XYZ studies at BESIII

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Summary. — A review of few of the most recent results on XYZ studies at BESIII is reported. Thanks to its unique data sample of $5.1fb^{-1}$ in the energy range between 3.8 and 4.6 GeV, BESIII can give a significant contribute in this field. Among the others we discuss some of the most recent results on Z_c states, the first observation of $e^+e^- \rightarrow \omega\chi_{c0}$ at s = 4.23 and 4.26 GeV as well as the measurements of the cross-sections of $\omega\chi_{cj}$ and $\eta J/\psi$.

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1. – Introduction

The BESIII experiment is installed at the BEPCII double-ring electron-positron collider at the Institute of High Energy Physics (IHEP, Beijing, PRC), with a beam energy tunable from 1.0 to 2.3 GeV. The BESIII detector is a magnetic spectrometer composed by a helium gas based Main Drift Chamber (MDC), a plastic scintillator Time-Of-Flight (TOF) system, a CSI(Tl) ElectroMagnetic Calorimeter (EMC) and a muon detector (MUC) based on Resistive Plate Chambers, immersed in a 1.0 T magnetic field provided by a super-conducting solenoidal magnet. Further details can be found in ref.[1].
In the last decade many unexpected states (the so-called XYZ states) have been discovered above the $D\overline{D}$ threshold, mostly at B-factories, in the higher mass charmonium spectrum. Several of them do not fit the conventional charmonium paradigm as simple quark-antiquark bound state, opening the door to various exotic hypotheses, e.g. $c\bar{c}$ hybrids, glueballs, hadronic molecules, tetraquarks and hadrocharmonia. This has produced a renewed strong interest in this field both from the experimental and the theoretical point of view, but up to now a firm conclusion about the nature of XYZ states has not been found. They are commonly distinguished in three main groups: the Y states are the vector neutral states, those with isospin equal to 1 are the Z ones and all of the rest are called X.

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The Y(4260) was first observed by BaBar in the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section [2] and subsequently confirmed by Cleo-c [3] and Belle [4]. Its production in electron-positron annihilations determines its quantum numbers to be $J^{pc} = 1^{--}$, while the absence of a similar structure in open charm channels suggest that it is not a conventional charmonium.
At BESIII, Y states can be produced directly in e^+e^- annihilations. To help to clarify the picture, a unique and high statistics data sample was collected in 2013 and 2014, reaching an integrated luminosity of 5.1 fb^{-1} [5] for a total of 18 different energy points and collecting the world's largest samples of Y(4260) and Y(4360). Based on this data, the BESIII collaboration may help to reveal the connections of Y states with X and Z states via radiative or hadronic transition and, in the meanwhile, the cross section of various channels can be investigated as a function of the center-of-mass(c.m.) energy.

2. – Z_c states

In 2013, the BESIII Collaboration observed a new charged charmonium-like state [9], referred to as $Z_c(3900)$, in the $J/\psi\pi^\pm$ mass distribution in the $e^+e^- \to J/\psi\pi^+\pi^-$ process, using a 525 pb^{-1} data sample collected at $\sqrt{s}$=4.260 GeV. An unbinned maximum likelihood fit to the M($J/\psi\pi^\pm$) results in a mass of (3899.0 ± 3.6 ± 4.9) MeV/c^2, a width of (46 ± 10 ± 20) MeV with a significance larger than 8σ and measuring a cross section of the process consistent with the Y(4260) production. This state was shortly afterwards confirmed by the Belle Collaboration in e^+e^- annihilations with radiative return to the Y(4260) [10] and in direct e^+e^- annihilations at 4.17 GeV in CLEO-c data [11]. This $Z_c(3900)$ couples strongly to charmonium and carries electric charge, so it should be at least a four-quark combination. Furthermore it is close to the $D\overline{D^*}$ threshold. An evidence for a structure in the $J/\psi\pi^0$ invariant mass distribution in the isospin-related channel $e^+e^- \to J/\psi\pi^0\pi^0$ was reported in CLEO-c data [11], opening the question whether a neutral patner of the charged $Z_c(3900)$ exists. In BESIII its neutral patner $Z_c(3900)^0$ has been searched for in the same process [12], based on a data sample of 2809.4 pb^{-1} in a center-of-mass energy range from 4.190 to 4.420 GeV. With the larger statistics data samples at the c.m. energies of 4.23, 4.26 and 4.36 GeV, a significant structure in the $J/\psi\pi^0$ invariant mass distribution was observed as shown in fig. 1 on the right, in which the fitting result are also reported. For all the data samples common fit parameters for the BreitWigner function were used to describe the signal. A mass of (3894.8 ± 2.3 ± 2.7) MeV/c^2 and a width of (29.6 ± 8.2 ± 8.2) MeV are obtained with a statistical significance larger than 10 σ and consistent with the ones determined for the charged states. Furthermore the Born cross sections for $e^+e^- \to J/\psi\pi^0\pi^0$ is almost the half of the ones for $e^+e^- \to J/\psi\pi^+\pi^-$, consistently with isospin symmetry expectation. Searching for other decay modes of $Z_c(3900)^+$, BESIII investigated the $e^+e^- \to h_c\pi^+\pi^-$[13]. The h_c is reconstructed via its radiative decay to η_c , that is fully reconstructed in 16 hadronic final states. At c.m. energies between 3.90 and 4.42 GeV the $h_c\pi^+$ invariant mass spectrum shows a narrow structure at about 4.02 GeV/c^2, very close to the $D^*\overline{D^*}$ threshold, referred to as $Z_c(4020)^+$. A simultaneous fit to the spectrum, neglecting possible interferences, results in a mass of (4022.9 ± 0.8 ± 2.7) MeV/c^2 and a width of (7.9 ± 2.7 ± 2.6) MeV. No significant $Z_c(3900)^+$ signal is observed and an upper limit of 11 pb at 90%$C.L.$ on the $Z_c(3900)^+$ production cross section was determined at 4.26 GeV. A similar analysis was performed in the $e^+e^- \to h_c\pi^0\pi^0$ channel, with the observation of a significant signal in the $h_c\pi^0$ invariant mass distribution at about the same mass of $Z_c(4020)^+$ [14]. The fitting result is a mass of (4023.9 ± 2.2 ± 3.8) MeV/c^2, with a

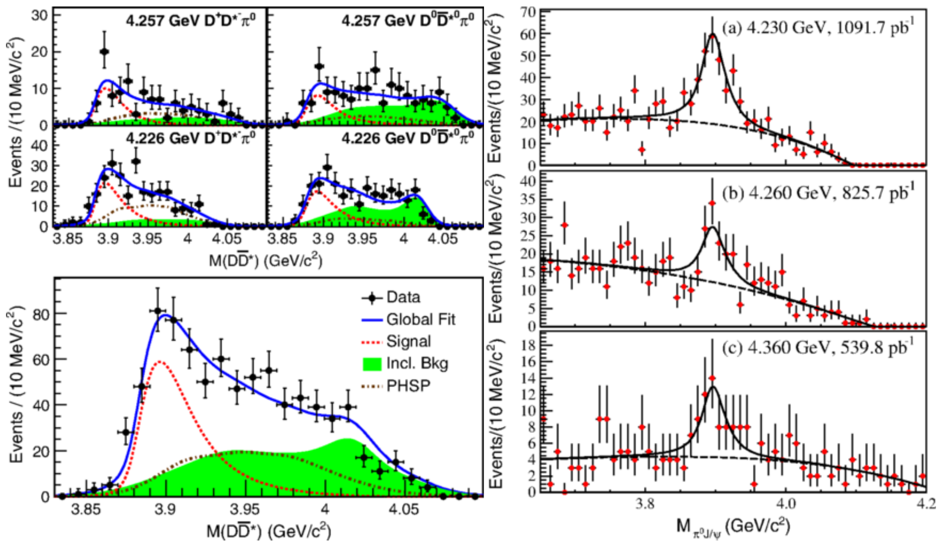

Fig. 1. – Simultaneous fit to the $J/\psi\pi^0$ invariant mass distribution for the three largest data sets collected at the c.m. energy of 4.230 GeV (b), 4.260 GeV (b), and 4.360 GeV (c) on the left [12]. Dots represent the data, solid lines the unbinned maximum likelihood fit results and dashed lines the fitted backgrounds. On the right, the projections of the simultaneous fit to the M($D\overline{D}^*$) distributions for $e^+e^- \to \pi^0(D\overline{D}^*)^0$ [17] for the two data samples and the two channels. The bottom plot represent the sum of the simultaneous fit for different decay modes at different c.m. energies.

width fixed to that of the charged $Z_c(4020)^+$ due to limited statistics.
Being the mass of $Z_c(3900)$ so close to $D\overline{D}^*$ threshold, suggestive of a moulecular hypothesis, BESIII searched for $e^+e^- \to \pi^\pm(D\overline{D}^*)^\mp$ process with the two data samples of 1092 pb^{-1} at 4.23 GeV and 826 pb^{-1} at 4.26 GeV. Exploiting the Double D-tag technique(*i.e.* full reconstruction of the D meson pair) and with reconstruction of the bachelor $\pi^\pm$in the final state, we confirmed with improved statistics and systematics, the observation of charged structure $Z_c(3885)^\mp$ [15], firstly found with Single D-Tag technique [16]. By a unbinned Maximum Likelihod fit of the M($(D\overline{D}^*)^\mp$) spectra, done simultaneously for the two data samples and the two channels, we determined a pole mass and a width of $(3881.7 \pm 1.6(stat) \pm 1.6(syst))$ MeV/c^2 and width $(26.6 \pm 2.0(stat) \pm 2.1(syst))$ MeV with a statistical significance larger than 10σ. Analysing the distribution of the π^- decay angle it was found that is consistent with a spin-parity assignment of $J^P = 1^+$.
The same data sets and analysis strategy were used to search for the neutral $Z_c(3885)^0$ state, investigating the process $e^+e^- \to \pi^0(D\overline{D}^*)^0$ [17]. An enhancement close to the $D\overline{D}^*$ threshold was found and the mass and width were found to be consistent with the ones reported for the charged $Z_c(3885)^\pm$ with a statistical significance larger than 10σ.
The $e^+e^- \to \pi^\pm(D^*\overline{D}^*)^\mp$ [18] were investigated using 1092 pb^{-1} at 4.23 GeV and 826 pb^{-1} at 4.26 GeV with a partial reconstruction technique and an enhancemnt close to the threshold was found in the $\pi^\pm$ recoiling mass spectrum, which we denoted as $Z_c(4025)^\pm$, with 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. Its production ratio is determined to be $0.65 \pm 0.09 \pm 0.06$.

Using the same technique and investigating $e^+e^- \to \pi^0(D^*\overline{D}^*)^0$ in the same data samples, the neutral $Z_c(4025)^0$ was found in the π^0 recoiling mass spectrum with a pole mass $(4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV/c^2, a width $(23.0 \pm 6.0 \pm 1.0)$ MeV and a significance larger than 7σ [19].

3. – X states

BESIII observed for the first time the process $e^+e^- \to \gamma X(3872) \to \gamma J/\psi\pi^-\pi^+$ at center-of-mass energies from 4.009 to 4.420 GeV [20]. The result for the mass of X(3872) is $(3871.9 \pm 0.7 \pm 0.2)$ MeV/c^2, in agreement with previous determinations [21]. The product of the X(3872) production cross section and its branching fraction to $J/\psi\pi^-\pi^+$ for 4.009, 4.229, 4.260, and 4.360 GeV data points is consistent with the expectation for the radiative transition process $Y(4260) \to \gamma X(3872)$.
More recently BESIII collaboration investigated the process $e^+e \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$ in 5 data samples at center-of-mass energies of 4.230, 4.260, 4.360, 4.420, and 4.600 GeV [22]. The X(3823) was observed with a statistical significance of 6.2σ with a measured mass of (3821.7±1.3±0.7)MeV/c^2, where the first error is statistical and the second systematic, and a width less than 16 MeV at the 90% confidence level. The products of the Born cross sections for $e^+e \to \pi^+\pi^- X(3823)$ and the branching ratio $B[X(3823) \to \gamma\chi_{c1,c2}]$ are also measured. These measurements are in good agreement with the assignment of the X(3823) state as the $\psi(^1D^2_3)$ charmonium state.

4. – Y states

Searching for new decay modes and measuring the line shape of the Y(4260) are very important for understanding its nature, trying to rule out some of the hypotheses arisen, e.g., as a quark-gluon charmonium hybrid, a tetraquark state, a hadroncharmonium, or a hadronic molecule. Hadronic transition to lower charmonia are sensitive probes, but light hadron ones can give also an important contribution.

4·1. *Measurement of $\omega\chi_{cj}$.* – In ref. [7], authors predicted a sizable coupling between the Y (4260) and the $\omega\chi_{c0}$ channel and suggested the Y(4260) resonance to be a conventional $c\bar{c}$ state for which the $\omega\chi_{c0}$ threshold effect plays a role in reducing the

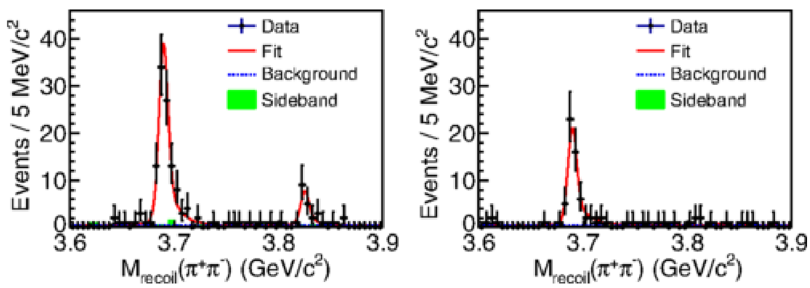

Fig. 2. – The $M_{recoil}(\pi^+\pi^-)$ distributions for the events of $\gamma\chi_{c1}$ on the left and $\gamma\chi_{c2}$ on the right. The dots with error bars are the data, red solid curve are the simultaneous fit results, dashed blue curve the background while the green shaded histograms are backgrounds from J/ψ mass sidebands [22].

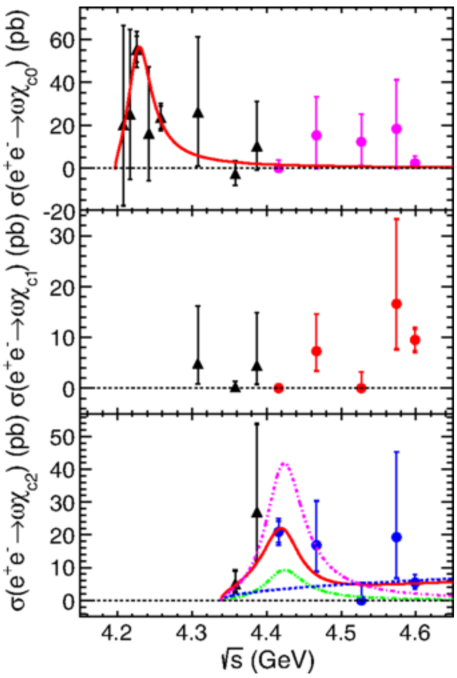

Fig. 3. – Measured Born cross section (center value) for $e^+e^- \to \omega\chi_{cj}(j = 0, 1, 2)$ [24] as a function of the center of mass energy from the top to the bottom. The triangle black points are from ref. [23].The $\sigma(e^+e^- \to \omega\chi_{c0})$ is fitted with a resonance represented by the solid curve in the plot on the top. The $\sigma(e^+e^- \to \omega\chi_{c2})$ is fitted with the coherent sum of the $\psi(4415)$ Breit-Wiegner function and a phase-space term and the solid curve in the bottom plot shows the result of the fitting while the blue dashed curve is the phase space contribution.

decay rates into open-charm channels. Based on data samples collected with the BESIII detector at 9 CM energies from 4.21 to 4.42 GeV, the production of $e^+e^- \to \omega\chi_{c0}$ was firstly searched for [23]. The ω is reconstructed by $\pi^+\pi^-\pi^0$ decay mode while χ_{c0} is reconstructed by its $\pi^+\pi^-$ and K^+K^- decays. A unbinned maximum likelihood fit was performed to the M$(\pi^+\pi^-)$ and M $(K^+K\ )$ distributions of selected events at $\sqrt{s} = 4.23$ and 4.26 GeV on both modes simultaneously with a signal statistical significance of 11.9 σ and 5.5 σ, respectively . The measured Born cross sections are (55.4 $\pm$ 6.0 $\pm$ 5.9) pb and (23.7 $\pm$ 5.3 $\pm$ 3.5) pb, respectively. For the other energy points, no significant signals were found and the upper limits on the cross section at the 90% C.L. were determined. Subsequently this study has been extended to the available 5 samples at higher center-of-mass energies from 4.416 to 4.599 GeV [24]. The $\chi_{c1,2}$ are reconstructed by their decays $\chi_{c1,2} \to \gamma J/\psi$ with $J/\psi \to l^+l^-(l = e, \mu)$. Using these data samples, signals of the processes $e^+e^- \to \omega\chi_{c1,2}$ were observed. Where no significant signal were found, the upper limits on the Born cross section at 90% C.L. were calculated. Interesting line shapes have been observed for $\omega\chi_{cj}$, shown in figure 3 as a function of the center-of-mass energy.

If we assume that the $\omega\chi_{c0}$ signals come from a resonance, the fitting results, shown in the same figure are $\Gamma_{ee} \times B(\omega\chi_{c0}) = (2.7 \pm 0.7)$ eV, M = (4229 $\pm$ 11) MeV/c^2 , and Γ_t=

(40 ± 14) MeV/c^2, which are consistent with the Y(4220) state observed in the cross section of $e^+e^- \to \pi^+\pi^- h_c$ [13]. The data may suggest that the Y(4260) observed in $e^+e^- \to \pi^+\pi J/\psi$ [9] have fine structures and the lower mass structure at about 4230 MeV/c^2 has a sizable coupling to the $\omega\chi_{c0}$ channel. There is an enhancement for $\omega\chi_{c2}$ around 4.42 GeV, which does not appear in the $\omega\chi_{c1}$ channel. The $\sigma(e^+e^- \to \omega\chi_{c2})$ is fitted with the coherent sum of the $\psi(4415)$ Breit-Wiegner function and a phase-space term that can describe well the shape with a branching fraction for $\psi(4415) \to \omega\chi_{c2}$ of the order of 10^{-3}. For $e^+e^- \to \omega\chi_{c1}$ the cross section seems to rise close to 4.6 GeV The different line-shapes observed suggest that their production mechanism is different and that nearby resonances, like $\psi(4415)$, show different branching fraction for the three decay channels.

4·2. *Measurement of $\eta J/\psi$* . – Using data samples collected at 17 center-of-mass energies from 3.810 to 4.600 GeV the BESIII collaboration studied the $e^+e^- \to \eta J/\psi$ process. Statistically significant η signals were observed at 8 energies and the Born cross-sections were measured [25]. Otherwise upper limits at the 90%$C.L.$ were set. A search for the $e^+e^- \to \pi^0 J/\psi$ process observed no significant signals and upper limits at the 90%$C.L.$ on the Born cross-section were set. A comparison of the measured Born cross-sections $\sigma(e^+e^- \to \eta J/\psi)$ with previous ones, shown in figure 4, results in a good agreement but with improved precision. Comparing our results with those of $e^+e^- \to J/\psi\pi^-\pi^+$ from Belle, a difference between the line-shapes can be observed suggesting that for these two channels in this energy range a different production mechanism is working.

4·3. *Other searches.* – The controversial Y(4140) state was firstly observed by CDF Collaboration, using exclusive$B^+ \to J/\psi\phi K^+$ decays, as a narrow structure near the

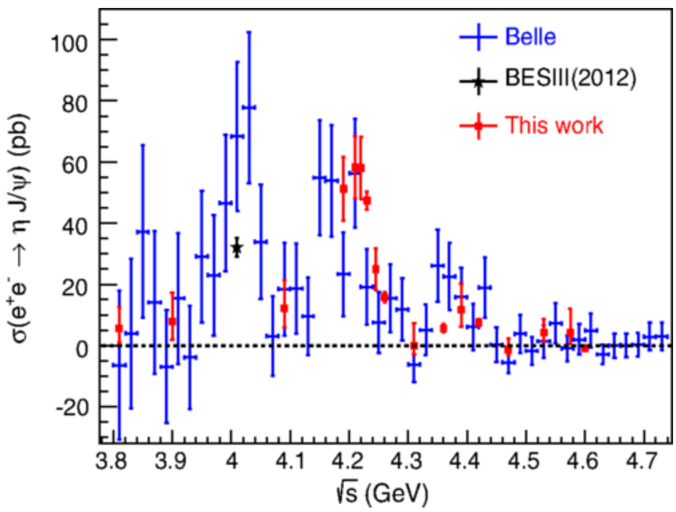

Fig. 4. – A comparison of the measured Born cross-sections $\sigma(e^+e^- \to \eta J/\psi)$ with previous ones. Blue dots are the Belle results on the same process, the black star is from BESIII result in 2012 [26] and the red squares are results from our recent analysis [25]. Both BESIII error bars include statistical and systematical uncertainties while for Belle they are only statistical .

$J/\psi\phi$ mass threshold with a statistical significance of 3.8σ [28] with mass and width fitted to be 4143.0 ± 2.9(stat) ± 1.2(syst) MeV and $11.7^{+8.3}_{-5.0}(stat) \pm 3.7(syst)$ MeV, respectively. However, its existence was not confirmed by the Belle, BABAR and LHCb [29] collaborations in the same process. Recently CMS and D0 [30] reported an observation of this state. Being well above the open charm threshold, this narrow structure is difficult to be interpreted as a conventional charmonium state while it is a good candidate for a molecular, tetraquark or hybrid charmonium state. Furthermore it is the first charmoniumlike state decaying into two vector mesons, one $c\bar{c}$ and one $s\bar{s}$ pair, both with $J^{PC} = 1^{--}$ so that the $\phi J/\psi$ system has positive C-parity and can be searched for in radiative transitions of Y(4260) or other charmonium/charmonium-like states. BESIII searched for it in its $J/\psi\phi$ decay investigating the process $e^+e^- \to \gamma J/\psi\phi$ using the highest statistics data samples at 4.23, 4.26 and 4.36 GeV, identifying the J/ψ by the usual leptonic decays and the ϕ by K^+K^-, $K^0_S K^0_L$, $\pi^+\pi^-\pi^0$ ones. No significant signal has been found. The upper limits of $\sigma(e^+e^- \to \gamma Y(4140)) \cdot B(Y(4140) \to J/\psi\phi)$ at 90% C.L. are calculated to be 0.35, 0.28 and 0.33 pb at 4.23, 4.26 and 4.36 GeV, respectively. They can be compared with the X(3872) production rates [20] measured with the same data samples by BESIII resulting to be of the same order of magnitude. BESIII collaboration studied also the isospin violating decay $Y(4260) \to J/\psi\eta\pi^0$ at six center-of mass energies from 4.009 to 4.599 GeV [33]. This isospin violating processes can probe the nature of Y(4260) because some prediction are available. While the J/ψ is reconstructed by $J/\psi \to e^+e^-/\mu^+\mu^-$, the neutral pion is reconstructed by $\pi^0 \to \gamma\gamma$ and the η with $\eta \to \gamma\gamma$ Distributions of the l^+l^- invariant mass are shown in figure 5 for the events both in the $\eta\pi^0$ signal region and in the sidebands for $\sqrt{s}$= 4.226 GeV on the left and 4.257 GeV on the right. Since no statistically significant signal exceeding the background was observed, upper limits on the Born cross section at the 90% C.L. for $e^+e^- \to J/\psi\eta\pi^0$ and $e^+e^- \to Z^0_C\pi^0 \to J/\psi\eta\pi^0$ were determined for all the energies. The upper limits are placed well above the prediction done using the molecule model. For the last channel it was determined to be 1.3 pb at $\sqrt{s}$=4.226 GeV and 2.0 at 4.257 GeV.

5. – Summary

BESIII achieved important results in the XYZ studies, based on a dedicated data-sample from 3.800 to 4.600 GeV, contributing to the lively discussion on this state search-

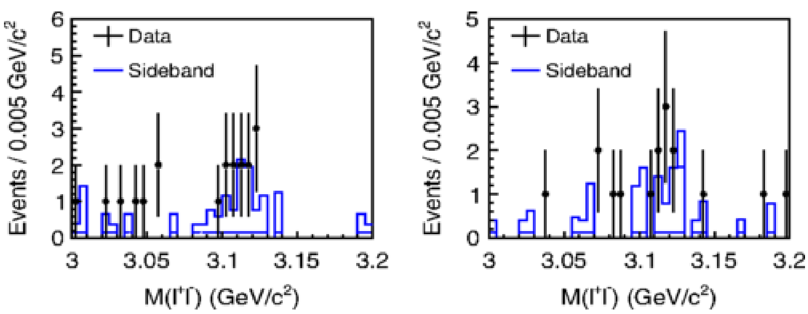

Fig. 5. – The plots show the M(l^+l^-) distributions for events in the $\eta\pi^0$ signal region (dots with error bars) and in the sidebands (histogram) for data at $\sqrt{s}$=4.226 GeV on the left and 4.257 GeV on the right [33]

ing for new ones, looking for connection between states and studying the cross sections as a function of the center-of-mass energies. Many analyses are not reported in this contribution and many others are on the way.

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