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Recent results from BESIII experiment

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The BESIII experiment at the BEPCII storage ring has accumulated the world's largest data samples in the τ-charm energy region, that are used for investigations of conventional and exotic hadrons, weak decays of the charmed particles, and searches for new physics. In this talk, we report the recent progress in these fields, including new results about the charmoniumlike states $X(3872)$, $Y(4260)$, and $Z_c(3900)$; the glueball candidates; the pure leptonic and semileptonic decays of D and D_s; and the baryon properties produced in e^+e^- annihilation.

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1. The BESIII experiment

The BESIII experiment is located at the campus of the Institute of High Energy Physics of Chinese Academy of Sciences in Beijing. The BESIII detector is a magnetic spectrometer [1] located at the Beijing Electron Positron Collider (BEPCII) [2]. The cylindrical core of the BESIII detector consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T (0.9 T in 2012) magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The acceptance of charged particles and photons is 93% over 4π solid angle. The charged-particle momentum resolution at 1 GeV$/c$ is 0.5%, and the dE/dx resolution is 6% for the electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution of the TOF barrel part is 68 ps, while that of the end cap part is 110 ps. The end cap TOF system is upgraded in 2015 with multi-gap resistive plate chamber technology, providing a time resolution of 60 ps [3].

The BESIII started taking data for physics in 2009. During its first ten years of operation, BESIII accumulated the world's largest data samples of 2.9 fb^{-1} D meson decays at the center-of-mass energy (E_{CM}) 3.773 GeV, and 3.2 fb^{-1} D_s meson decays at $E_{CM} = 4.178$ GeV, 10 billion J/ψ events, 0.5 billion $\psi(3686)$ events, and about 12 fb^{-1} data with E_{CM} between 4 and 4.6 GeV for studies of charmoniumlike states (XYZ states) and the Λ_c^+. BESIII also accumulated about 2 fb^{-1} data with E_{CM} between 2 and 4.6 GeV with fine step to study the hadron production cross sections and baryon properties. We report recent results in the studies of the XYZ states, the light hadron spectroscopy, charm decays, and first observation of hyperon polarization in e^+e^- annihilation. For a recent review of the BESIII physics program, please refer to Ref. [4].

2. New results on XYZ particles

In the conventional quark model, mesons are composed of one quark and one anti-quark, while baryons are composed of three quarks. However, many charmoniumlike states were discovered at two B-factories BaBar and Belle [5]. Whereas some of these are good candidates of charmonium states, many other states have exotic properties, which may indicate that exotic states, such as multi-quark state, hadronic molecule, or hybrid, have been observed [6].

BaBar and Belle experiments finished their data taking in 2008 and 2010, respectively, and the data are still used for various physics analyses. BESIII started the study of the XYZ particles since 2011 [7].

2.1 Evidence for $Z_c(3900) \to \rho\eta_c$

The BESIII experiment studied the $e^+e^- \to \pi^+\pi^- J/\psi$ process at $E_{CM} = 4.26$ GeV using a 525 pb^{-1} data sample and discovered the charged charmoniumlike state $Z_c(3900)$ [8].

BESIII searches for $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$ and intermediate states decay into $\rho\eta_c$ with data collected at 4.23, 4.26, and 4.36 GeV [9]. The recoil mass of one charged pion (equivalent to the invariant mass of $\rho^\pm\eta_c$) is shown in Fig. 1 for the data at $\sqrt{s} = 4.23$ GeV, the $Z_c(3900)^\pm$ signal is found while there is no significant $Z_c(4020)^\pm$ signal. The $\rho^\pm\eta_c$ invariant mass distribution is fitted with the contributions from $Z_c(3900)$ and $Z_c(4020)$ together with a smooth background. 240^{+56}_{-54} $Z_c(3900)^{\pm}$ events is observed with a statistical significance of 4.3σ (3.9σ including the systematical uncertainty). The $Z_c(3900)$ signals at other c.m. energies and the $Z_c(4020)$ signals at all the c.m. energies are not statistically significant.

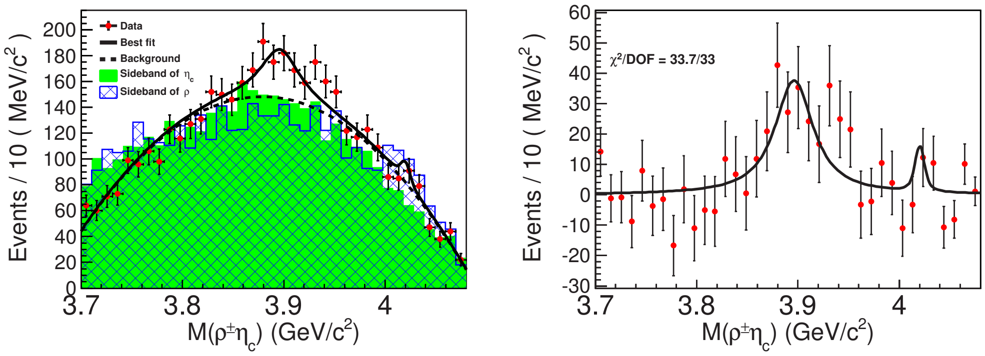

Figure 1: The $\pi^{\pm}$ recoil mass distribution in $e^+e^- \to \pi^{\pm}\rho^{\mp}\eta_c$ at $\sqrt{s} = 4.23$ GeV and the fit with $Z_c(3900/4020)^{\pm}$ signals (left panel); and the same plot with background subtracted (right panel). Dots with error bars are data, shaded histogram is from η_c sidebands, normalized to the number of backgrounds from the fit, the solid lines are total fit and the dotted line is background.

Using the results from Ref. [10], the ratio of the branching fractions of different $Z_c(3900)^{\pm}$ decays is calculated as $R_{Z_c(3900)} = \frac{\mathscr{B}(Z_c(3900)\to\rho\eta_c)}{\mathscr{B}(Z_c(3900)\to\pi J/\psi)} = 2.2\pm0.9$ at $\sqrt{s} = 4.23$ GeV and less than 5.6 at $\sqrt{s} = 4.26$ GeV at the 90% C.L. These results can be used to test various models of interpreting the nature of the $Z_c(3900)$ and $Z_c(4020)$.

2.2 Observation of $e^+e^- \to D\bar{D}_1(2420) + c.c.$ and $\pi^+\pi^-\psi(3770)$

To study the vector charmonium and charmoniumlike states, BESIII measured the $e^+e^- \to \pi^+\pi^- D\bar{D}$ final state, including both charged and neutral D pairs [11]. By checking the intermediate states decay into $D\bar{D}$ and $D\pi^+\pi^-$, $e^+e^- \to \pi^+\pi^-\psi(3770)$ and $e^+e^- \to D\bar{D}_1(2420) + c.c.$ are observed.

The process $e^+e^- \to \pi^+\pi^-\psi(3770)$ is observed for the first time at $\sqrt{s} = 4.42$ GeV with a statistical significance of 5.2σ, and evidence is found at $\sqrt{s} = 4.26$ and 4.36 GeV with statistical significance of 3.2σ and 3.3σ, respectively. The cross sections and upper limits at 90% confidence level (C.L.) are shown in Fig. 2. Clear structure is found in the cross section distribution, but due to the limited statistics, it is not clear whether the events are from the $Y(4390)$ or the $\psi(4415)$ or any other resonance. The cross section line-shape around 4.4 GeV looks similar to that of the channel $e^+e^- \to \pi^+\pi^- X(3823)$ [12], but the cross sections are larger by an order of magnitude.

The cross section of $e^+e^- \to D\bar{D}_1(2420) + c.c.$ is measured with $D_1(2420)$ decays to $D\pi\pi$ or $D^*\pi$. The process $D^0\bar{D}_1(2420)^0 + c.c.$ is observed for the first time with $D_1(2420)^0 \to D^0\pi^+\pi^-$ mode at $E_{CM} = 4.42$ GeV with a significance of 7.4σ. Evidences for the same mode are found at 4.36 and 4.60 GeV with significances of 3.2σ and 3.3σ, respectively. No evident signal is found in $D_1(2420)^0 \to D^{*+}\pi^-$ mode. Evidences are also found in $D^+D_1(2420)^- + c.c.$ mode at 4.36 and 4.42 GeV with statistical significances of 3.1σ and 3.0σ. Upper limits at other energy points are determined.

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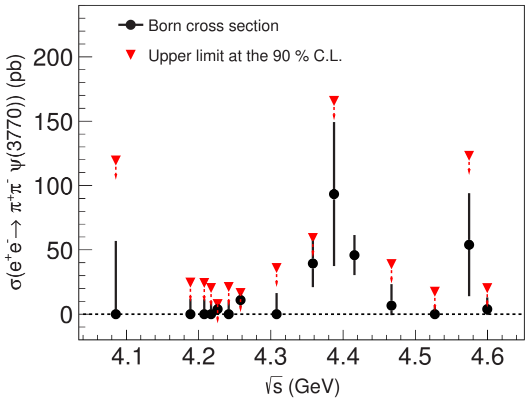

Figure 2: Cross sections of $e^+e^- \to \pi^+\pi^-\psi(3770)$ from the BESIII measurement. The dots with error bars are the central values of the cross sections, and the triangles are the upper limit at 90% C.L.

The products of the cross sections of $e^+e^- \to D\bar{D}_1(2420) + c.c.$ and the branching fractions of $D_1(2420) \to D\pi^+\pi^-$ or $D_1(2420) \to D^*\pi$ are shown in Fig. 3, which is at few tens pb level.

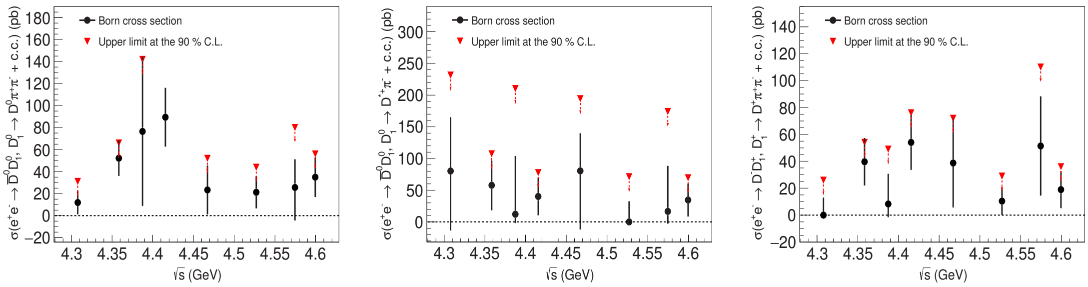

Figure 3: Cross sections of $e^+e^- \to D^0\bar{D}_1(2420)^0 + c.c. \to \pi^+\pi^- D^0\bar{D}^0$ (left), $e^+e^- \to D^0\bar{D}_1(2420)^0 + c.c. \to D^{*+}\bar{D}^0\pi^- \to \pi^+\pi^- D^0\bar{D}^0$ (middle), and $e^+e^- \to D^+D_1(2420)^- + c.c. \to \pi^+\pi^- D^+\bar{D}^-$ (right). The dots with error bars are the central values of the cross sections, and the triangles are the upper limit at 90% C.L.

A recent analysis with singly tagged D signal confirmed the above observations with improved significances [13].

2.3 Comprehensive study of $X(3872)$ decays

The $X(3872)$ was observed at BESIII with data sample at $E_{CM} = 4.23$, 4.26, and 4.36 GeV in the process $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$ [14].

Using all the data samples available at E_{CM} between 4.0 and 4.6 GeV, the other decay modes of the $X(3872)$ are measured and new decay modes are searched for. The decays $X(3872) \to \omega J/\psi$ [15], $\pi^0\chi_{c1}$ [16], $\bar{D}^0 D^{*0} + c.c.$, and $\gamma J/\psi$ are observed, while $X(3872) \to \gamma\psi(3686)$ and γD^+D^- are not significant (see Fig. 4). The ratios of the branching fractions of these modes to that of $X(3872) \to \pi^+\pi^- J/\psi$ are determined and shown in Table 1. The $X(3872) \to \omega J/\psi$ and $\pi^0\chi_{c1}$ are first observations, and confirm the big isospin violation in $X(3872)$ decays, and the absence of

$X(3872) \to \gamma\psi(3686)$ agrees with Belle measurement [17] and is much lower than the BaBar [18] and LHCb [19] measurements.

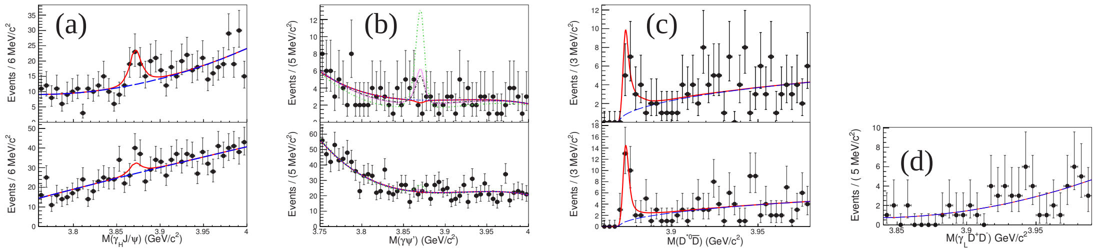

Figure 4: (a) Fit results for $X(3872) \to \gamma J/\psi$ where top panel is for $\mu^+\mu^-$ mode and bottom for e^+e^- mode. (b) Fit results for $X(3872) \to \gamma\psi(3686)$ where top panel is for $\pi^+\pi^- J/\psi$ mode and bottom for $\mu^+\mu^-$ mode. (c) Fit results for $X(3872) \to \bar{D}^0 D^{*0} + c.c.$ where top panel is for γD^0 mode and bottom for $\pi^0 D^0$ mode. (d) Fit results for $X(3872) \to \gamma D^+ D^-$. Dots with error bars are from data, red solid lines are the best fits, and blue dashed lines are the fitted backgrounds. The peaking curves in (b) are the expected signals according to the measurements from previous experiments.

Table 1: Relative branching fractions or the upper limit (UL) compared with $X(3872) \to \pi^+\pi^- J/\psi$.

mode	$\gamma J/\psi$	$\gamma\psi(3686)$	$\bar{D}^0 D^{*0} + c.c.$	$\gamma D^+ D^-$	$\omega J/\psi$	$\pi^0 \chi_{c1}$
ratio	0.79 ± 0.28	< 0.42	14.81 ± 3.80	< 0.99	$1.6^{+0.4}_{-0.3} \pm 0.2$	$0.88^{+0.33}_{-0.27} \pm 0.10$

3. Light hadron spectroscopy

3.1 PWA of J/ψ radiative decays

Radiative J/ψ decays proceed via the $J/\psi \to \gamma gg$ process and are expected to be ideal sources of glueballs. BESIII has performed systematic studies of radiative J/ψ decays using partial wave analysis (PWA) to search for and characterize glueball candidates.

The lowest mass scalar glueball is expected to have a mass between 1 and 2 GeV/c^2 and decay into meson pairs [20]. BESIII found three scalar mesons in this mass range in the radiative decay processes $J/\psi \to \gamma\pi^0\pi^0$ [21], $\gamma K^0_S K^0_S$ [22], and $\gamma\eta\eta$ [23]: the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. Of the three, the $f_0(1710)$ has the highest production rate; the branching fraction for $J/\psi \to \gamma f_0(1710)$ is nearly ten times higher than those for $f_0(1370)$ and $f_0(1500)$, and compatible with an LQCD calculated value for a glueball [24]. This suggests that the $f_0(1710)$ has the largest gluon component. Better measurements of the couplings of these states to $\pi^+\pi^-$, $K\bar{K}$, $\eta\eta$, and $\eta\eta'$ will supply additional insight into the relative $n\bar{n}$, $s\bar{s}$, and $\mathscr{G}$ content of these states.

The lowest lying tensor glueball is expected to have a mass above 2 GeV/c^2 [20], and PWA of $J/\psi \to \gamma K^0_S K^0_S$ [22], $\gamma\eta\eta$ [23], and $\gamma\phi\phi$ [25] revealed a tensor meson, the $f_2(2340)$, that decays to each one of these channels. However, its coupling to the $\pi\pi$ mode has not been established [21] and its total production rate appears to be substantially lower than the LQCD calculated value, which is of order 1% [26]. Much more effort is needed to establish and characterize the lowest tensor glueball.

3.2 States close to $p\bar{p}$ threshold in J/ψ decays

A narrow peak just at the $p\bar{p}$ threshold was observed in $J/\psi \to \gamma p\bar{p}$ by BESII experiment [27]. BESII also observed an $\eta'\pi^+\pi^-$ invariant mass peak in $J/\psi \to \gamma\eta'\pi^+\pi^-$ decays, the $X(1835)$ [28]. Subsequent BESIII studies of the $X(1835) \to \eta'\pi^+\pi^-$ line shape with 1.3 billion J/ψ events revealed an anomalous structure in its line shape at the $p\bar{p}$ threshold that could be equally well described as interference with a new narrow resonance that has a mass nearly equal to $2m_p$ or a wide resonance with an anomalously strong coupling to the $p\bar{p}$ final state [29].

States in this mass region were also reported in $J/\psi \to \omega\eta\pi^+\pi^-$ [30], $\gamma 3(\pi^+\pi^-)$ [31], and $\gamma\gamma\phi$ [32], and these also have line shape distortions near the $p\bar{p}$ mass threshold.

Coupled-channel PWA of the different processes may be the key for extracting reliable information from the data and for understanding the nature of the states in this mass region [33]. This is an important future direction for BESIII studies of light meson spectroscopy.

4. Charm meson decays

4.1 Pure leptonic decays of D^+ and D_s^+

The rates for purely leptonic charmed meson decays, $D_q^+ \to \ell^+\nu$ ($q = d$ or s; $\ell = e$, μ, or τ), are proportional to the product of $|V_{cq}|$, the relevant CKM matrix element, and $f_{D_q^+}$, the D_q^+-meson decay constant:

$$\Gamma(D_q^+ \to \ell^+\nu) = \frac{G_F^2 f_{D_q^+}^2}{8\pi}|V_{cq}|^2 m_\ell^2 m_{D_q^+}\left(1 - \frac{m_\ell^2}{m_{D_q^+}^2}\right)^2, \tag{4.1}$$

where m_ℓ is the lepton mass, and $m_{D_q^+}$ is the D_q^+-meson mass. Thus, determinations of $\Gamma(D_q^+ \to \ell^+\nu)$ directly measure the product $|V_{cq}|f_{D_q^+}$.

In a sample of 1.7M tagged $D^\pm$ mesons from $\psi(3770) \to D^+D^-$ decays, BESIII found 409 ± 21 $D^\pm \to \mu^\pm\nu$ signal events over a small background, corresponding to a world's best branching fraction measurement: $\mathscr{B}(D^+ \to \mu^+\nu) = (3.71 \pm 0.20) \times 10^{-4}$ [34], which translates to $f_{D^+}|V_{cd}| = (45.8 \pm 1.3)$ MeV. This result, in conjunction with the CKM matrix element $|V_{cd}|$ determined from a global SM fit [35], implies a value for the weak decay constant $f_{D^+} = 203.9 \pm 5.6$ MeV. Alternatively, using this result with an LQCD calculated value for f_{D^+} (212.7 ± 0.6 MeV) [36], one finds $|V_{cd}| = 0.2151 \pm 0.0060$. In either scenario, these are the most precise results for these quantities to date.

Recently, BESIII reported the first observation of $D^+ \to \tau^+\nu$ with $\tau \to \pi\nu$, with a significance of 5.1σ [39]. With 137 ± 27 observed signal events, the branching fraction is measured to be $\mathscr{B}(D^+ \to \tau^+\nu) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$. Taking the world average $\mathscr{B}(D^+ \to \mu^+\nu) = (3.74 \pm 0.17) \times 10^{-4}$ [35], the ratio $R_{\tau/\mu} = \Gamma(D^+ \to \tau^+\nu)/\Gamma(D^+ \to \mu^+\nu) = 3.21 \pm 0.64 \pm 0.43$ is obtained, which is consistent with the Standard Model expectation of lepton flavor universality (LFU). Using external inputs, these results give values for the D^+ decay constant f_{D^+} and the CKM matrix element $|V_{cd}|$ that are consistent with, but less precise than, other determinations.

BESIII also reported a measurement of $\mathscr{B}(D_s^+ \to \mu^+\nu)$ with 0.39M tagged D_s^+ mesons produced via $e^+e^- \to D_s^+D_s^{*-} + c.c.$ at $E_{CM} = 4.178$ GeV [37]. The 1139 ± 33 $D_s^\pm \to \mu^\pm\nu$ signal events were used to determine $\mathscr{B}(D_s^+ \to \mu^+\nu) = (5.49 \pm 0.22) \times 10^{-3}$, which corresponds to

$f_{D_s^+}|V_{cs}| = 246.2 \pm 5.0$ MeV. If $|V_{cs}|$ is fixed at its latest global SM fit value [35], the D_s^+ decay constant is determined to be $f_{D_s^+} = 252.9 \pm 5.1$ MeV. Alternatively, fixing $f_{D_s^+}$ at its value from recent LQCD calculations (249.9 ± 0.4 MeV) [36, 38], yields $|V_{cs}| = 0.985 \pm 0.020$. Either of these measurements qualify as the currently most precise value.

4.2 Semileptonic decays $D^0 \to \pi^- \ell^+ \nu$ and $K^- \ell^+ \nu$

Semileptonic decay rates, in conjunction with form factors determined from LQCD calculations, provide independent measurements of the $|V_{cs}|$ and $|V_{cd}|$. The most relevant measurements are for the $D^0 \to K^- \ell^+ \nu$ and $\pi^- \ell^+ \nu$ decay channels, with $\ell = e$ or μ.

The channels $D^0 \to K^- e^+ \nu$ and $D^0 \to \pi^- e^+ \nu$ were published four years ago [40]. The branching fractions of $D^0 \to K^- \mu^+ \nu$ (47K observed events) and $\pi^- \mu^+ \nu$ (2.3K observed events) are measured recently to be $(3.413 \pm 0.040)\%$ [41] and $(0.272 \pm 0.010)\%$ [42], respectively, with significantly improved precision compared with previous measurements. With $|V_{cs}|$ taken from a SM constrained fit [35], $f_+^K(0) = 0.7327 \pm 0.0049$ is obtained, in good agreement with the form factor measured in electronic mode with comparable precision.

Since the same hadronic form factors occur in $\pi/K e^+ \nu$ and $\pi/K \mu^+ \nu$ decays, they cancel in the ratio of branching fractions allowing for a model-independent test of LFU. The results listed above correspond to branching fraction ratios of $\mathscr{R}_\pi^0 \equiv \frac{\mathscr{B}(D^0 \to \pi^- \mu^+ \nu)}{\mathscr{B}(D^0 \to \pi^- e^+ \nu)} = 0.922 \pm 0.037$, and $\mathscr{R}_\pi^+ \equiv \frac{\mathscr{B}(D^+ \to \pi^0 \mu^+ \nu)}{\mathscr{B}(D^+ \to \pi^0 e^+ \nu)} = 0.964 \pm 0.045$ [42]. These are compatible with LFU-based theoretical expectations: $\mathscr{R}_\pi = 0.985 \pm 0.002$ [43, 44], within 1.7σ and 0.5σ, respectively. A study of the ratios of differential branching fractions for different four-momentum transfer regions was also performed [41, 42], and no evidence for LFU violation was found.

5. Hyperon polarization in e^+e^- annihilation

Baryons produced directly via e^+e^- annihilation into baryon anti-baryon ($B\bar{B}$) pairs or $J/\psi \to B\bar{B}$ decays can be polarized transversely due to a non-zero relative phase $\Delta\Phi$ between two complex amplitudes govern the process [45, 46]. This non-zero polarization enables separate measurements of the parity violating decay parameters for Λ and $\bar{\Lambda}$ and a comparison of them to test CP symmetry.

With 1.3B J/ψ events collected in 2009 and 2012, a total of 420K fully reconstructed $J/\psi \to \Lambda\bar{\Lambda}$ events with $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ were isolated with a nearly negligible, 400-event background. The data are described well with a large relative phase $\Delta\Phi = (42.4 \pm 0.8)^\circ$ while $\Delta\Phi = 0$ is clearly excluded by the data. The θ_Λ-dependent Λ ($\bar{\Lambda}$) transverse polarization, $P_y(\cos\theta_\Lambda)$, varies between -25% and $+25\%$ as a function of θ_Λ, the Λ direction relative to the e^+e^- beam axis [47].

BESIII's measured value of the $\Lambda \to p\pi^-$ parity-violating decay asymmetry parameter, $\alpha_- = 0.750 \pm 0.010$, differs by more than five standard deviations from the previous world average value of $\alpha_- = 0.642 \pm 0.013$ [35]. The measured decay asymmetry parameter for $\bar{\Lambda} \to \bar{p}\pi^+$ is $\alpha_+ = -0.758 \pm 0.012$, and consistent with the CP conserving expectation that $\alpha_+ = -\alpha_-$. These results translate into $A_{CP} \equiv (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+) = -0.006 \pm 0.014$, and provide a factor of two improvement in sensitivity over the best previous Λ-based measurement, $A_{CP} = +0.013 \pm 0.022$ [48], but still well above the SM expectation of $A_{CP}^{\rm SM} \sim 10^{-4}$ based on the CKM mechanism [49].

6. Summary and Perspectives

BESIII has achieved a lot in the studies of charm physics, hadron physics, τ physics, and so on, using the data samples collected in the τ-charm energy region. BESIII has now accumulated 10 billion J/ψ events for the study of light hadron spectroscopy, and also large data samples for charm physics. With the discovery of the charged charmoniumlike states $Z_c(3900)$ and $Z_c(4020)$, BESIII is also playing important role in the study of exotic states with charm quark, and this requires more data at E_{CM} above 4 GeV.

In support of this program and also other potential physics, the luminosity performance of BEPCII is being upgraded and the maximum center-of-mass energy is being increased. The topup injection of the accelerator increases the time-integrated luminosity by about 30%. A two-year-long program that involves upgrading the ring magnet power supplies and replacing some critical magnets will extend the maximum E_{CM} from 4.6 to 4.9 GeV. This will provide full coverage of the $Y(4660)$, improve the production rate of Λ_c baryons, and more results are expected from BESIII.

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