



## Searching a dark photon with HADES



HADES Collaboration

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## ARTICLE INFO

## Article history:

Received 4 November 2013  
 Received in revised form 17 February 2014  
 Accepted 19 February 2014  
 Available online 26 February 2014  
 Editor: D.F. Geesaman

## Keywords:

Dark photon  
 Hidden sector  
 Dark matter  
 Rare eta decays

## ABSTRACT

We present a search for the  $e^+e^-$  decay of a hypothetical dark photon, also named  $U$  vector boson, in inclusive dielectron spectra measured by HADES in the  $p(3.5 \text{ GeV}) + p$ ,  $\text{Nb}$  reactions, as well as the  $\text{Ar}(1.756 \text{ GeV/u}) + \text{KCl}$  reaction. An upper limit on the kinetic mixing parameter squared  $\epsilon^2$  at 90% CL has been obtained for the mass range  $M_U = 0.02\text{--}0.55 \text{ GeV}/c^2$  and is compared with the present world data set. For masses  $0.03\text{--}0.1 \text{ GeV}/c^2$ , the limit has been lowered with respect to previous results, allowing now to exclude a large part of the parameter region favored by the muon  $g-2$  anomaly. Furthermore, an improved upper limit on the branching ratio of  $2.3 \times 10^{-6}$  has been set on the helicity-suppressed direct decay of the eta meson,  $\eta \rightarrow e^+e^-$ , at 90% CL.

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## 1. Introduction

Observations of the cosmic electron and/or positron flux by ATIC [1], PAMELA [2], HESS [3,4], Fermi [5], and recently the AMS02 Collaboration [6] have revealed an unexpected excess at momenta above 10 GeV, in particular in the positron fraction  $e^+/(e^- + e^+)$ . These observations cannot easily be reconciled in a consistent way with known astrophysical sources [7] and alternative theoretical explanations have therefore been put forward. In particular, scenarios in which the excess radiation stems from the annihilation of weakly interacting dark matter particles [7,8] might offer an enticing solution to this puzzle. There is indeed compelling evidence from various astronomical and cosmological observations [9,10] that non-baryonic matter of some sort is responsible for 20–25% of the total energy density in the Universe. This so-called dark matter (DM) is assumed to be a relic from the Big Bang making itself noticeable by its gravitational action on the large-scale cosmic structures. To accommodate DM in elementary particle theory and to allow it to interact with visible matter, it has been proposed to supplement the Standard Model (SM) with an additional sector characterized by another  $U(1)'$  gauge symmetry [11–14]. The corresponding vector gauge boson – called  $U$  boson,  $A'$ ,  $\gamma'$ , or simply dark photon – would thereby mediate the annihilation of DM particles into charged lepton pairs. Indeed, from theoretical arguments a kinetic mixing of the  $U(1)'$  and  $U(1)$  symmetry groups would follow [15,16], providing a natural connection between the dark and SM sectors. For that purpose, a mixing parameter  $\epsilon$  has been introduced [11] relating the respective coupling strengths  $\alpha'$  and  $\alpha$  of the dark and SM photons to visible matter via  $\epsilon^2 = \alpha'/\alpha$ ; it is expected to be of order  $10^{-2}\text{--}10^{-8}$  [17,18]. Also, the mass of the  $U$  boson is thought to remain well below  $1 \text{ GeV}/c$  [17], resulting most likely in a small width  $\Gamma_U \ll 1 \text{ MeV}$  [19–21]. This is of particular interest for experimental searches because a dark photon would appear in the data as a rather narrow resonance.

Through the  $U(1)\text{--}U(1)'$  mixing term the  $U$  boson would be involved in all processes which include real or virtual photons [21]. On the other hand, any search for a  $U$  boson will have to deal with the large unavoidable background from standard QED radiative processes [22]. In recent years, a number of such searches have been conducted in various experiments done in the few-GeV beam energy regime, looking either at  $e^+e^-$  pair distributions produced in electron scattering [23,24] or in the electromagnetic decays of the neutral pion [25,26] and the  $\phi$  meson [27,28]. In particular, the latter experiment exploited the hypothetical  $\phi \rightarrow \eta + U \rightarrow 3\pi e^-e^+$  decay with the  $\phi$  produced in  $e^+e^-$  collisions. Reconstructing the  $e^+e^-$  invariant-mass distribution tagged by fully identified  $\eta$  mesons in either of their two 3-pion decay channels,  $\pi^0\pi^0\pi^0$  or  $\pi^+\pi^-\pi^0$ , a search for a narrow  $U \rightarrow e^+e^-$  signal was possible. In a similar fashion the WASA-at-COSY experiment [26] has covered the mass range  $M_U = 0.02\text{--}0.1 \text{ GeV}/c^2$  by investigating decays of

$\pi^0$  produced in proton-induced reactions at 0.55 GeV beam energy. Analyzing data obtained from high-flux neutrino production experiments at CERN [29] and at Serpukhov [30], regions in parameter space  $\epsilon^2$  vs.  $M_U$  corresponding to a long-lived  $U$  have been excluded as well. Note finally, that from the very precisely measured value of the anomalous gyromagnetic factors ( $g-2$ ) of the muon and electron [31], additional constraints are put on the allowed range of the mixing parameter  $\epsilon$  and the mass  $M_U$  [32,33].

Here, we present results of a search for a  $U \rightarrow e^-e^+$  decay signal in inclusive dielectron spectra obtained from 3.5 GeV proton-induced reactions on either a liquid hydrogen target or a solid niobium target, as well as  $\text{Ar}(1.756 \text{ GeV/u}) + \text{KCl}$  reaction. The reconstructed dielectron invariant-mass distribution from those reactions as well as data on the respective inclusive  $\pi^0$  and  $\eta$  production have been published elsewhere [34–37]. This Letter is organized as follows: In Section 2 we discuss the  $e^+e^-$  decay signature of a hypothetical dark photon. Section 3 presents the HADES experiment and data analysis, Section 4 describes in detail our  $U$ -boson search, in Section 5 we give a new upper limit on the direct  $\eta$  decay, and, finally, in Section 6 we summarize our findings.

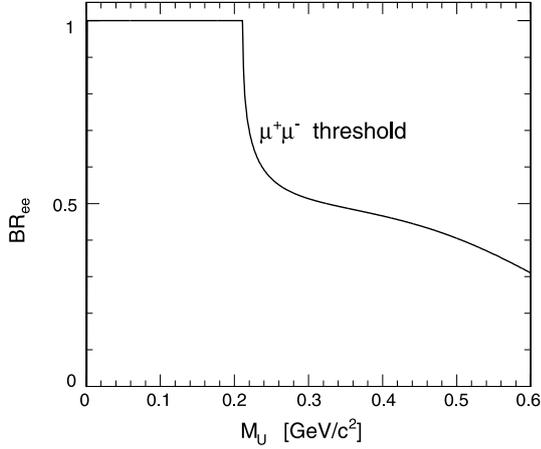
2. The  $U \rightarrow e^+e^-$  signature

Unlike the experiments described in [27,28,26], HADES has measured inclusive instead of exclusive dielectron production. This means that the reconstructed  $e^+e^-$  invariant-mass distribution  $dN/dM_{ee}$  consists of a superposition of contributions from different sources which at masses below  $0.6 \text{ GeV}/c^2$  are mainly the electromagnetic decays of the  $\pi^0$ , the  $\eta$ , and the  $\Delta$  resonance [34]. Transport model calculations [38,39] describe this dilepton cocktail quite well and show in particular that, in the relevant mass range, contributions from the  $\omega$  meson as well as from heavier nucleon resonances, e.g. the  $N^*(1440)$ ,  $N^*(1520)$ , and  $N^*(1535)$ , remain small. Considering baryon resonance decays in a search for signatures of a hypothetical  $U$  boson has actually been proposed first in [40].

Let us then estimate the  $U$ -boson yield by  $N_U = \sum_i N_U^{(i)}$ , where  $N_U^{(i)}$  refers to separable sources, such as  $i = \pi^0, \eta$  and  $\Delta$ , with the virtual photon (i.e. dilepton) replaced by a  $U$ . We obtain the ratios of widths from data via

$$\frac{\Gamma_{i \rightarrow \gamma U}}{\Gamma_{i \rightarrow \gamma \gamma}} = \frac{N_U^{(i)}}{N_i BR_{i \rightarrow \gamma \gamma}}, \quad (1a)$$

$$\frac{\Gamma_{\Delta \rightarrow NU}}{\Gamma_{\Delta \rightarrow N\gamma}} = \frac{N_U^{\Delta}}{N_{\Delta} BR_{\Delta \rightarrow N\gamma}}, \quad (1b)$$



**Fig. 1.** Assumed branching ratio  $BR_{ee}$  of a hypothetical  $U$  boson into an  $e^+e^-$  pair as a function of mass  $M_U$  according to Eq. (6).

where  $i = \pi^0$  and  $\eta$ . To get access to  $\epsilon^2$ , we use the expression

$$\frac{\Gamma_{i \rightarrow \gamma U}}{\Gamma_{i \rightarrow \gamma \gamma}} = 2\epsilon^2 |F_i(q^2 = M_U^2)| \frac{\lambda^{3/2}(m_i^2, m_\gamma^2, M_U^2)}{\lambda^{3/2}(m_i^2, m_\gamma^2, m_\gamma^2)}. \quad (2)$$

Here,  $\lambda$  is the standard triangle function for relativistic kinematics and  $F_i(q^2)$  is the electromagnetic transition form factor. Furthermore, for on-shell photons ( $m_\gamma^2 = 0$ ), one gets

$$\frac{\lambda^{3/2}(m_\eta^2, 0, M_U^2)}{\lambda^{3/2}(m_\eta^2, 0, 0)} = \left(1 - \frac{M_U^2}{m_\eta^2}\right)^3. \quad (3)$$

Note that, as the  $\Delta$  is a broad state, the decay width  $\Gamma_{\Delta \rightarrow NU}$  has to be averaged over the  $\Delta$  mass distribution  $A(m_\Delta)$ , assumed to be described by a Breit-Wigner shape of width  $\Gamma = 117$  MeV (see [41] for details):

$$\frac{\Gamma_{\Delta \rightarrow NU}}{\Gamma_{\Delta \rightarrow N\gamma}} = \epsilon^2 \int A(m_\Delta) |F_\Delta(M_U^2)| \frac{\lambda^{3/2}(m_\Delta^2, m_N^2, M_U^2)}{\lambda^{3/2}(m_\Delta^2, m_N^2, 0)} dm_\Delta. \quad (4)$$

One has to consider furthermore that, as the  $\eta$  and  $\Delta$  decays give access to masses larger than the  $\mu^+\mu^-$  threshold at  $2m_\mu = 0.21$  GeV/ $c^2$ , the observed  $U$  signal has to be corrected for the branching fraction into  $e^+e^-$ , that is  $BR_{ee} = BR_{U \rightarrow e^+e^-}$  [20]:

$$BR_{ee} = \Gamma_{ee}/\Gamma_{tot} = \frac{\Gamma_{ee}}{\Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{had}}. \quad (5)$$

Assuming lepton universality, that is  $\Gamma_{\mu\mu} = \Gamma_{ee}$  for  $M_U \gg 2m_\mu$ , and estimating the hadronic decay width by  $R(\sqrt{s}) = \sigma_{e^+e^- \rightarrow hadrons}/\sigma_{e^+e^- \rightarrow \mu^+\mu^-}$  factor (taken from [10]), such that  $\Gamma_{had} = R(M_U)\Gamma_{\mu\mu}$ , the branching relevant for our search is given by

$$BR_{ee} = \frac{1}{1 + \sqrt{1 - \frac{4m_\mu^2}{M_U^2}} \left(1 + \frac{2m_\mu^2}{M_U^2}\right) [1 + R(M_U)]}. \quad (6)$$

**Fig. 1** exhibits  $BR_{ee}$  as a function of  $M_U$ . Putting all together, we obtain

$$N_{U \rightarrow ee} = N_{U \rightarrow ee}^\eta + N_{U \rightarrow ee}^{\pi^0} + N_{U \rightarrow ee}^\Delta$$

$$\begin{aligned} &= \epsilon^2 BR_{ee} \left[ 2N_\eta BR_{\eta \rightarrow \gamma\gamma} |F_\eta|^2 (1 - M_U^2/m_\eta^2)^3 \right. \\ &\quad + 2N_{\pi^0} BR_{\pi^0 \rightarrow \gamma\gamma} |F_{\pi^0}|^2 (1 - M_U^2/m_{\pi^0}^2)^3 \\ &\quad \left. + N_\Delta BR_{\Delta \rightarrow N\gamma} \int A(m_\Delta) |F_\Delta|^2 \frac{\lambda^{3/2}(m_\Delta^2, m_N^2, M_U^2)}{\lambda^{3/2}(m_\Delta^2, m_N^2, 0)} dm_\Delta \right] \\ &= \epsilon^2 BR_{ee} L(M_U), \end{aligned} \quad (7)$$

where  $L(M_U)$  assembles all kinematic factors and source parameters in Eq. (7). If, however, no actual  $U$  signal is observed and only an upper limit on the  $U$  multiplicity can be given, Eq. (7) provides accordingly an upper bound on  $\epsilon^2$  as a function of  $M_U$ .

Note that our approach is based on the following assumptions: (i)  $i = \pi^0$ ,  $\eta$ , and  $\Delta$  saturate the sum over all  $U$ -boson sources, (ii) the estimate of  $BR_{U \rightarrow e^+e^-}$  is sufficiently accurate, (iii) the parametrization of the transition form factors  $|F_{\pi^0}(q^2)| = 1 + 0.032 q^2/m_{\pi^0}^2$  [10] and  $|F_\eta(q^2)| = (1 - \frac{q^2}{\Lambda^2})^{-1}$  with  $\Lambda = 0.72$  GeV [42,43] are accurate enough, (iv) the spectral distribution of the  $\Delta$  in Eq. (4) is correct, (v) the use of  $|F_\Delta(q^2)| = 1$  does not alter the result, since an experimental form factor is not known (although [44] argues on a weak  $q^2$  dependence), (vi) uncertainties in the estimates of the  $\Delta$  multiplicities by  $N_\Delta = (3/2)N_{\pi^0}$  are of minor importance due to the small value of  $BR_{\Delta \rightarrow N\gamma} = 0.006$  compared with  $BR_{\eta \rightarrow \gamma\gamma} = 0.393$ ,  $BR_{\pi^0 \rightarrow \gamma\gamma} = 0.988$  [10].

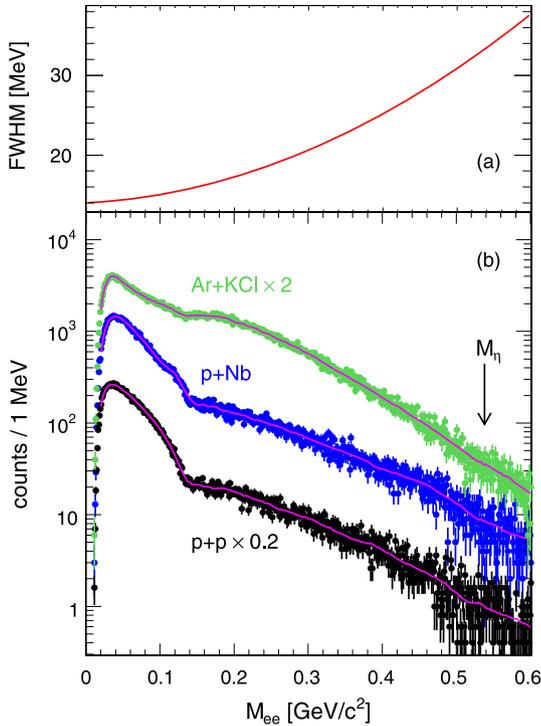
### 3. The HADES experiment

The high-acceptance dielectron spectrometer HADES operates at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, where it uses the beams from the heavy-ion synchrotron SIS18 in the few-GeV beam-energy range. A detailed description of the set-up can be found in [45].

In the experiments discussed here a proton beam with a kinetic energy of  $E_p = 3.5$  GeV and an average intensity of about  $2 \times 10^6$  particles per second was used to bombard either a solid 12-fold segmented niobium target (with 2.8% nuclear interaction probability) [35] or a liquid hydrogen target (1% interaction probability) [34]. In both experiments events were registered if at least three charged-particle hits were registered in the HADES time-of-flight wall (LVL1 trigger) and those events were actually recorded in case at least one electron or positron candidate was detected (LVL2 trigger). In the third experiment, a 4-fold segmented potassium chloride (KCl) target was bombarded with a  $^{40}\text{Ar}$  beam (kinetic beam energy of 1.75 GeV/u), the LVL1 trigger requiring at least 16 hits in the TOF wall [37].

In the data analysis, electrons and positrons were identified by applying selection cuts to the RICH, pre-shower and energy-loss signals. The particle momenta were obtained by tracking the charged particles through the HADES magnetic field; the latter were combined two-by-two to fully reconstruct the 4-momentum of  $e^+e^-$  pairs. A detailed description of this analysis is given in [37,45]. **Fig. 2** shows the resulting reconstructed invariant-mass distributions from the three reactions. As all reactions were investigated with the same setup, the detector acceptances and efficiencies were comparable. Still, as discussed in the next section, we have conducted separate searches in the three data sets and join the results in the end.

The production cross-sections (or multiplicities) of  $\eta$  and  $\pi^0$  mesons have been published in [34,36,37] for the  $p + p$ ,  $p + \text{Nb}$ , and  $\text{Ar} + \text{KCl}$  experiments, respectively. Recalculated total numbers of mesons ( $N_\eta$  and  $N_{\pi^0}$ ) produced in those experiments are listed in **Table 1**. For the  $\Delta$  resonance the factor  $3/2$  in  $N_\Delta = 3/2N_{\pi^0}$  has to be seen as an extreme, assuming that all pion production is mediated by  $\Delta$  decays, whereas model calculations typically favor



**Fig. 2.** (Color online.) (a) Dielectron mass resolution (FWHM) as a function of the  $e^+e^-$  invariant mass obtained from a Monte-Carlo simulation. (b) Measured inclusive  $e^+e^-$  invariant-mass distributions for 3.5 GeV p + p and p + Nb reactions, respectively, and 1.756 GeV/u Ar + KCl reactions in the HADES geometrical acceptance with single lepton momenta  $p_e > 0.05$  GeV and pair opening angles  $\theta_{e^+e^-} > 9^\circ$ . Error bars are statistical; magenta solid lines are envelopes of local polynomial fits used in the  $U$ -boson search (see Section 4). The arrow indicates the position where a direct  $\eta$  decay peak would appear ( $M_\eta = 0.548$  GeV/c<sup>2</sup>). Note that such a peak is not visible in our data, but an upper limit has been extracted at the expected position (see Section 5).

**Table 1**

Total number of triggered events  $N_{LVL1}$  as well as number of  $\pi^0$  ( $N_{\pi^0}$ ) and  $\eta$  ( $N_\eta$ ) mesons produced in the HADES p + p, p + Nb, and Ar + KCl experiments, respectively. The latter has been recalculated from the production data published in [34, 36,37]. Experimental uncertainties on the meson yields are of order 15–25%.

Reaction	$N_{LVL1}$	$N_{\pi^0}$	$N_\eta$
p + p	$3.0 \times 10^9$	$2.5 \times 10^9$	$1.5 \times 10^8$
p + Nb	$7.7 \times 10^9$	$5.9 \times 10^9$	$3.0 \times 10^8$
Ar + KCl	$2.2 \times 10^9$	$7.7 \times 10^9$	$1.9 \times 10^8$

smaller numbers [38]. In fact, because of the small electromagnetic branching  $BR_{N\gamma}$  of the  $\Delta$  resonance, its contribution to dark photon production is small compared to the  $\pi^0$  and  $\eta$ .

#### 4. The $U$ -boson search

As discussed above, the search for the  $U$  boson can be performed with HADES using all electromagnetic decays typically populated in few-GeV hadronic interactions, that is mostly  $\pi^0 \rightarrow \gamma U$ ,  $\eta \rightarrow \gamma U$ , and  $\Delta \rightarrow NU$ , followed by  $U \rightarrow e^+e^-$ . In contrast to previous experiments [26–28] focusing on a specific decay channel, our search is based on the inclusive measurement of all  $e^+e^-$  pairs produced in a given mass range. A background due to the respective Dalitz decays of the  $\pi^0$ ,  $\eta$ , and  $\Delta$  is always present. Indeed, because of their very similar decay kinematics, the latter sources cannot be discriminated from a  $U$ -boson signal via analysis cuts. It is also important to keep in mind that all of these lead to a rather featureless mass spectrum [38,39]. Therefore, we have to search for a peak structure on top of a smoothly varying con-

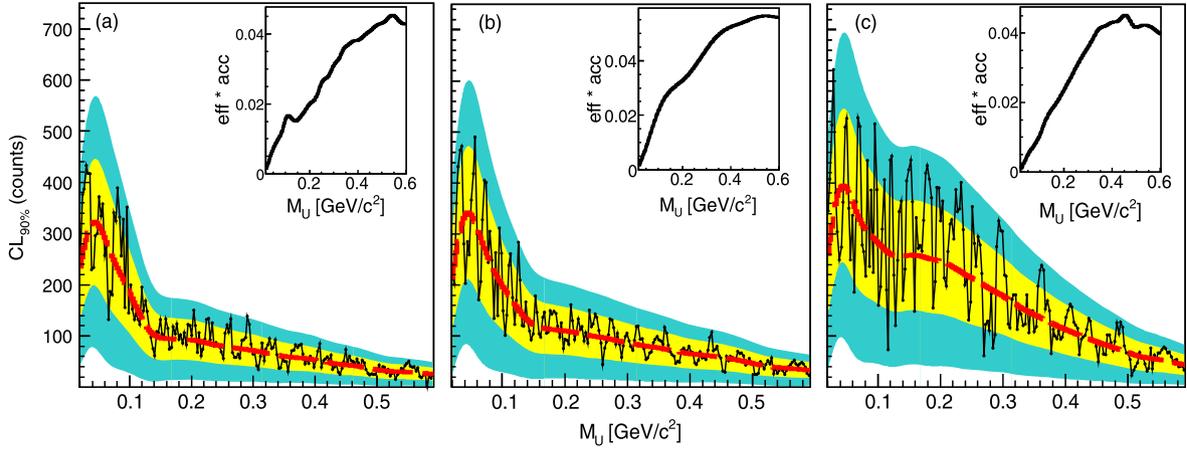
tinuum. Because of the expected long lifetime of the new particle the width of such a peak will be determined by the detector resolution. The upper frame of Fig. 2(a) shows the mass resolution obtained from a GEANT3-based Monte Carlo of  $e^+e^-$  decays detected in the HADES detector. The calculated peak width increases gradually with pair mass from about 15 MeV (fwhm) in the  $\pi^0$  region to about 30 MeV at the  $\eta$  mass of 0.55 GeV/c<sup>2</sup>.

The present analysis is based on the raw dilepton mass spectra, exhibited in Fig. 2(b), i.e. spectra not corrected for efficiency and acceptance. The low invariant-mass region of the spectra ( $M_{ee} < 0.13$  GeV/c<sup>2</sup>) is dominated by  $\pi^0$  Dalitz decays, at intermediate masses ( $0.13$  GeV/c<sup>2</sup>  $< M_{ee} < 0.55$  GeV/c<sup>2</sup>),  $\eta$  and  $\Delta$  Dalitz decays prevail, and the high-mass region is populated mostly by low-energy tails of vector-meson decays [34,35]. However, as the electromagnetic decay branching ratios decrease with increasing particle mass, resulting in low sensitivity, we restrict our search to  $M_U < 0.6$  GeV/c<sup>2</sup>.

The sensitivity of the experiment for observing a peak-like  $U \rightarrow e^+e^-$  mass signal depends evidently on various factors: the geometric acceptance of HADES for these decays, the combined detection and reconstruction efficiency of the  $e^+e^-$  signal, its mass resolution, and the signal-over-background ratio  $S/B$ . The latter one is not only given by the purity of the pair signal *per se*, it also reflects the amount of uncorrelated lepton pairs constituting the so-called combinatorial background (CB). Whereas a high purity of the dilepton signal is guaranteed by the overall good quality of the HADES lepton identification, the CB cannot be fully suppressed by analysis cuts. Although its contribution can be determined accurately in shape and normalization either by event-mixing techniques or from the yields of same-event like-sign pairs [45], it is always part of the total reconstructed pair yield and hence does contribute to the Poisson fluctuations of the latter.

Our search for a narrow resonant state in the  $e^+e^-$  mass distributions has been conducted in the following way: The  $dN/dM_{ee}$  spectra (Fig. 2(b)), measured in either of the analyzed reactions, was fitted piece-wise with a model function consisting of a 5th-order polynomial and a Gauss peak of fixed position  $M_{ee}$  and fixed width  $\sigma(M) = \text{fwhm}/2.35$  (from the simulation shown in Fig. 2(a)). The adjustment was done by sliding a fit window of width  $\pm 4\sigma(M)$  over the spectrum in steps of 3 MeV. In each step, the fit delivered a parameterization of the local background in presence of a possible Gaussian signal of given width  $\sigma(M)$ . The envelope of the adjusted polynomials is depicted in Fig. 2 by a solid line. From the fits it is apparent that no significant peak is present in our data. Consequently, a statistical likelihood-based test must be performed to determine at a given Confidence Level (CL) an upper limit (UL) for a possible  $U$ -boson signal [46]. Such tests are usually based on the profile likelihood ratio computed as a function of the signal strength  $S$  in presence of so-called nuisance parameters, e.g. the known (or estimated) background yield, the geometric acceptance, the detector and reconstruction efficiencies, and any overall normalization factors. As, in our case, background and  $e^+e^-$  efficiency corrections are needed to extract an absolute signal yield, and as both are known with limited accuracy only, we have used the method proposed by Rolke, Lopez and Conrad [47] to compute the UL at a confidence level  $CL = 90\%$ .

In our search, we have hence integrated the total observed dilepton yield as well as the adjusted smooth background over an interval  $\pm 1.5\sigma(M)$  centered at each examined mass  $M_U$ . Note that the chosen integration window assures 90% coverage of any hypothetical narrow signal at that mass. As we deal with sizable experimental yields, in the range of a few 100 to a few 1000 counts per inspected mass bin, we have applied the Root implementation [48] of the procedure [47] assuming a Gaussian error on the background as well as on the product of the acceptance and



**Fig. 3.** (Color online.) Extracted 90% CL upper limits on a narrow  $U \rightarrow e^+e^-$  signal as function of  $M_{ee}$  for p + p (a), p + Nb (b), and Ar + KCl (c) uncorrected HADES data (symbols). The computed experimental sensitivity (median UL) is shown as pink dashed curve and its error bands are given in yellow ( $\pm 1\sigma$ ) and cyan ( $\pm 2\sigma$ ). The inserts show the respective product of pair efficiency and pair acceptance,  $eff \times acc$  vs.  $M_{ee}$ .

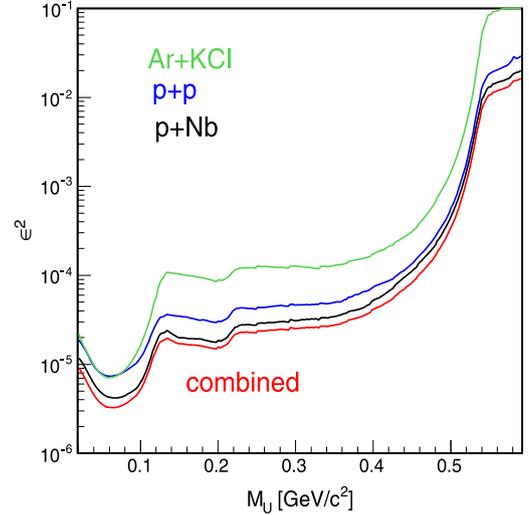
efficiency corrections ( $acc \times eff$ ). The Gaussian background error was provided by the polynomial least-square fit and the systematic error on all correction factors was determined to be 15%. This value encompasses in particular the error on the published particle production cross sections and electromagnetic branching ratios  $BR_{\gamma\gamma}$ .

The resulting upper limits, expressed as detectable counts, are shown in Fig. 3 for the mass range covered in this experiment, i.e. 0.02–0.55  $\text{GeV}/c^2$ . This figure also shows the expected sensitivity of our experiments, determined by running a Monte Carlo simulation in which the experimental mass spectrum was resampled channel by channel many times. In each such an iteration, the UL has been re-evaluated with the “zero-signal” hypothesis, i.e. assuming  $S = 0$ . This way, after 10,000 iterations, the median and standard deviation of the generated UL distributions could be computed as a function of pair mass [46]. The experimental sensitivity can in fact be characterized as the median significance with which a non-zero result of the search (at  $S = 0$ ) can be rejected at a given CL. Fig. 3 shows the obtained median UL together with its respective  $\pm 1\sigma$  and  $\pm 2\sigma$  error bands. Assuming a normally distributed UL, 68% (95%) of the sampled UL should be contained within the  $\pm 1\sigma$  ( $\pm 2\sigma$ ) corridor. Note that the UL determined from the actual data sets do fluctuate about the calculated median while staying indeed within the expected corridors with roughly the expected rate.

The inserts in Fig. 3 show, as a function of mass, the pair efficiency and acceptance correction factor,  $eff \times acc$ , obtained from detailed simulations. After having corrected the median UL for this factor, Eq. (7) was used to compute a corresponding upper limit  $UL(\epsilon^2)$  on the relative coupling strength  $\epsilon^2$  of a hypothetical dark vector boson. Fig. 4 shows the  $UL(\epsilon^2)$  as a function of  $M_U$  obtained from the three data sets separately. Evidently, the p + Nb data provide the strongest constraint. However, as the three data sets are of comparable statistical quality and result hence in upper limits of similar magnitude, it is natural to join them into a combined upper limit [49]. Since all experiments have been executed under very similar conditions, we use the following statistics-driven ansatz:

$$UL_{(1+2+3)} = \sqrt{(UL_{(1)}^{-2} + UL_{(2)}^{-2} + UL_{(3)}^{-2})^{-1}}. \quad (8)$$

The combined upper limit  $UL_{(1+2+3)}$  is overall about 10 to 20% lower than the p + Nb value taken alone. This is indeed expected from the moderate increase in pair statistics achieved by cumulating the data from all experiments and is consistent with a  $UL \propto 1/\sqrt{N}$  behavior.

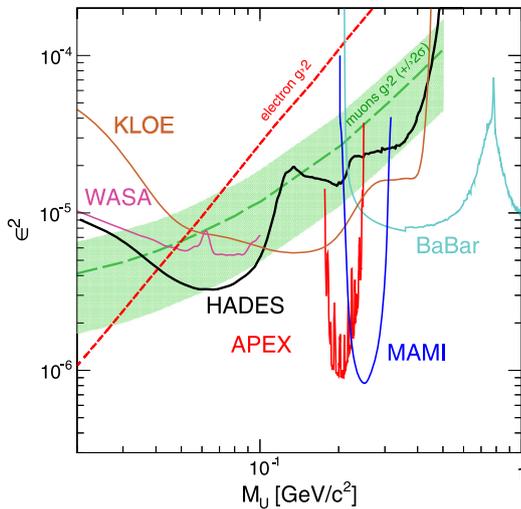


**Fig. 4.** (Color online.) Exclusion plot at 90% CL on  $\epsilon^2$  as function of  $M_U$  from the analyses of HADES in the reactions p(3.5 GeV) + Nb, as well as Ar(1.756 GeV/u) + KCl. Also shown is the combined UL computed with Eq. (8).

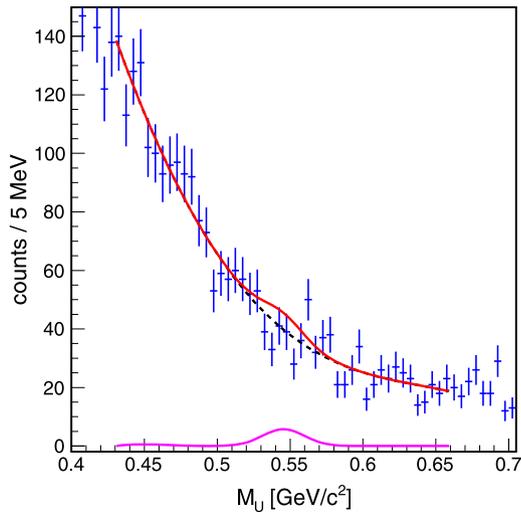
Finally, in Fig. 5 we show the HADES result together with a compilation of limits from the searches conducted by BaBar [50, 19,21], KLOE-2 [27,28], APEX [24], WASA at COSY [26], and A1 at MAMI [23]. At low masses ( $M_U < 0.1 \text{ GeV}/c^2$ ) we clearly improve on the recent result obtained by WASA [26], excluding now to a large degree the parameter range allowed by the muon  $g - 2$  anomaly (prediction with  $2\sigma$  interval is shown in Fig. 5). At higher masses, the sensitivity of our search is compatible with, albeit somewhat lower than the combined KLOE-2 analysis of  $\phi$  decays. Our data probe, however, the  $U$ -boson coupling in  $\eta$  decays and add hence complementary information. At masses above the  $\eta$  mass, the inclusive dilepton spectrum is fed by  $\Delta$  (and to some extent heavier baryon resonance) decays which offer only small sensitivity, partly due to the small electromagnetic branching ratio ( $BR_{N\gamma} \simeq 10^{-3} - 10^{-2}$ ) and partly due to the decreasing  $BR_{U \rightarrow ee}$  at high  $M_U$ .

## 5. UL on the rare decay $\eta \rightarrow e^+e^-$

The direct decay of the  $\eta$  meson into a lepton pair ( $e^+e^-$  or  $\mu^+\mu^-$ ) can only proceed through a 2-photon intermediate state. The  $e^+e^-$  decay is furthermore strongly suppressed by helicity



**Fig. 5.** (Color online.) The 90% CL upper limit on  $\epsilon^2$  versus the  $U$ -boson mass obtained from the combined analysis of HADES data (solid black curve). This result is compared with existing limits from the MAMI/A1, APEX, BaBar, WASA, and KLOE-2 experiments, as well as with the  $g-2$  constraints (see the text for citations).



**Fig. 6.** (Color online.) Zoom into the  $\eta$  peak region of the invariant-mass distribution of  $e^+e^-$  pairs reconstructed in the  $p(3.5 \text{ GeV}) + \text{Nb}$  reaction. The data is fitted with a polynomial (dashed black curve) onto which a Gaussian signal of strength  $S$  set equal to the found upper limit (CL = 90%) of  $BR_{\eta \rightarrow e^+e^-} < 2.5 \times 10^{-6}$  is superimposed (solid red and pink curves).

conservation. Calculations based on chiral perturbation theory and quark models put its branching ratio at  $BR_{\eta \rightarrow e^+e^-}^{QCD} \simeq 5 \times 10^{-9}$  [51, 52]. The previous 90% CL upper limit on the  $\eta \rightarrow e^+e^-$  decay branch, obtained from HADES  $p + p$  data [34], has been fixed by the 2012 review of the PDG [10] at  $BR_{\eta \rightarrow e^+e^-} < 5.6 \times 10^{-6}$ . The present analysis of our  $p + \text{Nb}$  data allows to set an improved limit (CL = 90%) at  $2.5 \times 10^{-6}$  (see Fig. 6). Combining the  $p + p$  and  $p + \text{Nb}$  results with the help of Eq. (8), a final limit of  $2.3 \times 10^{-6}$  can be given, i.e. about a factor 2.5 lower than the present PDG value, but still a far way above theoretical predictions [51,52].

## 6. Summary and outlook

Searching for a narrow resonance in dielectron spectra measured with HADES in the reactions  $p(\text{at } 3.5 \text{ GeV}) + p, \text{Nb}$ , as well as  $\text{Ar}(\text{at } 1.756 \text{ GeV/u}) + \text{KCl}$  we have established an upper limit

at 90% CL on the mixing  $\epsilon^2 = \alpha'/\alpha$  of a hypothetical dark photon  $U$  in the mass range  $M_U = 0.02\text{--}0.6 \text{ GeV}/c^2$ . Our UL sets a tighter constraint than the recent WASA search at low masses excluding to a large extent the parameter space preferred by the muon  $g-2$  anomaly. At higher masses, already surveyed by the recent KLOE-2 search, our analysis provides complementary information. We have thus covered for the first time in one and the same experiment a rather broad mass range. In addition, we have reduced the UL on the direct decay  $\eta \rightarrow e^+e^-$  by a factor 2.5 with respect to the known limit to  $2.3 \times 10^{-6}$ . In future experiments at the FAIR facility we expect to be able to increase our sensitivity by up to one order of magnitude.

## Acknowledgements

The HADES Collaboration gratefully acknowledges the support by BMBF grants 06DR9059D, 05P12CRGHE, 06FY171, 06MT238 T5, and 06MT9156 TP5, by HGF VH-NG-330, by DFG EClust 153, by GSI TMKRUE, by the Hessian LOEWE initiative through HIC for FAIR (Germany), by EMMI GSI, TU Darmstadt (Germany): VH-NG-823, Helmholtz Alliance HA216/EMMI, by grant GA CR 13-067595 (Czech Rep.), by grant NN202198639 (Poland), Grant UCY/3411-23100 (Cyprus), by CNRS/IN2P3 (France), by INFN (Italy), and by EU contracts RII3-CT-2005-515876 and HP2 227431.

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