

Charm physics and XYZ states at BESIII

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Abstract. The BESIII Experiment at the Beijing Electron Positron Collider (BEPC2) collected large data samples for electron-positron collisions with c.m. energy above $4 \text{ GeV}/c^2$ during 2013 and 2014. The analysis of these samples has resulted in a number of surprising discoveries, such as the discoveries of the electrically charged "Zc" structures, which, if resonant, cannot be accommodated in the traditional charm quark and anti-charm quark picture of charmonium. In this talk, we will review the current status of the analyses of the Zc structures, as well as a number of other interesting features in the new BESIII data samples. We'll also present the recent charm physics results from BESIII.

1. Introduction

BEPCII is a double ring e^+e^- collider in Beijing, China with the design luminosity of $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and the design c.m. energy $2.0 - 4.2 \text{ GeV}/c^2$. After the 2012 upgrade of BEPCII LINAC, the maximum c.m. energy was increased up to 4.6 GeV , making possible to study the XYZ states. BESIII is a general purpose 4π detector located at the BEPCII storage ring. Since 2009, the BESIII experiment has accumulated the world largest samples of J/ψ , $\psi(2S)$, $\psi(3770)$ and $Y(4260)$, as well as large 1.3 fb^{-1} R scan data sample and XYZ data at higher energies.

2. Charm physics at BESIII

There are several objectives for studying charmonia decays above open-charm threshold at BESIII. The open-charm physics program at BESIII includes studying pure leptonic, semileptonic and hadronic charm meson decays, searches for CP violations, neutral D mixing, rare or forbidden decays. The latter are sensitive to physics beyond the Standard Model.

Studies of leptonic and semileptonic decays of D mesons are the preferred way to determine the magnitude of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, $|V_{cs}|$ and $|V_{cd}|$, since the strong interaction binding can be described by the hadronic form factors or decay constants, which can be calculated, for instance, by Lattice QCD. Accessing these CKM matrix elements provides the way to test the unitarity of the CKM matrix. On the other hand, the CKM unitarity puts the constraints on $|V_{cs}|$ and $|V_{cd}|$ values. Using the CKM element values as an input, it's possible to access, for instance, $f_{D \rightarrow K/\pi}(q^2)$ hadronic form factors and other form factors with a great precision, providing a way to verify and calibrate the Lattice QCD calculations [7]. Although the statistics on charm physics available at the BESIII is significantly lower than that available on B- and super-B factories, the production at threshold provides extremely clean environment. Another important feature is the ability to use a tagging technique which allows to measure the absolute branching ratios.[25]



The charmonium produced in e^+e^- collision decays into pair of charm mesons. For instance, at the open-charm threshold the $\psi(3770)$ decays into a pair of D mesons. If a decay of one D meson (“tagged decay”) has been fully reconstructed in an event, then the existence of another \bar{D} decay (“signal decay”) in the same event is guaranteed. The tagged decays are reconstructed in the channels with larger branching fractions and lower background levels.

To improve resolution, the following two variables are used for the tagged decay selection: the beam-constrained mass $M_{BC} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D|^2}$ and $\Delta E = E_D - E_{\text{beam}}$, where E_D and \vec{p}_D are the reconstructed energy and 3-momentum of the D^- candidate, and E_{beam} is the beam energy.

3. Analysis of the $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$

The semileptonic decay $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$ has received particular attention due to the relative simplicity of its theoretical description and the large branching fraction. The matrix element of the decay can be factorized as the product of the leptonic and hadronic currents, which makes it a natural place to study the $K\pi$ system in the absence of interactions with other hadrons, and the hadronic transition form factors. The analysis[6] was done mainly for two purposes:

- i) Measure the different $K\pi$ amplitudes that contribute to this decay, including S -wave and radially excited P -wave and D -wave components. Accurate measurements of these contributions can provide helpful information for the B -meson semileptonic decays.
- ii) Measure the q^2 dependent transition form factors, where q^2 is the invariant mass square of the lepton pair of the $e\nu_e$ system. They can be compared with hadronic model expectations and lattice QCD computations [1].

Using the single D-tagging technique, 18262 signal events with a background level of about 0.7% are selected. The branching fractions are measured over the full $m_{K\pi}$ (the invariant mass of $K\pi$ pair) range and in the K^* -dominated region, respectively: $\mathcal{B}(D^+ \rightarrow K^- \pi^+ e^+ \nu_e) = (3.71 \pm 0.03 \pm 0.08)\%$, $\mathcal{B}(D^+ \rightarrow K^- \pi^+ e^+ \nu_e)_{[0.8,1]} = (3.33 \pm 0.03 \pm 0.07)\%$.

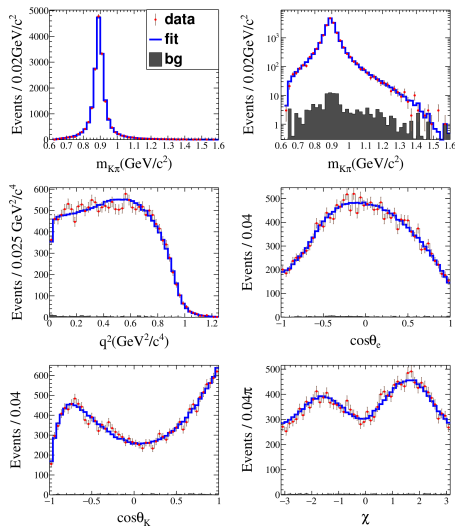


Figure 1. PWA solution and data projections of 5 kinematic variables.

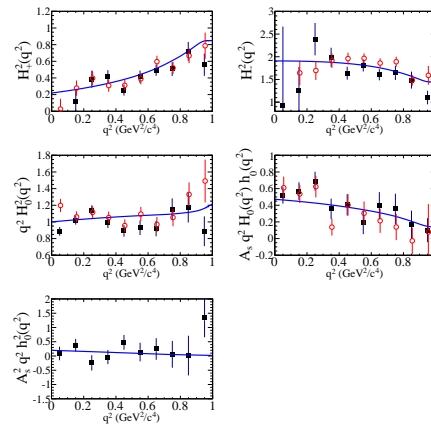


Figure 2. Model-independent helicity-basis form factor measurement results. Black dots: BESIII preliminary, red circles: CLEO-c[5], blue lines: BESIII preliminary PWA results.

A partial wave analysis (PWA) is also performed. It shows that the dominant $\bar{K}^*(892)^0$ component is accompanied by an S -wave contribution accounting for $(6.05 \pm 0.22 \pm 0.18)\%$ of the

total rate and that other components are negligible. The parameters of the $\bar{K}^*(892)^0$ resonance and of the form factors based on the spectroscopic pole dominance predictions are also measured. The vector pole mass m_V in this decay is measured for the first time: $m_V = 1.81^{+0.25}_{-0.17} \pm 0.01$ GeV/ c^2 .

By fitting the S -wave phase separately in 12 $m_{K\pi}$ bins, the S -wave phase variation with $m_{K\pi}$ is measured in a model-independent way and found to be in agreement with the PWA solution, which is based on the parameterization in the LASS scattering experiment.

Finally, a model-independent measurement of the q^2 dependence of the helicity form factors is performed using the projective weighting technique, which was introduced in Ref. [3]. It agrees well with the CLEO-c result[5] and the PWA solution (Fig. 2).

4. Study of $D^0 \rightarrow K^-/\pi^- e^+ \nu_e$

The study of dynamics of $D^0 \rightarrow K^- e^+ \nu_e$ and $D^0 \rightarrow \pi^- e^+ \nu_e$ decays published by BESIII last year is of particular interest. [12]

In this analysis, a careful selection procedure is performed to accurately measure both absolute and differential branching fractions of the said decays.

The absolute decay branching fractions are $\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033)\%$ and $\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.004 \pm 0.003)\%$. Using the differential form factors results, the products of hadronic form factors and the CKM matrix element $f_+^K(0)|V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$ and $f_+^\pi(0)|V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$ are determined.

Using the values of $|V_{cd(s)}|$ from SM constraint fit [13], the hadronic form factors f_+^K and f_+^π are extracted and their ratio is compared to LQCD and light cone sum rule (LCSR) calculations.

In turn, the values of $f_+^K(\pi)(0)$ calculated with LQCD and the measured $f_+^K(0)|V_{cd(s)}|$ products are used to extract the values of CKM matrix elements. The measurements of the said products are most precise to date and would give more precise values of $|V_{cs}|$ and $|V_{cd}|$ with their uncertainties decreasing to 0.6% and 1.4% respectively when the uncertainty in form factors calculation could be ignored (Fig. 3,4).

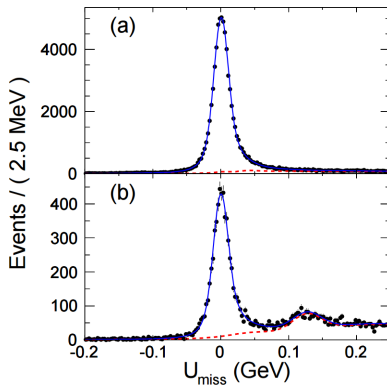


Figure 3. U_{miss} distributions of events for $D^0 \rightarrow K^- e^+ \nu_e$ and $D^0 \rightarrow \pi^- e^+ \nu_e$.

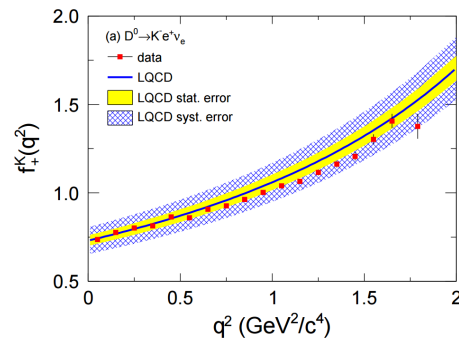


Figure 4. Comparison of the measured K form factor (squares with error bars) with the LQCD calculations [12][14].

5. Study of $D^+ \rightarrow \omega e^+ \nu_e$ and search for $D^+ \rightarrow \varphi e^+ \nu_e$

The amplitude analysis of $D^+ \rightarrow \omega e^+ \nu_e$ four-body decay is performed for the first time [15]. The single pole (SPD) model form factor ratios are calculated: $r_V = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06$ and $r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$. The absolute decay branching ratio is determined: $\mathcal{B}(D^+ \rightarrow \omega e^+ \nu_e) = (1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$.

In addition, the decay $D^+ \rightarrow \varphi e^+ \nu_e$ is searched for. The updated upper limit on the branching ratio is established: $\mathcal{B}(D^+ \rightarrow \varphi e^+ \nu_e) < 1.3 \times 10^{-5} (@90\% C.L.)$.

6. Observation of $D^+ \rightarrow \omega\pi^+$ and evidence for $D^0 \rightarrow \omega\pi^0$

The searches for singly Cabbibo-suppressed decays $D^+ \rightarrow \omega\pi^+$ and $D^0 \rightarrow \omega\pi^0$ are performed. Using the double D tag technique, the absolute branching fractions $\mathcal{B}(D^+ \rightarrow \omega\pi^+) = (2.79 \pm 0.57 \pm 0.16) \times 10^{-4}$ and $\mathcal{B}(D^0 \rightarrow \omega\pi^0) = (1.17 \pm 0.34 \pm 0.07) \times 10^{-4}$ are measured with the significance of 5.5σ and 4.1σ respectively. The $D^+ \rightarrow \omega\pi^+$ decay is observed for the first time [16].

7. XYZ States (Fig. 5)

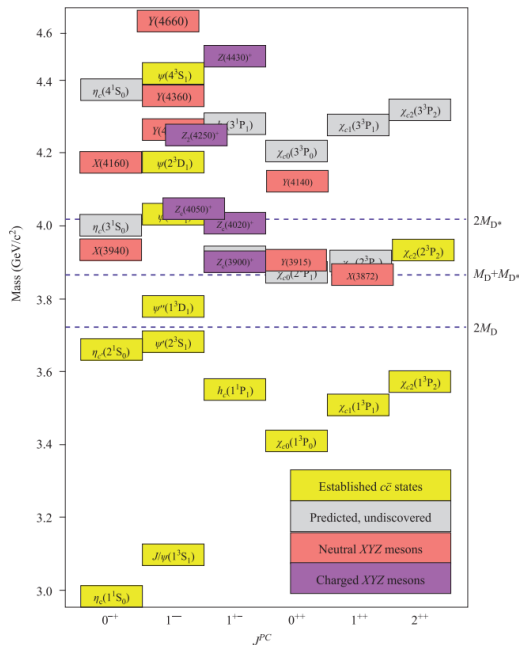


Figure 5. During the past decade strong evidence for mesons that do not fit into the $q\bar{q}$ scheme of the quark model has been accumulating. They include charmonium- (and bottomonium-) like states, called XYZ mesons, which do not fit into $c\bar{c}$ level scheme. [8]

In addition to $q\bar{q}$ mesons and qqq baryons of the original quark model [10], the QCD allows color-singlet states with a more complex structure. These “exotic” states include dibaryon, pentaquark, $qq + q\bar{q}$, loosely bound dimeson molecule and $q\bar{q}g$ hybrid state as well as glueball.

In 2013, using the data collected at $\sqrt{s} = 4.26 \text{ GeV}$, BESIII Collaboration observed charged charmoniumlike state $Z_c(3900)$. [11] Following this observation, the data collection plan was changed, which led to a number of significant results. [9]

8. Z_c states at BES-III

A charged charmoniumlike particle $Z_c(3900)^+$ has been observed through its $\pi^\pm J/\psi$ decay channel on BESIII, Belle and CLEO-c [11][19][20]. The state lies very close to the $D\bar{D}^*$ production threshold. Another Z_c state called $Z_c(3885)^+$ has been discovered by BESIII in $e^+e^- \rightarrow \pi^\pm(D\bar{D})^\mp$ process.

These states are coupled to charmonium and at the same time have a non-zero electric charge, which means that they cannot be described by conventional quark model as $q\bar{q}$ mesons.

In 2015, BESIII observed the state in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ decay with a mass $M = (3894.8 \pm 2.3 \pm 3.2) \text{ MeV}/c^2$ and significance of 10.4σ [18]. This state can be interpreted as $Z_c(3900)^0$, a neutral partner to $Z_c(3900)^+$, thus establishing an isospin triplet.

In another paper published by BESIII last year [21], the aforementioned $Z_c(3885)^+$ state is confirmed ($> 10\sigma$) using a double tag technique on larger data set at $\sqrt{s} = 4.23, 4.26 \text{ GeV}$. The polar angular distribution of the $\pi^\pm Z_c(3885)^\mp$ is found to be consistent with $J^P = 1^+$.

Finally, two neutral states were recently found by BESIII. The first one with the mass $M = (3885.7_{-5.7}^{+4.3} \pm 8.4) \text{ MeV}/c^2$ was observed in $e^+e^- \rightarrow \pi^0(D\bar{D}^*)^0$ process with the significance of 12σ [22]. Another state with the mass $M = (4025.5_{-4.7}^{+2.0} \pm 3.1) \text{ MeV}/c^2$ was discovered in $e^+e^- \rightarrow \pi + (D^*\bar{D}^*)$ decays (5.9σ significance) [23]. These states are attributed to the neutral partners of previously observed $Z_c(3885)^+$ and $Z_c(4025)^+$ [24] respectively, thus establishing two isospin triplets.

9. Summary

The recent progress in the charm physics and XYZ physics at BESIII are reported. A number of the analyses of a semileptonic, leptonic and rare D decays were published last year. More analyses are being performed at the moment using the high accumulated statistics for $D\bar{D}$, $D_s^+D_s^-$ and $\Lambda_c^+\Lambda_c^-$.

In 2013-2015, BESIII observed a total of four charged Z_c states: $Z_c(3900)^+$, $Z_c(3885)^+$, $Z_c(4020)^+$ and $Z_c(4025)^+$, and four neutral states, which can be associated with the charged ones. The nature of these states is yet to be discovered.

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