XYZ Physics at 2.1 GeV, 4.2 GeV and 10.86 GeV

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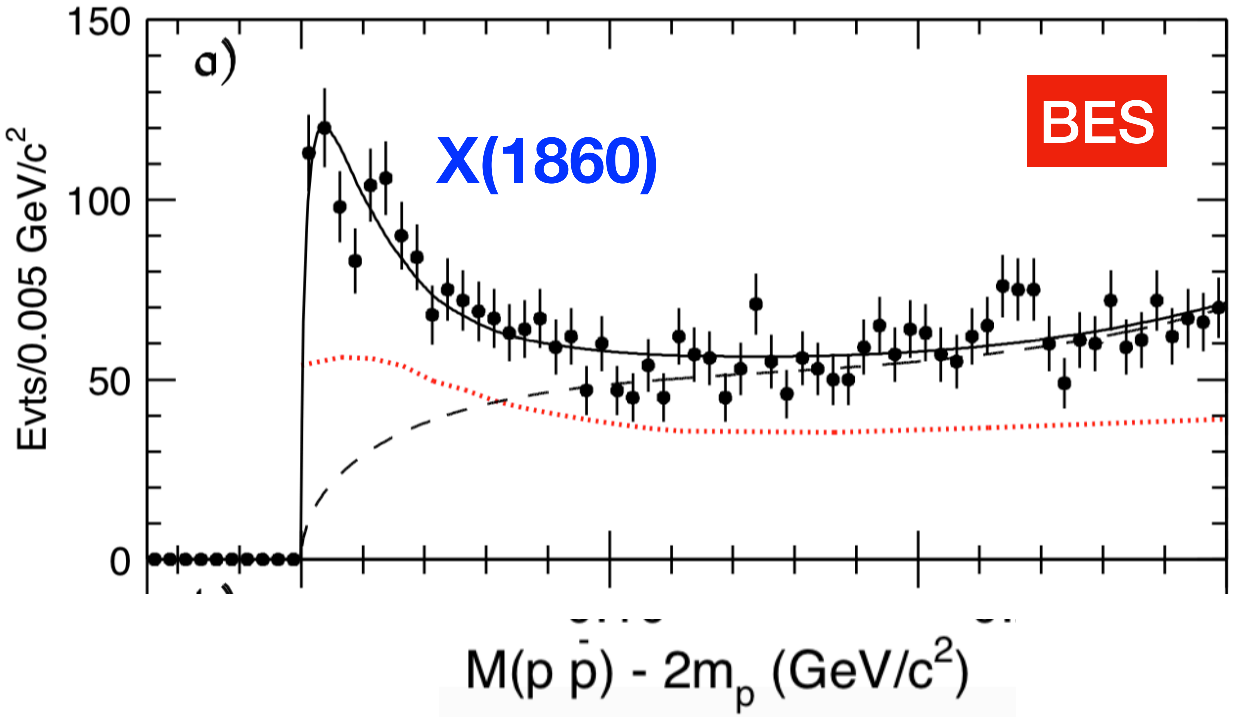
Outline

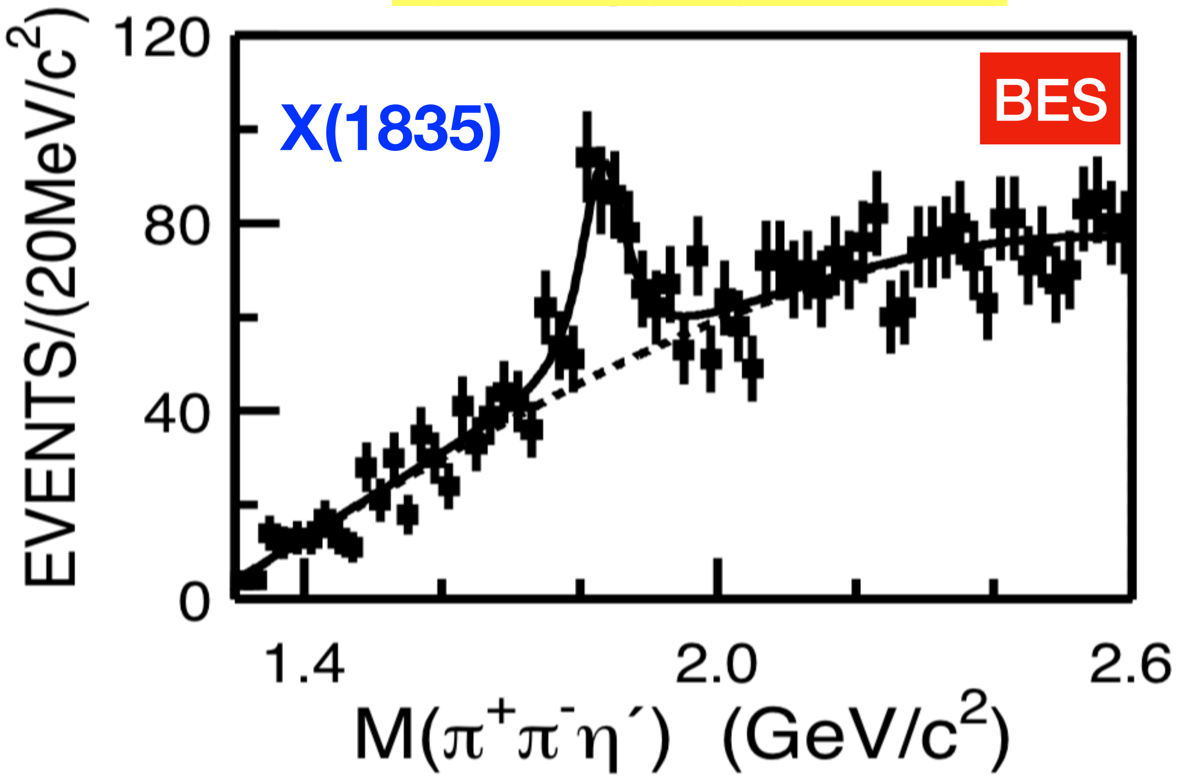
- The observations of XYZ states
- Y states at 2.1 GeV
- Y states at 4.2 GeV
- Physics around higher Upsilon states
- Summary

X(1860)和X(1835)

PRL 91 (2003) 022001



PRL 95 (2005) 262001



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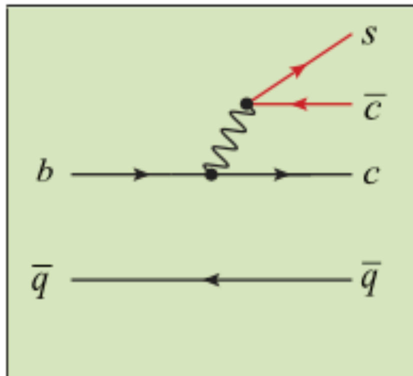
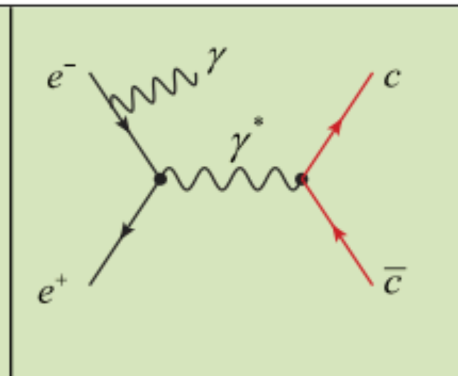
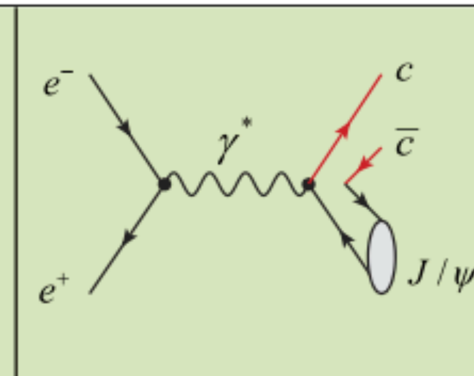
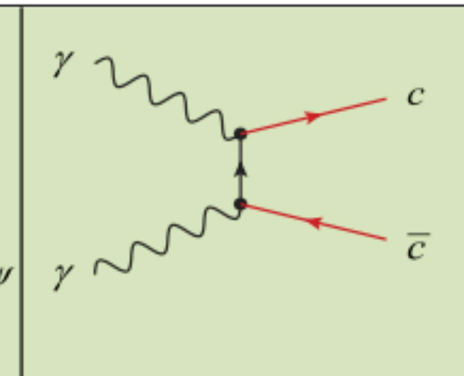
The observed charmonium-like XYZ states

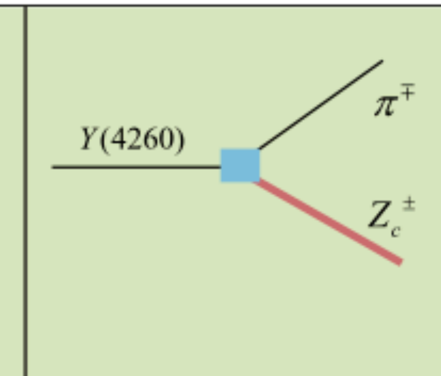
According to the production mechanisms, we can categorize them into five groups











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

see review

Physics Reports 639 (2016) 1–121

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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,**]

Discovery modes

States	Status	Mass [MeV]	Width [MeV]	I^GJ^{PC}/IJ^P	Observation	Note
$X(3872)$	∗∗∗∗	3871.69 ± 0.17 [1]	<1.2 [1]	0^+1^{++}	$B \to KX(3872)$: $\to J/\psi\rho^0, J/\psi\pi^+\pi^-$	Belle [63], BaBar [84]
					$B \to KX(3872)$: $\to J/\psi\omega(\to \pi^+\pi^-\pi^0)$	Belle [75], BaBar [90]
					$B \to KX(3872)$: $\to D^0\bar{D}^{*0}, D^0\bar{D}^0\pi^0$	Belle [76], BaBar [87]
					$B \to KX(3872)$: $\to \gamma J/\psi, \gamma\psi(3686)$	Belle [75], BaBar [86]
					$p\bar{p} \to \cdots + X(3872)(\to J/\psi\pi^+\pi^-)$	CDF [67], D0 [68]
					$pp \to \cdots + X(3872)$: $\to J/\psi\pi^+\pi^-$	LHCb [91], CMS [73]
					$pp \to \cdots + X(3872)$: $\to \gamma J/\psi, \gamma\psi(3686)$	LHCb [92]
					$e^+e^-[\to Y(4260)] \to \gamma X(3872)(\to J/\psi\pi^+\pi^-)$	BESIII [93]
$Y(4260)$	∗∗∗∗	4251 ± 9 [1]	120 ± 12 [1]	0^-1^{--}	$e^+e^- \to \gamma_{ISR}Y(4260)$: $\to J/\psi\pi^+\pi^-$	BaBar [62], CLEO [60], Belle [119]
					$e^+e^- \to \gamma_{ISR}Y(4260)$: $\to J/\psi f_0(980)$	BaBar [123]
					$e^+e^- \to \gamma_{ISR}Y(4260)$: $\to J/\psi\pi^0\pi^0$	CLEO [120]
					$e^+e^- \to Y(4260)$: $\to \pi^-Z_c(3900)^+(\to J/\psi\pi^+)$	BESIII [64], Belle [124]
					$e^+e^- \to Y(4260)$: $\to \pi^-Z_c(3885)^+(\to (D\bar{D}^*)^+)$	BESIII [159]
					$e^+e^- \to Y(4260)$: $\to \pi^-Z_c(4020)^+(\to h_c\pi^+)$	BESIII [160]
					$e^+e^- \to Y(4260)$: $\to \pi^-Z_c(4025)^+(\to (D^*\bar{D}^*)^+)$	BESIII [161]
					$e^+e^-[\to Y(4260)] \to \gamma X(3872)(\to J/\psi\pi^+\pi^-)$	BESIII [93]

States	Status	Mass [MeV]	Width [MeV]	I^GJ^{PC}/IJ^P	Observation	Note
$Y(3940)$	∗∗∗	$3919.1^{+3.8}_{-3.5} \pm 2.0$ [90]	$31^{+10}_{-8} \pm 5$ [90]	$0^+ ?^{?+}$	$B \to KY(3940)(\to J/\psi\omega)$	Belle [96], BaBar [97]
$Y(4140)$	∗∗∗	$4148.0 \pm 2.4 \pm 6.3$ [74]	$28^{+15}_{-11} \pm 19$ [74]	$0^+ ?^{?+}$	$B \to KY(4140)(\to J/\psi\phi)$	CDF [69], D0 [102], CMS [74]
$Y(4274)$	∗∗∗	$4274.4^{+8.4}_{-6.7} \pm 1.9$ [100]	$32.3^{+21.9}_{-15.3} \pm 7.6$ [100]	$0^+ ?^{?+}$	$B \to KY(4274)(\to J/\psi\phi)$	CDF [100], CMS [74]
					$\psi' \to J/\psi\pi^+\pi^-$	E705 [111],
$X(3823)$	∗∗∗∗	$3821.7 \pm 1.3 \pm 0.7$ [118]	<16 [118]	0^-2^{--}	$B \to KX(3823)(\to \gamma\chi_{c1})$	Belle [112],
					$e^+e^- \to \pi^+\pi^-X(3823)(\to \gamma\chi_{c1})$	BESIII [118]
$Y(4360)$	∗∗∗	4354 ± 10 [1]	78 ± 16 [1]	0^-1^{--}	$e^+e^- \to \gamma_{ISR}Y(4360)(\to \psi(3686)\pi^+\pi^-)$	BaBar [144],Belle [145]
$Y(4660)$	∗∗∗∗	4665 ± 10 [1]	53 ± 16 [1]	0^-1^{--}	$e^+e^- \to \gamma_{ISR}Y(4660)(\to \psi(3686)\pi^+\pi^-)$	Belle [145], BaBar [146]
$Y(4630)$		4634^{+8+5}_{-7-8} [147]	92^{+40+10}_{-24-21} [147]		$e^+e^- \to \gamma_{ISR}Y(4630)(\to \Lambda_c\bar{\Lambda}_c)$	Belle [147]
$X(3915)$	∗∗∗	$3915\pm3\pm2$ [152]	$17\pm10\pm3$ [152]	0^+0^{++}	$\gamma\gamma \to X(3915)(\to J/\psi\omega)$	Belle [152], BaBar [155]
$Z(3930)$	∗∗∗	$3929\pm5\pm2$ [151]	$29\pm10\pm2$ [151]	0^+2^{++}	$\gamma\gamma \to Z(3930)(\to D\bar{D})$	Belle [151], BaBar [154]
$Z^+(4430)$	∗∗∗	4478^{+15}_{-18} [1]	181 ± 31 [1]	1^+1^{+-}	$B \to KZ^+(4430)(\to \psi(3686)\pi^+)$	Belle [103],LHCb [108]
$Z_c(3900)$	∗∗∗∗	3888.7 ± 3.4 [1]	35 ± 7 [1]	1^+1^{+-}	$e^+e^- \to Y(4260) \to \pi^-Z_c(3900)^+(\to J/\psi\pi^+)$	BESIII [64], Belle [124],
					$e^+e^- \to \psi(4160) \to \pi^-Z_c(3900)^+(\to J/\psi\pi^+)$	Xiao et al. [61]
$Z_c(3885)$		$3883.9 \pm 1.5 \pm 4.2$ [159]	$24.8 \pm 3.3 \pm 11.0$ [159]		$e^+e^- \to Y(4260) \to \pi^-Z_c(3885)^+(\to (D\bar{D}^*)^+)$	BESIII [159]
$Z_c(4020)$	∗∗∗∗	$4022.9 \pm 0.8 \pm 2.7$ [160]	$7.9 \pm 2.7 \pm 2.6$ [160]	1^+1^{+-}	$e^+e^- \to Y(4260) \to \pi^-Z_c(4020)^+(\to h_c\pi^+)$	BESIII [160]
$Z_c(4025)$		$4026.3 \pm 2.6 \pm 3.7$ [161]	$24.8 \pm 5.6 \pm 7.7$ [161]		$e^+e^- \to Y(4260) \to \pi^-Z_c(4025)^+(\to (D^*\bar{D}^*)^+)$	BESIII [161]

Discovery modes (continued)

States	Status	Mass [MeV]	Width [MeV]	$I^G J^{PC}/IJ^P$	Observation	Note
$Y(4008)$	$*$	$4008 \pm 40^{+114}_{-28}$ [119]	$226 \pm 44 \pm 87$ [119]	$0^- 1^{--}$	$e^+e^- \to \gamma_{\rm ISR} Y(4008)(\to J/\psi\pi^+\pi^-)$	Belle [119]
$X(3940)$	$*$	$3942^{+7}_{-6} \pm 6$ [148]	$37^{+26}_{-15} \pm 8$ [148]	$?^? ?^{?+}$	$e^+e^- \to J/\psi X(3940)(\to \bar{D}D^*)$	Belle [148]
$X(4160)$	$*$	$4156^{+25}_{-20} \pm 15$ [148]	$139^{+111}_{-61} \pm 21$ [148]	$?^? ?^{?+}$	$e^+e^- \to J/\psi X(4160)(\to \bar{D}^*D^*)$	Belle [148]
$X(4350)$	$*$	$4350.6^{+4.6}_{-5.1} \pm 0.7$ [99]	$13^{+18}_{-9} \pm 4$ [99]	$?^? 0^{?+}/2^{?+}$	$\gamma\gamma \to X(4350)(\to J/\psi\phi)$	Belle [99]
$Z^+(4051)$	$*$	$4051 \pm 14^{+20}_{-41}$ [109]	82^{+21+47}_{-17-22} [109]	$? ?^?$	$B \to KZ^+(4051)(\to \chi_{c1}\pi^+)$	Belle [109]
$Z^+(4248)$	$*$	$4248^{+44+180}_{-29-35}$ [109]	$177^{+54+316}_{-39-61}$ [109]	$? ?^?$	$B \to KZ^+(4248)(\to \chi_{c1}\pi^+)$	Belle [109]
$Z^+(4200)$	$*$	4196^{+31+17}_{-29-13} [107]	$370^{+70+70}_{-70-132}$ [107]	1^+1^{+-}	$B \to KZ^+(4200)(\to J/\psi\pi^+)$	Belle [107]
$Z^+(4240)$	$*$	$4239 \pm 18^{+45}_{-10}$ [108]	$220 \pm 47^{+108}_{-74}$ [108]	$?0^-/?1^+$	$B \to KZ^+(4240)(\to \psi(3686)\pi^+)$	LHCb [108]
$Z_b(10610)$	$**$	10607.2±2.0 [172]	18.4±2.4 [172]	1^+1^{+-}	$\Upsilon(5S) \to \pi^\mp Z_b^\pm(10610) \begin{cases} \to\pi^\pm\Upsilon(nS)(n=1,2,3) \\ \to\pi^\pm h_b(mP)(m=1,2) \end{cases}$ $\Upsilon(10860) \to \pi^\mp Z_b^\pm(10610)(\to [B\bar{B}^* + \text{c.c.}]^\pm)$	Belle [172], Belle [177]
$Z_b(10650)$	$**$	10652.2±1.5 [172]	11.5±2.2 [172]	1^+1^{+-}	$\Upsilon(5S) \to \pi^\mp Z_b^\pm(10610) \begin{cases} \to\pi^\pm\Upsilon(nS)(n=1,2,3) \\ \to\pi^\pm h_b(mP)(m=1,2) \end{cases}$ $\Upsilon(10860) \to \pi^\mp Z_b^\pm(10650)(\to [B^*\bar{B}^*]^\pm)$	Belle [172], Belle [177]
$P_c(4380)^+$	$*$	$4380 \pm 8 \pm 29$ [2]	$205 \pm 18 \pm 86$ [2]	$\frac{1}{2}\ ?^?$	$\Lambda_b^0 \to K^- P_c(4380)^+(\to J/\psi p)$	LHCb [2]
$P_c(4450)^+$	$*$	$4449.8 \pm 1.7 \pm 2.5$ [2]	$39 \pm 5 \pm 19$ [2]	$\frac{1}{2}\ ?^?$	$\Lambda_b^0 \to K^- P_c(4450)^+(\to J/\psi p)$	LHCb [2]

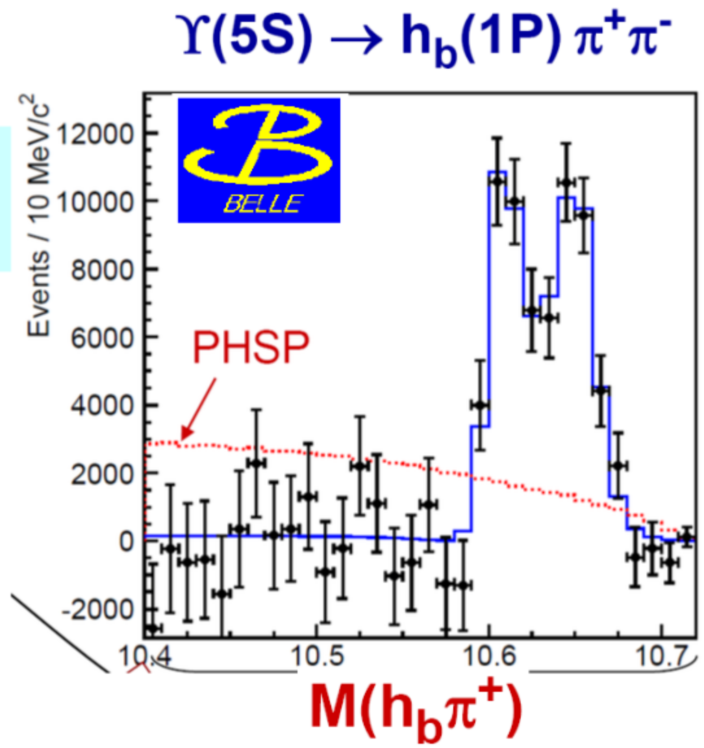
Abundant discovery modes—hidden-charm and open-charm decay channels

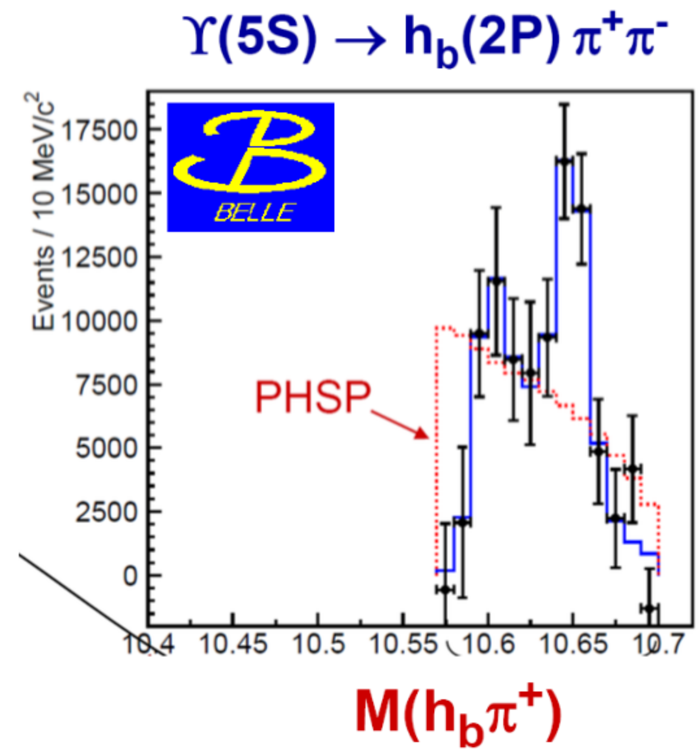
$Z_b(10610)$ and $Z_b(10650)$

Belle Collaboration
PRL108,122001 (2012)

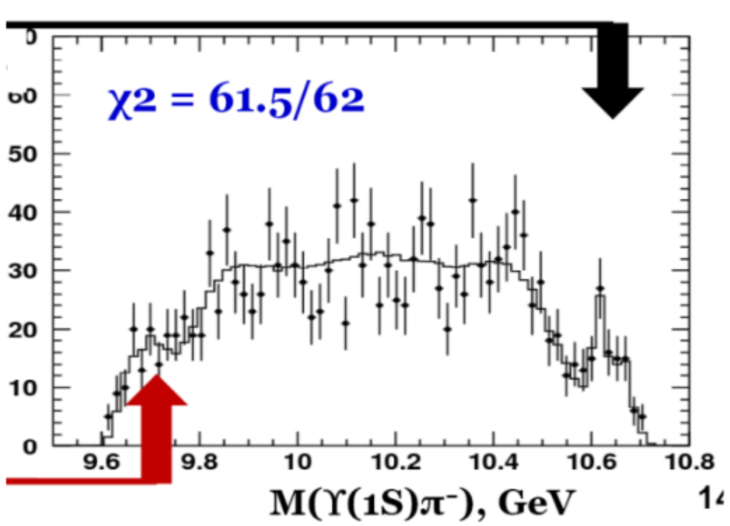
$Z_b(10610)$

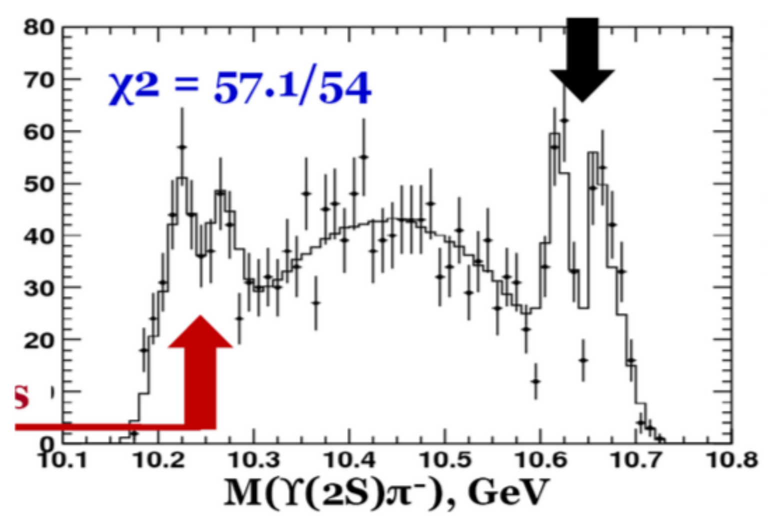
$Z_b(10650)$

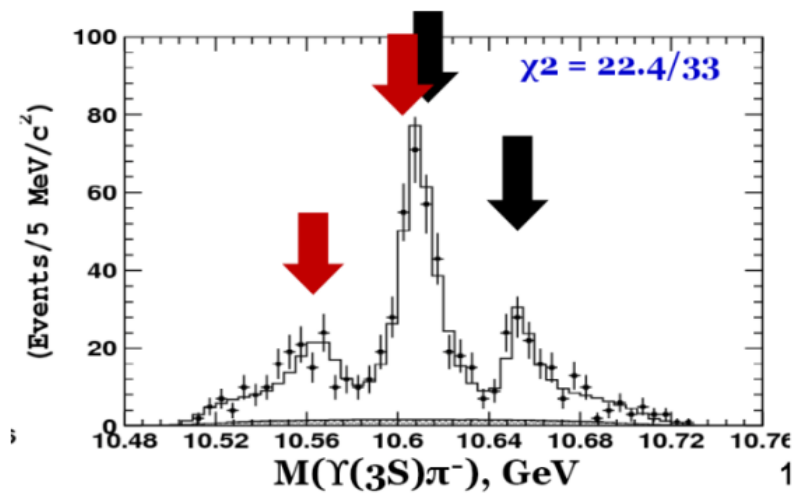




$\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$







XYZ Physics

Y(2175) **Y(4260)** **Y(10860)**

$e^+e^- \to Y(2175) \to \phi\pi\pi$ $e^+e^- \to Y(4260) \to J/\psi\pi\pi$ $e^+e^- \to \Upsilon(10860) \to \Upsilon\pi\pi$

- **Mass spectrum: conventional meson, exotic states**
- **Decay behavior**
- **Production**

Y states at 2.1 GeV

Experimental status of Y(2175)

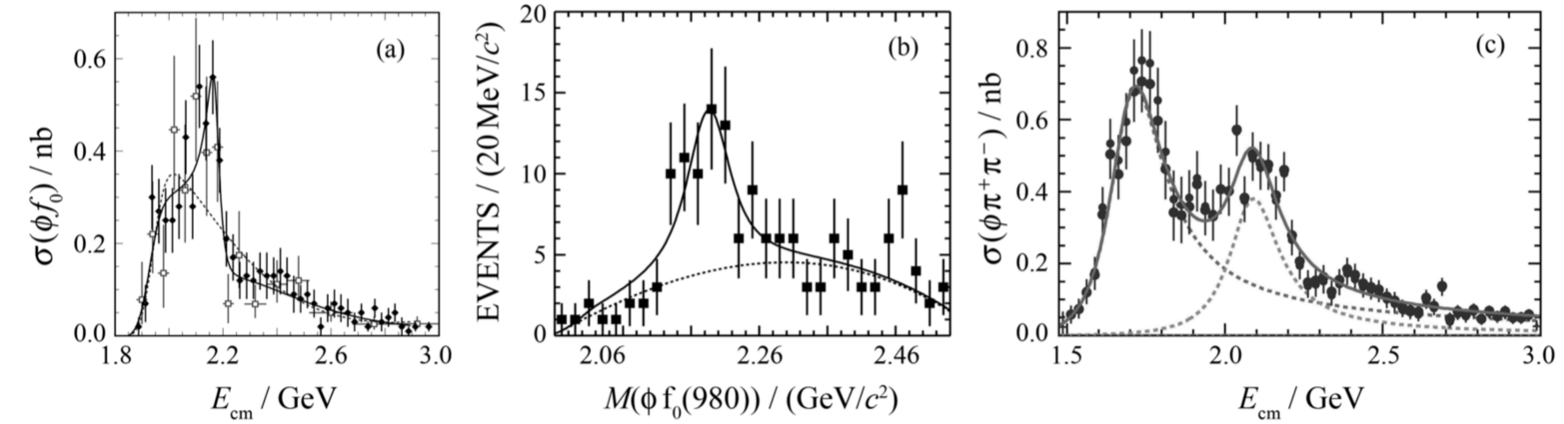
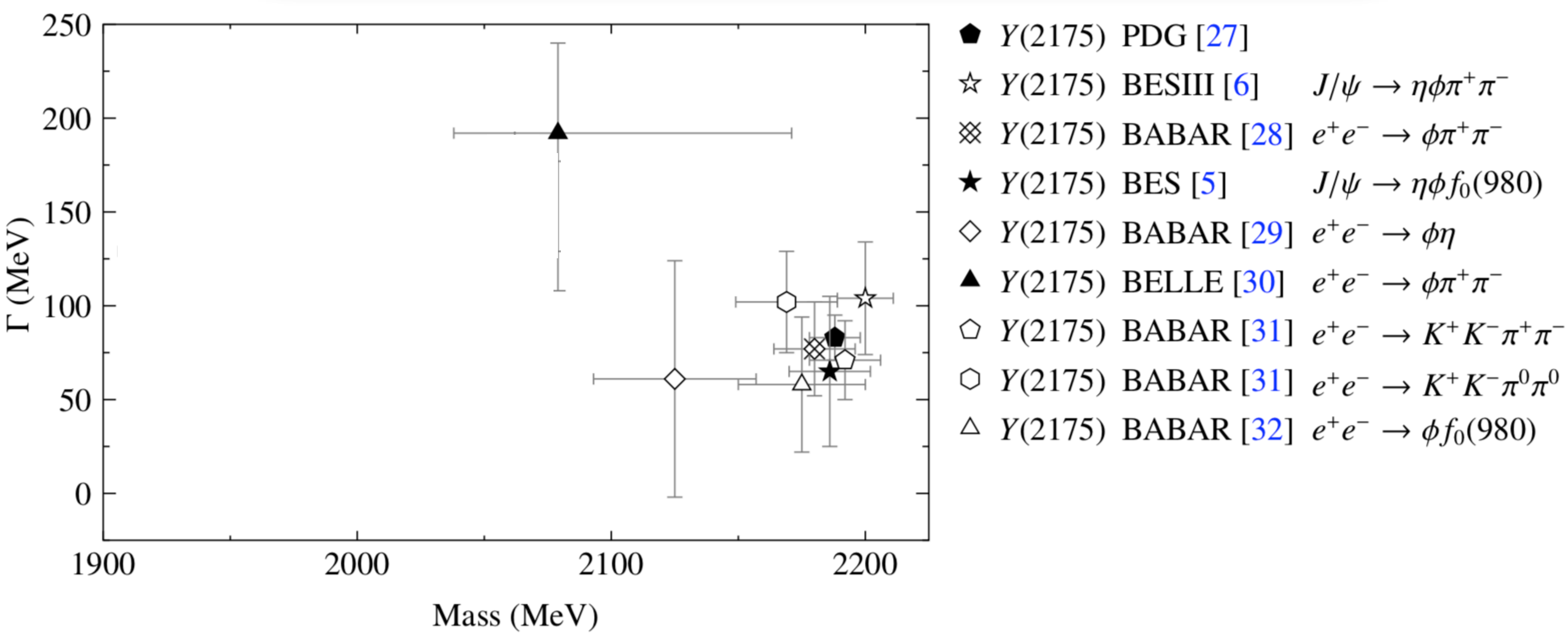


Fig. 1 (a) The invariant mass spectrum of $\phi f_0(980)$ in $e^+e^- \to \phi f_0(980)$ from BaBar data; (b) the invariant mass spectrum of $\phi f_0(980)$ in $J/\psi \to \eta\phi f_0(980)$ from BES data; (c) the invariant mass spectrum of $\phi\pi^+\pi^-$ in $e^+e^- \to \phi\pi^+\pi^-$ from Belle data.



Different explanations

- **Strangenium** $s\bar{s}$
- **Hybrid** $s\bar{s}g$
- **Three-body system** $\phi K\bar{K}$
- **Molecular state** $\Lambda\bar{\Lambda}$

See review

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2011 年 3 月　Nuclear Physics Review　Mar., 2011

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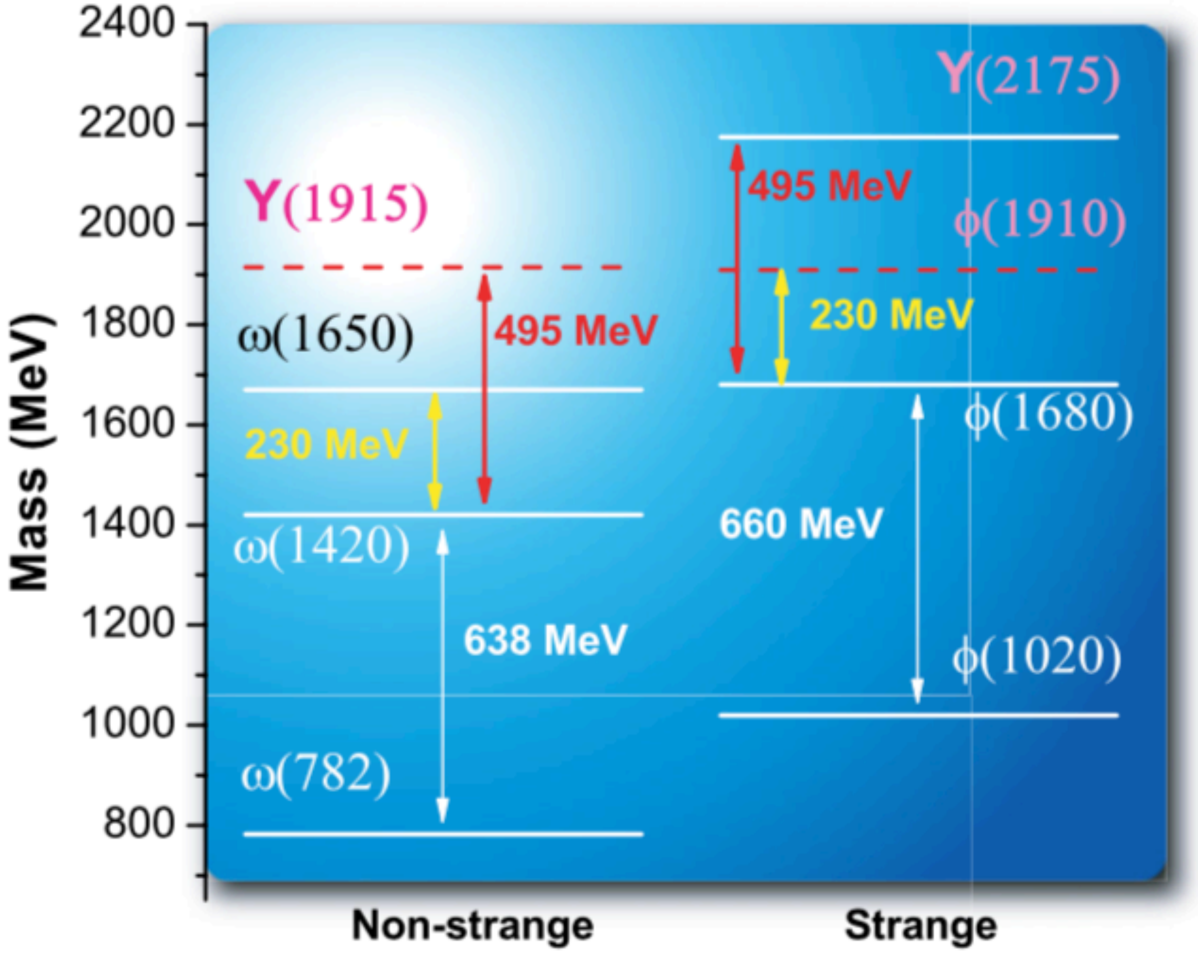
Y(2175): An Intriguing Hadron Observed in BaBar, BES and Belle Experiments*

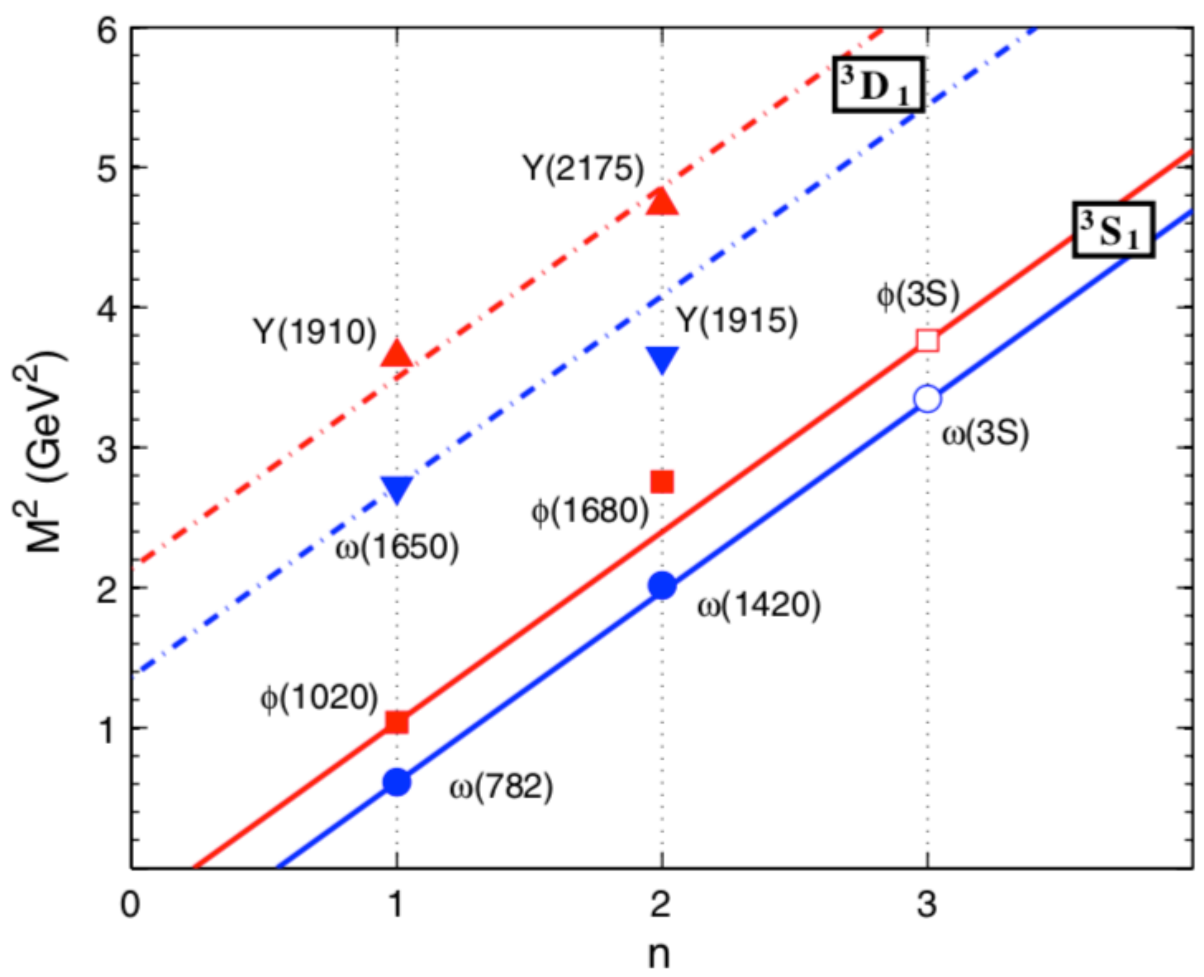
LIU Xiang[1,2]

PHYSICAL REVIEW D **85**, 074024 (2012)

Nonstrange partner of strangeonium-like state $Y(2175)$

Xiao Wang,[1,2] Zhi-Feng Sun,[1,2] Dian-Yong Chen,[1,3] Xiang Liu,[1,2,*,†] and Takayuki Matsuki[4,‡]

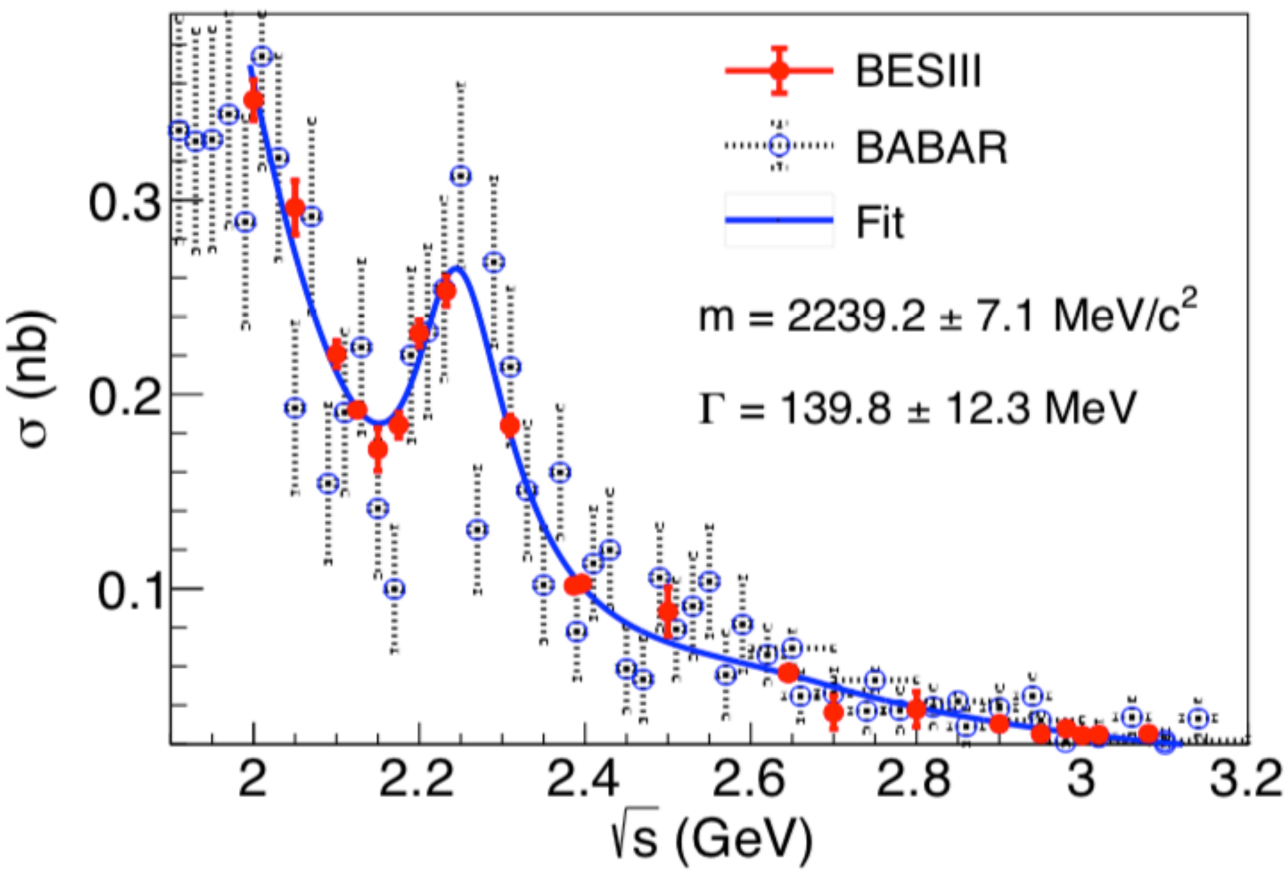


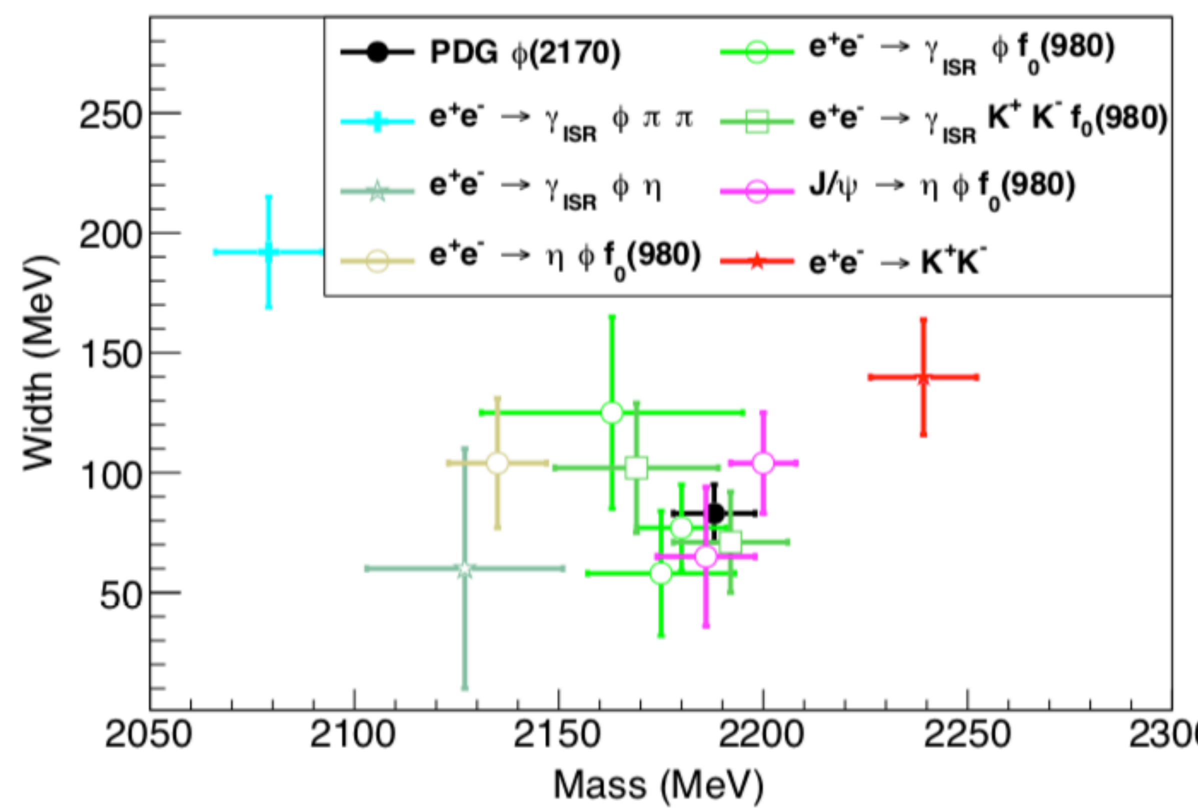


Y(2175) as 2D state in phi meson family

More news

BESIII arXiv:1811.08742





Difference of resonance parameter

PHYSICAL REVIEW D **88,** 034008 (2013)

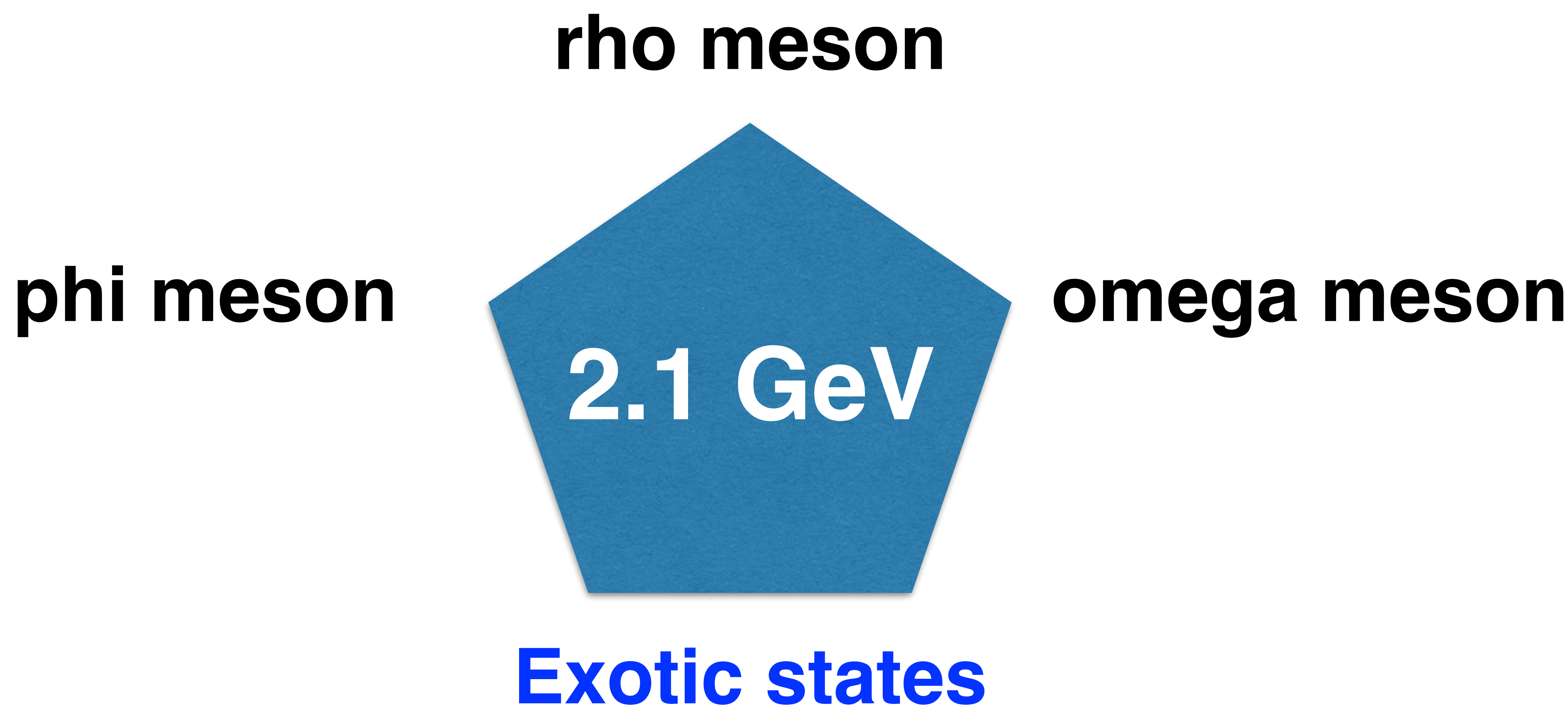
Towards two-body strong decay behavior of higher ρ and ρ_3 mesons

Li-Ping He,* Xiao Wang,† and Xiang Liu‡

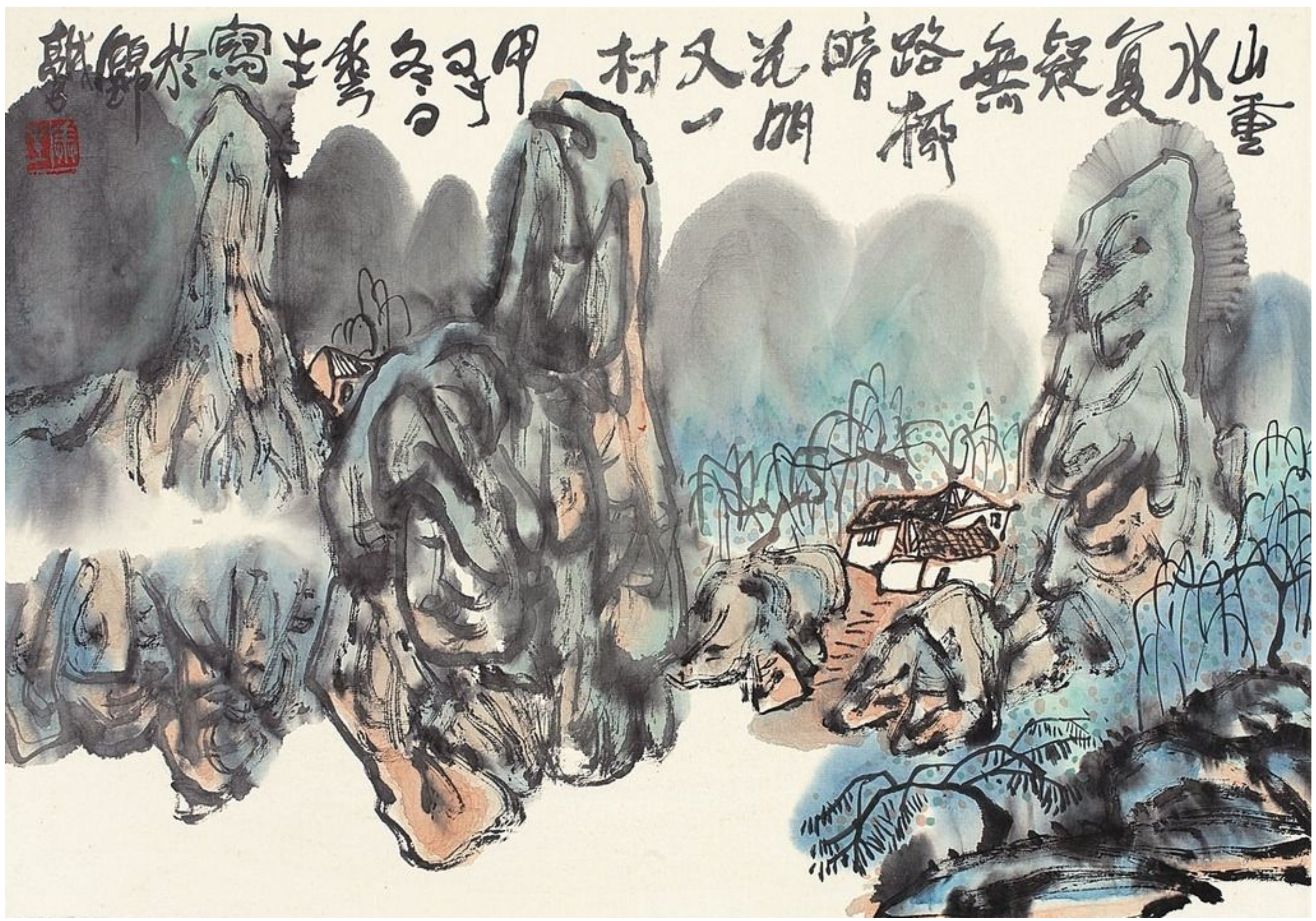
TABLE I. The experimental information of the observed ρ/ρ_3 states. Here, the masses and widths (in units of MeV) are average values taken from PDG [1]. The states marked by the superscript $\flat$, are as the states omitted form the summary table of PDG, while the states marked by the superscript $\natural$ are as further states listed in PDG.

State	Mass	Width
	$J^P = 1^-$	
$\rho(770)$	775.49 ± 0.34	146.2 ± 0.7
$\rho(1450)$	1465 ± 25	400 ± 60
$\rho(1570)^{\flat}$	$1570 \pm 36 \pm 62$	$144 \pm 75 \pm 43$
$\rho(1700)$	1720 ± 20	250 ± 100
$\rho(1900)^{\flat}$ [2]	$1909 \pm 17 \pm 25$	$48 \pm 17 \pm 2$
$\rho(2150)^{\flat}$	2149 ± 17	359 ± 40
$\rho(2000)^{\natural}$ [3–6]	2000 ± 30	260 ± 45
$\rho(2270)^{\natural}$ [3–6]	2265 ± 40	325 ± 80

We need to pay more attentions to the physics around this energy range

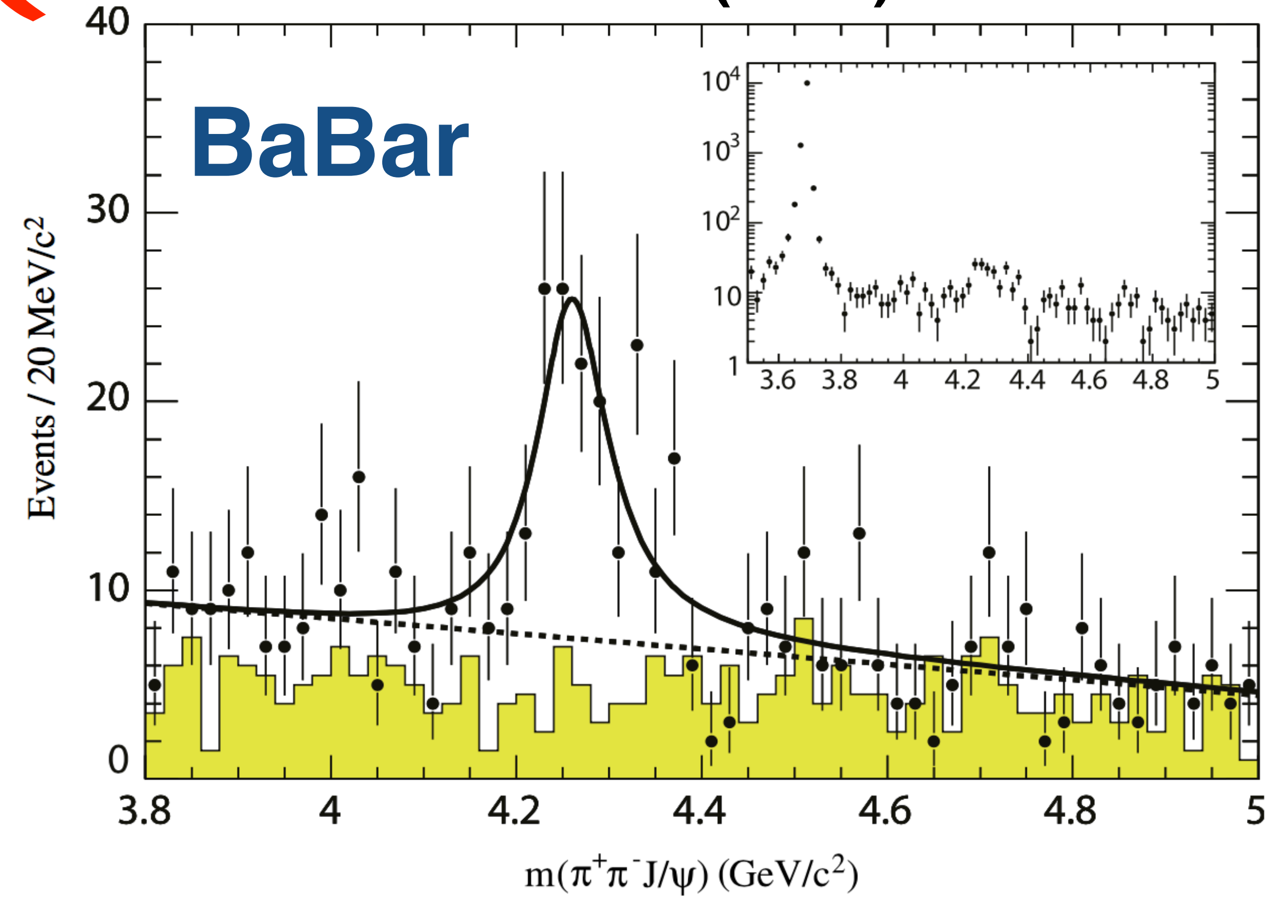


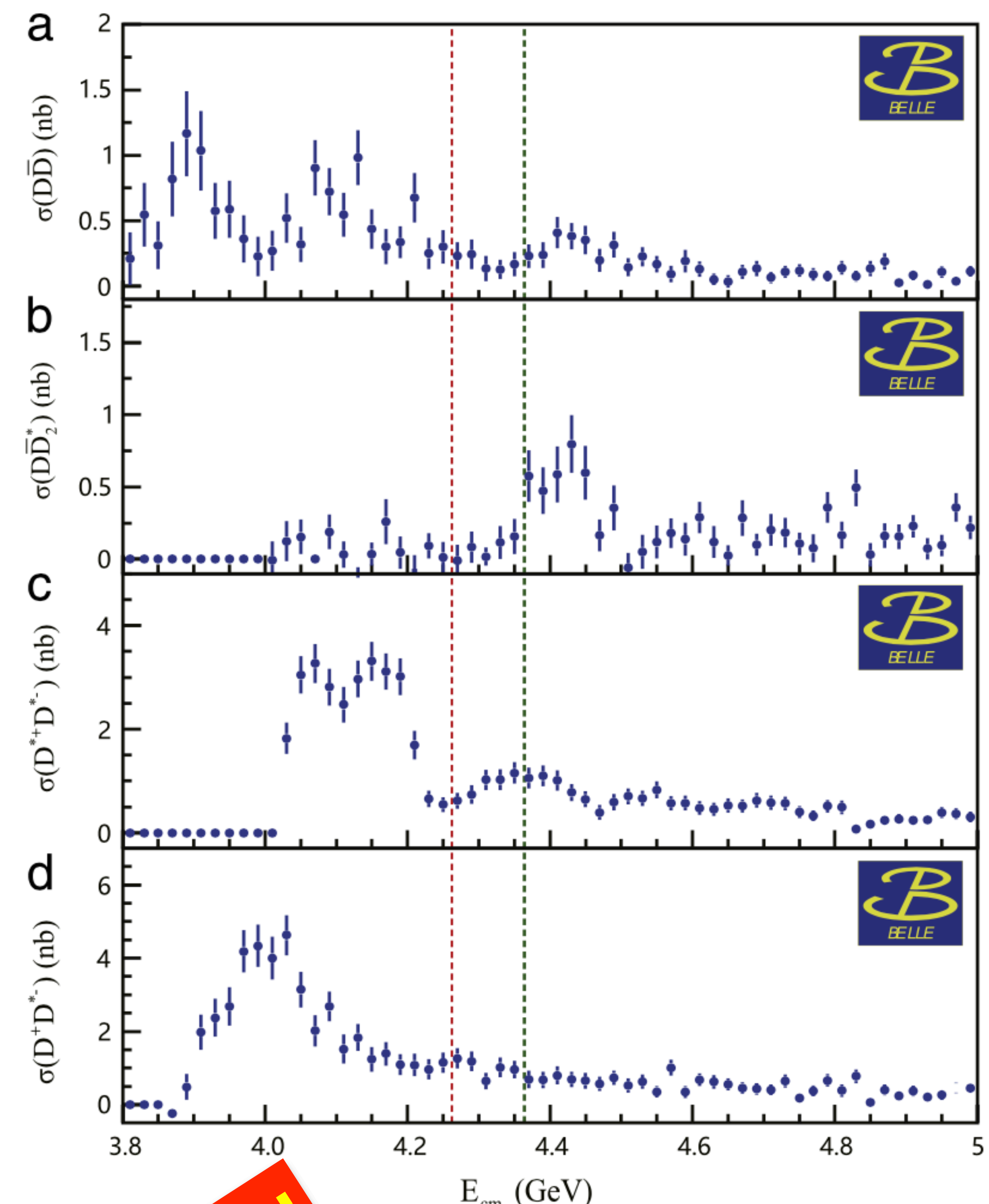
Y states at 4.2 GeV

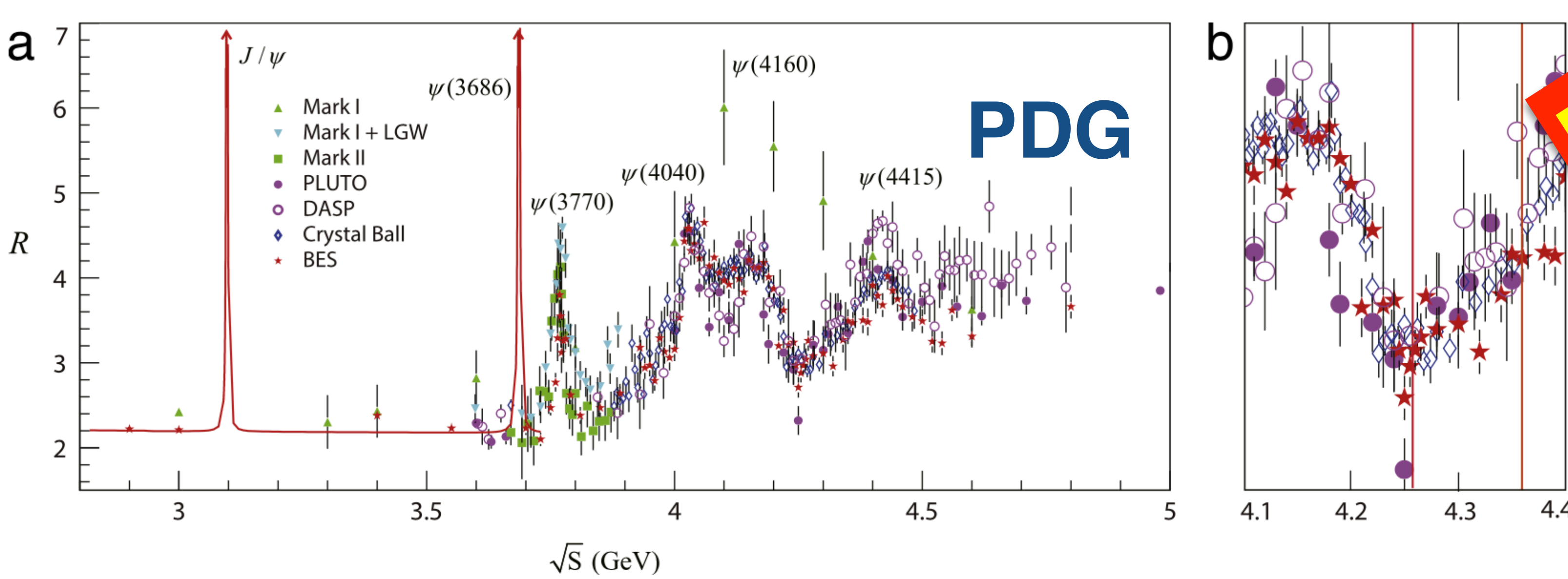


Y(4260)

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

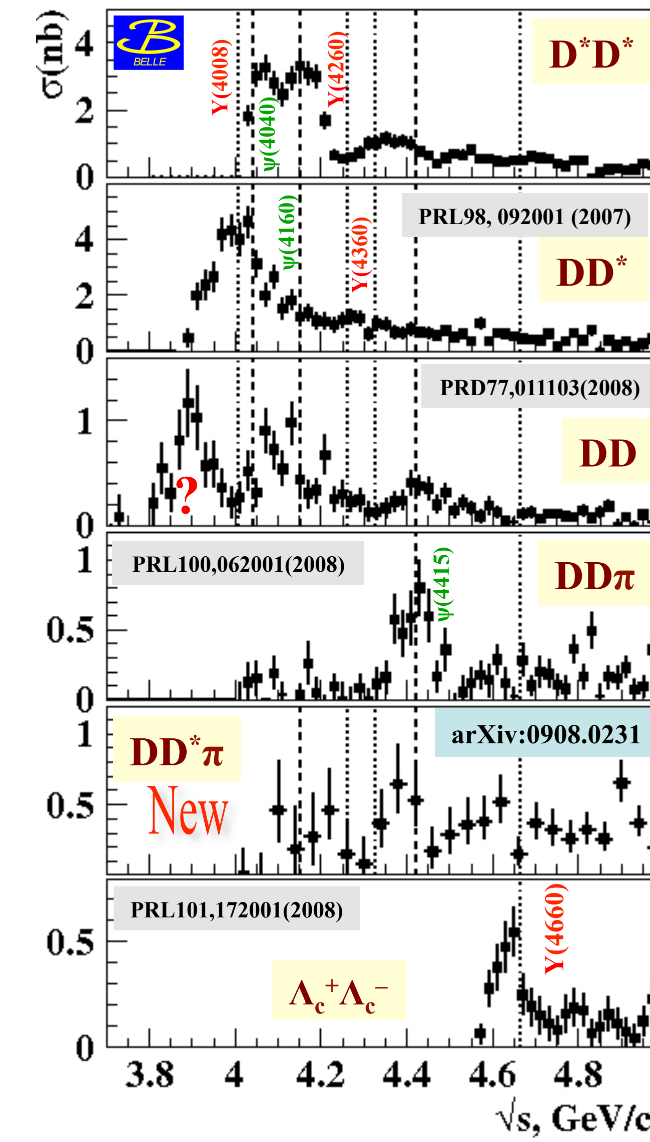
Eichten&Lane&Quigg

Mass spectrum Y(4260) ≠charmonium

Segovia&Yasser&Entem&Fernandez

Screened potential Y(4260) =Ψ(4S)

Li&Chao

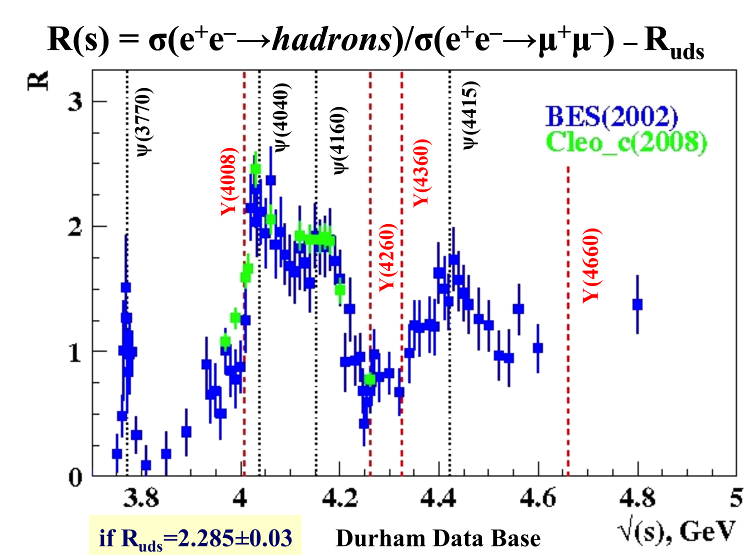


Difficulty

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

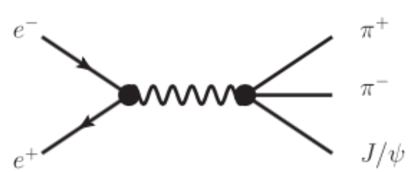
No evidence of Y(4260) in R scan data and open-charm decay channels



Non-resonant picture of Y(4260)

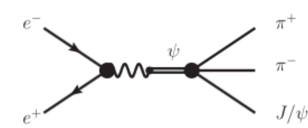
- **Asymmetric** **Y(4260) structure can be reproduced by** **Fano-like interference picture**

Continuum



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

Charmonium

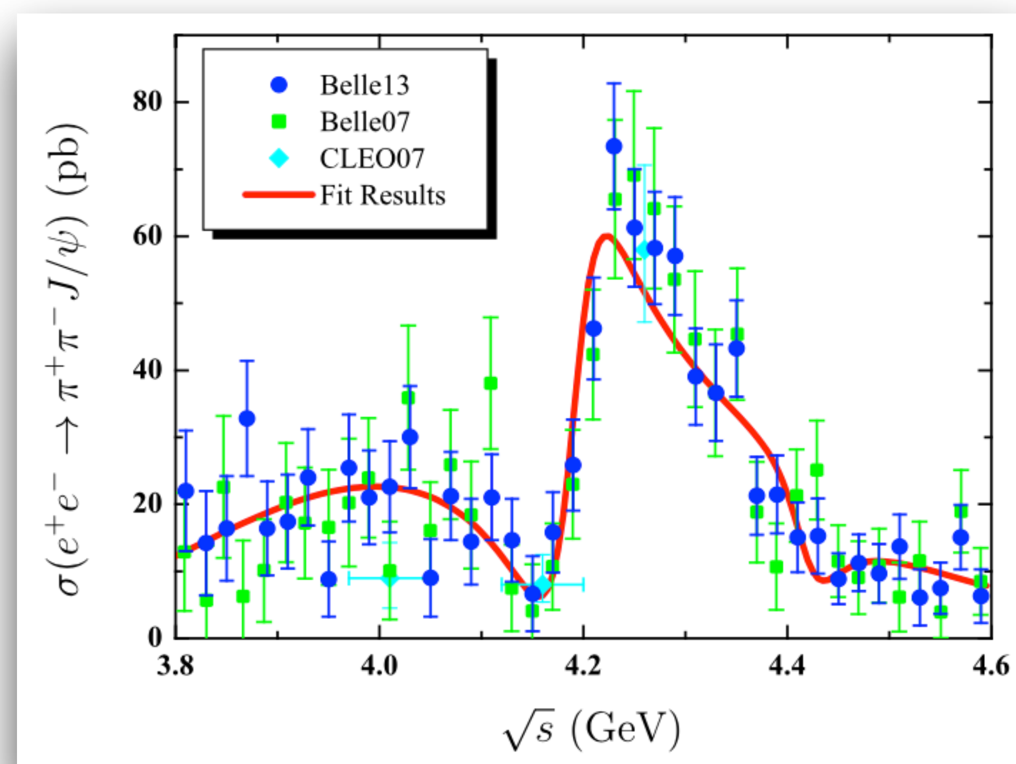


$\widehat{=} \frac{\sqrt{12\pi\Gamma_\psi^{e^+e^-}\times\mathcal{B}(\psi\to\pi^+\pi^-J/\psi)\Gamma_\psi}}{s-m_\psi^2+im_\psi\Gamma_\psi}\sqrt{\frac{\Phi_{2\to3}(s)}{\Phi_{2\to3}(m_\psi^2)}}$

Interference

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

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**

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

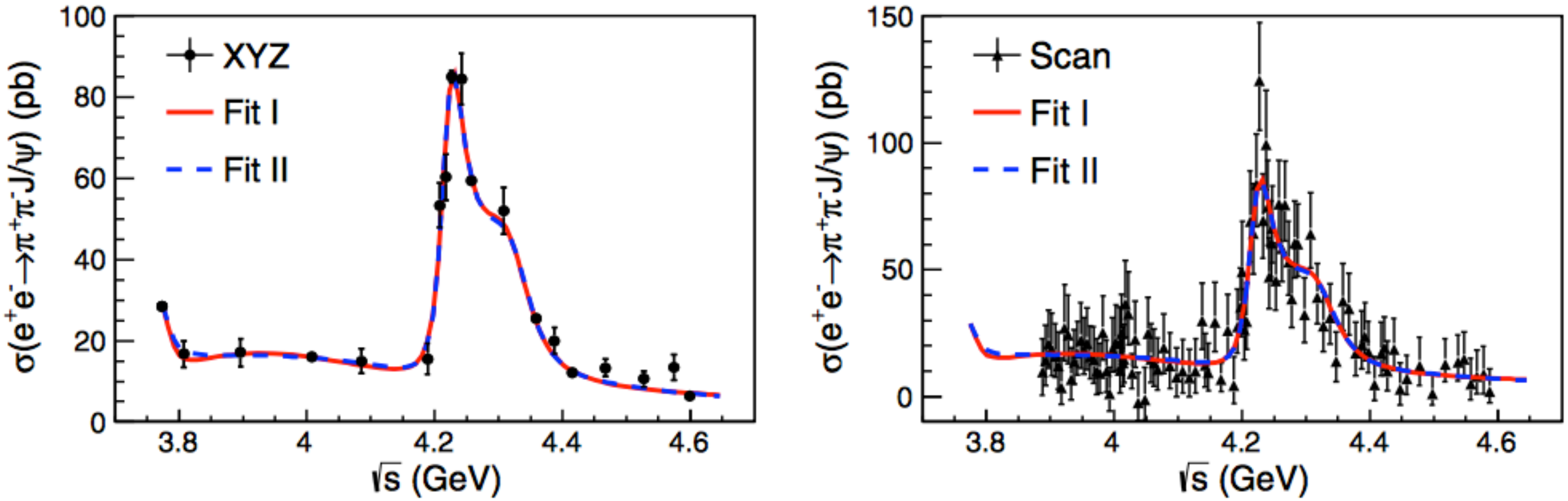


FIG. 1. Measured cross section $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ and simultaneous fit to the *XYZ* data (left) and scan data (right) with the coherent sum of three Breit-Wigner functions (red solid curves) and the coherent sum of an exponential continuum and two Breit-Wigner functions (blue dashed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

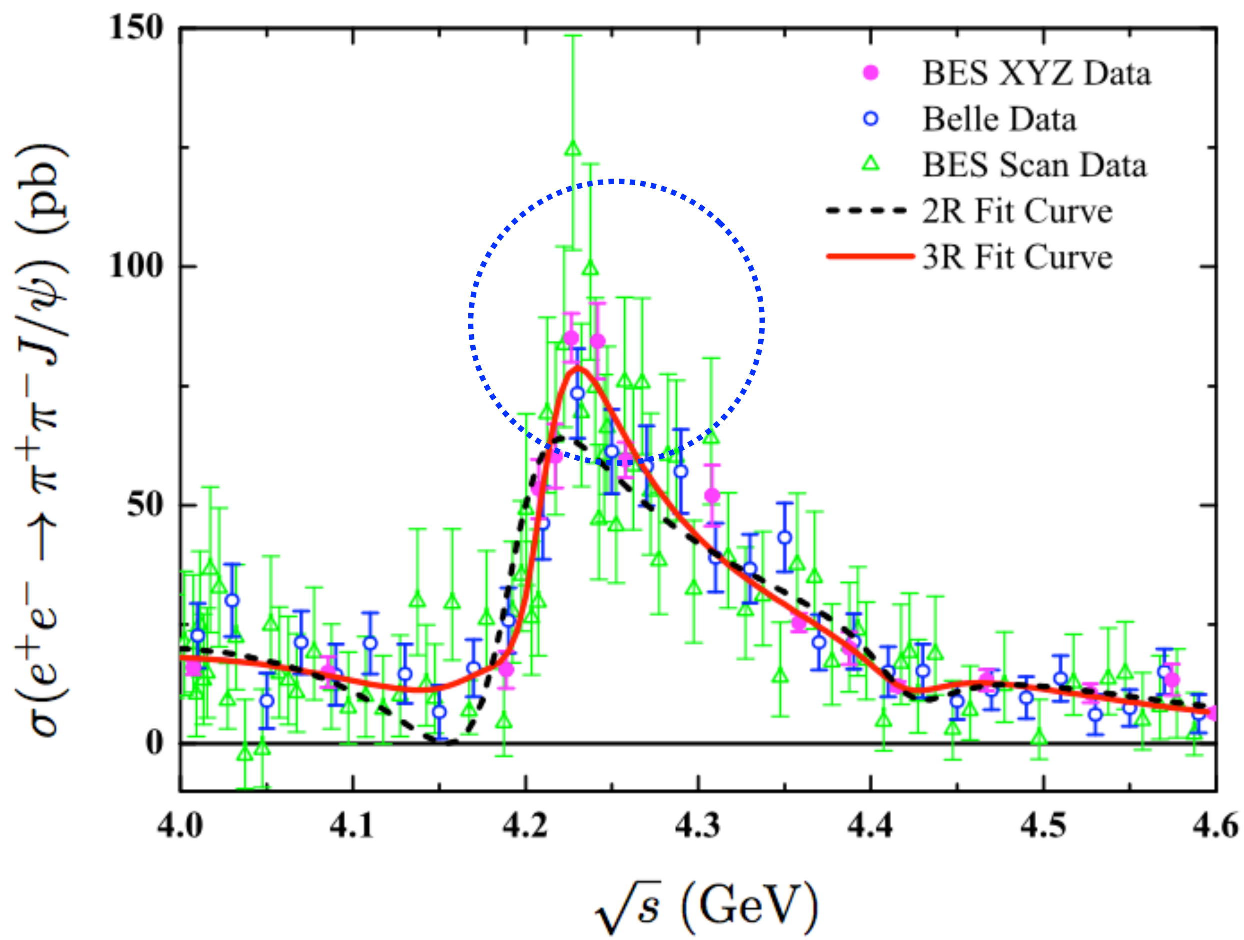


FIG. 2: (color online). Our fit to the cross sections for the $e^+e^- \to \pi^+\pi^- J/\psi$ process measured by the Belle [8] and BESIII collaborations [11] under the 2R and 3R fit schemes. Here, the BES scan data [11] are also listed for comparison.

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

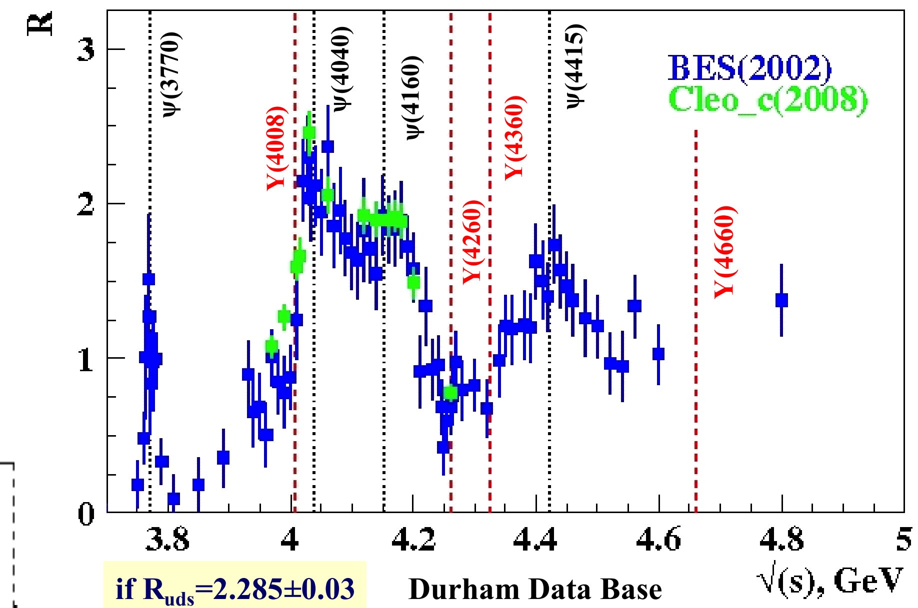
$$M = (4207 \pm 12) \quad \text{MeV}$$
$$\Gamma = (58 \pm 38) \quad \text{MeV}$$

What is Y(4220)?

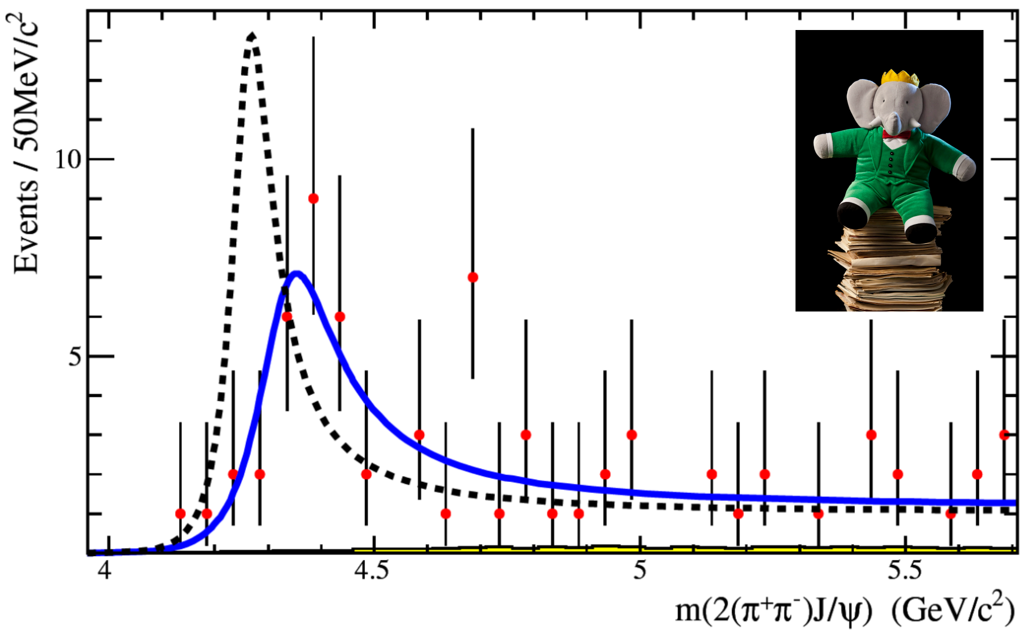
Y(4360)

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

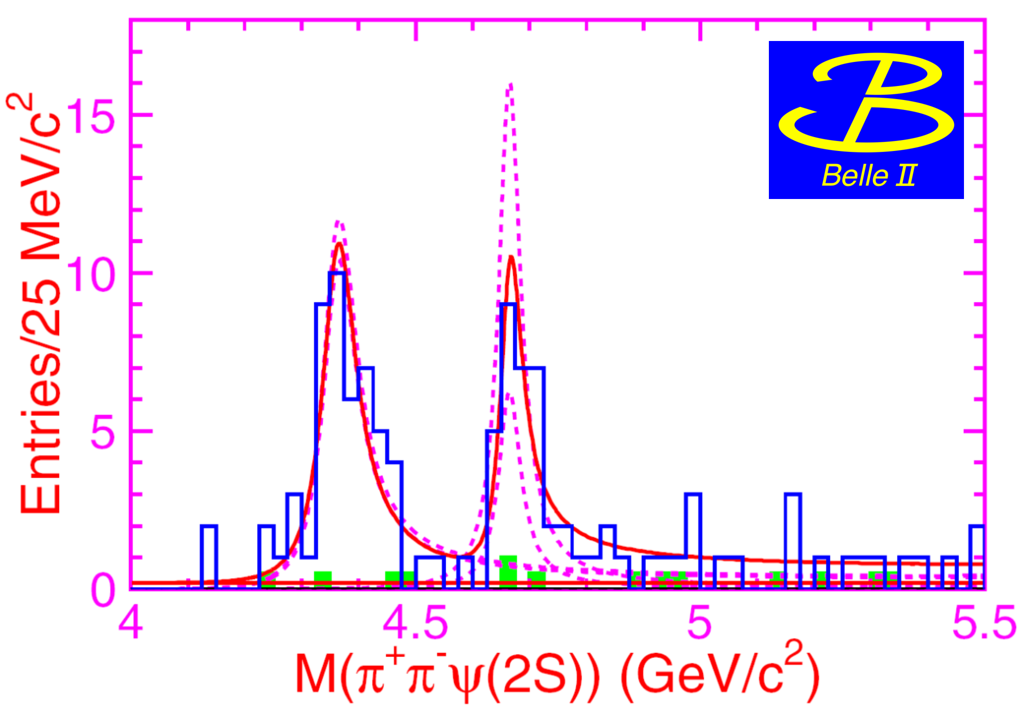
$R(s) = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-) - R_{uds}$

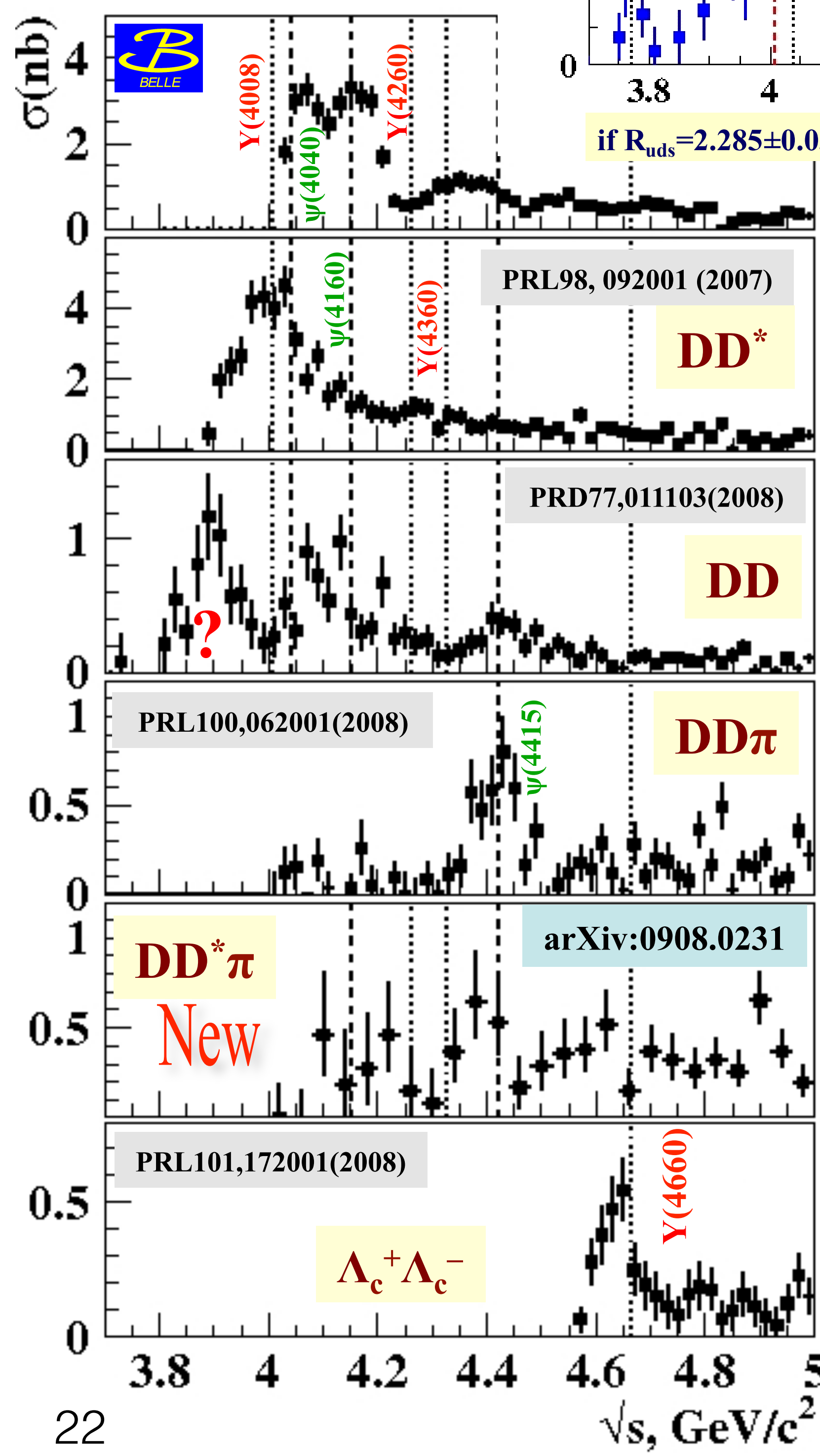


PRL 98:212001 (2007)



PRL 99:142002 (2007)

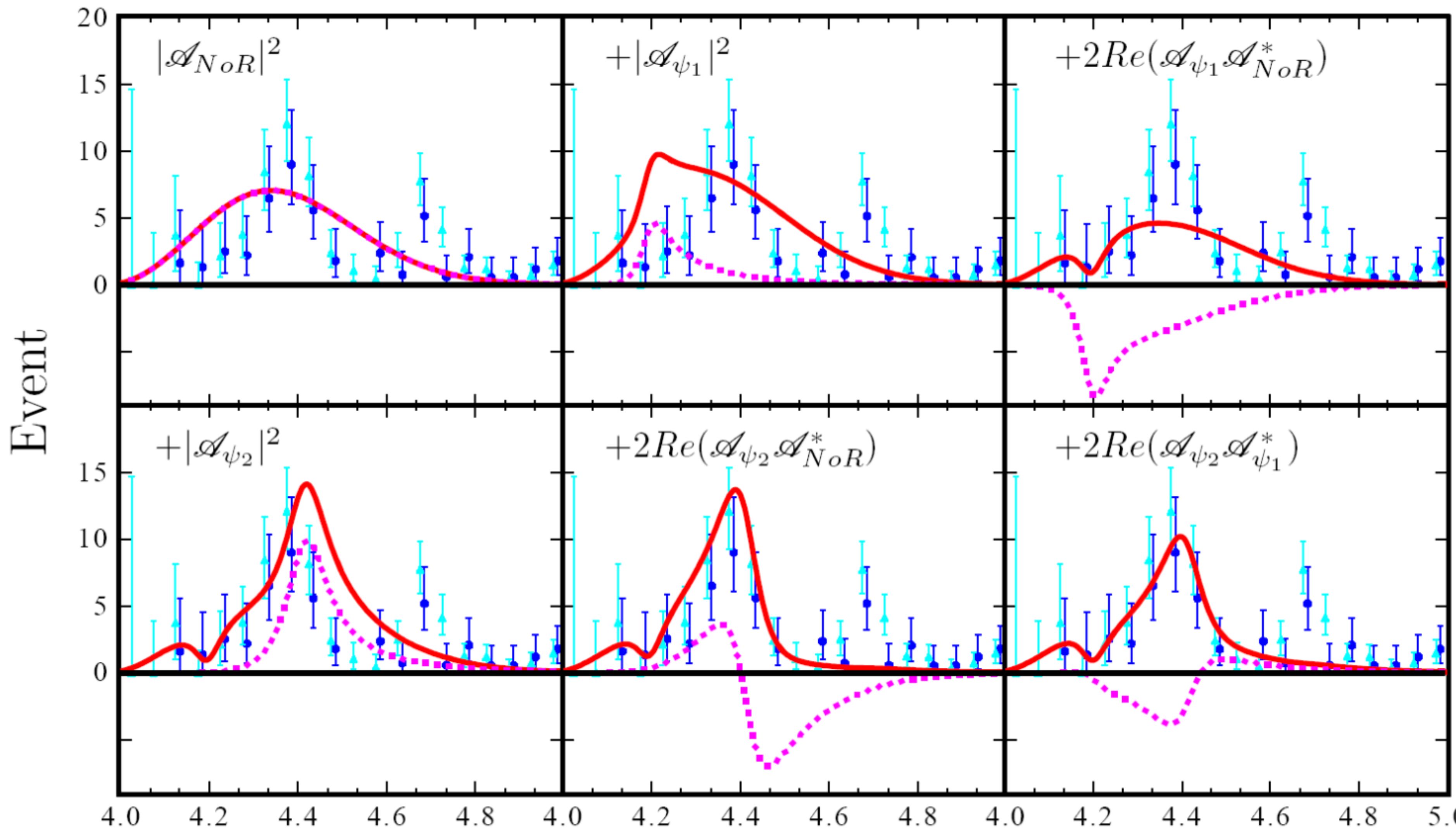




The situation of Y(4360) is similar to that of Y(4260)

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)**

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

Y(4220)+Y(4390)

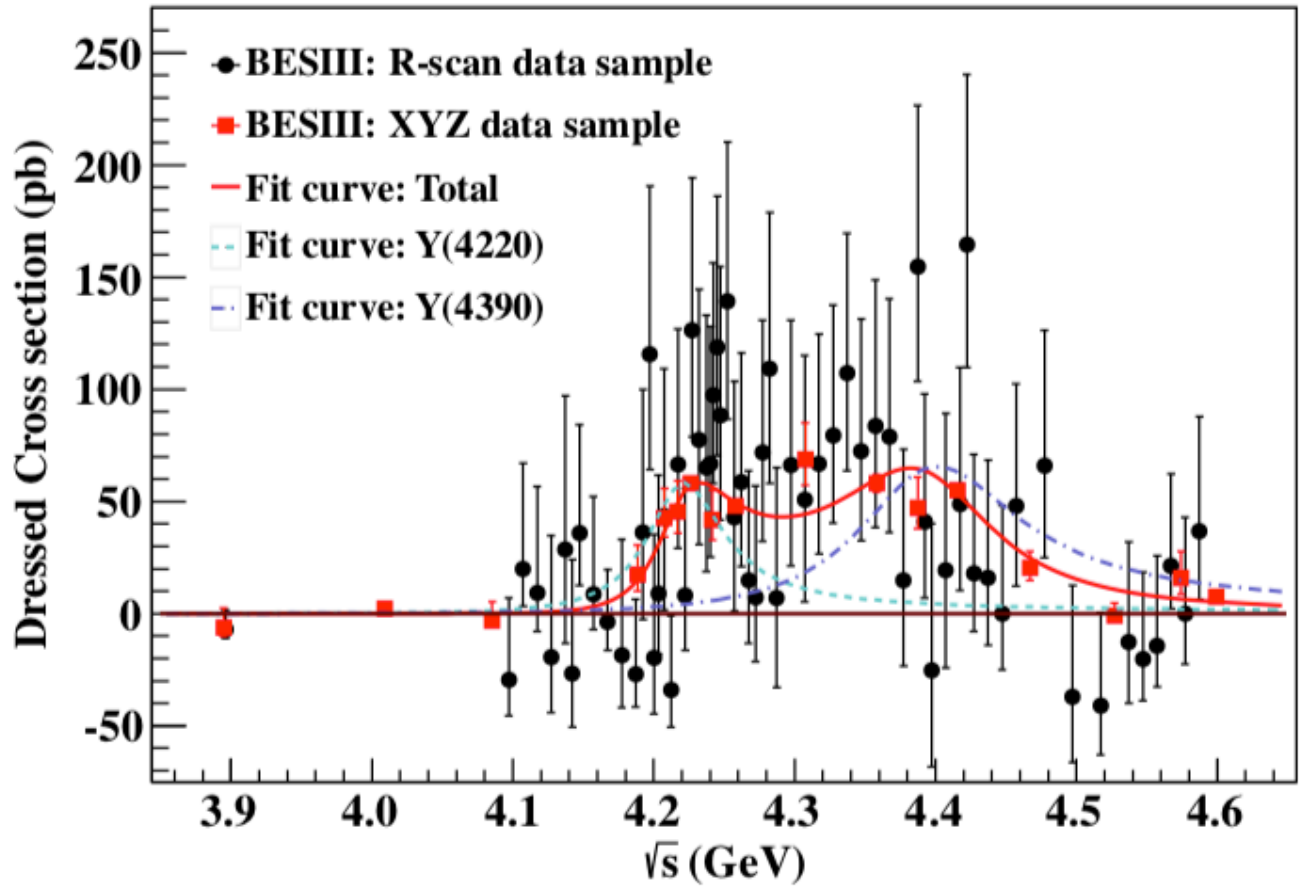


FIG. 2. Fit to the dressed cross section of $e^+e^- \to \pi^+\pi^- h_c$ with the coherent sum of two Breit-Wigner functions (solid curve). The dash (dash-dot) curve shows the contribution from the two structures $Y(4220)$ [$Y(4390)$]. The dots with error bars are the cross sections for the R-scan data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

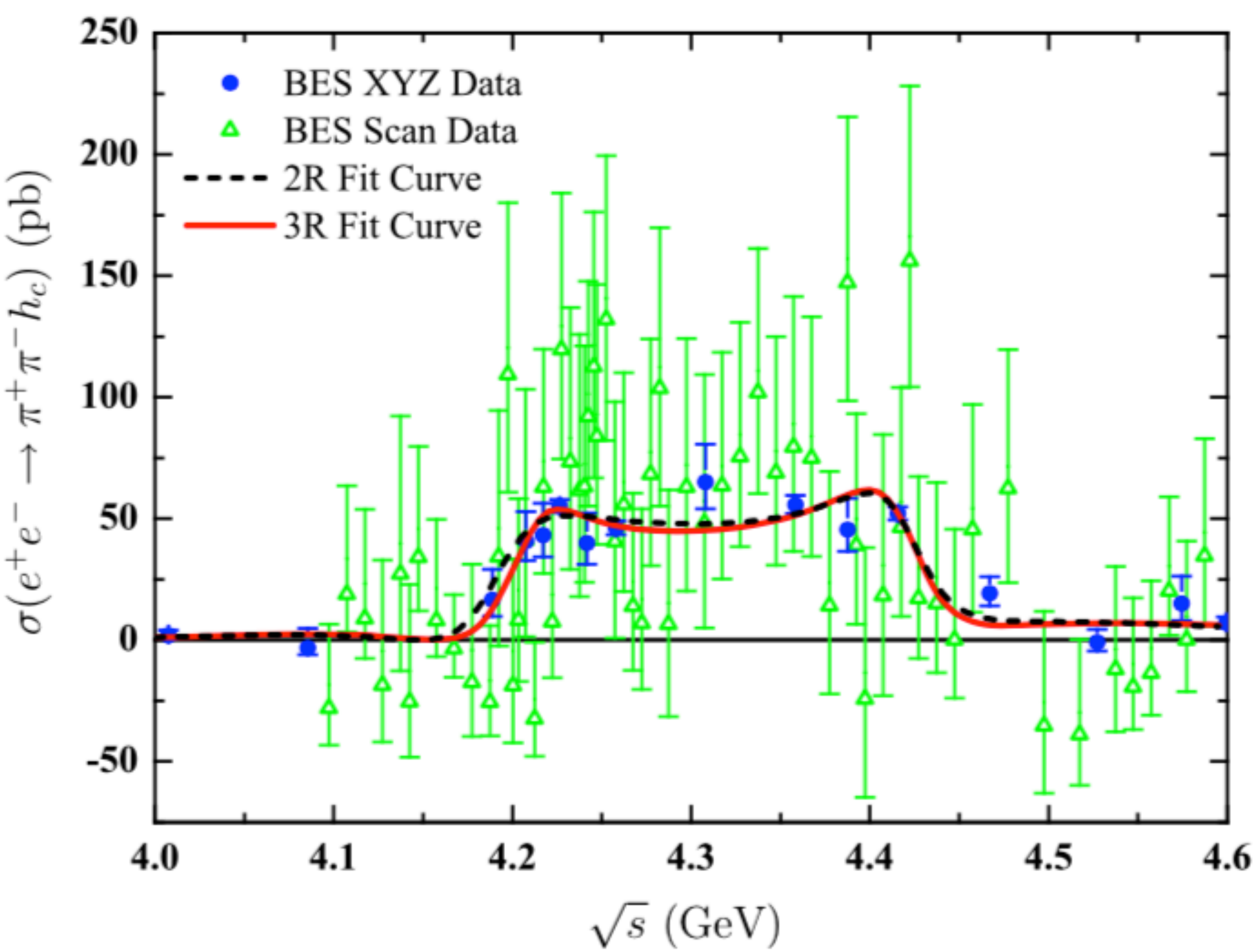
THE EUROPEAN PHYSICAL JOURNAL C

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)

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

Y(4260)

Y(4360)

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

Y(4660)

Y(4630)

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

BaBar PRD86:051102 ✗

Y(4008)

Y(4220)

Y(4320)

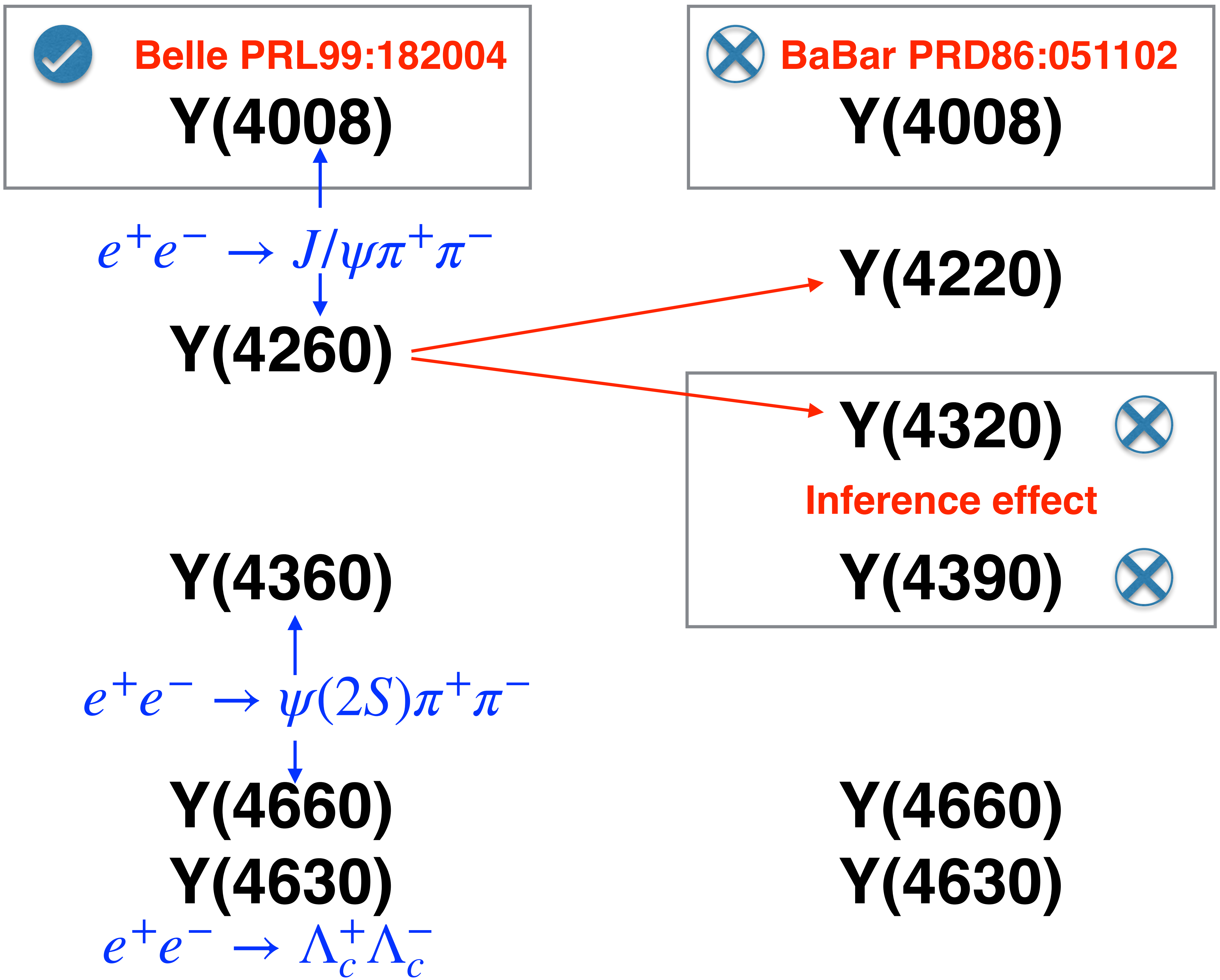
Inference effect

Y(4390)

Y(4660)

Y(4630)

Summary of Y states from electron and positron annihilations



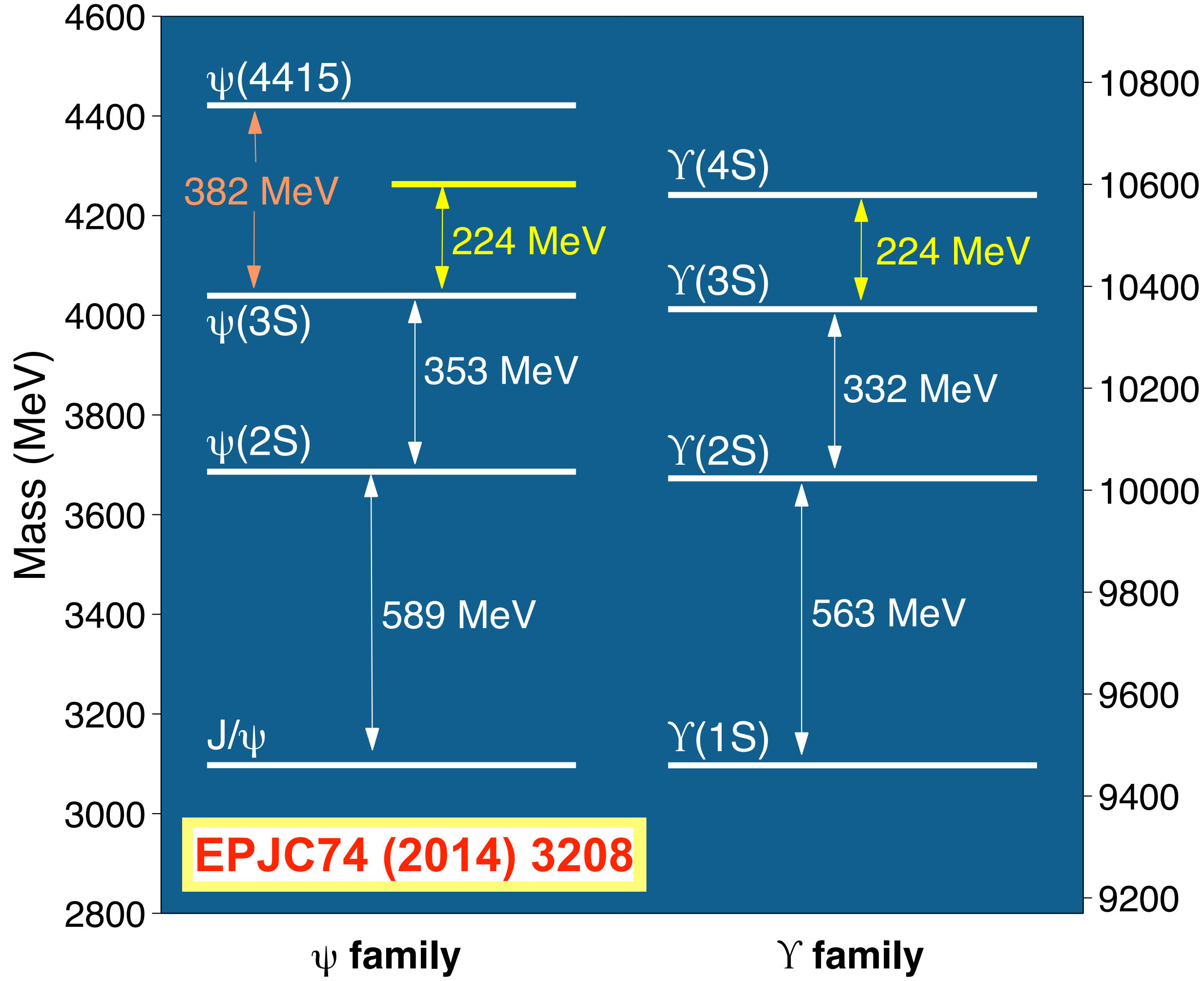
Summary of Y states from electron and positron annihilations

Y(4220)

Y(4660)
Y(4630)

The predicted ψ(4S) and its property

The similarity between J/ψ and Υ families



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

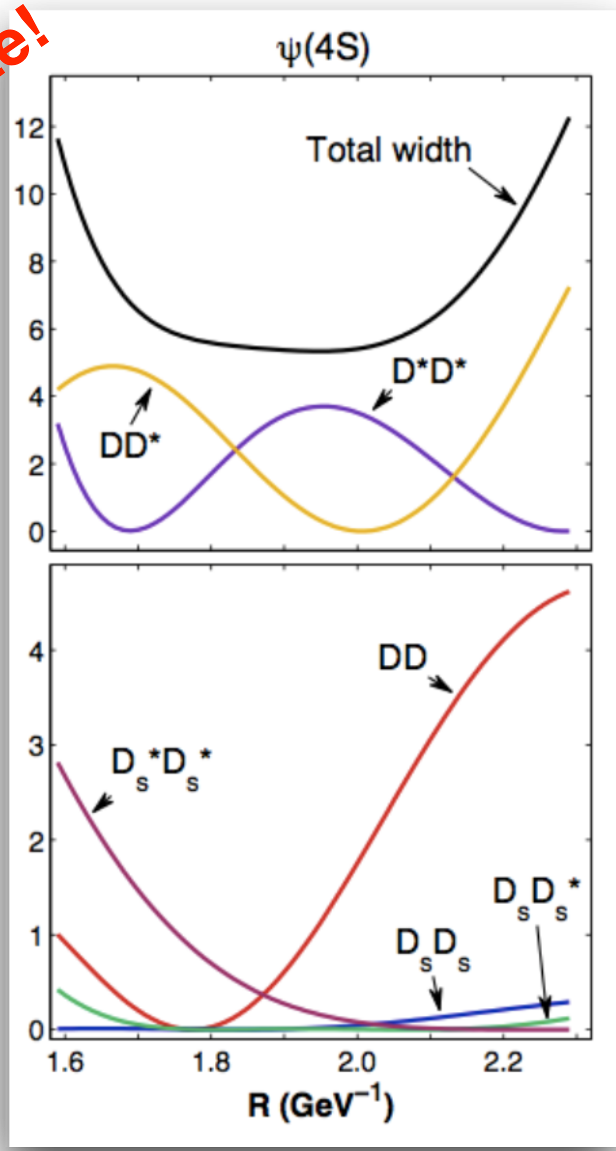
Consistent

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!

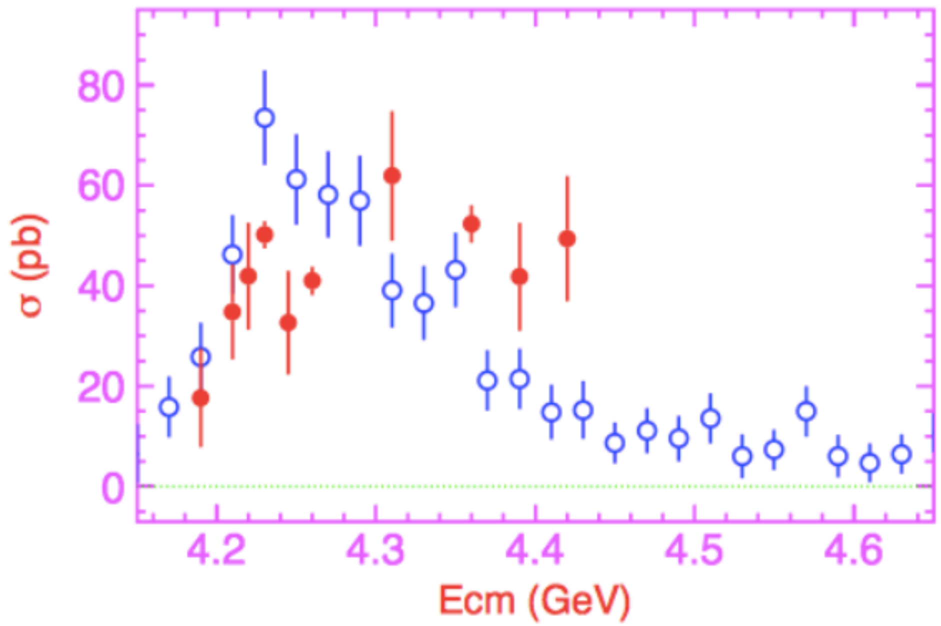
The predicted charmonium ψ(4*S*) has very narrow width around 6 MeV

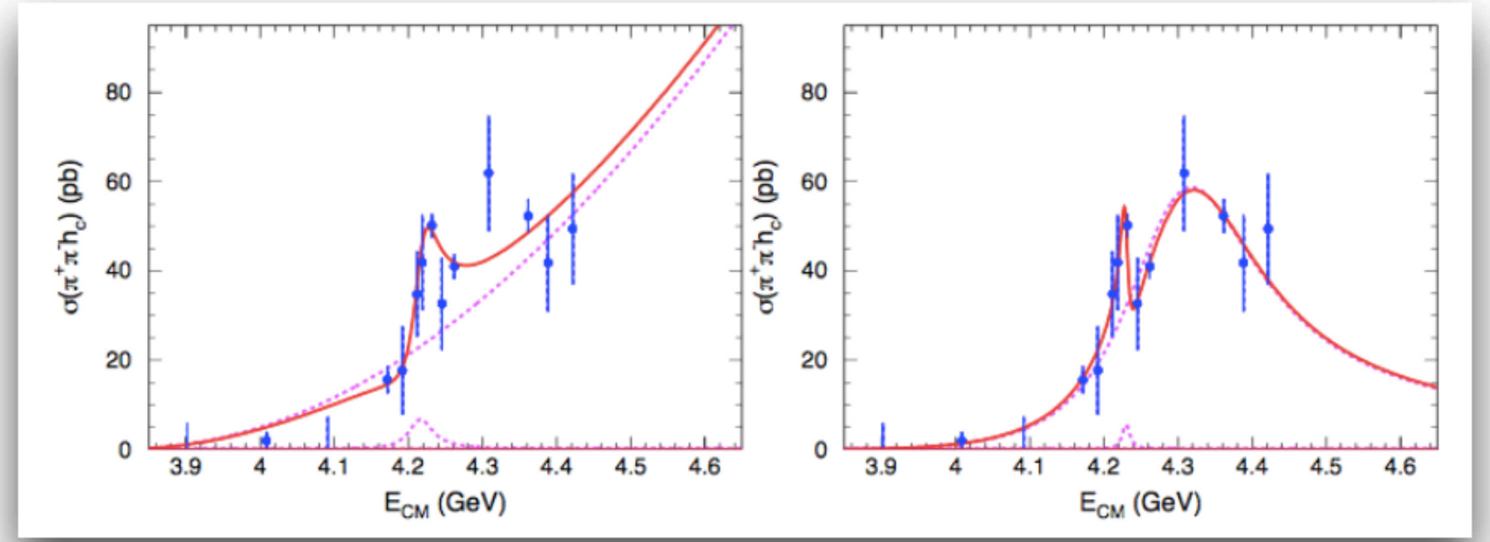
Y(4220)= ψ(4S)?

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"

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

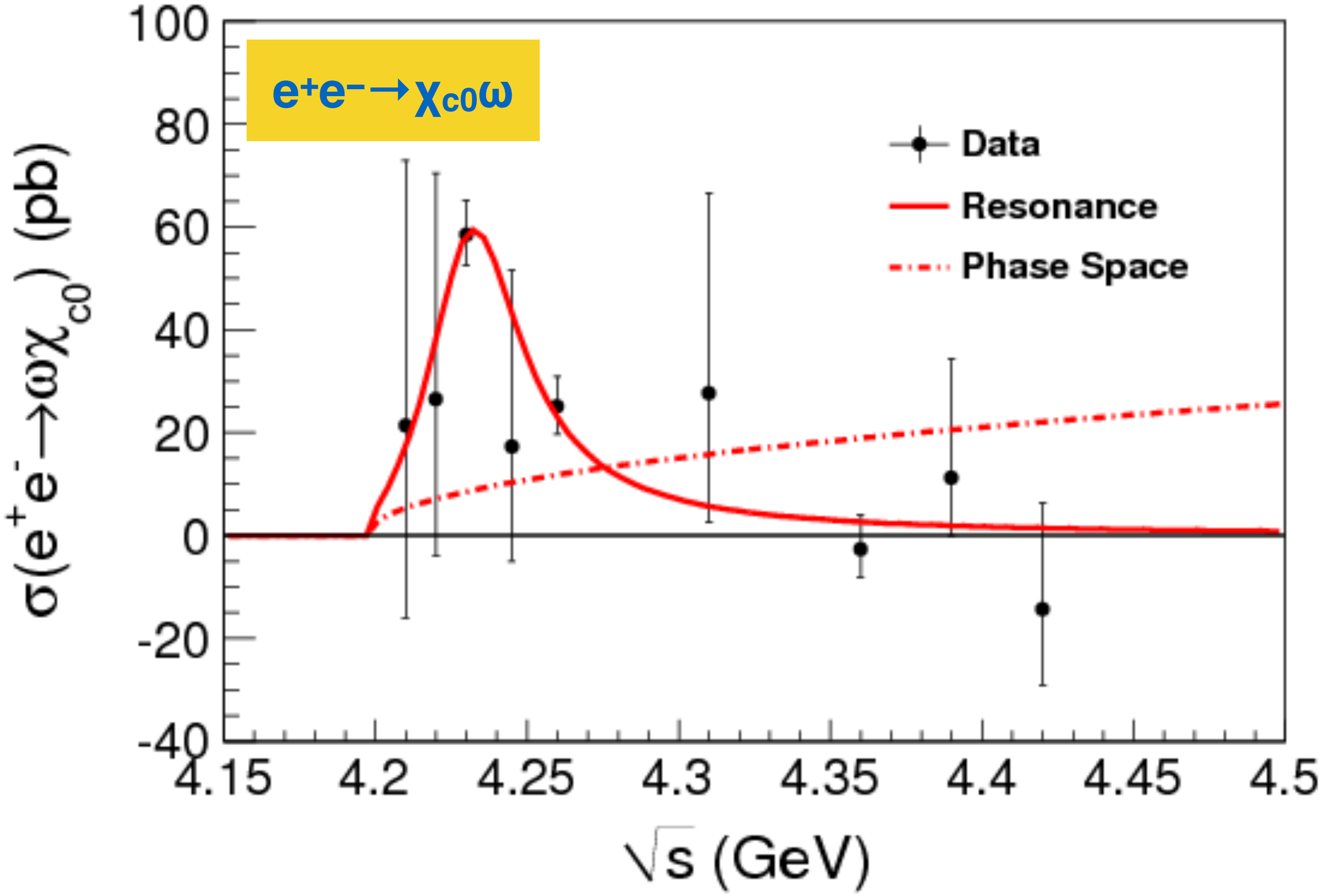
Is it the prediced higher charmonium with the mass around 4.26 GeV?

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)



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

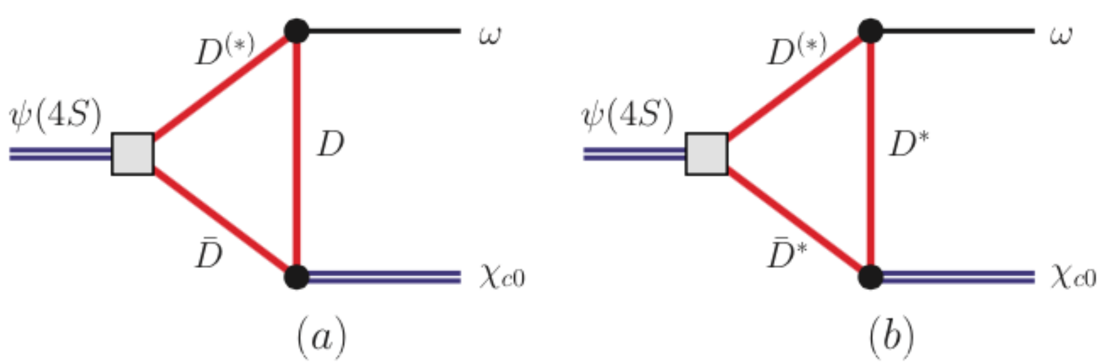
$e^+e^- \to \chi_{c1}\omega$ and $e^+e^- \to \chi_{c2}\omega$ are not significant

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

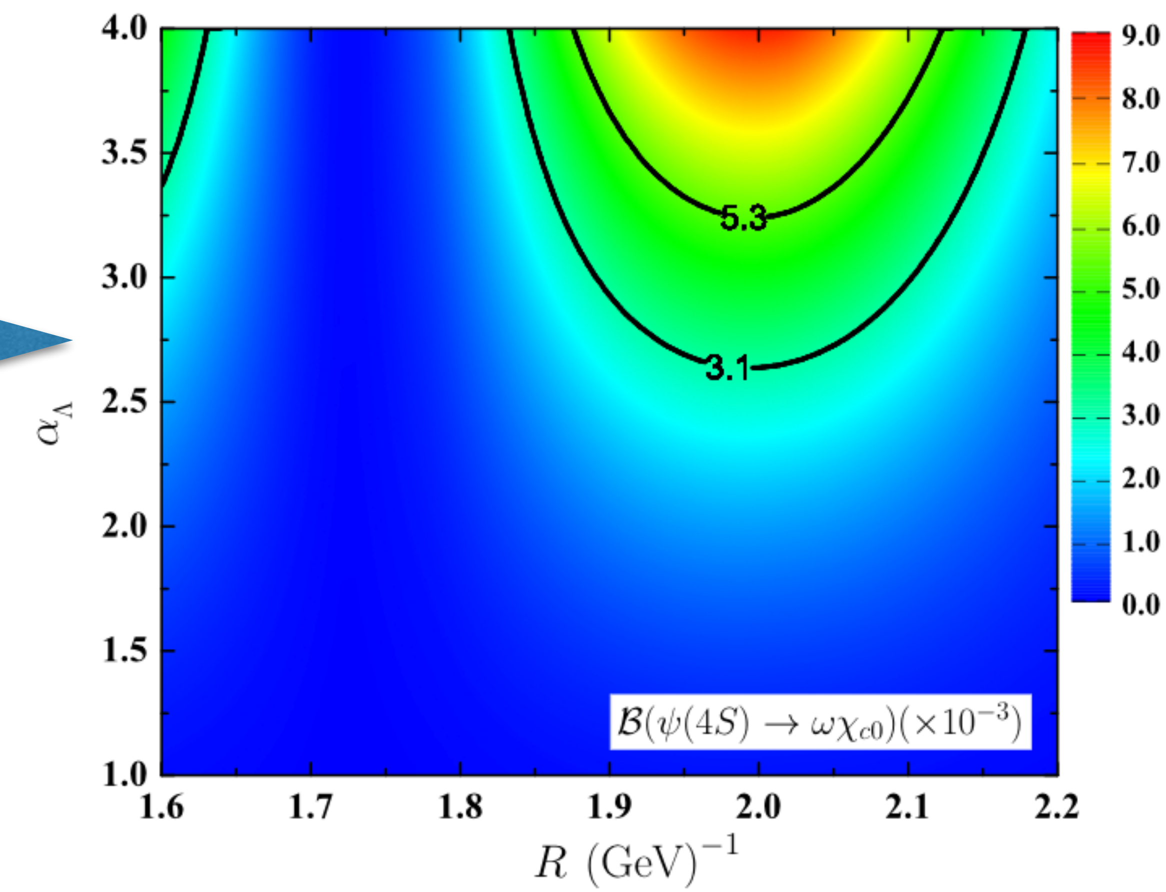
- $\psi(4S) \to \chi_{c0}\omega$ is **allowed**
- $\psi(4S) \to \chi_{c1}\omega$ and $\psi(4S) \to \chi_{c2}\omega$ are **forbidden kinematically**

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

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).

The total cross section can be described by

$$\sigma(m) = \left| \sum_{i=0}^{2} e^{i\phi_i} \mathrm{BW}_i(m) \sqrt{\frac{\mathrm{PS}_{2\to 3}(m)}{\mathrm{PS}_{2\to 3}(m_i)}} \right|^2, \qquad (1)$$

where ϕ_i is the phase angle between different resonances with $\phi_0 = 0$, and $\mathrm{PS}_{2\to 3}$ 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

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

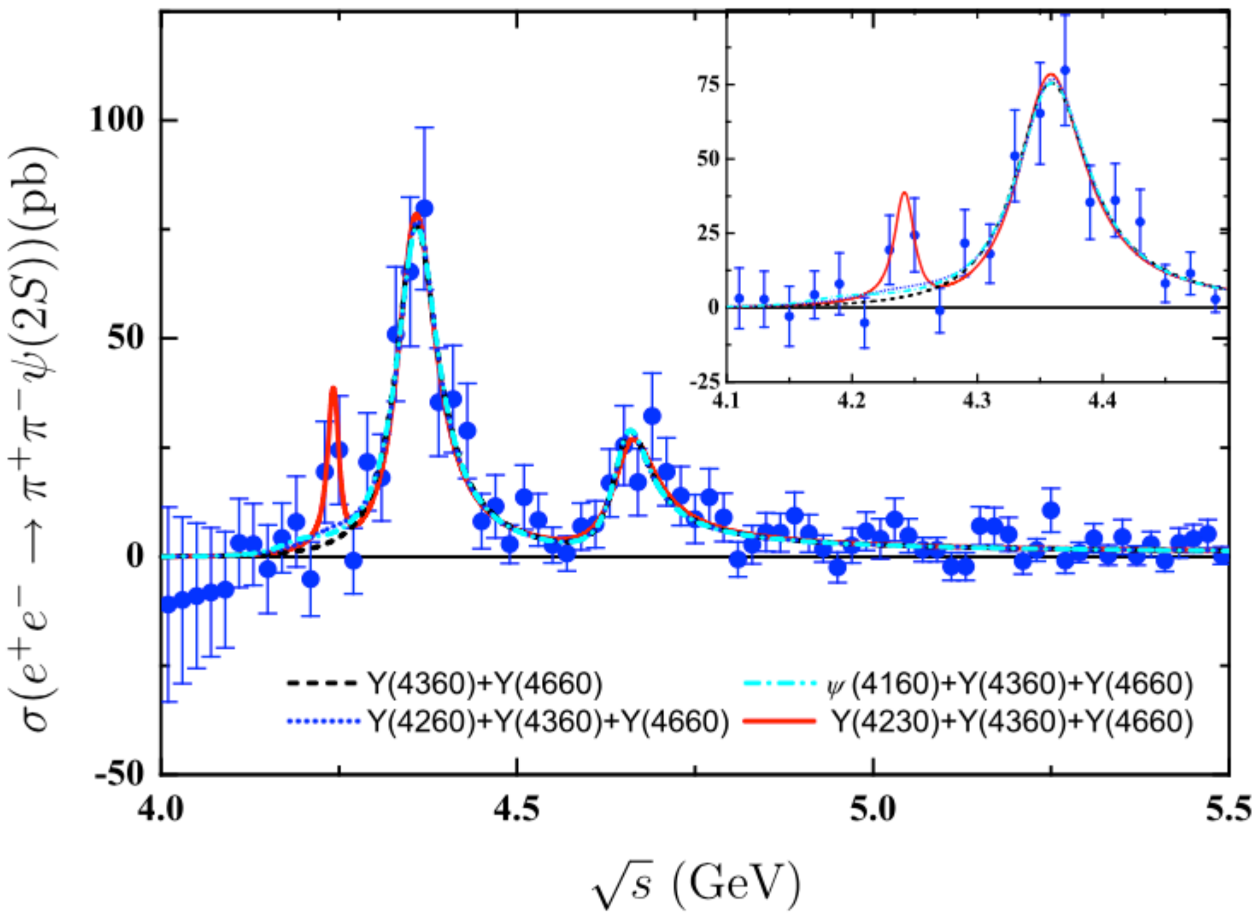


FIG. 2. A comparison of the fits to the cross sections for $e^+e^- \to \pi^+\pi^-\psi(2S)$ with different schemes.

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

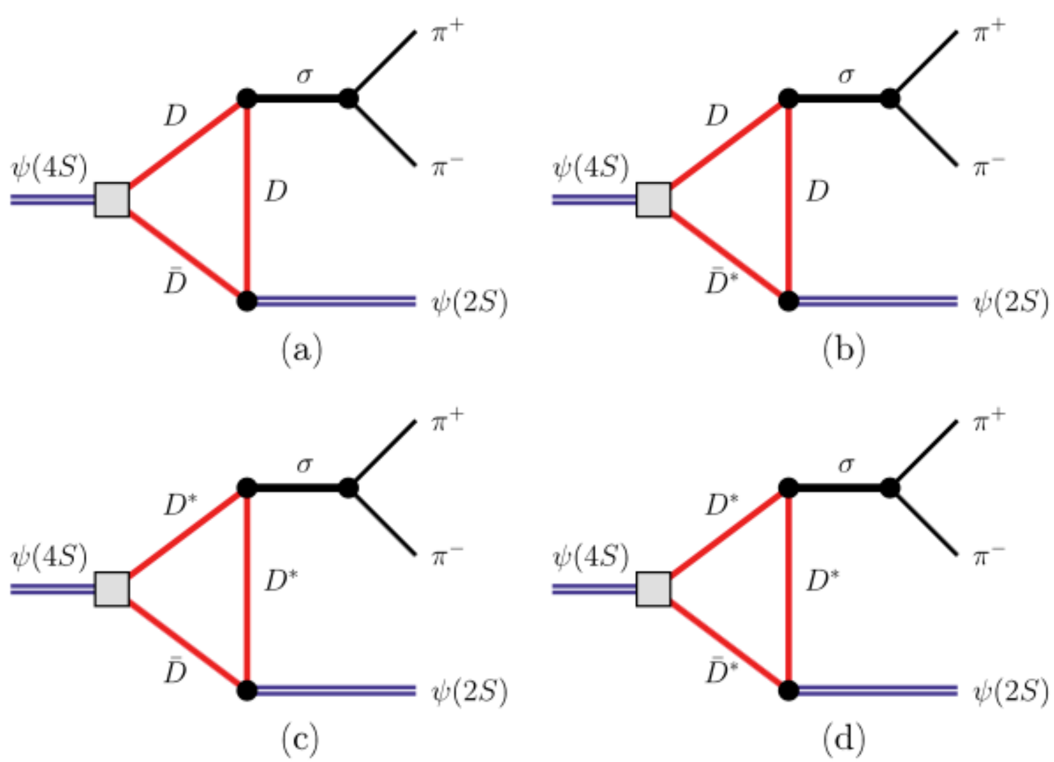


FIG. 3. Typical meson-loop contributions to $\psi(4S) \to \psi(2S)\pi^+\pi^-$, where the dipion comes from a σ meson.

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

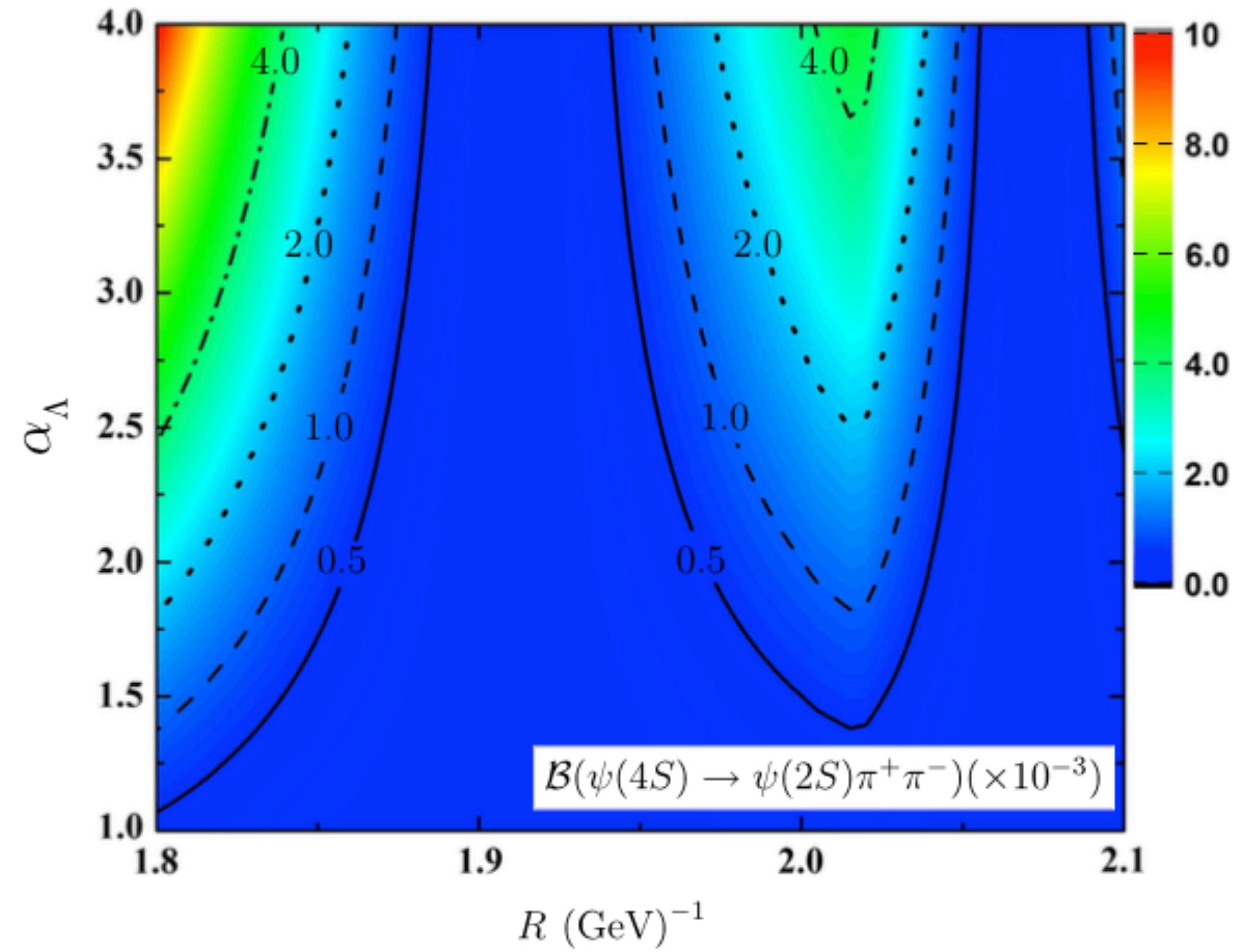


FIG. 4. The R and α_Λ dependence of the branching ratio for $\psi(4S) \to \psi(2S)\pi^+\pi^-$.

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

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

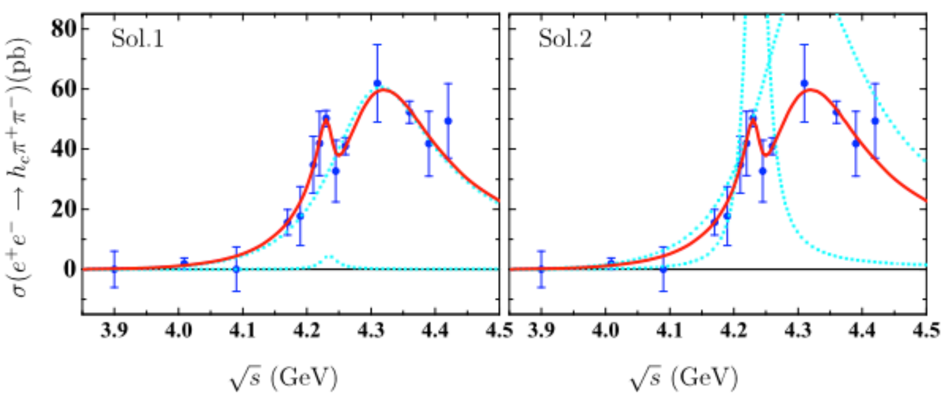


FIG. 6. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to h_c\pi^+\pi^-$ in scheme I. The cyan dashed and red solid curves are the resonance contributions and the fitting results, respectively.

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				$52.2/81$			

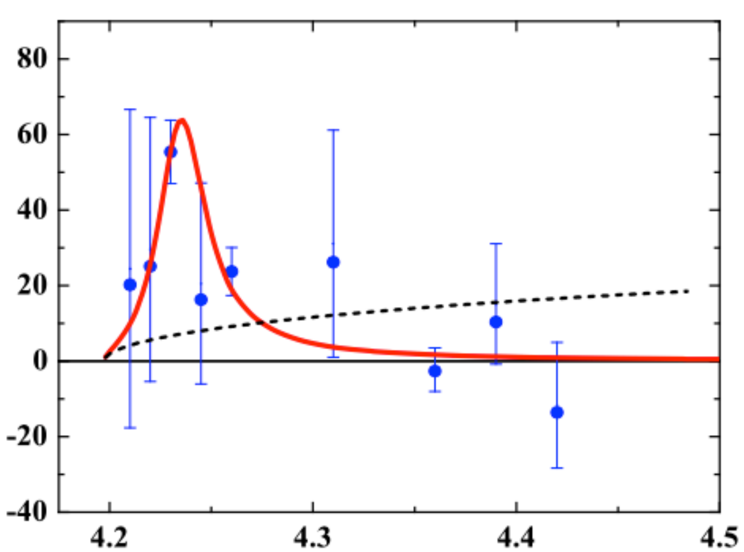


FIG. 7. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to \chi_{c0}\omega$ (solid curve) in scheme I. The dashed curve is the phase space of $e^+e^- \to \chi_{c0}\omega$.

Resonance parameter:

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

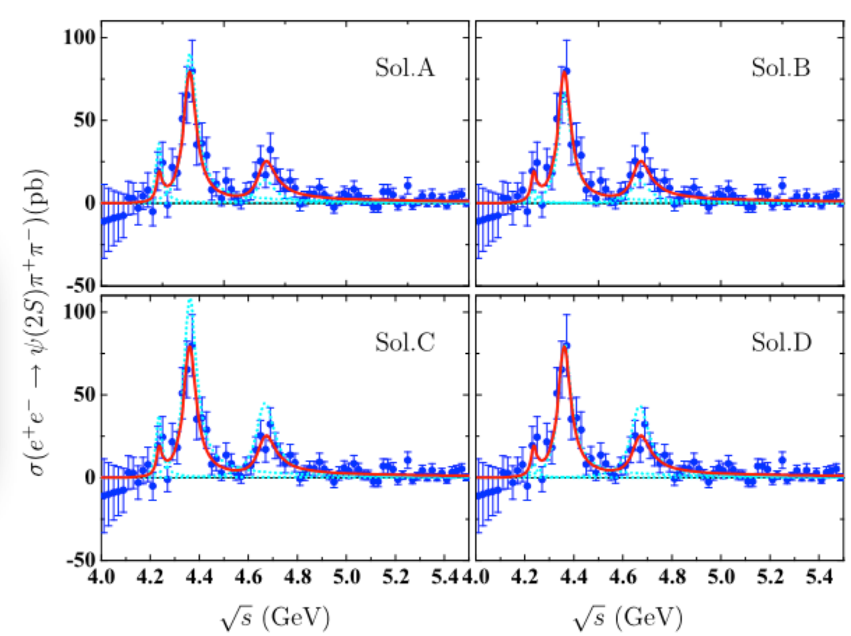


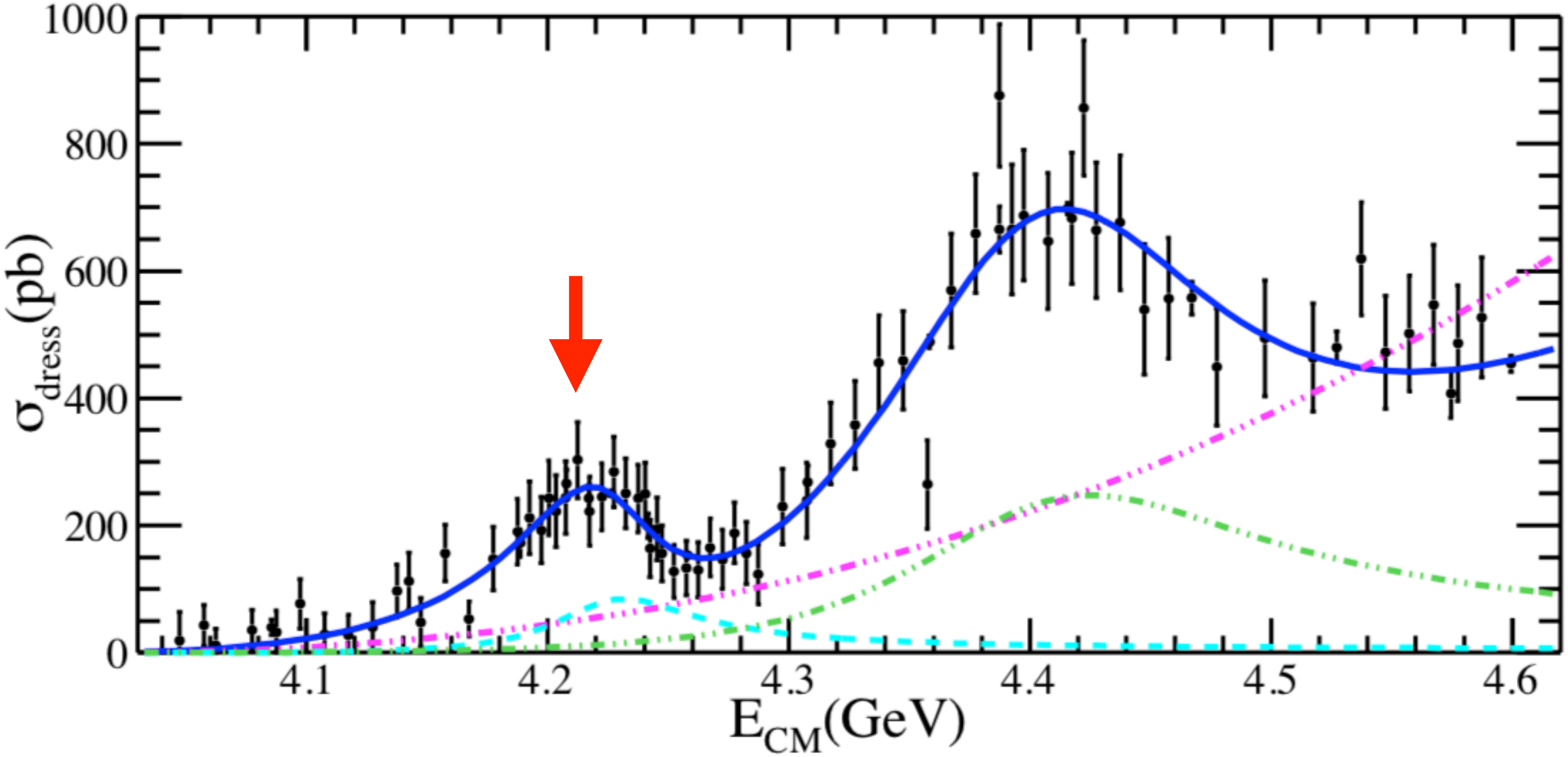
FIG. 5. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to \psi(2S)\pi^+\pi^-$ in scheme I. The cyan dashed and red solid curves are the resonance contributions and the fitting results, respectively.

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

arXiv:1808.02847

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

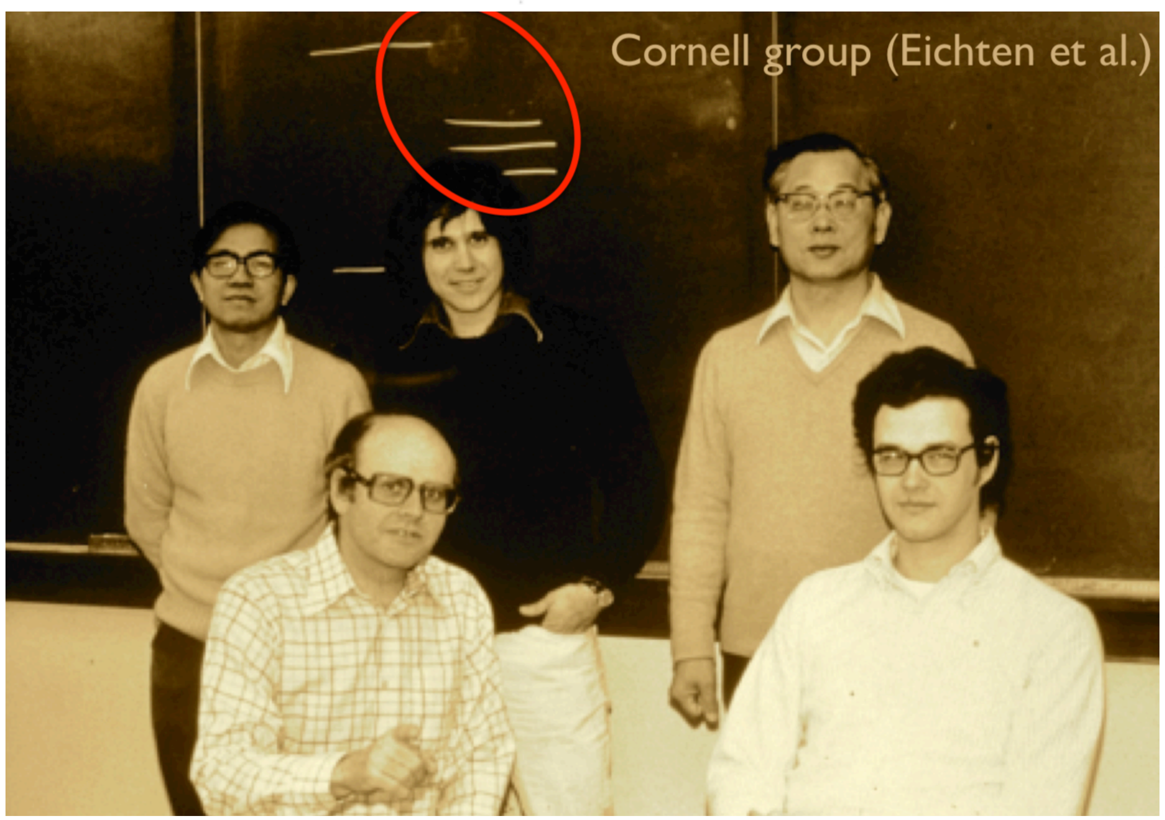


PHYSICAL REVIEW D VOLUME 17, NUMBER 11 1 JUNE 1978

Charmonium: The model

E. Eichten,* K. Gottfried, T. Kinoshita, K. D. Lane,* and T.-M. Yan†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 9 February 1978)

A comprehensive treatment of the charmonium model of the ψ family is presented. The model's basic assumption is a flavor-symmetric instantaneous effective interaction between quark color densities. This interaction describes both quark-antiquark binding and pair creation, and thereby provides a unified approach for energies below and above the threshold for charmed-meson production. If coupling to decay channels is ignored, one obtains the "naive" model wherein the dynamics is completely described by a single charmed-quark pair. A detailed description of this "naive" model is presented for the case where the instantaneous potential is a superposition of a linear and Coulombic term. A far more realistic picture is attained by incorporating those terms in the interaction that couple charmed quarks to light quarks. The coupled-channel formalism needed for this purpose is fully described. Formulas are given for the inclusive e^+e^- cross section and for e^+e^- annihilation into specific charmed-meson pairs. The influence of closed decay channels on ψ states below charm threshold is investigated, with particular attention to leptonic and radiative widths.



color gauge interaction leads to forces that are so strong at large distances that quarks are permanently confined in color-neutral bound states—the mesons and baryons. We also adopt this assumption.

Secondly, the large masses of the ψ resonances and charmed mesons lead to the assumption that the charmed quarks are so heavy that they may be treated nonrelativistically.[4] No one has yet succeeded in calculating the effective form of the interquark forces from quantum chromodynamics,[16] even in the nonrelativistic limit. To fill this gap we postulate that in this limit many of the gross features of the potential between the charmed quarks can be simulated by the potential

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}\,. \qquad (1.1)$$

Cornell potential

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)

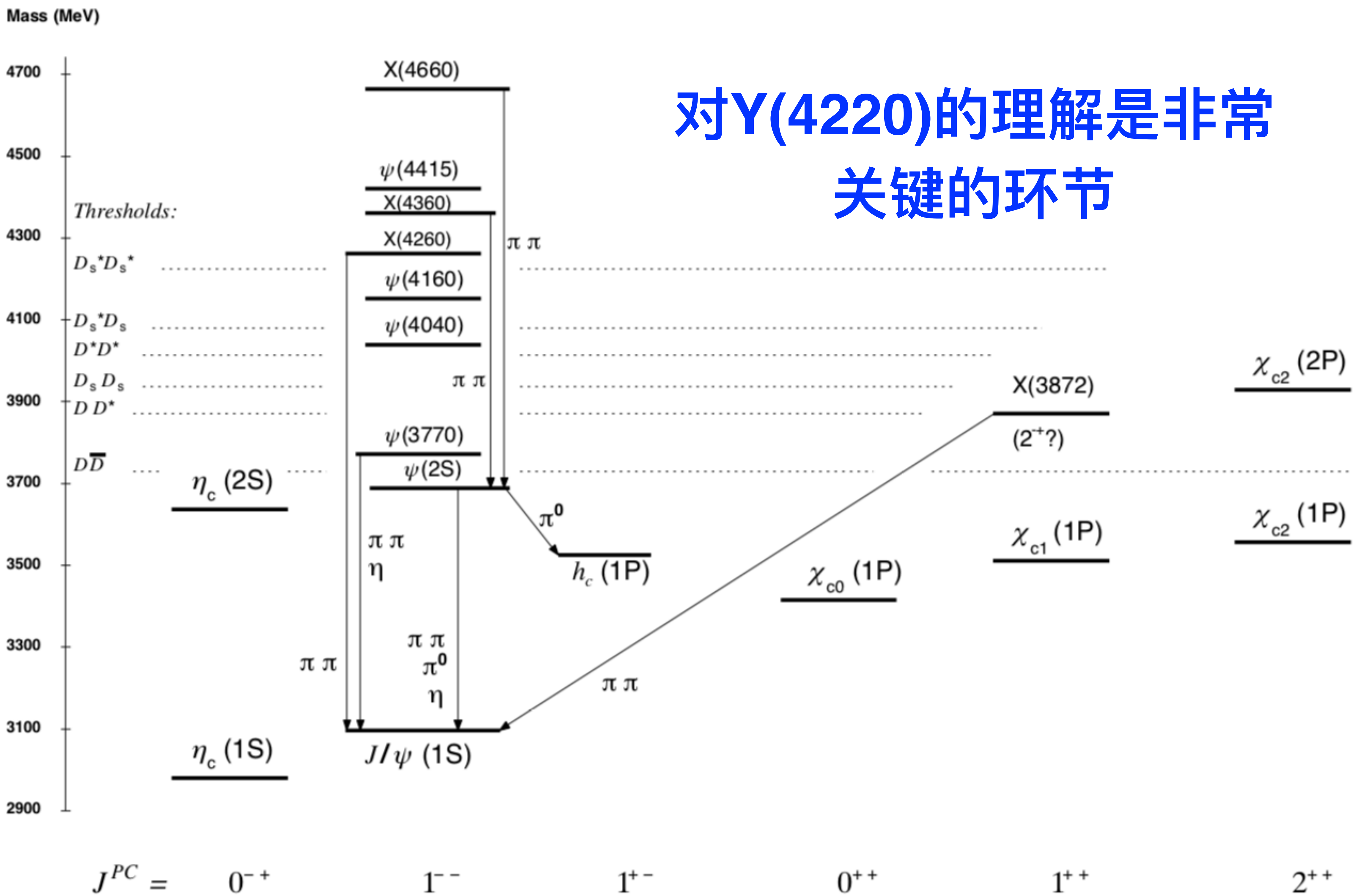
TABLE II. $c\bar{c}$ bound states in naive model, and their properties. Parameters used are m_c = 1.84 GeV, a = 2.34 GeV^{-1}, and κ = 0.52.

State	Mass (GeV)	Γ_{ee} (keV)[b]	$\langle v^2/c^2 \rangle$	$\langle r^2 \rangle^{1/2}$ (fm)	Candidate
1S	3.095[a]	4.8	0.20	0.47	ψ(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	ψ'(3684)
1D	3.81		0.23	1.0	ψ'(3772)[c]
3S	4.11	1.5	0.30	1.3	ψ(4028)
2D	4.19		0.29	1.35	ψ(4160)[d]
4S	4.46	1.1	0.35	1.7	ψ(4414)
5S	4.79	0.8	0.40	2.0	

psi(4415) as 4S state was proposed here

Is it a correct assignment?

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

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

$\psi(4160)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(4160)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
4191 ± 5 OUR AVERAGE				
4191^{+9}_{-8}	AAIJ	13BC	LHCB	$B^+ \to K^+ \mu^+ \mu^-$
4191.7 ± 6.5	[1] ABLIKIM	08D	BES2	$e^+ e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4193 ± 7	[2] MO	10	RVUE	$e^+ e^- \to$ hadrons
4151 ± 4	[3] SETH	05A	RVUE	$e^+ e^- \to$ hadrons
4155 ± 5	[4] SETH	05A	RVUE	$e^+ e^- \to$ hadrons
4159 ± 20	BRANDELIK	78C	DASP	$e^+ e^-$

$\psi(4415)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(4415)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4421 ± 4 OUR ESTIMATE				
4415.1± 7.9	[1] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4412 ±15	[2] MO	10	RVUE	$e^+e^- \to$ hadrons

$\psi(4415)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
62 ±20 OUR ESTIMATE				
71.5±19.0	[6] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
118 ±32	[7] MO	10	RVUE	$e^+e^- \to$ hadrons
77 ±20	[8] PAKHLOVA	08A	BELL	10.6 $e^+e^- \to D^0 D^- \pi^+ \gamma$
119 ±16	[9] SETH	05A	RVUE	$e^+e^- \to$ hadrons
118 ±35	[10] SETH	05A	RVUE	$e^+e^- \to$ hadrons
66 ±15	BRANDELIK	78C	DASP	e^+e^-
33 ±10	SIEGRIST	76	MRK1	e^+e^-

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

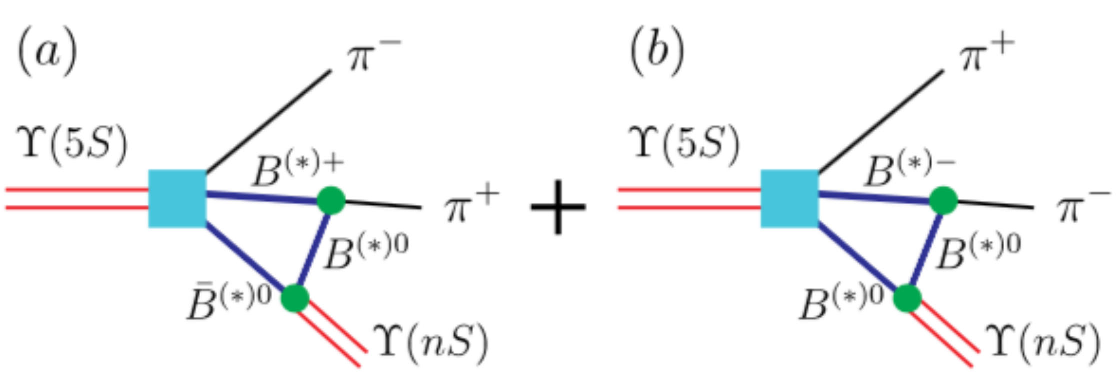
Predicted charged charmoniumlike structures in the hidden-charm dipion decay of higher charmonia

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

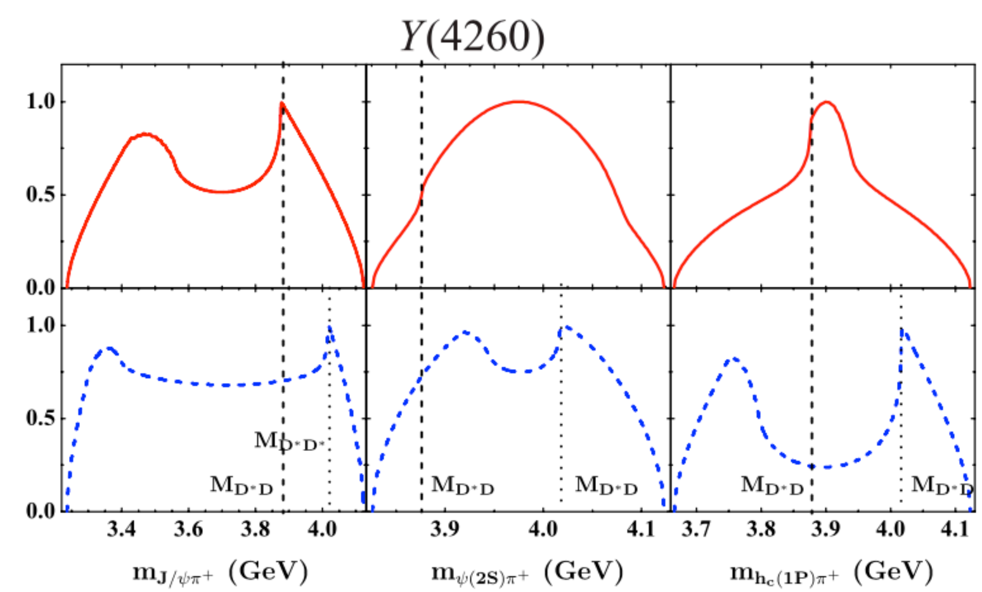
In this work, we predict two charged charmoniumlike enhancement structures close to the $D^*\bar{D}$ and $D^*\bar{D}^*$ thresholds, where the Initial Single Pion Emission mechanism is introduced in the hidden-charm dipion decays of higher charmonia $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ and charmoniumlike 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 $h_c(1P)\pi^+\pi^-$. 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*.

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

Initial Single Pioin Emission (ISPE) mechanism

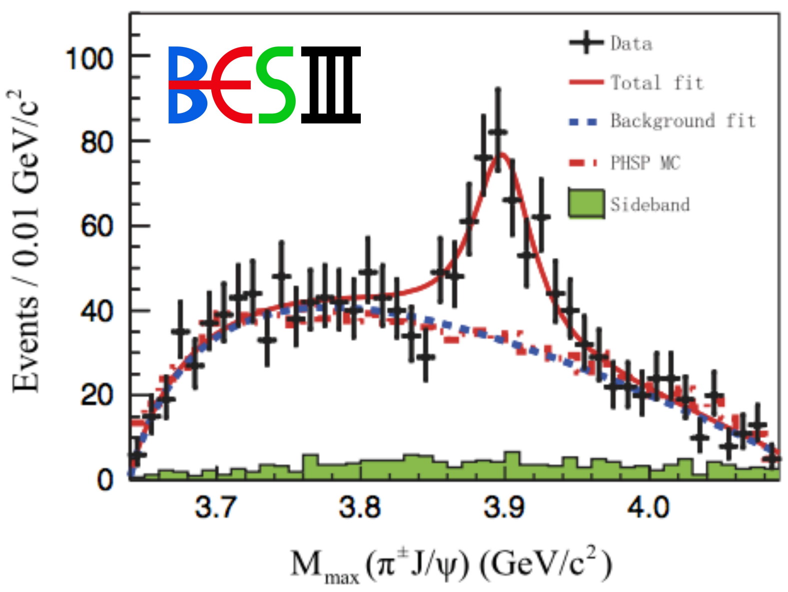


Chen, Liu, PRD84 (2011) 094003

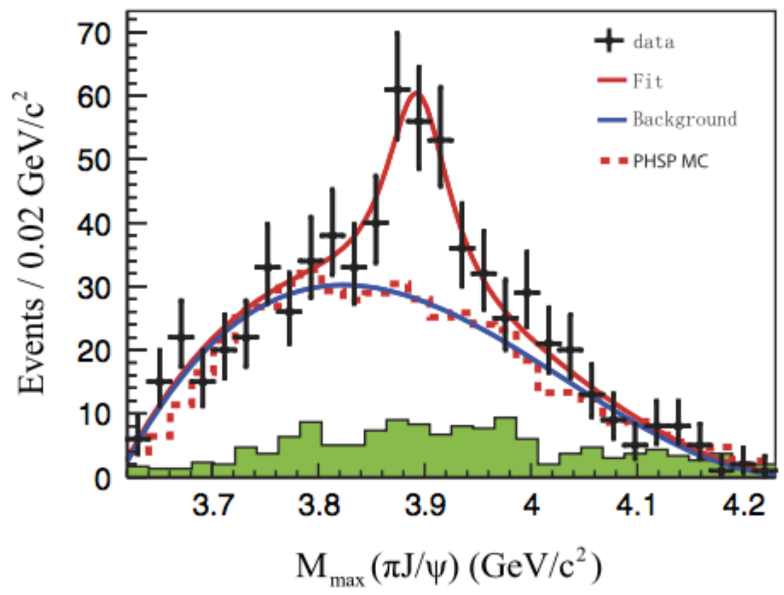


Discovery of Zc(3900)

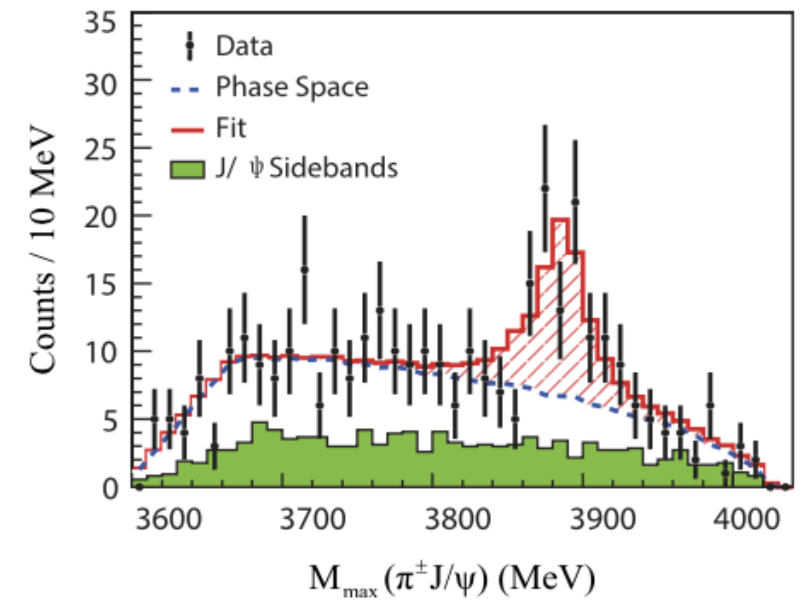
PRL110 (2013) 252001



PRL110 (2013) 252002

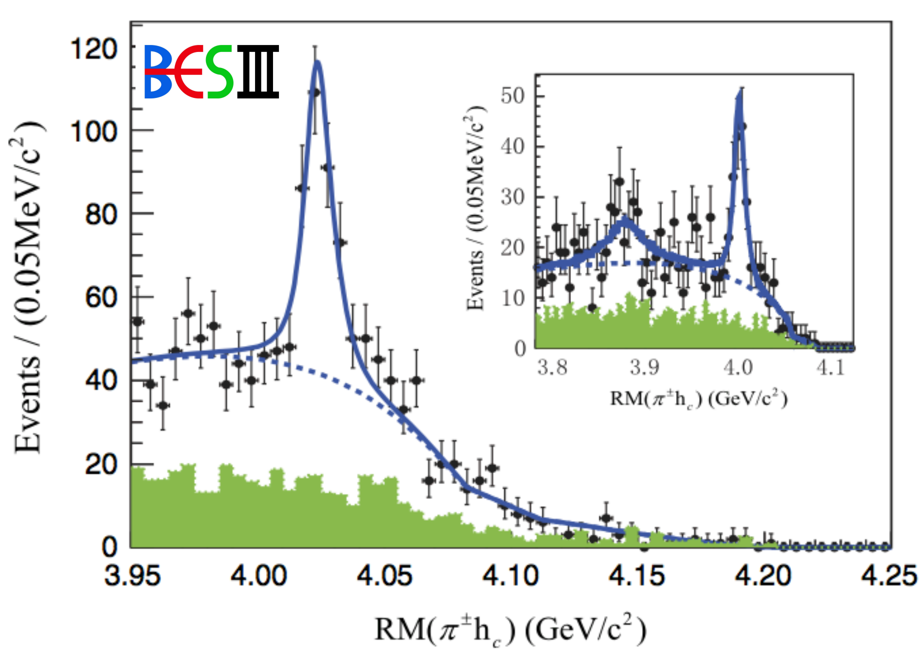


PLB773 (2013) 366



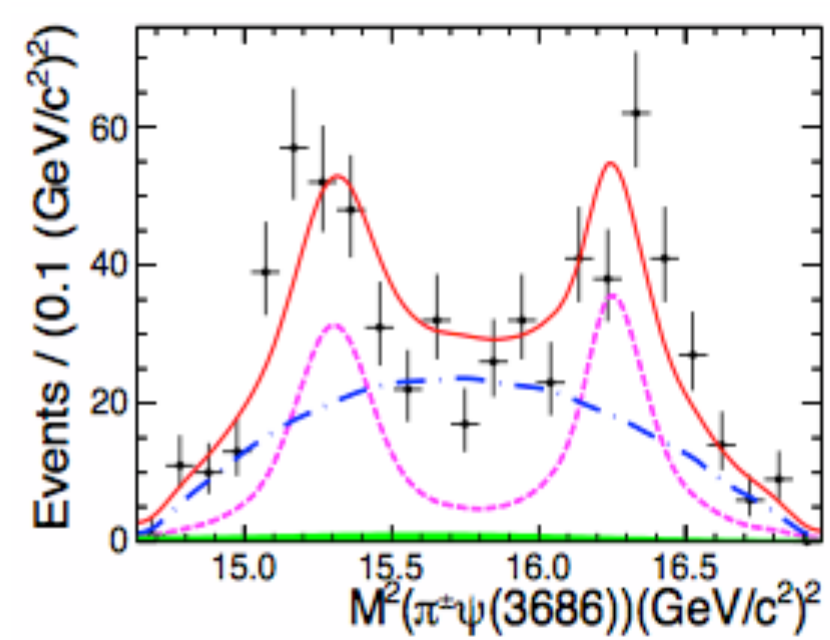
Discovery of Zc(4020)

PRL111 (2013) 242001



Discovery of Zc(4032)

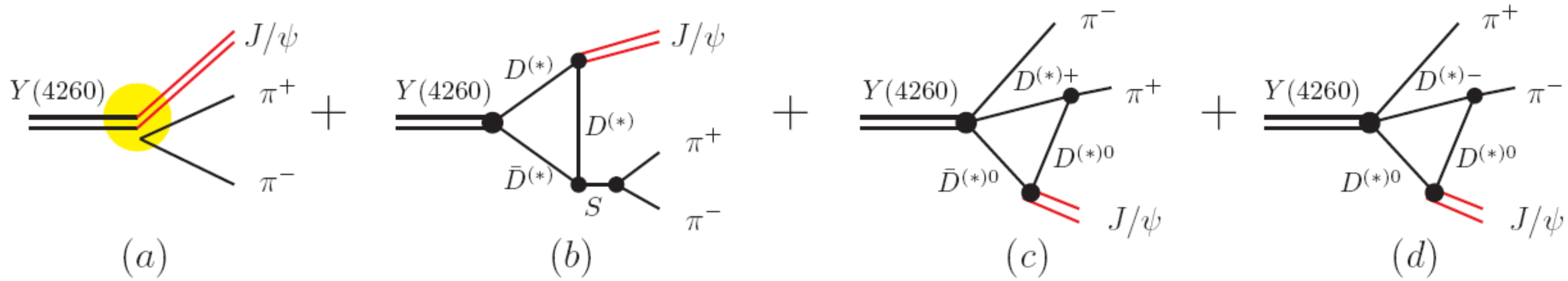
arXiv: 1703.08787



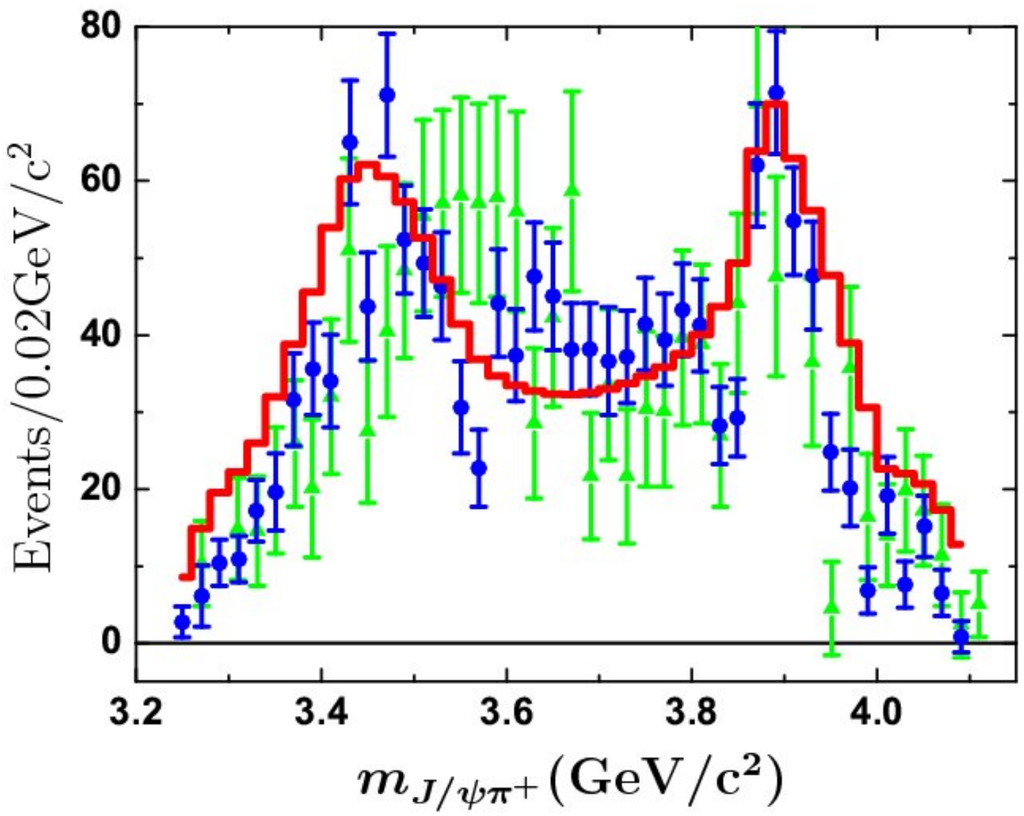
PHYSICAL REVIEW D **88,** 036008 (2013)

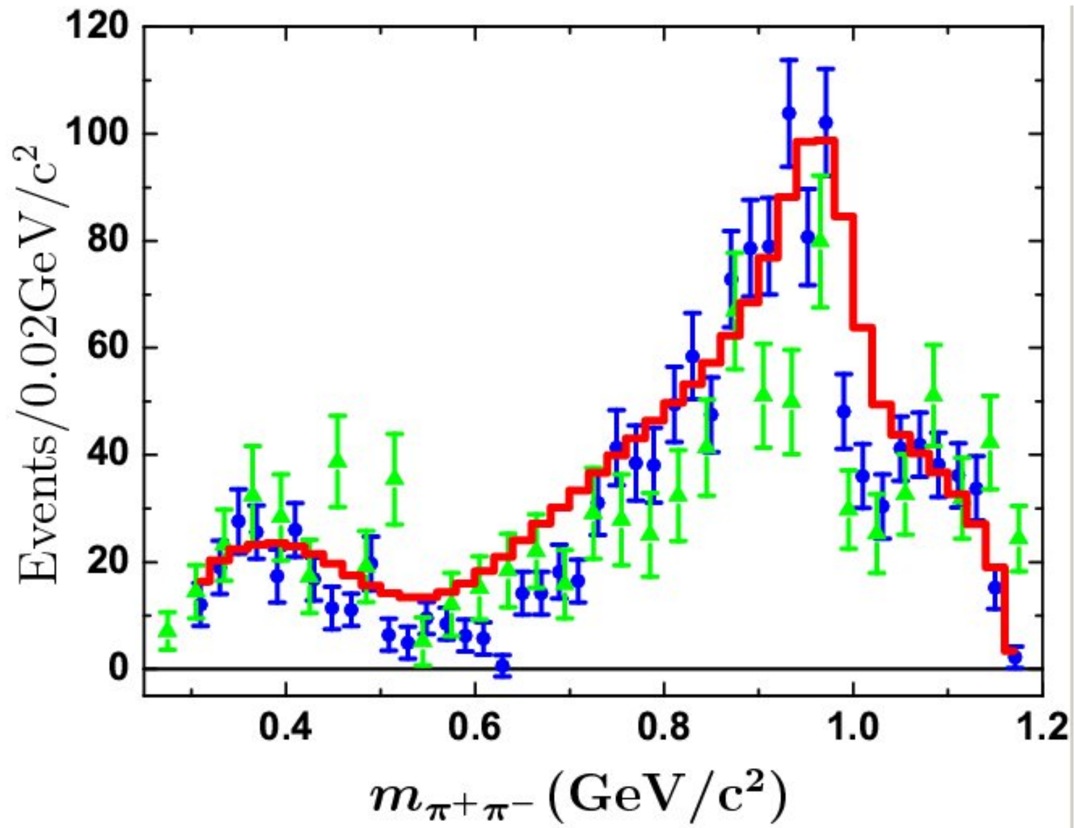
Reproducing the $Z_c(3900)$ structure through the initial-single-pion-emission mechanism

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)

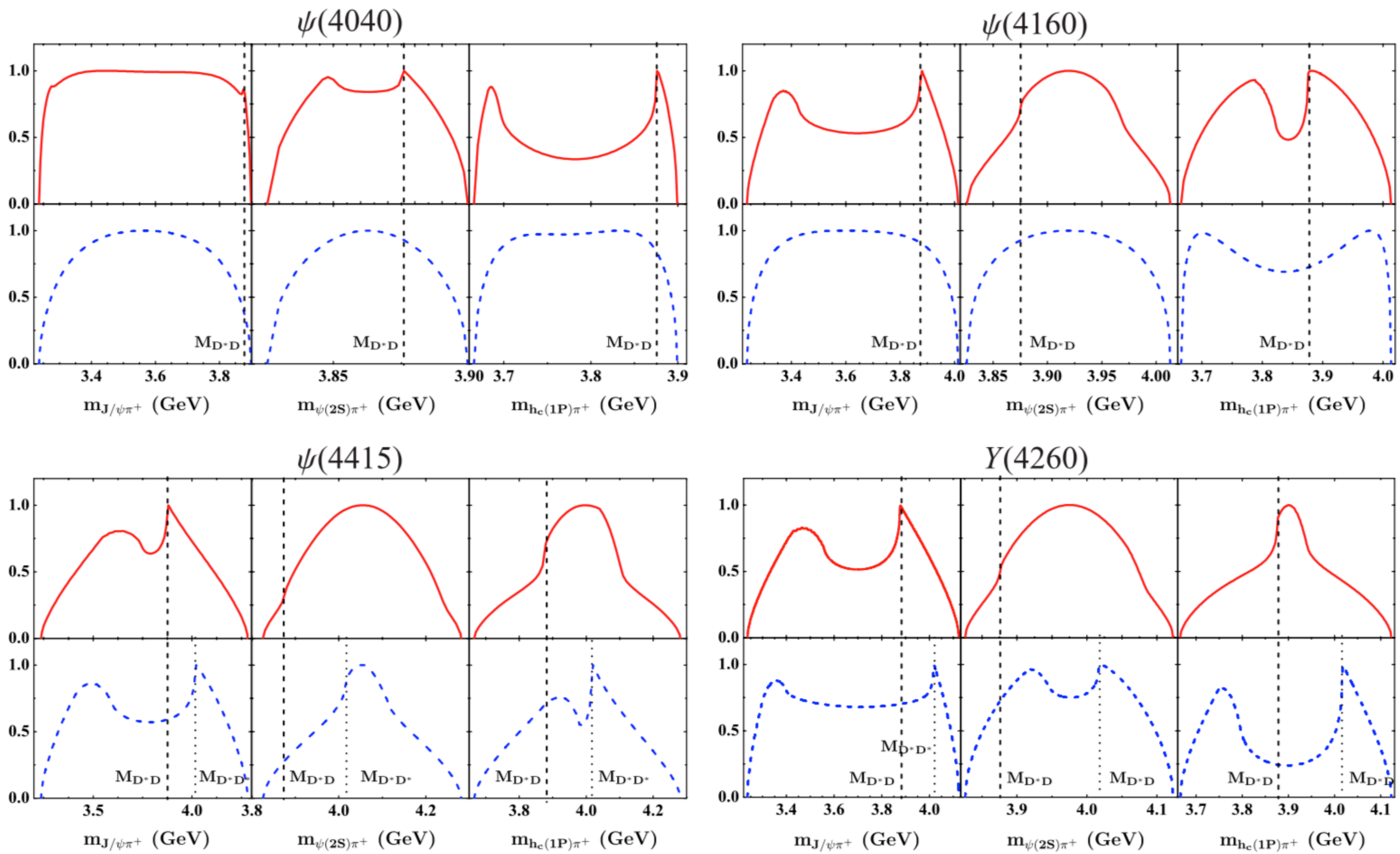
The possible exotic meson $Z_c(3900)$, found in e^+e^- reactions, is studied by the method of coupled-channel scattering in lattice QCD. The interactions among $\pi J/\psi$, $\rho\eta_c$, and $\bar{D}D^*$ channels are derived from $(2+1)$-flavor QCD simulations at $m_\pi = 410$–700 MeV. The interactions 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)

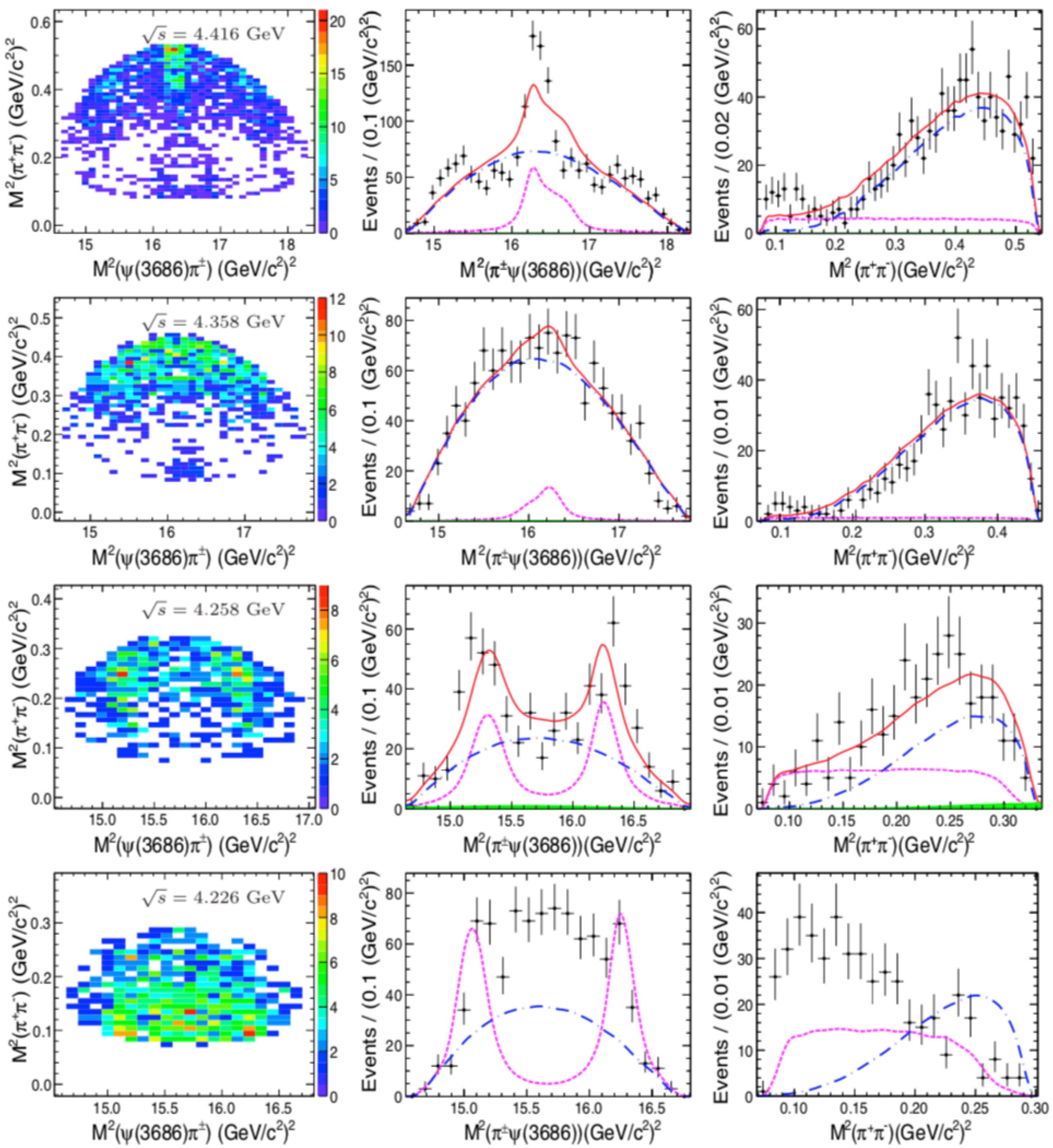
Predicted charged charmoniumlike structures in the hidden-charm dipion decay of higher charmonia

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

Predictions of Charged Charmoniumlike Structures with Hidden-Charm and Open-Strange Channels

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

PRL **110,** 232001 (2013) PHYSICAL REVIEW LETTERS week ending 7 JUNE 2013

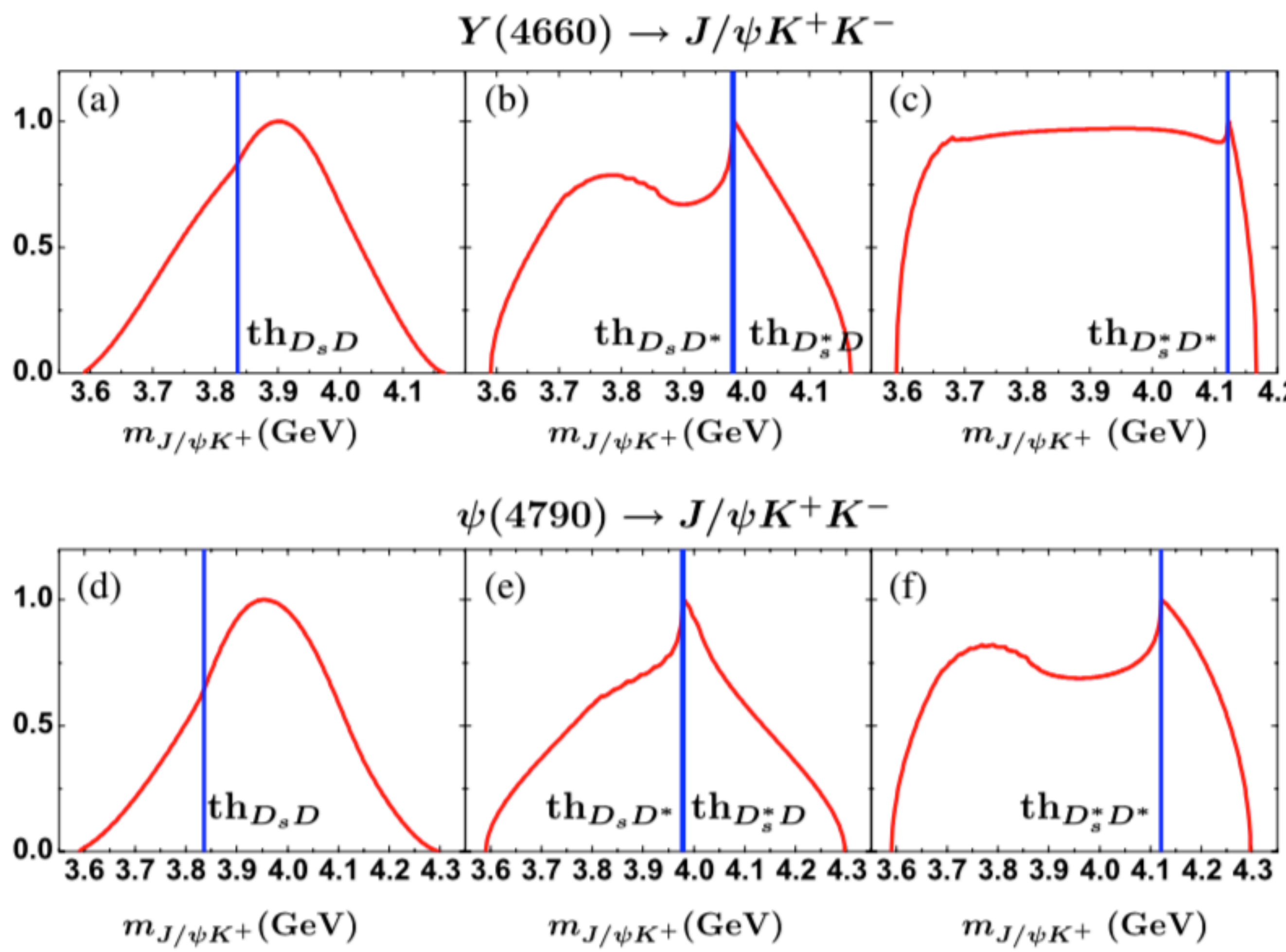
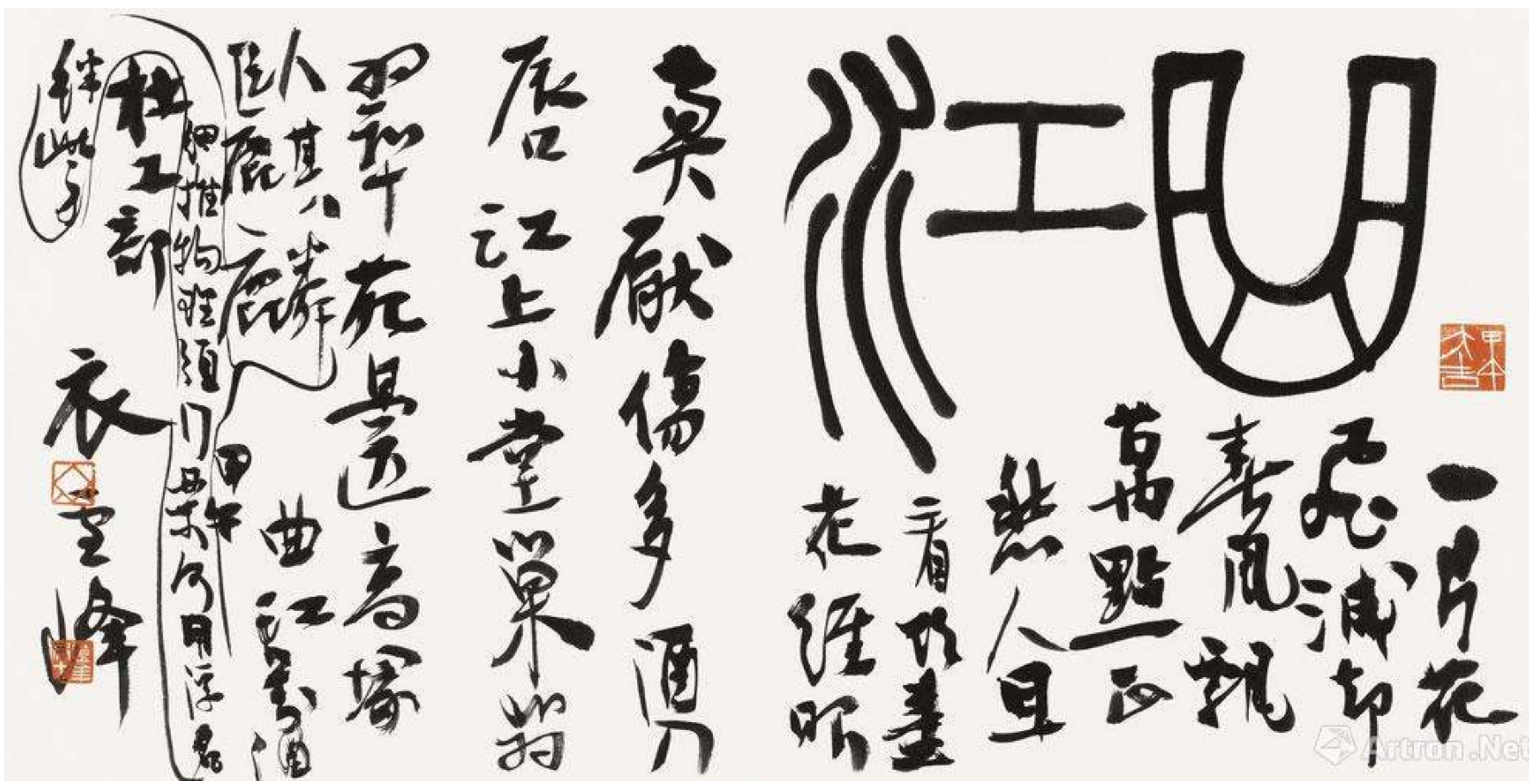


FIG. 3 (color online). Dependence of the distribution of $d\Gamma/dm_{J/\psi K^+}$ on the $J/\psi K^+$ invariant mass spectrum (red solid curves). The diagrams (a) and (d), the diagrams (b) and (e), and the diagrams (c) and (f), are the results considering the intermediate $D\bar{D}_s$ + H.c., $D^*\bar{D}_s + D\bar{D}_s^*$ + H.c., and $D^*\bar{D}_s^*$ + H.c. contributions, respectively. Here, the line shape of the distribution of $d\Gamma/dm_{J/\psi K^+}$ is normalized to 1.

Physics around higher Upsilon states



Examples for higher bottomonia

PHYSICAL REVIEW D **94**, 094039 (2016)

Prediction of anomalous $\Upsilon(5S) \to \Upsilon(1^3D_J)\eta$ transitions

Bo Wang* and Xiang Liu†

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

Dian-Yong Chen‡

Department of Physics, Southeast University, Nanjing 210094, China

(Received 27 September 2016; published 28 November 2016)

In this work, we study the hadronic loop contribution to the $\Upsilon(5S) \to \Upsilon(1^3D_J)\eta$ ($J = 1, 2, 3$) transitions. We predict that the branching ratios of $\Upsilon(5S) \to \Upsilon(1^3D_1)\eta$, $\Upsilon(5S) \to \Upsilon(1^3D_2)\eta$, and $\Upsilon(5S) \to \Upsilon(1^3D_3)\eta$ can reach up to $(0.5\text{–}5.1) \times 10^{-3}$, $(0.7\text{–}7.5) \times 10^{-3}$ and $(0.9\text{–}9.6) \times 10^{-4}$, respectively. Since these predicted hadronic transitions of $\Upsilon(5S)$ are comparable with these observed $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ ($n = 1, 2, 3$), we suggest for future experiments like Belle and BelleII to carry out the search for these anomalous $\Upsilon(5S) \to \Upsilon(1^3D_J)\eta$ transitions.

Eur. Phys. J. C (2018) 78:633
https://doi.org/10.1140/epjc/s10052-018-6086-4

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

Confirmed by Belle

Inclusive study of bottomonium production in association with an η meson in e^+e^- annihilations near $\Upsilon(5S)$

Belle Collaboration

Under these assumptions, we calculate the branching fraction $\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon_J(1D)] = (4.82 \pm 0.92 \pm 0.67) \times 10^{-3}$. Theoretical calculations that account for the effect of virtual B meson loops are in agreement with our result [37].

Eur. Phys. J. C (2017) 77:165
DOI 10.1140/epjc/s10052-017-4726-8

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Theoretical Physics

Exploring the $\Upsilon(6S) \to \chi_{bJ}\phi$ and $\Upsilon(6S) \to \chi_{bJ}\omega$ hidden-bottom hadronic transitions

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

Confirmed by Belle PRD98 (2018) 091102

Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{b1,2}(1P)$ and search for $e^+e^- \to \phi\chi_{b1,2}(1P)$ at $\sqrt{s}$ =10.96—11.05 GeV

$(2.5 \pm 0.6 \pm 2.0 \pm 0.7) \times 10^{-3}$ is consistent with the previous measurement [4], and $\mathcal{B}(\Upsilon(6S) \to \pi^+\pi^-\pi^0\chi_{bJ}) = (8.7 \pm 4.3 \pm 6.1^{+4.5}_{-2.5}) \times 10^{-3}$, which is consistent with the theoretical predictions [16], is measured for the first time.

PHYSICAL REVIEW D **98,** 054008 (2018)

Proposal of searching for the $\Upsilon(6S)$ hadronic decays into $\Upsilon(nS)$ plus $\eta^{(\prime)}$

Qi Huang,[1,2] Xiang Liu,[1,2,*] and Takayuki Matsuki[3,4,†]

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

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In this work, we propose a possible experimental research topic on the $\Upsilon(6S) \to \Upsilon(nS)\eta^{(\prime)}$ ($n = 1, 2, 3$) transitions. Considering the hadronic loop effect from the intermediate S-wave $B_{(s)}$ and $B^*_{(s)}$ mesons, we estimate the partial decay widths and the corresponding branching ratios of the $\Upsilon(6S) \to \Upsilon(nS)\eta^{(\prime)}$ hadronic decays, which become considerably large. With the running of the Belle II experiment, it becomes possible to explore these $\Upsilon(6S) \to \Upsilon(nS)\eta^{(\prime)}$ transitions.

Prediction:

$$\mathcal{B}[\Upsilon(6S) \to \Upsilon(1S)\eta] = 3.238 \times 10^{-3},$$

$$\mathcal{B}[\Upsilon(6S) \to \Upsilon(2S)\eta] = 1.947 \times 10^{-3},$$

$$\mathcal{B}[\Upsilon(6S) \to \Upsilon(3S)\eta] = 0.135 \times 10^{-3},$$

$$\mathcal{B}[\Upsilon(6S) \to \Upsilon(1S)\eta'] = 1.448 \times 10^{-3},$$

$$\mathcal{B}[\Upsilon(6S) \to \Upsilon(2S)\eta'] = 1.305 \times 10^{-6}.$$

Potential observation of the $\Upsilon(6S) \to \Upsilon(1^3D_J)\eta$ transitions at Belle II

Qi Huang,[1,2] Hao Xu,[1,2] Xiang Liu,[1,2,*] and Takayuki Matsuki[3,4,†]

[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*
[3] *Tokyo Kasei University, 1-18-1 Kaga, Itabashi, Tokyo 173-8602, Japan*
[4] *Theoretical Research Division, Nishina Center, RIKEN, Wako, Saitama 351-0198, Japan*

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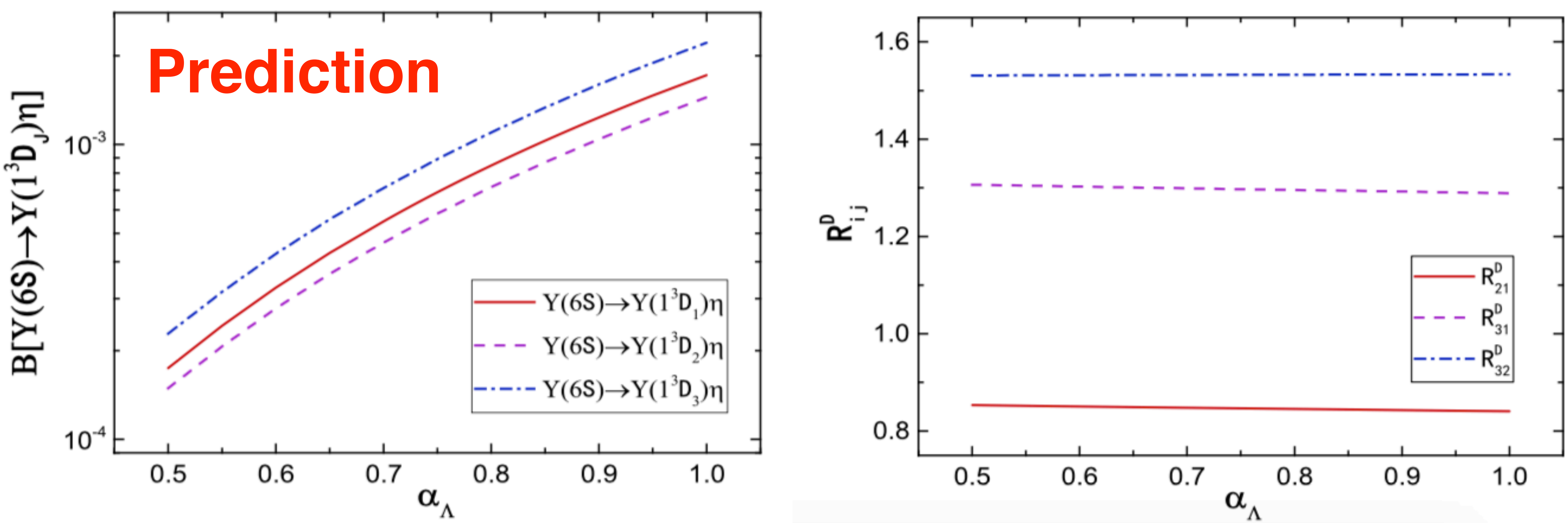
We perform the investigation of two-body hidden-bottom transitions of the $\Upsilon(6S)$, which include $\Upsilon(6S) \to \Upsilon(1^3D_J)\eta (J = 1, 2, 3)$ decays. For estimating the branching ratios of these processes, we consider contributions from the triangle hadronic loops composed of S-wave $B_{(s)}$ and $B^*_{(s)}$ mesons, which are a bridge to connect the $\Upsilon(6S)$ and final states. Our results show that both of the branching ratios of these decays can reach 10^{-3}. Because of such considerable potential to observe these two-body hidden-bottom transitions of the $\Upsilon(6S)$, we suggest the forthcoming Belle II experiment to explore them.



Eur. Phys. J. C (2018) 78:915
https://doi.org/10.1140/epjc/s10052-018-6372-1

THE EUROPEAN PHYSICAL JOURNAL C

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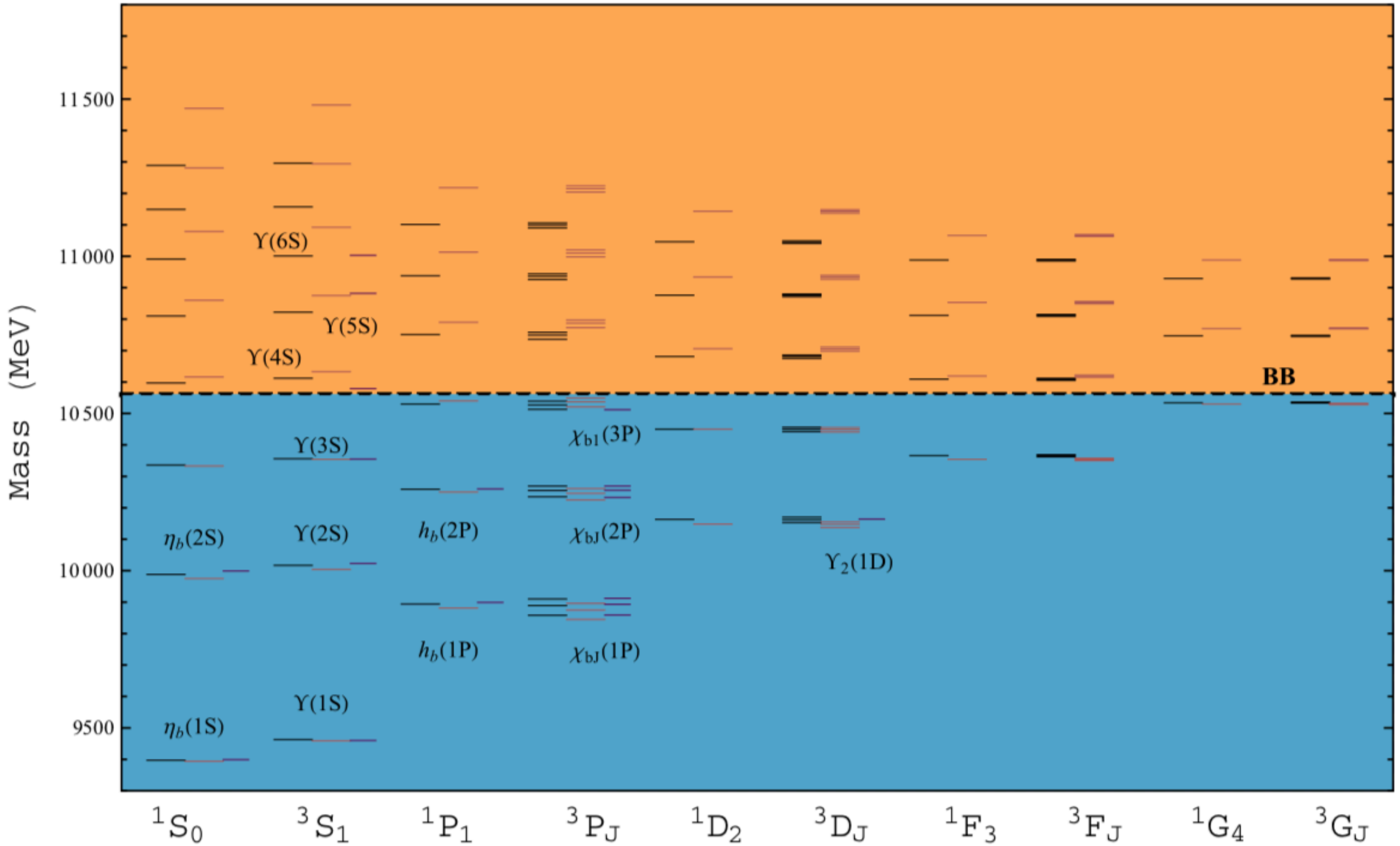
Regular Article - Theoretical Physics

Abundant physics

Higher bottomonium zoo

Jun-Zhang Wang[1,2,a], **Zhi-Feng Sun**[1,2,b], **Xiang Liu**[1,2,c], **Takayuki Matsuki**[3,4,d]



Summary

1. Abundant physics at 2.1 GeV, 4.2 GeV and 10.860 GeV
2. Chance and challenge for theorist and experimentalist
3. Theoretical and experimental joint effort

Thank you for your attention!