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Dark sector search at BESIII

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Using the world largest $\psi(3770)$ and J/ψ data samples taken by the BESIII detector, we perform several searches for the dark photon in a mass range of 0.01 to 3.4 GeV/c^2. No significant signal is observed. The kinematic mixing strength ε between the standard model photon and the dark photon is constrained in the range of $10^{-4} \sim 10^{-2}$.

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1. Introduction

In recent years, a few astrophysical anomalies have been observed that cannot be easily understood in the framework of the standard model (SM), such as the positron excess in the cosmic ray flux observed by PAMELA [1], ATIC [2], HESS [3] and AMS [4], the 511 keV γ ray signal from the galactic center observed by INTEGRAL [5] and the annual modulation measured by DAMA/LIBRA [6]. Motivated by these phenomena, many physical models related to the dark sector are proposed. In one of the simplest scenarios, an extra U_1 abelian gauge symmetry for dark sector is added to the SM as an extension, under which the SM particles are neutral and unchanged. The associated gauge boson is usually called dark photon (denoted as γ' here; also called the hidden photon, heavy photon, U boson or A' in the literature).

The dark photon can communicate with the SM photon through a small mixing [7] in the kinetic term of the QED Lagrangian:

$$\mathscr{L}_{mix} = -\frac{\varepsilon}{2} F^{\text{QED}}_{\mu\nu} F^{\mu\nu}_{\text{dark}} \tag{1.1}$$

where ε is the mixing strength, and $F^{\text{QED}}_{\mu\nu}$ and $F^{\mu\nu}_{\text{dark}}$ are the field strength for the SM and dark sector. Constrained by existing measurements, the typical scale of mixing strength ε and mass of dark photon $m_{\gamma'}$ are mostly in the range $10^{-5} \sim 10^{-2}$ and MeV/c^2 $\sim$ GeV/c^2, respectively [8]. The low-energy electron-positron colliders offer an ideal environment to probe the low-mass dark photon [9].

Due to the mixing of the dark photon and SM photon, the dark photon can be produced in conjunction with the SM photon, but at a highly suppressed rate. The natural width of the dark photon, suppressed by a factor of ε^2, is expected to be well below the current experimental reach. The usual method to search for the dark photon is through initial state radiation (ISR) process like $e^+e^- \to \gamma_{ISR} l^+l^-$ or meson decay, such as $\phi \to \eta e^+e^-$ [10] or $\pi^0 \to \gamma e^+e^-$[11, 12]. A resonant signal in the invariant mass spectrum of the lepton pair after excluding the contribution of SM would indicate the evidence of some exotic particle like the dark photon.

2. $e^+e^- \to \gamma'\gamma_{ISR} \to l^+l^-\gamma_{ISR}$

Using the $\psi(3770)$ data sample collected by BESIII, corresponding to an integrated luminosity of 2.93 fb^{-1}, we search for the dark photon through the ISR method in process $e^+e^- \to \gamma'\gamma_{ISR} \to e^+e^-\gamma_{ISR}$ and $e^+e^- \to \gamma'\gamma_{ISR} \to \mu^+\mu^-\gamma_{ISR}$ [13]. With this method, BaBar has searched the dark photon in the mass range $0.02 \sim 10.2$ GeV/c^2 [14]. The irreducible background is the QED process $e^+e^- \to e^+e^-\gamma_{ISR}$ and $e^+e^- \to \mu^+\mu^-\gamma_{ISR}$.

The radiator function, describing the radiation of an ISR photon, is peaked at small θ angles with respect to the beam axis. Unlike the treatment by Babar, the untagged ISR events, where the ISR photon is emitted at a small polar angle θ_γ and is not detected within the angular acceptance of the detector, is used in this work. The untagged method significantly increases the statistics of selected events.

The invariant mass of lepton pairs for selected events, dominated by the QED background, is shown in the Figure 1, in which the MC simulations are scaled to the luminosity of data. For the MC simulations, the processes $e^+e^- \to e^+e^-\gamma_{ISR}$ and $e^+e^- \to \mu^+\mu^-\gamma_{ISR}$ are generated with BABAYAGA [15] and PHOKHARA [16, 17], respectively. The dark photon mass range between 1.5 and 3.4 GeV/c^2 are studied excluding the window of [2.95, 3.2] GeV/c^2 around the J/ψ resonance. The continuum QED background is described by a fourth-order polynomial function and the dark photon signal as a narrow resonance.

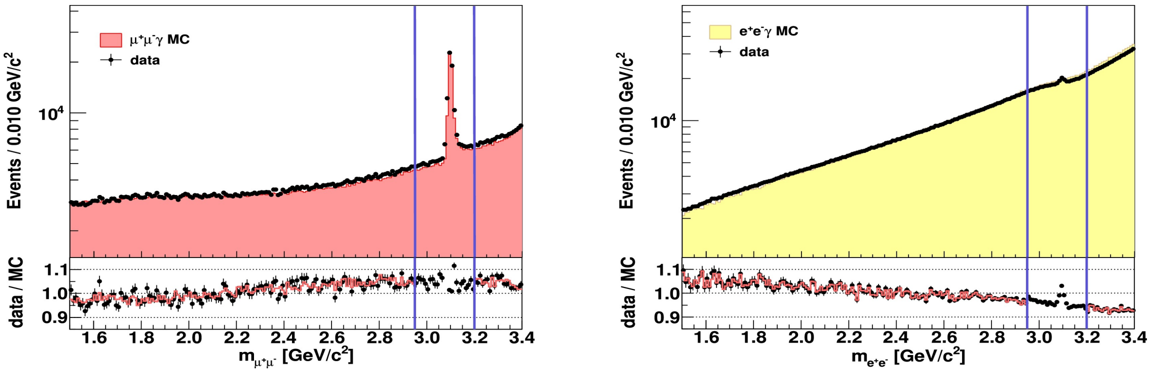

Figure 1: Invariant mass distributions for (left) e^+e^- and (right) $\mu^+\mu^-$. The dots represent data and the shaded histograms represent MC simulations. The lower panels show the difference between data and MC simulations.

The differences between the $l^+l^-\gamma_{ISR}$ event yields and the respective fourth-order polynomial are combined for electron and muon channels as in Figure 2. The observed statistical significance is less than 3σ everywhere in the studied region. Thus we calculate the exclusion limit of the mixing strength ε at the 90% confidence level.

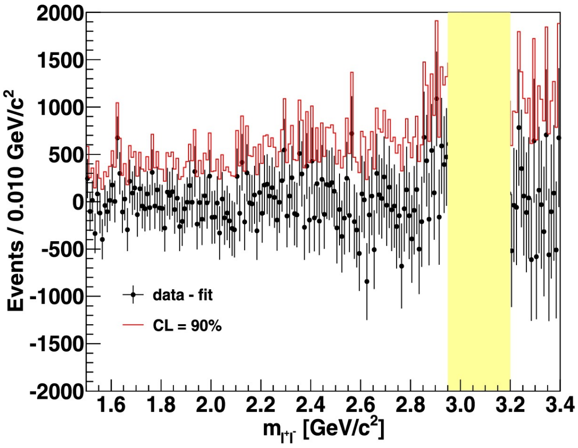

Figure 2: The sum of the differences between the electron channel and muon channel. The solid histogram represents the exclusion limit with the 90% confidence including the systematic uncertainty.

The constraint of the mixing strength ε is extracted with a direct normalization to the QED process only, which does not rely on the approximate theoretical radiator function. The exclusion reach of the mixing strength ε is between 10^{-3} and 10^{-4} as a function of dark photon mass at 90% confidence level, as shown in Figure 5. The limit is competitive in this range and some of the points are better than the world's best result from BaBar.

3. $J/\psi \to \gamma' P \to e^+e^-P$

We can also search for the dark photon in the meson three-body decay, in which there is a lepton pair from virtual photon conversion in the final state [18]. The invariant mass spectrum of the lepton pair is used to search for a narrow resonance on top of the featureless continuum background. In this work, with the 1.3 billion J/ψ events, we use the Dalitz decays $J/\psi \to e^+e^-P(P = \eta, \eta')$.

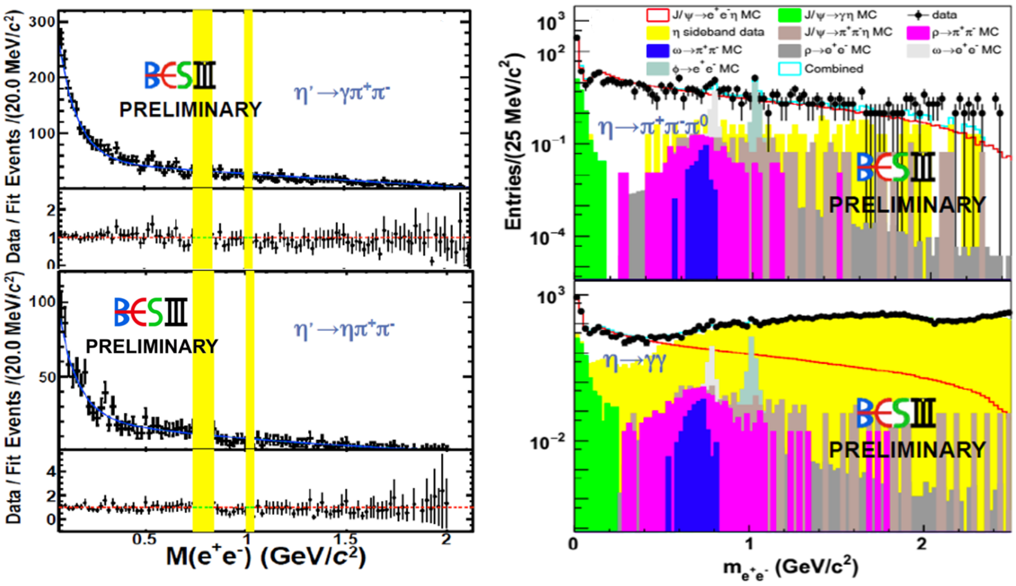

Figure 3: The invariant mass spectrum of the electron pair accompanying (left) η' and (right) η.

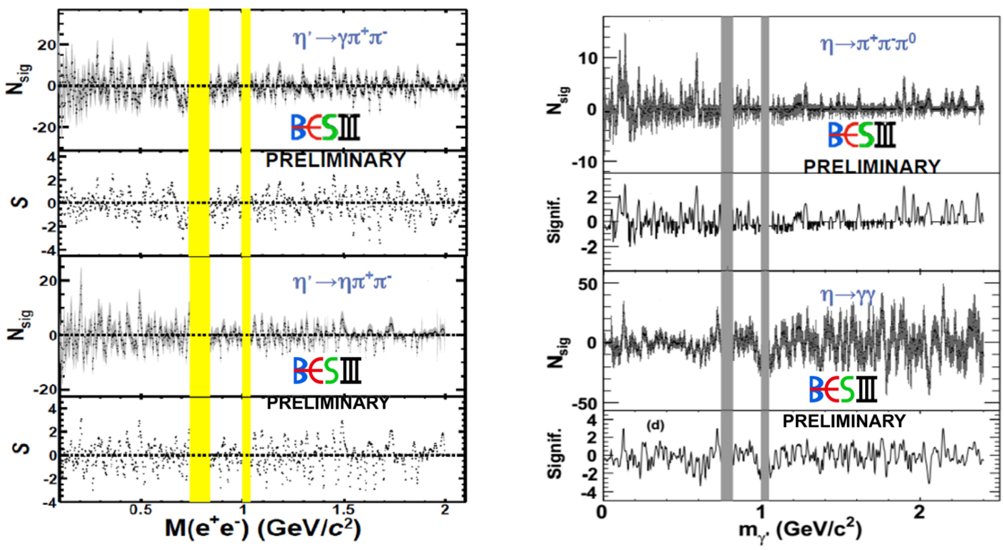

Figure 4: Upper limit of the observed dark photon signal events at 90% confidence level and corresponding statistical significance for (left) η' and (right) η.

The selected events candidates are reconstructed as Pe^+e^- in the final state, where each pseudoscalar meson P (η or η') is reconstructed via two sub channels, $\eta \to \gamma\gamma/\pi^0\pi^+\pi^-$ and

$\eta' \to \gamma\pi^+\pi^-/\eta\pi^+\pi^-$. The analyses are performed individually between the sub channels and then the results are combined to obtain the upper limit set for each pseudoscalar. The surviving events are mainly dominated by the corresponding Dalitz decay and non-pseudoscalar continuum background. The invariant mass spectrum of the electron pair is shown in Figure 3, in which the mass regions around the ρ/ω and ϕ mesons are excluded due to the contamination and corresponding lack of sensitivity. The continuum spectrum is fitted with a featureless second-order polynomial function plus an exponential function.

Scans with a dark photon signal above the continuum background are performed in the mass region [0.01, 2.4] GeV/c^2 for η ([0.1, 2.1] GeV/c^2 for η'). No significant structures are observed for η nor η'. The upper limit of the observed dark photon signal, at 90% confidence level, and its statistical significance are shown in Figure 4. The branching fraction product $\mathscr{B}(J/\psi \to P\gamma') \times \mathscr{B}(\gamma' \to e^+e^-)$, and $\mathscr{B}(J/\psi \to P\gamma')$ alone after factoring out the theoretical calculation of $\mathscr{B}(\gamma' \to e^+e^-)$ [19], is extracted as a function of the dark photon mass.

The mixing strength, determined with the formula in Ref. [9], is plotted in Figure 5. The result is not competitive but represents the first result from charmonium decay.

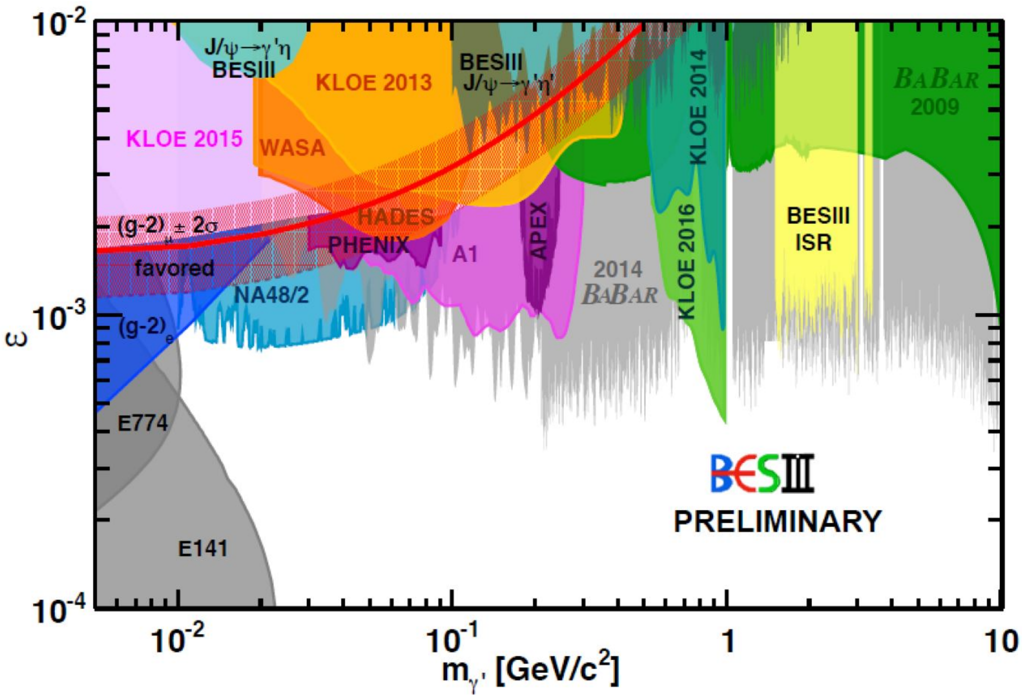

Figure 5: Exclusion limit at the 90% confidence level on the mixing strength ε as a function of the dark photon mass.

4. Invisible decay

Besides the decay to lepton pairs, the dark photon might undergo invisible decays in some models. BESIII has performed the invisible-decay search of η and η' [20], ω and ϕ [21]. These studies might prove promising for future dark sector search.

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5. Summary

At the BESIII experiment, we search for the dark photon through its lepton decay channels with the world's largest charmonium data sample using the ISR method and meson decay. No significant dark photon signal is observed in any studies and we set the upper limit of the mixing strength at 90% confidence level. In addition, the study of invisible decay of neutral mesons may also provide some sensitivity in future dark sector studies.

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