Finding Solution for Y Problem

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NCTS Annual Theory Meeting 2020: Particles, Cosmology and Strings

Dec. 9th – 11th, 2020

Outline

- **Y problems**
- **Fano-like interference**
- **Narrow structure around 4.2 GeV**
- **Constructing J/ψ family with updated data of charmonium-like Y states**

1. Y problems

Many light hadrons

(1950's &1960's)

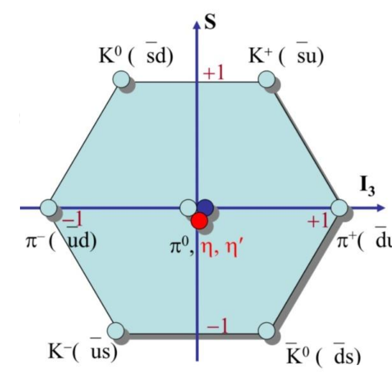
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN
California Institute of Technology, Pasadena, California

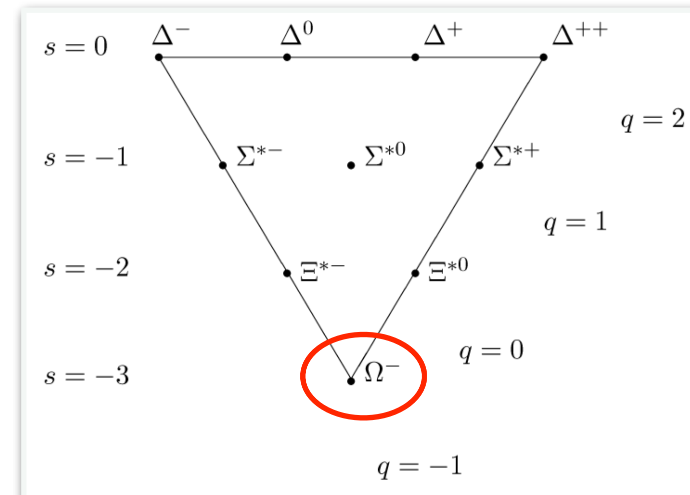
Received 4 January 1964

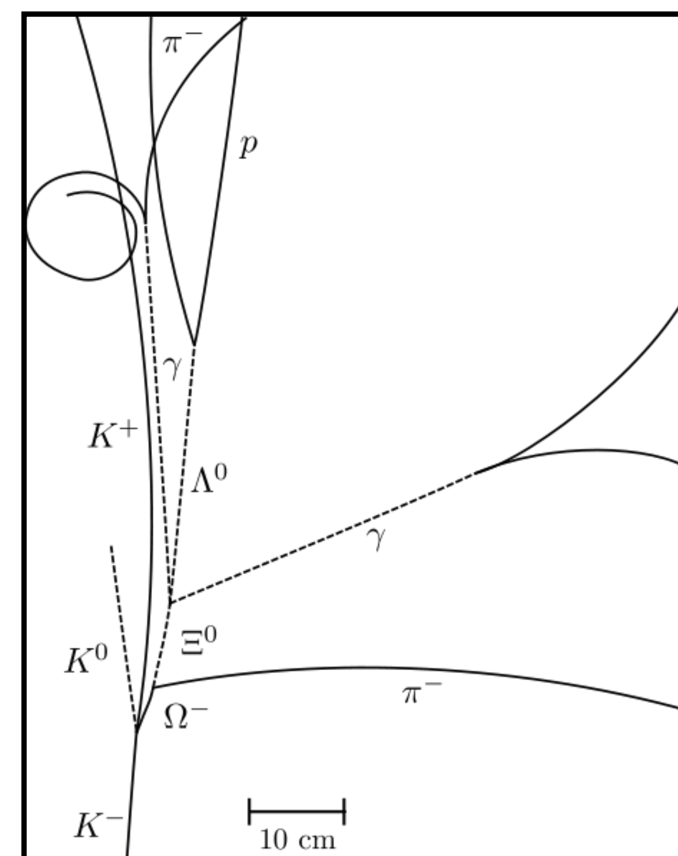


If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

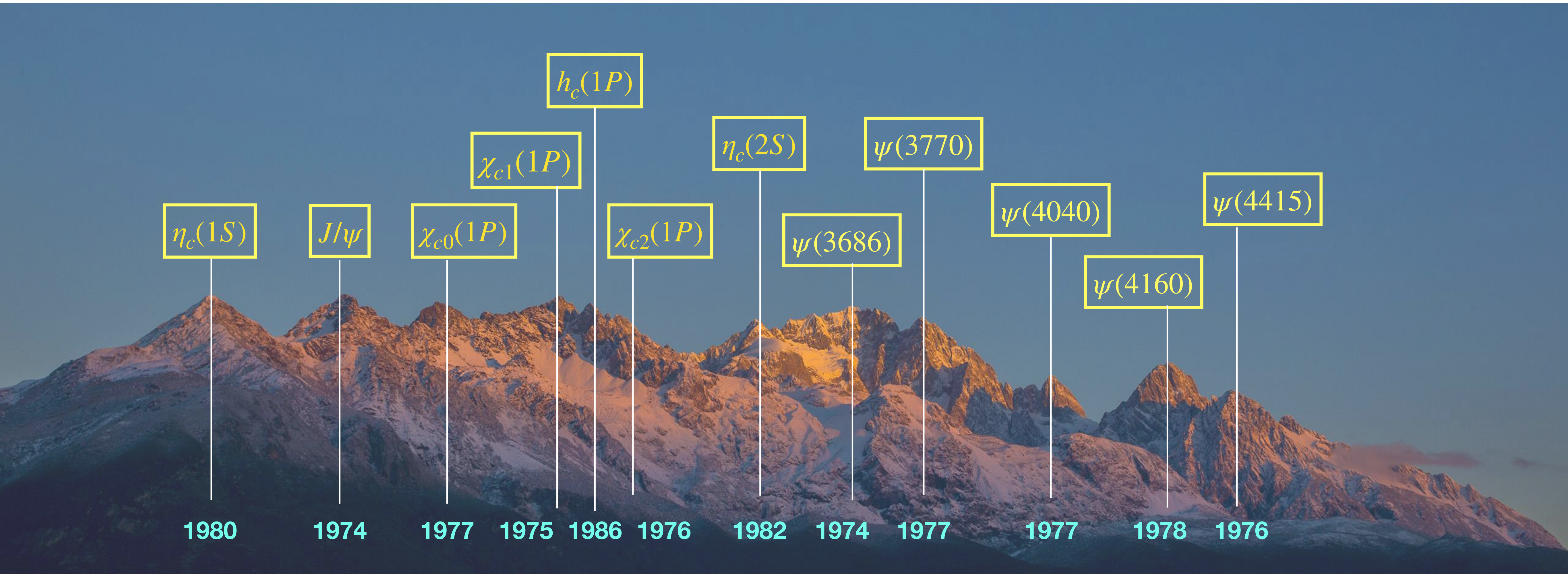
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest





Status of charmonium family

(1974-1982)



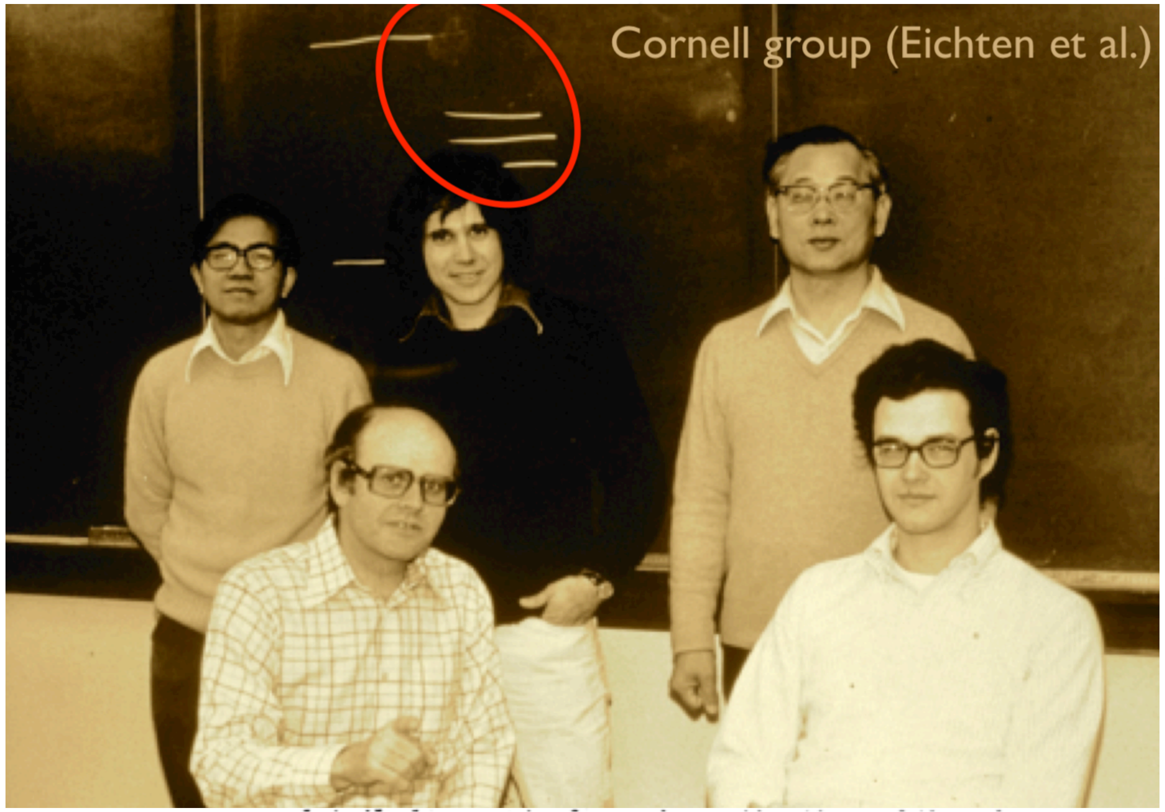
Most of charmonia listed in PDG were observed

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.

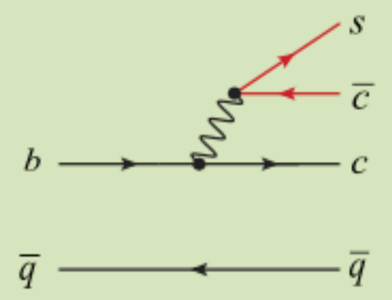
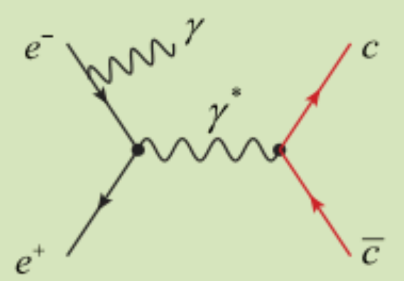
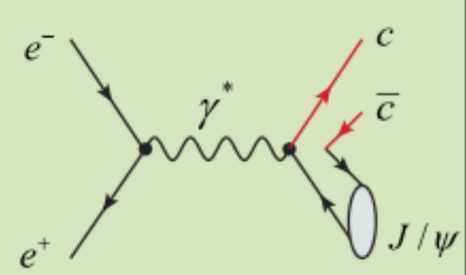
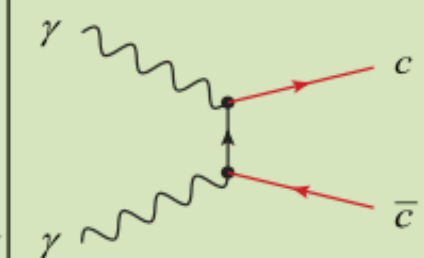
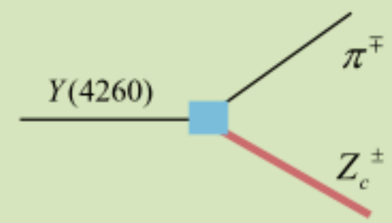
Secondly, the large masses of the ψ resonances and charmed mesons lead to the assumption that the charmed quarks are so heavy that they may be treated nonrelativistically.[4] No one has yet succeeded in calculating the effective form of the interquark forces from quantum chromodynamics,[16] even in the 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

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

Cornell potential

The observed charmonium-like XYZ states

(2003-now)

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

see review

Physics Reports 639 (2016) 1–121

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

ELSEVIER

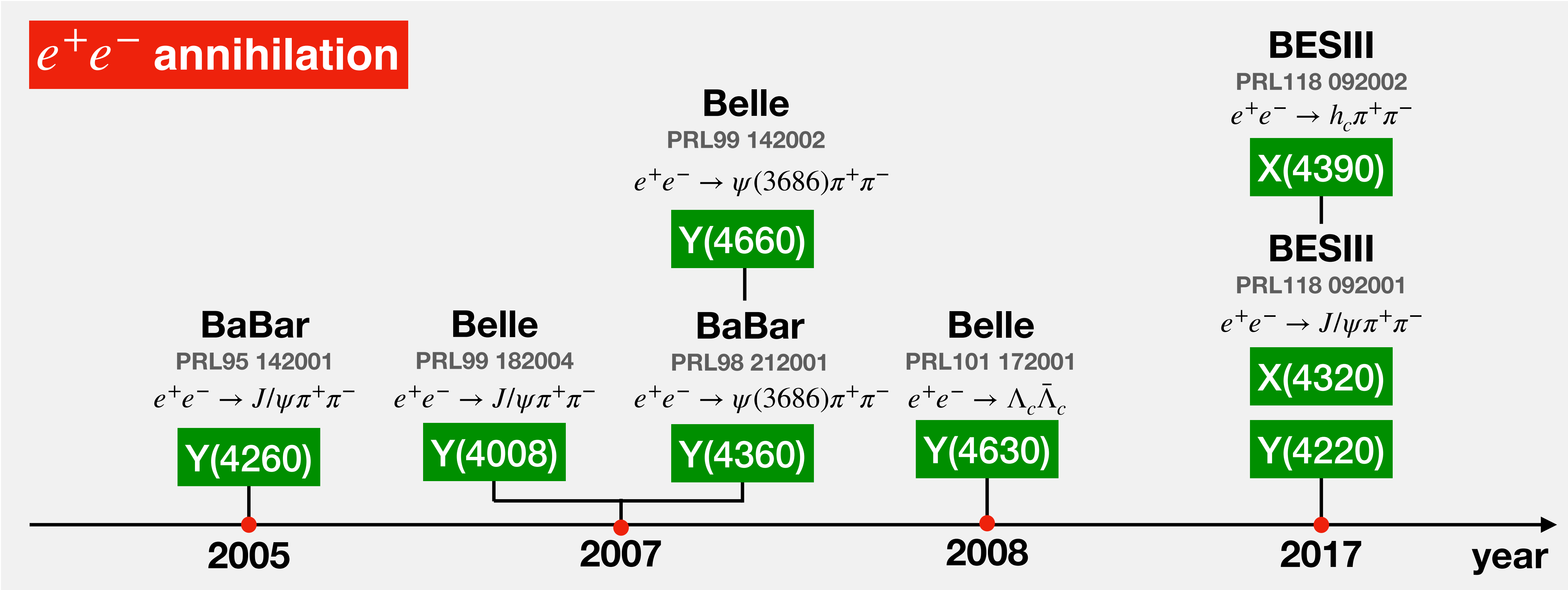
The hidden-charm pentaquark and tetraquark states

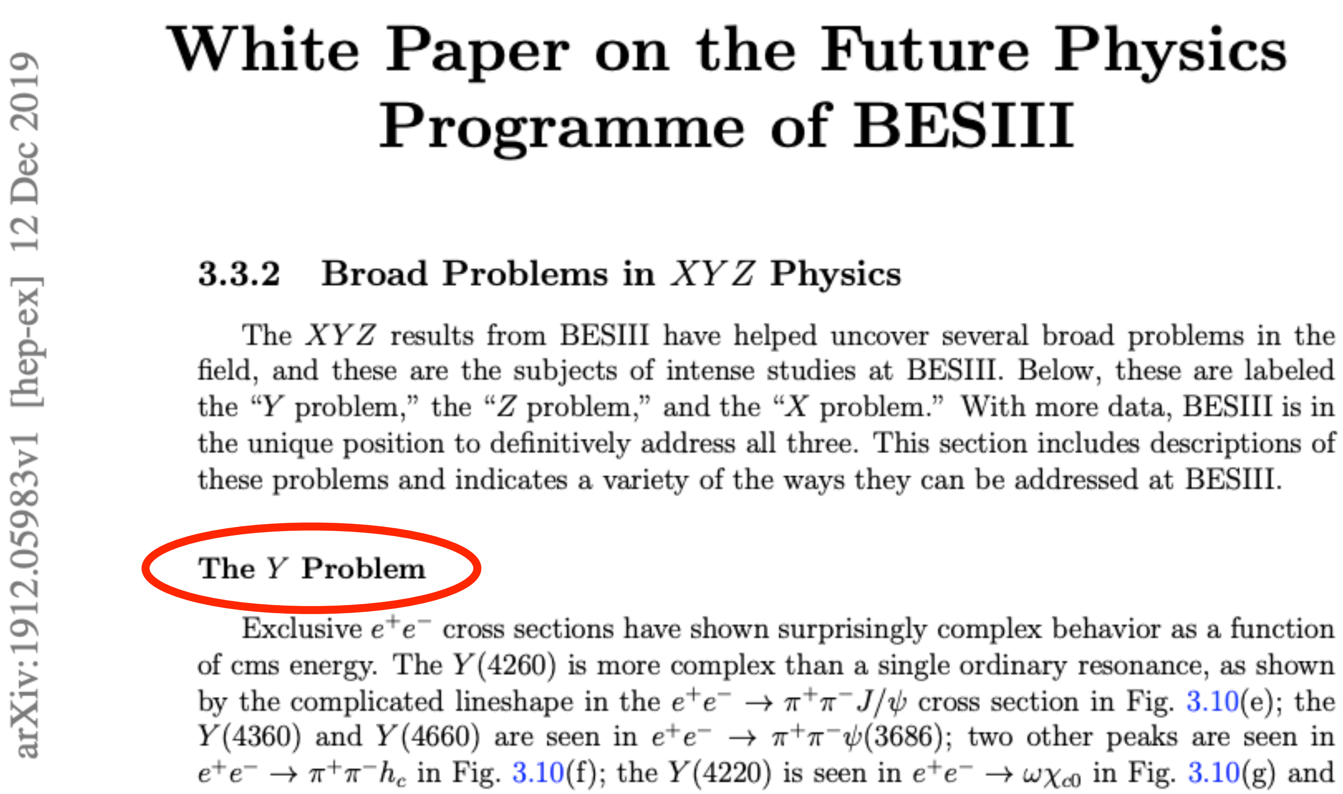
Hua-Xing Chen [a,b,1], Wei Chen [c,1], Xiang Liu [d,e,*], Shi-Lin Zhu [a,f,g,**]

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**




arXiv:1912.05983v1 [hep-ex] 12 Dec 2019

White Paper on the Future Physics Programme of BESIII

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

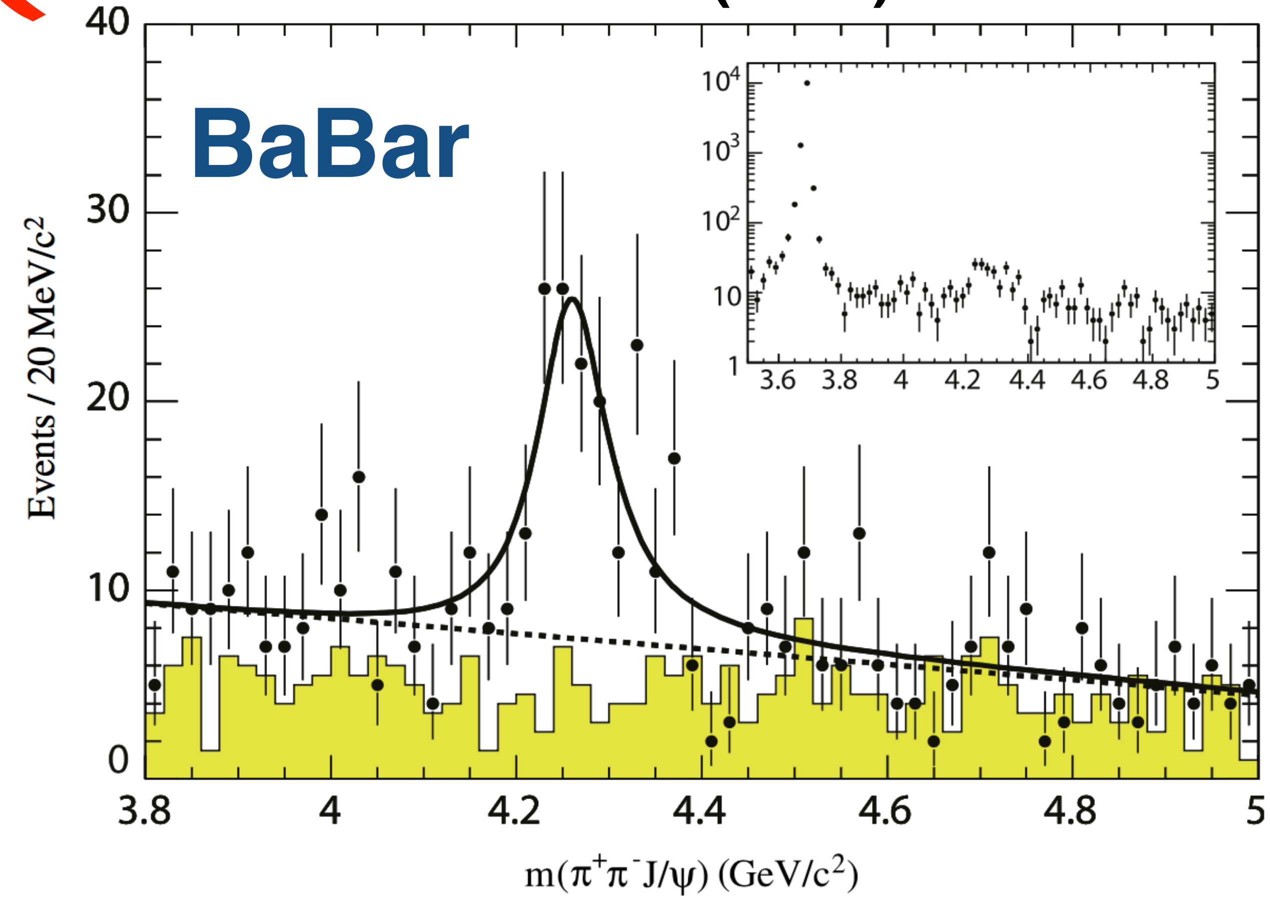
BESIII White paper

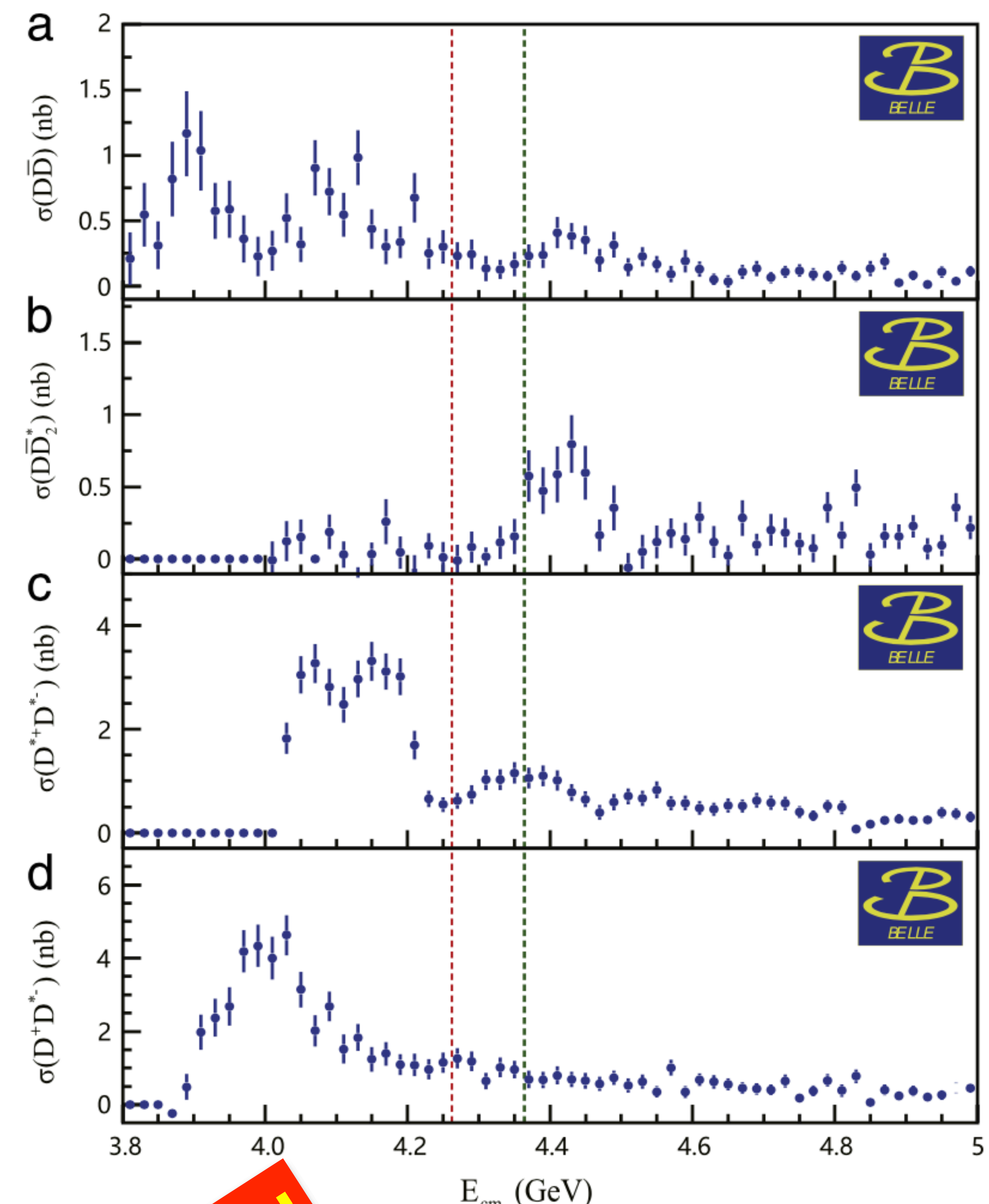
"The Y problem"

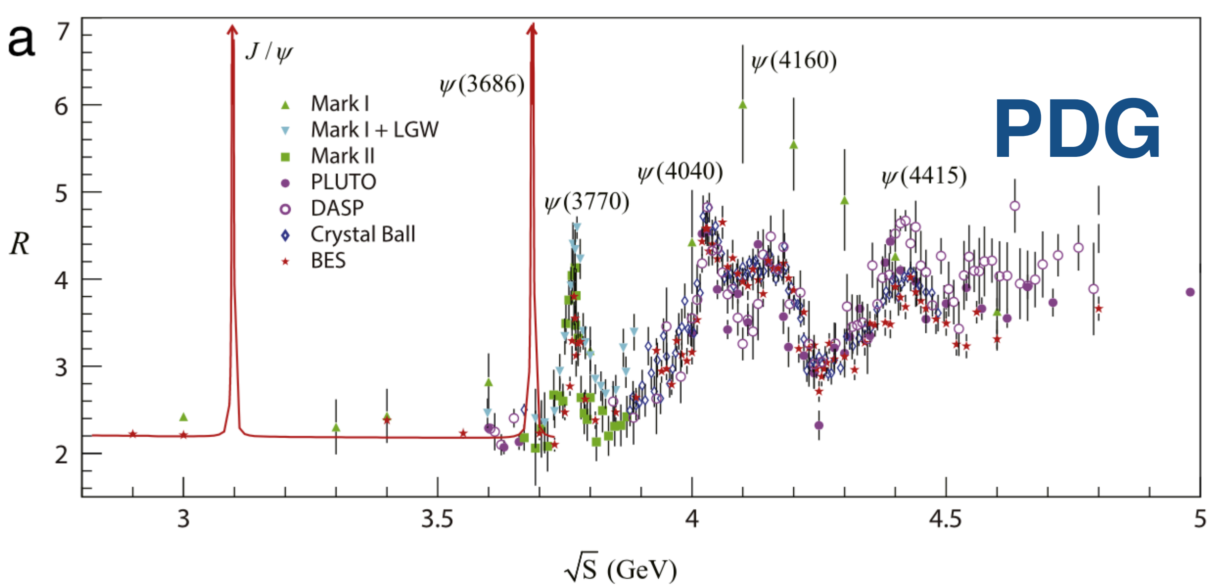
2. Fano-like interference

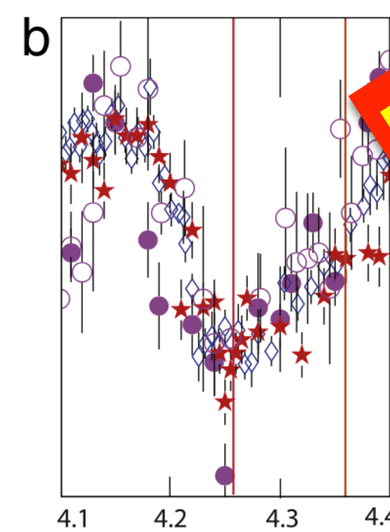
Y(4260)

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

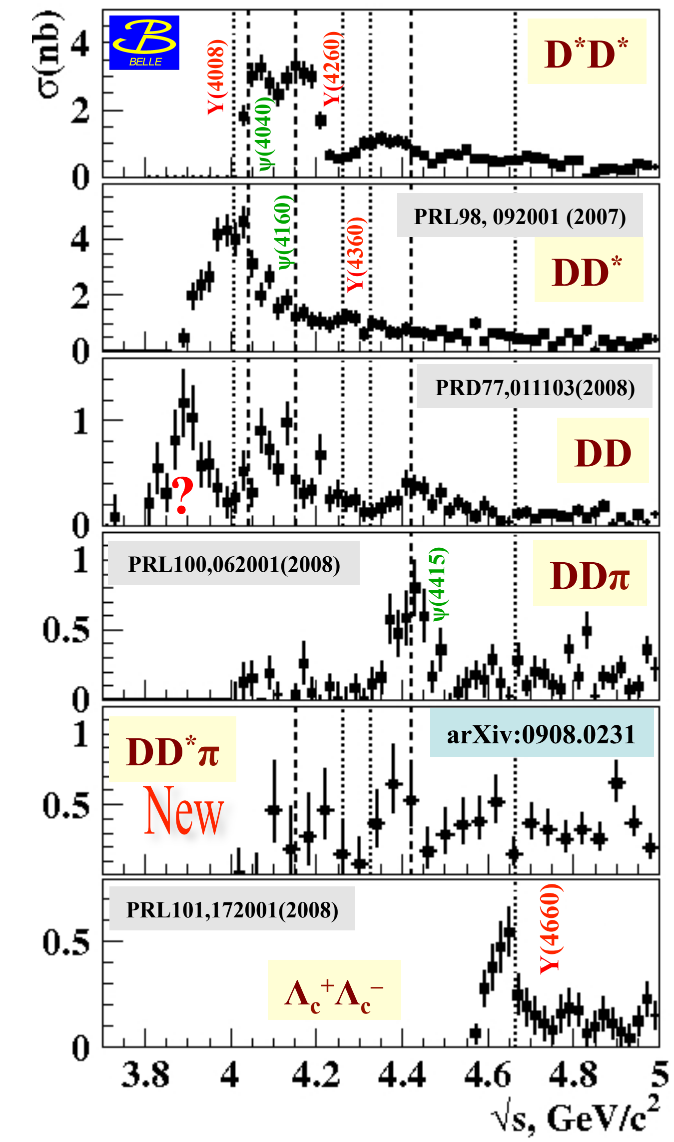
Eichten&Lane&Quigg

Mass spectrum Y(4260) ≠charmonium

Segovia&Yasser&Entem&Fernandez

Screened potential Y(4260) =Ψ(4S)

Li&Chao

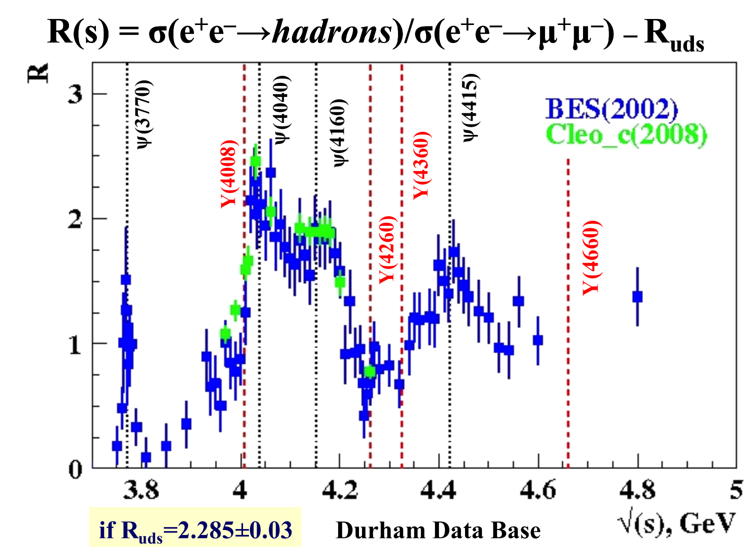


Difficulty

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

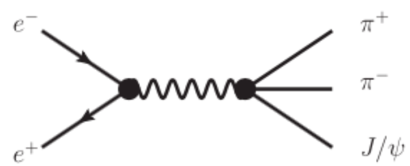
No evidence of Y(4260) in R scan data and open-charm decay channels



Non-resonant picture of Y(4260)

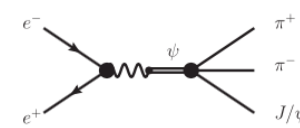
- **Asymmetric** Y(4260) structure can be reproduced by **Fano-like interference picture**

Continuum



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

Charmonium

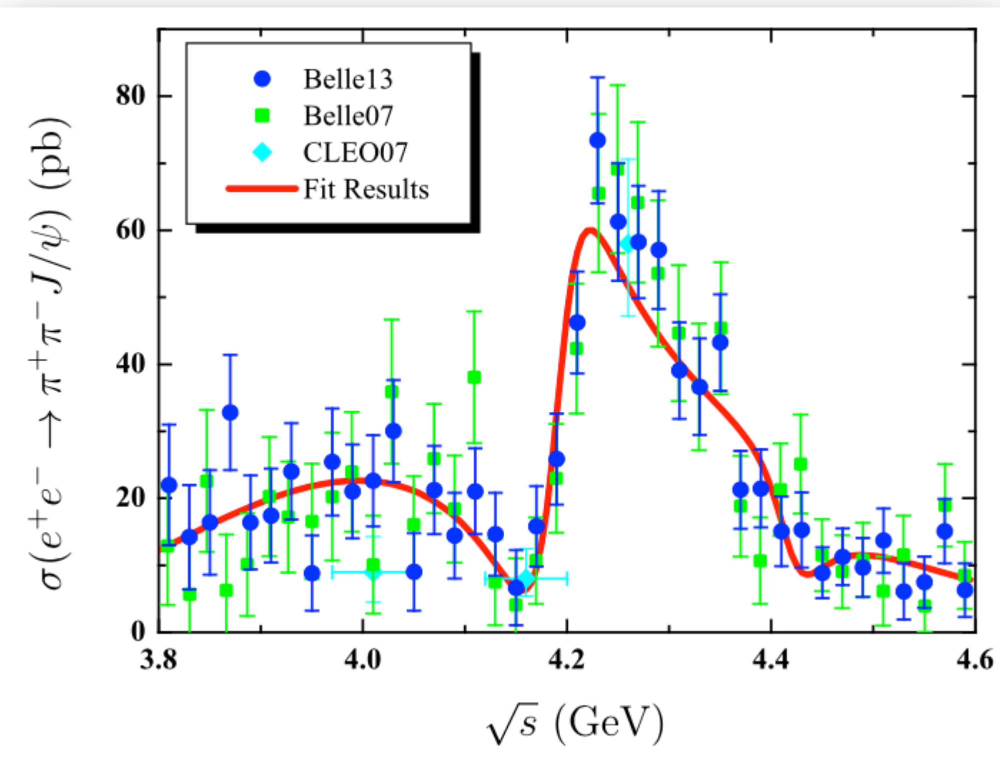


$$\widehat{=} \frac{\sqrt{12\pi\Gamma_\psi^{e^+e^-}\times\mathcal{B}(\psi\to\pi^+\pi^- J/\psi)\Gamma_\psi}}{s-m_\psi^2+im_\psi\Gamma_\psi}\sqrt{\frac{\Phi_{2\to3}(s)}{\Phi_{2\to3}(m_\psi^2)}}$$

Interference

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

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

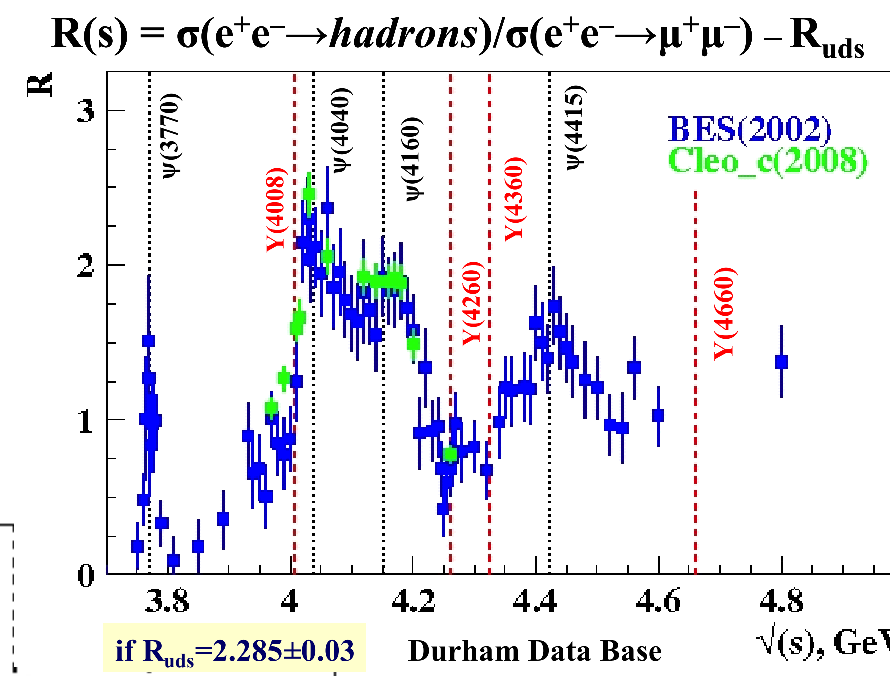


Success:

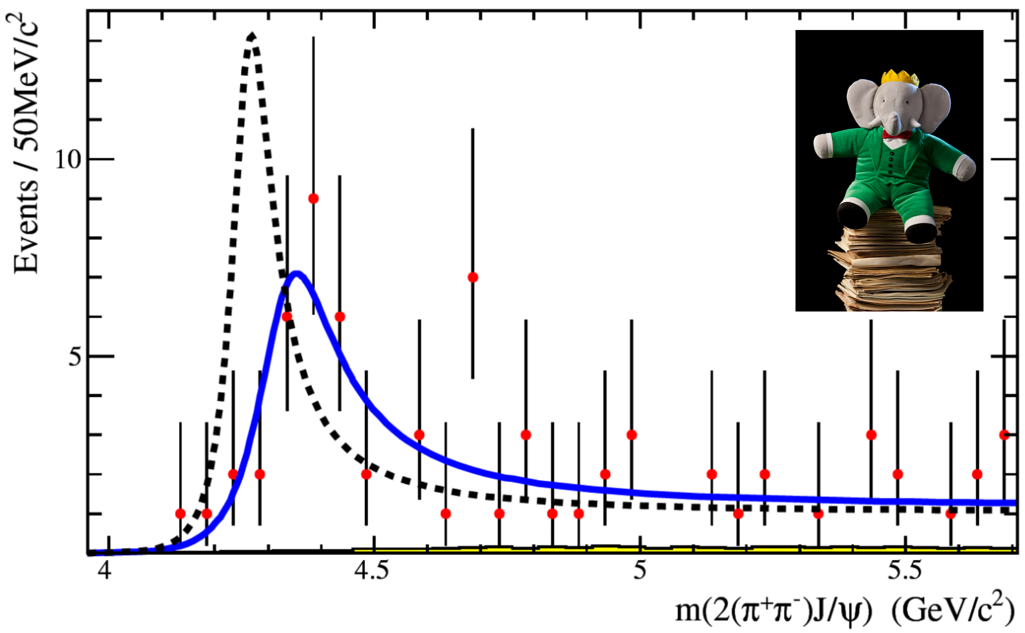
- **Explain** why $\psi(4160)$ and $\psi(4415)$ signals are missing in data
- Naturally **understand** why no evidence of Y(4260) in R scan data and the open-charm decay channels

Y(4360)

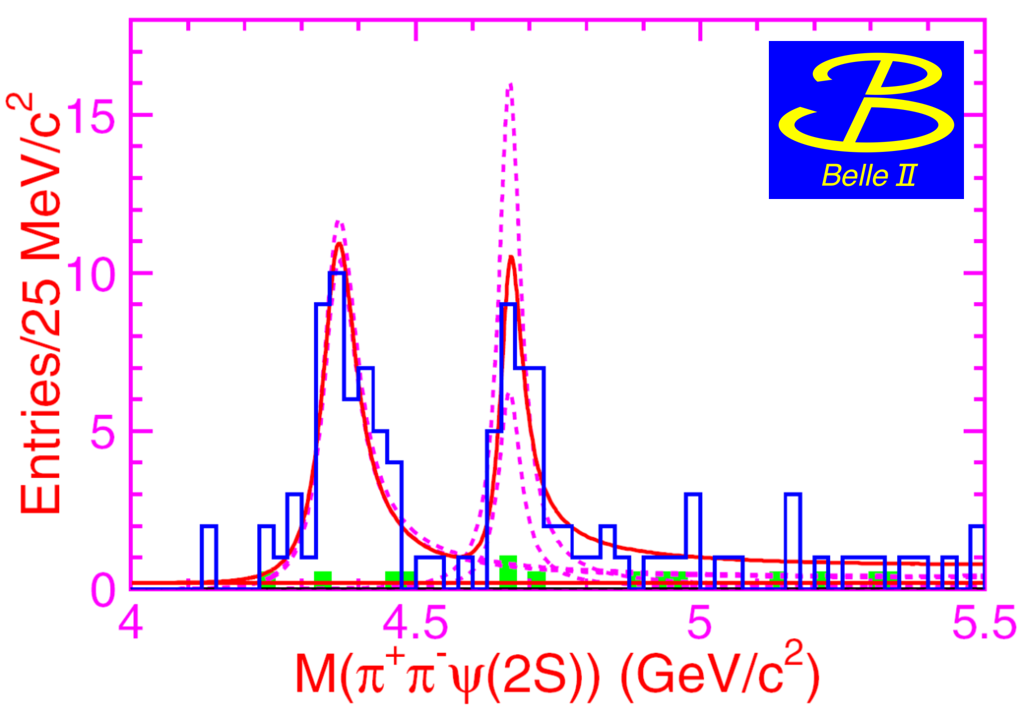
No evidence of *Y*(4260)/Y(4360) in the obtained open-charm process and *R*-value scan

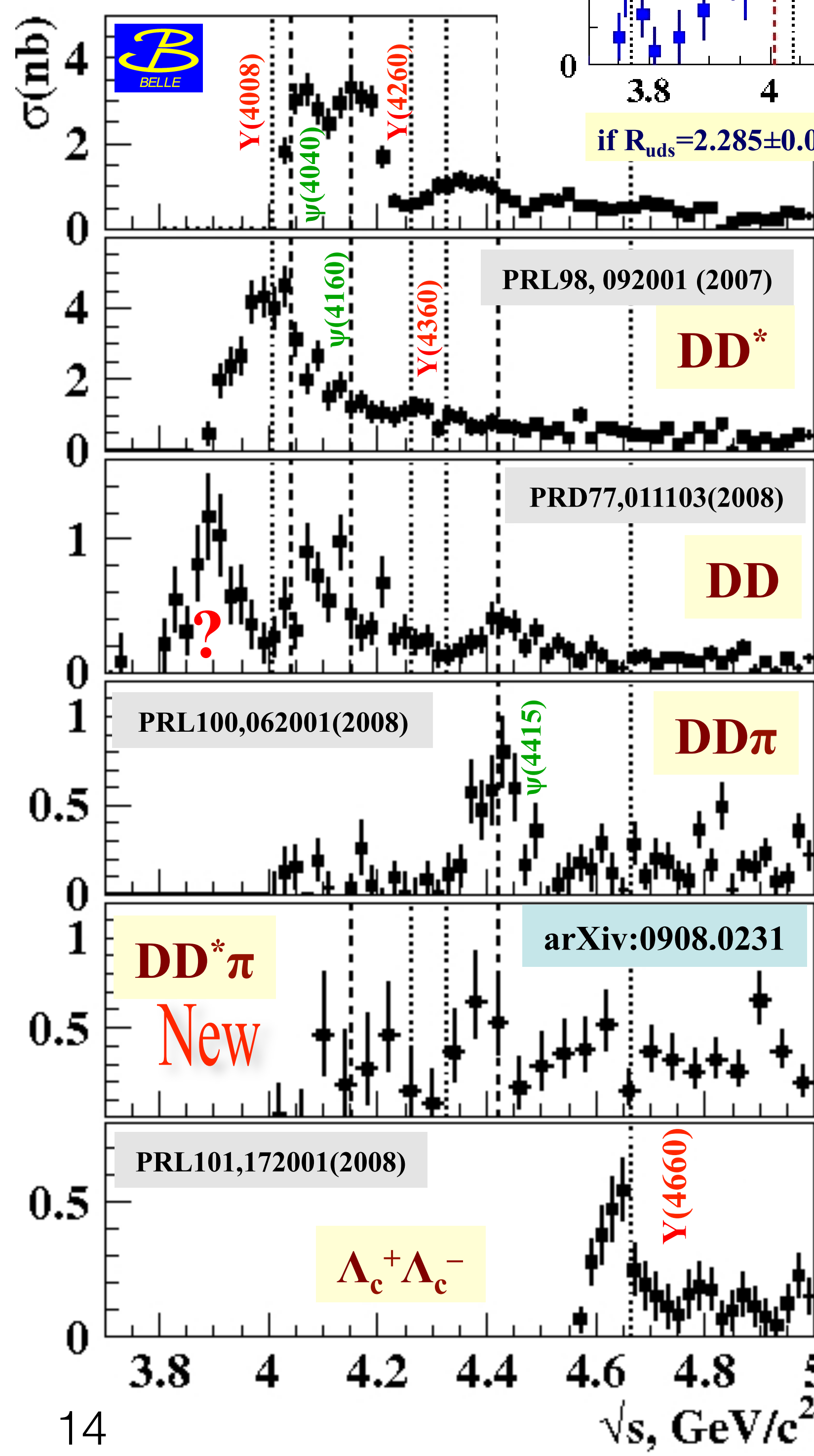


PRL 98:212001 (2007)



PRL 99:142002 (2007)

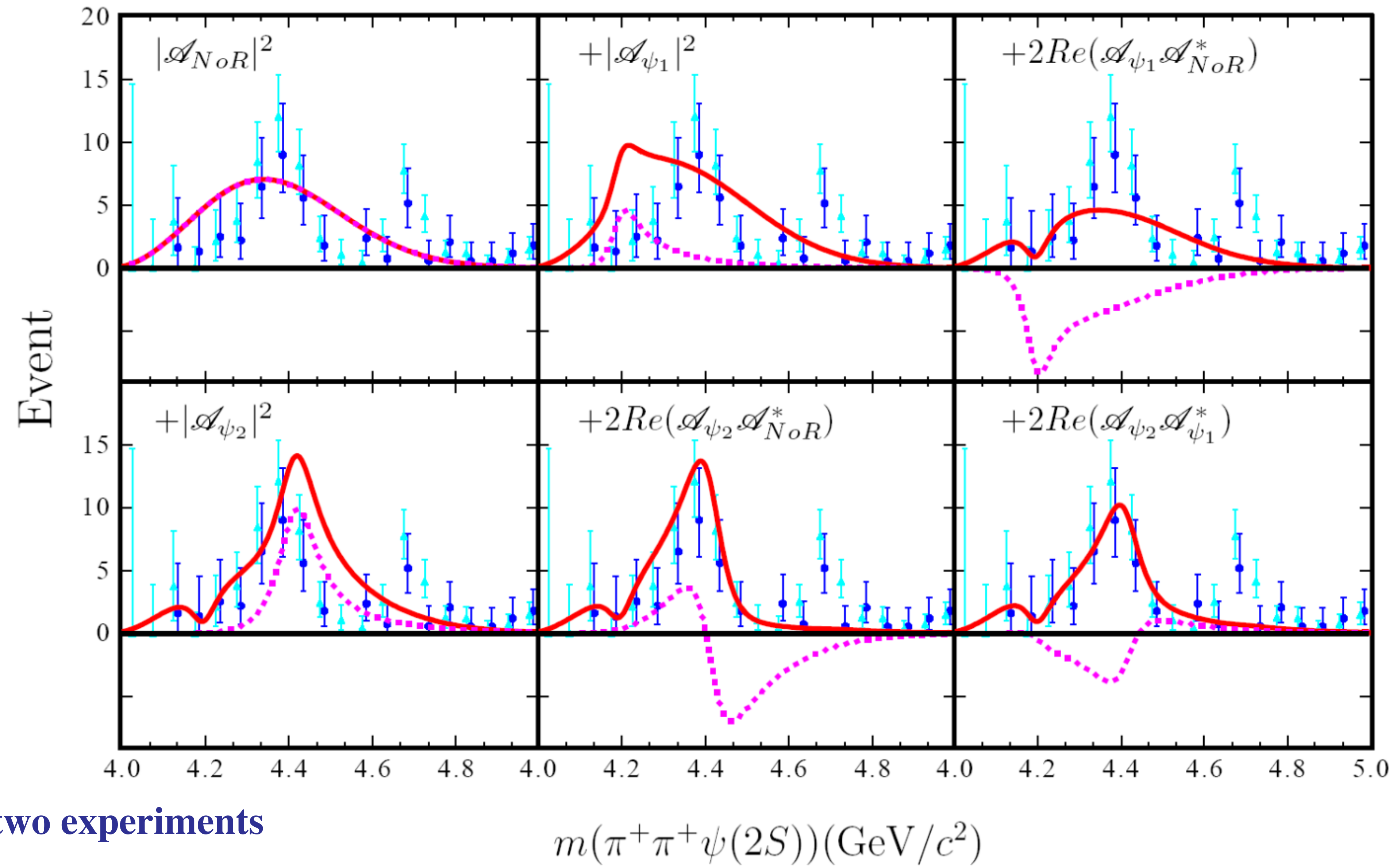




The situation of Y(4360) is similar to that of Y(4260)

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

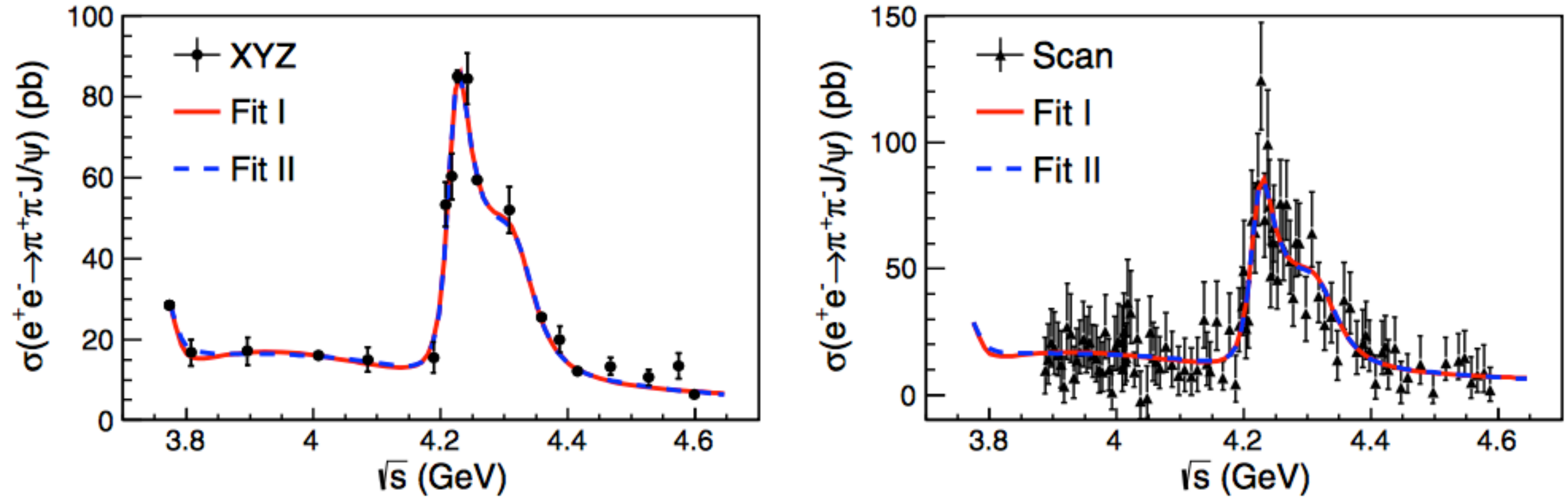


FIG. 1. Measured cross section $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ and simultaneous fit to the *XYZ* data (left) and scan data (right) with the coherent sum of three Breit-Wigner functions (red solid curves) and the coherent sum of an exponential continuum and two Breit-Wigner functions (blue dashed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

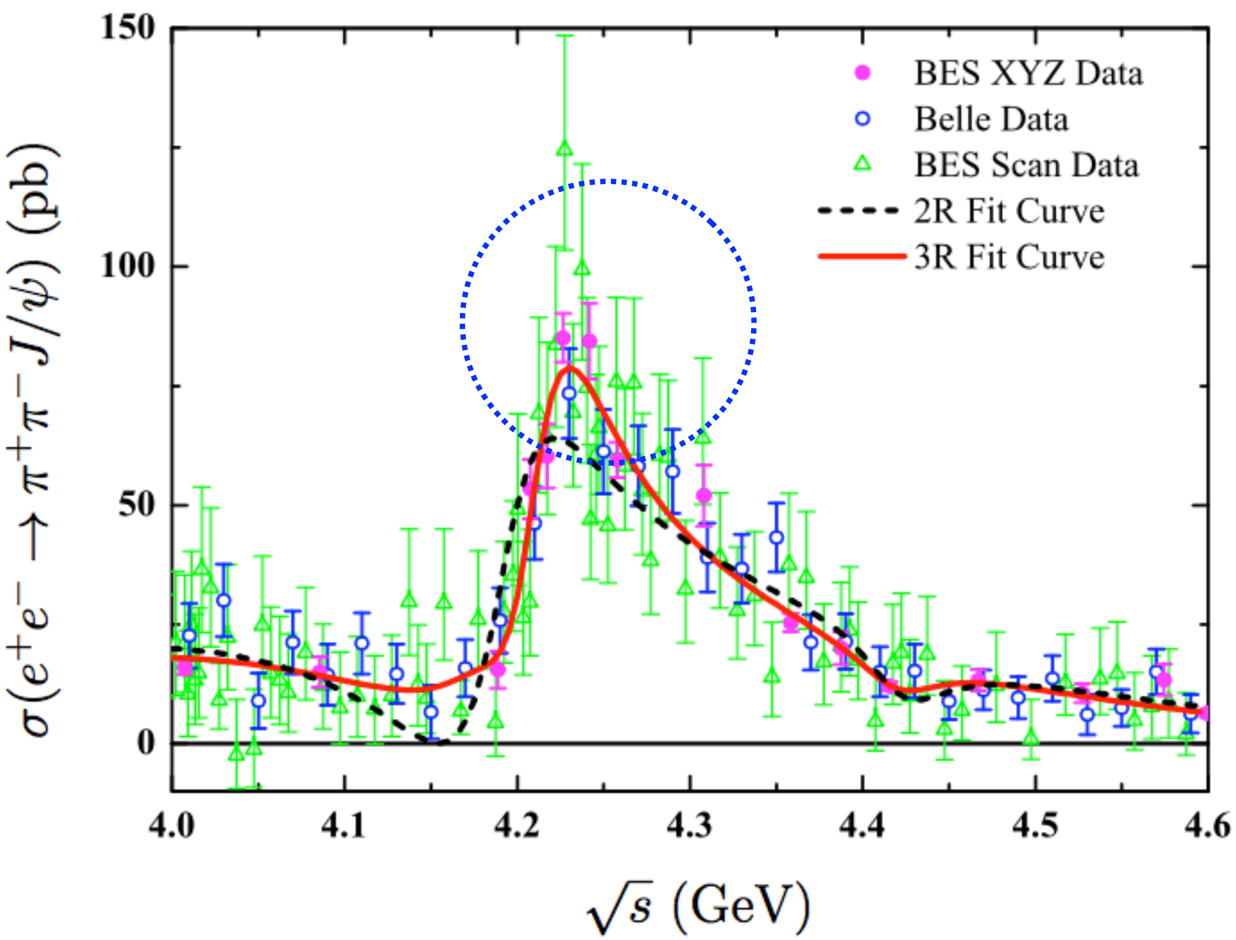


FIG. 2: (color online). Our fit to the cross sections for the $e^+e^- \to \pi^+\pi^- J/\psi$ process measured by the Belle [8] and BESIII collaborations [11] under the 2R and 3R fit schemes. Here, the BES scan data [11] are also listed for comparison.

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)?

PRL **118**, 092002 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

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

Y(4220)+Y(4390)

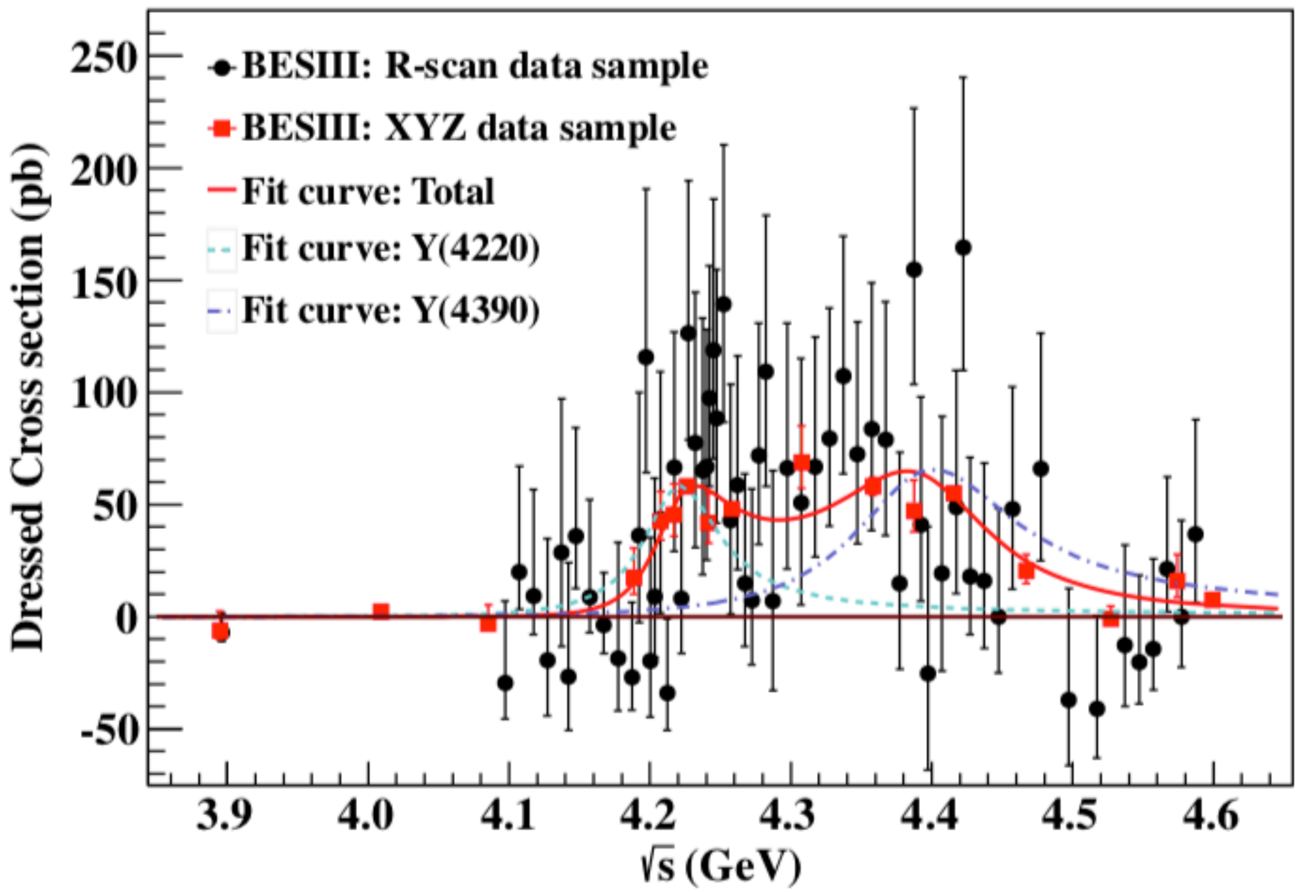


FIG. 2. Fit to the dressed cross section of $e^+e^- \to \pi^+\pi^- h_c$ with the coherent sum of two Breit-Wigner functions (solid curve). The dash (dash-dot) curve shows the contribution from the two structures $Y(4220)$ [$Y(4390)$]. The dots with error bars are the cross sections for the R-scan data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

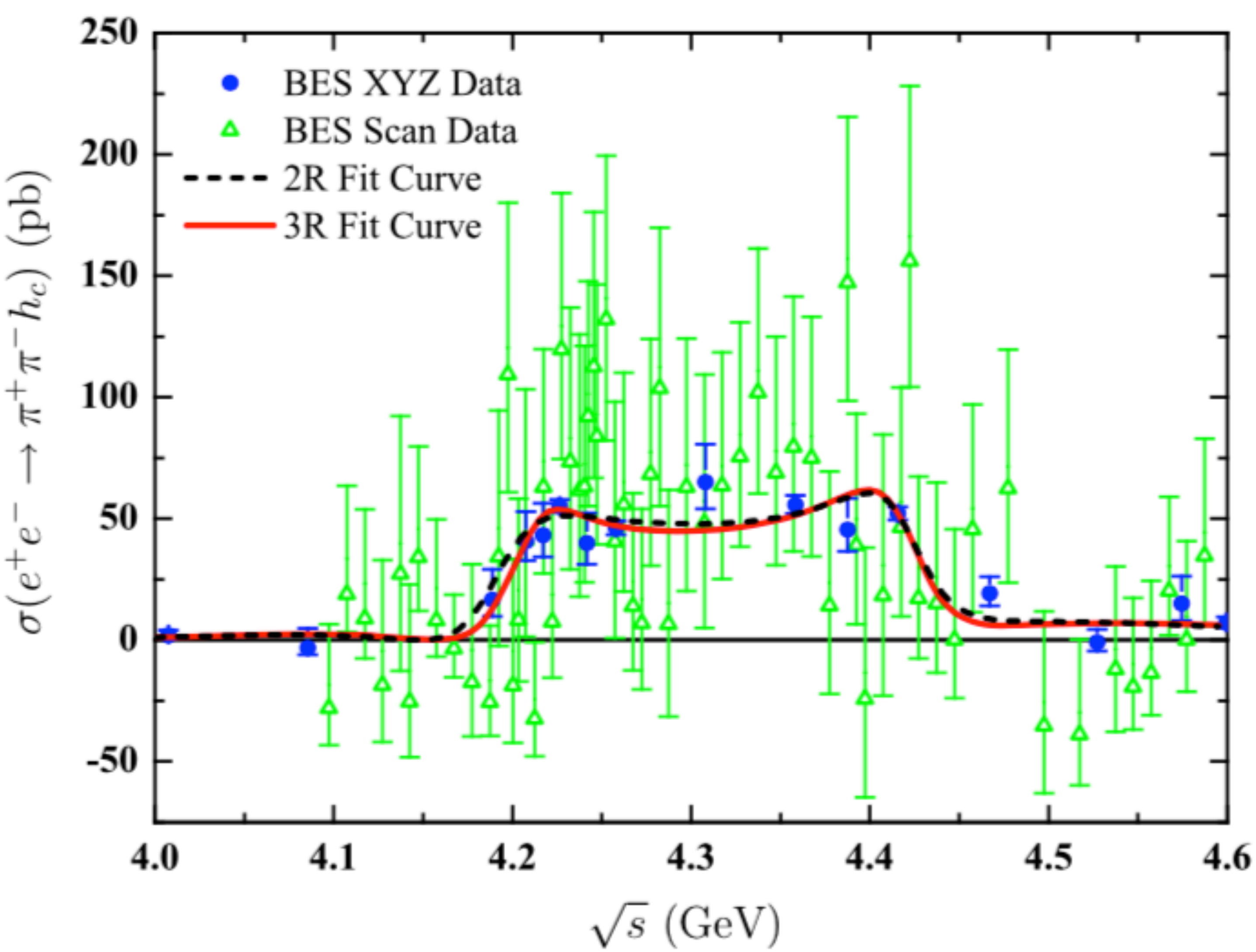
THE EUROPEAN PHYSICAL JOURNAL C

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

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)

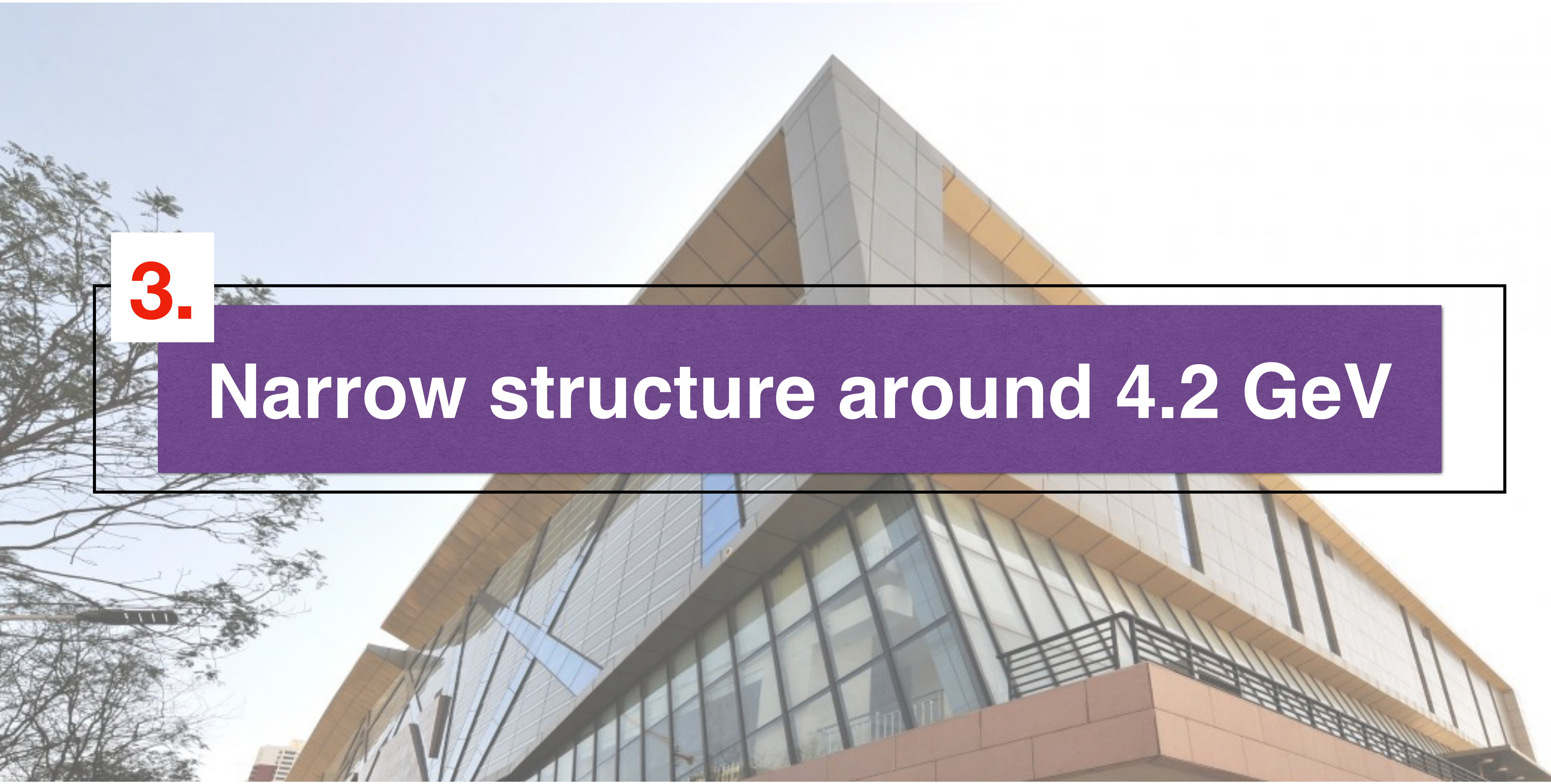
Y(4630)

Summary of Y states from electron and positron annihilations

Y(4220)

Y(4660)

Y(4630)



3. Narrow structure around 4.2 GeV

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)

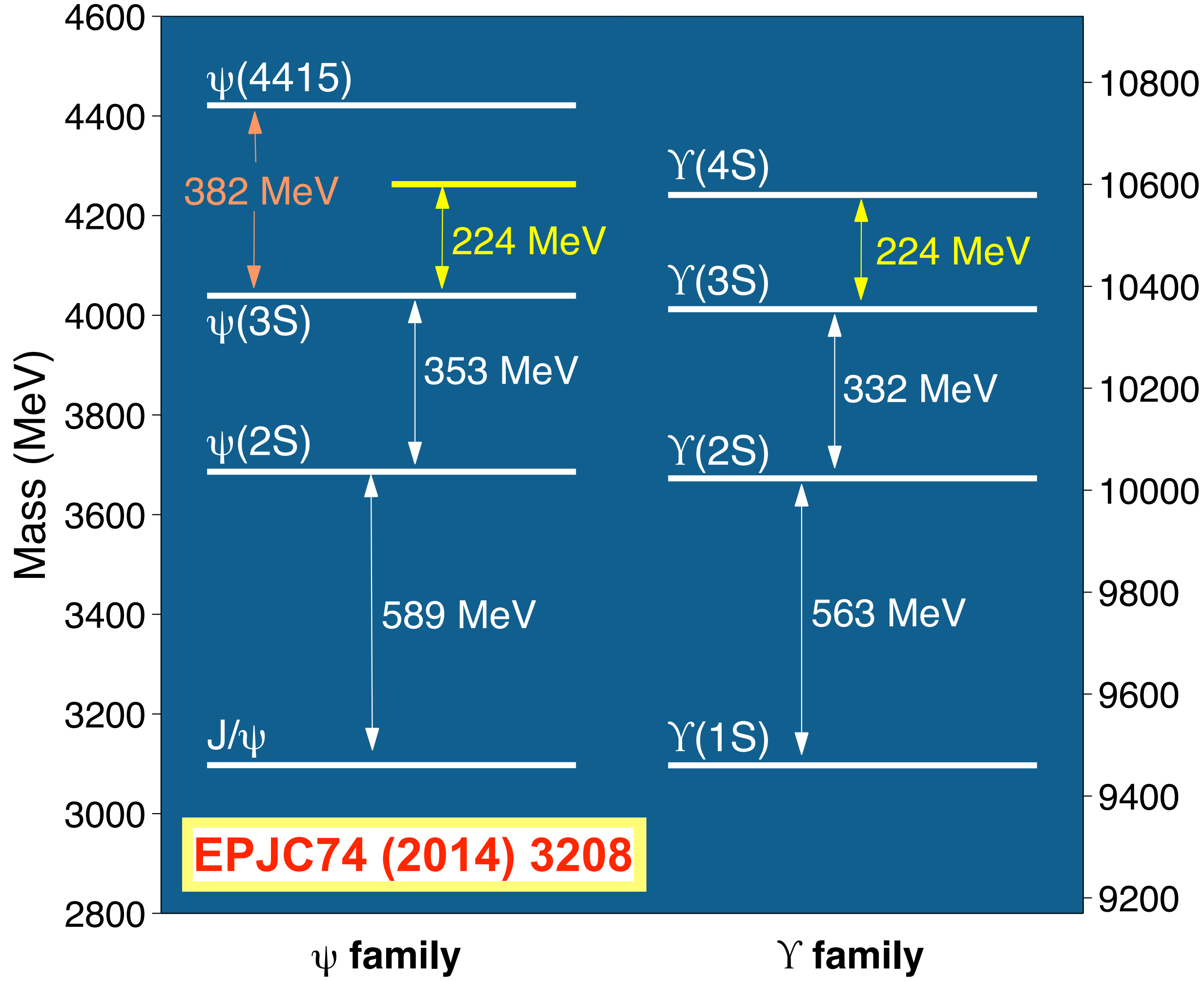
TABLE I. Calculated masses and leptonic widths for charmonium states with the screened potential (5) and parameters (8), where $\Gamma_{ee} = \Gamma^0_{ee}[1 - \frac{16}{3\pi}\alpha_s(m_c)]$ with $\alpha_s(m_c) = 0.28$ [16].

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

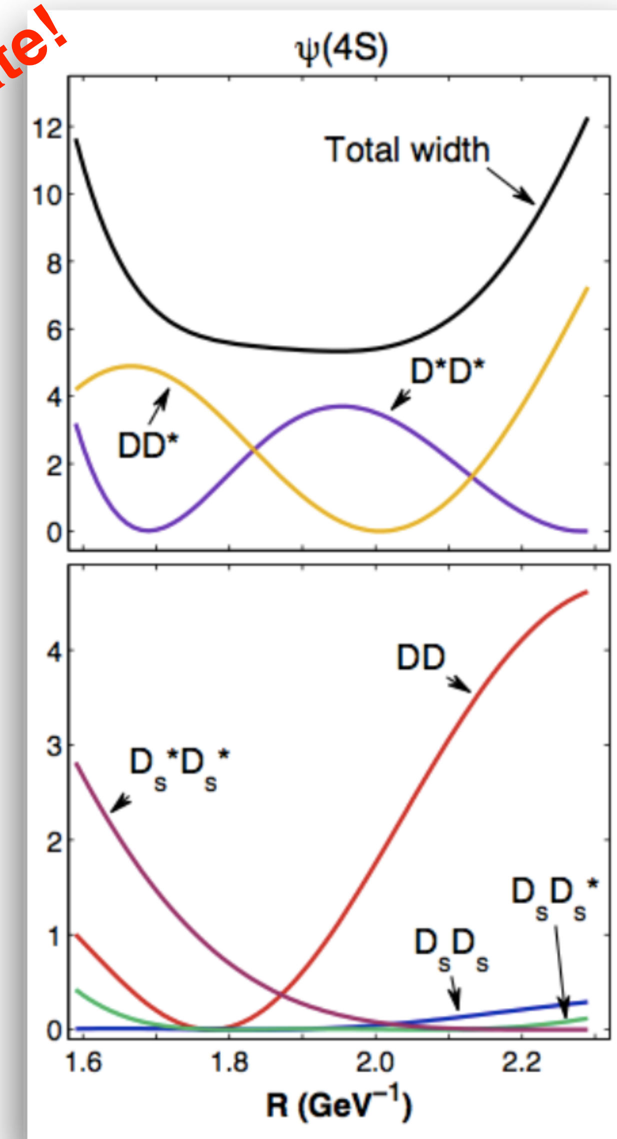
Consistent

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!

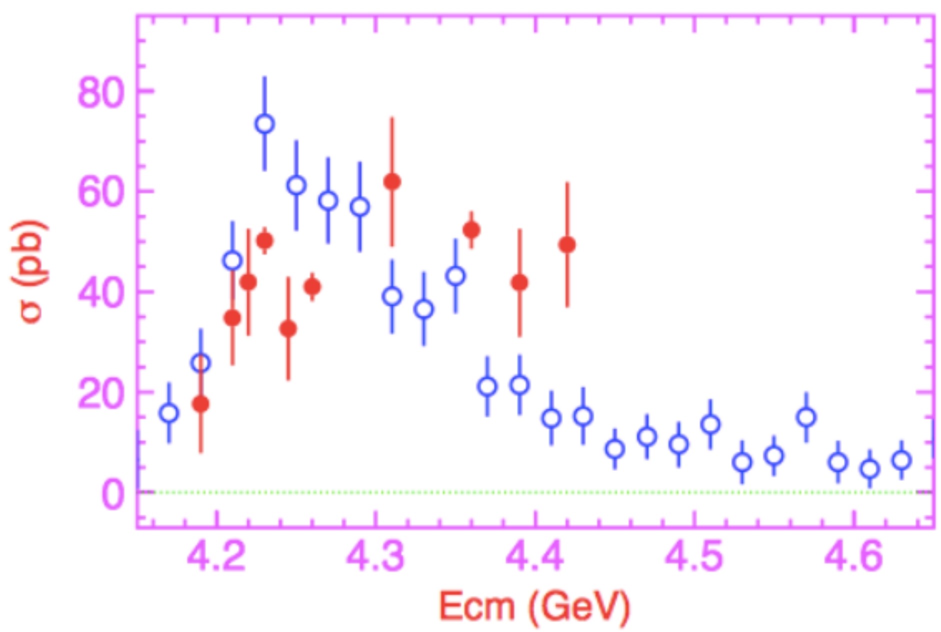
The predicted charmonium ψ(4*S*) has very narrow width around 6 MeV

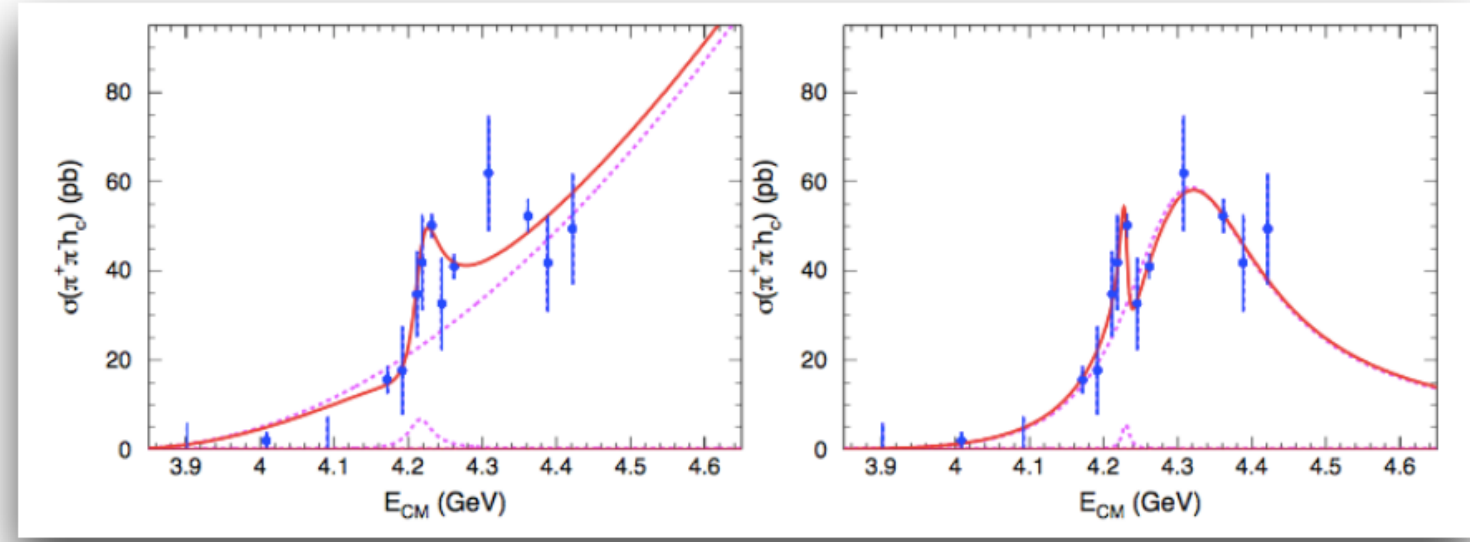
Y(4220)= ψ(4S)?

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"

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

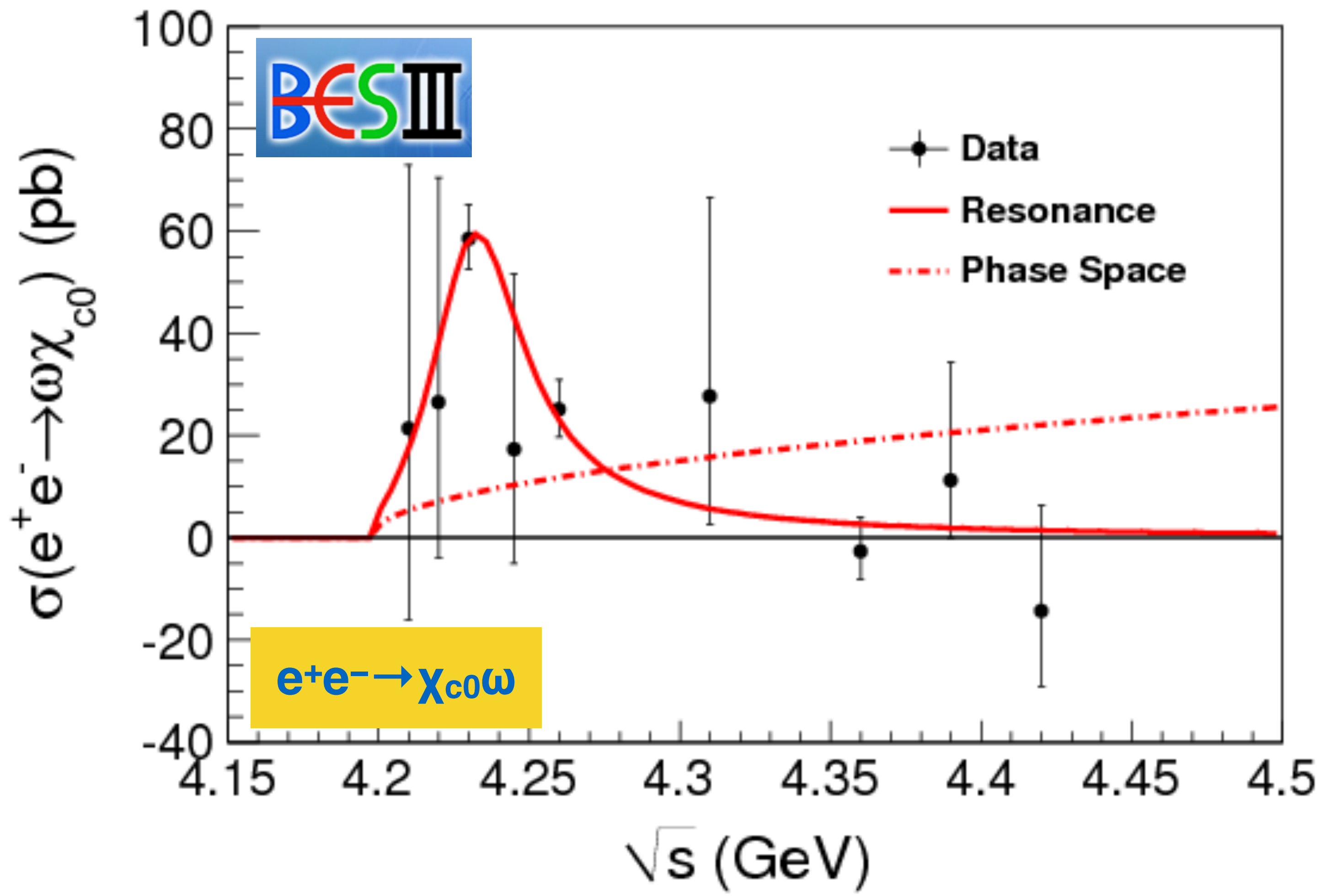
Is it the prediced higher charmonium with the mass around 4.26 GeV?

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)



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

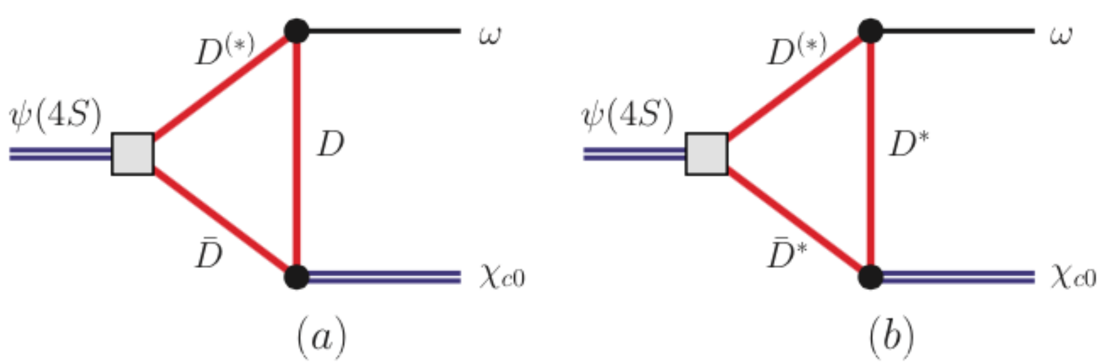
$e^+e^- \to \chi_{c1}\omega$ **and** $e^+e^- \to \chi_{c2}\omega$ **are not**

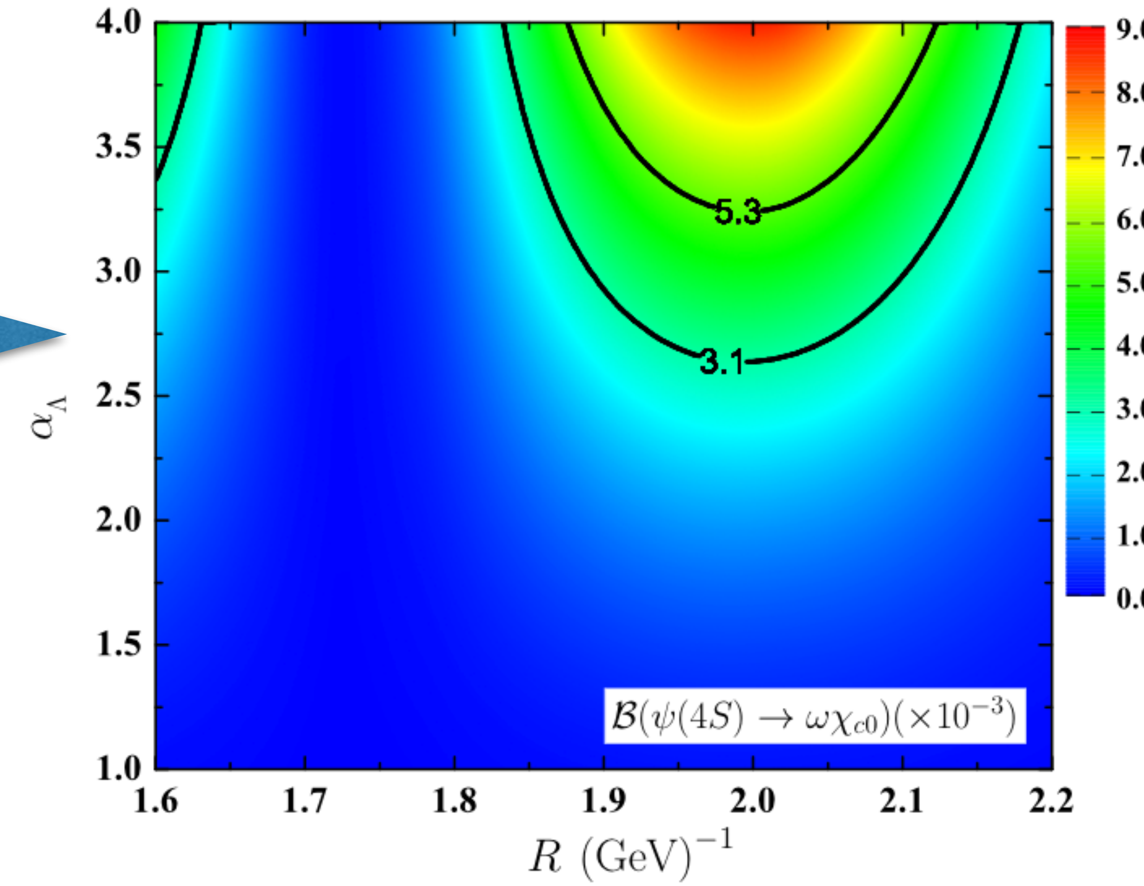
If taking the mass of ψ(4S) to be 4230 MeV (Expt.), we find:

- **$\psi(4S) \to \chi_{c0}\omega$ 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

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).

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

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

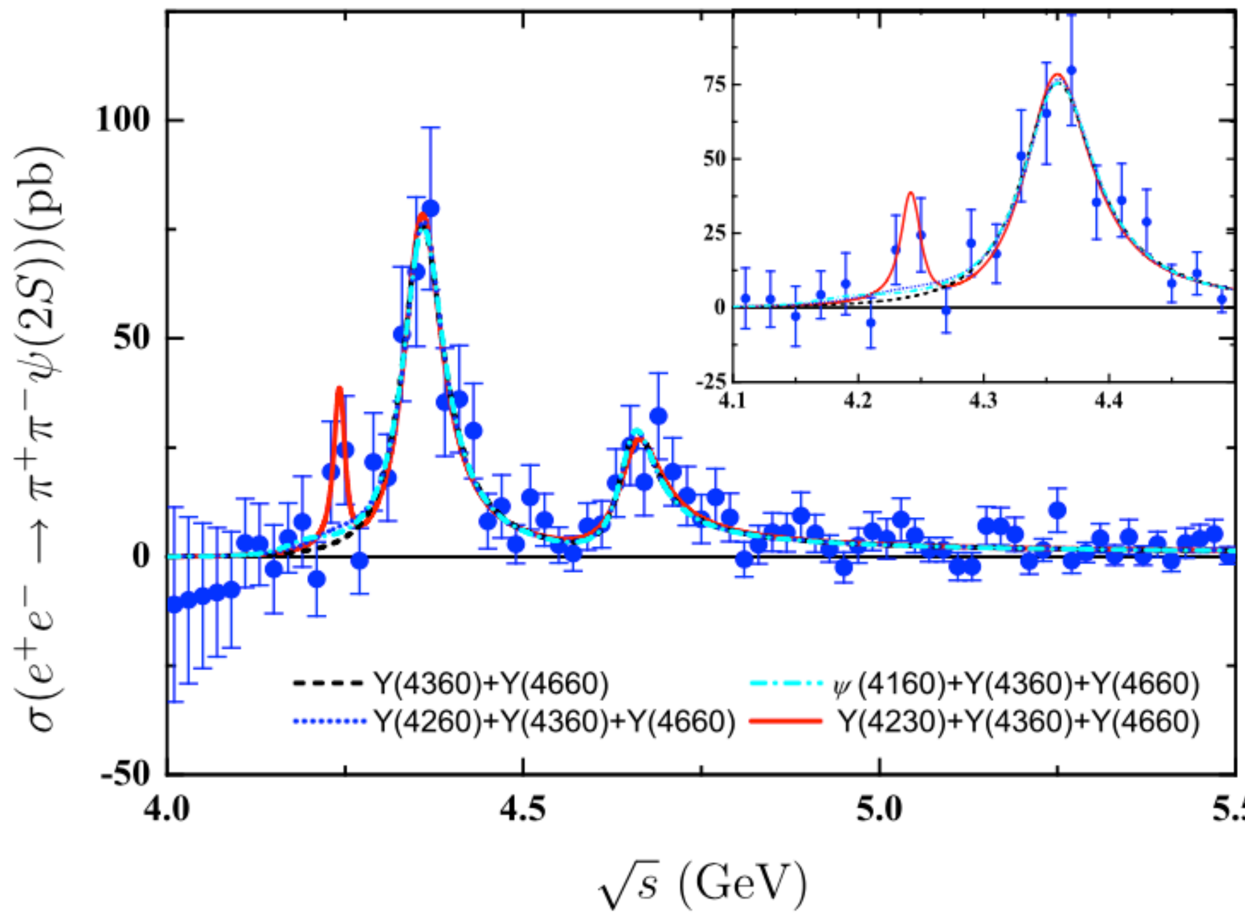


FIG. 2. A comparison of the fits to the cross sections for $e^+e^- \to \pi^+\pi^-\psi(2S)$ with different schemes.

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

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

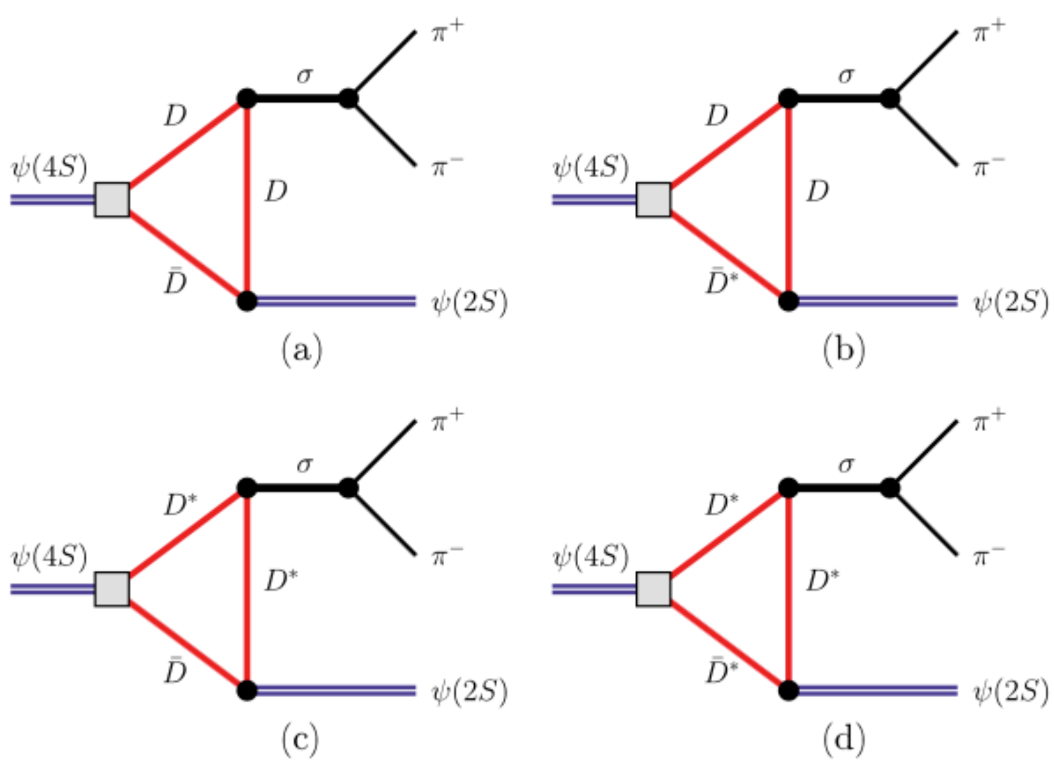


FIG. 3. Typical meson-loop contributions to $\psi(4S)\rightarrow\psi(2S)\pi^+\pi^-$, where the dipion comes from a σ meson.

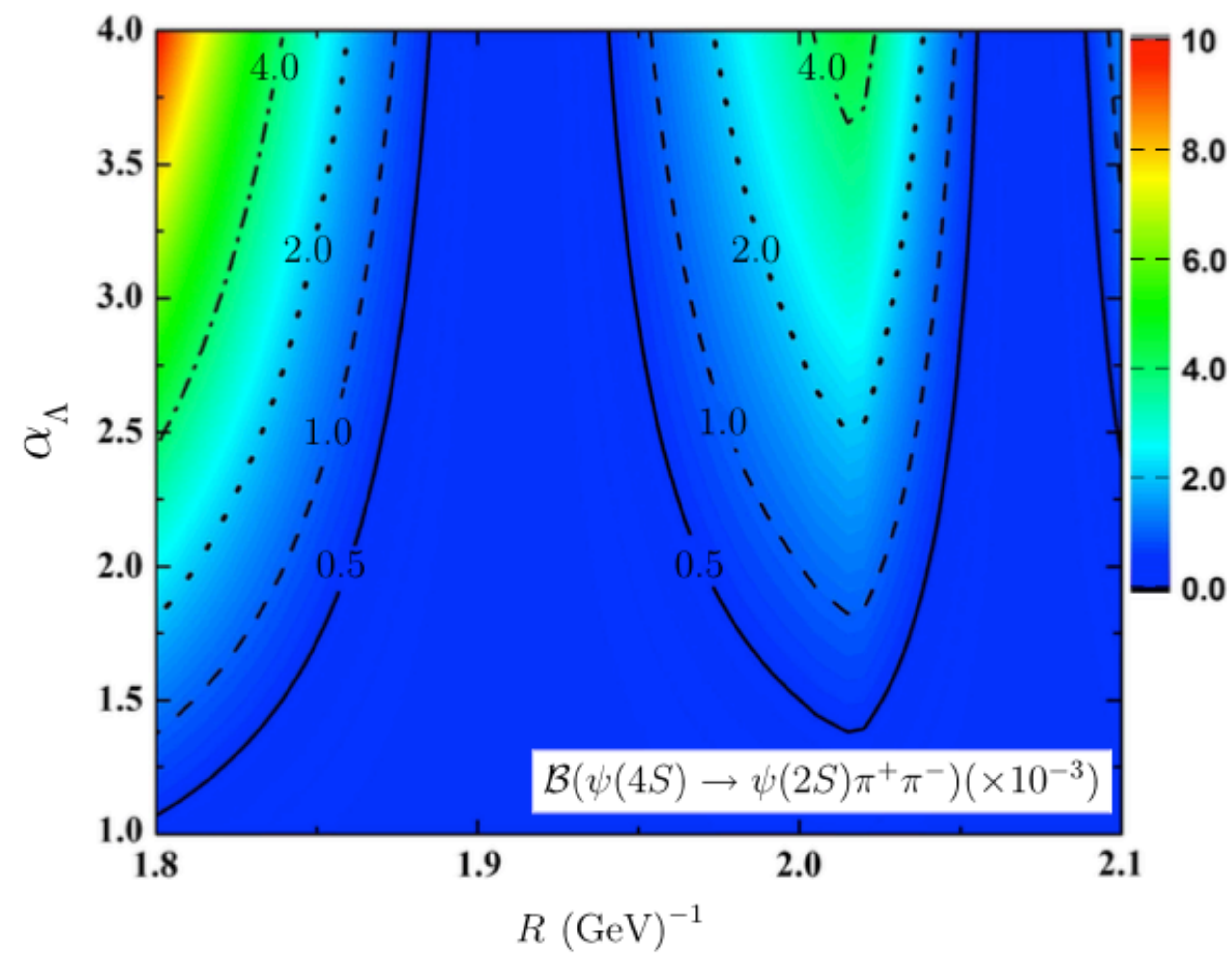


FIG. 4. The R and α_Λ dependence of the branching ratio for $\psi(4S)\rightarrow\psi(2S)\pi^+\pi^-$.

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

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

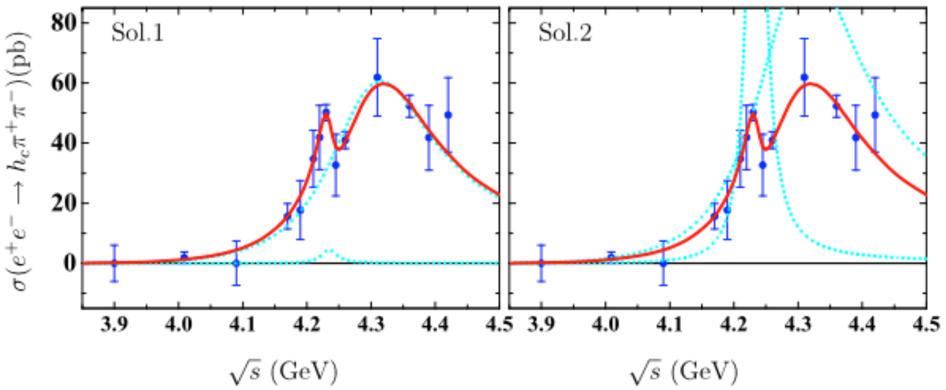


FIG. 6. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to h_c\pi^+\pi^-$ in scheme I. The cyan dashed and red solid curves are the resonance contributions and the fitting results, respectively.

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	$\psi(2S)\pi^+\pi^-$ Sol. A	Sol. B	Sol. C	Sol. D	$h_c\pi^+\pi^-$ Sol. 1	Sol. 2	$\chi_{c0}\omega$
$m_{Y(4230)}$				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			

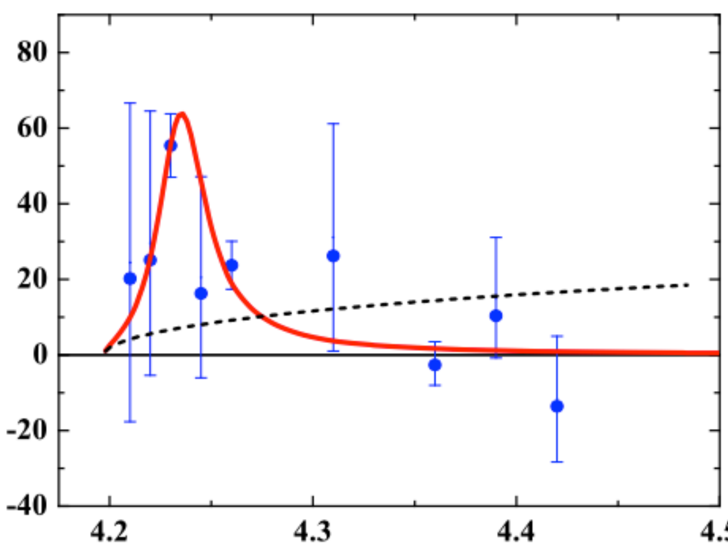


FIG. 7. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to \chi_{c0}\omega$ (solid curve) in scheme I. The dashed curve is the phase space of $e^+e^- \to \chi_{c0}\omega$.

Resonance parameter:

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

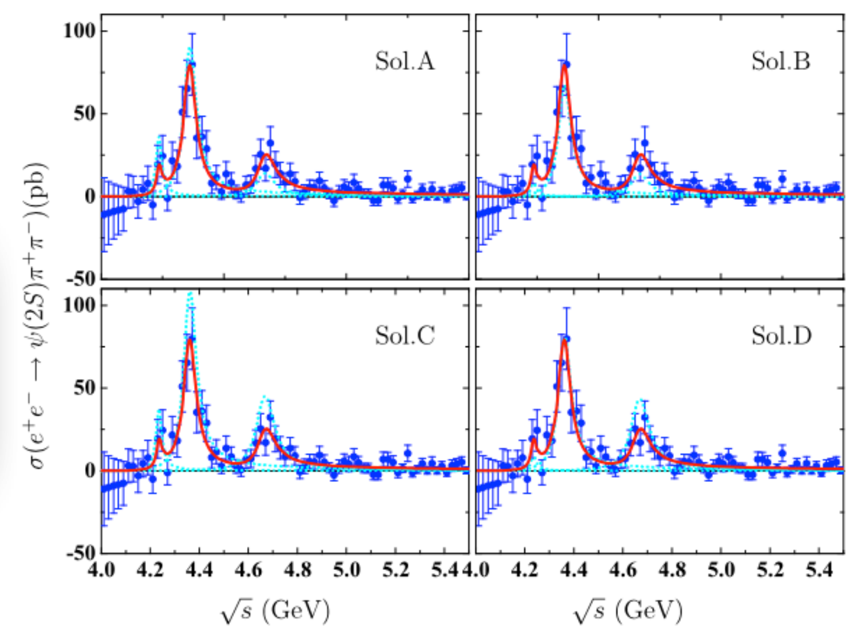
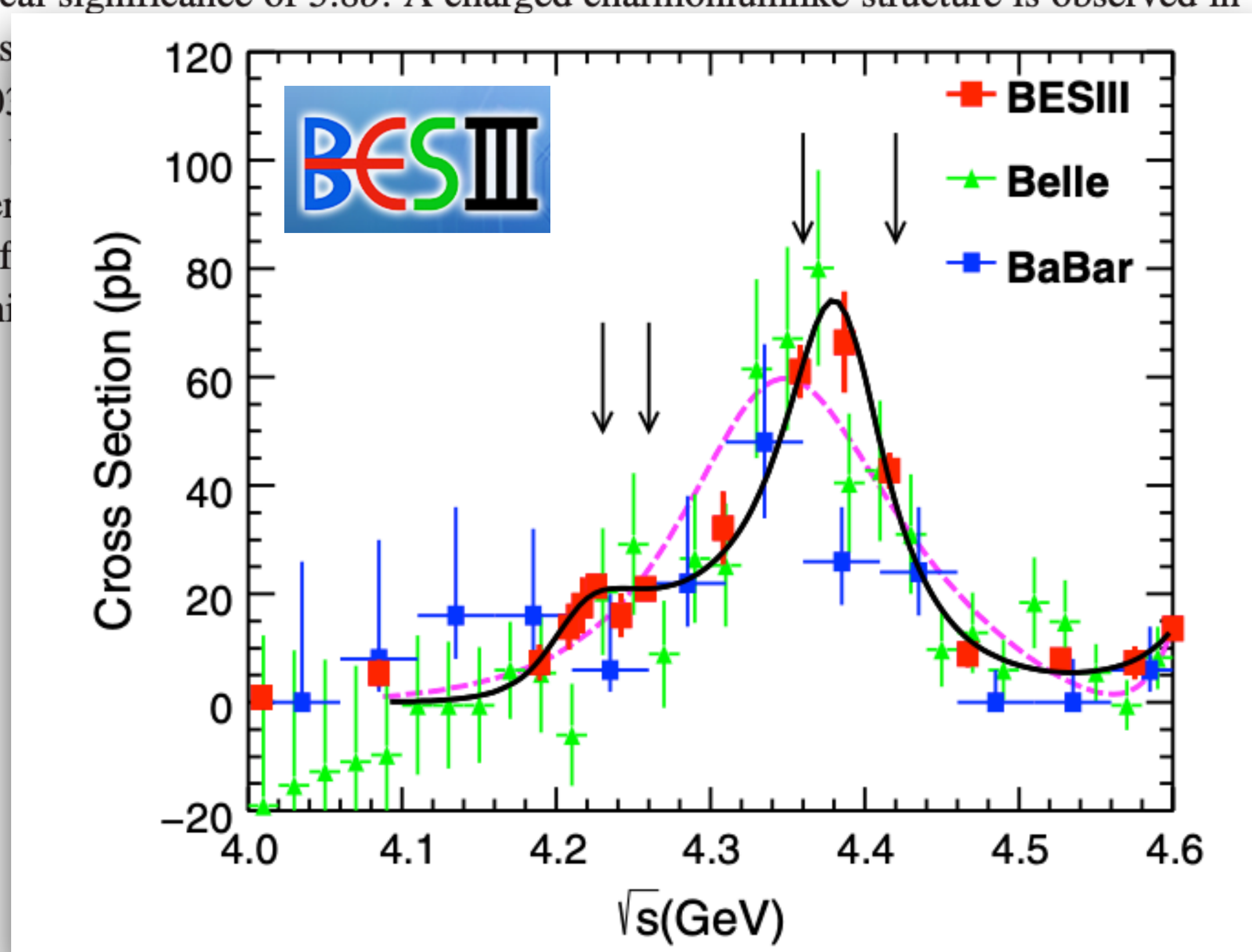


FIG. 5. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to \psi(2S)\pi^+\pi^-$ in scheme I. The cyan dashed and red solid curves are the resonance contributions and the fitting results, respectively.

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 kine... data has been found, and a f... uired to better understand thi...

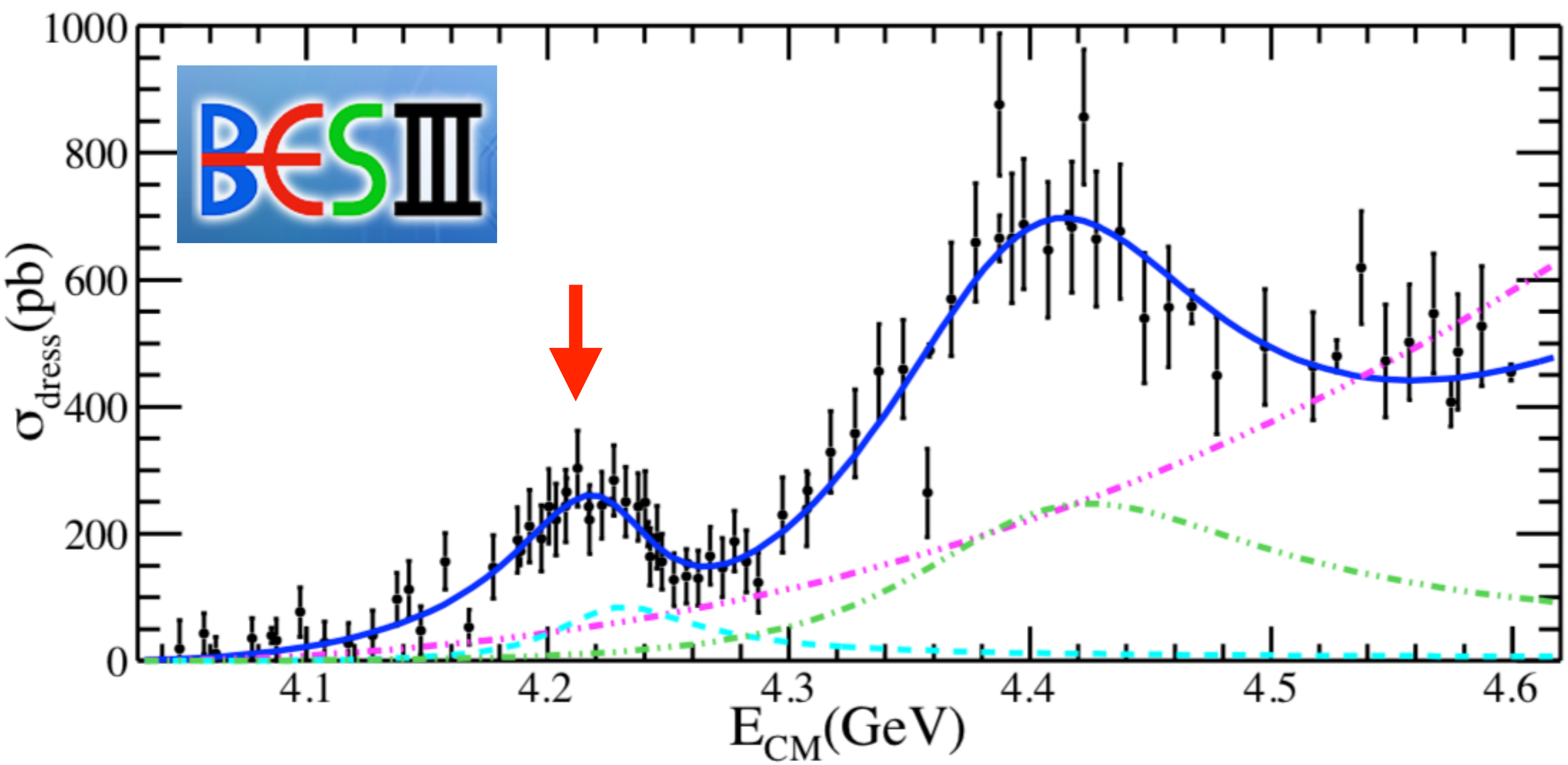


If Y(4220) narrow is ψ(4S), Y(4220) should be observed in open-charm decay channel!

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

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



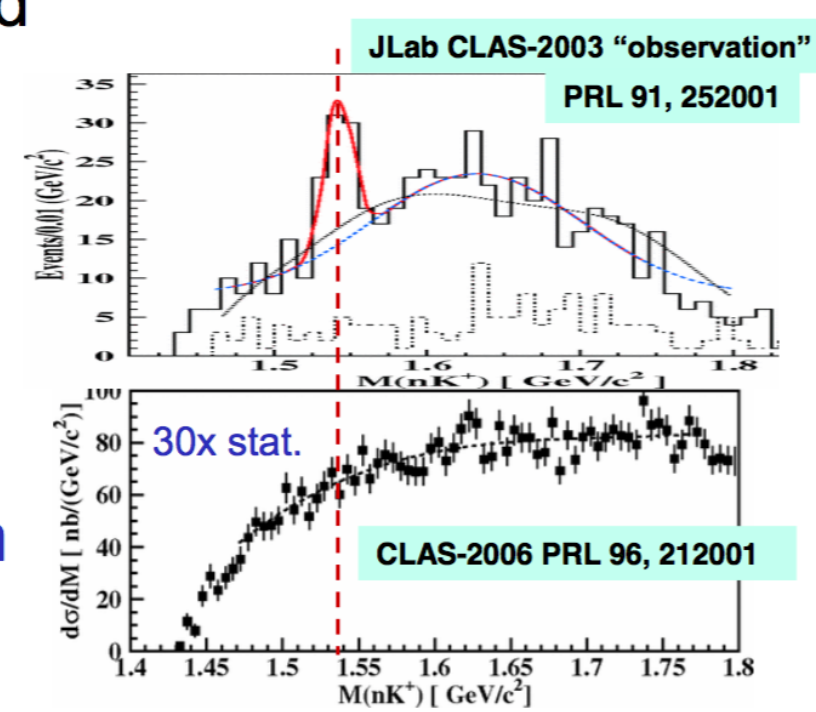
The pentaquark event shows that we are still far from understanding the nature of QCD

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"

$\gamma d \to pK^-K^+n$



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)

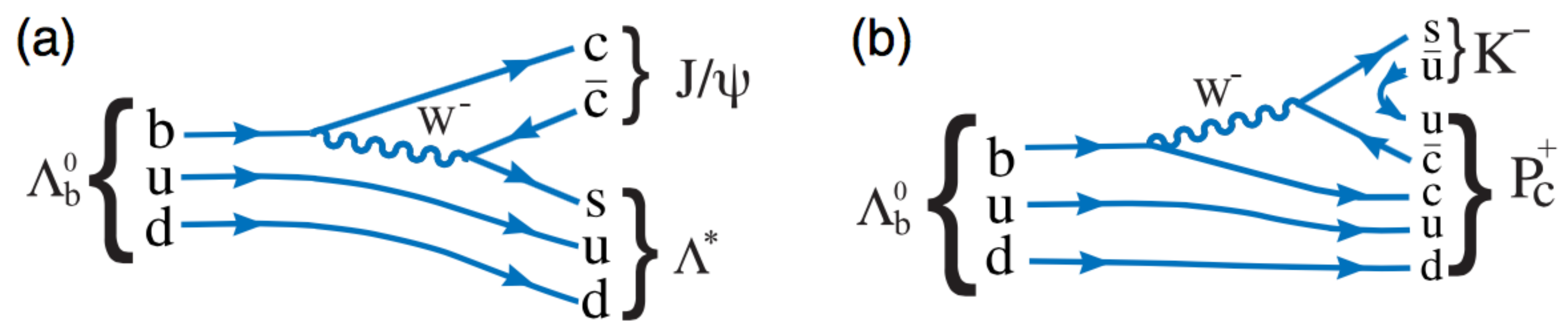
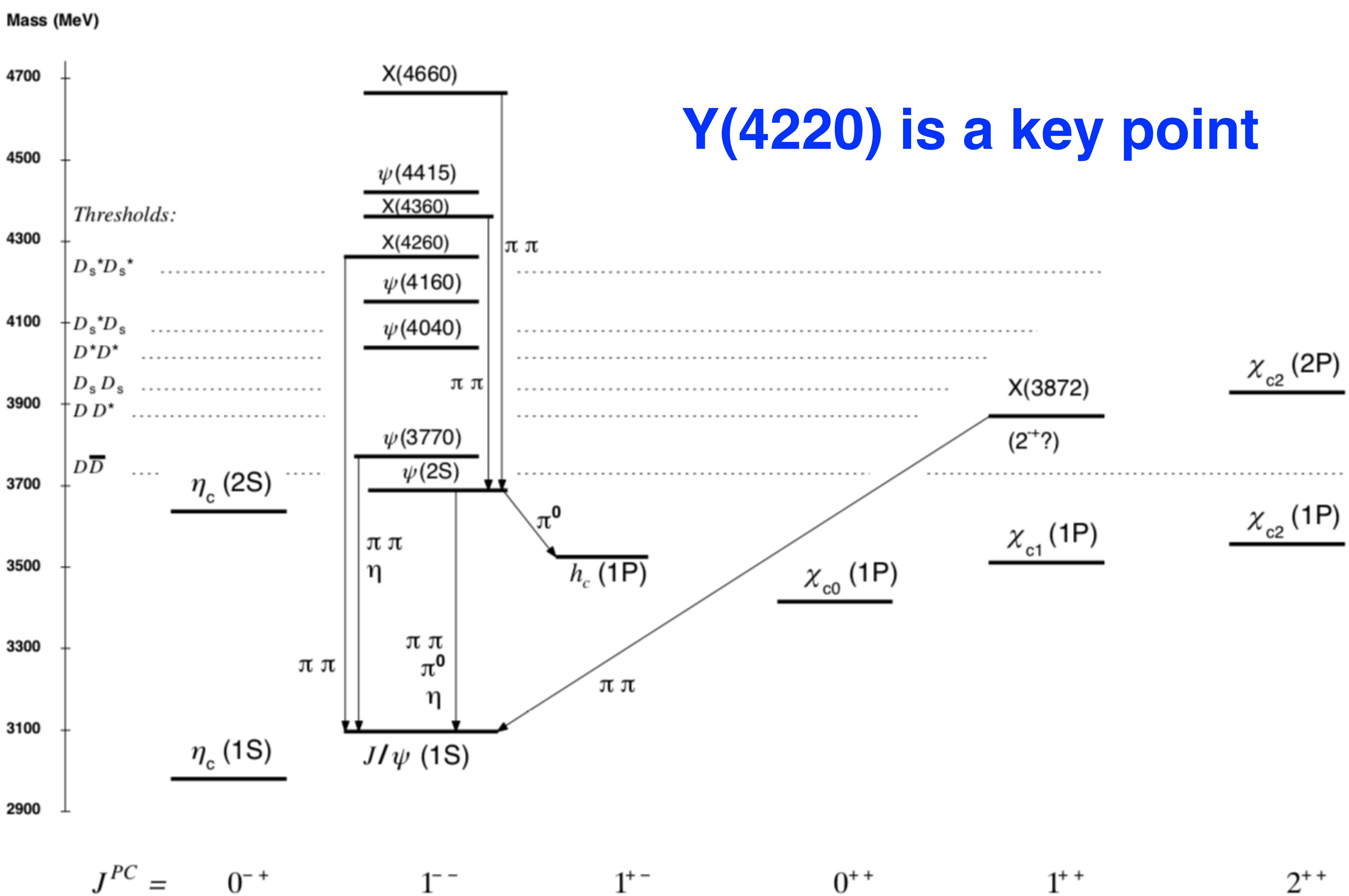


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi\Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

The status of Charmonium family shows our poor understanding of QCD non-perturbative behavior



Y(4220) is a key point

4.

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

PHYSICAL REVIEW D **99,** 114003 (2019)

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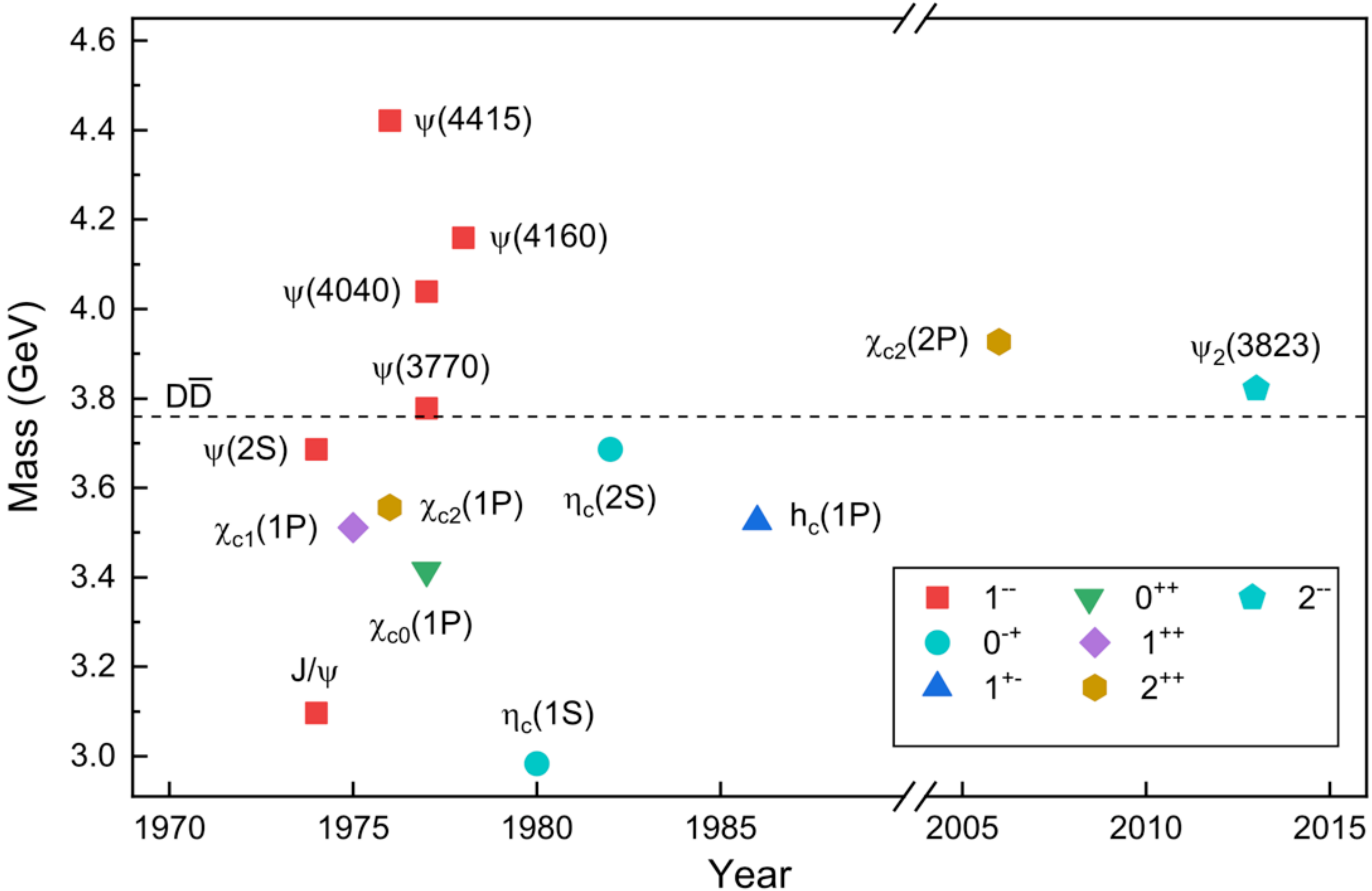
[2]*Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China*
[3]*School of Physics, Southeast University, Nanjing 211189, China*
[4]*Tokyo Kasei University, 1-18-1 Kaga, Itabashi, Tokyo 173-8602, Japan*
[5]*Theoretical Research Division,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

The present situation of charmonium family @2019



Depicting the mass spectrum with unquenched potential model

$$\tilde{H} = (p^2 + m_c^2)^{1/2} + (p^2 + m_{\bar{c}}^2)^{1/2} + \tilde{V}_{eff}(\mathbf{p}, \mathbf{r})$$

The linear confining $br + c$ including in the potential is modified as

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

Screening potential

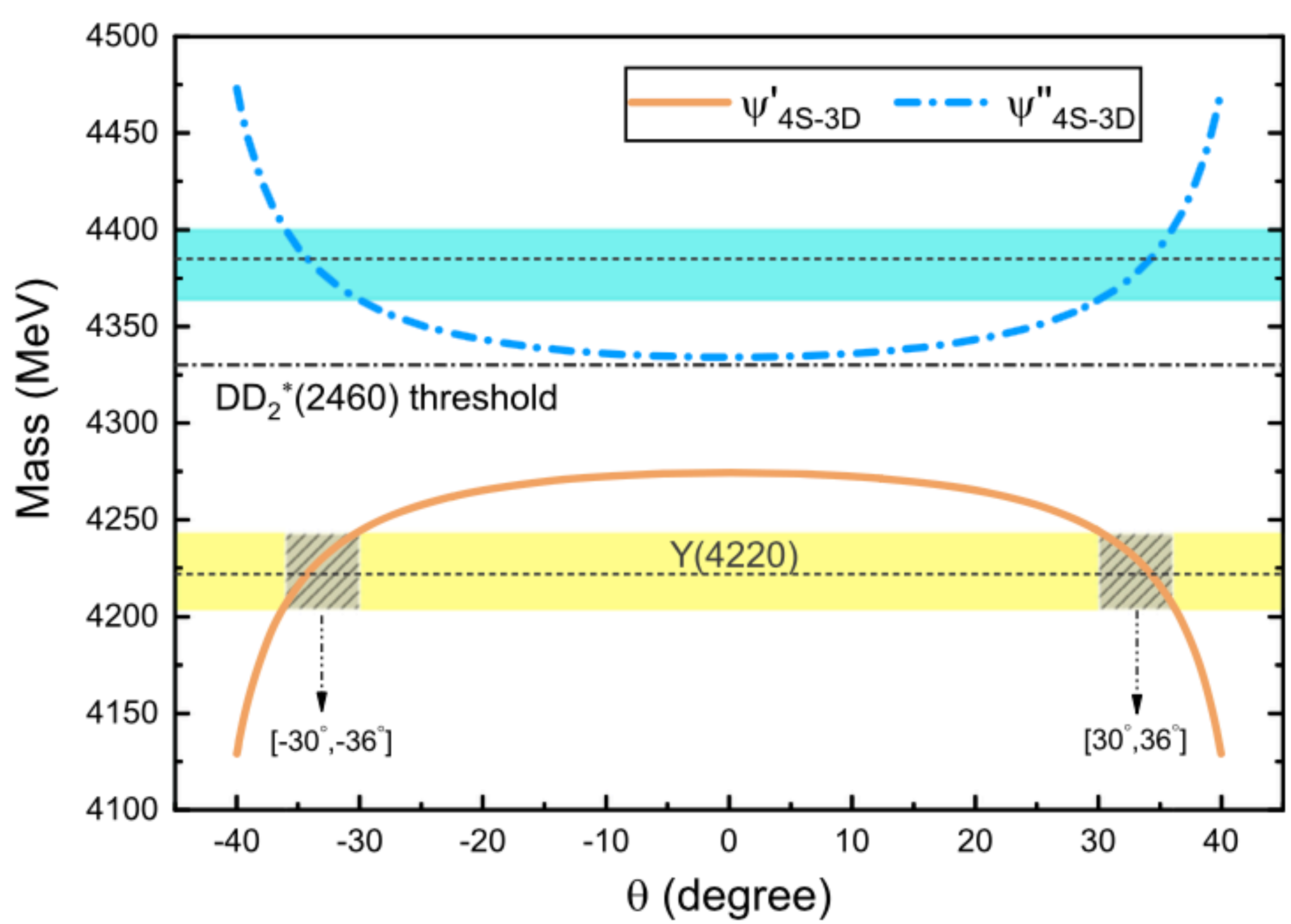
$$\begin{aligned} \varepsilon_c &= -0.084, & \varepsilon_t &= 0.012, \\ \varepsilon_{\mathrm{sov}} &= -0.053, & \varepsilon_{\mathrm{sos}} &= 0.083, \\ b &= 0.2687, & c &= -0.3673, \\ m_c &= 1.65\ \mathrm{GeV}, & \mu &= 0.15, \end{aligned}$$

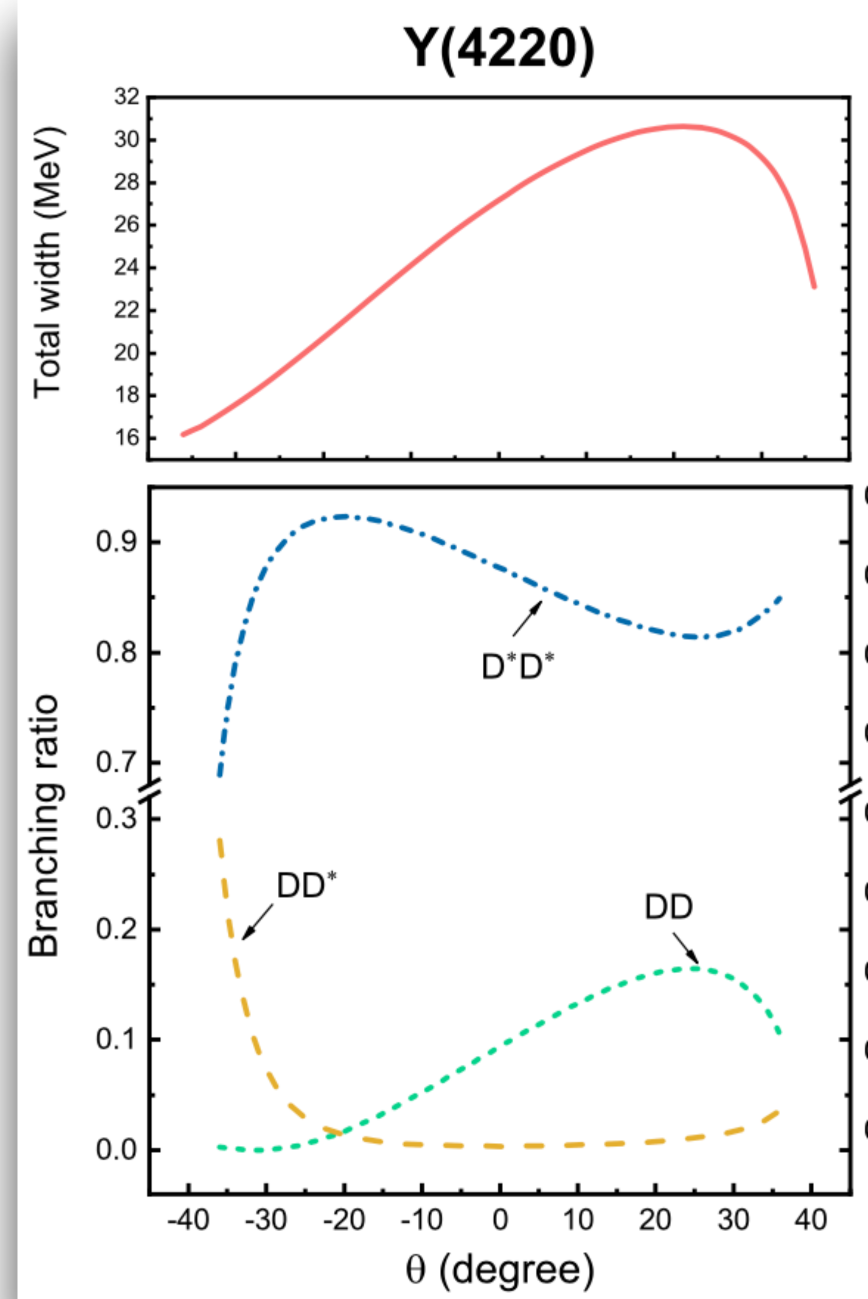
- **We need to reproduce the masses of these observed states**
- **Y(4220) is an important scaling point**

State	Mass	Expt. [9]	State	Mass	Expt. [9]
$\eta_c(1^1S_0)$	2981	2983.9 ± 0.5	$\psi(1^3D_1)$	3830	3778.1 ± 1.2
$\psi(1^3S_1)$	3096	3096.9 ± 0.006	$\psi_2(1^3D_2)$	3848	3822.2 ± 1.2
$\eta_c(2^1S_0)$	3642	3637.6 ± 1.2	$\psi_3(1^3D_3)$	3859	$\cdots$
$\psi(2^3S_1)$	3683	3686.097 ± 0.01	$\eta_{c2}(2^1D_2)$	4137	$\cdots$
$\eta_c(3^1S_0)$	4013	$\cdots$	$\psi(2^3D_1)$	4125	4159 ± 20
$\psi(3^3S_1)$	4035	4039 ± 1	$\psi_2(2^3D_2)$	4137	$\cdots$
$\eta_c(4^1S_0)$	4260	$\cdots$	$\psi_3(2^3D_3)$	4144	$\cdots$
$\psi(4^3S_1)$	4274	4230 ± 8	$\eta_{c2}(3^1D_2)$	4343	$\cdots$
$\eta_c(5^1S_0)$	4433	$\cdots$	$\psi(3^3D_1)$	4334	$\cdots$
$\psi(5^3S_1)$	4443	$\cdots$	$\psi_2(3^3D_2)$	4343	$\cdots$
$h_c(1^1P_1)$	3538	3525.38 ± 0.11	$\psi_3(3^3D_3)$	4348	$\cdots$
$\chi_{c0}(1^3P_0)$	3464	3414.71 ± 0.3	$\eta_{c2}(4^1D_2)$	4490	$\cdots$
$\chi_{c1}(1^3P_1)$	3530	3510.67 ± 0.05	$\psi(4^3D_1)$	4484	$\cdots$
$\chi_{c2}(1^3P_2)$	3571	3556.17 ± 0.07	$\psi_2(4^3D_2)$	4490	$\cdots$
$h_c(2^1P_1)$	3933	$\cdots$	$\psi_3(4^3D_3)$	4494	$\cdots$
$\chi_{c0}(2^3P_0)$	3896	3918.4 ± 1.9	$h_{c3}(1^1F_3)$	4074	$\cdots$
$\chi_{c1}(2^3P_1)$	3929	-	$\chi_{c2}(1^3F_2)$	4070	$\cdots$
$\chi_{c2}(2^3P_2)$	3952	3927.2 ± 2.6	$\chi_{c3}(1^3F_3)$	4075	$\cdots$
$h_c(3^1P_1)$	4200	$\cdots$	$\chi_{c4}(1^3F_4)$	4076	$\cdots$
$\chi_{c0}(3^3P_0)$	4177	$\cdots$	$h_{c3}(2^1F_3)$	4296	$\cdots$
$\chi_{c1}(3^3P_1)$	4197	$\cdots$	$\chi_{c2}(2^3F_2)$	4293	$\cdots$
$\chi_{c2}(3^3P_2)$	4213	$\cdots$	$\chi_{c3}(2^3F_3)$	4297	$\cdots$
$h_c(4^1P_1)$	4389	$\cdots$	$\chi_{c4}(2^3F_4)$	4298	$\cdots$
$\chi_{c0}(4^3P_0)$	4374	$\cdots$	$\eta_{c4}(1^1G_4)$	4250	$\cdots$
$\chi_{c1}(4^3P_1)$	4387	$\cdots$	$\psi_3(1^3G_3)$	4252	$\cdots$
$\chi_{c2}(4^3P_2)$	4398	$\cdots$	$\psi_4(1^3G_4)$	4251	$\cdots$
$\eta_{c2}(1^1D_2)$	3848	$\cdots$	$\psi_5(1^3G_5)$	4249	$\cdots$

Introducing 4S-3D mixing scheme

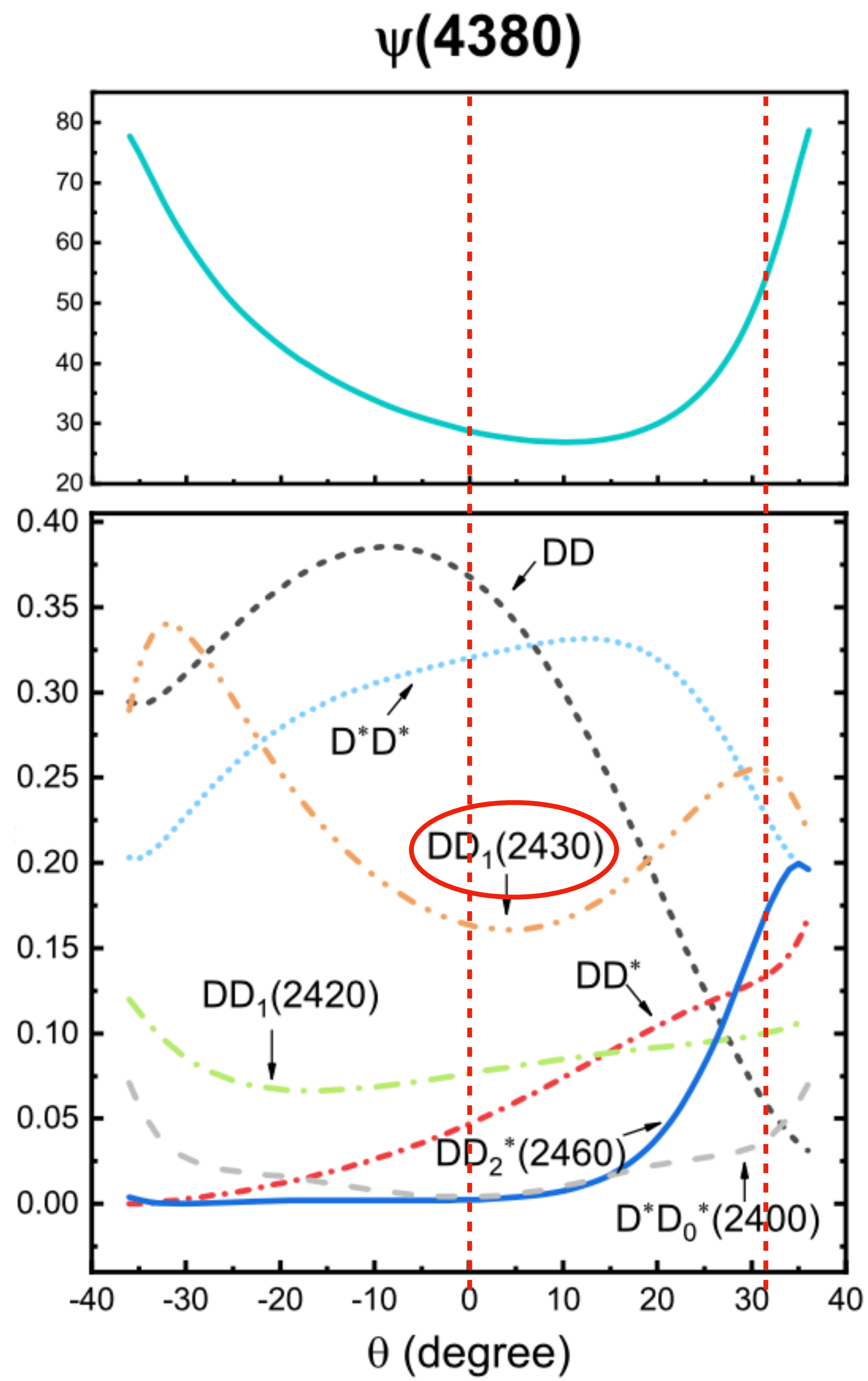
$$\begin{pmatrix} |\psi'_{4S-3D}\rangle \\ |\psi''_{4S-3D}\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |4^3S_1\rangle \\ |3^3D_1\rangle \end{pmatrix}$$



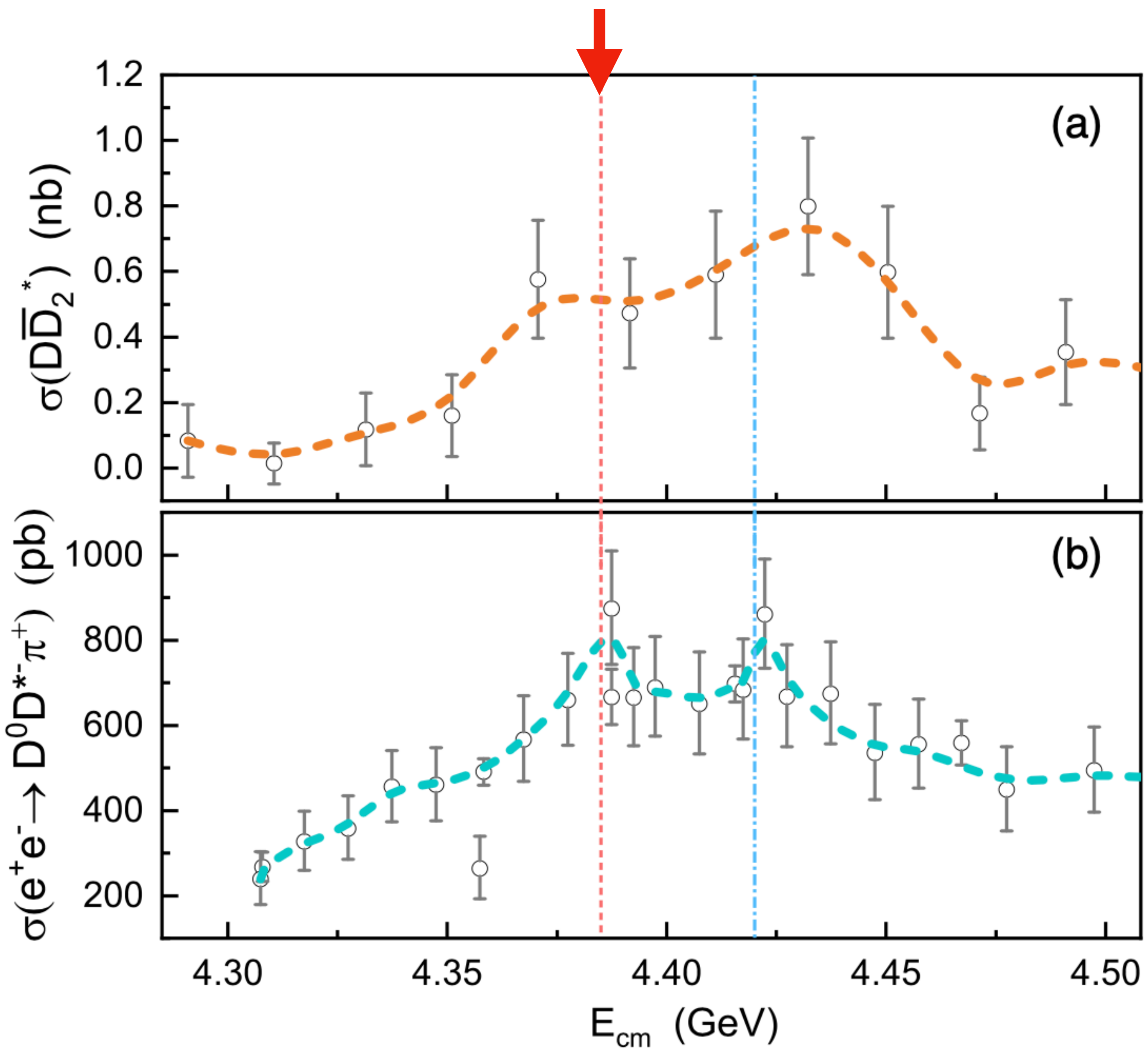


Our calculation supports this scenario

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

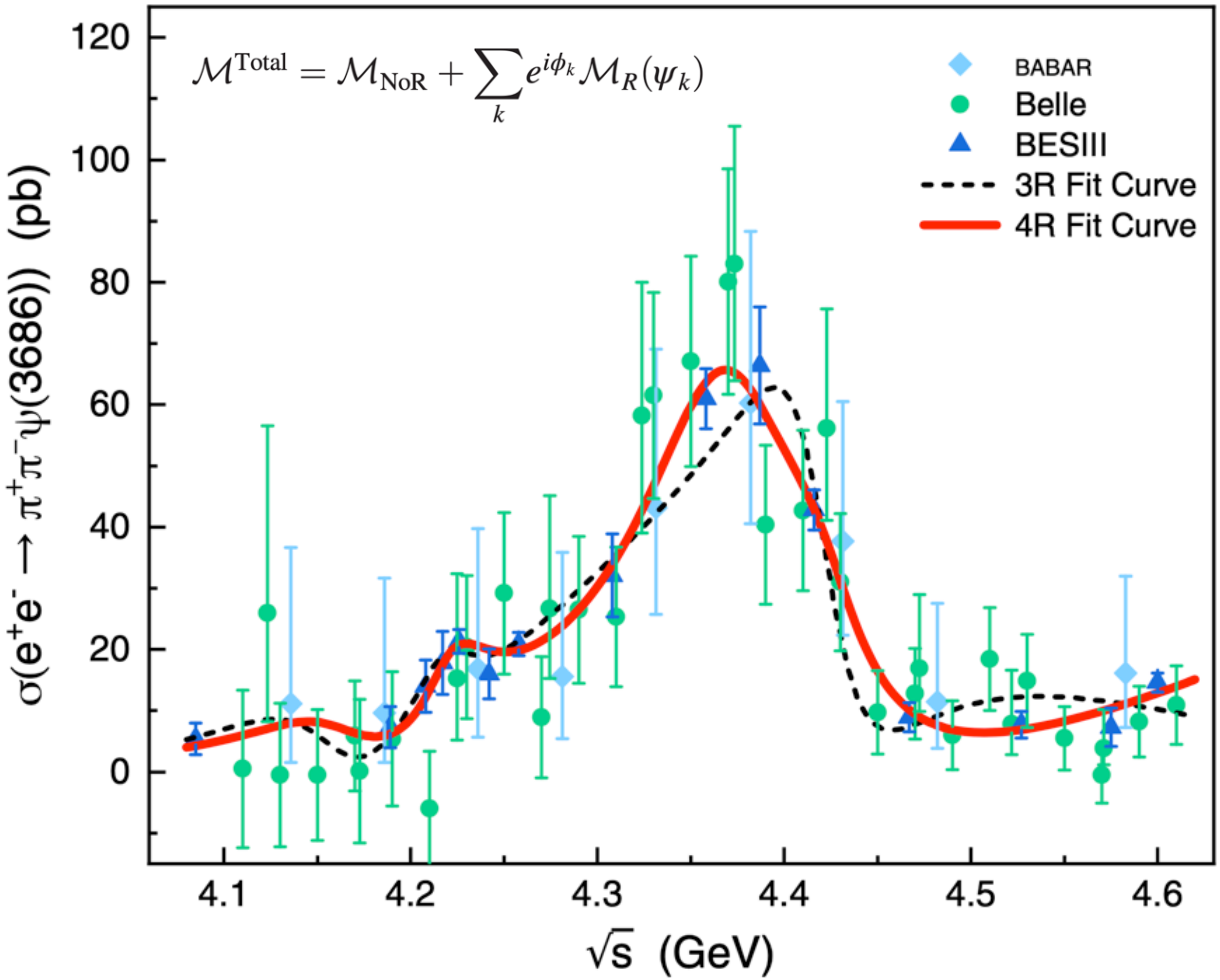


- The total width of ψ(4380) has a significant enhancement
- There exists sizable enhancement of $\psi(4380) \to DD_2(2460)$



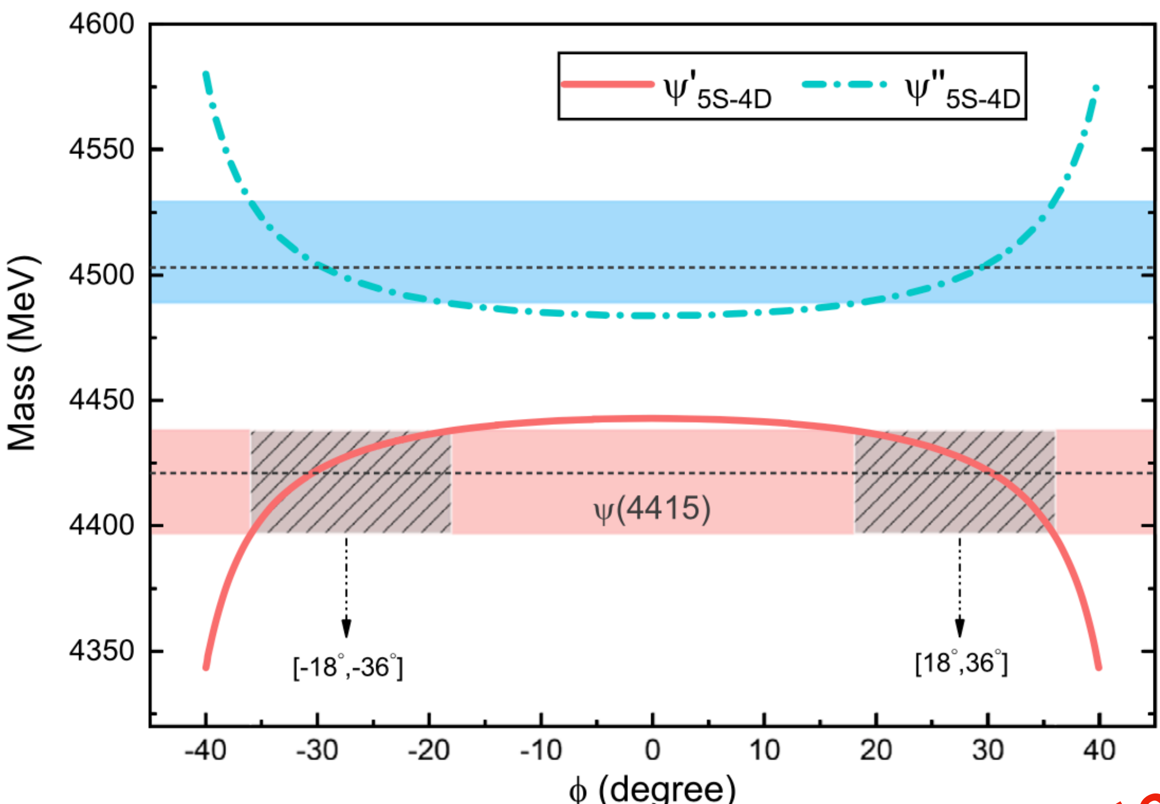
The experimental evidence for the prediction $\psi(4380)$

$$\psi(4160) + \psi(4415) + Y(4220) + \psi(4380)$$



Proposing 5S-4D mixing scheme

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

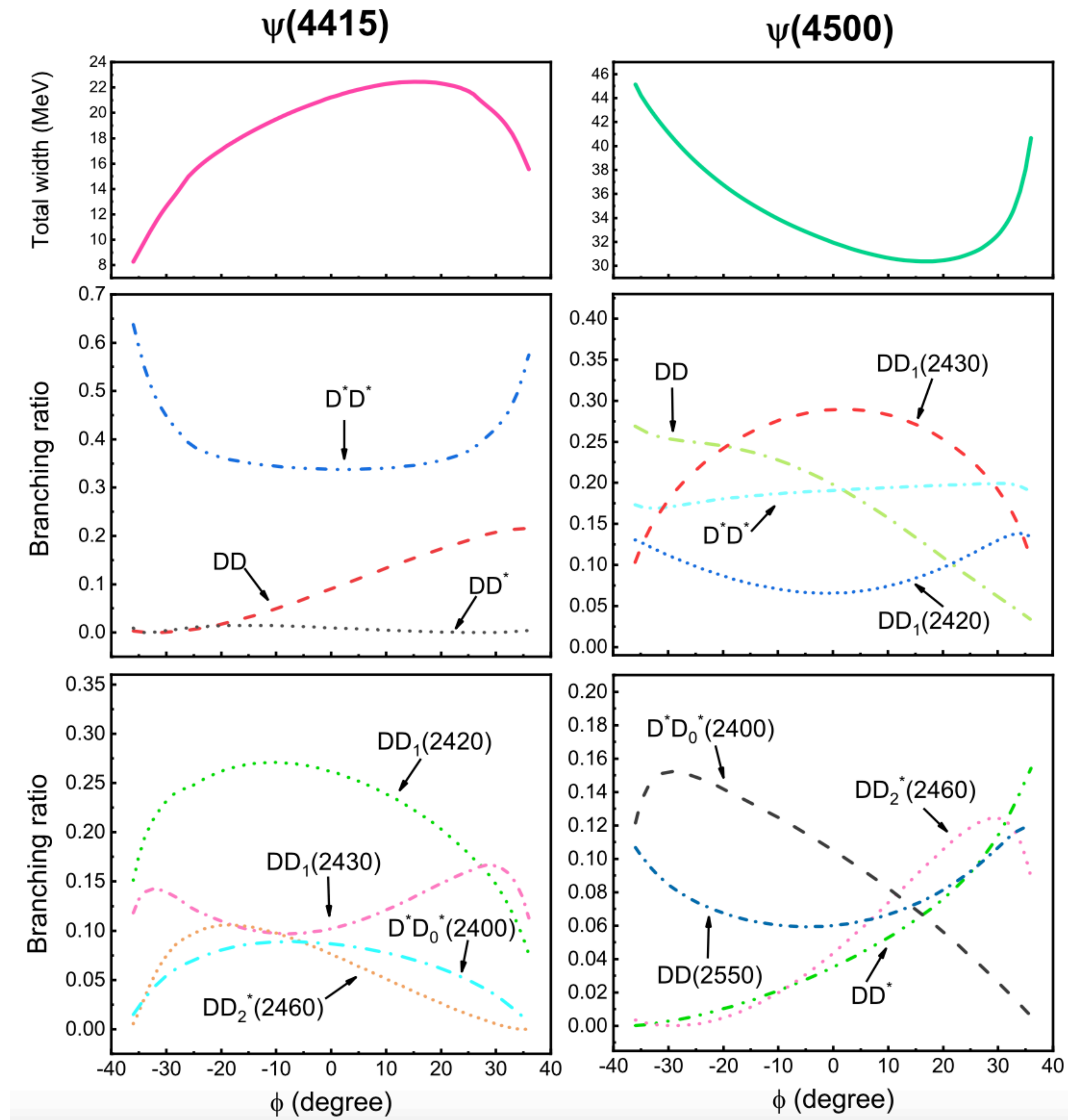


Experimental result

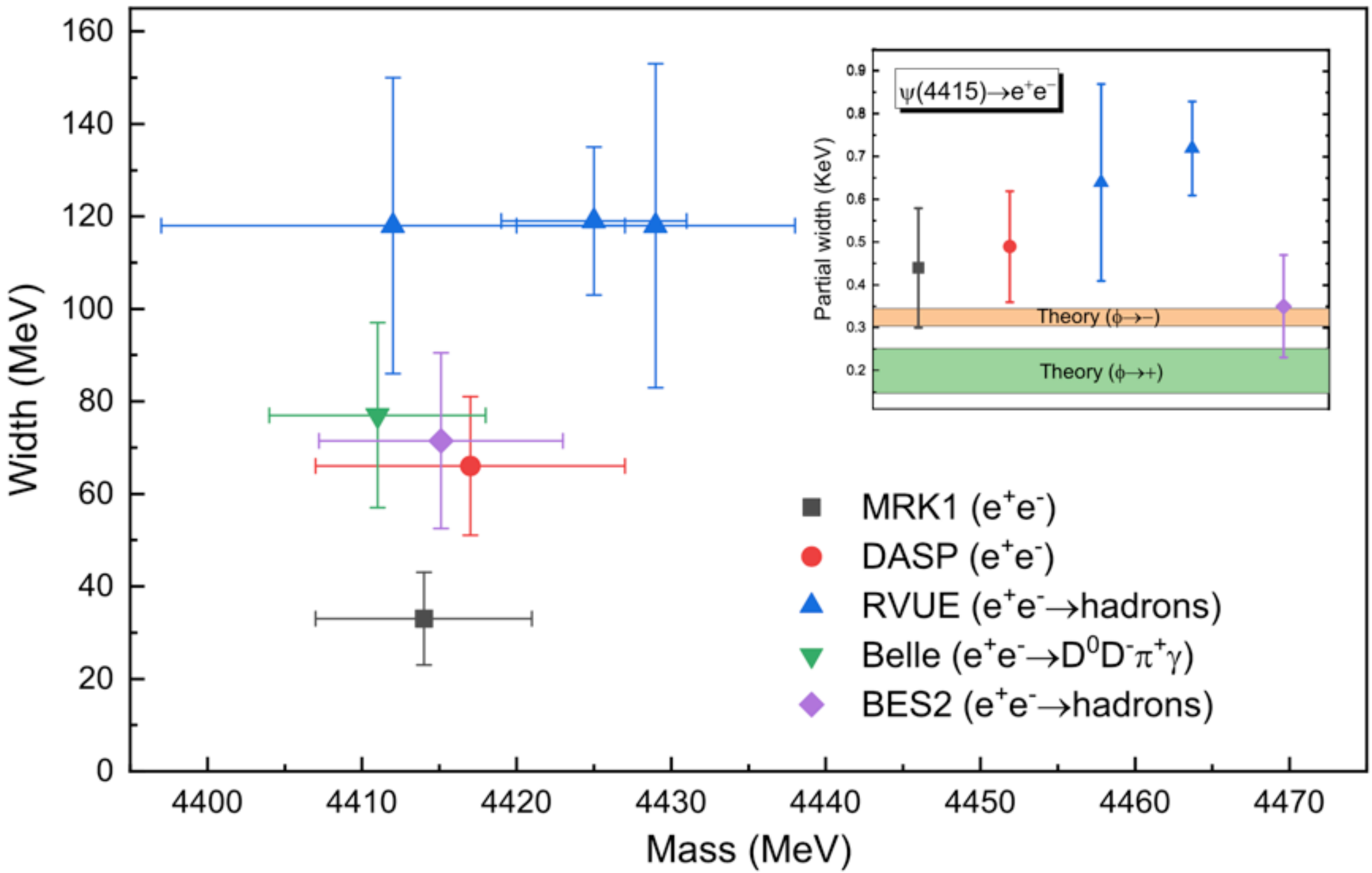
$$\frac{\Gamma(\psi(4415) \to D\bar{D})}{\Gamma(\psi(4415) \to D^*\bar{D}^*)} = 0.14 \pm 0.12 \pm 0.03,$$

$$\frac{\Gamma(\psi(4415) \to D^*\bar{D} + \text{c.c.})}{\Gamma(\psi(4415) \to D^*\bar{D}^*)} = 0.17 \pm 0.25 \pm 0.03,$$

Consistent



We still need more precise data of the resonance parameter of $\psi(4415)$



Summary

- **Y states** from e^+e^- annihilation may play **important role** to construct higher charmonia
- **Full of opportunity and challenge**
- **More theoretical and experimental efforts**

Thank you for your attention