Exploring Dark Photon Production and Kinetic Mixing Constraints in Heavy-Ion Collisions

Adrian William Romero Jorge (Uni. Frankfurt & FIAS & HFHF & ICIMAF)

&

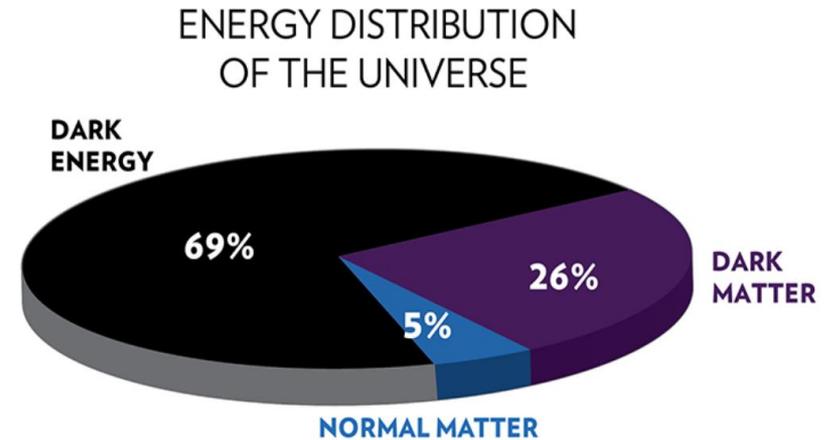**Elena Bratkovskaya** (GSI, Darmstadt & Uni. Frankfurt & HFHF)

&

Laura Sagunski (Uni. Frankfurt)

Structure of Universe

1933: F. Zwicky: observation of the Coma galaxy cluster -> Extra mass

❑ **Dark matter (DM) ~26%**

❑ **DM detected by astrophysical observations based on gravitational effects:**

ENERGY DISTRIBUTION OF THE UNIVERSE

DARK ENERGY 69%

DARK MATTER 26%

NORMAL MATTER 5%

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Structure of Universe

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- ❑ **Dark matter (DM) ~26%**

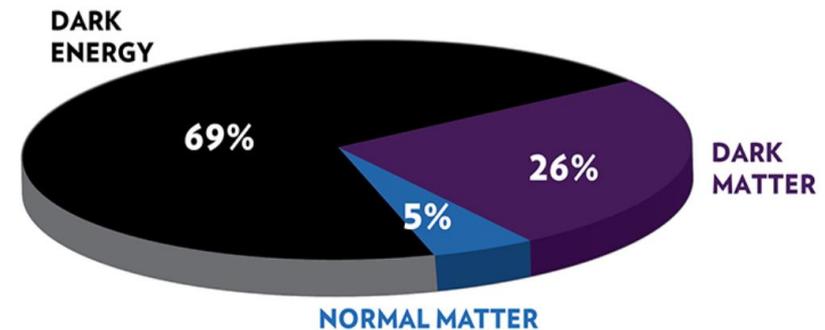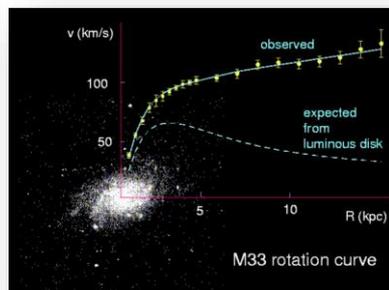- ❑ **DM detected by astrophysical observations based on gravitational effects:**

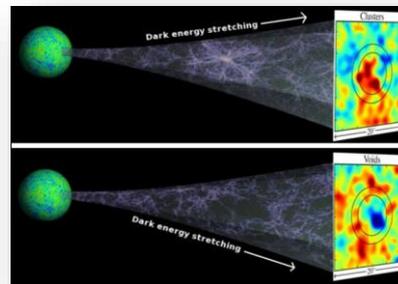ENERGY DISTRIBUTION OF THE UNIVERSE

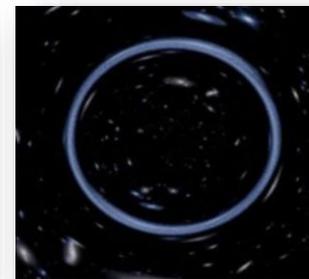chandra.harvard.edu

Galaxy Rotation Curves

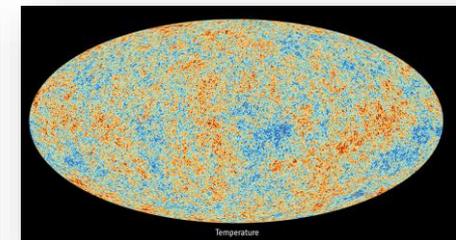arxiv.org/abs/physics/0007025

Structure Formation

Granett, Neyrinck, Szapudi

Gravitational lensing

NASA

Cosmic Microwave Background (CMB)

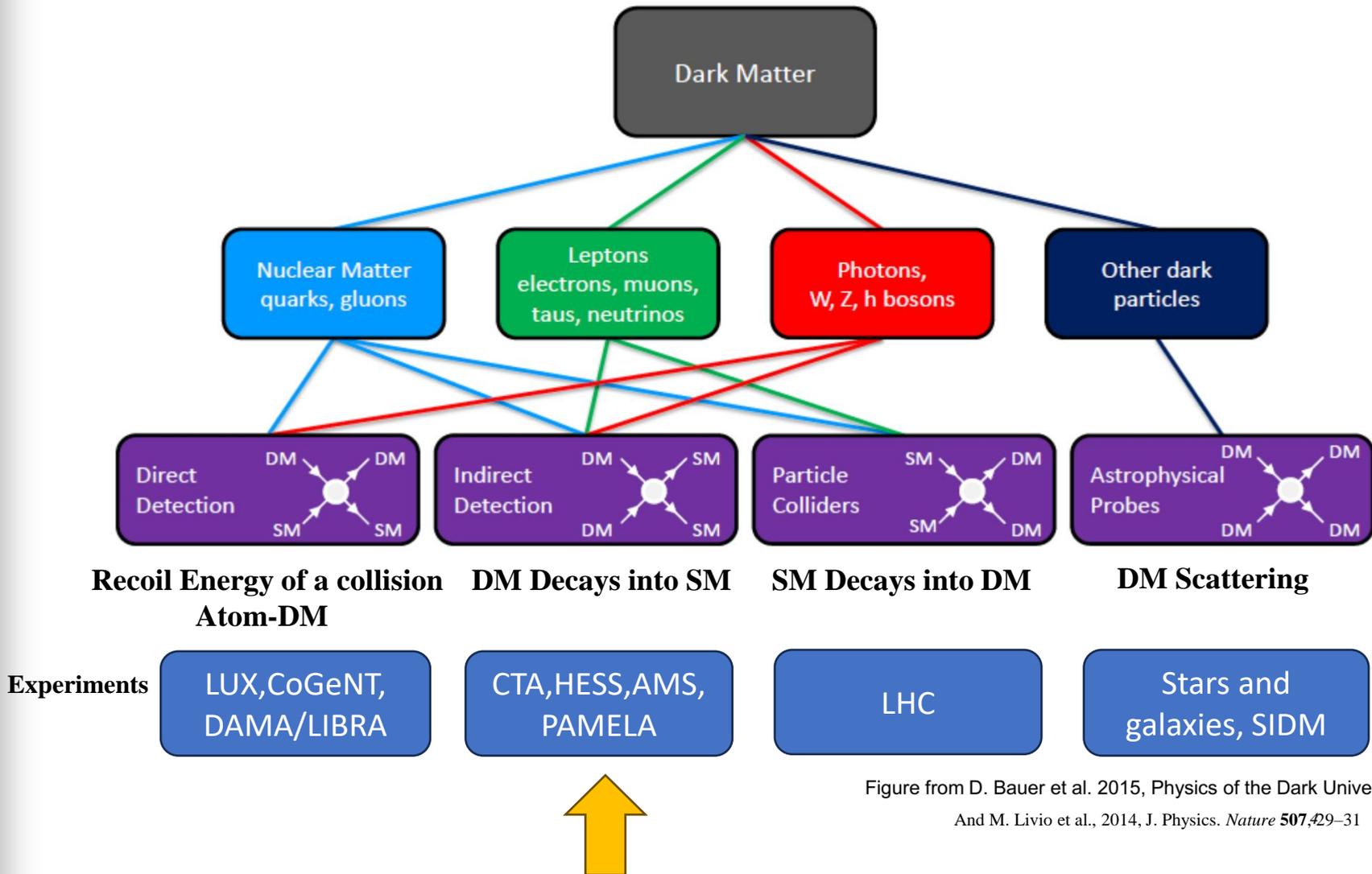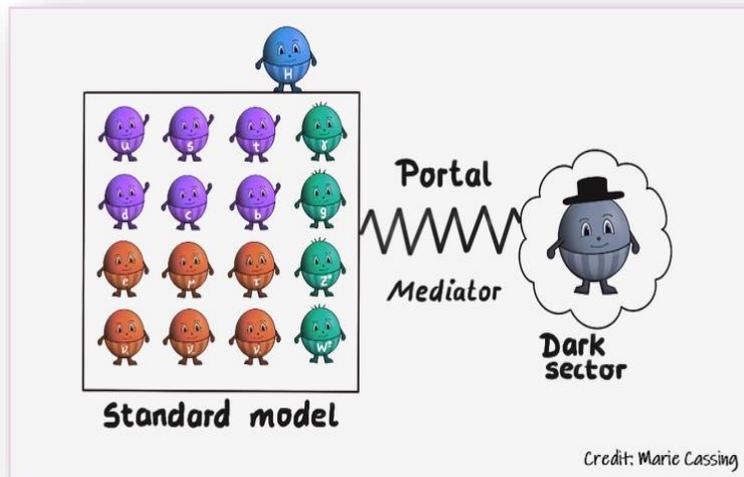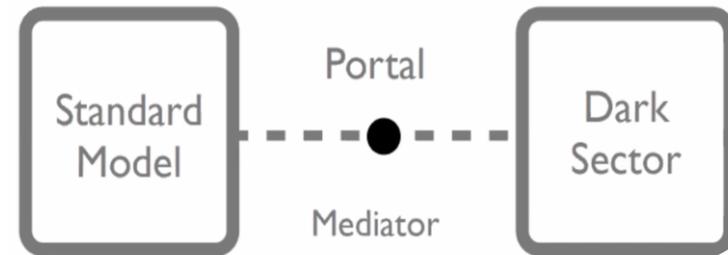ESA and the Planck Collaboration.

Dark Matter Detection

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

And M. Livio et al., 2014, J. Physics. *Nature* **507,** 29–31

Dark Matter Portals

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

Figure from Brian Battel

Credit: Marie Cassing

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

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

$$\mathcal{L}_U = -\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \boxed{\frac{\varepsilon}{2} B^{\mu\nu} F'_{\mu\nu}} - \frac{1}{2} m_U^2 A'^\mu A'_\mu$$

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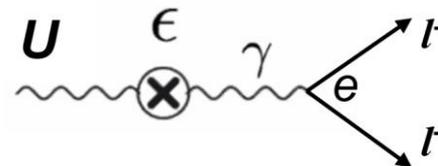B. Holdom, Phys. Lett. B 166, 196 (1986)

Dark photon field strength:

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

SM hypercharge field strength:

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

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

ε ➡ **Kinetic mixing parameter**

m_U ➡ **Dark photon mass**
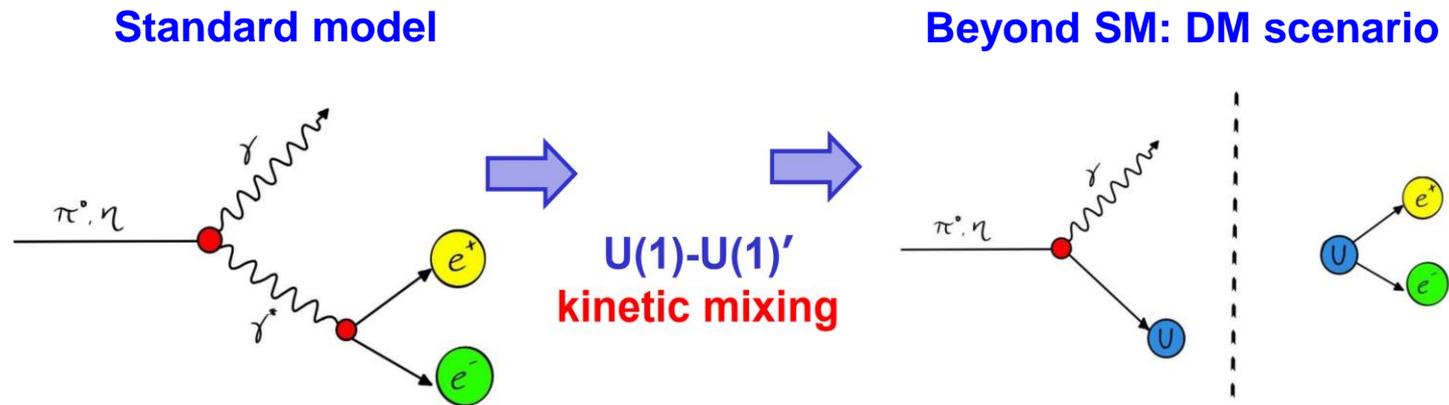

$\varepsilon^2 = \alpha'/\alpha$

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' or ' U- boson':** *A', V, U*
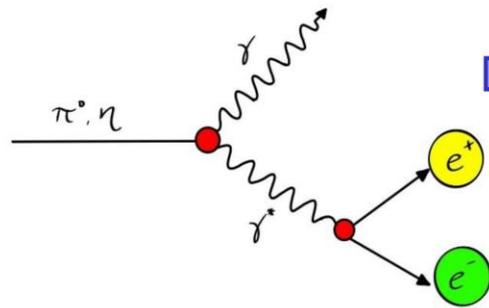
Dalitz decay of the dark photon to dileptons

❑ **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

Dalitz decay of the dark photon to dileptons

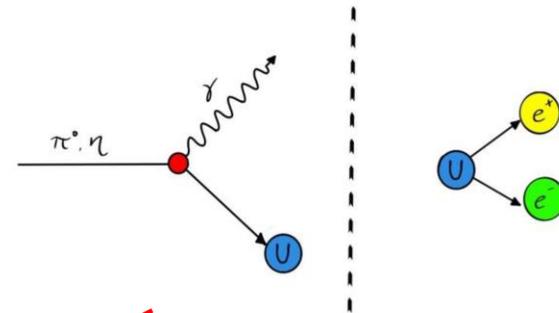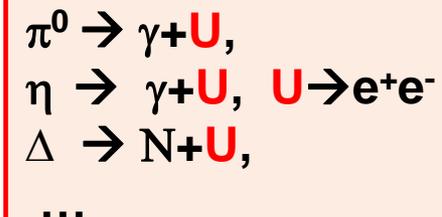☐ **Dalitz decays of pseudoscalar mesons π^0, η and Δ-resonances to dileptons via the U-boson mediator**
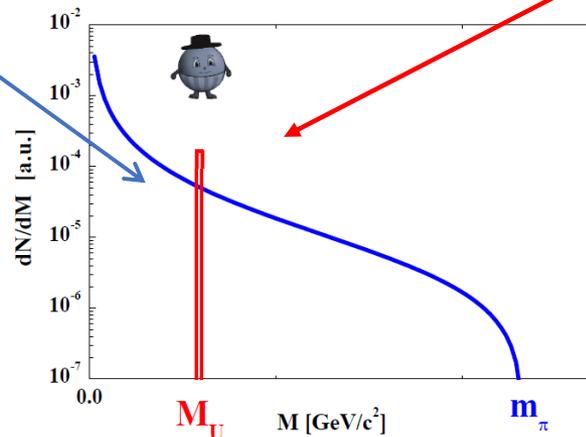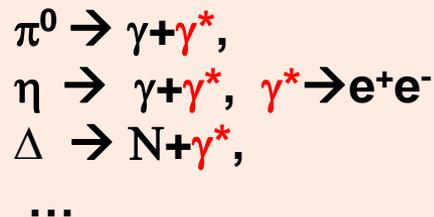

Standard model

Beyond SM: DM scenario

U(1)-U(1)'
kinetic mixing

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

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

M_U M [GeV/c²] m_π
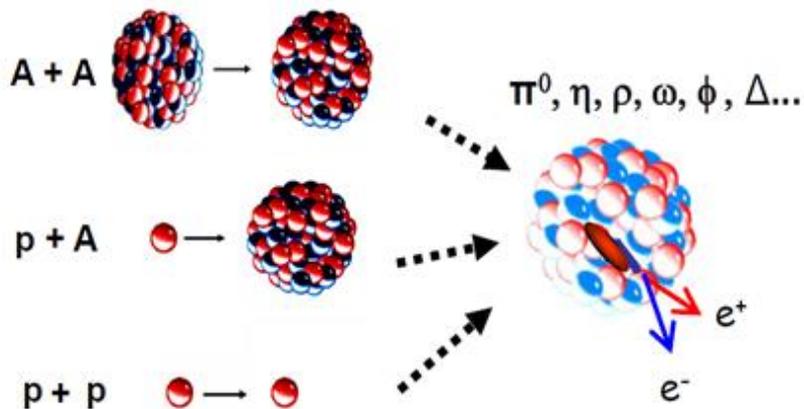
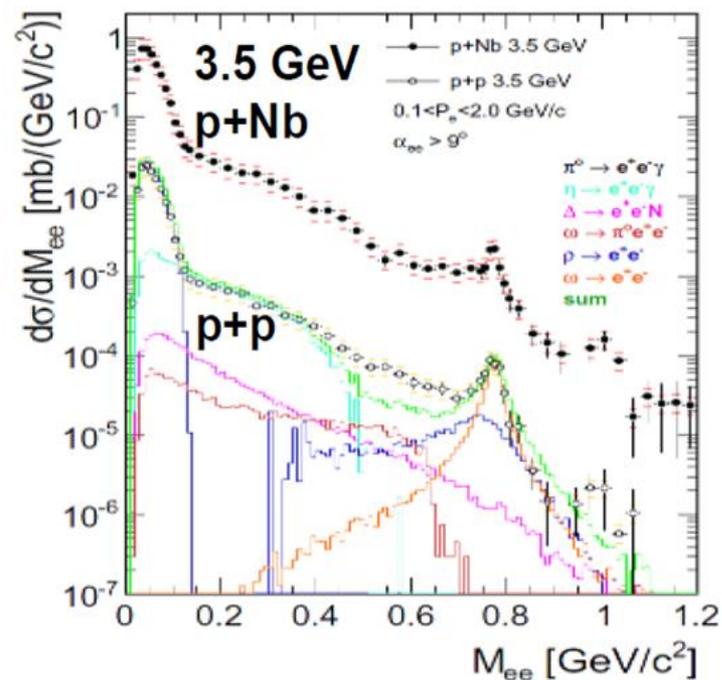B. Batell, M. Pospelov, and A. Ritz, PRD 80,095024 (2009)

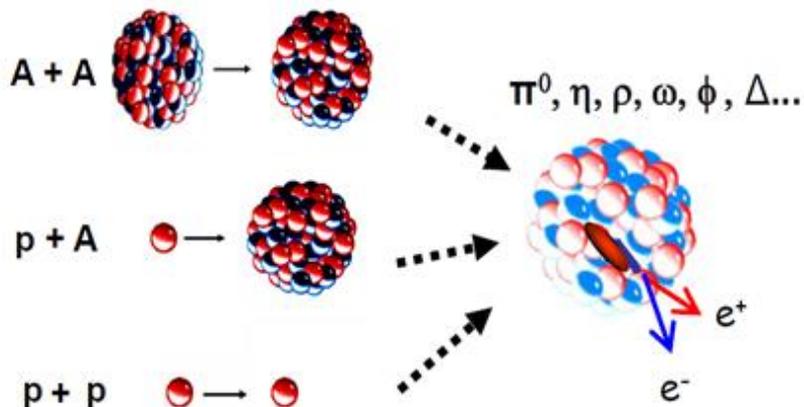# Possible dark photon observation by dilepton experiments

□ **Dilepton spectra from SM sources are well studied by dilepton experiments from SIS to LHC energies (HADES, STAR,…)**

□ **Hadron production by p+p, p+A, A+A**

□ **Dark photon production in hadronic decays by $\pi, \eta, \Delta, \omega, \phi, \rho, K, ...$ decays**

□ **Dalitz π^0, η and Δ decays are the dominant dilepton sources at low M**

Dilepton spectra at low M ('cocktail')

Possible dark photon observation by dilepton experiments

$\pi^0, \eta, \rho, \omega, \phi, \Delta...$

e^+
e^-

A + A
p + A
p + p

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❑ **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 $U \to e^+ e^-$ in heavy-ion experiments**

Dilepton spectra at low M ('cocktail')

3.5 GeV
p+Nb

p+Nb 3.5 GeV
p+p 3.5 GeV
$0.1 < P_e < 2.0$ GeV/c
$\alpha_{ee} > 9°$

$\pi^0 \to e^+ e^- \gamma$
$\eta \to e^+ e^- \gamma$
$\Delta \to e^+ e^- N$
$\omega \to \pi^0 e^+ e^-$
$\rho \to e^+ e^-$
$\omega \to e^+ e^-$
sum

p+p

$d\sigma/dM_{ee}$ [mb/(GeV/c^2)]

M_{ee} [GeV/c^2]

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 theoretical calculation of the 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
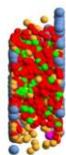
Dynamics: based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory
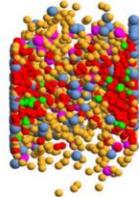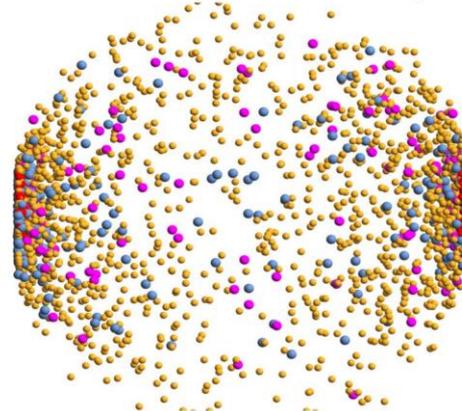
PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009)

Theoretical modeling of U-boson production

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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
200 GeV, b=2 fm

Quark Gluon Plasma: IQCD EoS. Non-perturbative QCD quasiparticles

Dynamical Hadronization

Hadronic interactions: Final hadrons+ leptons

- Baryons
- Antibaryons
- Mesons
- Quarks
- Gluons

➔ **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)

Dark photon production in PHSD

Dalitz Decay

$$\pi^0, \eta \to \gamma U$$
$$\Delta \to N U$$
$$\omega \to \pi^0 U$$
$$K^+ \to \pi^+ U$$

$$U \to e^+ e^-$$

Direct Decay

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

Dark photon production in PHSD

Production of hadron ➜ decay to U ➜ dilepton yield from U-boson decay of mass m_U:

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Direct Decay

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

$U \to e^+ e^-$

$$N^{U \to e^+ e^-} = \sum_{h=1}^{8} N_h^{U \to e^+ e^-}$$

$$h \to X + U$$

$$= Br^{U \to e^+ e^-} \times \sum_{h=1}^{8} N_{h \to XU}$$

$$N_{h \to XU} = N_h \, Br^{h \to XU}$$

Dark photon production in PHSD

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

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$$h \to X + U$$

$$N_{h \to XU} = N_h \, Br^{h \to XU}$$

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

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

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

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

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

Based on the model

B. Batel, et al. (2009) PRD 80, 095024

G. Agakishiev et al. (2014) PLB, 731, 265

I. Schmidt et al., PRD 104 (2021) 015008 as used in PHSD

D. Gorbunov et al. (2024) PLB, 852, 138599

M. Pospelov (2009) PRD 80, 095002

new channels in PHSD

B. Battel, et al. (2009) PRD 79, 115008

$$A(m_\Delta) \to Breit - Wiegner \, Func$$

Dark photon production in PHSD

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

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

J. Liu et al. JHEP 08, 050 (2015)

B. Batel, et al. (2009) PRD 80, 095024   I. Schmidt et al., PRD 104 (2021) 015008

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$$BR_{ee} \equiv BR_{U \to e^+ e^-} = \frac{\Gamma_{U \to e^+ e^-}}{\Gamma_{U \to e^+ e^-} + \Gamma_{U \to \mu^+ \mu^-} + \Gamma_{U \to hadron}}$$

J. Liu et al. JHEP 08, 050 (2015)

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

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

B. Batel, et al. (2009) PRD 80, 095024   I. Schmidt et al., PRD 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)

$$\frac{dN^{sumU}}{dM} = \sum_{h=1}^{8} \frac{dN_h^{U \to e^+ e^-}}{dM}$$

$$\frac{dN^{sumU}}{dM} = \varepsilon^2 \frac{dN_{\varepsilon^2=1}^{sumU}}{dM} \qquad (1)$$

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

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

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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.**

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

➡ **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

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

Dilepton mass spectra | Au+Au, 200 GeV, min-bias

Dilepton mass spectra | Au+Au, 200 GeV, min-bias

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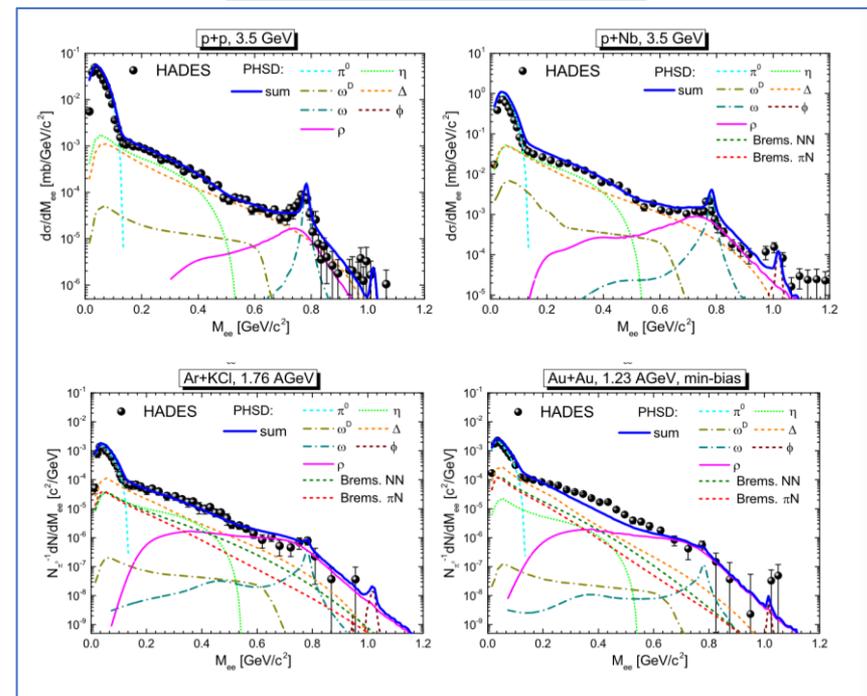
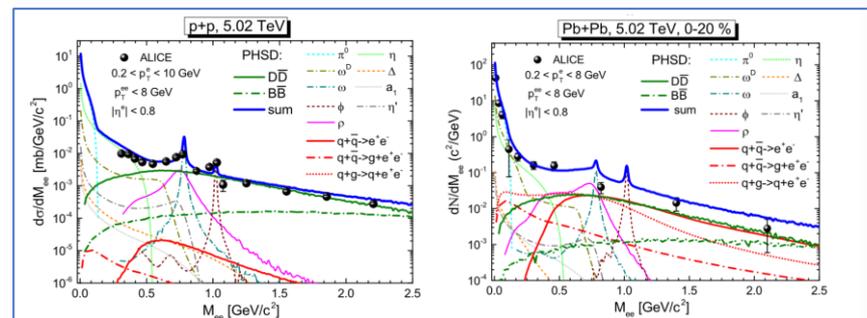# Dilepton spectra from PHSD from SIS18 to RHIC energies
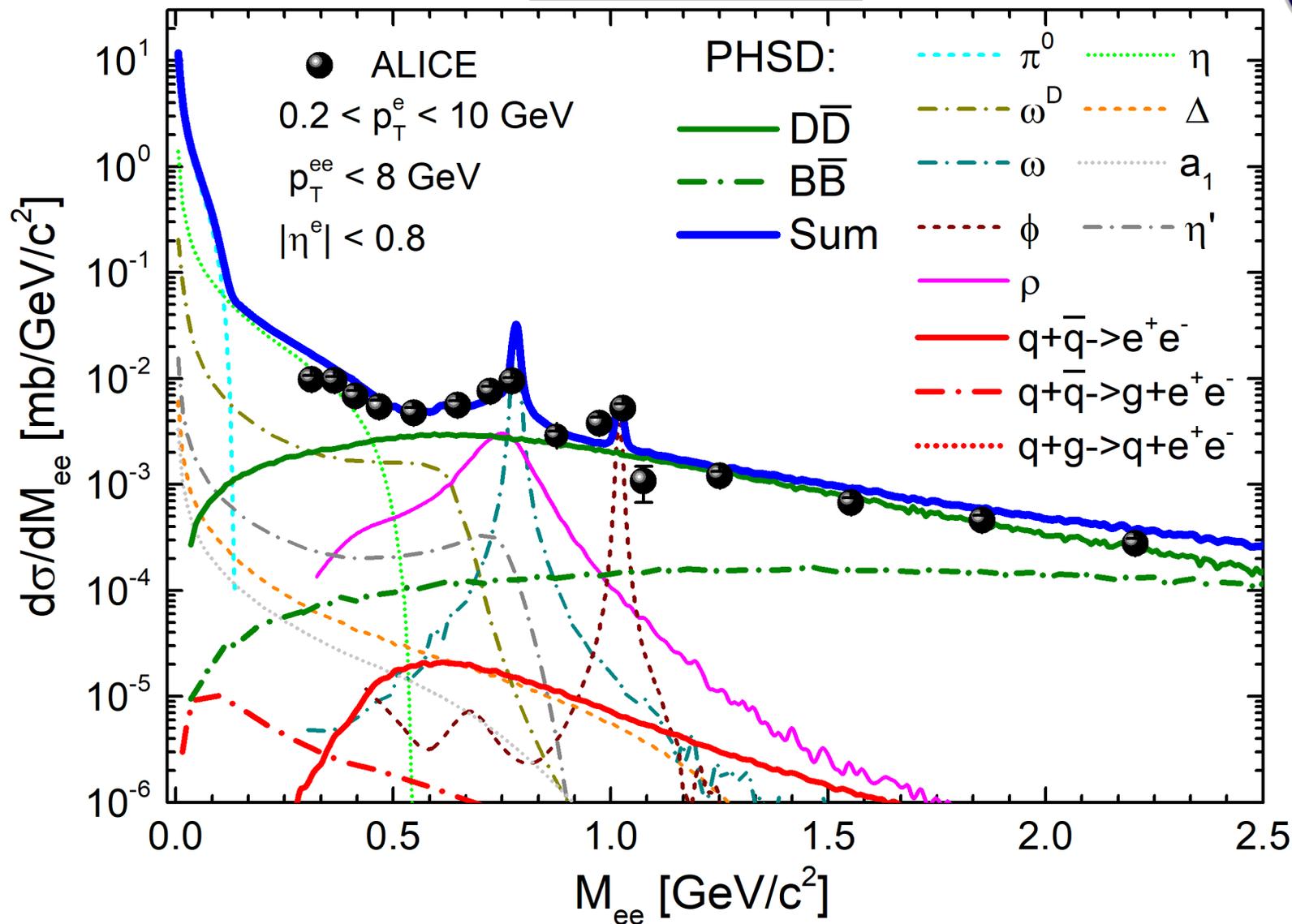
BES-LHC-STAR

SIS18-HADES

ALICE

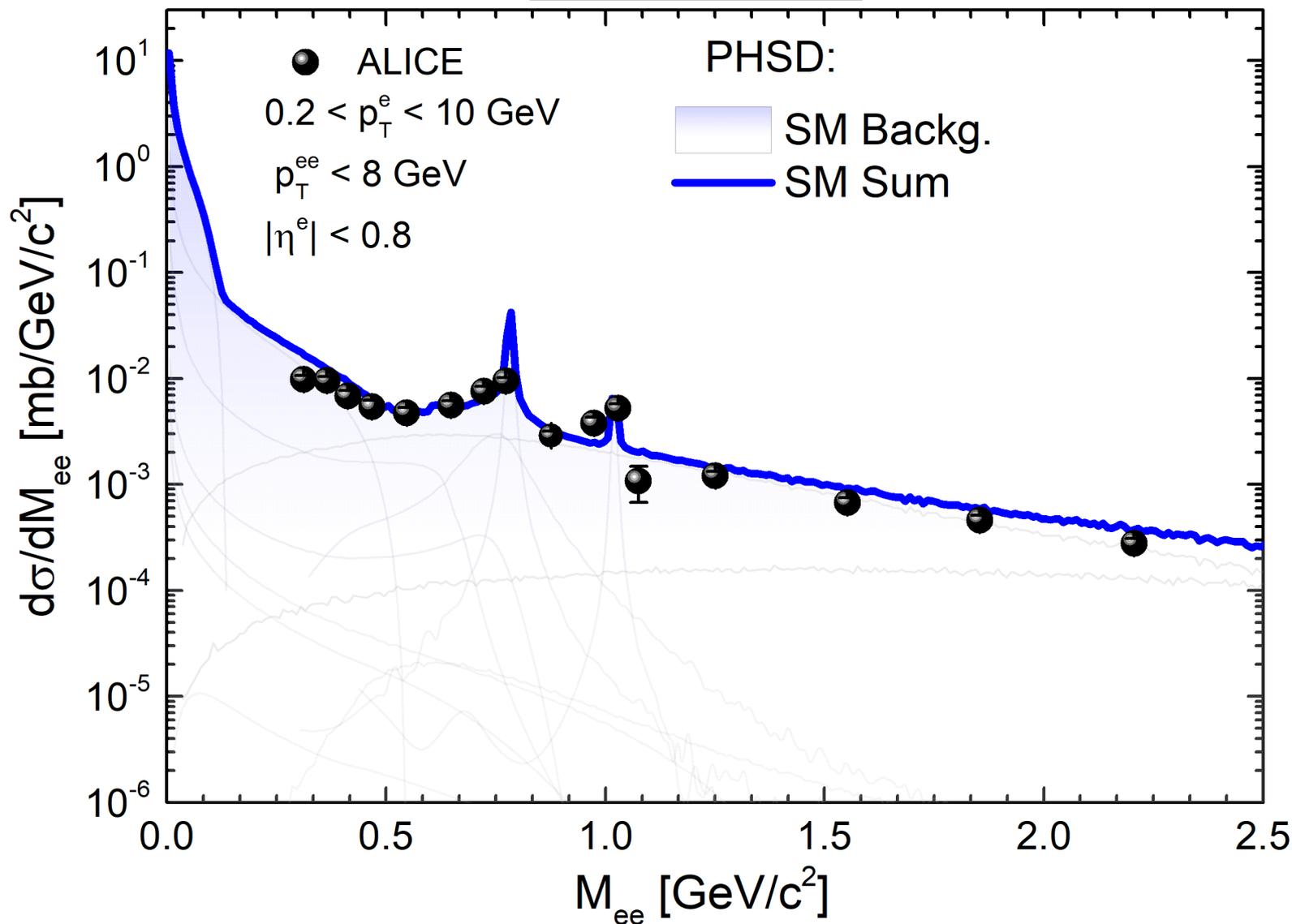- **The STAR/HADES/ALICE data, i.e. SM contributions (including exp. acceptance) are well described by the PHSD**

Dilepton mass spectra

p+p, 5.02 TeV

Dilepton mass spectra

p+p, 5.02 TeV

Dilepton mass spectra
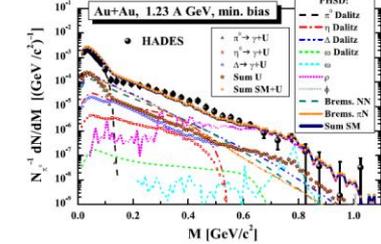
Dilepton mass spectra

p+p, 5.02 TeV

Dilepton mass spectra

p+p, 5.02 TeV

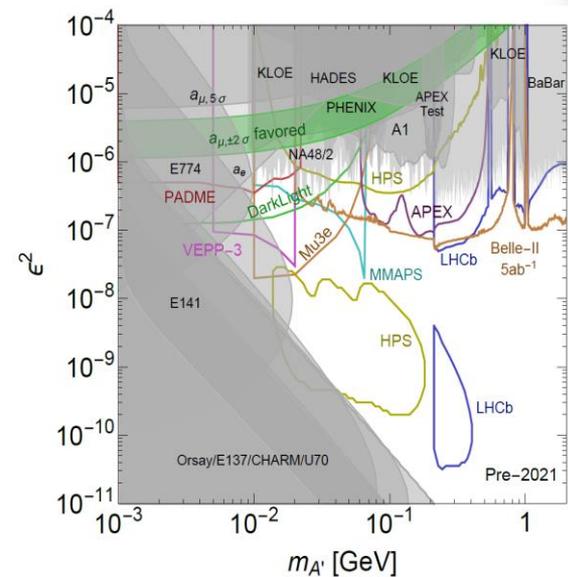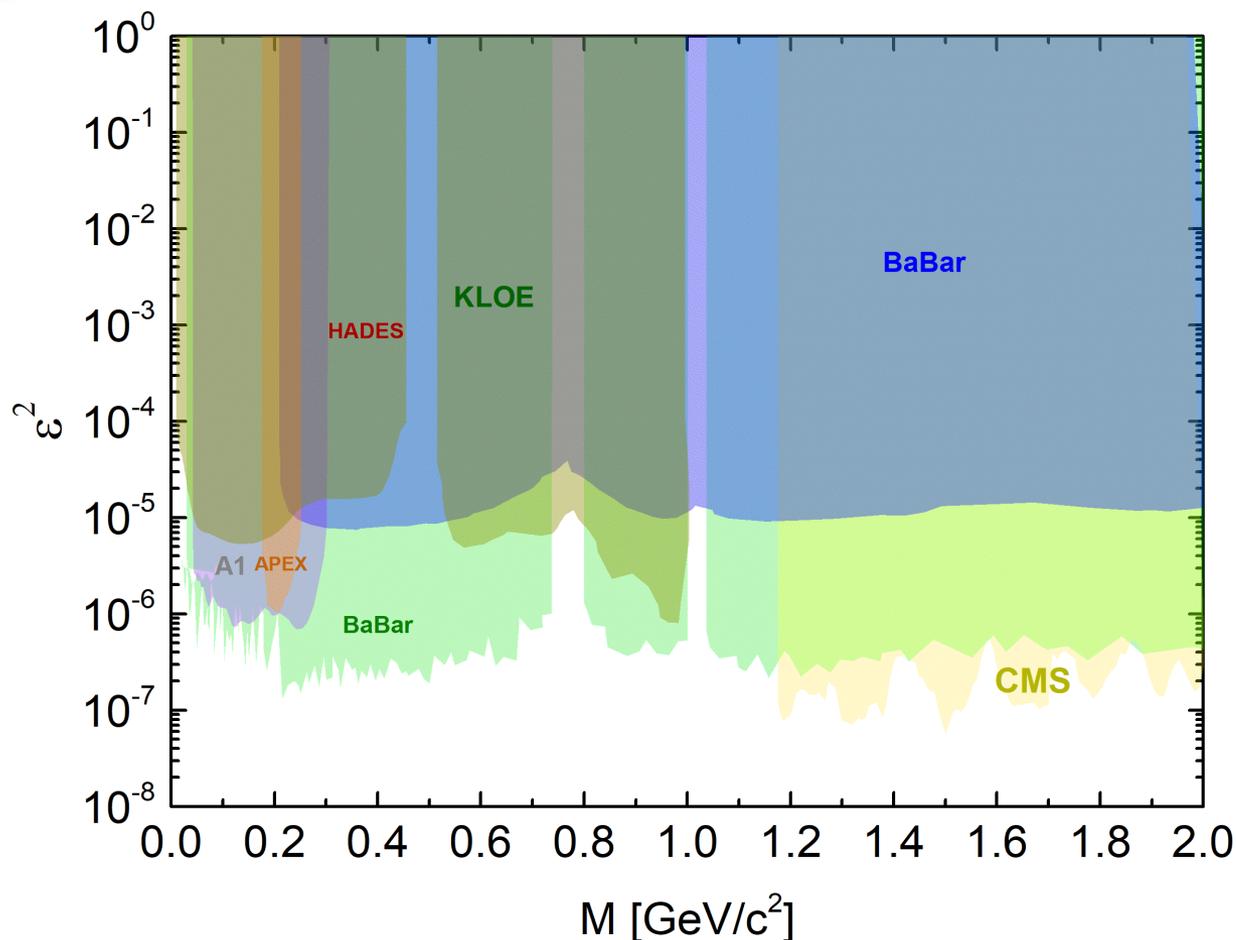# Dilepton spectra from U-boson decays

Dark Photon Channels

- **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**

I. Schmidt et al., PRD 104 (2021) 015008

Kinetic Mixing parameter $\varepsilon^2(M_U)$

The upper limit for the kinetic mixing parameter $\varepsilon^2(M_U)$ of 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

Kinetic Mixing parameter $\varepsilon^2(M_U)$

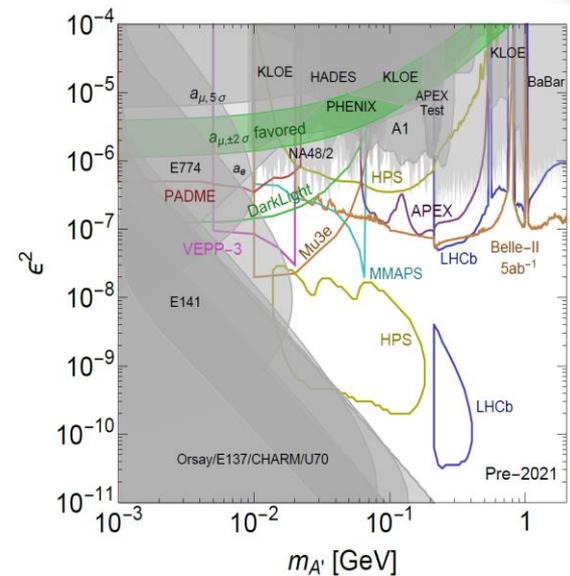**The upper limit for the kinetic mixing parameter $\varepsilon^2(M_U)$ of dark photons extracted from the PHSD dilepton spectra - with C_U allowed surplus of the total SM yield**

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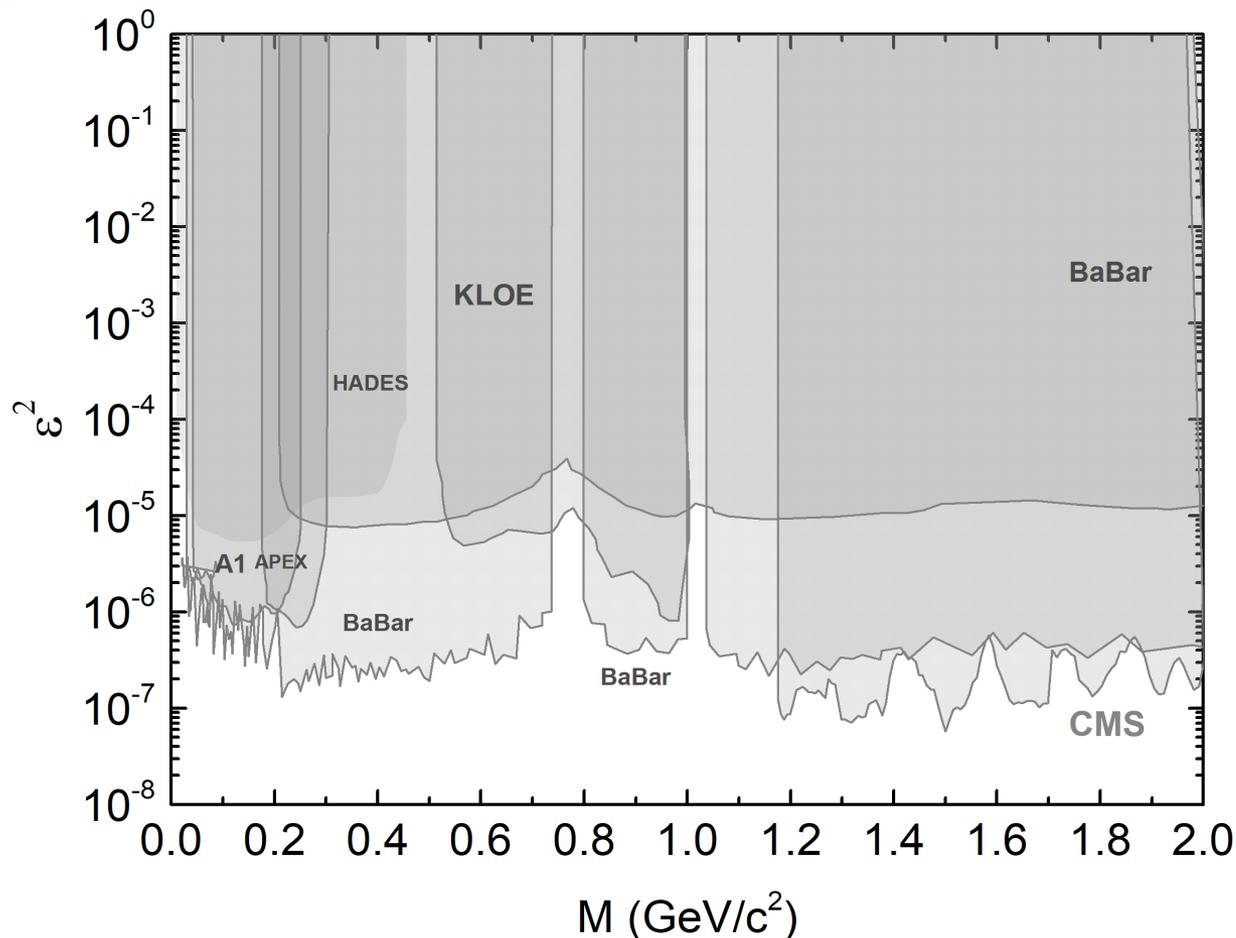
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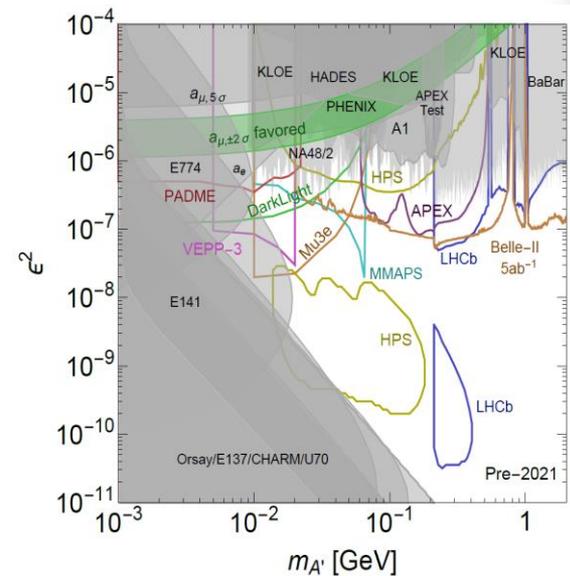

J. Alexander et al. (2016), 1608.08632

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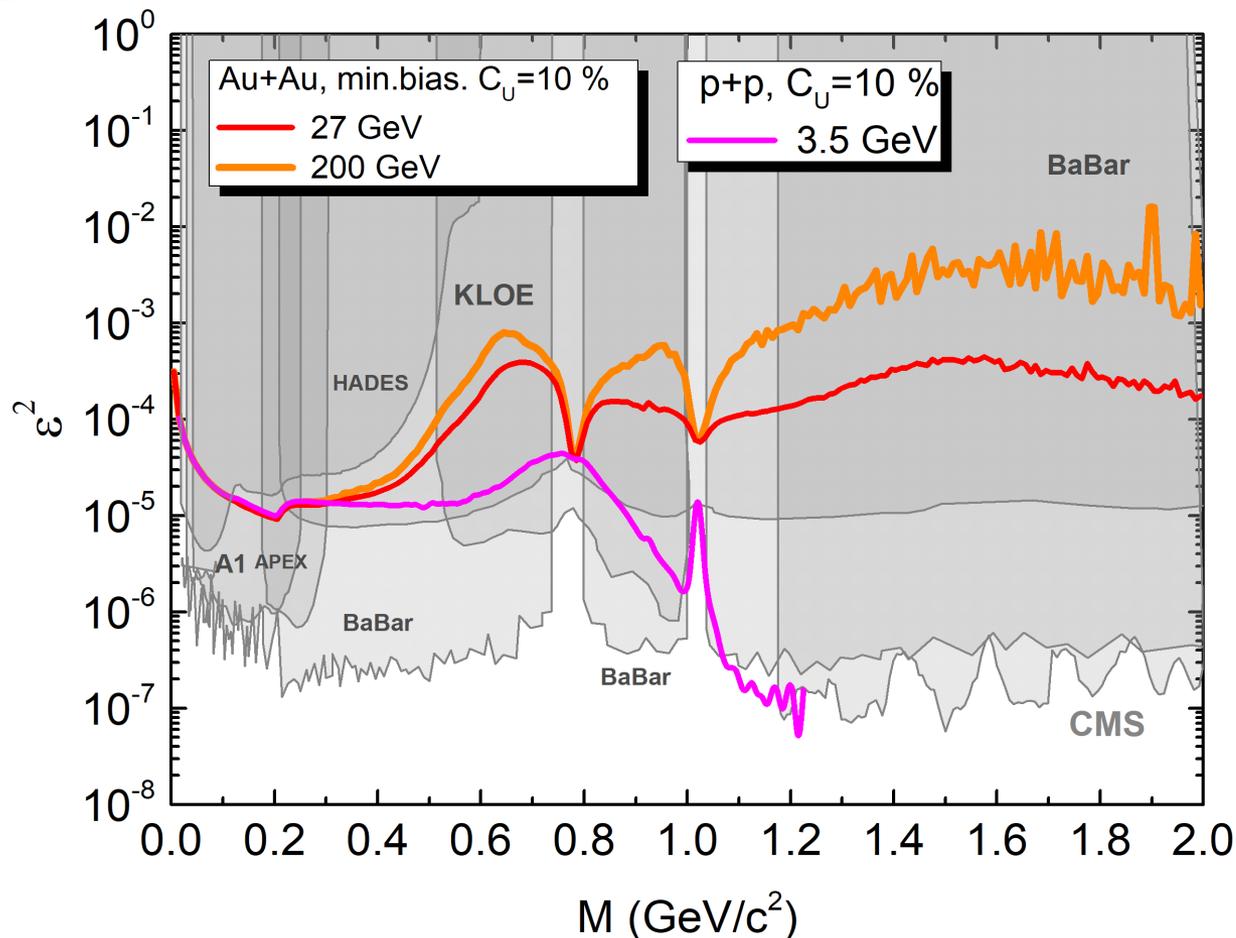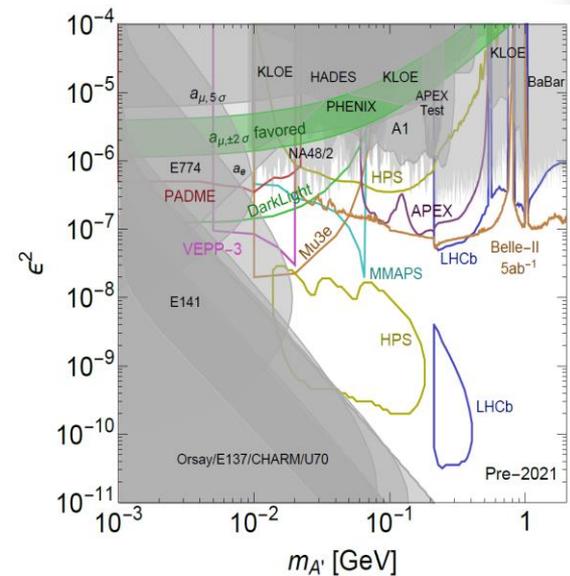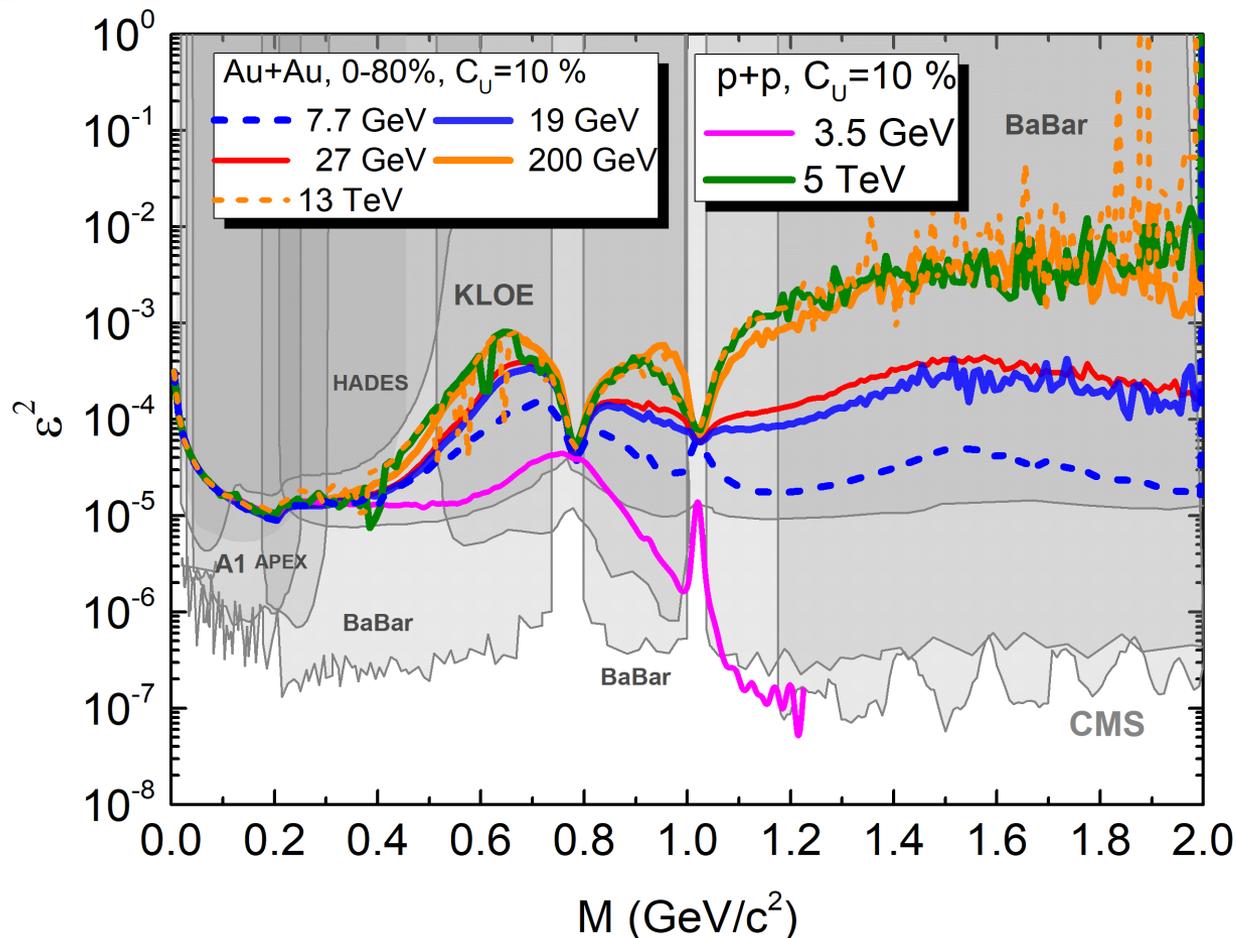

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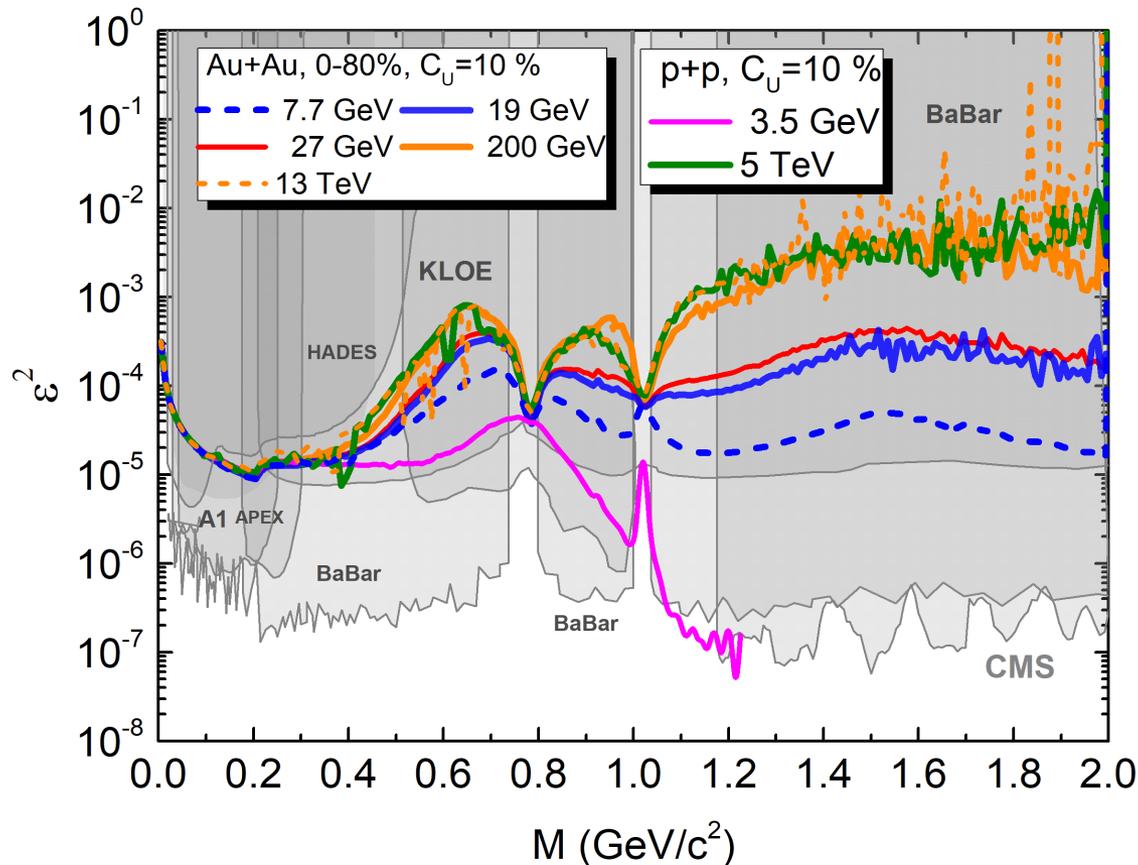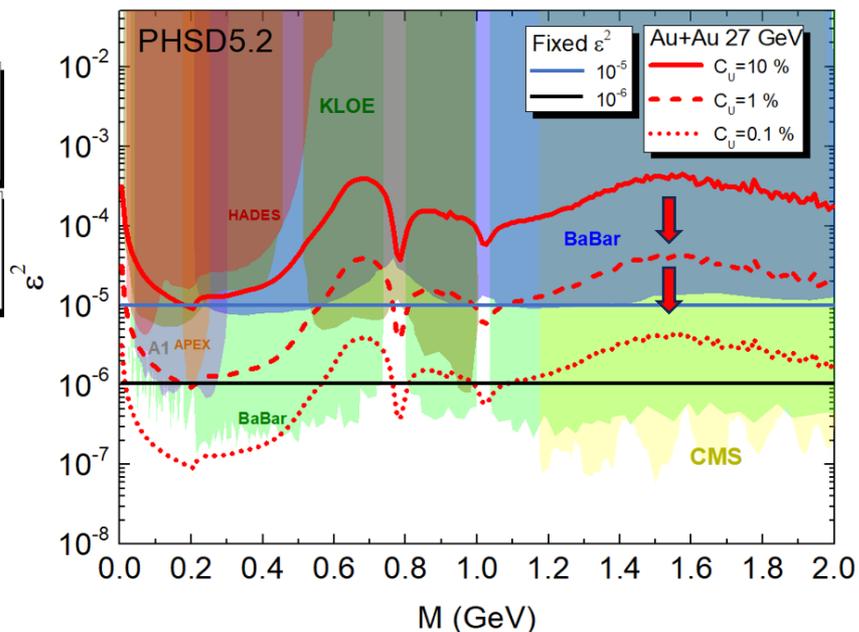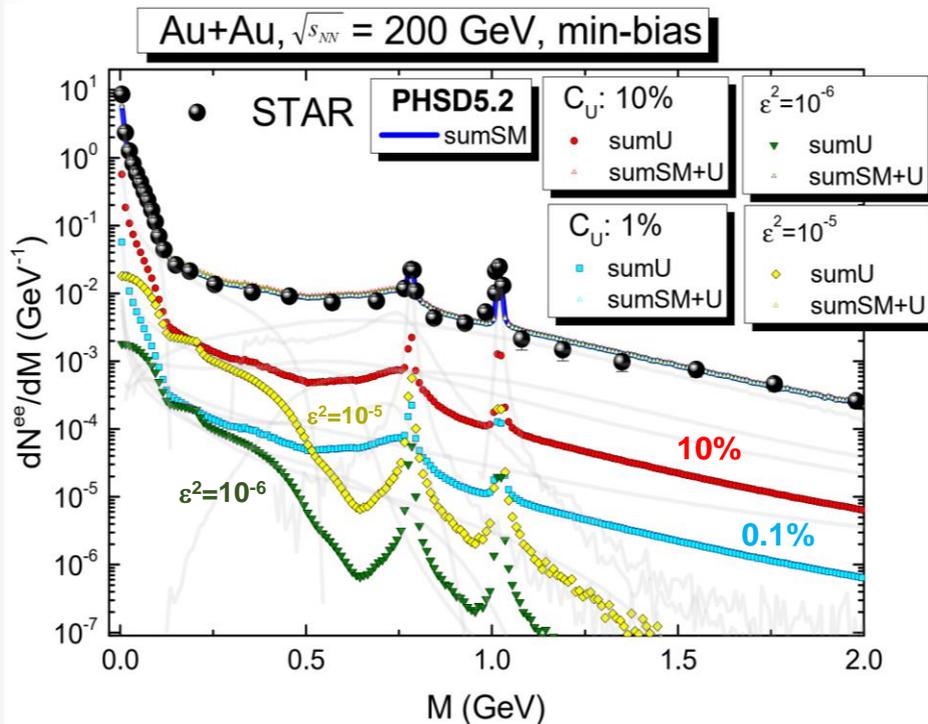

$\varepsilon^2(m_U)$ **for $C_U = 10\%$ is consistent with the exp. data from**
BaBar (0.2 < m_U < 0.9 GeV)
KLOE (0.2 < m_U < 1 GeV)

Experimental data of high precision are needed to reduce the upper limit for ε^2

Limits for the mixing parameter ε²(m_U)

❑ **The PHSD predictions for** $\varepsilon^2(m_U)$ **with 1% and 10% allowed surplus of the U-boson contributions over the total SM yield and fixed** $\varepsilon^2(m_U) = 10^{-5}$ **and** 10^{-6}

A1 (0.01 < m_U < 0.3 GeV)   **Au+Au 27 GeV for** $C_U = 1\%$

The theoretically extracted upper limit of the kinetic mixing parameter ε²(m_U) of light dark photons from dark photon decays:
- **strongly reduces by lowering the allowed 'surplus'**
➔ **exp. data of high precision are needed to reduce the upper limit for ε²(M_U)**

Summary

- ❑ **We presented 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 and A + A collisions from SIS18 up to RHIC energies**

- ❑ **For that we incorporated in the PHSD the production of U-bosons by the Dalitz decay of $\pi^0, \eta \to \gamma U, \Delta \to N U, \omega \to \pi^0 U, K^+ \to \pi^+ U$ and the direct decay of $\rho, \phi, \omega \to U$ with further dilepton decays $U \to e^+ e^-$, 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 BaBar, KLOE experiment between 0.2 < m_U < 1 GeV with $C_U = 10\%$ and A1 exp. for 0.01 < m_U < 0.3 GeV with $C_U = 1\%$, 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**

➜ **Perspectives:**

- ▪ Include dark photon decays from other possible channels
- ▪ Explore the axion portal

- ▪ Look for constraints in astrophysics and cosmology

Thanks to the Organizers !

Thank you for your attention !