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Searches for baryon and lepton number violations at BESIII

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Based on the data samples of $(1310.6 \pm 7.0) \times 10^6$ J/ψ events at the center-of-mass energy of $\sqrt{s} = 3.097$ GeV and 2.93 fb^{-1} at $\sqrt{s} = 3.773$ GeV, BESIII has searched for baryon number violation (BNV) and lepton number violation (LNV) processes in J/ψ, Σ^-, and D decays, respectively. No signal events are observed, and the corresponding upper limits on the branching fraction are determined. The Λ-$\bar{\Lambda}$ oscillation is also investigated in J/ψ decays, and the upper limits on the oscillation rate and oscillation parameter are extracted.

Keywords: Baryon number violation; Lepton number violation; Λ-$\bar{\Lambda}$ oscillation; BESIII.

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1. Introduction

The observed matter-antimatter asymmetry in the universe composes a serious challenge to our understanding of nature. In order to explain this asymmetry, Sakharov has proposed three conditions [1]: baryon number violation (BNV), CP invariance violation, and thermodynamic equilibrium violation. But in the standard model (SM), the baryon number is conserved as a consequence of the $SU(2) \times SU(1)$ and $SU(3)$ gauge symmetries. So searches for BNV processes will provide good opportunities to probe new physics beyond the SM, and shed light on the evolution of the universe. In addition, the neutrino oscillation observed by different experiments [2–4] indicates that the neutrinos have a tiny mass. And then it is very important to understand the nature of neutrinos: Dirac or Majorana neutrino. If the latter one, one can investigate the lepton number violation (LNV) processes with exchanging a Majorana neutrino, such as three-body or four-body decays of K, B, and D mesons, as well as τ lepton [5–7].

At BESIII, the BNV and LNV analyses in J/ψ, Σ^- and D decays have been performed by utilizing the data samples of $(1310.6 \pm 7.0) \times 10^6$ J/ψ events [8] at the center-of-mass energy of $\sqrt{s} = 3.097$ GeV, and 2.93 fb^{-1} at $\sqrt{s} = 3.773$ GeV [9], respectively. The D decays have been performed in the events of $\psi(3770) \to D\bar{D}$ with the numbers of total D^+D^- and $D^0\bar{D}^0$ pairs to be $(8,296 \pm 31 \pm 64) \times 10^3$ and $(10,597 \pm 28 \pm 98) \times 10^3$ [9]. Unless explicitly stated, charge-conjugated channels are also implied in the text.

2. J/ψ decays

2.1. $J/\psi \to \Lambda_c^+ e^-$

The $J/\psi \to \Lambda_c^+ e^-$ decay studied at BESIII [10] is the first constraint of BNV from charmonium decays. In the analysis, the Λ_c^+ is reconstructed by the combination of $pK^-\pi^+$, and its decay mechanism is modelled with the partial wave analysis result [11] by considering the nonresonant three-body decay, intermediate states: Δ^{++}, $\Delta(1600)^{++}$, excited Λ states, excited Σ states, as well as their interferences. Figure 1 shows the distribution of the invariant mass of $pK^-\pi^+$ ($M_{pK^-\pi^+}$), and no signals are observed in the signal region of Λ_c^+ mass. The upper limit (UL) on the branching fraction (BF) of $J/\psi \to \Lambda_c^+ e^-$ at 90% confidence level (CL) is set to be 6.9×10^{-8}, based on the frequentist method [12] with unbounded profile likelihood treatment of systematic uncertainties.

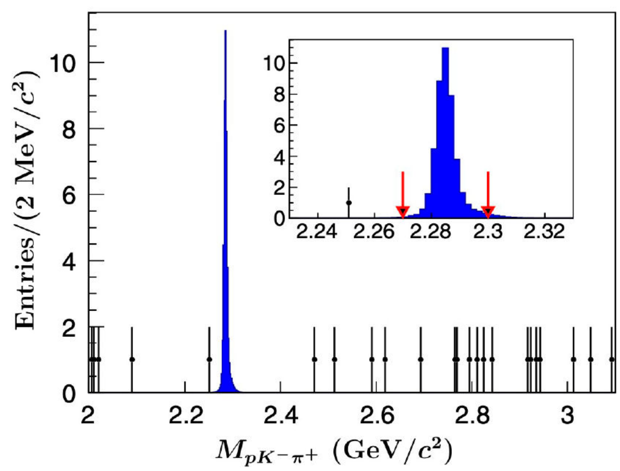

FIGURE 1. The distribution of $M_{pK^-\pi^+}$ in $J/\psi \to \Lambda_c^+(\to pK^-\pi^+)e^-$ decay. The dots with error bars are from data, and the blue filled histogram is from the signal MC simulation. The range between the two red arrows in the inset plot is the signal range of Λ_c^+ mass.

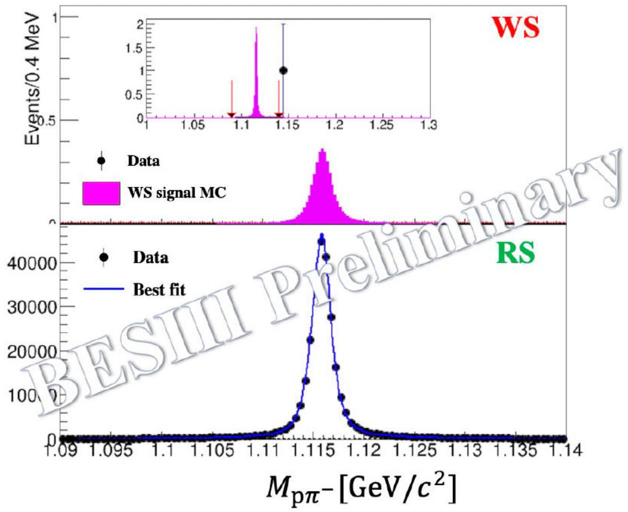

FIGURE 2. The BESIII preliminary results of $M_{p\pi^-}$ distributions in WS $J/\psi \to pK^-\Lambda(\to p\pi^-)$ decay , and RS $J/\psi \to pK^-\bar{\Lambda}(\to \bar{p}\pi^+)$ decay. The dots with error bars are from data, the blue solid line is the best fit, and the magenta filled histogram is the WS signal MC shape.

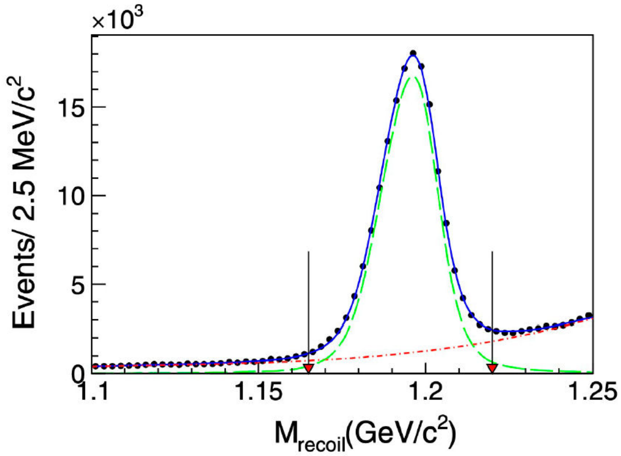

FIGURE 3. Fittting result of $M_{\rm recoil}$ distribution in ST events of $J/\psi \to \bar{\Sigma}(1385)^+\Sigma^-$ decay. The dots with error bars are from data, the blue solid line is the best fit, the green dashed line is the signal shape, and the red dotted-dashed line is the background shape. The range between the two arrows is the signal region of Σ^- mass.

2.2. Λ-$\bar{\Lambda}$ oscillation

BESIII reported the preliminary result of searching for the Λ-$\bar{\Lambda}$ oscillation in $J/\psi \to pK^-\bar{\Lambda}$ decay [13]. The right sign (RS) is $J/\psi \to pK^-\bar{\Lambda}(\to \bar{p}\pi^+)$, and the wrong sign (WS) is $J/\psi \to pK^-\Lambda(\to p\pi^-)$. No signals are observed in the signal region of Λ mass from the wrong sign mode, as shown in Fig. 2. The UL on the oscillation rate at 90% CL is set to be 4.4×10^{-6}, and the UL on oscillation parameter at 90% CL is estimated to be 3.8×10^{-15} MeV.

3. Σ^- decays

3.1. $\Sigma^- \to pe^-e^-$ and Σ^+X

In $\Sigma^- \to pe^-e^-$ and Σ^+X decays, the two down-type (d or s) quarks convert into two up-quarks [14, 15], which is very similar to neutrinoless double beta decays.

At BESIII, the Σ^- is produced from $J/\psi \to \bar{\Sigma}(1385)^+\Sigma^-$ [16]. Firstly, the $\bar{\Sigma}(1385)^+$ candidates are fully reconstructed with $\bar{\Sigma}(1385)^+ \to \pi^+\bar{\Lambda}(\to \bar{p}\pi^+)$, which is called as single tag (ST). And then, a fit to the recoil mass of $\bar{\Sigma}(1385)^+$ ($M_{\rm recoil}$) is performed, as shown in Fig. 3. The number of observed ST events is $N_{\rm ST} = 147743 \pm 563_{\rm stat.}$, and the BF of $J/\psi \to \bar{\Sigma}(1385)^+\Sigma^-$ is measured to be $(3.21 \pm 0.07_{\rm stat.}) \times 10^{-4}$. In the recoil side of the selected ST events, the Σ^- is studied with $\Sigma^- \to pe^-e^-$ and Σ^+X decays, which is called as double tag (DT). Here $\Sigma^+ \to p\pi^0$ and X means generic decays. Figure 4 shows the $M_{\rm recoil}$ of DT events, where no signals survived in the signal region of Σ^- mass. The UL on the BF of $\Sigma^- \to pe^-e^-$ is estimated to be 6.7×10^{-5}, while is 1.2×10^{-4} for $\Sigma^- \to \Sigma^+X$.

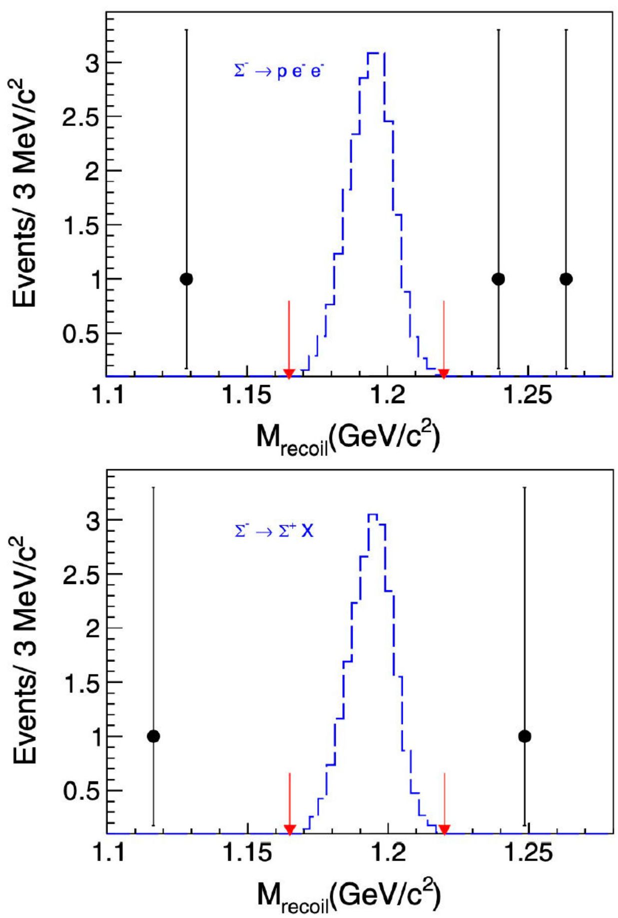

FIGURE 4. The $M_{\rm recoil}$ distributions in DT events of $J/\psi \to \bar{\Sigma}(1385)^+\Sigma^-$ decay with (a) $\Sigma^- \to pe^-e^-$ and (b) $\Sigma^- \to \Sigma^+X$. The dots with error bars are from data, and the blue dashed lines are from the signal MC simulations. The range between the two red arrows is the signal range of Σ^- mass.

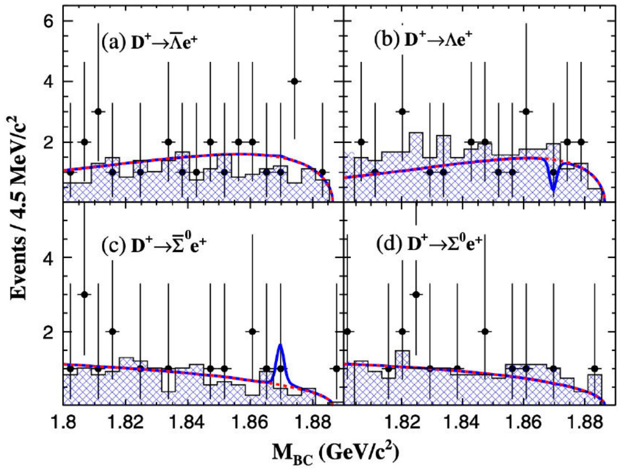

FIGURE 5. Fitting results of $M_{\rm BC}$ distributions for (a) $D^+ \to \bar{\Lambda}e^+$, (b) $D^+ \to \Lambda e^+$, (c) $D^+ \to \bar{\Sigma}^0 e^+$ and (d) $D^+ \to \Sigma^0 e^+$. The dots with error bars are from data, the blue sold lines are the best fits, the red dashed lines are the background components described with an ARGUS function, and the blue hatched histograms are the normalized MC-simulated backgrounds.

4. D decays

4.1. $D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+$ and $\Lambda(\Sigma^0)e^+$ decays

With a higher generation supersymmetry model, the predicted BF of $D^+ \to \bar{\Lambda}\ell^+(\ell = e, \mu)$ decay is no more than the level of 10^{-29} [17]. At BESIII, a blind analysis technique is adopted to search for $D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+$ and $\Lambda(\Sigma^0)e^+$ decays [18] with $\Sigma^0 \to \gamma\Lambda$, $\Lambda \to p\pi^-$. In an event, the best D^+ candidate is selected with the smallest $|\Delta E|$ for a specific signal mode, where ΔE is calculated with the formula

$$\Delta E = E_{D^+} - E_{\rm beam}. \quad (1)$$

Here E_{D^+} is the energy of the reconstructed D^+ candidate, and $E_{\rm beam}$ is the beam energy. And then, a maximum likelihood fit to the beam-constraint mass ($M_{\rm BC}$) is performed, where

$$M_{\rm BC} = \sqrt{E^2_{\rm beam} - |\vec{p}_{D^+}|^2}, \quad (2)$$

with $\vec{p}_{D^+}$ being the three-momentum of the reconstructed D^+ candidate. The fitting results are shown in Fig. 5. No significant signals are observed with the current statistics.

The ULs on signal events at 90% CL is set by scanning the normalized likelihood value (λ) with a given number of signal events in the $M_{\rm BC}$ fit. Here, the scanned λ curve is convolved with a Gaussian function, of which the corresponding width is incorporating the systematic uncertainties. The ULs on the BFs of $D^+ \to \Lambda e^+$, $\bar{\Lambda}e^+$, $\Sigma^0 e^+$, and $\bar{\Sigma}^0 e^+$ at 90% CL are then set to be 1.1×10^{-6}, 6.5×10^{-7}, 1.7×10^{-6}, and 1.3×10^{-6}, respectively.

4.2. $D \to K\pi e^+e^+$ decays

We also searched for the LNV $D^0 \to K^-\pi^-e^+e^+$, $D^+ \to K^0_S\pi^-e^+e^+$, and $D^+ \to K^-\pi^0e^+e^+$ decays [19], which

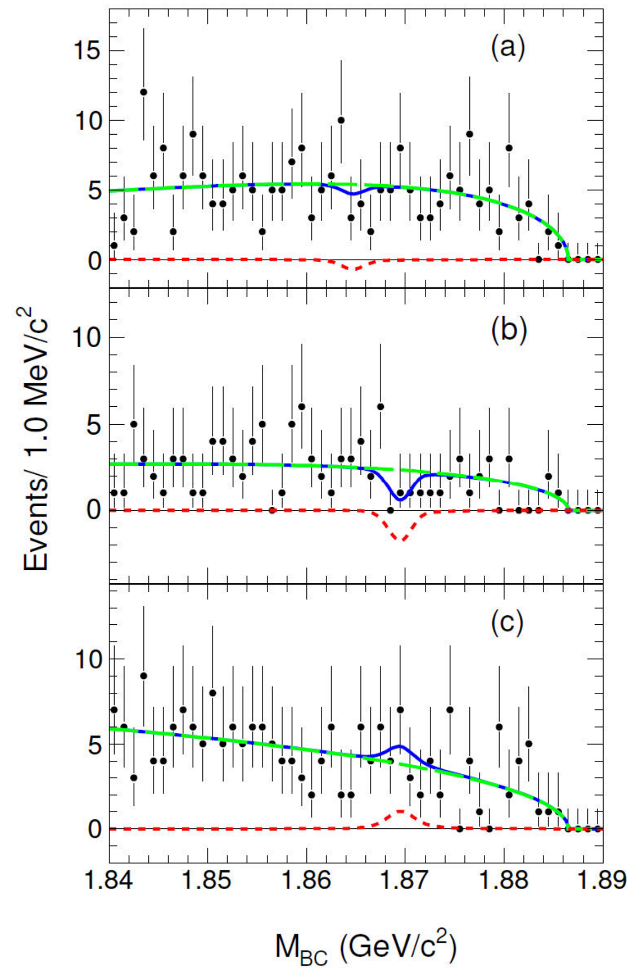

FIGURE 6. Fitting results of $M_{\rm BC}$ distributions for (a) $D^0 \to K^-\pi^-e^+e^+$, (b) $D^+ \to K^0_S\pi^-e^+e^+$, and $D^+ \to K^-\pi^0e^+e^+$. The dots with error bars are from data, the blue solid lines are the best fits, the green dashed lines are the background described with an ARGUS function, and the red dashed lines are the MC-simulation convolved with a Gaussian function.

can occur by exchanging a Majorana neutrino. With the same analysis method as Ref. [18], unbinned maximum likelihood fits to $M_{\rm BC}$ are performed, as shown in Fig. 6. No signals are observed. Considering the systematic uncertainties, the ULs of BFs of $D^0 \to K^-\pi^-e^+e^+$, $K^0_S\pi^-e^+e^+$, and $K^-\pi^0e^+e^+$ at 90% CL are set to be 2.8×10^{-6}, 3.3×10^{-6}, and 8.5×10^{-6}, respectively.

And then we investigated the heavy Majorana neutrino (ν_m) in $D^0 \to K^-e^+\nu_m$ and $D^+ \to K^0_S e^+\nu_m$ decays, where ν_m decays to π^-e^+. The ν_m with a mass range of [0.25, 1.0] GeV/c^2 is studied with the model independent method [6]. Since no signals were observed the profile likelihood [12] method incorporating the systematic uncertainty is adopted, and the ULs on BFs at 90% CL as a function of the mass of ν_m are obtained to be at the level of $10^{-7} \sim 10^{-6}$. The mixing matrix element $|V_{e\nu_m}|^2$ between the positron and the Majorana neutrino is also estimated as a function of the mass of ν_m.

5. Summary

The BNV and LNV processes have been searched in J/ψ, Σ^- and D decays at BESIII. For now, BESIII has collected about ten billions J/ψ events, which is the largest J/ψ sample directly from e^+e^- annihilation in the current world, and will help us to obtain better precision. In the future, BESIII will collect 20 fb^{-1} at $\sqrt{s} = 3.773$ GeV [20], and better constraints on BNV and LNV processes can be expected.

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