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Search for invisible decays of a dark photon using e^+e^- annihilation data at BESIII

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ABSTRACT

We report a search for a dark photon using 14.9 fb^{-1} of e^+e^- annihilation data taken at center-of-mass energies from 4.13 to 4.60 GeV with the BESIII detector operated at the BEPCII storage ring. The dark photon is assumed to be produced in the radiative annihilation process of e^+e^- and to predominantly decay into light dark matter particles, which escape from the detector undetected. The mass range from 1.5 to 2.9 GeV is scanned for the dark photon candidate, and no significant signal is observed. The mass dependent upper limits at the 90% confidence level on the coupling strength parameter ϵ for a dark photon coupling with an ordinary photon vary between 1.6×10^{-3} and 5.7×10^{-3} .

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1. Introduction

The Standard Model (SM) of particle physics is powerful but does not address several important phenomena that hint there is physics beyond the SM. One that is not included in the SM is the existence of dark matter (DM), which makes up $\sim 84\%$ of the matter in the universe [1,2]. DM interactions with ordinary matter are observed through the gravitational effects DM has on galaxies, but the lack of interaction between DM and SM particles via strong, weak, and electromagnetic forces makes it very challenging to detect directly in particle physics experiments. However, recent results from astrophysical observations [3–5], as well as the long-standing discrepancy between the experimental value and the theoretical prediction of the muon anomalous magnetic moment [6,7] indicate there could be a new force between the dark sector and the SM. The new force could be mediated by a $U(1)_D$ gauge boson γ' (referred to as a dark photon), which couples weakly to a SM photon through kinetic mixing ($\frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$) [8–12], where $F'_{\mu\nu}$ and $F_{\mu\nu}$ are the field strengths of the dark photon and the SM photon, respectively, and the mixing parameter ϵ gives the coupling strength between the dark photon and SM photon.

A dark photon with mass in the GeV range and ϵ value as high as $\epsilon \sim 10^{-3}$ has been predicted in Refs. [9,13,14]. The small value of epsilon and a suppression factor of ϵ^2 of the coupling between the dark photon and the SM photon make it very hard to be hunted. However, benefiting from high intensity facilities such as e^+e^- storage rings, a dark photon candidate could be produced in particle physics experiments. The dark photon would predominantly decay into a pair of DM particles ($\gamma' \rightarrow \chi\bar{\chi}$), which are the lightest DM particles (χ) with masses $m_\chi < m_{\gamma'}/2$ and thus be invisible. Previous measurements on the invisible γ' decays have been performed by the NA62 [15], NA64 [16,17], BaBar [18], E787 [19] and E949 [20] experiments. No evidence is found for a dark photon, and upper limits for ϵ have been set.

A dark photon can also be searched for at the BESIII experiment in the radiative annihilation process $e^+e^- \rightarrow \gamma\gamma'$, followed by an invisible decay of the γ' . The dark photon candidate of mass $m_{\gamma'}$

would be signified by the presence of a monochromatic photon with energy

$$E_\gamma = \frac{s - m_{\gamma'}^2}{2\sqrt{s}}, \quad (1)$$

where \sqrt{s} is the e^+e^- center-of-mass (c.m.) energy. Compared with the BaBar measurement, BESIII runs at a relative lower c.m. energy and can explore the low $m_{\gamma'}$ region with a finer binning scheme. A novel method by exploiting the muon detector to veto the dominant QED background is also developed and the purity of the final data sample is well controlled which is necessary for this search.

In this letter, we perform a measurement of the process $e^+e^- \rightarrow \gamma\gamma'$ at the BESIII experiment located at the Beijing Electron Positron Collider (BEPCII) [21], where the dark photon decays invisibly into a dark matter $\chi\bar{\chi}$ pair. Therefore, the signal process only contains monochromatic single photon events. We reconstruct the dark photon signal by seeking a narrow peak in the photon energy (E_γ) spectrum, which is related to the missing mass $m_{\gamma'}$ of the recoil system through Eq. (1). The analysis is based on the data sets taken at $\sqrt{s} = 4.13$ to 4.60 GeV, corresponding to an integrated luminosity of 14.9 fb^{-1} [22].

2. Detector and Monte Carlo simulation

The BESIII detector [23] records symmetric e^+e^- collisions provided by the BEPCII storage ring [21], which operates with a peak luminosity of $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in the center-of-mass energy range from 2.0 to 4.95 GeV. BESIII has collected large data samples in this energy region [24]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and 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 magnetic field. The solenoid is supported by an octagonal flux-return yoke with 9 layers of resistive plate counters interleaved with steel, comprising a muon

identification system (MUC). The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the specific energy loss (dE/dx) resolution is 6% for 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 in the TOF barrel region is 68 ps, while that in the end cap region is 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [25]. The spatial resolution in the MUC is better than 2 cm.

Simulated Monte Carlo (MC) samples produced with GEANT4-based [26] software, including the geometrical description of the BESIII detector and the detector response, are used to determine the detection efficiency, and to estimate potential backgrounds. The signal MC events for the reaction $e^+e^- \rightarrow \gamma\gamma'$ are generated using EVTGEN [27] for 29 different γ' mass hypotheses in the range from 1.5 to 2.9 GeV with a 50 MeV step size. The possible background sources are investigated with inclusive MC simulation samples, consisting of open-charm processes, the Initial-State-Radiation production of lower mass vector charmonium(-like) states, the continuum processes $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$), and the QED processes $e^+e^- \rightarrow (\gamma)e^+e^-, (\gamma)\mu^+\mu^-, (\gamma)\gamma\gamma$. The known decay modes of charmed hadrons are handled by EVTGEN [27] with known decay branching fractions taken from the Particle Data Group (PDG) [28], and the remaining unknown decays with LUNDCHARM [29]. The QED processes are generated with the BABAYAGANLO generator [30].

3. Event selection

The signal events have only one monochromatic photon. Thus, events with any reconstructed charged tracks in the MDC are rejected. Photon candidates are required to have deposited energy larger than 25 MeV in the barrel EMC region ($|\cos\theta| < 0.8$) or larger than 50 MeV in the end cap region ($0.86 < |\cos\theta| < 0.92$), where θ is the polar angle of each photon candidate. To remove contamination from fake photons (due to electronic noise of the EMC), the number of photons (N_γ) in each event should satisfy $1 \leq N_\gamma \leq 3$. The most energetic photon is regarded as the candidate for the signal photon. To suppress the overwhelming di-gamma background events, the polar angle of the signal photon is required to be within $|\cos\theta_\gamma| < 0.6$. As our signal events are purely neutral events, the event start time t_0 is determined from hits in TOF when available or otherwise the trigger time by the EMC. To suppress electronic noise and energy deposition unrelated to the physical events, the EMC time of the signal photon is required to be within $[-500, 1250]$ ns with respect to t_0 , where the values are obtained by studying a di-gamma control sample.

Backgrounds with multiple photons in the final state, such as $e^+e^- \rightarrow \gamma\gamma, \gamma\gamma\gamma$, etc., can be effectively suppressed by requiring the total deposited energy of showers except for the signal photon (denoted as E_{extra}) in the EMC be less than 80 MeV. To eliminate the backgrounds from neutral hadrons, such as $e^+e^- \rightarrow n\bar{n}$ which also produce showers in the EMC, two shower shape related variables, the lateral moment and energy ratio in 3×3 and 5×5 crystals around the central seed crystal ($E9/E25$), are used to distinguish showers caused by neutral hadrons from photons. The lateral moment is given by

$$\frac{\sum_{i=3}^n E_i r_i^2}{\sum_{i=3}^n E_i r_i^2 + E_1 r_0^2 + E_2 r_0^2}, \quad (2)$$

where n is the number of crystals associated with the shower, E_i is the deposited energy in the i th crystal and $E_1 > E_2 > \dots > E_n$, r_i is the lateral distance between the central and the i th crystal, and r_0 is the average distance between two crystals. The signal photon candidate is required to have a lateral moment larger than 0.14 and less than 0.3 as well as a value of $E9/E25 > 0.95$, which is

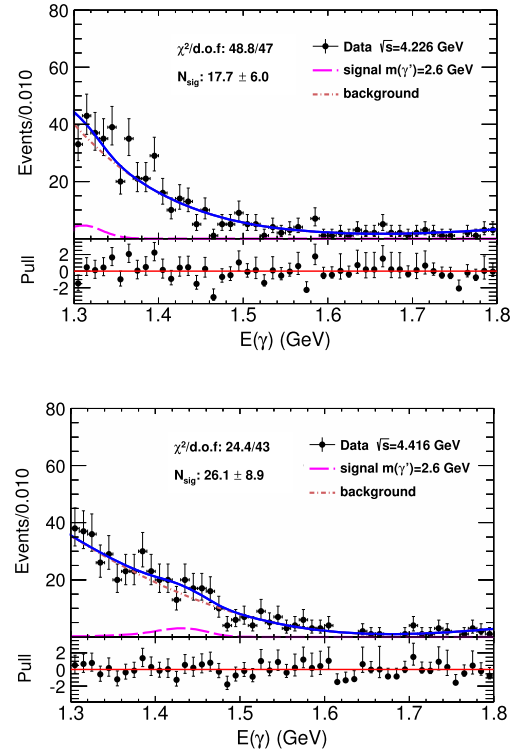


Fig. 1. The signal photon energy spectra at $\sqrt{s} = 4.226$ GeV (top) and $\sqrt{s} = 4.416$ GeV (bottom) with fit projections overlaid. The magenta dashed curves are the dark photon signal shapes with $m_{\gamma'} = 2.6$ GeV, which depend on the c.m. energy of the data set according to Eq. (1). Dots with error bars are data, the blue solid curves are the total fit results, and the red dot-dashed curves describe the background contributions.

optimized by studying the hadron background events from inclusive MC sample.

Due to the structure of the EMC, one of the photons from a di-gamma event can penetrate the calorimeter in the gap between the barrel and the endcap ($0.8 < |\cos\theta| < 0.86$), or occasionally pass between crystals in the zenith angle direction ($\cos\theta = 0$), producing a sole photon in the detector, and thereby mimicking a signal event. An escaped energetic photon often interacts in the outer detector material and produces secondary particles, which are then recorded by the MUC. To suppress this background, events with MUC hits within $|\cos\theta_{\text{hit}}| > 0.65$ or $|\cos\theta_{\text{hit}}| < 0.06$, where θ_{hit} is the polar angle of the MUC hit, are rejected.

4. The signal photon energy spectrum

After imposing the above event selection criteria, the signal photon energy spectra at $\sqrt{s} = 4.178$ and 4.226 GeV are shown as examples in Fig. 1. The trigger efficiency for single photon with $E(\gamma) < 1.3$ GeV in the barrel EMC is relatively low, and the background from di-gamma events is also high for the low energy region. In addition, a photon candidate with energy larger than 2 GeV will saturate the EMC electronics, which results in shower loss. Such effects would lead to a significant number of di-gamma background events when one energetic photon candidate is lost. Therefore, we only search for a dark photon signal within the range $1.3 < E(\gamma) < 1.8$ GeV corresponding to $1.5 < m_{\gamma'} < 2.9$ GeV, according to Eq. (1).

The production cross section for a dark photon candidate can be calculated by [11]

$$\sigma(e^+e^- \rightarrow \gamma\gamma') = \frac{2\pi\alpha^2}{s}\epsilon^2(1-x) \left(\left(1 + \frac{2x}{(1-x)^2}\right)\Theta - 2\cos\theta_c \right), \quad (3)$$

where $x = \frac{m_{\gamma'}^2}{s}$, $\Theta = \log \frac{(1+\cos\theta_c)^2}{(1-\cos\theta_c)^2}$, $\cos\theta_c = 0.6$ is the $\cos\theta$ limit for the signal photon polar angle, and α is the fine-structure constant. The coupling strength parameter ϵ^2 which determines the cross section is common and shared for all c.m. energy data samples. The expected signal yield at a certain c.m. energy is $N^{\text{sig}} = \mathcal{L}\sigma(e^+e^- \rightarrow \gamma\gamma')\epsilon_{\text{det}}\epsilon_{\text{trig}}$, where \mathcal{L} is the integrated luminosity of the data [22], ϵ_{det} is the signal detection efficiency and ϵ_{trig} is the trigger efficiency.

The detection efficiencies for signal events at each c.m. energy for specific values of $m_{\gamma'}$ are obtained by simulated signal MC samples, and depending on $m_{\gamma'}$ and the c.m. energy, vary between 1% and 6%. The trigger system at BESIII combines measurements from the MDC, EMC, as well as TOF detectors to suppress beam-related background and to record e^+e^- collision events as much as possible. The trigger condition valid for single photon events with $|\cos\theta_{\gamma'}| < 0.6$ only consists of EMC information, which requires an event at least has one reconstructed shower in the barrel region of the EMC, with a total deposit energy greater than 650 MeV [31]. The corresponding trigger efficiency for this condition is studied via radiative Bhabha events ($e^+e^- \rightarrow \gamma e^+e^-$) using a same method as described in Ref. [31]. In order to select a clean radiative Bhabha sample in the EMC barrel region, we require either $e^{\pm}\gamma$ or e^+e^- be detected by the endcap detector and a third e^{\mp} or γ hit the barrel EMC. We find $\epsilon_{\text{trig}} = (99.40 \pm 0.01)\%$ for events with $E(\gamma) > 1.3$ GeV, and the efficiency drops dramatically for $E(\gamma) < 1.3$ GeV.

To determine the signal yield for each $m_{\gamma'}$ hypothesis, a simultaneous unbinned maximum likelihood fit to the photon energy spectra is performed to all data sets. The signal yields for each data set depend on the common parameter ϵ , according to Eq. (3). In the fit, the signal probability density function (PDF) for each c.m. energy data is modeled by a templated shape constructed from the corresponding signal MC simulation convolved with a Gaussian function, which represents the photon energy resolution difference between data and MC simulation. The parameters of the Gaussian function are determined by a di-gamma control sample. The background shape for each c.m. energy data is described by a 4th-order Chebyshev polynomial function with free parameters to fit data. To obtain the signal yield for different $m_{\gamma'}$ candidates, we scan the $m_{\gamma'}$ region with a 50 MeV step size (in total 29 steps) and repeat the fit. Fig. 1 shows the fit results for a dark photon candidate with $m_{\gamma'} = 2.6$ GeV at $\sqrt{s} = 4.26$ and 4.416 GeV. After taking into account the uncertainty from the background model, the maximum local significance is determined to be 3.1σ at $m_{\gamma'} = 2.6$ GeV. The statistical significances are calculated by comparing the likelihoods with and without the signal components in the fit, and taking the change of the number of degrees of freedom into account. Fig. 2 shows the estimated local statistical significance for different $m_{\gamma'}$ hypotheses. The maximum global significance, taking the Look-Elsewhere Effect [32] into account, is determined to be 2.2σ . Therefore, a null result is reported for the search of a dark photon with invisible decays.

5. Systematic uncertainties

The systematic uncertainties for the ϵ measurement include those from the luminosity measurement, photon detection efficiency, selection criteria, photon resolution, and determination of the trigger efficiency. The luminosity of the data sets used is measured using large angle Bhabha scattering events, with an uncertainty less than 1.0% [22]. The signal process has only one signal

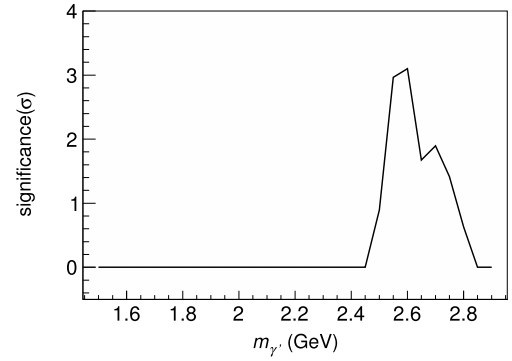


Fig. 2. Local statistical significance for dark photon candidates obtained from the fit to the photon energy spectrum as a function of $m_{\gamma'}$.

photon, and 1.0% is assigned as the uncertainty from the photon detection efficiency [34].

The systematic uncertainties from the requirement on the number of photons, EMC time, E_{extra} , EMC shower shapes, and MUC hits are investigated with a clean di-gamma control sample. We use two back-to-back photons with energies close to the beam energy to select a di-gamma control sample from the same data sets [22]. The systematic uncertainties, which are determined from the differences between signal MC events and di-gamma data events, are 1.4% for the number of photons, 1.4% for the EMC time, 0.3% for E_{extra} , 0.4% for EMC shower shapes, and 8.5% for the MUC hits. The relative large systematic uncertainty from MUC hits is due to the poor simulation of the raw informations as well as the noise from electronics.

In our fits to the photon energy spectra, the signal PDF is convolved with a Gaussian function to account for the resolution difference between data and MC simulation. The parameters of the Gaussian function are obtained from di-gamma data events with c.m. energies from 2.644 to 3.400 GeV to ensure the photon energy is similar to the signal process. To determine the systematic uncertainty due to the photon energy resolution, signal PDF, and background modeling, the fit is repeated with alternative signal and background shapes, i.e. varying the width of the Gaussian function used to convolve the signal shape according to its uncertainty, replacing the signal PDF to the sum of two Crystal Ball functions with a common mean value, and using the $(n+1)^{\text{th}}$ order polynomial functions for the background shape. The one with the largest upper limit value for ϵ is taken as the final result.

For the systematic uncertainty due to the trigger efficiency, the small trigger efficiency difference measured by electrons and photons in the EMC barrel, which is 1.0%, is taken as the systematic uncertainty.

Table 1 lists all considered sources of systematic uncertainties. Assuming they are independent, the total systematic uncertainty is the sum in quadrature of the individual contributions and is determined to be 8.9%. Compared with the statistical uncertainty of data which is in $\sim 30\%$ level (cf. Fig. 1), the systematic uncertainty is still much smaller and does not play a significant role in the ϵ measurement.

6. Upper limit for coupling strength

Since no significant dark photon signal is observed, we set an upper limit on ϵ at the 90% confidence level (C.L.). From Eq. (3), for a given dark photon mass, the expected signal event yield in data depends on ϵ . Applying a Bayesian method, a likelihood scan is performed by varying the value of ϵ in the simultaneous fit to all data sets,

Table 1
Sources of relative systematic uncertainties and their contributions (%).

Source	Uncertainty
Luminosity	1.0
Photon detection	1.0
Number of photons	1.4
EMC time	1.4
E_{extra}	0.3
Showers shapes	0.4
MUC hits	8.5
Trigger efficiency	1.0
Total	8.9

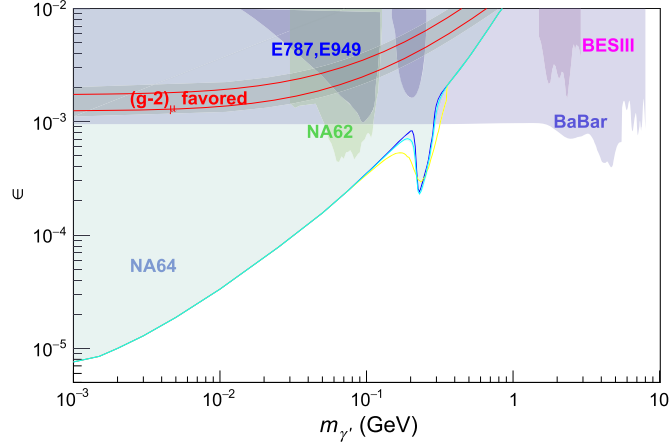


Fig. 3. Upper limit on the coupling strength (ϵ) between the dark sector and the SM at the 90% C.L. versus the dark photon mass measured by BESIII (magenta region), together with previous measurements [15–20], as well as the parameter region favored by the $(g-2)_\mu$ anomaly [33]. The two red lines correspond to $(g-2)_\mu + 2\sigma$ and $(g-2)_\mu - 2\sigma$ and take into account the latest result from Fermilab [7].

$$\int_0^{\epsilon_{90\%}} \mathcal{L}(\epsilon) d\epsilon = 90\% \int_0^{\infty} \mathcal{L}(\epsilon) d\epsilon \quad (4)$$

where $\mathcal{L}(\epsilon)$ is the ϵ -dependent likelihood value, and $\epsilon_{90\%}$ represents the coupling strength parameter which corresponds to 90% of the integral of the likelihood function from $\epsilon = 0$ to ∞ . To consider the systematic uncertainty, the likelihood curves are also convolved with a Gaussian function with its standard deviation set to the value of the total systematic uncertainty. The upper limits of ϵ at the 90% C.L. versus the dark photon mass are shown in Fig. 3, and $\epsilon_{90\%}$ varies within $(1.6 - 5.7) \times 10^{-3}$, depending on $m_{\gamma'}$ between 1.5 and 2.9 GeV.

7. Summary

In summary, using data collected at c.m. energies from 4.13 to 4.60 GeV corresponding to an integrated luminosity of 14.9 fb^{-1} , we search for the radiative annihilation production of a dark photon which decays invisibly at the BESIII experiment for the first time. No obvious signal is observed in the mass region between 1.5 and 2.9 GeV/c^2 , and the upper limit on the coupling strength parameter ϵ at the 90% C.L. is determined to be within $(1.6 - 5.7) \times 10^{-3}$ as a function of the dark photon mass. Our exclusion limits are below the $(g-2)_\mu$ anomaly values and are consistent with what already excluded by BaBar [18] in the mass range between 1.5 and 2.9 GeV. It also proves the capability of the BESIII detector to produce more competitive results with the coming 17 fb^{-1} data taken at 3.77 GeV [24].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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