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Search for dark photons in heavy-ion collisions

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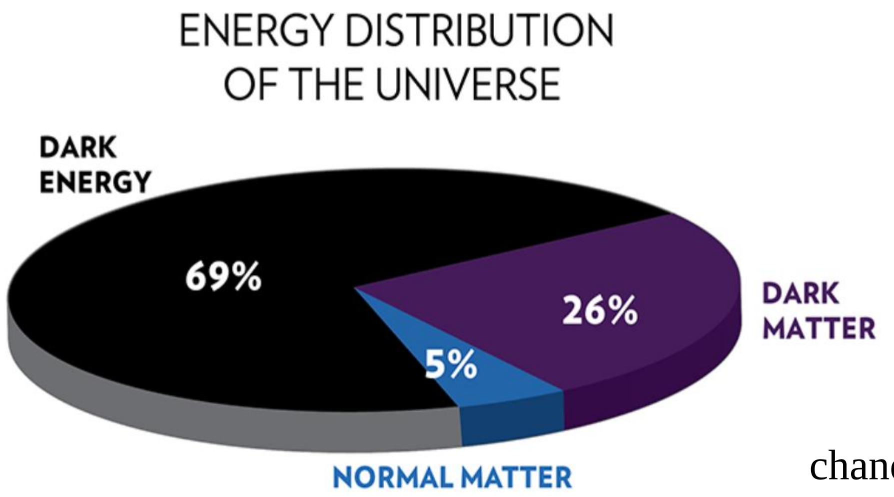
Structure of Universe

- Dark matter (DM) ~26%
- DM detected by astrophysical observations based on gravitational effects:

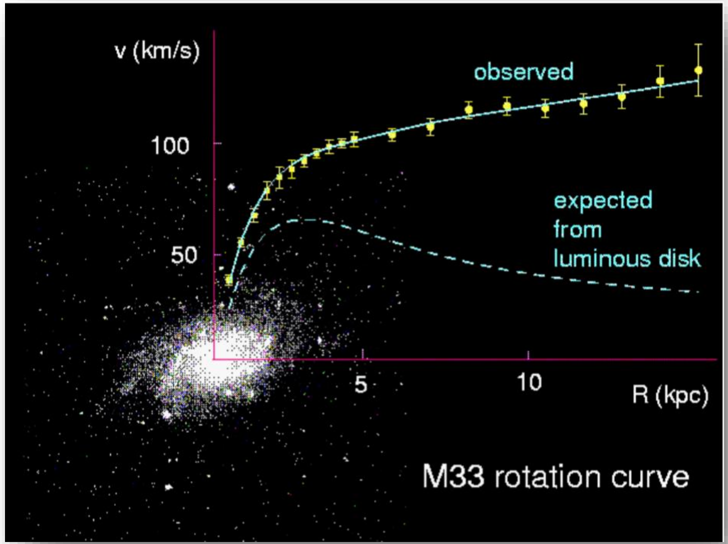
1933: F. Zwicky: observation of galaxy clusters

1970: V. Rubin: rotation anomalies in galaxies

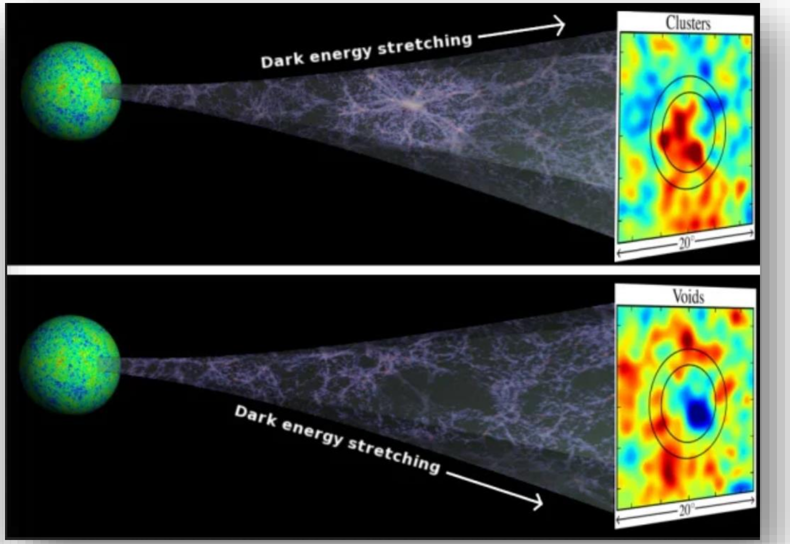


chandra.harvard.edu

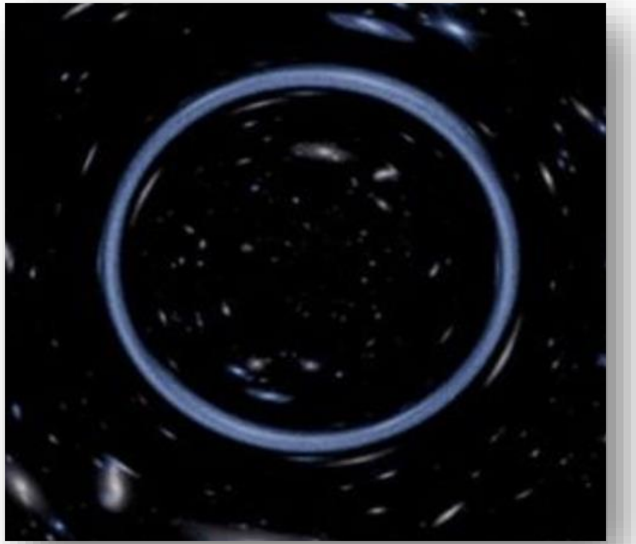
Hubble: gravitational lensing



arxiv.org/abs/physics/0007025



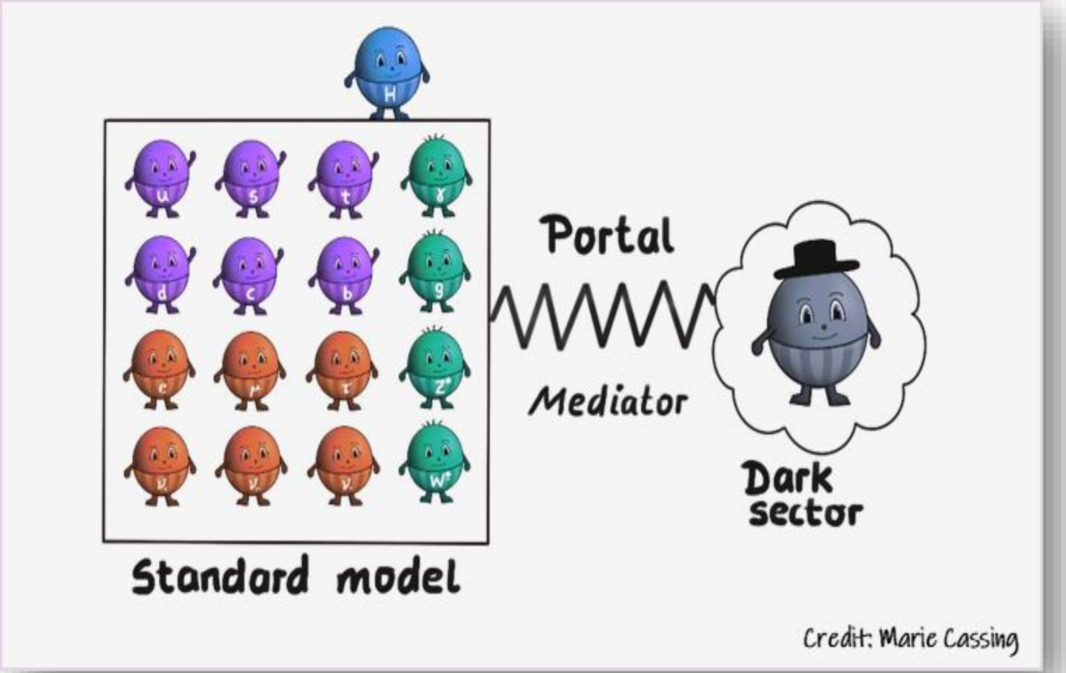
Granett, Neyrinck, Szapudi



NASA

Dark matter portals

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



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

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)

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

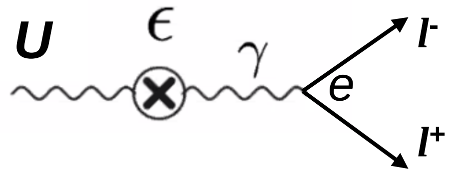
Dark photon field strength:

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

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

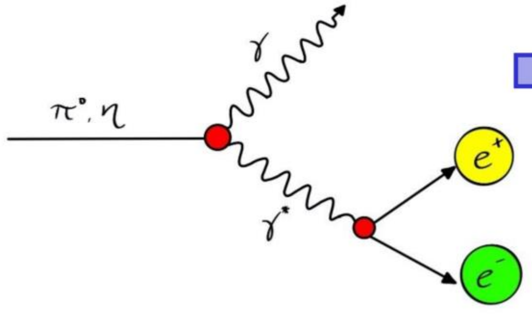
Unknown: kinetic mixing parameter ϵ and mass M_U

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

Dalitz decay of the dark photon to dileptons

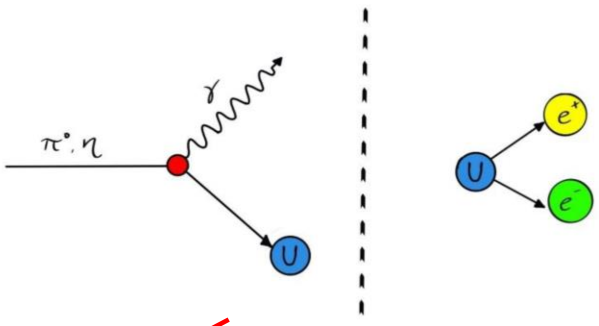
- Dalitz decays of pseudoscalar mesons π^0,η and Δ-resonances to **dileptons via the U-boson mediator**

Standard model

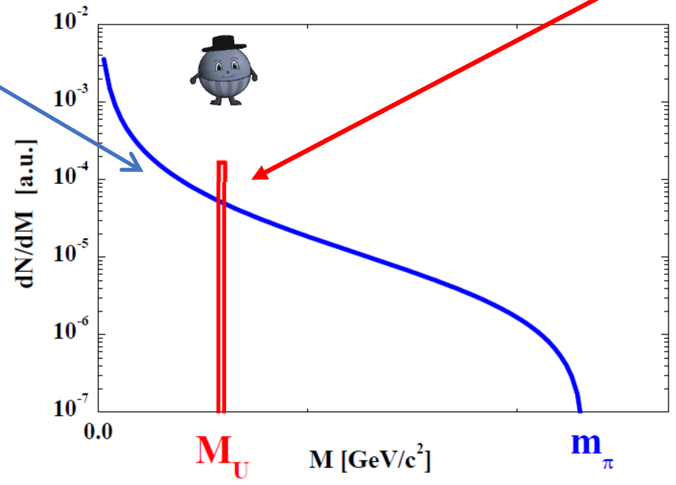


U(1)-U(1)′
kinetic mixing

Beyond SM: DM scenario

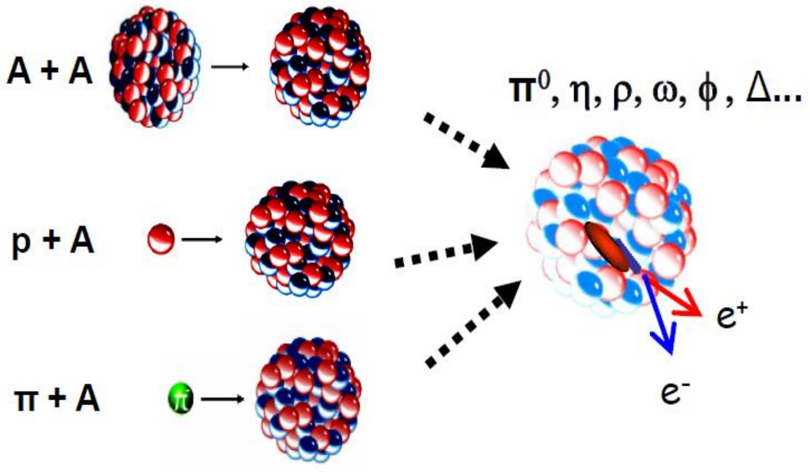


$\pi^0 \rightarrow \gamma+\gamma^*$,
$\eta \rightarrow \gamma+\gamma^*$, $\gamma^* \rightarrow e^+e^-$
$\Delta \rightarrow N+\gamma^*$,
…



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

Possible dark photon observation by dilepton experiments

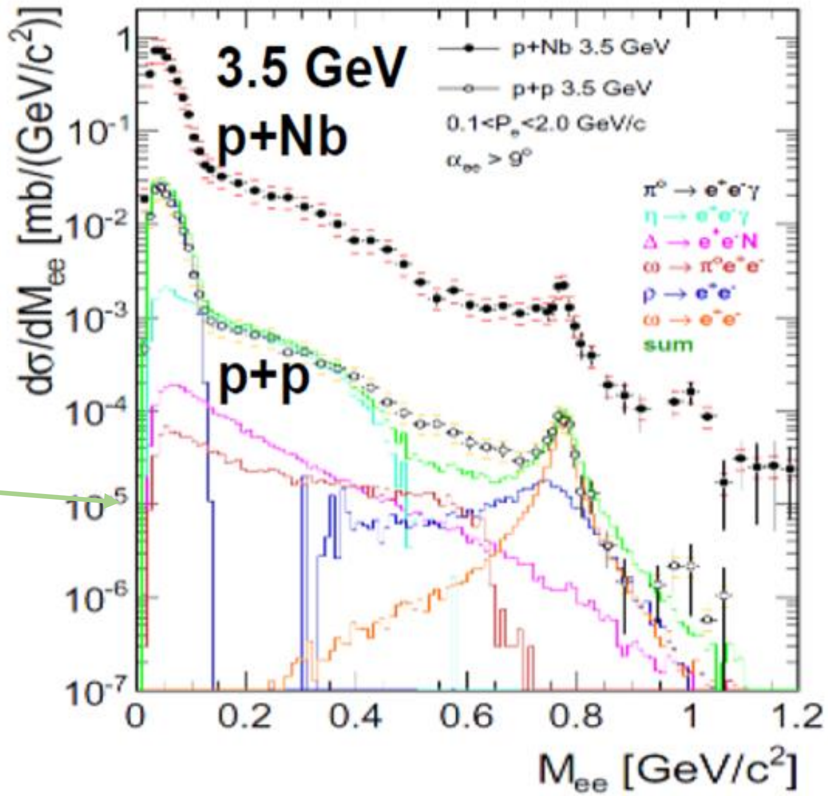


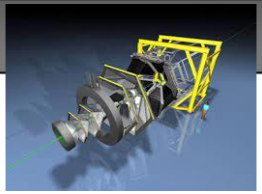
- Hadron production by p+p, p+A, A+A
- Hadron decay to dileptons
- Dalitz π^0,η and Δ decays are the **dominant dilepton sources at low M**

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

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

Dilepton spectra at low M (‘cocktail’)



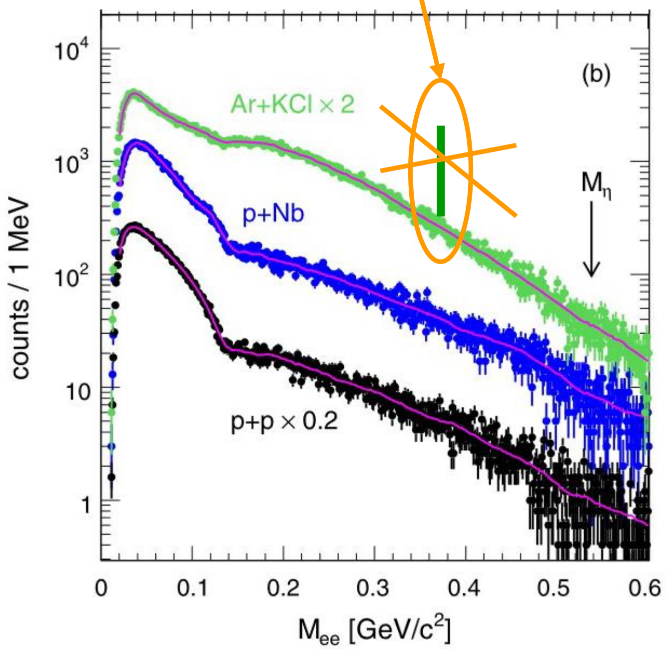


Search for dark photons with HADES (GSI)

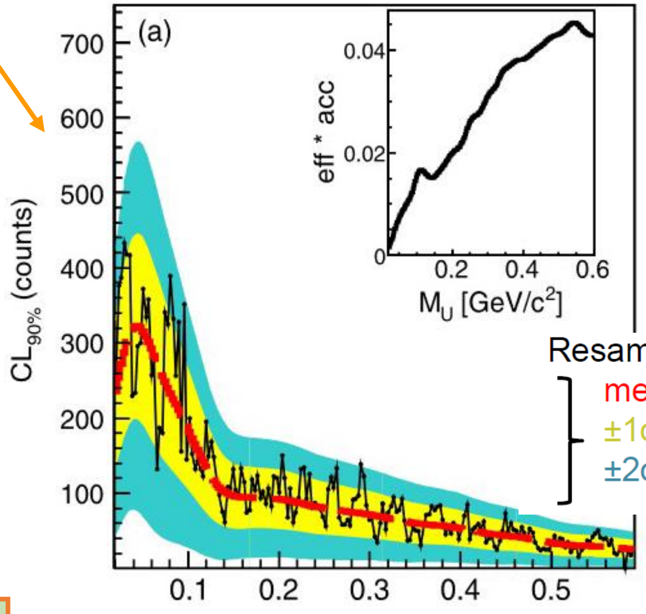
G. Agakishiev et al. (HADES), Phys. Lett. B 731, 265 (2014)

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

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

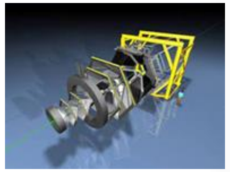


p+p, 3.5 GeV



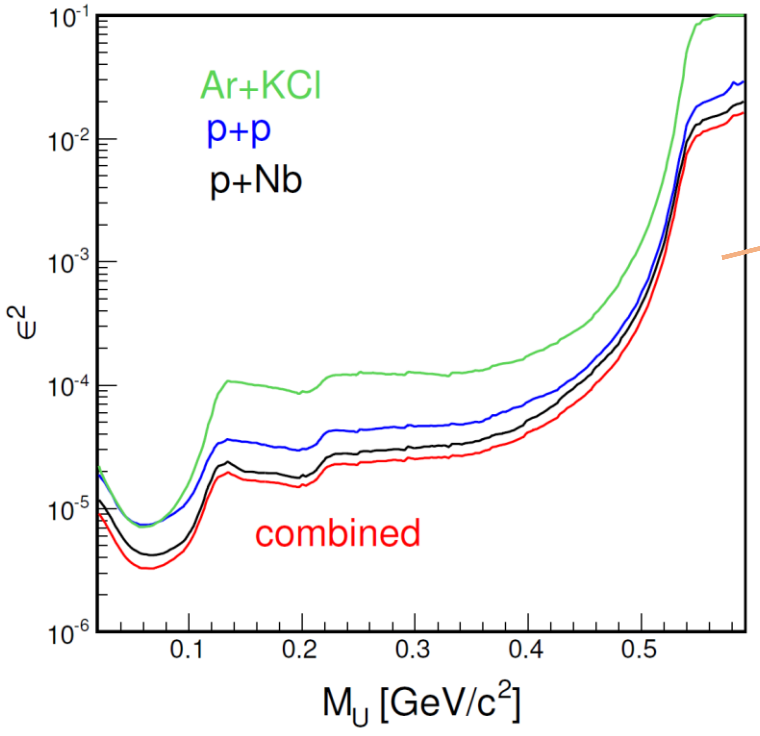
3) Transform this UL into an UL on the mixing parameter ε^2 based on the modelling of the U-boson production rate (B. Batell, M. Pospelov, and A. Ritz, PRD 80,095024 (2009))

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

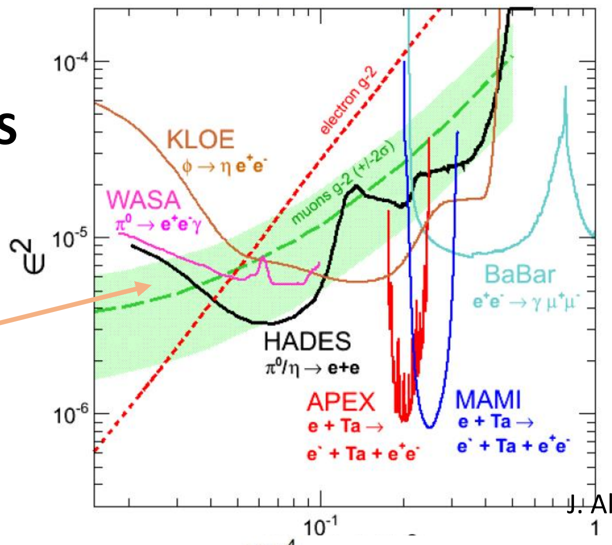


HADES coverage : $0.02 < M_U < 0.6$ GeV

Dark photons are not observed so far!

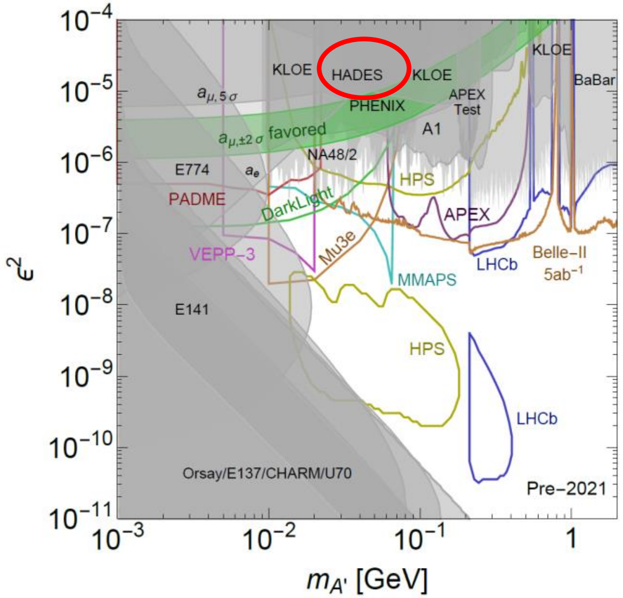
HADES 2014

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



J. Alexander et al. (2016), 1608.08632

World wide exp. data 2016

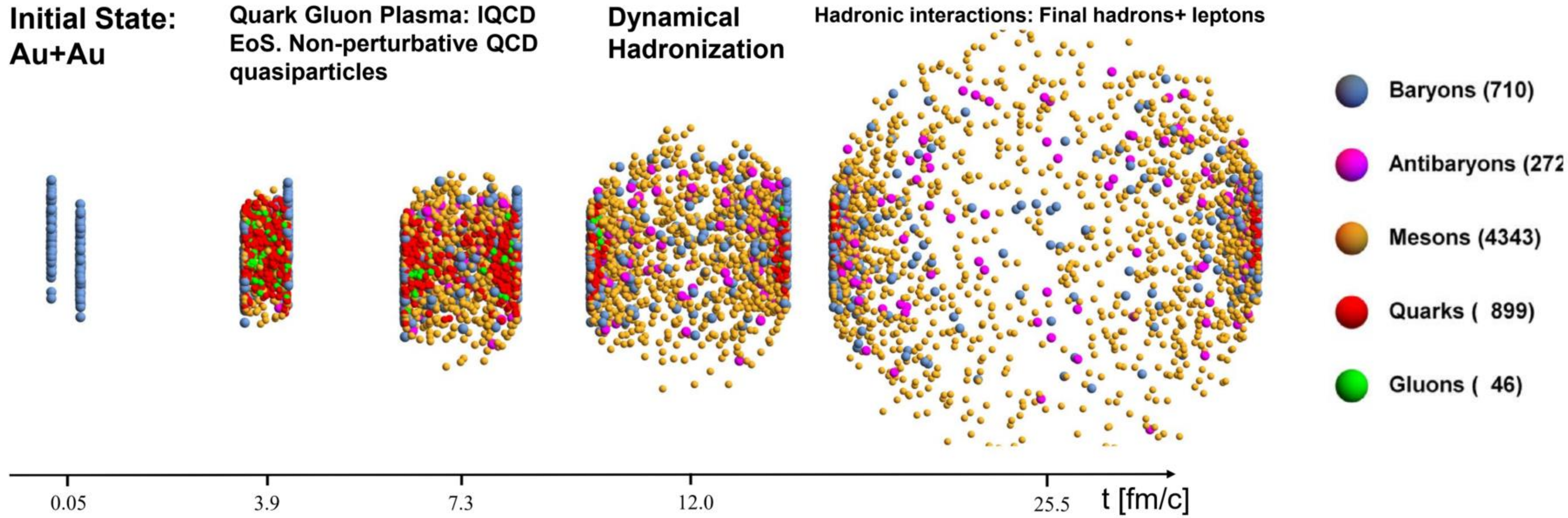


Theoretical modeling of U-boson production

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



➔ **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

Dark photon production in PHSD

Dalitz Decay

$\pi^0, \eta \rightarrow \gamma U$

$\Delta \rightarrow N U$

$\omega \rightarrow \pi^0 U$

$K^+ \rightarrow \pi^+ U$

Direct Decay

$\rho, \phi, \omega \rightarrow U$

$U \rightarrow e^+ e^-$

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

$$N^{U\rightarrow e^+e^-} = N_{\pi^0}^{U\rightarrow e^+e^-} + N_{\eta}^{U\rightarrow e^+e^-} + \cdots + N_{\omega}^{U\rightarrow e^+e^-}$$

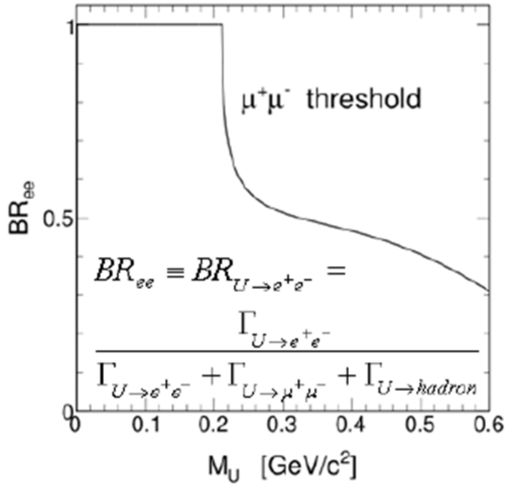
$$= Br^{U\rightarrow e^+e^-} \times \left(N_{\pi^0\rightarrow\gamma U} + N_{\eta\rightarrow\gamma U} + \cdots + N_{\omega\rightarrow U}\right)$$

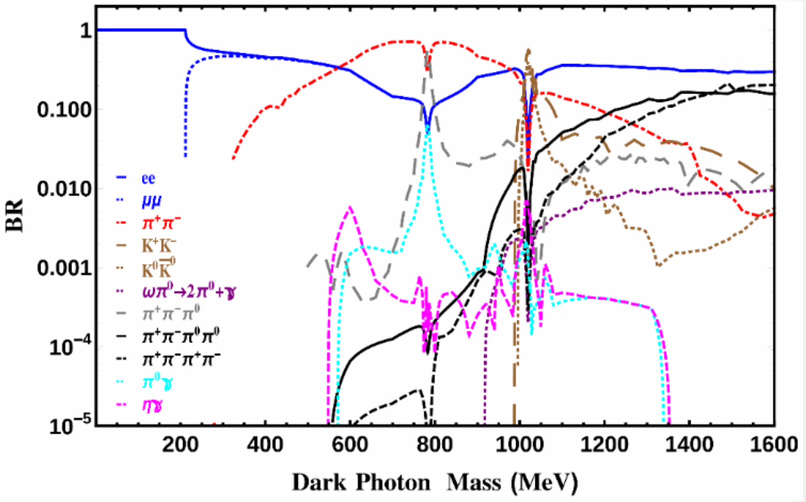
Branching ratio for the decay of U-bosons to e^+e^-

I. $$Br^{U\rightarrow e^+e^-} = \frac{\Gamma_{U\rightarrow e^+e^-}}{\Gamma_T(U)} = \frac{\Gamma_{U\rightarrow e^+e^-}}{\Gamma_{U\rightarrow e^+e^-} + \Gamma_{U\rightarrow\mu^+\mu^-} + \Gamma_{U\rightarrow hadrons}}$$

$$Br^{U\rightarrow e^+e^-} = \frac{1}{1 + \sqrt{1 - \frac{4m_\mu^2}{m_U^2}}\left(1 + \frac{2m_\mu^2}{m_U}\right)(1 + R(m_U))}$$

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





Dark photon production in PHSD

Dalitz Decay

$\pi^0, \eta \to \gamma U$

$\Delta \to NU$

$\omega \to \pi^0 U$

$K^+ \to \pi^+ U$

Direct Decay

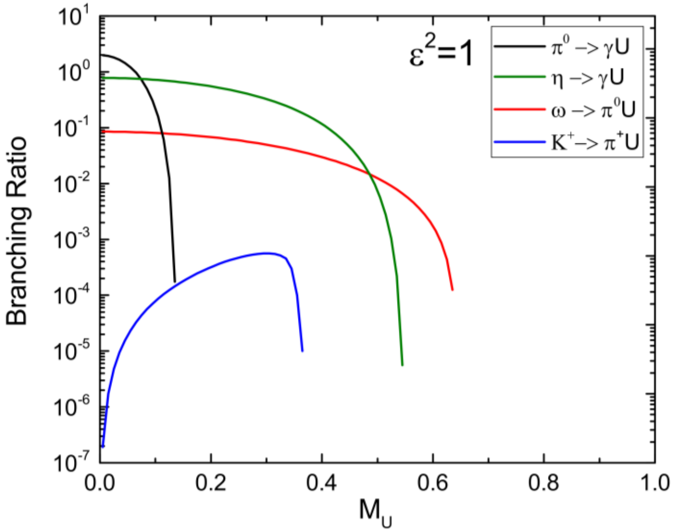
$\rho, \phi, \omega \to U$

$U \to e^+ e^-$

II. $(N_{\pi^0\to\gamma U} + N_{\eta\to\gamma U} + \dots + N_{\omega\to U})$

$$N_{\pi^0\to\gamma U} = N_{\pi^0}\, Br^{\pi^0\to\gamma U}$$

$$N_{\pi^0\to\gamma U} = N_{\pi^0}\, \varepsilon^2\, Br^{\pi^0\to\gamma U}_{\varepsilon^2=1}$$



Based on the model

$$Br(P\to\gamma U) = \varepsilon^2 Br(P\to\gamma\gamma)\left(1-\frac{m_U^2}{m_P^2}\right)^3 \qquad P = \pi, \eta$$

$$Br(\Delta\to NU) = \varepsilon^2 Br(\Delta\to N\gamma)\int A(m_\Delta)\frac{\lambda^{3/2}(m_\Delta, m_N, m_U)}{\lambda^{3/2}(m_\Delta, m_N, 0)}$$

HADES Col. (2014) PLB, 731, 265

$$Br(\omega\to\pi^0 U) = \varepsilon^2 Br(\omega\to\pi^0\gamma)\frac{\left[(m_\omega^2-(m_U+m_\pi))(m_\omega^2-(m_U-m_\pi))\right]^{3/2}}{(m_\omega^2-m_\pi^2)^3}$$

→ **NICA** Col. (2024) PLB, 852, 138599

$$Br(K^+\to\pi^+U) = \frac{\alpha\varepsilon^2}{\pi^2\,\Gamma_T(K)}\frac{m_U}{m_K}W'(m_U)\lambda^{1/2}(m_U, m_k, m_\pi)$$

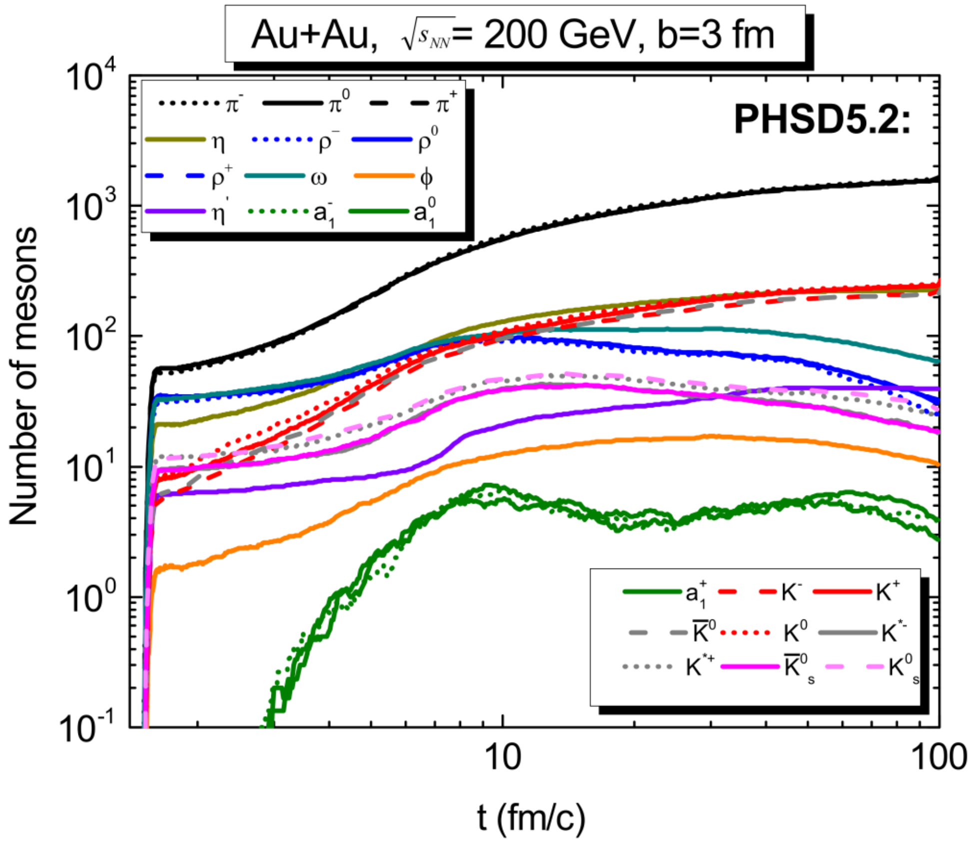
→ **Pospelov** (2009) PRD 80, 095002

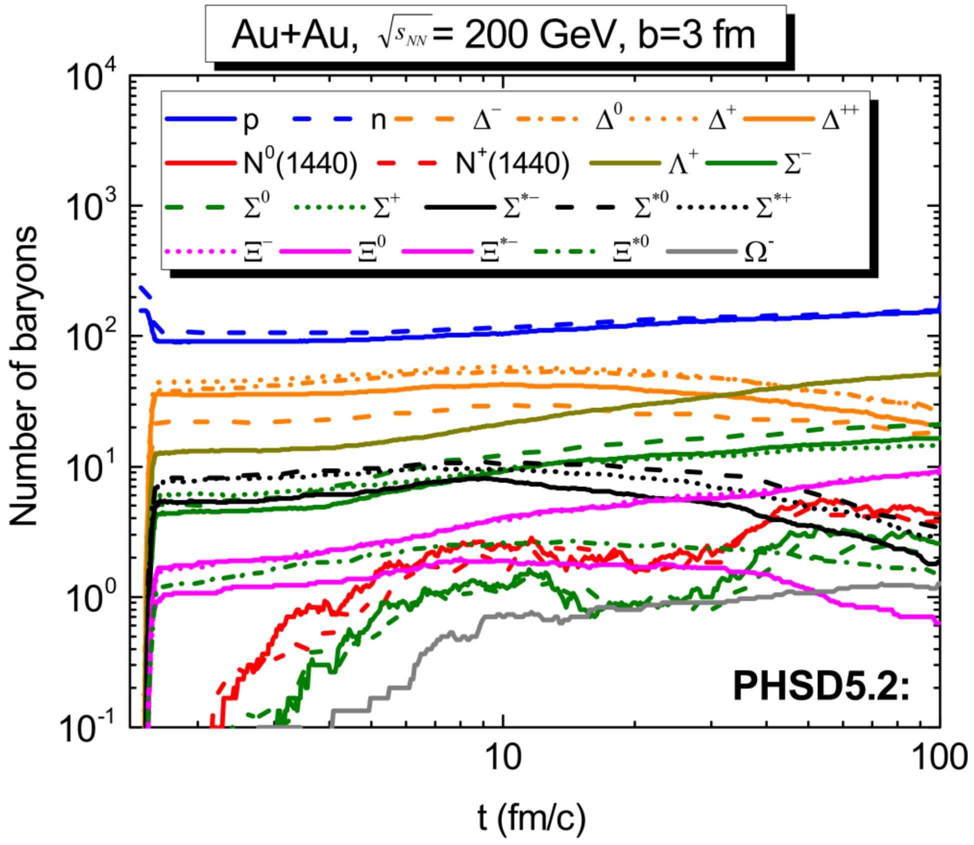
$$Br(V\to U) = \frac{\alpha\,\varepsilon^2 m_U}{3\Gamma_T(V)} \qquad V = \rho, \phi, \omega$$

→ **Battel** (2009) PRD 79, 115008

$A(m_\Delta) \to$ Breit – Wiegner Func.

Number of particles in Au+Au collision





Important number of kaon are created

Important number of kaon are created

Important number of kaon are created

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)

$$\frac{dN^{sumU}}{dM} = \frac{dN_{\pi^0}^{U\to e^+e^-}}{dM} + \frac{dN_{\eta}^{U\to e^+e^-}}{dM} + \ldots + \frac{dN_{\omega}^{U\to e^+e^-}}{dM} \qquad \frac{dN^{sumU}}{dM} = \varepsilon^2 \frac{dN_{\varepsilon^2=1}^{sumU}}{dM}$$

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

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

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.

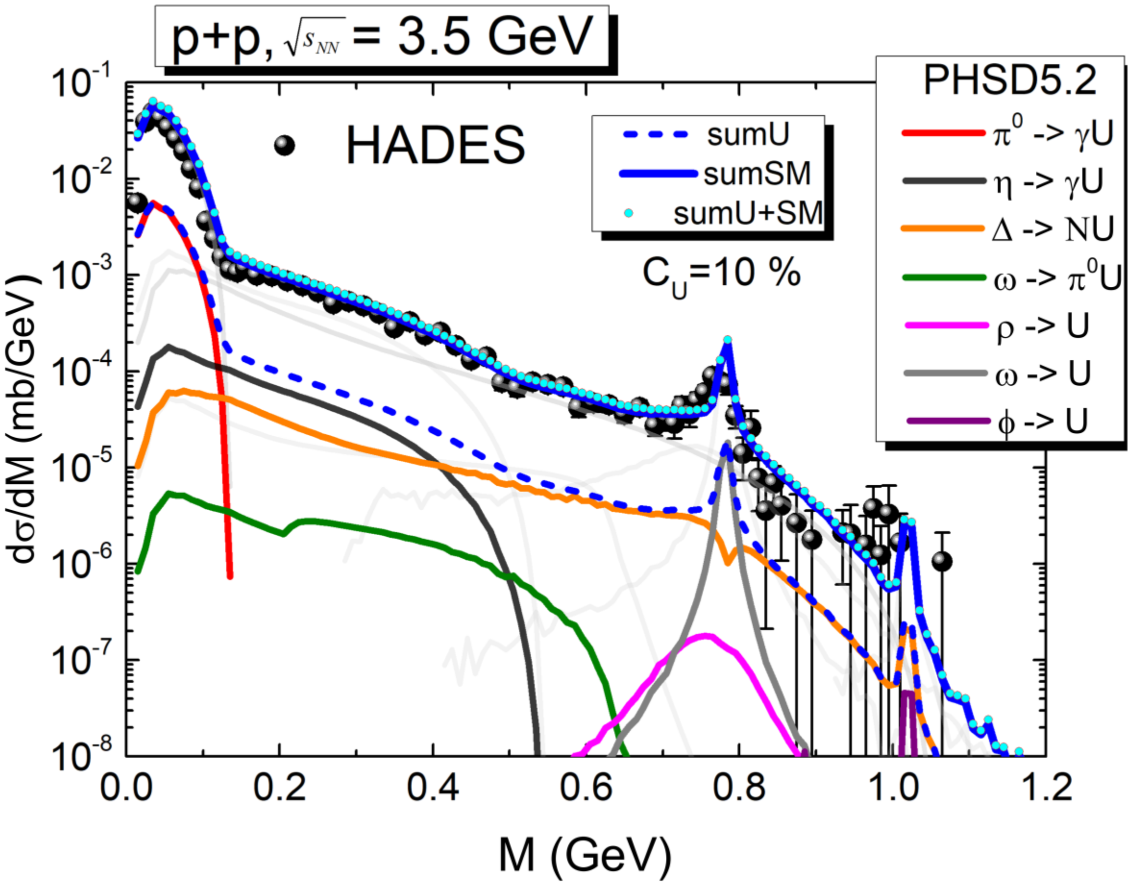
$$\frac{dN^{total}}{dM} = (1 + C_U)\frac{dN^{sumSM}}{dM}$$

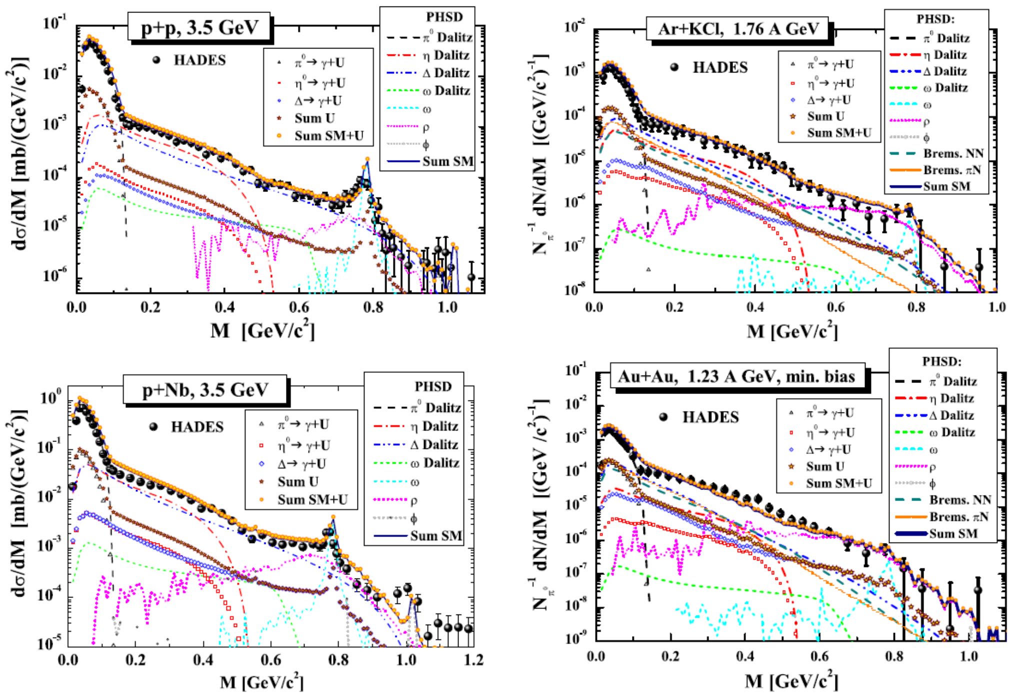
→ **C_U controls the allowed "surplus" dilepton yield resulting from dark photons on top of the total SM yield**

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

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

Dilepton spectra from U-boson decays at SIS18 energies vs. HADES data

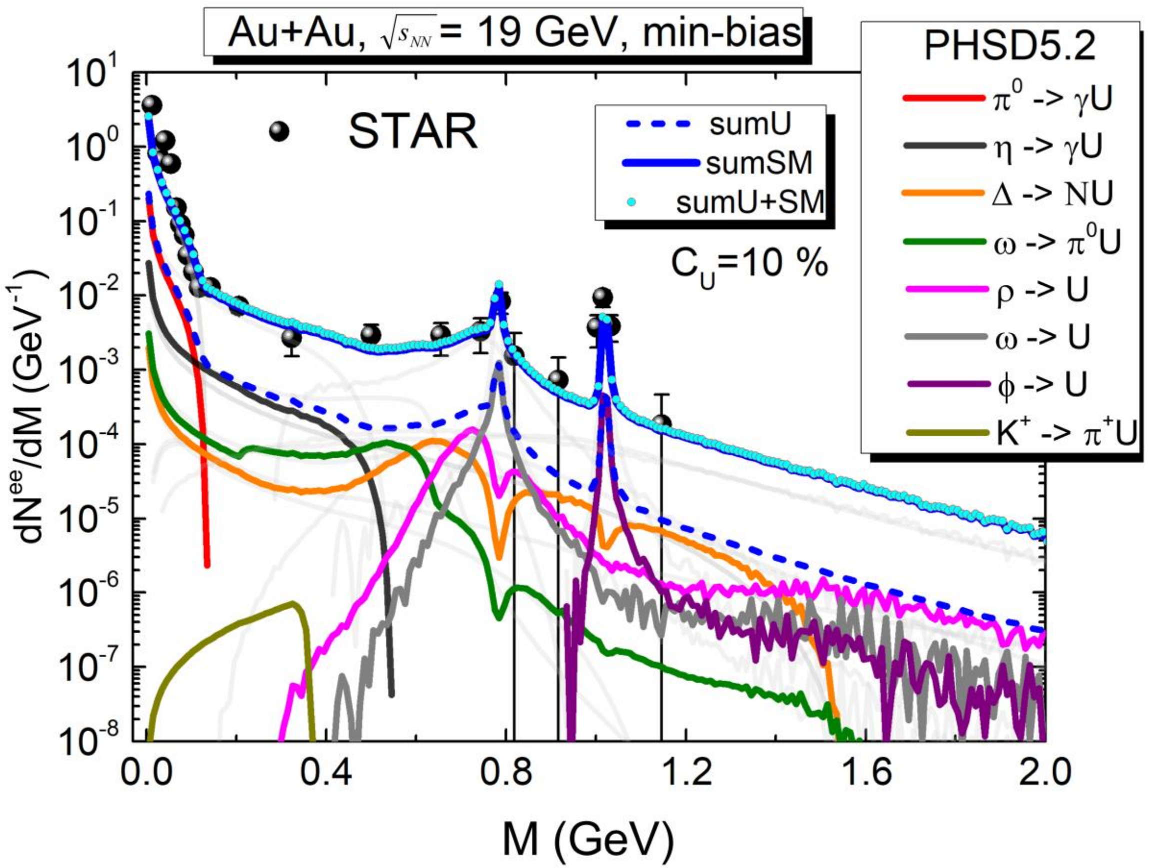


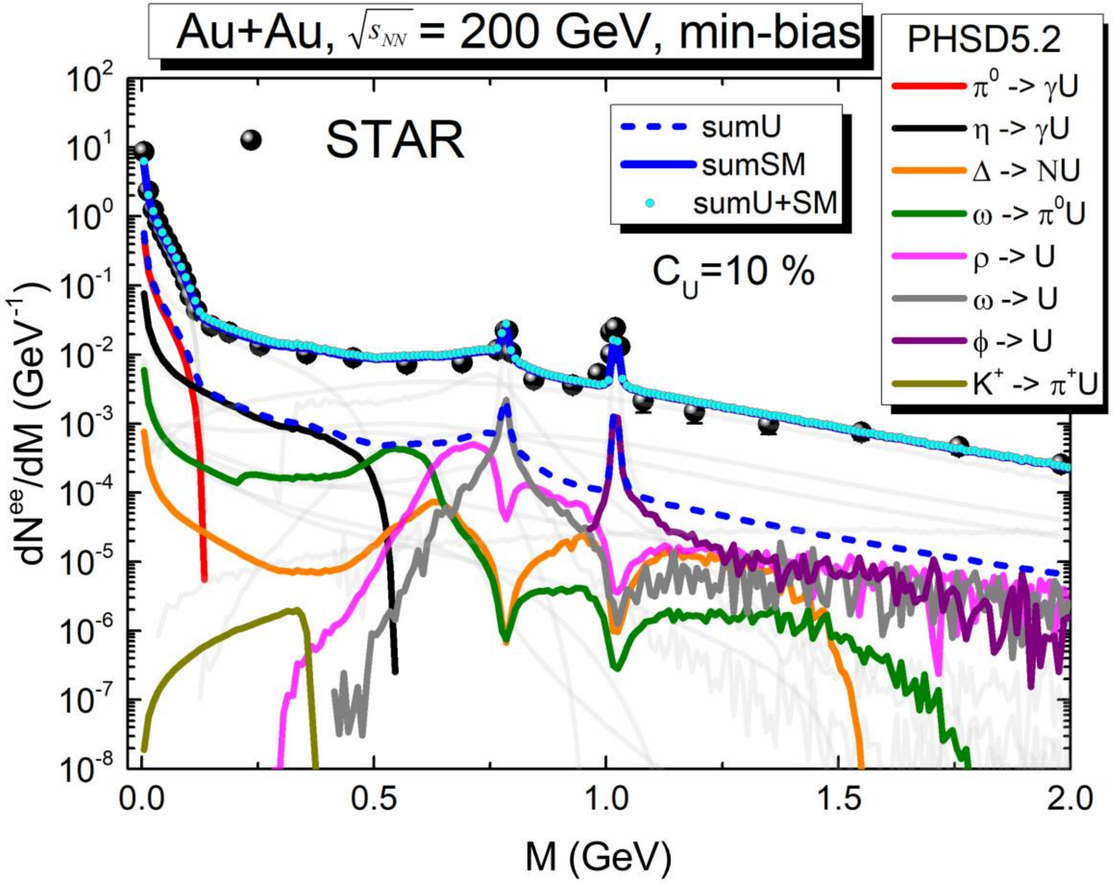


- The HADES data, i.e. SM contributions (including exp. acceptance) are well described by the PHSD
- The contributions from $U \rightarrow e^+e^-$ are added with C_U=10% allowed surplus of the total SM yield ➔ the total sum is still in a good agreement with exp. data

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

Dilepton spectra from U-boson decays at RHIC energies vs. STAR data





- **The HADES data, i.e. SM contributions (including exp. acceptance) are well described by the PHSD**
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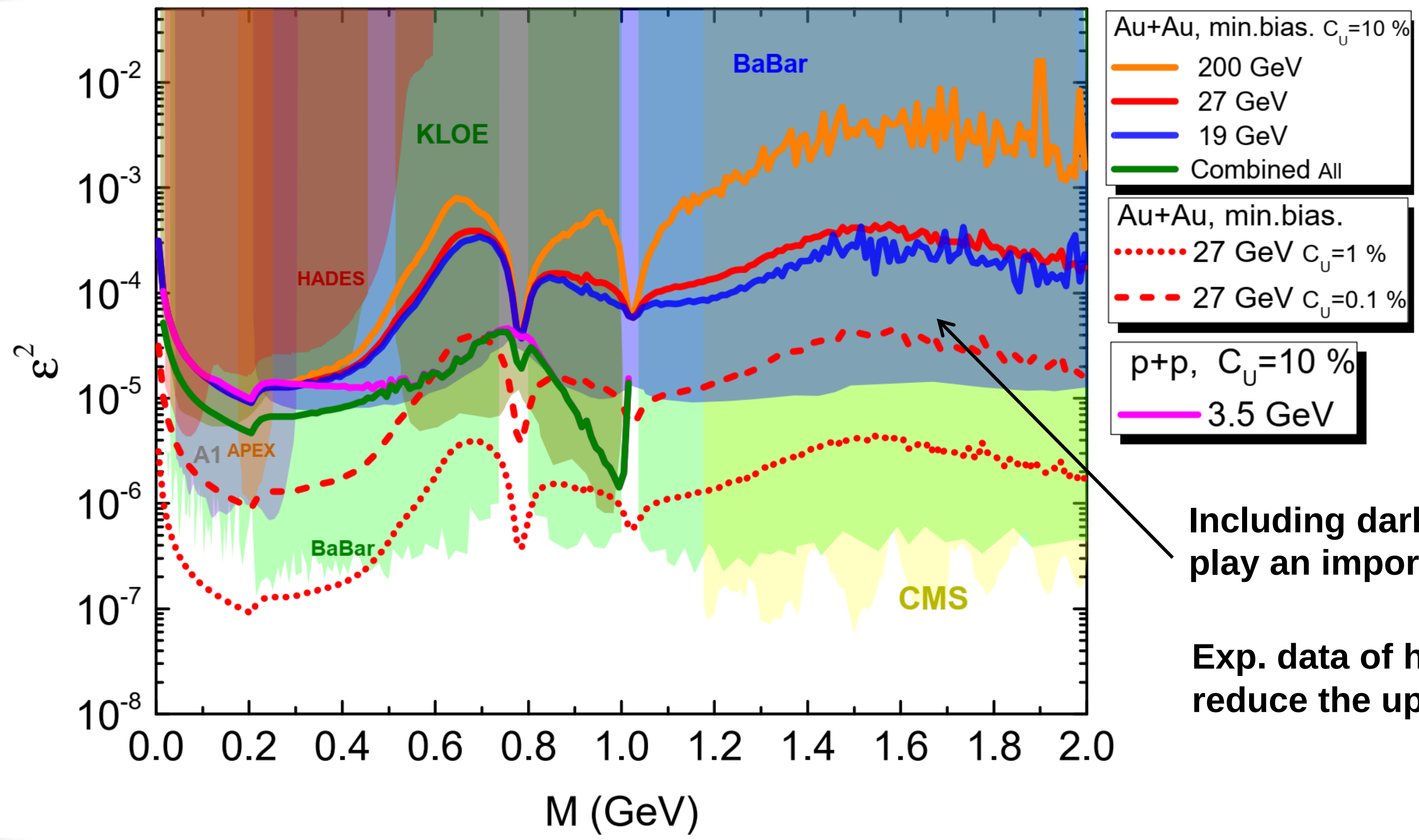
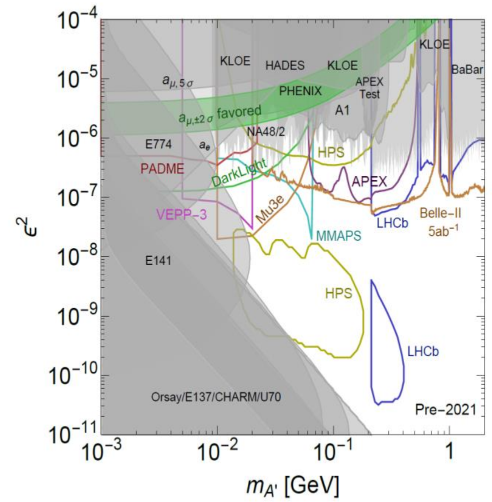
Ida Schmidt, E.B., Malgorzata Gumberidze, Romain Holzmann, Phys.Rev.D 104 (2021) 015008

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 C_U allowed surplus of the total SM yield



J. Alexander et al. (2016), 1608.08632



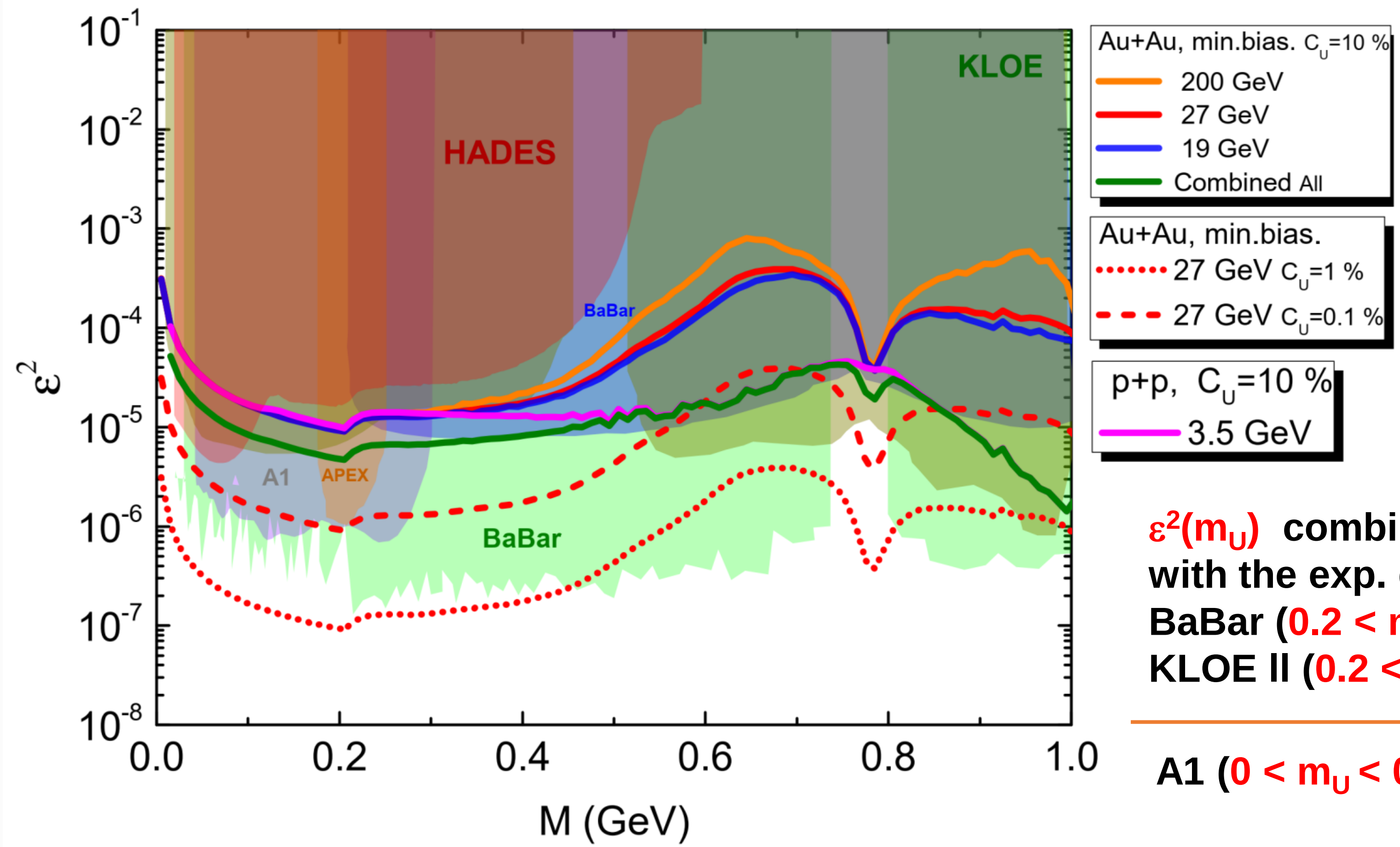
Including dark photon decays from QGP will play an important role at m_U < 1 GeV

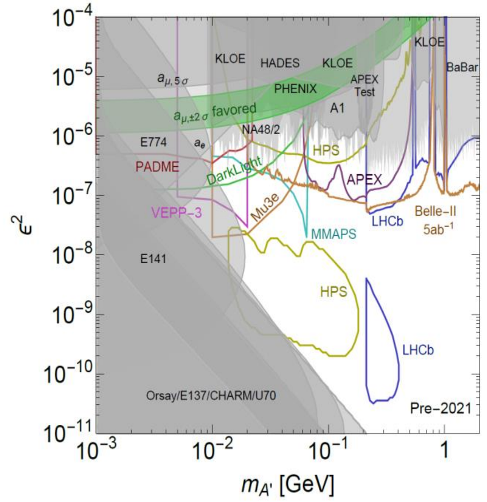
Exp. data of high precision is needed to reduce the upper limit for ε^2

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 C_U allowed surplus of the total SM yield

J. Alexander et al. (2016), 1608.08632





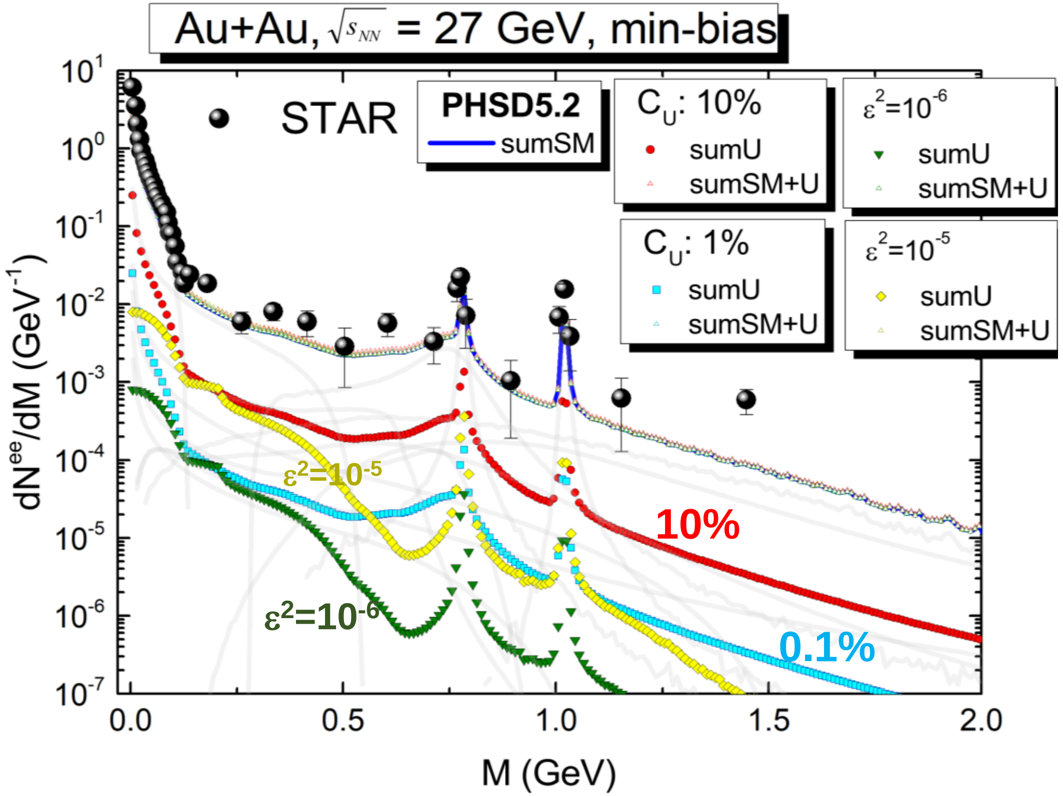
$\varepsilon^2(m_U)$ combined for $C_U = 10\%$ is consistent with the exp. data from
BaBar (0.2 < m_U < 1 GeV)
KLOE II (0.2 < m_U < 0.8 GeV)

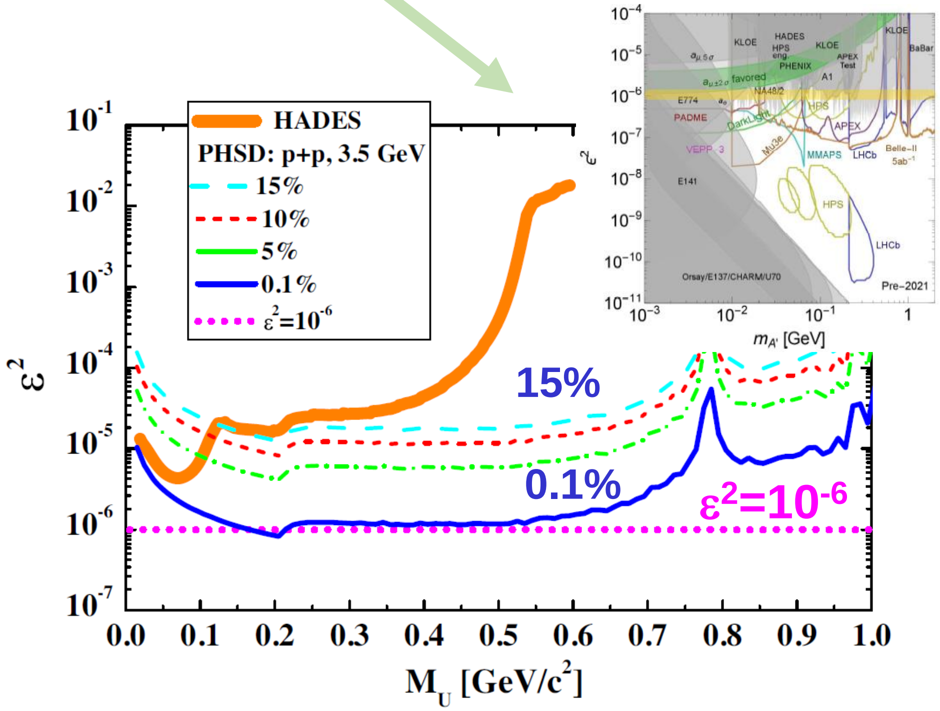
A1 (0 < m_U < 0.3 GeV) **$\varepsilon^2(m_U)$ combined for $C_U = 1\%$**

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

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





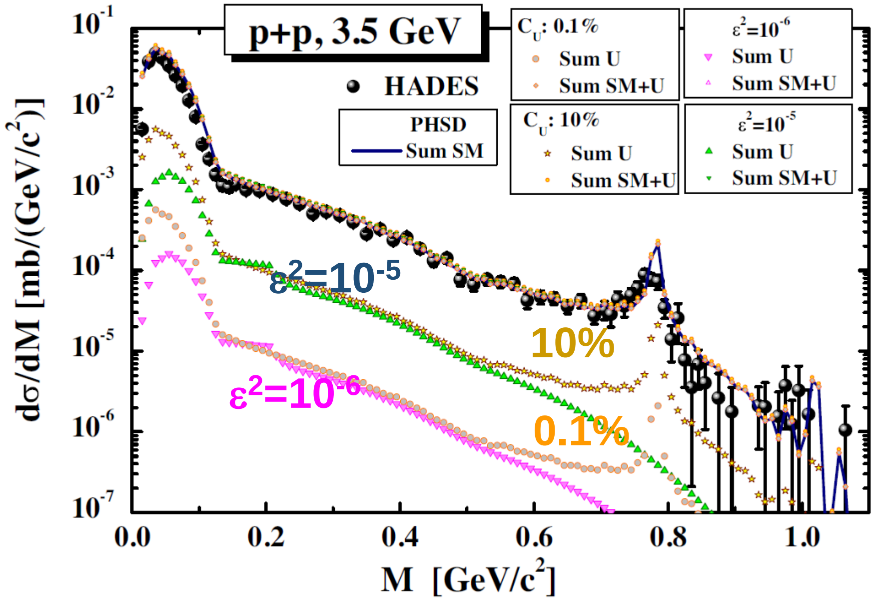
The **theoretically** extracted upper limit of the kinetic mixing parameter $\varepsilon^2(m_U)$ of light dark photons from dark photon decays:

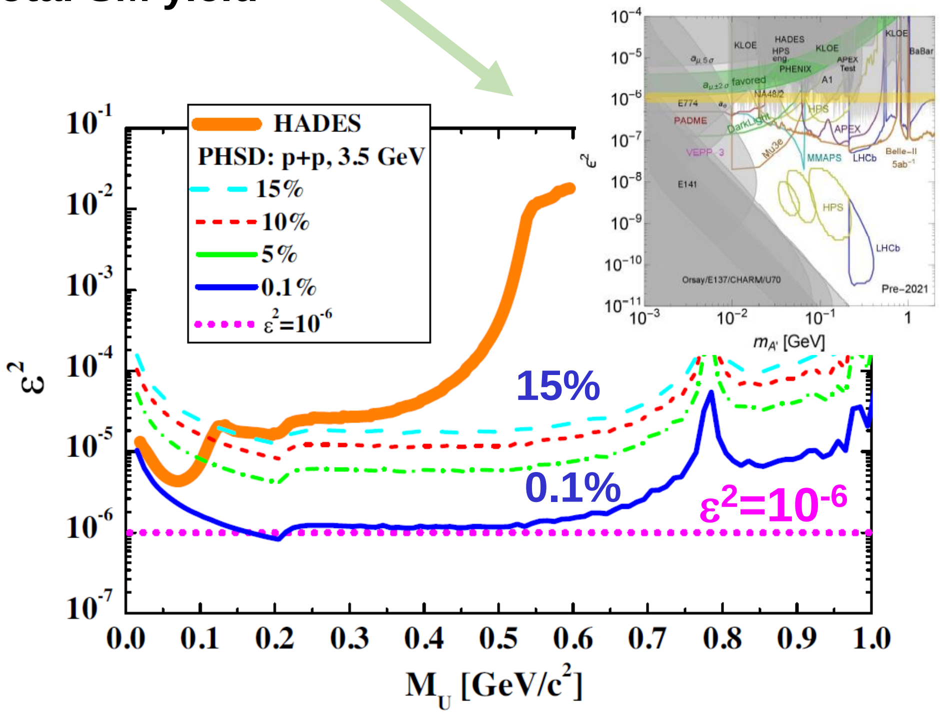
- strongly reduces by lowering the allowed ‚surplus'

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

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 $\varepsilon^2(M_U)$**

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 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 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

- 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

→ 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

- Include QGp U citar
- Decir SIDM

Thanks to

Ida Schmidt (Uni. Frankfurt)
Malgorzata Gumberidze, Romain Holzmann
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Thanks to the Organizers !

Thank you for your attention !