Theoretical review of XYZ*

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Abstract: In the past 12 years, dozens of charmonium-like states have been reported in experiment, Facing so abundant novel phenomena, theorists have paid more attentions to them for revealing the underlying mechanism relevant to these XYZ states. In this talk, I first gave a concise review of the observed XYZ states. And then, we mainly introduce the theoretical progresses on the study of XYZ states from our group, which include (1) the hadronic molecular state explanations to $Y(3940)$, $Y(4140)$ and $Y(4274)$; (2) the non-resonant explanation to $Y(4260)$ and $Y(4360)$; (3) the P-wave charmonium assignment to $Y(3915)$, $Z(3930)$ and $X(4350)$; (4) the initial single pion emission mechanism and the observation of $Z_c(3900)$.

Key words: Charmonium-like states, non-perturbative QCD, phenomenological model

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XYZ类粲偶素的理论回顾

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摘　要:
在过去的十二年中，实验上发现了大量的类粲偶素。面对如此多新奇的态，理论学家们致力于去解释这些XYZ粒子内在的动力学机制。在这个报告中，我首先简短地回顾已发现的XYZ态，然后主要介绍我们组在XYZ类粲偶素理论研究中的一些工作，其中主要包括：（1）将$Y(3940)$，$Y(4140)$ 和$Y(4274)$ 解释为强子分子态；（2）$Y(4260)$ 和$Y(4360)$的非共振态解释；（3）将$Y(3915)$，$Z(3930)$ 和$X(4350)$这三个态解释为P波粲偶素；（4）初态单π发射机制和对$Z_c(3900)$的研究。

关键词： 类粲偶素，非微扰QCD，唯象模型

1 Introduction

Due to experimental big progress on the observation of charmonium-like XYZ states, theoretical study of XYZ have became a hot research field full of challenges and opportunities. Studying charmonium-like XYZ states will be helpful to deepen our understanding of non-perturbative QCD.

In the following, I mainly focus on the XYZ states produced by B meson decays, the $\gamma\gamma$ fusion, e^+e^- annihilation, and the hadronic decays of $Y(4260)$. By combing with the progresses made by our group, In this talk I illustrate the present research status.

2 The observed XYZ states

Since the first charmonium-like state $X(3871)$ reported by BaBar in B meson decay $B \to KJ/\psi\pi^+\pi^-$ [1] , more and more charmonium-like states have been observed in the the past 12 years. According to the difference of production mechanism, these observed XYZ states can be categorized into five groups, which correspond to B meson decay, e^+e^- annihilation via initial state radiation, double charmonium production process, $\gamma\gamma$ fusion, and hadronic decays of $Y(4260)$.

In Table 1, I summarize these observed charmonium-like states, where the XYZ states listed in the first, the second, the third, the fourth and the fifth columns correspond to B meson decay, e^+e^- annihilation via initial

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state radiation, double charmonium production process, $\gamma\gamma$ fusion, and hadronic decays of $Y(4260)$, respectively, which provides an ideal platform to explore XYZ states experimentally.

For the connivence of reader, I also show the production and decay information relevant to these XYZ states in Eq. (1)-(5).

Table 1. The observed charmonium-like states.

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

$$B \to \left\{ \begin{array}{l} X(3872)K \to \underline{J/\psi\pi^+\pi^-}K \\ Y(3940)K \to \underline{J/\psi\omega}K \\ Z^+(4430)K \to \underline{\psi'\pi^+}K \\ \left.\begin{array}{l} Z^+(4051)K \\ Z^+(4248)K \end{array}\right\} \to \underline{\chi_{c1}\pi^+}K \\ \left.\begin{array}{l} Y(4140)K \\ Y(4274)K \end{array}\right\} \to \underline{J/\psi\phi}K \end{array} \right. , \tag{1}$$

$$e^+e^- \to \left\{ \begin{array}{l} Y(4260) \to \underline{J/\psi\pi^+\pi^-} \\ \left.\begin{array}{l} Y(4008) \\ Y(4360) \\ Y(4660) \end{array}\right\} \to \underline{\psi'\pi^+\pi^-} \\ Y(4630) \to \underline{\Lambda_c\bar{\Lambda}_c} \end{array} \right. , \tag{2}$$

$$e^+e^- \to \left\{ \begin{array}{l} X(3940)J/\psi \to \underline{D^*\bar{D}}J/\psi \\ X(4160)J/\psi \to \underline{D^{*+}D^{*-}}J/\psi \end{array} \right. , \tag{3}$$

$$\gamma\gamma \to \left\{ \begin{array}{l} X(3915) \to \underline{D\bar{D}} \\ X(4350) \to \underline{J/\psi\phi} \\ Z(3930) \to \underline{J/\psi\omega} \end{array} \right. , \tag{4}$$

$$e^+e^- \to \left\{ \begin{array}{l} Z_c(3900)\pi^\mp \to \underline{J/\psi\pi^\pm}\pi^\mp \\ Z_c(4025)\pi^\mp \to \underline{(D^*\bar{D}^*)^\pm}\pi^\mp \\ Z_c(4020)\pi^\mp \to \underline{h_c\pi^\pm}\pi^\mp \\ Z_c(3885)\pi^+ \to \underline{(D\bar{D}^*)^-}\pi^+ \end{array} \right. . \tag{5}$$

Facing so abundant novel phenomena, a crucial task is to reveal the underlying mechanism behind these phenomena. The observed XYZ states have stimulated extensive discussion of them, which have came a hot research filed in present hadron physics.

3 The hadronic molecular state explanations to $Y(3940)$, $Y(4140)$ and $Y(4274)$

$X(3872)$ is the first reported charmonium-like state in B meson decay $B \to KJ/\psi\pi^+\pi^-$ [1]. According to the quark model estimate, the mass of $X(3872)$ is not consistent with that of a 2^3P_1 charmonium (χ'_{c1}) state. Additionally, the observed decay mode $X(3872) \to J/\psi\rho$ is isospin violation. Thus, different theoretical explanations were proposed, which mainly include:

- The molecular state assignment was proposed in Refs. [2–6].
- $X(3872)$ was also explained as the 1^{++} cusp [7].
- The S-wave threshold effect due to the $D^0\bar{D}^{0*}$ threshold was suggested in Ref. [8].
- In Ref. [9], the hybrid charmonium assignment to $X(3872)$ was indicated.
- The diquark anti-diquark bound state [10] and the tetraquark state [11, 12] were given.
- $X(3872)$ may have a dominant $c\bar{c}$ component with some admixture of $D^0\bar{D}^{*0} + \bar{D}^0D^{*0}$ [13, 14].

Thus, further experimental and theoretical joint effort will be helpful to test different theoretical proposals of $X(3872)$.

In the following, I want to further introduce the hadronic molecular assignment to $Y(3940)$, $Y(4140)$ and $Y(4274)$ since there exist similarities between $Y(4140)$ and $Y(3940)$. Firstly, the production processes of $Y(4140)$ and $Y(3940)$ through B meson decays are very similar, i.e.,

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

Secondly, there exits mass gap relation:

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

Thirdly, $Y(4140)$ and $Y(3940)$ are close to the $D_s^*\bar{D}_s^*$ and $D^*\bar{D}^*$ thresholds, respectively, and satisfy another mass relation

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

Just considering these similarities, Liu and Zhu proposed a uniform molecular picture of $Y(4140)$ and

$Y(3940)$ in Ref. [15], where the flavor wave functions of $Y(4140)$ and $Y(3940)$ are [15]

$$|Y(4140)\rangle = |D_s^{*+}D_s^{*-}\rangle,$$
$$|Y(3940)\rangle = \frac{1}{\sqrt{2}}\Big[|D^{*0}\bar{D}^{*0}\rangle + |D^{*+}D^{*-}\rangle\Big],$$

respectively. To test this molecular state assignment to $Y(4140)$ and $Y(3940)$, a dynamical calculation was performed in Ref. [15] via adopting the one boson exchange model, where the pseudoscalar, vector and σ mesons are considered in the calculation, by which the effective potentials of the $D_s^*\bar{D}_s^*$ and $D^*\bar{D}^*$ interactions were obtained. With these effective potential, Liu and Zhu found the corresponding bound state solutions, which support the $D_s^*\bar{D}_s^*$ and $D^*\bar{D}^*$ molecular state explanations to $Y(4140)$ and $Y(3940)$ [15].

In 2010, CDF reported a charmonium-like state $Y(4274)$ by analyzing the $J/\psi\phi$ invariant mass spectrum [16]. In Ref. [17], Liu, Luo and Zhu suggested $Y(4274)$ to be an S-wave $D_s\bar{D}_{s0}(2317)$ molecular state, and predicted the existence of its partner, an and the S-wave $D\bar{D}_0(2400)$ molecular state [17].

Just shown Fig. 1, there exist two event clusters around the ranges of $\Delta M \sim 1.27$ GeV and $1.4 < \Delta M < 1.5$ GeV, which are marked by yellow and pink. The structure around $\Delta M \sim 1.27$ can be related to the $D_s\bar{D}'_{s1}(2460)$ or $D_s^*\bar{D}_{s0}(2317)$ system. The other one in the range $1.4 < \Delta M < 1.5$ GeV may result from the $D_s\bar{D}_{s1}(2536)$, $D_s\bar{D}_{s2}(2573)$, $D_s^*\bar{D}'_{s1}(2460)$ and $D_s^*\bar{D}_{s1}(2536)$ systems since the event cluster in the range $1.4 < \Delta M < 1.5$ GeV just overlaps with the corresponding thresholds. Further experimental study of these event clusters will be a interesting task.

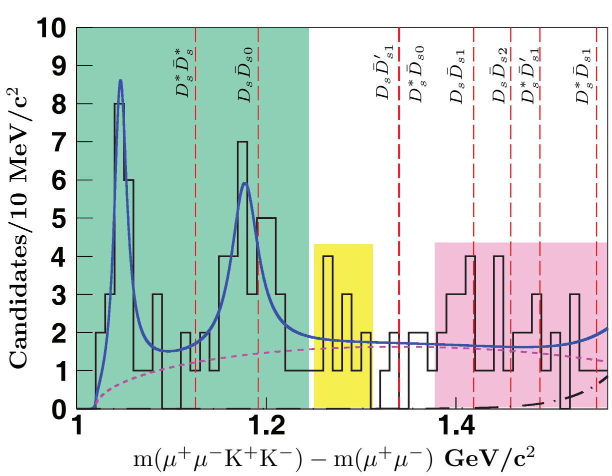

Fig. 1. (Color online.) The mass difference $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ distribution (histogram) for events in the B^+ mass window [16]. Besides $Y(4140)$, one explicit enhancement appears around 4274 MeV. Here, the purple dashed line is the background from the three-body phase space. The blue solid line is the fitting result with resonance parameters of $Y(4140)$ and $Y(4270)$ resonances in Ref. [16]. The vertical red dashed lines denote the thresholds of $D_s^*\bar{D}_s^*$, $D_s\bar{D}_{s0}(2317)$, $D_s\bar{D}'_{s1}(2460)$, $D_s^*\bar{D}_{s0}(2317)$, $D_s\bar{D}_{s1}(2536)$, $D_s\bar{D}_{s2}(2573)$, $D_s^*\bar{D}'_{s1}(2460)$ and $D_s^*\bar{D}_{s1}(2536)$. Taken from Ref. [17]

4 The non-resonant explanation to $Y(4260)$ and $Y(4360)$

For explaining $Y(4260)$ and $Y(4360)$, different exotic state explanations were proposed in literature, like a charmonium hybird [18–20], diquark-antidiquark state with the conponent $[cs][\bar{c}\bar{s}]$ [21, 22], different molecular states [23–28], and a charmonium hybrid state that couple to $D\bar{D}_1$ and $D\bar{D}_0$ channels [29]. Additionally, there were extensive discussion of $Y(4260)$ as conventional charmonium [30–33]

In this talk, I introduce the non-resonant explanation to $Y(4260)$ and $Y(4360)$ [34, 36].

For $e^+e^- \to J/\psi\pi^+\pi^-$ process, there exists direct production of $J/\psi\pi^+\pi^-$ by the e^+e^- annihilation. Here, the virtual photon from the e^+e^- annihilation directly interacts with $J/\psi\pi^+\pi^-$. Besides the e^+e^- annihilation directly into $J/\psi\pi^+\pi^-$, another important production mechanism of $e^+e^- \to J/\psi\pi^+\pi^-$ is through the intermediate charmonia (see Fig. 2 for more details).

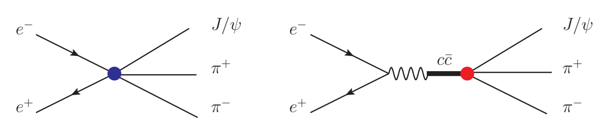

Fig. 2. (color online). The diagrams relevant to $e^+e^- \to J/\psi\pi^+\pi^-$. Here, Fig. 1(a) corresponds to the e^+e^- annihilation directly into $J/\psi\pi^+\pi^-$. Figure 1(b) is from the contributions of intermediate charmonia. Taken from Ref. [36].

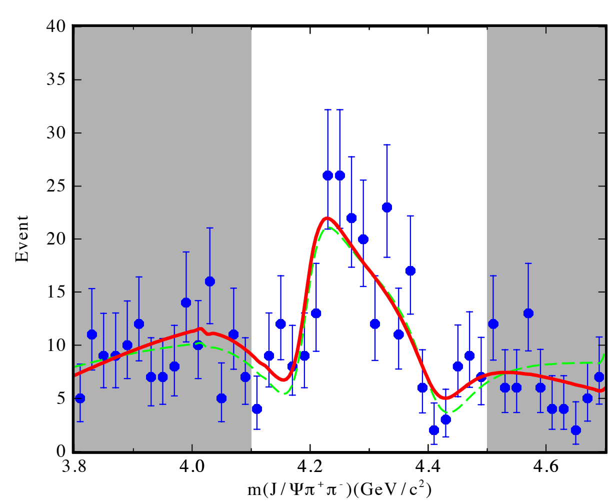

Fig. 3. (Color online). The obtained fitting result (solid [red] line) and the comparison with the experimental data (blue dots with error bar) measured by BaBar [35]. We also give the obtained fitting result by adopting the dipole form for $\mathcal{F}_{NOR}(s)$ ([green] dashed line). Here, our result is normalized to the experimental data. Taken from Ref. [36].

The result shown in Fig. 3 indicates that the $Y(4260)$ structure can be reproduced by the interference of production amplitudes of the $e^+e^- \to J/\psi\pi^+\pi^-$ processes via direct e^+e^- annihilation and through intermediate charmonia $\psi(4160)/\psi(4415)$ [36].

The similar idea was applied to study $Y(4360)$ in Ref. [34], where $Y(4360)$ signals can be described when introducing the interference of $\psi(4160)$ and $\psi(4415)$ with the continuum contribution. This fact shows that $Y(4260)$ and $Y(4360)$ are not genuine resonances. The non-resonant explanation to $Y(4260)$ and $Y(4360)$ can naturally answer why $Y(4260)$ and $Y(4360)$ are still missing in the R value scan and the corresponding open-charm decay channels.

5 The P-wave charmonium assignment to $Y(3915)$, $Z(3930)$ and $X(4350)$

If checking the PDG data [37], we found that there are three P-wave ground states $\chi_{c0}(3415)$, $\chi_{c1}(3510)$ and $\chi_{c2}(3556)$. The observation of $X(3915)$, $X(4350)$ and $Z(3930)$ provides us good chance to study the radial excitations of P-wave charmonium family. In the following, I summarize conclusion of the P-wave charmonium assignments to $\chi_{c0}(3415)$, $\chi_{c1}(3510)$ and $\chi_{c2}(3556)$ in Ref. [38]:

- $X(3872)$ and $Z(3930)$ can be regarded as $\chi'_{c1}(2P)$ with $J^{PC}=1^{++}$ [13, 14] and $\chi'_{c2}(2P)$ with $J^{PC}=2^{++}$, respectively.

- $X(3915)$ can be a χ'_{c0} state [38], since its mass is close to the predicted mass of χ'_{c0} predicted in Ref. [45]. Under this assignment can explain why the mass difference between $X(3915)$ and $Z(3930)$ is smaller than that between $X(3915)$ and $X(3872)$ [38].

- $X(4350)$ was explained as $\chi''_{c2}(2P)$ [38].

The above assignment to charmonium-like states observed in $\gamma\gamma$ fusion can be supported by the further study of two-body strong decay of $X(3915)$, $Z(3930)$ and $X(4350)$ [38], which are shown in Figures 4 and 5.

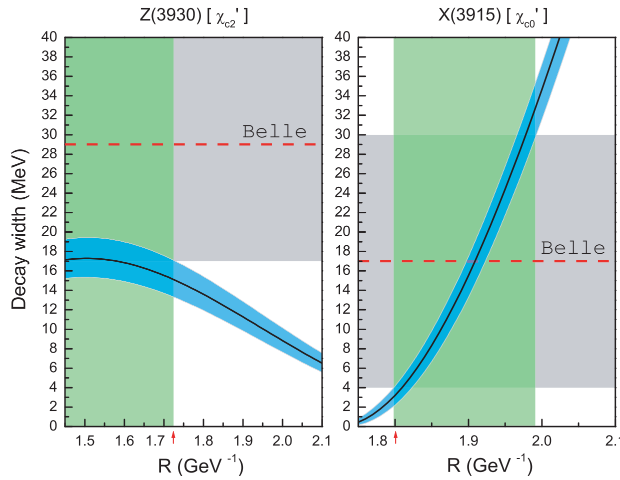

Fig. 4. (Color online.) The dependence of the decay width of $Z(3930)$ and $X(3915)$ on R under χ'_{c2} and χ'_{c0} assignment for $Z(3930)$ and $X(3915)$, respectively. The green band denotes the region of R resulting in the theoretical values consistent with Belle data. The solid lines with blue error bands are our calculation result. Taken from Ref. [38].

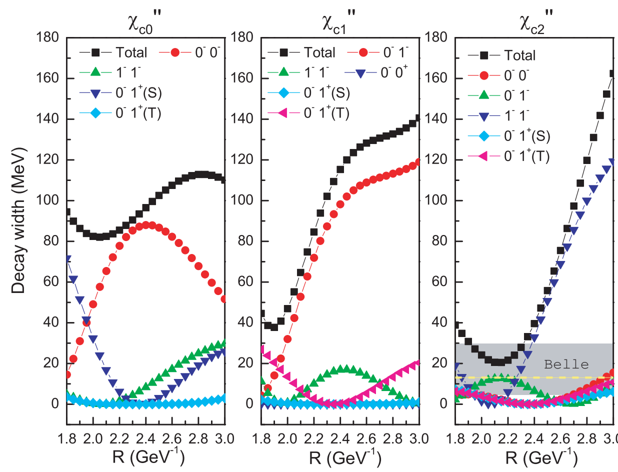

Fig. 5. (Color online.) The variation of the decay width of χ''_{cJ} ($J=0,1,2$) with R value. Here, we set the upper limit of the masses of P-wave states with the second radial excitation as 4.35 GeV. The yellow dash line and shaded grey band shown in diagram of χ''_{c2} denote the central value for the error of total width of $X(3915)$ measured by Belle. Taken from Ref. [38].

6 The initial single pion emission mechanism and the observation of $Z_c(3900)$

Belle observed two charged bottomoniumlike states $Z_b(10610)$ and $Z_b(10650)$ by studying the e^+e^- annihilation into hidden-bottom dipion channels [39]. $Z_b(10610)$ and $Z_b(10650)$ have two interesting properties. Firstly, the masses of $Z_b(10610)$ and $Z_b(10650)$ are close to that of $B\bar{B}^*$ and $B^*\bar{B}^*$, respectively. Secondly, $Z_b(10610)$ and $Z_b(10650)$ are charged states.

The initial single pion emission (ISPE) mechanism [40] was proposed to understand two bottomonium-like structures $Z_b(10610)$ and $Z_b(10650)$. The physical picture is that the emitted pion with continuous energy distribution produces $B^{(*)}$ and $\bar{B}^{(*)}$ with low momentum. Thus, the intermediate $B^{(*)}$ and $\bar{B}^{(*)}$ can easily interact with each other to transit into hidden-charm dipion final states together with one bottomonium. Under the ISPE mechanism, we explained why two bottomonium-like structures $Z_b(10610)$ and $Z_b(10650)$ appear in the $\Upsilon(nS)\pi^\pm$ and $h_b(mP)\pi^\pm$ invariant mass spectra, and are close to the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds, respectively [40].

If the ISPE mechanism is a universal mechanism existing in heavy quarkonium dipion decays, we can naturally apply this mechanism to study the hidden-charm dipion decays of higher charmonia, which is due to the similarity between charmonium and bottomonium [41]. This investigation can provide more predictions for the future experiment as an important test of the ISPE mechanism.

In Ref. [41], we predicted charged charmonium-like structures in the hidden-charm dipion decay of higher charmonia and charmonium-like state $Y(4260)$. The typical peculiarity of predicted charged charmonium-like structures is that they are near the $D\bar{D}^*$ or $D^*\bar{D}^*$ threshold.

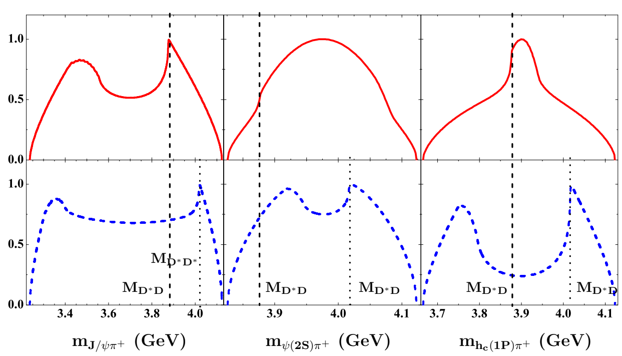

Fig. 6. (Color online.) The invariant mass spectra of $J/\psi\pi^+$, $\psi(2S)\pi^+$ and $h_c(1P)\pi^+$ for the $Y(4260)$ decays into $J/\psi\pi^+\pi^-$, $\psi(2S)\pi^+\pi^-$ and $h_c(1P)\pi^+\pi^-$. Here, the solid, dashed correspond to the results considering intermediate $D\bar{D}^*$+$h.c.$ and $D^*\bar{D}^*$ respectively. The vertical dashed lines and the dotted lines denote the threshhold of $D^*\bar{D}$ and $D^*\bar{D}^*$ respectively. Here, the maximum of the line shape is normalized to 1. Taken from Ref. [41].

In 2013, BESIII announced the observation of a charged charmonium-like structure $Z_c(3900)$ in $e^+e^- \to J/\psi\pi^+\pi^-$ at $\sqrt{s} = 4.26$ GeV [42], which is around the $D\bar{D}^*$ threshold. Almost at the same time, Belle also observed $Z_c(3900)$ [43]. The observation of $Z_c(3900)$ is consistent with our prediction in Ref. [41].

According to this research status, we studied $Z_c(3900)$ by considering the ISPE mechanism in Ref. [44], where other two mechanisms (the direct production and final state interaction) were included in the calculation. The $Z_c(3900)$ signal can be well reproduced. Thus, it is possible that $Z_c(3900)$ is not a genuine resonance.

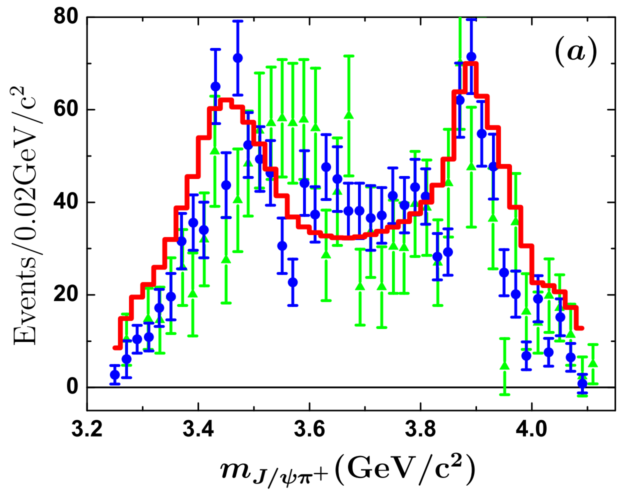

Fig. 7. (Color online). The distributions of the $J/\psi\pi^+$ invariant mass spectrum of $Y(4260) \to \pi^+\pi^- J/\psi$. The blue dots and green triangles with error bars are the experimental data given by BESIII [42] and Belle [43], respectively. The red histograms are our results considering contributions of the ISPE mechanism to the $Y(4260) \to \pi^+\pi^- J/\psi$ decay.Taken from Ref. [44].

7 Summary

In this talk, I gave a brief review of the present research status of XYZ states. Before closing this section, I summarize the conclusions:

- The hadronic molecular state explanations to $Y(3940)$, $Y(4140)$ and $Y(4274)$ were given in Ref. [15, 17].
- The non-resonant explanation to $Y(4260)$ and $Y(4360)$ was suggested in Refs. [34, 36].
- The P-wave charmonium assignment to $Y(3915)$, $Z(3930)$ and $X(4350)$ was proposed in Ref. [38]. Here, $X(3915)$, $Z(3930)$, and $X(4350)$ were explained to be $\chi'_{c0}(2P)$ with $J^{PC}=0^{++}$, $\chi'_{c2}(2P)$ with $J^{PC}=2^{++}$, and $\chi''_{c2}(2P)$, respectively.
- According to ISPE mechanism, charged charmonium-like state near $D\bar{D}^*$ threshold was predicted in Ref. [41], which may correspond to the observed $Z_c(3900)$ [44].

In the following years, we still need to pay more effort to reveal these underlying mechanisms behind these novel phenomena, which will be an intriguing research issue.

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