The predicted missing $\psi(4S)$ and the possible evidences from the present experimental data

Xiang Liu
Lanzhou University

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Outline

- **An overview of observed charmonium-like state XYZ**
- **Prediction of a missing higher charmonium around 4.26 GeV in *J*/ψ family**
- **The role of the predicted ψ(4S) in the observed** $e^+e^- \to \omega\chi_{c0}$
- **Others possible evidences**

  Open-charm and hidden-charm decay channels
- **Summary**

An overview of charmonium-like states XYZ

A summary of the observed XYZ states

截屏发图

$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_b(10610)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_b(10650)$
$Z^+(4430)$	$Y(4360)$	–	$Z(3930)$	$Z_c(3900)$
$Z^+(4051)$	$Y(4660)$	–	–	$Z_c(4025)$
$Z^+(4248)$	$Y(4630)$	–	–	$Z_c(4020)$
$Y(4140)$	–	–	–	$Z_c(3885)$
$Y(4274)$	–	–	–	–

X. Liu, Chin. Sci. Bull., 59: 3815–3830 (2014)

In past decade, more and more XYZ states have been reported by experiments

BaBar, Belle, CDF, D0, CLEOc, LHCb, CMS, BESIII

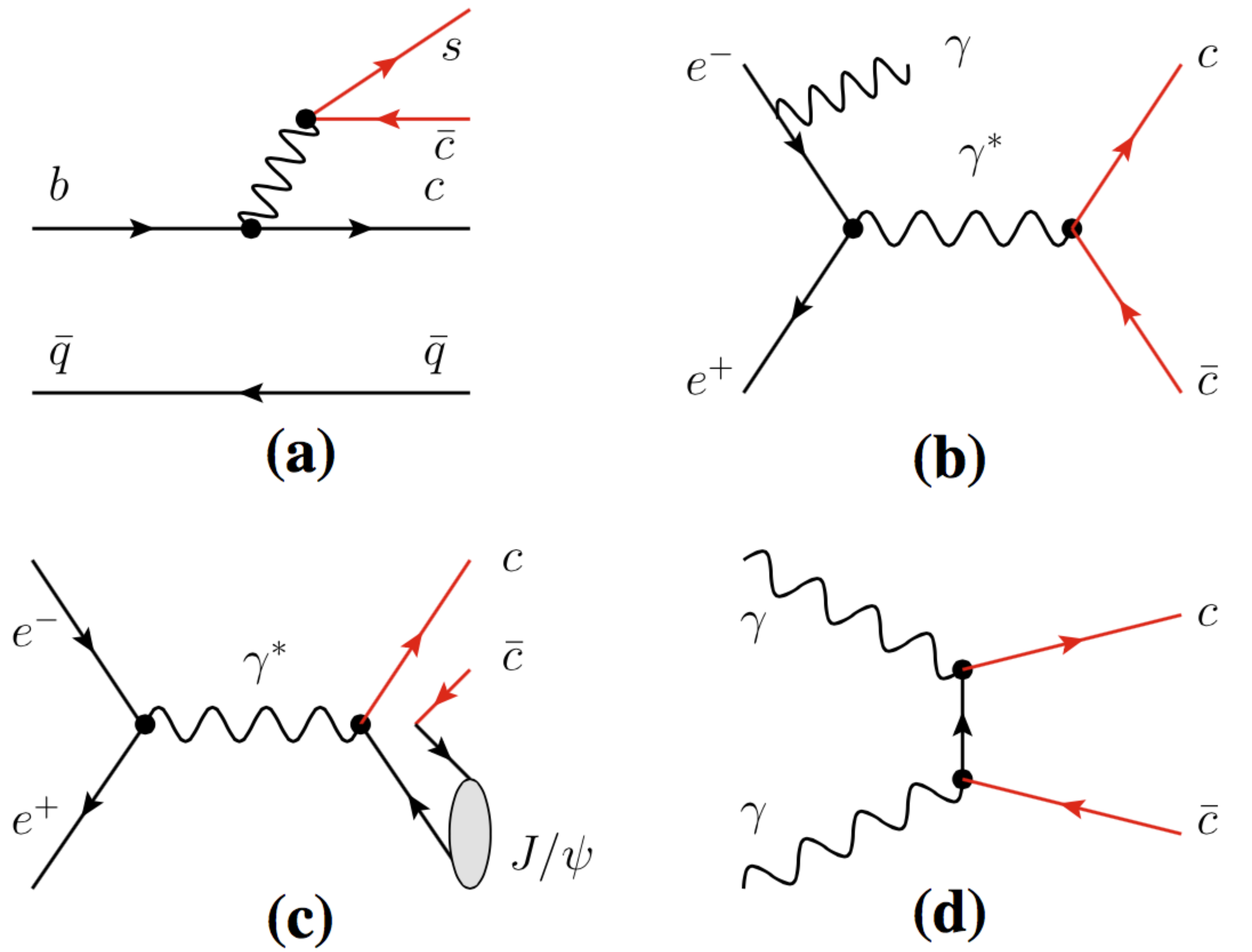
In general, the observed XYZ states can be categorized into five groups

e^+e^- annihilation

$X(3872)$
$Y(3940)$
$Z^+(4430)$
$Z^+(4051)$
$Z^+(4248)$
$Y(4140)$
$Y(4274)$

B meson decay

$Y(4260)$
$Y(4008)$
$Y(4360)$
$Y(4660)$
$Y(4630)$



$X(3940)$
$X(4160)$

$X(3915)$
$X(4350)$
$Z(3930)$

the double charm production

$\gamma\gamma$ fusion process

X. Liu, Chin. Sci. Bull., 59: 3815–3830 (2014)

How to explain these novel phenomenon

1. Resonance explanations:

$$
\text{hadron}\begin{cases}
\text{meson:} & q\bar{q},\quad Q\bar{q},\quad Q\bar{Q} \\
\text{baryon:} & qqq,\quad Qqq,\quad QQq,\quad \ldots \\
\text{exotic state:} & \begin{cases} \text{molecular state} \\ \text{hybrid} \\ \text{glueball} \\ \ldots, \end{cases}
\end{cases}
$$

Along this line, there were some theoretical efforts to explain these XYZ states

Y(4140) and Y(3940) as Ds*$\overline{\text{D}}$s* and D*$\overline{\text{D}}$* molecular states respectively

Liu & Zhu, PRD79:094026 (2009)

$$B \to K + \begin{cases} \underline{J/\psi\phi} \quad \Longrightarrow Y(4140), \\ \underline{J/\psi\omega} \quad \Longrightarrow Y(3940). \end{cases}$$

CDF, PRL102:242002 (2009)

BaBar, PRL101:082001 (2008)

$$M_{Y(4140)} - M_{Y(3930)} \sim M_\phi - M_\omega.$$

$$M_{Y(4140)} - 2M_{D_s^*} \approx M_{Y(3940)} - 2M_{D^*}.$$

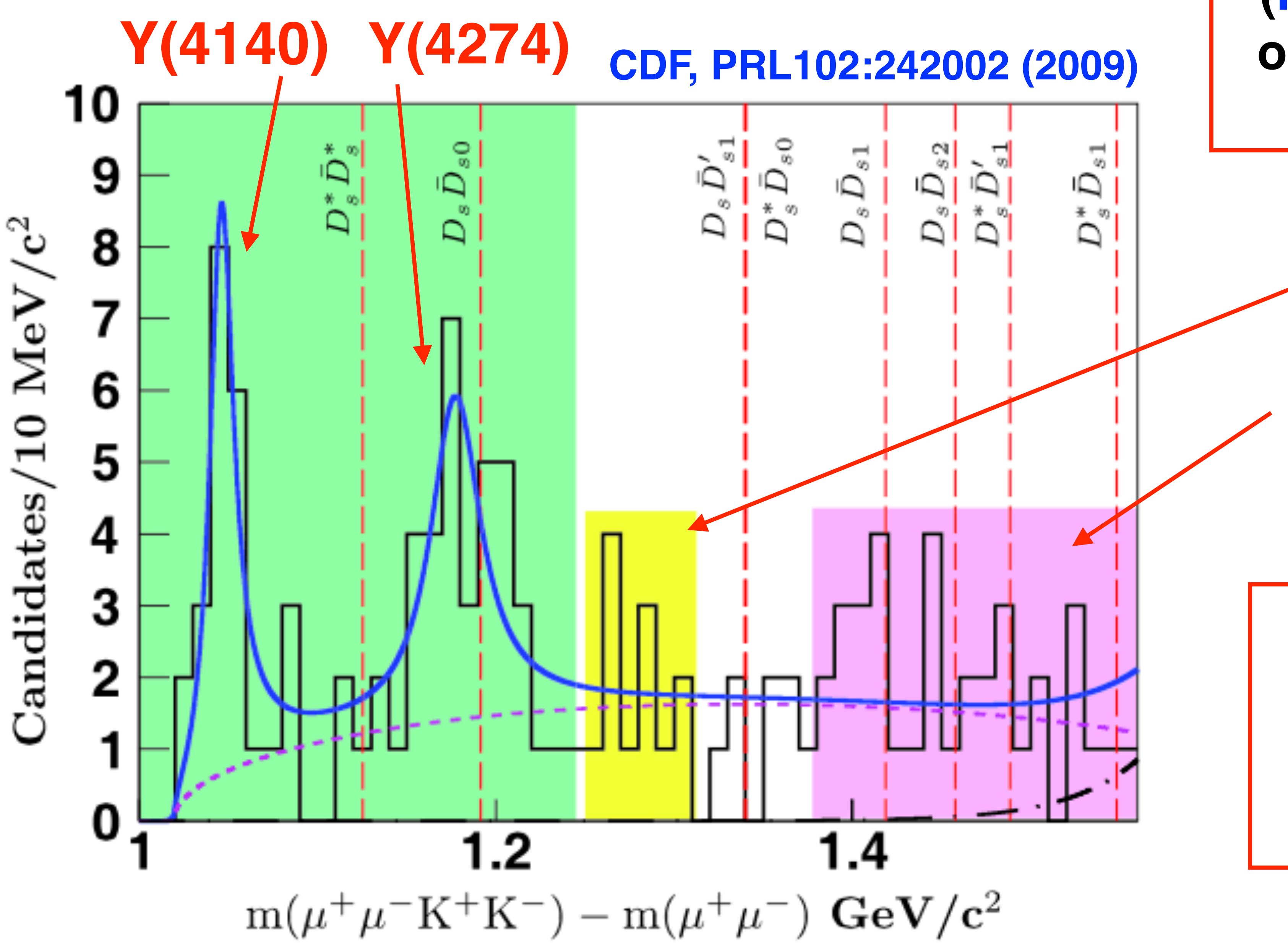
These similarities inspire us propose the hidden-charm molecular states explanations:

$$|Y(4140)\rangle = |D_s^{*+}D_s^{*-}\rangle,$$

$$|Y(3940)\rangle = \frac{1}{\sqrt{2}}\left[|D^{*0}\bar{D}^{*0}\rangle + |D^{*+}D^{*-}\rangle\right].$$

Y(4274) as the S-wave $D_s\bar{D}_{s0}(2317)$ molecular state

Liu, Luo, Zhu, Phys Lett B 699:341 (2009)



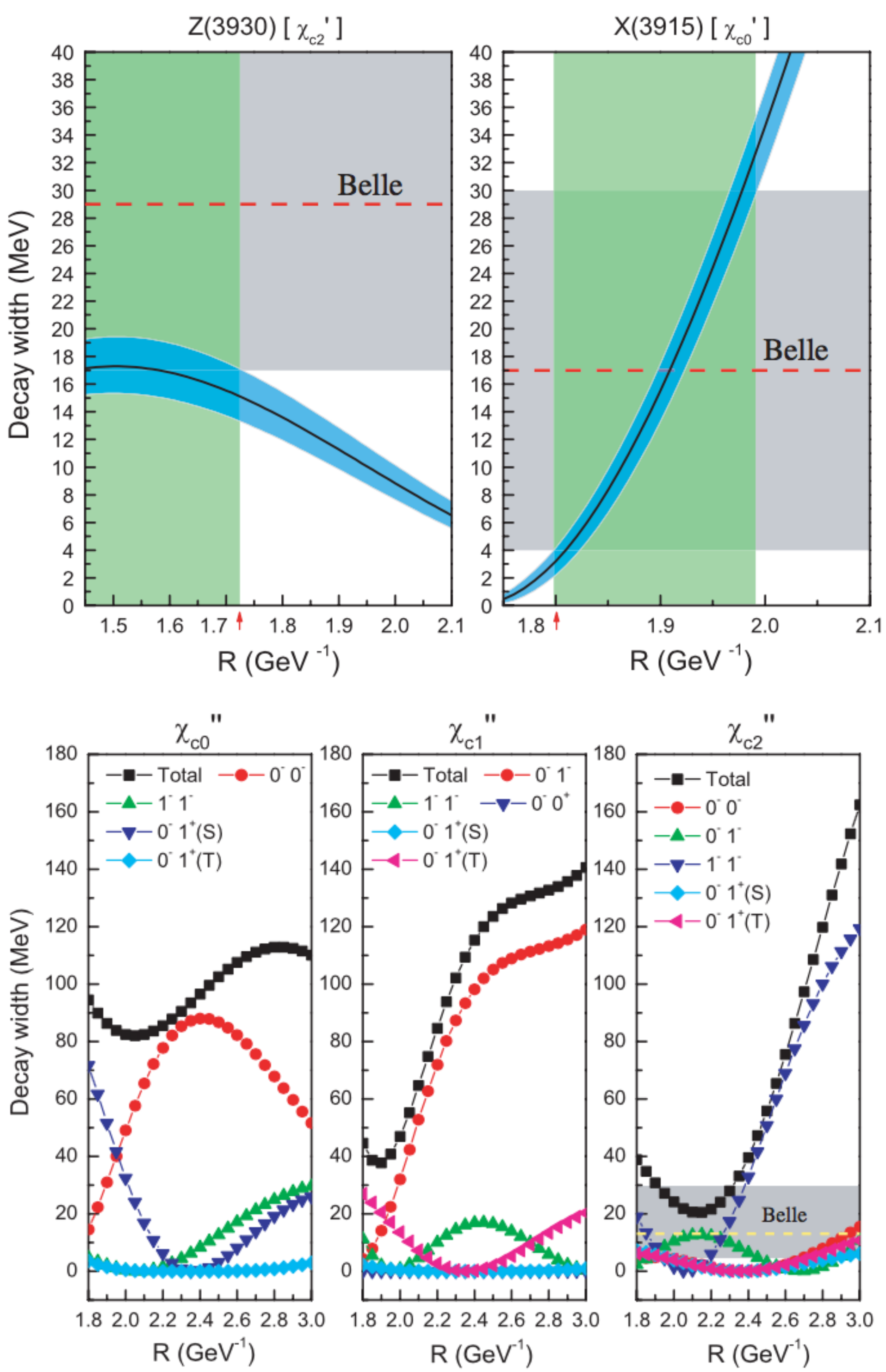
D0 (PRD89:012004) and CMS (PLB734:261) confirmed the observations of Y(4140) and Y(4274)

New hidden-charm molecular states?

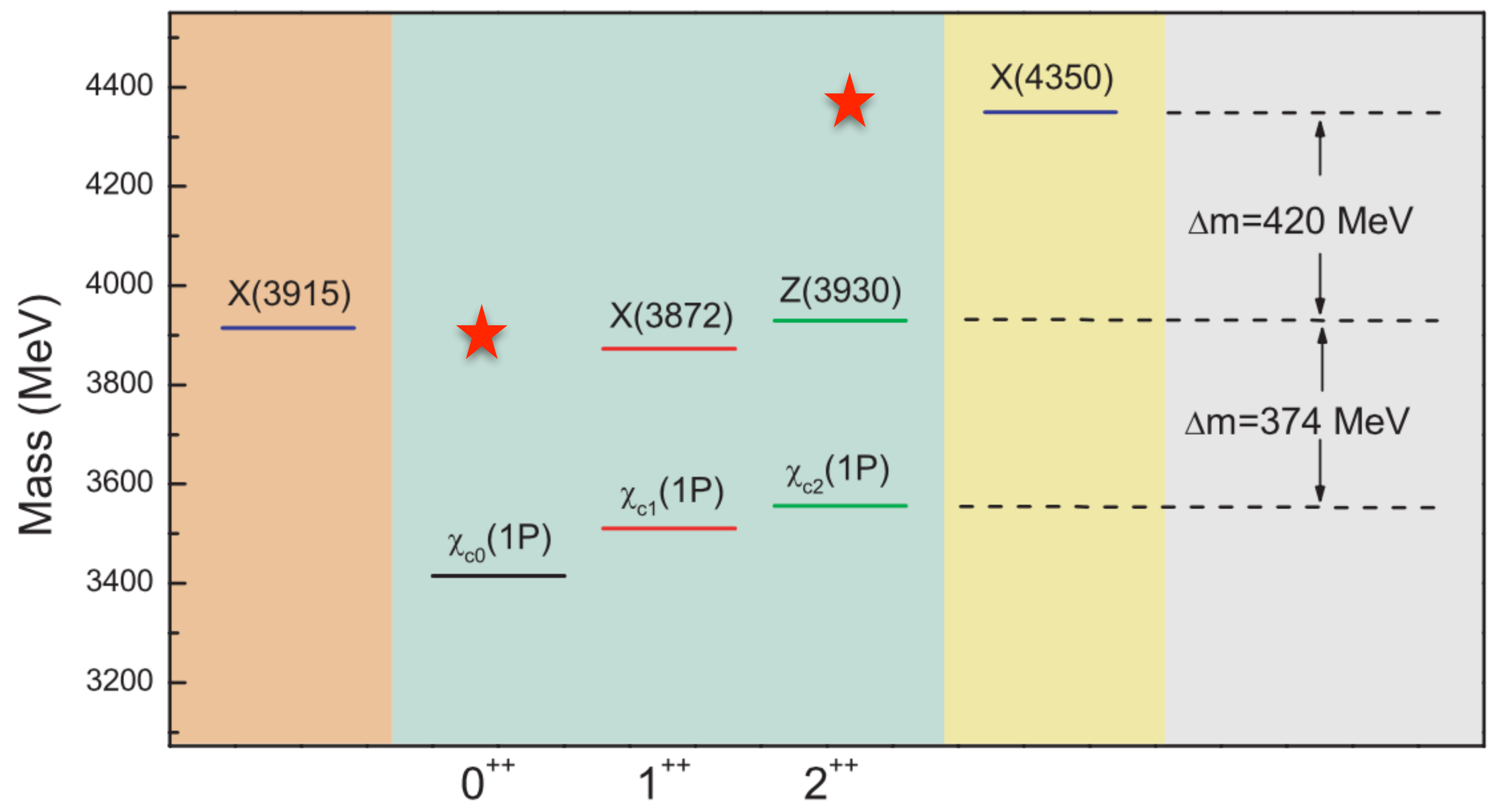
PRL 104, 122001 (2010) PHYSICAL REVIEW LETTERS week ending 26 MARCH 2010

$X(3915)$ and $X(4350)$ as New Members in the P-Wave Charmonium Family

Xiang Liu,[1,2,*,†] Zhi-Gang Luo,[3] and Zhi-Feng Sun[1,2]



$$\gamma\gamma \rightarrow \begin{cases} X(3915) \rightarrow \underline{D\bar{D}}, \\ X(4350) \rightarrow \underline{J/\psi\phi}, \\ Z(3930) \rightarrow \underline{J/\psi\omega}. \end{cases}$$



χ'_{c0} for $X(3915)$ and χ''_{c2} for $X(4350)$

2. Non-resonance explanations:

PHYSICAL REVIEW D **83**, 054021 (2011)

Nonresonant explanation for the $Y(4260)$ structure observed in the $e^+e^- \to J/\psi\pi^+\pi^-$ process

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

Interference effect from ψ(4160) and ψ(4415)

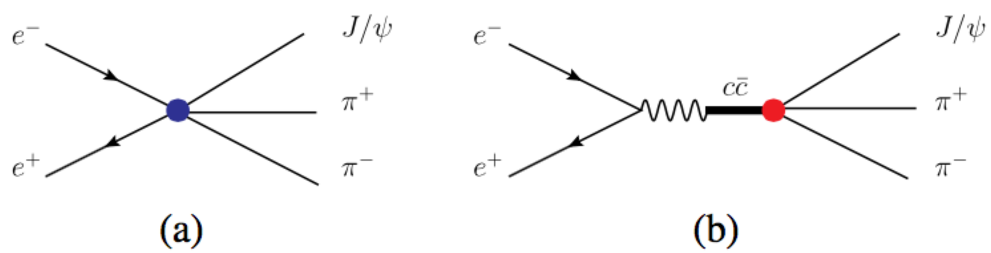
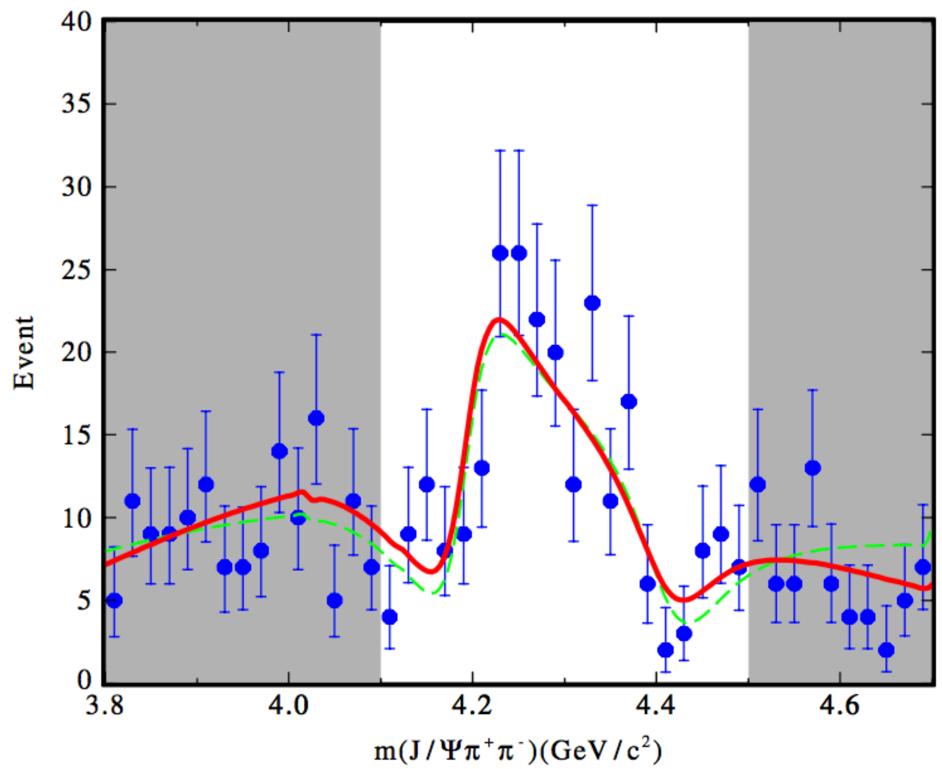


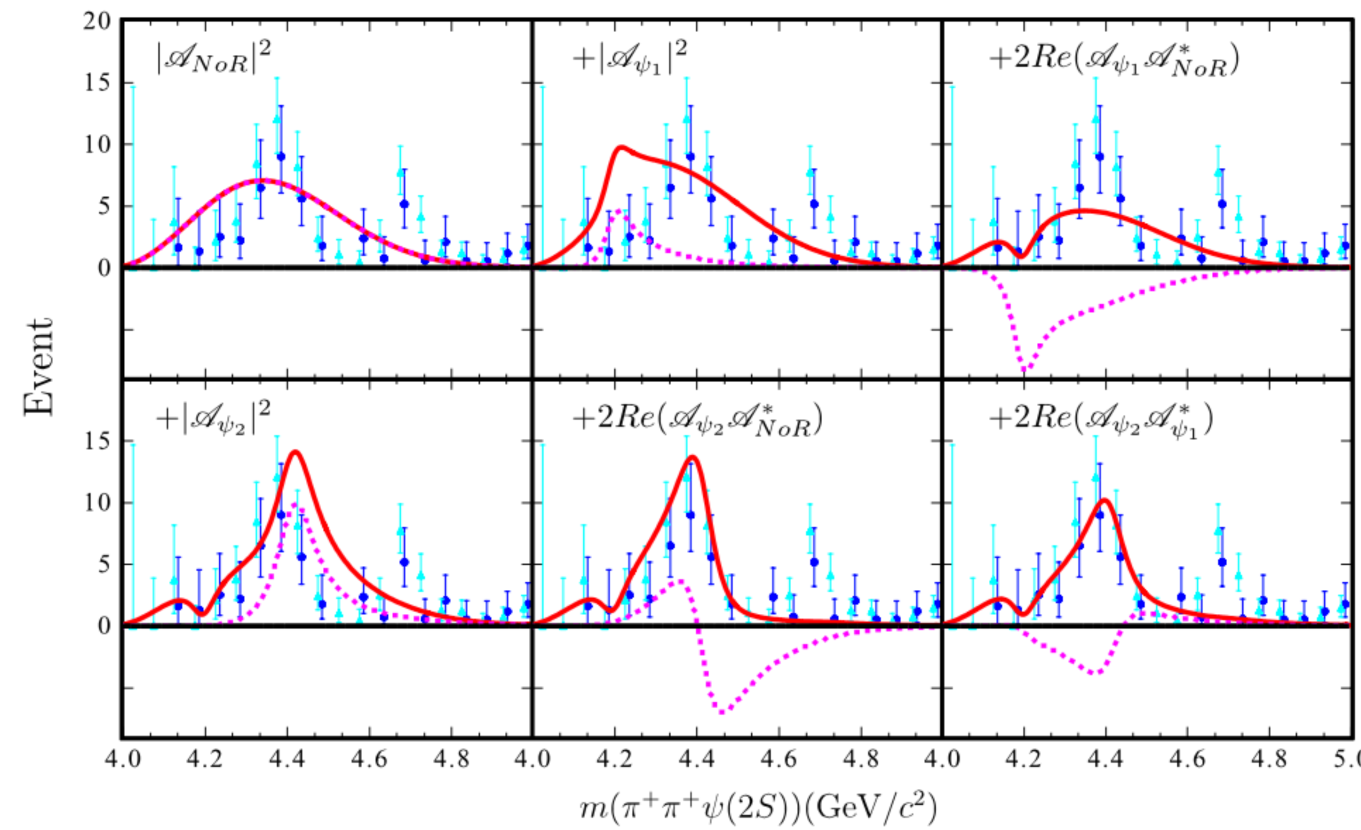
FIG. 1 (color online). The diagrams relevant to $e^+e^- \to J/\psi\pi^+\pi^-$. Here, Fig. 1(a) corresponds to the e^+e^- annihilation directly into $J/\psi\pi^+\pi^-$. Figure 1(b) is from the contributions of intermediate charmonia.



PHYSICAL REVIEW D **83**, 074012 (2011)

Novel explanation of charmoniumlike structure in $e^+e^- \to \psi(2S)\pi^+\pi^-$

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



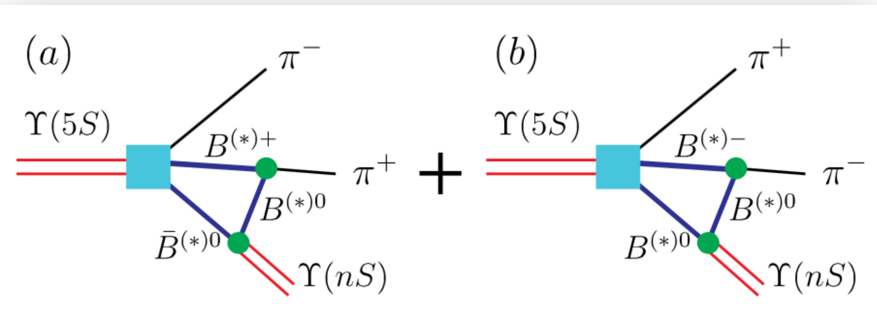
The Y(4260) and Y(4360) signals can be reproduced well

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

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

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

Chen, X. Liu, PRD84, 094003 (2011)



Initial Single Pion Emission (ISPE) mechanism

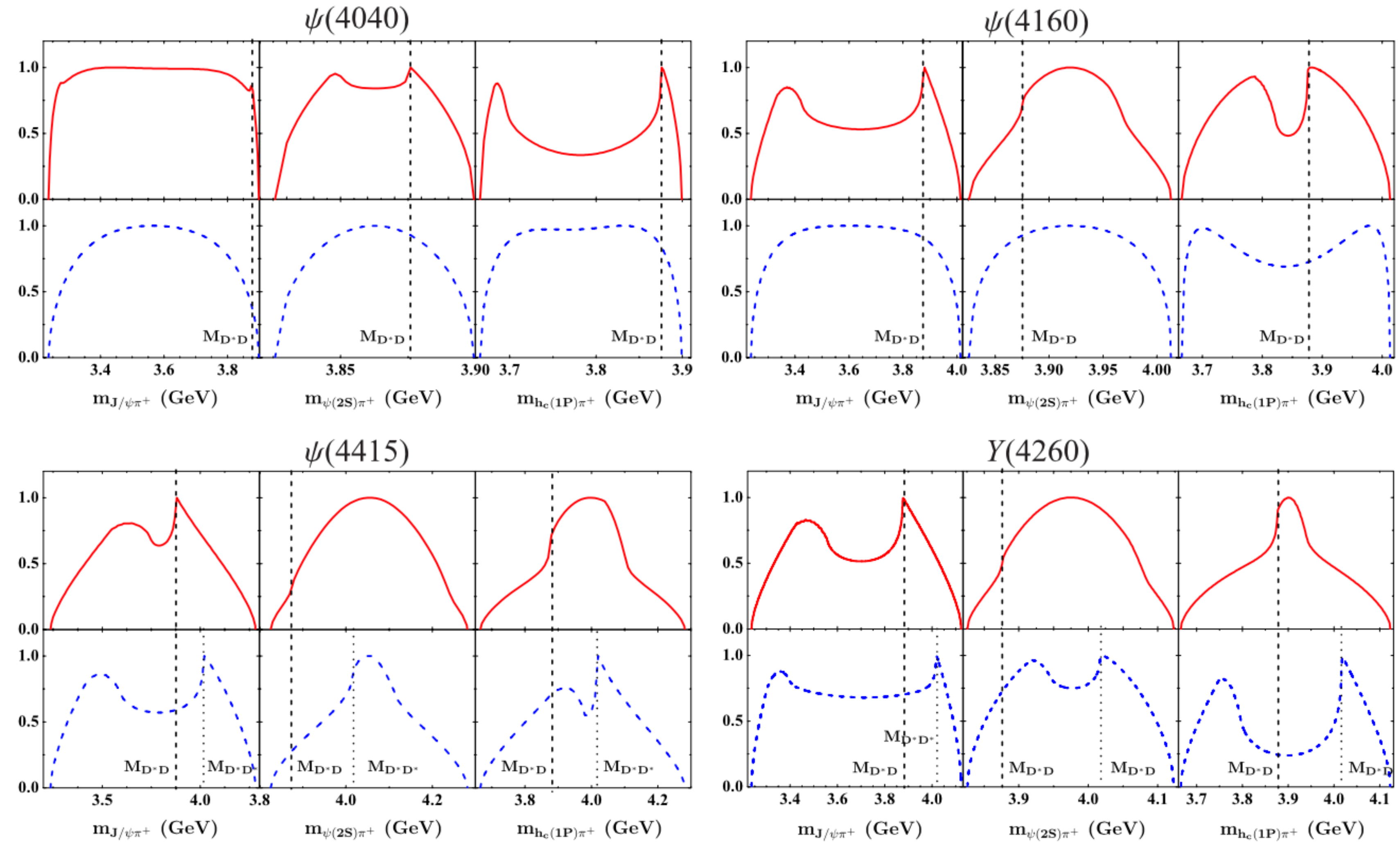


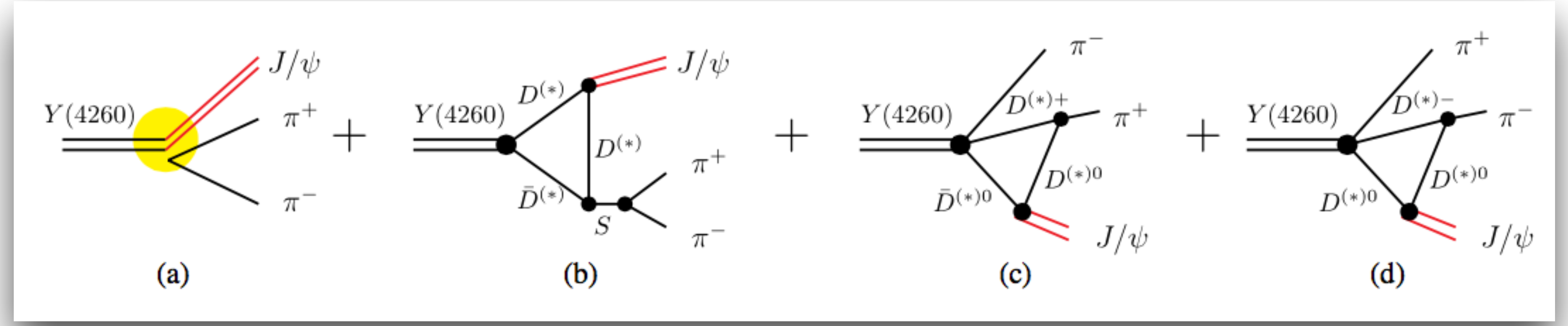
FIG. 4 (color online). (Color online.) The invariant mass spectra of $J/\psi\pi^+$, $\psi(2S)\pi^+$, and $h_c(1P)\pi^+$ for the $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, and $Y(4260)$ decays into $J/\psi\pi^+\pi^-$, $\psi(2S)\pi^+\pi^-$, and $h_c(1P)\pi^+\pi^-$. Here, the solid, dashed correspond to the results considering intermediate $D\bar{D}^*$ + H.c. and $D^*\bar{D}^*$, respectively, in Fig. 1. The vertical dashed lines and the dotted lines denote the threshold of $D^*\bar{D}$ and $D^*\bar{D}^*$, respectively. Here, the maximum of the line shape is normalized to 1.

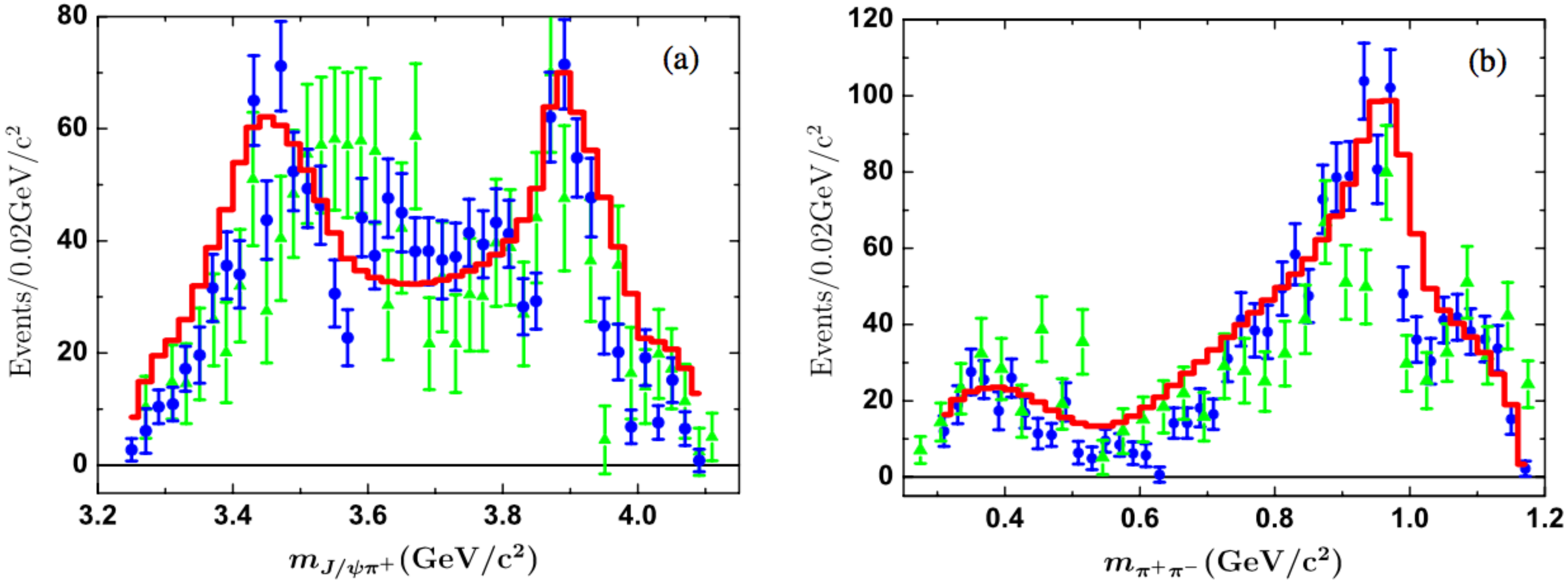
Predict charged charmonium-like structures near D*D or D*D* threshold

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

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

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



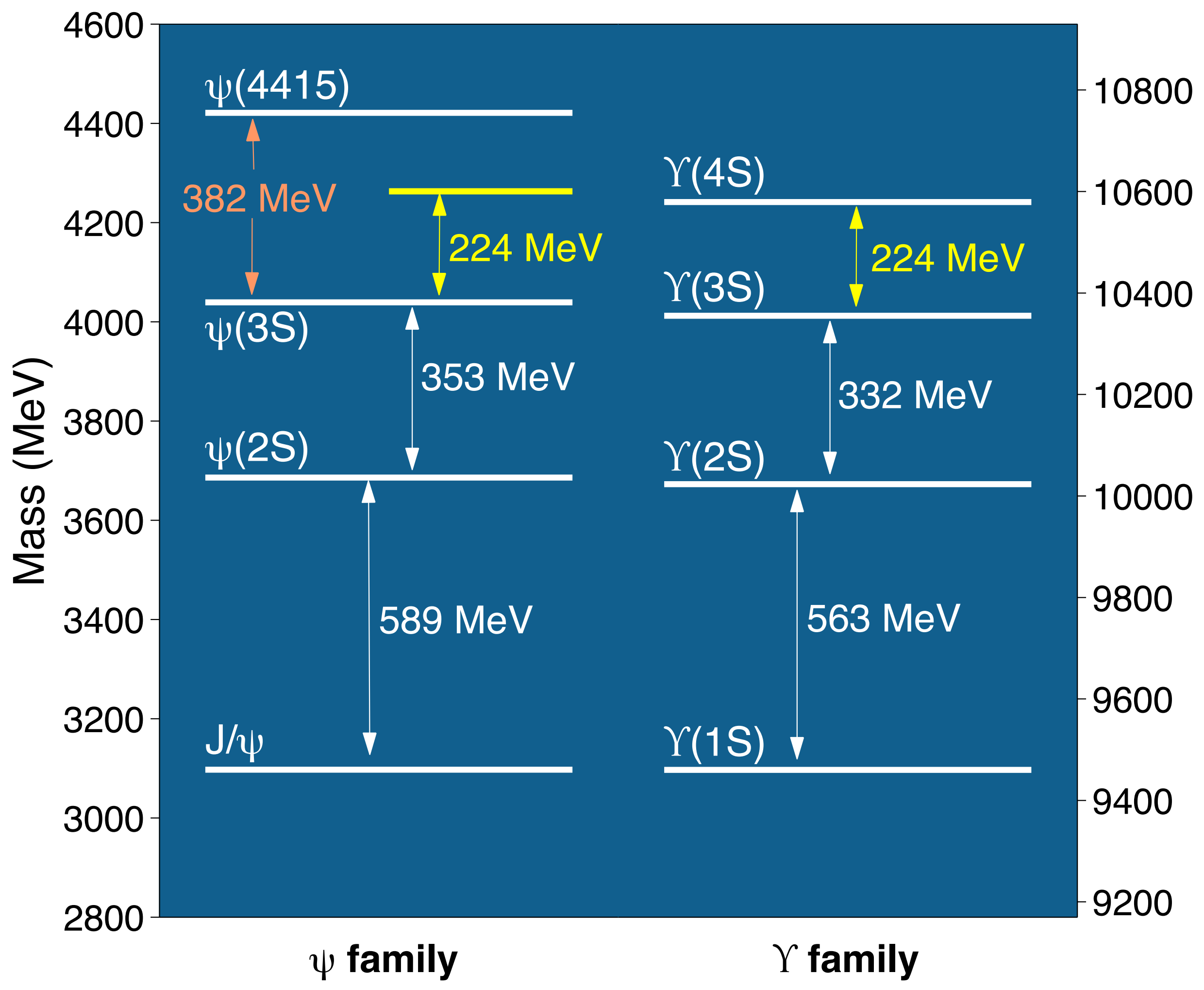


See Takayuki Matsuki's talk for more details of ISPE mechanism and the abundant predictions

Prediction of a missing higher charmonium around 4.26 GeV in *J*/ψ family

He, Chen, Xiang Liu, Matsuki, EPJC 74, 3208 (2014)

The similarity between J/ψ and Υ families



The comparison of the *J/ψ* family with the Υ family:

- **Similarity:**

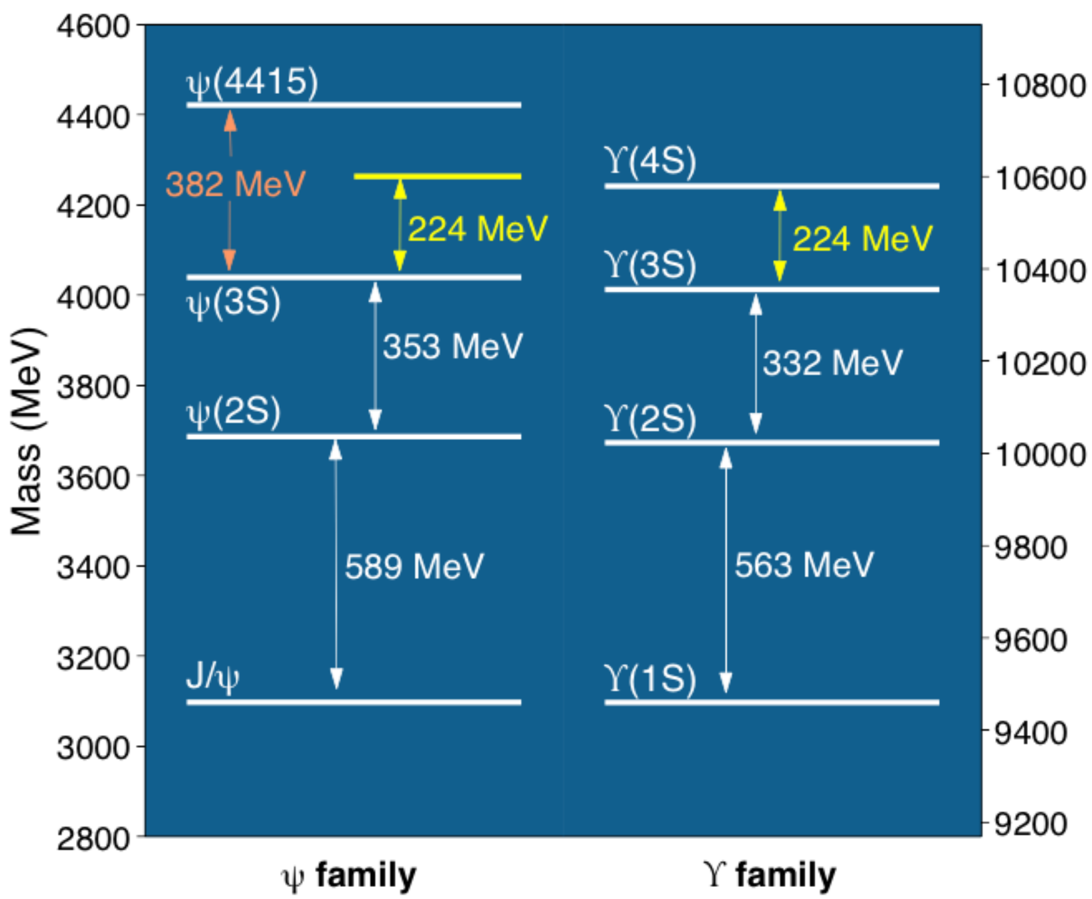
1.The mass gap between ψ(2*S*) and *J/ψ* is almost the same as that between Υ(2*S*) and Υ(1*S*)

2.There also exists the similarity of the mass differences, $M(\psi(3S)) - M(\psi(2S))$ and $M(\Upsilon(3S)) - M(\Upsilon(2S))$, where ψ(2*S*) and ψ(3*S*) correspond to ψ(3686) and ψ(4040), respectively

- **Violation:**

If ψ(4415) is ψ(4*S*), such a law is violated since the mass gap of ψ(4415) and ψ(3*S*) is larger than that of Υ(4*S*) and Υ(3*S*)

The possible reason to result in the above puzzling mass gap: **The properties of the charmonia above 4.1 GeV are still not understood well**



The mass spectrum analysis

- Compared with the J/ψ family, **the bottomonia** with the radial quantum numbers $n = 1, 2, 3, 4$ were **well established** both by experiment and theory.
- **Thus, the study of J/ψ family can be borrowed from Υ family.**
- If this law of mass gap relation still holds for states with $n = 3, 4$ in the J/ψ and Υ familes, we find that **the mass of $\psi(4S)$ should be located at 4263 MeV**, where we take the mass gap between $\Upsilon(4S)$ and $\Upsilon(3S)$ to add it to the mass of $\psi(3S)$.

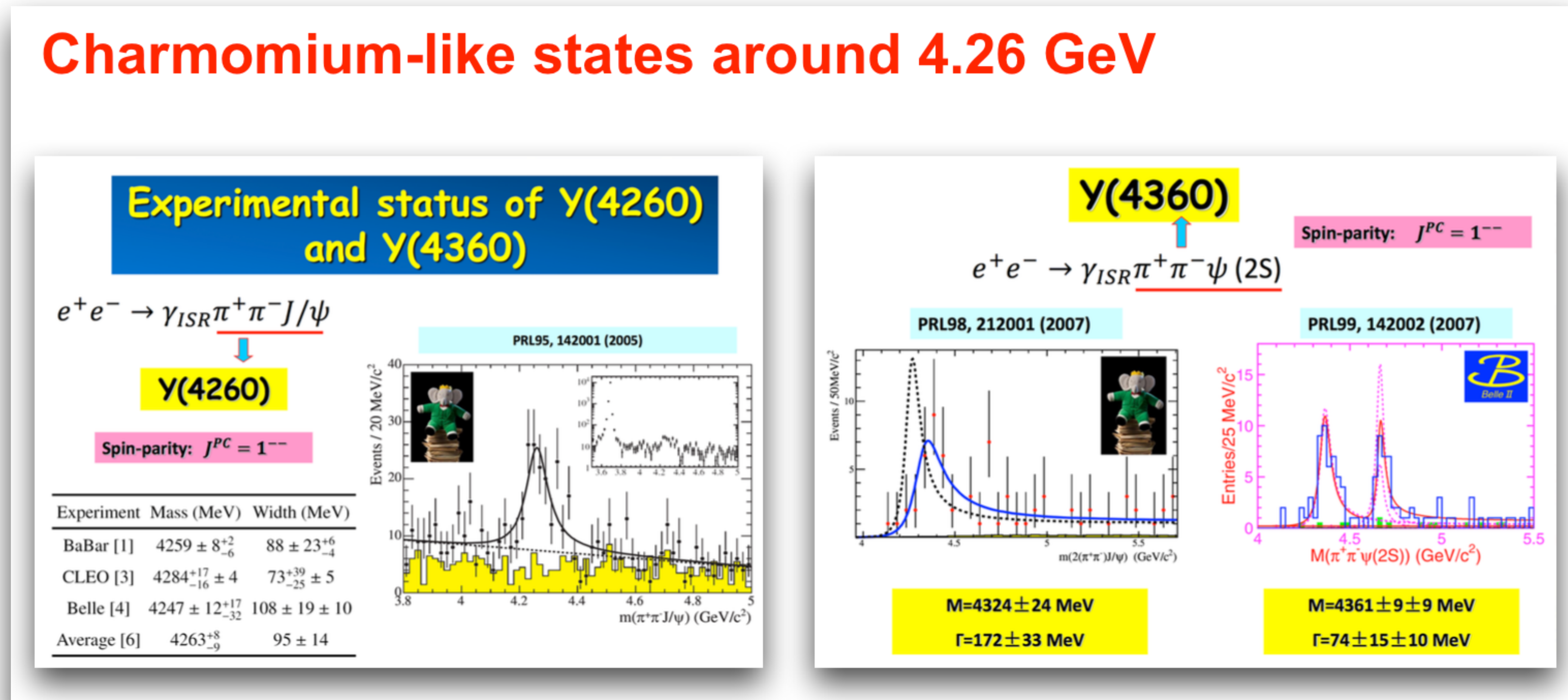
Consistent

The screening potential prediction of $\psi(4S)$ mass:

- **4273 MeV Li&Chao PRD79, 094004 (2009)**
- **4247 MeV Dong et al., PRD49, 1642 (1994)**

Questions:

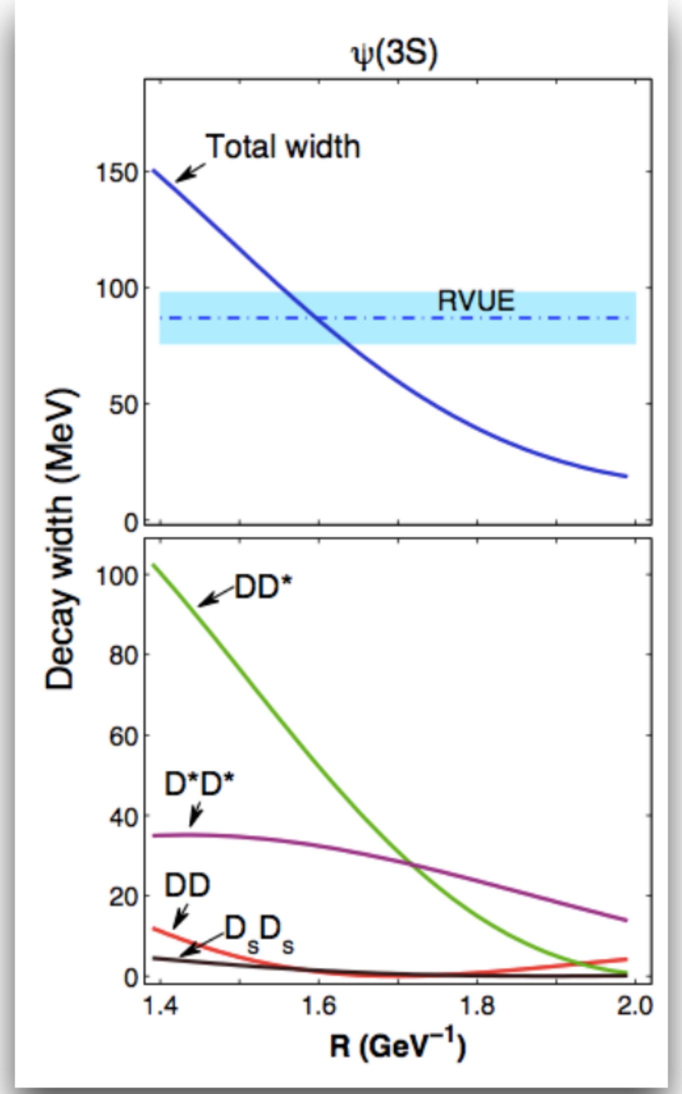
- If this predicted state exists in the J/ψ family, we must reveal its underlying properties to answer why there does not have any evidence in the present experiment
- Can Y(4260) or Y(4360) be as the candidate of predicted charmonium with mass around 4.26 GeV?



The decay behavior of the predicted charmonium around 4.26 GeV

We adopt the QPC model to study the decay behavior of the discussed charmonia (L. Micu, Nucl. Phys. B 10, 521 (1969))

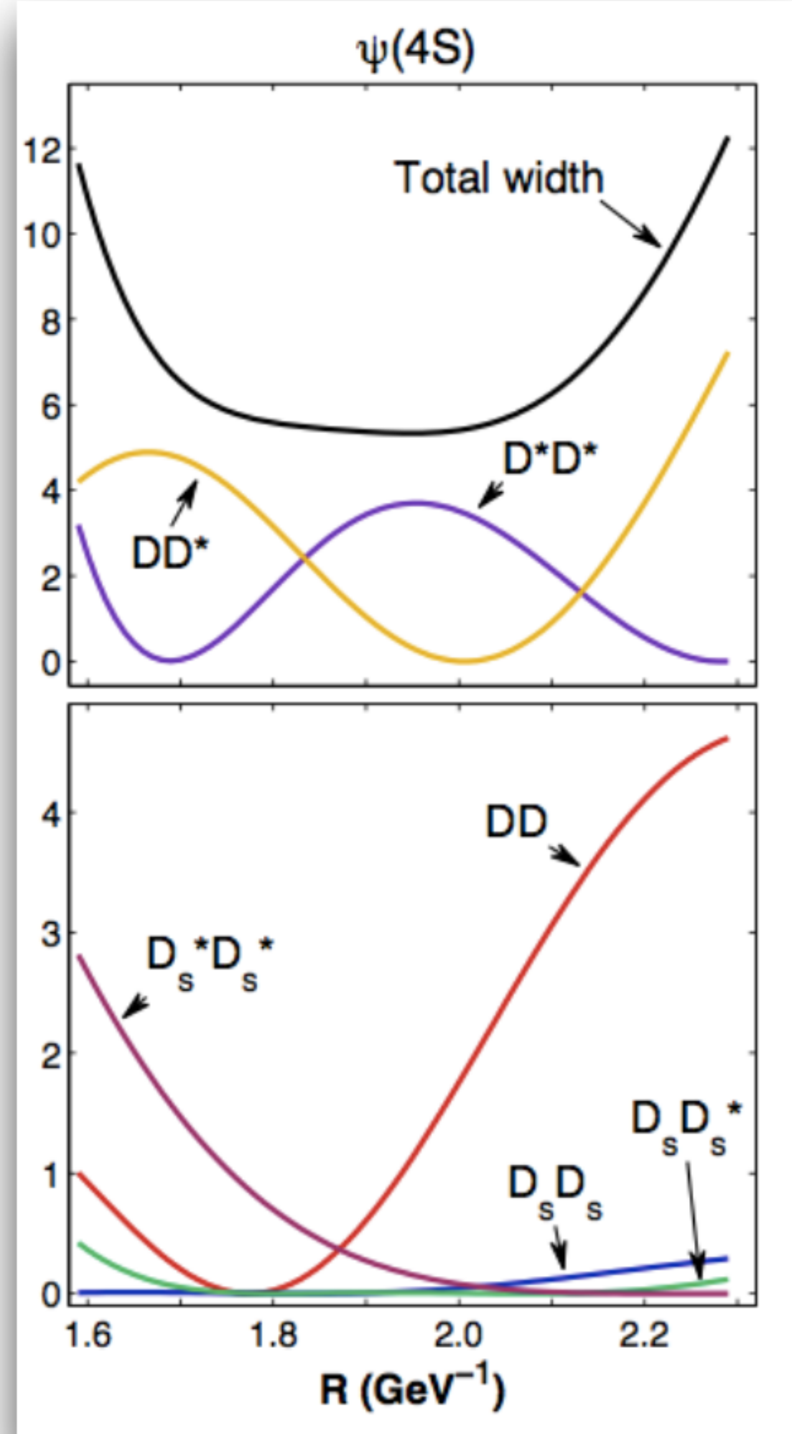
ψ(3S) decay behavior



- **Test the reliability of the calculation via ψ(3S) (ψ(4040))**
- **Reproduce the experimental data well of ψ(4040)**
- **Enable us to apply this model to safely study the decays of ψ(4*S*)**

$$\frac{\Gamma_{D\bar{D}}}{\Gamma_{D^*\bar{D}+H.c.}} = 0.24 \pm 0.05 \pm 0.12$$

$\psi(4S)$ decay behavior



Exclude $Y(4260)/Y(4360)$ as the candidate of $\psi(4S)$

A very interesting result of the decay behavior of $\psi(4S)$ can be found:

- The **total decay width** of $\psi(4S)$ is **stable** corresponding to the R range adopted, while its **partial decay widths** strongly **depend on the R value**
- **Due to node effect!**
- **The predicted charmonium $\psi(4S)$ has very narrow width around 6 MeV**
- **For the higher charmonia above the DD threshold, this phenomenon of $\psi(4S)$ presented here is unusual**

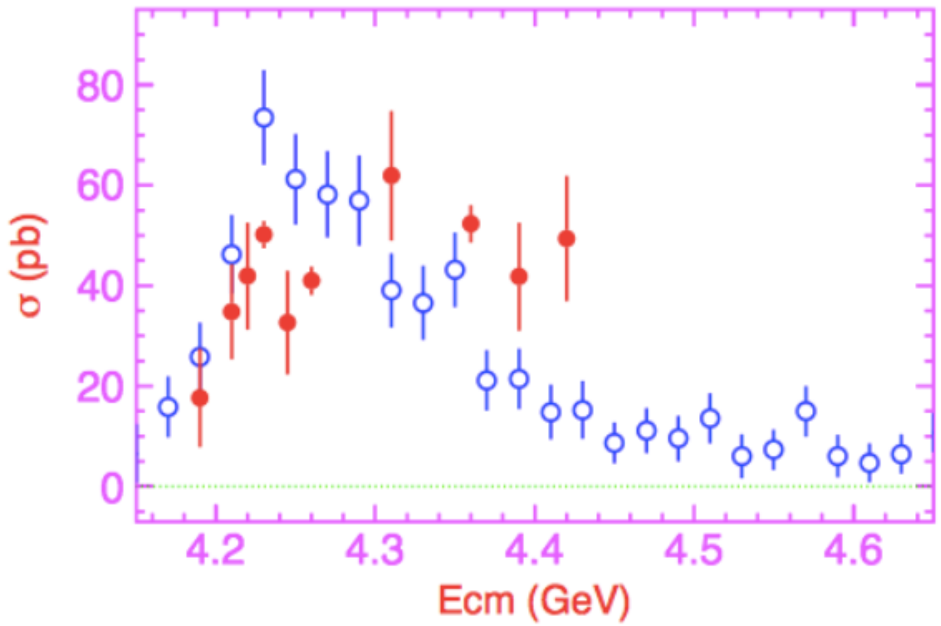
$\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ have widths 80 ± 10 MeV, 103 ± 8 MeV and 62 ± 20 MeV, respectively, all of which are large. Even $\psi(3770)$ which is just 43 MeV above the DD threshold has the width 27.2 MeV

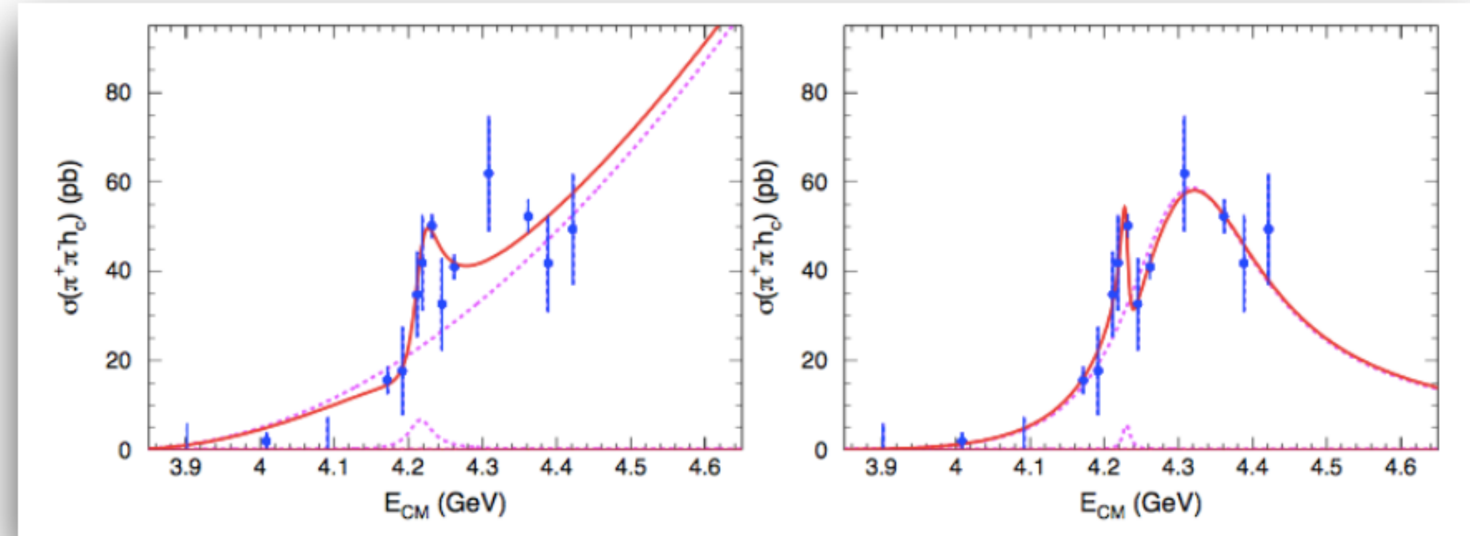
It is difficult to identify $\psi(4S)$ with very narrow width in experiment

Experimental evidence

Experimental data

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





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

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

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

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

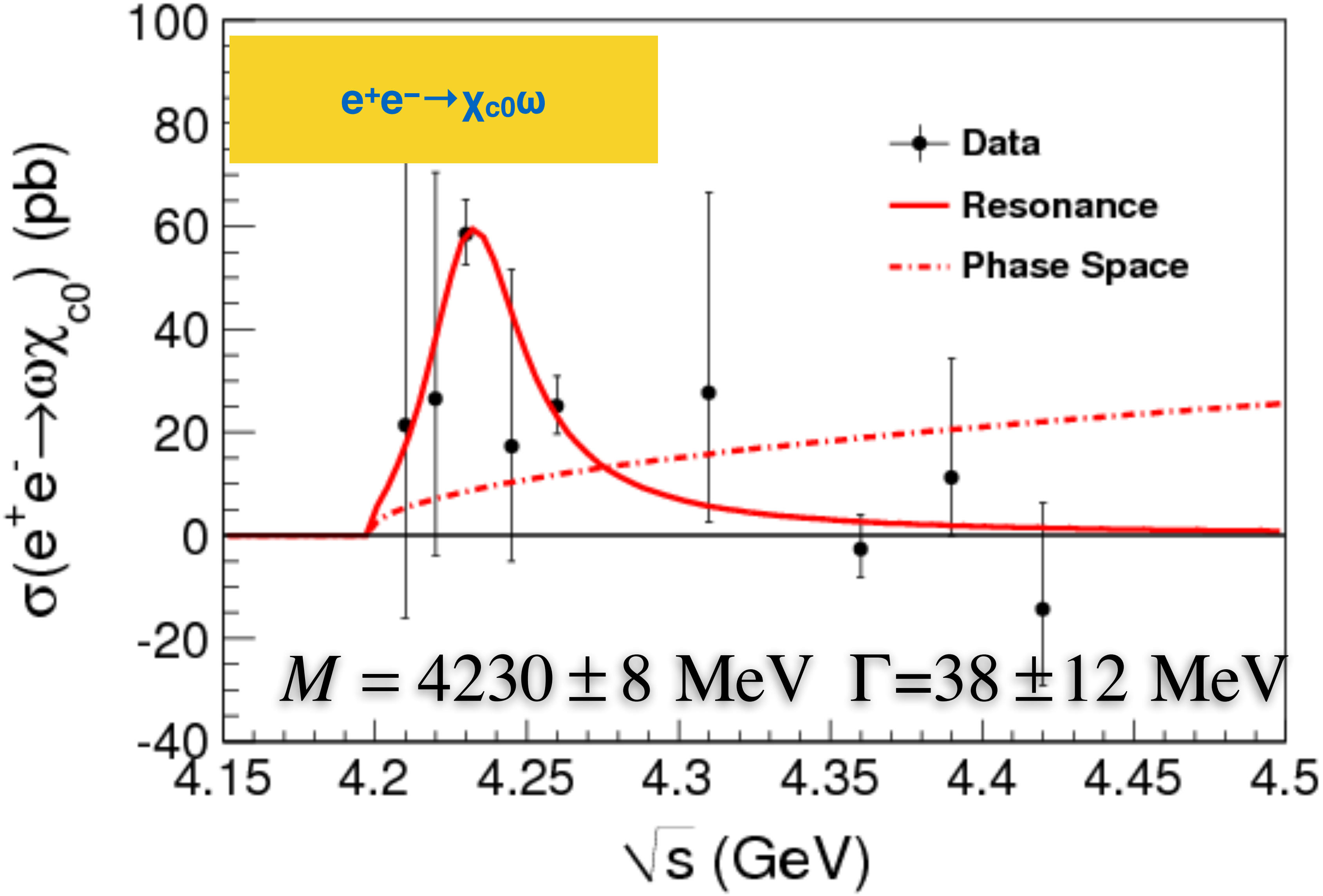
The role of the predicted $\psi(4S)$ in the observed $e^+e^-\to\chi_{c0}\omega$

Chen, Xiang Liu, Matsuki, PRD 91, 094023 (2015)

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

BESIII, PRL 114, 092003 (2015)

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



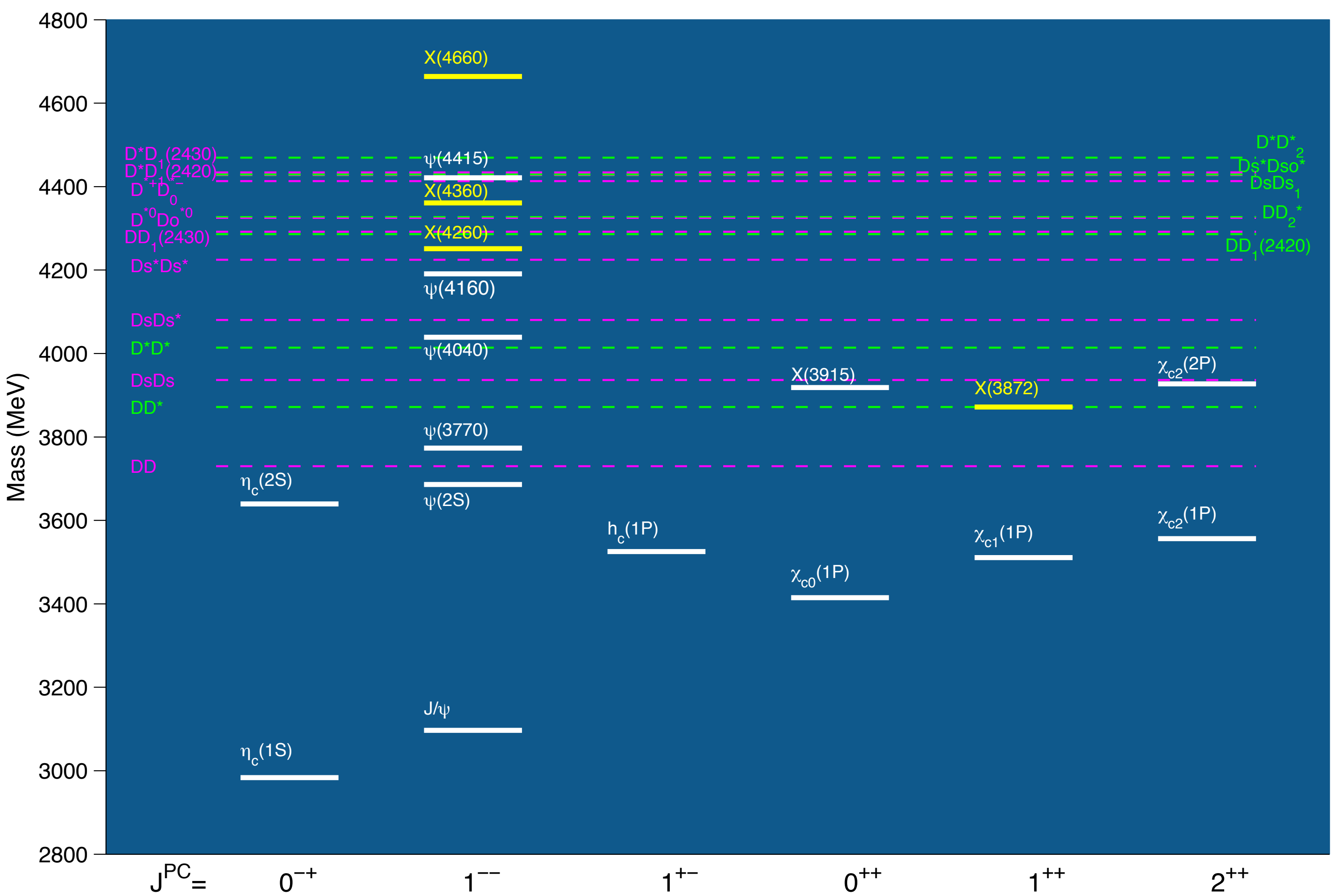
If taking the mass of $\psi(4S)$ to be 4230 MeV (Expt.), we find

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

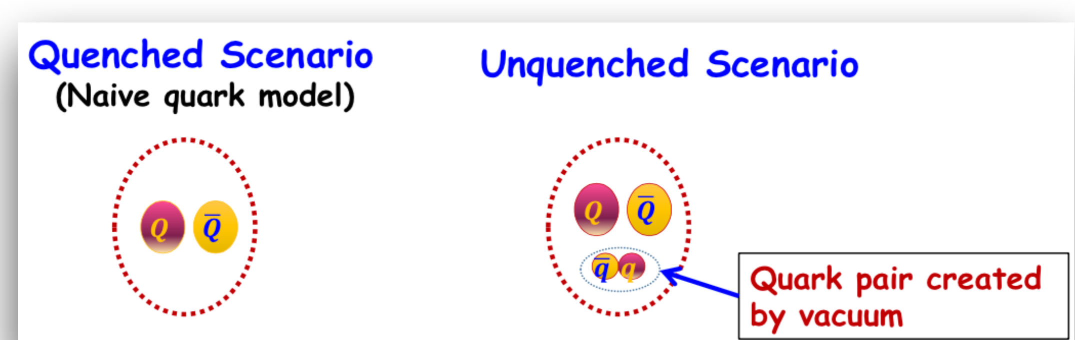
Introducing the predicted $\psi(4S)$ can naturally explain why only $e^+e^- \to \chi_{c0}\omega$ was reported by BESIII

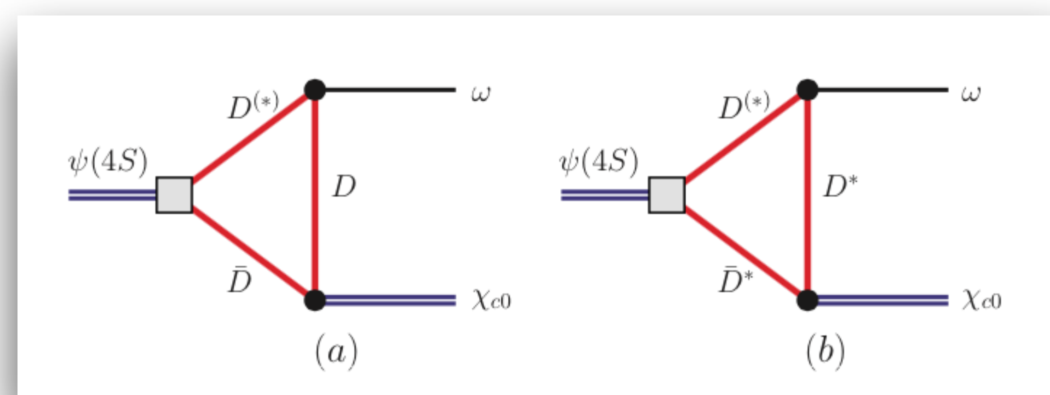
The study of the transition $\psi(4S) \to \omega\chi_{c0}$

For higher charmonia and bottomonia, the unquenched effect becomes more and more important since more channels are open



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





Adopt the effective Lagrangian approach to do the calculation

Heavy quark limit and chiral symmetry

$$\begin{aligned}
\mathcal{L}_{\psi\mathcal{D}^{(*)}\mathcal{D}^{(*)}} &= -ig_{\psi\mathcal{D}\mathcal{D}}\psi_\mu(\partial^\mu\mathcal{D}\mathcal{D}^\dagger - \mathcal{D}\partial^\mu\mathcal{D}^\dagger) \\
&+ g_{\psi\mathcal{D}^*\mathcal{D}}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu(\mathcal{D}^*_\alpha \overleftrightarrow{\partial}_\beta \mathcal{D}^\dagger - \mathcal{D}\overleftrightarrow{\partial}_\beta \mathcal{D}^{*\dagger}_\alpha) \\
&+ ig_{\psi\mathcal{D}^*\mathcal{D}^*}\psi^\mu(\mathcal{D}^*_\nu\partial^\nu\mathcal{D}^{*\dagger}_\mu - \partial^\nu\mathcal{D}^*_\mu\mathcal{D}^{*\dagger}_\nu \\
&- \mathcal{D}^*_\nu \overleftrightarrow{\partial}_\mu \mathcal{D}^{*\nu\dagger}), \qquad (1)
\end{aligned}$$

$$\mathcal{L}_{\chi_{c0}\mathcal{D}^{(*)}\mathcal{D}^{(*)}} = -g_{\chi_{c0}\mathcal{D}\mathcal{D}}\chi_{c0}\mathcal{D}\mathcal{D}^\dagger - g_{\chi_{c0}\mathcal{D}^*\mathcal{D}^*}\chi_{c0}\mathcal{D}^*_\mu\mathcal{D}^{*\mu\dagger}, \quad (2)$$

$$\begin{aligned}
\mathcal{L}_{\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{V}} &= -ig_{\mathcal{D}\mathcal{D}\mathcal{V}}\mathcal{D}^\dagger_i \overleftrightarrow{\partial}^\mu \mathcal{D}^j(\mathcal{V}_\mu)^i_j - 2f_{\mathcal{D}^*\mathcal{D}\mathcal{V}}\varepsilon_{\mu\nu\alpha\beta} \\
&\times(\partial^\mu\mathcal{V}^\nu)^i_j(\mathcal{D}^\dagger_i \overleftrightarrow{\partial}^\alpha \mathcal{D}^{*\beta j} - \mathcal{D}^{*\beta\dagger}_i \overleftrightarrow{\partial}^\alpha \mathcal{D}^j) \\
&+ ig_{\mathcal{D}^*\mathcal{D}^*\mathcal{V}}\mathcal{D}^{*\nu\dagger}_i \overleftrightarrow{\partial}^\mu \mathcal{D}^{*j}_\nu(\mathcal{V}_\mu)^i_j \\
&+ 4if_{\mathcal{D}^*\mathcal{D}^*\mathcal{V}}\mathcal{D}^{*\dagger}_{i\mu}(\partial^\mu\mathcal{V}^\nu - \partial^\nu\mathcal{V}^\mu)^i_j\mathcal{D}^{*j}_\nu, \qquad (3)
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{P}} &= -ig_{\mathcal{D}^*\mathcal{D}\mathcal{P}}(\bar{\mathcal{D}}\partial_\mu\mathcal{P}\mathcal{D}^{*\mu} - \bar{\mathcal{D}}^{*\mu}\partial_\mu\mathcal{P}\mathcal{D}) \\
&+ \frac{1}{2}g_{\mathcal{D}^*\mathcal{D}^*\mathcal{P}}\epsilon_{\mu\nu\alpha\beta}\bar{\mathcal{D}}^{*\mu}\partial^\nu\mathcal{P}\overleftrightarrow{\partial}^\alpha \mathcal{D}^{*\beta}, \qquad (4)
\end{aligned}$$

a general form of the decay amplitude is

$$\mathcal{M} = \int \frac{d^4q}{(2\pi)^4}\frac{\mathcal{V}_1\mathcal{V}_2\mathcal{V}_2}{\mathcal{P}_1\mathcal{P}_2\mathcal{P}_E}\mathcal{F}^2(q, m_E),$$

$$\mathcal{F}(q, m_E) = (m_E^2 - \Lambda^2)/(q^2 - \Lambda^2), \qquad \Lambda = \alpha_\Lambda\Lambda_{QCD} + m_E$$

The coupling constants of ψ(4*S*) interaction with charmed meson pair

He, Chen, Xiang Liu, Matsuki, Eur. Phys. J. C 74, 3208 (2014)

TABLE I: The concrete values of coupling constants of charmonium (J/ψ and χ_{c0}) interacting with charmed mesons, and those of charmed mesons interacting with light pseudoscalar/vector mesons [22–25].

Coupling	Value	Coupling	Value	Coupling	Value
$g_{J/\psi DD}$	7.44	$g_{J/\psi D^*D}$	2.49 GeV^{-1}	$g_{J/\psi D^*D^*}$	8.01
$g_{DD\mathcal{V}}$	3.47	$g_{D^*D\mathcal{V}}$	2.32 GeV^{-1}	$g_{D^*D^*\mathcal{V}}$	3.74
$f_{D^*D^*\mathcal{V}}$	4.67	$g_{\chi_{c0}DD}$	-25.00 GeV	$g_{\chi_{c0}D^*D^*}$	-8.96 GeV
$g_{D^*D\mathcal{P}}$	8.94	$g_{D^*D^*\mathcal{P}}$	17.32 GeV^{-1}		

$$\Gamma_{\psi(4S)\to DD} = \frac{g^2_{\psi(4S)DD}\lambda(m^2_{\psi(4S)}, m^2_D, m^2_D)^{3/2}}{24\pi m^5_{\psi(4S)}},$$

$$\Gamma_{\psi(4S)\to D^*D} = \frac{g^2_{\psi(4S)D^*D}\lambda(m^2_{\psi(4S)}, m^2_{D^*}, m^2_D)^{3/2}}{6\pi m^3_{\psi(4S)}},$$

$$\Gamma_{\psi(4S)\to D^*D^*} = \frac{g^2_{\psi(4S)D^*D^*}\lambda(m^2_{\psi(4S)}, m^2_{D^*}, m^2_{D^*})^{3/2}}{96\pi m^5_{\psi(4S)} m^4_{D^*}} \times(\lambda(m^2_{\psi(4S)}, m^2_{D^*}, m^2_{D^*}) + m^4_{\psi(4S)} + 12m^4_{D^*}),$$

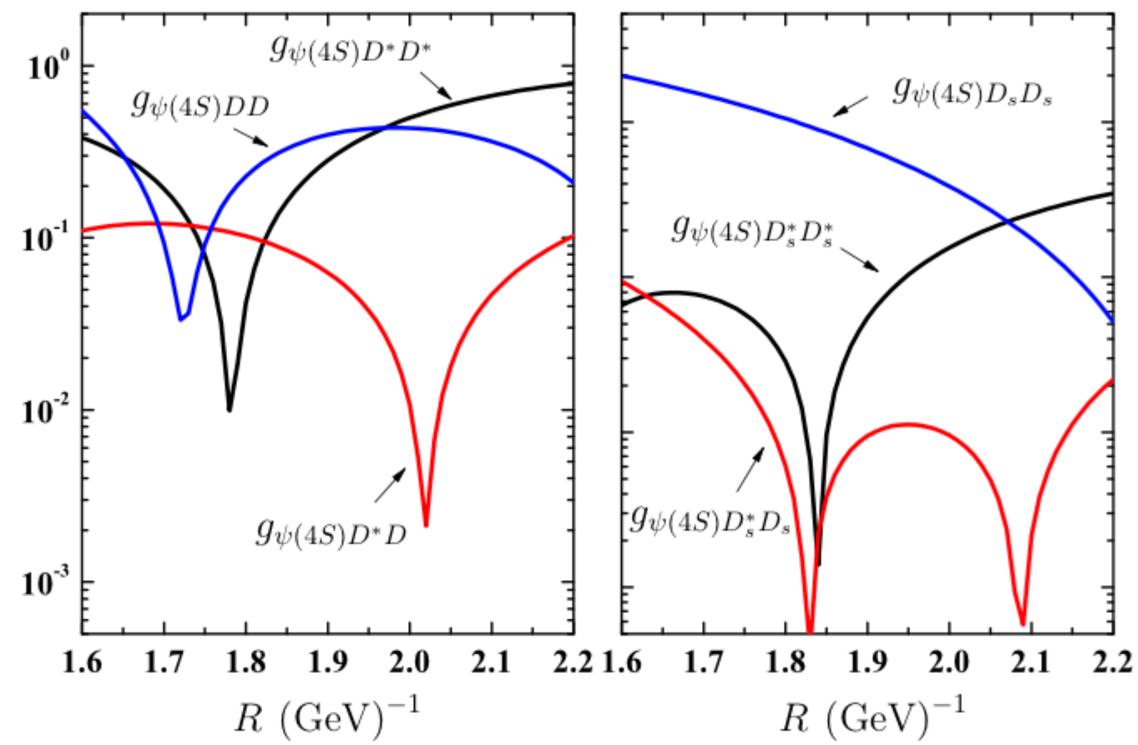


FIG. 2: (color online). The R dependence of the extracted coupling constants of $\psi(4S)$ interacting with charmed or charmed-strange mesons.

BESIII result (assuming the enhancement from ψ(4*S*)):

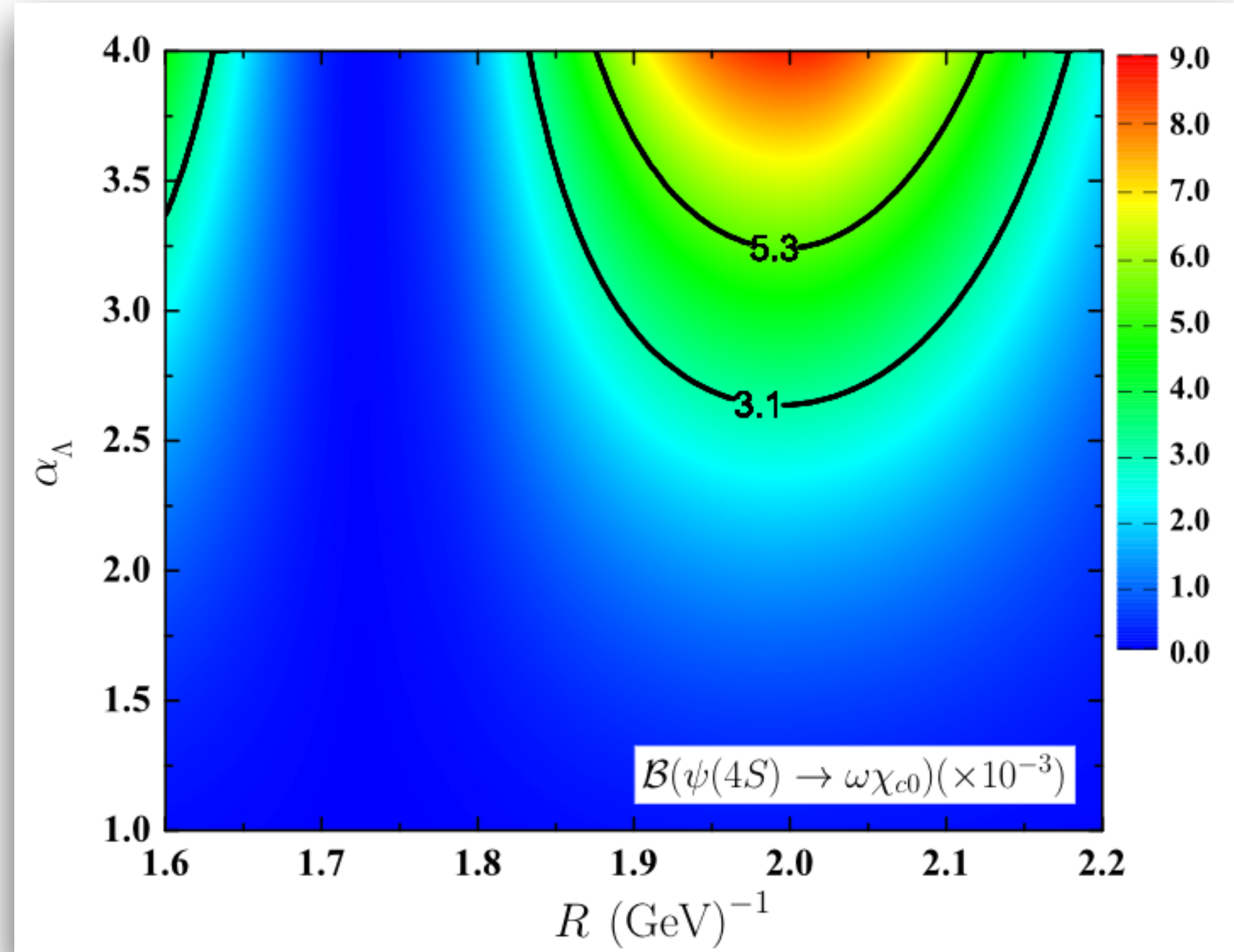
$$\Gamma(\psi(4S) \to e^+e^-)\mathcal{B}(\psi(4S) \to \omega\chi_{c0}) = (2.7 \pm 0.5 \pm 0.4)\,\mathrm{eV},$$

$$\Gamma(\psi(4S) \to e^+e^-) = 0.63\ \mathrm{keV}$$ Li&Chao PRD79, 094004

$$\Gamma(\psi(4S) \to e^+e^-) = 0.66\ \mathrm{keV}$$ Dong et al., PRD49, 1642

We extract

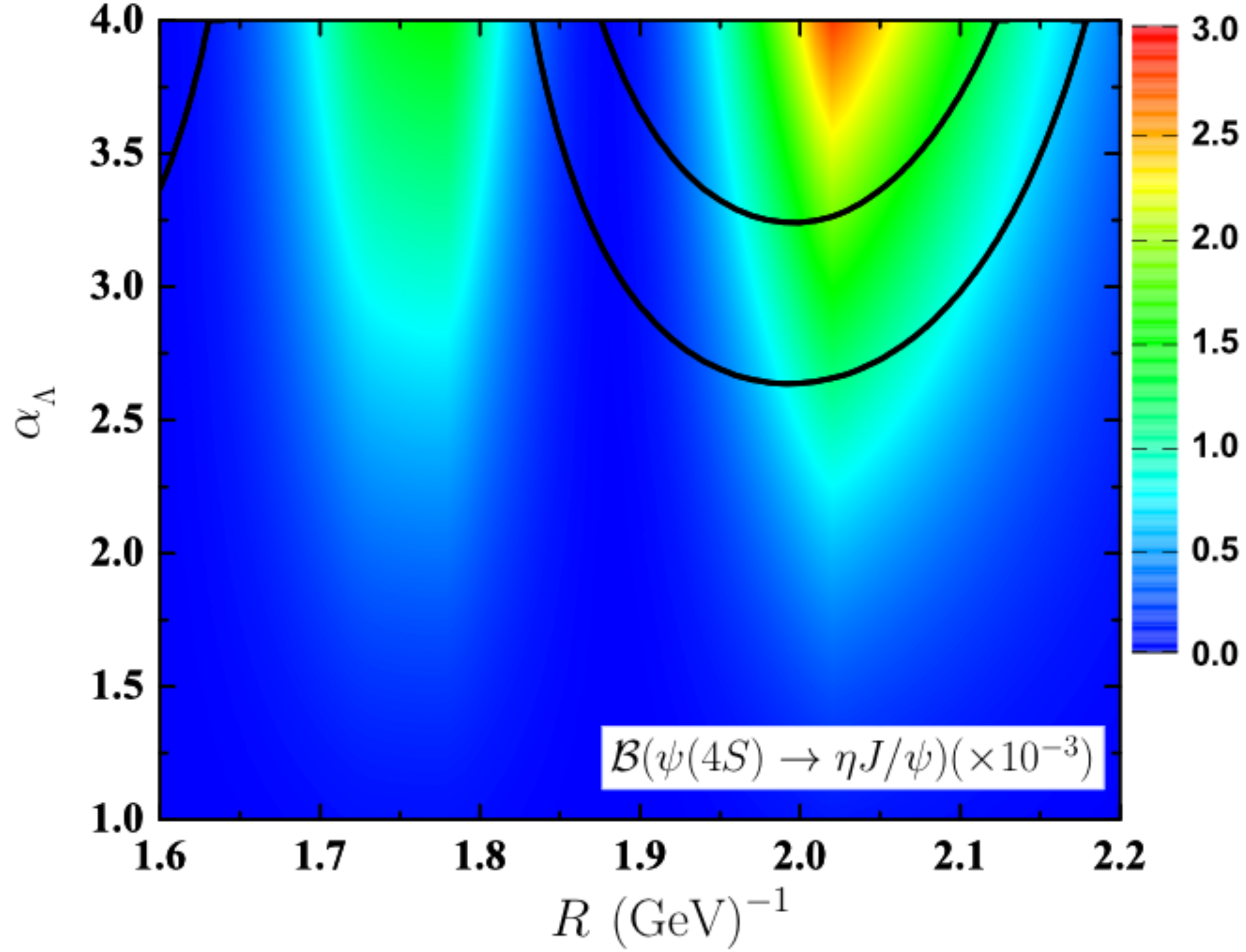
$$\mathcal{B}(\psi(4S) \to \omega\chi_{c0}) = (3.1 \sim 5.3)\times 10^{-3}$$



- **Our theoretical result overlaps with the experimental data in a reasonable parameter range of $2.6 < \alpha_\Lambda < 4.0$ and $1.83 < R < 2.17$**

Provide direct support for introducing the predicted $\psi(4S)$ contribution to explain $e^+e^- \to \omega\chi_{c0}$

Predict the upper limit of the branching ratio of ψ(4*S*) → η*J*/ψ



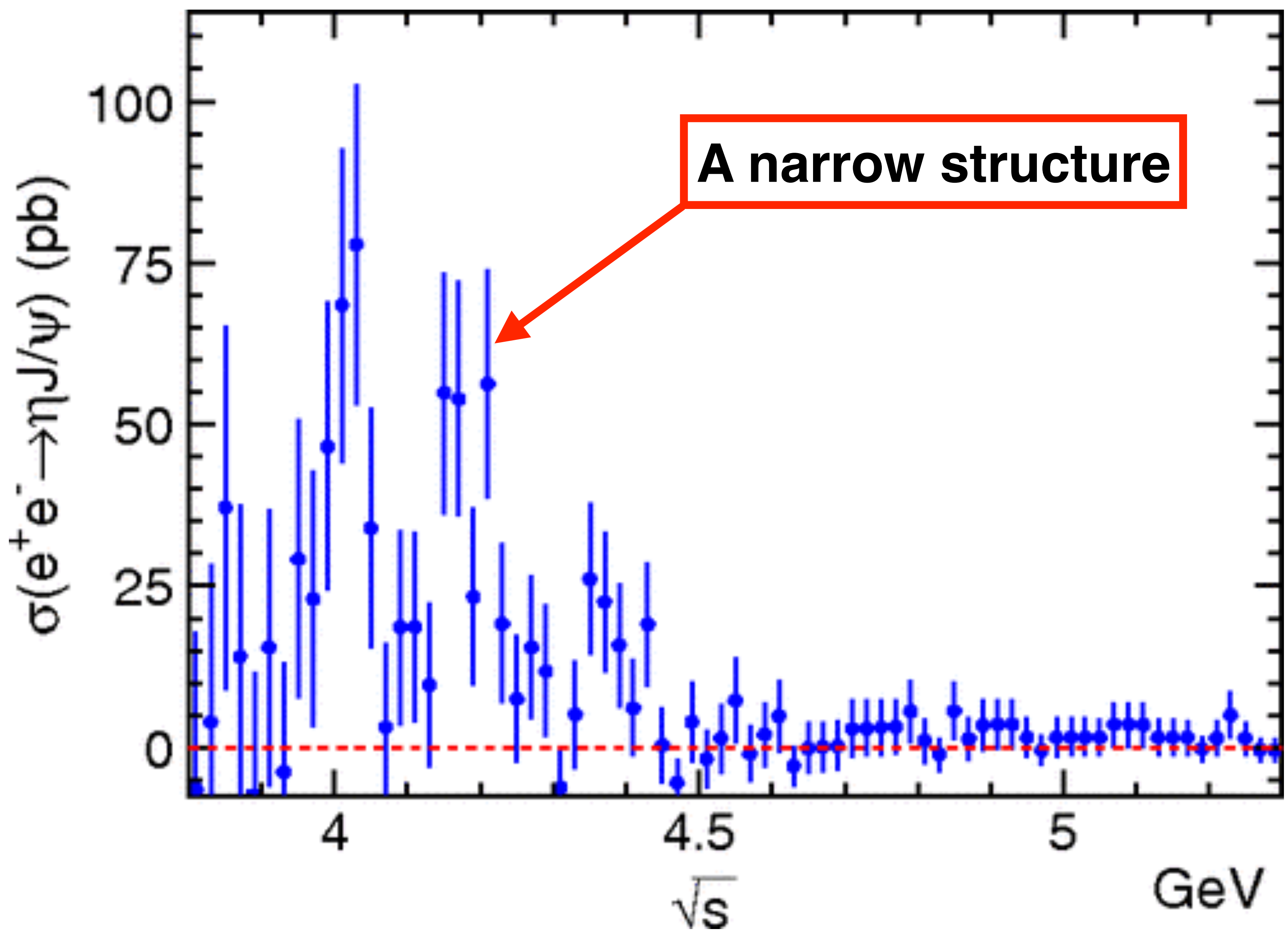
$$\mathcal{B}(\psi(4S)\to\eta J/\psi) < 1.9\times 10^{-3}$$

This branching ratio can be tested by future experiment

Others possible evidences of ψ(4*S*) in open-charm and hidden-charm decay channels

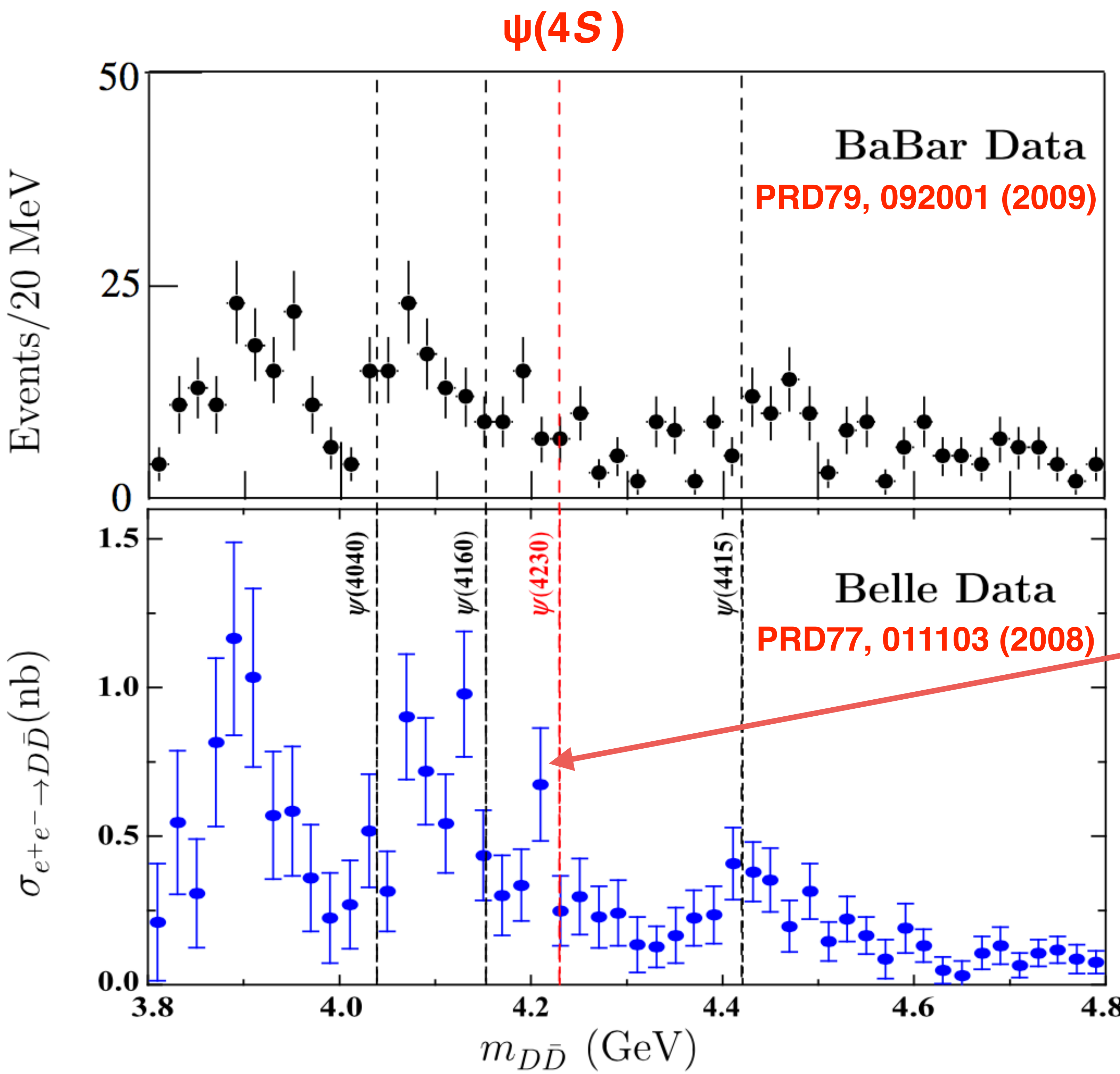
$$e^+e^- \to \eta J/\psi.$$

Belle, PRD87, 051101 (2013)



Thus, we suggest that Belle redo the analysis by including the predicted ψ(4S), which is an interesting issue.

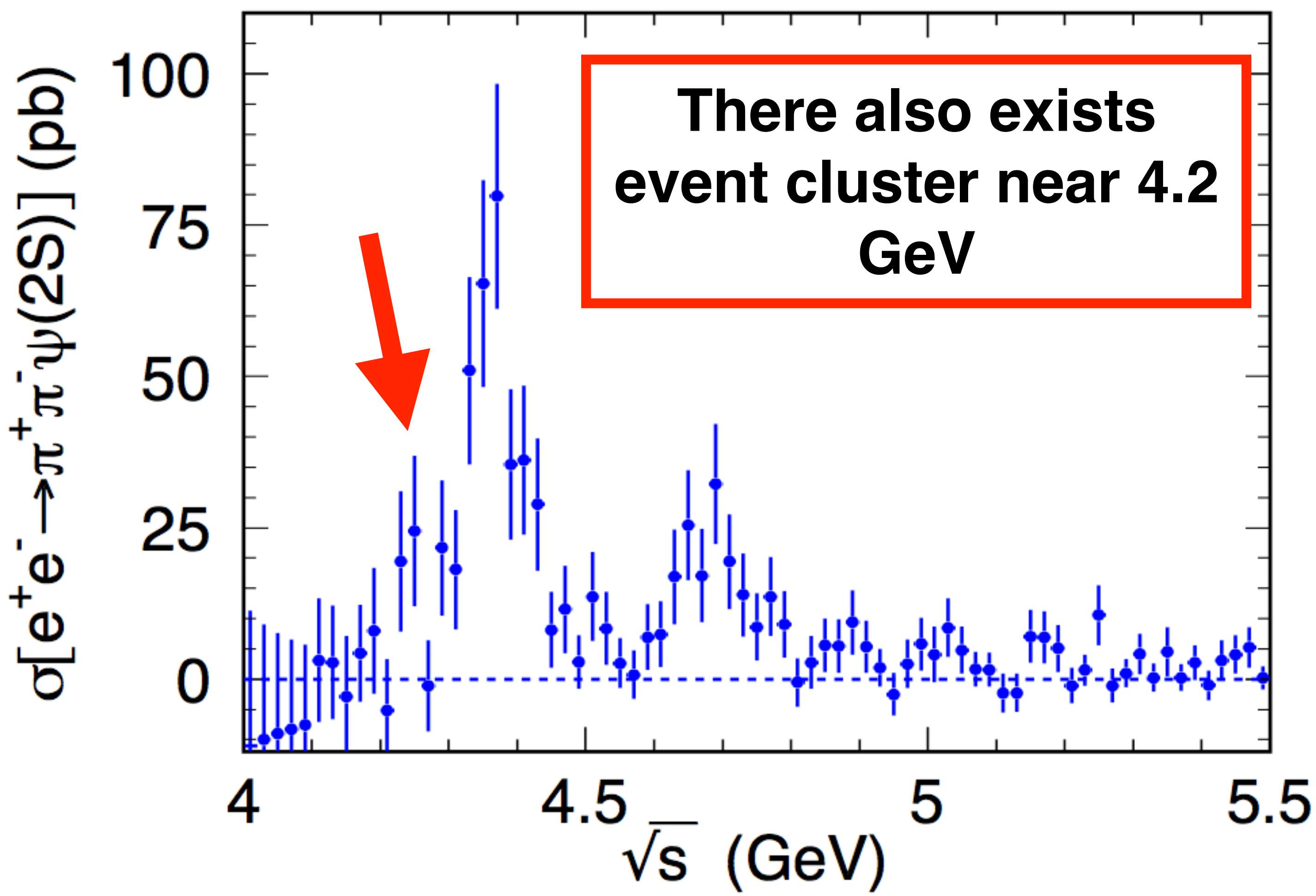
$e^+e^- \to D\bar{D}$

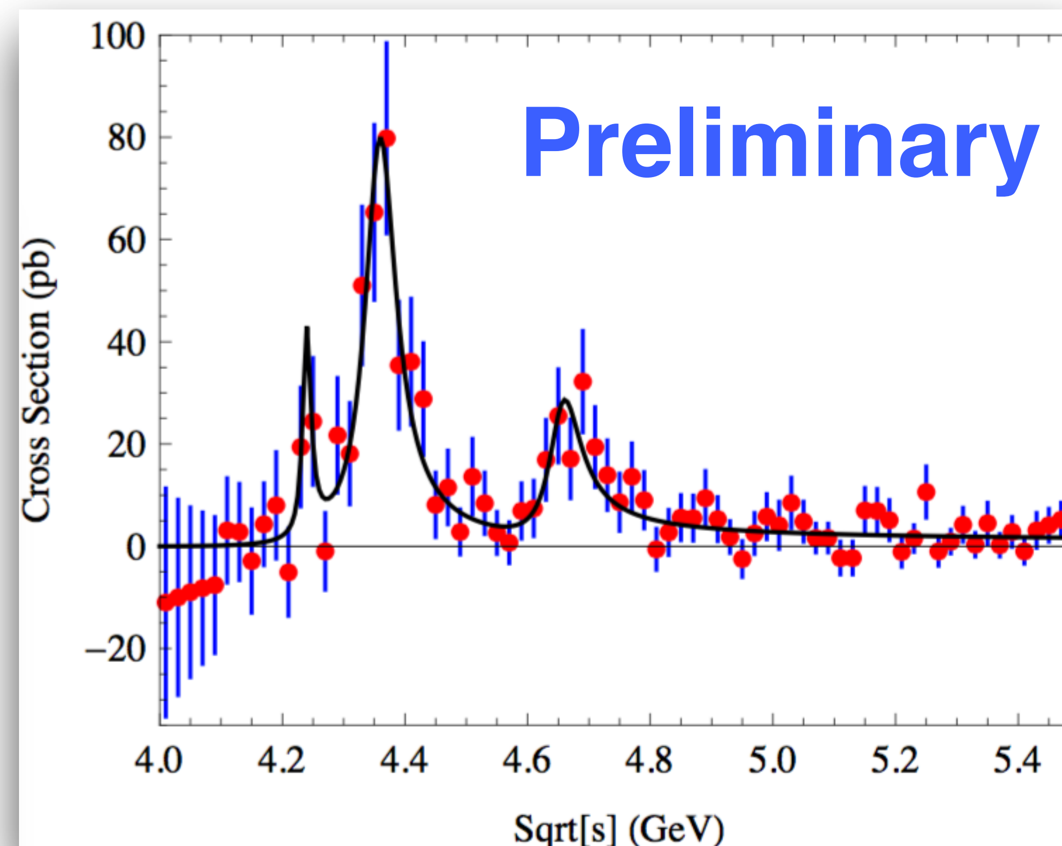


An enhancement structure

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

Belle, arXiv: 1410.7641





Our result of a combined fit by including ψ(4*S*), Y(4360) and Y(4660) (in progress)

Summary

- Predict a narrow higher charmonium ψ(4*S*)
- The introduction of ψ(4*S*) can explain recent BESIII's observation $e^+e^- \to \omega\chi_{c0}$
- The possible evidences of ψ(4*S*) in experiments

Process	Mass (MeV)	Width (MeV)
$e^+e^- \to \omega\chi_{c0}$ [1]	$4230 \pm 8 \pm 6$	$38 \pm 12 \pm 2$
$e^+e^- \to \pi^+\pi^- h_c$ [31]	4216 ± 7	39 ± 17
	4230 ± 10	12 ± 36

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

$e^+e^- \to D\bar{D}$

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

Are these narrow structures near 4.2 GeV due to the same origin

- Suggest BESIII, Belle and forthcoming BelleII to identify this missing ψ(4*S*)

Thank you for your attention