Study of the XYZ states at the BESIII *

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(Dated: August 7, 2015)

Abstract

With the world unique data samples above 4 GeV, BESIII experiment made significant contribution to the study of the charmonium and charmoniumlike states, i.e., the XYZ states. We review the results on the observation of the $Z_c(3900)$ and $Z_c(4020)$ states, observation of the $X(3872)$ in e^+e^- annihilation, observation of the charmonium $\psi(1\,^3D_2)$ state, measurement of the cross sections of $\omega\chi_{cJ}$ and $\eta J/\psi$, as well as the search for $e^+e^- \to \gamma\chi_{cJ}$ and $\gamma Y(4140)$. We also show a possible data taking proposal for BESIII to further strengthen the study of the XYZ and conventional charmonium states, and the perspectives at future experiments.

PACS numbers: 14.40.Gx, 13.25.Gv, 13.66.Bc

* Talk at the "International Workshop on Physics at Future High Intensity Collider 2-7 GeV in China", January 13-16, 2015, University of Science and Technology of China (USTC), Hefei, China.

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I. INTRODUCTION

Many charmonium and charmoniumlike states were discovered at B-factories in the first decade of the 21st century [1]. while some of them are good charmonium candidates as predicted in different models, many of these states have exotic properties, which may indicate that exotic states, such as multi-quark state, molecule, hybrid, or hadron-quarkonium, have been observed [2].

BESIII experiment [3] running at the BEPCII storage ring, started its first physics collision in the tau-charm energy region in 2008. After a few years running at the energies for its well-defined physics programs [4], i.e., at J/ψ and $\psi(2S)$ peaks in 2009, at $\psi(3770)$ peak in 2010 and 2011, BESIII experiment started to collect data for the study of the XYZ particles which was not written in the Yellow Book [4].

As the design center-of-mass (c.m.) energy of the BEPCII was 2.0-4.2 GeV, there was not many options for the data samples for the XYZ-related physics. BESIII took its first data sample at the peak of $\psi(4040)$ in May 2011 to search for the well-known $X(3872)$ in $\psi(4040)$ radiative transition and possibly the P-wave charmonium spin-triplet states in similar transitions. This sample is about 0.5 fb^{-1}, which is limited by the one month data taking time left after the $\psi(3770)$ data taking in 2010-2011 running year. The reason for not taking data at the peak of the $\psi(4170)$ is that the CLEO-c experiment has already collected a sample of about 0.6 fb^{-1} for the study of the D_s decays which can be used for similar studies.

The upgrade of the LINAC of the BEPCII in summer 2012 enabled the highest beam energy of the machine increases from 2.1 to 2.3 GeV, which made the data taking at higher c.m. energies (up to 4.6 GeV) possible, especially, this made the data taking at almost all the known vector states possible, including the $Y(4260)$, $Y(4360)$, the $\psi(4415)$, and marginally the $Y(4660)$.

The data taking at c.m. energy $\sqrt{s} = 4.26$ GeV turned out to be very fruitful, with one month's data taking of 525 pb^{-1} from December 14, 2012 to January 14, 2013, the charged charmoniumlike state, $Z_c(3900)$, was observed [5], resulting in a change of the data taking plan of 2012-2013 running year. More data at c.m. energy of 4.26 GeV and then 4.23 GeV were accumulated. The data taking at the $Y(4360)$ peak were also finished in Spring 2013, and the data at even higher energies (4.42 and 4.6 GeV) were taken in 2014 after a fine scan of the total hadronic cross sections between 3.8 and 4.6 GeV at more than 100 energy points with a total integrated luminosity of about 800 pb^{-1}.

So far the data samples dedicated for the XYZ study are shown in Table I, including the nominal c.m. energy, the measured c.m. energy, and the integrated luminosity at each energy point. These data were used for all the analyses presented in this article.

II. THE CHARGED CHARMONIUMLIKE STATES: Z_cS

BESIII experiment observed for the first time a charged charmoniumlike state close to the $D\bar{D}^*$ threshold, $Z_c(3900)/Z_c(3885)$, and a charged charmoniumlike state close to the $D^*\bar{D}^*$ threshold, $Z_c(4020)/Z_c(4025)$. Their neutral partners were also observed which confirm their isospin to be one.

TABLE I: The measured c.m. energy [6], integrated luminosity [7] of each data sample collected for the study of the XYZ states. The uncertainties on the integrated luminosities are statistical only, a 1% systematic uncertainty common to all the data points is not listed.

Data sample	c.m. energy (MeV)	$\mathcal{L}$ (pb^{-1})
3810	3807.65±0.10±0.58	50.54±0.03
3900	3896.24±0.11±0.72	52.61±0.03
4009	4007.62±0.05±0.66	481.96±0.01
4090	4085.45±0.14±0.66	52.63±0.03
4190	4188.59±0.15±0.68	43.09±0.03
4210	4207.73±0.14±0.61	54.55±0.03
4220	4217.13±0.14±0.67	54.13±0.03
4230	4226.26±0.04±0.65	1091.74±0.15
4245	4241.66±0.12±0.73	55.59±0.04
4260	4257.97±0.04±0.66	825.67±0.13
4310	4307.89±0.17±0.63	44.90±0.03
4360	4358.26±0.05±0.62	539.84±0.10
4390	4387.40±0.17±0.65	55.18±0.04
4420	4415.58±0.04±0.72	1073.56±0.14
4470	4467.06±0.11±0.73	109.94±0.04
4530	4527.14±0.11±0.72	109.98±0.04
4575	4574.50±0.18±0.70	47.67±0.03
4600	4599.53±0.07±0.74	566.93±0.11

A. Observation of the $Z_c(3900)$ and $Z_c(3885)$

1. *Observation of the* $Z_c(3900)$

BESIII experiment studied the process $e^+e^- \to \pi^+\pi^- J/\psi$ at a c.m. energy of 4.26 GeV using a 525 pb^{-1} data sample [5]. A structure at around 3.9 GeV/c^2 is observed in the $\pi^\pm J/\psi$ mass spectrum with a statistical significance larger than 8σ, which is referred to as the $Z_c(3900)$. A fit to the $\pi^\pm J/\psi$ invariant mass spectrum (see Fig. 1), neglecting interference, results in a mass of $(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and a width of $(46 \pm 10 \pm 20)$ MeV. Its production ratio is measured to be $R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = (21.5 \pm 3.3 \pm 7.5)\%$.

At Belle experiment, the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ is measured from 3.8 to 5.5 GeV using initial state radiation (ISR) method. The intermediate states in $Y(4260) \to \pi^+\pi^- J/\psi$ decays are investigated [8]. The $Z_c(3900)$ (was named $Z(3900)^+$ in the Belle paper) state with a mass of $(3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2 and a width of $(63 \pm 24 \pm 26)$ MeV is observed in the $\pi^\pm J/\psi$ mass spectrum (see Fig. 1) with a statistical significance larger than 5.2σ.

The $Z_c(3900)$ state was confirmed shortly after with CLEO-c data at a c.m. energy of 4.17 GeV [9], the mass and width agree with the BESIII and Belle measurements very well.

A neutral state $Z_c(3900)^0 \to \pi^0 J/\psi$ with a significance of 10.4σ was observed at BESIII in $e^+e^- \to \pi^0\pi^0 J/\psi$ with the data for c.m. energy ranges from 4.19 to 4.42 GeV [10]. The mass and width are measured to be $(3894.8 \pm 2.3 \pm 3.2)$ MeV/c^2 and $(29.6 \pm 8.2 \pm 8.2)$ MeV,

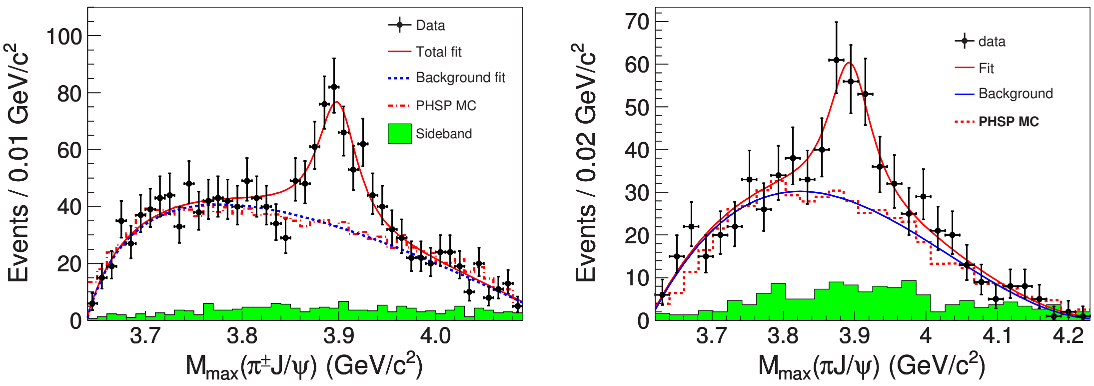

FIG. 1: Unbinned maximum likelihood fit to the distribution of the $M_{\rm max}(\pi J/\psi)$ (left panel from BESIII and right panel from Belle). Points with error bars are data, the curves are the best fit, the dashed histograms are the phase space distributions and the shaded histograms are the non-$\pi^+\pi^- J/\psi$ background estimated from the normalized J/ψ sidebands.

respectively. The state is interpreted as the neutral partner of the $Z_c(3900)^\pm$, since it decays to $\pi^0 J/\psi$ and its mass is close to the mass of $Z_c(3900)^\pm$. In agreement with the previous reported 3.5σ evidence for $Z_c(3900)^0$ in CLEO-c data [9]. The measured Born cross sections of $e^+e^- \to \pi^0\pi^0 J/\psi$ are about half of those for $e^+e^- \to \pi^+\pi^- J/\psi$ that were measured by Belle [8], consistent with the isospin symmetry expectation.

2. *Observation of the* $Z_c(3885)$

The $Z_c(3900)$ state observed in $\pi J/\psi$ final state is close to and above the $D\bar{D}^*$ mass threshold. With the same data sample at $\sqrt{s} = 4.26$ GeV, BESIII experiment reported on a study of $e^+e^- \to \pi^\pm (D\bar{D}^*)^\mp$. A structure (referred to as $Z_c(3885)$) is observed in the $(D\bar{D}^*)^\pm$ invariant mass distribution [11]. When fitted to a mass-dependent-width Breit-Wigner (BW) function, the pole mass and width are determined to be $(3883.9 \pm 1.5 \pm 4.2)$ MeV/c^2 and $(24.8 \pm 3.3 \pm 11.0)$ MeV, respectively (see Fig. 2). The angular distribution of the $Z_c(3885)$ system favors a $J^P = 1^+$ assignment for the structure and disfavors 1^- or 0^-. The production rate is measured to be $\sigma(e^+e^- \to \pi^\mp Z_c(3885)^\pm) \times \mathcal{B}(Z_c(3885)^\pm \to (D\bar{D}^*)^\pm) = (83.5 \pm 6.6 \pm 22.0)$ pb.

An important question is whether or not the $Z_c(3885)$ is the same as the $Z_c(3900)$ [5, 8]. The mass and width of the $Z_c(3885)$ are 2σ and 1σ, respectively, below those of the $Z_c(3900)$ observed by BESIII and Belle. However neither fit considers the possibility of interference with a coherent non-resonant background that could shift the results. A spin-parity quantum number determination of the $Z_c(3900)$ would provide an additional test of this possibility.

Assuming the $Z_c(3885)$ structure is due to the $Z_c(3900)$, one obtains $\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$. This ratio is much smaller than typical values for decays of conventional charmonium states above the open charm threshold. For example, $\Gamma(\psi(3770) \to D\bar{D})/\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) = 482 \pm 84$ [12] and $\Gamma(\psi(4040) \to D^{(*)}\bar{D}^{(*)})/\Gamma(\psi(4040) \to \eta J/\psi) = 192 \pm 27$ [13]. This may suggest very different dynamics in the $Y(4260)$-$Z_c(3900)$ system.

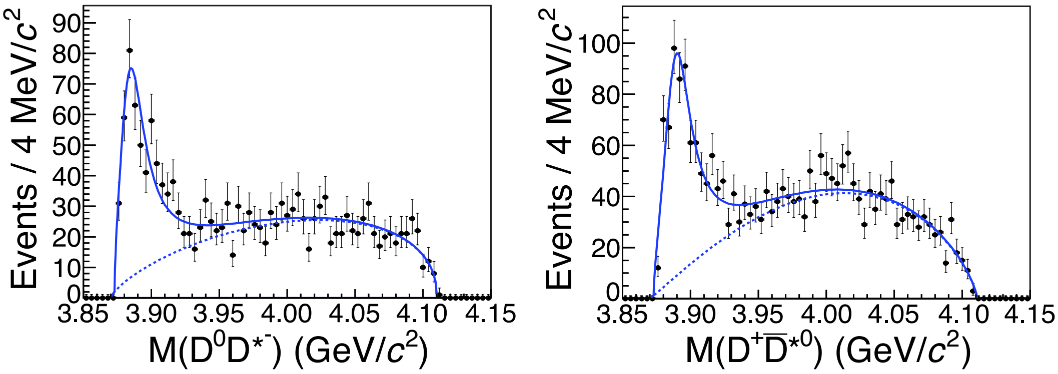

FIG. 2: The $M(D^0D^{*-})$ (left) and $M(D^+\bar{D}^{*0})$ (right) distributions for selected events at $\sqrt{s}$ = 4.26 GeV. The curves show the best fits.

B. Observation of the $Z_c(4020)$ and $Z_c(4025)$

1. *Observation of the* $Z_c(4020)$

BESIII measured $e^+e^- \to \pi^+\pi^-h_c$ cross sections [14] at c.m. energies between 3.90 and 4.42 GeV. Intermediate states are studied by examining the Dalitz plot of the selected $\pi^+\pi^-h_c$ candidate events. The h_c signal is selected using $3.518 < M_{\gamma\eta_c} < 3.538$ GeV/c^2, $\pi^+\pi^-h_c$ samples of 859 events at 4.23 GeV, 586 events at 4.26 GeV, and 469 events at 4.36 GeV are obtained with purities of 65%. While there are no clear structures in the $\pi^+\pi^-$ system, there is clear evidence for an exotic charmoniumlike structure in the $\pi^\pm h_c$ system as clearly shown in the Dalitz plot. Figure 3 (left) shows the projection of the $M(\pi^\pm h_c)$ (two entries per event) distribution for the signal events, as well as the background events estimated from normalized h_c mass sidebands. There is a significant peak at around 4.02 GeV/c^2 (the $Z_c(4020)$), and there are also some events at around 3.9 GeV/c^2 (inset of Fig. 3) (left), which could be the $Z_c(3900)$. The individual data sets at 4.23 GeV, 4.26 GeV and 4.36 GeV show similar structures.

An unbinned maximum likelihood fit is applied to the $M(\pi^\pm h_c)$ distribution summed over the 16 η_c decay modes. The data at 4.23, 4.26, and 4.36 GeV are fitted simultaneously with the same signal function with common mass and width. Figure 3 (left) shows the fit results. The mass of the $Z_c(4020)$ is measured to be $(4022.9 \pm 0.8 \pm 2.7)$ MeV/c^2, and the width is $(7.9 \pm 2.7 \pm 2.6)$ MeV. The statistical significance of the $Z_c(4020)$ signal is found to be greater than 8.9σ.

Adding a $Z_c(3900)$ with mass and width fixed to the BESIII measurement [5] in the fit, results in a statistical significance of 2.1σ (see the inset of Fig. 3 (left)). The upper limits on the production cross sections are set as $\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^-h_c) < 13$ pb at 4.23 GeV and < 11 pb at 4.26 GeV, at the 90% confidence level (C.L.). This is lower than that of $Z_c(3900) \to \pi^\pm J/\psi$ [5].

BESIII also observed $e^+e^- \to \pi^0\pi^0h_c$ at $\sqrt{s}$ = 4.23, 4.26, and 4.36 GeV for the first time [15]. The measured Born cross sections are about half of those for $e^+e^- \to \pi^+\pi^-h_c$, and agree with expectations based on isospin symmetry within systematic uncertainties. A narrow structure with a mass of $(4023.9 \pm 2.2 \pm 3.8)$ MeV/c^2 (the width was fixed to that

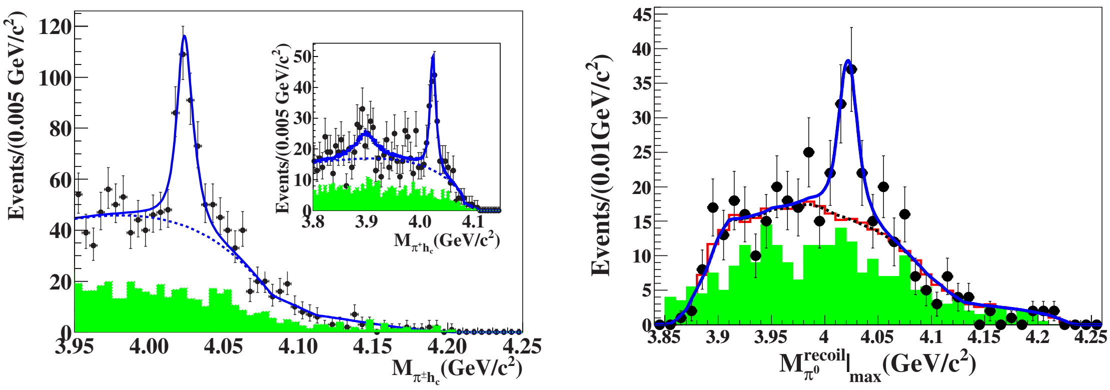

FIG. 3: Sum of the simultaneous fits to the $M(\pi^\pm h_c)$ (left panel) and $M(\pi^0 h_c)$ (right panel) distributions at 4.23, 4.26, and 4.36 GeV in the BESIII data; the inset in the left panel shows the sum of the simultaneous fit to the $M_{\pi^+ h_c}$ distributions at 4.23 GeV and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$. Dots with error bars are data; shaded histograms are normalized sideband background; the solid curves show the total fit, and the dotted curves the backgrounds from the fit.

measured in $e^+e^- \to \pi^+\pi^- h_c$ process [14] in the fit due to low statistics) is observed in the $\pi^0 h_c$ mass spectrum (Fig. 3 (right)). This structure is most likely the neutral isospin partner of the charged $Z_c(4020)$ observed in the $e^+e^- \to \pi^+\pi^- h_c$ process [14]. This observation indicates that there is no anomalously large isospin violations in $\pi\pi h_c$ and $\pi Z_c(4020)$ systems.

2. Observation of the $Z_c(4025)$

BESIII experiment also studied the process $e^+e^- \to (D^*\bar{D}^*)^\pm \pi^\mp$ at 4.26 GeV using a 827 pb^{-1} data sample [16]. Based on a partial reconstruction technique, the Born cross section is measured to be $(137 \pm 9 \pm 15)$ pb. A structure near the $(D^*\bar{D}^*)^\pm$ threshold in the $\pi^\mp$ recoil mass spectrum is observed, which is denoted as the $Z_c(4025)$ (see Fig. 4 (left)). The measured mass and width of the structure are $(4026.3 \pm 2.6 \pm 3.7)$ MeV/c^2 and $(24.8 \pm 5.6 \pm 7.7)$ MeV, respectively, from a fit with a constant-width BW function for the signal. Its production ratio $\frac{\sigma(e^+e^- \to Z_c^\pm(4025)\pi^\mp \to (D^*\bar{D}^*)^\pm \pi^\mp)}{\sigma(e^+e^- \to (D^*\bar{D}^*)^\pm \pi^\mp)}$ is determined to be $0.65 \pm 0.09 \pm 0.06$.

Using data at $\sqrt{s} = 4.23$ and 4.26 GeV, a structure was observed in the π^0 recoil mass spectrum in the process $e^+e^- \to D^{*0}\bar{D}^{*0}(D^{*+}D^{*-})\pi^0$ [17]. Assuming that the enhancement is due to a neutral state decaying to $D^*\bar{D}^*$, the mass and width of its pole position are determined to be $(4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV/c^2 and $\Gamma = (23.0 \pm 6.0 \pm 1.0)$ MeV, respectively (see Fig. 4 (right)). The Born cross section $\sigma(e^+e^- \to Z_c(4025)^0\pi^0 \to (D^{*0}\bar{D}^{*0} + D^{*+}D^{*-})\pi^0)$ is measured to be $(61.6 \pm 8.2 \pm 9.0)$ pb at 4.23 GeV and $(43.4 \pm 8.0 \pm 5.4)$ pb at 4.26 GeV. The ratio $\frac{\sigma(e^+e^- \to Z_c(4025)^0\pi^0 \to (D^*\bar{D}^*)^0\pi^0)}{\sigma(e^+e^- \to Z_c(4025)^+\pi^- \to (D^*\bar{D}^*)^+\pi^-)}$ is compatible with unity at $\sqrt{s} = 4.26$ GeV, which is expected from isospin symmetry. In addition, the $Z_c(4025)^0$ has mass and width very close to those of the $Z_c(4025)^\pm$, which couples to $(D^*\bar{D}^*)^\pm$. Therefore, the observed $Z_c(4025)^0$ state is a good candidate to be the isospin partner of $Z_c(4025)^\pm$.

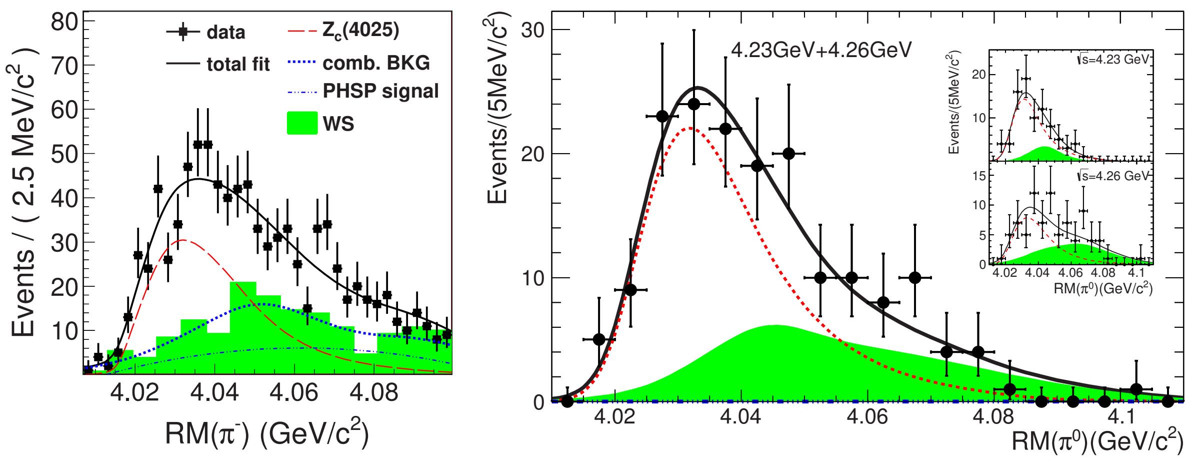

FIG. 4: Unbinned maximum likelihood fit to the $\pi^{\mp}$ recoil mass spectrum (left) in $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$ at $\sqrt{s} = 4.26$ GeV, and to the π^0 recoil mass spectrum (right) in $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$ at $\sqrt{s} = 4.23$ and 4.26 GeV at BESIII.

The $Z_c(4025)$ parameters agree within 1.5σ of those of the $Z_c(4020)$, it is very probably that they are the same state. As the results on the $Z_c(4025)^{\pm}$ is only from the data at 4.26 GeV, extending the analysis to the data at 4.23 GeV and 4.36 GeV will probably give us a definite answer.

III. OBSERVATION OF $Y(4260) \to \gamma X(3872)$

BESIII reported the observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$, with J/ψ reconstructed through its decays into lepton pairs ($\ell^+\ell^- = e^+e^-$ or $\mu^+\mu^-$) [18].

The $M(\pi^+\pi^- J/\psi)$ distribution (summed over all energy points), as is shown in Fig. 5 (left), is fitted to extract the mass and signal yield of the $X(3872)$. The ISR $\psi(2S)$ signal is used to calibrate the absolute mass scale and to extract the resolution difference between data and Monte Carlo (MC) simulation. Figure 5 shows the fit result, the measured mass of $X(3872)$ is $(3871.9 \pm 0.7 \pm 0.2)$ MeV$/c^2$. From a fit with a floating width one obtains a width of $(0.0^{+1.7}_{-0.0})$ MeV, or less than 2.4 MeV at the 90% C.L. The statistical significance of $X(3872)$ is 6.3σ.

The Born-order cross section is measured and the results are listed in Table II. For 4.009 and 4.36 GeV data, since the $X(3872)$ signal is not significant, upper limits on the production rates are given at 90% C.L. The measured cross sections at around 4.26 GeV are an order of magnitude higher than the NRQCD calculation of continuum production [**?**], this may suggest the $X(3872)$ events come from a resonant decays.

The energy-dependent cross sections are fitted with a $Y(4260)$ resonance (parameters fixed to PDG [12] values), a linear continuum, or an $E1$-transition phase space ($\propto E_{\gamma}^3$) term. Figure 5 (right) shows all the fit results, which give $\chi^2/\mathrm{ndf} = 0.49/3$ (C.L.=92%), 5.5/2 (C.L.=6%), and 8.7/3 (C.L.=3%) for a $Y(4260)$ resonance, linear continuum, and phase space distribution, respectively. The $Y(4260)$ resonance describes the data better than the other two options.

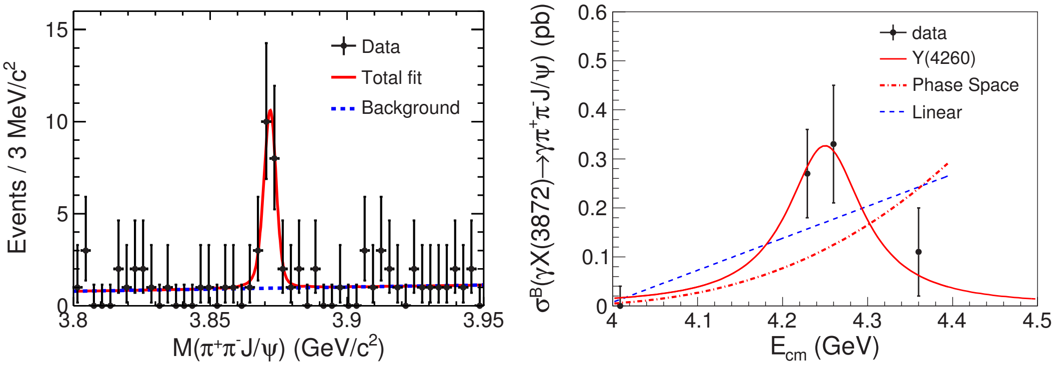

FIG. 5: Left panel: fit the $M(\pi^+\pi^- J/\psi)$ distribution observed at BESIII. Dots with error bars are data, the curves are the best fit. Right panel: fit to $\sigma^B[e^+e^- \to \gamma X(3872)] \times \mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi]$ measured by BESIII with a $Y(4260)$ resonance (red solid curve), a linear continuum (blue dashed curve), or an $E1$-transition phase space term (red dotted-dashed curve). Dots with error bars are data.

TABLE II: The product of the Born cross section $\sigma^B(e^+e^- \to \gamma X(3872))$ and $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ at different energy points. The upper limits are given at 90% C.L.

$\sqrt{s}$ (GeV)	$\sigma^B[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (pb)
4.009	$0.00 \pm 0.04 \pm 0.01$ or < 0.11
4.229	$0.27 \pm 0.09 \pm 0.02$
4.260	$0.33 \pm 0.12 \pm 0.02$
4.360	$0.11 \pm 0.09 \pm 0.01$ or < 0.36

These observations strongly support the existence of the radiative transition process $Y(4260) \to \gamma X(3872)$. The $Y(4260) \to \gamma X(3872)$ could be another previously unseen decay mode of the $Y(4260)$ resonance. This, together with the transitions to the charged charmoniumlike state $Z_c(3900)$ [5, 8, 9], suggest that there might be some commonality in the nature of the $X(3872)$, $Y(4260)$, and $Z_c(3900)$, the model developed to interpret any one of them should also consider the other two. As an example, the authors of Ref. [19] put all these states into a molecular picture to calculate $e^+e^- \to \gamma X(3872)$ cross sections.

Combining with the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section measurement at $\sqrt{s} = 4.26$ GeV from BESIII [5], one obtains $\sigma^B[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi]/\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi) = (5.2\pm1.9)\times10^{-3}$, under the assumption that $X(3872)$ and $\pi^+\pi^- J/\psi$ produced only from $Y(4260)$ decays. If one takes $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] = 5\%$ [20], then $\mathcal{R} = \frac{\mathcal{B}[Y(4260)\to\gamma X(3872)]}{\mathcal{B}(Y(4260)\to\pi^+\pi^- J/\psi)} \sim 0.1$.

IV. OBSERVATION OF $\psi(1\,^3D_2)$

BESIII reported the observation of the $X(3823)$ in the process $e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$ with a statistical significance of 6.2σ, in data samples at c.m. energies $\sqrt{s}$ =4.23, 4.26, 4.36, 4.42, and 4.60 GeV [21].

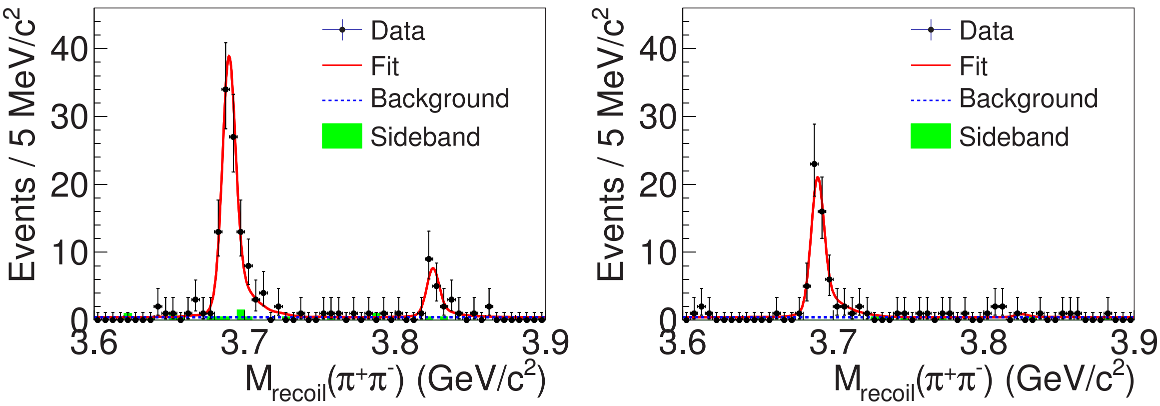

FIG. 6: Simultaneous fit to the $M_{\rm recoil}(\pi^+\pi^-)$ distribution of $\gamma\chi_{c1}$ events (left) and $\gamma\chi_{c2}$ events (right), respectively. Dots with error bars are data, red solid curves are total fit, dashed blue curves are background, and the green shaded histograms are J/ψ mass sideband events.

Figure 6 shows the fit results to $\pi^+\pi^-$ recoil mass distributions for events in χ_{c1} and χ_{c2} signal regions. The fit yields 19 ± 5 $X(3823)$ signal events in the $\gamma\chi_{c1}$ mode, the measured mass of the $X(3823)$ is $(3821.7 \pm 1.3 \pm 0.7)$ MeV$/c^2$, where the first error is statistical and second systematic. For the $\gamma\chi_{c2}$ mode, no significant $X(3823)$ signal is observed and an upper limit on its production rate is determined. The limited statistics doesnot allow a measurement of the intrinsic width of $X(3823)$. From a fit using BW function (with a width parameter that is allowed to float) convolved with Gaussian resolution, $\Gamma[X(3823)] <$ 16 MeV at the 90% C.L. (including systematic errors) is determined. The measurement agrees well with the values found by Belle [22].

The production cross sections of $\sigma^B(e^+e^- \to \pi^+\pi^- X(3823)) \cdot \mathcal{B}(X(3823) \to \gamma\chi_{c1}, \gamma\chi_{c2})$ are also measured at these c.m. energies. The cross sections of $e^+e^- \to \pi^+\pi^- X(3823)$ were fit with the $Y(4360)$ shape or the $\psi(4415)$ shape with their resonance parameters fixed to the PDG values [12]. Figure 7 shows the fit results, which give the Kolmogorov-Smirnov statistic $D^{\rm H1}_{5,\rm obs} = 0.151$ for the $Y(4360)$ hypothesis (H1) and $D^{\rm H2}_{5,\rm obs} = 0.169$ for the $\psi(4415)$ hypothesis (H2), based on the Kolmogorov-Smirnov [23] test. Thus, both the $Y(4360)$ and $\psi(4415)$ hypotheses ($D^{\rm H1}_{5,\rm obs}, D^{\rm H2}_{5,\rm obs} < D_{5,0.1} = 0.509$) are accepted at a 90% C.L.

The $X(3823)$ resonance is a good candidate for the $\psi(1\,^3D_2)$ charmonium state. According to potential models [24], the D-wave charmonium states are expected to be within a mass range of 3.82 to 3.85 GeV. Among these, the $1\,^1D_2 \to \gamma\chi_{c1}$ transition is forbidden due to C-parity conservation, and the amplitude for $1\,^3D_3 \to \gamma\chi_{c1}$ is expected to be small [25]. The mass of $\psi(1\,^3D_2)$ is in the $3.810 \sim 3.840$ GeV$/c^2$ range that is expected for several phenomenological calculations [26]. In this case, the mass of $\psi(1\,^3D_2)$ is above the $D\bar{D}$ threshold but below the $D\bar{D}^*$ threshold. Since $\psi(1\,^3D_2) \to D\bar{D}$ violates parity, the $\psi(1\,^3D_2)$ is expected to be narrow, in agreement with the observation, and $\psi(1\,^3D_2) \to \gamma\chi_{c1}$ is expected to be a dominant decay mode [26, 27]. From the cross section measurement, the ratio $\frac{\mathcal{B}[X(3823)\to\gamma\chi_{c2}]}{\mathcal{B}[X(3823)\to\gamma\chi_{c1}]} < 0.42$ (where systematic uncertainty cancel) at the 90% C.L. is obtained, which also agrees with expectations for the $\psi(1\,^3D_2)$ state [27].

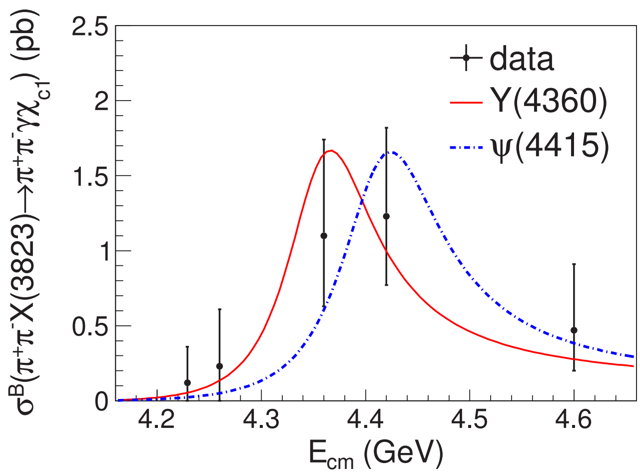

FIG. 7: Comparison of the energy-dependent cross sections of $\sigma^B[e^+e^- \to \pi^+\pi^- X(3823)] \cdot \mathcal{B}(X(3823) \to \gamma\chi_{c1})$ to the $Y(4360)$ and $\psi(4415)$ line shapes. Dots with error bars (statistical only) are data. The red solid (blue dashed) curve shows a fit with the $Y(4360)$ ($\psi(4415)$) line shape.

V. SEARCH FOR $e^+e^- \to \gamma\chi_{cJ}$ AND $e^+e^- \to \gamma Y(4140)$

Using data samples collected at $\sqrt{s}$ = 4.009, 4.23, 4.26, and 4.36 GeV, BESIII performed a search for $e^+e^- \to \gamma\chi_{cJ}$ ($J = 0, 1, 2$) with the subsequent decay $\chi_{cJ} \to \gamma J/\psi$ and $J/\psi \to \mu^+\mu^-$. Evidence for the processes $e^+e^- \to \gamma\chi_{c1}$ and $e^+e^- \to \gamma\chi_{c2}$ are reported with statistical significances of 3.0σ and 3.4σ, respectively [28]. No evidence for $e^+e^- \to \gamma\chi_{c0}$ is observed. The corresponding Born cross sections of $e^+e^- \to \gamma\chi_{cJ}$ at different c.m. energies are calculated. Under the assumption of the absence of χ_{cJ} signals, the upper limits on the Born cross sections at the 90% C.L. are calculated, too. These upper limits on the Born cross section of $e^+e^- \to \gamma\chi_{cJ}$ are compatible with the theoretical prediction from an NRQCD calculation [29].

The $Y(4140)$ was searched for via $e^+e^- \to \gamma\phi J/\psi$ at $\sqrt{s} = 4.23$, 4.26, and 4.36 GeV and no significant $Y(4140)$ signal was observed in either data sample [30]. The upper limits of the product of cross section and branching fraction $\sigma[e^+e^- \to \gamma Y(4140)] \cdot \mathcal{B}(Y(4140) \to \phi J/\psi)$ at the 90% C.L. are estimated as 0.35, 0.28, and 0.33 pb at $\sqrt{s} = 4.23$, 4.26, and 4.36 GeV, respectively.

These upper limits can be compared with the $X(3872)$ production rates [18], which were measured with the same data samples (see Sec. III). The latter are $\sigma[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) = [0.27 \pm 0.09(\text{stat}) \pm 0.02(\text{syst})]$ pb, $[0.33 \pm 0.12(\text{stat}) \pm 0.02(\text{syst})]$ pb, and $[0.11 \pm 0.09(\text{stat}) \pm 0.01(\text{syst})]$ pb at $\sqrt{s} = 4.23, 4.26$, and 4.36 GeV, respectively, which are of the same order of magnitude as the upper limits of $\sigma[e^+e^- \to \gamma Y(4140)] \cdot \mathcal{B}(Y(4140) \to \phi J/\psi)$ at the same energy.

The branching fraction $\mathcal{B}(Y(4140) \to \phi J/\psi)$ has not previously been measured. Using the partial width of $Y(4140) \to \phi J/\psi$ calculated under the molecule hypothesis [31], and the total width of the $Y(4140)$ measured by CDF [32], the branching fraction is estimated roughly to be 30%. A rough estimation for $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ is 5% [20]. Combining these numbers, the ratio $\sigma[e^+e^- \to \gamma Y(4140)]/\sigma[e^+e^- \to \gamma X(3872)]$ is estimated to be at the order of 0.1 or even smaller at $\sqrt{s} = 4.23$ and 4.26 GeV.

VI. STRUCTURES IN $e^+e^- \to$ charmonium + hadrons

A. Observation of $e^+e^- \to \omega\chi_{c0}$

Based on data samples collected between $\sqrt{s} = 4.21$ and 4.42 GeV, the process $e^+e^- \to \omega\chi_{c0}$ is observed at $\sqrt{s} = 4.23$ and 4.26 GeV for the first time [33], and the Born cross sections are measured to be $(55.4 \pm 6.0 \pm 5.9)$ and $(23.7 \pm 5.3 \pm 3.5)$ pb, respectively. For other energy points, no significant signals are found and upper limits on the cross section at the 90% C.L. are determined.

The data reveals a sizeable $\omega\chi_{c0}$ production around 4.23 GeV/c^2 as predicted in Ref. [34]. By assuming the $\omega\chi_{c0}$ signals come from a single resonance, the $\Gamma_{ee}\mathcal{B}(\omega\chi_{c0})$, mass, and width of the resonance are determined to be $(2.7 \pm 0.5 \pm 0.4)$ eV, $(4230 \pm 8 \pm 6)$ MeV/c^2, and $(38 \pm 12 \pm 2)$ MeV, respectively (the fit is shown in Fig. 8). The parameters are consistent well with those of the narrow structure in the $e^+e^- \to \pi^+\pi^- h_c$ process [35] but inconsistent with those obtained by fitting a single resonance to the $\pi^+\pi^- J/\psi$ cross section [36]. This suggests that the observed $\omega\chi_{c0}$ signals be unlikely to originate from the $Y(4260)$.

The $e^+e^- \to \omega\chi_{c1,2}$ channels are also sought for, but no significant signals are observed; upper limits at the 90% C.L. on the production cross sections are determined. The very small measured ratios of $e^+e^- \to \omega\chi_{c1,2}$ cross sections to those for $e^+e^- \to \omega\chi_{c0}$ are inconsistent with the prediction in Ref. [37].

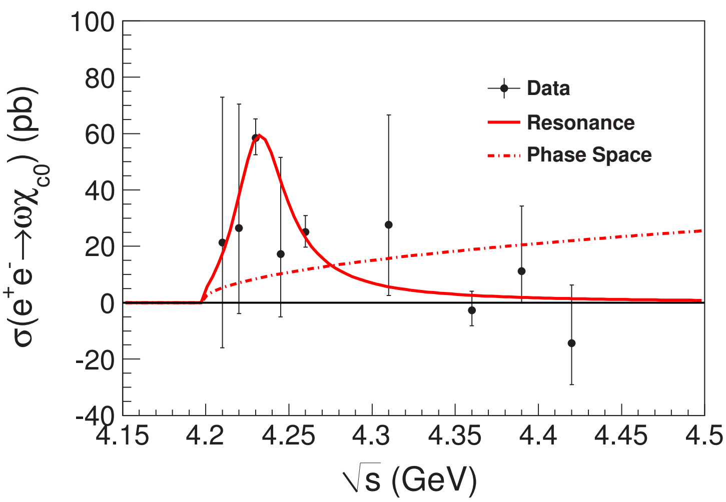

FIG. 8: Fit to $\sigma(e^+e^- \to \omega\chi_{c0})$ with a resonance (solid curve), or a phase space term (dot-dashed curve). Dots with error bars are the dressed cross sections. The uncertainties are statistical only.

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

Using data samples collected at energies from 3.81 to 4.60 GeV, BESIII performed an analysis of $e^+e^- \to \eta J/\psi$ [13]. Statistically significant η signals are observed and the corresponding Born cross sections are measured. In addition, the process $e^+e^- \to \pi^0 J/\psi$ is searched for, no significant signals are observed and the upper limits at the 90% C.L. on the Born cross section are set.

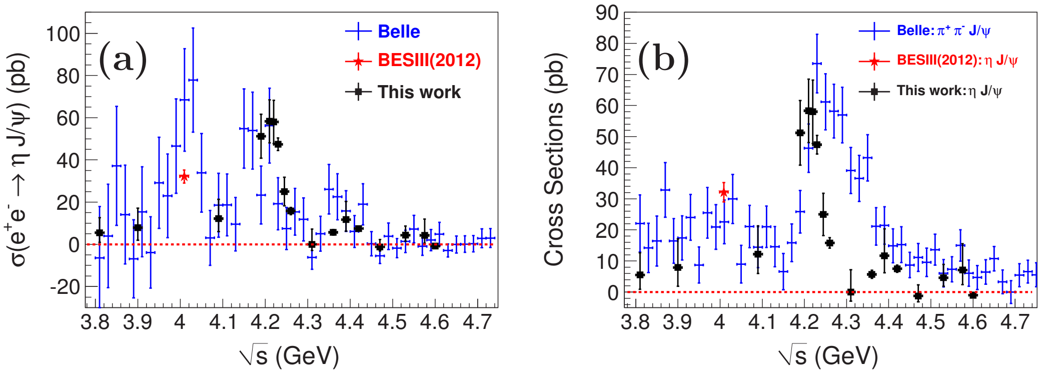

FIG. 9: A comparison of the measured Born cross sections of $e^+e^- \to \eta J/\psi$ to those of the previous measurements [38, 39] (a), and to those of $e^+e^- \to \pi^+\pi^- J/\psi$ from Belle [8]. In these two plots, the black square dots and the red star dots are the results of $\eta J/\psi$ obtained from BESIII. The blue dots are results of $\eta J/\psi$ (a) and $\pi^+\pi^- J/\psi$ (b) from Belle. The errors are statistical only for Belle's results, and are final combined uncertainties for BESIII's results.

A comparison of the Born cross sections $\sigma(e^+e^- \to \eta J/\psi)$ in this measurement to that of previous results [38, 39] is shown in Fig. 9 (a), and a very good agreement is achieved. The measured Born cross sections are also compared to that of $e^+e^- \to \pi^+\pi^- J/\psi$ obtained from Belle [8] as shown in Fig. 9 (b). Different line shapes are observed in these two processes, which indicate that the production mechanism of the $\eta J/\psi$ clearly differs from that of $\pi^+\pi^- J/\psi$ in the vicinity of $\sqrt{s}$ = 4.1-4.6 GeV. This could indicate the existence of a rich spectrum of Y states in this energy region with different coupling strengths to the various decay modes.

VII. MORE DATA FOR XYZ STUDY?

Although BESIII has achieved a lot in the study of the XYZ states as well as the conventional charmonium states, as has been shown in previous sections, there are also more questions to answer, with currently available data, and more importantly, with possible data samples BESIII can take in the next few years.

A few topics which need to be studied with more data are listed below.

- In the X sector:
  - Where are the $X(3872)$ and $\psi(1\,^3D_2)$ coming from, from resonance decays or from continuum production?

  - May the other X states, such as the XYZ(3940), $X(3915)$, $X(4140)$ (the $Y(4140)$), $X(4350)$ be produced in a similar way?
  - May the charmonium 2P, 3P states and the S-wave spin-singlet states (3S, 4S, 5S) be observed in radiative transitions?

- In the Y/ψ sector:
  - Is the $Y(4260)$ structure a single resonance, or it has more complicated sub-structure? Is the $Y(4008)$ a real resonance?
  - What are the other decay modes of the $Y(4360)$?
  - What are hidden in $e^+e^- \to \pi^+\pi^- h_c$ line shape?
  - Is the $Y(4660)$ observed in $e^+e^- \to \pi^+\pi^-\psi(2S)$ the same as the $Y(4630)$ observed in $e^+e^- \to \Lambda_c^+\Lambda_c^-$?
  - What is the correlation between charm production ($e^+e^- \to$ open charm final states) and the charmonium production?
  - Where is the vector charmonium $3D$ state?
  - Are there charmonium states between $\psi(4160)$ and $\psi(4415)$, and/or between $\psi(4415)$ and $Y(4660)$?
  - May the vector charmonium hybrid state be observed [40]?

- In the Z sector:
  - Are the Z_c states produced from resonance decays or from continuum production?
  - Is there a Z_{cs} state decaying into $K^\pm J/\psi$ or $D_sD^* + c.c.$, $D_s^*D + c.c.$?
  - Are there more Z_c and Z_{cs} states?

- In the C sector:
  - May the $D_{s0}(2317)$ be produced and studied?
  - May the other excited charmed mesons be produced and studied with high energy data?

BESIII is going to take about 3 fb^{-1} data in the vicinity of the $\psi(4160)$ for the study of the D_s decay properties. These data can be used for understanding part of the questions listed above. Here a few specific topics are listed.

1. In $e^+e^- \to \pi^+\pi^- J/\psi$ there is a dip at around 4.17 GeV and a sharp increase at around 4.23 GeV [8], the data may help to know where the turning point is.

2. For the $e^+e^- \to \omega\chi_{c0}$ [33], we are lack of data points close to threshold for claiming a narrow structure.

3. For the $e^+e^- \to K^+K^- J/\psi$, it seems there is a structure around 4.2 GeV [41].

4. In the $e^+e^- \to \eta J/\psi$, the line shape is different from $e^+e^- \to \pi^+\pi^- J/\psi$, with a peak at around 4.2 GeV, but there is no data point on the left side.

5. In $e^+e^- \to \eta h_c$, is there a structure close to threshold? What does $e^+e^- \to \eta' J/\psi$ line shape look like close to threshold?

6. Are the $e^+e^- \to \gamma\chi_{cJ}$ signals from $\psi(4160)$ or $Y(4260)$, or something else [28]?

7. Search for F-wave charmonium states via $\psi(4160)$ decays.

8. Search for $\gamma\chi_c(2P)$, γXYZ(3940), $\gamma X(3915)$ from $\psi(4160)$ decays.

The data are always the more the better, but as we need to take data at many data points and the data taking time is anyhow limited, we need to put lower limits on the number of data points and on the luminosity needed at one point to ensure meaningful measurement of the physics quantities of interest.

As we need the cross sections of all the open charm modes in high precision and the cross sections of some hadronic transition modes in fitting the resonant parameters of the vector states, we need to have enough data points to show the excitation curve of any of the existing vector resonances and possible still hidden structures in the full energy range.

Some special points need to be considered: (1) the thresholds of all the open charm and charmonium+hadron final states; (2) possible energy regions where large interference effect is expected; (3) energy regions where narrow structures are expected; (4) energy regions which were not well explored before; and (5) the beam energy spread.

As has been known from calculation and from measurements, the energy spread of the BEPCII at the energy range between 3.8 and 5.0 GeV is around 1.4 to 2.0 MeV. In this case, we would not use energy step finer than three times the energy spread, that is, unless very necessary, we would not take data at energy point less than 5 MeV from an existing data point. So we would take data with 5 MeV step in the energy regions we expect narrow structure or dramatic effect, such as the thresholds for open charm or hidden charm final states, and the low mass shoulder of the $Y(4260)$ where interference effect has been reported [8]. Otherwise, a 10 MeV step will be taken.

The limit on the data size is set according to the precision of the hadronic transition modes which typically have cross sections at a few to a few tens picobarn. From the analyses shown in previous sections, we find that the integrated luminosity of 500 pb^{-1} is needed to reach a reasonably high precision for most of the interested modes. To search for the XYZ and charmonium states via radiative transition, a data sample of at least 500 pb^{-1} is also needed to reach a 5σ level observation of a signal if the production rate is 1×10^{-4} or higher. Detailed MC study of the precision one can reach or the exact luminosity needed for each energy points is needed as the background levels may be very different at different resonant peak.

With the above principles keep in mind, we find a data sample at a few c.m. energies from 4.0 GeV to the maximum energy BEPCII can reach (so far it is 4.6 GeV), with 10 MeV step, and 500 pb^{-1} at each energy, will be desired for a comprehensive study of the XYZ and charmonium states. As BESIII has already accumulated about 5 fb^{-1} (see Table I), another 25 fb^{-1} data should be accumulated. This will take about 5 years at BEPCII [4].

VIII. XYZ STUDY AT FUTURE EXPERIMENTS

Belle-II [42] will start data taking in 2018 and will accumulate 50 ab^{-1} data at the $\Upsilon(4S)$ peak by 2024. This data sample can be used to study the XYZ and charmonium states in many different ways [1], among them ISR can produce events in the same energy range BESIII can cover. Figure 10 shows the effective luminosity at BEPCII energy in the Belle-II data sample. One can see that for 10 ab^{-1} Belle-II data, one can have about 400-500 pb^{-1} data every 10 MeV between 4 and 5 GeV, comparable to the data sample we proposed in previous section. Of course, the ISR analyses have a lower efficiency than in direct e^+e^- collision due to the extra ISR photons and the boost of the events along the beam direction. Even these effects are taken into account, the full Belle-II data sample which corresponds to about 2,000-2,300 pb^{-1} data every 10 MeV between 4 and 5 GeV will result in similar statistics for modes like $e^+e^- \to \pi^+\pi^- J/\psi$. There is an advantage at the Belle-II as the data at different energies are accumulated at the same time, the analysis is much simpler than at BESIII at 60 data points, and Belle-II can produce data above 4.6 GeV, the BEPCII maximum energy so far. Possible upgrade of BEPCII to increase the maximum c.m. energy will expand the physics reach of BESIII obviously.

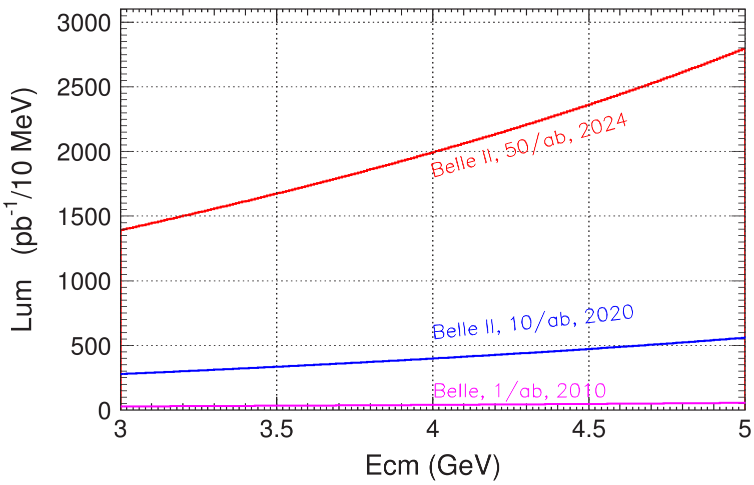

FIG. 10: Effective luminosity at low energy in the Belle and Belle-II data samples.

The HIEPA project [43] being discussed at this workshop will improve the forementioned studies in many aspects: c.m. energy up to 7 GeV, luminosity improves by a factor of 100. These will allow a finer scan in the full energy region with more integrated luminosity. This will allow a better understanding of all the studies we listed in previous sections.

IX. CONCLUSION

With the world largest data samples above 4 GeV, BESIII experiment made significant contribution to the study of the charmonium and the XYZ states. To further strengthen such studies, BESIII may take more data between 4.0 and 4.6 GeV (or even higher if possible), these data will be complimentary to the Belle-II study with many other production mechanisms. The HIEPA project is the hope of a systematic understanding of the natures of the XYZ as well as the charmonium states.

Acknowledgments

This work is supported in part by National Natural Science Foundation of China (NSFC) under contracts Nos. 11235011 and 11475187; the Ministry of Science and Technology of China under Contract No. 2015CB856701, and the CAS Center for Excellence in Particle Physics (CCEPP).

[1] A. J. Bevan *et al.* [BaBar and Belle Collaborations], Eur. Phys. J. C **74**, 3026 (2014).
[2] For a recent review, see N. Brambilla *et al.*, Eur. Phys. J. C **71**, 1534 (2011).
[3] M. Ablikim *et al.* [BESIII Collaboration], Nucl. Instrum. Methods Phys. Res., Sect. A **614**, 345 (2010).
[4] D. M. Asner *et al.*, Int. J. Mod. Phys. A **24**, S1 (2009).
[5] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **110**, 252001 (2013).
[6] M. Ablikim *et al.* [BESIII Collaboration], in prepration.
[7] M. Ablikim *et al.* [BESIII Collaboration], arXiv:1503.03408 [hep-ex].
[8] Z. Q. Liu *et al.* [Belle Collaboration], Phys. Rev. Lett. **110**, 252002 (2013).
[9] T. Xiao, S. Dobbs, A. Tomaradze and K. K. Seth, Phys. Lett. B **727**, 366 (2013).
[10] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **110**, 252001 (2013).
[11] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **112**, 022001 (2014).
[12] K. A. Olive *et al.* [Particle Data Group], Chin. Phys. C **38**, 090001 (2014).
[13] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **86**, 071101 (2012).
[14] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **111**, 242001 (2013).
[15] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **113**, no. 21, 212002 (2014).
[16] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **112**, 132001 (2014).
[17] M. Ablikim *et al.* [BESIII Collaboration], arXiv:1507.02404 [hep-ex].
[18] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **112**, 092001 (2014).
[19] Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meissner, Qian Wang and Qiang Zhao, Phys. Lett. B **725**, 127 (2013).
[20] C. Z. Yuan (for the Belle Collaboration), arXiv:0910.3138 [hep-ex]. We take 5% from the range presented in the paper of $2.3\% < \mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] < 6.6\%$ at 90% C.L.
[21] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **115**, no. 1, 011803 (2015).
[22] V. Bhardwaj *et al.* [Belle Collaboration], Phys. Rev. Lett. **111**, 032001 (2013).
[23] A. Kolmogorov, G. Inst. Ital. Attuari. **4**, 83 (1933).
[24] E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, and T. M. Yan, Phys. Rev. D **17**, 3090 (1978); Phys. Rev. D **21**, 203 (1980).
[25] T. Barnes, S. Godfrey and E. S. Swanson, Phys. Rev. D **72**, 054026 (2005).
[26] S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985); W. Kwong, J. Rosner, and C. Quigg, Annu. Rev. Nucl. Part. Phys. **37**, 343 (1987); D. Ebert, R. N. Faustov, and V. O. Galkin,

Phys. Rev. D **67**, 014027 (2003); E. J. Eichten, K. Lane, and C. Quigg, Phys. Rev. D **69**, 094019 (2004); M. Blank and A. Krassnigg, Phys. Rev. D **84**, 096014 (2011).
[27] C. F. Qiao, F. Yuan, and K. T. Chao, Phys. Rev. D **55**, 4001 (1997).
[28] M. Ablikim *et al.* [BESIII Collaboration], Chin. Phys. C **39**, no. 4, 041001 (2015).
[29] K. T. Chao, Z. G. He, D. Li, C. Meng, hep-ex/arXiv:1310.8597.
[30] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **91**, no. 3, 032002 (2015).
[31] T. Branz, T. Gutsche, V. E. Lyubovitskij, Phys. Rev. D **80**, 054019 (2009).
[32] T. Aaltonen *et al.* [CDF Collaboration], arXiv: 1101.6058.
[33] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **114**, no. 9, 092003 (2015).
[34] L. Y. Dai, M. Shi, G. Y. Tang, H. Q. Zheng, arXiv:1206.6911v2.
[35] Chang-Zheng Yuan, Chinese Physics C **38**, 043001 (2014).
[36] B. Aubert *et al.* [BaBar Collaboration]. Phys. Rev. Lett. **95**, 142001 (2005).
[37] L. Ma, X. H. Liu, X. Liu, S. L. Zhu, arXiv:1406.6879.
[38] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D. **86**, 071101(R) (2012).
[39] X. L. Wang *et al.* [Belle Collaboration], Phys. Rev. D. **87**, 051101(R) (2013).
[40] P. Guo, A. P. Szczepaniak, G. Galata, A. Vassallo and E. Santopinto, Phys. Rev. D **78**, 056003 (2008); J. J. Dudek and E. Rrapaj, Phys. Rev. D **78**, 094504 (2008).
[41] C. P. Shen *et al.* [Belle Collaboration], Phys. Rev. D **89**, no. 7, 072015 (2014).
[42] T. Abe *et al.* [Belle-II Collaboration], arXiv:1011.0352 [physics.ins-det].
[43] Z. G. Zhao, talk at the "International Workshop on Physics at Future High Intensity Collider 2-7 GeV in China", January 13-16, 2015, University of Science and Technology of China (USTC), Hefei, China.