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BESIII studies of exotic quark states

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Summary. — We present new results on exotic quark states from the BESIII experiment located at the Beijing Electron Positron Collider II.

PACS 13.66.Bc – Production by electron-positron collisions.
PACS 14.40.Lb – Charmed mesons.
PACS 14.40.Pq – Heavy quarkonia.
PACS 13.25.Gv – Decays of hadronic quarkonia.

1. – Charmonium spectroscopy

One of the main physics topics of the BESIII experiment is the charmonium spectroscopy. The charmonium spectrum consists of eight narrow states below the open charm threshold (3.73 GeV) and several tens of states above the threshold. Below the threshold almost all states are well established. On the other hand, very little is known above the threshold, there are several new "Charmonium-like" states that are very difficult to accommodate in the charmonium spectrum. From 2009, a lot of data were taken by the BESIII experiment, in the energy region of about 4 GeV in order to study X, Y and Z states recently observed in the charm mass region. These new states have properties that are not in agreement with the theoretical expectations for charmonium states. There are a lot of interpretations in literature: $c\bar{c}$ states, hybrids, glueballs, hadronic molecules, tetraquarks, etc., but more experimental informations are needed to reach a conclusion.

2. – Observation of $e^+e^- \to \gamma X(3872)$

The $X(3872)$ was first observed 10 years ago by Belle [1] in $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ decays and it was subsequently confirmed by several other experiments [2-4]. Until now the $X(3872)$ was only observed in B meson decays and hadron collisions. Since the $X(3872)$ is a 1^{++} state, it should be able to produced through the radiative transition of an excited vector charmonium or charmonium-like states such as ψ or a Y.

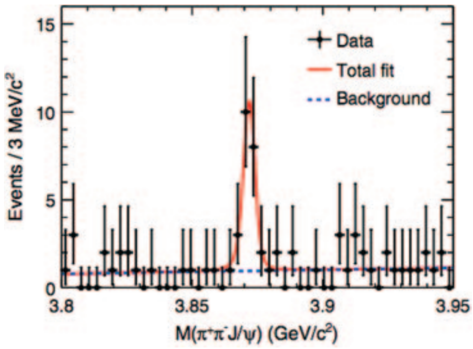

Fig. 1. – Fit to the $M(\pi^+\pi^- J/\psi)$ distribution. Dots with error bars are data, the red curve shows the total fit result while the blue dashed curve shows the background contribution.

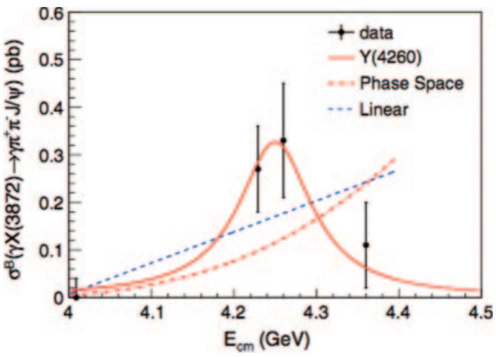

Fig. 2. – Fit to the $M(\pi^+\pi^- J/\psi)$ distribution. Dots with error bars are data, the red curve shows the total fit result while the blue dashed curve shows the background contribution.

BESIII experiment report the first observation of the process $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$, $J/\psi \to \ell^+\ell^-$ ($\ell^+\ell^- = e^+e^-$ or $\mu^+\mu^-$) [5] using data at e^+e^- center-of-mass energies from $\sqrt{s} = 4.009\,\text{GeV}$ to $4.420\,\text{GeV}$. The fit to the $\pi^+\pi^- J/\psi$ invariant mass distribution is shown in fig. 1. The fit is done using a MC simulated signal histogram convolved with a Gaussian function which represents the resolution difference between data and MC simulation as the signal shape, and a linear function for the background. The peak of the $X(3872)$ is evident and the statistical significance is 6.3σ. The parameters of the $X(3872)$ extracted from the fit are: $m = 3871.9 \pm 0.7 \pm 0.2\,\text{MeV/c}^2$ and $\Gamma < 2.4\,\text{MeV}$ at 90% confidence level (CL).

The energy-dependent cross section with a $Y(4260)$ has been studied. Figure 2 shows all the fit results, which give $\chi^2/ndf = 0.49/3$ (CL = 92%), 5.5/2 (CL = 6%) and 8.7/3 (CL = 3%) for a $Y(4260)$, linear continuum and phase space distribution respectively. The $Y(4260)$ resonance describes the data better than the other two options. These observations strongly support the existence of the radiative transition process $Y(4260) \to \gamma X(3872)$.

3. – Observation of the $\psi(1^3D_2)$ state in $e^+e^- \to \pi^+\pi^-\gamma\chi_{c1}$

Recently, the Belle Collaboration reported evidence for a narrow resonance $X(3823) \to \gamma\chi_{c1}$ in B meson decays with 3.8σ significance and the mass and width

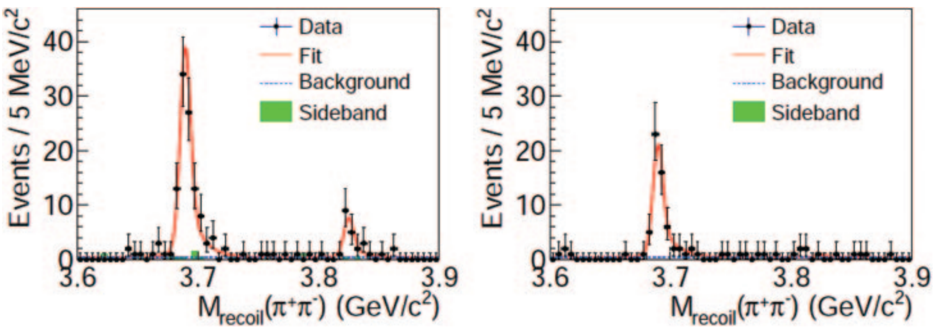

Fig. 3. – Simultaneous fit to the $M_{recoil}(\pi^+\pi^-)$ distribution of $\gamma\chi_{c1}$ events (left) and $\gamma\chi_{c2}$ events (right), respectively. Dots with error bars are data, red solid curves are total fit, dashed blue curves are background and the green shaded histograms are J/ψ mass sidebands events.

suggested that this is a good candidate for the 1^3D_2 charmonium state [6]. In the following we denote the 1^3D_2 state as ψ_2.

BESIII reported a search for the production of the ψ_2 state via the process $e^+e^- \to \pi^-\pi^-X$ using $4.67\,\mathrm{fb}^{-1}$ data collected at the center-of-mass energies that range from $\sqrt{s} = 4.19$ to $4.60\,\mathrm{GeV}$. The ψ_2 candidates are reconstructed in their $\gamma\chi_{c1}$ and $\gamma\chi_{c2}$ decay modes, with $\chi_{c1,c2} \to \gamma J/\psi$ and $J/\psi \to \ell^+\ell^-$ ($\ell = e$ or μ) [7].

An unbinned maximum-likelihood fit to the $M_{recoil}(\pi^+\pi^-)$ invariant mass distribution is performed to extract the $X(3823)$ parameters. The signal shape are represented by MC simulated $\psi(2S)$ and $X(3823)$ histograms, convolved with Gaussian functions with mean and width parameters left free in the fit to account for the mass and resolution difference between data and MC simulation, respectively. The background is parameterized as a linear function. A simultaneous fit with a common $X(3823)$ mass is applied to the data sets with independent signal yields at $\sqrt{s} = 4.230$, 4.260, 4.360, 4.420 and $4.600\,\mathrm{GeV}$ (data sets with small luminosities are merged to nearby data sets with larger luminosities) for the $\gamma\chi_{c1}$ and $\gamma\chi_{c2}$ modes, respectively. Figure 3 shows the fit results where the $X(3823)$ is observed with statistical significance of 6.2σ in $\gamma\chi_{c1}$ modes. The $X(3823)$ parameters extracted from the fit are: $m = 3821.7 \pm 1.3 \pm 0.7\,\mathrm{MeV/c^2}$ and $\Gamma < 16\,\mathrm{MeV}$ al 90% CL. These measurements are in good agreement with the assignment of the $X(3823)$ as the $\psi(1^3D_2)$ charmonium states.

4. – Study of $e^+e^- \to \omega\chi_{cJ}$ at center-of-mass energies from 4.21 to 4.42 GeV

BESIII reported the study of $e^+e^- \to \omega\chi_{cJ}$ based on the data collected at nine center-of-mass energy points in the range $\sqrt{s} = 4.21$–$4.4\,\mathrm{GeV}$ [8]. The ω is reconstructed via its $\pi^+\pi^-\pi^0$ decay mode, the χ_{c0} state is via $\pi^+\pi^-$ and K^+K^- decays, and the $\chi_{c1,2}$ states are via $\chi_{c1,2} \to \gamma J/\psi$, $J/\psi \to \ell^+\ell^-$ ($\ell = e, \mu$). Figure 4 shows the $M(\pi^+\pi^-)$ and $M(K^+K^-)$ at $\sqrt{s} = 4.23$ and $4.26\,\mathrm{GeV}$. While the process $e^+e^- \to \omega\chi_{c0}$ is observed for the first time, there are no significant signals for the process $e^+e^- \to \omega\chi_{c1,c2}$. An unbinned maximum-likelihood fit is performed on the $\pi^+\pi^-$ and K^+K^- modes simultaneously. The signal is described with a shape determined from the simulated signal Monte Carlo sample and the background is described with an Argus function. For the $\sqrt{s} = 4.23\,\mathrm{GeV}$ the signal statistical significance is 11.9σ while for the $\sqrt{s} = 4.26\,\mathrm{GeV}$ the signal statistical significance is 5.5σ. By assuming the $\omega\chi_{c0}$ signals come from a single resonance, we extract $m = 4320 \pm 8 \pm 6\,\mathrm{Mev/c^2}$ and $\Gamma = 28{\pm}12{\pm}2\,\mathrm{MeV}$. The parameters

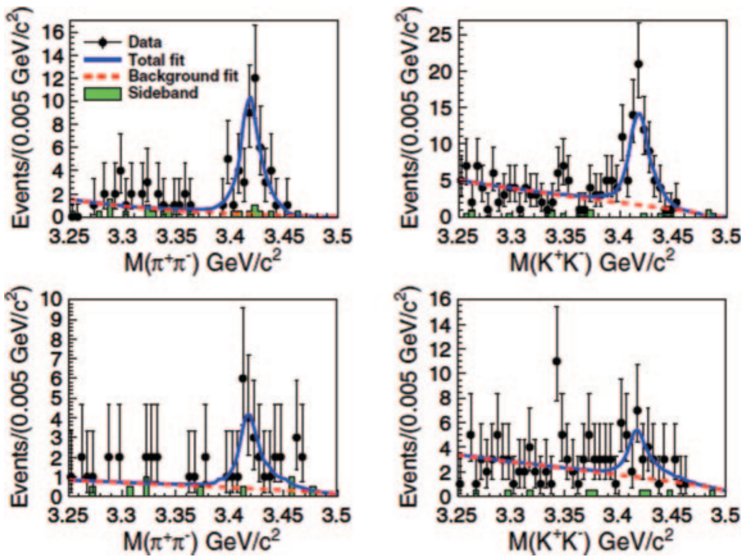

Fig. 4. – Fit to the invariant mass distributions $M(\pi^+\pi^-)$ (left) and $M(K^+K^-)$ (right) at $\sqrt{s} = 4.23\,\mathrm{GeV}$ (top) and $4.26\,\mathrm{GeV}$ (bottom). Points with error bars are data, the solid curves are the fit results, the dashed lines indicate the background and the shaded histograms show the normalized ω sideband events.

are inconsistent with those obtained by fitting a single resonance to the $\pi^+\pi^- J/\psi$ cross section. This suggests that the observed $\omega\chi_{c0}$ are unlikely to originate from the $Y(4260)$.

5. – Search for the $Y(4140)$ via $e^+e^- \to \gamma\phi J/\psi$ at $\sqrt{s} = 4.23, 4.26$ and 4.36 GeV

The CDF experiment first reported evidence for a new state called $Y(4140)$ in the decay $B^+ \to \phi J/\psi K^+$ [9]. In a subsequent analysis, CDF claimed the observation of the $Y(4140)$ with a statistical significance greater than 5σ [10]. However the existence of the $Y(4140)$ was not confirmed by the Belle [11] or LHCb [12] Collaborations in the same process, nor by the Belle Collaboration in two-photon production [11]. Recently, the CMS [13] and D0 [14] collaborations reported the observation of the $Y(4140)$. The BaBar Collaboration found no evidence for this resonance [15].

BESIII reported results of a search for $Y(4140)$ decays into $\phi J/\psi$ through the process $e^+e^- \to \gamma\phi J/\psi$ with data taken at center-of-mass energies of $\sqrt{s} = 4.23$, 4.25 and $4.36\,\mathrm{GeV}$ with $1094\,\mathrm{pb}^{-1}$, $827\,\mathrm{pb}^{-1}$ and $545\,\mathrm{pb}^{-1}$ respectively. No significant signal is observed in the $\phi J/\psi$ invariant mass distribution. The upper limits of the product of cross section and branching fraction $\sigma[e^+e^-\gamma Y(4140)] \times \mathcal{B}(Y(4140) \to \phi J/\psi)$ at the 90% CL are estimated as 0.35, 0.28 and 0.33 pb at $\sqrt{s} = 4.23$, 4.26 and $4.36\,\mathrm{GeV}$, respectively.

6. – Observation of a charged charmonium-like structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV

BESIII presented a study of the process $e^+e^- \to \pi^+\pi^- J/\psi$ [16] at a center-of-mass energy of $\sqrt{s} = (4.26 \pm 0.001)\,\mathrm{GeV}$, which corresponds to the peak to the $Y(4260)$ cross section. The analysis was performed with a $525\,\mathrm{pb}^{-1}$ data sample. They observed a charged structure in the $\pi^\pm J/\psi$ invariant mass spectrum, which they refereed to as

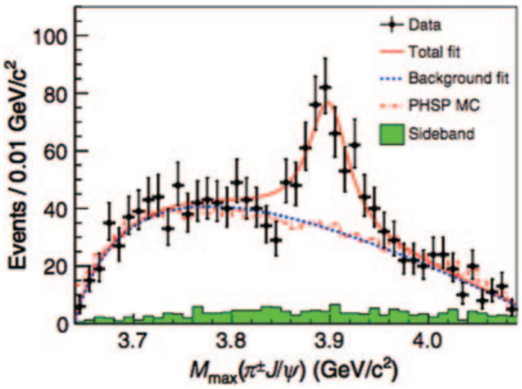

Fig. 5. – Fit to the $M(\pi^{\pm}J/\psi)$ distribution. Dots with error bars are data; the red solid curve shows the total fit, and the blue dotted curve the background from the fit; the red dot-dashed histogram shows the results of a phase space Monte Carlo simulation; and the green shaded histogram shows the normalized J/ψ sidebands events.

the $Z_c(3900)$, as shown in fig. 5. An unbinned maximum-likelihood fit is applied to the $\pi^{\pm}J/\psi$ invariant mass distribution. The signal shape is parameterized as an S-wave Breit-Wigner function convolved with a Gaussian with a mass resolution fixed at the Monte Carlo simulated value. The significance is found to be greater than 8σ. The $Z_c(3900)$ parameters extracted from the fit are: $m = 3899.0 \pm 3.6 \pm 4.9\,\mathrm{MeV/c^2}$ and $\Gamma = 46 \pm 10 \pm 20\,\mathrm{MeV}$. This structure couples to charmonium and has an electric charge, which is suggestive of a state containing more quarks than just a charm and anticharm quark.

7. – Observation of $Z_c^0(3900)$ in $e^+e^- \to \pi^0\pi^0 J/\psi$

A very recent BESIII analysis search for the neutral isospin partner of $Z_c(3900)^{\pm}$. Evidence for a structure in the invariant $J/\psi\pi^0$ mass distribution is observed by CLEO-c in the process $e^+e^- \to \pi^0\pi^0 J/\psi$ [17]. BESIII studied the same channel at three different center-of-mass energies, $\sqrt{s} = 4.23$, 4.26 and 4.36 GeV and they observed a clear structure in the invariant $J/\psi\pi^0$ mass with significance greater than 10σ, as shown in fig. 6. The mass and width are measured to be $3894.8 \pm 2.3 \pm 2.7\,\mathrm{MeV/c^2}$ and $29.6 \pm 8.2 \pm 8.2\,\mathrm{MeV}$ respectively. They interpret this state as the neutral partner of the four-quark candidate $Z_c^{\pm}(3900)$.

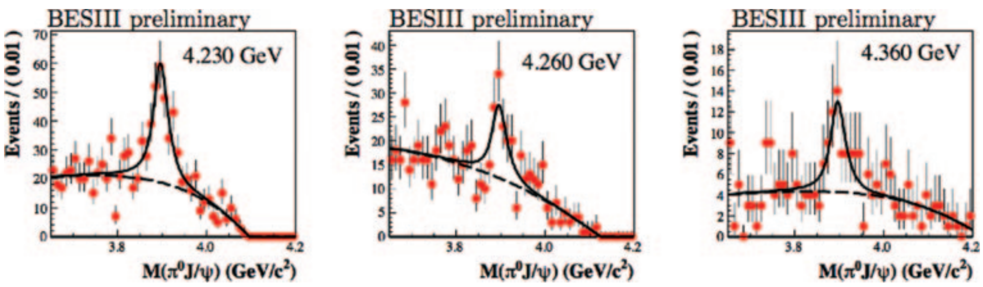

Fig. 6. – The simultaneously fitted $\pi^0 J/\psi$ mass spectra for $\sqrt{s} = 4.23$, 4.26 and 4.36 GeV.

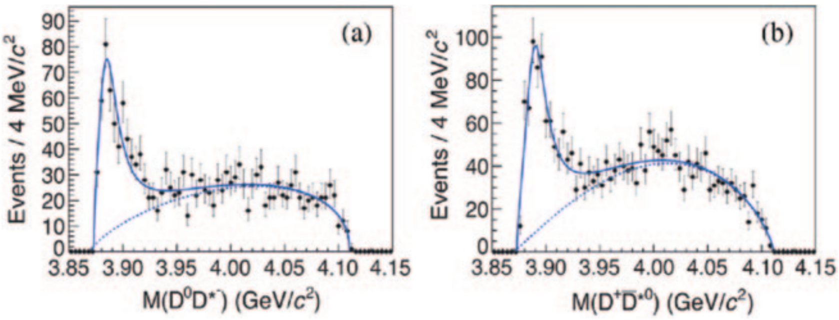

Fig. 7. – Fit to the invariant mass distributions for (a) D^0D^{*-} and (b) $D^+\bar{D}^{*0}$ events. The dots with error bars are the data, the solid line is the total fit, and dashed line describes the background distribution.

8. – Observation of a charged $(D\bar{D}^*)^{\pm}$ mass peaking $e^+e^- \to \pi D\bar{D}^*$ at $\sqrt{s} = 4.26$ GeV

BESIII studied the process $e^+e^- \to (D\bar{D}^*)^{\mp}\pi^{\pm}$ at $\sqrt{s} = 4.26$ GeV using 525 pb^{-1} [18]. They used a single D tag method: the bachelor $\pi^{\pm}$ is detected, and only one final state D meson is fully reconstructed. The other D meson is inferred from energy momentum conservation. For the $(D\bar{D}^*)^{\pm}$ system, they reconstructed the D meson from $K\pi$ and $K\pi\pi$ decays. The invariant mass distribution of the $D\bar{D}^*$ system shows a clear enhancement at the $(D\bar{D}^*)^{\pm}$ threshold, labeled as $Z_c(3885)^{\pm}$ (see fig. 7) with a statistical significance greater than 18σ. The fit is done with a Breit-Wigner function plus a smooth threshold function and the parameters extracted from the fit of the $Z_c(3885)^{\pm}$ are: $m = 3883.9 \pm 1.5 \pm 4.2\,\mathrm{MeV/c^2}$ and $\Gamma = 24.8 \pm 3.3 \pm 11.0\,\mathrm{MeV}$. The bachelor $\pi^{\pm}$ angle distribution in analyzed in order to determine the $Z_c(3885)$ quantum numbers. The resulting distribution in consistent with a spin-parity assignment of $J^P = 1^+$ and rules out 0^- as well as 1^-. A new preliminary analysis, which uses 1090 pb^{-1} and a double-tag technique, improves and confirms the results obtained in ref. [18]. An important issue is whether or not the $Z_c(3900)$ and $Z_c(3885)$ have the same origin. The determination of the J^{PC} quantum numbers of $Z_c(3900)$ would be necessary to answer this question. However, if we assume that the $Z_c(3885)$ structure is due to the $Z_c(3900)$, the ratio of partial decay width is determined to be $\Gamma(Z_c(3885) \to D\bar{D}^*)/\Gamma(Z_c(3900) \to J/\psi\pi) = 6.2 \pm 1.1 \pm 2.7$, which is much smaller than typical values for decays of conventional charmonium states above the open charm threshold.

9. – Observation of a charged charmonium-like structure $Z_c(4020)$ in $e^+e^- \to \pi^+\pi^-h_c$

BESIII studied the process $e^+e^- \to \pi^+\pi^-h_c$ at 13 center-of-mass energies from 3.900 to 4.420 GeV [19]. The h_c is reconstructed via the decay $h_c \to \gamma\eta_c$ where the η_c is reconstructed into 16 hadronic decay modes. An unbinned maximum-likelihood fit is applied to the $M_{\pi^{\pm}h_c}$ distribution summed over the 16 η_c decay modes. An enhancement is clear and it is labeled as $Z_c(4020)^{\pm}$ as shown in fig. 8. The signal shape is parameterized as a constant width relativistic Breit-Wigner function convoluted with a Gaussian with a mass resolution determined from data, while the background shape is parameterized as an ARGUS function. The statistical significance is greater than 8.9σ and the parameters

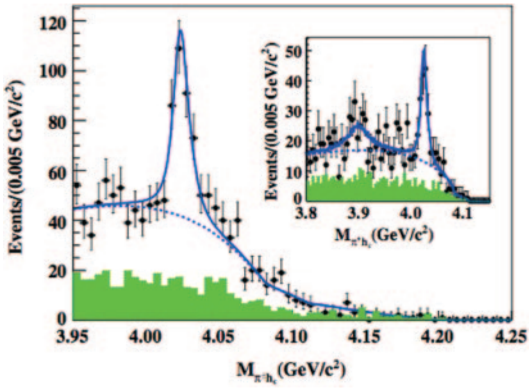

Fig. 8. – Sum of the simultaneous fits to the $M_{\pi^\pm h_c}$ distributions at 4.23, 4.26 and 4.36 GeV. The inset shows the sum of the simultaneous fit to the $M_{\pi^\pm h_c}$ distributions at 4.23 and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$. Dots with error bars are data; shaded histograms are the normalized sideband background; the solid curves show the total fit, and the dotted curves the background from the fit.

extracted from the fit are: $m = 4022.9 \pm 0.8 \pm 2.7\,\mathrm{MeV/c^2}$ and $\Gamma = 7.9 \pm 2.7 \pm 2.6\,\mathrm{MeV}$. There is no significant evidence of the $Z_c(3900)$ structure in the $M_{\pi^\pm h_c}$ mass spectrum: adding the $Z_c(3900)$ mass and width fixed to [16], we find a significance of 2.1σ.

10. – Observation of $e^+e^- \to \pi^0\pi^0 h_c$ and a neutral charmonium-like structure $Z_c(4020)^0$

A neutral structure, the $Z_c(4020)^0$ is expected to couple to the $\pi^0 h_c$ final state and be produced in $e^+e^- \to \pi^0\pi^0 h_c$. BESIII studied the $e^+e^- \to \pi^0\pi^0 h_c$ at $\sqrt{s} = 4.23$, 4.25 and 4.36 GeV and reported the observation of the $Z_c(4020)^0$ in the $\pi^0 h_c$ spectrum with a statistical significance greater than 5σ [20]. The result is shown in fig. 9 and the

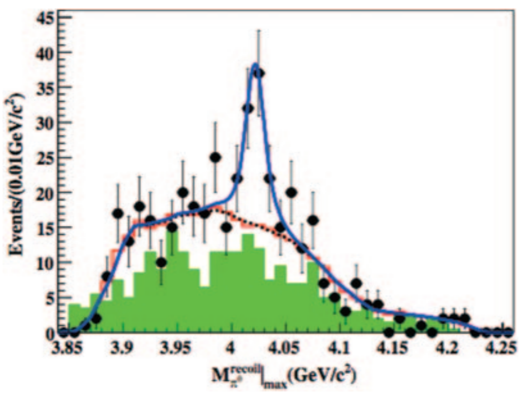

Fig. 9. – Sum of the simultaneous fits to the $M_{\pi^0}^{recoil}$ distribution at 4.23, 4.26 and 4.36 GeV. Dots with error bars are data; the green shaded histogram shows the normalized h_c sidebands events; the black dashed curve is the background from the ft; the red histogram shows the result from a phase space Monte Carlo simulation; the solid blue line shows the total fit.

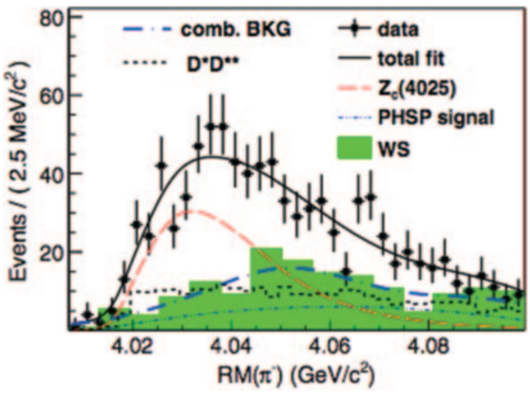

Fig. 10. – Unbinned maximum-likelihood fit to the π^- recoil mass spectrum in data. Points with error bars are the data, solid line is the best-fit results. Background, $Z_c(4025)^+$ signal, and phase space signal component (PHSP) are also shown.

fit is done using a Breit-Wigner function and fixing the width to the value extracted from [19]. The $Z_c(4020)^0$ mass extracted from the fit is $4023.9 \pm 2.2 \pm 3.8\,\text{MeV/c}^2$. Further investigation are needed to understand the nature of $Z_c(4020)$.

11. – Observation of a charged charmonium-like structure in $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ at $\sqrt{s} = 4.26\,\text{GeV}$

BESIII studied the process $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ at a center-of-mass energy $\sqrt{s} = 4.260 \pm 0.001\,\text{GeV}$ [21]. The charged D meson from $D^{*\pm} \to D^\pm\pi^0$ is reconstructed by its decay into $K\pi\pi$, and at least one π^0 in the final state is required in order to suppress background events. In the recoil mass spectrum of the bachelor $\pi^\mp$, a structure near the $D^*\bar{D}^*)^\pm$ threshold is observed with a statistical significance of 13σ and labeled as $Z_c(4023)$ as shown in fig. 10. The distribution is fitted with a Breit-Wigner function and the parameters extracted from the fit are: $m = 4026 \pm 2.6 \pm 3.7\,\text{MeV/c}^2$ and $\Gamma = 24.8 \pm 5.6 \pm 7.7\,\text{MeV}$. Unfortunately, the statistics do not allow to perform a spin-parity analysis of $Z_c(4025)$ and so further investigation of the $Z_c(4020)$ and $Z_c(4025)$ are mandatory in order to understand if whether or not both are due to the same source.

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