Search for dark photons in heavy-ion collisions

Elena Bratkovskaya
(GSI, Darmstadt & Uni. Frankfurt)
&
Ida Schmidt, Malgorzata Gumberidze, Romain Holzmann
(Frankfurt Uni, GSI, Darmstadt)
Adrian William Romero Jorge
(Havana Uni. & GSI, Darmstadt)


Kazimir Malevich, “Black Square” (1915)

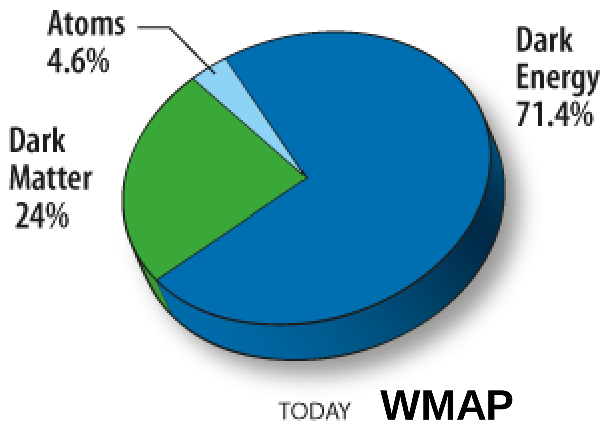
10th international conference on
High Energy Physics in the LHC Era
(HEP-2023)

9-13 January 2023, Valparaíso, Chile

Structure of Universe

- Dark matter (DM) ~24%

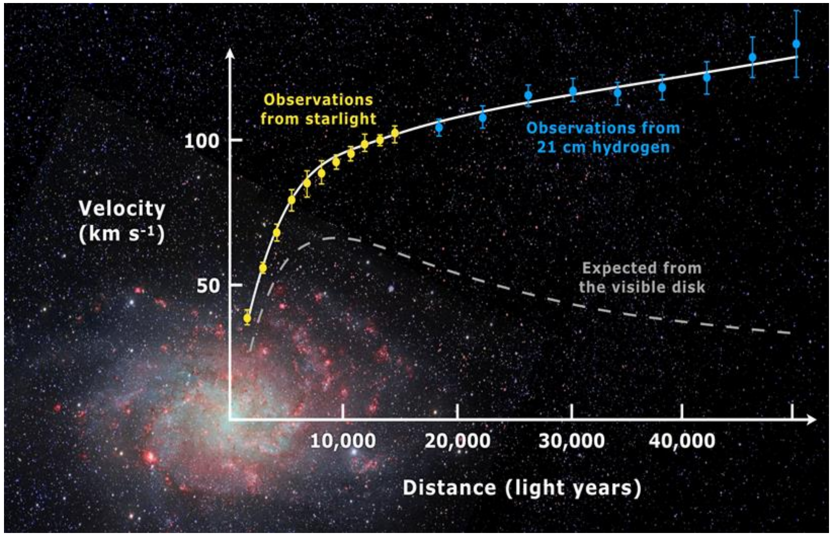
- DM detected by astrophysical observations based on gravitational effects:



WMAP

1933: F. Zwicky: observation of galaxy clusters

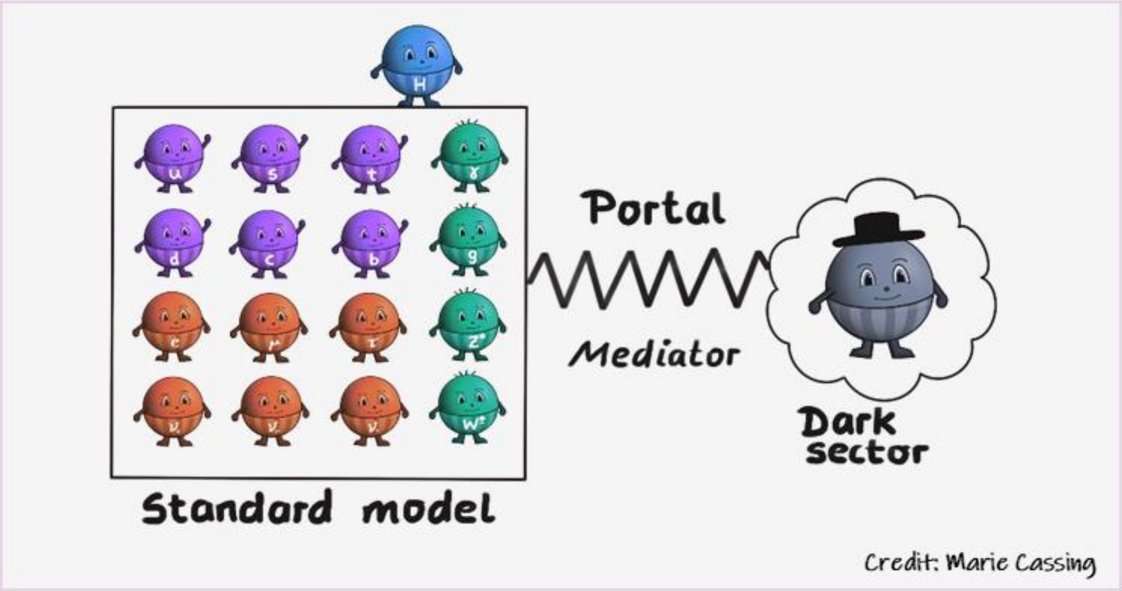
1970: V. Rubin: rotation anomalies in galaxies



Hubble: gravitational lensing

Dark matter portals

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



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

J. Alexander et al. (2016), 1608.08632

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)

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

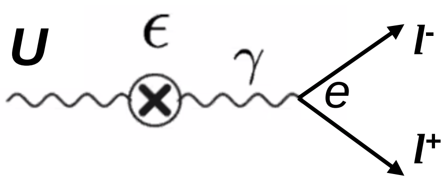
Dark photon field strength:

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

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

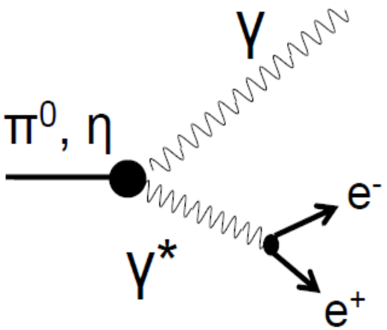
Unknown: kinetic mixing parameter ϵ and mass M_U

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

Dalitz decay of the dark photon to dileptons

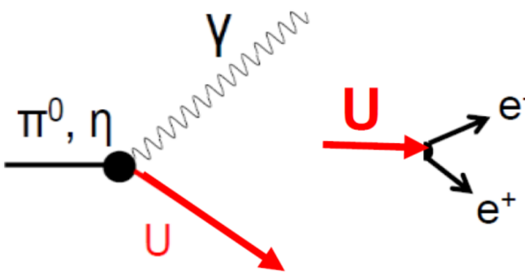
- Dalitz decays of pseudoscalar mesons π^0,η and Δ-resonances to **dileptons via the U-boson mediator**

Standard model

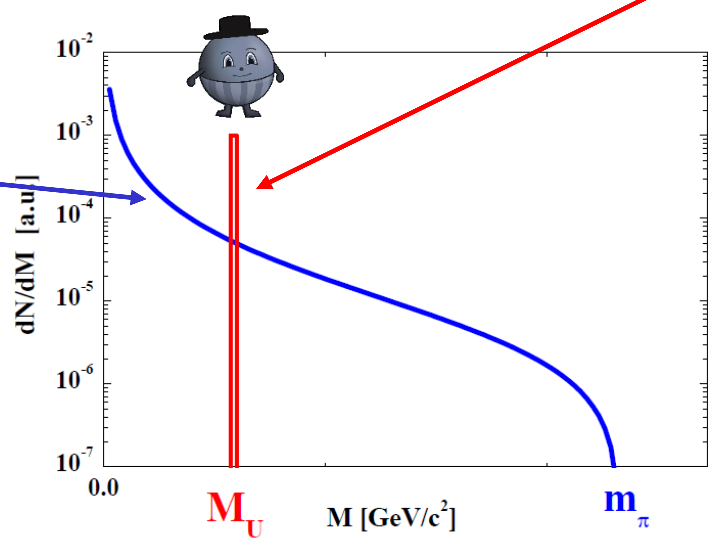


U(1)-U(1)′
kinetic mixing

Beyond SM: DM scenario

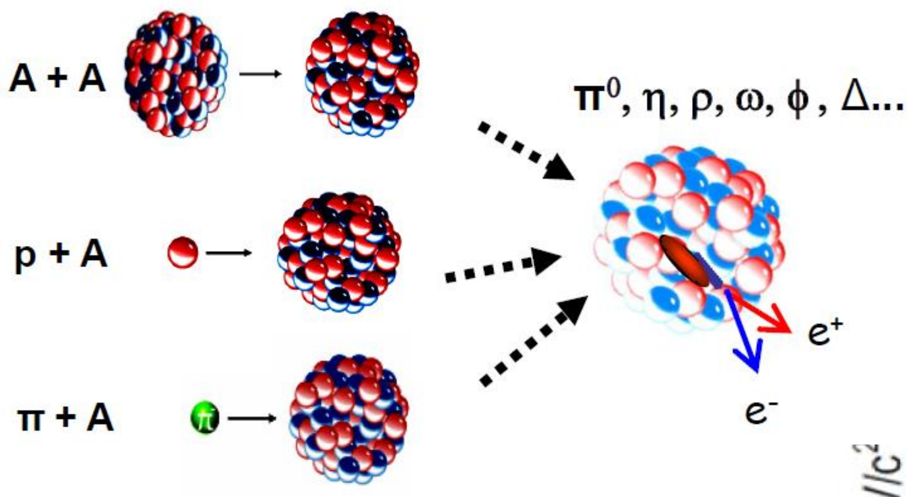


$\pi^0 \rightarrow \gamma+\gamma^*$,
$\eta \rightarrow \gamma+\gamma^*$, $\gamma^* \rightarrow e^+e^-$
$\Delta \rightarrow N+\gamma^*$,



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

Possible dark photon observation by dilepton experiments

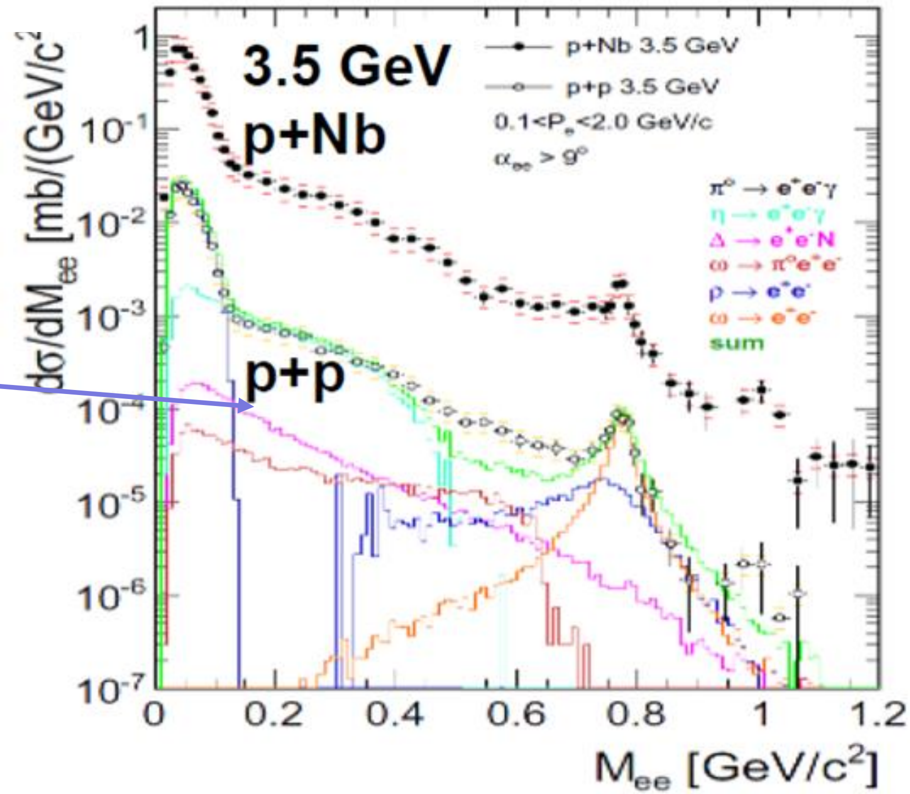


- Dilepton spectra from SM sources are well studied by dilepton experiments from SIS to LHC energies

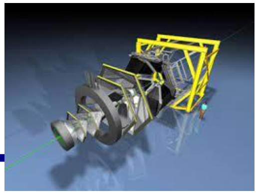
- Hadron production by p+p, p+A, A+A
- Hadron decay to dileptons
- Dalitz π^0,η and Δ decays are the dominant dilepton sources at low M

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

Dilepton spectra at low M ('cocktail')



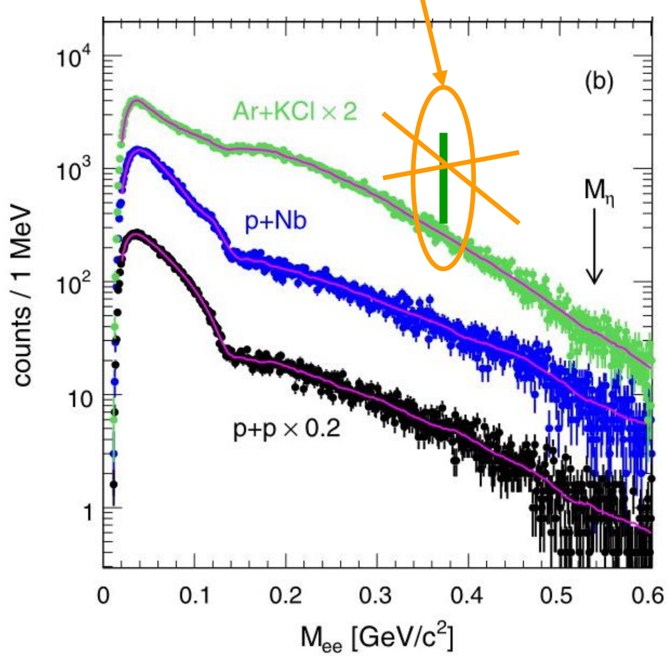
Search for dark photons with HADES (GSI)



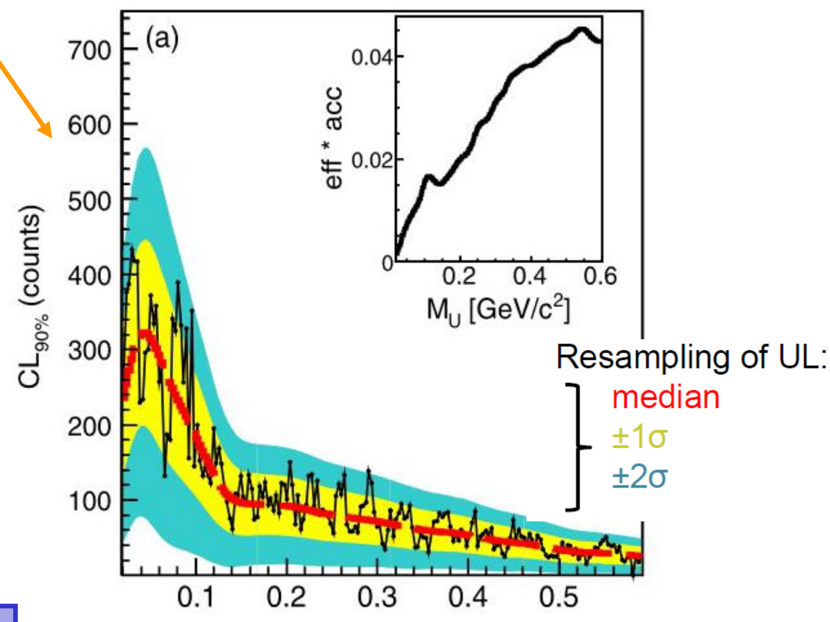
HADES data:
p+p, p+Nb at 3.5 GeV, Ar+KCl at 1.76 A GeV

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

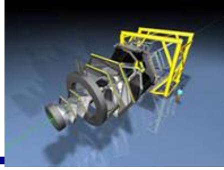


p+p, 3.5 GeV



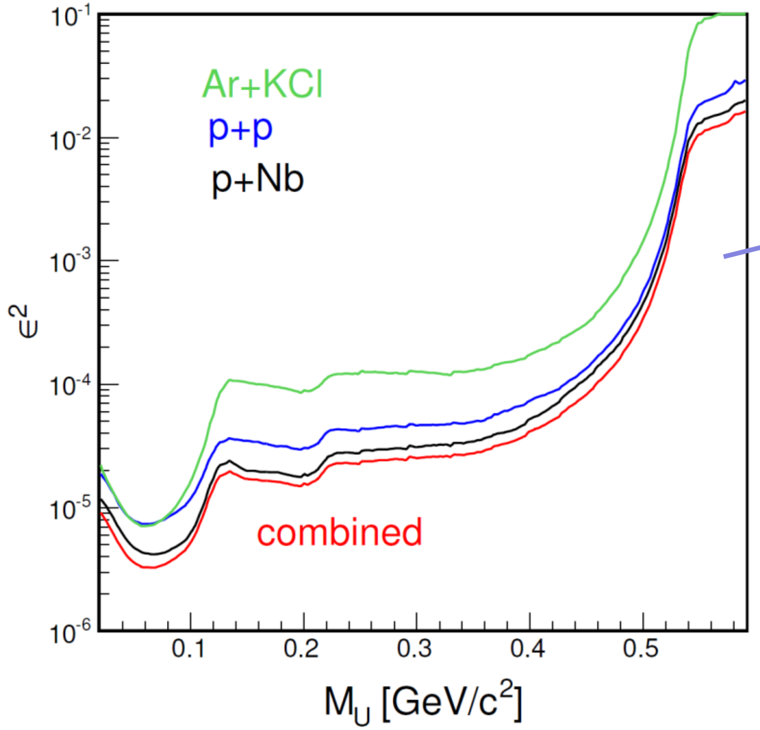
3) Transform this UL into an UL on the mixing parameter ε^2 based on the modelling of the U-boson production rate (B. Batell, M. Pospelov, and A. Ritz, PRD 80,095024 (2009))

Search for dark photons with HADES



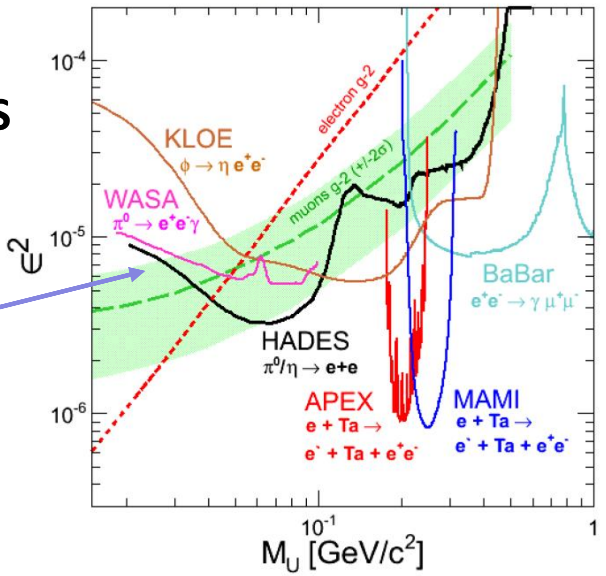
G. Agakishiev et al. (HADES), Phys. Lett. B 731, 265 (2014)

Upper limit on the mixing parameter ε^2



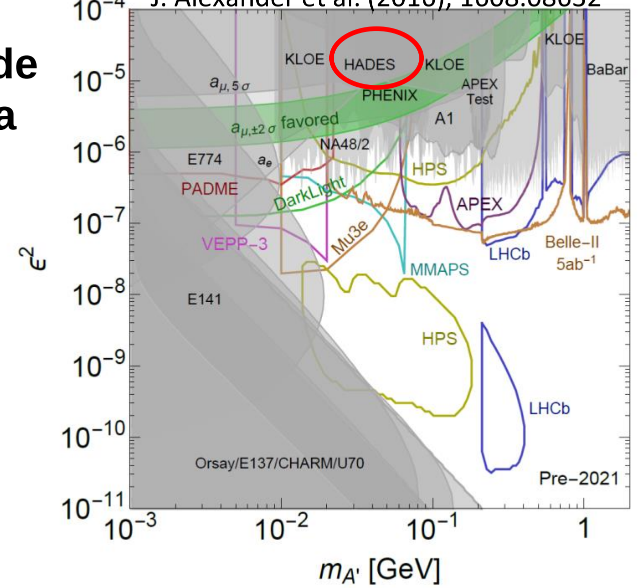
HADES 2014

HADES: Phys. Lett. B 731 (2014) 265



World wide exp. data 2016

J. Alexander et al. (2016), 1608.08632



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-Hadron-String Dynamics (PHSD) is a **non-equilibrium microscopic transport approach** for the description of strongly-interacting hadronic and partonic matter created in heavy-ion collisions

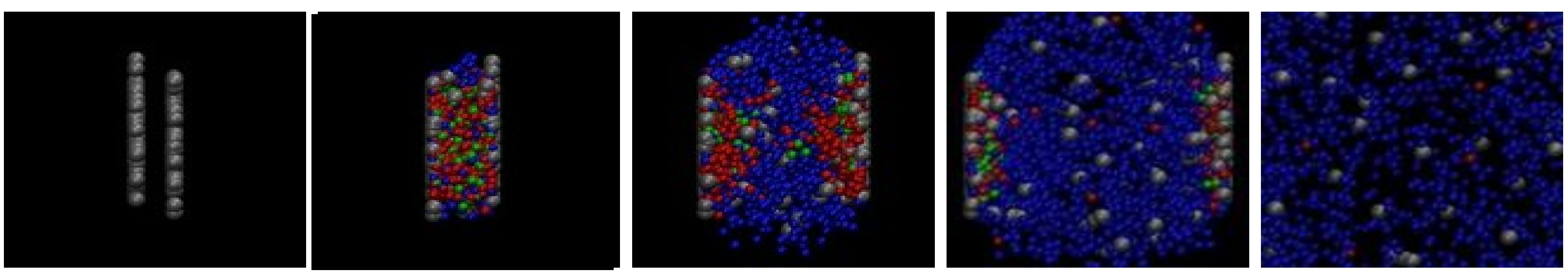
Dynamics: based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory

Initial state: Au+Au

Quark-Gluon Plasma: lQCD EoS
non-perturbative QCD - quasiaprticles

Dynamical
Hadronization

Hadronic interactions
→final hadrons + leptons



time

→ **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:

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

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

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

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

The yield of U-bosons of mass M_U:

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

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

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 $\pi^0(\eta) \rightarrow \gamma+\gamma$:**

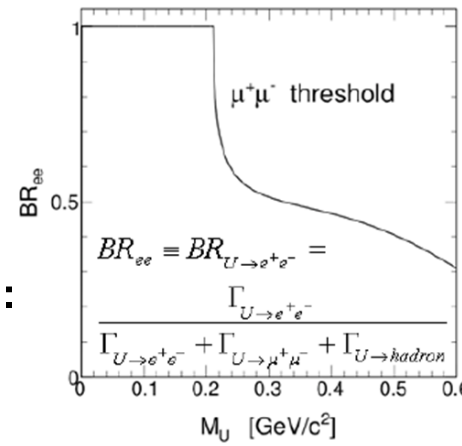
$$\frac{\Gamma_{i\to\gamma U}}{\Gamma_{i\to\gamma\gamma}} = 2\epsilon^2|F_i(q^2=M_U^2)|\frac{\lambda^{3/2}(m_i^2,m_\gamma^2,M_U^2)}{\lambda^{3/2}(m_i^2,m_\gamma^2,m_\gamma^2)} \qquad i=\pi^0,\eta$$

Formfactor

II.) $Br^{U\to e^+e^-}$ **Branching ratio for the decay of U-bosons to e+e- :**

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

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



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)

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

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

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

3) Obtain constraints by requesting that dN^{total}/dM (SM+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.

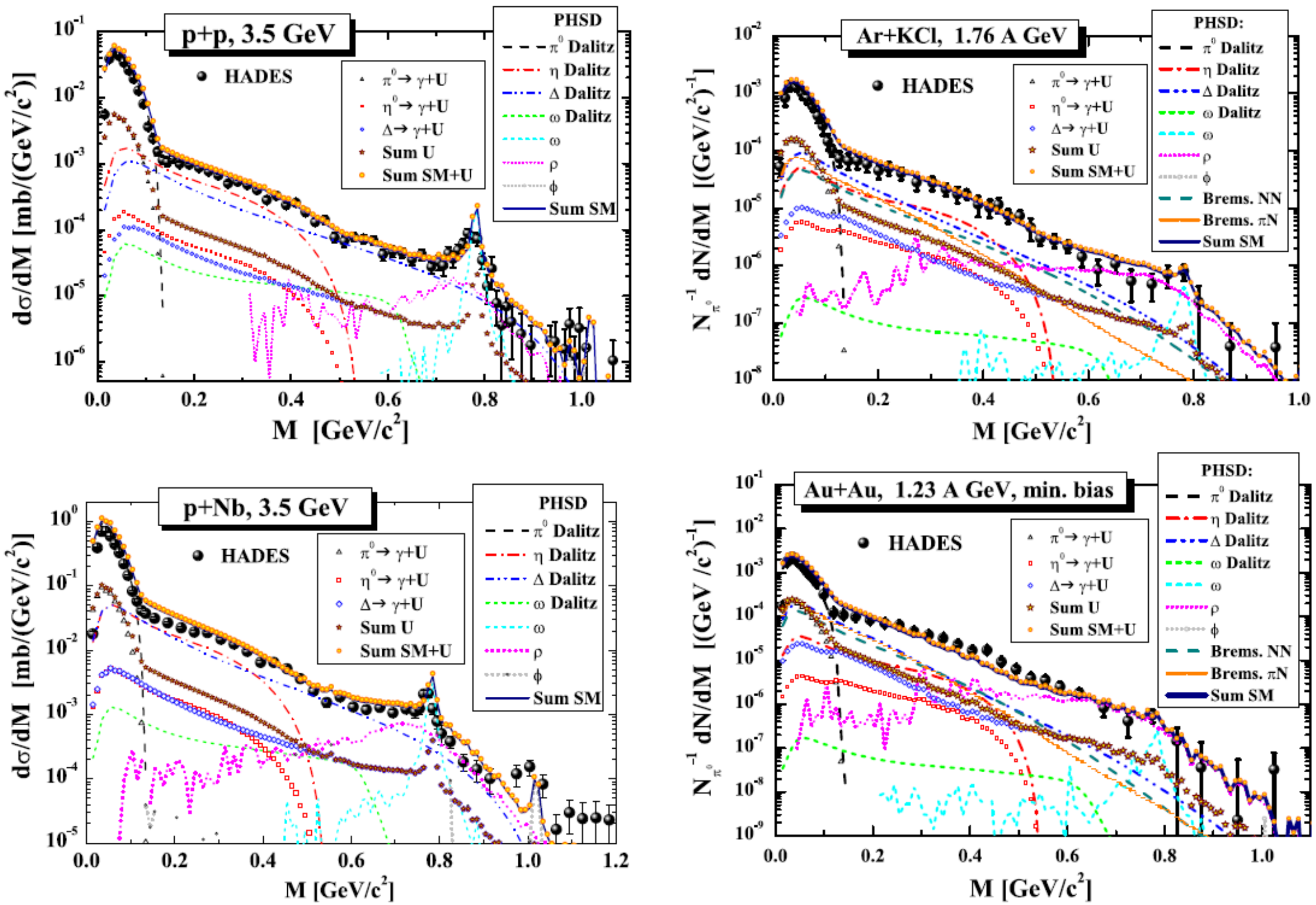
$$\frac{dN^{total}}{dM} = (1 + C_U)\frac{dN^{sumSM}}{dM}$$

→ 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

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

Dileptons yields including dark photons vs. HADES data

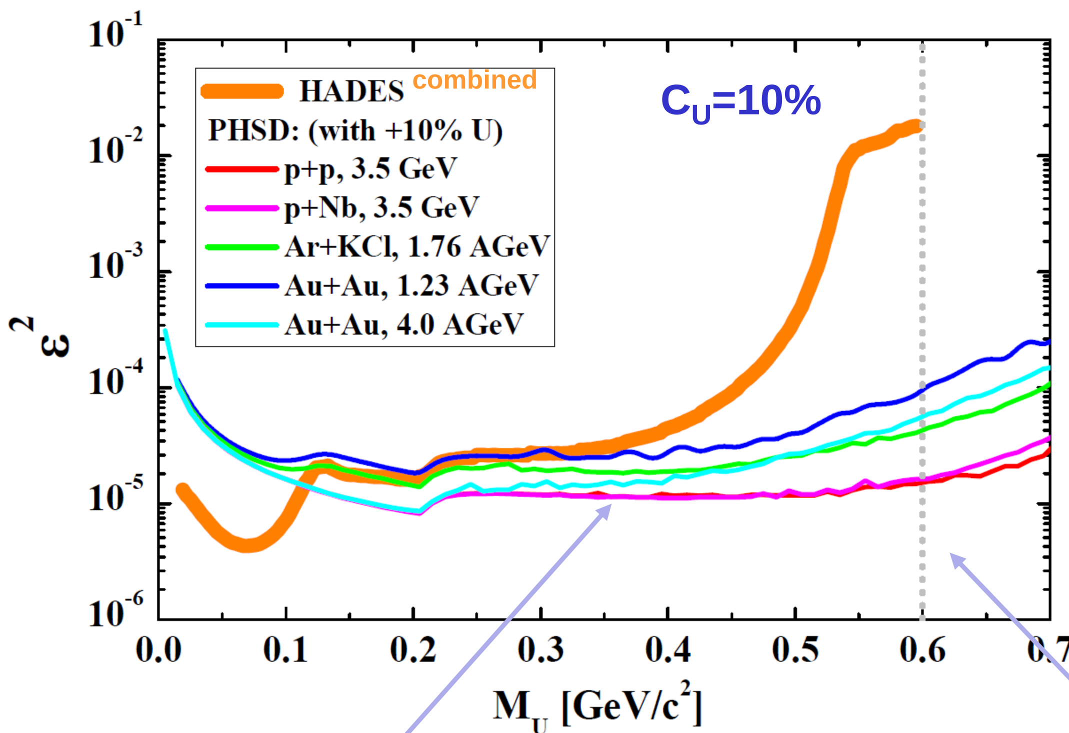


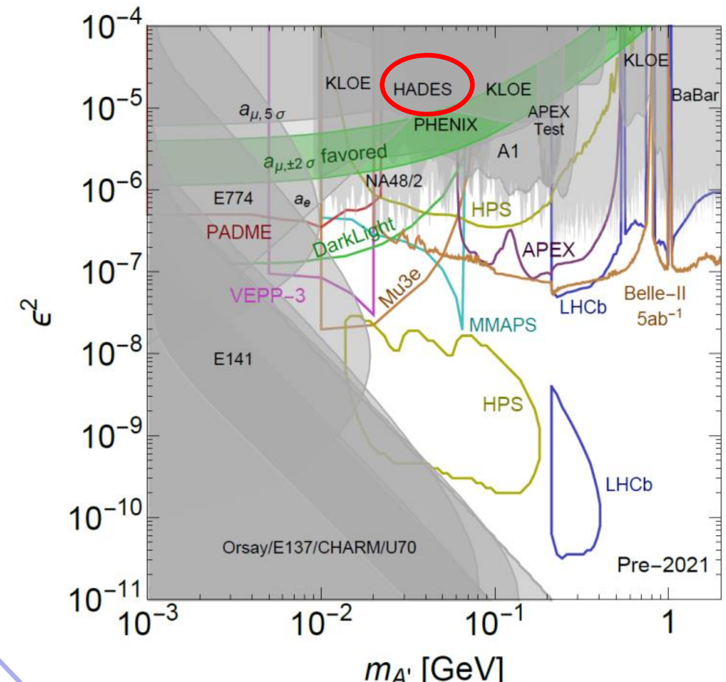
- The HADES data, i.e. SM contributions (including exp. acceptance) are well described by the PHSD
- The contributions from U→e+e- are added with C_U=10% allowed surplus of the total SM yield ➔ the total sum is still in a good agreement with exp. data

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





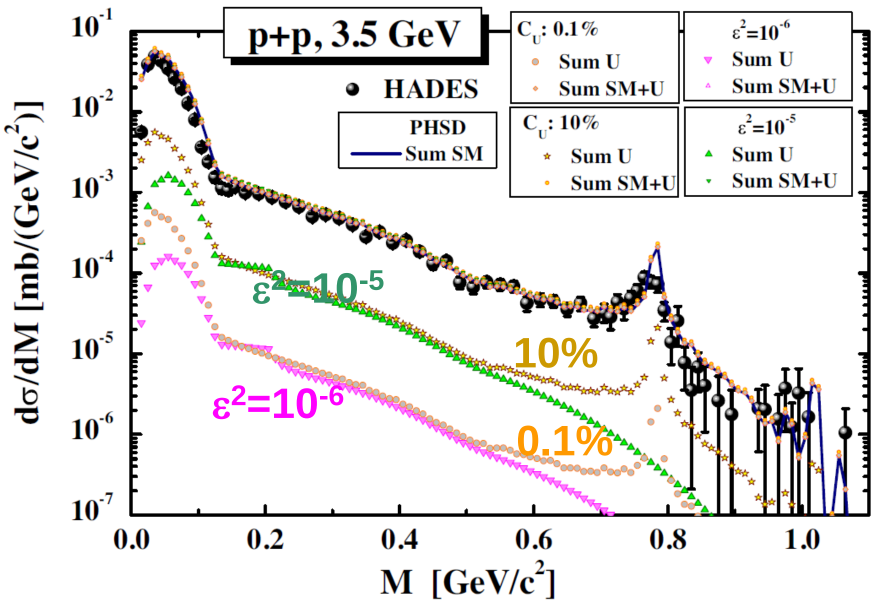
Validity range of extracted kinetic mixing parameter: $0 < M_U < 0.6$ GeV based on low energy dilepton spectra

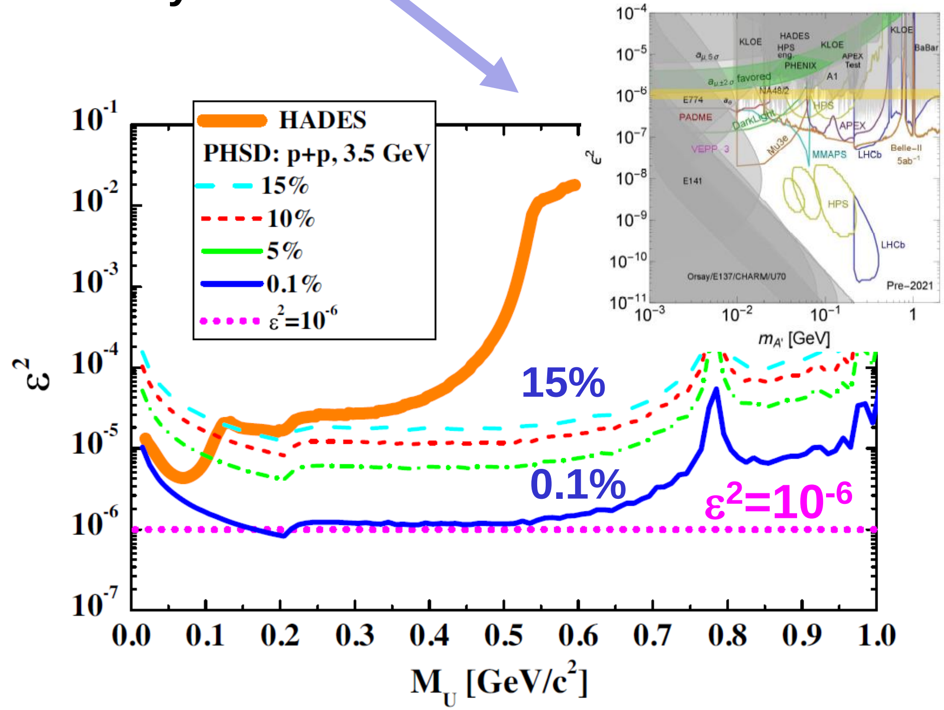
Possible contribution from other dark photon channels

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 lowering the allowed ‚surplus'**

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

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

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), $U \rightarrow e^+e^-$ from p + p, p + A and heavy-ion collisions at SIS 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 $U \rightarrow e^+e^-$ 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