Theoretical review of XYZ

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Outline

- The observed charmonium-like states XYZ
- XYZ states from B meson decays
- X(3915), X(4350) and Z(3930) produced by the two-photon fusion
- Y states directly from the e+e- annihilation
- Charged bottomoniulike and charmoniumlike states announced by Belle and BESIII
- Summary

The observed charmonium-like states XYZ

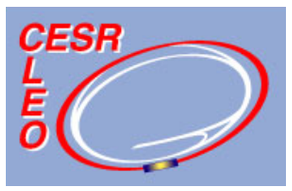
A summary of the observed XYZ states

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

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

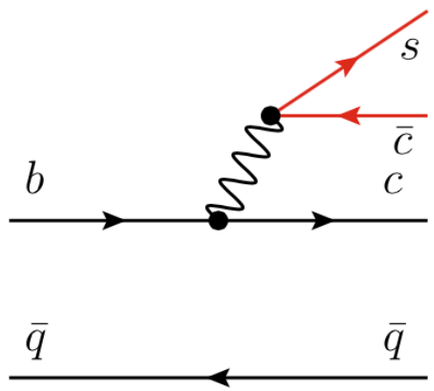


In general, the observed XYZ states can be categorized into five groups

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

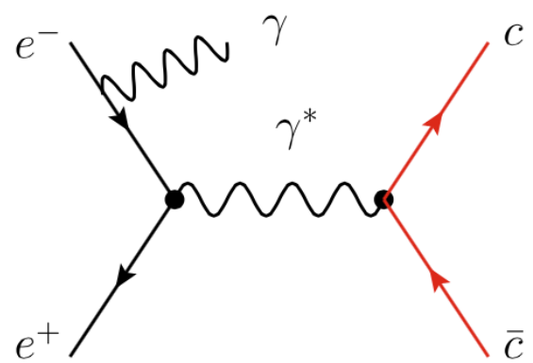
e^+e^- annihilation

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



(a)

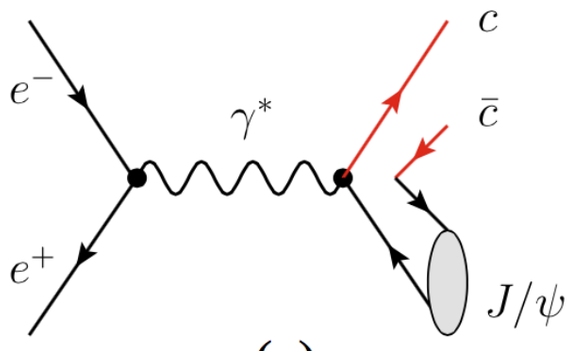
B meson decay



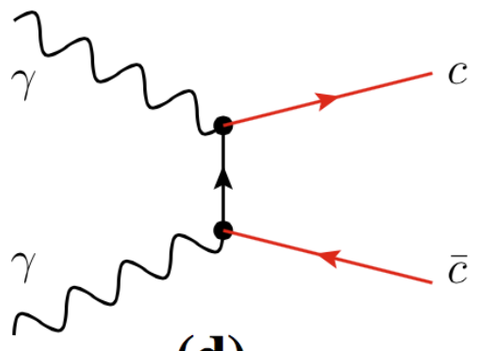
(b)

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

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



(c)



(d)

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

the double charm production

$\gamma\gamma$ fusion process

How to explain these novel phenomenon

XYZ states from B meson decays

$$
B \to \begin{cases} X(3872)K \to \underline{J/\psi\pi^+\pi^-}K, \\ Y(3940)K \to \underline{J/\psi\omega}K, \\ Z^+(4430)K \to \underline{\psi'\pi^+}K, \\ \left.\begin{matrix} Z^+(4051)K \\ Z^+(4248)K \end{matrix}\right\} \to \underline{\chi_{c1}\pi^+}K, \\ \left.\begin{matrix} Y(4140)K \\ Y(4274)K \end{matrix}\right\} \to \underline{J/\psi\phi}K, \end{cases}
$$

Abundant experimental informaiton for X(3872)

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

$m(D^0D^{*0}) = (3871.81 \pm 0.36)$ MeV

PDG average mass of $X(3872)$: (3871.68 ± 0.17) MeV

The possible theoretical explanations for X(3872)

(1) $D^*\bar{D}^*$ **molecular state**

(2) a dominant $c\bar{c}$ component with some admixture of $D^0\bar{D}^{*0} + \bar{D}^0 D^{*0}$

Belle

$$\frac{BR[X(3872) \to \gamma J/\psi]}{BR[X(3872) \to J/\psi\pi^+\pi^-]} = 0.14 \pm 0.05,$$

$$\frac{BR[X(3872) \to D^0\bar{D}^0\pi^0]}{BR[X(3872) \to \pi^+\pi^- J/\psi]} = 9.4^{+3.6}_{-4.3}$$

BaBar

$$\frac{BR[X(3872) \to \gamma J/\psi]}{BR[X(3872) \to J/\psi\pi^+\pi^-]} \approx 0.25$$

$$\frac{BR[B^0 \to X(3872)K^0]}{BR[B^+ \to X(3872)K^+]} \approx 1.62$$

$$\frac{BR(X(3872) \to \psi'\gamma)}{BR(X(3872) \to J/\psi\gamma)} = 3.4 \pm 1.4$$

These experimental ratios are crucial to test the structure of X(3872)

The molecular explanations to XYZ states observed from B meson decays are very popular

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

Liu & Zhu, PRD79:094026 (2009)

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

CDF, PRL102:242002 (2009)

BaBar, PRL101:082001 (2008)

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

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

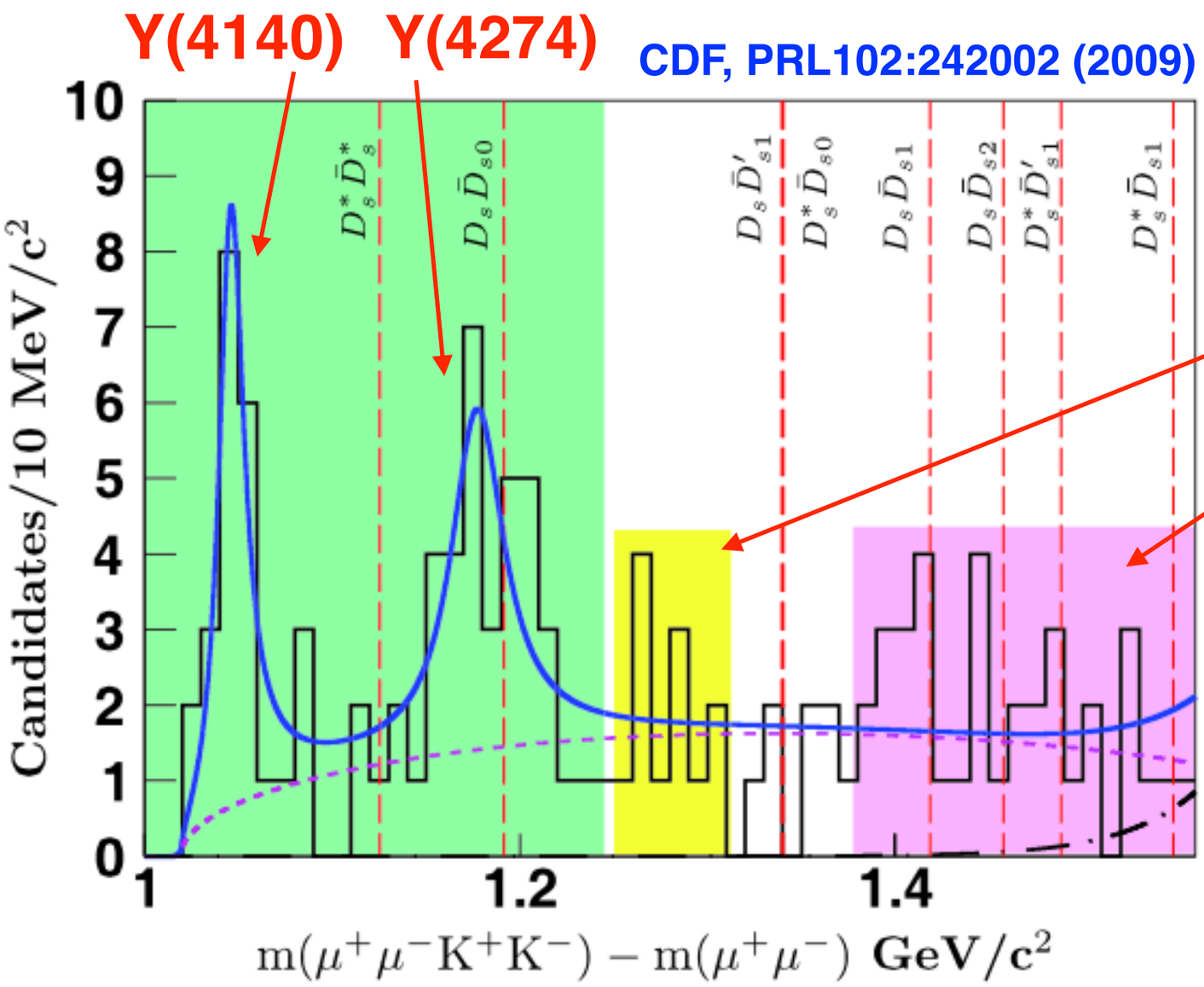
These similarities inspire us propose the hidden-charm molecular states explanations:

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

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

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)

There exist event clusters

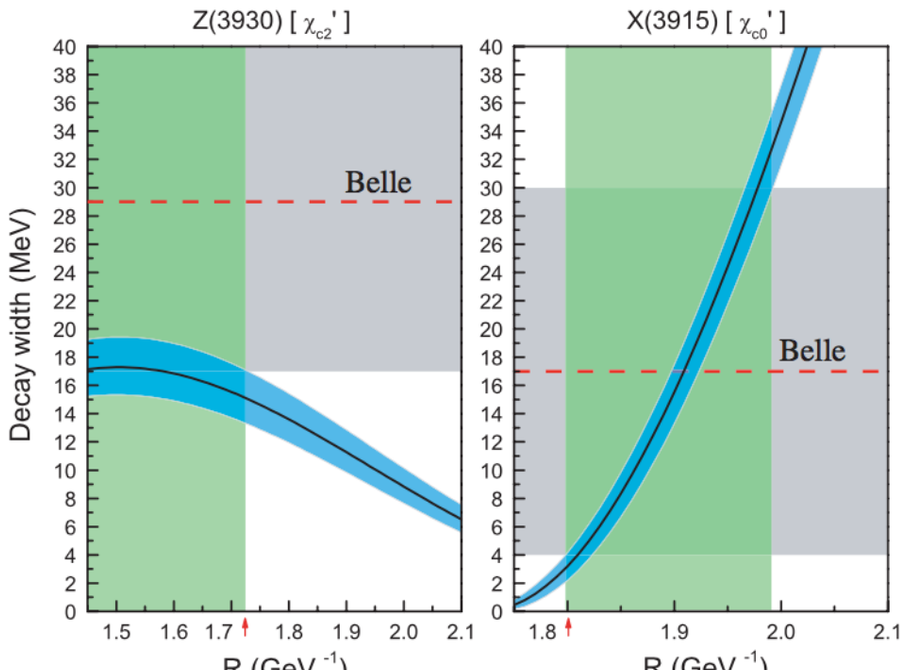
New hidden-charm molecular states?

X(3915), X(4350) and Z(3930) produced by the two-photon fusion

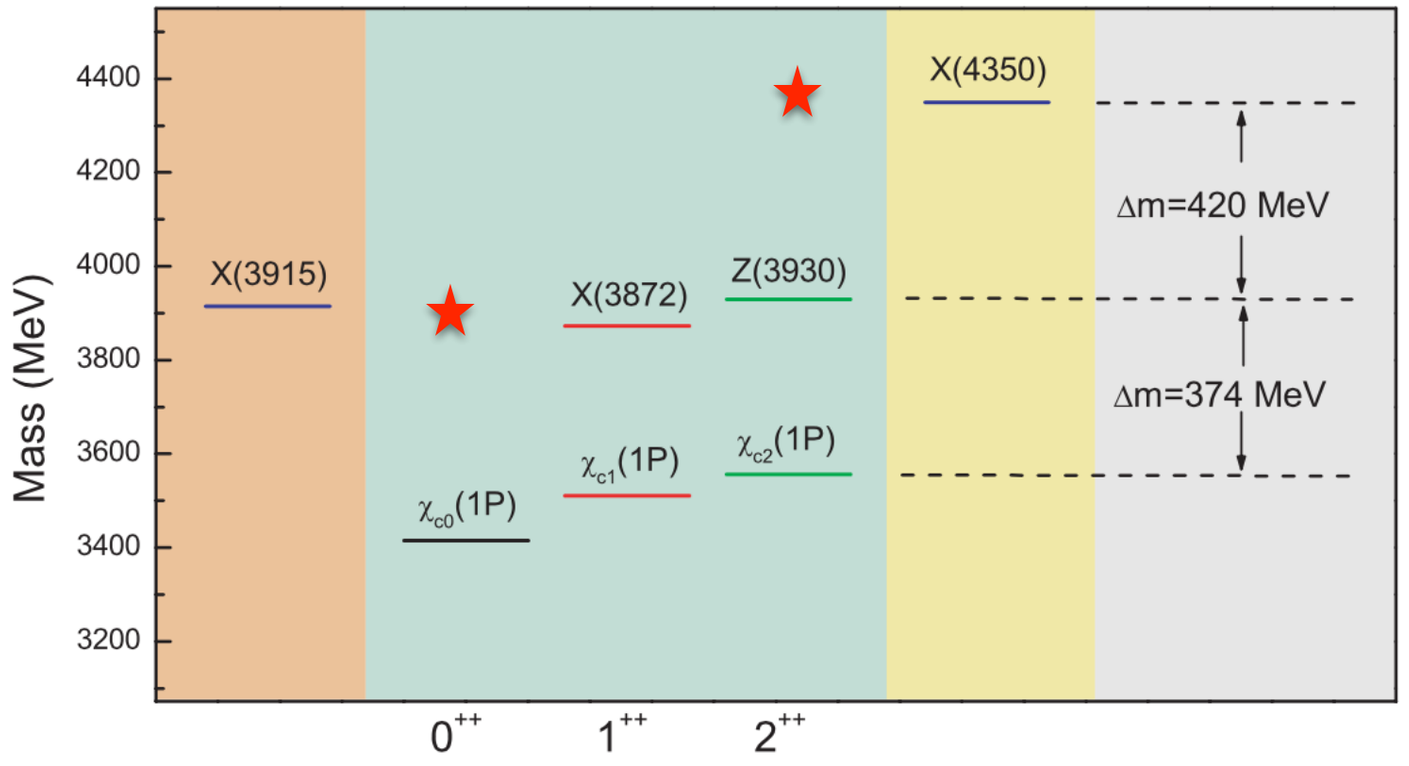
$$\gamma\gamma \to \begin{cases} X(3915) \to \underline{D\bar{D}}, \\ X(4350) \to \underline{J/\psi\phi}, \\ Z(3930) \to \underline{J/\psi\omega}. \end{cases}$$

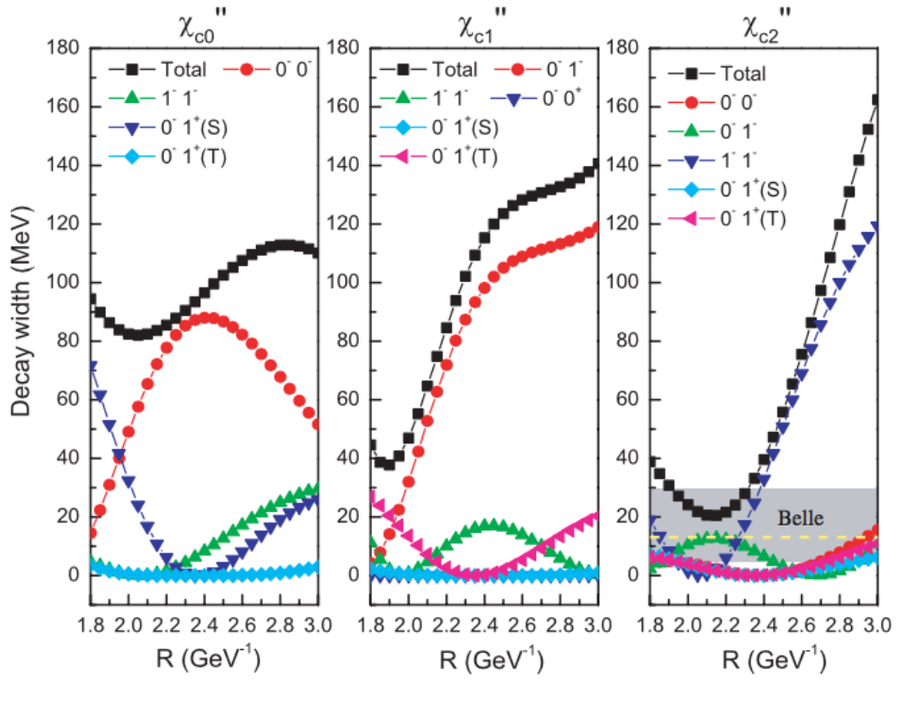
$X(3915)$ and $X(4350)$ as New Members in the P-Wave Charmonium Family

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



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





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

Y states directly from the e+e- annihilation

$$
e^+e^- \to \begin{cases} Y(4260) \to \underline{J/\psi\pi^+\pi^-}, \\ \left.\begin{array}{l} Y(4008) \\ Y(4360) \\ Y(4660) \end{array}\right\} \to \underline{\psi'\pi^+\pi^-}, \\ Y(4630) \to \underline{\Lambda_c\bar{\Lambda}_c}. \end{cases}
$$

Non-resonance explanations to Y(4260) and Y(4360)

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,*]

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,*,†]

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

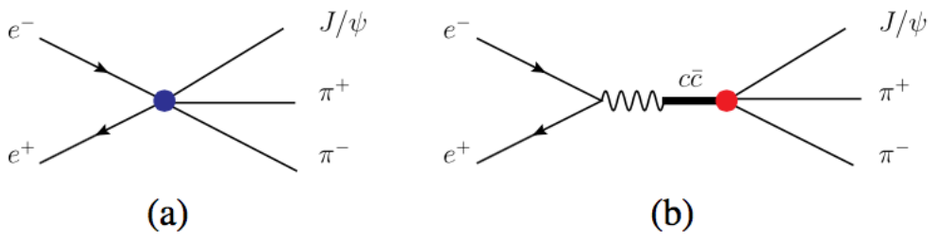
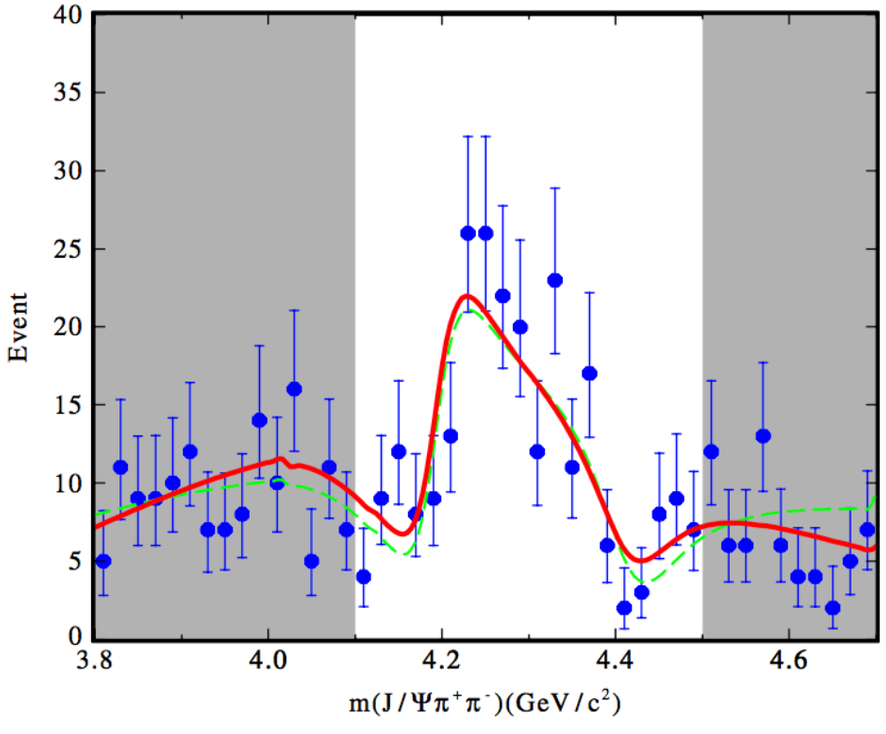
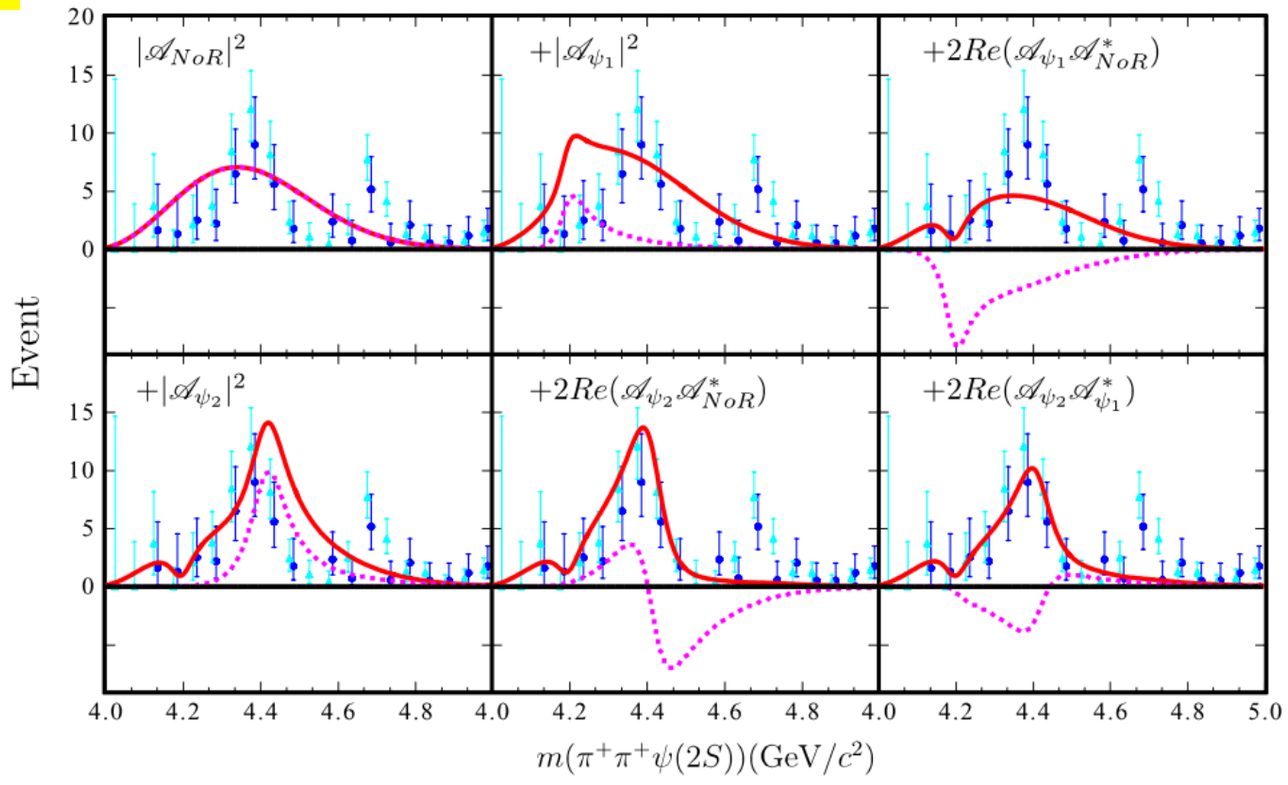


FIG. 1 (color online). The diagrams relevant to $e^+e^- \to J/\psi\pi^+\pi^-$. Here, Fig. 1(a) corresponds to the e^+e^- annihilation directly into $J/\psi\pi^+\pi^-$. Figure 1(b) is from the contributions of intermediate charmonia.





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

Charged bottomoniulike and charmoniumlike states announced by Belle and BESIII

$$
e^+e^- \to \begin{cases} Z_b(10610)\pi^\mp \\ Z_b(10650)\pi^\mp \end{cases} \to \begin{cases} \underline{\Upsilon(nS)\pi^\pm}\pi^\mp\ (n=1,2), \\ \underline{h_b(mP)\pi^\pm}\pi^\mp\ (m=1,2,3), \\ \underline{(B\bar{B}^* + c.c.)^\pm}\pi^\mp\ \ \underline{(B^*\bar{B}^*)^\pm}\pi^\mp, \end{cases} \\
\begin{cases} Z_c(3900)\pi^\mp \to \underline{J/\psi\pi^\pm}\pi^\mp, \\ Z_c(4025)\pi^\mp \to \underline{(D^*\bar{D}^*)^\pm}\pi^\mp, \\ Z_c(4020)\pi^\mp \to \underline{h_c\pi^\pm}\pi^\mp, \\ Z_c(3885)\pi^+ \to \underline{(D\bar{D}^*)^-}\pi^+. \end{cases}
$$

Initial Single Pion Emission (ISPE) mechanism

D.Y. Chen, Xiang Liu, Phys.Rev.D84:094003,2011

First propose a new decay mechanism existing in Y(5S) decay

the ISPE mechanism

The emitted pion with continuous energy distribution

→ $B^{(*)}$ and $\overline{B}^{(*)}$ with low momentum

→Easily interacte with each other

→ $B^{(*)}\overline{B}^{(*)}$ →Y(nS)π

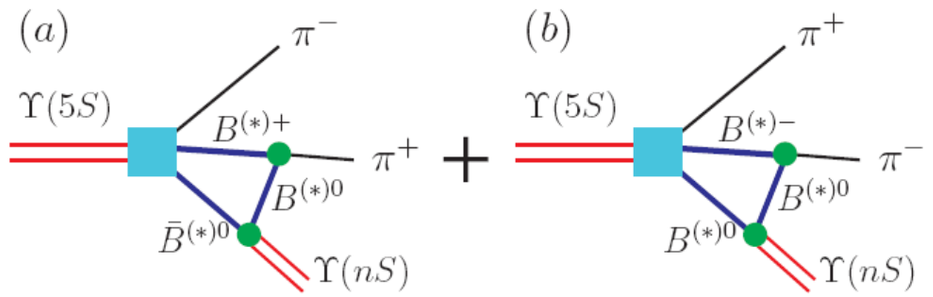


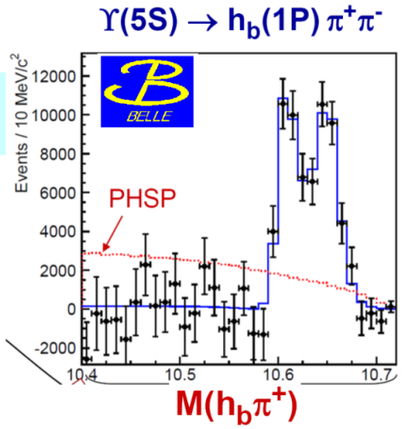
FIG. 2: (Color online.) The schematic diagrams for $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ by the ISPE mechanism. Here, diagrams (a) and (b) are related to each other by particle antiparticle conjugation, i.e., $B^{(*)} \rightleftharpoons \bar{B}^{(*)}$ and $\pi^+ \rightleftharpoons \pi^-$. After performing the transformations $B^{(*)+} \rightleftharpoons B^{(*)0}$, $B^{(*)-} \rightleftharpoons \bar{B}^{(*)0}$ and $\pi^+ \rightleftharpoons \pi^-$, we obtain the remaining diagrams. By replacing $\Upsilon(nS)$ with $h_b(mP)$, one obtains the diagrams for $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$.

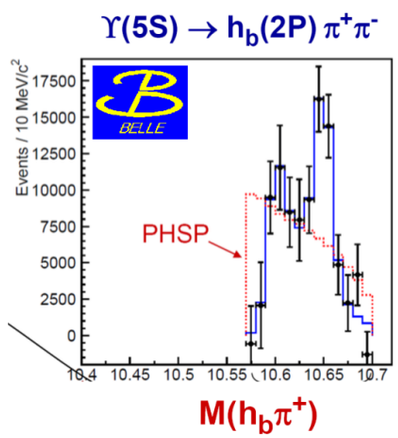
Zb(10610) and Zb(10650)

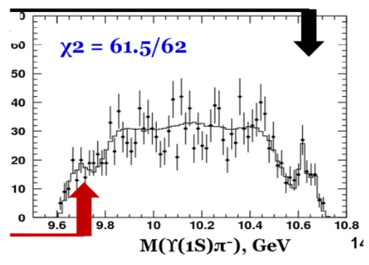
Belle Collaboration
PRL108,122001 (2012)

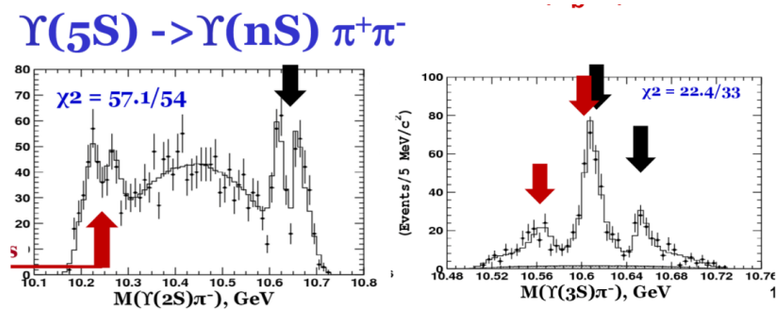
$Z_b(10610)$

$Z_b(10650)$









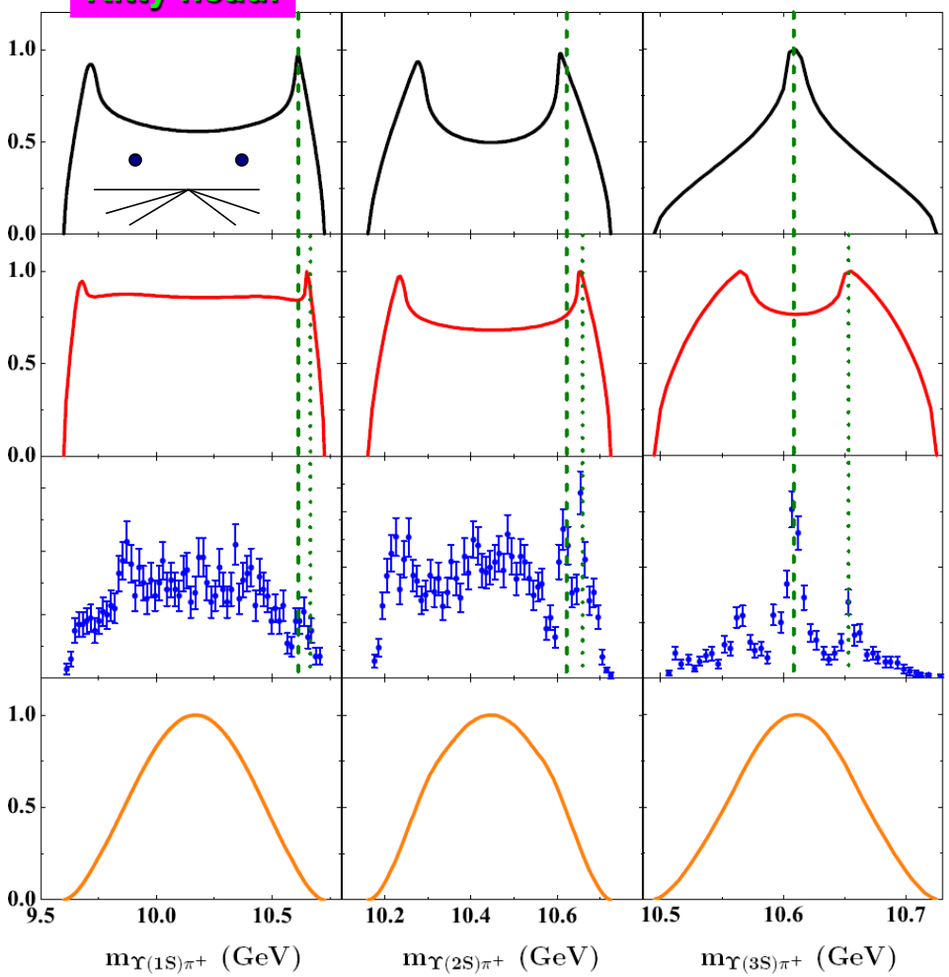
Kitty head!

BB̄*

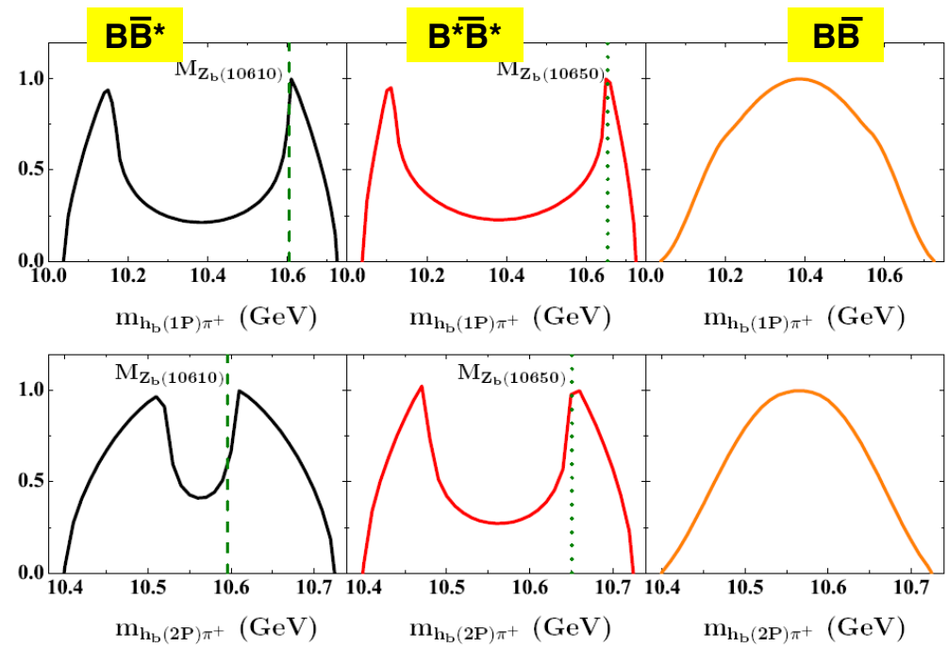
B*B̄*

Exp

BB̄



D.Y. Chen, Xiang Liu, Phys.Rev.D84:094003,2011



- Explain why the charged structures near $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds can be found in the hidden-charm dipion decays of Υ(5S)
- We cannot find the sharp peak close to the $B\bar{B}$ threshold

Novel charged structures
existing in the hidden-charm dipion decays of
higher charmonia or charmonium-like states

Motivation:

If the ISPE mechanism is an universal mechanism in heavy quarkonium dipion decays, we naturally extend the ISPE mechanism to study the hidden-charm dipion decays of higher charmonia

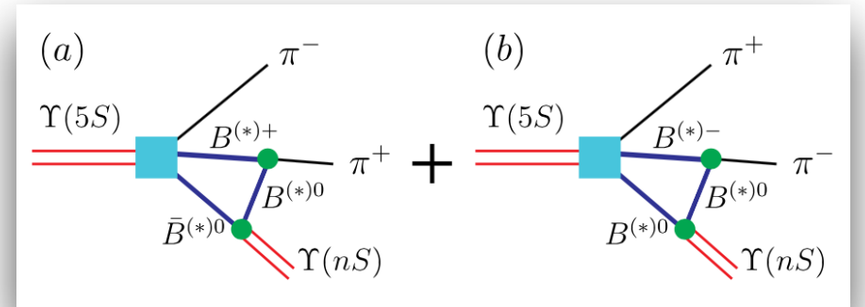
- The **similarity** between **charmonium and bottomonium**
- Give **predictions** for future experiment
- **An important test to the ISPE mechanism**

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

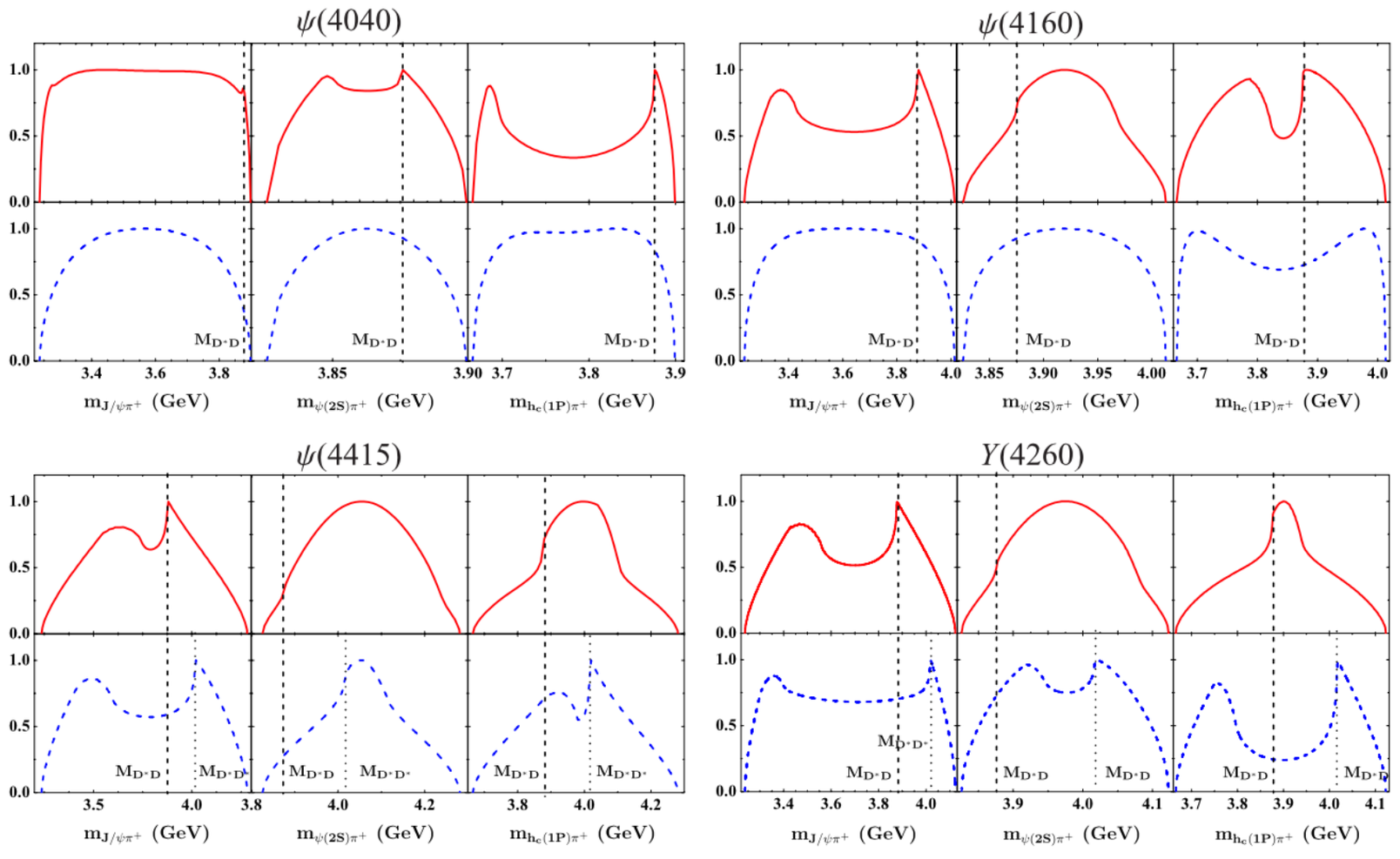


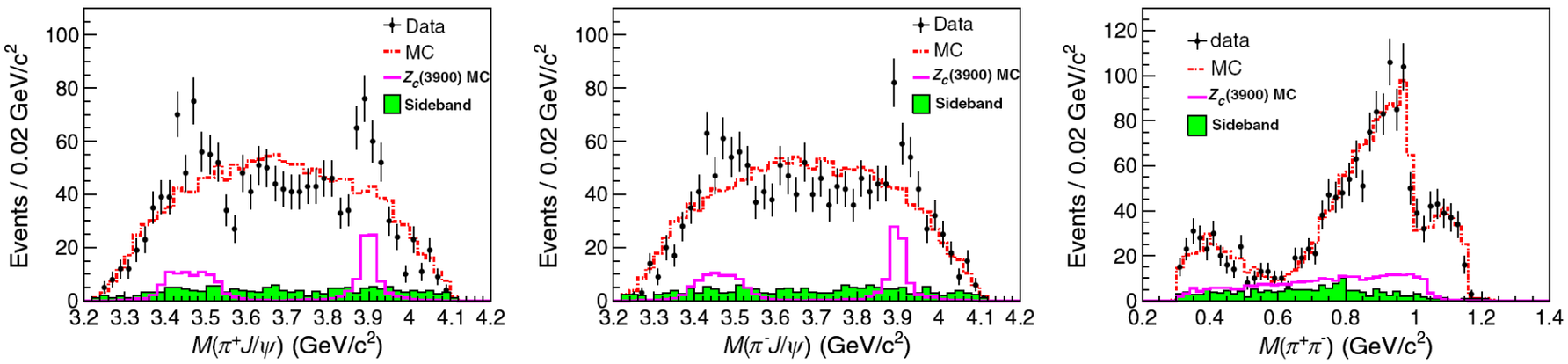
FIG. 4 (color online). (Color online.) The invariant mass spectra of $J/\psi\pi^+$, $\psi(2S)\pi^+$, and $h_c(1P)\pi^+$ for the $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, and $Y(4260)$ decays into $J/\psi\pi^+\pi^-$, $\psi(2S)\pi^+\pi^-$, and $h_c(1P)\pi^+\pi^-$. Here, the solid, dashed correspond to 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.

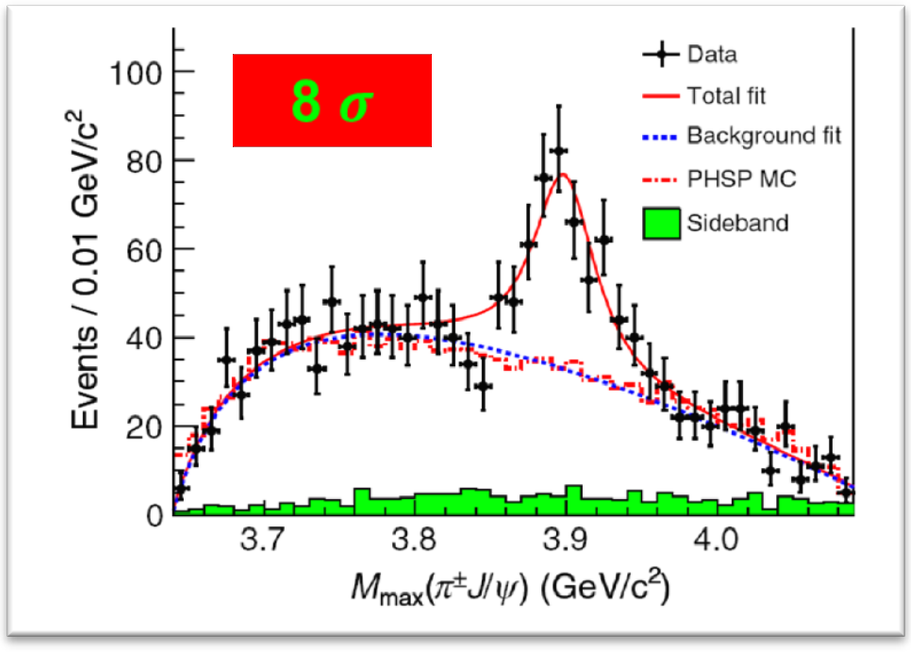
Predict charged charmonium-like structures near D*D or D*D* threshold

Zc(3900) observed by BESIII

PRL 110, 252001 (2013) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV





BESIII, PRL 110, 252001 (2013)

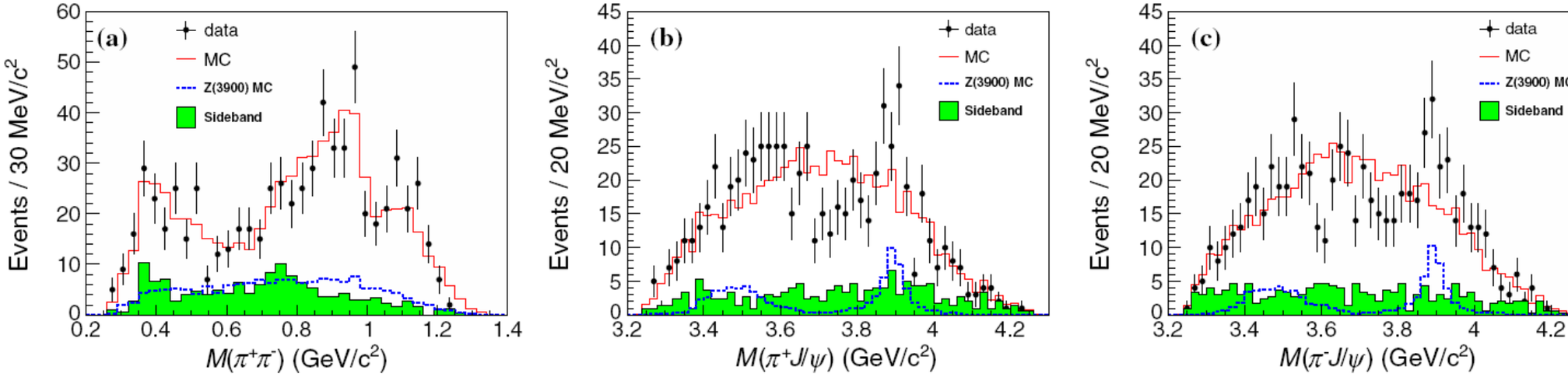
$$m = (3899.0 \pm 3.6 \pm 4.9)\ \mathrm{MeV/c^2}$$
$$\Gamma = (46 \pm 10 \pm 20)\ \mathrm{MeV}$$

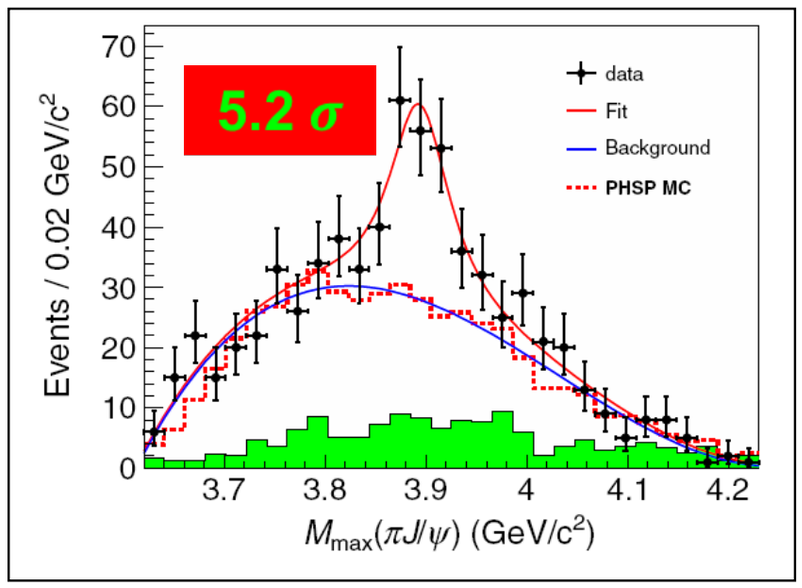
- A **charged** charmonium-like structure
- **Near** the $D\bar{D}^*$ **threshold**

Zc(3900) confirmed by Belle

BESIII, PRL 110, 252002 (2013)

$$e^+e^- \to Y(4260) \to J/\psi\pi^+\pi^-$$





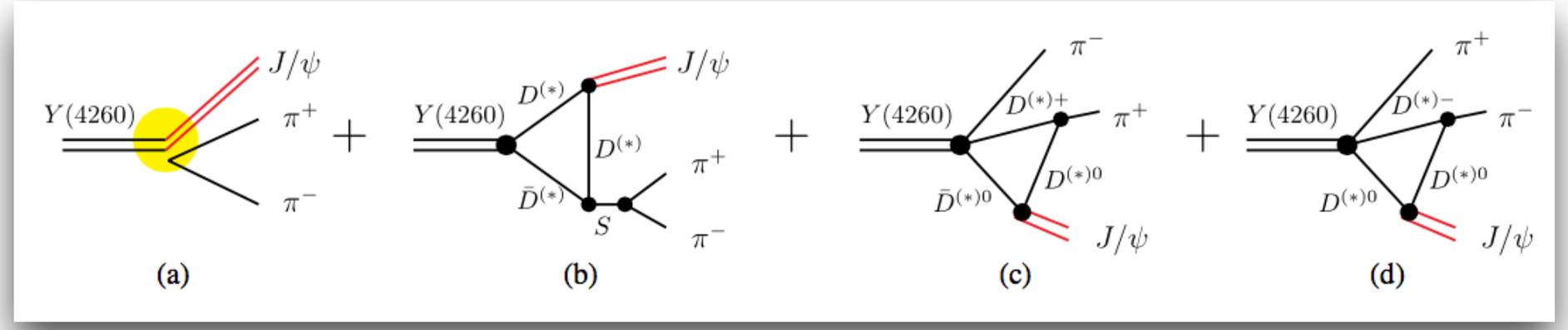
Belle confirmed the BESIII observation of Zc(3900)!

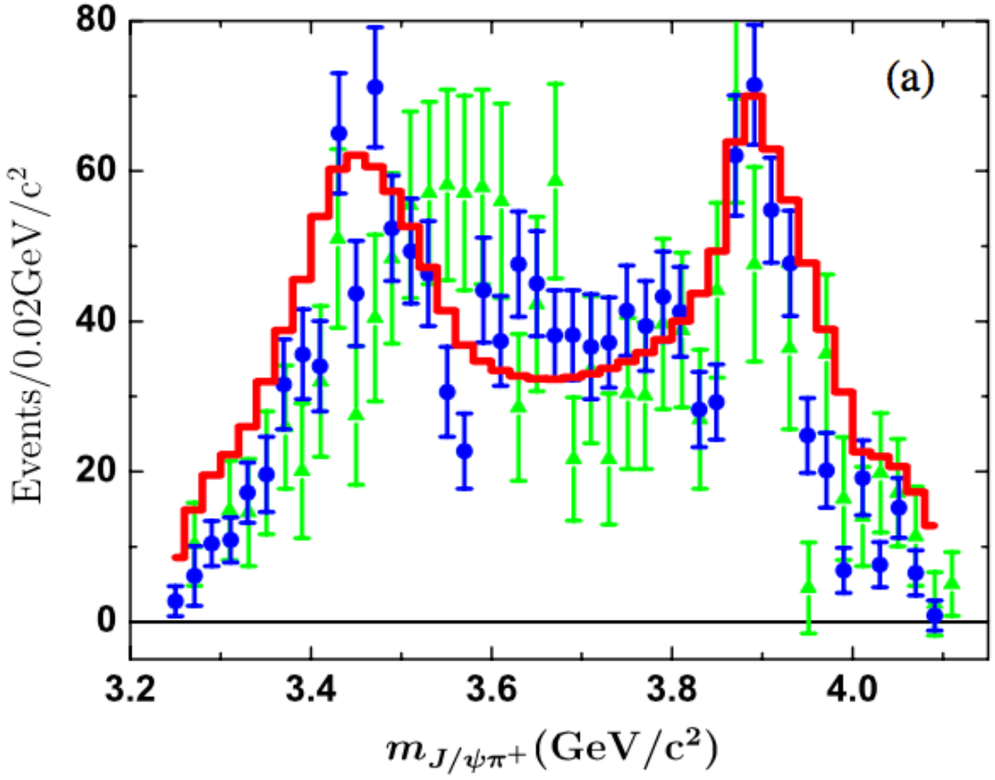
$$m = (3894.5 \pm 6.6 \pm 4.5)\ \mathrm{MeV/c^2}$$
$$\Gamma = (63 \pm 24 \pm 26)\ \mathrm{MeV}$$

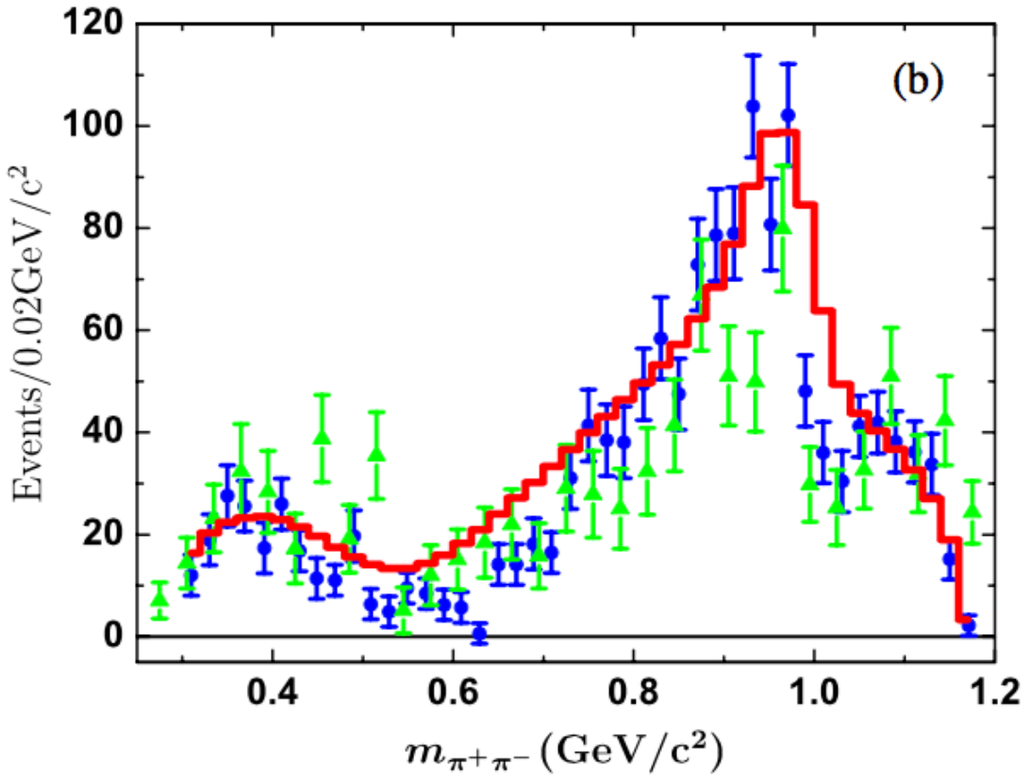
PHYSICAL REVIEW D **88,** 036008 (2013)

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,‡]







Summary

- **More and more novel phenomena of XYZ states have been reported**

- **Identify these XYZ states as resonances (charmonia or exotic states)**

- **Non-resonance phenomena**

1. **Y(4260) and Y(4360) are not genuine resonances**

2. **Zc(3900) can be reproduce by the ISPE mechanism**

We still need more theoretical and experimental joint efforts

Thank you for your attention