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Hadron Spectroscopy at BESIII

Shuangshi FANG (for the BESIII collaboration)

Institute of High Energy Physics, Beijing, China

Abstract

The BESIII detector has collected the largest data samples around $\tau - charm$ energy region since the upgrade was completed in 2008. The hadron spectroscopy, as one of the main physics goals, was extensively studied and many important progresses were achieved these years. In this report the recent results on the study of hadron spectroscopy were presented, including the light hadron spectroscopy and the observations of the charmonium-like Z_c particles.

Keywords: the BESIII detector, hadron spectroscopy, charmonium decays

1. Introduction

A precise determination of the hadron spectroscopy would help us understand the substructure of observed hadrons and verify the theory, Quantum Chromodynamics (QCD), for describing the strong interactions. In addition, the hadron spectroscopy also provides informations for those particles beyond the quark model, e.g., glueballs, hybrids and multiquark states, which are expected from the QCD. In the last decays, considerable progresses on the hadron spectroscopy have been made, in particular the new observations from the BESII and the XYZ particles from Belle and BaBar, from the charmonium (or charm) and bottomium (or B meson) decays in e^+e^- annihilation decays.

Since the upgrade was completed in 2008, the BESIII detector [1], has collected the world's largest data samples at τ-charm energy region including 1.3 billion J/ψ events, 4.5 million $\psi(3686)$ events, 2.9 fb^{-1} at the peak of the $\psi(3770)$ resonance, and 1.8 fb^{-1} around the peak of the Y(4260) resonance, which offers us a unique opportunity to study the hadron spectroscopy and search for the new hadrons. In this talk I present a brief review about the recent results that have been obtained from these data samples.

2. Light hadron spectroscopy

2.1. The structures around 1.85 GeV observed in J/ψ radiative decays

In 2003 BESII reported the first observation of $p\bar{p}$ mass threshold enhancement in $J/\psi \rightarrow \gamma p\bar{p}$, which attracted both experimental and theoretical attentions to investigate its nature. Using the 225×10^6 J/ψ events collected by the BESIII detector in 2009, a Partial Wave Analysis (PWA) of $J/\psi \rightarrow \gamma p\bar{p}$ [2] with $M_{p\bar{p}} < 2.2$ GeV/c^2 was performed to determine its spin-parity, mass and width. In the analysis, the final state interactions were considered by including the Julich formulation [3]. The PWA results indicate that the 0^{-+} assignment fit for this structure is better than that for 0^{++} or other J^{PC} assignments. The mass, width and product branching fraction of the $X(p\bar{p})$ are measured to be $M = 1832^{+19+18}_{-5-17} \pm 19$ (model) MeV$/c^2$, $\Gamma = 13 \pm 39^{+10}_{-13} \pm 4$ (model) MeV (a total width of $\Gamma <$ 76 MeV$/c^2$ at the 90% C.L.) and $B(J/\psi \rightarrow \gamma X)B(X \rightarrow p\bar{p}) = (9.0^{+0.4+1.5}_{-1.1-5.0} \pm 2.3\ (\text{model})) \times 10^{-5}$, respectively.

We also observed the structures around 1.85 GeV in the other J/ψ decays, X(1835) in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ [4], X(1870) in $J/\psi \rightarrow \omega\pi^+\pi^-\eta$ [5]. To search for their new decays, the $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$ [6] is analyzed using the 225.3 million J/ψ events taken at the BESIII detector in 2009, and a structure, X(1840), is observed. Fig. 1 (a) shows the $3(\pi^+\pi^-)$ invariant mass spectrum in $J/\psi \rightarrow$

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$\gamma 3(\pi^+\pi^-)$ and the fit gives M= $1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV/c^2 and $\Gamma = 83 \pm 14 \pm 11$ MeV with a statistical significance of 7.6σ. The product branching fraction is determined to be $B(J/\psi \to \gamma X(1840))B(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36^{+0.60}_{-0.74}) \times 10^{-5}$.

A study of the doubly OZI suppressed decays of $J/\psi \to \gamma\omega\phi$ [7] is performed and a strong deviation ($> 30\sigma$) from three-body $J/\psi \to \gamma\omega\phi$ phase space is observed near the $\omega\phi$ mass threshold. Assuming that the enhancement is due to the presence of a resonance $X(1810)$, A PWA with a tensor covariant amplitude found that its spin-parity is 0^{++} and the resonance parameters are determined to be: $M = 1795 \pm 7^{+13}_{-5} \pm 19$(model) MeV/$c^2$ and $\Gamma = 95 \pm 10^{+21}_{-34} \pm 75$(model) MeV, which are consistent with the previous work from BESII [8].

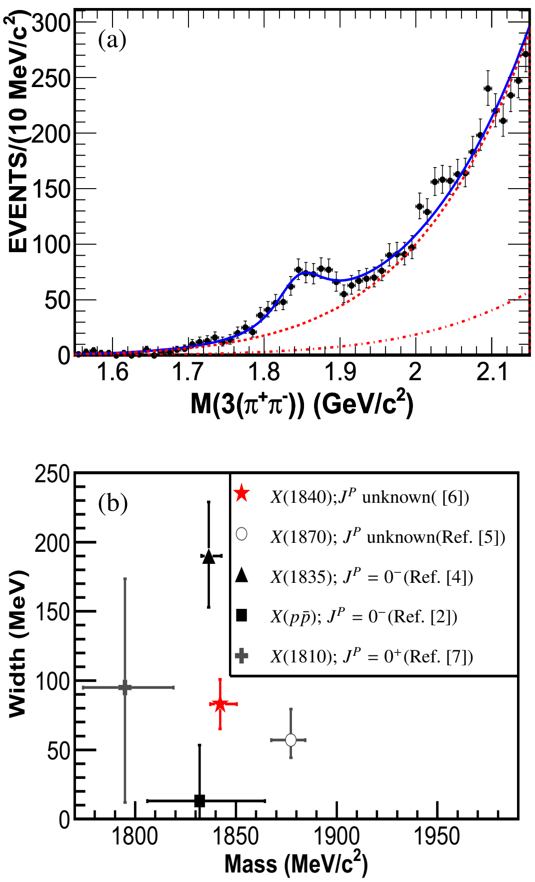

Figure 1: The fit of mass spectrum of $3(\pi^+\pi^-)$ (a) and comparisons of observations at BESIII. The error bars include statistical, systematic, and, where applicable, model uncertainties (b).

The comparison to the BESIII results of the masses and widths of the $X(p\bar{p})$, $X(1835)$, $X(1870)$, X(1840) and $X(1810)$ are displayed in Fig. 1 (b). The mass of $X(1840)$ is in agreement with $X(p\bar{p})$, while its width is significantly broader. Therefore, based on these data, one cannot determine whether $X(1840)$ is a new state or the signal of a $3(\pi^+\pi^-)$ decay mode of $X(p\bar{p})$. Further study, including an amplitude analysis to determine the spin and parity of the $X(1840)$, is needed to establish the relationship between these experimental observations.

2.2. PWA of $J/\psi \to \gamma\eta\eta$ [9]

For $J/\psi \to \gamma\eta\eta$, the PWA results shown in Fig. 2 indicate that the scalar contributions are mainly from $f_0(1500)$, $f_0(1710)$ and $f_0(2100)$, while no evident contributions from $f_0(1370)$ and $f_0(1790)$ are seen. Recently, the production rate of the pure gauge scalar glueball in J/ψ radiative decays predicted by the lattice QCD [10] was found to be compatible with the production rate of J/ψ radiative decays to $f_0(1710)$; this suggests that $f_0(1710)$ has a larger overlap with the glueball compared to other glueball candidates (e.g., $f_0(1500)$). In this analysis, the production rates of $f_0(1710)$ and $f_0(2100)$ are both about one order of magnitude larger than that of the $f_0(1500)$, which are consistent with, at least not contrary to, lattice QCD predictions. The tensor components, which are dominantly from $f_2'(1525)$, $f_2(1810)$ and $f_2(2340)$, also have a large contribution in $J/\psi \to \gamma\eta\eta$ decays. The significant contribution from $f_2'(1525)$ is shown as a clear peak in the $\eta\eta$ mass spectrum; a tensor component exists in the mass region from 1.8 GeV/c^2 to 2 GeV/c^2, although we cannot distinguish $f_2(1810)$ from $f_2(1910)$ or $f_2(1950)$; and the PWA requires a strong contribution from $f_2(2340)$, although the possibility of $f_2(2300)$ cannot be ruled out.

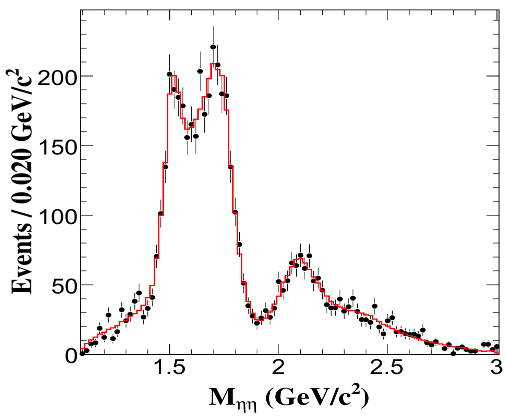

Figure 2: The invariant mass of $\eta\eta$ (dots with error bars) and the PWA fit projections (histogram).

2.3. PWA of $\psi(3686) \to p\bar{p}\pi^0$ [11]

To search for new excited N^* baryons, we performed a PWA of $\psi(3686) \to p\bar{p}\pi^0$ and found that the dominant contributions are from 7 N^* intermediate resonances. Among these N^* resonances, two new resonances are significant, one $1/2^+$ resonance with a mass of $2300^{+40+109}_{-30-0}$ MeV/c^2 and width of $340^{+30+110}_{-30-58}$ MeV, and one $5/2^-$ resonance with a mass of 2570^{+19+34}_{-10-10} MeV/c^2 and width of 250^{+14+69}_{-24-21} MeV. For the remaining 5 N^* intermediate resonances, the mass and width values from the PWA shown in Table. 1 are consistent with those from established resonances.

Table 1: Summary of the PWA results for $\psi' \to p\bar{p}\pi^0$.

Resonance	M(MeV/c^2)	Γ(MeV/c^2)
$N(1440)$	1390^{+11+21}_{-21-30}	$340^{+46+70}_{-40-156}$
$N(1520)$	1510^{+3+11}_{-7-9}	115^{+20+0}_{-15-40}
$N(1535)$	1535^{+9+15}_{-8-22}	120^{+20+0}_{-20-42}
$N(1650)$	1650^{+5+11}_{-5-30}	150^{+21+14}_{-22-50}
$N(1720)$	1700^{+30+32}_{-28-35}	$450^{+109+149}_{-94\ -44}$
$N(2300)$	$2300^{+40+109}_{-30-0}$	$340^{+30+110}_{-30-58}$
$N(2570)$	2570^{+19+34}_{-10-10}	250^{+14+69}_{-24-21}

2.4. Observation of $\eta' \to \pi^+\pi^-\pi^{+(0)}\pi^{-(0)}$ [12] and $\eta' \to \gamma\gamma\pi^0$

Based on a sample of 1.3 billion J/ψ events taken with the BESIII detector, we report the first observation of $\eta' \to \pi^+\pi^-\pi^{+(0)}\pi^{-(0)}$ decays via J/ψ radiative decays. Fig. 3(a) and Fig. 3(b) show the $M_{\pi^+\pi^-\pi^+\pi^-}$ and $M_{\pi^+\pi^-\pi^{+(0)}\pi^{-(0)}}$, respectively, where the η' peaks are clearly observed and the dominant background events are from the other η' decays, but none of them contribute to the η' peak. The branching fractions are determined to be $B(\eta' \to \pi^+\pi^-\pi^+\pi^-)=(8.63\pm0.69\pm0.64)\times10^{-5}$ and $B(\eta' \to \pi^+\pi^-\pi^0\pi^0)= (1.82 \pm 0.35 \pm 0.18) \times 10^{-4}$, which are consistent with the theoretical predictions based on the combination of chiral perturbation theory (ChPT) and vector-meson dominance [13], but could rule out the broken-$SU_6 \times O_3$ quark model.

In addition we also observed the $\eta' \to \gamma\gamma\pi^0$ for the first time coming from $J/\psi \to \gamma\eta'$. The clear η' peak is seen in the $\gamma\gamma\pi^0$ mass spectrum shown in Fig. 4. MC study indicates that the peaking background events mainly come from $\eta' \to \gamma\omega(\rho)$ with $\omega(\rho) \to \gamma\pi^0$. The preliminary result is determined to be $B(\eta' \to \gamma\gamma\pi^0) = (6.91 \pm 0.51 \pm 0.54) \times 10^{-4}$.

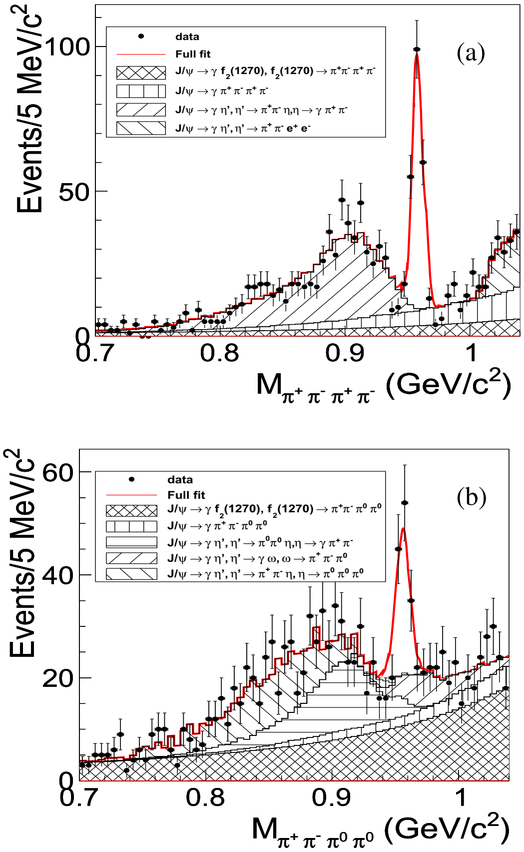

Figure 3: The invariant mass distributions of (a) $\pi^+\pi^-\pi^+\pi^-$ and (b) $\pi^+\pi^-\pi^0\pi^0$ and the fit results .

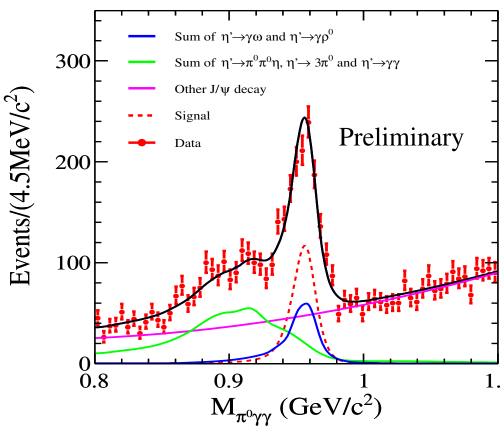

Figure 4: The invariant mass distributions of $\gamma\gamma\pi^0$ and the fit results.

3. Charmonium-like Z_c particles

3.1. Observation of $Z_c(3900)$ [14]

Using 525 pb^{-1} data sample taken at a center-of-mass energy of 4.260 GeV, we reported the observation of a prominent resonance-like charged structure, $Z_c(3900)$, in the $\pi^{\pm}J/\psi$ invariant mass distribution for $e^+e^- \to \pi^+\pi^-J/\psi$ events. With a S-wave Breit-Wigner (BW) function, a fit to the distribution of $M_{\max}(\pi^{\pm}J/\psi)$ [Fig. 5], the larger one of the two mass combinations $M(\pi^+J/\psi)$ and $M(\pi^-J/\psi)$ in each event, yields $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c^2 and $\Gamma = 46 \pm 10 \pm 20$ MeV. Shortly after the BESIII announcement, it was confirmed by the Belle [15] and CLEO [16]. This structure couples to charmonium and has an electric charge, which implies a state containing more quarks than just a charm and anti-charm quark.

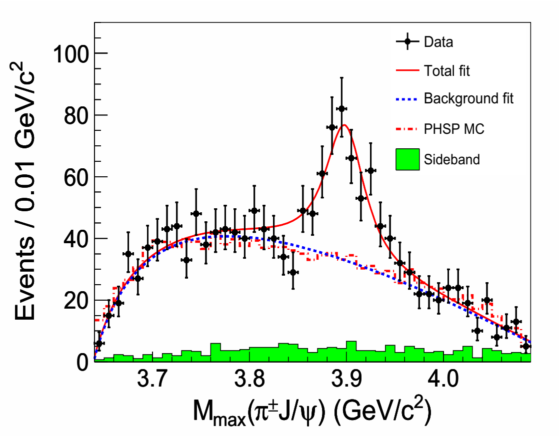

Figure 5: Fit to the $M_{max}(\pi^{\pm}J/\psi)$.

To investigate its isopsin, the $e^+e^- \to \pi^0\pi^0J/\psi$ was performed to search for its neutral partner. Evidence for a neutral $Z_c(3900)$ was observed in $e^+e^- \to \pi^0\pi^0J/\psi$ using the data taken at the center of mass energies of 4.230 GeV, 4.260 GeV and 4.360 GeV, respectively. A neutral structure, the $Z_c^0(3900)$ is seen in the π^0J/ψ mass spectra, take $M_{\pi^0J/\psi}$ for 4.230 GeV data shown in Fig. 6 for example. By combining all data samples, the significance is greater than 10σ. The mass and width are obtained to be $M = 3894.8 \pm 2.3$ MeV/c^2 and $\Gamma = 29.6 \pm 8.2)$ MeV, where the errors are statistical only. The preliminary results are in good agreement with those of the $Z_c^{\pm}$ obtained from $e^+e^- \to \pi^+\pi^-J/\psi$.

3.2. Observation of $Z_c(3885)$ [17]

The $Z_c(3900)$ mass is ~20 MeV/c^2 above the $D\bar{D}^*$ mass threshold, which is suggestive of a virtual $D\bar{D}^*$

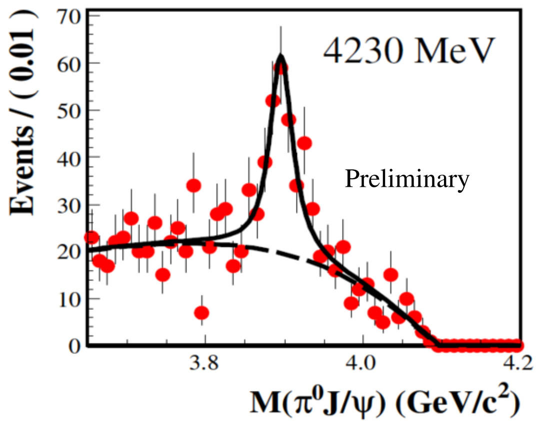

Figure 6: Fit to $\pi^0 J/\psi$ mass spectrum.

molecule-like structure, a charmed-sector analog of the $Z_b(1610)$. Therefore, it is important to measure the rate for $Z_c(3900)$ decays to $D\bar{D}^*$ and compare it to that of the $\pi J/\psi$.

We performed a study of the process $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$ at $\sqrt{s} = 4.26$ GeV with a 525 pb^{-1} data sample collected with the BESIII detector. The $\pi^+(D\bar{D}^*)^-$ final states are selected by means of a partial reconstruction technique in which only the bachelor π^+ and one final-state D meson are detected, and the presence of the $\bar{D}^*$ is inferred from energy-momentum conservation. The D mesons are reconstructed in the $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decay channels. A distinct charged structure, denoted as $Z_c(3885)$, is observed in the $(D\bar{D}^*)^{\mp}$ invariant mass distribution shown in Fig. 7 (a) and Fig. 7 (b). When fitted to a Breit-Wigner lineshape, the pole mass and width are determined to be $M_{\rm pole} = 3883.9 \pm 1.5 \pm 4.2$ MeV/c^2 and $\Gamma_{\rm pole} = 24.8 \pm 3.3 \pm 11.0$ MeV. The mass and width of $Z_c(3885)$ are 2σ and 1σ, respectively, below those of the $Z_c(3900)$. To investigate its spin-parity, we analyzed the angular distribution of $|\cos\theta_\pi|$ and found it favours a $J^P = 1^+$ quantum number assignment.

3.3. Observation of $Z_c(4020)$ [18, 19]

To search for the new decay modes of $Z_c(3900)$, we performed the study of $e^+e^- \to \pi^+\pi^-h_c$ using the data samples taken at center-of-mass energies from 3.90 GeV to 4.42 GeV. The $h_c \to \gamma\eta_c$ is reconstructed with η_c's 16 exclusive decay modes. The $M_{\pi^{\pm}h_c}$ distribution summed over the 16 η_c decay modes is shown in Fig. 8, where a narrow structure, referred to as $Z_c(4020)$, is clearly seen, but no significant $Z_c(3900)$ signal is observed. Similar to $Z_c(3900)$, the $Z_c(4020)$ also carries

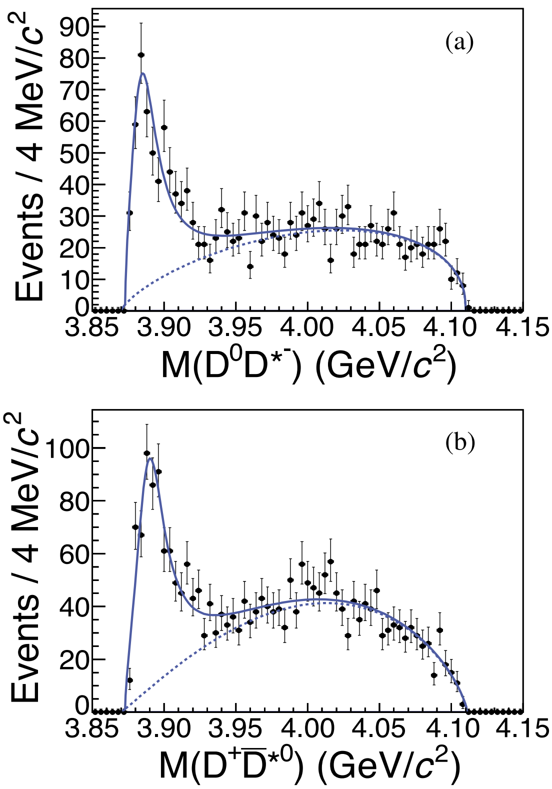

Figure 7: Fit to the $M(D^0D^{*-})$ (a) and $M(D^+\bar{D}^{*0})$ (b).

an electric charge and couples to charmonium. A fit to the $\pi^{\pm}h_c$ invariant mass spectrum gives $M = (4022.9 \pm 0.8 \pm 2.7)$ MeV/c^2 and $\Gamma = (7.9 \pm 2.7 \pm 2.6)$ MeV, respectively, with a statistical significance of greater than 8.9σ.

Table 2: Energies ($\sqrt{s}$) and born cross section ratios $\mathcal{R}_{\pi Z_c(4020)}$.

$\sqrt{s}$ (GeV)	$R_{\pi Z_c(4020)}$
4.230	$0.77 \pm 0.31 \pm 0.25$
4.260	$1.21 \pm 0.50 \pm 0.38$
4.360	$1.00 \pm 0.48 \pm 0.32$

Most recently we reported the evidence of a netural $Z_c(4020)$ [19] in the process $e^+e^- \rightarrow \pi^0\pi^0h_c$. A fit to the π^0h_c invariant mass spectrum shown in Fig. 9 with the width of the $Z_c^{\pm}(4020)$ fixed to that of its charged isospin partner and possible interferences with non-$Z_c^{\pm}(4020)$ amplitudes neglected, gives a mass of $(4023.9 \pm 2.2 \pm 3.8)$ MeV/c^2 for the $Z_c^0(4020)$. The ratios of Born cross section for $e^+e^- \rightarrow \pi Z_c(4020) \rightarrow \pi\pi h_c$ between neutral and charged modes, $\mathcal{R}_{\pi Z_c(4020)} = \frac{\sigma(e^+e^-\rightarrow\pi^0Z_c^0(4020)\rightarrow\pi^0\pi^0h_c)}{\sigma(e^+e^-\rightarrow\pi^{\pm}Z_c^{\mp}\rightarrow\pi^{\pm}\pi^{\mp}h_c)}$, at three center-of-mass energies are listed in Table 2.

The measured Born cross sections are about half of those for $e^+e^- \rightarrow \pi^+\pi^-h_c$, and agree with expectations based on isospin symmetry within systematic uncertainties, which indicate that there is no anomalously large isospin violations in $\pi\pi h_c$ and $\pi Z_c(4020)$ system.

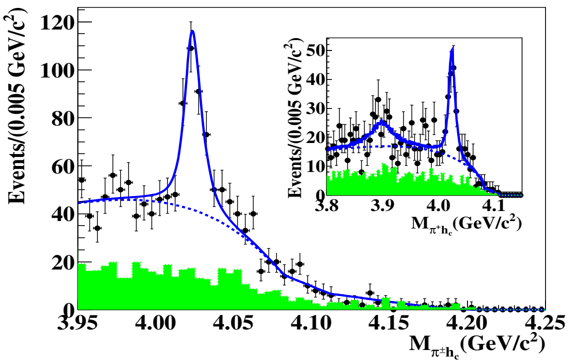

Figure 8: Fit to $M_{\pi^{\pm}h_c}$, where the inset shows the sum of the simultaneous fit to the $M_{\pi^{+}h_c}$ distributions at 4.23 GeV and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$.

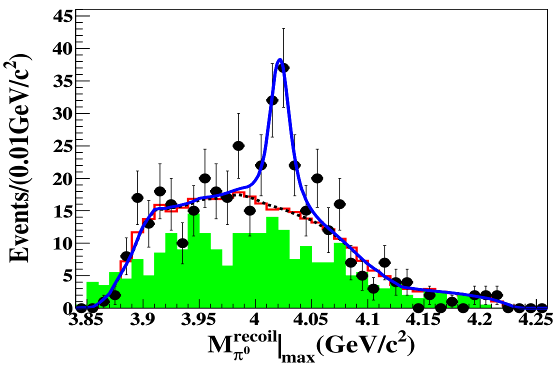

Figure 9: Fit to π^0 recoil mass spectrum.

3.4. Observation of $Z_c(4025)$ [20]

The narrow $Z_c(4020)$ observed in $e^+e^- \rightarrow \pi^+\pi^-h_c$ is very close to $D^*\bar{D}^*$ mass threshold. Therefore, a search of Z_c candidates via their direct decays into $D^*\bar{D}^*$ pairs is strongly motivated. Based on a 827 pb^{-1} data sample taken at a center-of-mass energy of 4.26 GeV, we presented the study of the process $e^+e^- \rightarrow (D^*\bar{D}^*)^{\pm}\pi^{\mp}$.

A structure near the $(D^*\bar{D}^*)^{\pm}$ threshold, denoted as the $Z_c(4025)$, is seen in the mass spectrum recoiling against $\pi^{\mp}$[Fig. 10]. An unbinned maximum likelihood fit to the spectrum of $RM(\pi^-)$ results in a mass of $(4026.3 \pm 2.6 \pm 3.7)$ MeV/c^2 and a width of $(24.8 \pm 5.6 \pm 7.7)$ MeV. After taking into account the systematic uncertainties, the statistical significance is larger than 10σ.

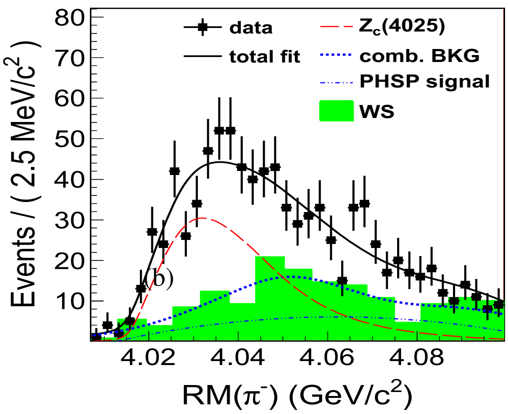

Figure 10: Fit to the π^- recoil mass spectrum.

Table. 3 gives a summary of the charmonium-like Z_c states observed at BESIII. For both $Z_c^{\pm}(3900)$ and $Z_c^{\pm}(4020)$, their neutral partners are evident, which indicates they are the isospin triplets and shows a hint of a new hadron spectroscopy; $Z_c(3900)$ and $Z_c(4020)$ are close to the $D\bar{D}^*$ and $D^*\bar{D}^*$mass threshold, respectively. Of great interest is the similar structures are also seen in the $D\bar{D}^*$ and $D^*\bar{D}^*$ mass spectrum though the mass and width are not consistent well with those by fitting the mass spectrum of $\pi J/\psi$ and πh_c, which inspired many speculations on their natures. However, based on these data, one cannot determine whether $Z_c(3900)$ and $Z_c(3885)$ ($Z_c(4020)$ and $Z_c(4025)$) are the same state or not. Further study, including an amplitude analysis to determine the spin and parity of them, is needed to establish the relationship between different experimental observations in this mass region and determine the nature of these structures.

Table 3: Summary of the charmonium-like Z_c states at BESIII.

$Z_c \rightarrow$	M(MeV/c^2)	Γ(MeV)
$\pi^{\pm} J/\psi$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$
$\pi^0 J/\psi$	3894.8 ± 2.3 (Prel.)	29.6 ± 8.2 (Prel.)
$(D\bar{D}^*)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$\pi^{\pm} h_c$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$
$\pi^0 h_c$	$4023.9 \pm 2.2 \pm 3.8$	
$(D^*\bar{D}^*)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$

4. Summary

Based on the data samples taken at the peak of J/ψ, $\psi(3686)$ and around $\Upsilon(4260)$, the recent progresses on the hadron spectroscopy are reported in this talk.

For the light hadron spectroscopy, besides the confirmation of the $p\bar{p}$ mass threshold enhancement, $X(1835)$ and $X(1810)$ in J/ψ radiative decays, another structure around 1.84 GeV, X(1840), is observed in $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$; the two new excited nucleon states, $N(2300)$ and $N(2570)$, are found in $\psi(3686) \rightarrow p\bar{p}\pi^0$; the new decay modes of $\eta' \rightarrow \pi^+\pi^-\pi^{+(0)}\pi^{-(0)}$ and $\eta' \rightarrow \gamma\gamma\pi^0$ are observed for the first time. For the study of charmonium-like states, four interesting structures, $Z_c(3900)$, $Z_c(3885)$, $Z_c(4020)$ and $Z_c(4025)$, are observed, which inspired many theoretical interpretations. However, further Further study on these structures with large statistics of data is strongly needed to determine their properties and then clarify their natures.

The above interesting results not only underline the importance of the study of hadron spectroscopy, but also demonstrate the effectiveness of a programmatic approach to study hadron spectroscopy at BESIII. With the high statistics data accumulated at the BESIII detector, more interesting results are expected to be coming soon.

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