三个典型能区矢量介子态关联的新现象研究

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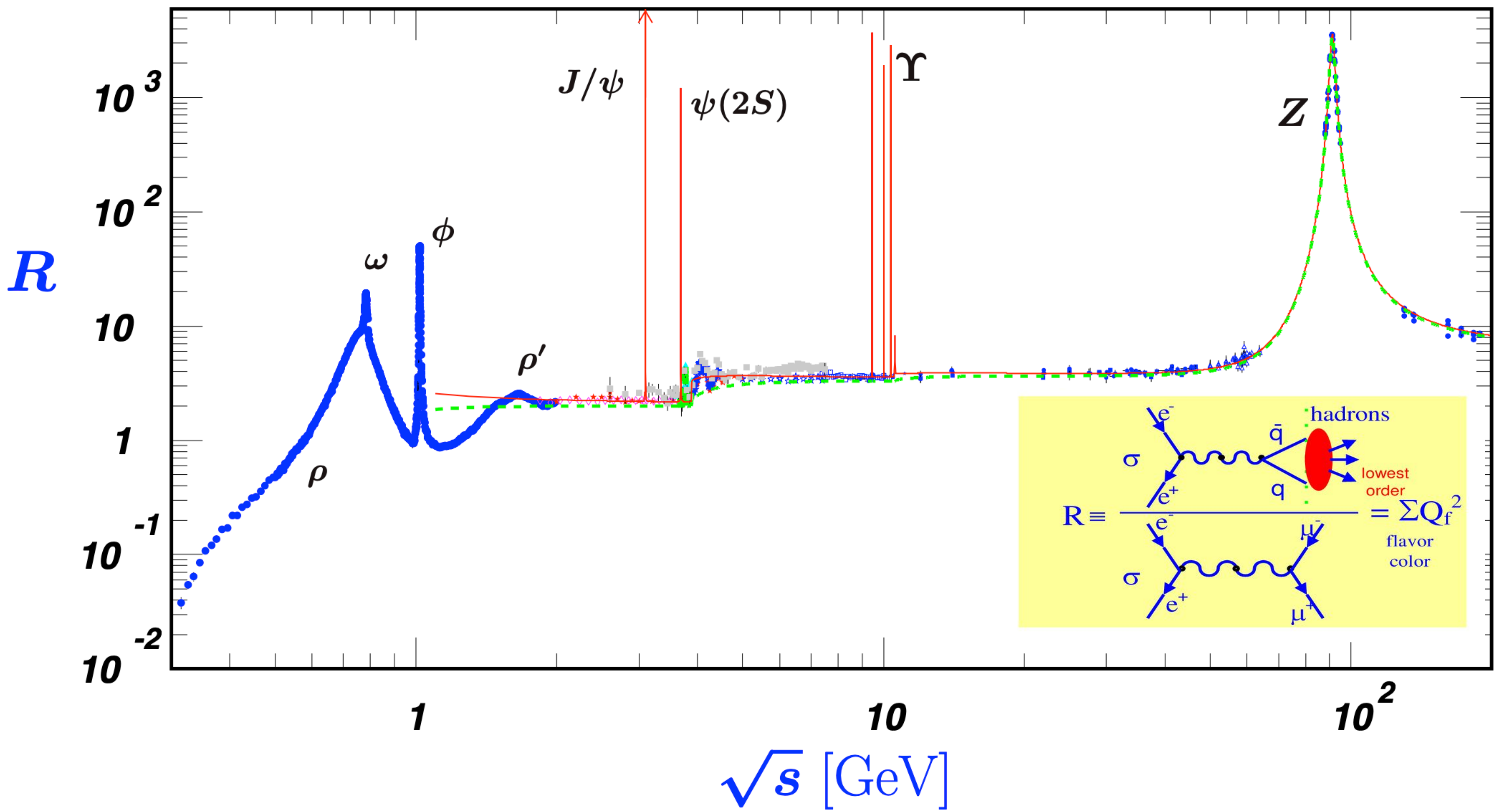
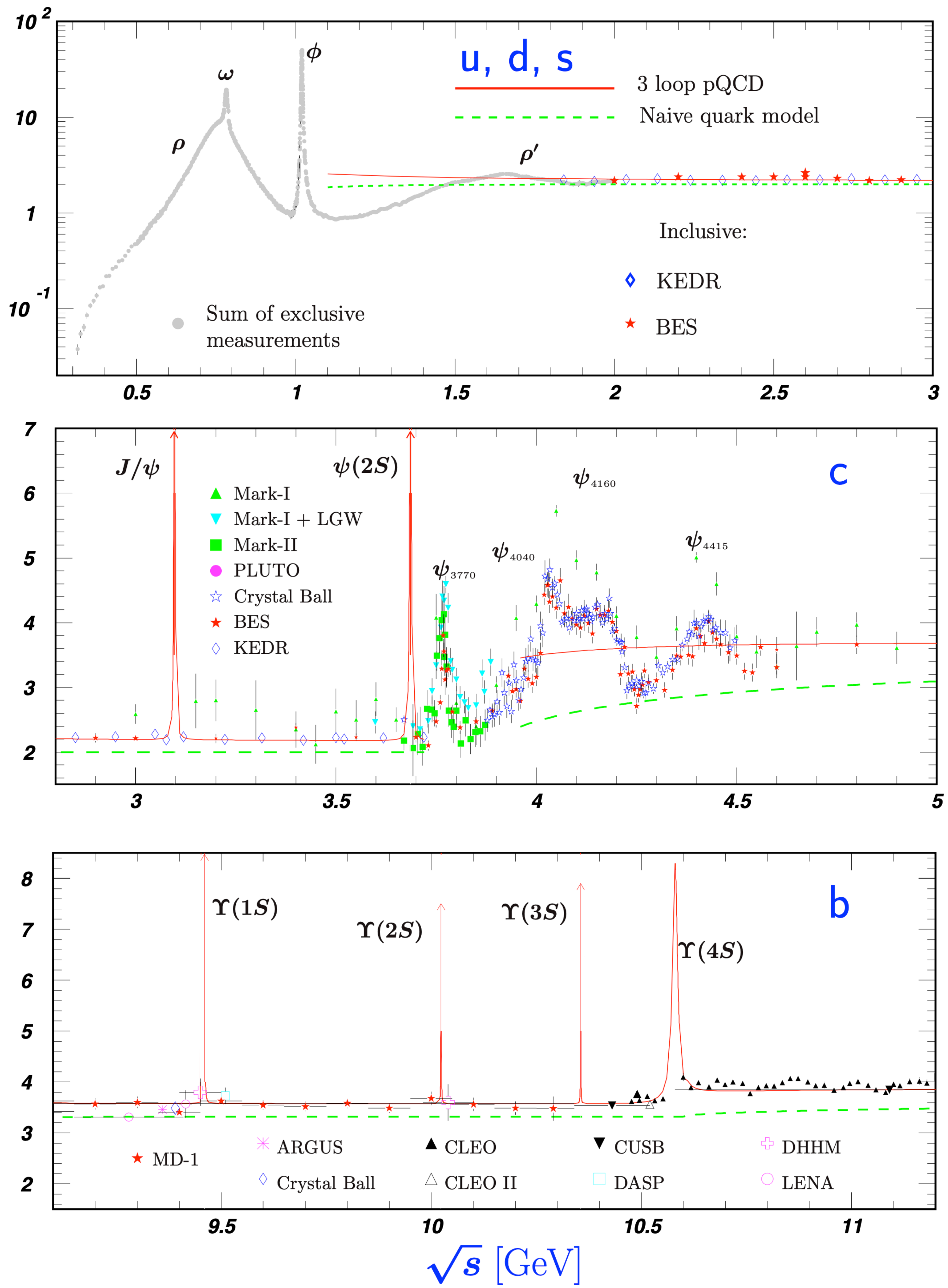
郑州大学 2025年8月25日

R value measurement

One of the most fundamental quantities in particle physics



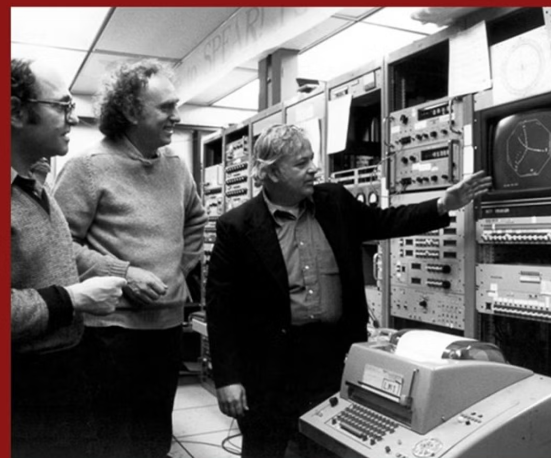


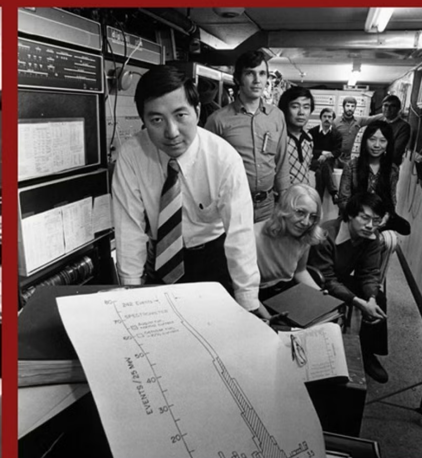
Abundant phenomena around three energy points

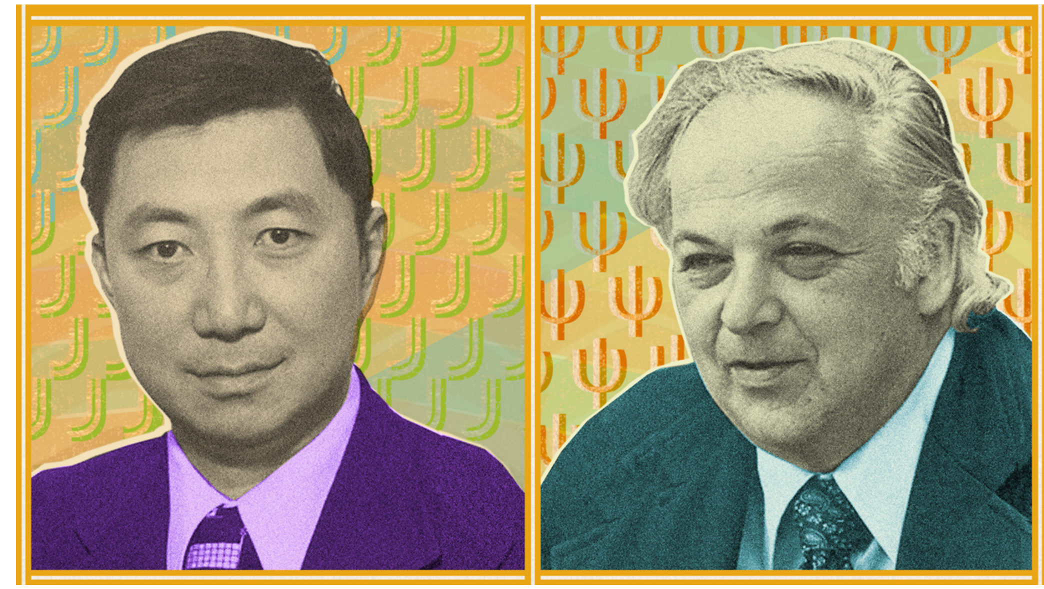
$$e^+e^- \rightarrow \begin{cases} \Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^- \\ Y(4260) \rightarrow J/\psi\pi^+\pi^- \\ Y(2175) \rightarrow \phi\pi^+\pi^- \end{cases}$$

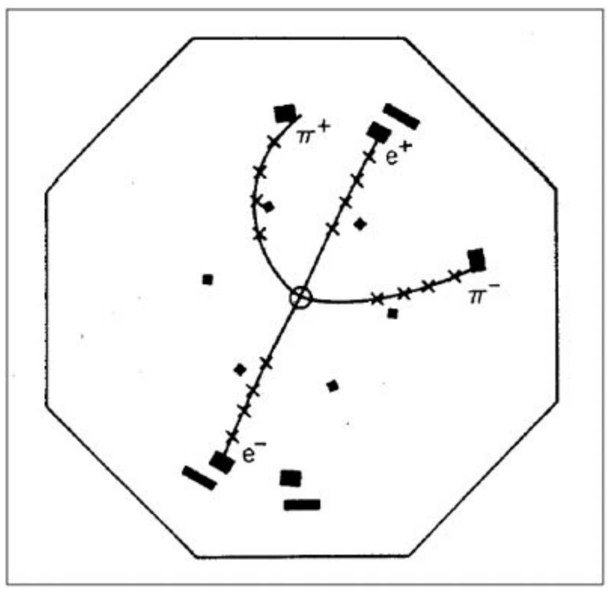
Similar behavior

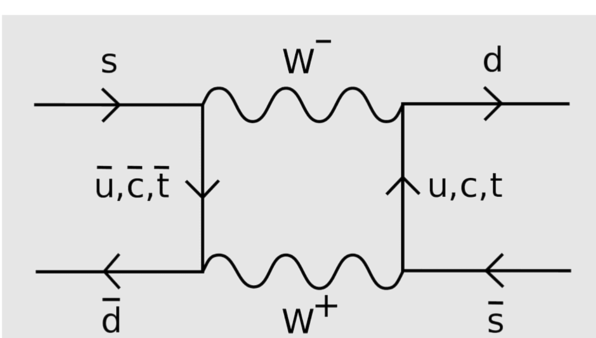
Charmonium and Cornell model











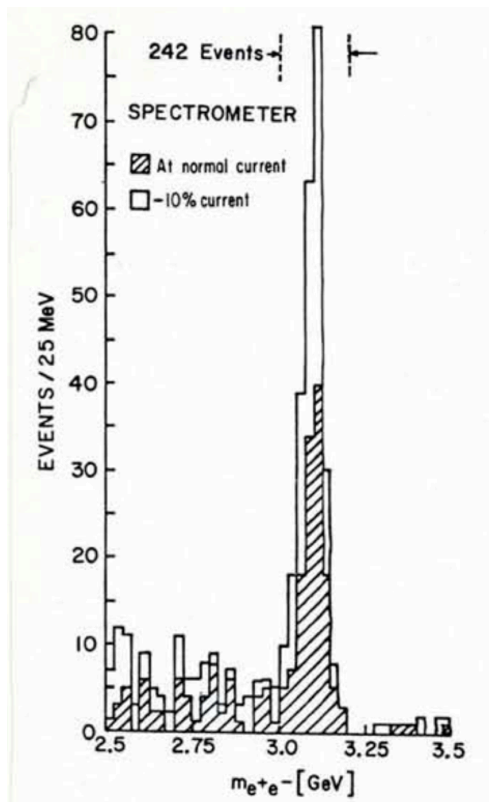
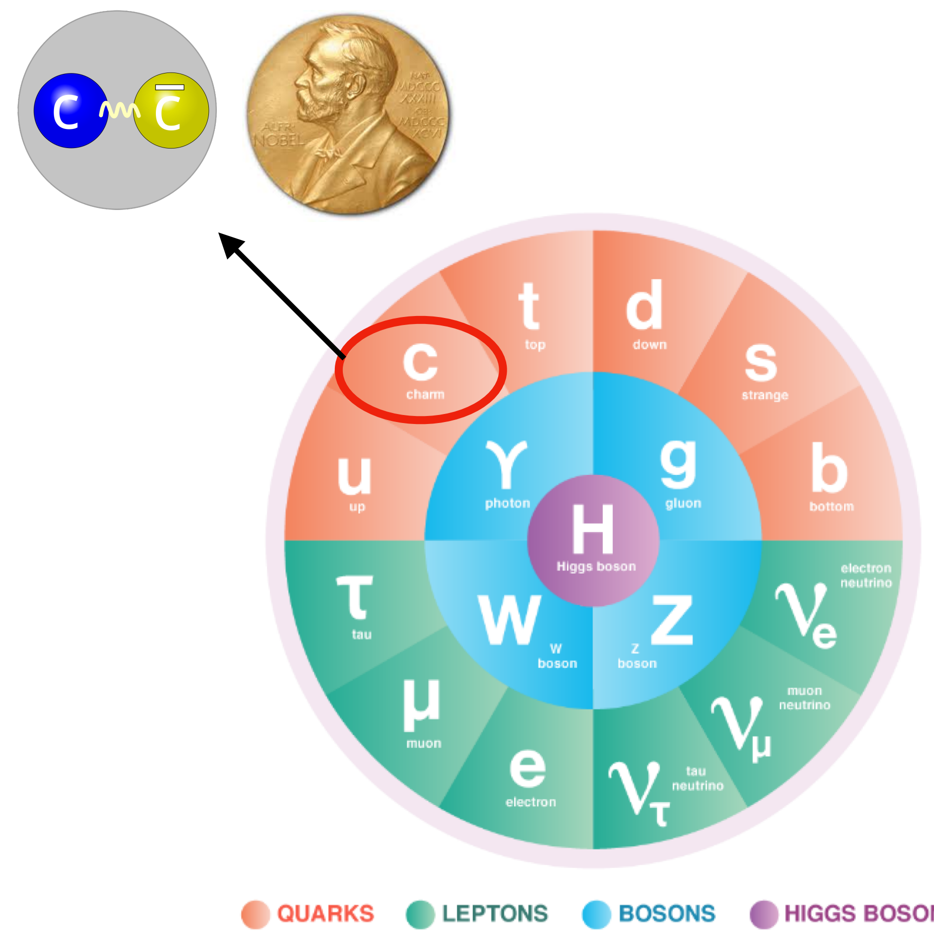
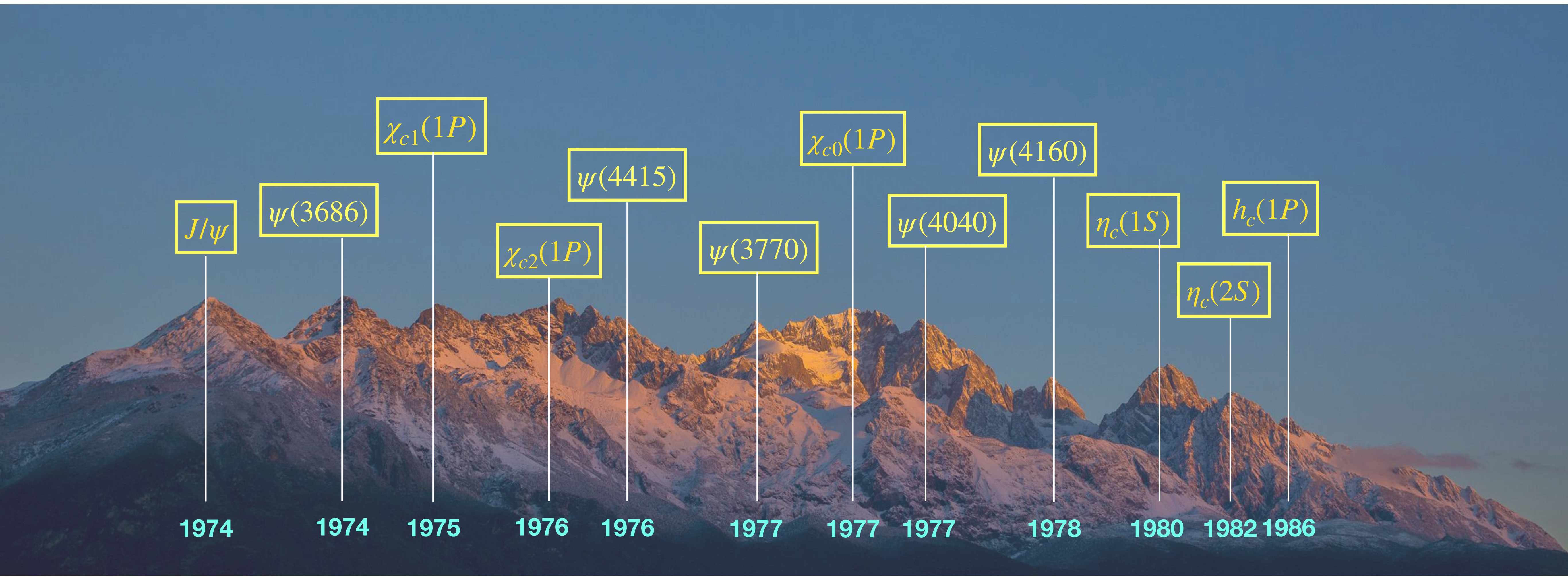


Fig. 1 The J-ψ signal detected by Ting and his group at BNL. The J-ψ appears as a quite striking peak in the distribution of the total mass of the electron-positron pairs.



These findings constitute the main body of the current charmonium family in PDG

(1974-1986)



Charmonium and Cornell model

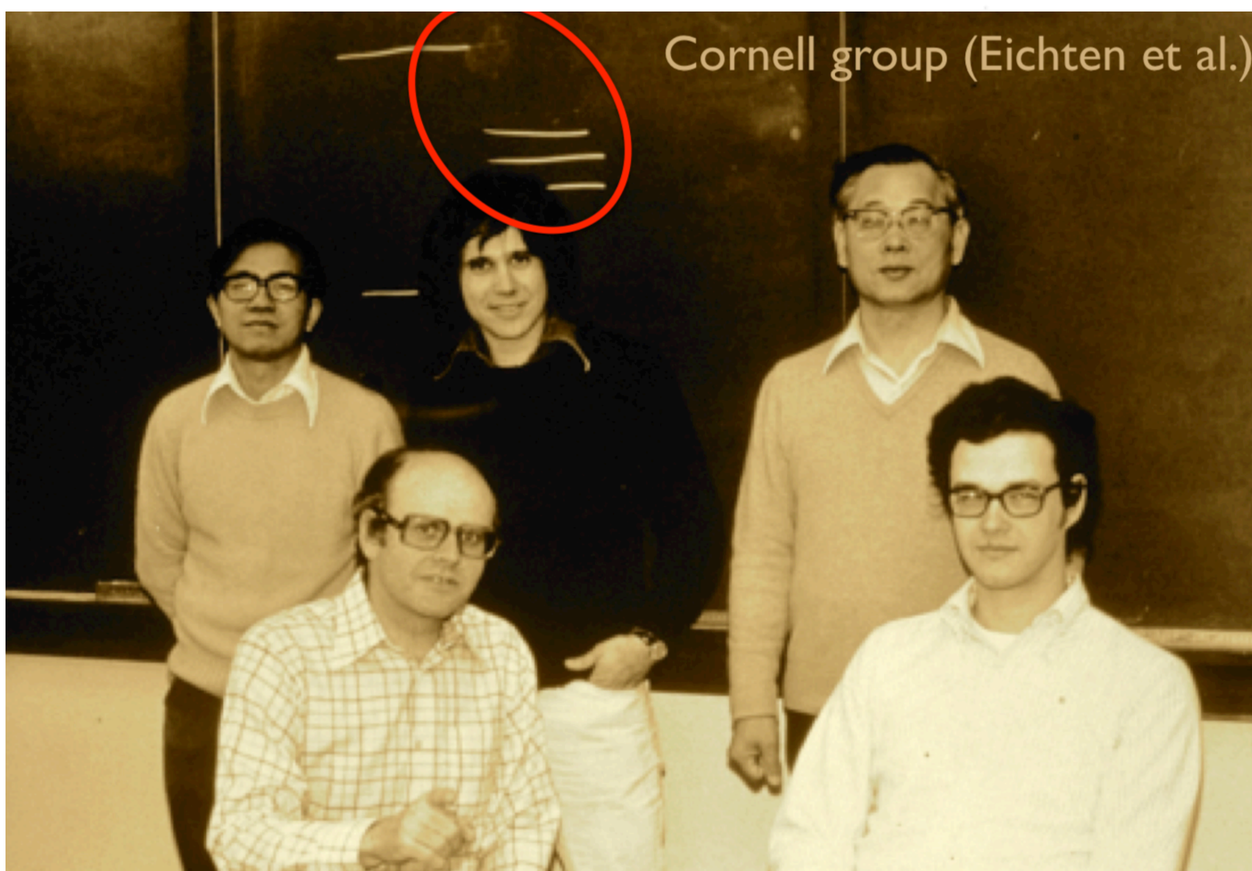
Cornell model: Typical quenched model

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.



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gy range.[3,9]
ovide a

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.

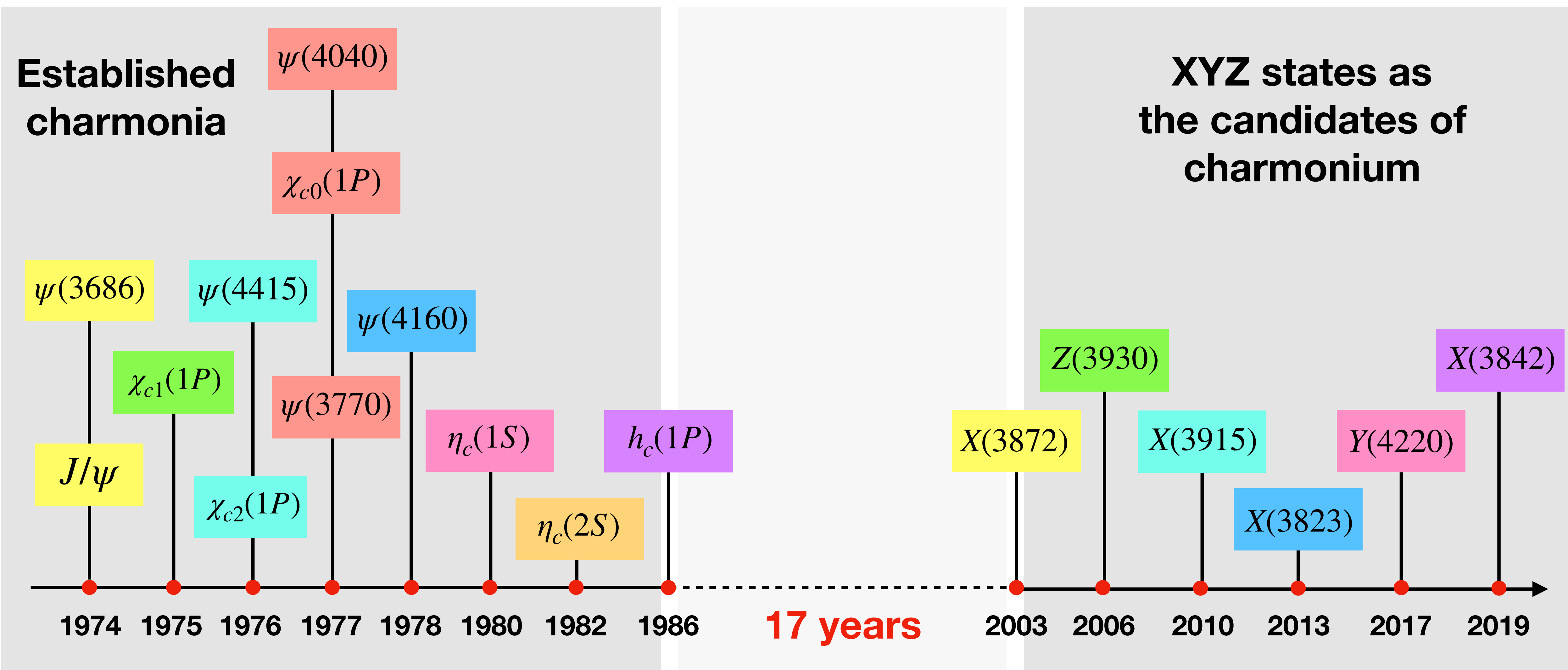
Secondly, the large masses of the ψ resonances and charmed mesons lead to the assumption that the charmed quarks are so heavy that they may be treated nonrelativistically.[4] No one has yet succeeded in calculating the effective form of the interquark forces from quantum chromodynamics,[16] even in the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

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

Cornell potential

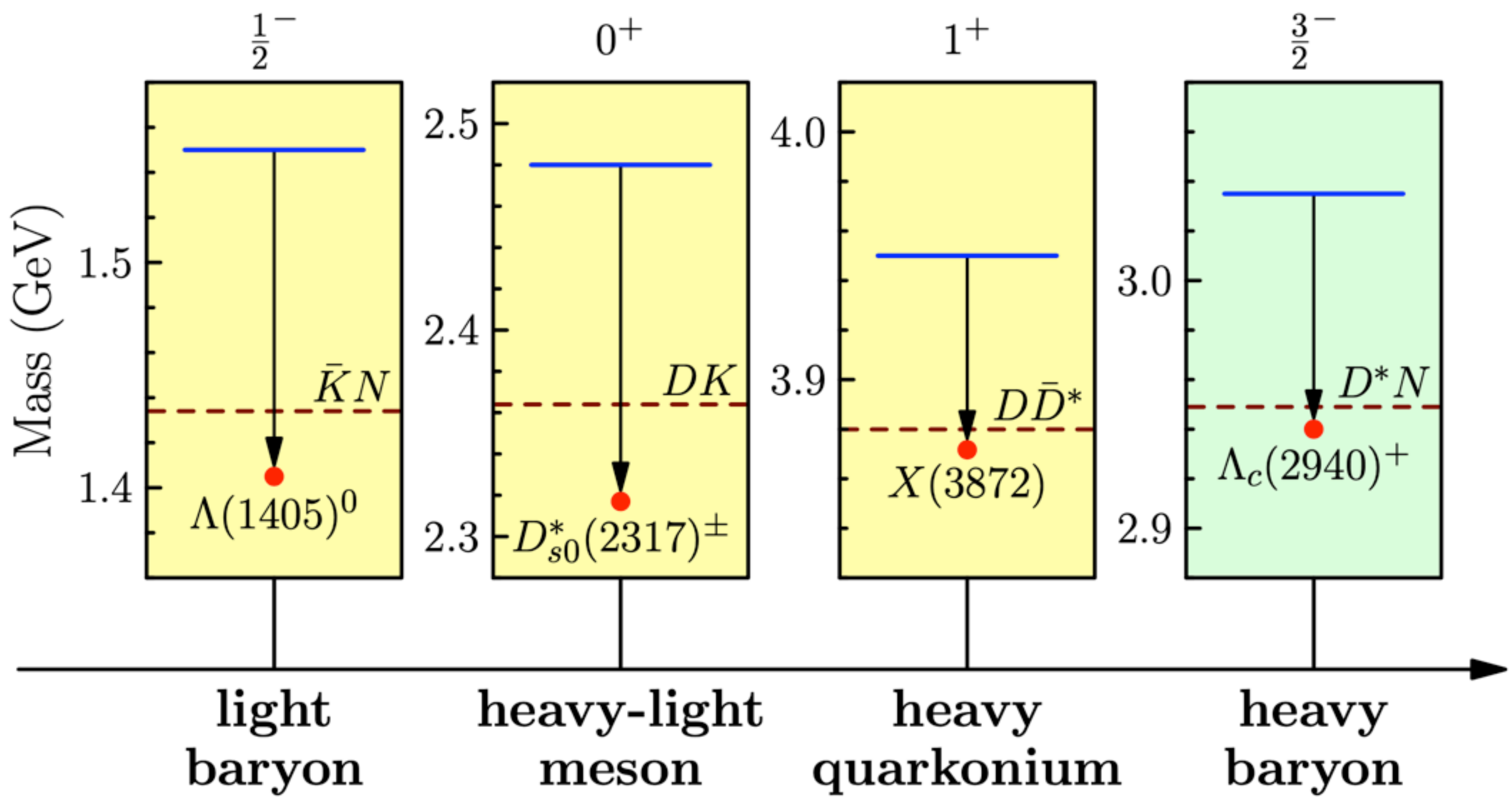
Charmonium and Cornell model

粲偶素发现**催生**了淬火势模型　　　　淬火势模型**落伍**于新强子态发现



Unquenched effect

Low mass puzzle for some typical new hadronic states

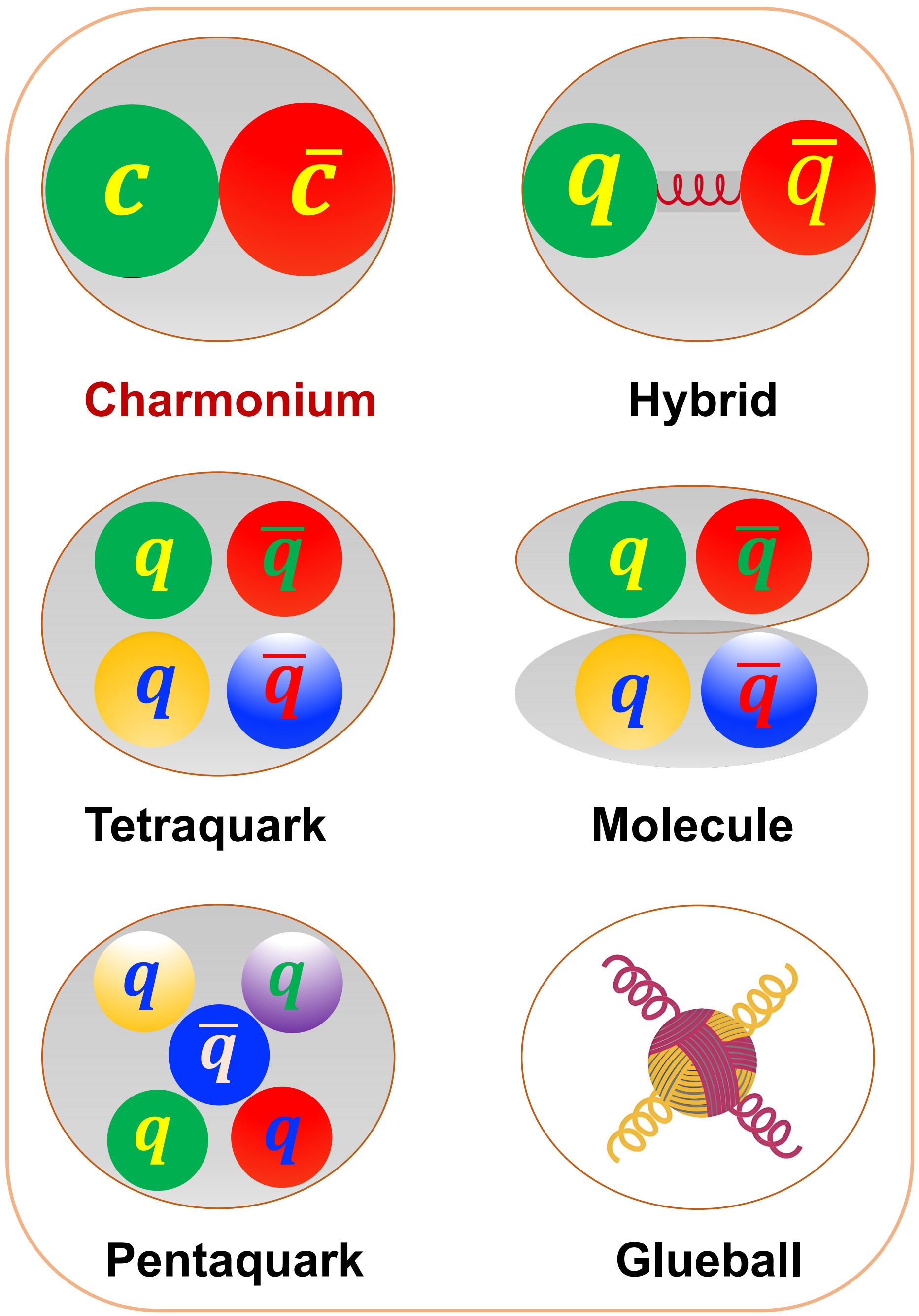


Luo, Chen, Liu, XL, EPJC 80 (2020) 301

Unquenched effect

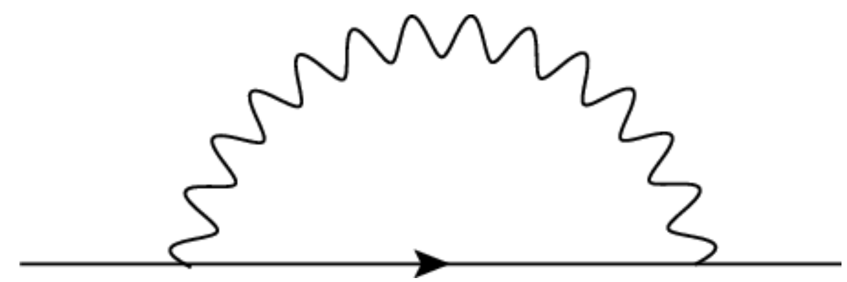
Two approaches to solve low mass puzzle

① Exotic state

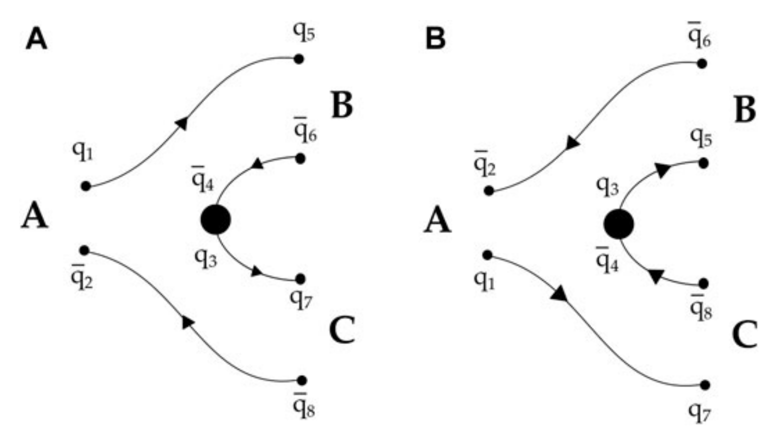


② Unquenched potential model

- Self energy of electron



- Coupled-channel effect



Quenched model → Unquenched model

Unquenched effect

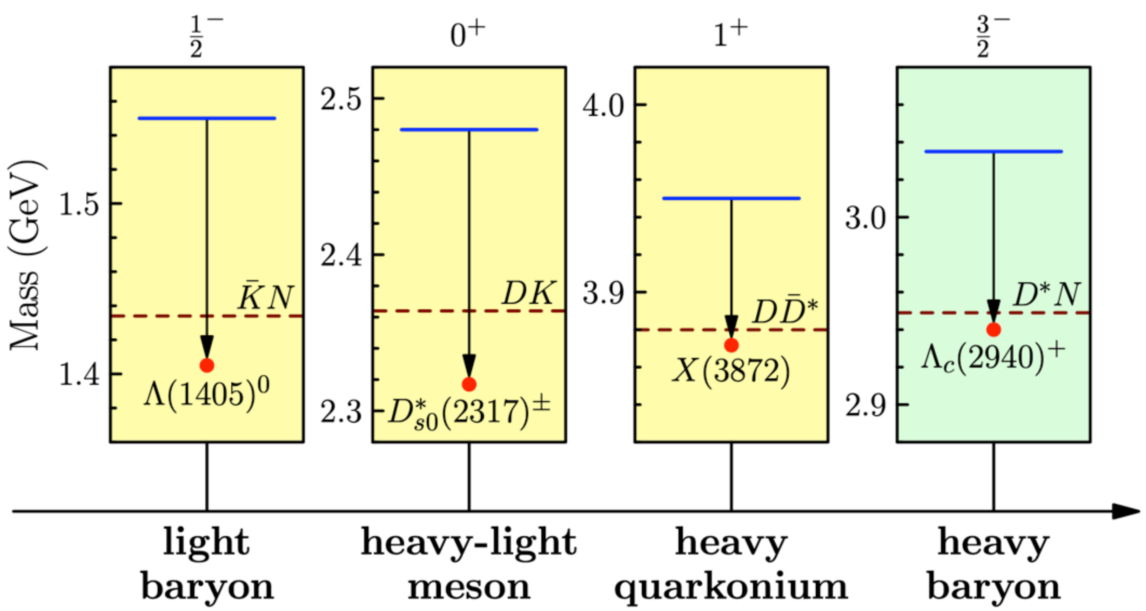
Eur. Phys. J. C (2020) 80:301
https://doi.org/10.1140/epjc/s10052-020-7874-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Resolving the low mass puzzle of $\Lambda_c(2940)^+$

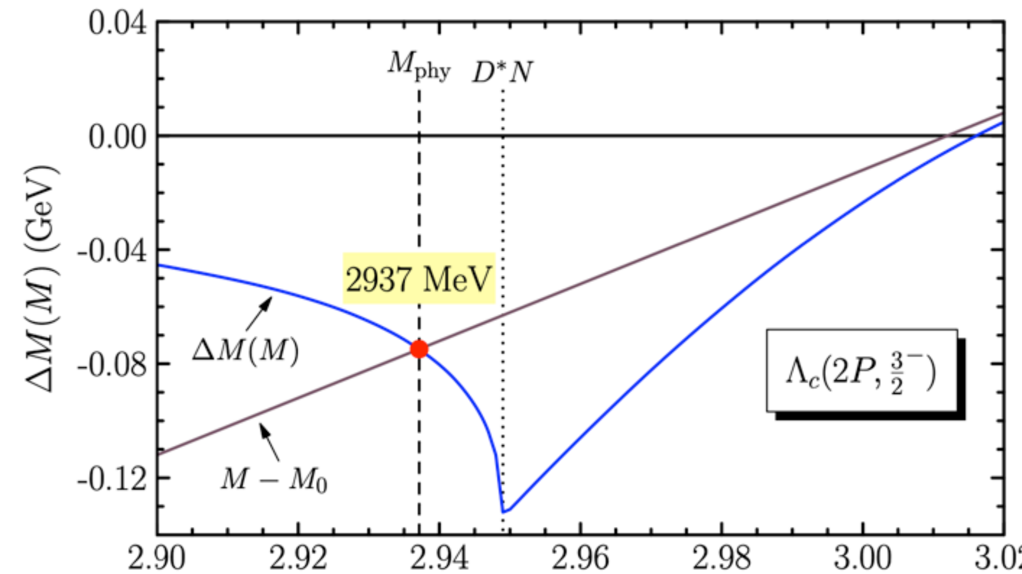
Si-Qiang Luo[1,3,a], Bing Chen[2,3,b], Zhan-Wei Liu[1,3,c], Xiang Liu[1,3,d]

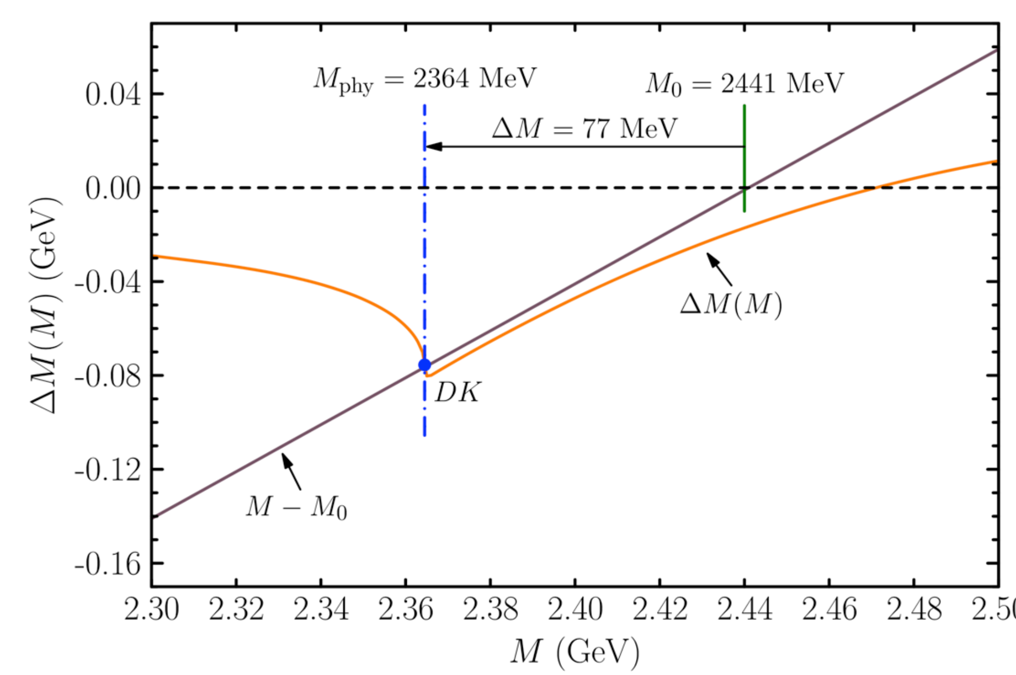


Solve the low mass puzzles!

$$M - M_0 - \Delta M(M) = 0,$$

$$\Delta M(M) = \mathrm{Re}\int_0^\infty \mathrm{d}q\, q^2 \frac{\left|\mathcal{M}^{\Lambda_c^{\mathrm{bare}}(2P,3/2^-)\to D^*N}(q)\right|^2}{M - E_{D^*N}(\mathbf{q})}$$





Luo, Chen, X. Liu, Matsuki, PRD 103 (2021) 074027

Quenched vs. Unquenched pictures

Quenched

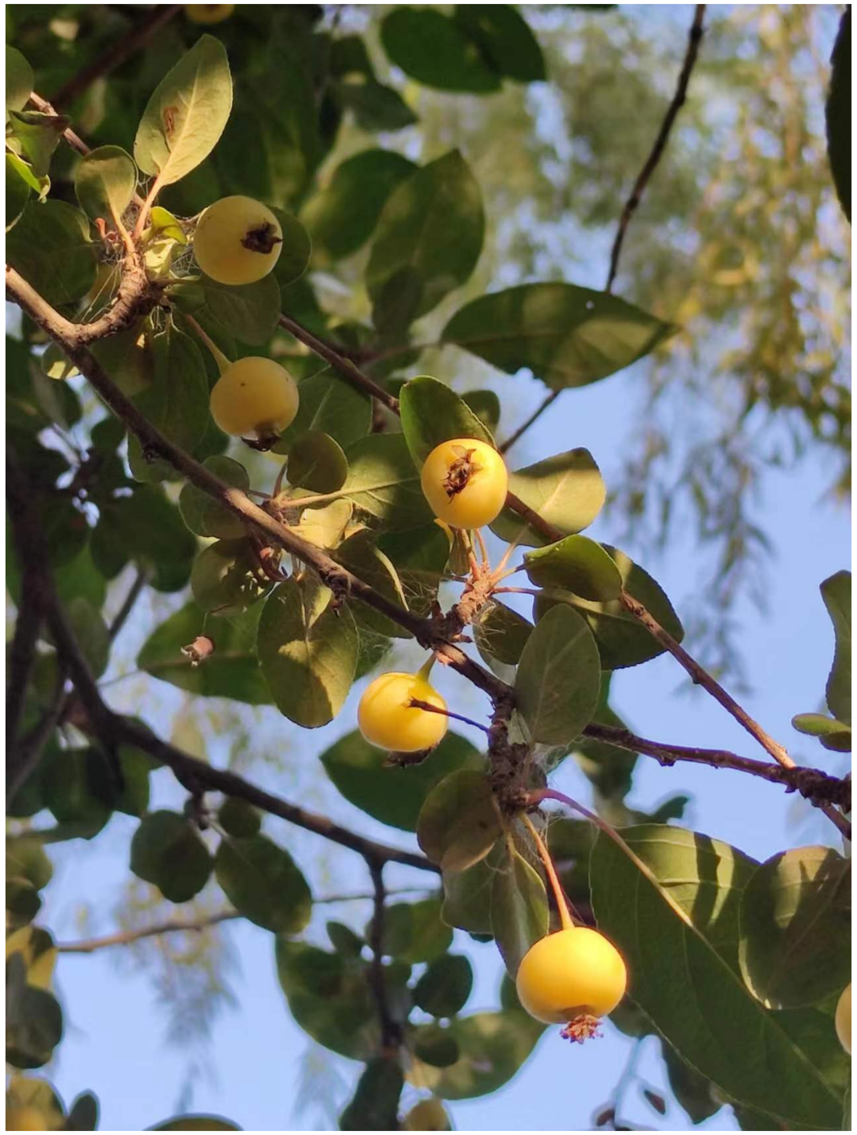
Unquenched

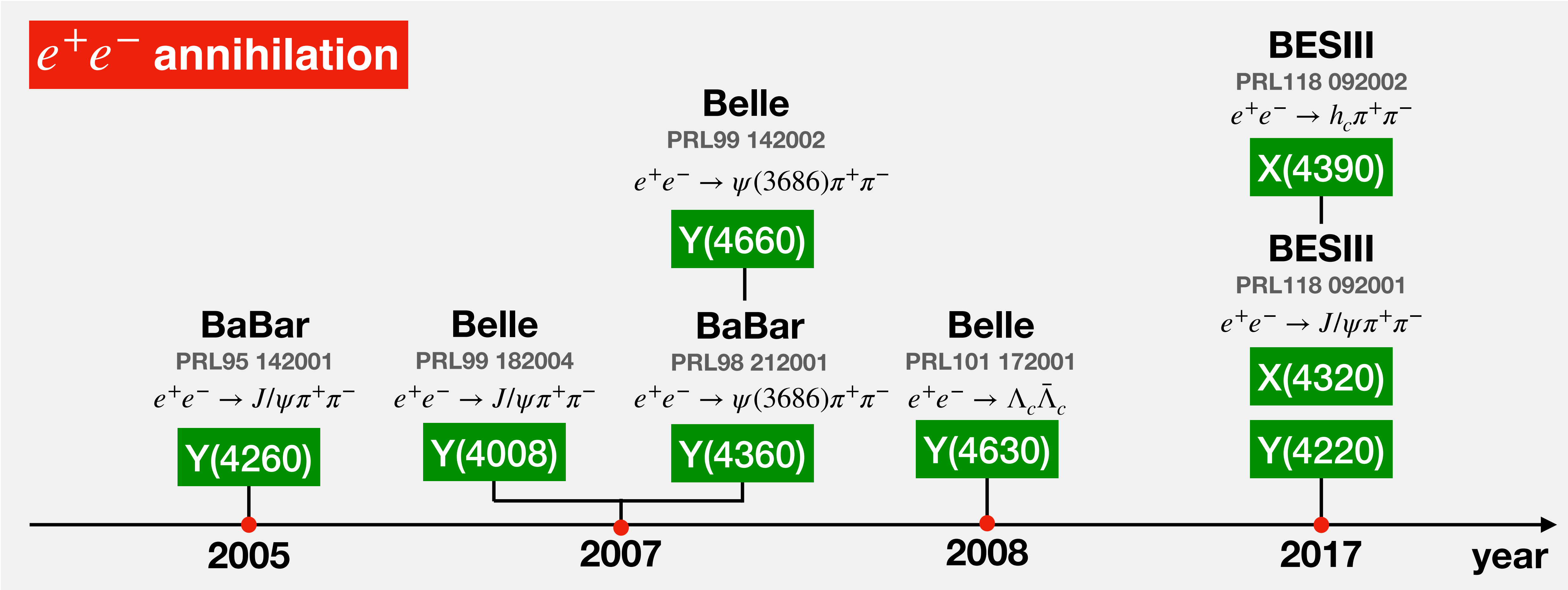
Outline

- Solution to Y problem
- Decoding Y(10750)
- The reported Y states around 2 GeV and light flavor vector mesons
- Summary

1

Solution to Y problem

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

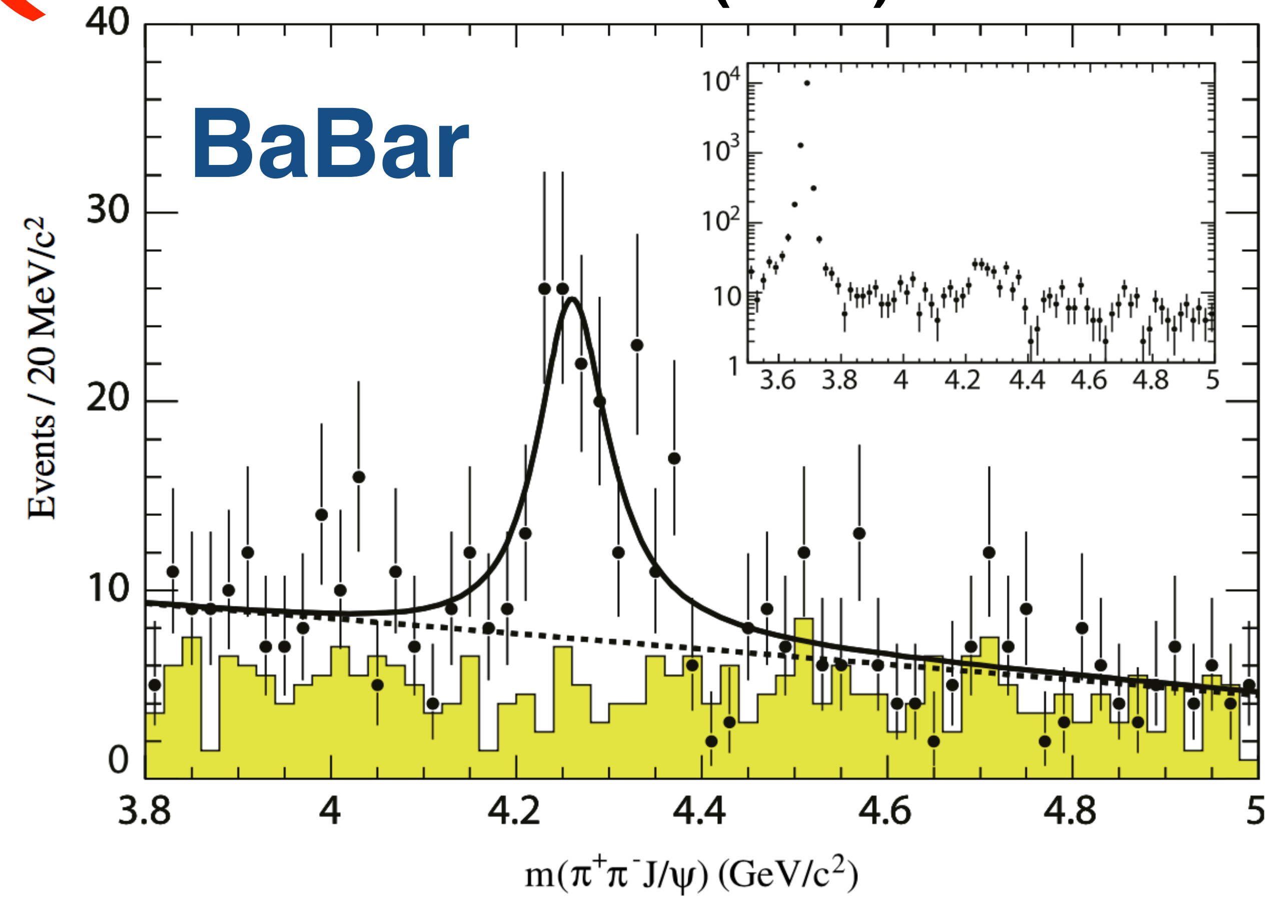
Exclusive e^+e^- cross sections have shown surprisingly complex behavior as a function of cms energy. The $Y(4260)$ is more complex than a single ordinary resonance, as shown by the complicated lineshape in the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section in Fig. 3.10(e); the $Y(4360)$ and $Y(4660)$ 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

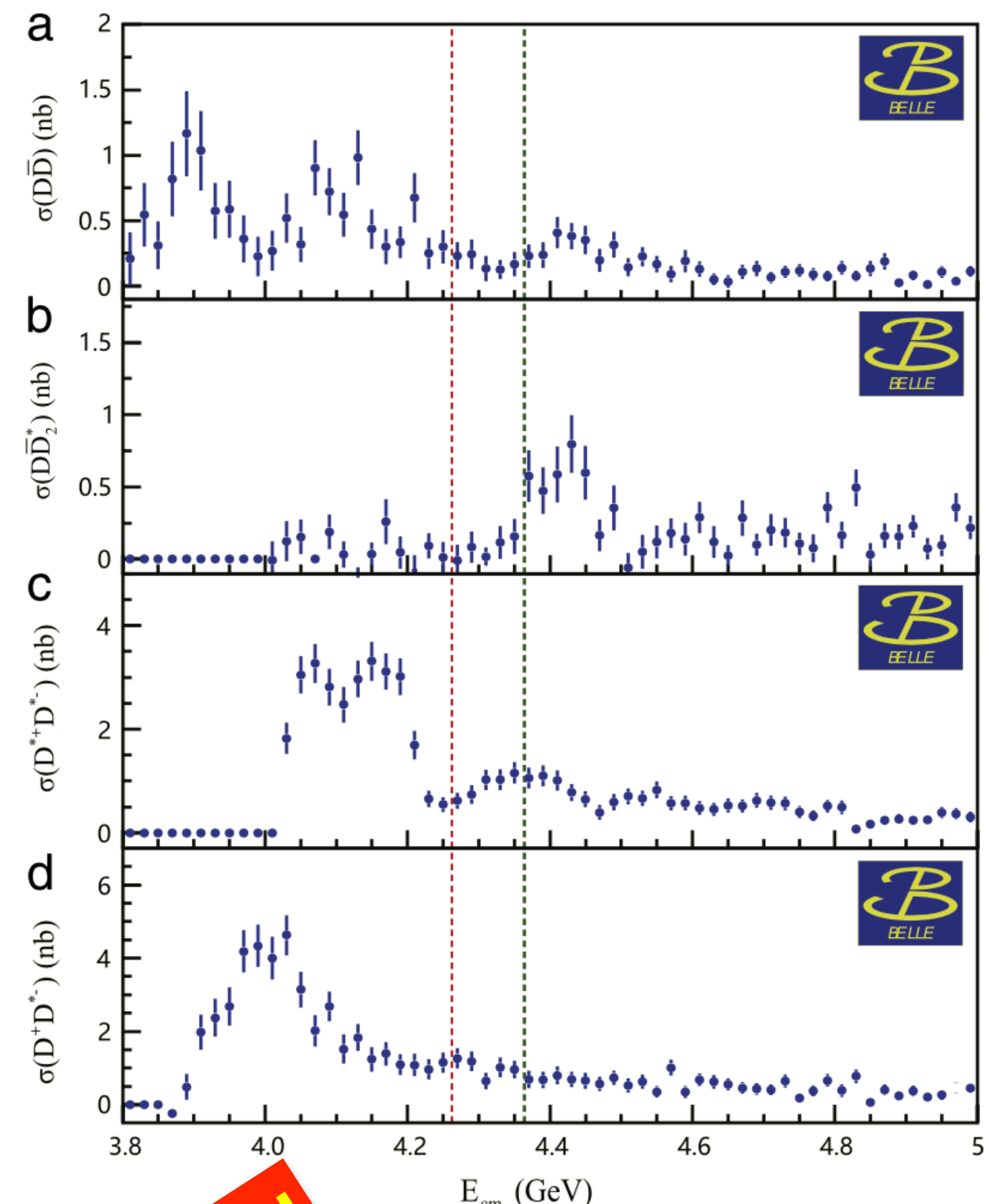
BESIII White paper

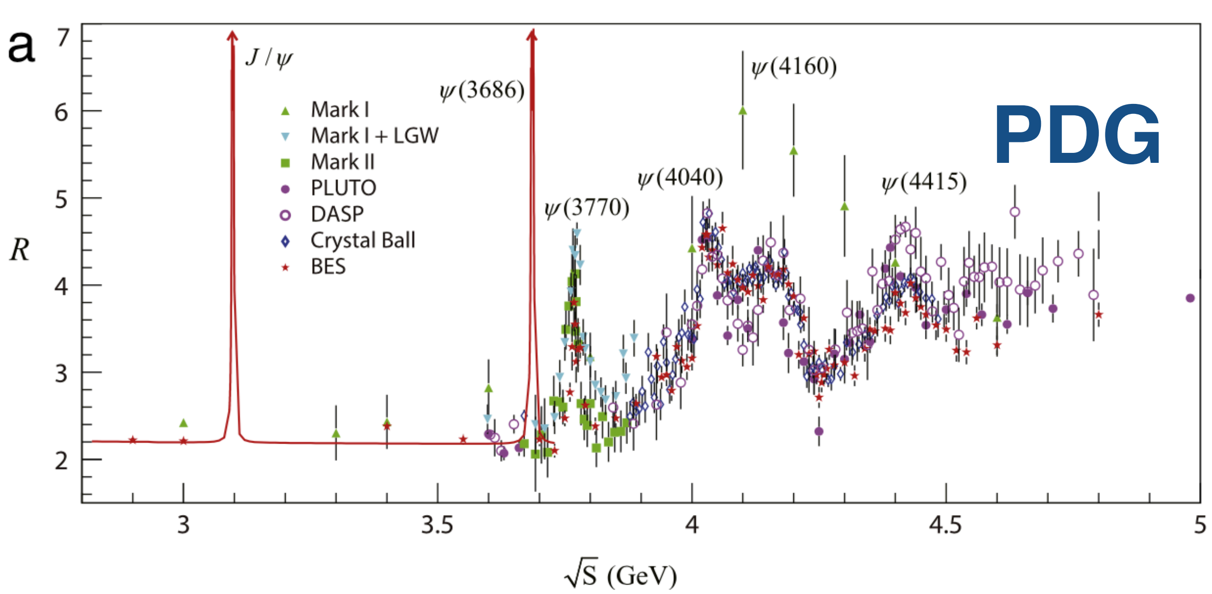
"The Y problem"

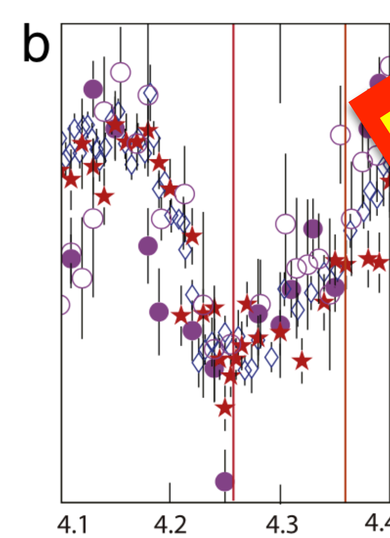
Y(4260)

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)

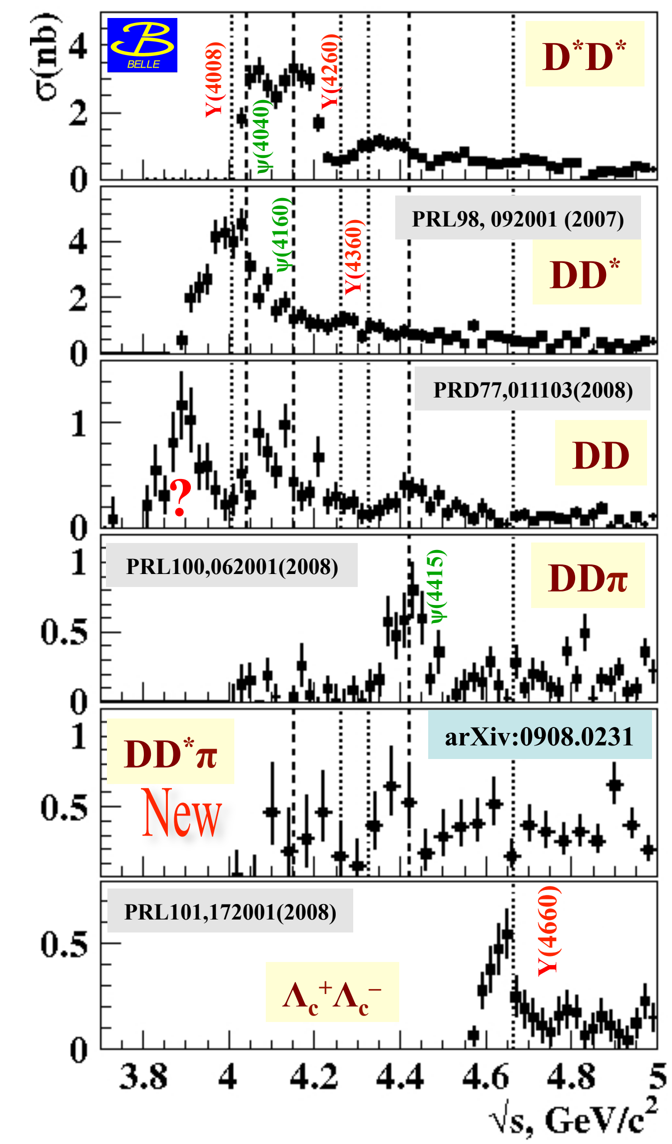
Li&Chao

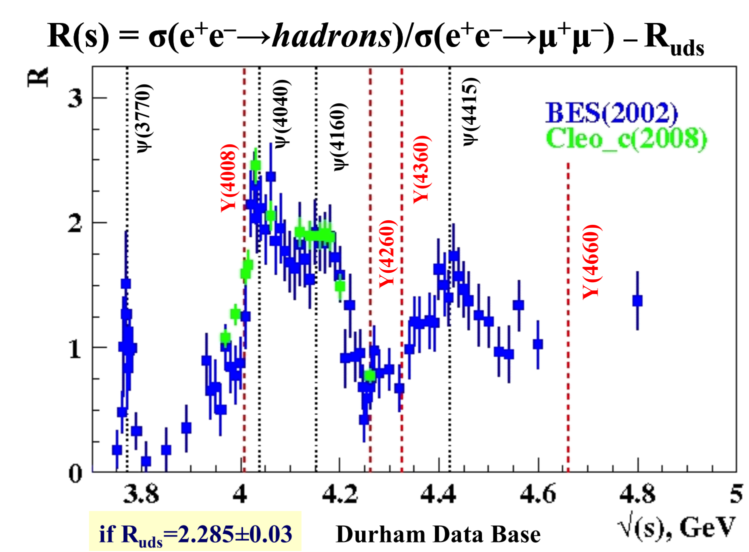
Difficulty

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

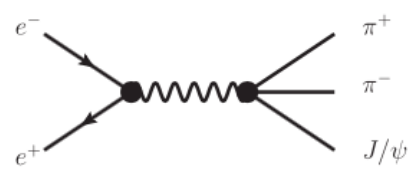




Non-resonant picture of Y(4260)

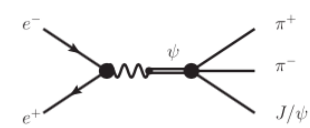
- **Asymmetric** **Y(4260) structure can be reproduced by** **Fano-like interference picture**

Continuum



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

Charmonium

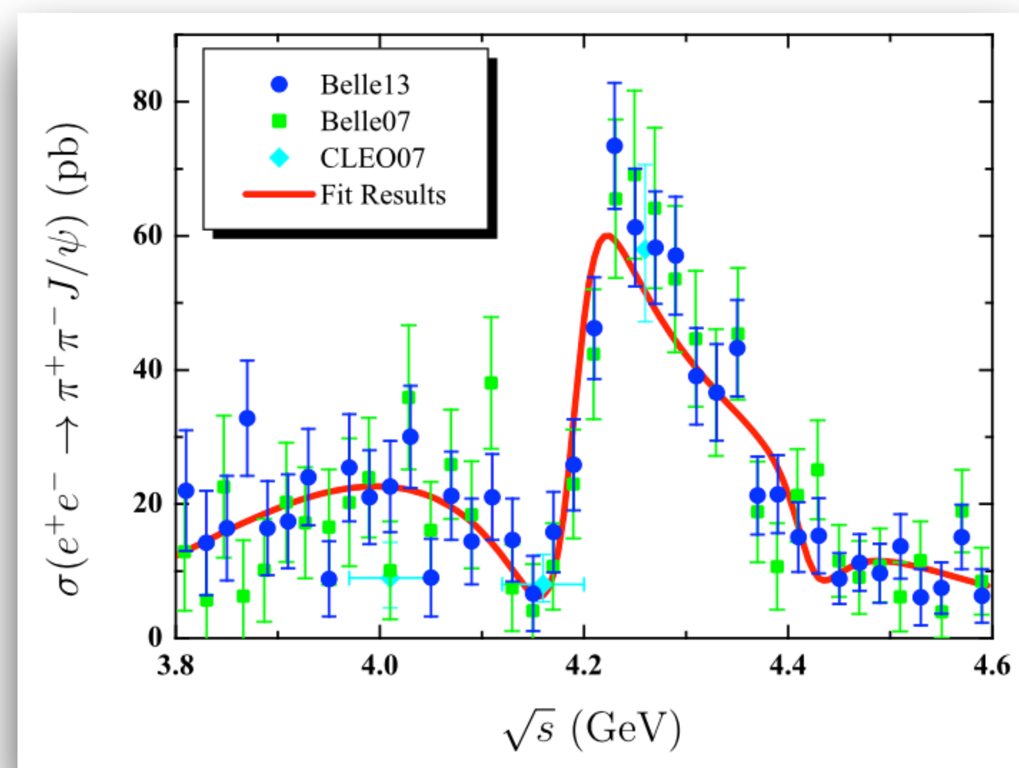


$\widehat{=} \frac{\sqrt{12\pi\Gamma_\psi^{e^+e^-}\times\mathcal{B}(\psi\to\pi^+\pi^- J/\psi)\Gamma_\psi}}{s-m_\psi^2+im_\psi\Gamma_\psi}\sqrt{\frac{\Phi_{2\to3}(s)}{\Phi_{2\to3}(m_\psi^2)}}$

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

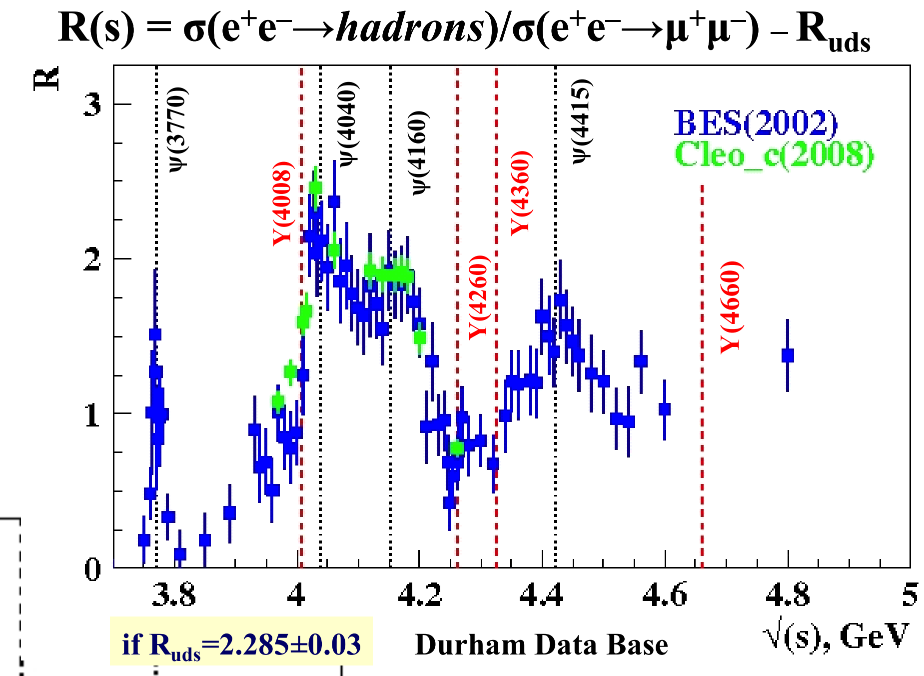


Success:

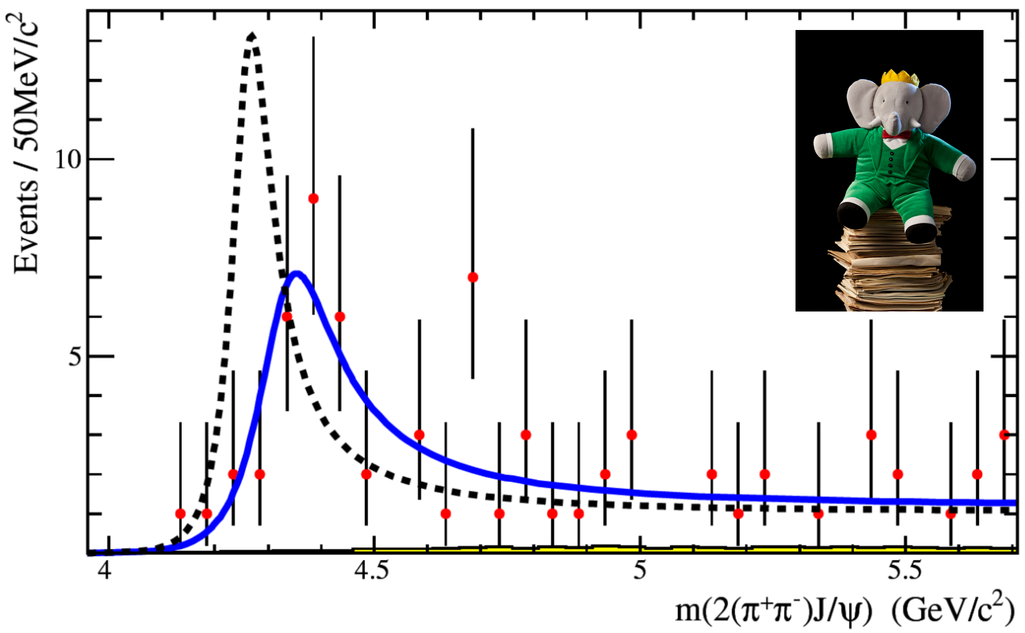
- **Explain** **why $\psi(4160)$ and $\psi(4415)$ signals are missing in data**
- **Naturally** **understand** **why no evidence of $Y(4260)$ in R scan data and the open-charm decay channels**

Y(4360)

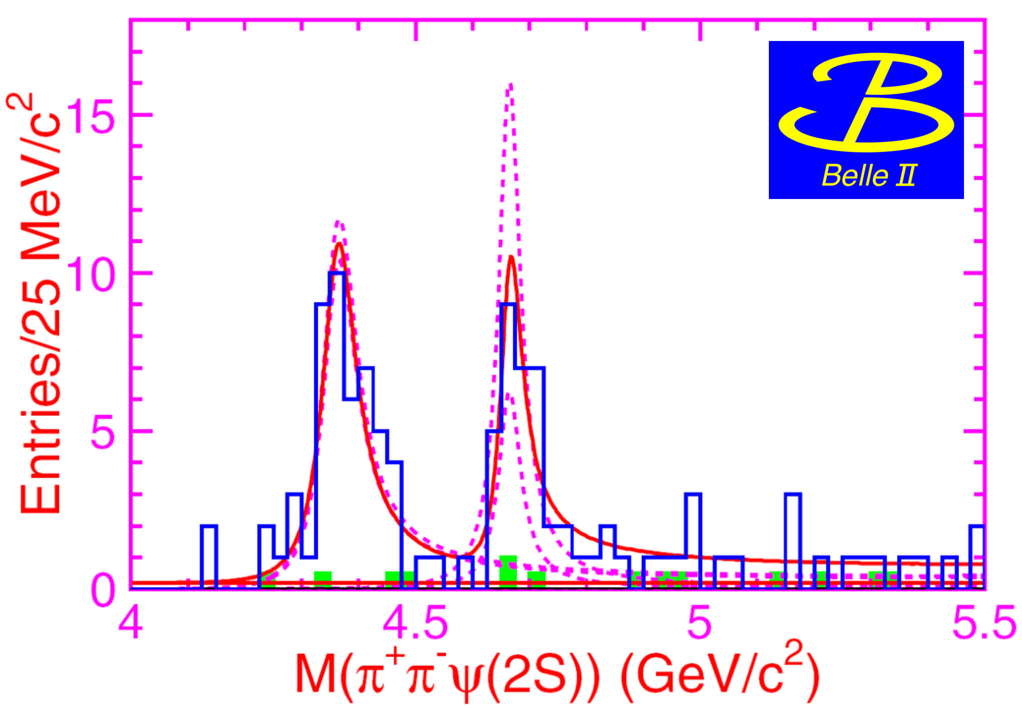
No evidence of *Y*(4260)/Y(4360) in the obtained open-charm process and *R*-value scan

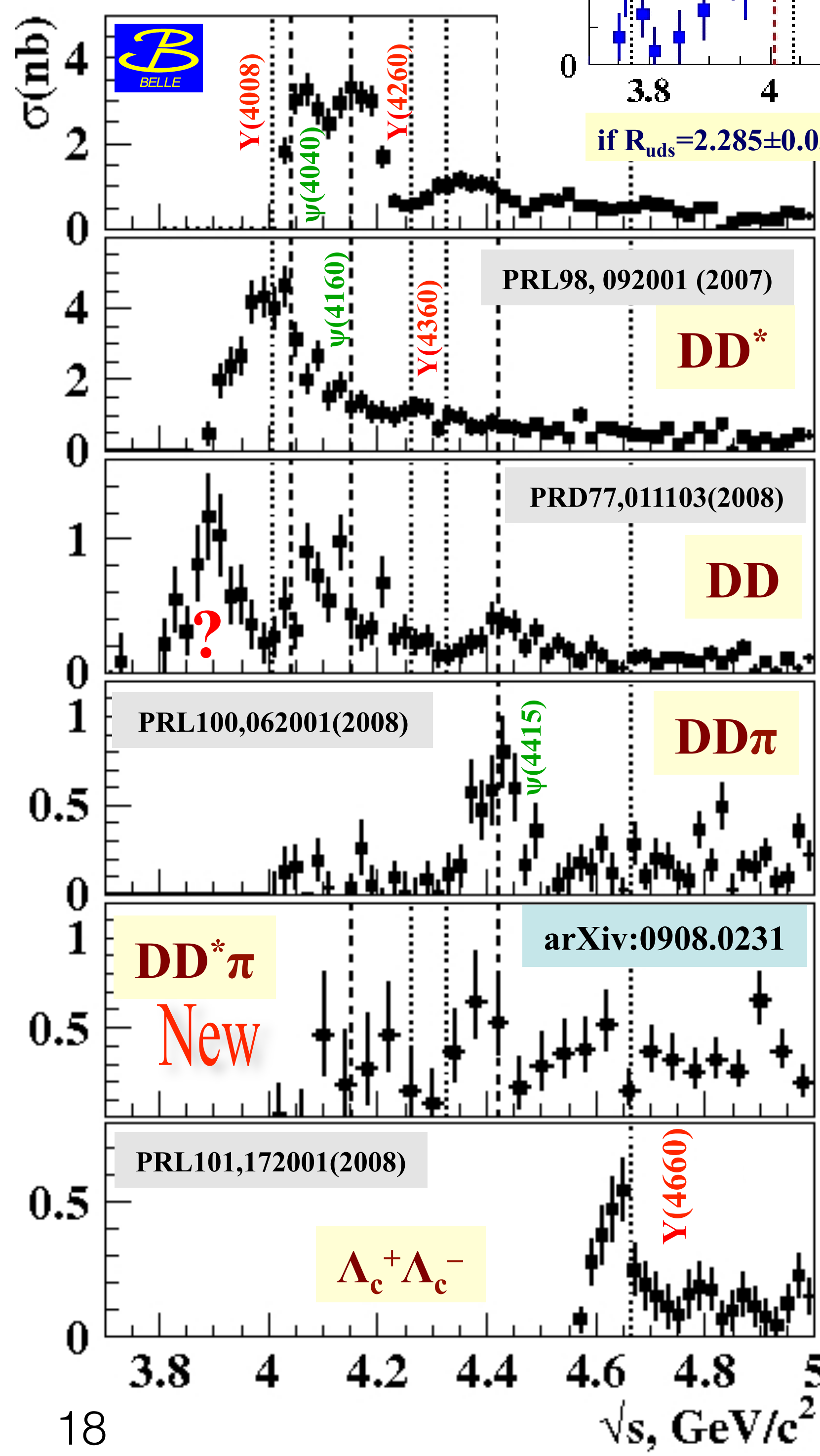


PRL 98:212001 (2007)



PRL 99:142002 (2007)

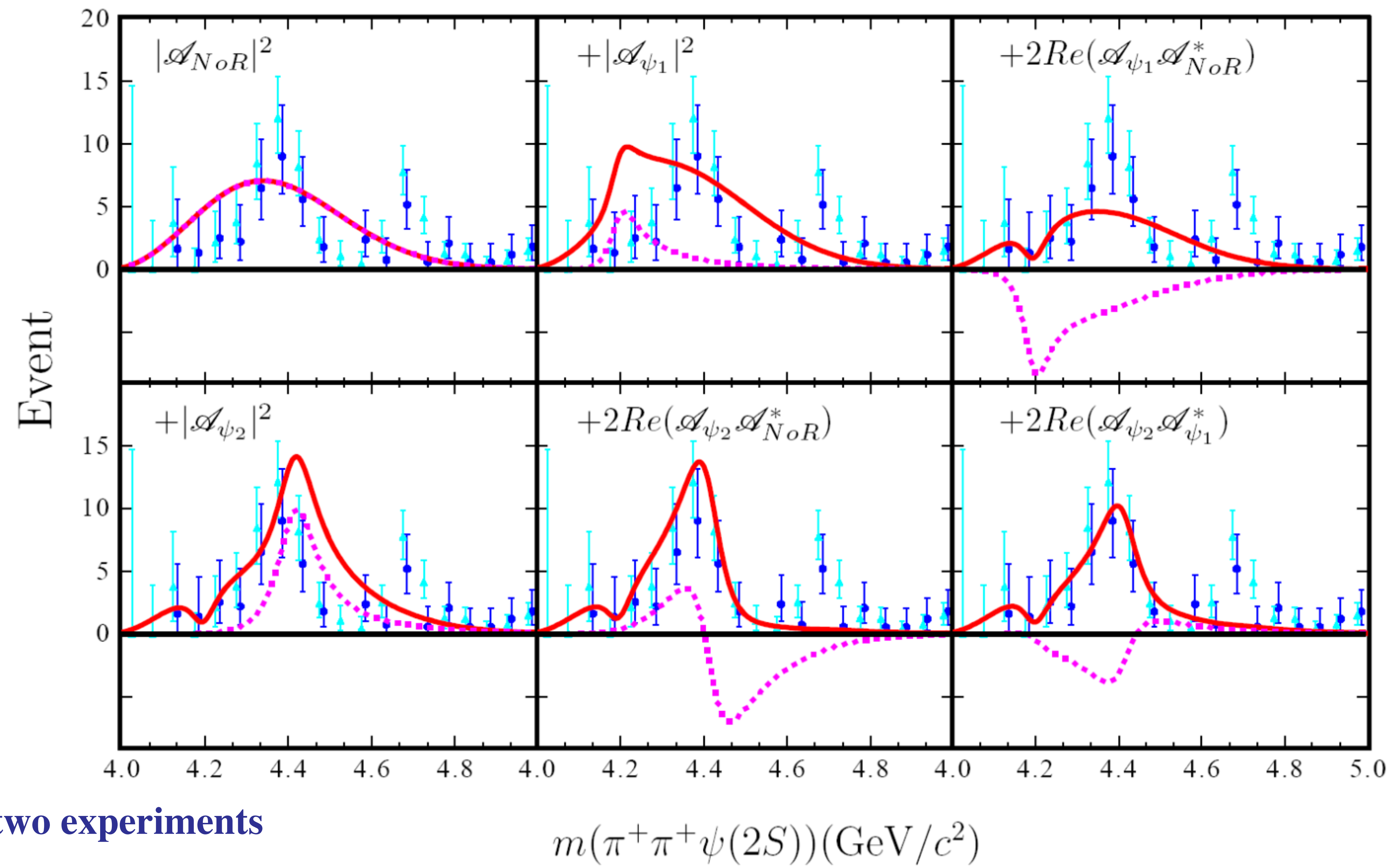




The situation of Y(4360) is similar to that of Y(4260)

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

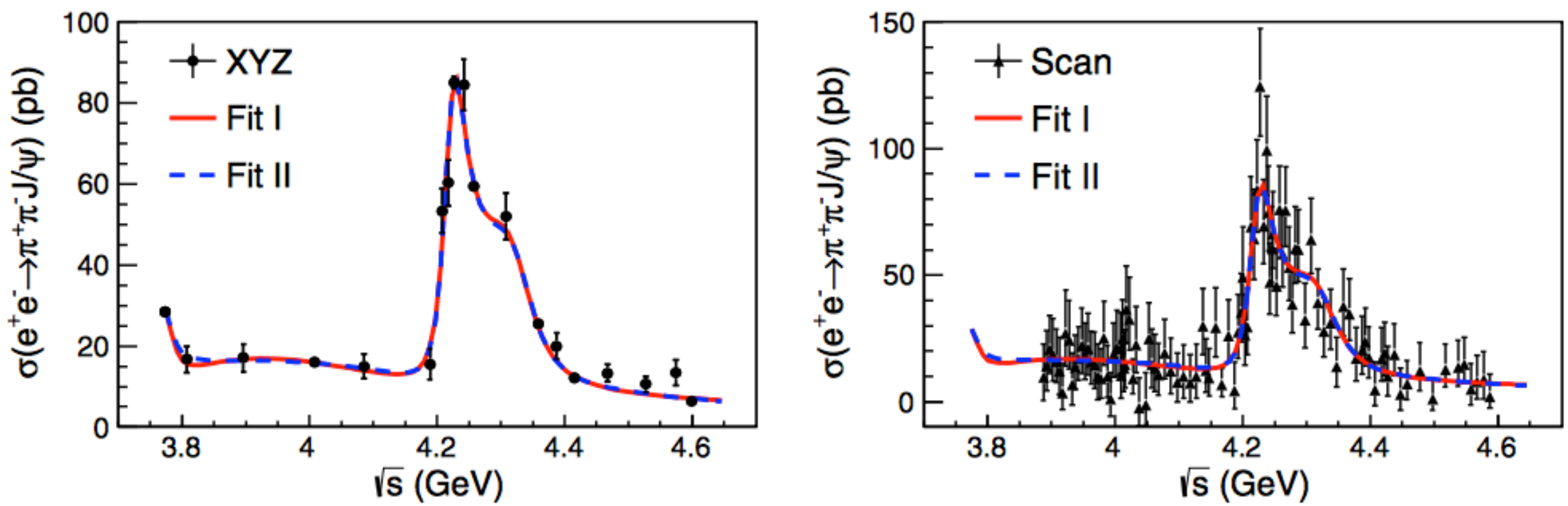


FIG. 1. Measured cross section $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ and simultaneous fit to the *XYZ* data (left) and scan data (right) with the coherent sum of three Breit-Wigner functions (red solid curves) and the coherent sum of an exponential continuum and two Breit-Wigner functions (blue dashed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

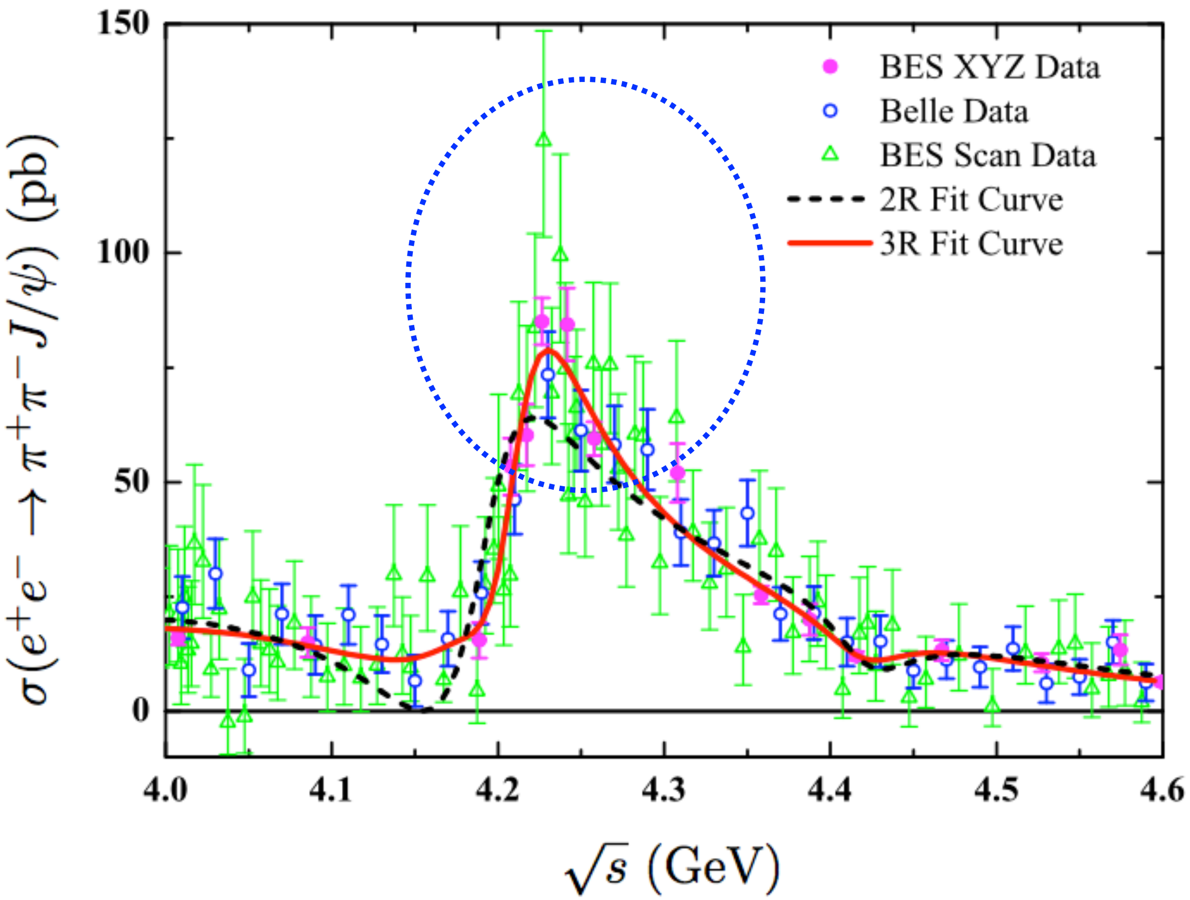


FIG. 2: (color online). Our fit to the cross sections for the $e^+e^- \to \pi^+\pi^- J/\psi$ process measured by the Belle [8] and BESIII collaborations [11] under the 2R and 3R fit schemes. Here, the BES scan data [11] are also listed for comparison.

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)?

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

Y(4220)+Y(4390)

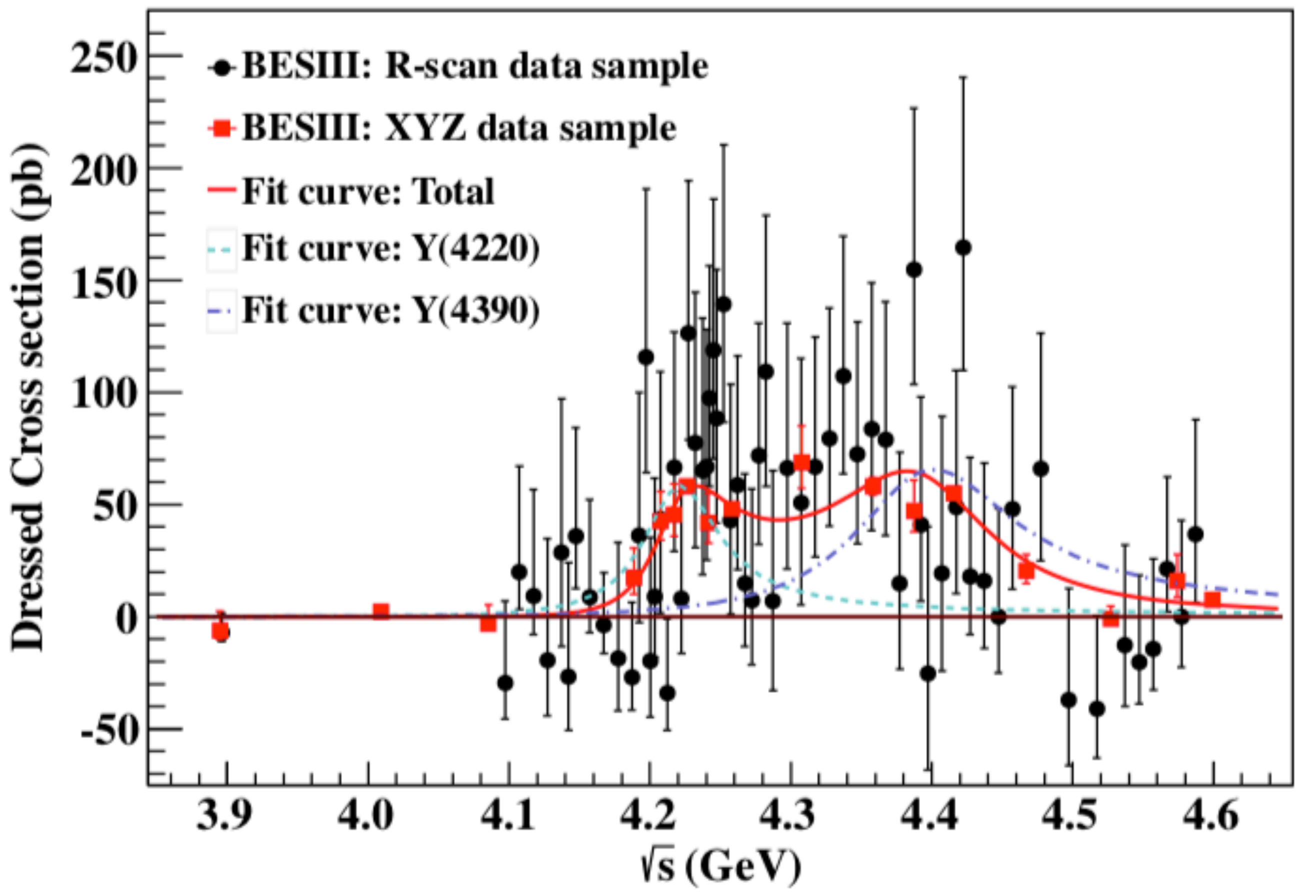


FIG. 2. Fit to the dressed cross section of $e^+e^- \to \pi^+\pi^- h_c$ with the coherent sum of two Breit-Wigner functions (solid curve). The dash (dash-dot) curve shows the contribution from the two structures $Y(4220)$ [$Y(4390)$]. The dots with error bars are the cross sections for the R-scan data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

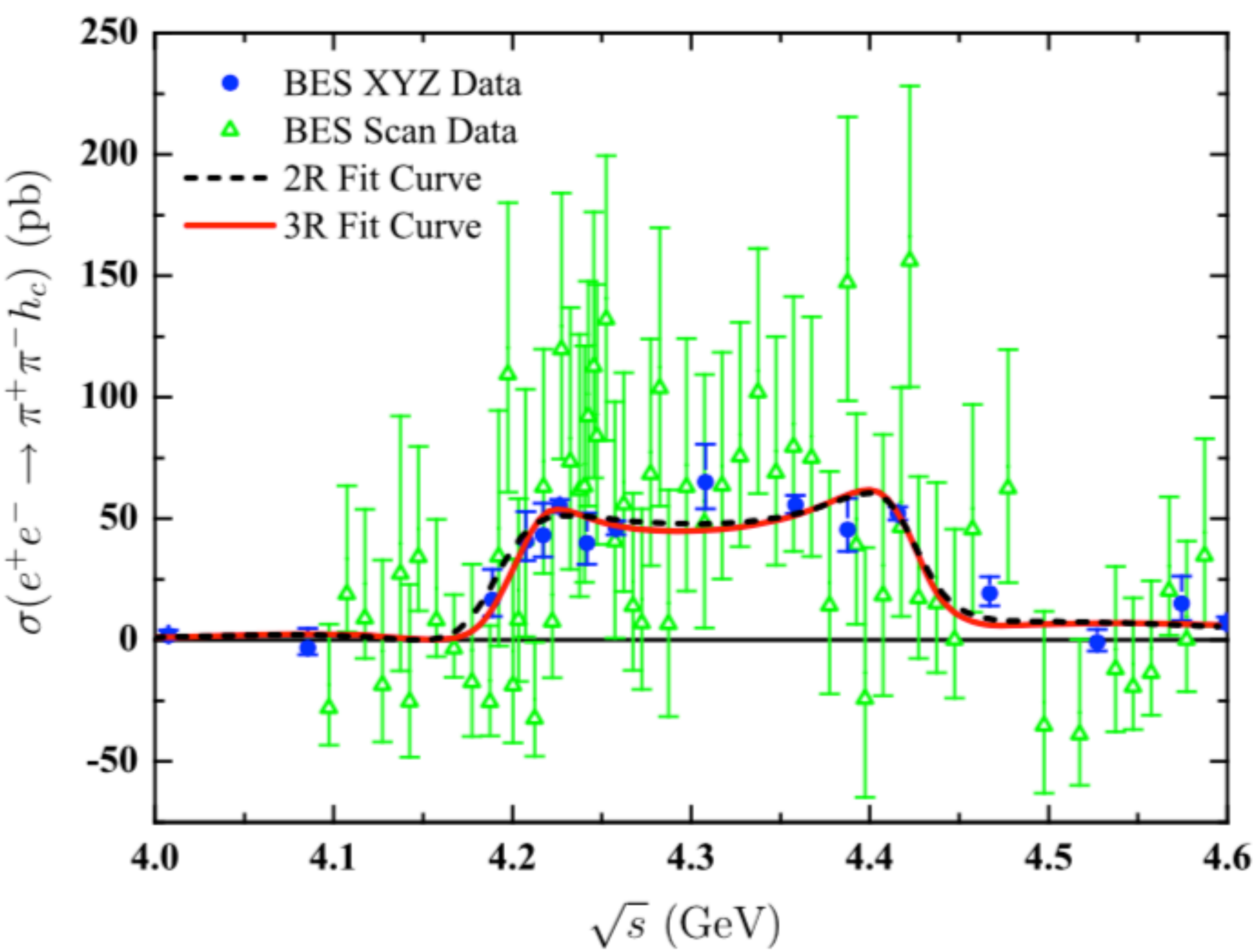
THE EUROPEAN PHYSICAL JOURNAL C

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	BaBar PRD86:051102
Y(4008)	Y(4008)
$e^+e^- \to J/\psi\pi^+\pi^-$	Y(4220)
Y(4260)	Y(4320)
	Inference effect
Y(4360)	Y(4390)
$e^+e^- \to \psi(2S)\pi^+\pi^-$	
Y(4660)	Y(4660)
Y(4630)	Y(4630)
$e^+e^- \to \Lambda_c^+\Lambda_c^-$	

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

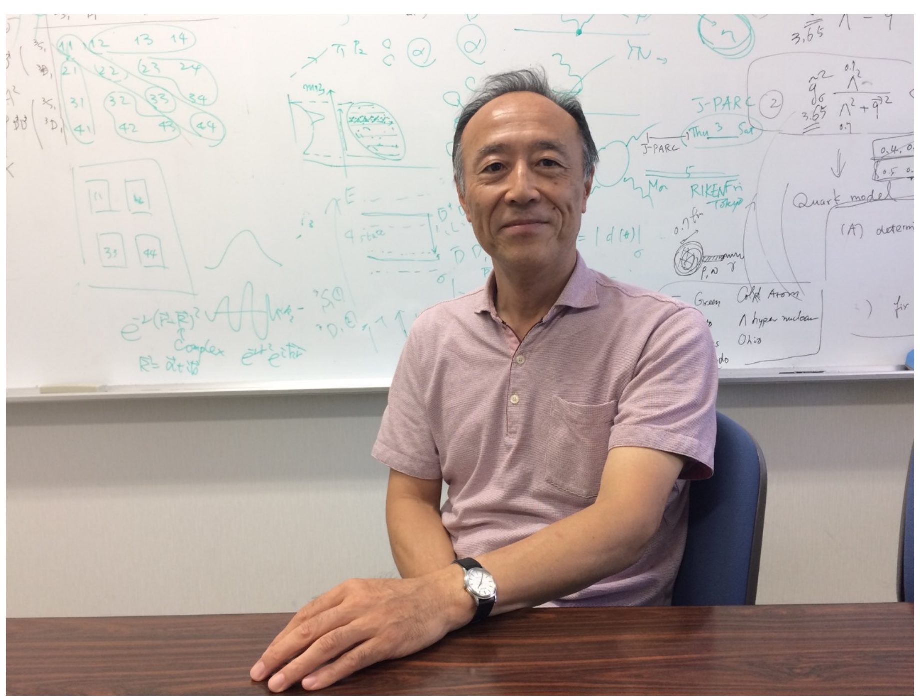
Y(4390)

Y(4660)

Y(4630)

Resonance killer

2014年，我在访问日本大阪大学期间，Atsushi Hosaka教授给我取的绰号



Past

Y(4008)

↑

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

↓

Y(4260)

Y(4360)

↑

$e^+e^- \to \psi(3686)\pi^+\pi^-$

↓

Y(4660)
Y(4630)

↑

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

Now

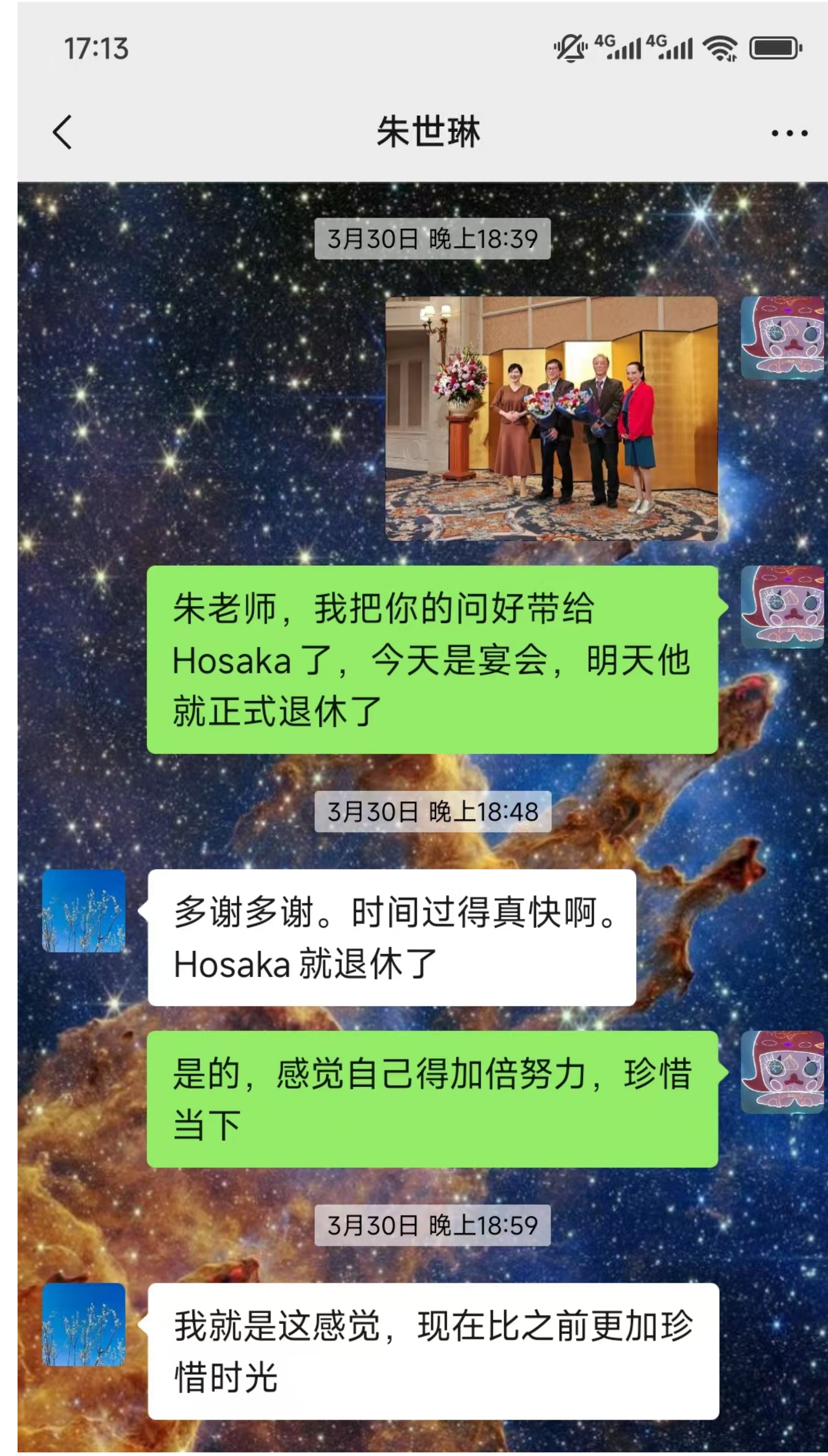
Y(4008)
BaBar PRD86:051102

Y(4220)

Y(4320)
Inference effect
Y(4390)

Y(4660)
Y(4630)


The 21st International Conference on Hadron Spectroscopy and Structure
HADRON2025
Toyonaka Campus, Osaka University, Japan, March 27 - 31, 2025


17:13
朱世琳
3月30日 晚上18:39
朱老师，我把你的问好带给Hosaka了，今天是宴会，明天他就正式退休了
3月30日 晚上18:48
多谢多谢。时间过得真快啊。Hosaka 就退休了
是的，感觉自己得加倍努力，珍惜当下
3月30日 晚上18:59
我就是这感觉，现在比之前更加珍惜时光

“奥卡姆的剃刀”

（Occam’s razor或Ockham’srazor）

- 在科学界是一个广为人知、但也许并未得到广泛认可的原理。这一原理是由十四世纪的逻辑学家、奥卡姆的威廉（Williamof Occam）首先提出的。

奥卡姆的威廉（William of Occam，约1285年—1349年），英国经院哲学家。圣方济各会修士。邓斯·司各脱的学生和后来的论敌。以复兴唯名论著称。认为思想并非对现实的衡量，将哲学与神学截然分开，曾被教皇约翰22世召去以异端邪说问罪。

- 奥卡姆位于英格兰的萨里郡，是威廉的出生地。

- “奥卡姆的剃刀”原理通常表述为：“**如无必要，勿增实体**”（Entities must not be multiplied beyond necessity），其中“剃刀”的含义在于**剪除一个理论模型中那些不必要的假设或参量**，或者从**两个处于竞争地位、结论相同的理论模型中选择那个形式或结构更简单的模型**。

- 因此**“奥卡姆的剃刀”**与科学思辨中的**简单性原则**有某种异曲同工之妙。

就科学研究而言，“奥卡姆的剃刀”经常具有启发性或指导性意义

一个简单的例子是太阳系中星体的运动。原则上人们既可以从“地心说”出发也可以从“日心说”出发来计算太阳、月亮和地球的相对运动状态，但哥白尼注意到“地心说”比“日心说”需要更多的假设才能得到相同的结果，因此他宁愿选择后者。

这个选择的过程，恰好就是“剃刀”发挥作用、去繁就简的过程，引导人们最终以“日心说”为基础建立了完整的太阳系模型。正如威廉本人在其著作《**箴言书注**》中所强调的那样，**切勿浪费较多的东西去做用较少的东西同样可以做好的事情**。换句话说，**无必要的东西均可被剪除**。

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?

1995

PHYSICAL REVIEW D VOLUME 51, NUMBER 9

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)

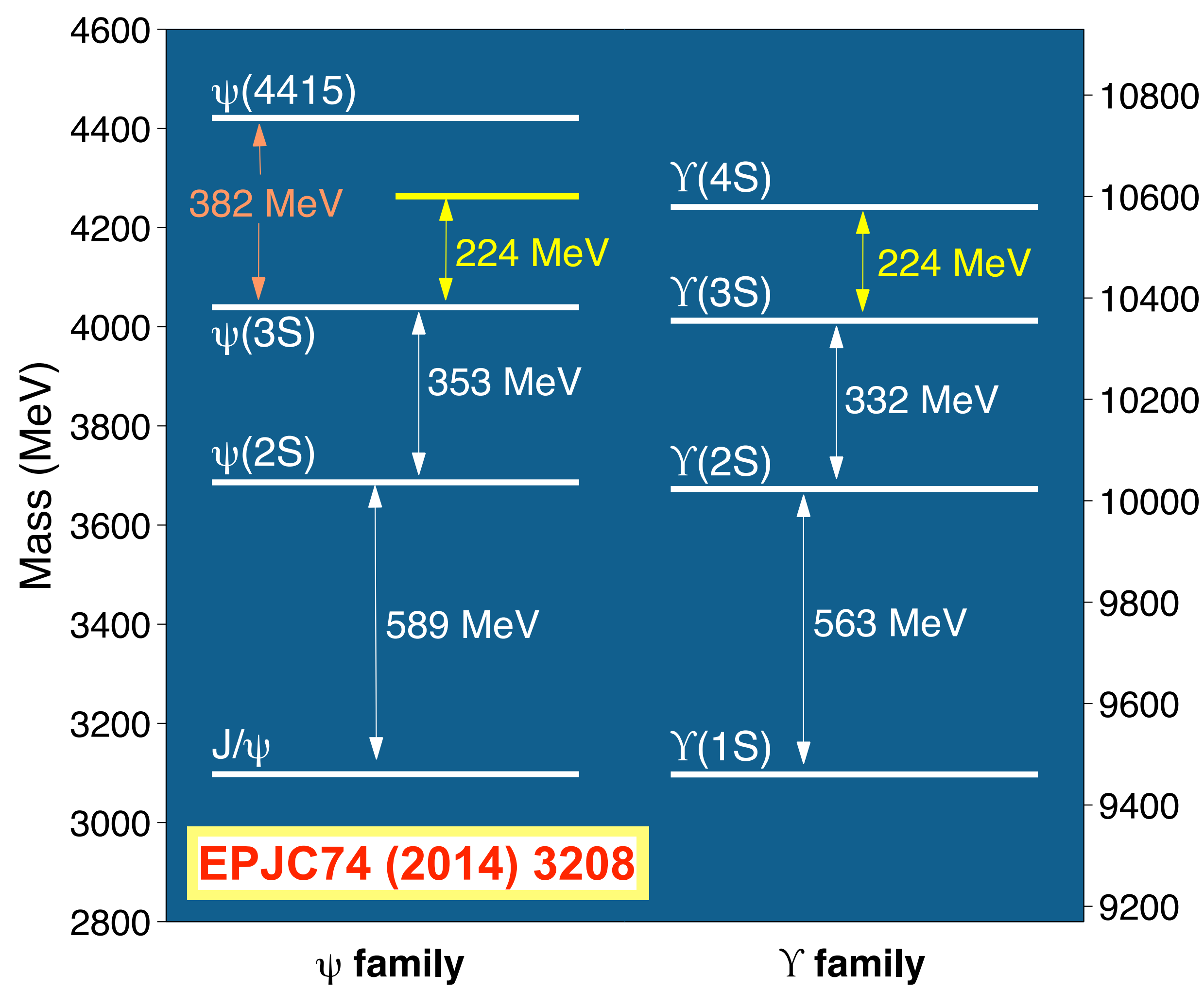
TABLE I. Calculated masses and leptonic widths for charmonium states with the screened potential (5) and parameters (8), where $\Gamma_{ee} = \Gamma^0_{ee}[1 - \frac{16}{3\pi}\alpha_s(m_c)]$ with $\alpha_s(m_c) = 0.28$ [16].

States	Mass (MeV)	Γ^0_{ee} (keV)	Γ_{ee} (keV)	Γ^{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				$\chi(3526)_{c.o.g.}$
$1D$	3805				$\psi(3770)$
$2D$	4105				

The predicted $\psi(4S)$ and its property

2014

The similarity between J/ψ and Υ families



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

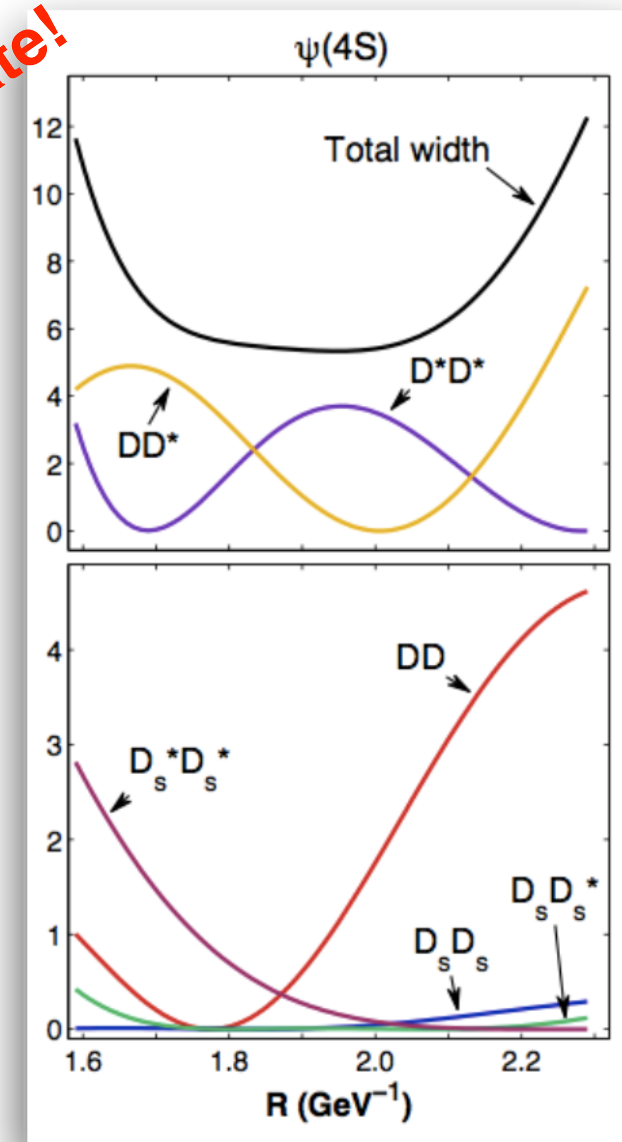
Consistent

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!

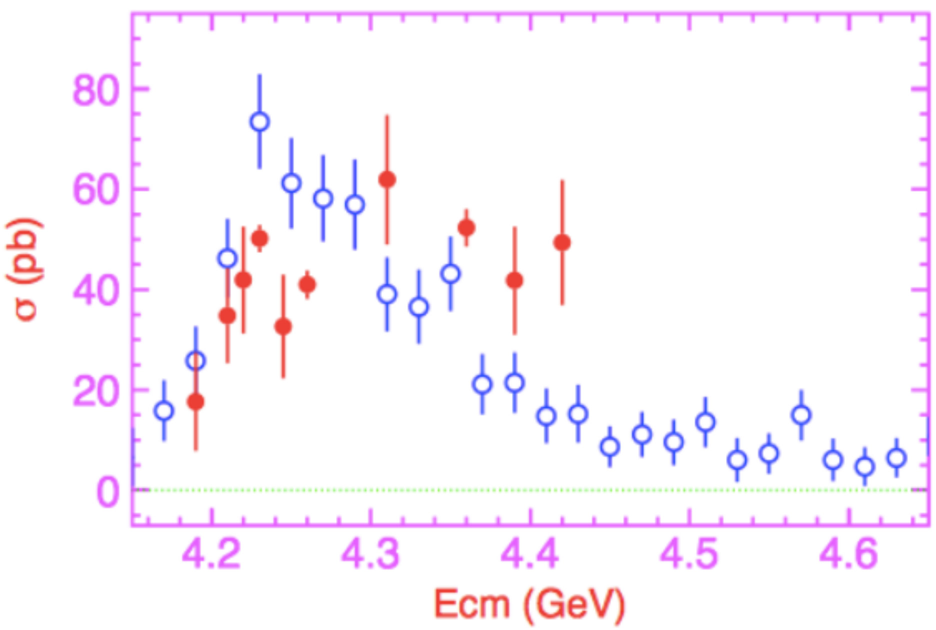
The predicted charmonium ψ(4*S*) has very narrow width around 6 MeV

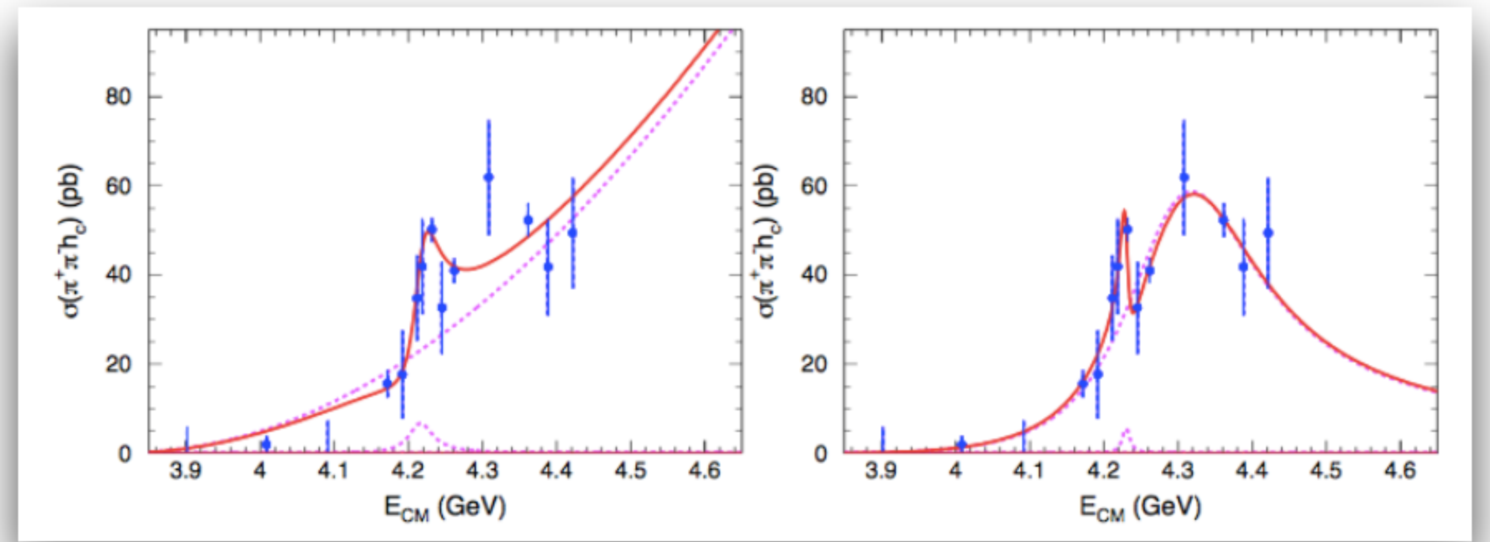
Y(4220)= ψ(4S)?

Experimental data

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"

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

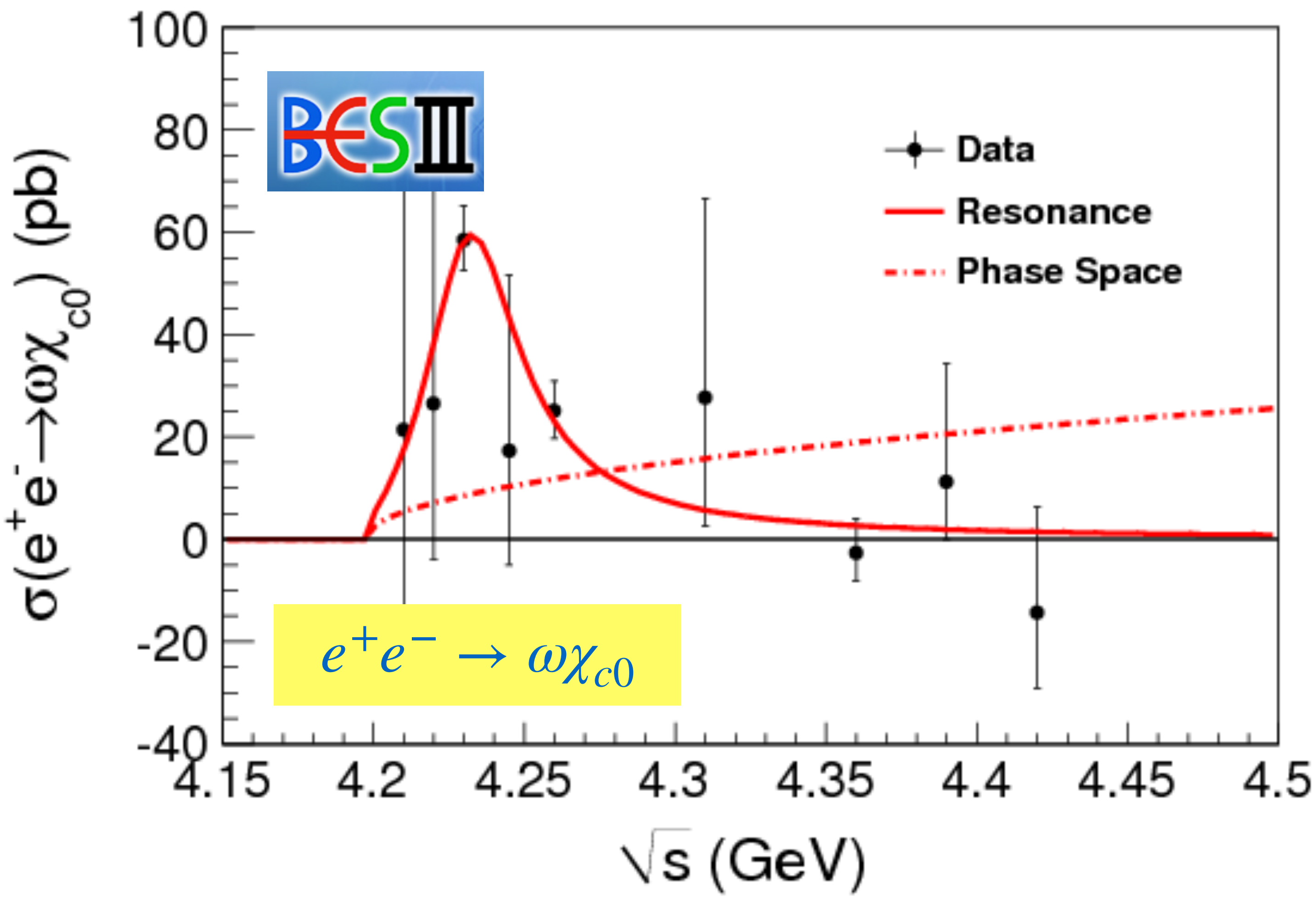
Is it the prediced higher charmonium with the mass around 4.26 GeV?

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)



$M = 4230 \pm 8$ MeV $\Gamma = 38 \pm 12$ MeV

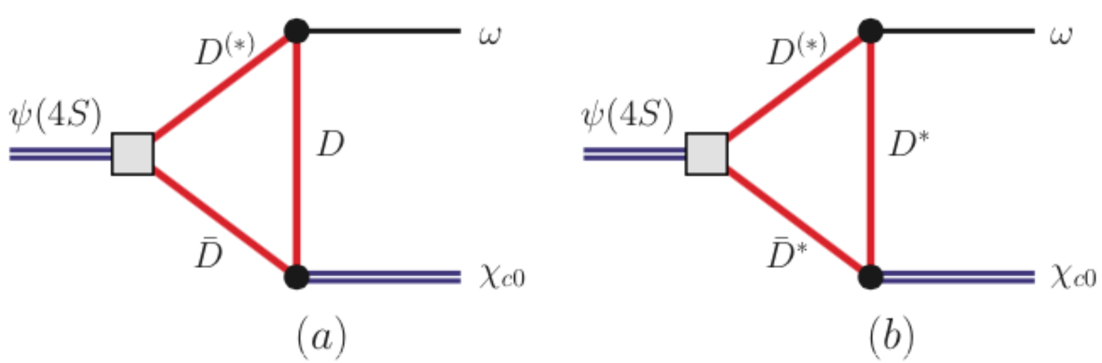
$e^+e^- \to \chi_{c1}\omega$ **and** $e^+e^- \to \chi_{c2}\omega$ **are not significant**

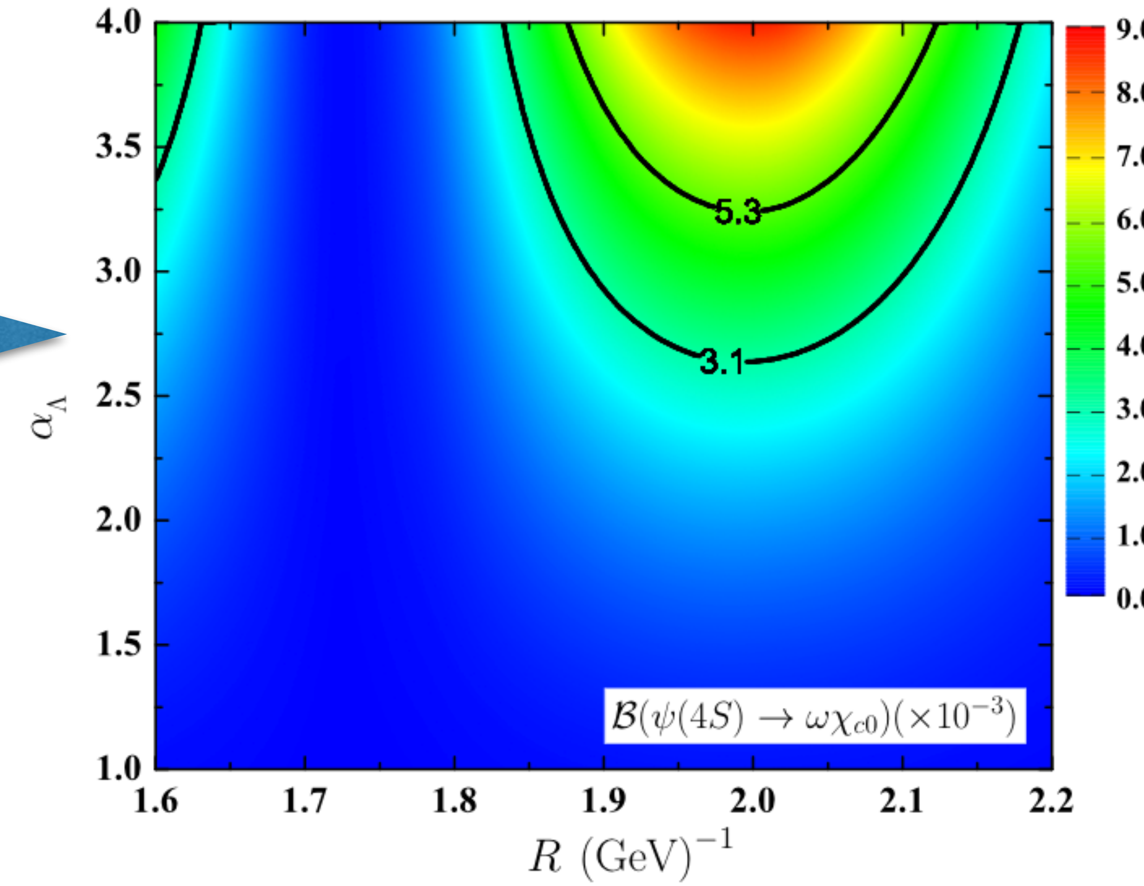
If taking the mass of ψ(4S) to be 4230 MeV (Expt.), we find:

- $\psi(4S) \to \chi_{c0}\omega$ **is allowed**
- $\psi(4S) \to \chi_{c1,2}\omega$ **modes 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)

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

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

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

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

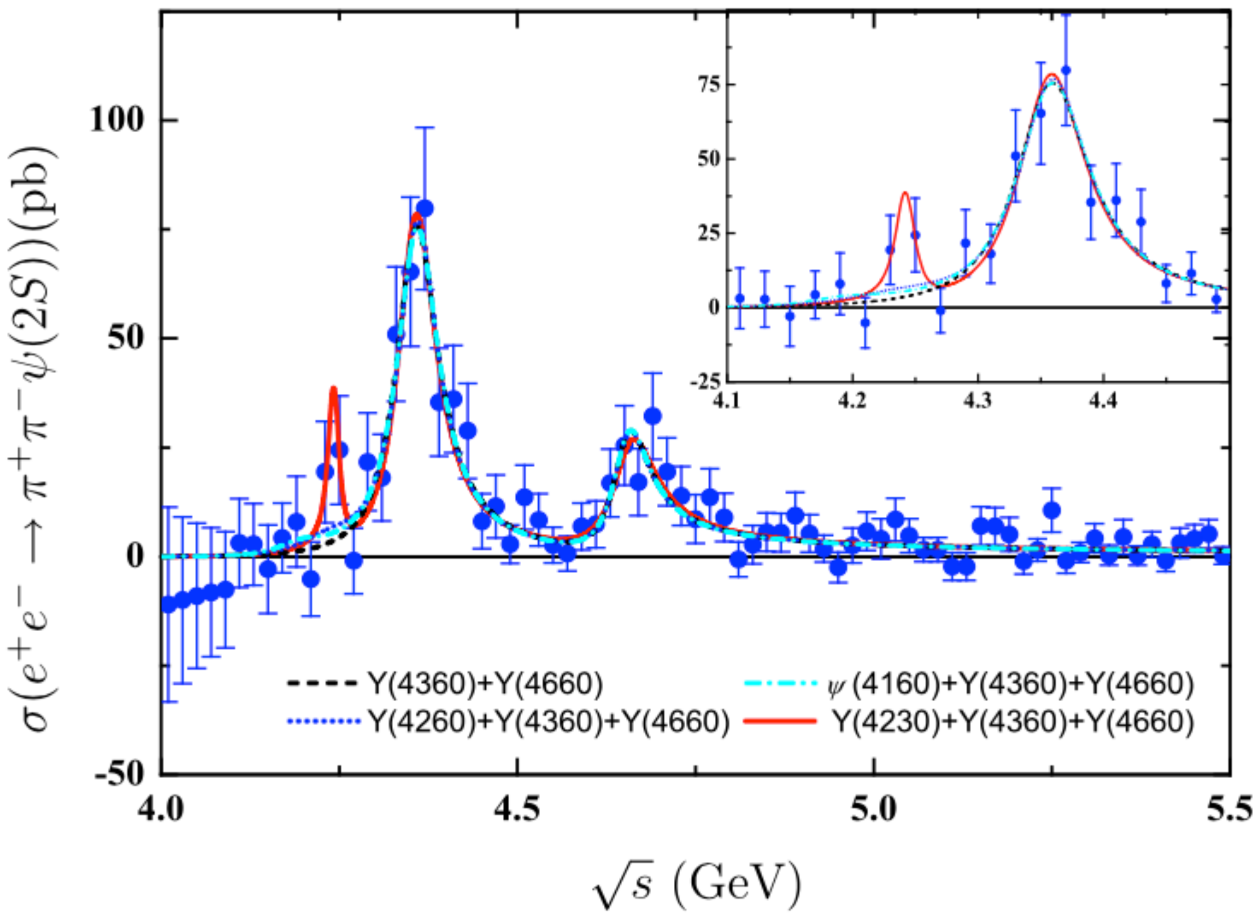


FIG. 2. A comparison of the fits to the cross sections for $e^+e^- \to \pi^+\pi^-\psi(2S)$ with different schemes.

Resonance parameter:

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

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

By introducing $\psi(4S)$, 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 $e^+e^- \to \psi(2S)\pi^+\pi^-$

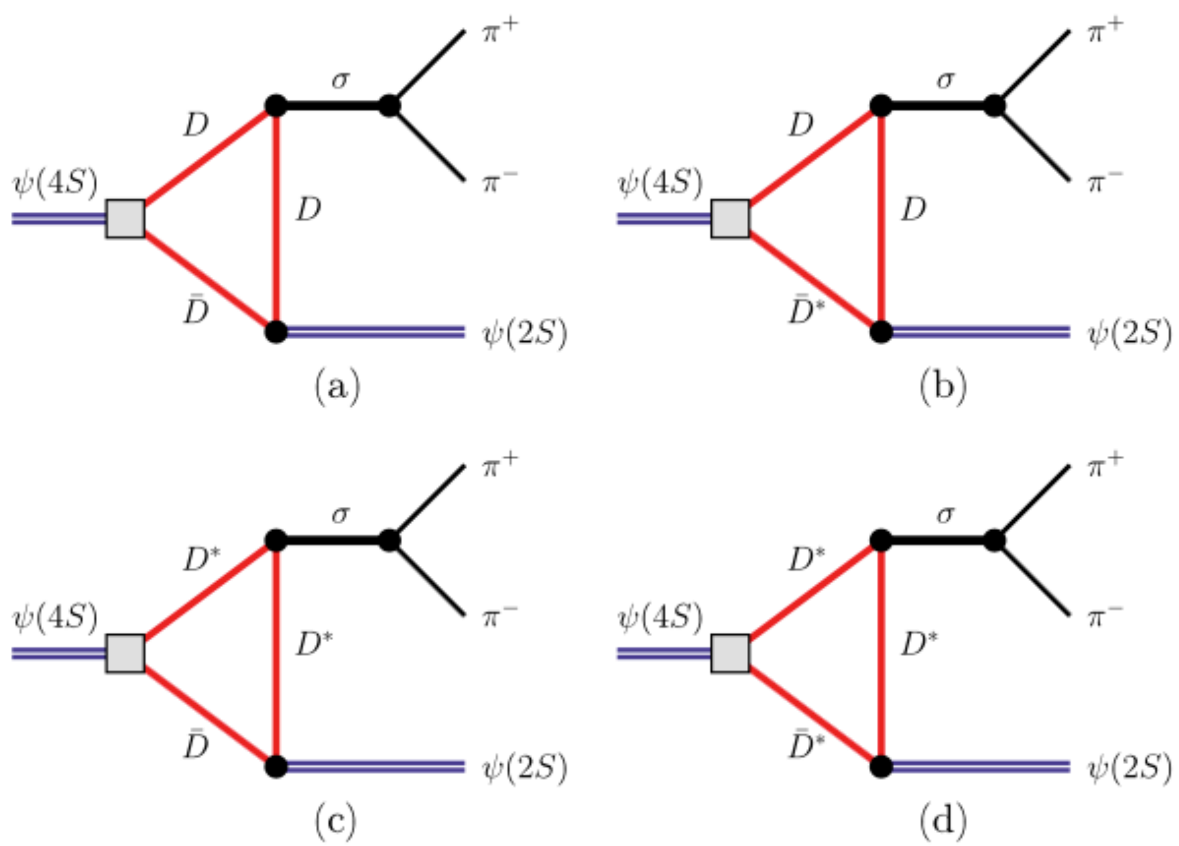


FIG. 3. Typical meson-loop contributions to $\psi(4S) \to \psi(2S)\pi^+\pi^-$, where the dipion comes from a σ meson.

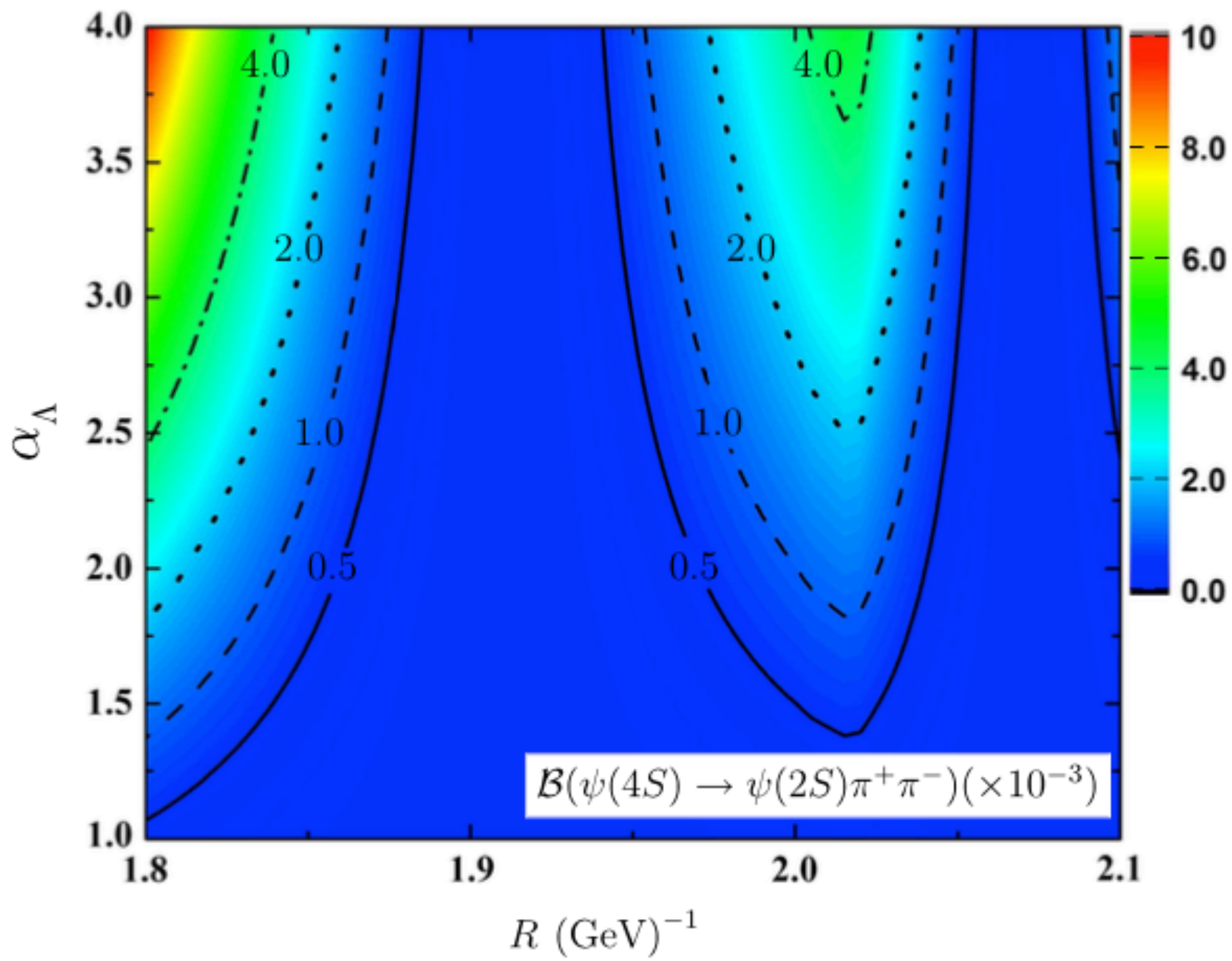


FIG. 4. The R and α_Λ dependence of the branching ratio for $\psi(4S) \to \psi(2S)\pi^+\pi^-$.

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

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

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

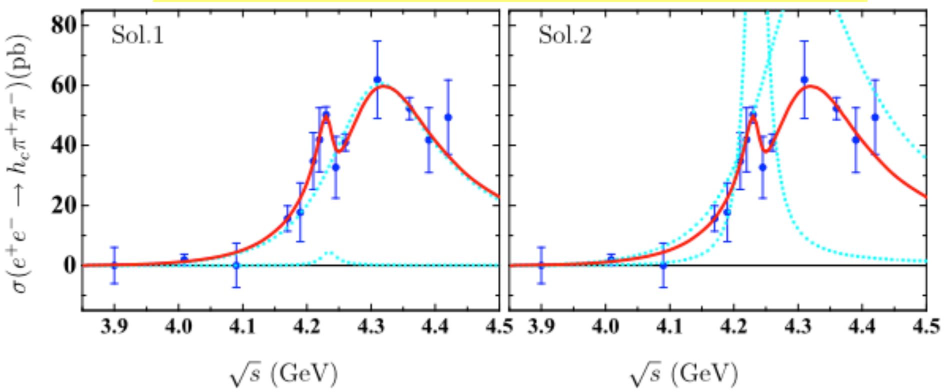


FIG. 6. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to h_c\pi^+\pi^-$ in scheme I. The cyan dashed and red solid curves are the resonance contributions and the fitting results, respectively.

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				$52.2/81$			

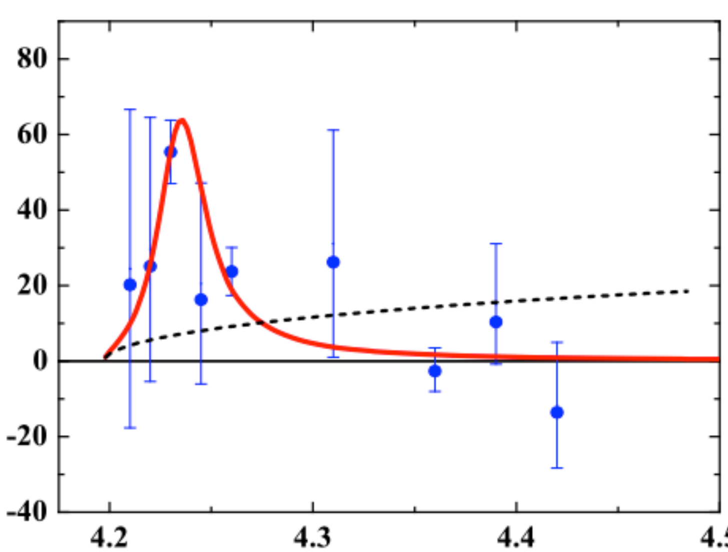


FIG. 7. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to \chi_{c0}\omega$ (solid curve) in scheme I. The dashed curve is the phase space of $e^+e^- \to \chi_{c0}\omega$.

Resonance parameter:

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

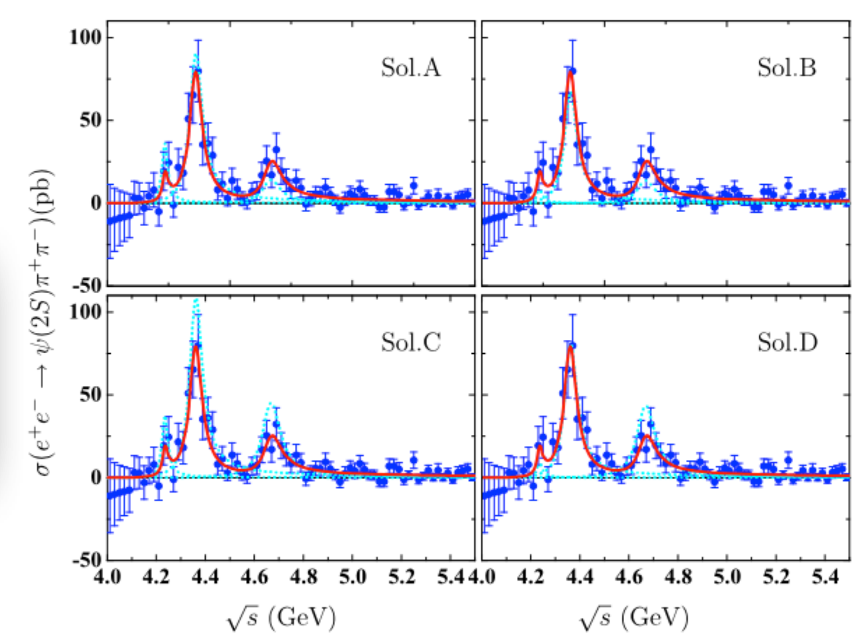
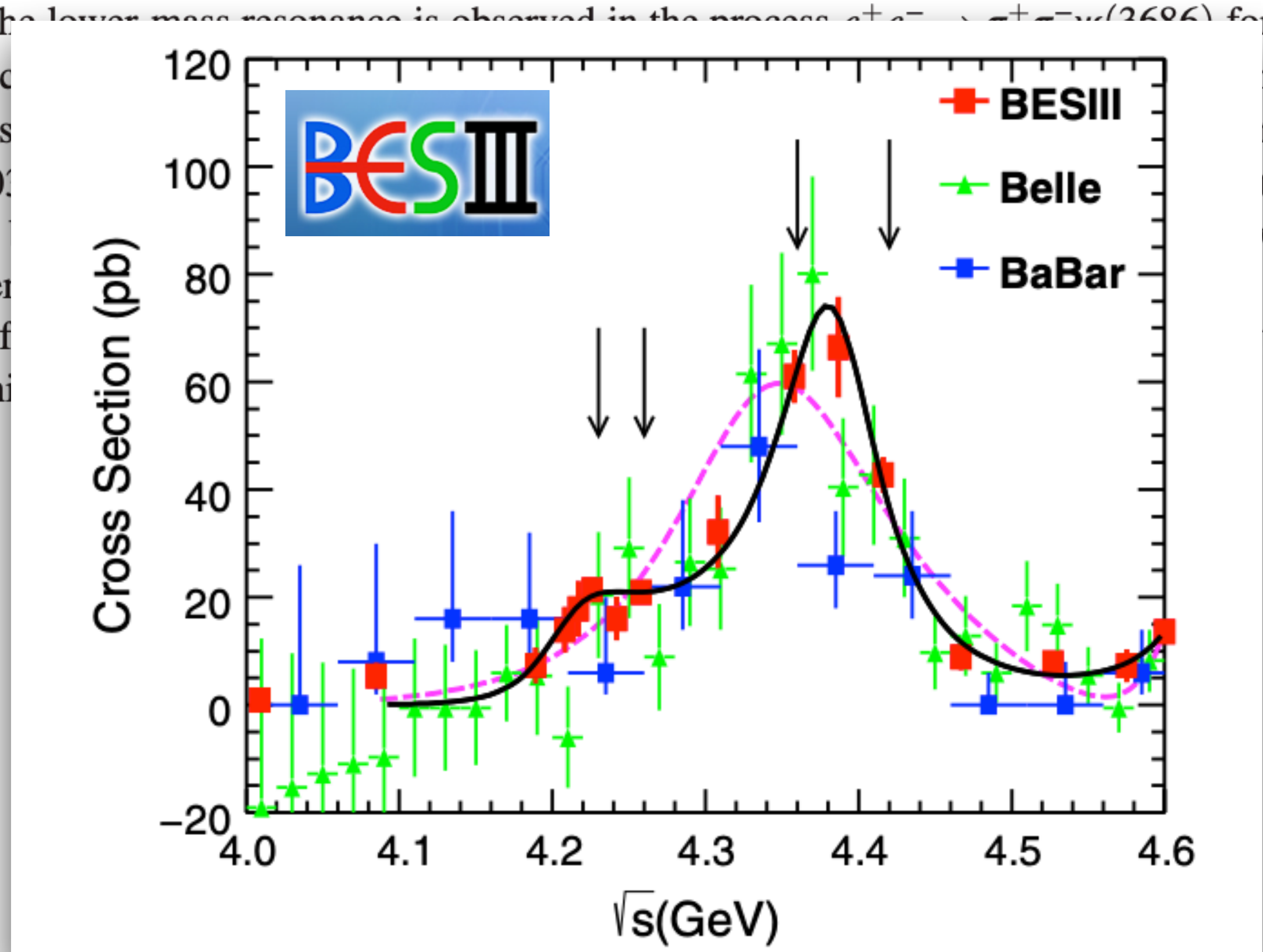


FIG. 5. The different solutions of the resonance contributions and our fitting results for the cross section for $e^+e^- \to \psi(2S)\pi^+\pi^-$ in scheme I. The cyan dashed and red solid curves are the resonance contributions and the fitting results, respectively.

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 $M = 4209.5 \pm 7.4 \pm 1.4$ MeV/c^2 and $\Gamma = 80.1 \pm 24.6 \pm 2.9$ MeV, and the second has $M = 4383.8 \pm 4.2 \pm 0.8$ MeV/c^2 and $\Gamma = 84.2 \pm 12.5 \pm 2.1$ MeV, where the first errors are statistical and the second systematic. Th
for the first time
with a statistic
$\pi^\pm\psi(3686)$
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

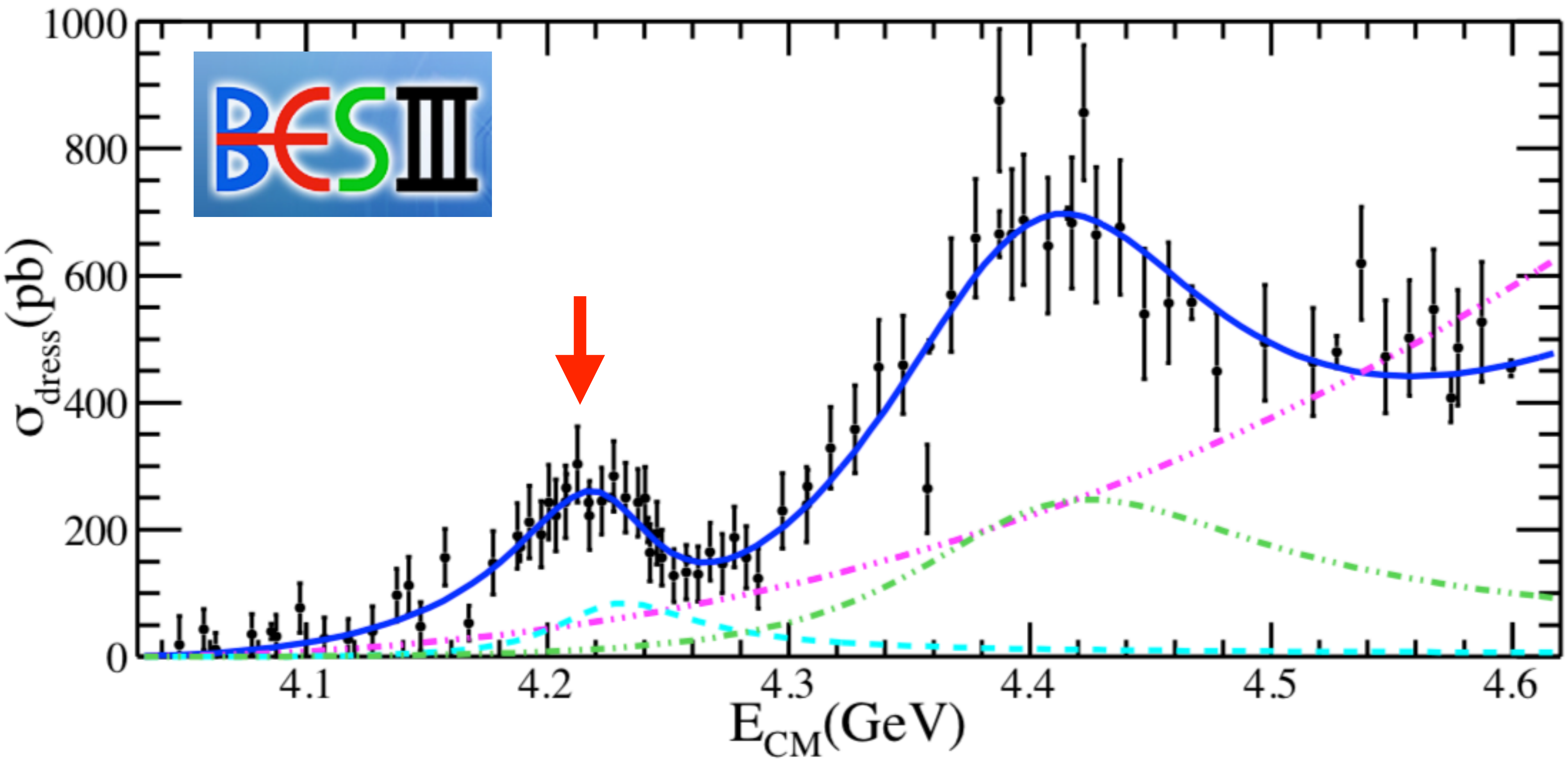


If Y(4220) is ψ(4S), Y(4220) should be observed in open-charm decay channel!

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

$$M = 4228.6 \pm 4.1 \pm 5.9\,\text{MeV}$$
$$\Gamma = 77.1 \pm 6.8 \pm 6.9\,\text{MeV}$$

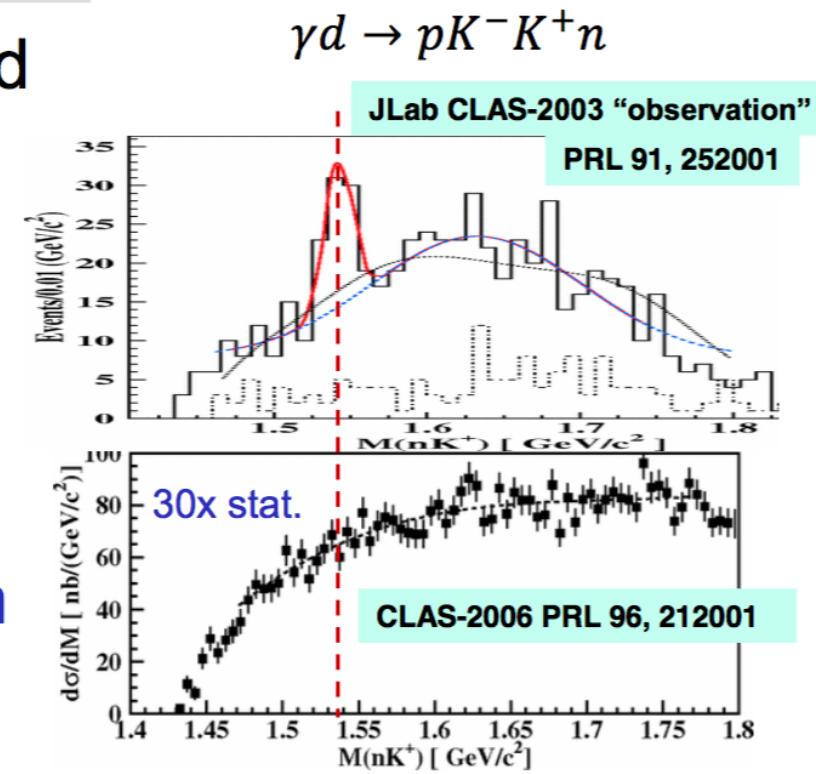


The pentaquark event shows that we are still far from understanding the nature of QCD

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"



Borrowed from Li-Ming Zhang's talk at PhiPsi2015

The observation of pentaquark $P_c(4380)$ and $P_c(4450)$

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)

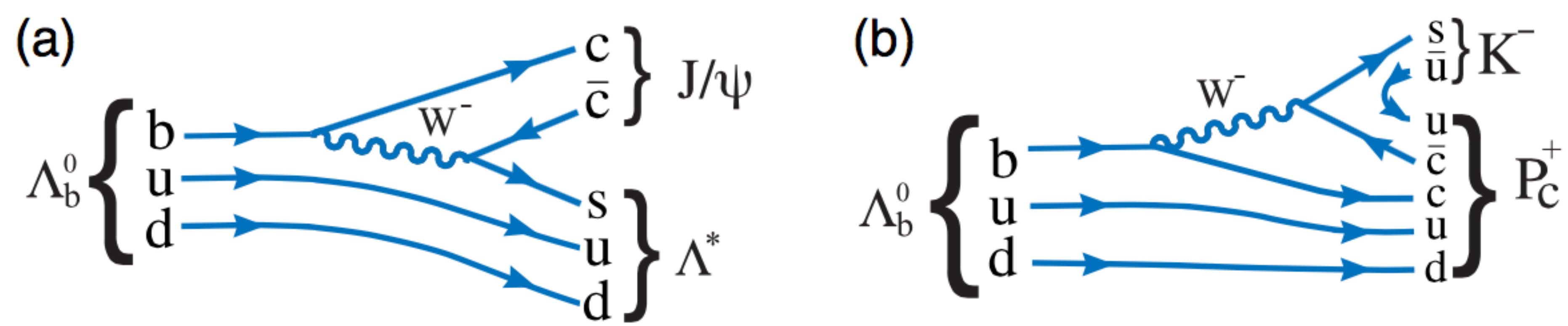
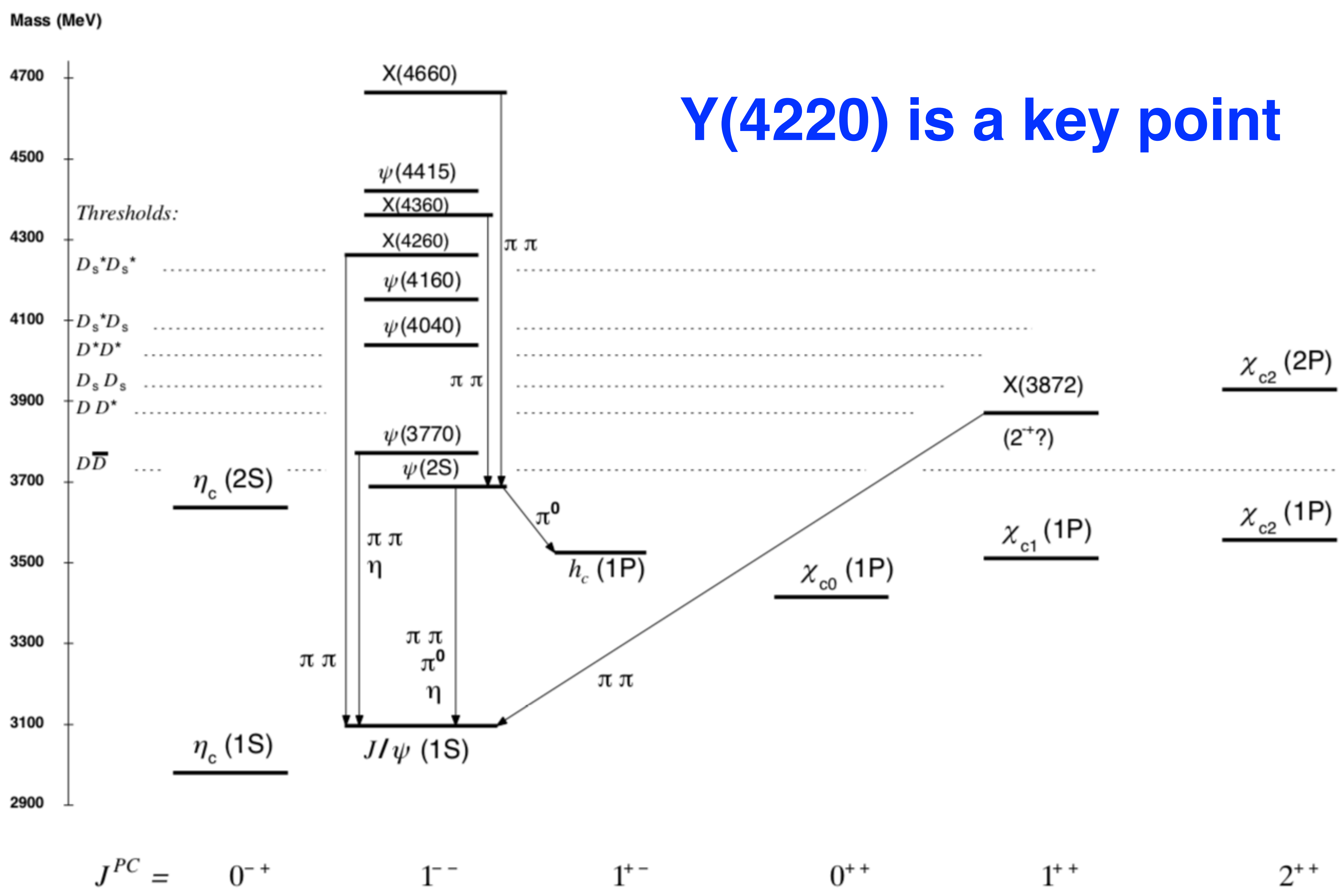


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

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



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*

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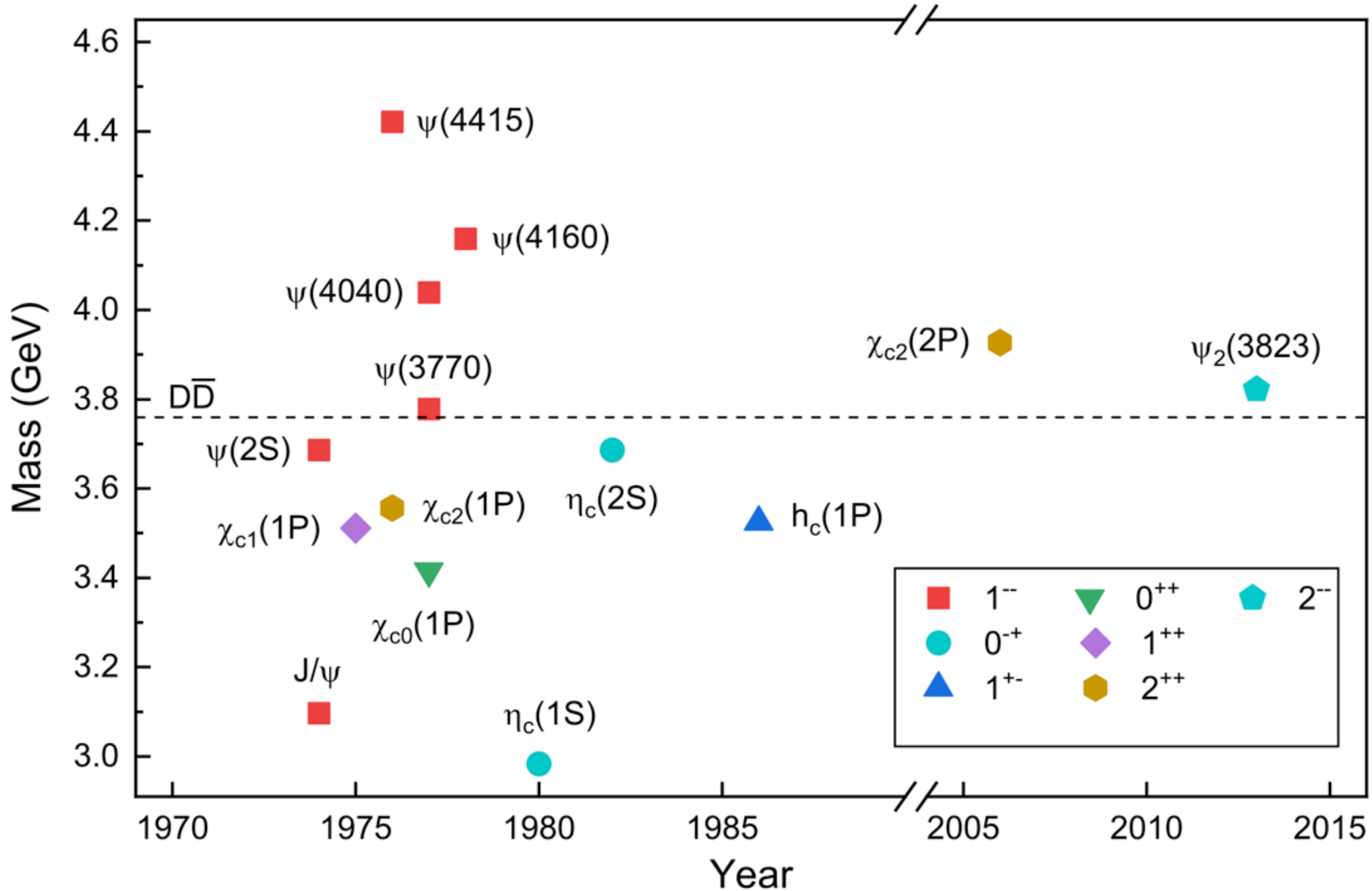
(Received 20 March 2019; published 5 June 2019)

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

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

$$\begin{aligned} \epsilon_c &= -0.084, & \epsilon_t &= 0.012, \\ \epsilon_{\text{sov}} &= -0.053, & \epsilon_{\text{sos}} &= 0.083, \\ b &= 0.2687, & c &= -0.3673, \\ m_c &= 1.65\ \text{GeV}, & \mu &= 0.15, \end{aligned}$$

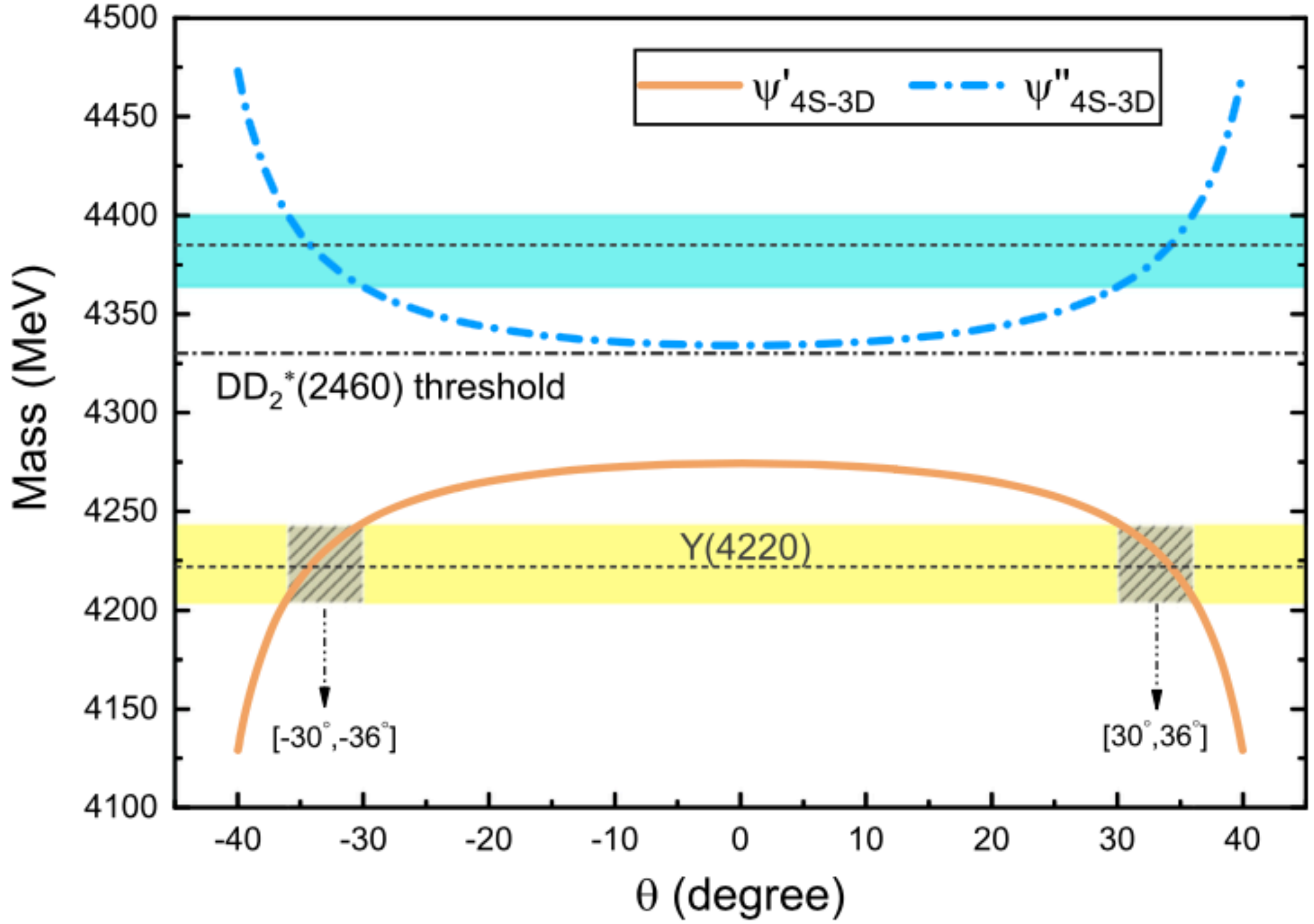
- **We need to reproduce the masses of these observed states**
- **Y(4220) is an important scaling point**

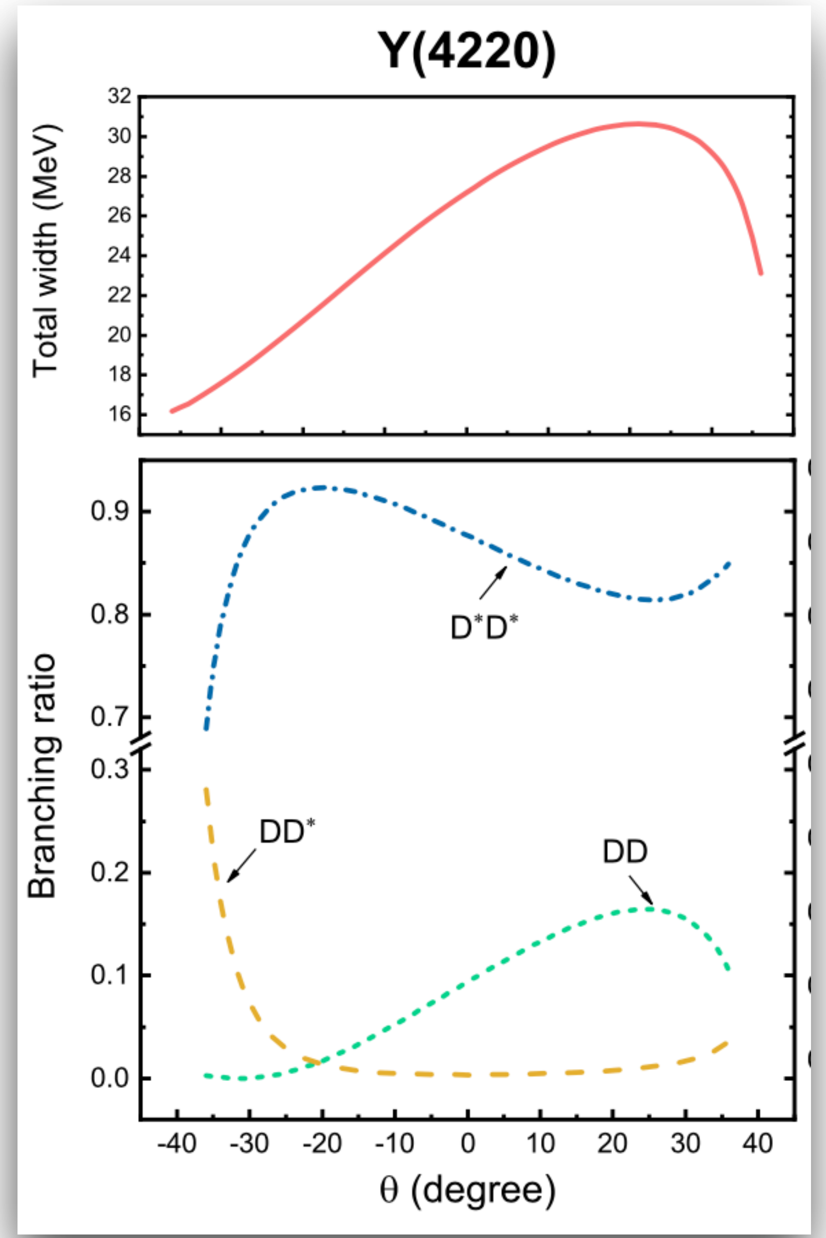
Mass spectrum for charmonium under unquenched picture

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

Introducing 4S-3D mixing scheme

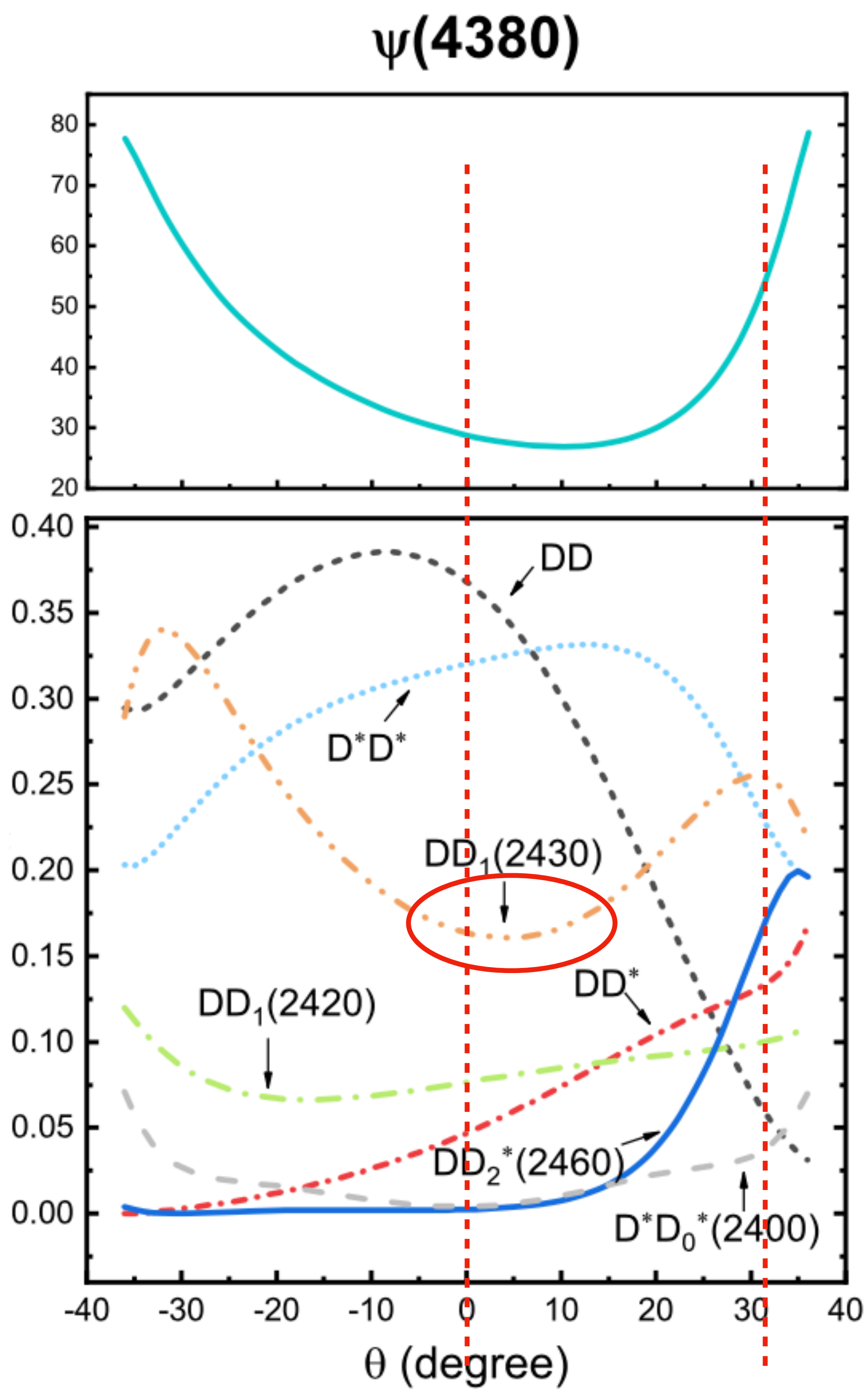
$$\begin{pmatrix} |\psi'_{4S-3D}\rangle \\ |\psi''_{4S-3D}\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |4^3S_1\rangle \\ |3^3D_1\rangle \end{pmatrix}$$



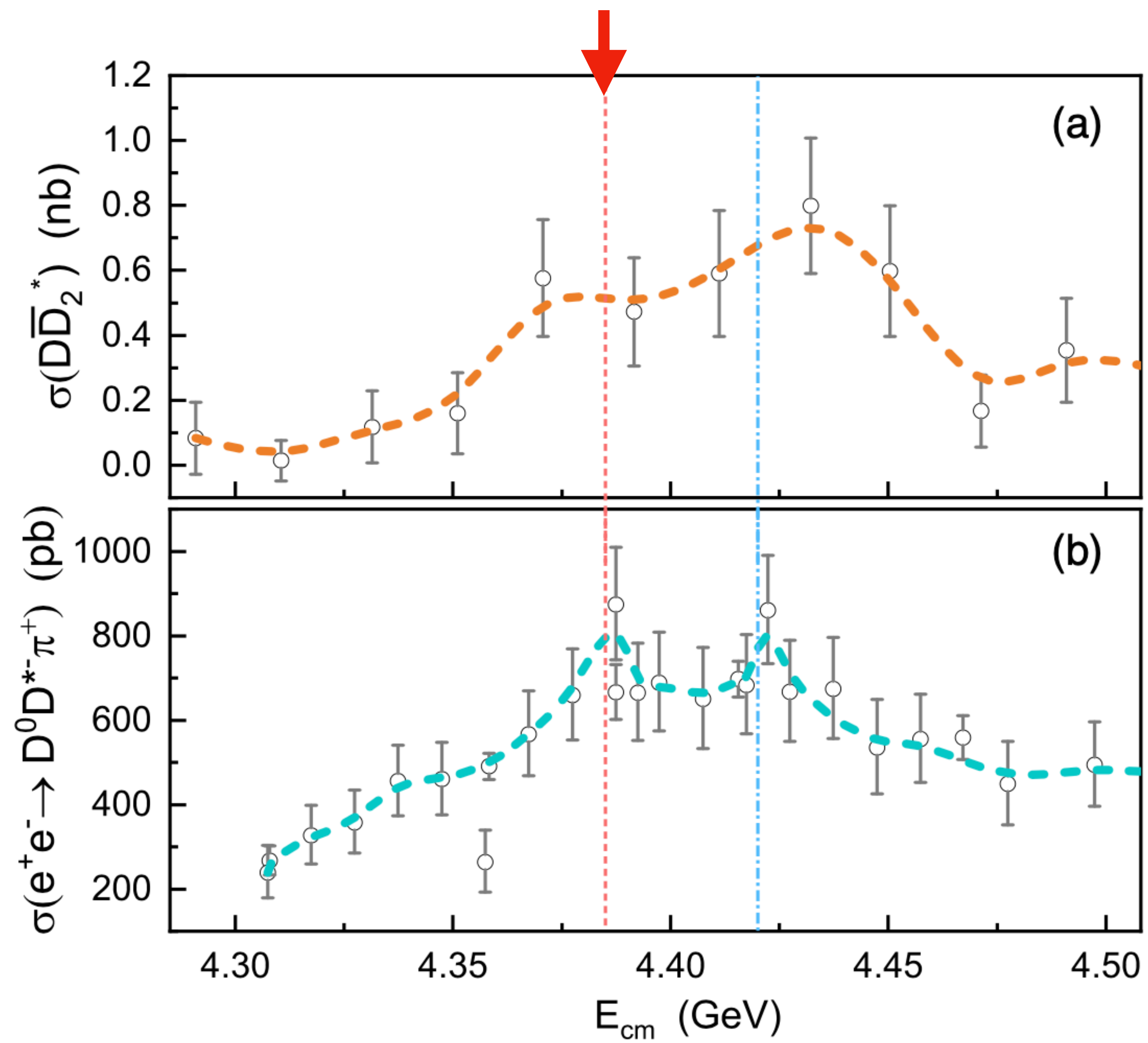


Our calculation supports this scenario

Predicting $\psi(4380)$ the partner of $Y(4220)$

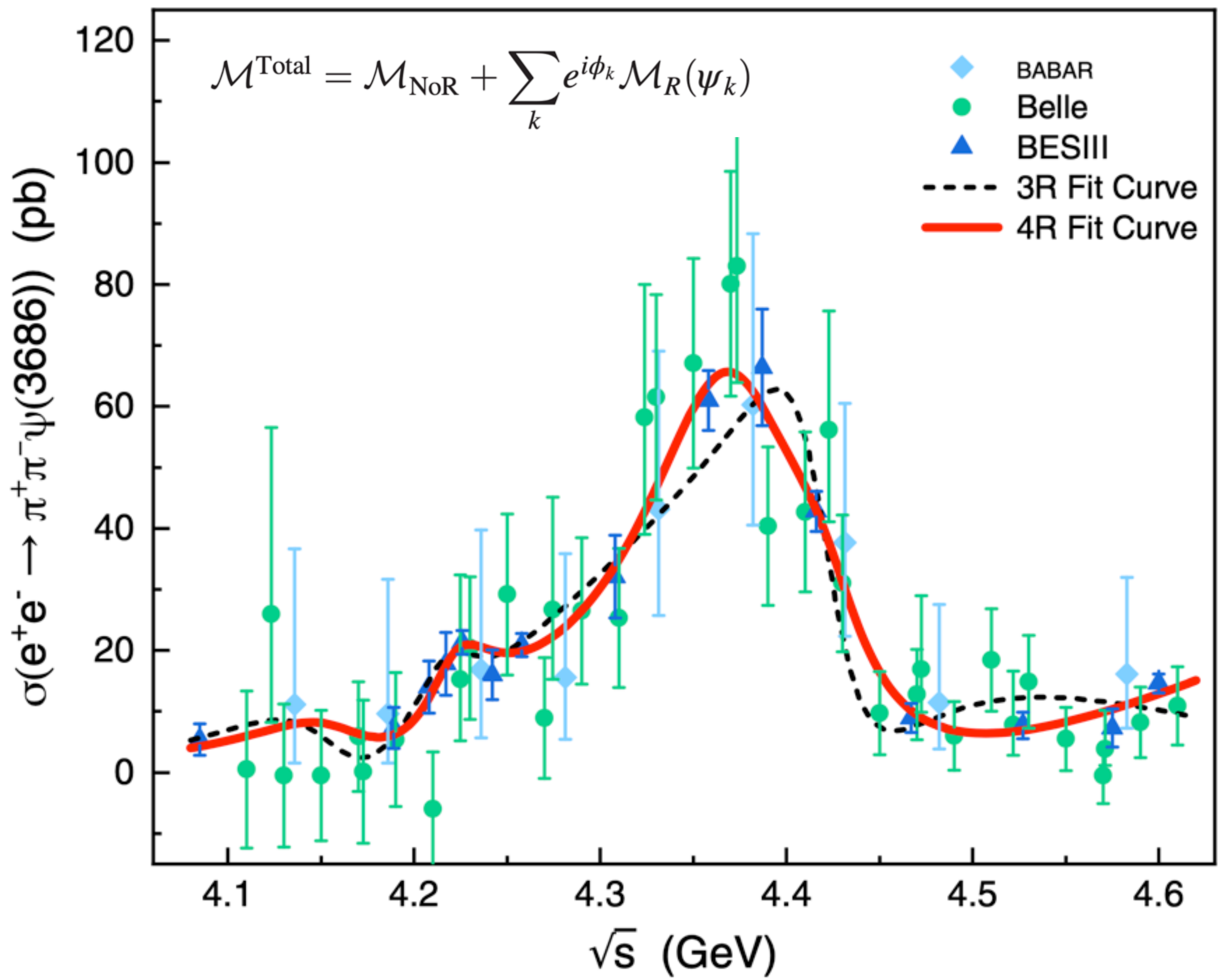


- **The total width of ψ(4380) has a significant enhancement**
- **There exists sizable enhancement of** $\psi(4380) \to DD_2(2460)$



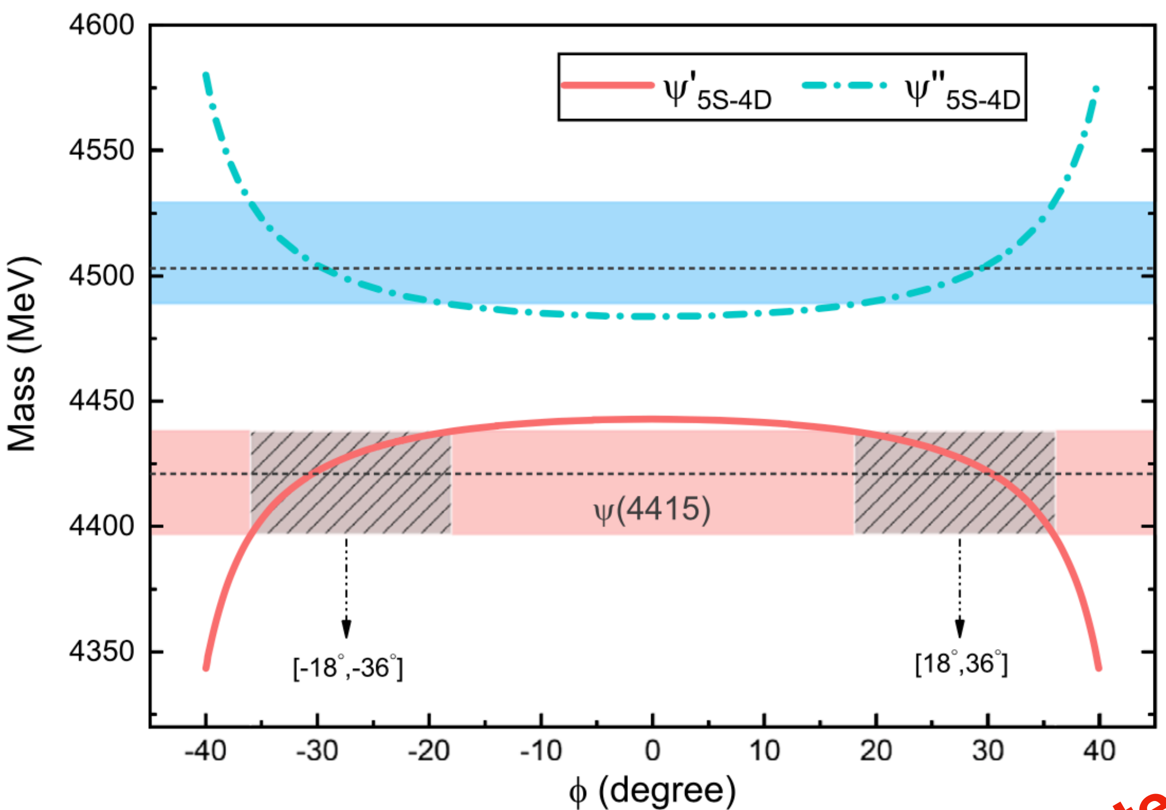
The experimental evidence for the prediction $\psi(4380)$

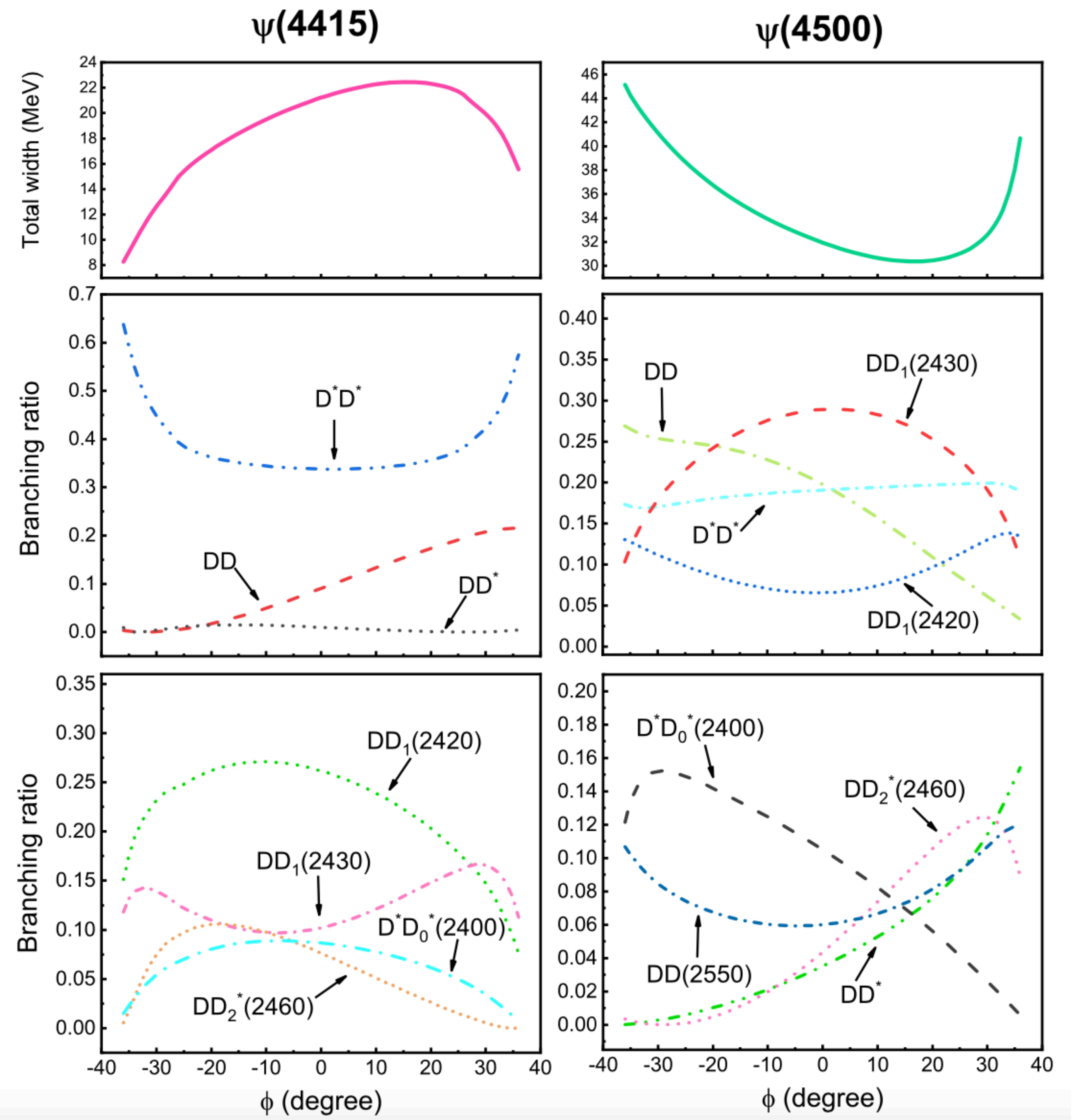
$$\psi(4160) + \psi(4415) + Y(4220) + \psi(4380)$$



Proposing 5S-4D mixing scheme

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





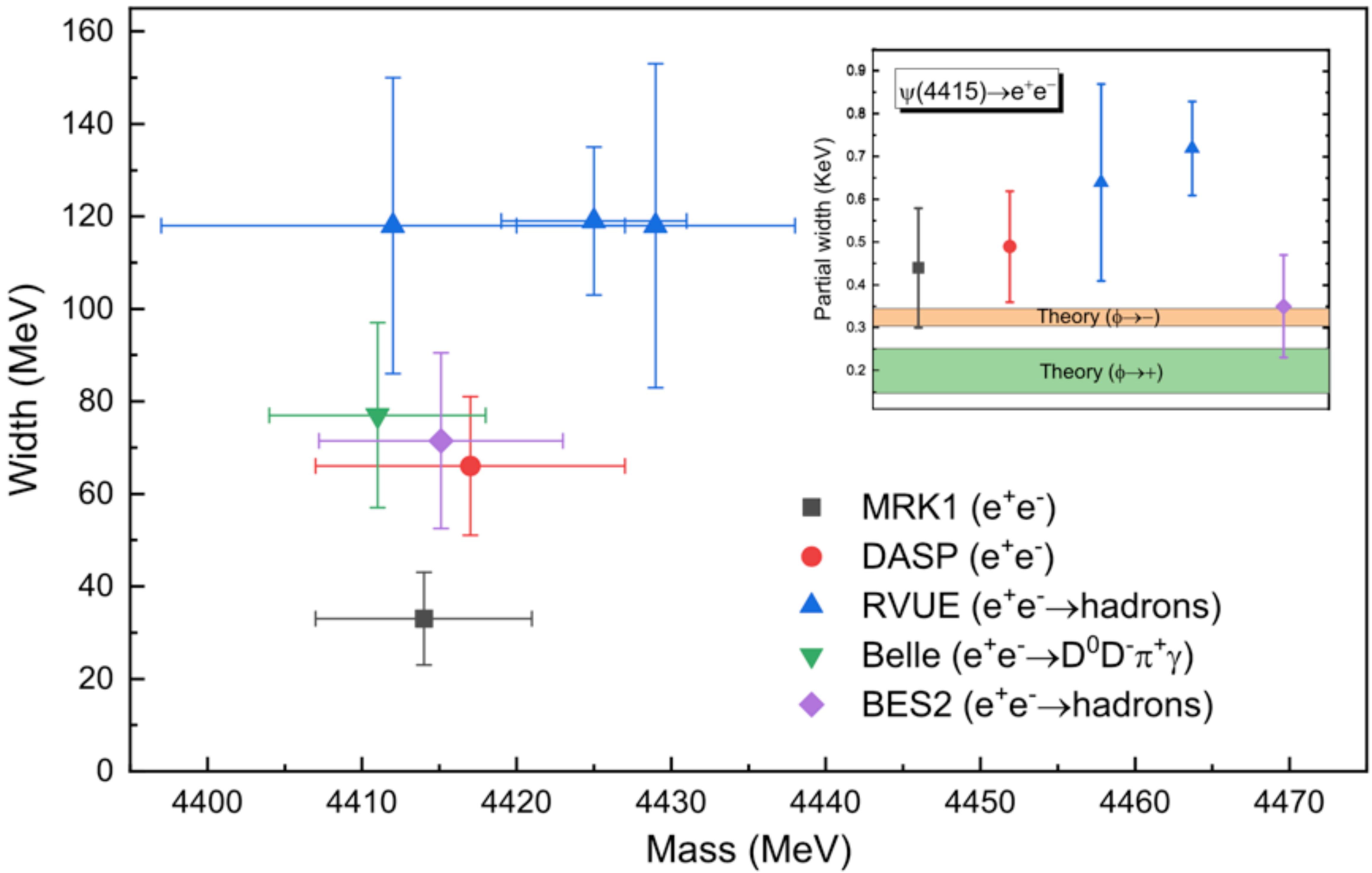
Experimental result

Consistent

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

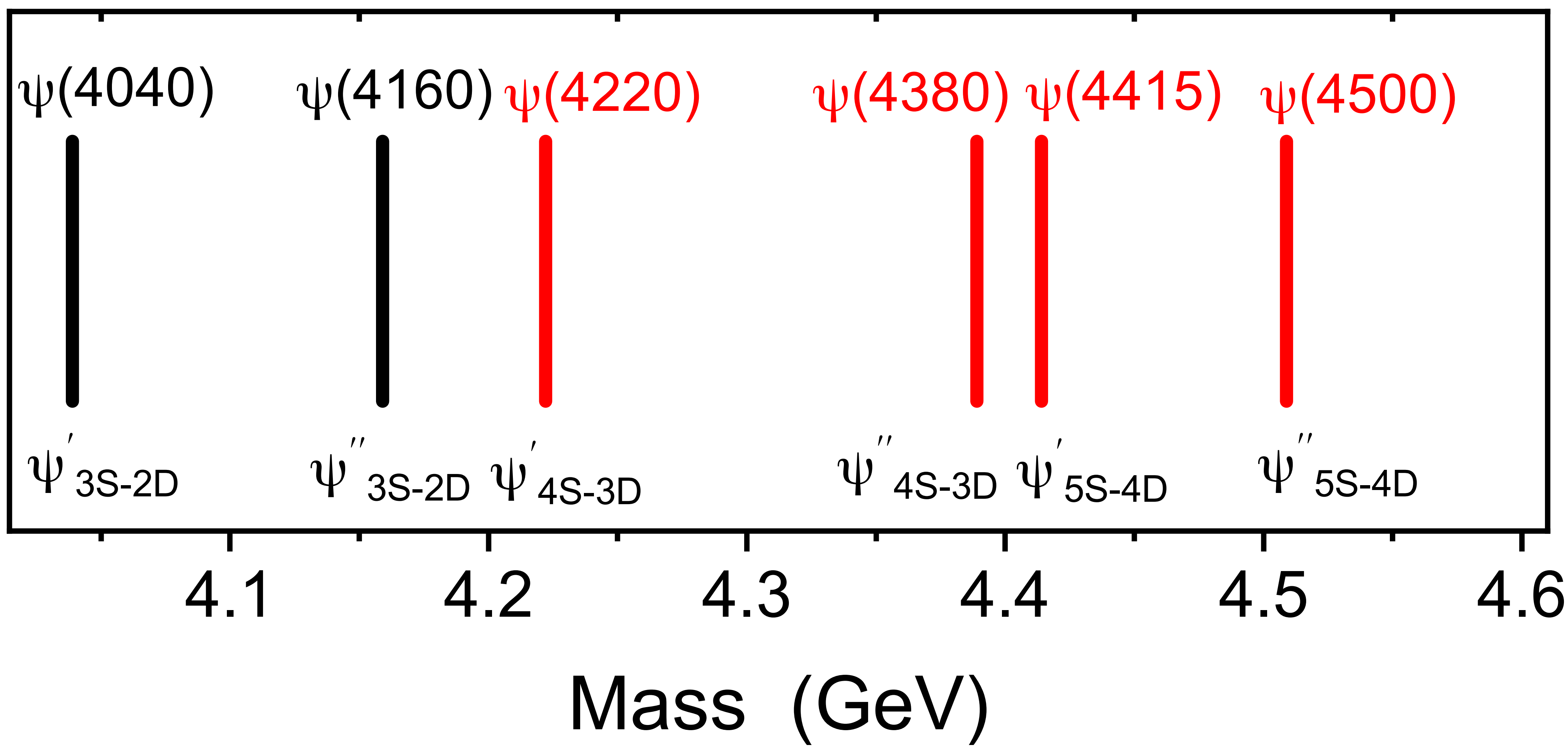
$$\frac{\Gamma(\psi(4415) \to D^*\bar{D} + \text{c.c.})}{\Gamma(\psi(4415) \to D^*\bar{D}^*)} = 0.17 \pm 0.25 \pm 0.03,$$

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



Six charmonia given by unquenched model

Mass spectrum for charmonium in the 4-4.5 GeV range



Unquenched potential model

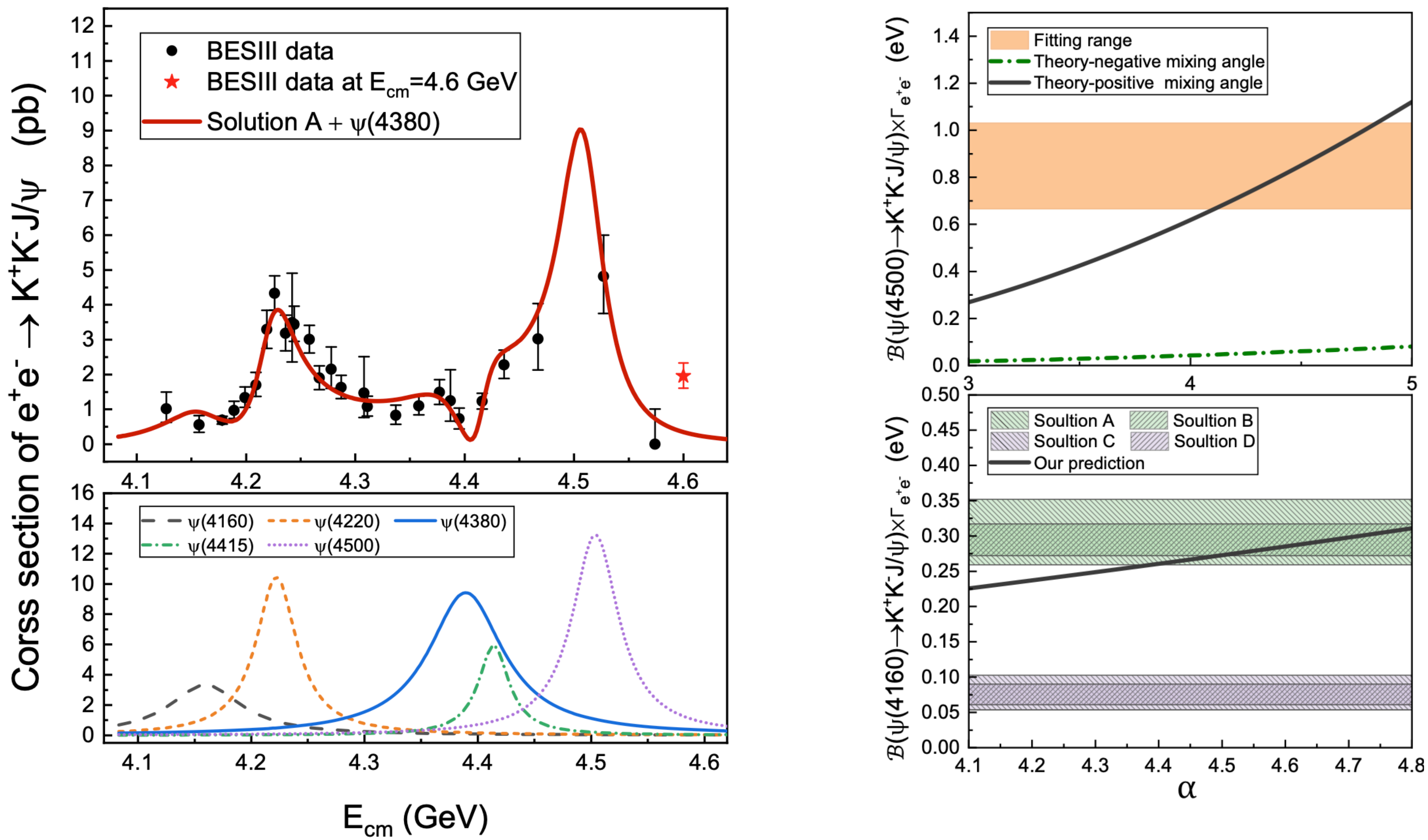
Wang, Chen, X. Liu, Matsuki, PRD 99 (2019) 114003

Six charmonia given by unquenched model

PHYSICAL REVIEW D **107,** 054016 (2023)

Confirming the existence of a new higher charmonium $\psi(4500)$ by the newly released data of $e^+e^- \to K^+K^-J/\psi$

Jun-Zhang Wang[1,2,*] and Xiang Liu[2,3,4,†]



BESIII: CPC 46 (2022) 111002

Six charmonia given by unquenched model

Phys. Lett. B 849 (2024) 138456

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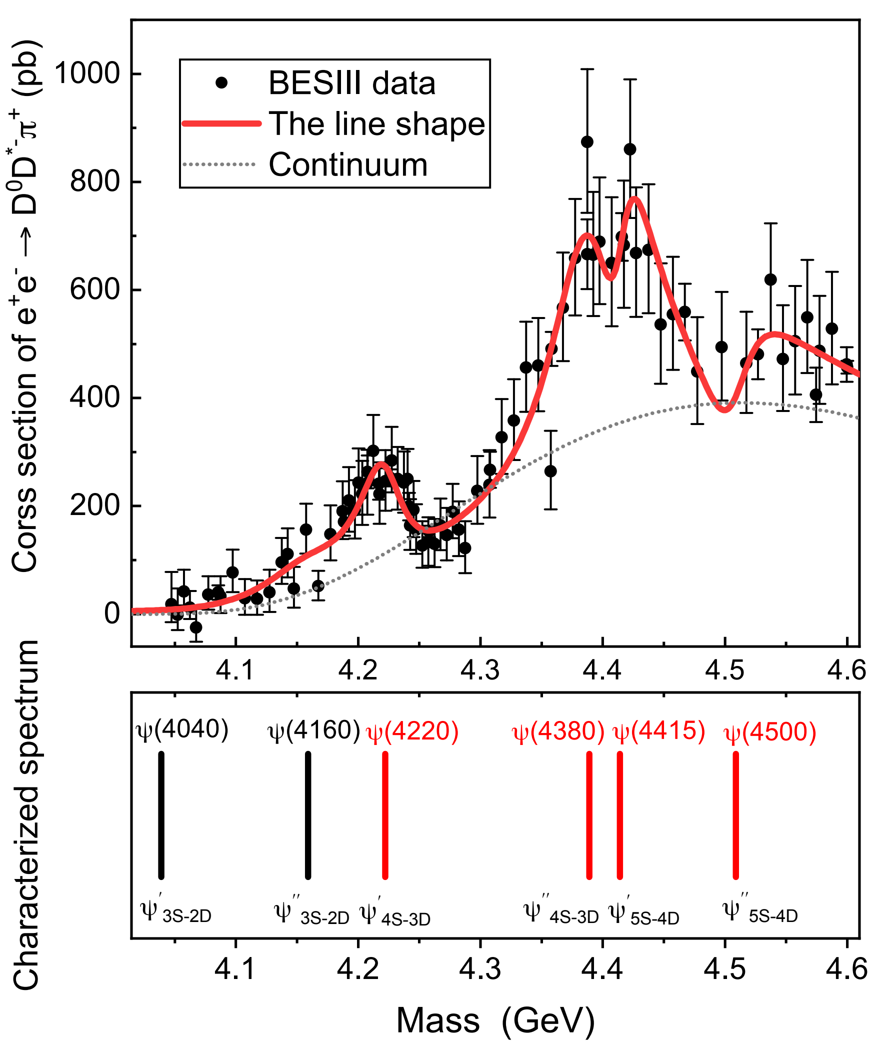
Letter

Identifying a characterized energy level structure of higher charmonium well matched to the peak structures in $e^+e^- \to \pi^+ D^0 D^{*-}$

Jun-Zhang Wang [a,b], Xiang Liu [b,c,d,e,*]



A B S T R A C T

Recent progresses on charmoniumlike state have significantly enriched the discovery of new hadronic states, providing exciting opportunities for further investigations into the fascinating realm of charmonium physics. In this letter, we focus on the vector charmonium family and perform a detailed analysis of the recently observed $e^+e^- \to \pi^+ D^0 D^{*-}$ process. Our findings demonstrate a agreement between the observed peak structures and the predicted characterized energy level structure of higher vector charmonia including the $\psi(4220)$, $\psi(4380)$, $\psi(4415)$, and $\psi(4500)$, which are derived from an unquenched potential model. This discovery challenges conventional understanding of higher charmonia above 4 GeV and offers fresh insights into the dynamics of charm and anti-charm quarks in the formation of these states. Furthermore, the identification of these higher charmonia in the precisely measured $\pi^+ D^0 D^{*-}$ open-charm decay channel would serve as compelling evidence supporting the unquenched scenario and contribute to a deeper understanding of the nonperturbative aspects of the strong interaction.

Table 1
The fitted parameters of describing the cross section distribution of $e^+e^- \to \pi^+ D^0 D^{*-}$ based on the scheme involving the characterized energy level structures of higher charmonia, where the $\chi^2/d.o.f. = 0.74$.

Parameters	a_0 (GeV^{-2})	g (GeV^{-3})	$R_{\psi(4160)}$ (eV)	$R_{\psi(4220)}$ (eV)	$R_{\psi(4380)}$ (eV)	$R_{\psi(4415)}$ (eV)
Values	0.445 ± 0.025	34.5 ± 18.1	0.726 ± 0.527	2.70 ± 0.63	19.0 ± 4.6	2.34 ± 1.23
Parameters	$R_{\psi(4500)}$ (eV)	$\phi_{\psi(4160)}$ (rad)	$\phi_{\psi(4220)}$ (rad)	$\phi_{\psi(4380)}$ (rad)	$\phi_{\psi(4415)}$ (rad)	$\phi_{\psi(4500)}$ (rad)
Values	1.60 ± 0.42	1.97 ± 0.65	2.07 ± 0.15	1.44 ± 0.16	6.04 ± 0.24	5.76 ± 0.31

BESIII: Phys. Rev. Lett. 130, 121901 (2023)

Six charmonia given by unquenched model

PHYSICAL REVIEW D **109,** 094048 (2024)

How higher charmonia shape the puzzling data of the $e^+e^- \to \eta J/\psi$ cross section

Tian-Cai Peng,[1,2,3,4,*] Zi-Yue Bai,[1,2,3,4,†] Jun-Zhang Wang,[1,5,‡] and Xiang Liu[1,2,3,4,6,§]

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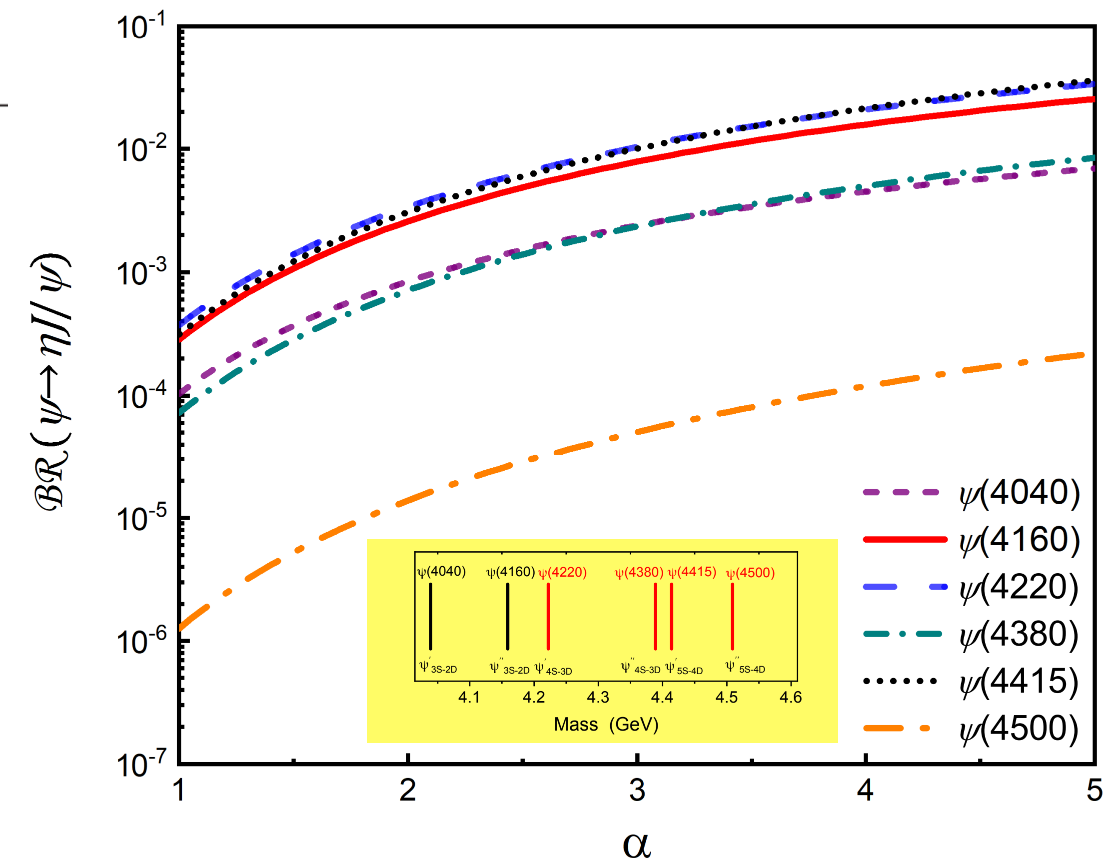
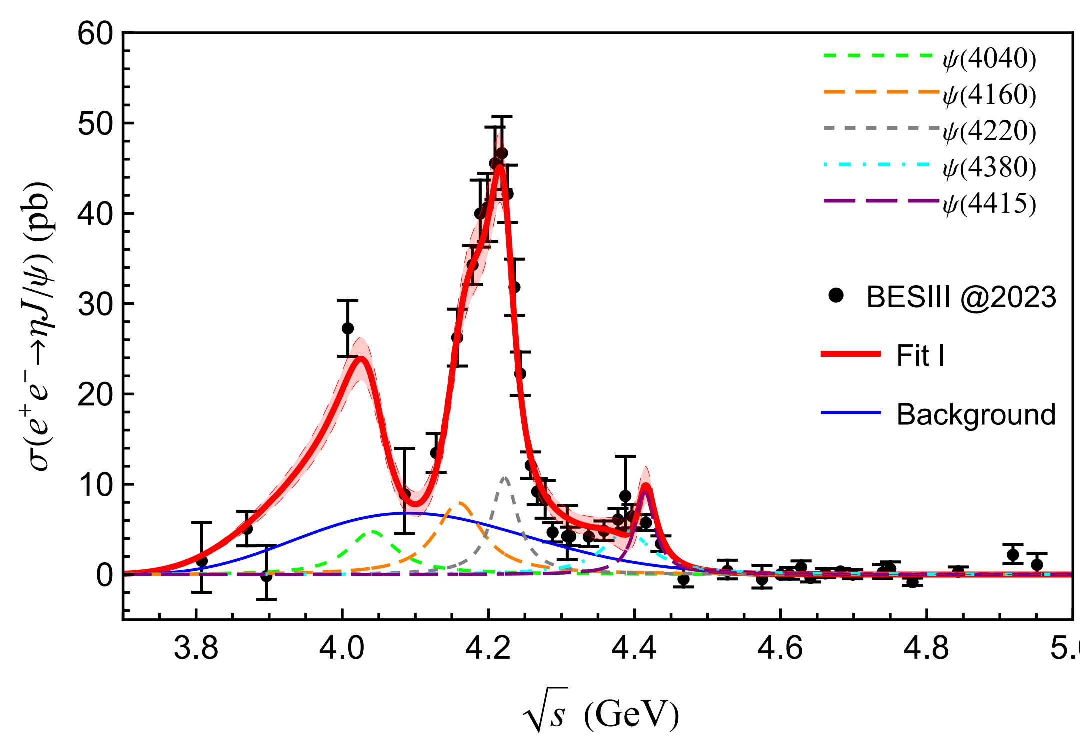
(Received 8 March 2024; accepted 6 May 2024; published 31 May 2024)

Recently, the BESIII collaboration performed a precise measurement of the $e^+e^- \to \eta J/\psi$ cross section. It is puzzling that the resonance parameters of the reported $Y(4230)$ show a substantial divergence from the previously measured results in both the open-charmed and hidden-charmed decay channels, and the line shape asymmetry of the data approaching 4.2 GeV also suggests that it might be difficult to characterize the details of the structure around 4.2 GeV by a single resonance. This has motivated our great curiosity about how the charmonium states are distributed in the measured energy range and how they shape the puzzling data of the $e^+e^- \to \eta J/\psi$ cross section. In this work, we use five theoretically constructed charmonia in the range of 4.0–4.5 GeV, i.e., $\psi(4040)$, $\psi(4160)$, $\psi(4220)$, $\psi(4380)$, and $\psi(4415)$, to apply a combined fit to the data, in which their calculated decay ratios into $\eta J/\psi$ via hadronic loop mechanism are taken as input. The fit results can reproduce the measured cross section data well, especially for the subtle line shape around 4.2 GeV, showing that the structure around 4.2 GeV is possible from the contribution of both $\psi(4160)$ and $\psi(4220)$.

BESIII: PRD 109 (2024) 092012

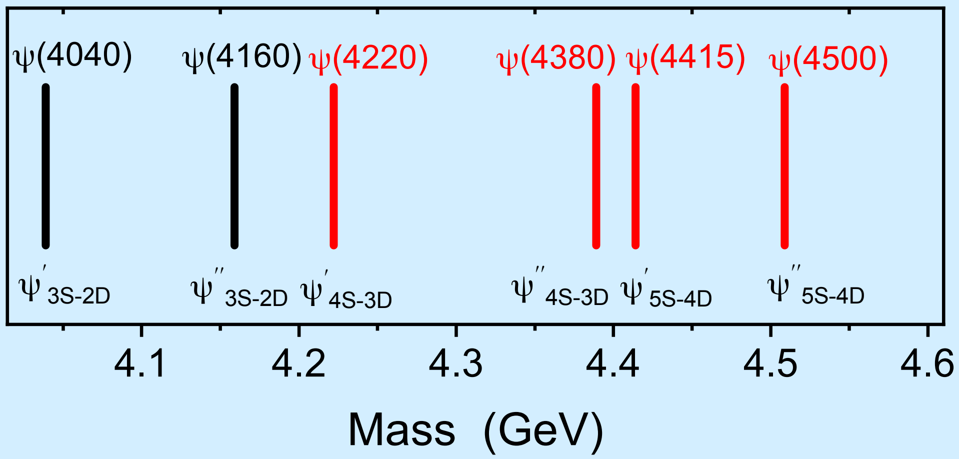




Six charmonia given by unquenched model

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

Mass spectrum of charmonium given by Unquenched potential model



Wang, Chen, X. Liu, Matsuki, PRD 99 (2019) 114003

Mass spectrum given by quenched model

PHYSICAL REVIEW D VOLUME 21, NUMBER 1 1 JANUARY 1980

Charmonium: Comparison with experiment

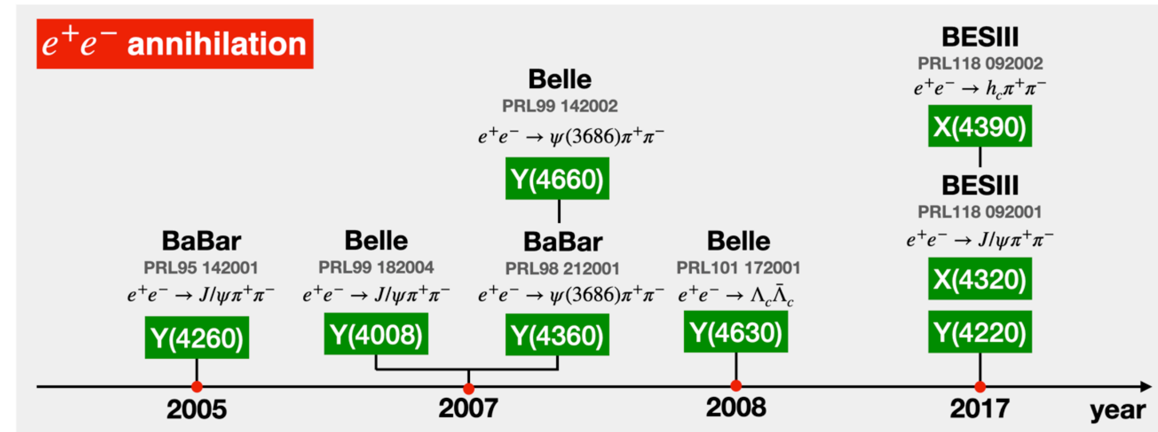
E. Eichten,* K. Gottfried, T. Kinoshita, K. D. Lane,* and T. M. Yan
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 25 June 1979)

Cornell potential

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]	$\langle \frac{v^2}{c^2} \rangle$	$\langle r^2 \rangle^{1/2}$ (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	

A solution for "Y problem" based on unquenched model

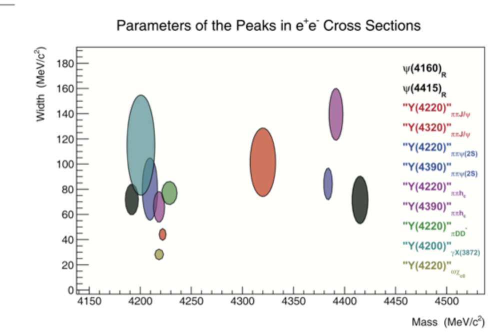


Chinese Physics C Vol. 44, No. 4 (2020)

Future Physics Programme of BESIII*

(1) 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 line shape of 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), etc. A summary of the masses and widths of resonances extracted from recent BESIII results is shown in Fig. 3.11.



PRD 83 (2011) 054021
PRD 83 (2011) 074012
EPJC 74 (2014), 3208
PRD 91 (2015) 094023
PRD 93 (2016) 014011
PRD 93 (2016) 034028
PRD 96 (2017) 094004
EPJC 78 (2018) 136
EPJC 79 (2019) 613
PRD 99 (2019) 114003
PRD 101 (2020) 034001
PRD 104 (2021) 094001
PLB 833 (2022) 137292
PRD 107 (2023) 054016
PLB 849 (2024) 138456
PRD 109 (2024) 094048
PRD 111 (2025) 054021
PRD 111 (2025) 054023
PLB 868 (2025) 139644

Mixing scheme for $\psi(4220)$ induced by a coupled-channel approach

We seek to address this question within this year

Phys. Lett. B 868 (2025) 139644

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PHYSICS LETTERS B

Letter

Check for updates

Coupled-channel study of $4S$-$3D$ mixing dynamics in $\psi(4220)$ and $\psi(4380)$

Zi-Long Man [a,b,c,d], Si-Qiang Luo [a,b,c,d], Zi-Yue Bai [a,b,c,d], Xiang Liu [a,b,c,d,*]

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[b] Lanzhou Center for Theoretical Physics, Key Laboratory of Theoretical Physics of Gansu Province, Key Laboratory of Quantum Theory and Applications of MoE, Gansu Provincial Research Center for Basic Disciplines of Quantum Physics, Lanzhou University, Lanzhou 730000, China
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ARTICLE INFO

Editor: S.-L. Zhu

ABSTRACT

Among charmoniumlike XYZ states, the $\psi(4220)$ and $\psi(4380)$ states have emerged as key candidates for exploring the charmonium spectrum. In this work, we propose a $4S$-$3D$ charmonium mixing scheme for the $\psi(4220)$ and $\psi(4380)$, induced by coupled-channel effects. By constructing a coupled-channel model, we identify the dynamical mechanism responsible for the large mixing angle observed in previous studies, which cannot be explained by conventional potential models alone. Our analysis reveals that the DD_1 channel significantly influences the lower state ($\psi(4220)$), while the D^*D_1 channel primarily affects the higher state ($\psi(4380)$). Furthermore, we investigate the two-body Okubo-Zweig-Iizuka (OZI)-allowed strong decay behaviors of these states, providing insights into their total widths. This study not only supports the $4S$-$3D$ mixing scheme but also offers a deeper understanding of the role of coupled channels in shaping the charmonium spectrum above 4 GeV. Our results align with experimental observations and provide a framework for interpreting future data on charmonium states.

Mixing scheme for $\psi(4220)$ induced by a coupled-channel approach

$$\underbrace{\begin{pmatrix} M^0_{4S} & 0 \\ 0 & M^0_{3D} \end{pmatrix}}_{\text{Bare}} + \underbrace{\begin{pmatrix} 0 & \langle 4S|H_T|3D\rangle \\ \langle 3D|H_T|4S\rangle & 0 \end{pmatrix}}_{\text{Potential model}}$$

$$+ \underbrace{\sum_{BC}\begin{pmatrix} \langle 4S|-\bigcirc_{BC}-|4S\rangle & \langle 4S|-\bigcirc_{BC}-|3D\rangle \\ \langle 3D|-\bigcirc_{BC}-|4S\rangle & \langle 3D|-\bigcirc_{BC}-|3D\rangle \end{pmatrix}}_{\text{Coupled-channel contribution}}$$

The tensor term in the potential model is insufficient to generate large mixing

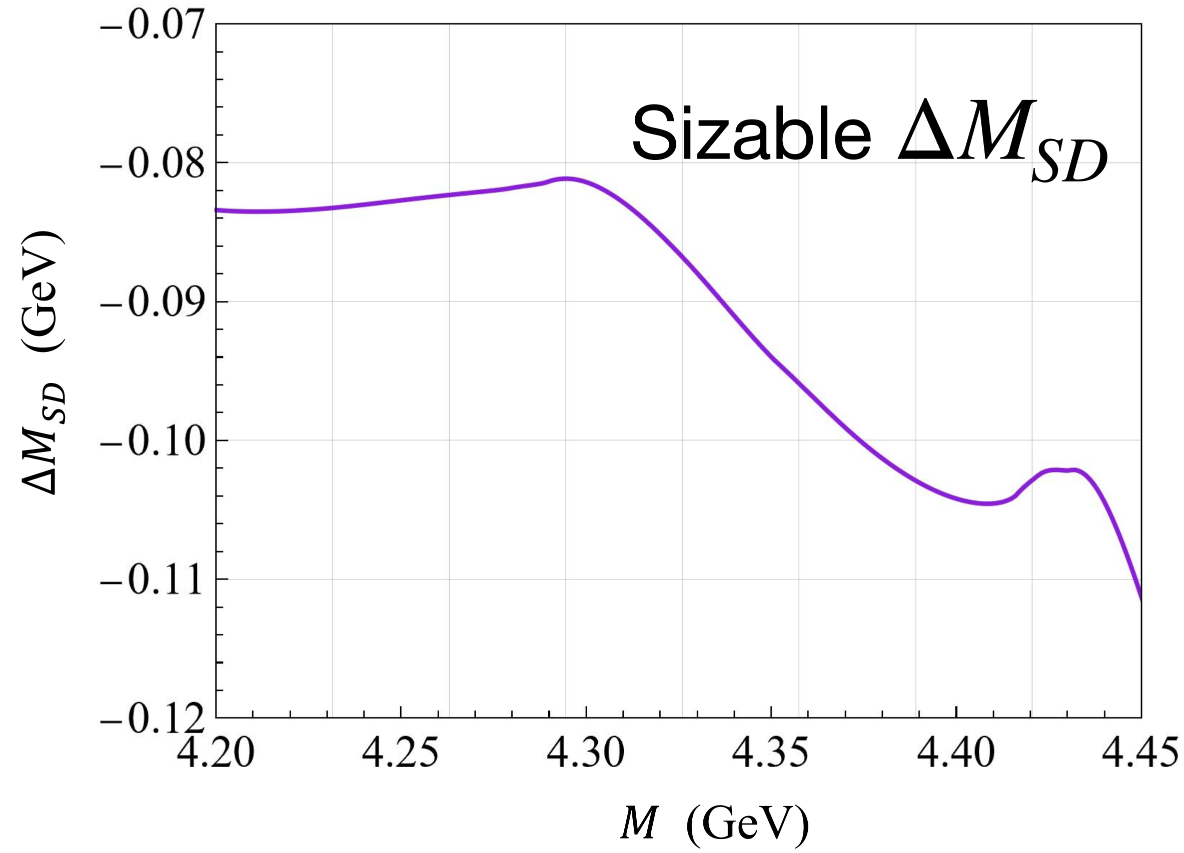
$$\begin{pmatrix} M^0_S & \langle\psi_S|H_{\rm T}|\psi_D\rangle \\ \langle\psi_D|H_{\rm T}|\psi_S\rangle & M^0_D \end{pmatrix}\begin{pmatrix} C_S \\ C_D \end{pmatrix} = M\begin{pmatrix} C_S \\ C_D \end{pmatrix}$$

$$H_T = \frac{4\alpha_s}{3m_c m_{\bar c} r^3}\left(\frac{3(\boldsymbol{S}_c\cdot\boldsymbol{r})(\boldsymbol{S}_{\bar c}\cdot\boldsymbol{r})}{r^2} - \boldsymbol{S}_c\cdot\boldsymbol{S}_{\bar c}\right)$$

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

The coupled-channel effect results in large S-D mixing scheme

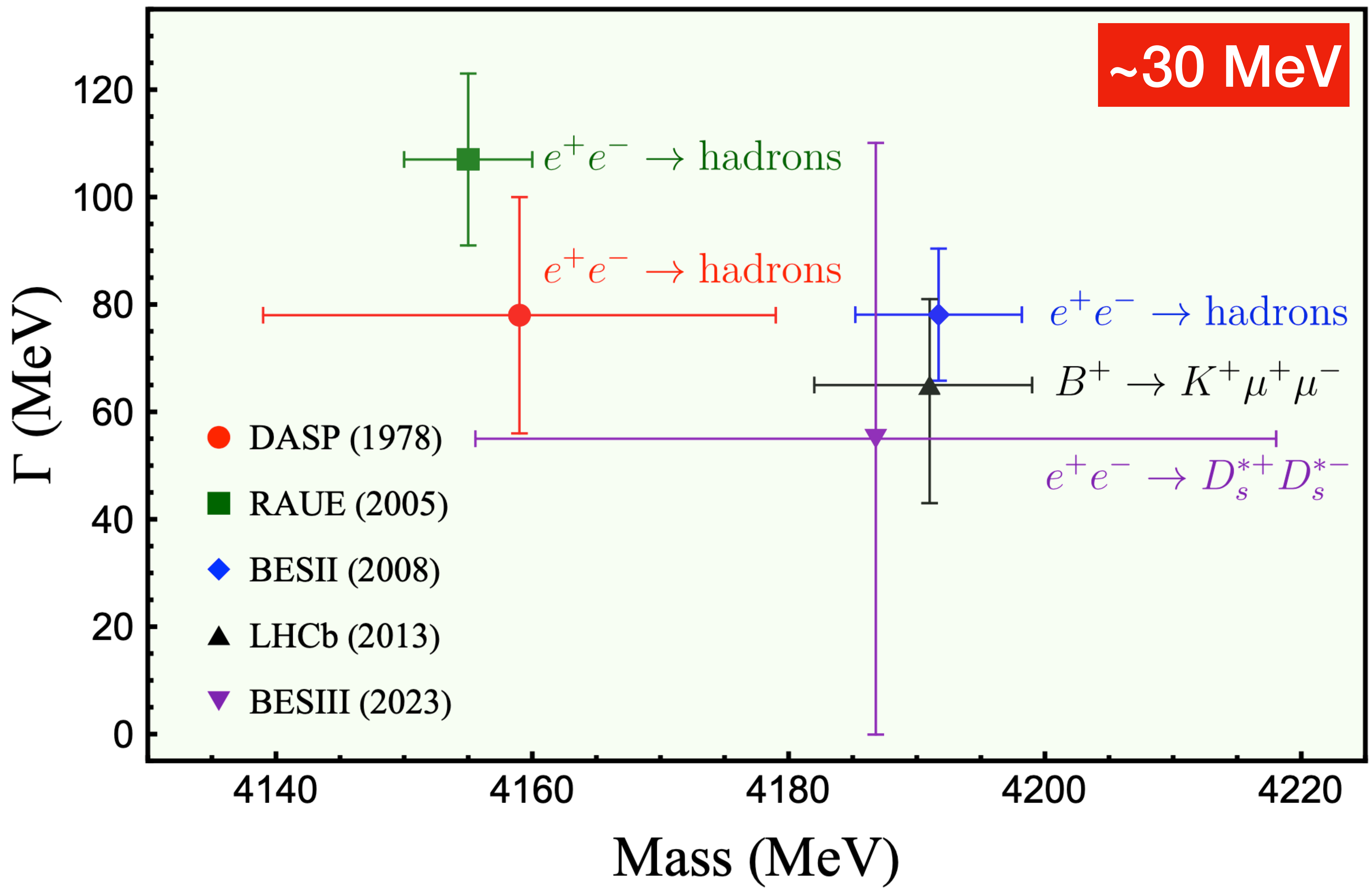
$$\det\begin{vmatrix} M^0_S + \Delta M_S(M) - M & \langle\psi_S|H_T|\psi_D\rangle + \Delta M_{SD}(M) \\ \langle\psi_D|H_T|\psi_S\rangle + \Delta M_{SD}(M) & M^0_D + \Delta M_D(M) - M \end{vmatrix} = 0$$



Mixing angle: $\theta = 35°$

Reevaluating the $\psi(4160)$ resonance paramete

The mass changes from 4160 MeV to 4190 MeV



$\psi(4160)$ was discovered in 1978 by the DASP Collaboration

TOTAL CROSS SECTION FOR HADRON PRODUCTION BY e^+e^--ANNIHILATION AT CENTER OF MASS ENERGIES BETWEEN 3.6 AND 5.2 GeV

DASP Collaboration

Phys. Lett. B 76, 361 (1978)

The total cross section for e^+e^- annihilation into hadronic final states between 3.6 and 5.2 GeV was measured by the nonmagnetic inner detector of DASP, which has similar trigger and detection efficiencies for photons and charged particles. The measured difference in $R = \sigma_{had}/\sigma_{\mu\mu}$ between 3.6 GeV and 5.2 GeV is $\Delta R = 2.1 \pm 0.3$. We observe three peaks at cm energies of 4.04, 4.16 and 4.417 GeV, the parameters of which, when interpreted as resonances, are given.

Table 1
Resonance parameters of the best fit described in the text and shown in fig. 2. The errors include statistical effects, the uncertainties of the detection efficiency, and some coarse estimate of interference between the resonance amplitudes.

Mass (MeV)	Γ_{tot} (MeV)	$\Gamma_{e^+e^-}$ (keV)
4040±10	52±10	0.75±0.15
4159±20	78±20	0.77±0.23
4417±10	66±15	0.49±0.13

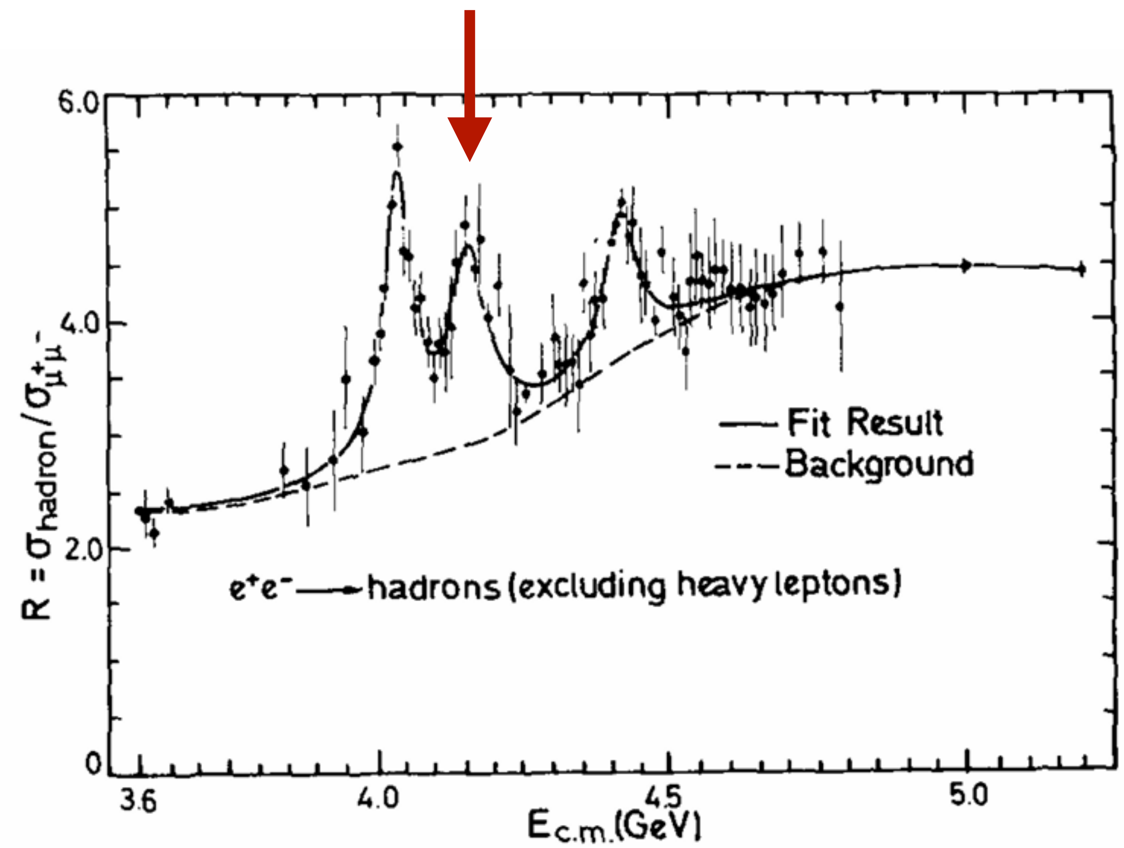


Fig. 2. The ratio $R = \sigma_{hadron}/\sigma_{\mu^+\mu^-}$ without heavy lepton production versus energy. Only statistical errors are indicated. The fit to the data described in the text is indicated and separately the nonresonant background term.

Resonance parameter for $\psi(4160)$

Confirmed by BES from the R value measurement

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Physics Letters B 660 (2008) 315–319

PHYSICS LETTERS B

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Determination of the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ resonance parameters

BES Collaboration

Table 1: The resonance parameters of the high mass charmonia in this work together with the values in PDG2004 [11], PDG2006 [12] and K. Seth's evaluations [13] based on Crystal Ball and BES data. The total width $\Gamma_{tot} \equiv \Gamma_r(M)$ in Eq.(8).

		$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M (MeV/c^2)	PDG2004	3769.9±2.5	4040±10	4159±20	4415±6
	PDG2006	3771.1±2.4	4039±1.0	4153±3	4421±4
	CB (Seth)	-	4037±2	4151±4	4425±6
	BES (Seth)	-	4040±1	4155±5	4455±6
	BES (this work)	3771.4±1.8	4038.5±4.6	4191.6±6.0	4415.2±7.5
Γ_{tot} (MeV)	PDG2004	23.6±2.7	52±10	78±20	43±15
	PDG2006	23.0±2.7	80±10	103±8	62±20
	CB (Seth)	-	85±10	107±10	119±16
	BES (Seth)	-	89±6	107±16	118±35
	BES (this work)	25.4±6.5	81.2±14.4	72.7±15.1	73.3±21.2
Γ_{ee} (keV)	PDG2004	0.26±0.04	0.75±0.15	0.77±0.23	0.47±0.10
	PDG2006	0.24±0.03	0.86±0.08	0.83±0.07	0.58±0.07
	CB (Seth)	-	0.88±0.11	0.83±0.08	0.72±0.11
	BES (Seth)	-	0.91±0.13	0.84±0.13	0.64±0.23
	BES (this work)	0.18±0.04	0.81±0.20	0.50±0.27	0.37±0.14
δ (degree)	BES (this work)	0	133±68	301±61	246±86

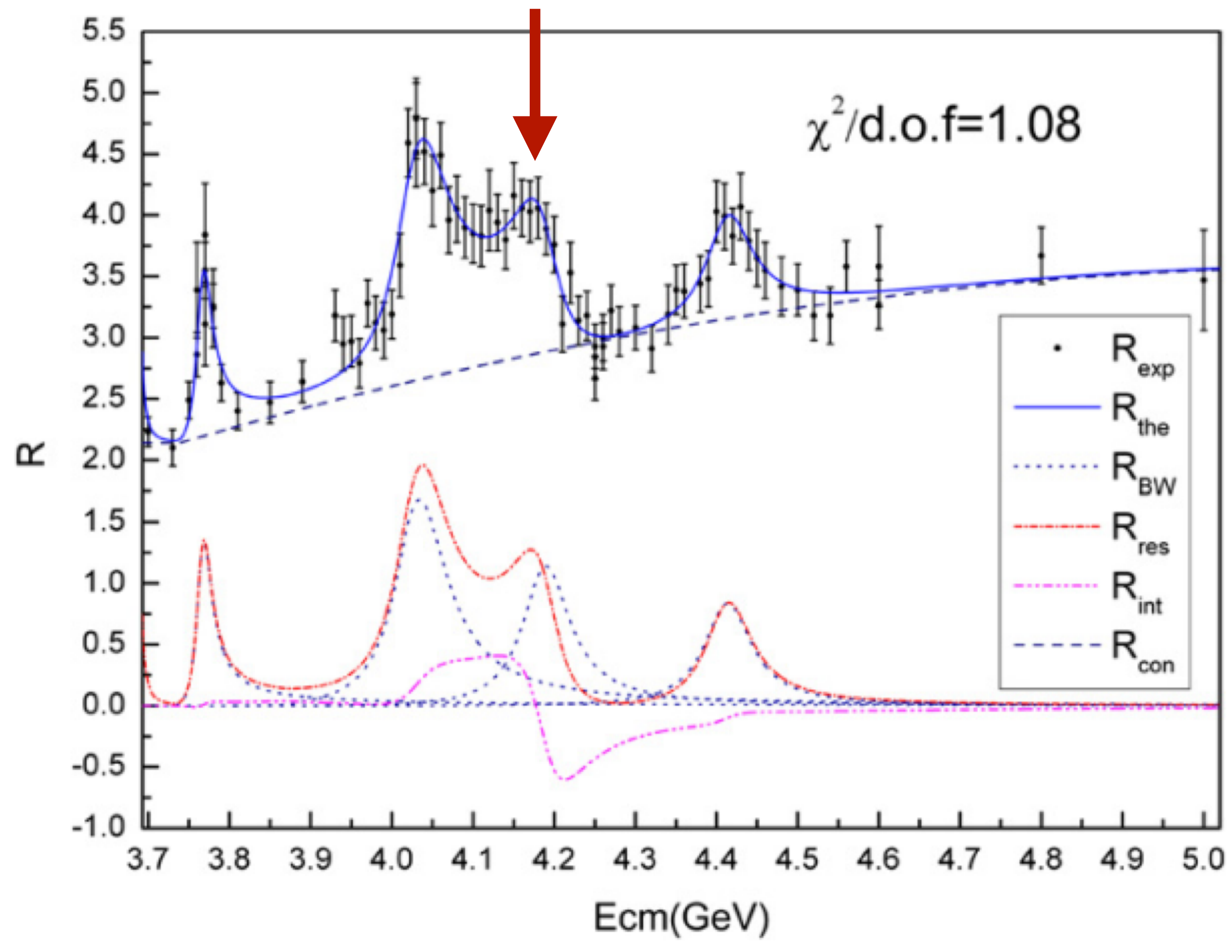


Fig. 1. The fit to the R values for the high mass charmonia structure. The dots with error bars are the updated R values. The solid curve shows the best fit, and the other curves show the contributions from each resonance R_{BW}, the interference R_{int}, the summation of the four resonances $R_{\mathrm{res}} = R_{\mathrm{BW}} + R_{\mathrm{int}}$, and the continuum background R_{con} respectively.

Resonance parameter for $\psi(4160)$

Higher mass with 4190 MeV obtained by LHCb

PRL **111,** 112003 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Observation of a Resonance in $B^+ \to K^+\mu^+\mu^-$ Decays at Low Recoil

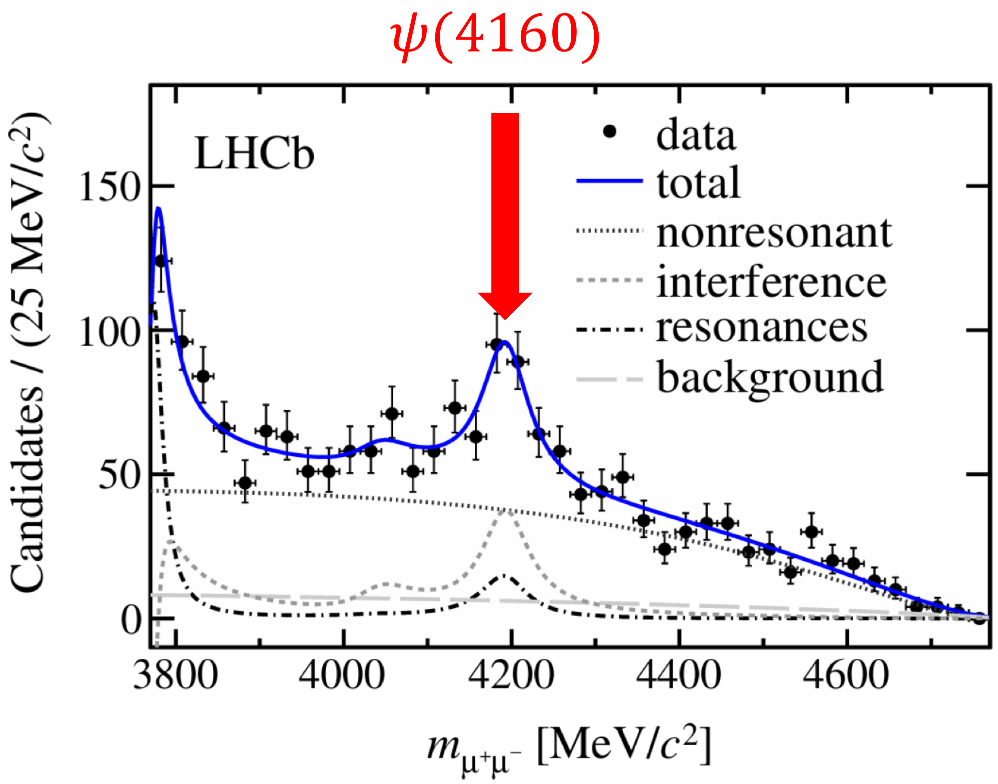


FIG. 1 (color online). Dimuon mass distribution of data with fit results overlaid for the fit that includes contributions from the nonresonant vector and axial vector components, and the $\psi(3770)$, $\psi(4040)$, and $\psi(4160)$ resonances. Interference terms are included and the relative strong phases are left free in the fit.

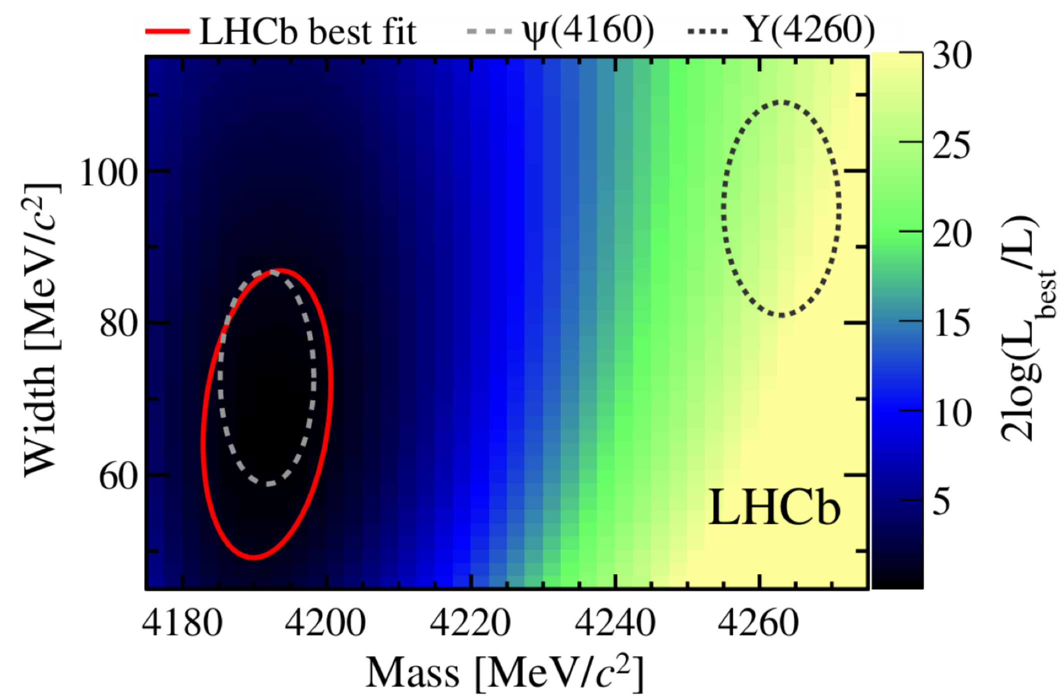


FIG. 3 (color online). Profile likelihood as a function of mass and width of a fit with a single extra resonance. At each point all other fit parameters are reoptimized. The three ellipses are (red, solid line) the best fit and previous measurements of (gray, dashed line) the $\psi(4160)$ [4] and (black, dotted line) the $Y(4260)$ [21] states.

BESIII also got the similar result

$M(D_s^{*+})+M(D_s^{*-}) = 4214$ MeV

PHYSICAL REVIEW LETTERS **131,** 151903 (2023)

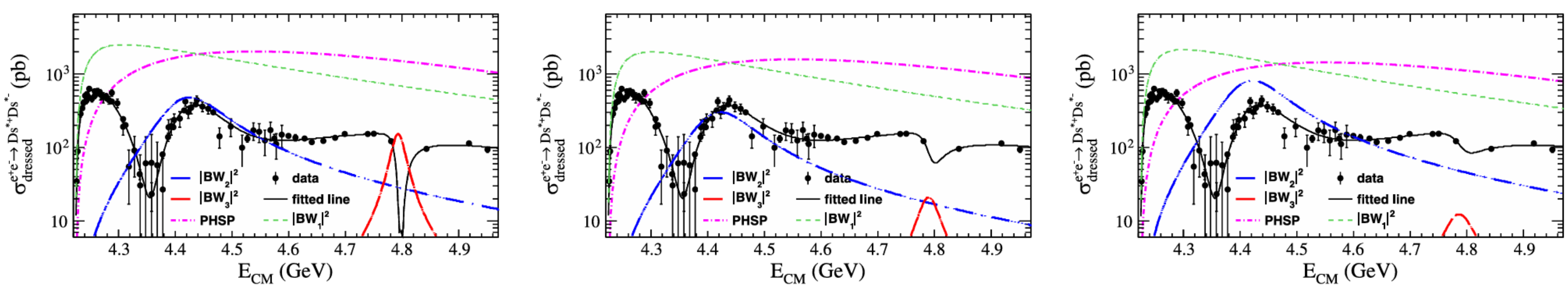
Precise Measurement of the $e^+e^- \to D_s^{*+}D_s^{*-}$ Cross Sections at Center-of-Mass Energies from Threshold to 4.95 GeV

The process $e^+e^- \to D_s^{*+}D_s^{*-}$ is studied with a semi-inclusive method using data samples at center-of-mass energies from threshold to 4.95 GeV collected with the BESIII detector operating at the Beijing Electron Positron Collider. The Born cross sections of the process are measured for the first time with high precision in this energy region. Two resonance structures are observed in the energy-dependent cross sections around 4.2 and 4.4 GeV. By fitting the cross sections with a coherent sum of three Breit-Wigner amplitudes and one phase-space amplitude, the two significant structures are assigned masses of $(4186.8 \pm 8.7 \pm 30)$ and $(4414.6 \pm 3.4 \pm 6.1)$ MeV$/c^2$, widths of $(55 \pm 15 \pm 53)$ and $(122.5 \pm 7.5 \pm 8.1)$ MeV, where the first errors are statistical and the second ones are systematic. The inclusion of a third Breit-Wigner amplitude is necessary to describe a structure around 4.79 GeV.

The BW1 should be $\psi(4220)$ instead of $\psi(4160)$

TABLE I. The fitting results of the dressed cross sections.

	Result 1	Result 2	Result 3
M_1 (MeV$/c^2$)	4186.8 ± 8.7	4194.1 ± 6.8	4195.6 ± 6.5
Γ_1 (MeV)	55 ± 15	61.1 ± 8.5	61.7 ± 7.7
M_2 (MeV$/c^2$)	4414.6 ± 3.4	4411.9 ± 3.2	4411.1 ± 3.2
Γ_2 (MeV)	122.5 ± 7.5	120.2 ± 7.4	119.9 ± 7.3
M_3 (MeV$/c^2$)	4793.3 ± 6.7	4789.7 ± 8.7	4786.0 ± 9.4
Γ_3 (MeV)	27.1 ± 6.5	42 ± 75	60 ± 34

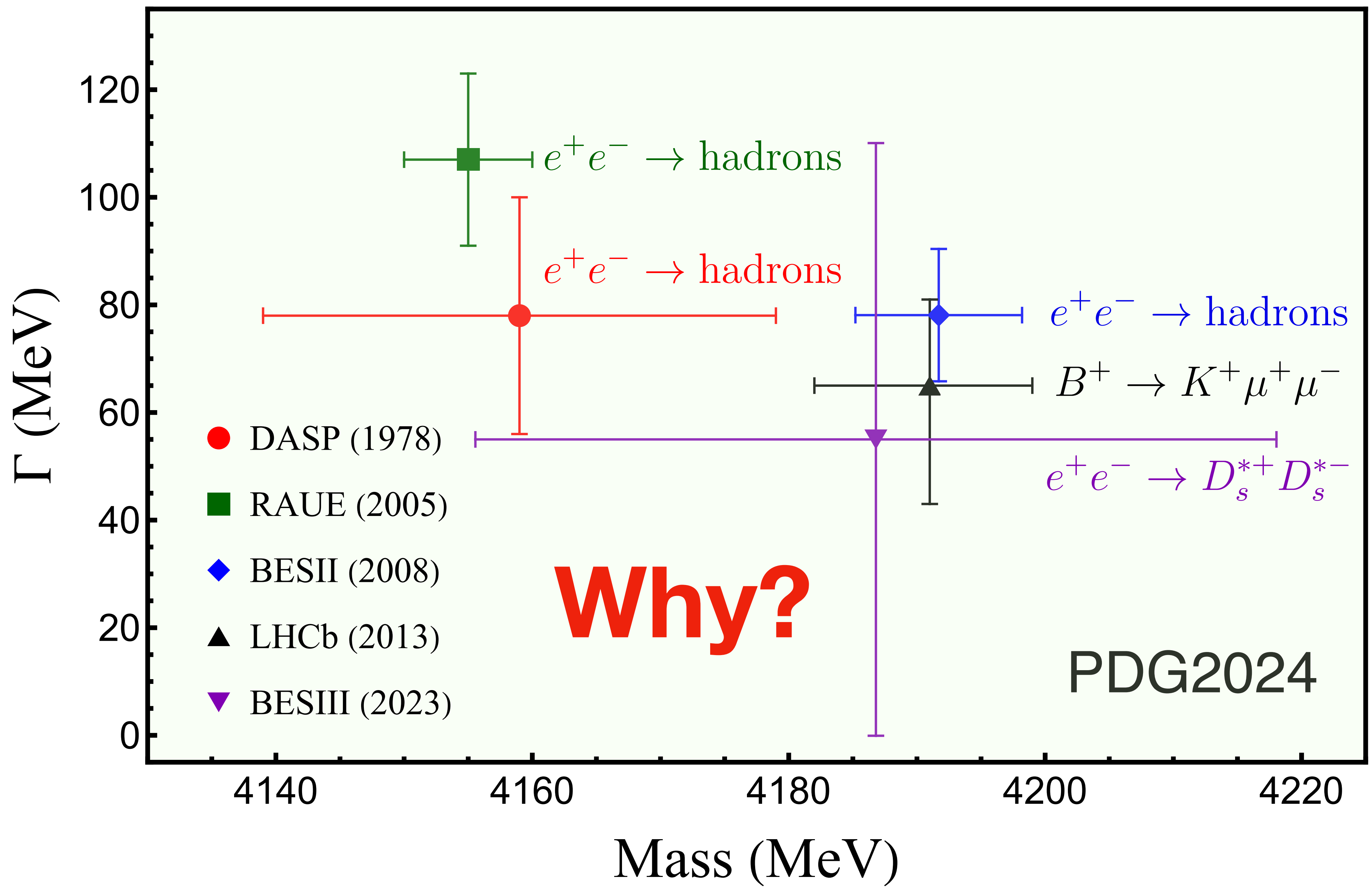


(a) (b) (c)

FIG. 2. Three fitting results for the measured dressed cross sections of $e^+e^- \to D_s^{*+}D_s^{*-}$. The black dots with error bars are for the measured dressed cross sections. In each plot, the black curve represents the fit; the green dashed, blue two-dashed, and red long-dashed ones are for the three BW amplitudes from the fit, respectively, and the pink dot-dashed is for the PHSP contributions.

Resonance parameter for $\psi(4160)$

Different data from different experiments



Reevaluating the resonance parameter

Peng, Bai, Wang, XL, PRD111 (2025) 054023

The decay process $B^+ \to K^+\mu^+\mu^-$ can occur through three distinct mechanisms, where the dimuon pair ($\mu^+\mu^-$) couples to a Z^0 boson, a photon (γ), or a vector resonance. These contributions are represented by the amplitudes $\mathcal{A}^{AV}_{non-res}(Z^0)$, $\mathcal{A}^{V}_{non-res}(Z^0$ and $\gamma)$, and $\mathcal{A}^{n}_{res}$. The subscripts AV and V are used to denote the first two terms, reflecting the axial-vector (AV) and vector (V) nature of the couplings involved. The total amplitude is

$$\mathcal{A}_{Tot} = \mathcal{A}^{AV}_{non-res} + \mathcal{A}^{V}_{non-res} + \sum_n f_n e^{i\delta_n} \mathcal{A}^{n}_{res}, \quad (2)$$

Vector Charmonium

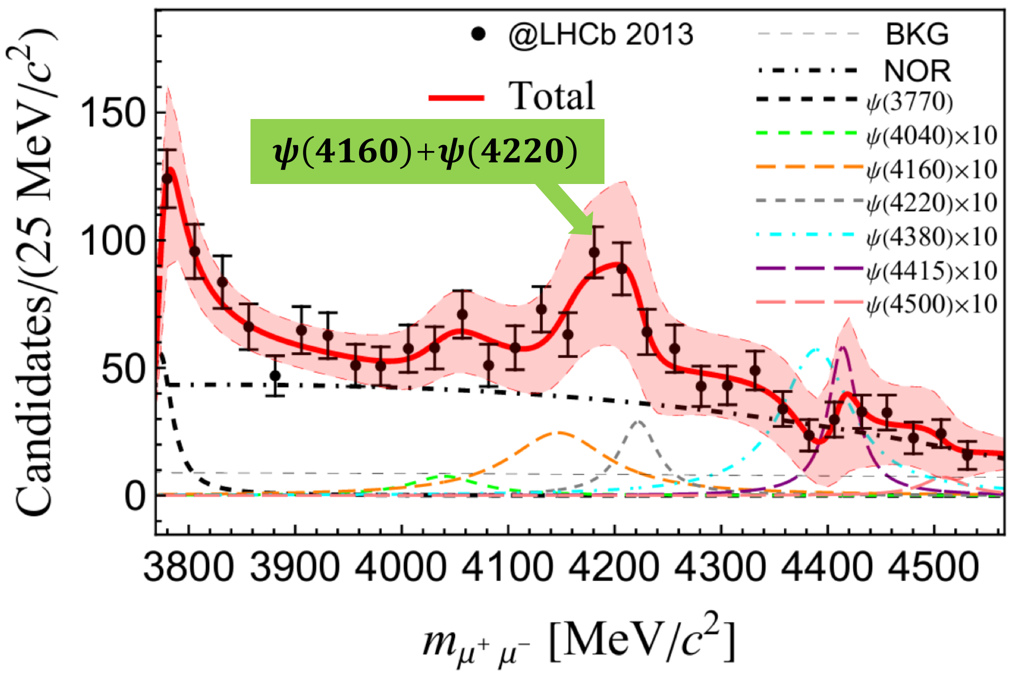


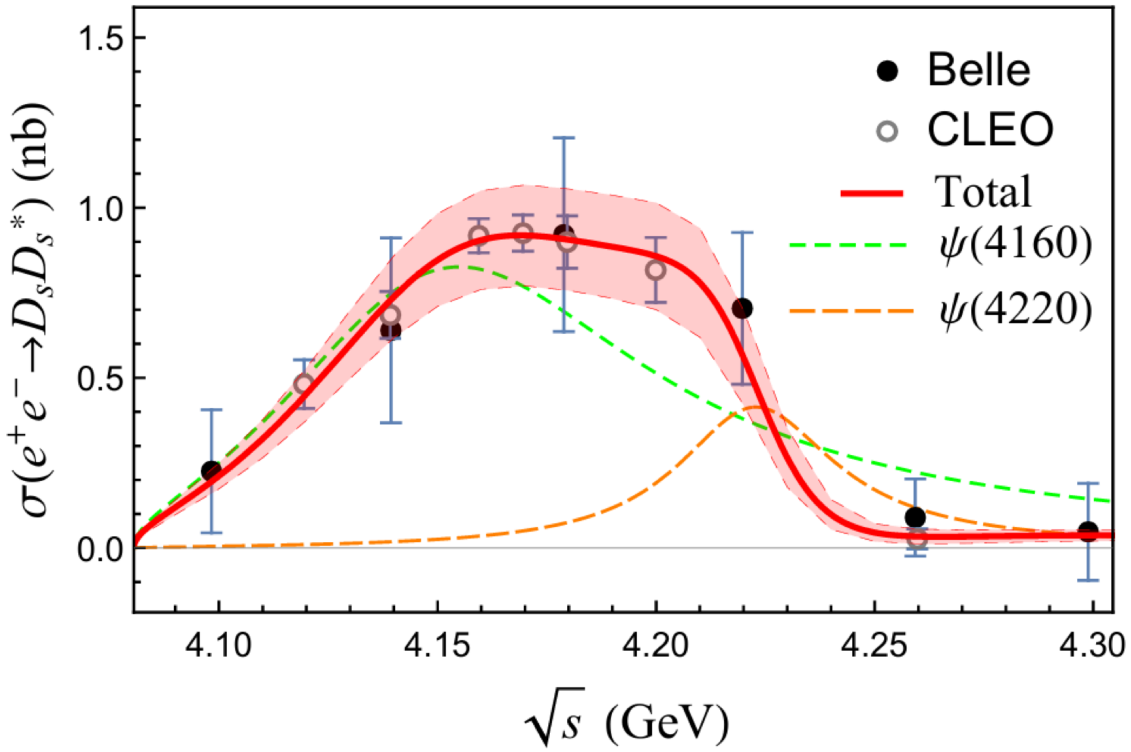
TABLE I: The masses and widths of higher charmonium states in the range of 4.0–4.5 GeV, which were obtained from the theoretical predictions [13–15], as well as some experimental values [3, 4].

States	Mass (MeV)	Γ (MeV)
$\psi(3770)$	3773.7 ± 0.7 [3]	27.2 ± 1.0 [3]
$\psi(4040)$	4040 ± 4 [3]	84 ± 12 [3]
$\psi(4160)$	4159 ± 22 [4]	78 ± 22 [4]
$\psi(4220)$	4222	44
$\psi(4380)$	4389	80
$\psi(4415)$	4414	33
$\psi(4500)$	4509	50

TABLE II: The parameter values obtained from fitting the experimental data are as follows. The factors f_i (in units of MeV) are chosen to ensure that the resonance amplitudes have the same dimensions as the nonresonance contribution. The phases δ_i (in radians) correspond to the seven ψ states: $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4220)$, $\psi(4380)$, $\psi(4415)$, and $\psi(4500)$, listed in succession.

Parameters (MeV)	Value	Parameters (rad)	Value
f_1	46.37 ± 2.52	δ_1	0.95 ± 0.05
f_2	4.83 ± 0.33	δ_2	2.30 ± 0.17
f_3	7.12 ± 0.56	δ_3	1.67 ± 0.11
f_4	8.85 ± 0.56	δ_4	4.36 ± 0.32
f_5	9.87 ± 0.74	δ_5	5.66 ± 0.42
f_6	9.29 ± 0.49	δ_6	2.74 ± 0.20
f_7	3.57 ± 0.26	δ_7	5.00 ± 0.30
	$\chi^2/\text{d.o.f.} = 0.90$		

Resonance parameter for $\psi(4160)$



$\psi(4160)+\psi(4220)$

$$\sigma(s) = |\mathrm{BW}_1(s) + \mathrm{BW}_2(s)e^{i\phi}|^2$$

$$\mathrm{BW}(s) = \frac{\sqrt{12\pi\Gamma_\psi^{ee}\Gamma_{\mathrm{tot}}\mathcal{B}(\psi\to D_s\bar{D}_s^*)}}{s - M^2 + iM\Gamma_{\mathrm{R}}}\sqrt{\frac{\mathrm{PS}(\sqrt{s})}{\mathrm{PS}(M)}}$$

TABLE III: The fitting parameters $m_{\psi(4160)}$, $\Gamma_{\psi(4160)}$, Γ_ψ^{ee} and $\mathcal{B}_\psi$ represent mass, total width, di-lepton width and branch ratio of $\psi\to D_s\bar{D}_s^*$, respectively, and ϕ (rad) is the phase between the resonance amplitudes associated with the $\psi(4160)$ and $\psi(4220)$ in the $e^+e^-\to D_s\bar{D}_s^*$ cross section.

Parameters	Best fit	I	II	III	IV
$m_{\psi(4160)}$ (MeV)	4145.76 ± 5.48	4140 (fixed)	4150 (fixed)	4160 (fixed)	4170 (fixed)
$\Gamma_{\psi(4160)}$ (MeV)	104.83 ± 23.71	113.98 ± 24.01	108.78 ± 23.65	127.17 ± 17.65	143.37 ± 25.24
$\Gamma^{ee}_{\psi(4160)}\mathcal{B}_{\psi(4160)}$ (eV)	98.02 ± 26.88	108.43 ± 29.8	109.14 ± 30.04	168.42 ± 35.09	207.29 ± 25.91
$\Gamma^{ee}_{\psi(4220)}\mathcal{B}_{\psi(4220)}$ (eV)	22.09 ± 8.82	23.23 ± 10.00	21.32 ± 10.96	51.12 ± 34.72	66.81 ± 22.22
ϕ (rad)	2.91 ± 0.27	2.90 ± 0.23	3.01 ± 0.30	3.35 ± 0.23	3.25 ± 0.14
χ^2/d.o.f.	0.22	0.31	0.26	0.79	1.88

Peng, Bai, Wang, XL, PRD111 (2025) 054023

Resonance parameter for $\psi(4160)$

Is the 3S-2D mixing strong for the charmonia $\psi(4040)$ and $\psi(4160)$?

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Man, Luo, XL, arXiv:2507.18536

In this work, we revisit the 3S-2D mixing scheme for the charmonia $\psi(4040)$ and $\psi(4160)$. We introduce a coupled-channel mechanism—distinct from the tensor-force contribution in potential models, which alone is insufficient to induce significant mixing—to describe the mixing between these states. Our analysis yields mixing angles of $\theta_1 = 7^\circ$ and $\theta_2 = 10^\circ$, inconsistent with the larger angle inferred from experimental data, such as the di-lectronic widths of the $\psi(4040)$ and $\psi(4160)$. We discuss possible origins of this discrepancy and emphasize the need for future experiments to resolve it. Precise measurements of the resonance parameters and di-lectronic decay widths, via both inclusive and exclusive processes, will be crucial in clarifying this issue.

TABLE I. The obtained 3S-2D mixing angle for the $\psi(4040)$ and $\psi(4160)$.

$\Gamma_{e^+e^-}^{\psi(4040)}$ (keV)	$\Gamma_{e^+e^-}^{\psi(4160)}$ (keV)	Mixing angle
0.86 ± 0.07 [12]	0.83 ± 0.08 [13]	$\phi = -35^\circ, +55^\circ$ [4] [a]
		$\phi = -37^\circ$ [5] [a]
		$\theta = 34.8^\circ, -55.7^\circ$ [6] [a]
	0.48 ± 0.22 [14]	$\theta = 20^\circ$ [9] [b]
		$\phi = 45^\circ$ [10] [c]
		$\phi = -21.1^\circ, 62.6^\circ$ [11] [d]

[a] Extracted from the ratio (1.04) of those two di-electronic widths.
[b] Fitting the di-electronic width of the $\psi(4160)$.
[c] Extracted from the ratio (1.79) of those two di-electronic widths.
[d] Fitting the di-electronic widths of the $\psi(4040)$ and $\psi(4160)$.

[4] K.-T. Chao, Interpretations for the $X(4160)$ observed in the double charm production at B factories, Phys. Lett. B **661**, 348 (2008), arXiv:0707.3982 [hep-ph].

[5] B.-Q. Li and K.-T. Chao, Higher Charmonia and X, Y, Z states with Screened Potential, Phys. Rev. D **79**, 094004 (2009), arXiv:0903.5506 [hep-ph].

[6] A. M. Badalian, B. L. G. Bakker, and I. V. Danilkin, The S-D mixing and di-electron widths of higher charmonium 1^{--} states, Phys. Atom. Nucl. **72**, 638 (2009), arXiv:0805.2291 [hep-ph].

[9] J.-Z. Wang and X. Liu, Confirming the existence of a new higher charmonium $\psi(4500)$ by the newly released data of $e^+e^- \to K^+K^-J/\psi$, Phys. Rev. D **107**, 054016 (2023), arXiv:2212.13512 [hep-ph].

[10] C. A. Bokade and Bhaghyesh, Conventional and XYZ charmonium states in a relativistic screened potential model, Phys. Rev. D **111**, 014030 (2025), arXiv:2408.06759 [hep-ph].

[11] Z. Zhao, K. Xu, A. Limphirat, W. Sreethawong, N. Tagsinsit, A. Kaewsnod, X. Liu, K. Khosonthongkee, S. Cheedket, and Y. Yan, Mass spectrum of 1^{--} heavy quarkonium, Phys. Rev. D **109**, 016012 (2024), arXiv:2304.06243 [hep-ph].

Resonance parameter for $\psi(4160)$

3S-2D Mixing scheme

$$\begin{pmatrix} |\psi'_{3S\text{-}2D}\rangle \\ \psi''_{3S\text{-}2D}\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\psi(3^3S_1)\rangle \\ |\psi(2^3D_1)\rangle \end{pmatrix}$$

$$\det \begin{vmatrix} M_S^0 + \Delta M_S(M) - M & \langle\psi_S|H_\mathrm{T}|\psi_D\rangle + \Delta M_{SD}(M) \\ \langle\psi_D|H_\mathrm{T}|\psi_S\rangle + \Delta M_{SD}(M) & M_D^0 + \Delta M_D(M) - M \end{vmatrix} = 0.$$

- **Tensor term in potential model**
- **Coupled channel mechanism**

$$H_T(r) = \frac{4\alpha_s}{3r_{ij}^3} S_{ij},$$

$$S_{ij} = \frac{3\mathbf{S}_i \cdot \mathbf{r}_{ij}\mathbf{S}_j \cdot \mathbf{r}_{ij}}{r_{ij}^2} - \mathbf{S}_i \cdot \mathbf{S}_j,$$

$$\theta = 0.3^\circ$$

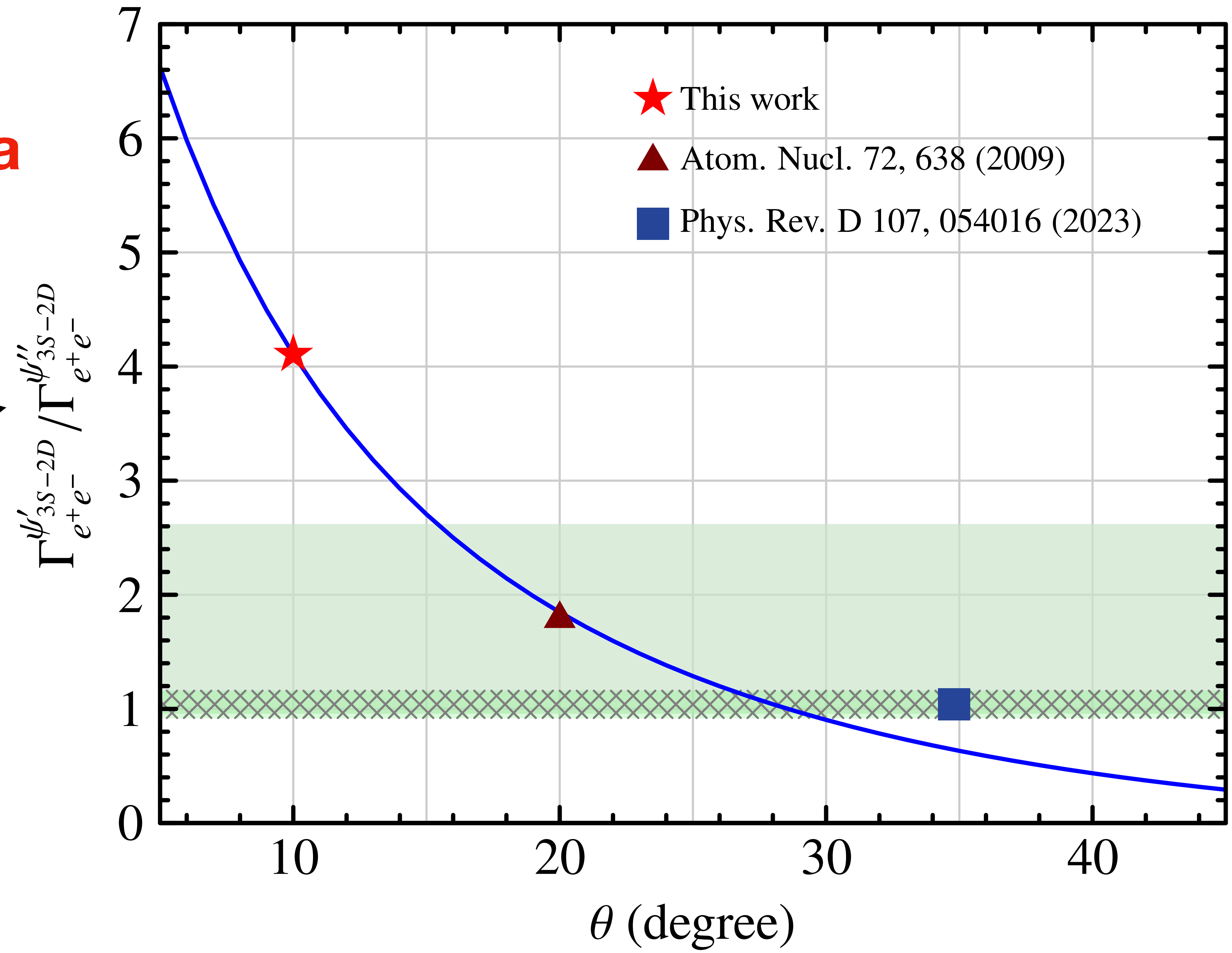
TABLE III. The $3S$-$2D$ mixing angles for $\psi'_{3S\text{-}2D}$ and $\psi''_{3S\text{-}2D}$ are induced by the coupled channel effects. The mixing states are expressed as $C_{S1(2)}|\psi(3^3S_1)\rangle + C_{D1(2)}|\psi(2^3D_1)\rangle$.

States	$C_{S1(2)}$	$C_{D1(2)}$	Mixing angle
$\psi'_{3S\text{-}2D}$	−0.992	0.128	$\theta_1 = 7^\circ$
$\psi''_{3S\text{-}2D}$	0.180	0.984	$\theta_2 = 10^\circ$

Man, Luo, XL, arXiv:2507.18536

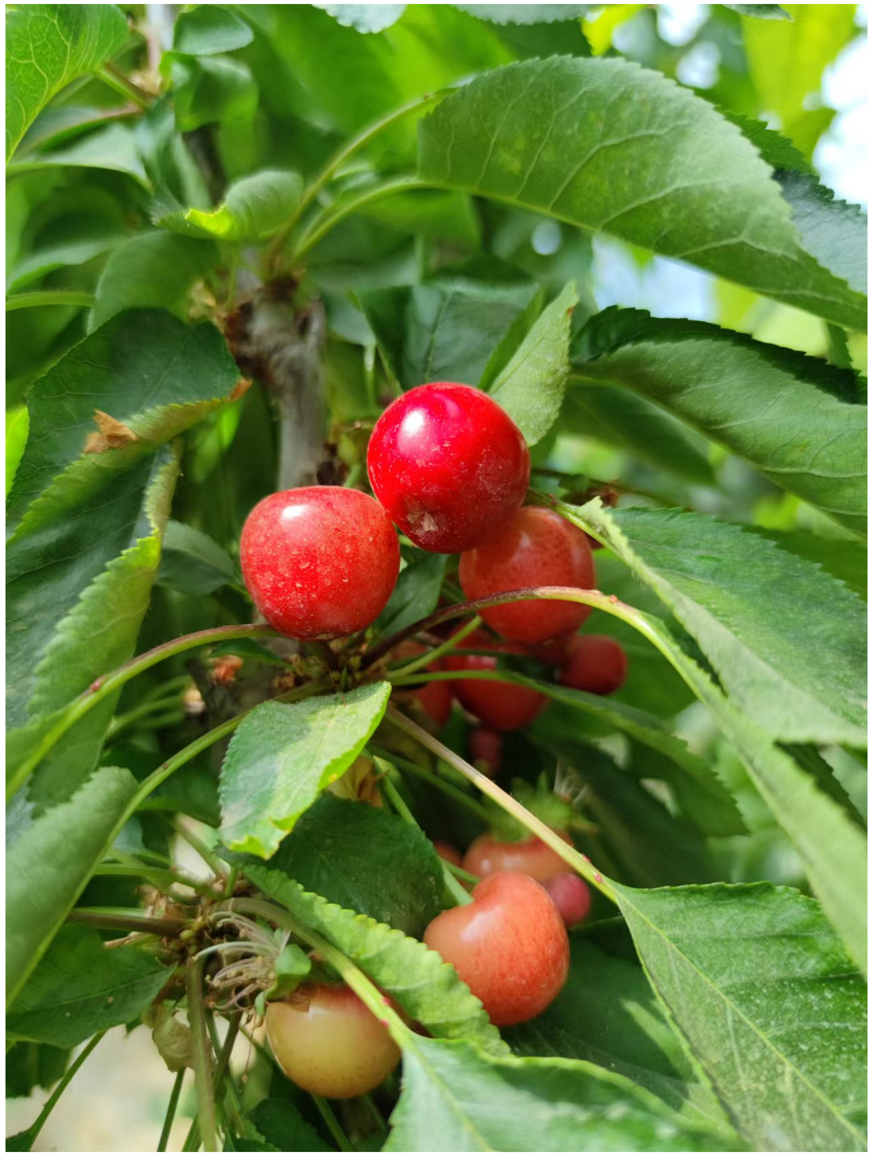
Resonance parameter for $\psi(4160)$

We need
more data
to test it!



Peng, Bai, Wang, XL, PRD111 (2025) 054023

2 Decoding Y(10750)



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Observation of a new structure near 10.75 GeV in the energy dependence of the $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ cross sections

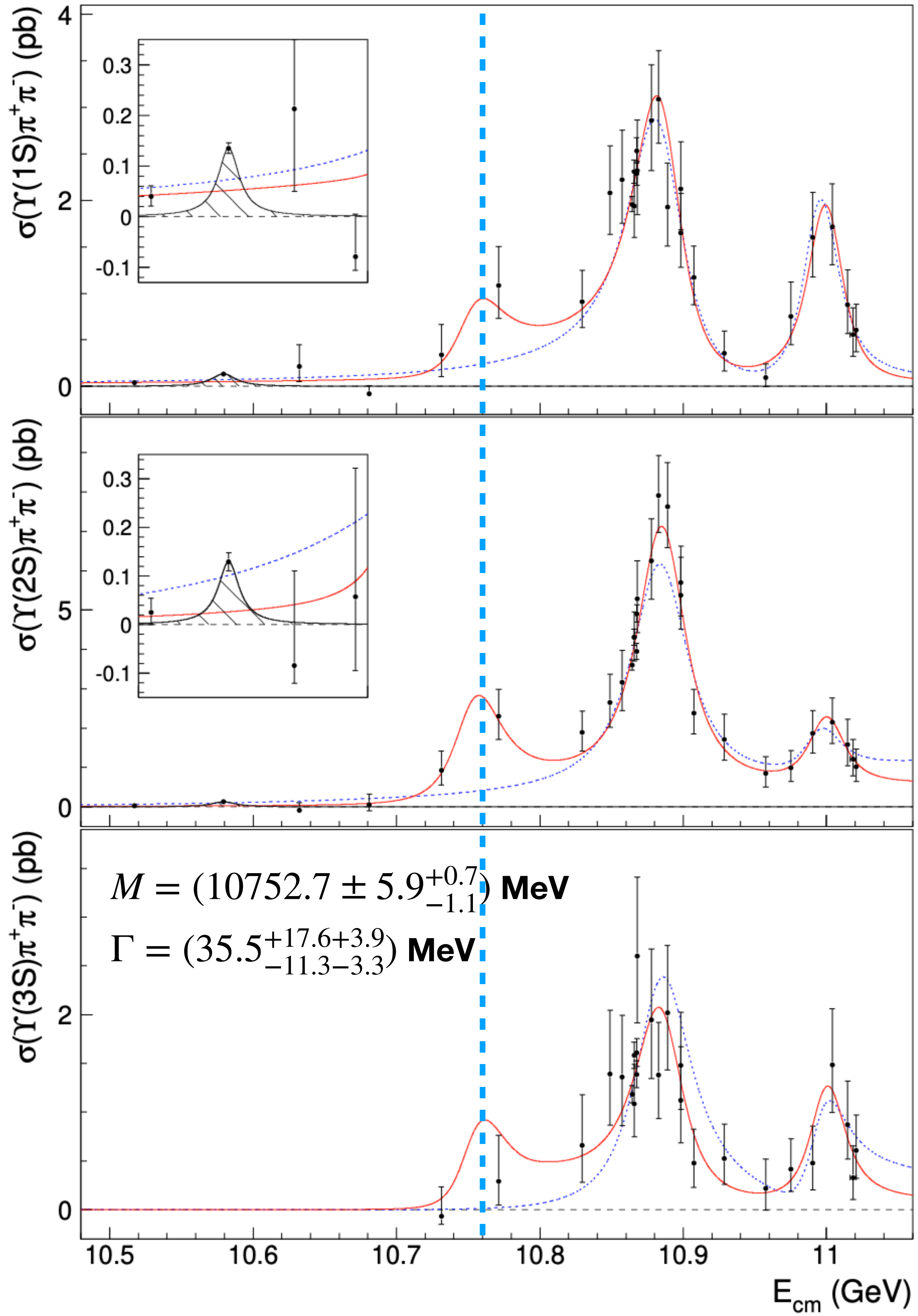
JHEP 10 (2019) 220

The BELLE collaboration

	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$	$23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$	$35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$

When treating the $\Upsilon(10753)$ as a conventional bottomonium state, we have to face a serious problem. The calculation of the mass spectrum of the bottomonium family [18–22] shows that the predicted masses of $\Upsilon(4S)$, $\Upsilon(3D)$, $\Upsilon(5S)$, and $\Upsilon(4D)$ are around (10607–10640) MeV, (10653–10717) MeV, (10818–10878) MeV, and (10853–10928) MeV, respectively. Obviously, the mass of the observed $\Upsilon(10753)$ cannot fall into these predicted mass ranges, which makes it difficult to assign the $\Upsilon(10753)$ to a bottomonium state. Naturally, the exotic state explanations [12–15] were given as a way to solve this mass problem.

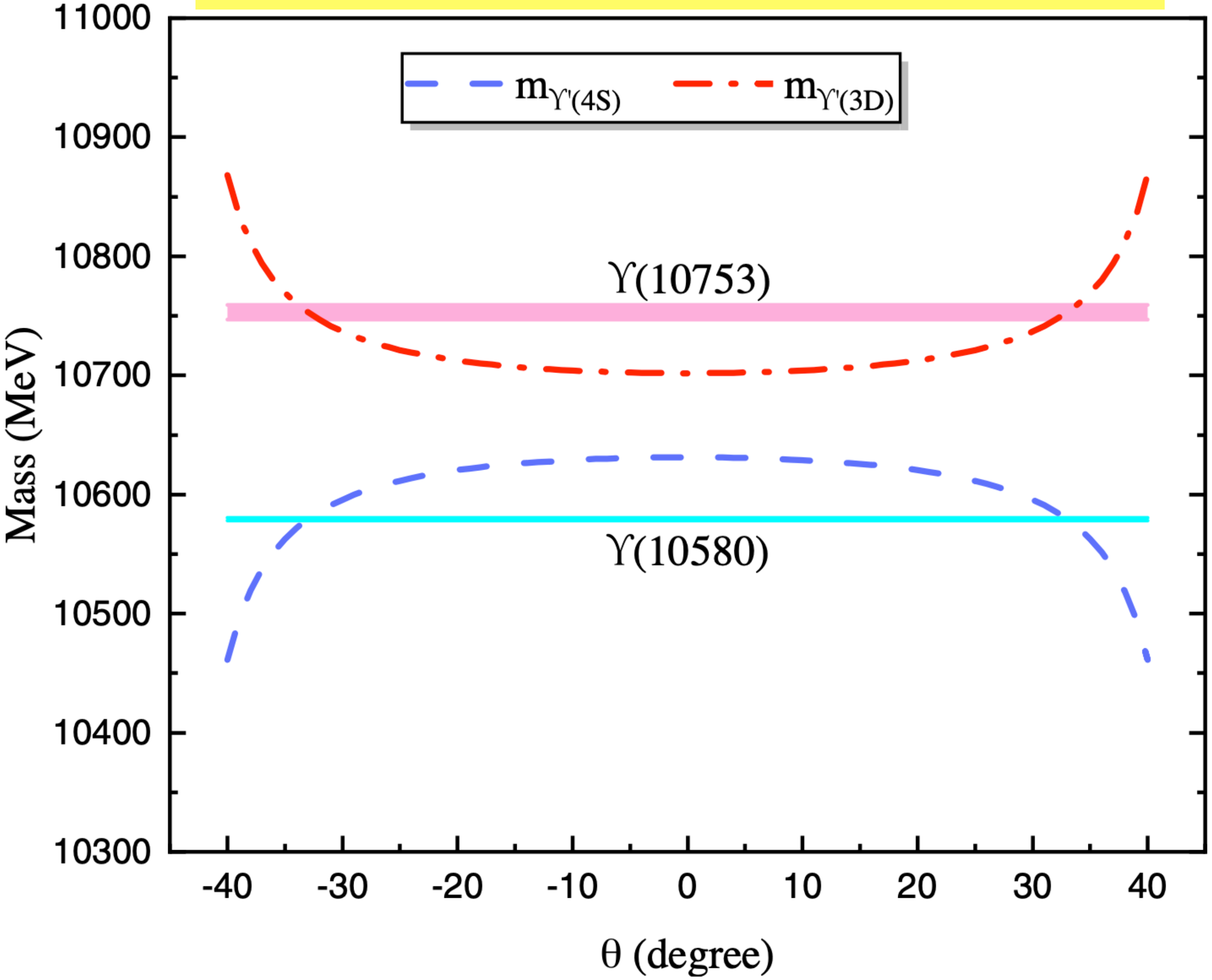
PRD104 (2021) 034036.pdf



The 4S-3D mixing scheme

$$\begin{pmatrix} \Upsilon'_{4S} \\ \Upsilon'_{3D} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \Upsilon_{4S} \\ \Upsilon_{3D} \end{pmatrix}$$

Li, Bai, Huang, XL, PRD104 (2021) 034036

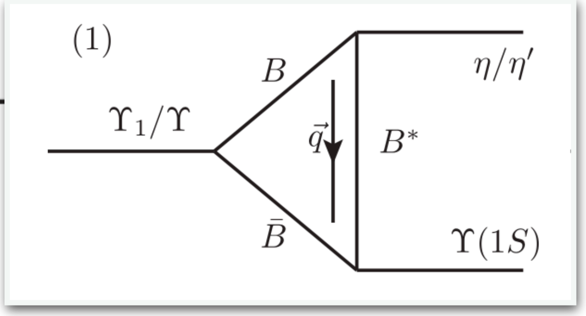


$$m^2_{\Upsilon'(4S)} = \frac{1}{2}\Big[m^2_{\Upsilon(4S)} + m^2_{\Upsilon(3D)} - \sqrt{(m^2_{\Upsilon(4S)} - m^2_{\Upsilon(3D)})^2\ \sec^2 2\theta}\Big],$$

$$m^2_{\Upsilon'(3D)} = \frac{1}{2}\Big[m^2_{\Upsilon(4S)} + m^2_{\Upsilon(3D)} + \sqrt{(m^2_{\Upsilon(4S)} - m^2_{\Upsilon(3D)})^2\ \sec^2 2\theta}\Big],$$

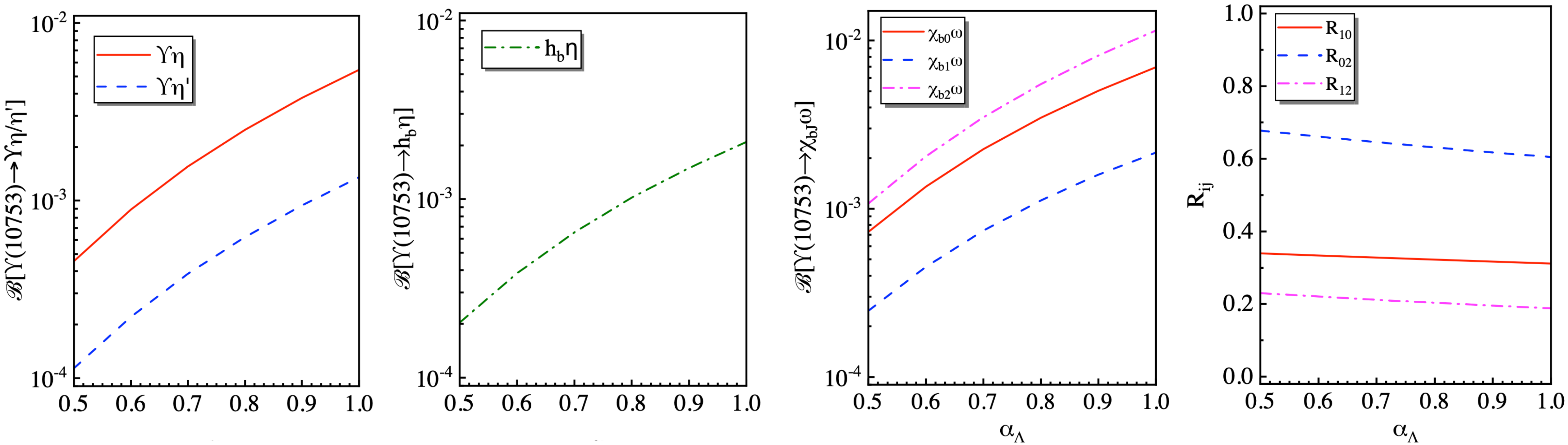
$Y(10750)$ still can be a bottomonium

PHYSICAL REVIEW D **104**, 034036 (2021)



Hidden-bottom hadronic decays of $\Upsilon(10753)$ with a $\eta^{(\prime)}$ or ω emission

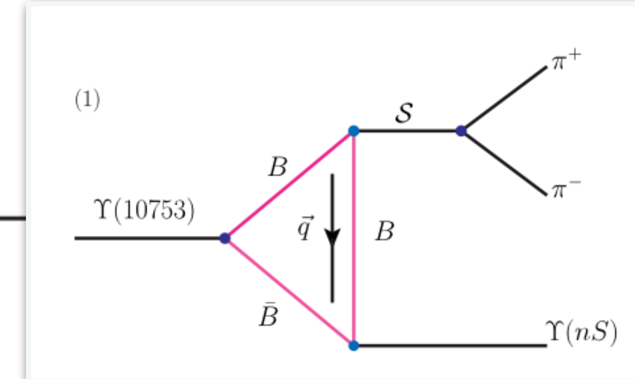
Yu-Shuai Li,[1,2,§] Zi-Yue Bai,[1,2,†] Qi Huang,[3,4,‡] and Xiang Liu[1,2,4,*]



$$\mathcal{B}[\Upsilon(10753)\to\Upsilon(1S)\eta] = (0.46\text{–}5.46)\times10^{-3},$$
$$\mathcal{B}[\Upsilon(10753)\to\Upsilon(1S)\eta'] = (0.11\text{–}1.35)\times10^{-3},$$
$$\mathcal{B}[\Upsilon(10753)\to h_b(1P)\eta] = (0.20\text{–}2.09)\times10^{-3}.$$

$$\mathcal{B}[\Upsilon(10753)\to\chi_{b0}\omega] = (0.73\text{–}6.94)\times10^{-3},$$
$$\mathcal{B}[\Upsilon(10753)\to\chi_{b1}\omega] = (0.25\text{–}2.16)\times10^{-3},$$
$$\mathcal{B}[\Upsilon(10753)\to\chi_{b2}\omega] = (1.08\text{–}11.5)\times10^{-3}.$$

PHYSICAL REVIEW D **105**, 074007 (2022)



$\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$ decays induced by hadronic loop mechanism

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In this work, we investigate the $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$ ($n = 1, 2, 3$) processes by considering the hadronic loop mechanism, where $\Upsilon(10753)$ is assigned to a conventional bottomonium in the $4S$-$3D$ mixing scheme. Our results of the concerned processes own considerable branching ratios, which can reach up to the order of magnitude of 10^{-4}–10^{-3}. We indicate that the measured $\Gamma_{e^+e^-} \times \mathcal{B}[\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-]$ values given by Belle can be reproduced well. This fact supports the former bottomonium assignment to the $\Upsilon(10753)$ in the $4S$-$3D$ mixing scheme. Obviously, it is a good opportunity for the ongoing Belle II experiment if the predicted result in this work can be tested further.

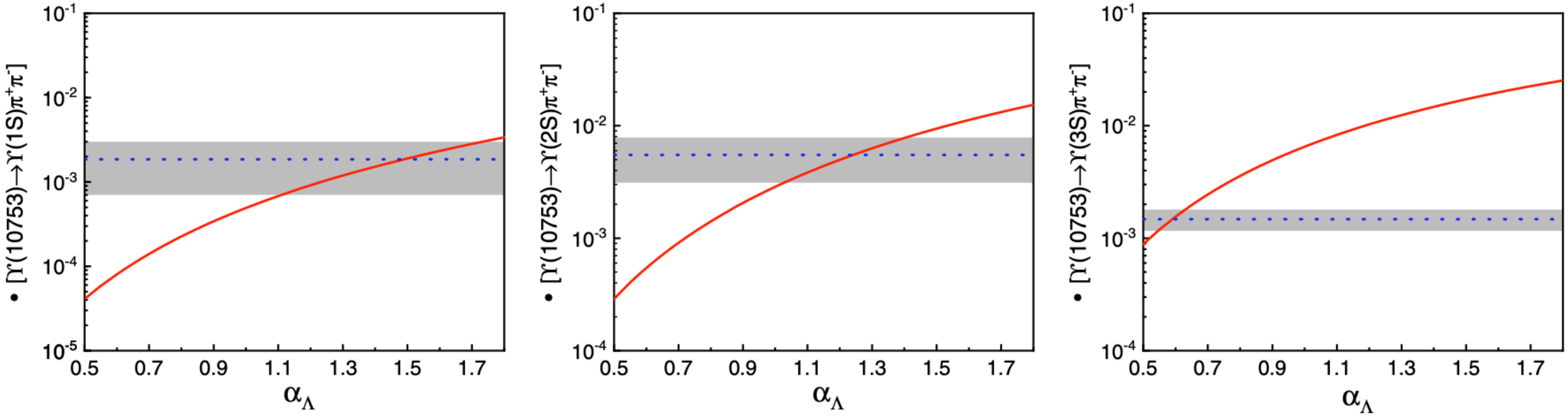


FIG. 2. The α_Λ dependence of the branching ratios $\mathcal{B}[\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-]$ ($n = 1, 2, 3$). Here, the red solid lines are our predicted values by the hadronic loop mechanism, while the LT Gray bands with the blue dotted lines represent the extracted ones with errors. We should indicate that the common α_Λ range is fixed as $0.5 < \alpha_\Lambda < 1.8$ for the discussed transitions since α_Λ is of order 1 as suggested in Ref. [35].

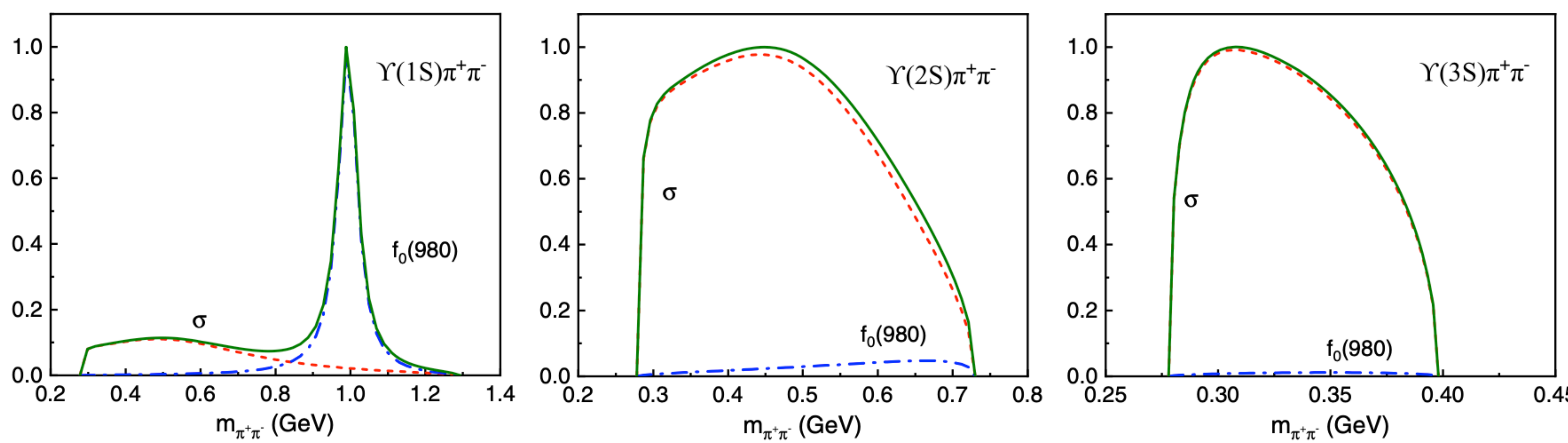
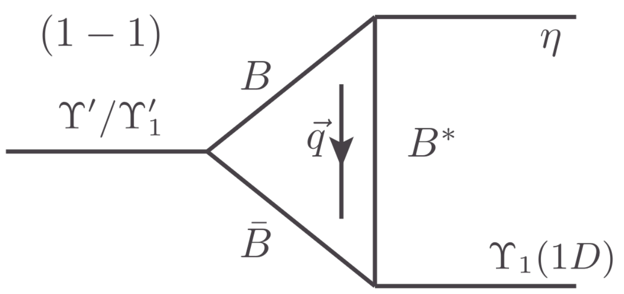


FIG. 4. The line shapes of the di-pion invariant mass spectrum distributions $d\Gamma[\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-]/dm_{\pi^+\pi^-}$ ($n = 1, 2, 3$) with the maximum being normalized to 1. Here, the red dashed line and blue dash-dot line correspond to the contributions from σ and $f_0(980)$, respectively, and the blue solid line corresponds to the total contribution.

PHYSICAL REVIEW D **105,** 114041 (2022)



Investigating the $\Upsilon(10753) \to \Upsilon(1^3D_J)\eta$ transitions

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[2]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
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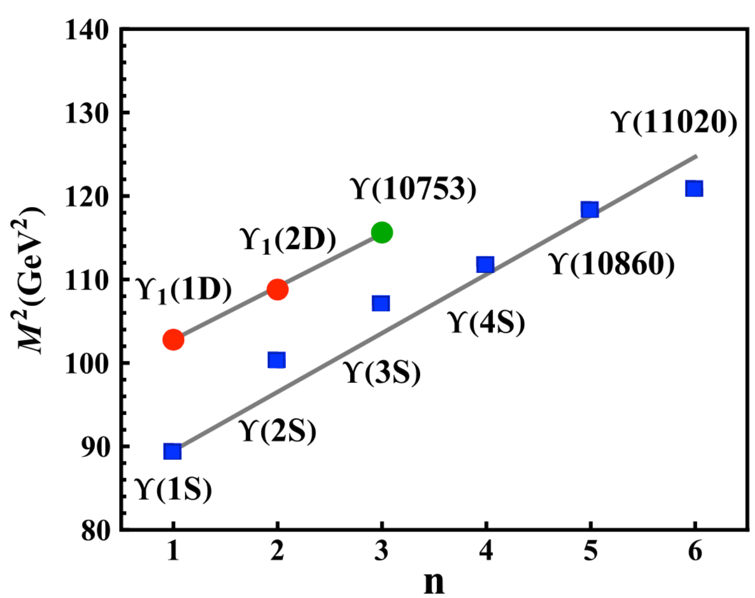
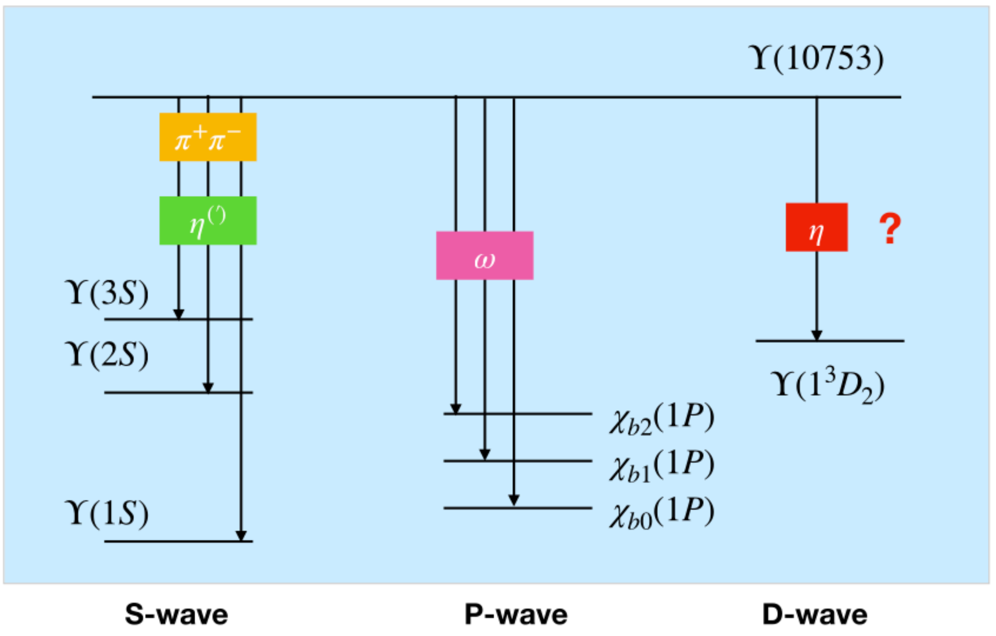
In this work we investigate the $\Upsilon(10753) \to \Upsilon(1^3D_J)\eta$ ($J = 1, 2, 3$) processes, where the $\Upsilon(10753)$ is assigned as a conventional bottomonium under the $4S$–$3D$ mixing scheme. Our result shows that the concerned processes have considerable branching ratios, i.e., branching ratios $\mathcal{B}[\Upsilon(10753) \to \Upsilon(1^3D_1)\eta]$ and $\mathcal{B}[\Upsilon(10753) \to \Upsilon(1^3D_2)\eta]$ can reach up to the order of magnitude of 10^{-4}–10^{-3}, while $\mathcal{B}[\Upsilon(10753) \to \Upsilon(1^3D_3)\eta]$ is around 10^{-6}–10^{-5}. With the running of Belle II, it is a good opportunity for finding out the concerned hidden-bottom hadronic decays.

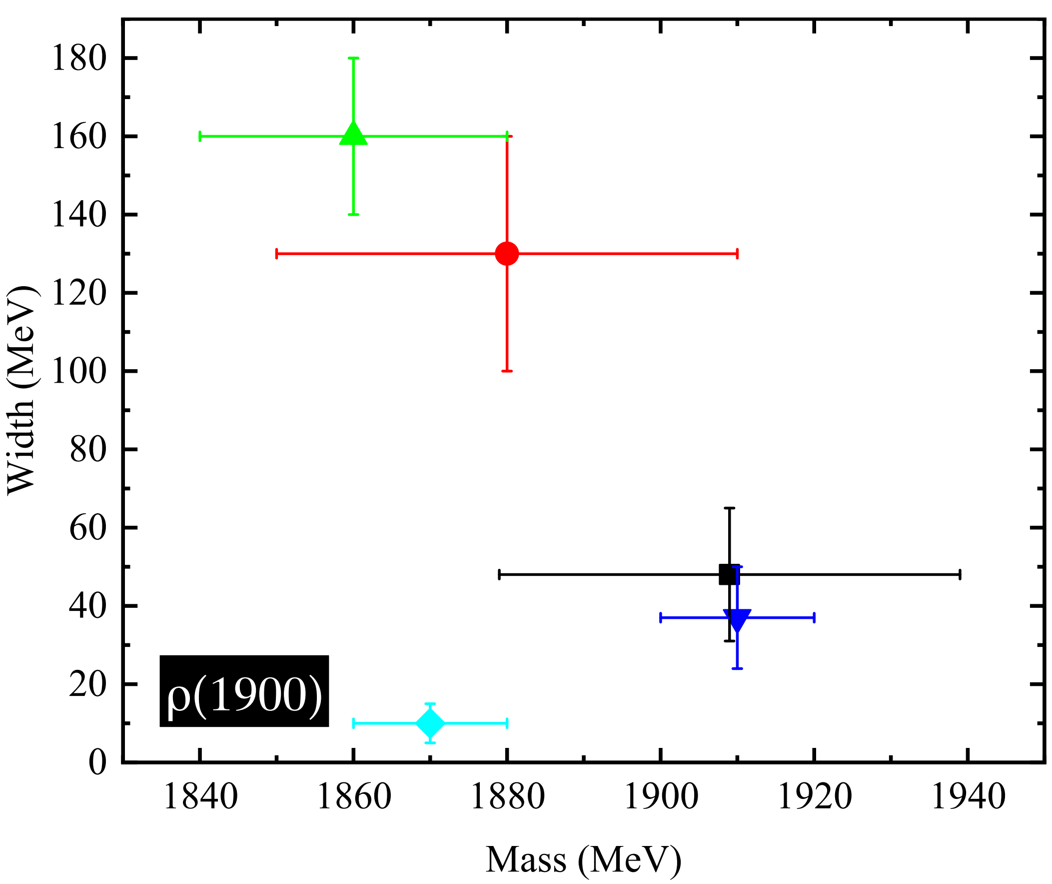


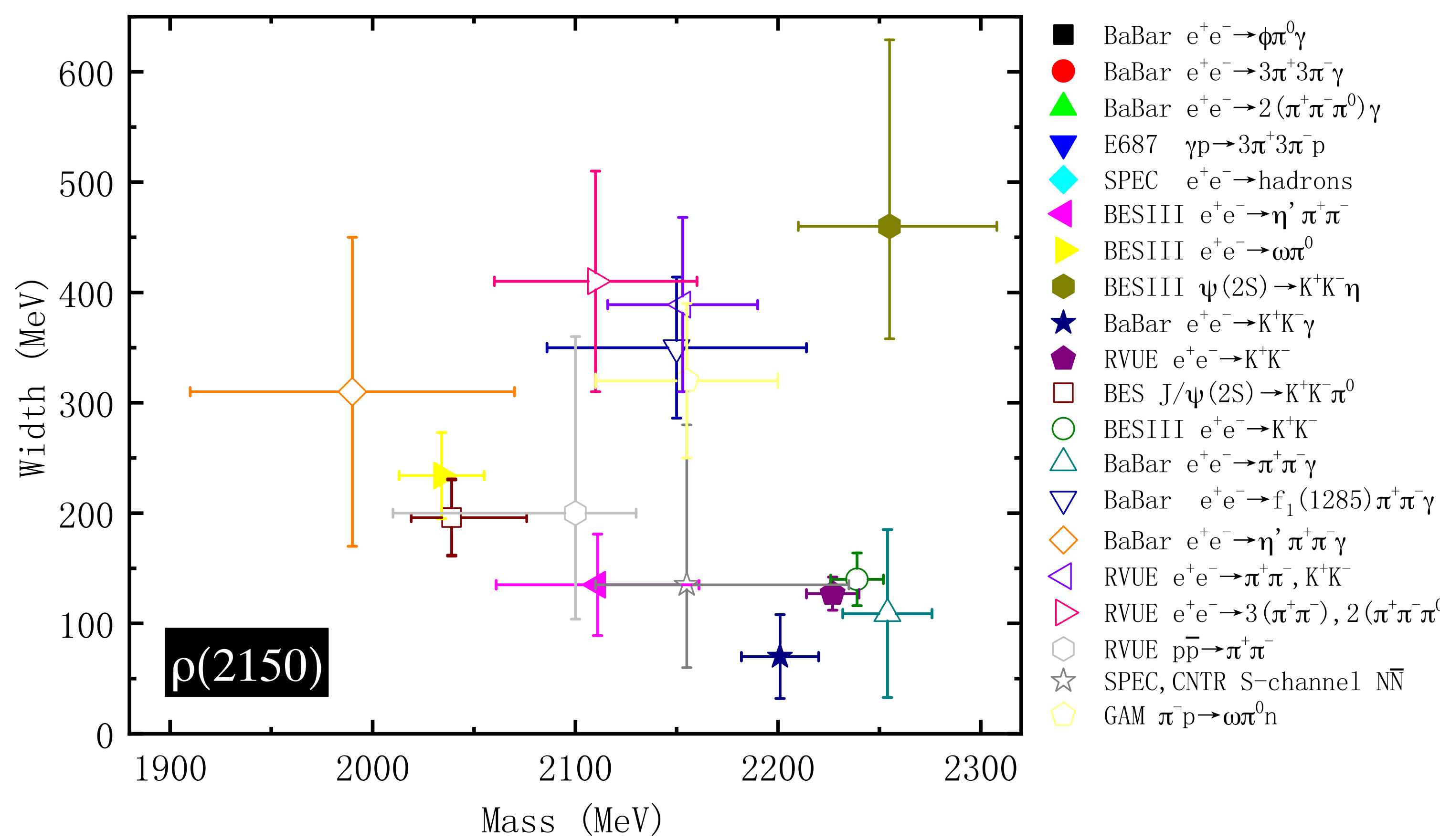


3

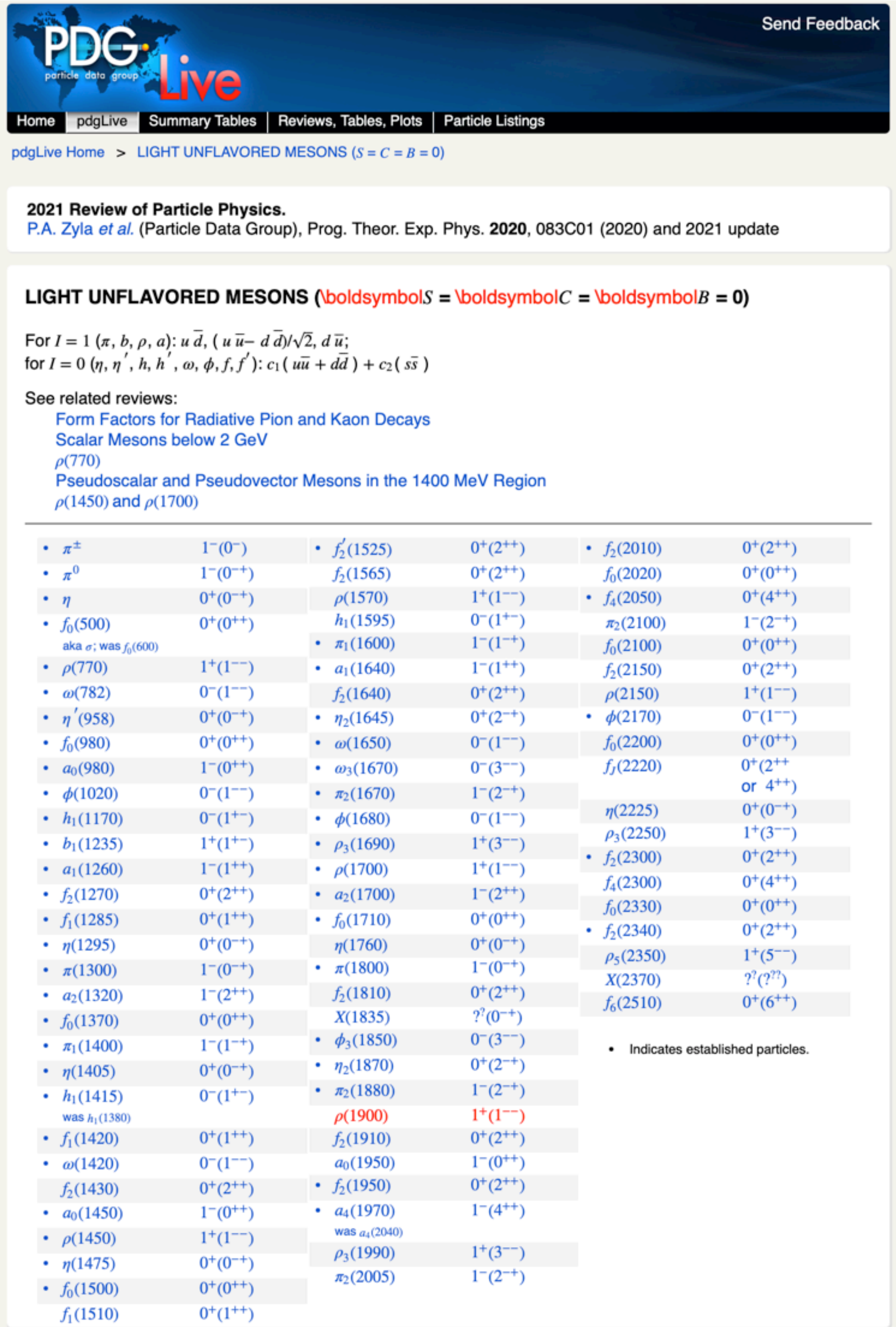
The reported Y states around 2 GeV and light flavor vector mesons

Light flavor vector meson family is far from being established





A key step to construct meson spectroscopy



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pdgLive Home > LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

2021 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

LIGHT UNFLAVORED MESONS (\boldsymbol$S$ = \boldsymbol$C$ = \boldsymbol$B$ = 0)

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ ($\eta, \eta', h, h', \omega, \phi, f, f'$): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

See related reviews:
- Form Factors for Radiative Pion and Kaon Decays
- Scalar Mesons below 2 GeV
- $\rho(770)$
- Pseudoscalar and Pseudovector Mesons in the 1400 MeV Region
- $\rho(1450)$ and $\rho(1700)$

• $\pi^{\pm}$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(500)$ aka σ; was $f_0(600)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $h_1(1415)$ was $h_1(1380)$	$0^-(1^{+-})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$
$f_1(1510)$	$0^+(1^{++})$

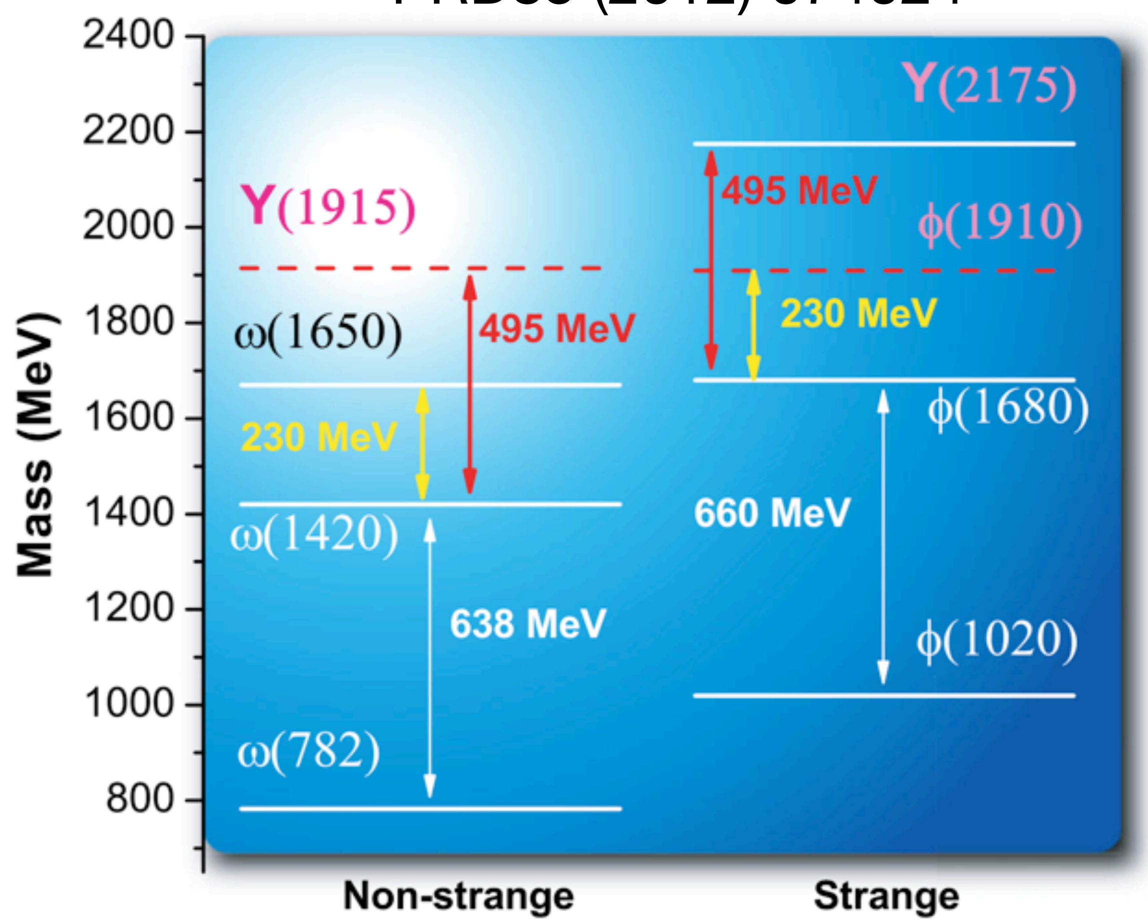
• $f_2'(1525)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$
$h_1(1595)$	$0^-(1^{+-})$
• $\pi_1(1600)$	$1^-(1^{-+})$
• $a_1(1640)$	$1^-(1^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$
• $\omega(1650)$	$0^-(1^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$
• $\pi_2(1670)$	$1^-(2^{-+})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
• $a_2(1700)$	$1^-(2^{++})$
• $f_0(1710)$	$0^+(0^{++})$
$\eta(1760)$	$0^+(0^{-+})$
• $\pi(1800)$	$1^-(0^{-+})$
$f_2(1810)$	$0^+(2^{++})$
$X(1835)$	$?^?(0^{-+})$
• $\phi_3(1850)$	$0^-(3^{--})$
• $\eta_2(1870)$	$0^+(2^{-+})$
• $\pi_2(1880)$	$1^-(2^{-+})$
$\rho(1900)$	$1^+(1^{--})$
$f_2(1910)$	$0^+(2^{++})$
$a_0(1950)$	$1^-(0^{++})$
• $f_2(1950)$	$0^+(2^{++})$
• $a_4(1970)$ was $a_4(2040)$	$1^-(4^{++})$
$\rho_3(1990)$	$1^+(3^{--})$
$\pi_2(2005)$	$1^-(2^{-+})$

• $f_2(2010)$	$0^+(2^{++})$
$f_0(2020)$	$0^+(0^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_0(2100)$	$0^+(0^{++})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
• $\phi(2170)$	$0^-(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
$f_0(2330)$	$0^+(0^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$X(2370)$	$?^?(?^{??})$
$f_6(2510)$	$0^+(6^{++})$

• Indicates established particles.

- Light flavor meson: an important group
  - incompleteness
  - Behavior of higher excitations?
- Mess situation of light flavor vector mesons around 2 GeV
  - Overlap of mass spectrum

PRD85 (2012) 074024



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

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

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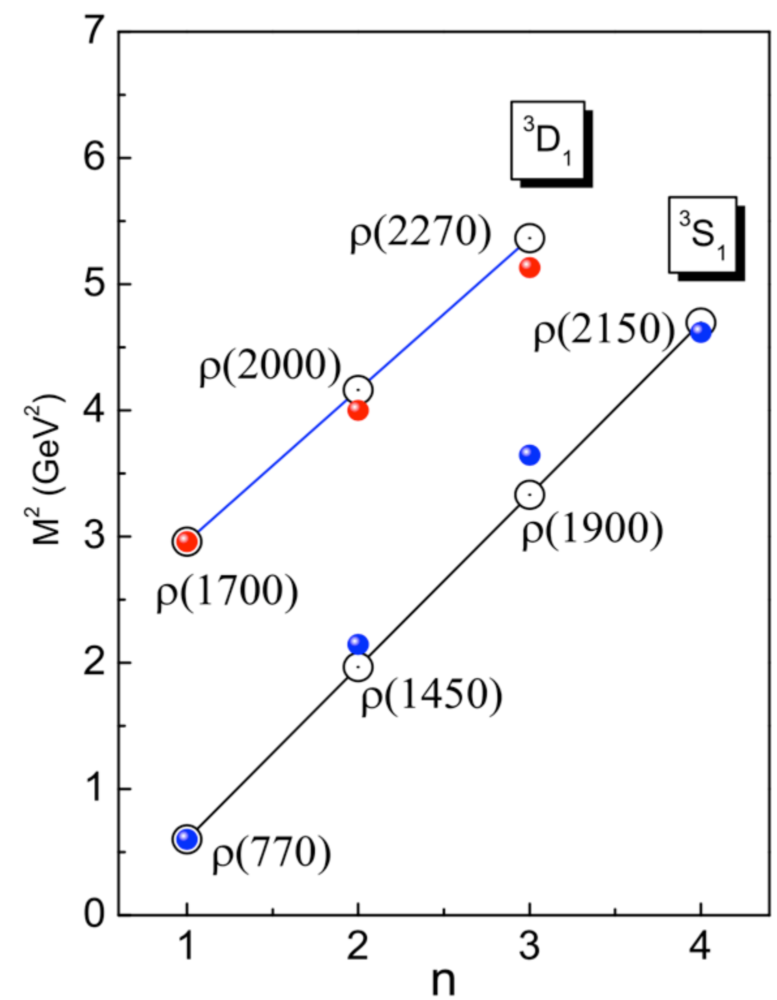
(Received 25 June 2013; published 6 August 2013)

In this work, we systematically study the two-body strong decay of the ρ/ρ_3 states, which are observed and grouped into the ρ/ρ_3 meson family. By performing the phenomenological analysis, the underlying properties of these states are obtained and tested. What is more important is that abundant information of their two-body strong decays is predicted, which will be helpful to further and experimentally study these states.

DOI: 10.1103/PhysRevD.88.034008 PACS numbers: 14.40.Be, 12.38.Lg, 13.25.Jx

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



PHYSICAL REVIEW D **101,** 074022 (2020)

Study of the ω meson family and newly observed ω-like state $X(2240)$

Cheng-Qun Pang,[1,2,*] Ya-Rong Wang,[1,2] Jing-Fu Hu,[1,2] Tian-Jie Zhang,[3] and Xiang Liu[2,4,5,†]

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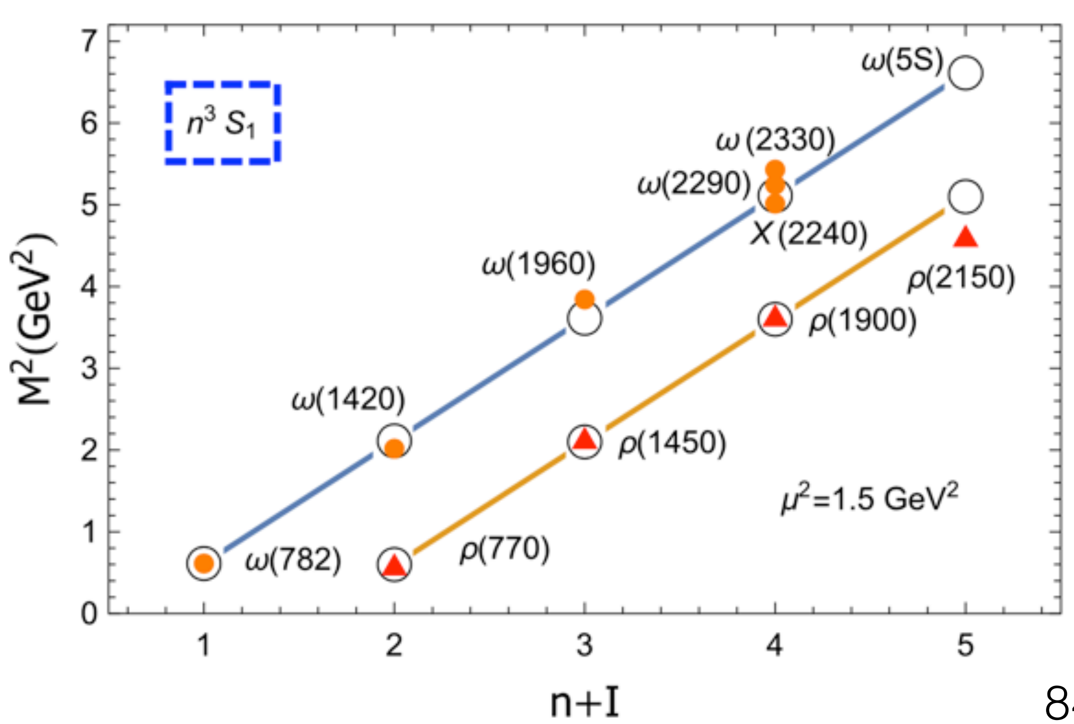
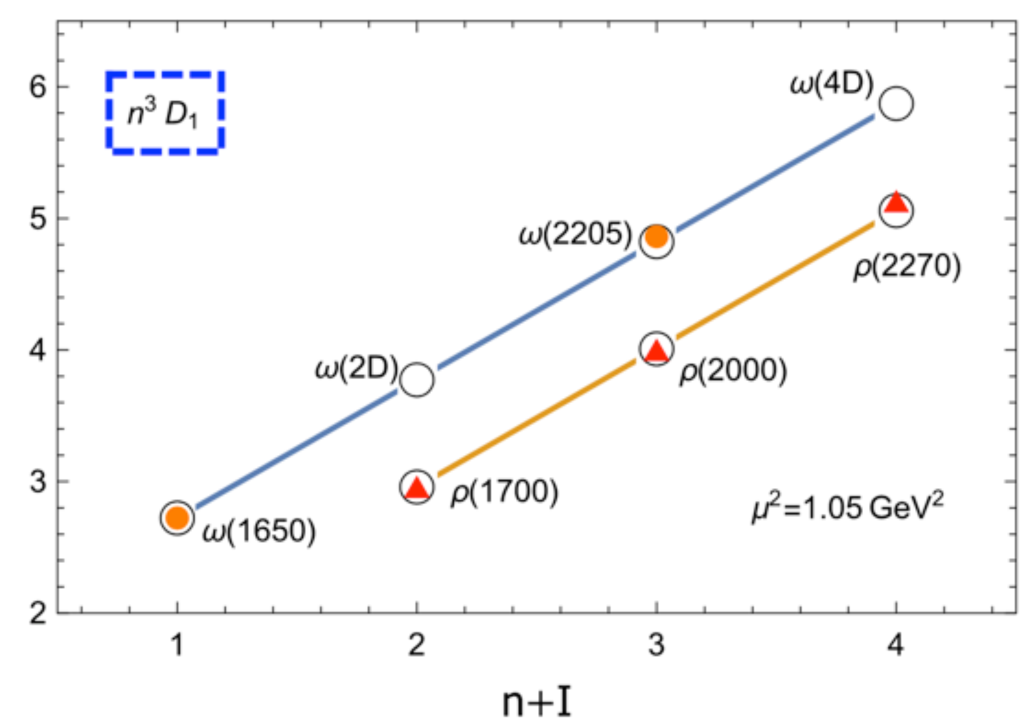
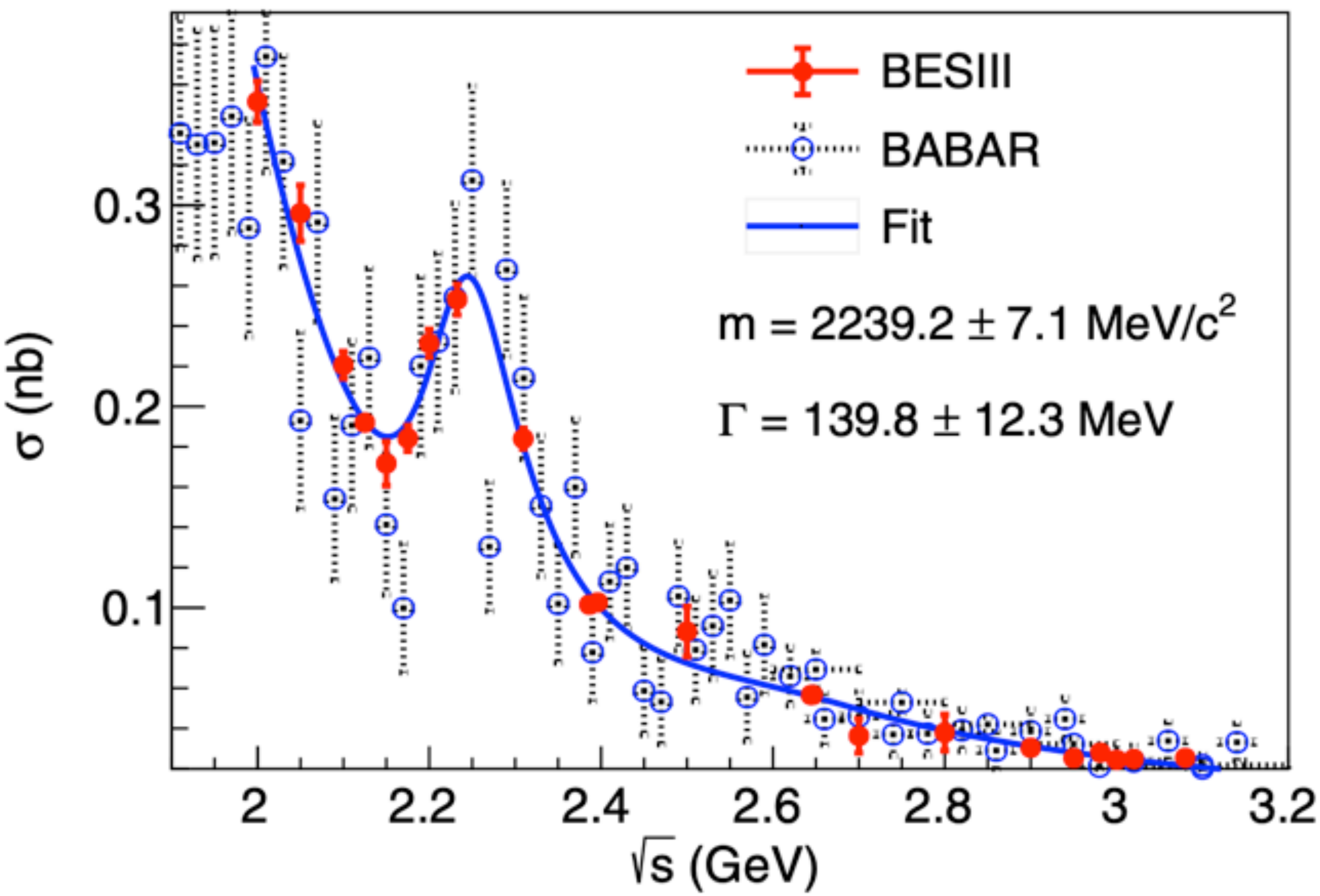
Since the present ω meson family has not been established, in this work we carry out an investigation of the mass spectrum and Okubo-Zweig-Iizuka allowed a two-body strong decay of the S-wave and the D-wave ω mesons, and make the comparison with the experimental data of these reported ω states and the ω-like $X(2240)$ state observed by BESIII. By this study, we not only suggest the possible assignments to these observed ω states under the framework of the ω meson family, but also predict three ω mesons [$\omega(5S)$, $\omega(2D)$, and $\omega(4D)$] which are still missing in experiment. The present study may provide valuable information to further construct the ω meson family. Considering the present running status of BESIII, we also suggest that BESIII should pay more attention to the issue of the ω meson by accumulating more data.





We should emphasize data

BESIII, PRD99 (2019) 032001



Except for resonance parameter, there exist cross section data

基于质量谱和衰变宽度支撑下的截面数据的研究

Toward $e^+e^- \to \pi^+\pi^-$ annihilation inspired by higher ρ mesonic states around 2.2 GeV

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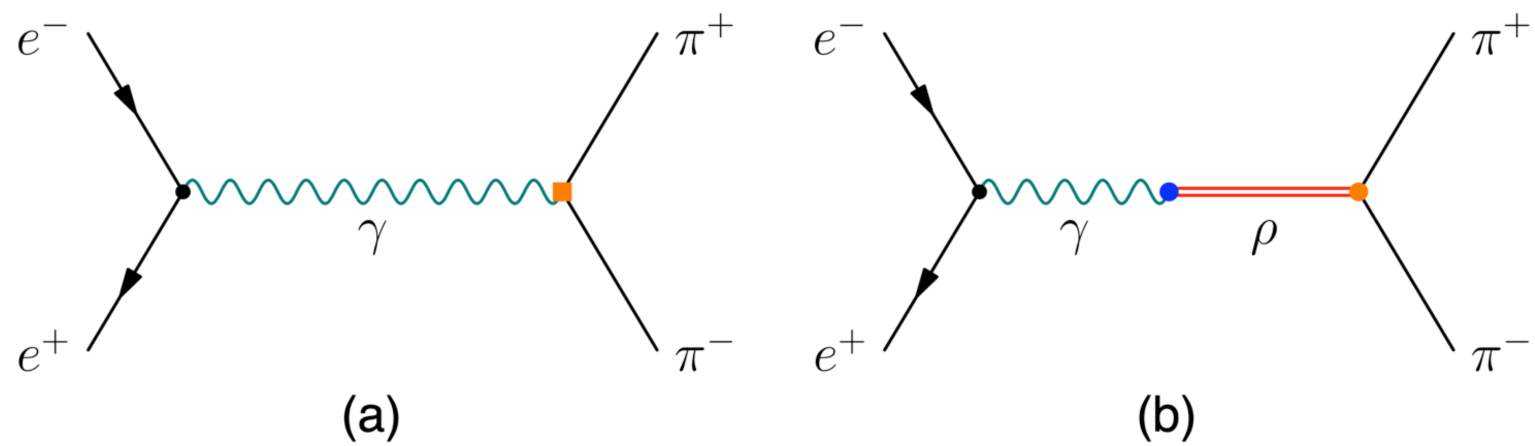
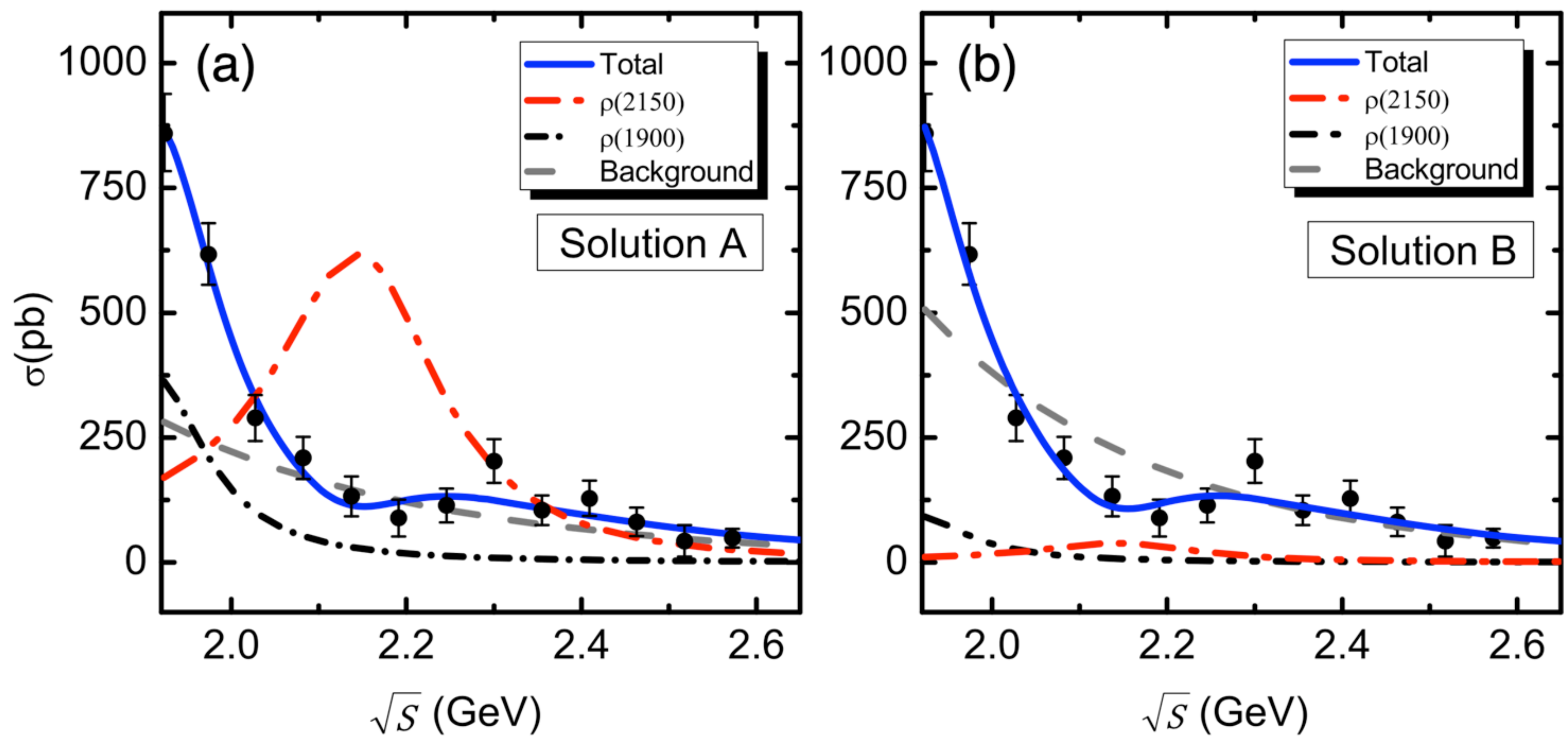
Very recently, the *BABAR* Collaboration indicated that there exists an explicit enhancement structure near 2.2 GeV when focusing on the $e^+e^- \to \pi^+\pi^-$ process again, which inspires our interest in studying the production of higher ρ mesonic states. Since the branching ratio of $\pi^+\pi^-$ channel of D–wave ρ states are much smaller than S–wave states, we choose $\rho(1900)$ and $\rho(2150)$ as the intermediate states in $e^+e^- \to \pi^+\pi^-$, where $\rho(1900)$ and $\rho(2150)$ are treated as $\rho(3S)$ and $\rho(4S)$ states, respectively. Our result indicates that the *BABAR*'s data of $e^+e^- \to \pi^+\pi^-$ around 2 GeV can be depicted well, which shows that this enhancement structure near 2.2 GeV existing in $e^+e^- \to \pi^+\pi^-$ can be due to the contribution from two ρ mesons, $\rho(1900)$ and $\rho(2150)$. Additionally, this conclusion can be enforced by the consistence of the extracted values of $\Gamma_{e^+e^-}\mathcal{B}(\pi^+\pi^-)$ of $\rho(1900)$ and $\rho(2150)$ in the whole fitting processes and the corresponding theoretical calculations. The present study of $e^+e^- \to \pi^+\pi^-$ data may provide valuable information to establish the ρ meson family.

PHYSICAL REVIEW D **102**, 034037 (2020)

挑选合适的矢量介子态

作为输入量的双轻子宽度和dipion宽度被限定





PHYSICAL REVIEW D **104,** 054045 (2021)

Deciphering the light vector meson contribution to the cross sections of e^+e^- annihilations into the open-strange channels through a combined analysis

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[3]*Key Laboratory for Microstructural Material Physics of Hebei Province, School of Science, Yanshan University, Qinhuangdao 066004, China*
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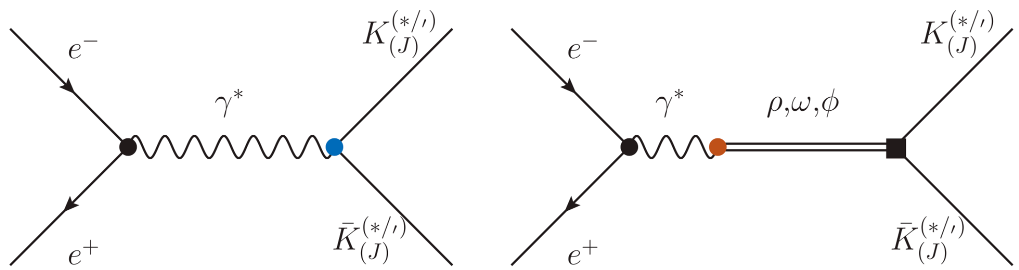
In this work, we perform a combined analysis to the measured data of the cross section of open-strange processes $e^+e^- \to K^+K^-$, $e^+e^- \to K\bar{K}^* +$ c.c., $e^+e^- \to K^{*+}K^{*-}$, $e^+e^- \to K_1(1270)^+K^-$, $e^+e^- \to K_1(1400)^+K^-$, $e^+e^- \to K_2^*(1430)\bar{K} +$ c.c., and $e^+e^- \to K(1460)^+K^-$ with the support of study of hadron spectroscopy. We reveal the contribution of the possible light vector mesons around 2 GeV to reproduce the cross section data of the reported open-strange processes from e^+e^- annihilation which may provide a new perspective to construct the light vector meson family and understand the $Y(2175)$.

以强子谱学为支撑

TABLE IV. The branching ratios of two-body open-strange strong decay and dilepton widths of ρ and ω meson states above 2.0 GeV. Here, the tiny branching ratio is marked as "$\cdots$".

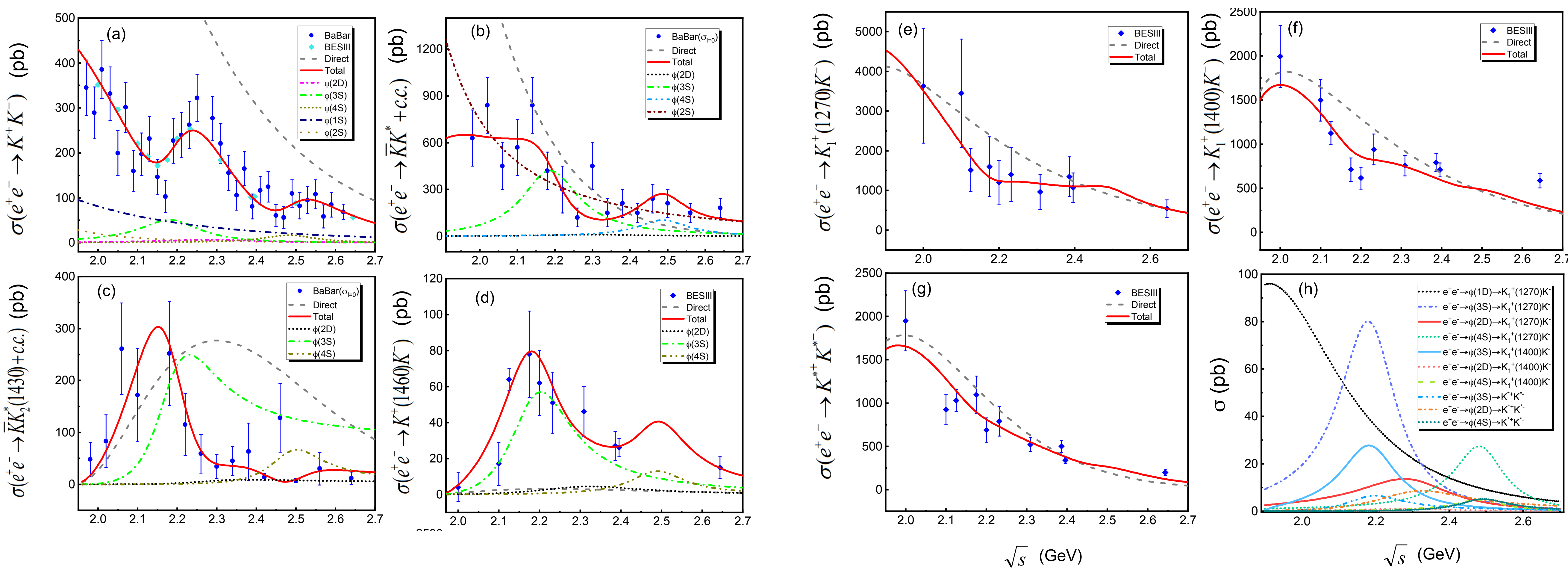
States	$\rho(2D)$	$\rho(4S)$	$\rho(3D)$	$\rho(5S)$	$\omega(2D)$	$\omega(4S)$	$\omega(3D)$	$\omega(5S)$
Mass (GeV)	2.003	2.180	2.283	2.422	2.003	2.180	2.283	2.422
$\Gamma_{e^+e^-}$ (keV)	0.020	0.063	0.016	0.036	0.0022	0.007	0.0018	0.004
$\Gamma_{\rm Total}$ (MeV)	179	102	158	80	181	104	94	69
$\mathcal{B}(KK)$	0.006	0.002	0.002	$\cdots$	0.006	0.002	0.003	$\cdots$
$\mathcal{B}(KK^*)$	0.001	$\cdots$	$\cdots$	$\cdots$	0.001	$\cdots$	$\cdots$	$\cdots$
$\mathcal{B}(K^*K^*)$	$\cdots$	0.003	$\cdots$	0.003	$\cdots$	0.003	0.001	0.003
$\mathcal{B}(KK_1(1270))$	$\cdots$	0.010	$\cdots$	0.004	$\cdots$	0.010	$\cdots$	0.005
$\mathcal{B}(KK^*(1410))$	$\cdots$	0.001	$\cdots$	$\cdots$	$\cdots$	0.001	$\cdots$	$\cdots$
$\mathcal{B}(K^*K_1(1270))$	$\cdots$	0.004	$\cdots$	0.004	$\cdots$	0.004	$\cdots$	0.005
$\mathcal{B}(KK(1460))$	0.002	0.003	0.003	0.001	0.002	0.002	0.005	0.001



(a) (b)

TABLE VI. The fitted parameters in the combined analysis to the experimental data of seven open-strange processes from e^+e^- collisions. The listed phase angles θ_ϕ are in units of radian.

Processes	$f_{\rm Dir}$	a (GeV^{-2})	$\theta_{\phi(1S)}$	$\theta_{\phi(2S)}$	$\theta_{\phi(1D)}$	$\theta_{\phi(3S)}$	$\theta_{\phi(2D)}$	$\theta_{\phi(4S)}$
$e^+e^-\to K^+K^-$	-0.29	0.33	6.09 ± 0.04	0.52 ± 0.06	$\cdots$	2.54 ± 0.02	5.77 ± 0.05	2.80 ± 0.05
$e^+e^-\to K\bar{K}^*+$c.c.	1.95 ± 0.07	0.85 ± 0.01	$\cdots$	3.51 ± 0.10	$\cdots$	2.74 ± 0.17	1.32 ± 0.41	4.84 ± 0.38
$e^+e^-\to K^{*+}K^{*-}$	-2.68 ± 0.05	0.89 ± 0.01	$\cdots$	$\cdots$	$\cdots$	2.14 ± 0.47	2.57 ± 0.36	3.05 ± 0.49
$e^+e^-\to K_1(1270)^+K^-$	0.78 ± 0.07	0.22 ± 0.01	$\cdots$	$\cdots$	2.47 ± 0.52	5.02 ± 0.63	4.87 ± 1.10	1.28 ± 0.95
$e^+e^-\to K_1(1400)^+K^-$	0.87 ± 0.16	0.28 ± 0.04	$\cdots$	$\cdots$	$\cdots$	4.62 ± 0.21	5.79 ± 0.65	6.28 ± 0.33
$e^+e^-\to K_2^*(1430)\bar{K}+$c.c.	1.09 ± 0.11	0.80 ± 0.02	$\cdots$	$\cdots$	$\cdots$	3.54 ± 0.10	1.11 ± 0.51	4.67 ± 0.24
$e^+e^-\to K(1460)^+K^-$	-0.12 ± 0.22	0.46 ± 0.35	$\cdots$	$\cdots$	$\cdots$	6.22 ± 0.18	5.55 ± 0.64	6.26 ± 1.30



PHYSICAL REVIEW D **105,** 074035 (2022)

Identifying the contribution of higher ρ mesons around 2 GeV in the $e^+e^- \to \omega\pi^0$ and $e^+e^- \to \rho\eta'$ processes

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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]*Lanzhou Center for Theoretical Physics, Key Laboratory of Theoretical Physics of Gansu Province, and Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China*
[4]*Joint Research Center for Physics, Lanzhou University and Qinghai Normal University, Xining 810000, China*
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The properties of the light vector meson states around 2.0 GeV have been poorly understood for a long time, which has become a barrier to the expansion to higher light vector meson spectrum. Recently, the BESIII collaboration released the measurements of the $e^+e^- \to \omega\pi^0$ and $e^+e^- \to \rho\eta'$ reactions above 2.0 GeV, both of which are ideal processes to study the isovector ρ meson family. In this work, through carrying out a combined analysis of the Born cross section data for the above two processes with the theoretical support on mass spectrum, and production and strong decay behaviors of the ρ meson family around 2.0 GeV, we identify the enhancement structure near 2034 MeV observed in $e^+e^- \to \omega\pi^0$ to be the interference contribution from two resonances $\rho(1900)$ and $\rho(2150)$, and another enhancement structure at 2111 MeV reported in $e^+e^- \to \rho\eta'$ to be the contributions from $\rho(2000)$ and $\rho(2150)$. This conclusion means that the $e^+e^- \to \omega\pi^0$ and $e^+e^- \to \rho\eta'$ are the excellent golden channels to establish $\rho(1900)$ and $\rho(2000)$, especially for a D-wave state $\rho(2000)$, whose experimental search in the e^+e^- collision should be quite challenging. The relevant cross section measurements with higher precision are expected in the future BESIII and Belle II experiments.

Different schemes for depicting the data

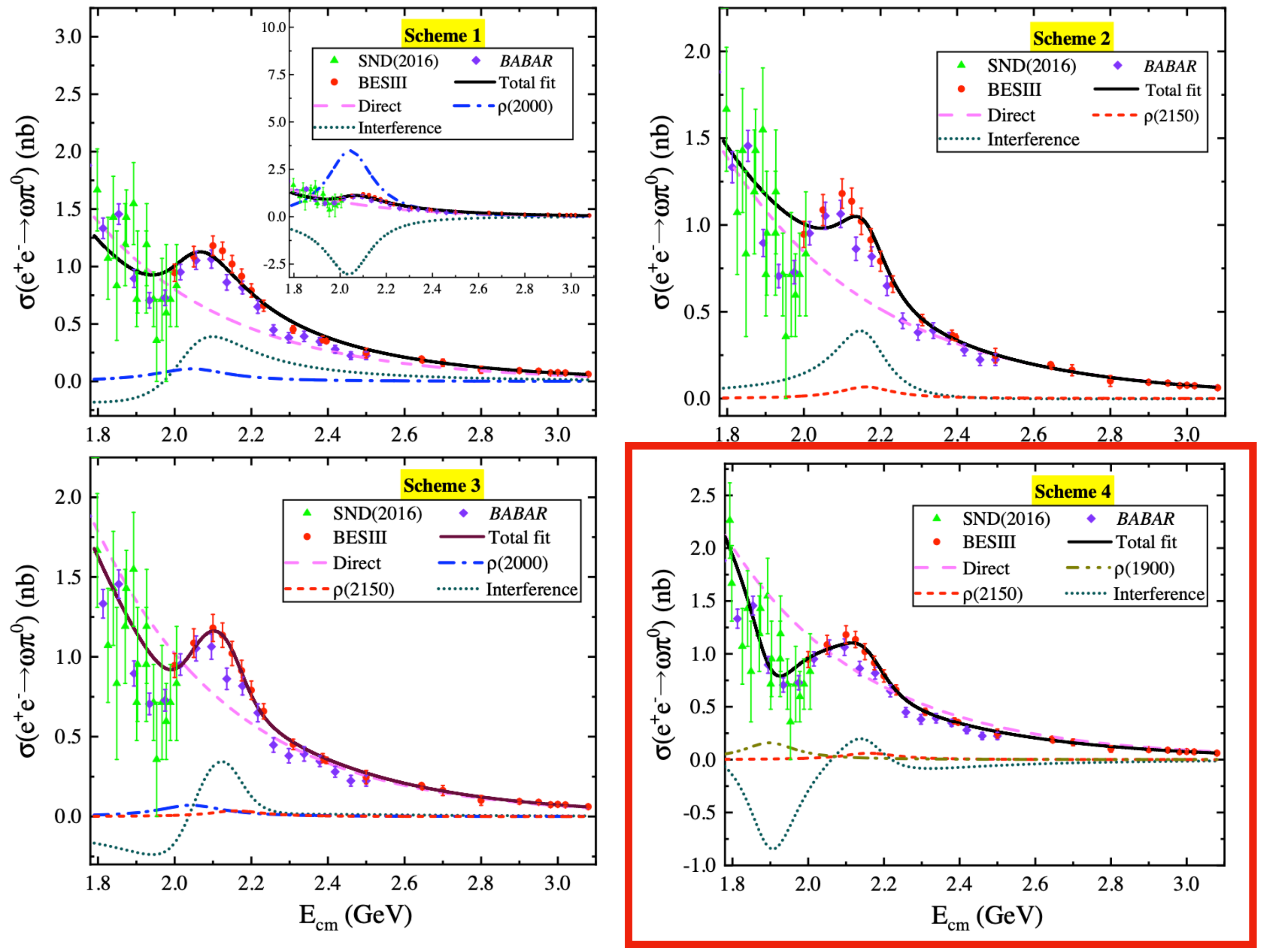
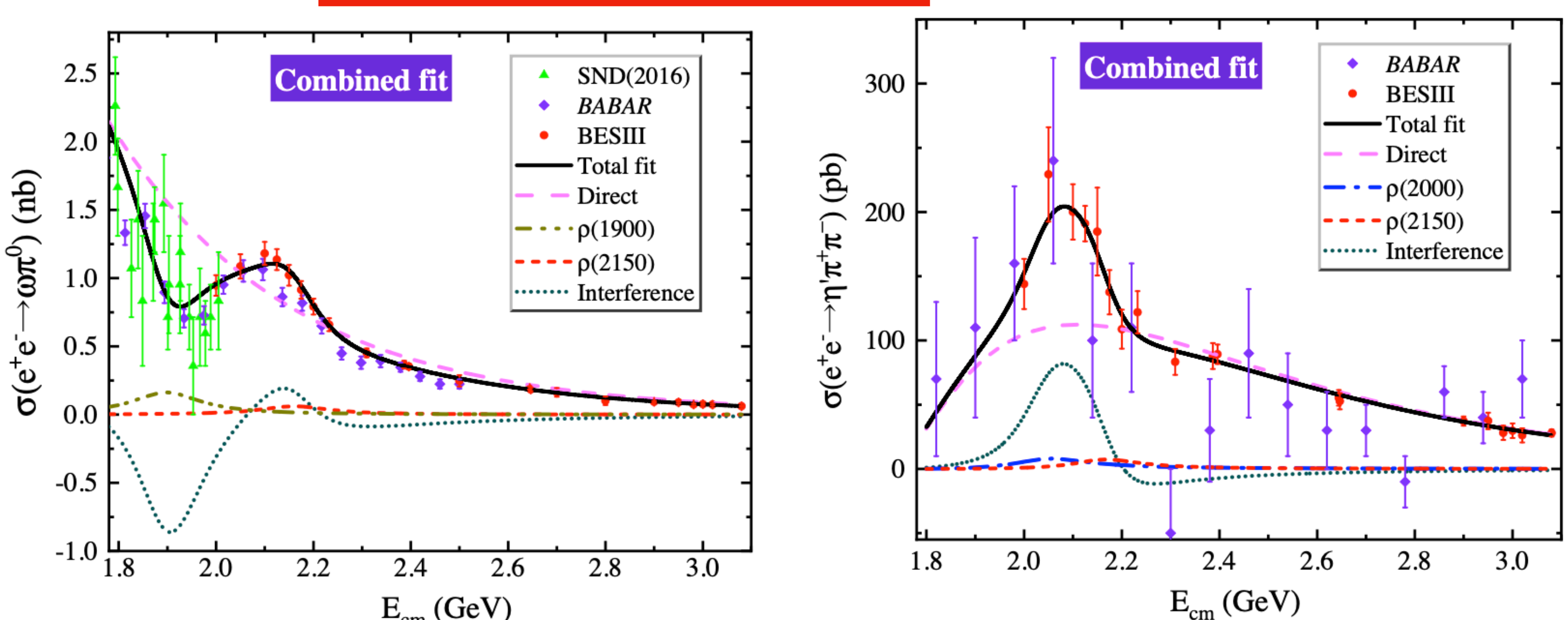


TABLE IV. The parameters of the combined fit to the experimental data of the Born cross sections of $e^+e^- \to \omega\pi^0$ [1,28] and $e^+e^- \to \eta'\pi^+\pi^-$ [2] processes. Here, subscripts 1 and 2 indicate the corresponding parameters belonging to $e^+e^- \to \omega\pi^0$ and $e^+e^- \to \eta'\pi^+\pi^-$, respectively.

Parameters	Values
$\Gamma_{\rho(1900)}$ (MeV)	173 ± 18
$\Gamma_{\rho(2000)}$ (MeV)	194 ± 38
$\Gamma_{\rho(2150)}$ (MeV)	175 ± 22
$\Gamma_{e^+e^-}\mathcal{B}(\rho(1900) \to \omega\pi^0)$ (eV)	6.88 ± 1.92
$\Gamma_{e^+e^-}\mathcal{B}(\rho(2000) \to \omega\pi^0)$ (eV)	3.37 ± 0.79
a_1 (GeV^{-2})	3.41 ± 0.33
b_1 (GeV^{-1})	0.64 ± 0.04
$\phi_1^{\rho(1900)}$ (rad)	4.34 ± 0.14
$\phi_1^{\rho(2150)}$ (rad)	2.11 ± 0.14
$\Gamma_{e^+e^-}\mathcal{B}(\rho(2000) \to \rho\eta')$ (eV)	0.44 ± 0.21
$\Gamma_{e^+e^-}\mathcal{B}(\rho(2150) \to \rho\eta')$ (eV)	0.51 ± 0.27
a_2 (GeV^{-2})	1.78 ± 0.15
b_2 (GeV^{-1})	0.64 ± 0.06
$\phi_2^{\rho(2000)}$ (rad)	6.17 ± 0.29
$\phi_2^{\rho(2150)}$ (rad)	4.58 ± 0.42
χ^2/d.o.f.	0.74



Role of the $\omega(4S)$ and $\omega(3D)$ states in mediating the $e^+e^- \to \omega\eta$ and $\omega\pi^0\pi^0$ processes

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The $e^+e^- \to \omega\eta$ and $e^+e^- \to \omega\pi^0\pi^0$ processes are ideal platforms to search for higher ω states. Focusing on the observations of two enhancement structures around 2.2 GeV existing in $e^+e^- \to \omega\eta$ and $e^+e^- \to \omega\pi^0\pi^0$ at BESIII, we analyze how the $\omega(4S)$ and $\omega(3D)$ states play the role in the $e^+e^- \to \omega\eta$ and $e^+e^- \to \omega\pi^0\pi^0$ processes. The present study is supported by theoretical ω mesonic spectroscopy. For reproducing the data of the cross sections of $e^+e^- \to \omega\eta$ and $\omega\pi^0\pi^0$, the intermediate $\omega(4S)$ and $\omega(3D)$ should be introduced, which indicates that the enhancement structures around 2.2 GeV existing in $e^+e^- \to \omega\eta$ and $\omega\pi^0\pi^0$ contain the $\omega(4S)$ and $\omega(3D)$ signals. Nonetheless, in the process $e^+e^- \to \omega\eta$, the $\omega(4S)$ plays a dominant role, while the $\omega(4S)$ and $\omega(3D)$ have similar sizable contributions in the process of $e^+e^- \to \omega\pi^0\pi^0$, which leads to a difference in the line shape of enhancement structure in the cross sections under the interference effect. Thus, we find a solution to alleviate the puzzling difference of resonance parameter of two reported enhancement structures around 2.2 GeV existing in $e^+e^- \to \omega\eta$ and $e^+e^- \to \omega\pi^0\pi^0$ at BESIII. The present study provides valuable information to construct ω meson family, which can be accessible at future experiment like BESIII.

Role of the $\omega(4S)$ and $\omega(3D)$ states in mediating the $e^+e^- \to \omega\eta$ and $\omega\pi^0\pi^0$ processes

Qin-Song Zhou,[1,2,*] Jun-Zhang Wang,[1,2,†] and Xiang Liu[1,2,3,4,‡]

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

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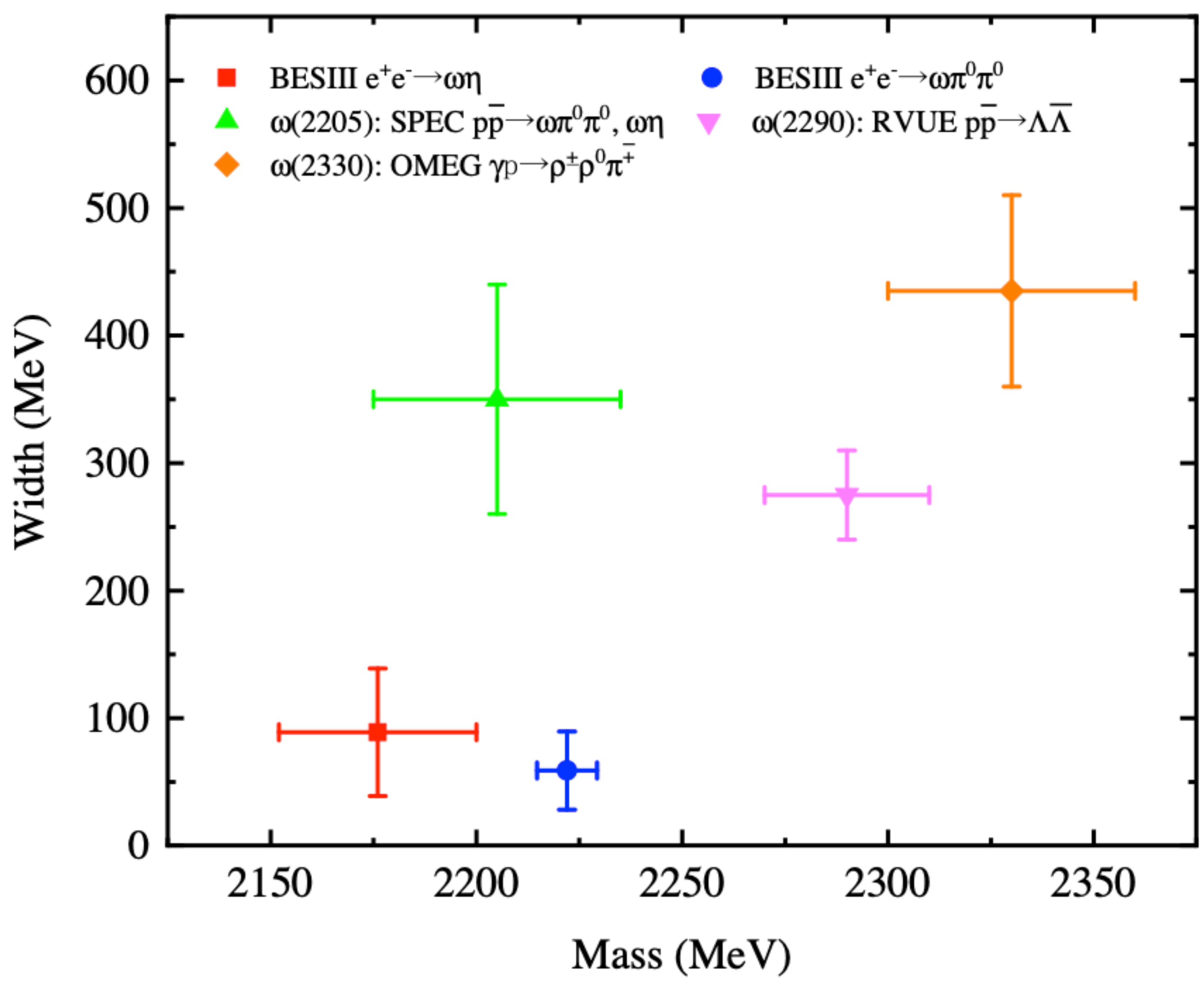

The e^- ... gher ω states. Focusing ... $^+e^- \to \omega\eta$ and $e^+e^- \to$ ... $^+e^- \to \omega\eta$ and $e^+e^- \to$ ... ctroscopy. For reproduci ... S) and $\omega(3D)$ should be ... ing in $e^+e^- \to$ $\omega\eta$ and ω ... $\omega\eta$, the $\omega(4S)$ plays a d ... the process of $e^+e^- \to$ ... cross sections under the ... of resonance parameter ... η and $e^+e^- \to$ $\omega\pi^0\pi^0$ at ... ily, which can be accessible at future experiment like BESIII.

TABLE II. The parameters obtained by fitting the experimental data of the Born cross sections of $e^+e^- \to \omega\eta$ [2], and the χ^2/n.d.f value is 1.59 for this fitting.

Parameters	Values	Parameters	Values
$g_{\gamma\omega\eta}$ (GeV^{-1})	0.053 ± 0.001	$b_{\omega\eta}$ (GeV^{-1})	1.63 ± 0.05
$\phi_{\omega(4S)}$ (rad)	2.79 ± 0.15	$\phi_{\omega(3D)}$ (rad)	6.17 ± 0.47

TABLE III. The parameters obtained by fitting the experimental data of the Born cross sections of $e^+e^- \to \omega\pi^0\pi^0$ [5], and the χ^2/n.d.f value is 1.79 for this fitting.

Parameters	Values	Parameters	Values
$g_{\gamma\omega\pi^0\pi^0}$	4.84 ± 0.02	$b_{\omega\pi^0\pi^0}$ (GeV^{-1})	1.12 ± 0.01
$\phi_{\omega(4S)\rho}$ (rad)	1.82 ± 0.55	$\phi_{\omega(4S)\rho(1450)}$ (rad)	0.54 ± 0.23
$\phi_{\omega(4S)b_1(1235)}$ (rad)	4.81 ± 0.03	$\phi_{\omega(3D)\rho(1450)}$ (rad)	5.34 ± 0.72
$\phi_{\omega(3D)b_1(1235)}$ (rad)	1.79 ± 0.05		

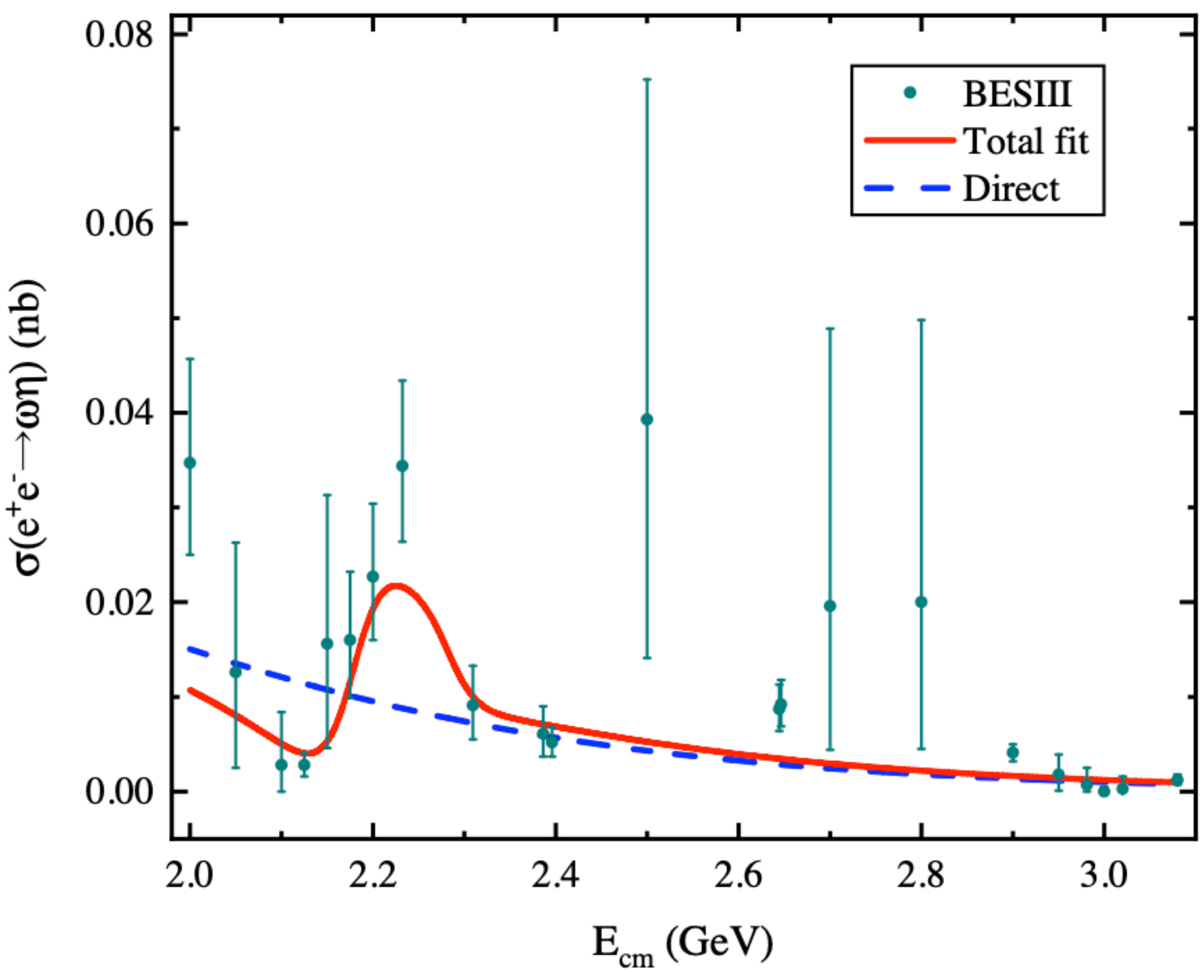

FIG. 8. The fitted result of the experimental data of the Born cross sections of $e^+e^- \to \omega\eta$ [2].

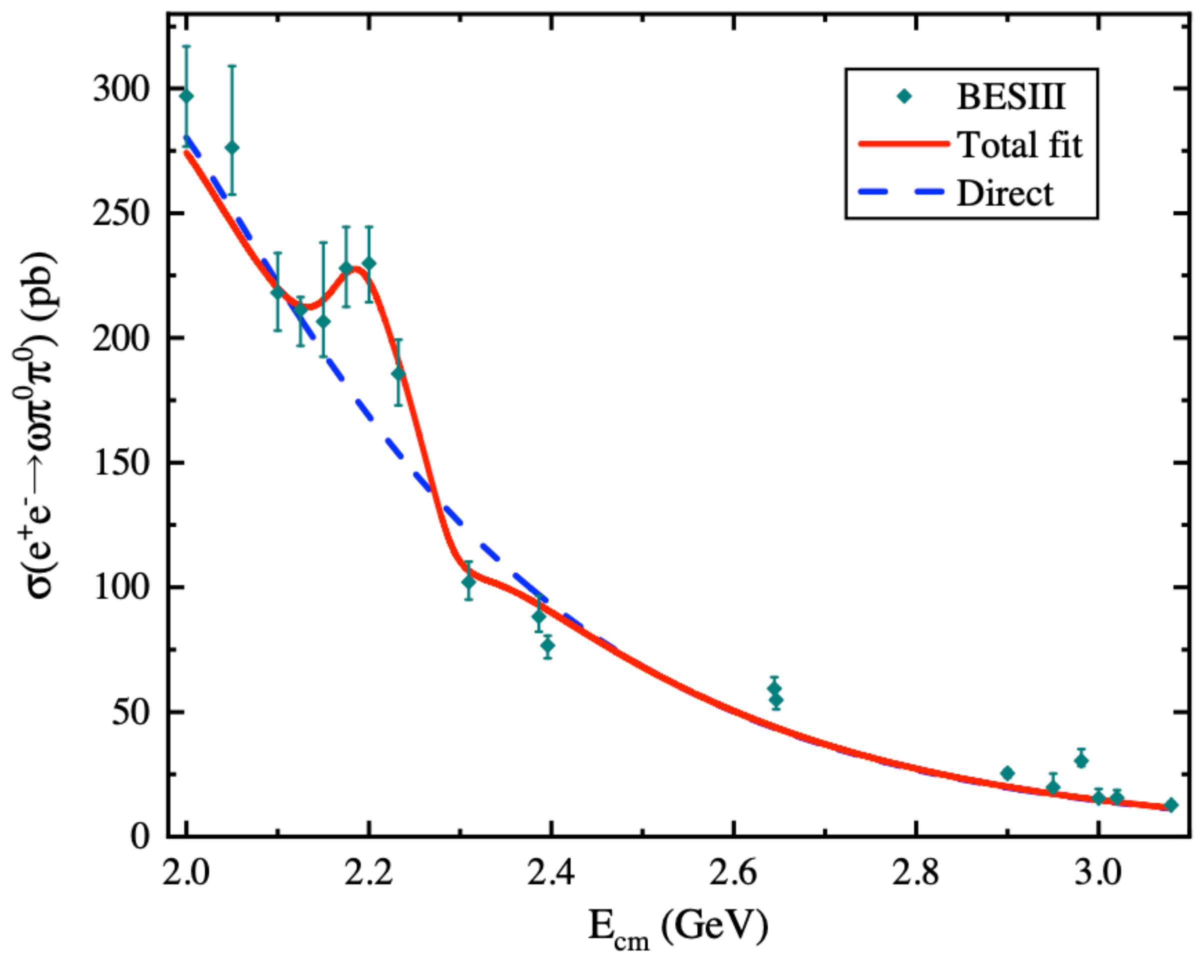

FIG. 9. The fitted result of the experimental data of the Born cross sections of $e^+e^- \to \omega\pi^0\pi^0$ [5].

Mixing scheme for ω meson

PHYSICAL REVIEW D **111,** 054013 (2025)

Role of $4S-3D$ mixing in explaining the ω-like $Y(2119)$ observed in $e^+e^- \to \rho\pi$ and $\rho(1450)\pi$

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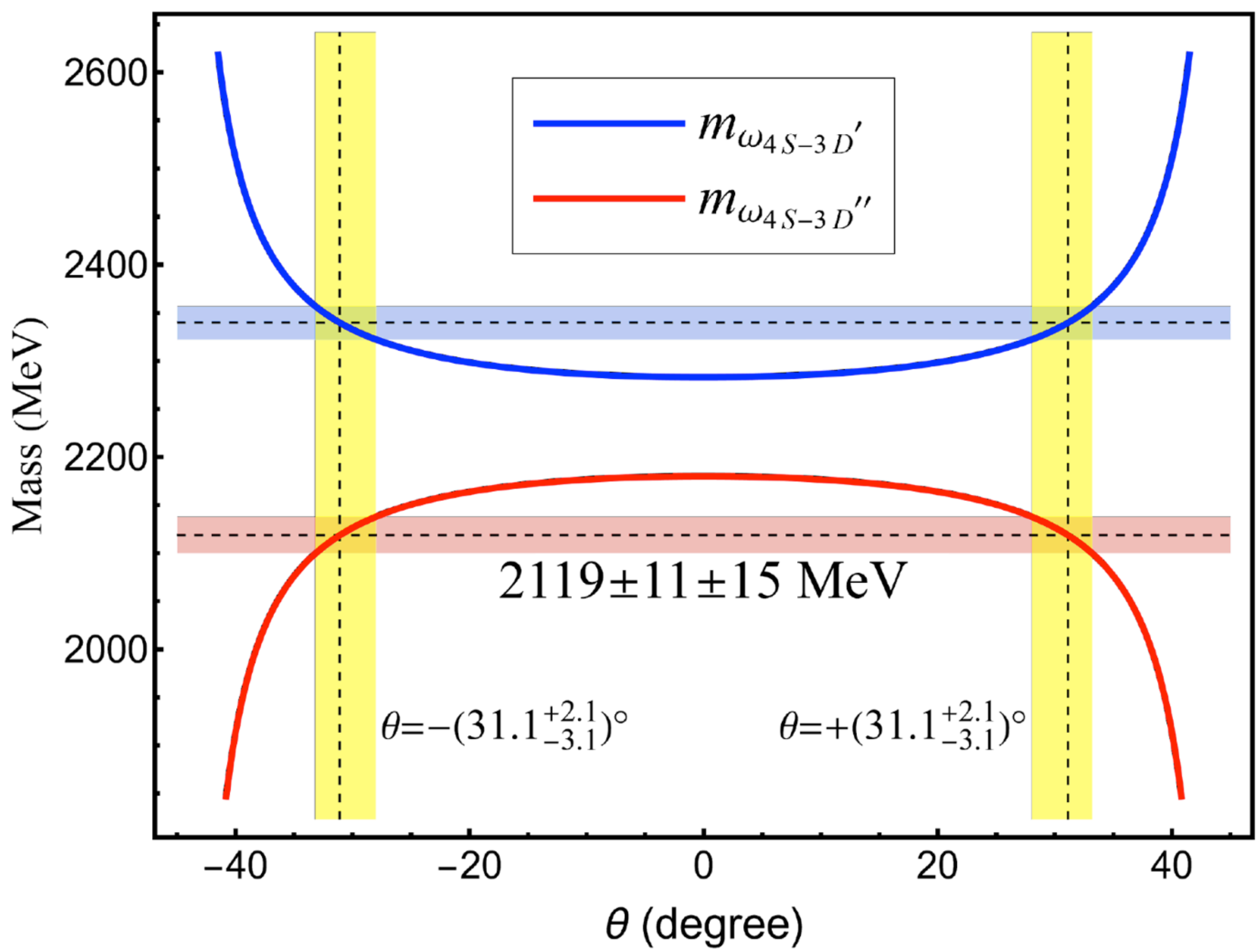
The BESIII Collaboration has recently reported a new resonance structure in the cross-section analyses of the $e^+e^- \to \rho\pi$ and $e^+e^- \to \rho(1450)\pi$ processes, displaying characteristics akin to an ω meson. However, its measured mass, $M = 2119 \pm 11 \pm 15$ MeV, significantly deviates from the predictions of the unquenched relativized potential model for conventional ω vector meson spectroscopy. To address this discrepancy, we propose a $4S-3D$ mixing scheme and investigate the corresponding decay properties within this framework. Our analysis demonstrates that the mixed state ω'_{4S-3D} exhibits excellent agreement with the observed resonance, not only in mass and width but also in the products of its dielectron width and branching ratios, $\Gamma^{\mathcal{R}}_{e^+e^-} \times \mathcal{B}_{\mathcal{R}\to\rho\pi}$ and $\Gamma^{\mathcal{R}}_{e^+e^-} \times \mathcal{B}_{\mathcal{R}\to\rho(1450)\pi\to\pi^+\pi^-\pi^0}$. The determined mixing angle, $\theta = -(31.1^{+2.1}_{-3.1})^\circ$, strongly supports the interpretation of this structure as the ω'_{4S-3D} state. Furthermore, we predict dominant decay channels for ω'_{4S-3D} and its partner state ω''_{4S-3D}. These predictions, together with the proposed mixing mechanism, provide crucial guidance for future experimental studies aimed at probing this structure and rigorously testing the $4S-3D$ mixing hypothesis.

Mixing scheme for ω meson

PHYSICAL REVIEW D **111,** 054013 (2025)

Role of $4S-3D$ mixing in explaining the ω-like $Y(2119)$ observed in $e^+e^- \to \rho\pi$ and $\rho(1450)\pi$

Zi-Yue Bai,[1,2,3,*] Qin-Song Zhou,[2,4,5,†] and Xiang Liu[1,2,3,4,‡]



4 Summary

“To expand out from one point”—由点及面

① 构建轻强子谱

CERN-EP-2021-025
LHCb-PAPER-2020-044
March 2, 2021

Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

LHCb collaboration†

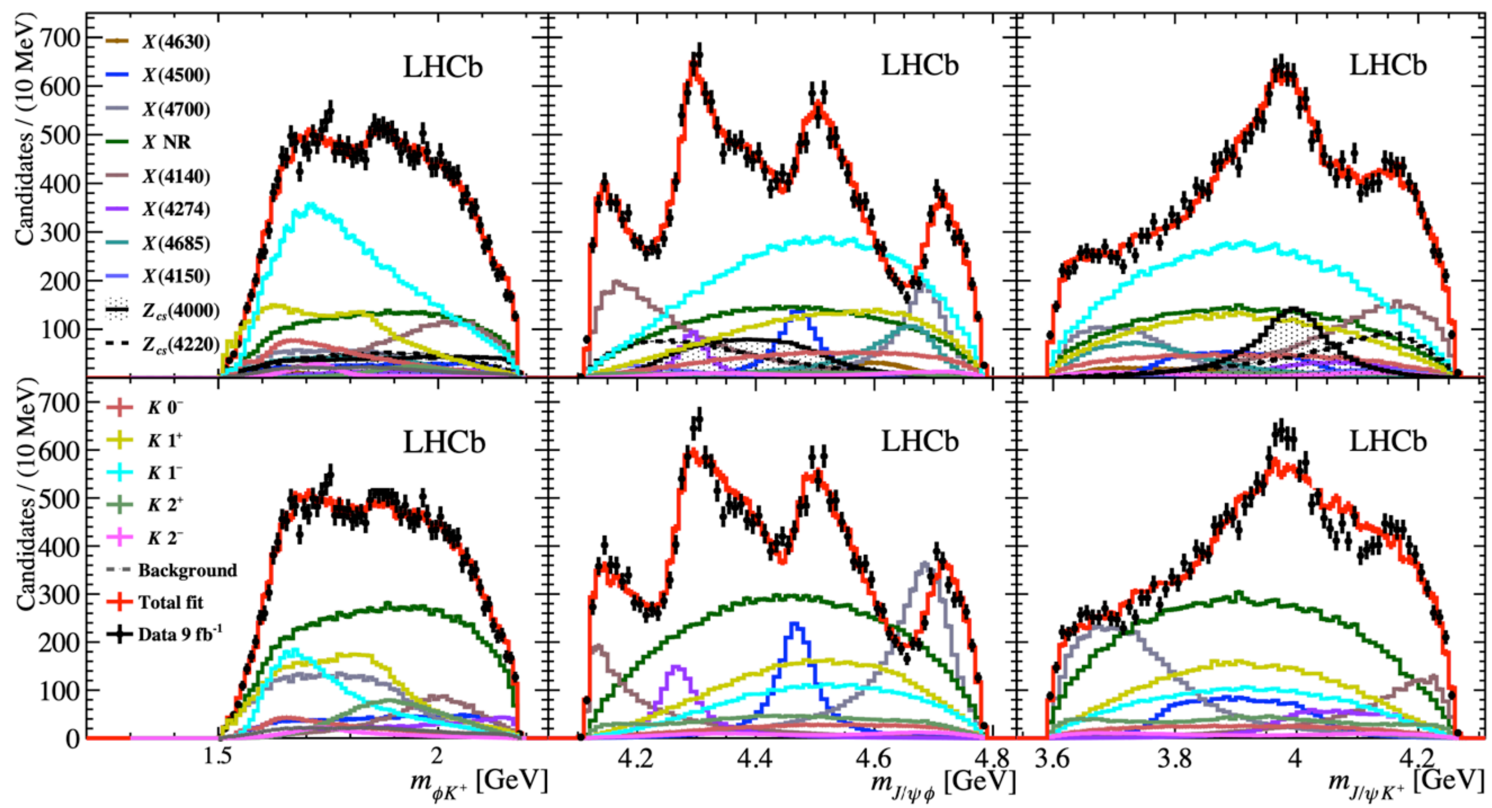
Abstract

The first observation of exotic states with a new quark content $c\bar{c}u\bar{s}$ decaying to the $J/\psi K^+$ final state is reported with high significance from an amplitude analysis of the $B^+ \to J/\psi\phi K^+$ decay. The analysis is carried out using proton-proton collision data corresponding to a total integrated luminosity of 9 fb^{-1} collected by the LHCb experiment at centre-of-mass energies of 7, 8 and 13 TeV. The most significant state, $Z_{cs}(4000)^+$, has a mass of $4003 \pm 6\,^{+4}_{-14}$ MeV, a width of $131 \pm 15 \pm 26$ MeV, and spin-parity $J^P = 1^+$, where the quoted uncertainties are statistical and systematic, respectively. A new 1^+ $X(4685)$ state decaying to the $J/\psi\phi$ final state is also observed with high significance. In addition, the four previously reported $J/\psi\phi$ states are confirmed and two more exotic states, $Z_{cs}(4220)^+$ and $X(4630)$, are observed with significance exceeding five standard deviations.

Submitted to Phys. Rev. Lett.

†Authors are listed at the end of this paper.

对轻强子谱的**理解程度**直接**决定**了类粲偶素**XYZ态**的确立



Kaon family

② 理论家要重视实验数据点

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https://doi.org/10.1140/epjc/s10052-020-08621-4

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Theoretical Physics

Universal non-resonant explanation to charmoniumlike structures $Z_c(3885)$ and $Z_c(4025)$

Jun-Zhang Wang[1,2,a], **Dian-Yong Chen**[3,b], **Xiang Liu**[1,2,c], **Takayuki Matsuki**[4,d]

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We noticed that the BESIII Collaboration once argued that $Z_c(3885)$ cannot be due to the reflection from the $D_1(2420)$ [11], which is based on a Monte Carlo simulation and the comparison with experimental data of measured asymmetric parameter $\mathcal{A}_{\text{data}} = 0.12 \pm 0.06$ [11]. In fact, as theorist, we only believe the experimental data provided by the experimentalist. To some extent, exploring the underly mechanism behind the experimental data should be left to the theorist. Thus, we restudied this interesting possibility of $Z_c(3885)$ and $Z_c(4025)$ structures as the reflection from $D_1(2420)$.

As theorist, we only believe the experimental data provided by the experimentalist.

③ 加强理论家和实验家之间的沟通

延续理论家和实验家交流对话的传统


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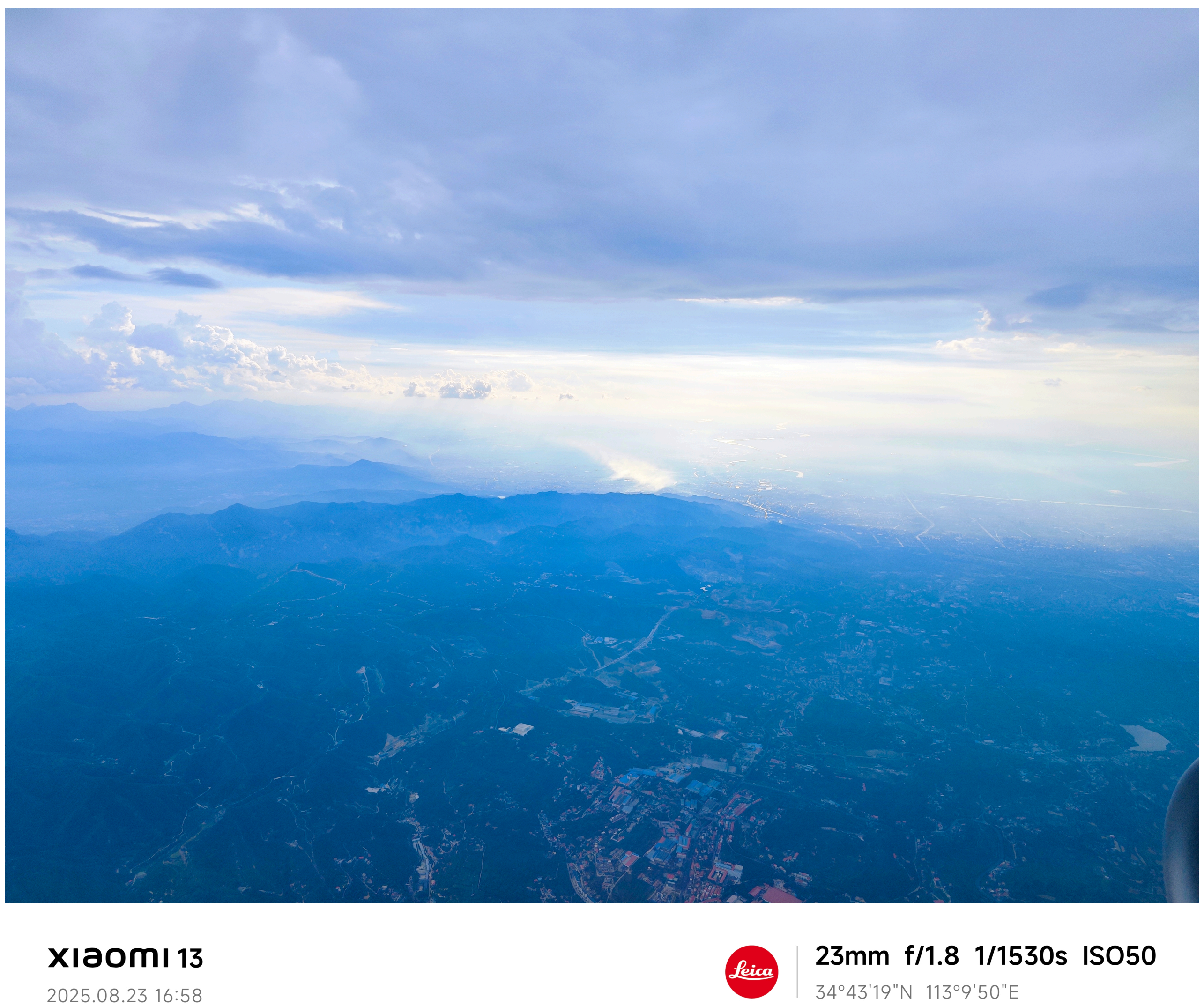
偶成

偶现昙花如露电

终成强子悟真常




Thank you
for your
attention!