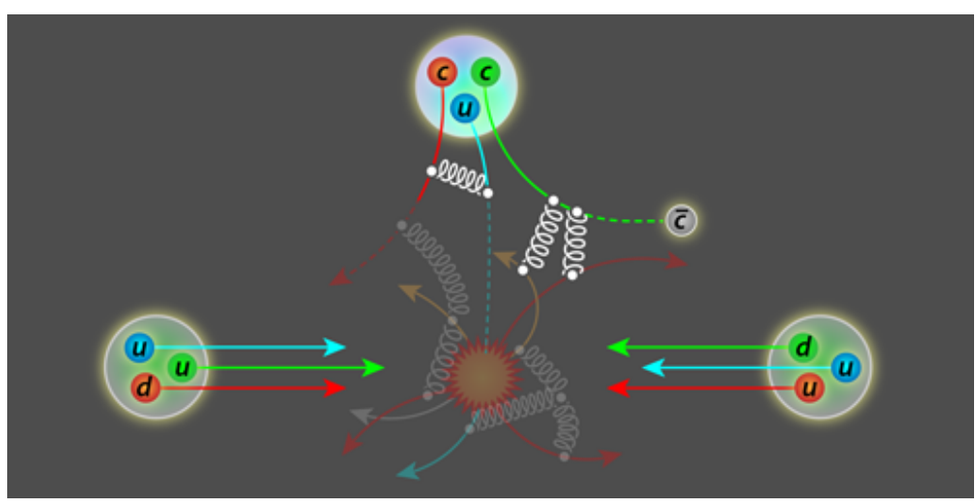
R. Aaij *et al.*[*]

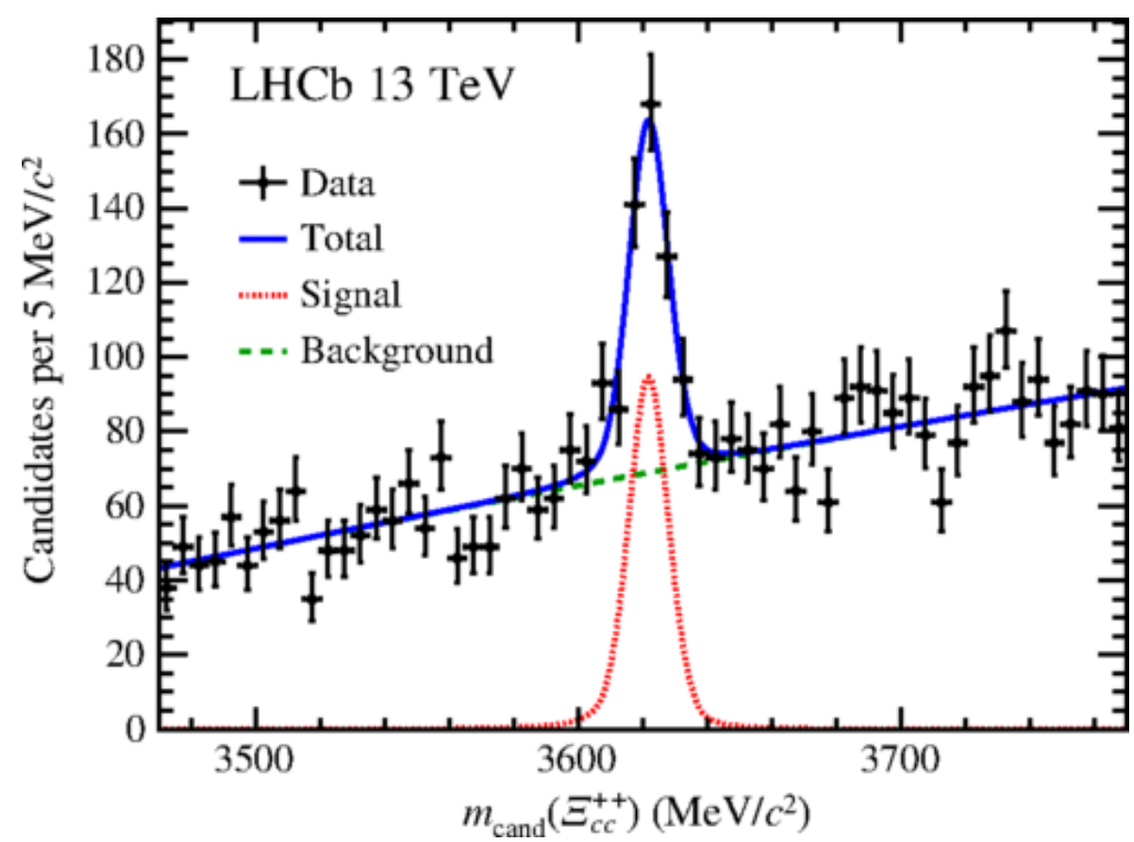
(LHCb Collaboration)

(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The difference between the masses of the Ξ_{cc}^{++} and Λ_c^+ states is measured to be $1334.94 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.})$ MeV/c^2, and the Ξ_{cc}^{++} mass is then determined to be $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)$ MeV/c^2, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb^{-1}, and confirmed in an additional sample of data collected at 8 TeV.

DOI: 10.1103/PhysRevLett.119.112001





PHYSICAL REVIEW D **96,** 114030 (2017)

Prediction of triple-charm molecular pentaquarks

Rui Chen,[1,2,3,*] Atsushi Hosaka,[3,†] and Xiang Liu[1,2,‡]

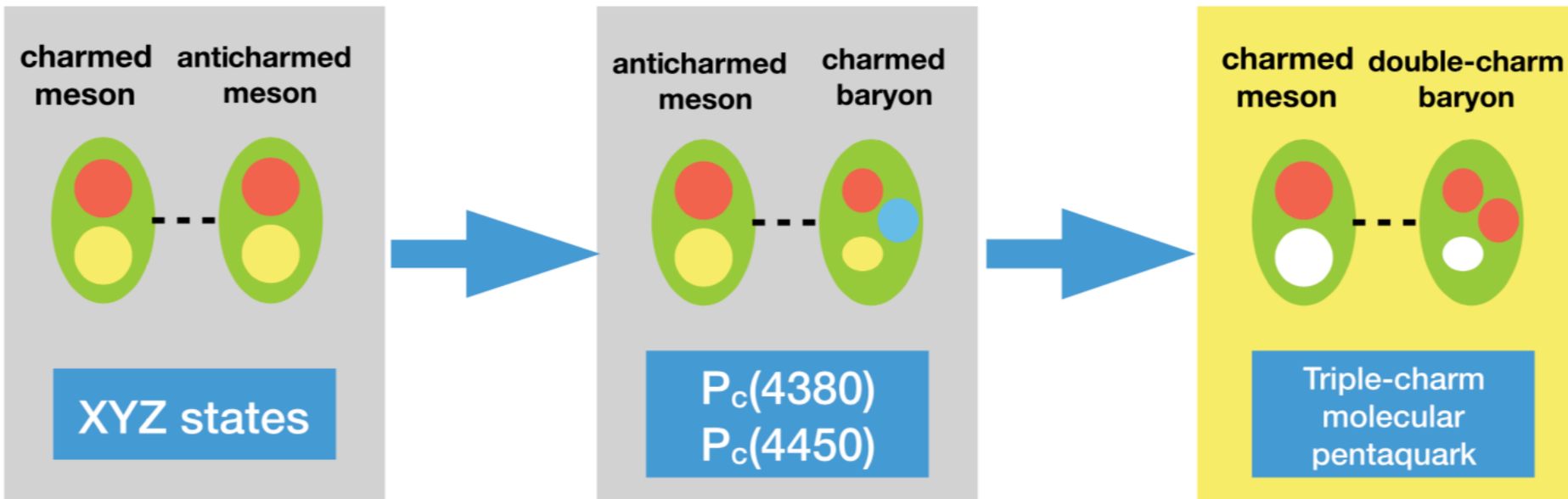
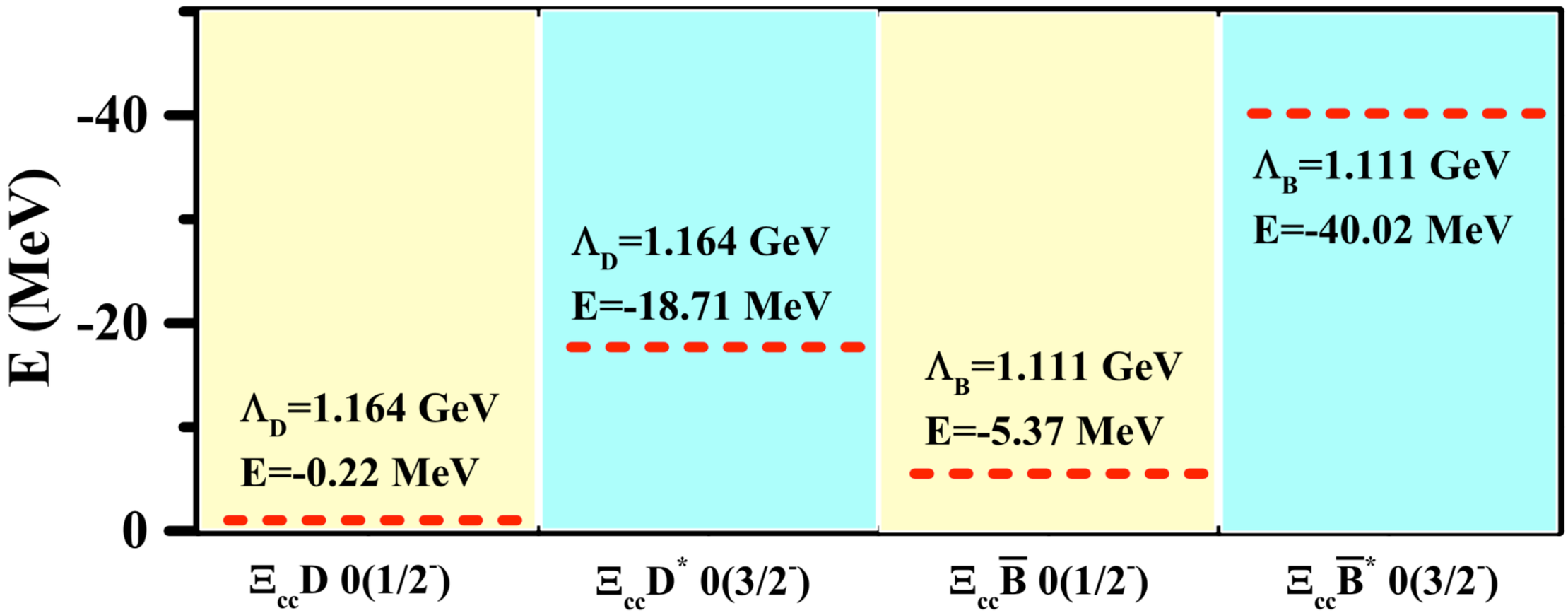


FIG. 1. Evolution of interaction of hadrons and the corresponding connections with charmoniumlike XYZ states, $P_c(4380)/P_c(4450)$, and triple-charm molecular pentaquark.

Chen, Hosaka, Liu, PRD96 (2017) 114030



Experimental search for triple-charm molecular pentaquarks will be interesting issue, especially for LHCb

Decay modes: $\Omega_{ccc}\sigma, \Omega_{ccc}\omega, \Omega_{ccc}\pi\pi$

PHYSICAL REVIEW D **99,** 054021 (2019)

Possible triple-charm molecular pentaquarks from $\Xi_{cc}D_1/\Xi_{cc}D_2^*$ interactions

Fu-Lai Wang,* Rui Chen,† Zhan-Wei Liu,‡ and Xiang Liu§

School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China and Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China

(Received 14 January 2019; published 25 March 2019)

In this work, we explore a systematic investigation on S-wave interactions between a doubly charmed baryon $\Xi_{cc}(3621)$ and a charmed meson in a T doublet (D_1, D_2^*). We first analyze the possibility for forming $\Xi_{cc}D_1/\Xi_{cc}D_2^*$ bound states with the heavy quark spin symmetry. Then, we further perform a dynamical study on the $\Xi_{cc}D_1/\Xi_{cc}D_2^*$ interactions within a one-boson-exchange model by considering both the $S-D$ wave mixing and coupled channel effect. Finally, our numerical results conform the proposals from the heavy quark spin symmetry analysis: the $\Xi_{cc}D_1$ systems with $I(J^P) = 0(1/2^+, 3/2^+)$ and the $\Xi_{cc}D_2^*$ systems with $I(J^P) = 0(3/2^+, 5/2^+)$ can possibly be loose triple-charm molecular pentaquarks. Meanwhile, we also extend our model to the $\Xi_{cc}\bar{D}_1$ and $\Xi_{cc}\bar{D}_2^*$ systems, and our results indicate the isoscalars of $\Xi_{cc}\bar{D}_1$ and $\Xi_{cc}\bar{D}_2^*$ can be possible molecular candidates.

TABLE V. Bound state solutions for the $\Xi_{cc}D_1/\Xi_{cc}D_2^*$ states with $I(J^P) = 0, 1(1/2^+, 3/2^+)$. Cutoff Λ, binding energy E, and root-mean-square radius $r_{\rm rms}$ are in units of GeV, MeV, and fm, respectively. $P(\%)$ denotes the probability for the different channels. Here, we label the probability for the corresponding channel in a bold manner.

(I, J^P)	Λ	E	$r_{\rm rms}$	$\mathrm{P}(\Xi_{cc}D_1\vert^2\mathbb{S}_{\frac{1}{2}}\rangle)$	$\mathrm{P}(\Xi_{cc}D_1\vert^2\mathbb{D}_{\frac{1}{2}}\rangle)$	$\mathrm{P}(\Xi_{cc}D_2^*\vert^4\mathbb{D}_{\frac{1}{2}}\rangle)$	$\mathrm{P}(\Xi_{cc}D_2^*\vert^6\mathbb{D}_{\frac{1}{2}}\rangle)$
$(0, \frac{1}{2}^+)$	0.90	−0.47	3.84	**99.51**	0.43	$o(10^{-3})$	0.05
	0.93	−3.76	1.60	**99.44**	0.46	$o(10^{-3})$	0.09
	0.96	−10.78	1.04	**99.59**	0.32	$o(10^{-3})$	0.09
$(1, \frac{1}{2}^+)$	2.30	−0.33	4.41	**99.62**	0.33	$o(10^{-3})$	0.05
	3.15	−3.65	1.63	**98.46**	1.19	0.03	0.32
	4.00	−10.24	1.04	**96.70**	2.30	0.09	0.92

(I, J^P)	Λ	E	$r_{\rm rms}$	$\mathrm{P}(\Xi_{cc}D_1\vert^4\mathbb{S}_{\frac{3}{2}}\rangle)$	$\mathrm{P}(\Xi_{cc}D_1\vert^2\mathbb{D}_{\frac{3}{2}}\rangle)$	$\mathrm{P}(\Xi_{cc}D_1\vert^4\mathbb{D}_{\frac{3}{2}}\rangle)$	$\mathrm{P}(\Xi_{cc}D_2^*\vert^4\mathbb{S}_{\frac{3}{2}}\rangle)$	$\mathrm{P}(\Xi_{cc}D_2^*\vert^4\mathbb{D}_{\frac{3}{2}}\rangle)$	$\mathrm{P}(\Xi_{cc}D_2^*\vert^6\mathbb{D}_{\frac{3}{2}}\rangle)$
$(0, \frac{3}{2}^+)$	1.00	−0.53	3.64	**88.65**	0.17	0.81	10.35	$o(10^{-3})$	$o(10^{-3})$
	1.01	−2.44	1.68	**65.67**	0.14	0.67	**33.50**	$o(10^{-3})$	$o(10^{-3})$
	1.02	−6.49	0.96	**41.91**	0.08	0.34	**57.65**	$o(10^{-3})$	0.01
$(1, \frac{3}{2}^+)$	1.50	−0.22	4.87	**99.36**	0.05	0.24	0.29	$o(10^{-3})$	0.01
	1.63	−1.67	2.23	**95.76**	0.07	0.44	3.50	0.17	0.06
	1.76	−6.95	0.99	**57.95**	0.04	0.29	**40.91**	0.44	0.37

The most promising pentaquark moleculars

Isoscalar

$$\Xi_{cc}D_1(J^P = 1/2^+, 3/2^+)$$

$$\Xi_{cc}D_2^*(J^P = 3/2^+, 5/2^+)$$

Exotic triple-charm deuteronlike hexaquarks

Rui Chen,[1,2,3] Fu-Lai Wang,[1,2,*] Atsushi Hosaka,[3,†] and Xiang Liu[1,2,‡]

[1]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
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(Received 22 April 2018; revised manuscript received 12 May 2018; published 8 June 2018)

Adopting the one-boson-exchange model, we perform a systematic investigation of interactions between a doubly charmed baryon (Ξ_{cc}) and an S-wave charmed baryon (Λ_c, $\Sigma_c^{(*)}$, and $\Xi_c^{(\prime,*)}$). Both the $S-D$ mixing effect and coupled-channel effect are considered in this work. Our results suggest that there may exist several possible triple-charm deuteronlike hexaquarks. Meanwhile, we further study the interactions between a doubly charmed baryon and an S-wave anticharmed baryon. We find that a doubly charmed baryon and an S-wave anticharmed baryon can be easily bound together to form shallow molecular hexaquarks. These heavy flavor hexaquarks predicted here can be accessible at future experiment like LHCb.

TABLE IV. Bound state properties (binding energy E and root-mean-square radius r_{RMS}) for the molecular hexaquarks composed of a doubly charmed baryon and an S-wave anticharmed baryon. Here, E, r_{RMS}, and Λ are in units of MeV, fm, and GeV, respectively.

$I(J^P)$	Λ	E	r_{RMS}	$I(J^P)$	Λ	E	r_{RMS}	$I(J^P)$	Λ	E	r_{RMS}	$I(J^P)$	Λ	E	r_{RMS}
$\Xi_{cc}\bar{\Lambda}_c$								$\Xi_{cc}\bar{\Xi}_c$							
$1/2(0^+/1^+)$	1.00	−0.48	4.00					$0(0^+/1^+)$	0.95	−0.78	3.26	$1(0^+/1^+)$	1.10	−0.39	4.20
	1.10	−6.77	1.35						1.00	−5.09	1.50		1.30	−6.20	1.36
	1.20	−19.44	0.90						1.05	−13.06	1.04		1.50	−16.50	0.92
$\Xi_{cc}\bar{\Sigma}_c$				$\Xi_{cc}\bar{\Sigma}_c^*$				$\Xi_{cc}\bar{\Xi}_c'$				$\Xi_{cc}\bar{\Xi}_c^*$			
$1/2(0^+)$	0.80	−0.84	3.01	$1/2(1^+)$	0.80	−0.41	4.01	$0(0^+)$	0.85	−0.95	2.87	$0(1^+)$	0.85	−1.08	2.72
	0.95	−7.46	1.27		0.84	−3.86	1.60		0.95	−8.72	1.20		0.90	−7.14	1.24
	1.10	−10.97	1.18		0.88	−12.52	1.01		1.05	−19.52	0.93		0.95	−19.73	0.84
$1/2(1^+)$	0.92	−0.57	3.76	$1/2(2^+)$	0.95	−0.14	5.60	$0(1^+)$	0.95	−0.78	3.27	$0(2^+)$	1.00	−0.64	3.60
	0.96	−4.74	1.59		1.05	−4.93	1.65		1.00	−5.78	1.44		1.50	−6.90	1.31
	1.00	−13.93	1.06		1.15	−15.19	1.12		1.05	−16.19	0.98		1.80	−16.64	0.94
$3/2(0^+)$	1.35	−0.20	5.14	$3/2(1^+)$	1.00	−0.59	3.57	$1(0^+)$	1.20	−0.14	5.43	$1(1^+)$	1.20	−0.49	3.89
	1.70	−4.14	1.64		1.55	−4.40	1.60		1.50	−4.71	1.54		1.50	−4.71	1.54
	2.05	−9.94	1.16		1.85	−11.84	1.08		1.80	−11.84	1.07		1.80	−11.84	1.07
$3/2(1^+)$	1.00	−0.59	3.57	$3/2(2^+)$	1.00	−0.71	3.32	$1(1^+)$	1.10	−1.75	2.26	$1(2^+)$	1.00	−0.18	5.09
	1.10	−4.31	1.56		1.10	−4.42	1.54		1.20	−5.84	1.37		1.15	−5.16	1.43
	1.20	−11.00	1.08		1.20	−10.73	1.08		1.30	−11.81	1.04		1.30	−15.42	0.93

4

ISPE mechanism and charged Zc

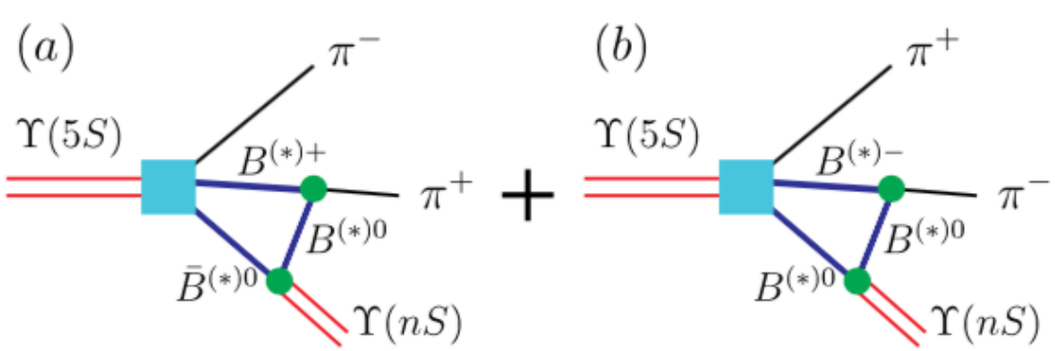
PHYSICAL REVIEW D **84**, 034032 (2011)

Predicted charged charmoniumlike structures in the hidden-charm dipion decay of higher charmonia

Dian-Yong Chen[1,3] and Xiang Liu[1,2,*,†]

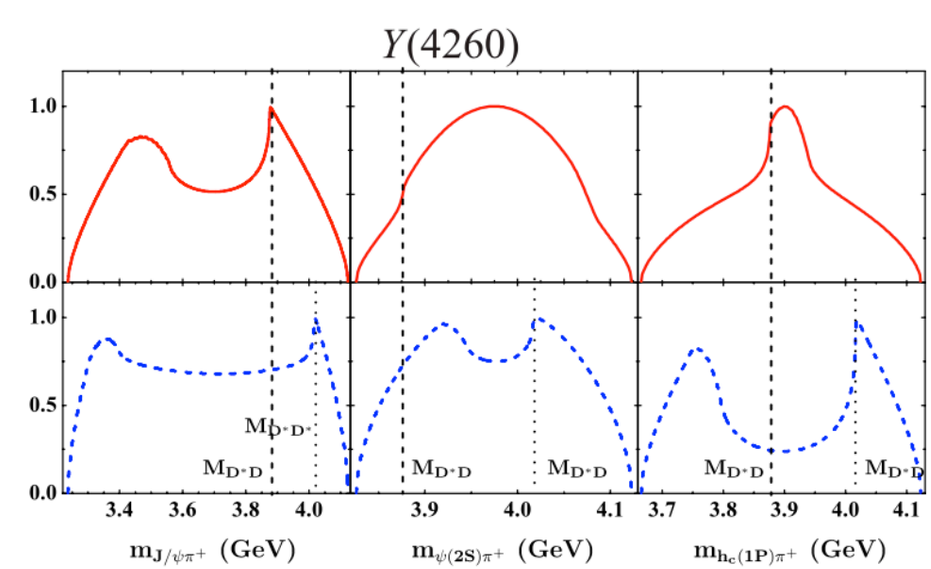
In this work, we predict two charged charmoniumlike enhancement structures close to the $D^*\bar{D}$ and $D^*\bar{D}^*$ thresholds, where the Initial Single Pion Emission mechanism is introduced in the hidden-charm dipion decays of higher charmonia $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ and charmoniumlike state $Y(4260)$. We suggest BESIII to search for these structures in the $J/\psi\pi^+$, $\psi(2S)\pi^+$ and $h_b(1P)\pi^+$ invariant mass spectra of the $\psi(4040)$ decays into $J/\psi\pi^+\pi^-$, $\psi(2S)\pi^+\pi^-$ and $h_b(1P)\pi^+\pi^-$. In addition, the experimental search for these enhancement structures in the $J/\psi\pi^+$, $\psi(2S)\pi^+$ and $h_c(1P)\pi^+$ invariant mass spectra of the $\psi(4260)$ hidden-charm dipion decays will be accessible at Belle and *BABAR*.

Initial Single Pioin Emission (ISPE) mechanism



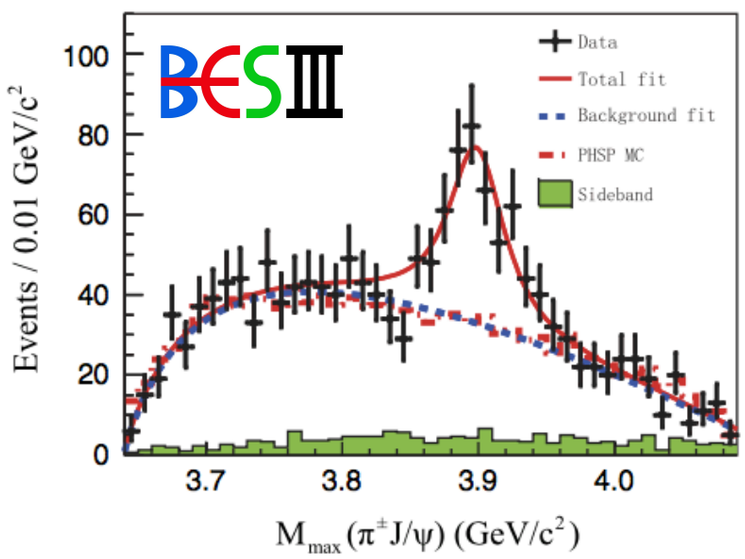
Chen, Liu, PRD84 (2011) 094003

Explicitly predict charged charmonium-like structures existing in hidden-charm dipion decays of Y(4260)

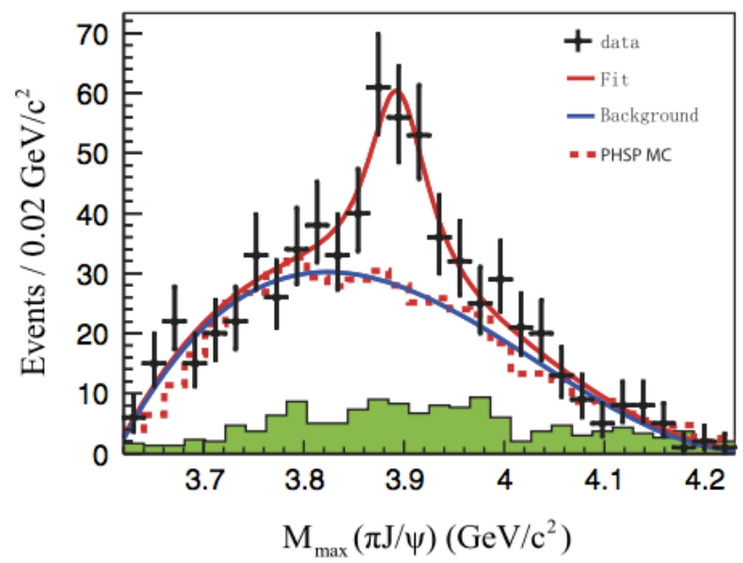


Discovery of Zc(3900)

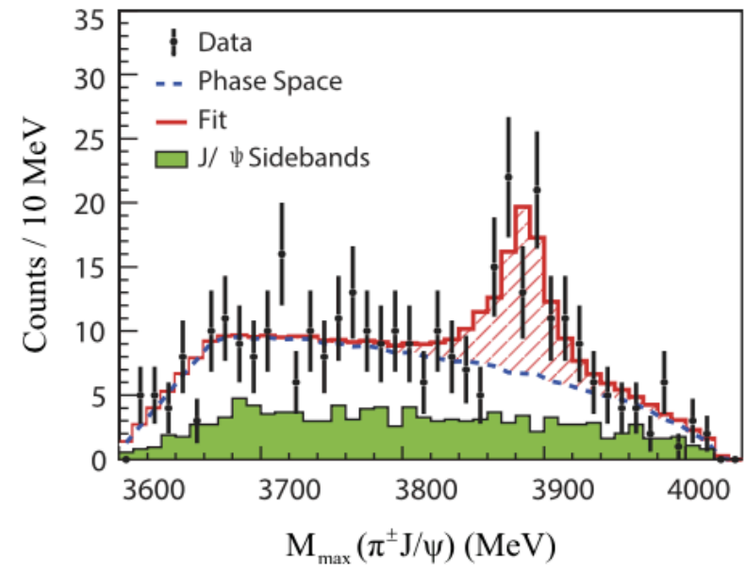
PRL110 (2013) 252001



PRL110 (2013) 252002

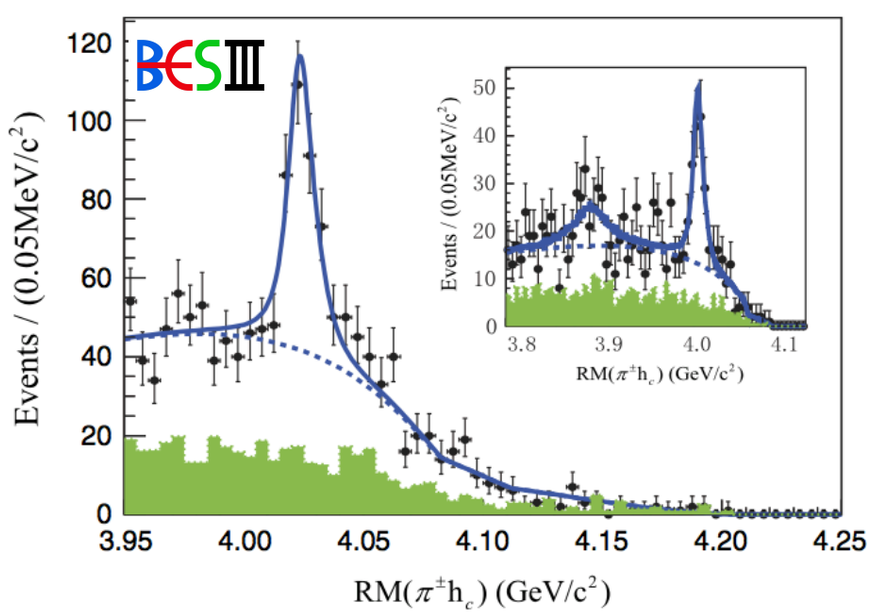


PLB773 (2013) 366



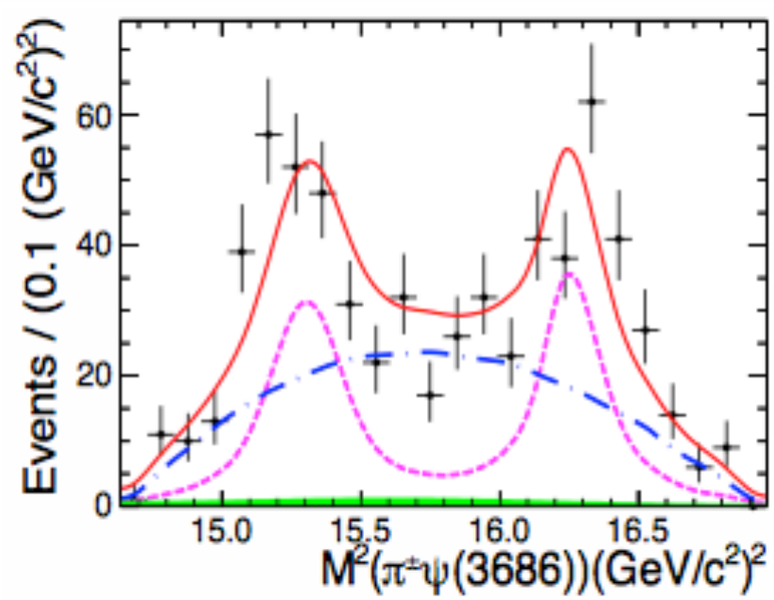
Discovery of Zc(4020)

PRL111 (2013) 242001



Discovery of Zc(4032)

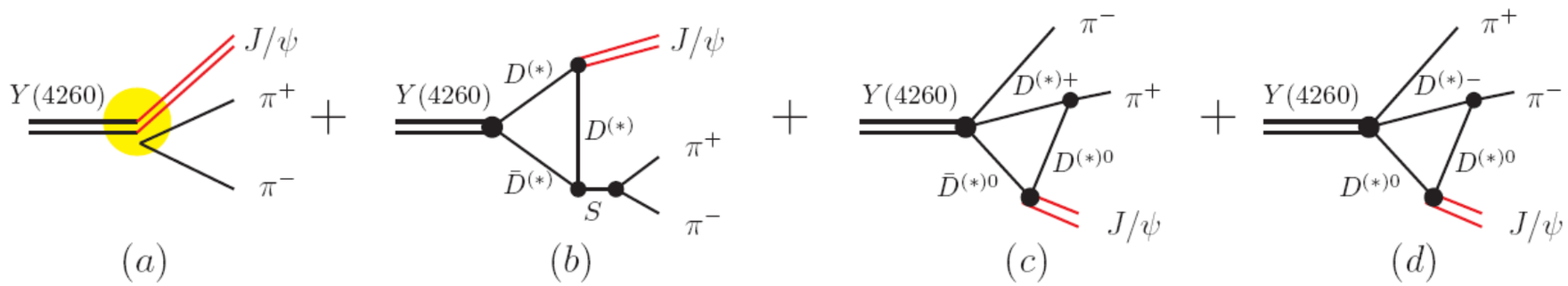
arXiv: 1703.08787



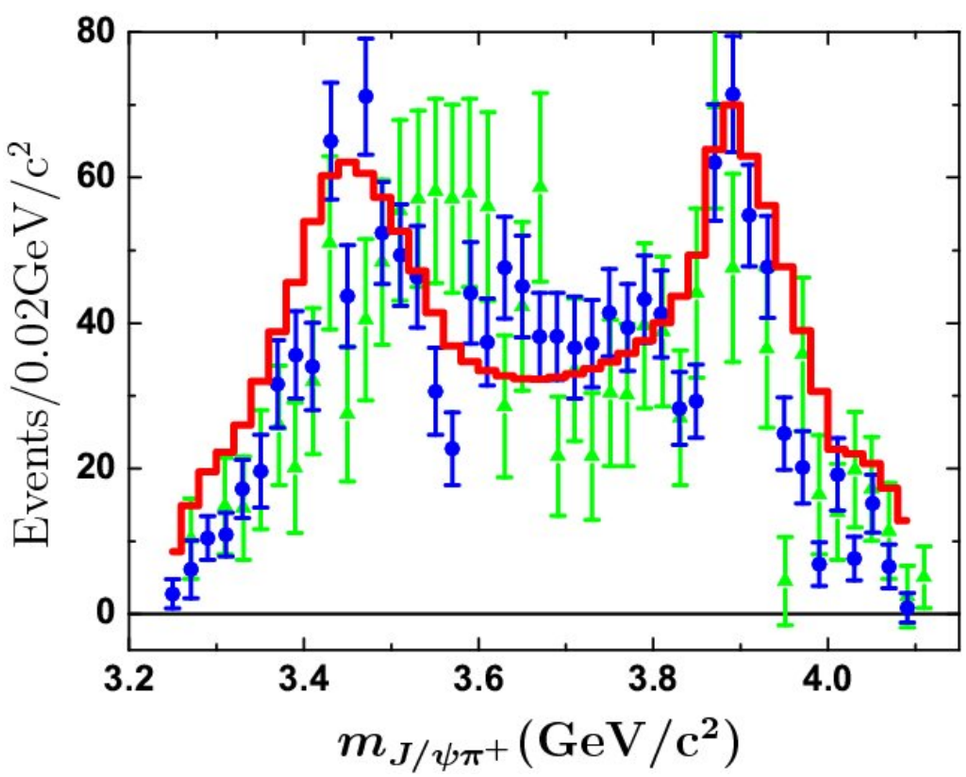
PHYSICAL REVIEW D **88,** 036008 (2013)

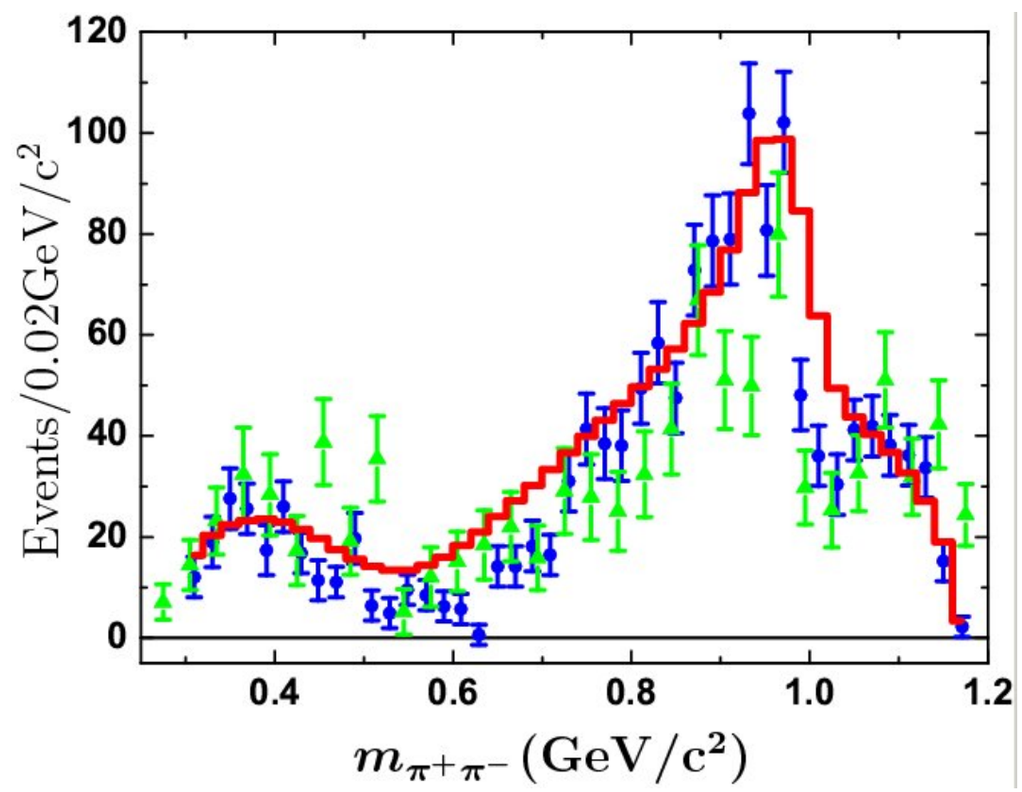
Reproducing the $Z_c(3900)$ structure through the initial-single-pion-emission mechanism

Dian-Yong Chen,[1,3,*] Xiang Liu,[1,2,†] and Takayuki Matsuki[4,‡]



Reproduce Zc(3900) via the ISPE mechanism





Lattice QCD simulation

PRL **117,** 242001 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

Fate of the Tetraquark Candidate $Z_c(3900)$ from Lattice QCD

Yoichi Ikeda,[1,2] Sinya Aoki,[3,4] Takumi Doi,[2] Shinya Gongyo,[3] Tetsuo Hatsuda,[2,5] Takashi Inoue,[6] Takumi Iritani,[7] Noriyoshi Ishii,[1] Keiko Murano,[1] and Kenji Sasaki[3,4]

(HAL QCD Collaboration)

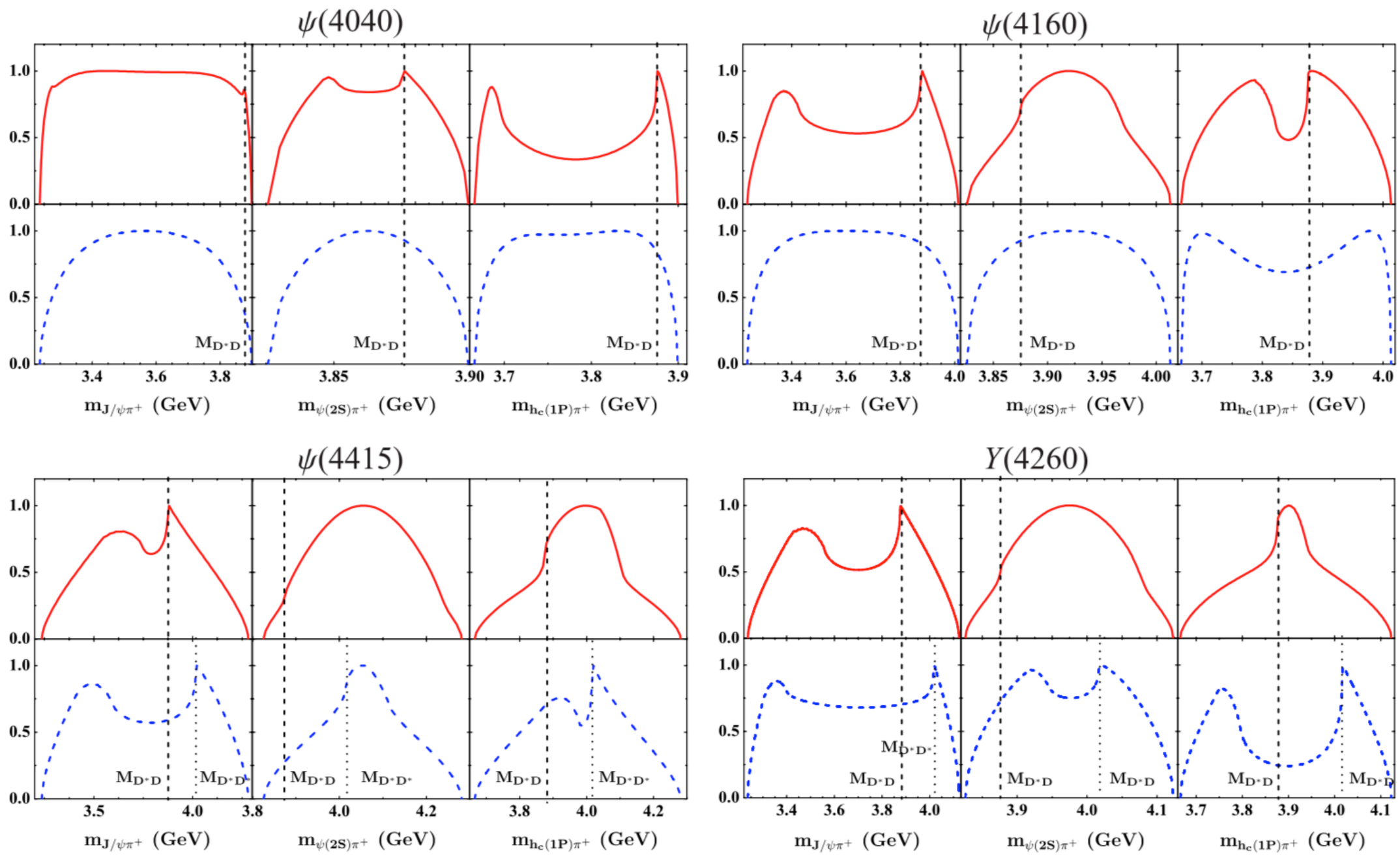
The possible exotic meson $Z_c(3900)$, found in e^+e^- reactions, is studied by the method of coupled-channel scattering in lattice QCD. The interactions among $\pi J/\psi$, $\rho\eta_c$, and $\bar{D}D^*$ channels are derived from $(2+1)$-flavor QCD simulations at $m_\pi = 410$–700 MeV. The interactions are dominated by the off-diagonal $\pi J/\psi$-$\bar{D}D^*$ and $\rho\eta_c$-$\bar{D}D^*$ couplings, which indicates that the $Z_c(3900)$ is not a usual resonance but a threshold cusp. Semiphenomenological analyses with the coupled-channel interaction are also presented to confirm this conclusion.

Lattice QCD simulation does not support exotic resonance explanation to Zc(3900)

PHYSICAL REVIEW D **84,** 034032 (2011)

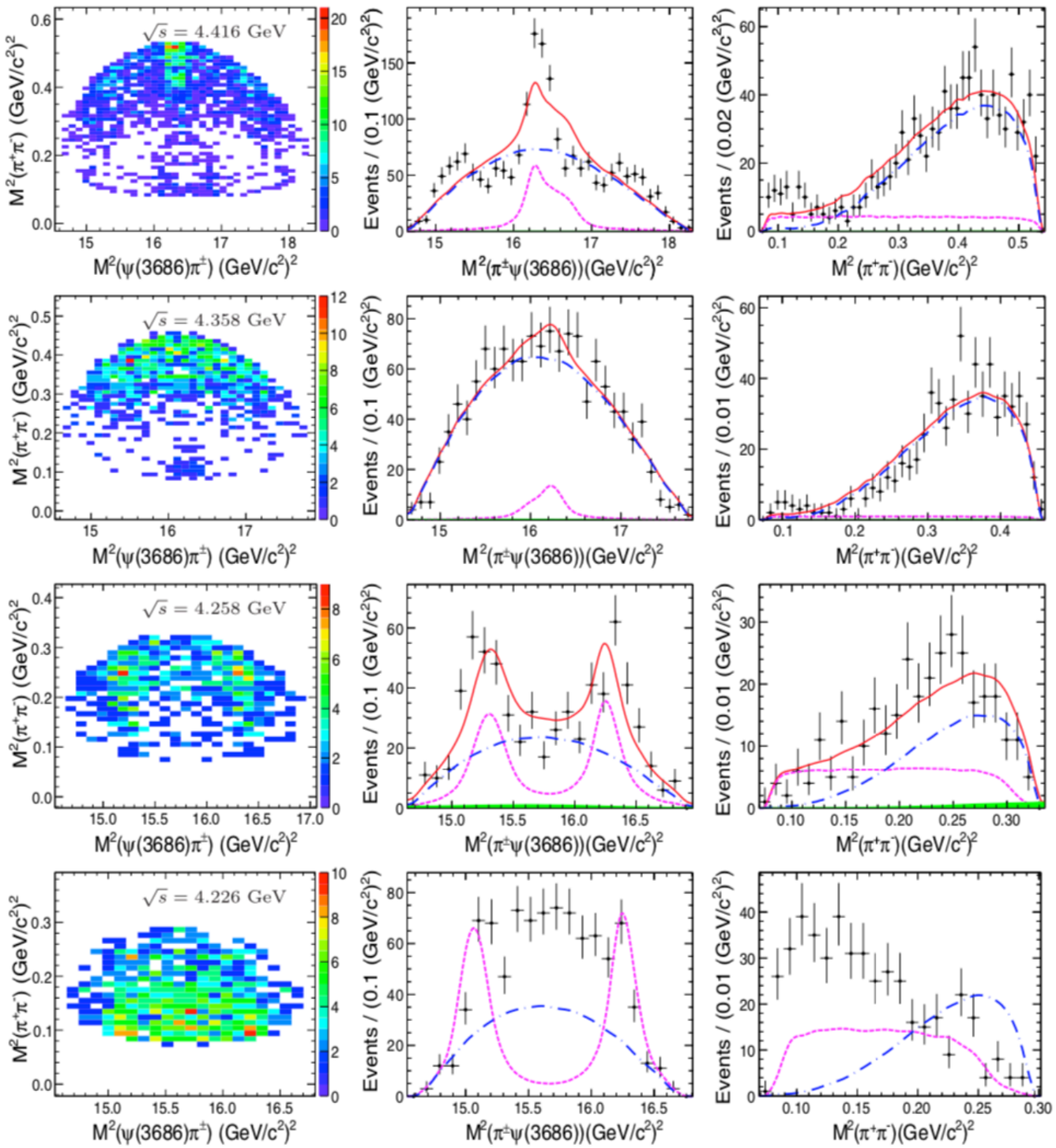
Predicted charged charmoniumlike structures in the hidden-charm dipion decay of higher charmonia

Dian-Yong Chen[1,3] and Xiang Liu[1,2,*,†]



PHYSICAL REVIEW D **96,** 032004 (2017)

Measurement of $e^+e^- \to \pi^+\pi^-\psi(3686)$ from 4.008 to 4.600 GeV and observation of a charged structure in the $\pi^\pm\psi(3686)$ mass spectrum



$\sqrt{s} = 4.416\,GeV$

$\sqrt{s} = 4.358\,GeV$

$\sqrt{s} = 4.258\,GeV$

$\sqrt{s} = 4.226\,GeV$

The line shapes of structures changes with increasing energy

Consistent with our prediction

Eur. Phys. J. C (2019) 79:613
https://doi.org/10.1140/epjc/s10052-019-7121-9

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Charged charmoniumlike structures in the $e^+e^- \to \psi(3686)\pi^+\pi^-$ process based on the ISPE mechanism

Qi Huang[1,2,a], **Dian-Yong Chen**[3,b], **Xiang Liu**[1,2,c], **Takayuki Matsuki**[4,5,d]

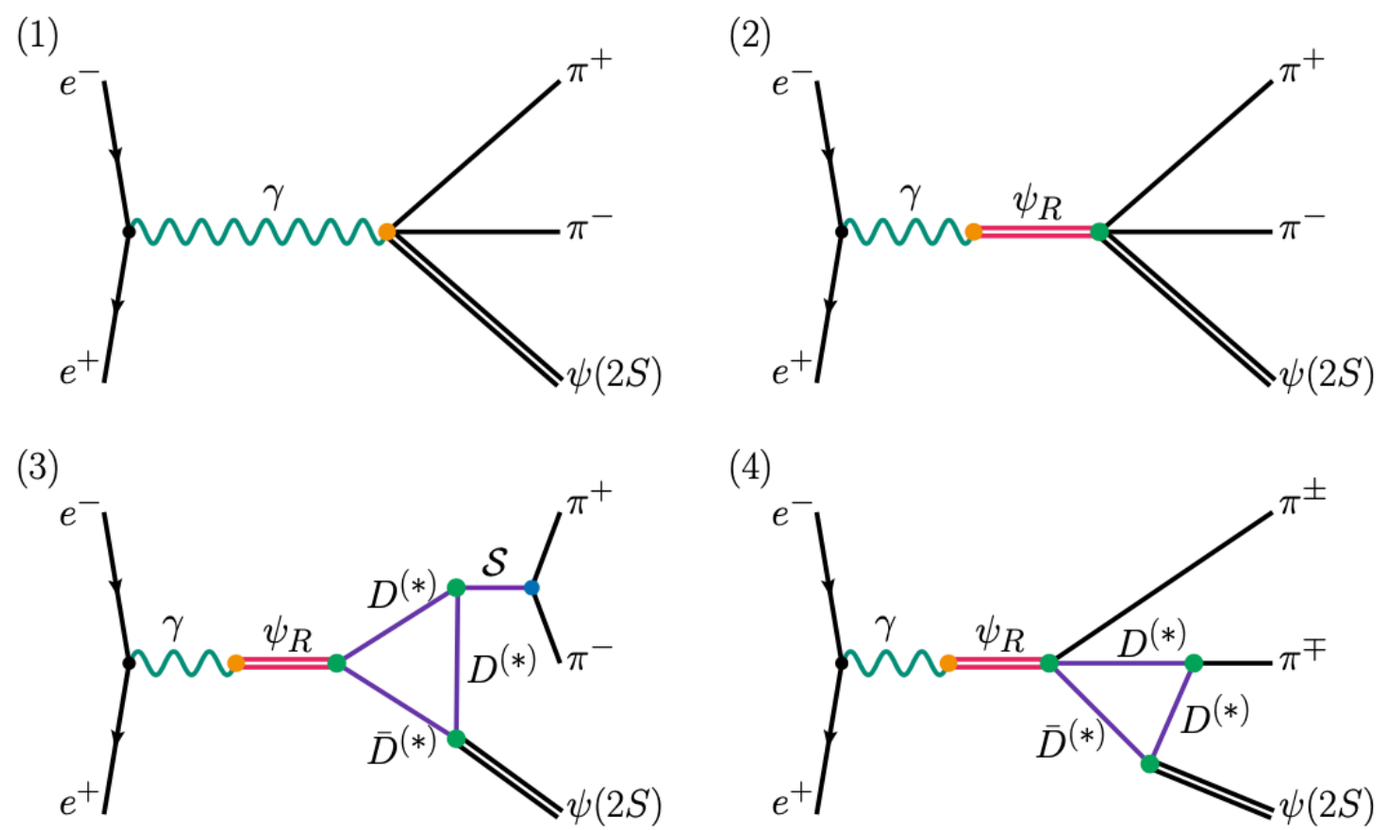
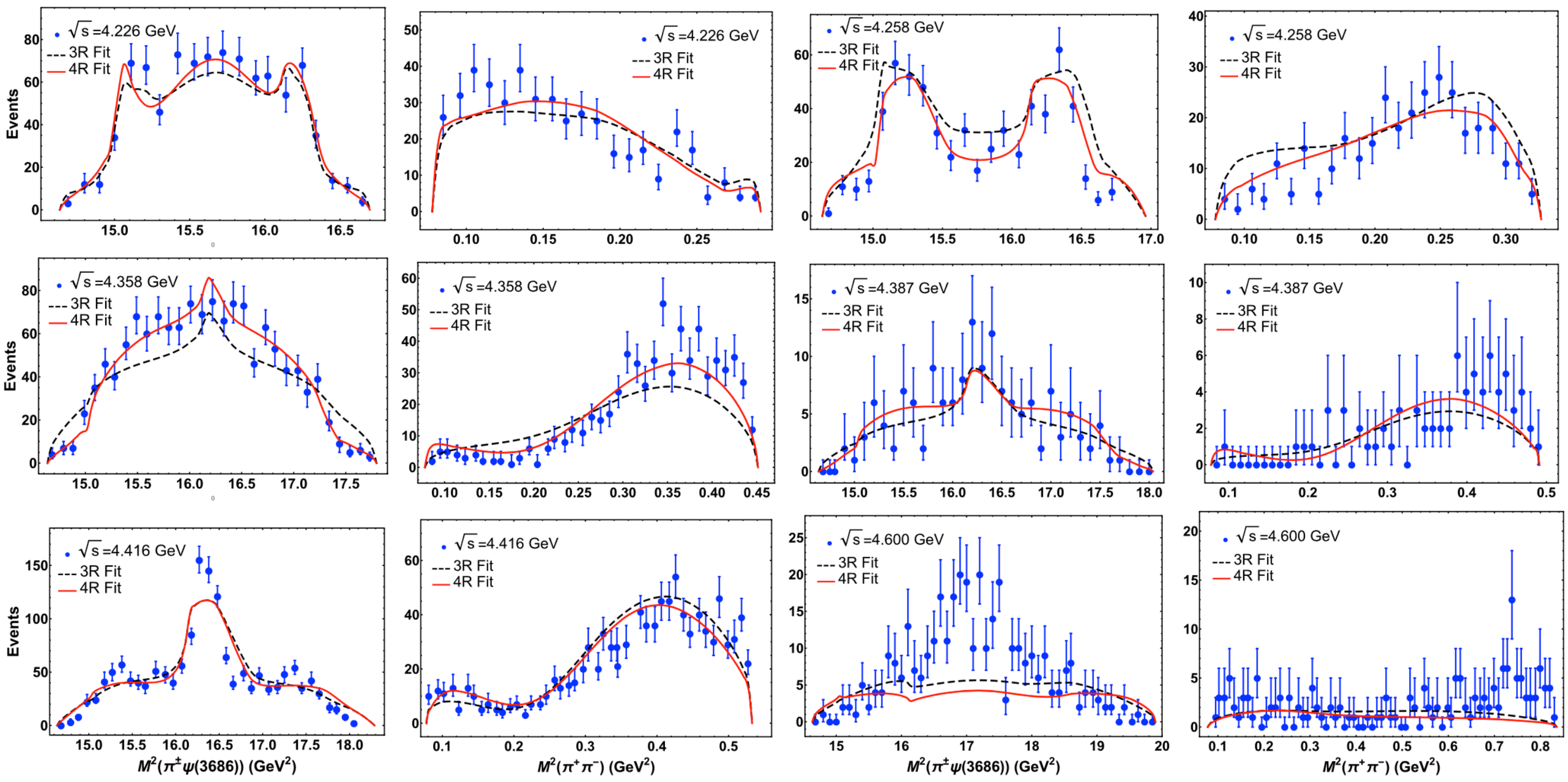


Fig. 2 Feynman diagrams depicting the decay mechanisms which give contributions to the process $e^+e^- \to \psi(3686)\pi^+\pi^-$

Huang, Chen, X.Liu, Matsuki, EPJC 79 (2019) 613

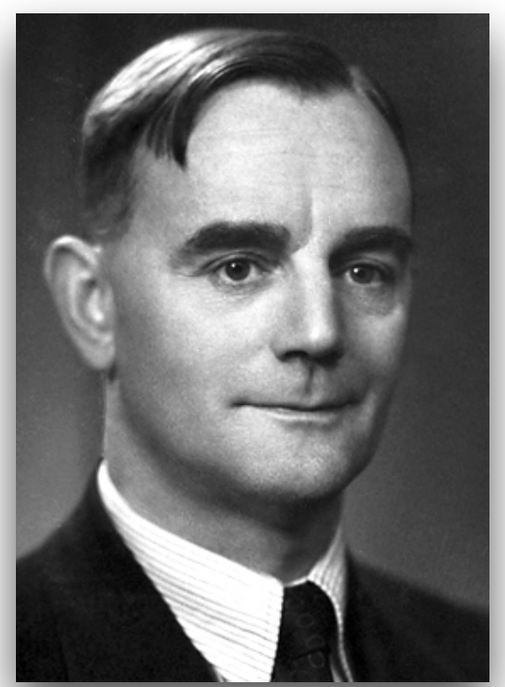


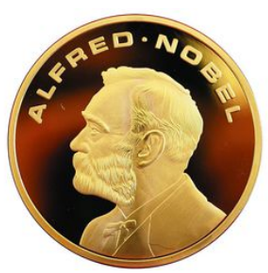
5

Summary

Observation of Pion

In 1947, the first true mesons, the charged pions, were found by the collaboration of Cecil Powell, César Lattes, Giuseppe Occhialini, *et al.*, at the University of Bristol, in England.





Cecil Frank Powell

The Nobel Prize in Physics **1950** 'for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method'.

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

$\pi^{\pm}$

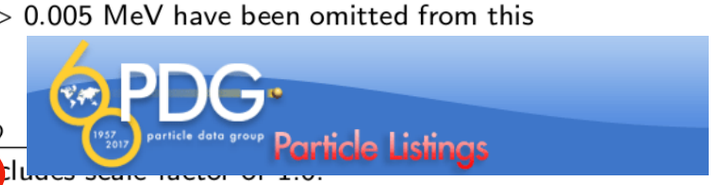
$I^G(J^P) = 1^-(0^-)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** 1 (1988).

$\pi^{\pm}$ MASS

The most accurate charged pion mass measurements are based upon x-ray wavelength measurements for transitions in π^--mesonic atoms. The observed line is the blend of three components, corresponding to different K-shell occupancies. JECKELMANN 94 revisits the occupancy question, with the conclusion that two sets of occupancy ratios, resulting in two different pion masses (Solutions A and B), are equally probable. We choose the higher Solution B since only this solution is consistent with a positive mass-squared for the muon neutrino, given the precise muon momentum measurements now available (DAUM 91, ASSAMAGAN 94, and ASSAMAGAN 96) for the decay of pions at rest. Earlier mass determinations with pi-mesonic atoms may have used incorrect K-shell screening corrections.

Measurements with an error of > 0.005 MeV have been omitted from this Listing.



VALUE (MeV)	*DOCUMENT ID*		
139.57061±0.00024 OUR FIT	Error includes scale factor of 1.5.		
139.57061±0.00023 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.		
139.57077±0.00018	[1] TRASSINELLI 16	CNTR	X-ray transitions in pionic

Well-established Pseudoscalar mesons listed in PDG

Mesons (pi, K, D, B, psi, Upsilon, ...)

Light Unflavored Mesons (S = C = B = 0)

Leptonic Decays of Charged Pseudoscalar Mesons
pi+−
pi0
eta
f(0)(500)
rho(770)
omega(782)
eta'(958)
f(0)(980)
a(0)(980)
phi(1020)
h(1)(1170)
eta(1295)
pi(1300)
a(2)(1320)
f(0)(1370)
h(1)(1380)
pi(1)(1400)
eta(1405)

omega(1650)
omega(3)(1670)
pi(2)(1670)
phi(1680)
rho(3)(1690)
rho(1700)
a(2)(1700)
f(0)(1710)
eta(1760)
pi(1800)
f(2)(1810)
X(1835)
rho(1900)
f(2)(1910)
a(0)(1950)
f(2)(1950)
rho(3)(1990)
f(2)(2010)
f(0)(2020)

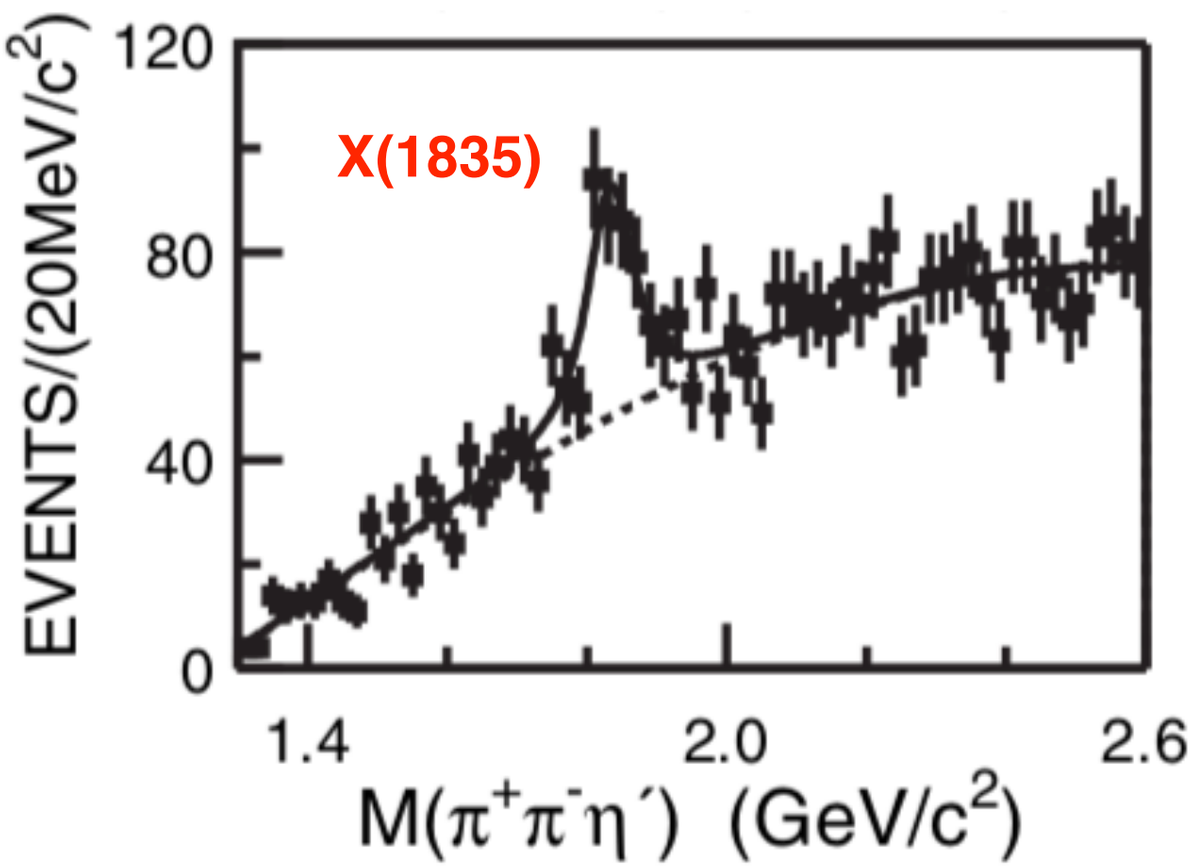
a(1)(1420)
f(2)(1430)
a(0)(1450)
rho(1450)
eta(1475)
f(0)(1500)
f(1)(1510)
f(2)'(1525)
f(2)(1565)
rho(1570)
h(1)(1595)
pi(1)(1600)
a(1)(1640)
f(2)(1640)

pi(2)(2100)
f(0)(2100)
f(2)(2150)
rho(2150)
phi(2170)
f(0)(2200)
f(J)(2220)
eta(2225)
rho(3)(2250)
f(2)(2300)
f(4)(2300)
f(0)(2330)
f(2)(2340)
rho(5)(2350)

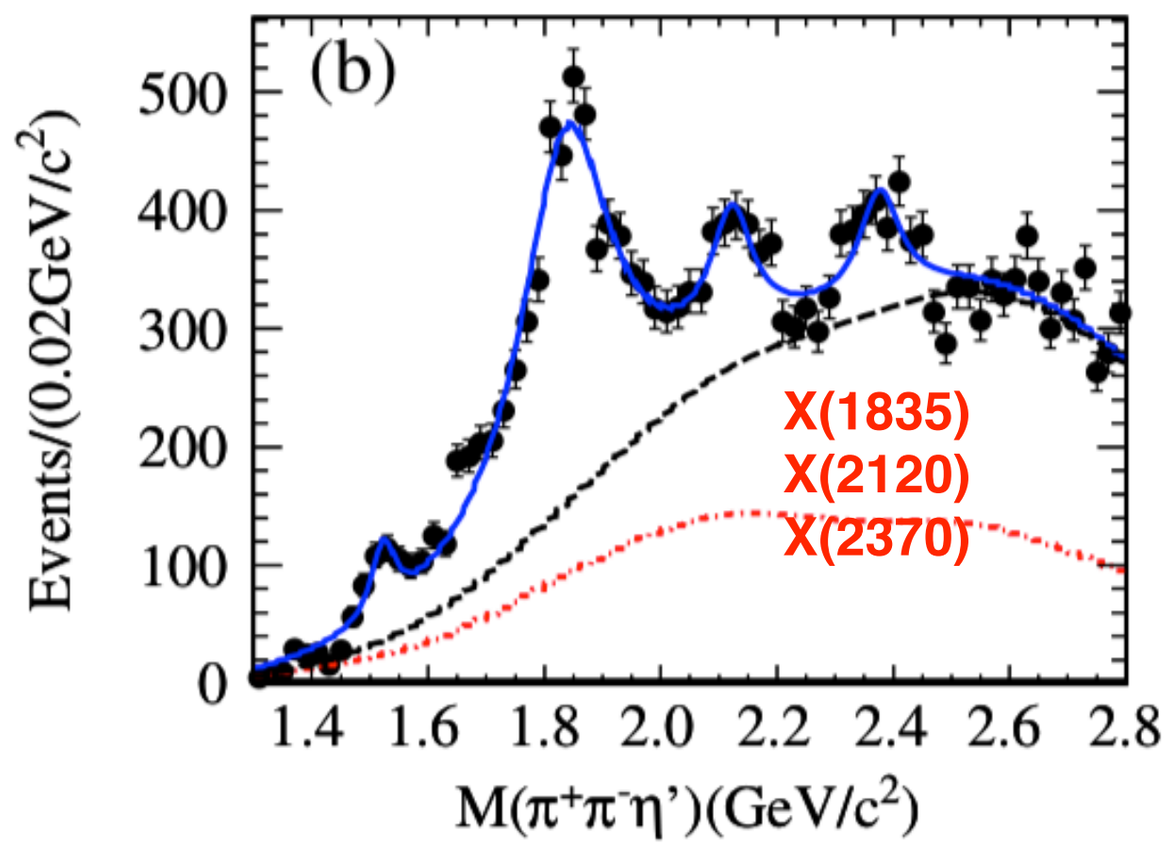
Seven pseudoscalar mesons were observed in the past decades

The exploration to pesudoscalar states

BESII PRL95 (2005) 262001



BESIII PRL106 (2011) 072002



Observation of an Anomalous Line Shape of the $\eta'\pi^+\pi^-$ Mass Spectrum near the $p\bar{p}$ Mass Threshold in $J/\psi \to \gamma\eta'\pi^+\pi^-$

Peak around 2640 MeV

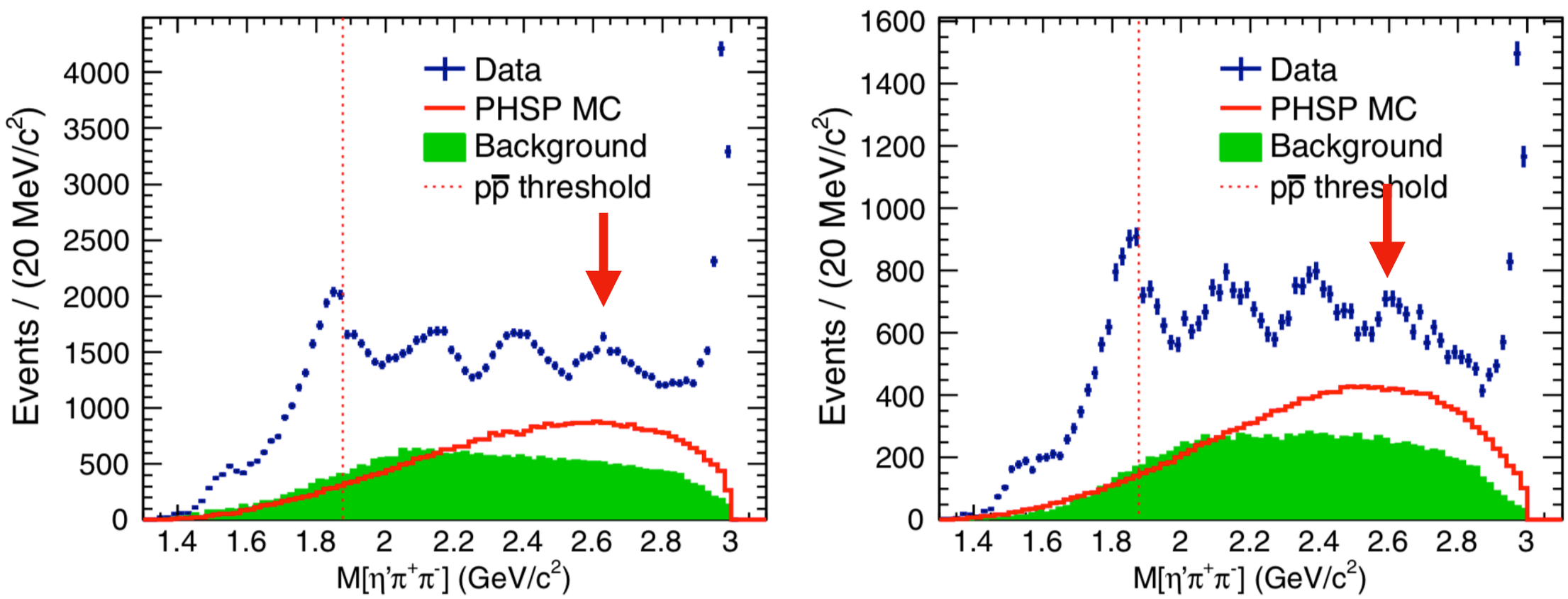
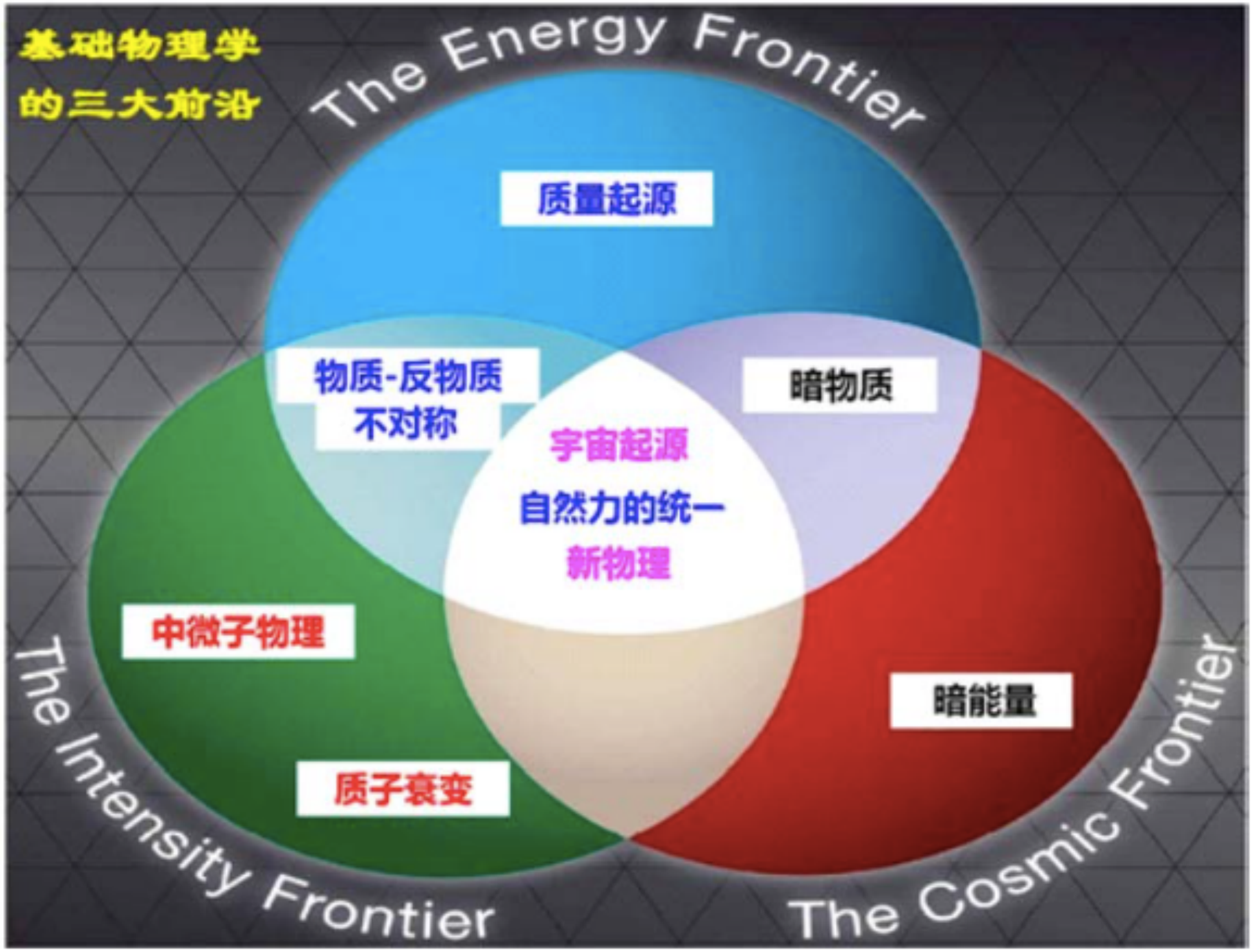


FIG. 1. The $\eta'\pi^+\pi^-$ invariant mass spectra after the application of all selection criteria. The plot on the left side shows the spectrum for events with the $\eta' \to \gamma\pi^+\pi^-$ channel, and that on the right shows the spectrum for the $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ channel. In both plots, the dots with error bars are data, the shaded histograms are the background, the solid histograms are phase space (PHSP) MC events of $J/\psi \to \gamma\eta'\pi^+\pi^-$ (arbitrary normalization), and the dotted vertical line shows the position of the $p\bar{p}$ mass threshold.



强子物理是精度前沿的代表

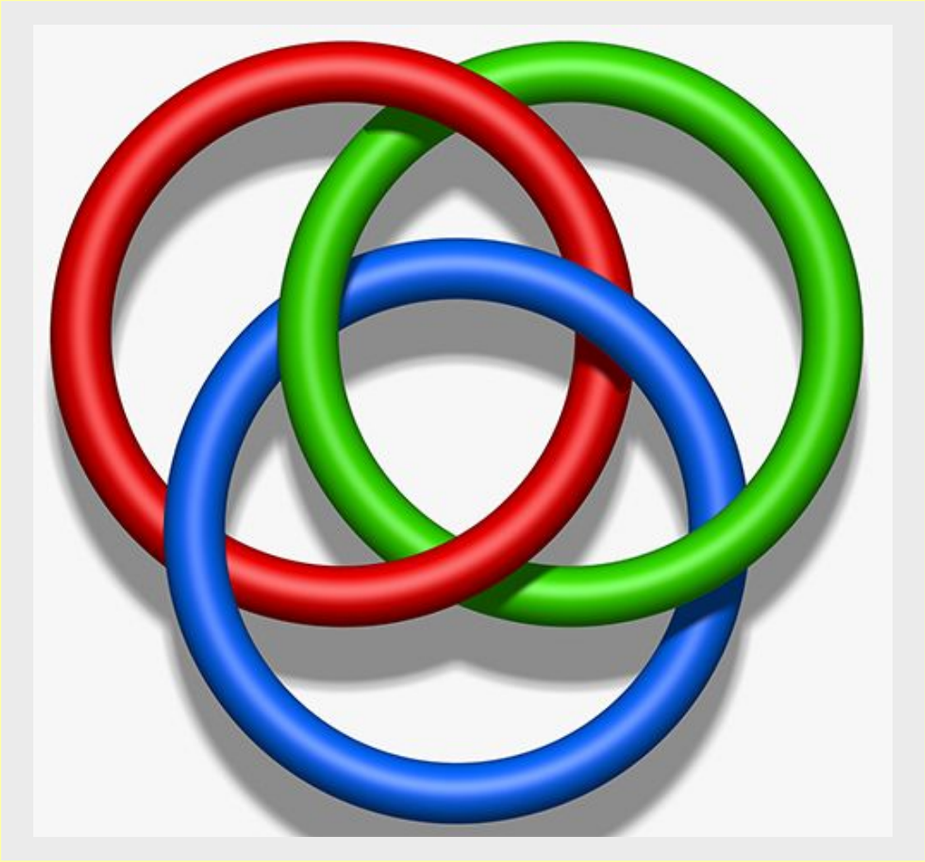
“精度”体现在

理论计算

实验数据

Studying XYZ states

Experimental analysis



Lattice QCD

Phenomenological models

Thank you for your attention!