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# Dark photon search in the mass range between 1.5 and 3.4 GeV/$c^2$

BESIII Collaboration

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ABSTRACT

Using a data set of 2.93 fb$^{-1}$ taken at a center-of-mass energy $\sqrt{s} = 3.773$ GeV with the BESIII detector at the BEPCII collider, we perform a search for an extra U(1) gauge boson, also denoted as a dark photon. We examine the initial state radiation reactions $e^+e^- \to e^+e^-\gamma_{\rm ISR}$ and $e^+e^- \to \mu^+\mu^-\gamma_{\rm ISR}$ for this search, where the dark photon would appear as an enhancement in the invariant mass distribution of the leptonic pairs. We observe no obvious enhancement in the mass range between 1.5 and 3.4 GeV/$c^2$ and set a 90% confidence level upper limit on the mixing strength of the dark photon and the Standard Model photon. We obtain a competitive limit in the tested mass range.



Several astrophysical anomalies, which cannot be easily understood in the context of the Standard Model (SM) of particle physics or astrophysics, have been discussed in relation to a dark, so far unobserved sector [1], which couples very weakly with SM particles. The most straightforward model consists of an extra U(1) force carrier, also denoted as a dark photon, $\gamma'$, which couples to the SM via kinetic mixing [2]. It has been shown in Ref. [1] that the dark photon has to be relatively light, on the MeV/$c^2$ to GeV/$c^2$ mass scale, to explain the astrophysical observations. Furthermore, it was realized, that a dark photon of similar mass could also explain the presently observed deviation on the level of 3 to 4$\sigma$ between the measurement and the SM prediction of $(g-2)_\mu$ [3]. These facts and the work by Bjorken and collaborators [4] triggered searches for the dark photon at particle accelerators in a world wide effort [5,6]. Different experimental setups can be used, like fixed-target (e.g. Refs. [7,8]), beam dump (e.g. Refs. [9,10]), or low-energy collider experiments (e.g. Refs. [11,12]). The mixing strength $\varepsilon = \alpha'/\alpha$, where $\alpha'$ is the coupling of the dark photon to the electromagnetic charge and $\alpha$ the fine structure constant, is constrained by previous measurements to be below approximately $10^{-2}$ [4].

In this letter we present a dark photon search, using 2.93 fb$^{-1}$ [13] of data taken at $\sqrt{s} = 3.773$ GeV obtained with the Beijing Spectrometer III (BESIII). The measurement exploits the process of initial state radiation (ISR), in which one of the beam particles radiates a photon. In this way, the available energy to produce final states is reduced, and the di-lepton invariant masses below the center-of-mass energy of the $e^+e^-$ collider become available. The same method has been used by the BaBar experiment [11,12], where a dark photon mass $m_{\gamma'}$ between 0.02 and 10.2 GeV/$c^2$ and $\varepsilon$ values in the order of $10^{-3}$–$10^{-4}$ have been excluded. We search for the processes $e^+e^- \to \gamma'\gamma_{\rm ISR} \to l^+l^-\gamma_{\rm ISR}$ ($l = \mu, e$) with leptonic invariant masses $m_{l^+l^-}$ between 1.5 and 3.4 GeV/$c^2$. The ISR QED processes $e^+e^- \to \mu^+\mu^-\gamma_{\rm ISR}$ and $e^+e^- \to e^+e^-\gamma_{\rm ISR}$ are irreducible background channels. However, the dark photon width is expected to be smaller than the resolution of the experiment [4] and, thus, a $\gamma'$ signal would lead to a narrow structure at the mass of the dark photon in the $m_{l^+l^-}$ mass spectrum on top of the continuum QED background.

The BESIII detector is located at the double-ring $e^+e^-$ Beijing Electron Positron Collider (BEPCII) [14]. The cylindrical BESIII detector covers 93% of the full solid angle. It consists of the following detector systems. (1) A Multilayer Drift Chamber (MDC) filled with a helium-gas mixture, composed of 43 layers, which provides a spatial resolution of 135 μm and a momentum resolution of 0.5% for charged tracks at 1 GeV/$c$ in a magnetic field of 1 T. (2) A Time-of-Flight system (TOF), built with 176 plastic scintillator counters in the barrel part, and 96 counters in the end caps. The time resolution in the barrel (end caps) is 80 ps (110 ps). For momenta up to 1 GeV/$c$, this provides a 2$\sigma$ K/$\pi$ separation. (3) A CsI(Tl) Electro-Magnetic Calorimeter (EMC) with an energy resolution of 2.5% in the barrel and 5% in the end caps at an energy of 1 GeV. (4) A Muon Counter (MUC) consisting of nine barrel and eight end-cap resistive plate chamber layers with a 2 cm position resolution.

For the simulation of ISR processes $e^+e^- \to \mu^+\mu^-\gamma_{\rm ISR}$ and $\pi^+\pi^-\gamma_{\rm ISR}$, the PHOKHARA event generator [15,16], which includes ISR and final state radiation (FSR) corrections up to next-to-leading order, is used. Bhabha scattering is simulated with BABAYAGA 3.5 [17]. Continuum Monte Carlo (MC) events, as well as the resonant $\psi(3770)$ decays to $D\bar{D}$, non-$D\bar{D}$, and the ISR

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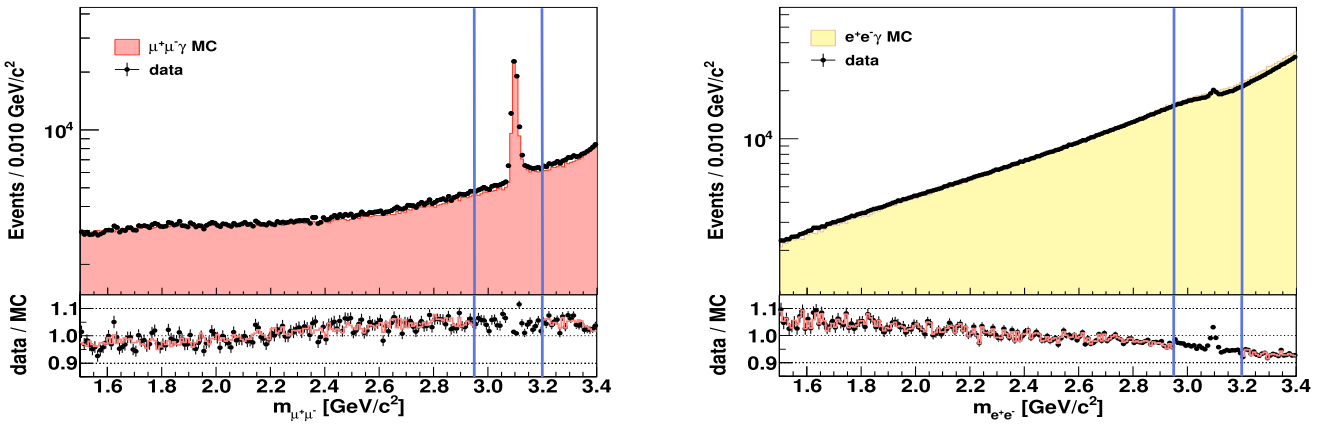


**Fig. 1.** Leptonic invariant mass distributions $m_{\mu^+\mu^-}$ and $m_{e^+e^-}$ after applying the selection requirements. Shown is data (points) and MC simulation (shaded area), which is scaled to the luminosity of the data set. The marked area around the $J/\psi$ resonance is excluded in the analysis. The lower panel shows the ratio of data and MC simulation (points) and the ratio of fit curve and MC simulation (histogram).

production of $\psi'$ and $J/\psi$, are simulated with the KKMC generator [18]. All MC generators, which are the most appropriate choices for the processes studied, have been interfaced with the GEANT4-based [19,20] detector simulation.

The selection of $\mu^+\mu^-\gamma_{\rm ISR}$ and $e^+e^-\gamma_{\rm ISR}$ events is straightforward. We require the presence of two charged tracks in the MDC with net charge zero. The points of closest approach from the interaction point (IP) for these two tracks are required to be within a cylinder of 1 cm radius in the transverse direction and $\pm 10$ cm of length along the beam axis. The polar angle with respect to the beam axis $\theta$ of the tracks is required to be in the fiducial volume of the MDC: $0.4 < \theta < \pi - 0.4$ radians. In order to suppress spiraling tracks, we require the transverse momentum $p_t$ to be above 300 MeV/$c$ for both tracks.

Muon particle identification is used [21]. The probabilities for being a muon $P(\mu)$ and being an electron $P(e)$ are calculated using information from MDC, TOF, EMC, and MUC. For both charged tracks, $P(\mu) > P(e)$ is required. To select electrons, the ratio of the measured energy in the EMC, $E$, to the momentum $p$ obtained from the MDC is used. Both charged tracks must satisfy $E/p > 0.8$ $c$.

The radiator function [22], which describes the radiation of an ISR photon, is peaked at small $\theta$ values with respect to the beam axis. Different from BaBar, we use untagged ISR events, where the ISR photon is emitted at a small angle $\theta_\gamma$ and is not detected within the angular acceptance of the EMC, to increase statistics. A one constraint (1C) kinematic fit, applying energy and momentum conservation, is performed with the hypothesis $e^+e^- \to \mu^+\mu^-\gamma_{\rm ISR}$ or $e^+e^- \to e^+e^-\gamma_{\rm ISR}$, using as input the two selected charged track candidates, as well as the four momentum of the initial $e^+e^-$ system. The constraint is the mass of a missing photon. The fit quality condition $\chi^2_{\rm 1C}/({\rm dof}=1) < 20$ is applied in the $\mu^+\mu^-\gamma_{\rm ISR}$ case, where dof is the degree of freedom. To suppress non-ISR background, the angle of the missing photon, $\theta_\gamma$, predicted by the 1C kinematic fit, is required to be smaller than 0.1 radians or greater than $\pi - 0.1$ radians. We apply stronger requirements for the $e^+e^-\gamma_{\rm ISR}$ final state, to provide a better suppression of the non-ISR background which is higher in the $e^+e^-$ channel compared to the $\mu^+\mu^-$ channel. In this case, $\chi^2_{\rm 1C}/({\rm dof}=1) < 5$, and $\theta_\gamma < 0.05$ radians, or $\theta_\gamma > \pi - 0.05$ radians.

Background in addition to the radiative QED processes $\mu^+\mu^-\gamma_{\rm ISR}$ and $e^+e^-\gamma_{\rm ISR}$, which is irreducible, is studied with MC simulations and is negligible for the $e^+e^-\gamma_{\rm ISR}$ final state, and on the order of 3% for $\mu^+\mu^-$ invariant masses below 2 GeV/$c^2$ due to muon misidentification, and negligible above. This remaining background comes mostly from $\pi^+\pi^-\gamma_{\rm ISR}$ events. We subtract their contribution using a MC sample, produced with the PHOKHARA generator. The subtraction of this background leads to a systematic uncertainty due to the generator precision smaller than 0.5%.

The $\mu^+\mu^-$ and $e^+e^-$ invariant mass distributions, $m_{\mu^+\mu^-}$ and $m_{e^+e^-}$, which are shown separately in Fig. 1, are mainly dominated by the QED background but could contain the signal sitting on top of these irreducible events. For comparison with data, MC simulation, scaled to the luminosity of data, is shown, although it is not used in the search for the dark photon. In this analysis, the dark photon mass range $m_{\gamma'}$ between 1.5 and 3.4 GeV/$c^2$ is studied. Below 1.5 GeV/$c^2$ the $\pi^+\pi^-\gamma_{\rm ISR}$ cross section with muon misidentification dominates the $m_{\mu^+\mu^-}$ spectrum. Above 3.4 GeV/$c^2$ the hadronic $q\bar{q}$ process can not be suppressed sufficiently by the $\chi^2_{\rm 1C}$ requirement. In order to search for narrow structures on top of the QED background, 4th order polynomial functions to describe the continuum QED are fitted to the data distributions shown in Fig. 1. The mass range around the narrow $J/\psi$ resonance between 2.95 and 3.2 GeV/$c^2$ is excluded.

The differences between the $\mu^+\mu^-\gamma_{\rm ISR}$ and $e^+e^-\gamma_{\rm ISR}$ event yields and their respective 4th order polynomials are added. The combined differences are represented by the black dots in Fig. 2. A dark photon candidate would appear as a peak in this plot. The observed statistical significances are less than $3\sigma$ everywhere in the explored region. The significance in each invariant mass bin is defined as the combined differences between data and the 4th order polynomials, divided by the combined statistical errors of both final states. In conclusion, we observe no dark photon signal for 1.5 GeV/$c^2$ $< m_{\gamma'} <$ 3.4 GeV/$c^2$, where $m_{\gamma'}$ is equal to the leptonic invariant mass $m_{l^+l^-}$. The exclusion limit at the 90% confidence level is determined with a profile likelihood approach [23]. Also shown in Fig. 2 as a function of $m_{l^+l^-}$ is the bin-by-bin calculated exclusion limit, including the systematic uncertainties as explained below.

To calculate the exclusion limit on the mixing parameter $\varepsilon^2$, the formula from Ref. [4] is used

$$\frac{\sigma_i(e^+e^- \to \gamma'\gamma_{\rm ISR} \to l^+l^-\gamma_{\rm ISR})}{\sigma_i(e^+e^- \to \gamma^*\gamma_{\rm ISR} \to l^+l^-\gamma_{\rm ISR})} = \frac{N_i^{\rm up}(e^+e^- \to \gamma'\gamma_{\rm ISR} \to l^+l^-\gamma_{\rm ISR})}{N_i^{\rm B}(e^+e^- \to \gamma^*\gamma_{\rm ISR} \to l^+l^-\gamma_{\rm ISR})} \cdot \frac{1}{\epsilon} = \frac{3\pi \cdot \varepsilon^2 \cdot m_{\gamma'}}{2N_f^{l^+l^-}\alpha \cdot \delta_m^{l^+l^-}}, \quad (1)$$

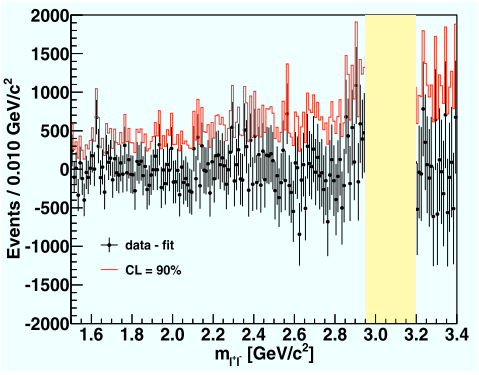


**Fig. 2.** The sum of the differences between the $\mu^+\mu^-\gamma_{\rm ISR}$ and $e^+e^-\gamma_{\rm ISR}$ event yields and their respective 4th order polynomials (dots with error bars). The solid histogram represents the exclusion limit with the 90% confidence, calculated with a profile likelihood approach and including the systematic uncertainty. The region around the $J/\psi$ resonance between 2.95 and 3.2 GeV/$c^2$ is excluded.

where $i$ represents the $i$-th mass bin, $\alpha$ is the electromagnetic fine structure constant, $m_{\gamma'}$ the dark photon mass, $\gamma^*$ the SM photon, and $\delta_m^{l^+l^-}$ ($l=\mu,\ e$) the bin width of the lepton pair invariant mass spectrum, 10 MeV/$c^2$. The mass resolution of the lepton pairs determined with MC for $e^+e^-$ and $\mu^+\mu^-$ is between 5 and 12 MeV/$c^2$. The cross section ratio upper limit in Eq. (1) is determined from the exclusion upper limit ($N^{\rm up}$) corrected by the efficiency loss ($\epsilon$) due to the bin width divided by the number of $\mu^+\mu^-\gamma_{\rm ISR}$ and $e^+e^-\gamma_{\rm ISR}$ events ($N^{\rm B}$) corrected as described below. The efficiency loss caused by the incompleteness of signal events in one bin is calculated with $\int_{-5\ {\rm MeV}/c^2}^{5\ {\rm MeV}/c^2} {\rm G}(0,\sigma)\,dm / \int_{-\infty}^{\infty} {\rm G}(0,\sigma)\,dm$, where ${\rm G}(0,\sigma)$ is the Gaussian function used to describe the mass resolution.

The QED cross section $\sigma_i(e^+e^- \to \gamma^*\gamma_{\rm ISR} \to l^+l^-\gamma_{\rm ISR})$ must only take into account annihilation processes of the initial $e^+e^-$ beam particles, where a dark photon could be produced. Thus, the event yield of the $e^+e^-\gamma$ final state has to be corrected due to the existence of SM Bhabha scattering. This correction is obtained in bins of $m_{e^+e^-}$ by dividing the $e^+e^-$ annihilation events only by the sum of events of the annihilation and Bhabha scattering processes. The first is generated with the PHOKHARA event generator by generating the $\mu^+\mu^-\gamma$ final state and replacing the muon mass with the electron mass. The latter is generated with the BABAYAGA@NLO generator [24]. The correction factor varies between 2% and 8% depending on $m_{e^+e^-}$.

The number of final states for the dark photon $N_f^{l^+l^-}$ includes the phase space above the $l^+l^-$ production threshold of the leptons $l=\mu, e$, and is given by $N_f^{l^+l^-} = \Gamma_{tot}/\Gamma_{ll}$ [25], where $\Gamma_{ll} \equiv \Gamma(\gamma' \to l^+l^-)$ is the leptonic $\gamma'$ width and $\Gamma_{tot}$ is the total $\gamma'$ width. These widths are taken from Ref. [25]

$$\Gamma_{ll} = \frac{\alpha\varepsilon^2}{3m_{\gamma'}^2}(m_{\gamma'}^2 + 2m_l^2)\sqrt{m_{\gamma'}^2 - 4m_l^2} \tag{2}$$

$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu}\cdot(1 + R(\sqrt{s}))\,, \tag{3}$$

where $\Gamma_{ee} \equiv \Gamma(\gamma' \to e^+e^-)$, $\Gamma_{\mu\mu} \equiv \Gamma(\gamma' \to \mu^+\mu^-)$, and $R(\sqrt{s})$ is the total hadronic cross section $R$ value [26] as a function of $\sqrt{s}$.

The systematic uncertainties are included in the calculation of the exclusion limit. The main source is the uncertainty of the $R$ value taken from Ref. [26], which enters the calculation of the $N_f^{l^+l^-}$ and leads to a mass dependent systematic uncertainty between 3.0 and 6.0%. Other sources are background subtraction as described above (<0.5%), the fitting error of the polynomial fit to data (<1%), the Bhabha scattering correction factor using the PHOKHARA and BABAYAGA@NLO event generator (<1%), and data-MC differences of the leptonic mass resolution. To quantify the latter one, we study the data-MC resolution difference of the $J/\psi$ resonance for the $\mu^+\mu^-$ and $e^+e^-$ decays, separately. The resonance is fitted with a double Gaussian function in data and MC simulation, and the width difference is $(3.7\pm1.8)$% for $\mu^+\mu^-$ and $(0.7\pm5.3)$% for $e^+e^-$. The differences are taken into consideration in the calculations, and the uncertainty in the differences (1%) is taken as the systematic uncertainty of the data-MC differences. The mass dependent total systematic uncertainty, which varies from 3.5 to 6.5% depending on mass, is used bin-by-bin in the upper limit.

The final result, the mixing strength $\varepsilon$ as a function of the dark photon mass, is shown in Fig. 3, including the systematic uncertainties. It provides a comparable upper limit to BaBar [11,12] in the studied $m_{\gamma'}$ mass range. Also shown are the exclusion limits from KLOE [27–30], WASA-at-COSY [31], HADES [32], PHENIX [33], A1 at MAMI [7,8], NA48/2 [34], APEX [35], and the beam-dump experiments E774 [9], and E141 [10]. The $\varepsilon$ values, which would explain the discrepancy between the measurement and the SM calculation of the anomalous magnetic moment of the muon [3] are displayed in Fig. 3 as the bold solid line with a $2\sigma$ band.

In conclusion, we perform a search for a dark photon in the mass range between 1.5 and 3.4 GeV/$c^2$, where we do not observe

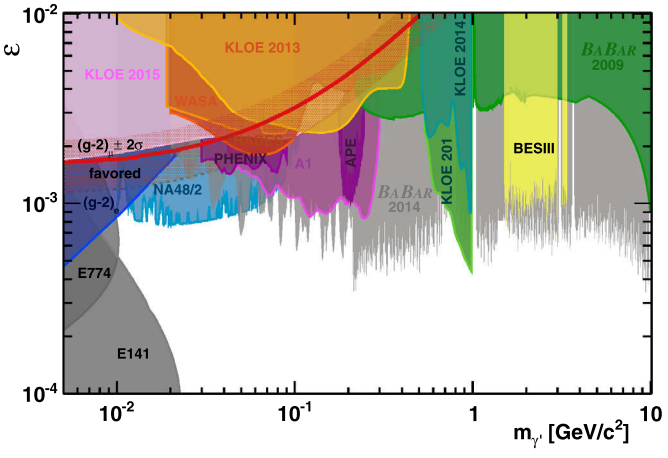


**Fig. 3.** Exclusion limit at the 90% confidence level on the mixing parameter $\varepsilon$ as a function of the dark photon mass. The bold solid line represents the $\varepsilon$ values, which would explain the discrepancy between the measurement and the SM calculation of the anomalous magnetic moment of the muon [3], together with its $2\sigma$ band.

a significant signal. We set upper limits on the mixing parameter $\varepsilon$ between $10^{-3}$ and $10^{-4}$ as a function of the dark photon mass with a confidence level of 90%. This is a competitive limit in this dark photon mass range. The BESIII results, which are based on two years of data taking, are already competitive to the large BaBar data samples, based on 9 years of running. This is possible due to the use of untagged ISR events for the dark photon search as well as the fact that the center-of-mass energy of the BEPCII collider is closer to the mass region tested. We also use a different analysis approach, which has no dependence on the radiator function.

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## References

[1] N. Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer, N. Weiner, Phys. Rev. D 79 (2009) 015014.
[2] B. Holdom, Phys. Lett. B 166 (1986) 196–198.
[3] M. Pospelov, Phys. Rev. D 80 (2009) 095002.
[4] J.D. Bjorken, R. Essig, P. Schuster, N. Toro, Phys. Rev. D 80 (2009) 075018.
[5] B. Batell, M. Pospelov, A. Ritz, Phys. Rev. D 79 (2009) 115008.
[6] H.B. Li, T. Luo, Phys. Lett. B 686 (2010) 249–253.
[7] H. Merkel, et al., A1 Collaboration, Phys. Rev. Lett. 106 (2011) 251802.
[8] H. Merkel, et al., A1 Collaboration, Phys. Rev. Lett. 112 (2014) 221802.
[9] A. Bross, et al., E774 Collaboration, Phys. Rev. Lett. 67 (1991) 2942.
[10] E.M. Riordan, et al., E141 Collaboration, Phys. Rev. Lett. 59 (1987) 755.
[11] B. Aubert, et al., BaBar Collaboration, Phys. Rev. Lett. 103 (2009) 081803.
[12] J.P. Lees, et al., BaBar Collaboration, Phys. Rev. Lett. 113 (2014) 201801.
[13] M. Ablikim, et al., BESIII Collaboration, Phys. Lett. B 753 (2016) 629–638.
[14] M. Ablikim, et al., BESIII Collaboration, Nucl. Instr. Meth. A 614 (2010) 345–399.
[15] G. Rodrigo, H. Czyż, J.H. Kuhn, M. Szopa, Eur. Phys. J. C 24 (2002) 71.
[16] H. Czyz, J.H. Kuhn, A. Wapienik, Phys. Rev. D 77 (2008) 114005.
[17] G. Balossini, C.M.C. Calame, G. Montagna, O. Nicrosini, F. Piccinini, Nucl. Phys. B 758 (2006) 227–253.
[18] S. Jadach, B.F.L. Ward, Z. Was, Comput. Phys. Commun. 130 (2000) 260–325.
[19] J. Allison, et al., GEANT4 Collaboration, IEEE Trans. Nucl. Sci. 53 (2006) 270–278.
[20] S. Agostinelli, et al., GEANT4 Collaboration, Nucl. Instr. Meth. A 506 (2003) 250–303.
[21] D.M. Asner, et al., Int. J. Mod. Phys. A 24 (S1) (2009) 794.
[22] V.P. Druzhinin, S.I. Eidelman, S.I. Serednyakov, E.P. Solodov, Rev. Mod. Phys. 83 (2011) 1545.
[23] W.A. Rolke, A.M. Lopez, J. Conrad, Nucl. Instrum. Methods Phys. Res., Sect. A 551 (2005) 493–503.
[24] G. Balossini, C. Bignamini, C.M.C. Calame, G. Montagna, O. Nicrosini, F. Piccinini, Phys. Lett. B 663 (2008) 209–213.
[25] T. Beranek, H. Merkel, M. Vanderhaeghen, Phys. Rev. D 88 (2013) 015032.
[26] C. Patrignani, et al., Particle Data Group, Chin. Phys. C 40 (2016) 100001.
[27] F. Archilli, et al., KLOE-2 Collaboration, Phys. Lett. B 706 (2012) 251–255.
[28] D. Babuski, et al., KLOE-2 Collaboration, Phys. Lett. B 736 (2014) 459–464.
[29] A. Anastasi, et al., KLOE-2 Collaboration, Phys. Lett. B 750 (2015) 633–637.
[30] A. Anastasi, et al., KLOE-2 Collaboration, Phys. Lett. B 757 (2016) 356–361.
[31] P. Adlarson, et al., WASA-at-COSY Collaboration, Phys. Lett. B 726 (2013) 187–193.
[32] G. Agakishiev, et al., HADES Collaboration, Phys. Lett. B 731 (2014) 265–271.
[33] A. Adare, et al., PHENIX Collaboration, Phys. Rev. C 91 (2015) 031901.
[34] J.R. Batley, et al., NA48/2 Collaboration, Phys. Lett. B 746 (2015) 178–185.
[35] S. Abrahamyan, et al., APEX Collaboration, Phys. Rev. Lett. 107 (2011) 191804.