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Observation of charmonium-like structure in $\pi\pi\psi(3686)$ at BESIII

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Summary. — Based on data samples of 5.2 fb^{-1} collected with the BESIII detector operating at the BEPCII collider with center-of-mass energies ($\sqrt{s}$) from 4.009 to 4.600 GeV, the processes $e^+e^- \to \pi^+\pi^-\psi(3686)$ and $e^+e^- \to \pi^0\pi^0\psi(3686)$ are studied. The Born cross sections are measured. A charmonium-like structure around 4040 MeV/c^2 is observed in the $\pi\psi(3686)$ invariant mass spectrum.

1. – Introduction

The vector (1^{--}) charmonium-like Y-states, $Y(4360)$, were firstly observed and subsequently confirmed in the process $e^+e^- \to (\gamma_{ISR})\pi^+\pi^-\psi(3686)$ by BaBar, Belle experiments [1, 2]. Like others Y-family states, *e.g.*, $Y(4260)$ observed in the process $e^+e^- \to (\gamma_{ISR})\pi^+\pi^- J/\psi$ [3-5], the nature of $Y(4360)$ has remained mysterious. It is natural to study $Y(4360)$ in the process of $\pi\pi$ transition to $\psi(3686)$. In recent years, a new pattern of charmonium-like states, the $Z_c^{\pm}$'s, was observed in the systems of a charged pion and a low mass charmonium state [5-8], as well as in charmed mesons pairs [9-11]. By analogy, it is interesting to search for Z_c in $e^+e^- \to \pi\pi\psi(3686)$ processes.

In the paper, we study the processes $e^+e^- \to \pi^+\pi^-\psi(3686)$ and $e^+e^- \to \pi^0\pi^0\psi(3686)$ at center-of-mass energies ($\sqrt{s}$) from 4.009 to 4.600 GeV. For the charged process $e^+e^- \to \pi^+\pi^-\psi(3686)$, $\psi(3686)$ is reconstructed with two modes, $\psi(3686) \to \pi^+\pi^- J/\psi$ (mode I) and $\psi(3686) \to$ neutrals $+ J/\psi$ (mode II) where mode II includes processes $\psi(3686) \to \pi^0\pi^0 J/\psi$, $\psi(3686) \to \pi^0 J/\psi$, $\psi(3686) \to \eta J/\psi$, and $\psi(3686) \to \gamma\chi_{cJ} \to \gamma\gamma J/\psi$. For the neutral process $e^+e^- \to \pi^0\pi^0\psi(3686)$, $\psi(3686)$ is reconstructed with $\psi(3686) \to \pi^+\pi^- J/\psi$.

Now BESIII have the preliminary results.

2. – Cross section measurement

To extract the number of $\pi^+\pi^-\psi(3686)$, the $\psi(3686)$ mass spectrum is fitted using the MC simulated signal shape convoluted with a Gaussian function, together with a linear background for all the 16 c.m. energies for the charged channel. For the neutral

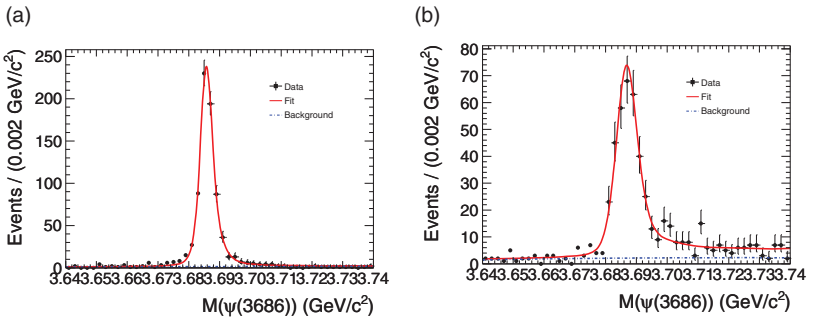

Fig. 1. – The distribution of $M(\psi(3686))$ in data at $\sqrt{s} = 4.42\,\text{GeV}$, for (a) mode I, which is the closest $\pi^+\pi^- J/\psi$ combination to $\psi(3686)$ PDG mass after performing 5C or 2C kinematic fit, and (b) mode II, which is the recoil mass of $\pi^+\pi^-$ candidates. Dots with error bars are data and the curves are the fit described in the text.

channel, the $\psi(3686)$ mass spectrum is described with MC simulated shapes of $e^+e^- \to \pi^0\pi^0\psi(3686)$ and $e^+e^- \to \pi^+\pi^-\psi(3686)$, together with a linear background. The fits to data are shown in figs. 1, 2.

The Born cross section is calculated from

$$\sigma^B = \frac{N^{obs}}{\mathcal{L}_{int}\ (1+\delta^r)\ (1+\delta^v)\ \mathcal{B}r\ \epsilon}, \tag{1}$$

where $\mathcal{L}_{int}$ is the integrated luminosity, $(1+\delta^r)$ is the ISR correction factor, $(1+\delta^v)$ is the vacuum polarization factor, $\mathcal{B}r$ is the product of the branching fraction in the decay chain, and ϵ is the detection efficiency.

The comparison of the results with previous experimental results are shown in fig. 3.

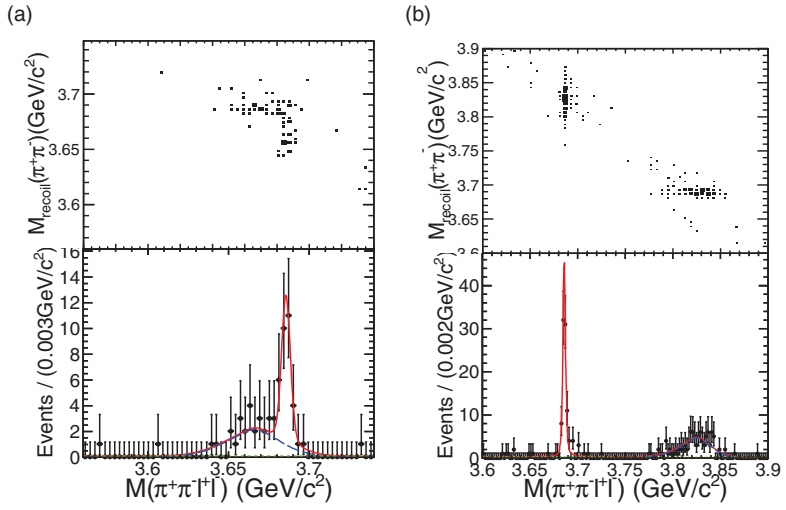

Fig. 2. – Scatter plot of $M_{recoil}(\pi^+\pi^-)$ *vs.* $M(\pi^+\pi^- l^+ l^-)$ (top) and the $M(\pi^+\pi^- l^+ l^-)$ spectrum (bottom). Dots with error bars are data; the solid curves show the results of the best fit; the long dashed (blue) curves for the background $e^+e^- \to \pi^+\pi^-\psi(3686)$; the short dashed (green) curves for the other backgrounds. Different columns represent data at $\sqrt{s} =$ (a) 4.258, (b) 4.416 GeV, respectively.

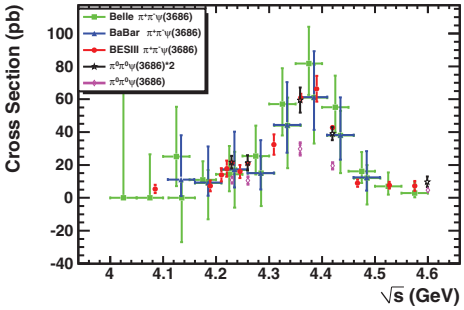

Fig. 3. – The lineshape of $e^+e^- \to \pi\pi\psi(3686)$ in the range 4.009–4.600 GeV, the dots in red represent the measurement of charged channel from this analysis, the pink diamond is the measurement of neutral channel from this analysis, the square in green is the measurement from BELLE experiment, and the triangle in blue is the measurement from BABAR experiment.

3. – Study of intermediate states

To extract the parameters of $Z_c(4040)$ at 4.26 GeV, 4.36 GeV and 4.42 GeV, an unbinned maximum likelihood fit is performed on the Dalitz plots of $M^2(\pi_1\psi(3686))$ *vs.* $M^2(\pi_2\psi(3686))$ (denoted as x and y in eq. (2), respectively) to extract the properties of observed structure at $\sqrt{s} = 4.416$ GeV.

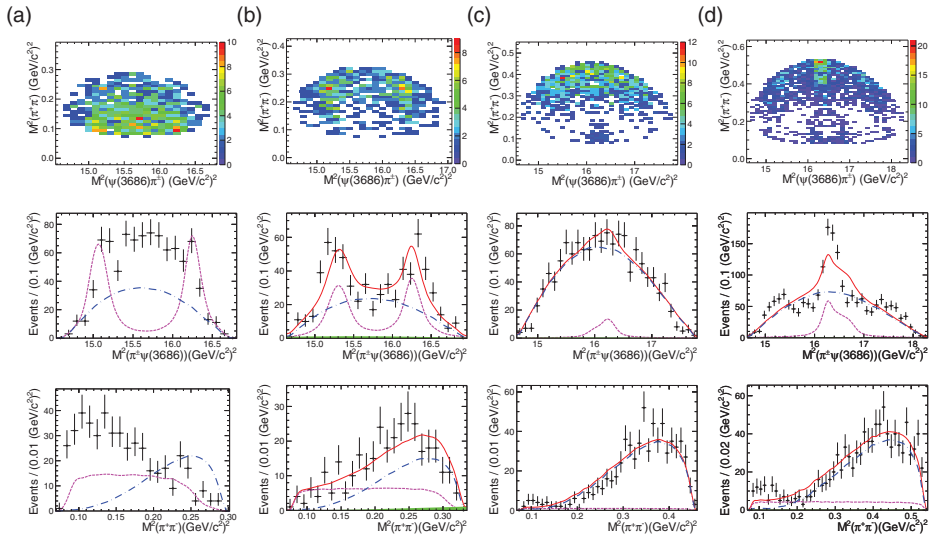

Fig. 4. – The Dalitz plots $M^2(\pi^+\pi^-)$ *vs.* $M^2(\pi^\pm\psi(3686))$ (top row) as well as the distributions of $M^2(\pi^\pm\psi(3686))$ (middle row) and of $M^2(\pi^+\pi^-)$ (bottom row) for the data samples at $\sqrt{s} = 4.226$ (column a), 4.258 (column b), 4.358 (column c), and 4.416 (column d) GeV. Dots with error bars are data. For plots at $\sqrt{s} = 4.226$ GeV, the dashed (pink) and dash-dotted (blue) curves show the shapes from intermediate state and direct process $e^+e^- \to \pi^+\pi^-\psi(3686)$ obtained from the JPIPI MC model (with arbitrary scale). For plots at 4.258, 4.358, 4.416 GeV, the solid curves (red) are projections from the fit; the dashed curves (pink) show the shape of the intermediate state; the dash-dotted curves (blue) show the shape from the direct process $e^+e^- \to \pi^+\pi^-\psi(3686)$; the shaded histograms (green) show the non-$\psi(3686)$ background estimated with the $\psi(3686)$ sideband. In all plots, the two $\psi(3686)$ decay modes are combined.

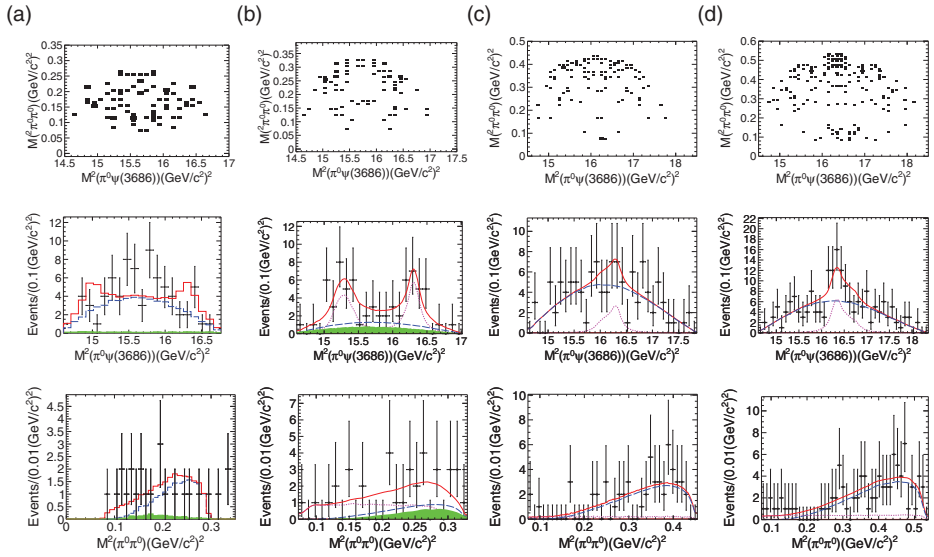

Fig. 5. – The Dalitz distributions $M^2(\pi^0\pi^0)$ *vs.* $M^2(\pi^0\psi(3686))$ (top row) as well as the distributions of $M^2(\pi^0\psi(3686))$ (middle row) and of $M^2(\pi^0\pi^0)$ (bottom row) for the data samples at $\sqrt{s} = 4.226$ (column a), 4.258 (column b), 4.358 (column c), and 4.416 (column d) GeV. Dots with error bars are data. For plots at $\sqrt{s} = 4.226\,\text{GeV}$, the red solid lines are the distributions for intermediate states, the blue dashed lines for the process $e^+e^- \to \pi^0\pi^0\psi(3686)$ simulated with the JPIPI model (both with an arbitrary scale). For plots at 4.258, 4.358, 4.416 GeV, the solid curves (red) are projections from the fit; the short dashed curves (pink) show the shape of the intermediate states; the long dashed curves (blue) show the shape from the direct process $e^+e^- \to \pi^0\pi^0\psi(3686)$. The green shaded histograms are for the background $e^+e^- \to \pi^+\pi^-\psi(3686)$ estimated with MC simulation.

In the fit, the Z_c signal is described with a S-wave Breit-Wigner function which can be parameterized with

$$\epsilon(x,y)\cdot\left(\frac{p\cdot q}{(M_R^2-x)^2+M_R^2\cdot\Gamma^2}+\frac{p\cdot q}{(M_R^2-y)^2+M_R^2\cdot\Gamma^2}\right)\otimes\sigma(x,y), \tag{2}$$

where $\sigma(x,y)$ is a 2-dimensional Gaussian function representing the mass resolution and its parameters are extracted from the MC simulation. $\epsilon(x,y)$ is a 2-dimensional detection efficiency plane extracted from phase space (PHSP) MC simulation. p or q is the momentum of $\psi(3686)$ or Z_c in the $\pi\psi(3686)$ or the initial e^+e^- rest frame, respectively.

The PDF of the process $e^+e^- \to \pi\pi\psi(3686)$ without an intermediate state is taken from the JPIPI model MC simulation, and that of the non-$\psi(3686)$ background is described with the distribution of events in the $\psi(3686)$ sideband region.

For the charge channel, the fit yields a mass of $M_R = (4032.1 \pm 2.4)\,\text{MeV}/c^2$ and a width of $\Gamma = (26.1 \pm 5.3)\,\text{MeV}$ and a significance of 9.2σ. For the neutral channel, the fit with a width fixed to that of the charged structure observed in $e^+e^- \to \pi^+\pi^-\psi(3686)$ yields a mass of $M_R = (4038.7 \pm 6.5)\,\text{MeV}/c^2$ and a significance of 6.0σ.

Similar fits are carried out to the data samples at $\sqrt{s} = 4.258$ and 4.358 GeV, respectively, where the parameters of the charmonium-like state are fixed to those obtained in the data sample at $\sqrt{s} = 4.416\,\text{GeV}$. The fits to data are shown in figs. 4, 5.

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