PROCEEDINGS OF SCIENCE

XYZ studies at BESIII

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The BESIII experiment installed at the Beijing Electron Positron Collider provided many evidences of the existence of the exotic states X,Y,Z. These states cannot be described with the simplest quark model paradigm, but their structure seems to be more complex, including more quarks. This work gives a list of the resonances discovered by the BESIII Collaboration through the respective identification channels.

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1. The BESIII experiment

The BESIII experiment [1] is installed at the BEPCII e^+e^- collider at IHEP, Beijing, P.R. China. The collider has been drawn to reach a peak luminosity of 10^{33} cm^{-2}s^{-1} with an energy in the center of mass ranging from 2 to 4.6 GeV. The experiment derives from two upgrades of the apparatus (collider included) that in the first (started in 1989) and in the second (started in 1996) data taking campaign provided several important results in the τ-charm energy region. With the third upgrade, the BESIII data taking campaign started in 2003 already providing very significant results.

The apparatus works in a 1 T axial magnetic field produced by a superconducting solenoid (SSM), considered to be optimum for the measurements of charged tracks in the τ-charm energy region. Tracks are reconstructed by a multilayer drift chamber (MDC), installed around the beryllium beam pipe to cover 93% of the solid angle. The MDC is surrounded by the Time-of-flight (TOF) system, consisting of two layers of plastic scintillators counters. A CsI(Tl) electromagnetic calorimeter (EMC) is installed in the region between the TOF and the SSM. The apparatus is then completed with an external muon identifier (MU) made by RPCs layers alternated with steel plates for the flux return yoke.

	Sub-system		
MDC	σ_p/p (1 GeV/c)		0.5%
	σ (dE/dx)		6%
EMC	σ_E/E (1 GeV/c)		2.5%
	Pos. res. (1 GeV/c)		0.6 cm
TOF	σ_T (ps)	Barrel	100
		End cap	110
Muon	No. of layers (barrel/end cap)		9/8
	cut-off momentum (MeV/c)		0.4
Solenoid magnetic field (T)			1.0
$\Delta\Omega/4\pi$			93%

Table 1: Sub-detector performances

2. Charmonium states

Charmonium states are described in the QCD potential model as quark-antiquark pair bound by single-gluon-exchange [2]. A non-relativistic Schrödinger equation provides the energy levels, characterized by the quantum number n, and the relative orbital angular momentum, defined with the quantum number L. Orbital levels are then labeled with $S,P,D,\ldots$ for $L=0,1,2,\ldots$ and the total spin of the quark-antiquark system can be $S=0$ (spin singlet) or $S=1$ (spin triplet). The parity eigenvalue of the system is $P=(-1)^{L+1}$ while for the charge conjugation operator we have the eigenvalue $C=(-1)^{L+S}$. Further considerations can be promoted taking into account the spin-dependent interactions which produce splitting within multiplets. Moreover the QCD lattice calculations are in good agreement with the phenomenological potentials.

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3. Exotic charmonium states

Anyway QCD does not forbid the so-called *multiquark* states, such as meson-antimeson molecular states. The light mesons $f_0(980)$ and $a_0(980)$ are strong candidates for $K\bar{K}$ molecules. The combination of the three lightest quarks with the respective antiquarks gives rise to the well-known octet of flavor-$SU(3)$. Extending this mechanism [3] two quark triplets can be combined to form a "diquark" antitriplet of antisymmetric qq states. Each diquark has a color, so they must combine with other colored quark states thereby forming multiquark color-singlet states. States like tetraquark, pentaquark, dybarion, hybrids and glue-balls are called *exotic* states and they can find place in the charmonium spectrum [4] (fig. 1).

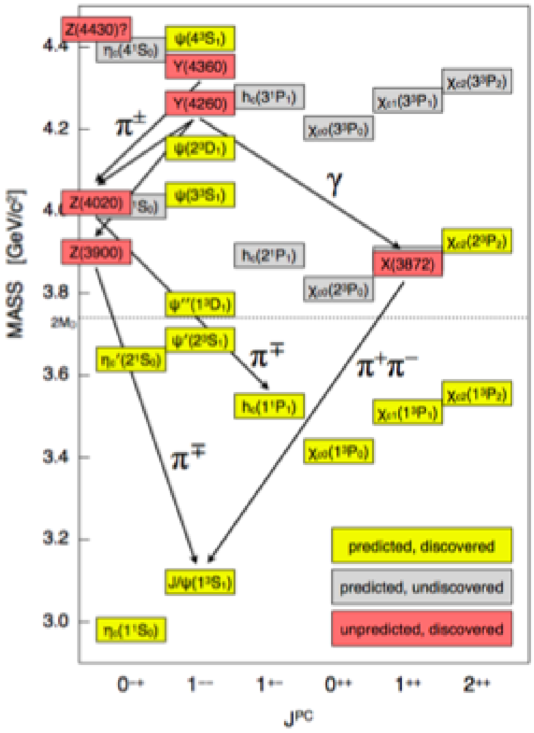

Figure 1: Charmonium states with hypothetical hadron/photon connections between the exotic states.

4. The Z states at BESIII

From the analysis of 525 pb^{-1} data sample collected at $\sqrt{s} = 4.26$ GeV the BESIII collaboration reported in 2013 [6] the discovery of a structure around 3900 MeV in the invariant mass of the $\pi^{\pm}J/\psi$ (fig. 2). The results of the fit give a resonance with a mass $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c^2 and a width $\Gamma = 46 \pm 10 \pm 20$ MeV/c^2 and a significance of 8σ. From the different fits of $M(\pi^+J/\psi)$ and $M(\pi^-J/\psi)$ the masses, the widths and the production rates of $Z_c(3900)^+$ and $Z_c(3900)^-$ agree each other within statistical errors. This particle carries en electric charge and it couples with charmonium state suggesting that its structure is composed of more than a quark-antiquark pair. This particle is actually candidate to be a tetraquark state and its discovery has been confirmed by Belle and CLEO-c [7, 8]. To clarify the structure of this particle further analyses have been made by BESIII collaboration studying other channels, supported by the evidence provided by CLEO-c [8] for a neutral partner to the charged $Z_c(3900)^{\pm}$. Looking at the $\pi^0 J/\psi$ invariant mass a signal around 3900 MeV/c^2 is visible with a significance of 10.4σ (fig. 3). This resonance has mass[1] $M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c^2 and width $\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV/c^2 [9], completing the isospin triplets of the $Z(3900)$. At higher center of mass energy a study on the $e^+e^- \to \pi^+\pi^- h_c$ channel [10] has been performed. Also in this case a charged structure in the $\pi^{\pm}h_c$ invariant mass is observed (fig. 4 (left)), with a mass $M = 4022.9 \pm 0.8 \pm 2.7$ MeV/c^2 and width $\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV/c^2 and a significance of the signal over 8.9σ. Like the previous case of the isospin triplet of $Z(3900)$, also in this case the study of the neutral partner channel [11] evidenced a structure around 4020 MeV/c^2 (fig. 4 (right)). In this case the events are selected requiring $M^{\rm recoil}_{\pi^0\pi^0}$ in the range $[3.51, 3.55]$ GeV/c^2. From the two combinations of the π^0 recoil mass in each event, the one with the largest π^0 recoil mass value is retained. For both triplets the region of the energy is very close to the $D\bar{D}^*$ production, indeed from the channels $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$, using data sample collected at $\sqrt{s} = 4.26$ GeV, it has been revealed the existence [12] of a $Z_c(3885)^{\pm}$ from the $(D\bar{D}^*)^{\pm}$ invariant mass distribution. The distributions of the D^0D^{*-} (a) and $D^+\bar{D}^{*0}$ (b) invariant masses recoiling from the bachelor pion in $\pi^+D^0(\pi^-D^+)$ tag events are shown in fig. 5. Both distributions have a peak at the $m_D + m_{\bar{D}}$ mass threshold. While reconstructing the bachelor π and the $D\bar{D}$ pair [13] we obtain the distribution in fig. 6. From the first analysis (single tag method) the particle has mass $M = 3883.9 \pm 1.5 \pm 4.2$ MeV/c^2 and width $\Gamma = 24.8 \pm 3.3 \pm 11.0$ MeV/c^2; the second analysis (double tag method) gives $M = 3881.7 \pm 1.6 \pm 2.1$ MeV/c^2 and $\Gamma = 26.6 \pm 2.0 \pm 2.3$ MeV/c^2. A further result provided by BESIII experiment is the measurement of the $e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)$, where three Z resonances around 4025 MeV/c^2 have been observed [14, 15]. For charged particles we have $M = 4026.3 \pm 2.6 \pm 3.7$ MeV/c^2 and $\Gamma = 24.8 \pm 5.6 \pm 7.7$ MeV/c^2, while for the neutral state $M = 4025.5^{+2.0}_{-4.7} \pm 3.1$ MeV/c^2 and $\Gamma = 23.0 \pm 6.0 \pm 1.0$ MeV/c^2. In the first case the significance of the signal is larger than 10σ, in the latter is above 5.9σ.

5. The X states at BESIII

The X state has been discovered by Belle [16] and studied at BESIII through the process $e^+e^- \to \gamma\pi^+\pi^- J/\psi$, looking at the invariant mass of $\pi^+\pi^- J/\psi$ [17] (see fig. 7). One conjecture on the nature of this particle is that it is a $D\bar{D}^*$ bound state. The particle has been observed with a significance of 6.3σ summing dataset collected at different $\sqrt{s}$ (4.23, 4.26 and 4.36 GeV), obtaining $M = 3871.9 \pm 0.7 \pm 0.2$ MeV/c^2 and $\Gamma < 2.4$ MeV/c^2 at 90% confidence level.
Anyway other channels have been studied in BESIII, most of them suggesting that this is a tetraquark state, like in $X(3872) \to \gamma J/\psi$ [18] or in radiative decays of the $Y(4260)$ [19]. The very large datasets provided by the experiment allowed to study also the channel $e^+e^- \to \pi^+\pi^-\gamma\chi_{c1}$ finding a peak around 3820 MeV/c^2. Using data at different $\sqrt{s}$ the collaboration obtained [20] $M = 3821.9 \pm 1.3 \pm 0.7$ MeV/c^2 with a significance of 6.2σ (fig. 8).

[1]The first error is to be intended as the statistical one and the second as the systematic one. This convention is applied to the whole text

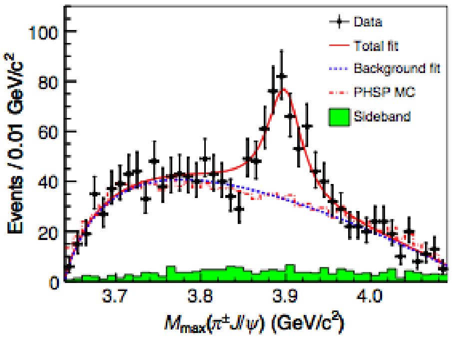

Figure 2: Invariant mass of $\pi^{\pm}J/\psi$ with evidence of a resonance around 3900 MeV/c^2. Dots with error bars are the data, the red solid line is the total fit, the blue dotted curve is the background form the fit, the red dotted-dashed histogram shows the result of a space-phase Monte Carlo simulations and the green shaded histograms shows the normalized J/ψ sideband events.

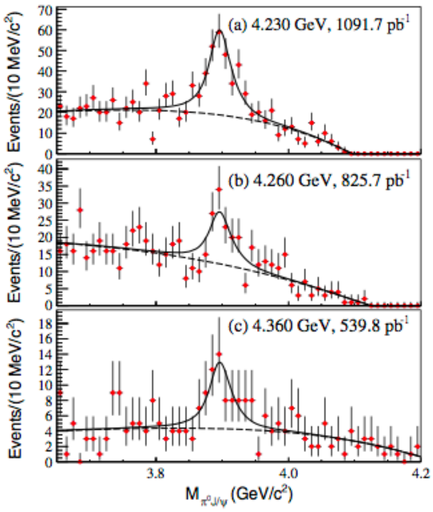

Figure 3: $\pi^0 J/\psi$ mass spectra for (a) $E_{c.m.} = 4230$, (b) $E_{c.m.} = 4260$ and (c) $E_{c.m.} = 4360$ MeV. Dots represent the data, solid lines represent the fitted results and dashed lines represent the fitted background.

6. The Y states at BESIII

BESIII collaboration studies the nature of the Y resonances through several channels. One of the most relevant result is the growing of the cross section for the $e^+e^- \rightarrow \omega\chi_{c0}$ at 4.23 GeV [21] (see fig. 9). This resonance has mass $M = 4230 \pm 8 \pm 6$ MeV/c^2 and width $\Gamma = 38 \pm 12 \pm 2$ MeV/c^2, with a significance larger than 9σ. Other searches have been performed from the collaboration [22, 23, 24, 25], in some cases leading to significant upper limit on the Y production.

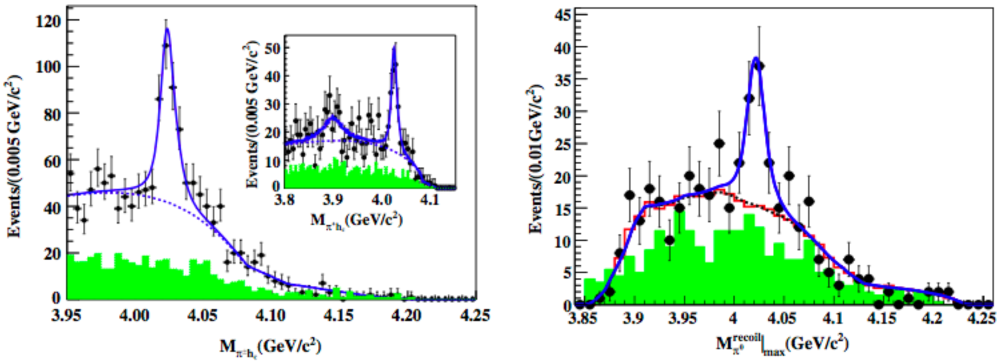

Figure 4: Sum of the simultaneous fits to the M($\pi^{\pm}h_c$) (left) and $M^{\rm recoil}_{\pi^0}|_{max}$ (right) distributions at $\sqrt{s} = 4.23, 4.26$ and 4.36 GeV/c^2. In the inset the invariant mass is extended down to 3.8 GeV/c^2 to include the $Z_c(3900)$. Dots with error bars are the data, shaded histograms are the normalized sideband background, the solid curve shows the total fit and the dotted curves are the background from the fit.

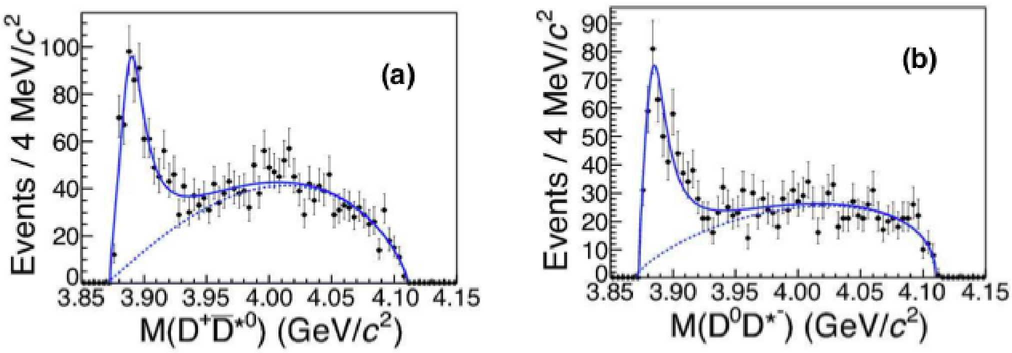

Figure 5: $M(D^0\bar{D}^{*-})$ (a) and $M(D^+\bar{D}^{*0})$ (b) invariant mass.

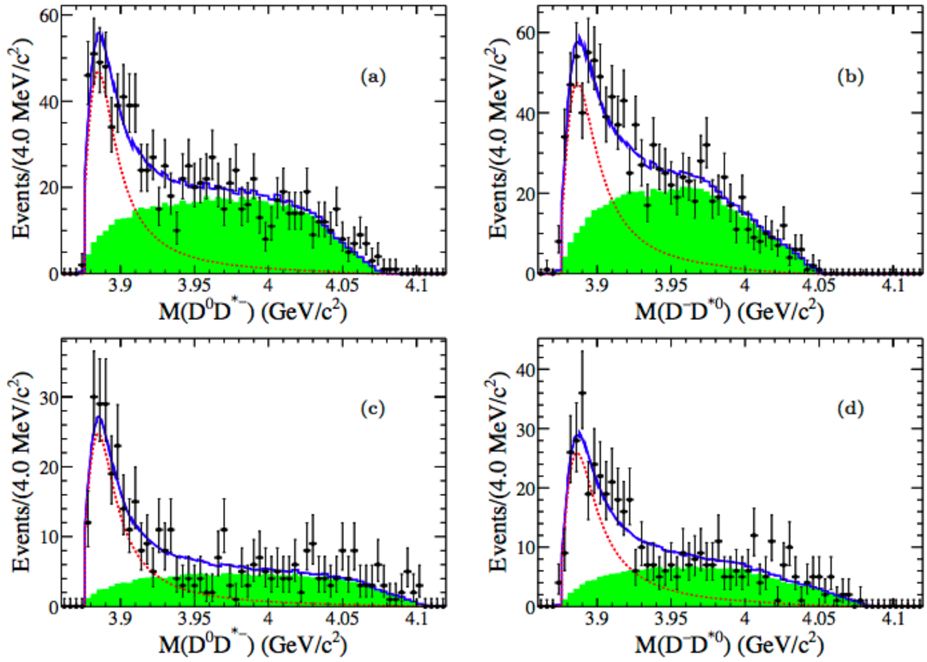

Figure 6: Simultaneous fits to the $M(D\bar{D}^{*})$ distributions at $\sqrt{s} = 4.23$ GeV (a,b) and 4.26 GeV (c,d).

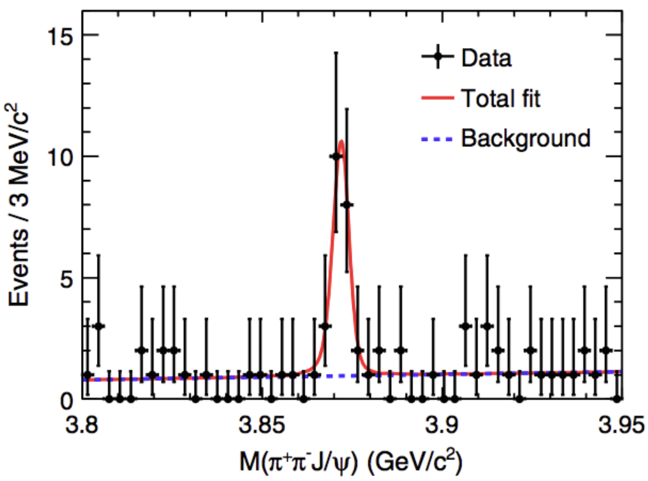

Figure 7: Invariant mass of $\pi^{+}\pi^{-}J/\psi$. The dots with errors are the data, the red solid line is the total fit and the dashed blue line is the background from the fit.

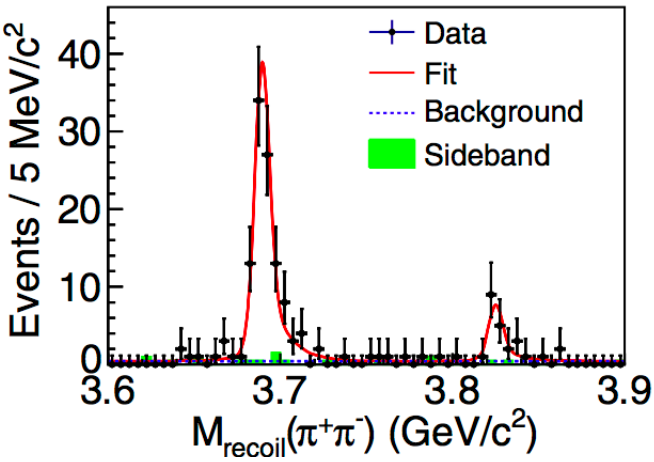

Figure 8: Evidence of the $X(3823)$ in the reconstructed recoil mass of $\pi^+\pi^-$.

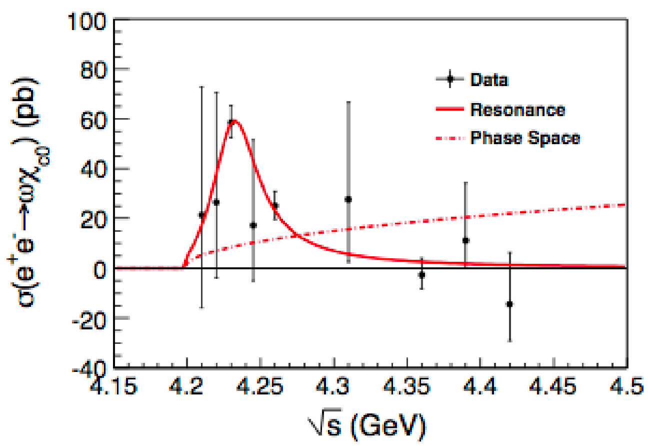

Figure 9: $\sigma(e^+e^- \to \omega\chi_{c0})$ as a function of the $\sqrt{s}$. It is evident the endorsed cross section around 4.23 GeV, interpreted as a Y resonance.

7. Conclusions

The outstanding amount of data provided by the BESIII experiment at BEPC-II collider in Beijing allowed the collaboration to make significant studies of the exotic charmonium states. The discovery of the $Z_c(3900)$ is one of the highlights of the year 2013 in HEP. The details of each decay/production channel cannot be reported in a single paper. Since the nature of these states is still unclear, more data are needed to deeply understand their quark structure. The data taking campaign is still ongoing with plans to upgrade the apparatus to improve all these measurements.

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