Received: 1 December 2022 | Accepted: 2 December 2022

DOI: 10.1002/asna.20220104

PROCEEDING

Astronomische Nachrichten

Search for dark photons in heavy-ion collisions

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Funding information
European Union's Horizon 2020 research and innovation program, Grant/Award Number: 824093

Abstract

The vector U-bosons, or so-called "dark photons," are one of the possible candidates for the dark matter mediators. They are supposed to interact with the standard matter via a "vector portal" due to the $U(1) - U(1)'$ symmetry group mixing which might make them visible in particle and heavy-ion experiments. While there is no confirmed observation of dark photons, the detailed analysis of different experimental data allows us to estimate the upper limit for the kinetic mixing parameter ε^2 depending on the mass M_U of U-bosons which is also unknown. We have introduced a procedure to define theoretical constraints on the upper limit of $\varepsilon^2\,(M_U)$ from heavy-ion (as well as $p+p$ and $p+A$) dilepton data. Our analysis is based on the microscopic Parton-Hadron-String Dynamics transport approach where we incorporated the decay of hypothetical U-bosons to dileptons, $U \to e^+e^-$, where the U-bosons themselves are produced by the Dalitz decay of pions $\pi^0 \to \gamma U$, η-mesons $\eta \to \gamma U$, and Delta resonances $\Delta \to NU$. The extension of our procedure to other dark matter candidates is foreseen.

KEYWORDS

dark matter, dark photons, heavy-ions

1 | INTRODUCTION

Dark photons (DPs), also called U-bosons or "hidden" photons A', are one of the possible candidate particles proposed as dark matter (DM) mediators. They are supposed to interact with the standard model (SM) particles via a "vector portal" due to the $U(1) - U(1)'$ gauge symmetry group mixing (Holdom 1986), which might make them visible in collisions of elementary particles and/or heavy ions. The corresponding Lagrangian is defined by the hypercharge field-strength tensor of the SM photon field and the DM vector boson field: $\mathcal{L} \sim \varepsilon^2/2F_{\mu\nu}F^{\mu\nu\prime}$. Here ε^2 is a kinetic mixing parameter, which characterizes the strength of the interaction between SM and DM particles (Batell et al. 2009a, 2009b; Boehm & Fayet 2004; Fayet 1980, 2004; Pospelov et al. 2008). This mixing allows for the decay of U-bosons to a pair of leptons, $U \to e^+e^-$ or $\mu^+\mu^-$. Light U-bosons can be produced in the decay of SM particles, for example, through Dalitz decays of pseudoscalar mesons, such as pions ($\pi^0 \to \gamma U$) and η-mesons ($\eta \to \gamma U$), as well as in the Dalitz decay of baryonic resonances, such as Δ's ($\Delta \to NU$). This provides the opportunity to observe dark photons in dilepton experiments from low (SIS) to ultrarelativistic (LHC) energies, which stimulated a lot of experimental as well as theoretical activities—cf. the review (Battaglieri et al. 2017).

The HADES Collaboration at GSI, Darmstadt, performed an experimental DP search in dilepton experiments at the SIS18 accelerator with both proton and heavy-ion beams (Agakishiev et al. 2014). The HADES experiment presented an upper limit for the kinetic mixing parameter ε^2 in the mass range of $M_u = 0.02$–0.55 GeV based on the experimental measurements of e^+e^- pairs from $p+\mathrm{i}$ and $p+\mathrm{Nb}$ collisions at 3.5 GeV as well as Ar + KCl collisions at 1.76 *A*GeV. Their result is consistent with the world data collected by various other experiments (Battaglieri et al. 2017). Later, the HADES result has been superseded by A1 (Merkel et al. 2014), NA48/2 (Batley et al. 2015), and BaBar (Lees et al. 2014, 2017) measurements which further lowered the limit for ε^2 in this mass range. The NA48/2 experiment investigated a large sample of π^0 Dalitz decays obtained from inflight weak decays of kaons, the BaBar collider experiment used their accumulated e^+e^- data sets to survey a very large mass range up to $M_U = 8$ GeV, and the MAMI-A1 experiment (Merkel et al. 2014) investigated electron scattering off a ^{181}Ta target at energies between 180 and 855 MeV to search for a DP signal. In the mass range discussed here, $M_U = 20$–500 MeV, the limit on ε^2 has thus been pushed down to about 10^{-6}. Furthermore, a recent measurement of the excess electronic recoil events by the XENON1T Collaboration might be also interpreted in favor of DM sources, and in particular, dark photons are possible candidates (Aprile et al. 2020). Also, some anomaly in the dilepton angular correlations measured in the $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$ reactions has been observed by the ATOMKI experiment (Krasznahorkay et al. 2016). Moreover, the experimental search for dark photons, as well as other candidates for dark matter, is in the focus of LHC experiments (Batell et al. 2022; d'Enterria et al. 2022).

2 | MODELING OF THE U-BOSON PRODUCTION AND THEIR DILEPTON DECAY IN THE PARTON-HADRON-STRING DYNAMICS

In Schmidt et al. (2021) a procedure to define theoretical constraints on the upper limit of $\varepsilon^2(M_U)$ from heavy-ion (as well as $p+p$ and $p+A$) dilepton data has been introduced. For that goal, the light-dark photon production channels have been incorporated in the microscopic Parton-Hadron-String Dynamics (PHSD) transport approach (Bratkovskaya et al. 2011; Cassing & Bratkovskaya 2008; Linnyk et al. 2016), which describes the whole evolution of heavy-ion collisions based on microscopic transport theory by solving the equation-of-motion for each degree-of-freedom (partonic and hadronic) and their interactions. The PHSD model provides a consistent description of the production of hadrons, as well as of electromagnetic probes (dileptons and photons), in $p+p$, $p+A$, and $A+A$ collisions from SIS18 to LHC energies (Linnyk et al. 2016; Song et al. 2018), that is, it provides a rather good estimate of the SM backgrounds in searches for dark photon radiation to dileptons.

The electromagnetic part of all conventional dilepton sources – $\pi^0, \eta, \omega, \Delta$ Dalitz decays as well as direct decay of vector mesons ρ, ω and ϕ – are calculated following our early work (Bratkovskaya et al. 2001). We note that we account for the in-medium effects of the vector meson dynamics such as a "collisional broadening" scenario for the spectral functions (Bratkovskaya & Cassing 2008). However, here we adopt the "Wolf model" for the differential electromagnetic decay width of the Δ resonance (Wolf et al. 1990) which is a default setting in the PHSD 4.0 used for this study. The details of the evaluation of the Δ Dalitz decays are given in Bratkovskaya et al. (2013).

For the bremsstrahlung from pp and pn reactions ($NN \to NN\gamma^* \to NNe^+e^-$) as well as from πN "quasi-elastic" scattering ($\pi N \to \pi N\gamma^* \to \pi Ne^+e^-$) we adopt the results from the OBE model calculations by Kaptari and Kämpfer in Kaptari & Kaempfer (2006) as implemented in the PHSD in Bratkovskaya & Cassing (2008) and used for the dilepton study at SIS18 energies in Bratkovskaya et al. (2013).

Now we step to the description of e^+e^- pair production from U-boson decays $U \to e^+e^-$ in the PHSD approach. We note that at SIS18 energies, which are the focus of our present study, the dominant production channels of dileptons for $M < 0.6$ GeV are the Dalitz decays of π^0, η, and the Δ resonance (Bratkovskaya et al. 2013; Bratkovskaya & Cassing 2008). Thus, one expects that if the hypothetical dark photons have a mass $M_U < 0.6$ GeV, they might stem from the Dalitz decays of π^0, η, and the Δ resonance, too. The evaluation of the corresponding partial decay widths of pseudoscalar mesons and Δ baryons to U-bosons due to the $U(1) - U(1)'$ mixing has been performed by Batell et al. (2009a, 2009b) and employed also in the HADES experimental search for dark photons in Agakishiev et al. (2014).

In our study we follow the strategy of Agakishiev et al. (2014) and consider three production channels of dark photons which are dominant for low energy heavy-ion collisions as measured by the HADES Collaboration (Agakishiev et al. 2014), that is, dark photons from Dalitz decay of (1) neutral pions: $\pi^0 \to \gamma + U$, (2) and η-mesons: $\eta \to \gamma + U$, (3) Δ resonances: $\Delta \to N + U$, where $U \to e^+e^-$.

The dilepton yield from a U-boson decay of mass M_U can be evaluated as the sum of all possible contributions (for a given mass M_U):

$$N^{U\to e^+e^-} = N_{\pi^0}^{U\to e^+e^-} + N_{\eta}^{U\to e^+e^-} + N_{\Delta}^{U\to e^+e^-},$$
$$= Br^{U\to e^+e^-} \left(N_{\pi^0\to\gamma U} + N_{\eta\to\gamma U} + N_{\Delta\to NU}\right), \quad (1)$$

where $Br^{U\to e^+e^-}$ is the branching ratio for the decay of U-bosons to e^+e^-. We assume that the width of the U-boson is zero (or very small), that is, it contributes only to a single dM bin of the dilepton spectra from SM sources. Accordingly, if $M_U > m_\eta$, only the Δ channel is kinematically possible in Equation (1).

On the other hand, the yield of U-bosons of mass M_U themselves can be estimated from the coupling to π^0, η and Δ decays to the virtual photons (Agakishiev et al. 2014):

$$N_{m\to\gamma U} = N_m Br_{m\to\gamma\gamma} \cdot \frac{\Gamma_{m\to\gamma U}}{\Gamma_{m\to\gamma\gamma}}, \quad m = \pi^0, \eta, \quad (2)$$

$$N_{\Delta\to NU} = N_\Delta Br_{\Delta\to N\gamma} \cdot \frac{\Gamma_{\Delta\to NU}}{\Gamma_{\Delta\to N\gamma}}. \quad (3)$$

Following References Batell et al. (2009a, 2009b) the ratio of the partial widths for the Dalitz decays of π^0, η-mesons to U-bosons and real photons can be evaluated as follows:

$$\frac{\Gamma_{m\to\gamma U}}{\Gamma_{m\to\gamma\gamma}} = 2\varepsilon^2 \mid F_m\left(q^2 = M_U^2\right)\mid \frac{\lambda^{3/2}\left(m_m^2, m_\gamma^2, M_U^2\right)}{\lambda^{3/2}\left(m_m^2, m_\gamma^2, m_\gamma^2\right)}, \quad (4)$$

for $m = \pi^0, \eta$. Here ε^2 is the kinetic mixing parameter and λ is the triangle function ($\lambda(x,y,z) = (x-y-z)^2 - 4yz$) from the expression of particle 3-momentum. Since $m_\gamma = 0$ one obtains:

$$\frac{\lambda^{3/2}\left(m_m^2, 0, M_U^2\right)}{\lambda^{3/2}\left(m_m^2, 0, 0\right)} = \left(1 - \frac{M_U^2}{m_m^2}\right)^3. \quad (5)$$

Here, M_U is the U-boson mass, F_m are the electromagnetic transition form factors for π^0 and η; they are taken as in our previous studies (Bratkovskaya et al. 2013; Bratkovskaya & Cassing 2008) and in the experimental HADES study (Agakishiev et al. 2014) as well:

$$|F_{\pi^0}\left(q^2\right)| = 1 + 0.032\frac{q^2}{m_{\pi^0}^2}, |F_\eta\left(q^2\right)| = \left(1 - \frac{q^2}{\Lambda^2}\right)^{-1}, \quad (6)$$

with $\Lambda = 0.72$ GeV.

The U-boson production by the Δ Dalitz decay $\Delta \to NU$ has been proposed by Batell et al. (2009a). For the evaluation of the partial decay widths of a broad Δ resonance, one has to take into account the Δ spectral function $A(M_\Delta)$ as used also in the HADES study (Agakishiev et al. 2014):

$$\frac{\Gamma_{\Delta\to NU}}{\Gamma_{\Delta\to N\gamma}} = \varepsilon^2 \int A(M_\Delta) |F_\Delta\left(M_U^2\right)| \times \frac{\lambda^{3/2}\left(M_\Delta^2, m_N^2, M_U^2\right)}{\lambda^{3/2}\left(M_\Delta^2, m_N^2, m_\gamma^2\right)} dM_\Delta, \quad (7)$$

where M_Δ is the mass of the Δ resonance distributed according to the spectral function $A(M_\Delta)$, m_N the mass of the remaining nucleon. Following the reference Agakishiev et al. (2014), we adopted $|F_\Delta\left(M_U^2\right)| = 1$ since an experimental formfactor is unknown.

In the PHSD the spectral function of a Δ resonance of mass M_Δ is taken in the relativistic Breit-Wigner form (Bratkovskaya et al. 2013):

$$A_\Delta(M_\Delta) = C_1 \cdot \frac{2}{\pi} \frac{M_\Delta^2 \Gamma_\Delta^{tot}(M_\Delta)}{\left(M_\Delta^2 - M_{\Delta 0}^2\right)^2 + \left(M_\Delta \Gamma_\Delta^{tot}(M_\Delta)\right)^2}. \quad (8)$$

with $M_{\Delta 0}$ being the pole mass of the Δ. The factor C_1 is fixed by the normalization condition:

$$\int_{M_{min}}^{M_{lim}} A_\Delta(M_\Delta)\, dM_\Delta = 1, \quad (9)$$

where $M_{lim} = 2$ GeV is chosen as an upper limit for the numerical integration. The lower limit for the vacuum spectral function corresponds to the nucleon-pion decay, $M_{\min} = m_\pi + m_N$. In NN collisions, the Δ's can be populated up to the mass $M_{\max} = \sqrt{s} - m_N$ and hence the available part of the spectral function depends on the collision energy. We recall that for the total decay width of the Δ resonance $\Gamma_\Delta^{\rm tot}(M_\Delta)$ in the PHSD we adopt the "Monitz model" (Koch et al. 1984) (cf. also Wolf et al. (1990)).

We note that when accounting for the mass-dependent total width of the Δ resonance our calculation for U-boson production by the Δ Dalitz decay differs from the evaluation in Agakishiev et al. (2014) where a constant total width of the Δ has been used. As discussed in Bratkovskaya et al. (2013) (see Section VI), the shape of the spectral function strongly depends on the actual form of $\Gamma_\Delta^{tot}(M_\Delta)$.

The branching ratio for the decay of U-bosons to e^+e^-, entering Equation (1), is adopted from Batell et al. (2009b) and used also in Agakishiev et al. (2014):

$$Br^{U\to ee} = \frac{\Gamma_{U\to e^+e^-}}{\Gamma_{tot}^U} = \frac{1}{1 + \sqrt{1 - \frac{4m_\mu^2}{M_U^2}}\left(1 + \frac{2m_\mu^2}{M_U}\right)(1 + R(M_U))}. \quad (10)$$

Here m_μ is the muon mass. The total decay width of a U-boson is the sum of the partial decay widths of hadrons, e^+e^- and $\mu^+\mu^-$ pairs: $\Gamma^U_{\text{tot}} = \Gamma_{U\to\text{hadr}} + \Gamma_{U\to e^+e^-} + \Gamma_{U\to\mu^+\mu^-}$. The Expression (10) has been evaluated using that $\Gamma_{U\to\mu^+\mu^-} = \Gamma_{U\to e^+e^-}$ due to lepton universality for $M_U \gg 2m_\mu$. The hadronic decay widths of U-bosons is chosen such that $\Gamma_{U\to\text{hadr}} = R\left(\sqrt{s} = M_U\right)\Gamma_{U\to\mu^+\mu^-}$, where the factor $R(\sqrt{s}) = \sigma_{e^+e^-\to\text{hadrons}}/\sigma_{e^+e^-\to\mu^+\mu^-}$ is taken from Beringer et al. (2012).

3 | CONSTRAINTS ON $\varepsilon^2\,(M_U)$

Since the kinetic mixing parameter ε^2 is unknown as well as the mass of the U-boson, we invent the following procedure to obtain the constraints on $\varepsilon^2\,(M_U)$: for each bin in dilepton mass dM, which is taken to be 10 MeV in our simulations, corresponding to a typical experimental mass resolution of dileptons, we calculate the integrated yield of dileptons from U-bosons of masses $\left[M_U, M_U + dM\right]$ according to Equation (1) and divide by the bin size dM. The resulting dilepton yield per bin dM we denote as dN^{sumU}/dM, which is the sum of all contributions (kinematically possible in the mass bin) from the dilepton decay of U-bosons produced by the Dalitz decays of π^0, η and the Δ resonance. Assuming that ε^2 is a constant in dM we can write that $dN^{\text{sumU}}/dM = \varepsilon^2 dN^{\text{sumU}}_{\varepsilon=1}/dM$ where the notation $dN^{sumU}_{\varepsilon=1}/dM$ is the dilepton yield calculated without ε^2 or formally with $\varepsilon = 1$.

Thus, the total sum of all possible sources of dileptons, from the SM channels and from U-boson decays, can be written as

$$\frac{dN^{\text{total}}}{dM} = \frac{dN^{\text{sumSM}}}{dM} + \frac{dN^{\text{sumU}}}{dM},$$

$$= \frac{dN^{\text{sumSM}}}{dM} + \varepsilon^2 \frac{dN^{\text{sumU}}_{\varepsilon=1}}{dM}. \tag{11}$$

Now we can obtain constraints on $\varepsilon^2\,(M_U)$ by requesting that the total sum dN^{total}/dM cannot surplus the sum of SM channels by more than a fraction C_U in each bin dM. The C_U controls the additionally "allowed" di-electron yields resulting from dark photons on top of the total SM yield (e.g., $C_U = 0.1$ indicating that the dark photons add 10% extra yield to the SM yield, $C_U = 0.2$ meaning 20% extra, etc.). We then express this as

$$\frac{dN^{\text{total}}}{dM} = (1 + C_U)\,\frac{dN^{\text{sumSM}}}{dM}. \tag{12}$$

Combining Equations (12) and (11), one obtains that the kinetic mixing parameter ε^2 for M_U can be evaluated as

$$\varepsilon^2\,(M_U) = C_U \cdot \left(\frac{dN^{sumSM}}{dM}\right) \Big/ \left(\frac{dN^{sumU}_{\varepsilon=1}}{dM}\right). \tag{13}$$

Equation (13) allows computing ε^2 for each bin $\left[M_U, M_U + dM\right]$ and presents the properly weighted dilepton yield from dark photons relative to the SM contributions. Moreover, now we can apply the experimental acceptance for e^+e^- pairs from U-boson decays in the same way as for the SM channels and compare our results to the experimental data. The latter will allow us to explore the possible range of the factor C_U that controls the additional yield from dark photons to the SM contributions. Since the dark photons have not been observed in any dilepton experiments, one can require that this enhancement should be still in acceptable agreement with experimental data, that is, within the experimental error bars (under the condition that the SM yield agrees well with experimental data).

In Figure 1, we present the comparison of the PHSD results for the differential cross section $d\sigma/dM$ for e^+e^-

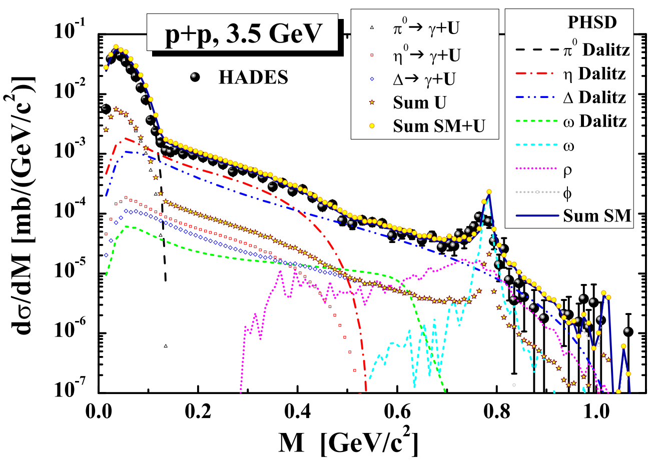

FIGURE 1 The Parton-Hadron-String Dynamics (PHSD) results for the differential cross section $d\sigma/dM$ for e^+e^- production in $p+p$ at 3.5 GeV beam energy in comparison to the experimental measurements by the HADES Collaboration (Agakishiev et al. 2012). The individual colored lines display the contributions from the various standard model (SM) channels of dilepton production in the PHSD calculations (cf. color coding in the legend). The contributions from $U \to e^+e^-$ (with 10% allowed surplus of the total SM yield) produced by Dalitz decays of π^0 are shown as black triangles, of η as red squared, of Δ-resonance as blue rhombus, their sum—as brown stars and the sum of dileptons from all SM channels and U-decays—as yellow dots. The theoretical calculations are passed through the corresponding HADES acceptance filter and mass/momentum resolution.

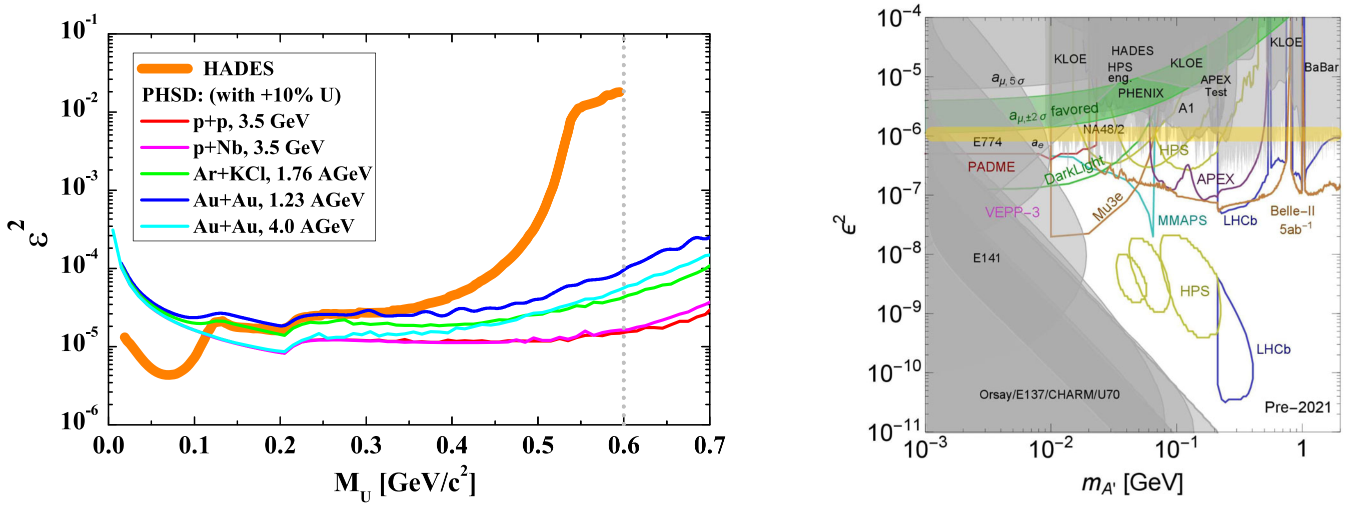

FIGURE 2 Left: Kinetic mixing parameter ε^2 extracted from the Parton-Hadron-String Dynamics (PHSD) dilepton spectra for $p + p$ at 3.5 GeV (red line), $p +$ Nb at 3.5 GeV (magenta line), Ar + KCl at 1.76 AGeV (green line), Au + Au at 1.23 AGeV (blue line), Au + Au at 4.0 AGeV in comparison to the combined HADES results (orange line) (Agakishiev et al. 2014). The PHSD results are shown with a 10% allowed surplus of the U-boson contributions over the total SM yield, that is, $C_U = 0.1$. Right: Compilation of the experimental upper limits for ε^2 versus the mass of dark photons set by worldwide experiments. The yellow band indicate $\varepsilon^2 = 10^{-6}$ for orientation. The figure is adopted from Battaglieri et al. (2017).

production in $p + p$ at 3.5 GeV beam energy to the experimental measurements by the HADES Collaboration (Agakishiev et al. 2012). The theoretical calculations are passed through the corresponding HADES acceptance filter and mass/momentum resolution. Here the contributions from $U \to e^+e^-$ is presented for a 10% allowed surplus of the total SM yield. We recall that the PHSD results for the dilepton spectra including U-boson contributions for Ar + KCl at 1.76 AGeV (green line), Au + Au at 1.23 AGeV and Au + Au at 4.0 AGeV are presented in Schmidt et al. (2021).

By varying the parameter $\varepsilon^2 (M_U)$ in the model calculations, one can obtain upper constraints on $\varepsilon^2 (M_U)$ based on pure theoretical results for dilepton spectra under the constraint that the "surplus" of DM contribution does not overshine the SM contributions (which are equivalent to the measured dilepton spectra) within any requested accuracy.

In Figure 2 (left) we show the results for the kinetic mixing parameter ε^2 versus M_U extracted from the PHSD dilepton spectra for $p + p$ at 3.5 GeV (red line), $p +$ Nb at 3.5 GeV (magenta line), Ar + KCl at 1.76 AGeV (green line), Au + Au at 1.23 AGeV (blue line), Au + Au at 4.0 AGeV in comparison to the combined HADES results (orange line) from Agakishiev et al. (2014). The PHSD results are shown with a 10% allowed surplus of the U-boson contributions over the total SM yield. The right plot of Figure 2 shows the compilation of the experimental upper limits for ε^2 versus the mass of dark photon set by worldwide experiments (Battaglieri et al. 2017).

For the illustration of the $\varepsilon^2 (M_U)$ dependence on the surplus, C_U we show in Figure 3 the kinetic mixing parameter ε^2 extracted from the PHSD dilepton spectra for $p + p$ at 3.5 GeV calculated for different ε^2 scenarios in comparison with the combined HADES results (orange line) (Agakishiev et al. 2014) (as in Figure 2). The PHSD results are shown with 0.1%, 5%, 10%, 15% allowed surplus of the U-boson contributions over the total SM yield (cf. color coding in the legend). The dotted magenta line shows the constant $\varepsilon^2 = 10^{-6}$ which approximately corresponds to the surplus $C_U = 0.1\%$ and is in line with the present knowledge on the upper limit at the considered mass range based on the compilation of the world wide experiments (Agrawal et al. 2021) (yellow band in Figure 3).

4 | SUMMARY

In this contribution, we summarized the basic ideas and the numerical results from Schmidt et al. (2021) where the first microscopic transport calculations, based on the PHSD approach, for the dilepton yield from the decay of hypothetical dark photons (or U-bosons), $U \to e^+e^-$, from $p + p$, $p + A$ and heavy-ion collisions at SIS18 energies have been presented. For that in Schmidt et al. (2021), we incorporated in the PHSD the production of U-bosons by the Dalitz decay of pions $\pi^0 \to \gamma U$, η-mesons $\eta \to \gamma U$,

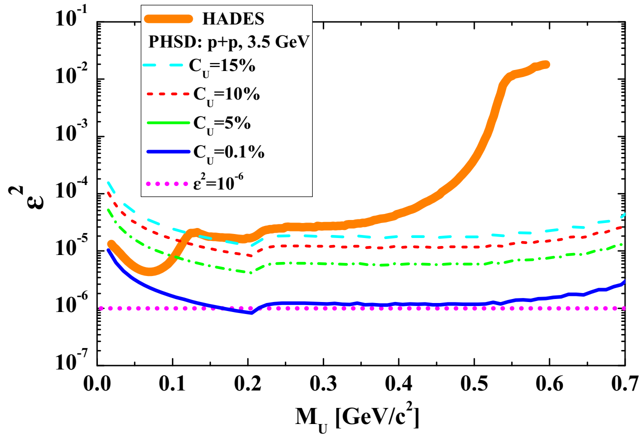

FIGURE 3 The kinetic mixing parameter ε^2 extracted from the Parton-Hadron-String Dynamics (PHSD) dilepton spectra for $p+p$ at 3.5 GeV calculated for different ε^2 scenarios in comparison to the combined HADES results (orange line) (Agakishiev et al. 2014) (as in Figure 2). The PHSD results are shown with 0.1%, 5%, 10%, 15% allowed surplus of the U-boson contributions over the total standard model (SM) yield (cf. color coding in the legend). The dotted magenta line shows the constant $\varepsilon^2 = 10^{-6}$.

and Delta resonances $\Delta \to NU$ decays based on the theoretical model by Batell, Pospelov, and Ritz from in Batell et al. (2009a, 2009b) which describes the interaction of DM and SM particles by the $U(1) - U(1)'$ mixing. The strength of these interactions is defined by the kinetic mixing parameter ε^2 which is a parameter in the model. Moreover, the mass of the U-boson M_U is also unknown, that is, $\varepsilon^2 = \varepsilon^2\,(M_U)$.

The basic ideas of our procedure are the following:

(1) There is NO evidence for experimental observation of dark photons in dilepton experiments so far. (2) The theoretical model (PHSD) provides a good description of exp. data on SM dileptons (from SIS to LHC energies). (3) The dark photon yield is proportional to $\varepsilon_U\,(M_U)$. (4) Use the theoretical spectra—instead of experimental data—to estimate an upper limit for $\varepsilon_U\,(M_U)$ from the constraint that an additional yield from dark photons cannot exceed the total yield from standard sources by more than a small factor (for each M_U), which we can vary in our calculations. (5) A variation of this 'surplus' factor C_U can provide the range of possible $\varepsilon_U\,(M_U)$ and can be related to the experimental accuracy, for example, via error bars, mass resolution, acceptance etc.

Thus, this procedure allowed us to estimate the $\varepsilon^2\,(M_U)$ mixing parameter in the mass interval of $M_U < 0.6$ GeV (where the considered U-boson production channels are dominant) based on pure theoretical results for dilepton spectra from SM sources and dark photon decay with any "requested" accuracy.

We note that our analysis can help to estimate the requested accuracy for future experimental searches of light DPs in dilepton experiments. This procedure can be extended for searches for DP of any masses with the corresponding production and decay channels implemented in the PHSD code. Moreover, it can be extended for an estimate of the contribution of other dark matter candidates to the hadronic observables in heavy-ion experiments.

ACKNOWLEDGMENTS

The authors acknowledge the COST Action THOR, CA15213, and CRC-TR 211"Strong-interaction matter under extreme conditions"—project Nr. 315477589—TRR 211 as well as the European Union's Horizon 2020 research and innovation program under grant agreement No 824093 (STRONG-2020). The computational resources have been provided by the LOEWE-Center for Scientific Computing. Open Access funding enabled and organized by Projekt DEAL.

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How to cite this article: Bratkovskaya, E., Schmidt, I., Gumberidze, M., & Holzmann, R. 2022, *Astron. Nachr.*, e20220104. https://doi.org/10.1002/asna.20220104