Search for dark photons in heavy-ion collisions

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Kazimir Malevich, “Black Square” (1915)

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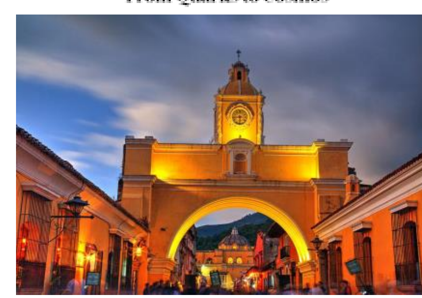
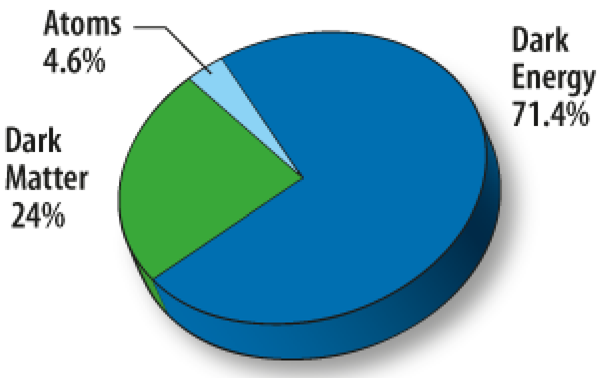
IWARA
From Quarks to Cosmos



Structure of Universe

- Dark matter (DM) ~24%

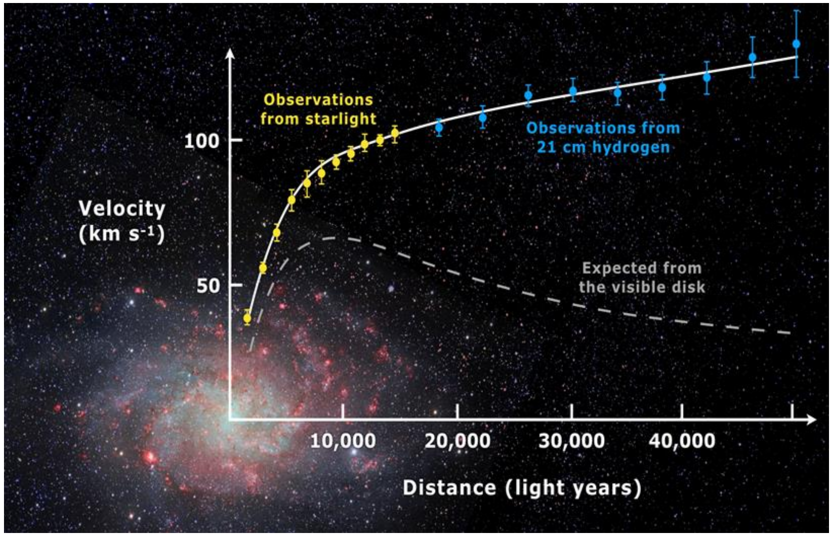
- DM detected by astrophysical observations based on gravitational effects:



WMAP

1933: F. Zwicky: observation of galaxy clusters

1970: V. Rubin: rotation anomalies in galaxies



Hubble: gravitational lensing

Dark matter portals

Search for non-gravitational dark matter (DM) interactions with normal matter, i.e. with standard model (SM) particles

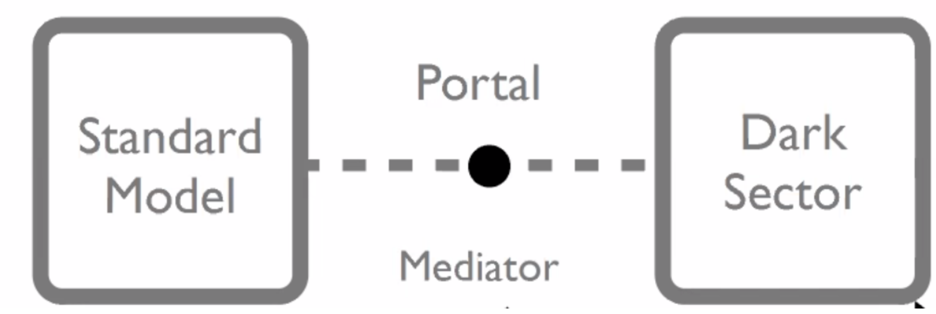


Figure from Brian Battel

$$\mathcal{L} \supset \begin{cases} -\dfrac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, & \text{Higgs portal} \\ y_n L H N\,, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}\,, & \text{axion portal.} \end{cases}$$

J. Alexander et al. (2016), 1608.08632

Dark matter detection

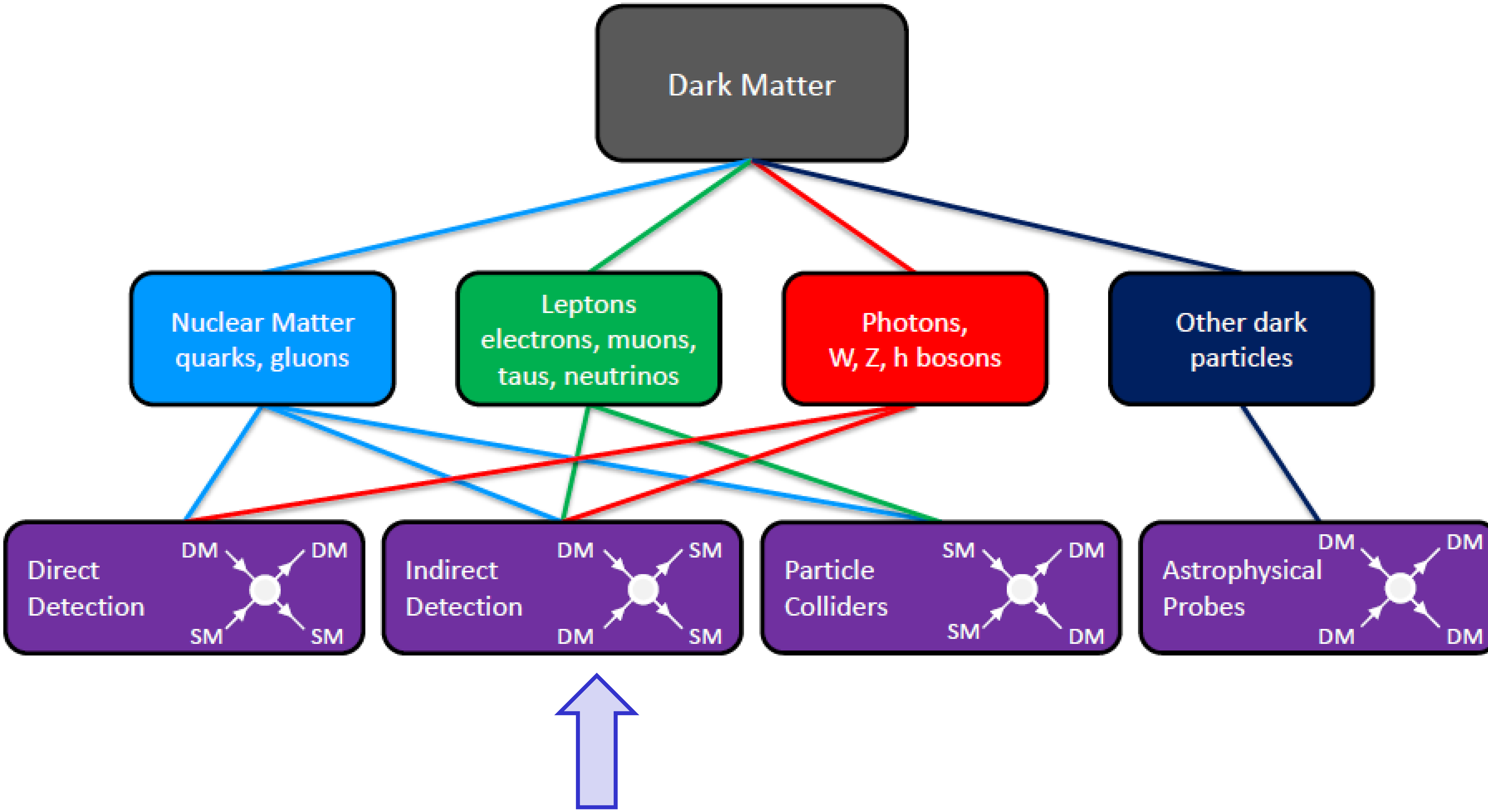


Figure from D. Bauer et al. 2015, Physics of the Dark Universe, 7, 16

Vector portal

The 'vector' portal assumes the mixing of SM and DM via a U(1)-U(1)′ gauge symmetry group mixing

L.B. Okun, Sov. Phys. 56 JETP (1982);
B. Holdom, Phys. Lett. B 166, 196 (1986)

$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \boxed{\frac{1}{2}\frac{\epsilon}{\cos\theta_W}B^{\mu\nu}F'_{\mu\nu}} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$

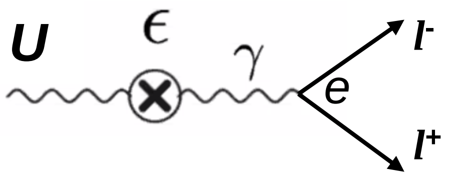
Dark photon field strength:

$$F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu A'_\mu$$

SM hypercharge field strength:

$$B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu$$

ϵ- kinetic mixing parameter:



$\varepsilon^2 = \alpha'/\alpha$

Due to the kinetic mixing the dark photon (U-boson) couples to the electromagnetic current with strength ϵe

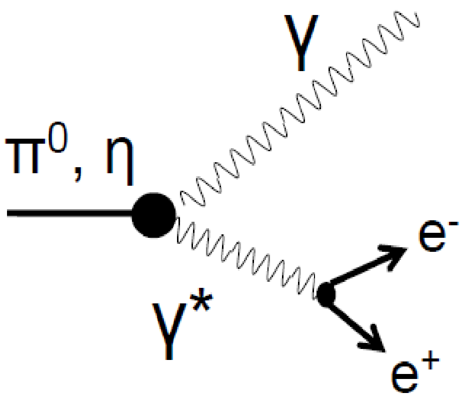
Unknown: kinetic mixing parameter ϵ and mass M_U

*** Notation in literature for the 'dark photon': *A', V, U-* boson**

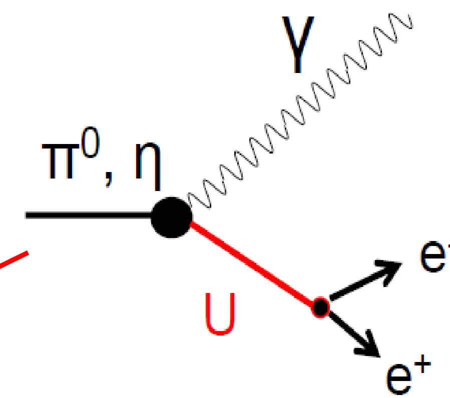
Dalitz decay of the dark photon to dileptons

- Dalitz decays of pseudoscalar mesons π^0,η and Δ-resonances to **dileptons via the U-boson mediator**

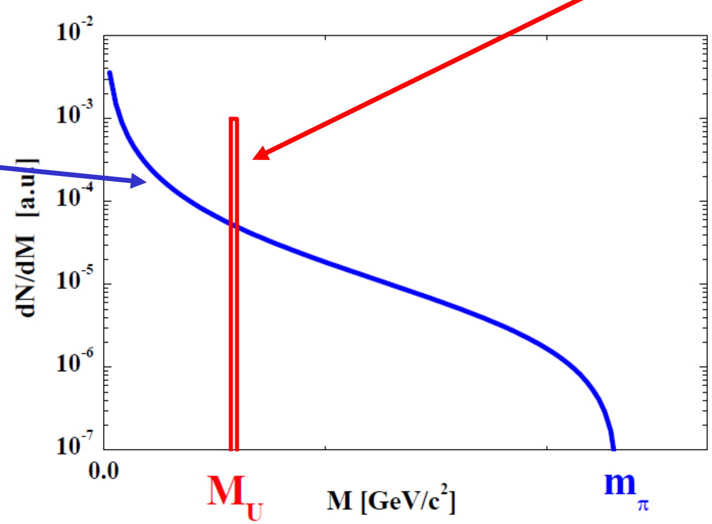
Standard model | **Beyond SM: DM scenario**



U(1)-U(1)′ kinetic mixing

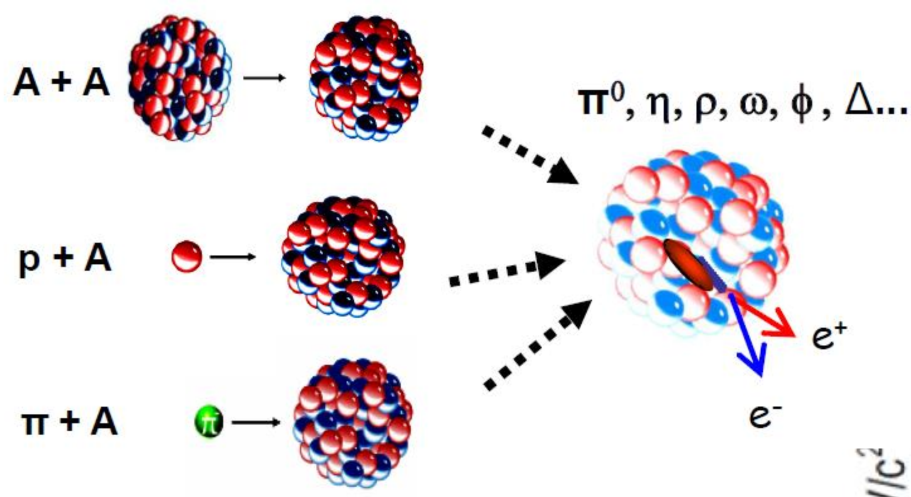


$\pi^0 \rightarrow \gamma+\gamma^*$,
$\eta \rightarrow \gamma+\gamma^*$, $\gamma^* \rightarrow e^+e^-$
$\Delta \rightarrow N+\gamma^*$,



$\pi^0 \rightarrow \gamma+U$,
$\eta \rightarrow \gamma+U$, $U \rightarrow e^+e^-$
$\Delta \rightarrow N+U$,

Possible dark photon observation by dilepton experiments

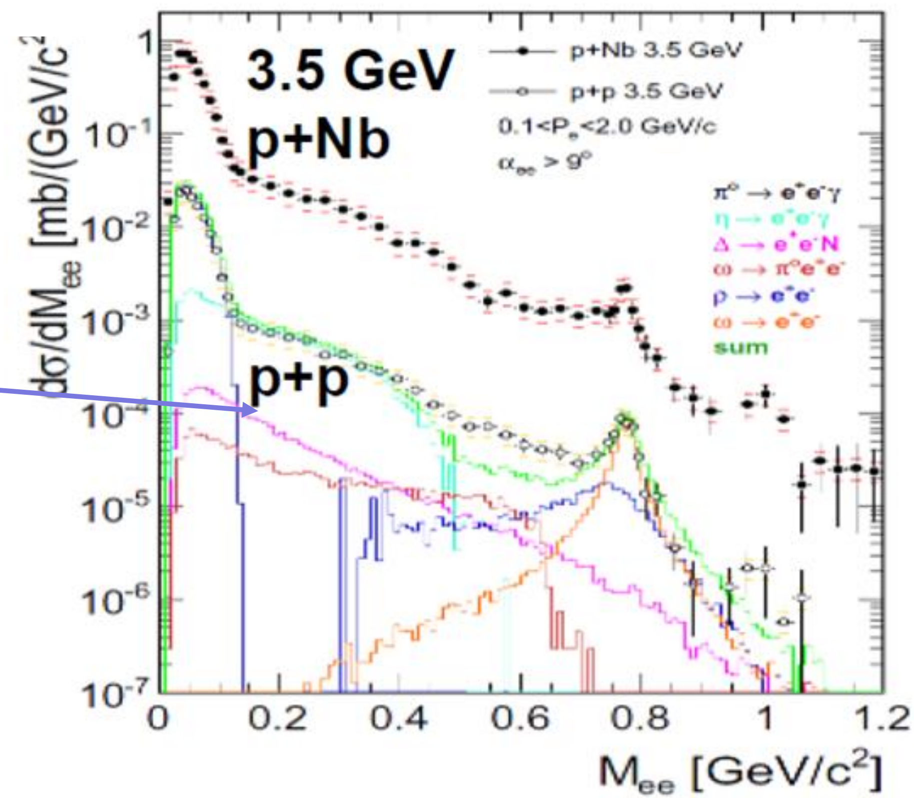


- Dilepton spectra from SM sources are well studied by dilepton experiments from SIS to LHC energies

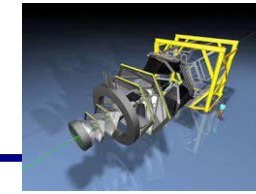
- Hadron production by p+p, p+A, A+A
- Hadron decay to dileptons
- Dalitz π^0,η and Δ decays are the dominant dilepton sources at low M

➔ Possibility for an experimental observation of dark photons by electromagnetic decays U→ e^+e^- in heavy-ion experiments

Dilepton spectra at low M ('cocktail')



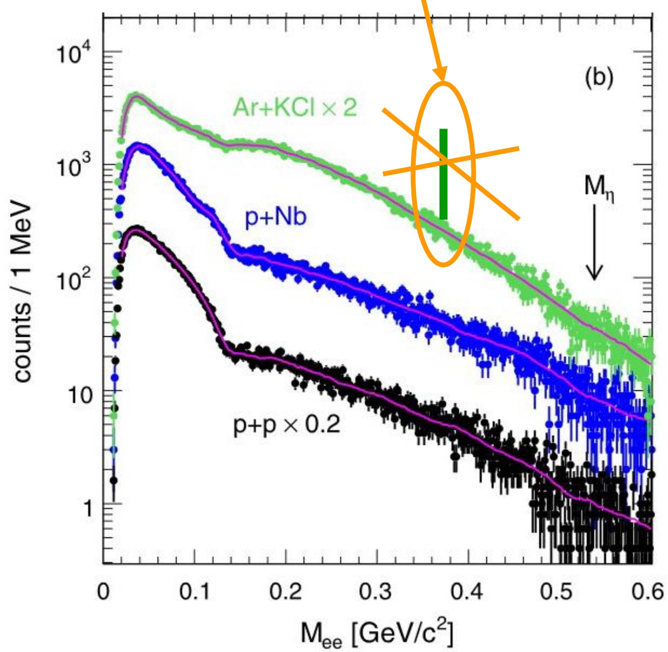
Search for dark photons with HADES (GSI)



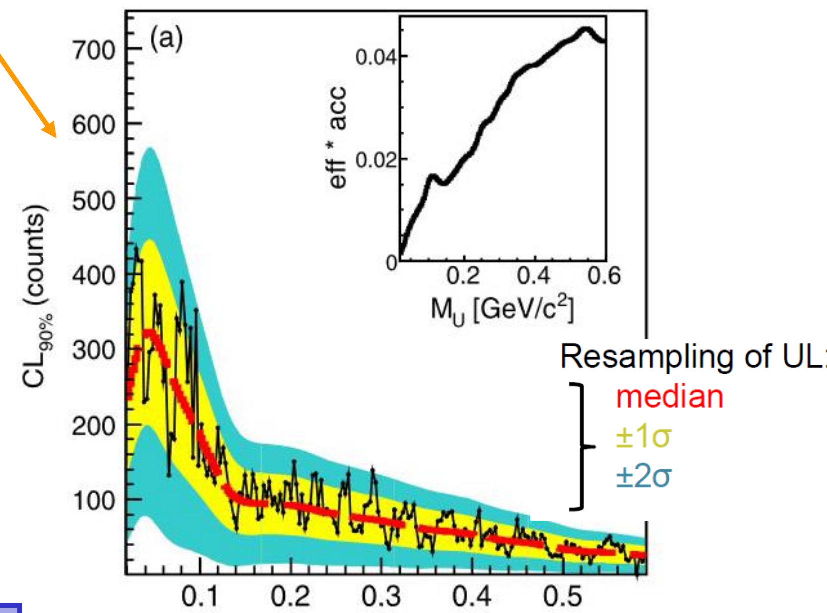
HADES data:
p+p, p+Nb at 3.5 GeV, Ar+KCl at 1.76 A GeV

G. Agakishiev et al. (HADES), Phys. Lett. B 731, 265 (2014)

1) Search for a peak structure in the raw dN/dM spectrum taking into account mass resolution: fit with 5th-order polynomial + Gauss peak for each fixed M bin
2) If no peak found, get an UL (upper limit) on peak

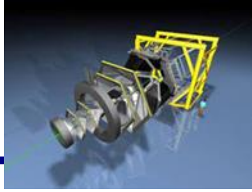


p+p, 3.5 GeV



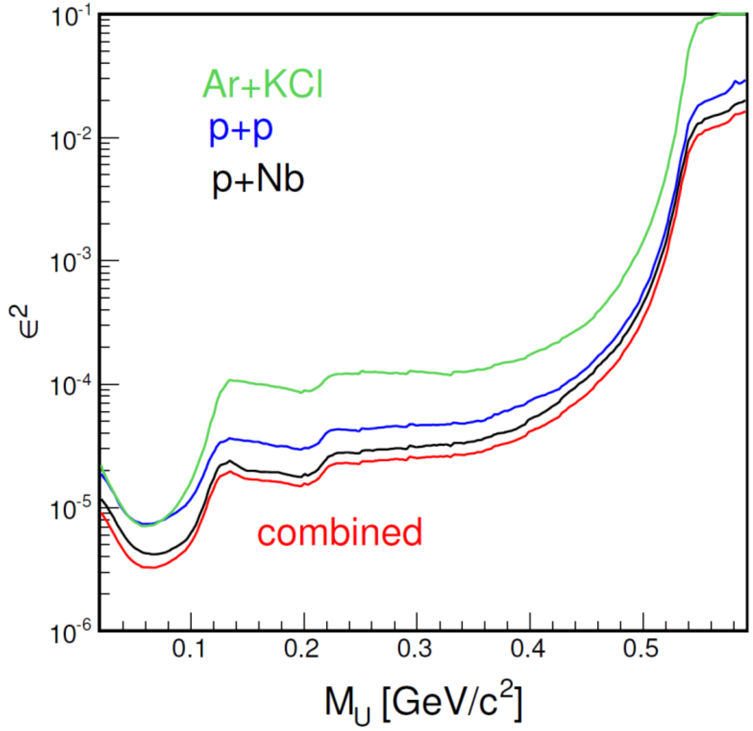
3) Transform this UL into an UL on the mixing parameter ε^2 based on the modelling of the U-boson production rate (B. Batell, M. Pospelov, and A. Ritz, PRD 80,095024 (2009))

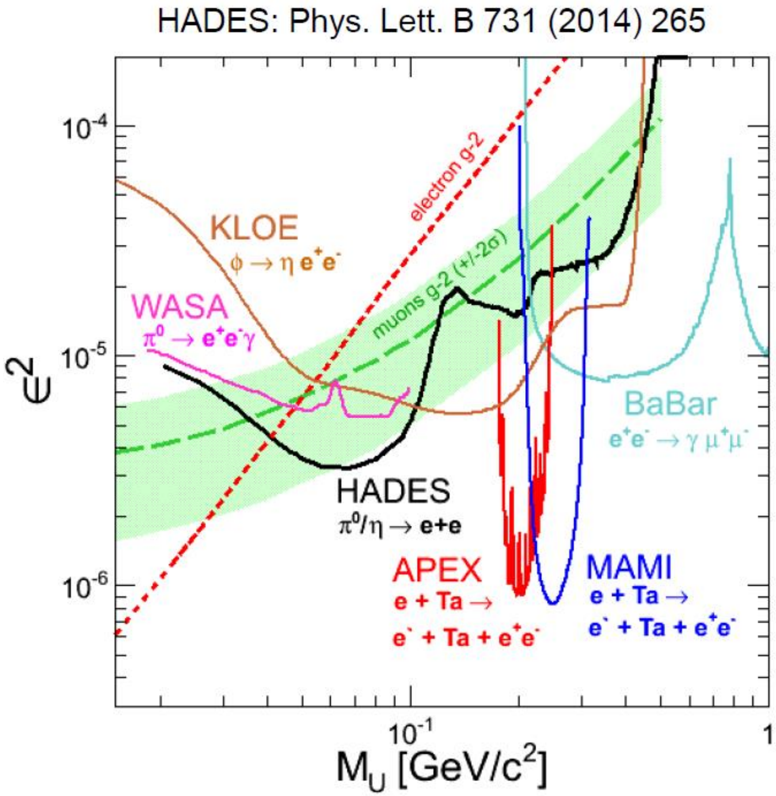
Search for dark photons with HADES



G. Agakishiev et al. (HADES), Phys. Lett. B 731, 265 (2014)

Upper limit on the mixing parameter ε^2





HADES coverage : 0.02 < M_U < 0.6 GeV

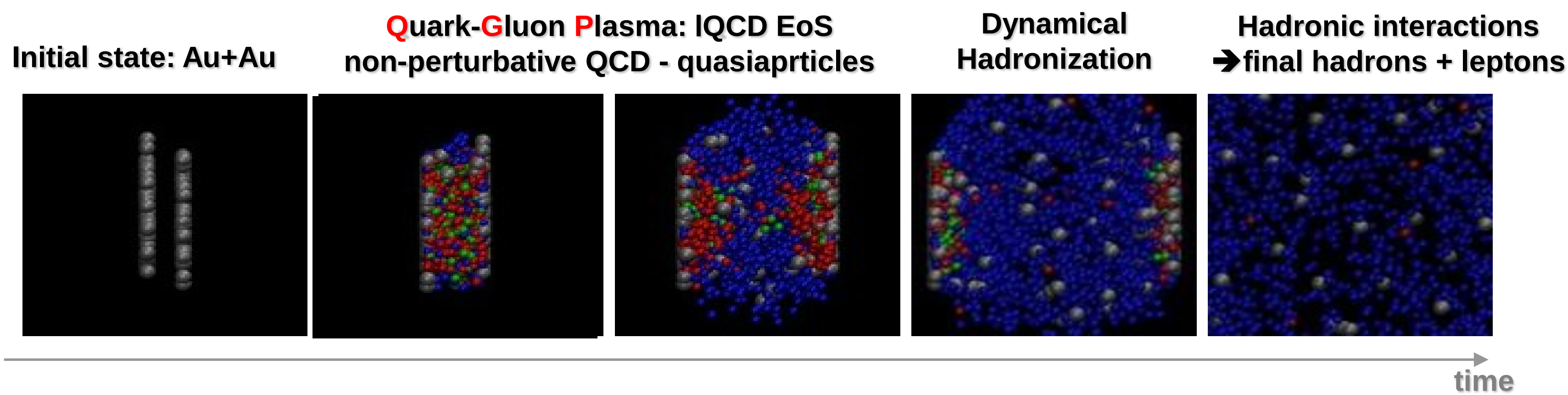
Dark photons are not observed so far!

Theoretical modeling of U-boson production

Goal: estimate the upper limit for the kinetic mixing parameter $\varepsilon^2(M_U)$ of the U-boson from the theoretically calculated dilepton spectra using the microscopic PHSD transport approach

Parton-**H**adron-**S**tring **D**ynamics (PHSD) is a non-equilibrium microscopic transport approach for the description of strongly-interacting hadronic and partonic matter created in heavy-ion collisions

Dynamics: based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory



➔ PHSD provides a good description of 'bulk' hadronic observables as well as dilepton spectra from SIS to LHC energies

PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

Light dark photon production in PHSD

Production of hadron → decay to U → dilepton yield from U-boson decay of mass M_U:

$\pi^0 \rightarrow \gamma + U$,
$\eta \rightarrow \gamma + U$, $U \rightarrow e^+e^-$
$\Delta \rightarrow N + U$,

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

- **Dalitz decay of π^0, η mesons and Δ-resonances to U-bosons and real photons or N**

Based on the model:
(used in the HADES analysis)

B. Batell, M. Pospelov, and A. Ritz, Phys. Rev. D 79, 115008 (2009); Phys. Rev. D 80,095024 (2009)

- **Ratio of the partial widths $\pi^0(\eta) \rightarrow \gamma + U$ and $\pi^0(\eta) \rightarrow \gamma + \gamma$:**

$$\frac{\Gamma_{i\to\gamma U}}{\Gamma_{i\to\gamma\gamma}} = 2\epsilon^2 |F_i(q^2 = M_U^2)| \frac{\lambda^{3/2}(m_i^2, m_\gamma^2, M_U^2)}{\lambda^{3/2}(m_i^2, m_\gamma^2, m_\gamma^2)} \qquad i = \pi^0, \eta$$

- **Ratio of the partial widths $\Delta \rightarrow N + U$ and $\Delta \rightarrow \gamma + N$:**

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

Formfactors:

$$|F_{\pi^0}(q^2)| = 1 + 0.032\frac{q^2}{m_{\pi^0}^2}$$

$$|F_\eta(q^2)| = \left(1 - \frac{q^2}{\Lambda^2}\right)^{-1}$$

$$\Lambda = 0.72\,\mathrm{GeV}$$

$$|F_\Delta(M_U^2)| = 1$$

Spectral function of Δ-resonance:

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

Dark photon production in PHSD

I.) $\left(N_{\pi^0\to\gamma U}+N_{\eta\to\gamma U}+N_{\Delta\to NU}\right)$

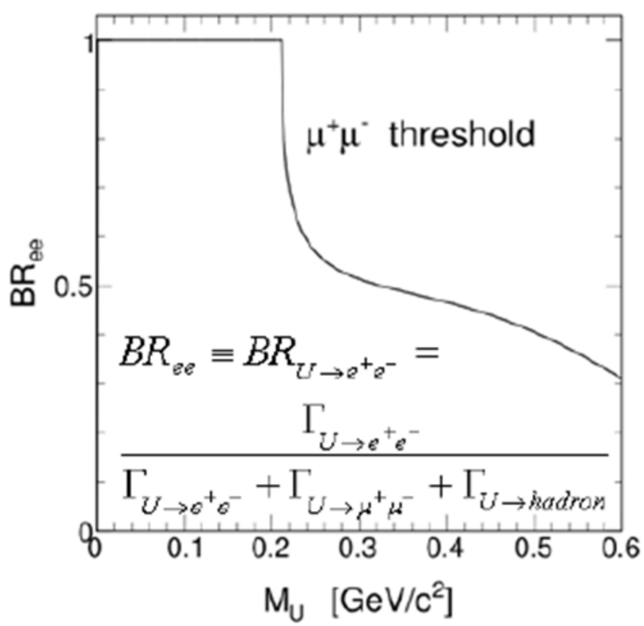
The yield of U-bosons of mass M_U:

$$N_{i\to\gamma U}=N_i Br_{i\to\gamma\gamma}\cdot\frac{\Gamma_{i\to\gamma U}}{\Gamma_{i\to\gamma\gamma}},\quad i=\pi^0,\eta$$

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

II.) $Br^{U\to e^+e^-}$

Branching ratio for the decay of U-bosons to e+e- : $Br_{ee}= Br^{U\to ee}=\frac{\Gamma_{U\to e^+e^-}}{\Gamma^U_{tot}}$



$$\Gamma^U_{tot}=\Gamma_{U\to hadr}+\Gamma_{U\to e^+e^-}+\Gamma_{U\to\mu^+\mu^-}$$

$$\Gamma_{U\to hadr}=R(\sqrt{s}=M_U)\Gamma_{U\to\mu^+\mu^-}$$

$$R(\sqrt{s})=\sigma_{e^+e^-\to hadrons}/\sigma_{e^+e^-\to\mu^+\mu^-}$$

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

How to obtain theoretical constraints on $\varepsilon^2(M_U)$?

Basic ideas:

1) **There is NO evidence for an experimental observation of dark photons in dilepton experiments so far**

2) **Theoretical model (PHSD) provides a good description of exp. data on SM dileptons (from SIS to LHC energies)**

3) **Dark photon yield is proportional to $\varepsilon^2(M_U)$**

4) **Use the theoretical spectra – instead of exp. data – to estimate an upper limit for $\varepsilon^2(M_U)$ from the constraint that an additional yield from dark photons can not 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) **Variation of this 'surplus' factor can provide the range of possible $\varepsilon^2(M_U)$ and can be related to experimental accuracy e.g. via error bars, mass resolution, acceptance etc.**

Ida Schmidt, E.B., Malgorzata Gumberidze, Romain Holzmann, Phys.Rev.D 104 (2021) 015008

Procedure to obtain constraints on $\varepsilon^2(M_U)$

1) For each bin $[M_U, M_U + dM]$ calculate the sum of all U→e+e- contributions (kinematically possible in this mass bin)

$$\frac{dN^{sumU}}{dM} = \frac{dN_{\pi^0}^{U\to e^+e^-}}{dM} + \frac{dN_{\eta}^{U\to e^+e^-}}{dM} + \frac{dN_{\Delta}^{U\to e^+e^-}}{dM}$$

Can be presented as $$\frac{dN^{sumU}}{dM} = \epsilon^2 \frac{dN_{\epsilon=1}^{sumU}}{dM}$$

2) Calculate the sum of all SM contributions and 'dark matter' (DM) contributions :

$$\frac{dN^{total}}{dM} = \frac{dN^{sumSM}}{dM} + \frac{dN^{sumU}}{dM} = \frac{dN^{sumSM}}{dM} + \epsilon^2 \frac{dN_{\epsilon=1}^{sumU}}{dM}.$$

3) Obtain constraints by requesting that dN^{total}/dM cannot exceed the sum of SM channels (i.e. exp. data!) by more than a factor C_U in each bin dM, i.e.

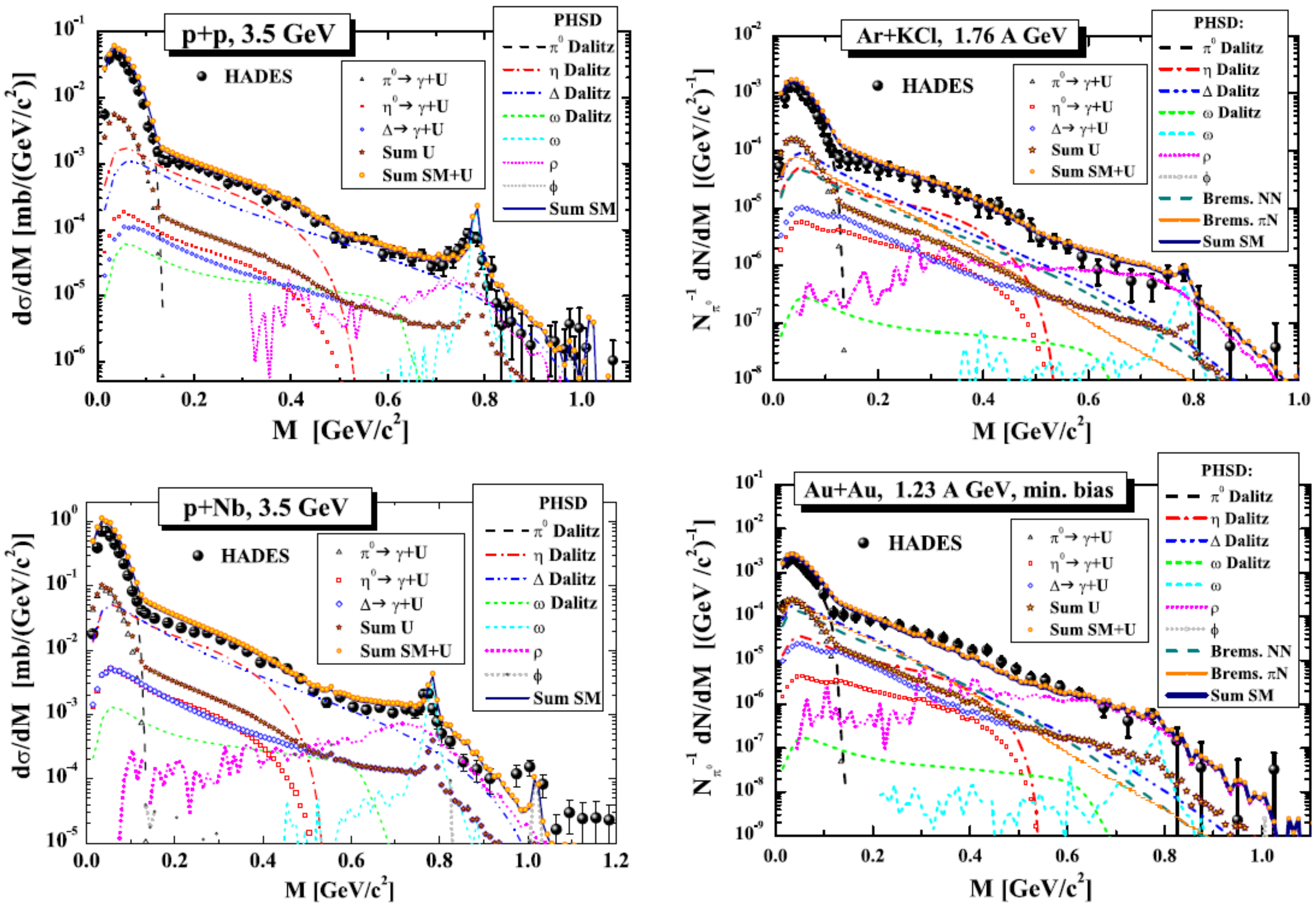
$$\frac{dN^{total}}{dM} = (1 + C_U) \frac{dN^{sumSM}}{dM}$$

→ C_U controls the allowed "surplus" dilepton yield resulting from dark photons on top of the total SM yield

4) Calculate $\varepsilon^2(M_U)$ by assuming C_U : e.g. C_U =0.1 → 10% DM extra yield to the SM yield

$$\epsilon^2(M_U) = C_U \cdot \left(\frac{dN^{sumSM}}{dM}\right) \Big/ \left(\frac{dN_{\epsilon=1}^{sumU}}{dM}\right)$$

Dileptons yields including dark photons vs. HADES data

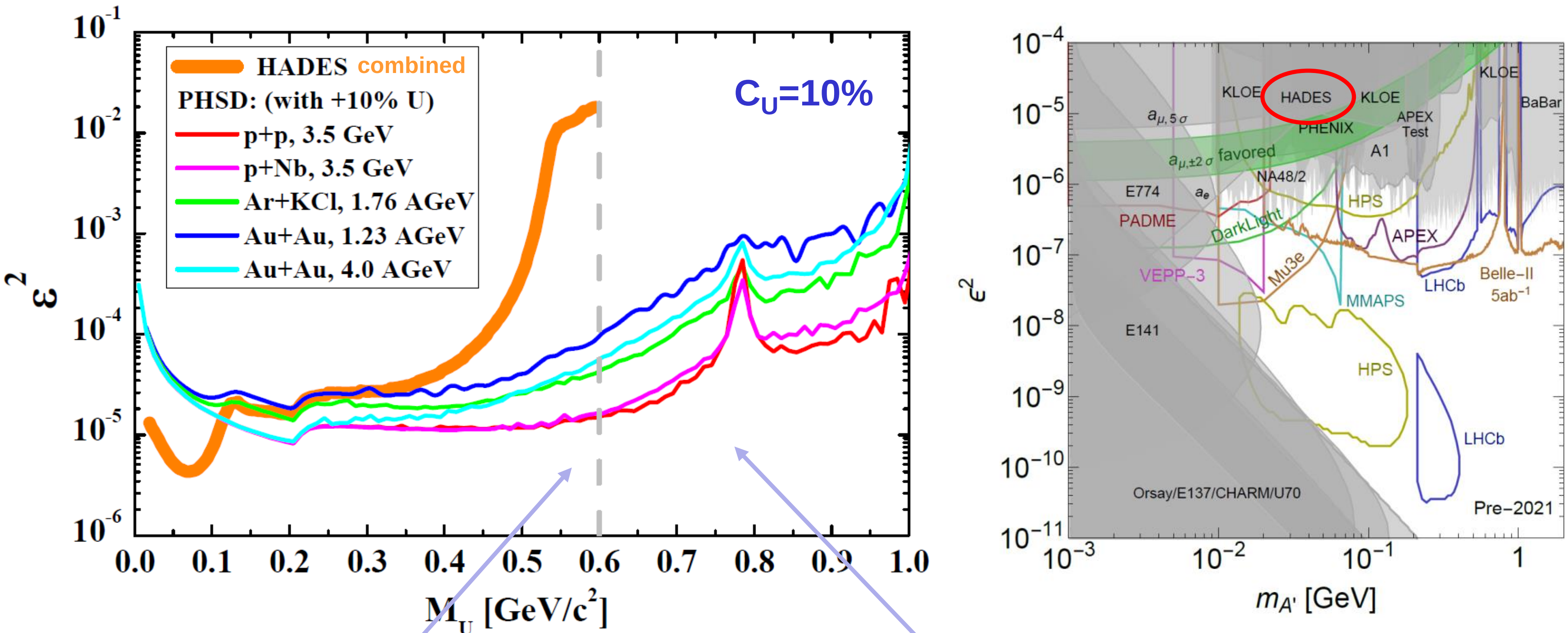


- **The HADES data, i.e. SM contributions (including exp. acceptance) are well described by the PHSD**
- **The contributions from U→e+e- are added with C_U=10% allowed surplus of the total SM yield ➔ the total sum is still in a good agreement with exp. data**

Ida Schmidt, E.B., Malgorzata Gumberidze, Romain Holzmann, Phys.Rev.D 104 (2021) 015008

Mixing parameter $\varepsilon^2(M_U)$

The upper limit for the kinetic mixing parameter $\varepsilon^2(M_U)$ of light dark photons extracted from the PHSD dilepton spectra - with 10% allowed surplus of the total SM yield



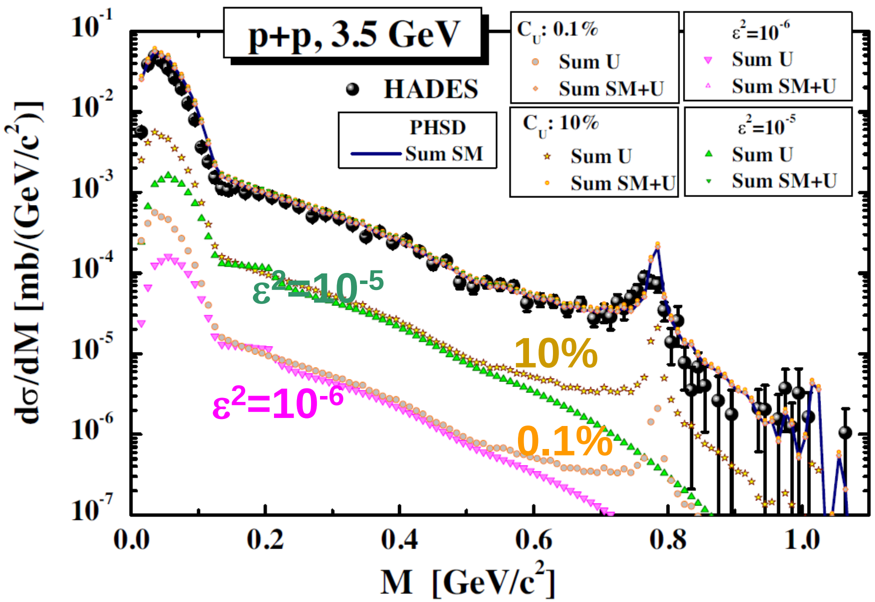
Validity range of extracted kinetic mixing parameter: $0 < M_U < 0.6$ GeV based on low energy dilepton spectra

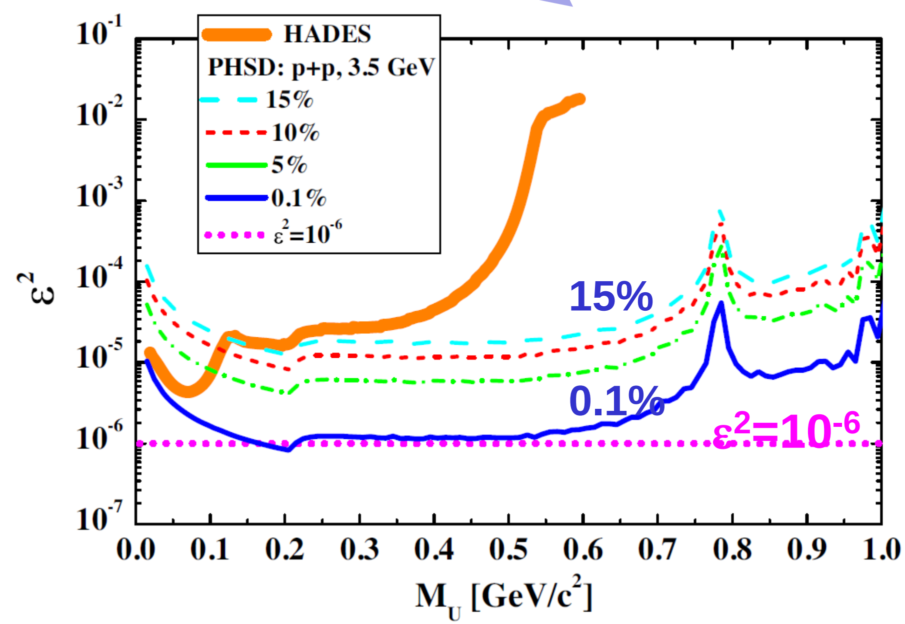
Possible contribution from other dark photon channels

Ida Schmidt, E.B., Malgorzata Gumberidze, Romain Holzmann, Phys.Rev.D 104 (2021) 015008

Limits for the mixing parameter $\varepsilon^2(M_U)$

- **The PHSD predictions for $\varepsilon^2(M_U)$ with 0.1%, 5%, 10%, and 15% allowed surplus of the U-boson contributions over the total SM yield**





The theoretically extracted upper limit of the kinetic mixing parameter $\varepsilon^2(M_U)$ of light dark photons from Dalitz decays of π^0,η mesons and Δ-resonances:

- strongly reduces by reducing the allowed ‚surplus'

➔ exp. data of high presision is needed to reduce the upper limit for $\varepsilon^2(M_U)$

Summary

- We presented first microscopic transport calculations, based on the PHSD approach, for the dilepton yield from the decay of hypothetical dark photons (or U-bosons), U→e+e- from p + p, p + A and heavy-ion collisions at SIS18 energies

- For that we incorporated in the PHSD the production of U-bosons by the Dalitz decay $\pi^0 \rightarrow \gamma$+U, $\eta \rightarrow \gamma$+U, $\Delta \rightarrow$ N+U with further dilepton decays U→e^+e^- based on the theoretical model by Batell, Pospelov and Ritz, which describes the interaction of DM and SM particles by the U(1)-U(1)′ mixing

- We introduced a procedure to define theoretical constraints on the upper limit of the kinetic mixing parameter $\varepsilon^2(M_U)$:
Since dark photons are not observed in dilepton experiments so far, we can require that their contribution can not exceed some limit which would make them visible in experimental data

- We found that the extracted upper limit of $\varepsilon^2(M_U)$ is consistent with the experimental results of the HADES experiment for $0.15 < M_U < 0.4$ GeV, as well as with the world-wide experimental compilation

→ Proposed theoretical procedure allows:

- to check any theoretical ideas on the $\varepsilon^2(M_U)$ independent on exp. data
- to study the influence of exp. acceptance, system and centrality selection
- to perform the simulation for testing experimental set-ups for the search of U-bosons