Dark photon and Axion-like particle search at BESIII

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Abstract. Numerous indirect astronomical and cosmological evidences have suggested the existence of dark matter (DM) in the universe. Its existence provides a strong hint that there may be a dark sector, consisting of particles that do not interact with the known strong, weak, or electromagnetic force. Intriguingly, this dark sector might couple to the Standard Model via portals, which include the possibility of axion-like particle , light Higgs boson, dark photon and spin-$\frac{1}{2}$ fermions. BESIII experiment has collected the largest data samples at the J/ψ and $\psi(3686)$ on threshold in the world, which provides a clean reaction environment to search for dark sector and new physics. This proceeding summarizes the recent results in the search of dark photon and axion-like particles published by the BESIII Collaboration.

1 Introduction

The Standard Model (SM) of particle physics has been a cornerstone in understanding the subatomic world over the past several decades, providing a comprehensive framework for explaining a multitude of observed phenomena. Despite its successes, the SM is also facing a great challenge. While the SM provides a theoretically consistent description of all known particles and their interactions (excluding gravity) up to the Planck scale [1], it conspicuously fails to account for several pieces of evidence for new physics beyond the SM. A prominent piece of this puzzle is the phenomenon of Dark Matter (DM). Accumulating indirect evidence from astronomical and cosmological observations points to the existence of dark matter and dark energy, which the SM cannot explain. So far, the presence of DM is inferred via gravitational effects on visible matter only. Thus, the nature of DM is still elusive. The existence of DM provides a strong hint that there may be a *dark sector*, consisting of particles that do not interact with the known strong, weak, or electromagnetic forces. The dark sector may communicate weakly with the visible sector through a portal interaction linking gauge invariant SM operators to a mediator. Guided by the SM's gauge symmetries and field content, the theoretical landscape proposes three primary renormalizable portals: the vector, scalar, and neutrino portals. [2] At the dimension five level and beyond, an array of portal couplings becomes feasible, notably including the Axion-Like Particle (ALP) portal couplings to photons and gluons. Experiments at e^+e^- colliders can perform a wide range of searches for different mediator. Specifically, high-intensity e^+e^- collider experiments, such as the BESIII experiment, are uniquely positioned to probe dark sector particles and axion-like particles (ALPs), benefiting from a well-measured CM energy and a clean environment [3]. The BESIII detector, detailed in Ref. [4], records symmetric e^+e^- collisions provided by the BEPCII

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storage ring [5] in the center-of-mass energy range from 2.0 GeV to 4.95 GeV, with a peak luminosity of 1×10^{33} $cm^{-2}s^{-1}$ achieved at $\sqrt{s}$= 3.77 GeV. In this proceeding, we review the recent results in the search of dark photon and axion-like particles at BESIII.

2 Search for an axion-like particle

ALPs are pseudo-Goldstone bosons, which were introduced from some spontaneously broken global symmetry to solve the strong CP [6–9] or hierarchy problems [10]. Among all the topic, the ALP-photon coupling constant $g_{a\gamma\gamma}$ is mostly discussed. In the most common scenarios , the ALP, a, will predominantly couple to photons with $g_{a\gamma\gamma}$, assuming the branching fraction of a decaying to photons is 100% . ALPs have independent masses and couplings bounded by experiments. Experimental bounds on $g_{a\gamma\gamma}$ with m_q range of MeV/c^2 to GeV/c^2 mainly from e^+e^- colliders.

The ALPs can be produced through two distinct mechanisms: non-resonant and resonant production [11]. The most direct method for generating ALPs at electron-positron facilities is via the non-resonant process, $e^+e^- \to \gamma a$. Additionally, since vector quarkonia such as J/ψ is a narrow resonance coupled to the electromagnetic current, it can lead to significant resonant contributions, as seen in the decay process $J/\psi \to \gamma a$.

A recent study by the BESIII collaboration has explored the potential for ALPs decaying into two photons in the J/ψ radiative decays via $J/\psi \to \gamma a, a \to \gamma\gamma$ [12]. . The mass range for the ALPs a (m_a) in this investigation was between 0.165 and 2.84 GeV/c^2. In order to preclude the high pollution from quantum electrodynamics (QED) background, the J/ψ sample was selected by analysing 2.3 Billion $\psi(3686)$ data in the $\psi(3686) \to \pi^+\pi^- J/\psi$ decay.

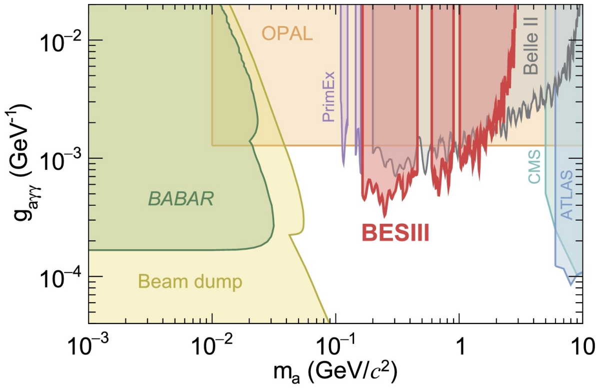

Figure 1. Exclusion limits at the 95% CL in the ALP-photon coupling $g_{a\gamma\gamma}$ versus ALP mass m_a plane obtained from this analysis. All measurements assume a 100% ALP decay branching fraction into photons.

The ALP signal is searched over the two-photon invariant mass distribution, $M_{\gamma\gamma}$. There are three entries per event from all possible combinations of the three selected photons. According to the studies of MC simulation, the background is dominated by peaking contributions from $J/\psi \to \gamma\pi^0$, $J/\psi \to \gamma\eta$ and $J/\psi \to \gamma\eta'$ The mass intervals around the π^0, η and η' mass window are excluded due to the peaking backgrounds. A series of 1-dimensional unbinned maximum-likelihood fits are performed to $M_{\gamma\gamma}$ distribution, and the cprresponding signal yields are determined with different ALP mass hypotheses. No evidence of significant narrow ALP production is found in the J/ψ data set at any ALP mass point. The 95% confidence level (C.L.) upper limits on $\mathcal{B}(J/\psi \to \gamma a\ )$ as a function of m_a is computed with a one-sided frequentest profile-likelihood The corresponding results are summarized in Fig. 1, where the exclusion limits in the ALP-photon coupling $g_{\gamma\gamma}$ versus ALP mass m_a plane obtained from this analysis is shown, together with the constraints of other experiments. The limits on $\mathcal{B}(J/\psi \to \gamma a\ )$ range from 8.3×10^{-8} to 1.8×10^{-6} over the search region, and the constraints on the ALP-photon coupling are the most stringent to date for $0.165 \leq m_a \leq 1.468$ GeV/c^2.

3 Search for massless dark photon

The concept of a massless dark photon (γ') emerges from the theory postulating the spontaneous breaking of the Abelian group $U(1)D$ [13, 14]. If $U(1)D$ remains unbroken, the massless dark photon can be identified with no direct interactions with SM fermions. However, the γ' can still exert influence on the SM via higher-dimensional operators generated by loop diagrams involving particles that are charged under $U(1)D$ and also coupled to SM field.

The massless dark photon may also enhance the decay rate of flavor-changing neutral current (FCNC) processes in the charm-sector [15]. According to the SM, FCNC transitions are significantly suppressed by the Glashow, Iliopoulos, and Maiani (GIM) mechanism[18]. Any observation of FCNC decay would suggest the presence of new physics.

An experimental search for a massless dark photon in $\Lambda_c \to p\gamma'$ decay is presented [16] using 4.5 pb^{-1} of e^+e^- collision data collected with the BESIII detector at centre-of mass energies between 4.6 and 4.699 GeV using a Double Tag (DT) technique [17]. A data sample of $\bar{\Lambda}_c^-$ baryon, referred to as the single-tag (ST) sample, is reconstructed by using ten exclusive hadronic decay modes, while the subset of those events in which a signal decay $\Lambda_c^+ \to p\gamma'$ candidate is reconstructed in the system recoiling against the $\bar{\Lambda}_c^-$ candidate are denoted as DT candidates. As is illustrated in Fig. 2, the recoil mass spectrum $M^2_{\text{rec}}(\bar{\Lambda}_c^- p)$ is utilized to extract the signal events, no significant dark photon signal was observed. The study sets a 90% C.L. upper limit for the branching ratio $\mathcal{B}(\Lambda_c^+ \to p\gamma')$ at less than 8×10^{-5}. This result is below the sensitivity of theory prediction in Ref. [14], which predicts the BF to be 1.6×10^{-5} or 9.1×10^{-6} with different inputs of form factors. With larger Λ_c^+ samples collected at BESIII in the near future, we expect to establish a more stringent constraint on $\mathcal{B}(\Lambda_c^+ \to p\gamma')$.

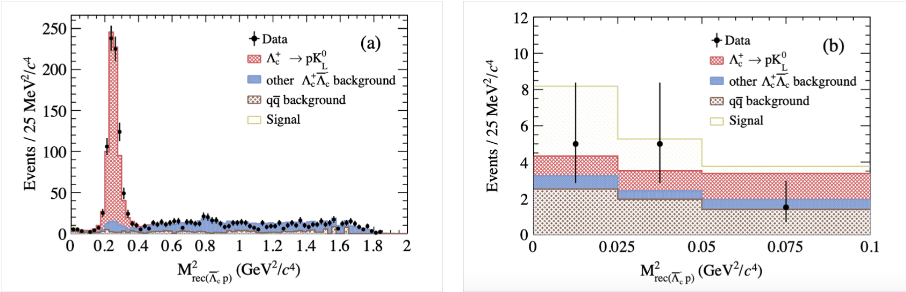

Figure 2. (a) The full spectrum of $M^2_{\text{rec}}(\bar{\Lambda}_c^- p)$ of the accepted DT candidate events from the combined seven data samples. (b) The spectrum of $M^2_{\text{rec}}(\bar{\Lambda}_c^- p)$ of the accepted DT candidate events from the combined data in the signal region.

4 Search for invisible decay of Λ baryon

Dark matter may be represented by baryon matter with invisible final state [18]. In the asymmetric dark matter scenario , the dark matter and baryon asymmetry puzzles may be related and the dark matter mass could be in the order of GeV [19]. Those models have been used to explain the discrepancy of neutron lifetime measurements in the beam method and the bottle method, by requiring 1% of the neutrons to decay into dark matter particles.

The first search for invisible decays of the Λ baryon [20] is carried out in the process $J/\psi \to \Lambda\bar{\Lambda}$ based on $(1.0087 \pm 0.0044)\times10^{10}$ J/ψ events. In $J/\psi \to \Lambda\bar{\Lambda}$ decay, the ST events in which $\bar{\Lambda}$ baryon candidate is reconstructed with its dominant decay mode of $\bar{\Lambda} \to \bar{p}\pi$. Then the recoil side is used to infer the invisible decays of Λ baryon. Since the invisible decay final states do not deposit any energy in the EMC, the sum of energies of all the EMC showers not associated with any charged tracks, E_{EMC}, ca be used to distinguish signal from the backgrounds. Overall, E_{EMC} can be divided into three contributions, $E_{EMC} = E^{\pi^0}_{EMC} + E^{n}_{EMC} + E^{\rm noise}_{EMC}$, where $E^{\pi^0}_{EMC}$, E^{n}_{EMC} and $E^{\rm noise}_{EMC}$ are the energy due to electromagnetic showers from π^0 decays, neutrons and shower unrelated to the events. The E_{EMC} distribution is expected to peak at zero energy position for the signal-like events and deviate from zero energy position for background from $\Lambda to n\pi^0$, as is shown in Fig. 3. No signals are detected for the invisible decays of Λ baryon, and the upper limit of the BF is set to be 7.4×10^{-5} at the 90% C.L. This is the first search for invisible decays of baryons and is pivotal in constraining dark sector models related to baryon asymmetry.

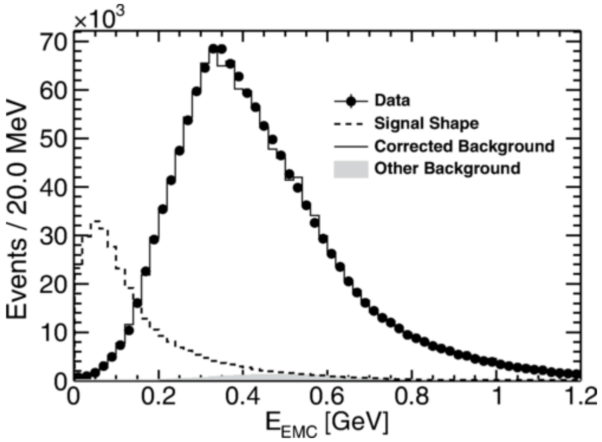

Figure 3. (a) The E_{EMC} distribution for data(black dots with uncertainty), signal MC (dashed line) and background shape from $\Lambda \to n\pi^0$ (solid line). (b) Distribution of the estimated $\mathcal{B}(\Lambda \to \text{invisible})$ in pseudosamples.

5 Search for invisible decay of dark photon

Directly detection of the DM is very challenging in particle physics experiment, as DM only interact with ordinary matter through the gravitational effects. However, recent results from astrophysical observations [21], as well as the long-standing discrepancy between the experimental value and the theoretical prediction of the muon anomalous magnetic moment [22] 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 ($\frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$) [23], 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 recent study at the BESIII experiment conducted a search for the dark photon in the radiative annihilation process $e^+e^- \to \gamma\gamma'$ [24], with the γ' undergoing an invisible decay. The dark photon candidate of mass $m_{\gamma'}$ would be signified by the presence of a monochromatic photon with energy $E_\gamma = \frac{s - m^2_{\gamma'}c^4}{2\sqrt{s}}$, where $\sqrt{s}$ is the e^+e^- center-of-mass energy. No obvious signal is observed in the mass region between 1.5 and 2.9 GeV/c^2. The upper limit on the coupling strength parameter ϵ at the 90% C.L. as a function of the dark photon mass is illustrated in Fig. 4. This limit is established to be within (1.6-5.7)$\times 10^{-3}$.

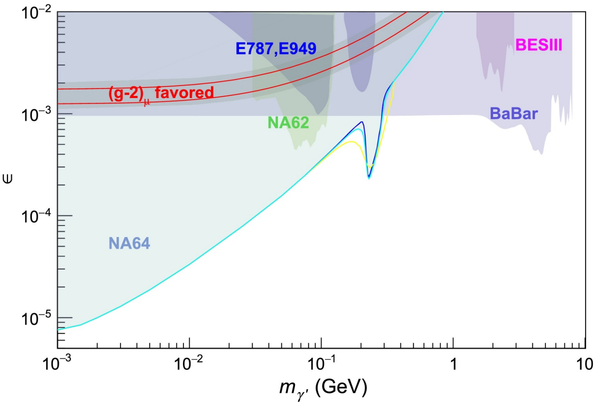

Figure 4. Upper limit on the coupling strength ϵ between the dark sector and the SM at the 90% CL versus the dark photon mass measured by BESIII (magenta region), together with previous measurements.

6 Summary and outlook

BESIII plays an active role in dark sector and axion-like particle search, with many first searches or best limits. Several searches for dark matter and axion-like particles have been performed using the data samples collected at several energy points, including J/ψ and $\psi(3686)$ resonances. No significant signal is found in these scenarios, and the exclusion limits are helpful to constrain the new physics models beyond the SM.

References

[1] R. Essig *et al.* Dark Sectors and New, Light, Weakly-Coupled Particles, arXiv:1311.0029 [hep-ph]

[2] Brian Batell, Nikita Blinov, Christopher Hearty, Robert McGehee, Exploring Dark Sector Portals with High Intensity Experiments, arXiv:2207.06905 [hep-ph]

[3] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **93**, 052005(2016)

[4] M. Ablikim *et al.* (BESIII Collaboration), Nucl. Instrum. Meth. A 614, 345 (2010).

[5] C. H. Yu *et al.*, Proceedings of the 7th International Particle Accelerator Conference, Busan, Korea, TUYA01, 2016

[6] R.D. Peccei, H.R. Quinn, Phys. Rev. Lett. **38** (1977) 1440.
[7] R.D. Peccei, H.R. Quinn, Phys. Rev. D **16** (1977) 1791.
[8] F. Wilczek, Phys. Rev. Lett. **40** (1978) 279.
[9] S. Weinberg, Phys. Rev. Lett. **40** (1978) 223.
[10] P.W. Graham, D.E. Kaplan, S. Rajendran, Phys. Rev. Lett. **115** (2015) 221801.
[11] L. Merlo *et al.*, JHEP **06**, 091 (2019).
[12] M. Ablikim *et al.* (BESIII Collaboration), Phys. Lett. B **838**, 137698 (2023)
[13] M. Fabbrichesi, E. Gabrielli, and B. Mele, Phys. Rev. Lett. **119**, 031801 (2017).
[14] J. Y. Su and J. Tandean, Phys. Rev. D **101**, 035044 (2020).
[15] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970).
[16] M. Ablikim*et al.* (BESIII Collaboration), Phys. Rev. D **106**, 072008 (2022).
[17] J. Adler *et al.*, Phys. Rev. Lett. **62**, 1821 (1989).
[18] G. Alonso-Alvarez *et al.*, Phys. Rev. D **105**, 115005 (2022)
[19] A. T. Yue *et al.*, Phys. Rev. Lett. **111**, 222501 (2013).
[20] M. Abilikim *et al.* (BESIII Collaboration), Phys. Rev. D **105**, L071101 (2022)
[21] M. Aguilar *et al.* (AMS Collaboration), Phys. Rev. Lett. **110**, 141102 (2013).
[22] B. Abi*et al.* (Muon g-2 Collaboration), Phys. Rev. Lett. **126**, 141801 (2021).
[23] B. Holdom, Phys. Lett. B **166**, 196 (1986).
[24] M. Ablikim *et al.* (BESIII Collaboration), Phys. Lett. B **839**, 137785 (2023).