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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 been hard at work to reveal the underlying mechanism relevant to these *XYZ* states. A concise review of the observed *XYZ* states is first given. Then, an introduction is presented to the theoretical progress made by our group in the study of *XYZ* states, which includes 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 12 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. 本文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 3 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

0 Introduction

Due to big experimental advances in the observation of charmonium-like *XYZ* states, theoretical study of *XYZ* has 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

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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 $Y(4260)$. Combing the progress made by our group, I will illustrate the present research status.

1 The observed XYZ states

Since the first charmonium-like state $X(3871)$ was 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 in production mechanisms, the observed XYZ states can be categorized into five groups: B meson decay, e^+e^- annihilation via initial state radiation, double charmonium production process, $\gamma\gamma$ fusion, and hadronic decays of $Y(4260)$.

In Tab. 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 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.

Tab. 1 The observed charmonium-like states

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

For readers' connivence, I also show the production and decay information relevant to these XYZ states in Eq. (1)～(5).

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

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

$$e^+e^-\to\begin{cases} X(3940)J/\psi\to \underline{D^*\bar{D}}J/\psi \\ X(4160)J/\psi\to \underline{D^{*+}D^{*-}}J/\psi \end{cases} \tag{3}$$

$$\gamma\gamma\to\begin{cases} X(3915)\to \underline{D\bar{D}} \\ X(4350)\to \underline{J/\psi\phi} \\ Z(3930)\to \underline{J/\psi\omega} \end{cases} \tag{4}$$

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

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 has become a hot research filed in present hadron physics.

2 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:

① The molecular state assignment[2-6].

② $X(3872)$ was also explained as the 1^{++} cusp[7].

③ The S-wave threshold effect due to the $D^0 \bar{D}^{0*}$ threshold[8].

④ The hybrid charmonium assignment to $X(3872)$[9].

⑤ The diquark anti-diquark bound state[10] and the tetraquark state[11-18].

⑥ $X(3872)$ may have a dominant $c\bar{c}$ component with some admixture of $D^0 \bar{D}^{*0} + \bar{D}^0 D^{*0}$[19-20].

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

In the following, I will 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.,

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

Secondly, there exits a mass gap relation:

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

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 et al. proposed a uniform molecular picture of $Y(4140)$ and $Y(3940)$ in Ref. [21], where the flavor wave functions of $Y(4140)$ and $Y(3940)$ are[21]

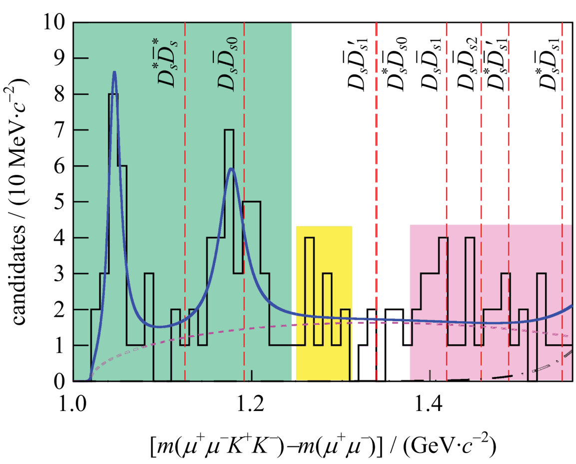
$$|Y(4140)\rangle = |D_s^{*+} D_s^{*-}\rangle,$$

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

respectively. To test this molecular state assignment to $Y(4140)$ and $Y(3940)$, a dynamical calculation was performed in Ref. [21] 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 potentials, Liu et al. found the corresponding bound state solutions, which support the $D_s^* \bar{D}_s^*$ and $D^* \bar{D}^*$ molecular state explanations of $Y(4140)$ and $Y(3940)$[21].

In 2010, CDF reported a charmonium-like state $Y(4274)$ by analyzing the $J/\psi\phi$ invariant mass spectrum[22]. In Ref. [23], Liu et al. suggested $Y(4274)$ to be an S-wave $D_s \bar{D}_{s0}(2317)$ molecular state, and predicted the existence of its partner, an S-wave $D \bar{D}_0(2400)$ molecular state[23].

As shown in Fig. 1, there exist two event clusters around the ranges of $\Delta M \approx 1.27$ GeV and 1.4 GeV $< \Delta M <$ 1.5 GeV, which are marked by yellow and pink. The structure around $\Delta M \approx 1.27$ 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 GeV $< \Delta M <$ 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 GeV $< \Delta M <$ 1.5 GeV just overlaps with the corresponding thresholds. Further



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. [22]. 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. [23]

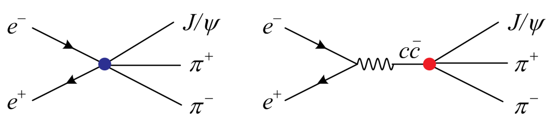
Fig. 1　The mass difference $\Delta M = m(\mu^+ \mu^- K^+ K^-) - m(\mu^+ \mu^-)$ distribution (histogram) for events in the B^+ mass window[22] experimental study of these event clusters will be an interesting task.

3 The non-resonant explanation of $Y(4260)$ and $Y(4360)$

For explaining $Y(4260)$ and $Y(4360)$, different exotic state explanations were proposed in literature, like a charmonium hybird[24-26], diquark-antidiquark state with the component $[cs][\bar{c}\bar{s}]$[27-28], different molecular states[29-34], and a charmonium hybrid state that couples to $D\bar{D}_1$ and $D\bar{D}_0$ channels[35]. Additionally, there were extensive discussions of $Y(4260)$ as conventional charmonium[36-39].

In this paper, I introduce the non-resonant explanation to $Y(4260)$ and $Y(4360)$[40,42].

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).



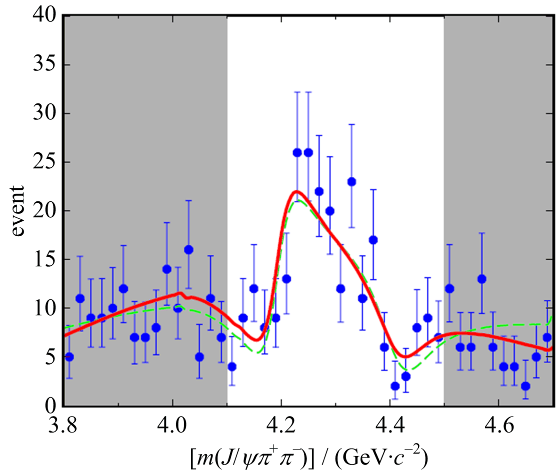
(a) the e^+e^- annihilation directly into $J/\psi\pi^+\pi^-$ (b) from the contributions of intermediate charmonia

Taken from Ref. [42].

Fig. 2 The diagrams relevant to $e^+e^- \to J/\psi\pi^+\pi^-$

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 $\psi(4160)/\psi(4415)$[42].

The similar idea was applied to study $Y(4360)$ in Ref. [40], 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



We also give the obtained fitting result by adopting the dipole form for $\mathscr{F}_{NOR}(s)$ (green dashed line). Here, our result is normalized to the experimental data. Taken from Ref. [42].

Fig. 3 The obtained fitting result (red solid line) and the comparison with the experimental data (blue dots with error bar) measured by BaBar[41]

$Y(4360)$ are not genuine resonances. The non-resonant explanation of $Y(4260)$ 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.

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

Checking the PDG data[43], 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 with a good chance to study the radial excitations of P-wave charmonium family. In the following, I conclusions of the P-wave charmonium assignments to $\chi_{c0}(3415)$, $\chi_{c1}(3510)$ and $\chi_{c2}(3556)$ in Ref. [44]:

① $X(3872)$ and $Z(3930)$ can be regarded as $\chi'_{c1}(2P)$ with $J^{PC}=1^{++}$[19-20] and $\chi'_{c2}(2P)$ with $J^{PC}=2^{++}$, respectively.

② $X(3915)$ can be an χ'_{c0} state[44], since its mass is close to the predicted mass of χ'_{c0} predicted in Ref. [51]. This assignment can explain why the mass difference between $X(3915)$ and $Z(3930)$ is smaller than that between $X(3915)$ and X

(3872)[44].

③ $X(4350)$ was explained as $\chi''_{c2}(2P)$[44].

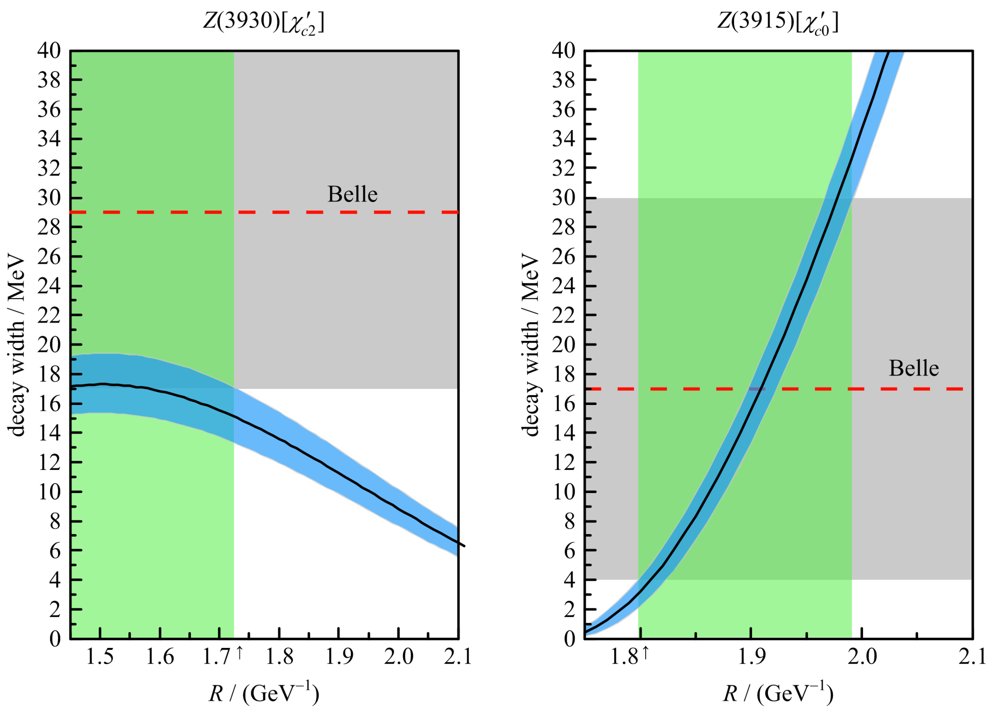
The above assignment to charmonium-like states observed in $\gamma\gamma$ fusion can be supported by the further study of two-body strong decay of $X(3915)$, $Z(3930)$ and $X(4350)$[44], as shown in Figs. 4 and 5.

5 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[45]. $Z_b(10610)$ 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.

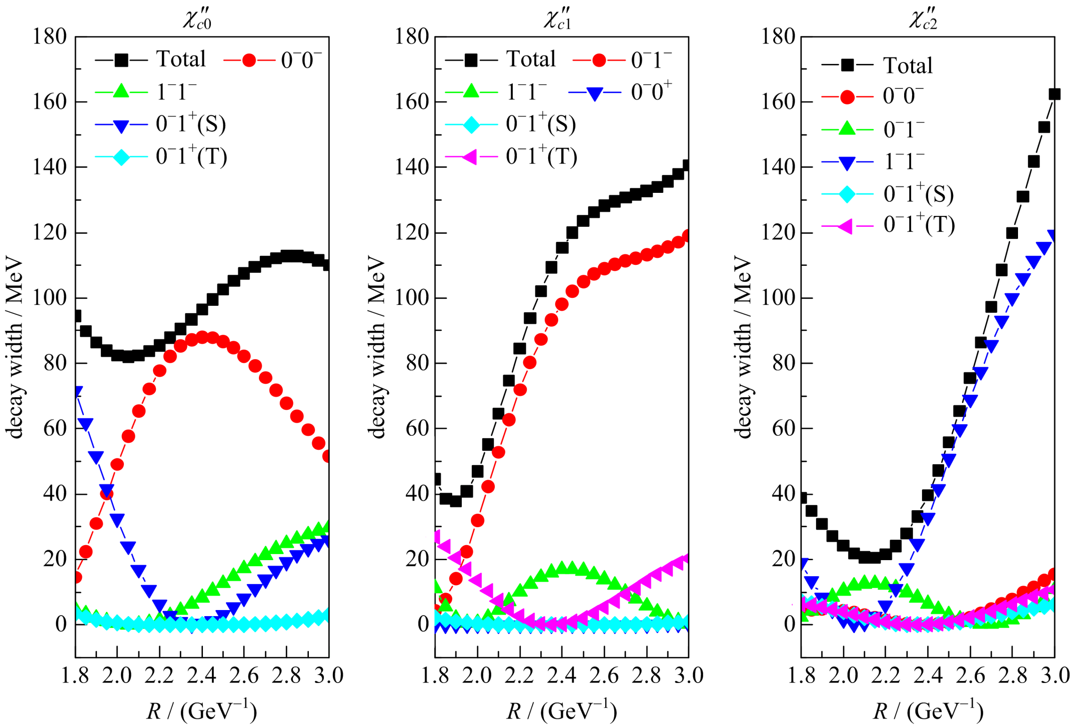
The initial single pion emission (ISPE) mechanism[46] was proposed to understand two bottomonium-like structures Z_b(10610) and $Z_b(10650)$. The physical picture is that the emitted pion with continuous energy distribution produces $B^{(*)}$ and $\bar{B}^{(*)}$ with low momentum. Thus, the intermediate $B^{(*)}$ 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[46].

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[47]. This investigation can provide more predictions for the future experiment as an important test of the ISPE



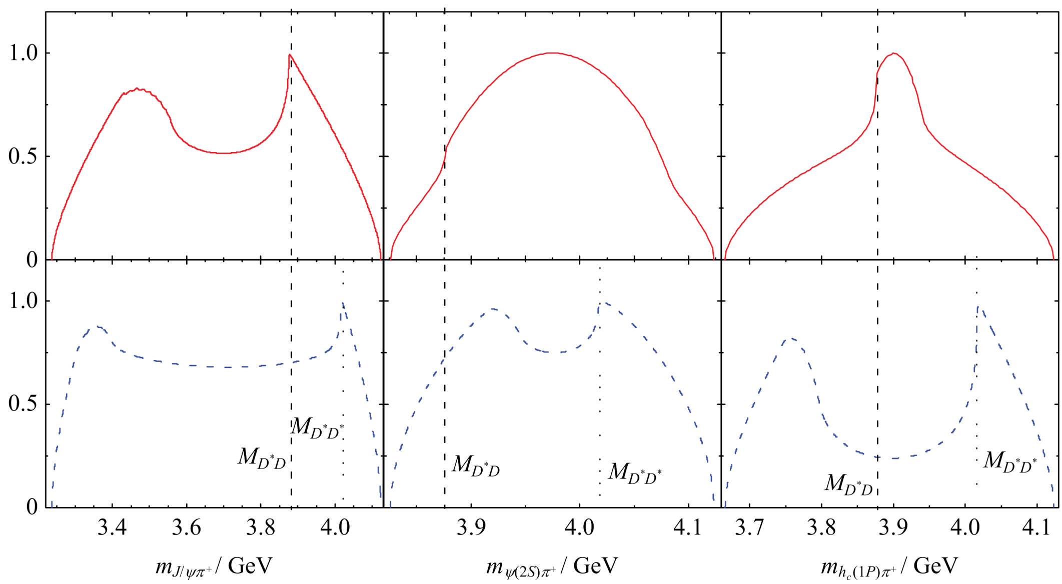
The green band denotes the region of R resulting in the theoretical values consistent with Belle data. The solid lines with blue error bands are our calculation result. Taken from Ref. [44].

Fig. 4 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



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. [44].

Fig. 5 The variation of the decay width of χ''_{cJ} ($J=0,1,2$) with R value



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. The maximum of the line shape is normalized to 1. Taken from Ref. [47].

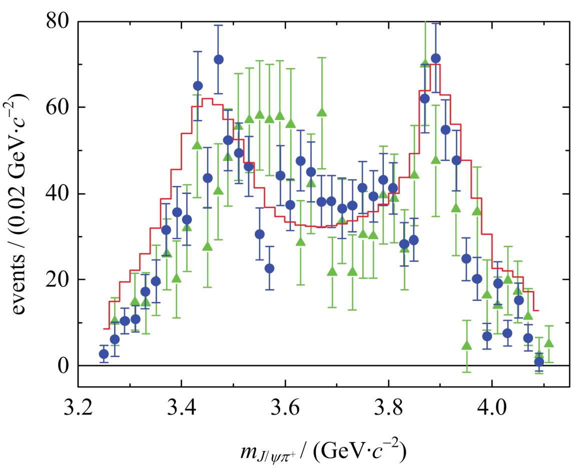
Fig. 6 The invariant mass spectra of $J/\psi\pi^+$, $\psi(2S)\pi^+$ and $h_c(1P)\pi^+$ for the $Y(4260)$ decays into $J/\psi\pi^+\pi^-$, $\psi(2S)\pi^+\pi^-$ and $h_c(1P)\pi^+\pi^-$

mechanism.

In Ref. [47], 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.

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[48], which is around the $D\bar{D}^*$ threshold. Almost at the same time, Belle also observed $Z_c(3900)$[49]. The observation of $Z_c(3900)$ is consistent with our prediction in Ref. [47].

According to this research status, we studied $Z_c(3900)$ by considering the ISPE mechanism in Ref. [50], 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.



The blue dots and green triangles with error bars are the experimental data given by BESIII[48] and Belle[49], 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. [50].

Fig. 7 The distributions of the $J/\psi\pi^+$ invariant mass spectrum of $Y(4260)\to\pi^+\pi^-J/\psi$

6 Conclusion

In this paper, I gave a brief review of the present research status of *XYZ* states. The conclusions are summarized as follows:

① The hadronic molecular state explanations of $Y(3940)$, $Y(4140)$ and $Y(4274)$ were given in Refs. [21,23].

② The non-resonant explanation of $Y(4260)$ and $Y(4360)$ was suggested in Refs. [40,42].

③ The P-wave charmonium assignment to $Y(3915)$, $Z(3930)$ and $X(4350)$ was proposed in Ref. [44]. 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.

④ According to ISPE mechanism, charged charmonium-like state near $D\bar{D}^*$ threshold was predicted in Ref. [47], which may correspond to the observed $Z_c(3900)$[50].

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

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(下转第 586 页)