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Search for invisible decays at BESIII

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Search for physics beyond the standard model is a highly topical in modern particle physics. So far, BESIII experiment has collected the world's largest data sets at the J/ψ and $\psi(3686)$ resonances. The huge data samples and a clean reaction environment provide a ideal place to search for new physics. We report recent searches of the invisible decays $J/\psi \to \gamma +$ invisible and the first search for the $\Lambda \to$ invisible in the baryon sector.

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1. Introduction

Despite its phenomenal successes, the standard model (SM) still leaves many unanswered questions. For example, the cosmological dark matter cannot be composed of SM fields. There are strong indirect evidence for the existence of dark matter obtained via astronomy, but there is no direct evidence from collider experiments yet. Understanding the nature of dark matter and finding direct evidence for its existence are among the primary goals of contemporary astronomy and particle physics [1]. On the other hand, the SM also does not explain the observed asymmetry between matter and antimatter in the universe, and the asymmetry indicates that baryon number conservation is violated [2].

Search for invisible decays is one way to search for dark matter and might provide a window into what may lie beyond SM. Benefiting from a well measured center-of-mass energy and a clean reaction environment, BESIII [3] has unique advantage in studying the invisible decays. BESIII has accumulated the largest data sets in the world at the J/ψ, $\psi(3686)$, and $\psi(3770)$ resonances [4]. With these huge data samples, BESIII has performed several searches for invisible decays. This report shows two recent results about invisible decays.

2. Search for the decay $J/\psi \to \gamma$ + invisible [5]

A series of supersymmetric Standard Models [8], including the next-to-minimal supersymmetric model (NMSSM) [6], predict a light CP-odd pseudoscalar Higgs boson A^0 and a series of neutralinos. The light stable neutralino χ^0 can couple with Standard Model particles via the A^0 boson, and the A^0 can be produced in the radiative decay of a quarkonium vector state [7].

In this work, the search for J/ψ radiative decays into a weakly interacting neutral particle, namely an invisible particle, is performed using the J/ψ produced through the process $\psi(3686) \to \pi^+\pi^- J/\psi$ in a data sample of $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ decays. The analysis strategy is to first tag J/ψ events by selecting two oppositely charged pions, and then to search for the decay $J/\psi \to \gamma$ + invisible within the tagged J/ψ sample. The branching fraction of the decay $J/\psi \to \gamma$ + invisible is calculated using:

$$\mathcal{B}(J/\psi \to \gamma + \text{invisible}) = \frac{\mathrm{N_{sig}} * \epsilon_{\mathrm{J}/\psi}}{\mathrm{N_{J/\psi}} * \epsilon_{\mathrm{sig}}}, \tag{1}$$

where N_{sig} and $N_{J/\psi}$ are the yields of the signal candidates of $J/\psi \to \gamma$ + invisible and $\psi(3686) \to \pi^+\pi^- J/\psi$, respectively. And ϵ_{sig} and $\epsilon_{J/\psi}$ are the corresponding detection efficiencies. By fitting to the recoil mass of two oppositely charged pions, the number of tagged J/ψ events is the J/ψ signal region ([3.082, 3,112] GeV/c^2) is obtained to be $(8848 \pm 1) \times 10^4$, and the the corresponding $\epsilon_{J/\psi}$ is determined as 56.8%.

The decay $J/\psi \to \gamma$ + invisible is searched in the remaining J/ψ candidate events by requiring no additional charged track is present and there is exactly one photon candidate. In such invisible decay search, the dominant backgrounds are from $\psi(3686) \to \pi^+\pi^- J/\psi$ with J/ψ decays into final states including neutral hadrons, e.g., $n\bar{n}$, $\gamma K_L K_L$, $\pi^0 n\bar{n}$. To further suppress these backgrounds, requirements on the shower shape variables, i.e., the second moment, the lateral moment, the ratio of energy in 3×3 and 5×5 crystals, as well as the number of crystals and energy of the shower are further implemented, where these selection criteria are optimized with the control samples of γ, $\bar{n}/n$ and K_L selected from the decay processes $J/\psi \to \pi^+\pi^-\pi^0$, $J/\psi \to p\pi^-\bar{n}+c.c.$ and $J/\psi \to K\pi K_L$, $J/\psi \to \pi^+\pi^-\phi$, respectively.

The variable E^*_γ, which is defined as the energy of the selected photon in the J/ψ rest frame, is used to identify the signal. The distribution of E^*_γ above 1.25 GeV for the selected events is shown in Fig. 1. Unbinned likelihood fits are performed on the E^*_γ range from 1.25 to 1.65 GeV$/c^2$, corresponding to a mass from 0 up to 1.2 GeV$/c^2$ for the invisible particle. As no strong peaks are observed in all fits, the upper limits are calculated by using the modified frequentist method known as CLs [8] combined with the asymptotic approximation [9].

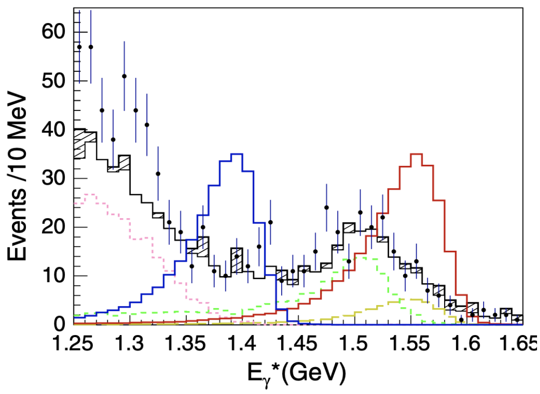

Figure 1: The E^*_γ distribution. Data is shown with black dots. The total background from $\psi(3686) \to \pi^+\pi^-J/\psi$, estimated from MC simulation, is shown with the black solid line and includes contributions from the subsequent decays $J/\psi \to \gamma\pi^0$ (long dashed yellow line), $\gamma\eta$ (short dashed green line), and $\gamma K_L K_L$ (dotted pink line). Non-J/ψ backgrounds are estimated using J/ψ sideband events (hatched histogram). The red and blue solid lines show the signal shape with 0 and 1 GeV/c^2 mass assumptions, respectively.

After taking into account all systematic uncertainties and the signal detection efficiencies, the expected upper limits on the branching fraction of $J/\psi \to \gamma +$ invisible at the 90% confidence level (C.L.) are calculated with the CLs approach and are shown in Fig. 2. The observed upper limit for a zero mass of the invisible particle is improved by a factor 6.2 compared to the previous results [10]. To further investigate the physical parameters in NMSSM, the upper limits of $g_c \times \tan^2\beta \times \sqrt{\mathcal{B}(A^0 \to \text{invisible})}$ are extracted for $\tan\beta = 0.7$,0.8 and 0.9, individually, as presented in Fig. 2. Here, the g_c is the Yukawa coupling of the A^0 field to the charm quark, and $\tan\beta$ is the usual ratio of vacuum expectation values [11]. We obtain better sensitivity in the range $\tan\beta \leq 0.6$ compared to the Belle results [12].

3. Search for invisible decays of the Λ baryon [13]

The search for invisible decays of neutral hadrons is highly interesting, since such decays could involve a potential dark matter candidate. Dark matter may be represented by baryon matter with invisible final state [14]. In the asymmetric dark matter scenario [15], the dark matter and baryon asymmetry puzzles may be related and the dark matter mass could be in the order of GeV. Those models have been used to explain the discrepancy of neutron lifetime measurements in the beam

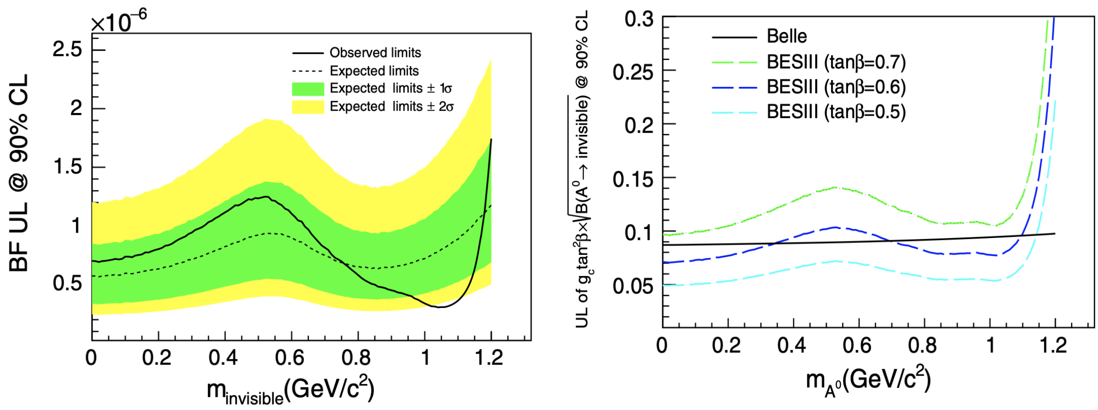

Figure 2: Left plot: upper limits at the 90% C.L. for the branching fractions. Right plot: upper limit at the 90% C.L. for $g_c \times tan^2\beta(g_b) \times \sqrt{\mathcal{B}(A^0 \to invisible)}$.

method [16] and the bottle method [17], by requiring 1% of the neutrons to decay into dark matter particles [18].

In this work, taking advantage of the clean environment of $\Lambda\bar{\Lambda}$ pairs produced in $J/\psi \to \Lambda\bar{\Lambda}$, the first experimental search for invisible decays of the Λ baryon is carried out using 10 billion J/ψ events. The $\bar{\Lambda}$ is reconstructed via $\bar{\Lambda} \to \bar{p}\pi^+$, allowing to search for invisible decays of the recoiling Λ. Invisible $\bar{\Lambda}$ decays are not pursued in this work due to the bad simulation of the dominant background from $\bar{\Lambda} \to \bar{n}\pi^0$.

The branching fraction for the signal decay can be given by:

$$\mathcal{B}(\Lambda \to \text{invisible}) = \frac{\text{N}_{\text{sig}}}{\text{N}_{\text{tag}} * (\epsilon_{\text{sig}}/\epsilon_{\text{tag}})}, \tag{2}$$

where N_{tag} is the number of events with a $\bar{\Lambda}$ detected, N_{sig} the number of events in which the signal decay of the accompanying Λ is also detected, ϵ_{tag} is the efficiency of only detecting the $\bar{\Lambda}$ in $J/\psi \to \Lambda\bar{\Lambda}$, and ϵ_{sig} is the detection efficiency when both $\bar{\Lambda}$ and Λ decays are selected.

By fitting to the recoil mass distribution $RM(\bar{p}\pi^+)$, the $\bar{\Lambda}$ single tag yield is obtained to 4154428 ± 2040 within ± 40 MeV$/c^2$ of the nominal Λ mass with $\epsilon_{\text{tag}} = 32.11\%$. As the invisible Λ decay final states do not deposit any energy in the electromagnetic calorimeter (EMC), the sum of energies of all the EMC showers not associated with any charged tracks, E_{EMC}, is used as a discriminator. For the $\Lambda \to$ invisible process, the dominant background is from the $\Lambda \to n\pi^0$. The energy deposit in the EMC for the $\Lambda \to n\pi^0$ background can be divided into three parts,

$$E_{\text{EMC}} = E_{\text{EMC}}^{\pi^0} + E_{\text{EMC}}^{n} + E_{\text{EMC}}^{\text{noise}}, \tag{3}$$

where $E_{\text{EMC}}^{\pi^0}$, E_{EMC}^{n}, and $E_{\text{EMC}}^{\text{noise}}$ is the energy deposited by π^0 decays, neutrons, and unrelated showers to the event. Among them, $E_{\text{EMC}}^{\pi^0}$ is retained based on MC simulations. For the sum of E_{EMC}^{n} and $E_{\text{EMC}}^{\text{noise}}$ is extracted from a neutron control sample of $J/\psi \to \Lambda(n\pi^0)\bar{\Lambda}(\bar{p}\pi^+)$ due to the simulation of the energy deposits of neutrons in the EMC is unreliable. The distribution of E_{EMC} is shown in Fig. 3, where the resulting E_{EMC} distribution for the $\Lambda \to n\pi^0$ background and for other remaining minor Λ decay background contributions. The estimated background is found to agree well with the data, thus no obvious signal is observed. An upper limit at 90% C.L. on the decay rate is determined to be $\mathcal{B}(\Lambda \to \text{invisible}) < 5.4 \times 10^{-5}$. The result is consistent with the prediction of 4.4×10^{-7} from the mirror model [19]. This result sheds light on the neutron lifetime measurement puzzle and helps to constrain dark sector models related to the baryon asymmetry.

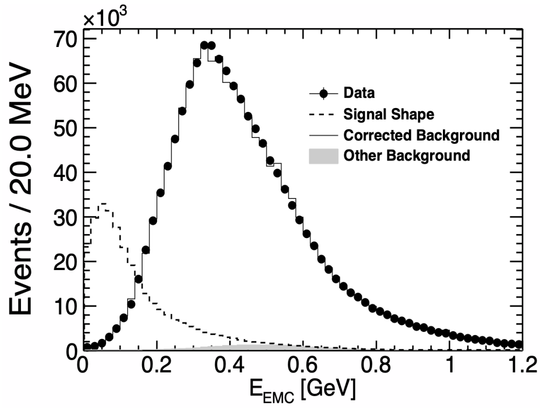

Figure 3: The E_{EMC} distribution. The dots with uncertainties represent data. The dashed line shows the signal shape, where the corresponding yield is normalized arbitrarily for clarity. The solid line shows the $\Lambda \to n\pi^0$ background shape including the correction. The grey filled area shows the other background contributions.

4. Summary

In summary, with 10 billion J/ψ and 448 million $\psi(3686)$ data samples collected with BESIII detector, invisible decays of radiative J/ψ and Λ baryon are searched. There is no significant signal found, and the upper limits at 90% confidence level is reported. Furthermore, with huge e^+e^- annihilation data samples, more interesting results for the new physics search are expected in the next years.

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