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Search for dark photons in heavy-ion collisions

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

FIAS Frankfurt Institute for Advanced Studies

CARLO & KARIN GIERSCH STIFTUNG

CRC-TR 211 Strong-interaction matter under extreme conditions

HFHF Helmholtz Forschungsakademie Hessen für FAIR

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

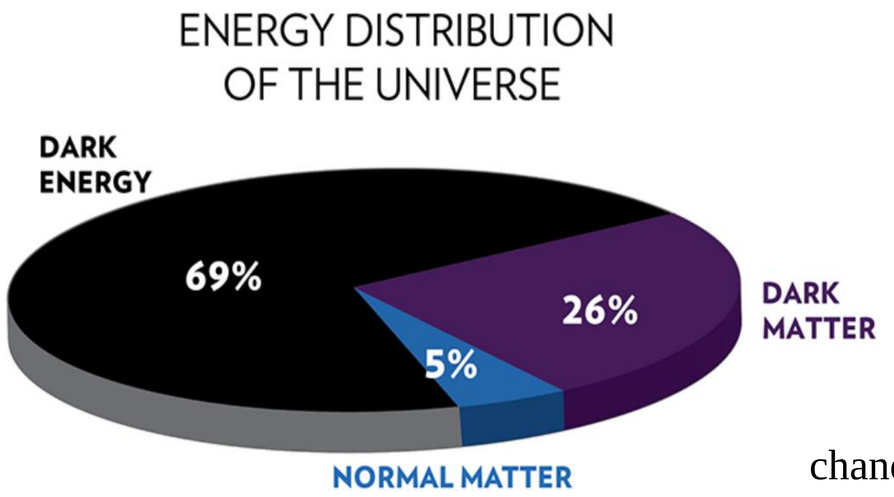
DARK MATTER LAB

Structure of Universe

- Dark matter (DM) ~26%

- DM detected by astrophysical observations based on gravitational effects:

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



chandra.harvard.edu

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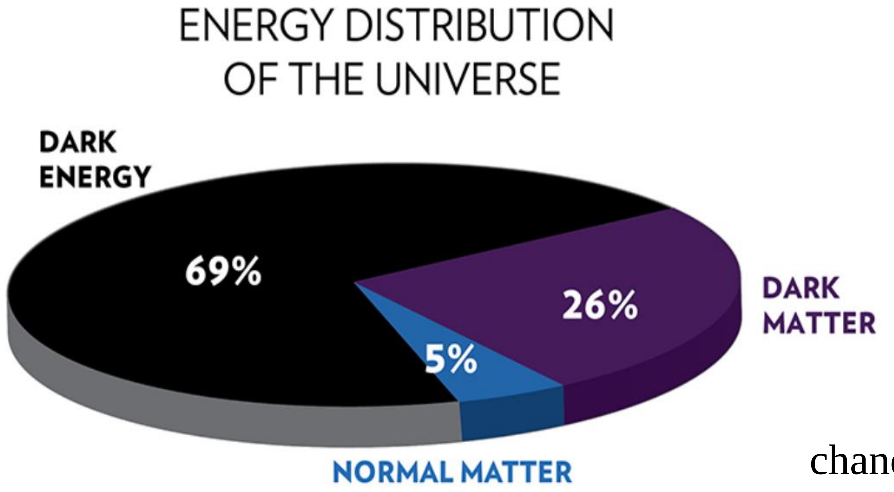

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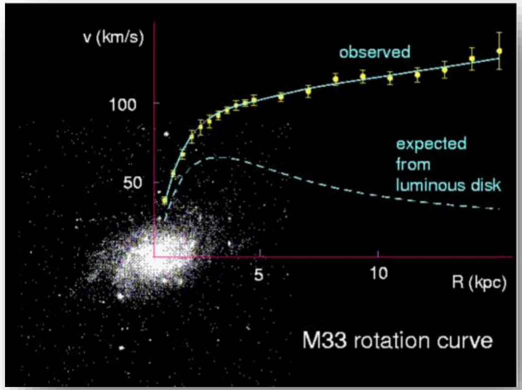
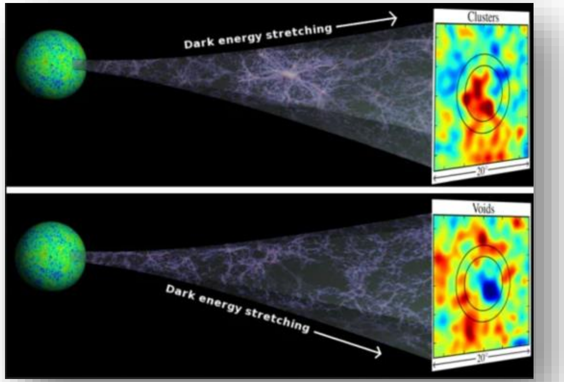
Galaxy Rotation Curves



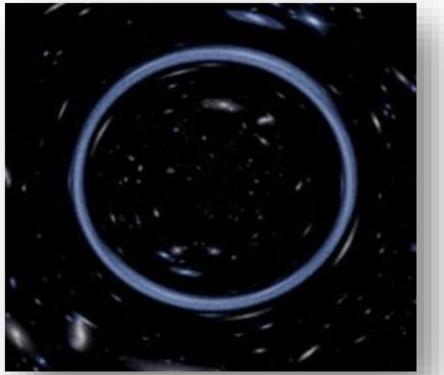
arxiv.org/abs/physics/0007025

Structure Formation



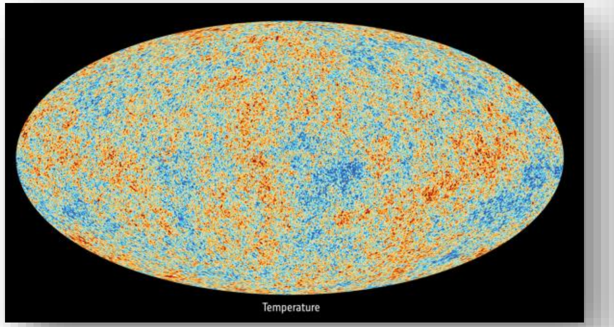
Granett, Neyrinck, Szapudi

Gravitational lensing



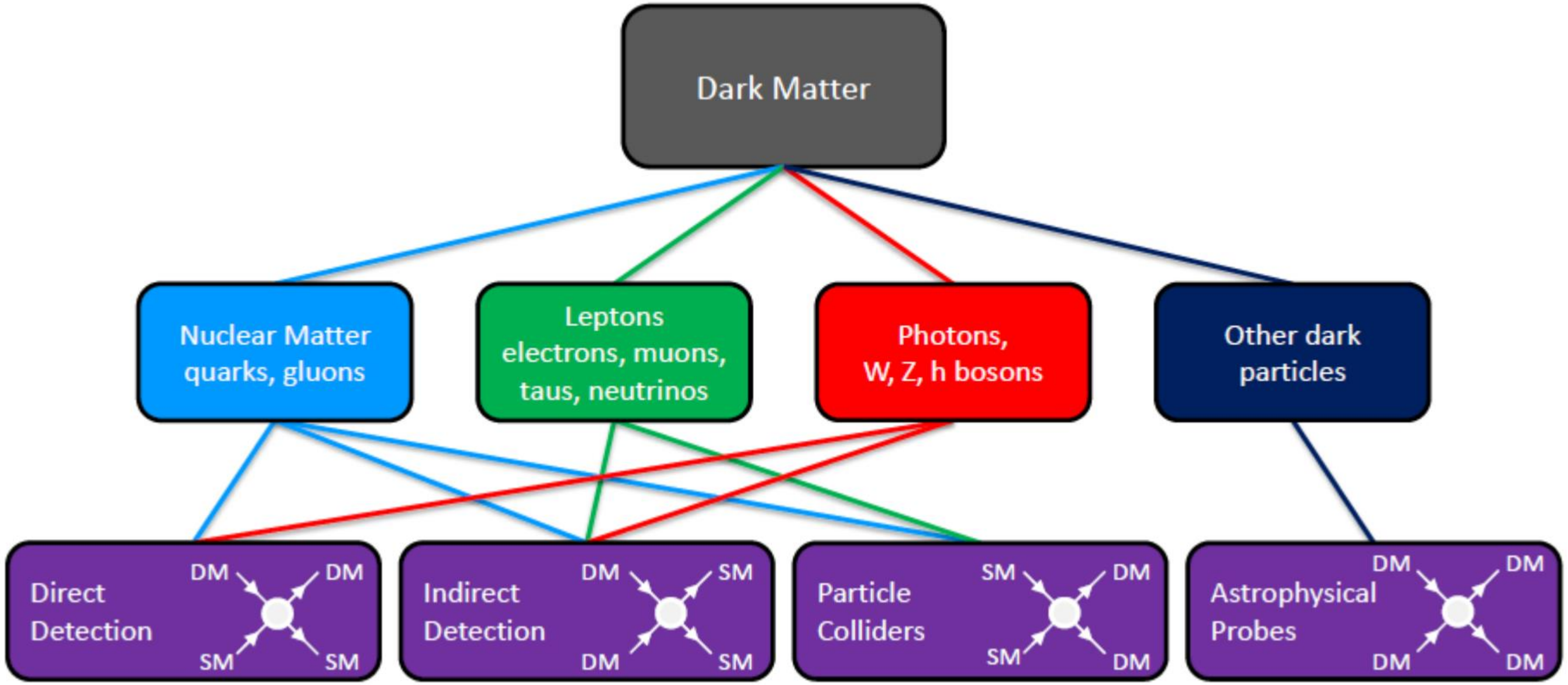
NASA

CMB



ESA and the Planck Collaboration.

Dark Matter Detection



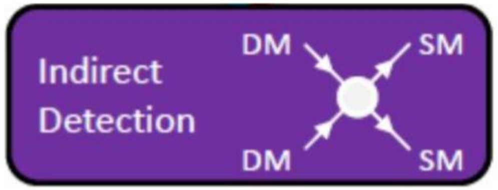
	Recoil Energy of a collision Atom-DM	DM Decays into SM	SM Decays into DM	DM Scattering
Experiments	LUX,CoGeNT, DAMA/LIBRA	CTA,HESS,AMS, PAMELA	LHC	Star and galaxy, helioseismology

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



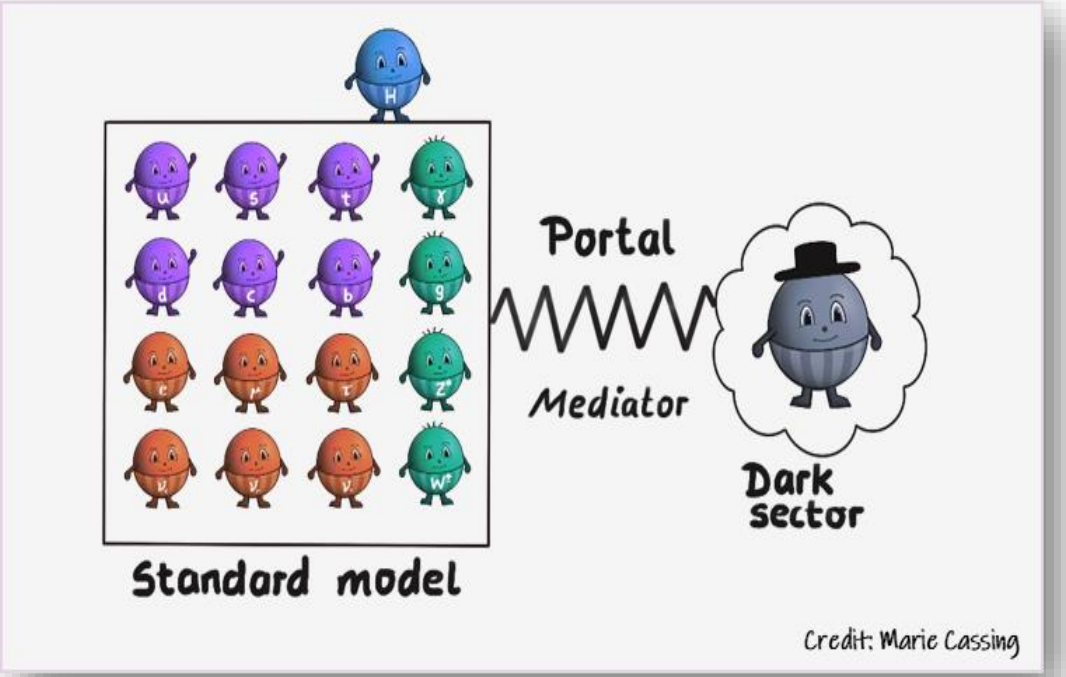
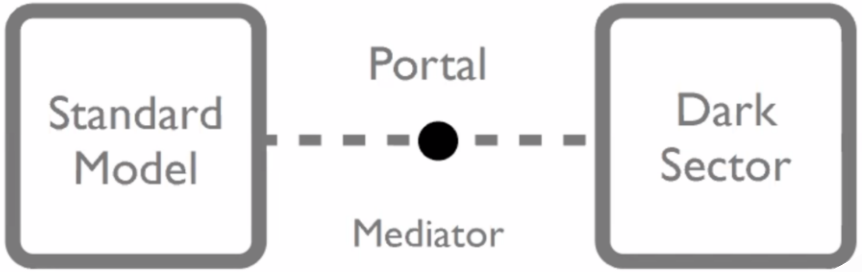


Figure from Brian Battel



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

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)

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

Dark photon field strength:

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

SM hypercharge field strength:

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

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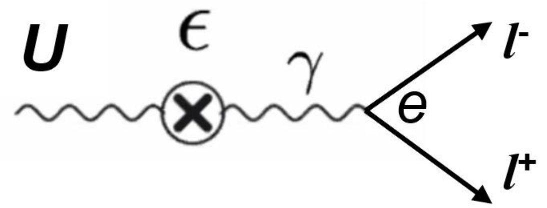
ε ➡ **Kinetic mixing parameter**

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

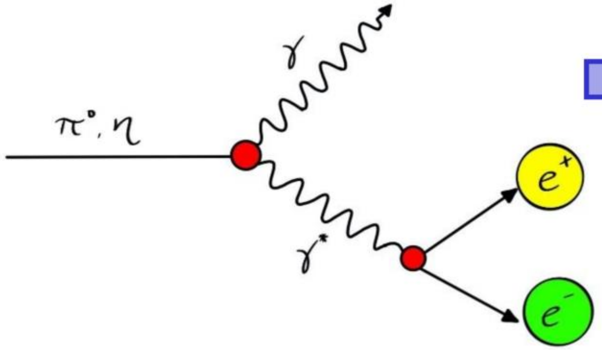
Unknown: kinetic mixing parameter ε **and mass** m_U

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

Dalitz decay of the dark photon to dileptons

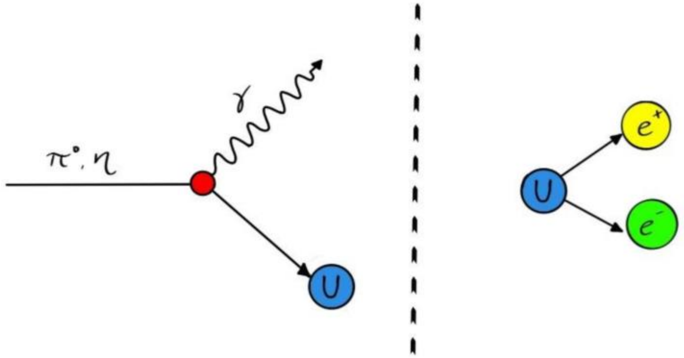
- Dalitz decays of pseudoscalar mesons π^0,η and Δ-resonances to dileptons via the U-boson mediator

Standard model



U(1)-U(1)′ kinetic mixing

Beyond SM: DM scenario



B. Batell, M. Pospelov, and A. Ritz, PRD 80,095024 (2009)

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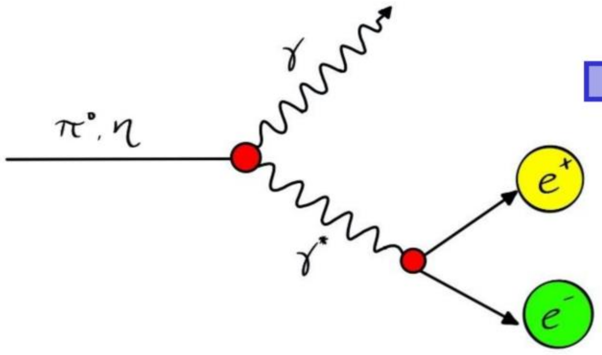

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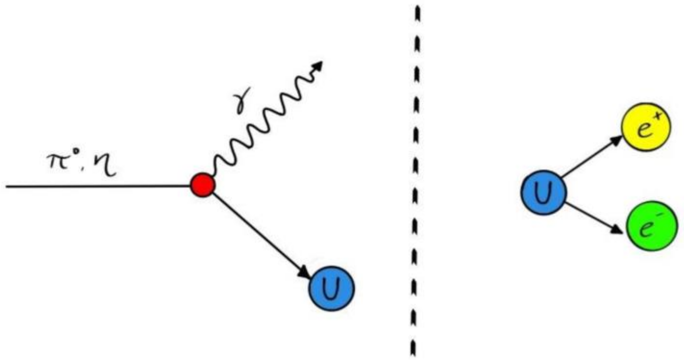
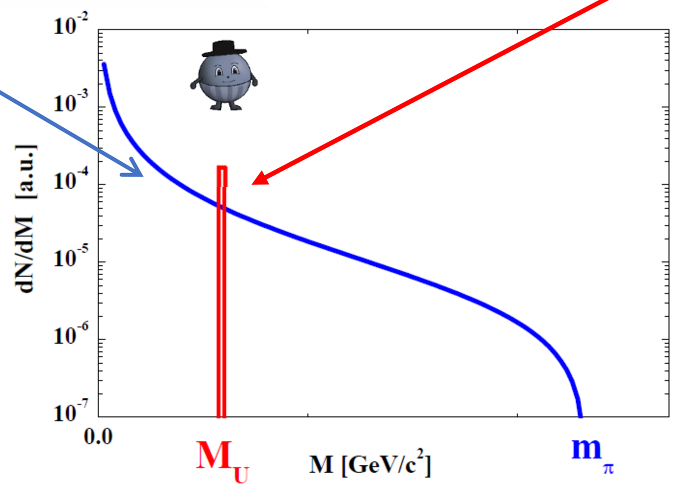


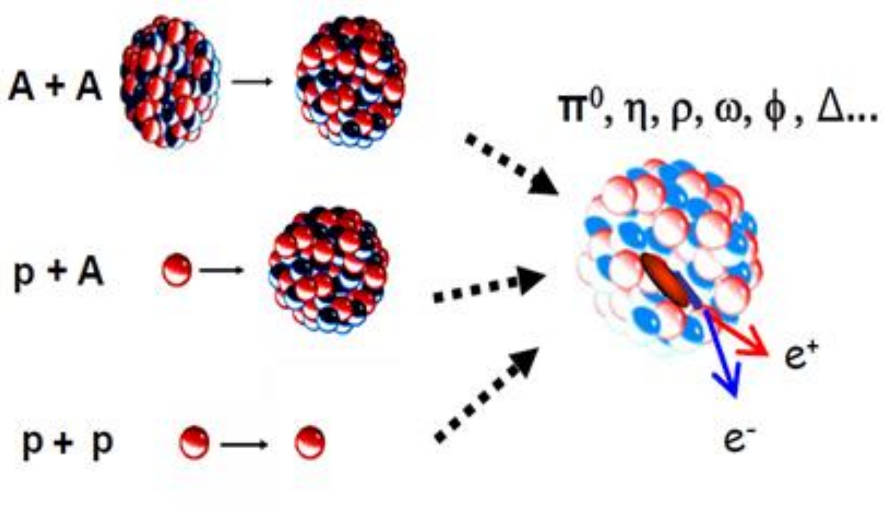
$\pi^0 \rightarrow \gamma + \gamma^*$,
$\eta \rightarrow \gamma + \gamma^*$, $\gamma^* \rightarrow e^+e^-$
$\Delta \rightarrow N + \gamma^*$,
…



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

B. Batell, M. Pospelov, and A. Ritz, PRD 80,095024 (2009)

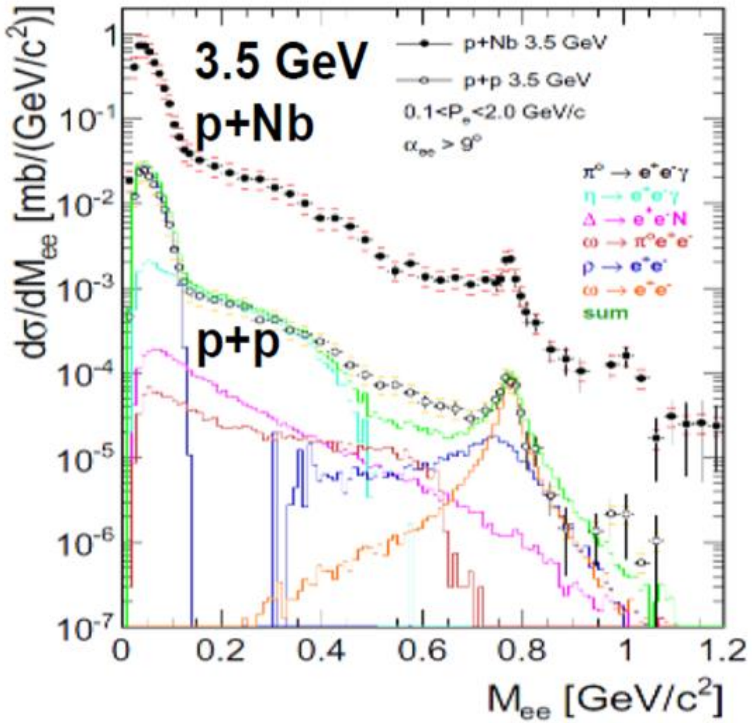
Possible dark photon observation by dilepton experiments



- Hadron production by p+p, p+A, A+A
- Dark photon production in hadronic decays by $\pi, \eta, \Delta, \omega, \phi, \rho, K, \ldots$ decays

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

Dilepton spectra at low M ('cocktail')



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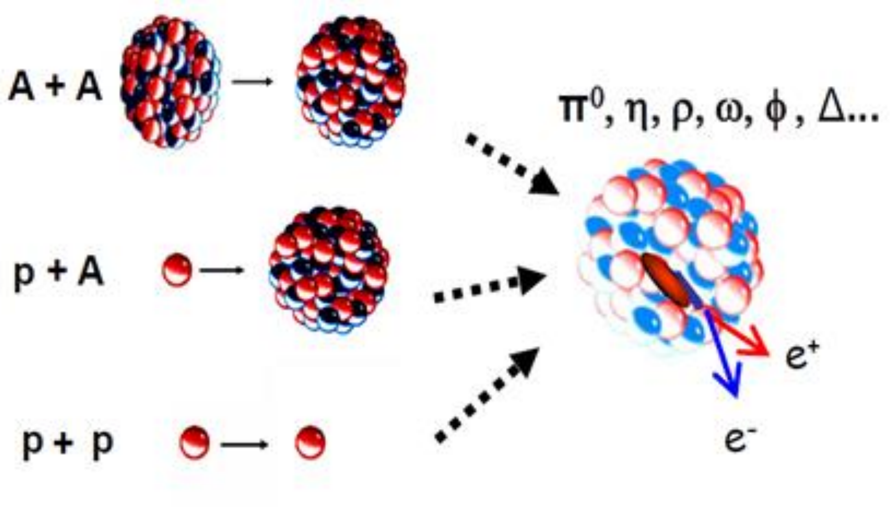
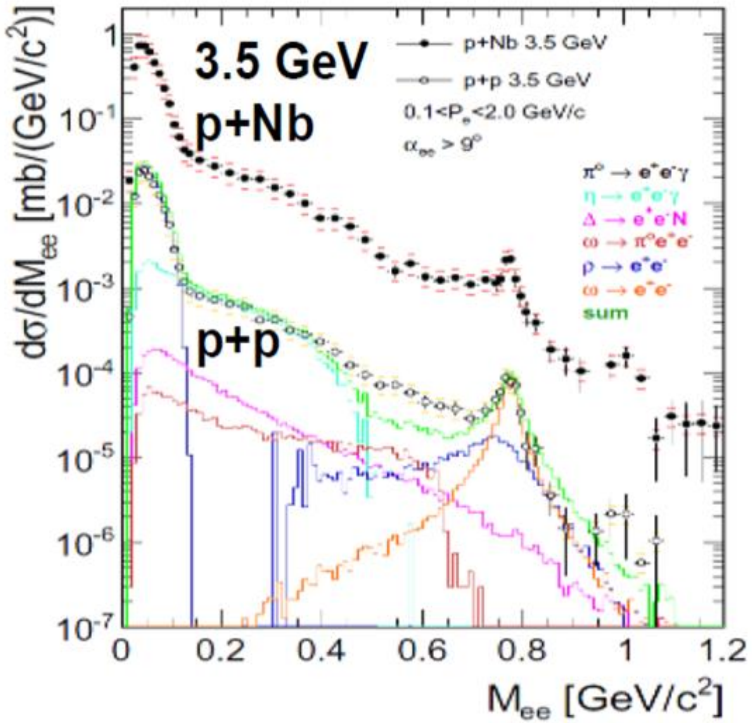


- Hadron production by p+p, p+A, A+A
- Dark photon production in hadronic decays by $\pi, \eta, \Delta, \omega, \phi, \rho, K, \ldots$ decays
- Dalitz π^0,η and Δ decays are the dominant dilepton sources at low M

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

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

Dilepton spectra at low M ('cocktail')



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

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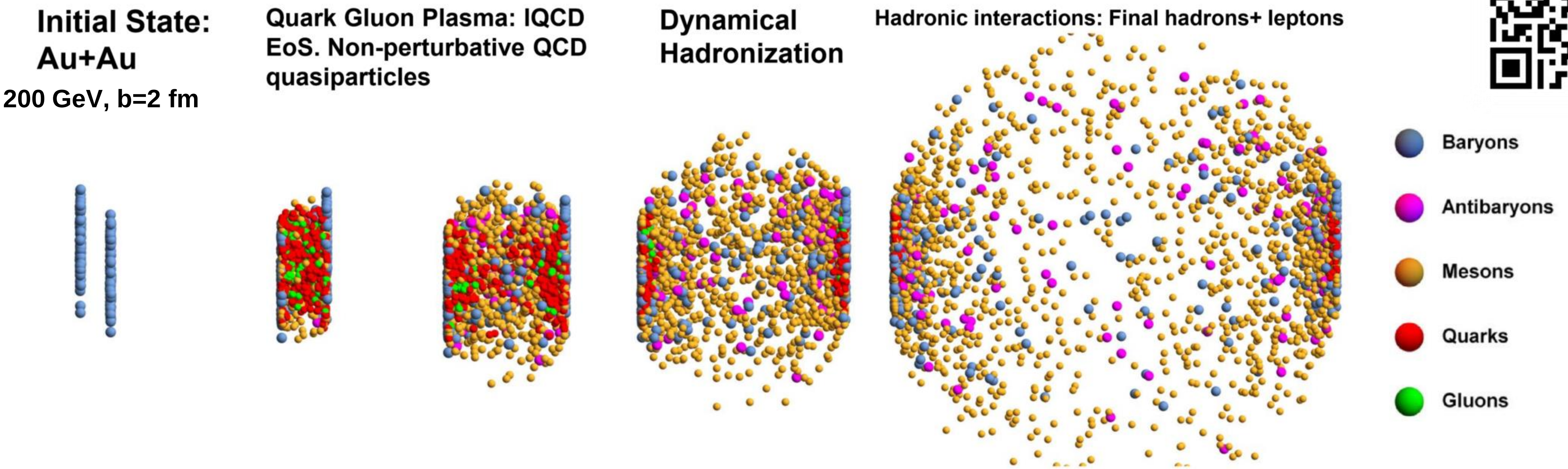

➔ **PHSD** provides a good description of 'bulk' hadronic observables as well as dilepton spectra from SIS to LHC energies

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

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

Direct Decay

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

$$U \rightarrow e^+ e^-$$

Dark photon production in PHSD

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Direct Decay

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

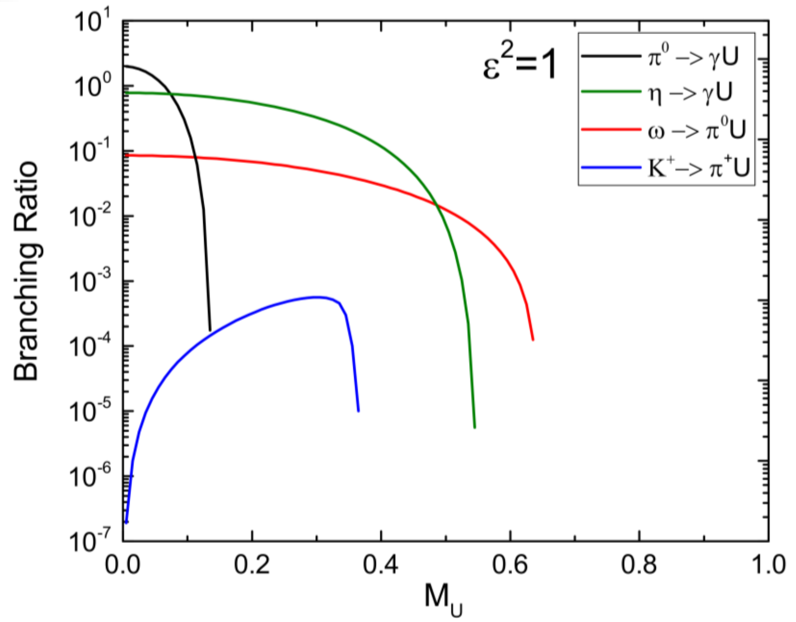
Production of hadron ➔ decay to U ➔ dilepton yield from U-boson decay of mass m_U:

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

$$= Br^{U\to e^+e^-} \times (N_{\pi^0\to\gamma U} + N_{\eta\to\gamma U} + \dots + N_{\omega\to U})$$

$U \to e^+e^-$

$$N_{A\to BU} = N_A\, Br^{A\to BU}$$



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

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

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

$$Br(\omega\to\pi^0 U) = \varepsilon^2 Br(\omega\to\pi^0\gamma)\frac{[(m_\omega^2-(m_U+m_\pi))(m_\omega^2-(m_U-m_\pi))]^{3/2}}{(m_\omega^2-m_\pi^2)^3}$$ → D. Gorbunov et al. (2024) PLB, 852, 138599

$$Br(K^+\to\pi^+ U) = \frac{\alpha\varepsilon^2}{\pi^2\,\Gamma_T(K)}\frac{m_U}{m_K}W'(m_U)\lambda^{1/2}(m_U,m_k,m_\pi)$$ → M. Pospelov (2009) PRD 80, 095002

$$Br(V\to U) = \frac{\alpha\varepsilon^2 m_U}{3\Gamma_T(V)} \qquad V=\rho,\phi,\omega$$ → B. Battel , et al. (2009) PRD 79, 115008

new channels in PHSD

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

Dark photon production in PHSD

Dalitz Decay

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

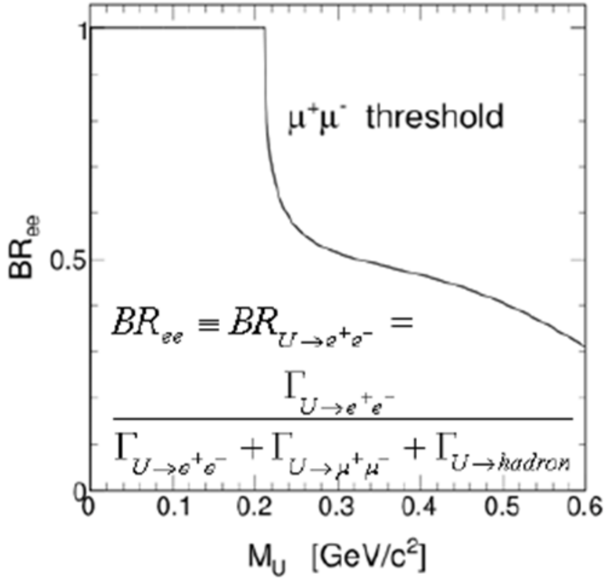
Direct Decay

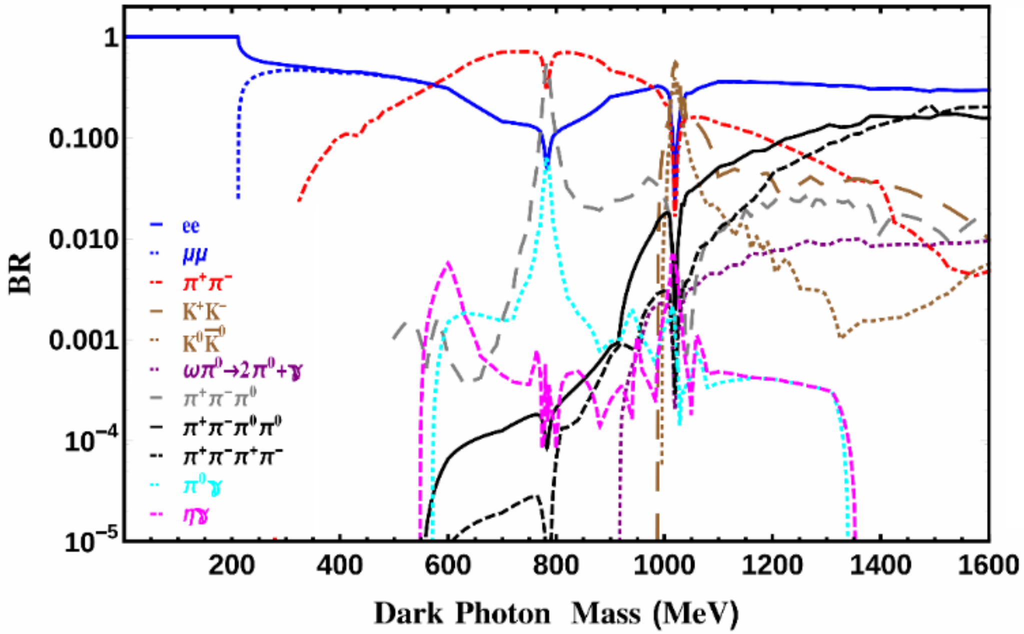
$$\rho, \phi, \omega \to U$$

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

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)

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

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

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)

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

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

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

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

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

PHSD

1) For each bin $[m_U, m_U + dm]$ calculate the sum of all $U \to e^+e^-$ contributions (kinematically possible in this mass bin)

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

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

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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.

$$(3) \qquad \frac{dN^{total}}{dM} = (1 + C_U) \frac{dN^{sumSM}}{dM}$$

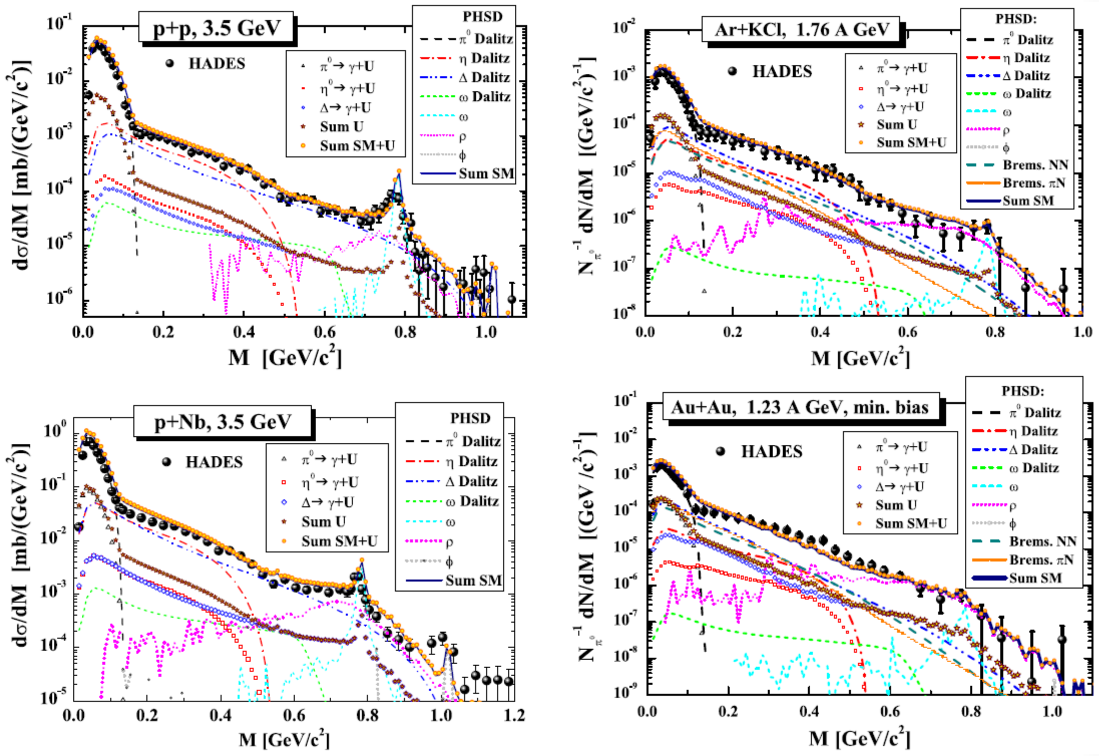
→ C_U controls the allowed "surplus" dilepton yield resulting from dark photons on top of the total SM yield

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

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

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

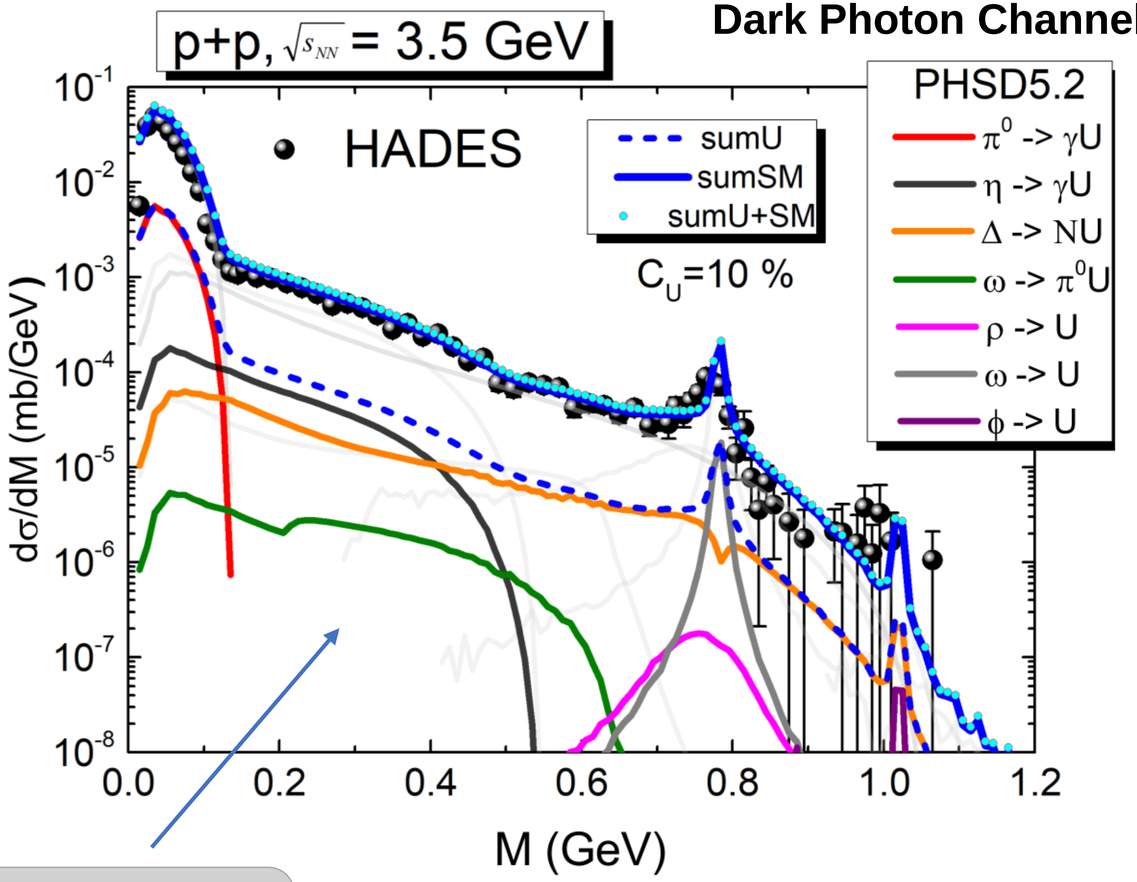
- **The HADES data, i.e. SM contributions (including exp. acceptance) are well described by the PHSD**



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

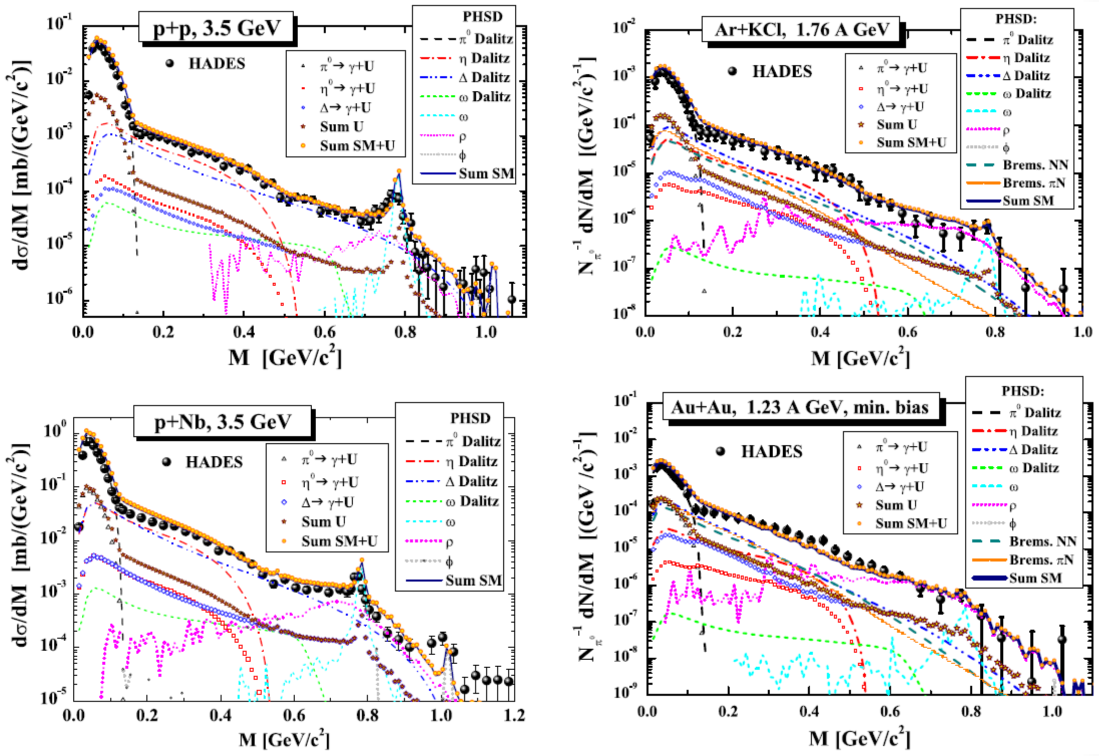
Dilepton spectra from U-boson decays at SIS18 energies vs. HADES data

Dark Photon Channels



Gray lines display SM decay channels

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

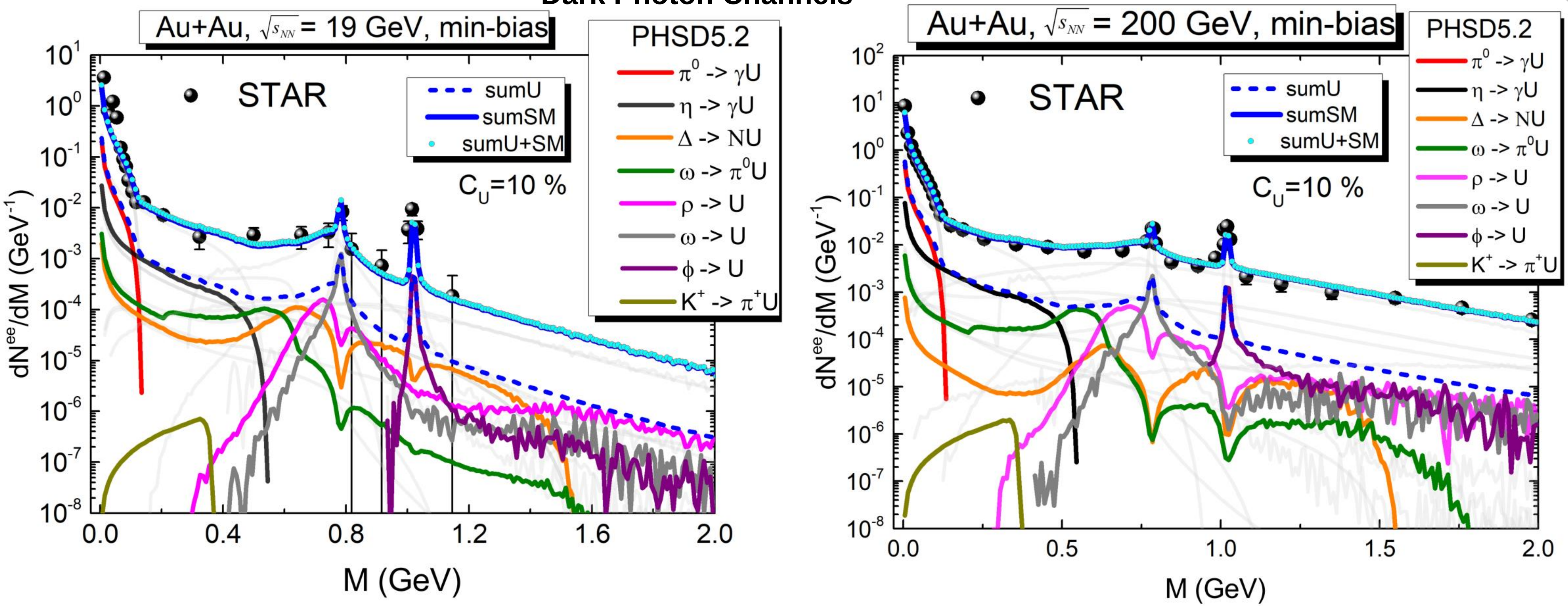


I. Schmidt et al., PRD 104 (2021) 015008

- 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

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

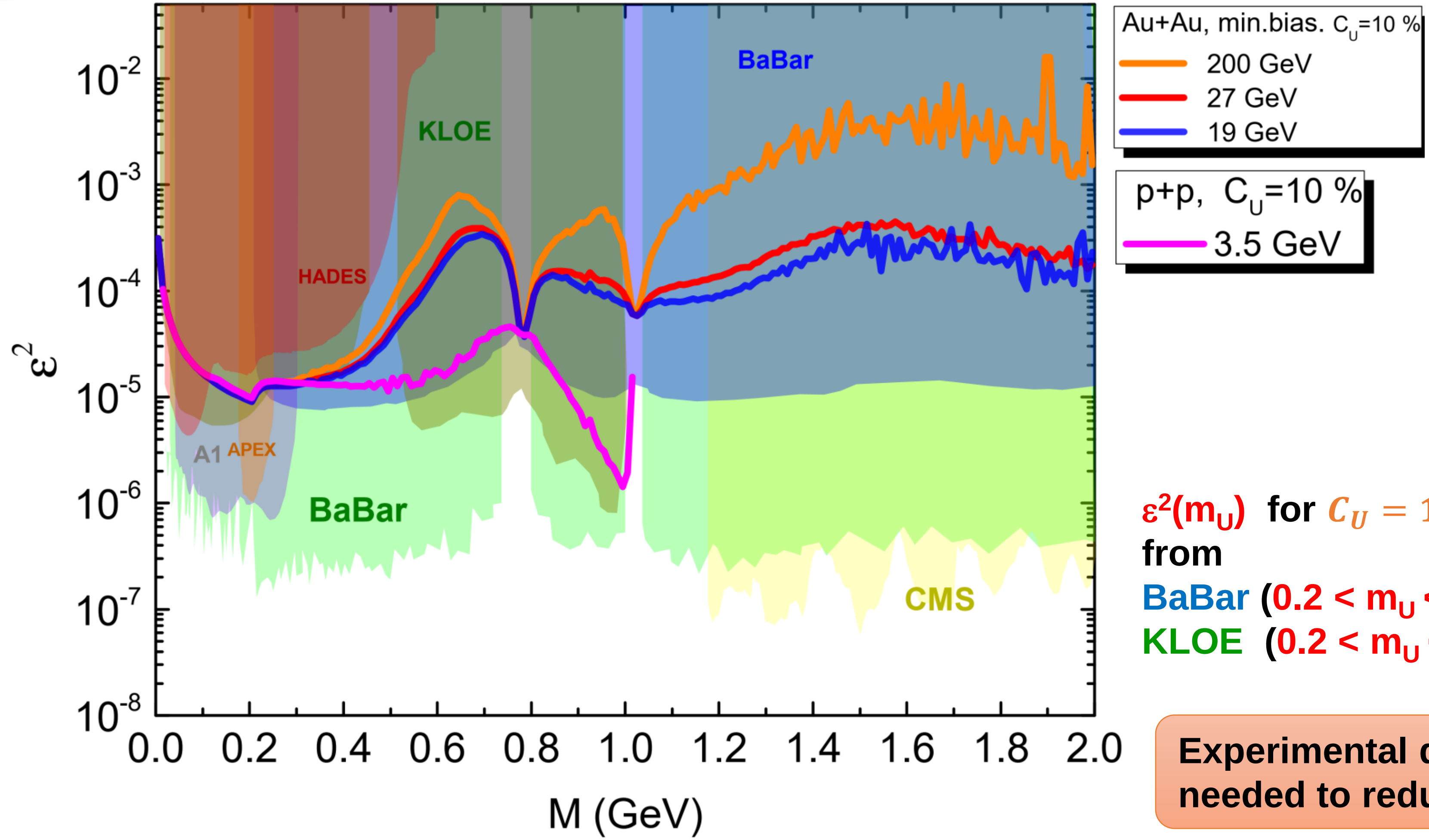
Dark Photon Channels

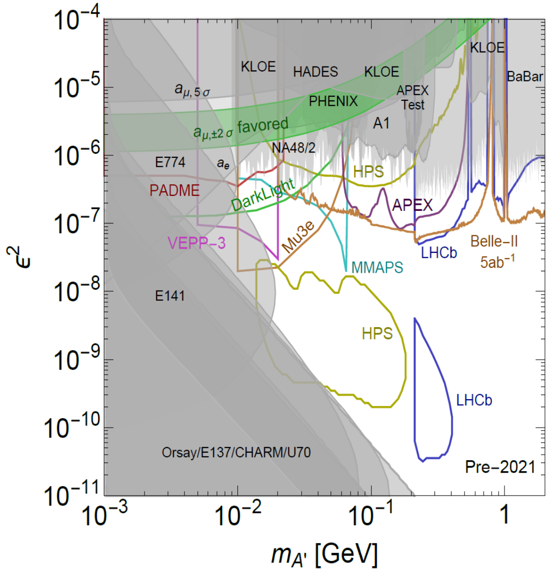


- **The STAR data, i.e. SM contributions (including exp. acceptance) are well described by the PHSD**
- **The contributions from $U \rightarrow e^+e^-$ are added with C_U=10% allowed surplus of the total SM yield ➔ the total sum is still in a good agreement with exp. data**

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





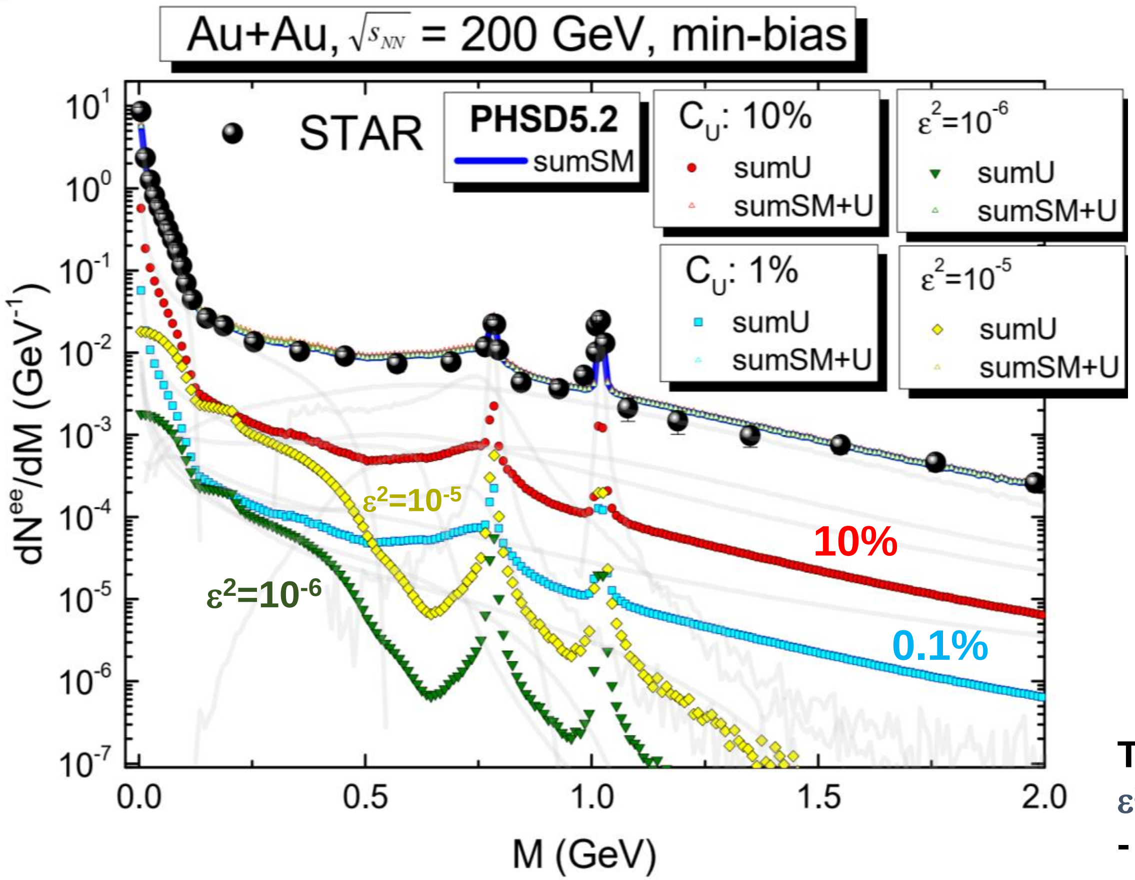
J. Alexander et al. (2016), 1608.08632

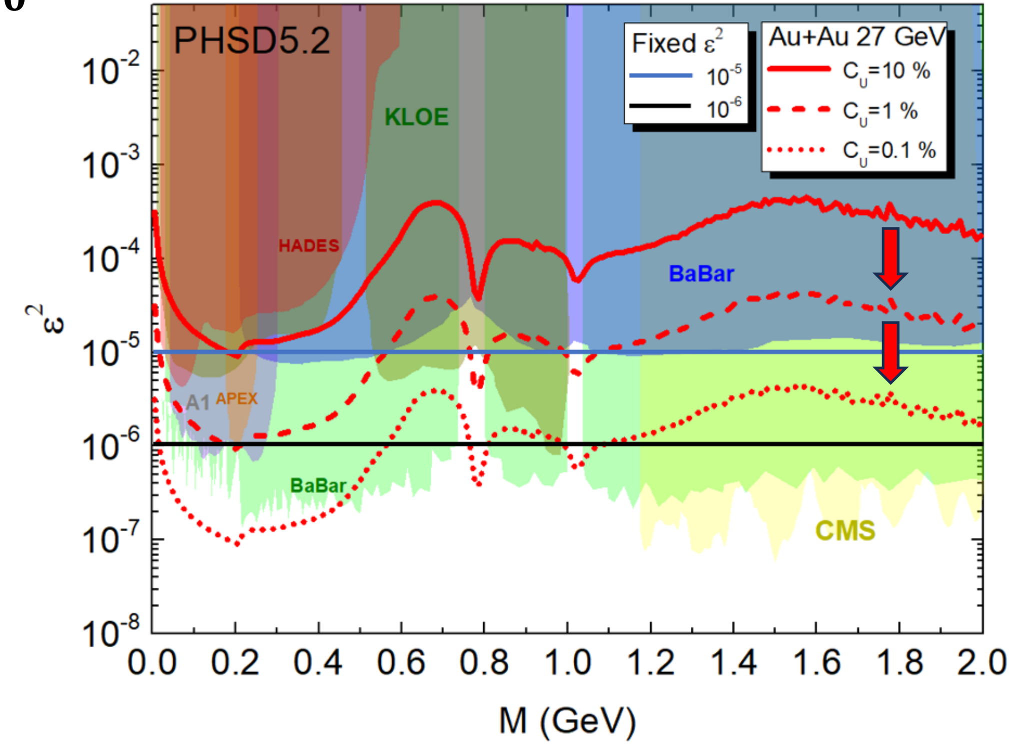
$\varepsilon^2(m_U)$ for $C_U = 10\%$ is consistent with the exp. data from
BaBar (0.2 < m_U < 0.9 GeV)
KLOE (0.2 < m_U < 1 GeV)

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

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

- 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 $\varepsilon^2(m_U)$ 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 $\varepsilon^2(M_U)$

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 $\pi^0, \eta \rightarrow \gamma U, \Delta \rightarrow NU, \omega \rightarrow \pi^0 U, K^+ \rightarrow \pi^+ U$ and the direct decay of $\rho, \phi, \omega \rightarrow U$ with further dilepton decays $U \rightarrow e^+e^-$, 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

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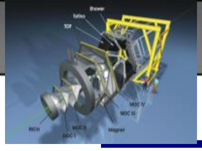
➔ **Perspectives:**

- 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 !

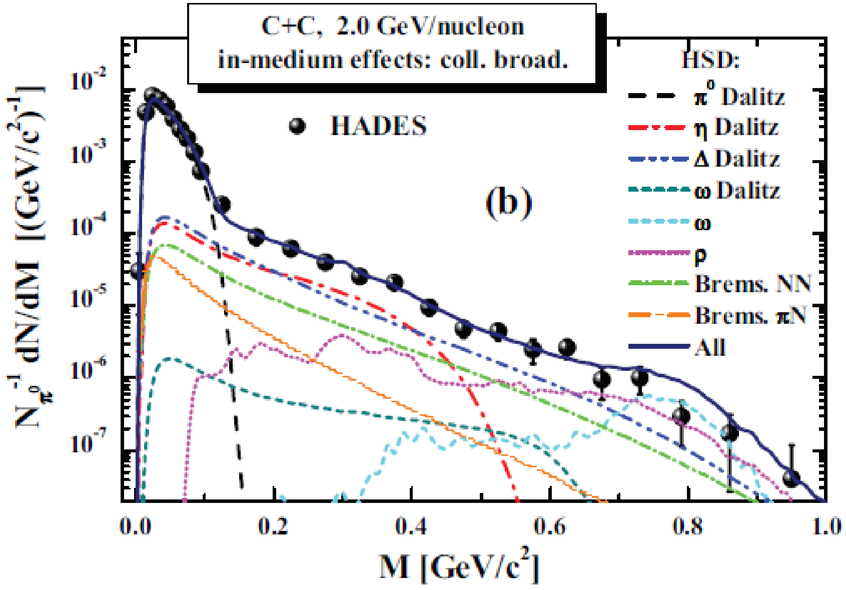
Extras



Dileptons at SIS energies - HADES

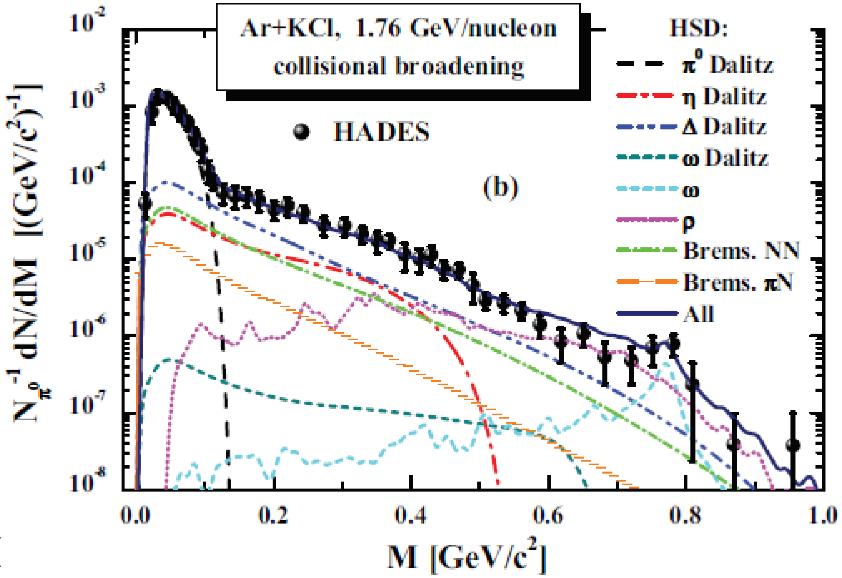
- **HADES:** dilepton yield dN/dM scaled with the **number of pions $N_{\pi 0}$**

- **Dominant hadronic sources for $M>m_{\pi}$:**
  - η, Δ Dalitz decays
  - NN bremsstrahlung
  - direct ρ decay



➢ **ρ meson** = strongly interacting resonance
strong collisional broadening of the ρ width

- In-medium effects are more pronounced for heavy systems such as Ar+KCl than C+C
- The peak at M~0.78 GeV relates to ω/ρ mesons decaying in vacuum



E. Bratkovskaya, J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (

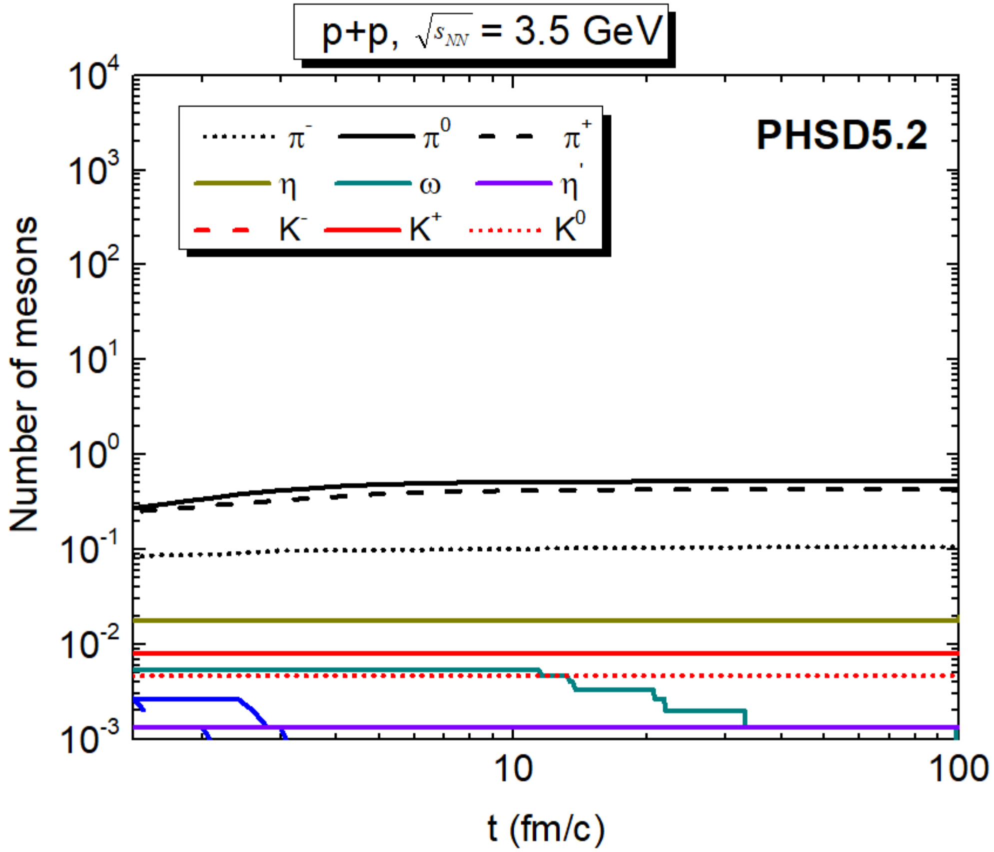
from the three data sets separately. Evidently, the p + Nb data provide the strongest constraint. However, as the three data sets are of comparable statistical quality and result hence in upper limits of similar magnitude, it is natural to join them into a combined upper limit [49]. Since all experiments have been executed under very similar conditions, we use the following statistics-driven ansatz:

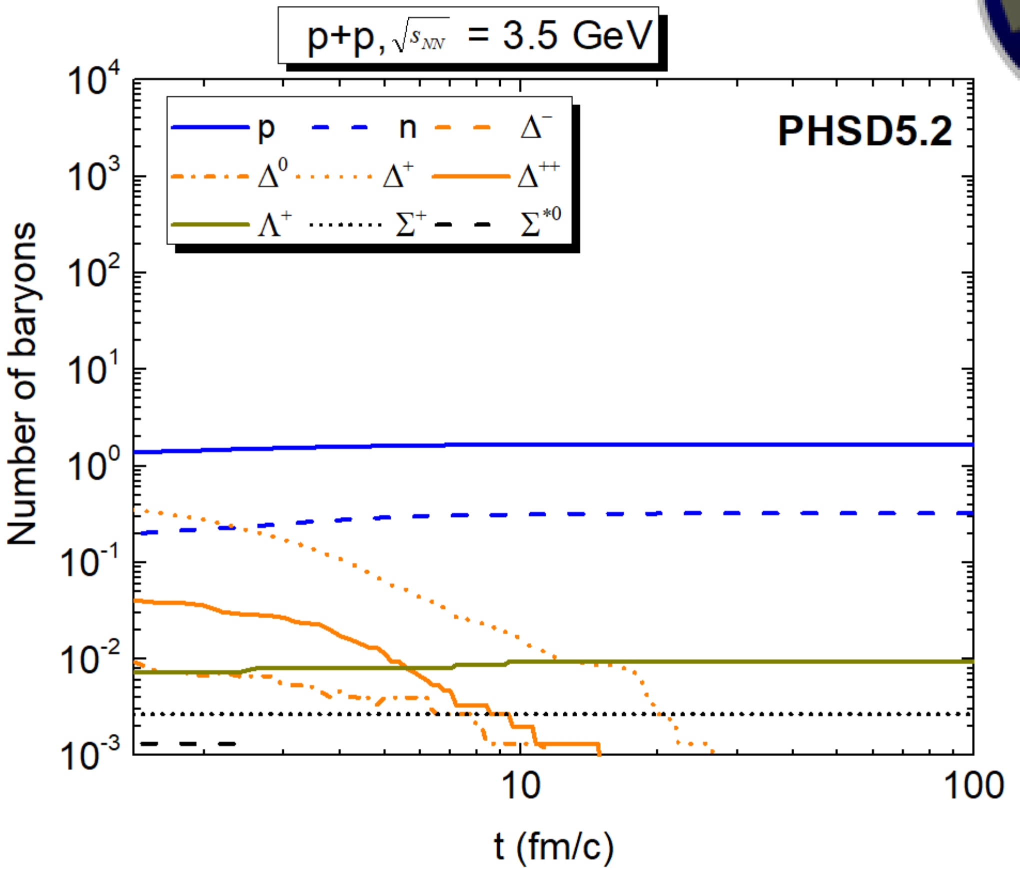
$$UL_{(1+2+3)} = \sqrt{\left(UL_{(1)}^{-2} + UL_{(2)}^{-2} + UL_{(3)}^{-2}\right)^{-1}}. \quad (8)$$

The combined upper limit $UL_{(1+2+3)}$ is overall about 10 to 20% lower than the p + Nb value taken alone. This is indeed expected from the moderate increase in pair statistics achieved by cumulating the data from all experiments and is consistent with a $UL \propto 1/\sqrt{N}$ behavior.

Number of particles in Au+Au collision

Time evolution of the number of particles in phsd at low energy (SIS18)



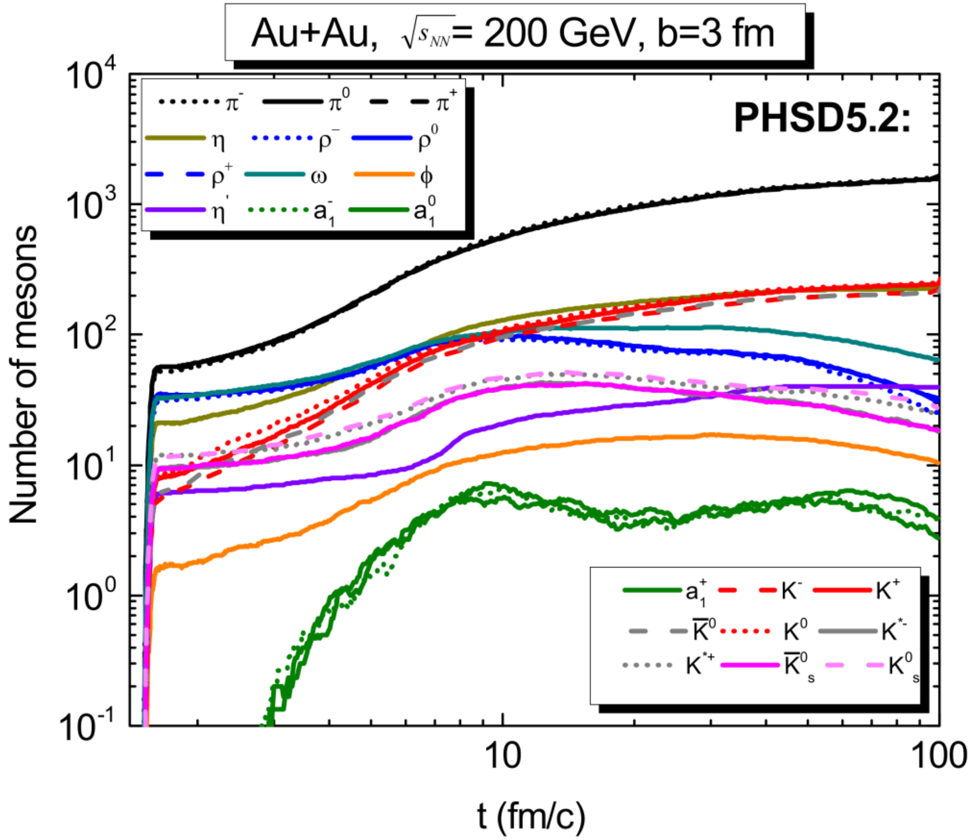


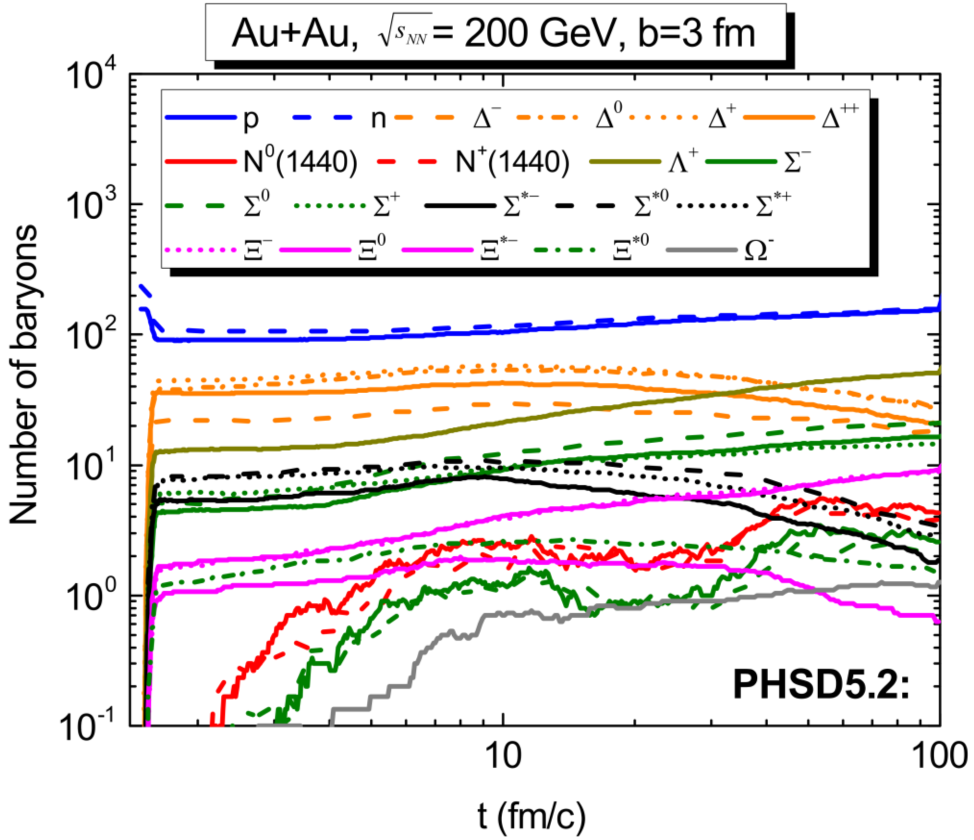
π dominates and a small fraction of η are relevant

p, n and a small fraction of Δ are relevant at the beginning of the collision

Number of particles in Au+Au collision

Time evolution of the number of particles in phsd at high energy (RHIC)





π, η, K **dominate and a large number of** $\omega, \rho, \phi, \eta'$ **are created**

p, n **dominate and an large number of** Δ, Λ, Σ **are created**

Dark photon production in PHSD

Dalitz Decay

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

$\Delta \rightarrow NU$

$\omega \rightarrow \pi^0 U$

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

Direct Decay

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

$U \rightarrow e^+e^-$

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

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

Based on the model: **HADES** Col. (2014) PLB, 731, 265

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

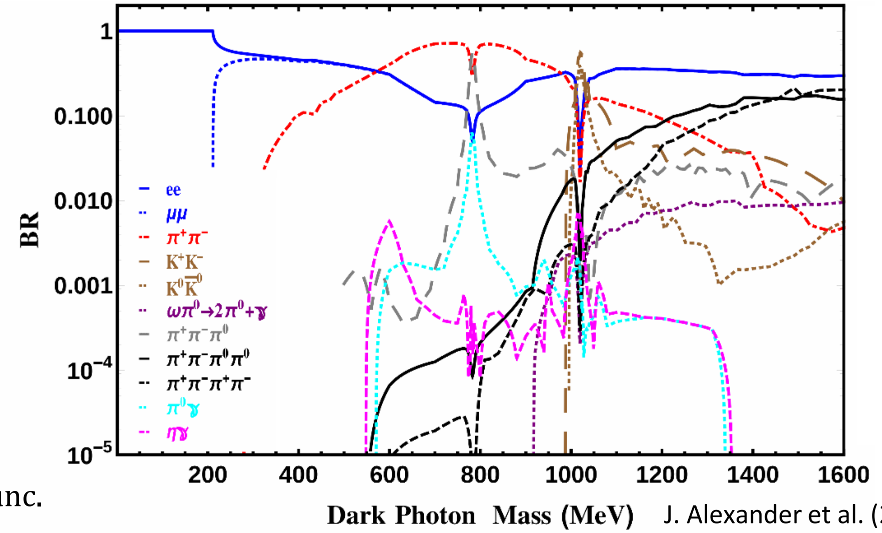
→ **NICA** Col. (2024) PLB, 852, 138599

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

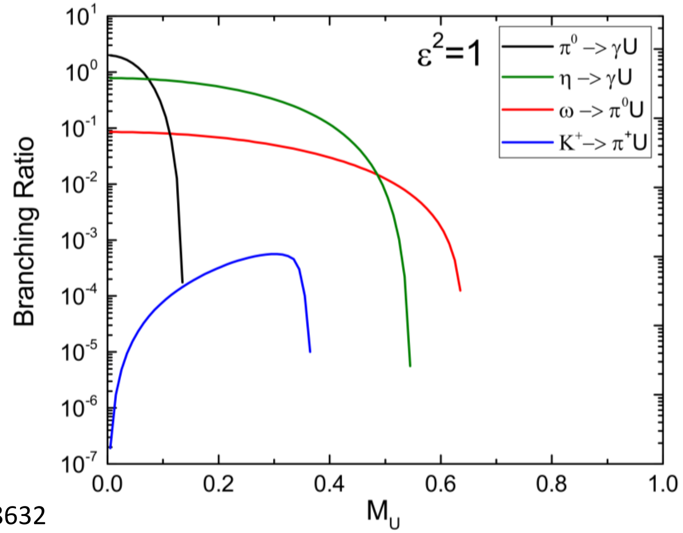
→ **Pospelov** (2009) PRD 80, 095002

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

→ **Battel** (2009) PRD 79, 115008

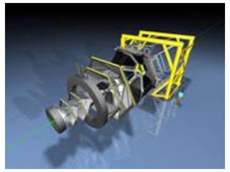


J. Alexander et al. (2016), 1608.08632



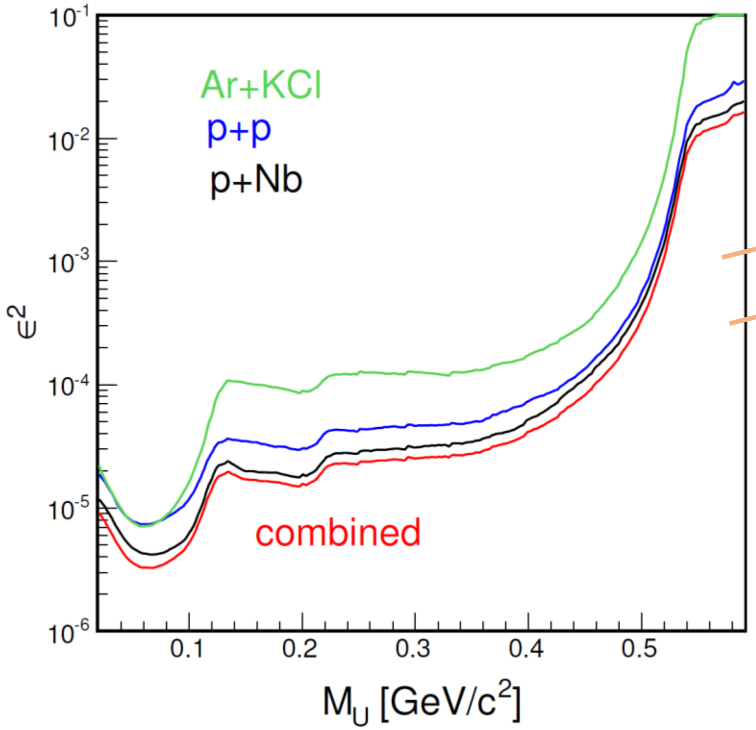
$A(m_\Delta) \rightarrow$ Breit – Wiegner Func.

Search for dark photons with HADES



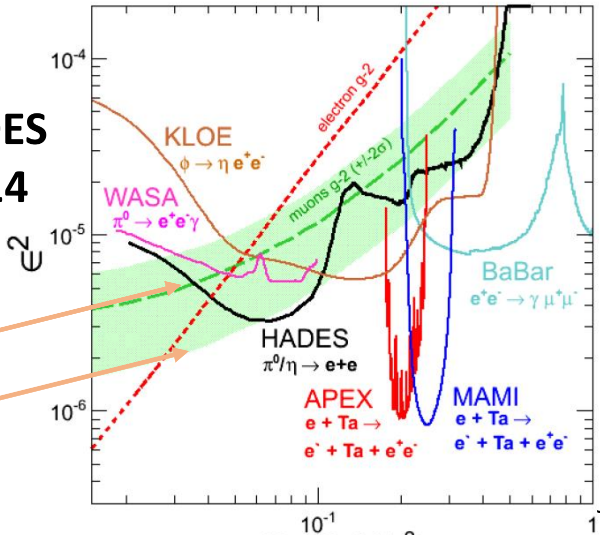
G. Agakishiev et al. (HADES), Phys. Lett. B 731, 265 (2014)

Upper limit on the mixing parameter ε^2



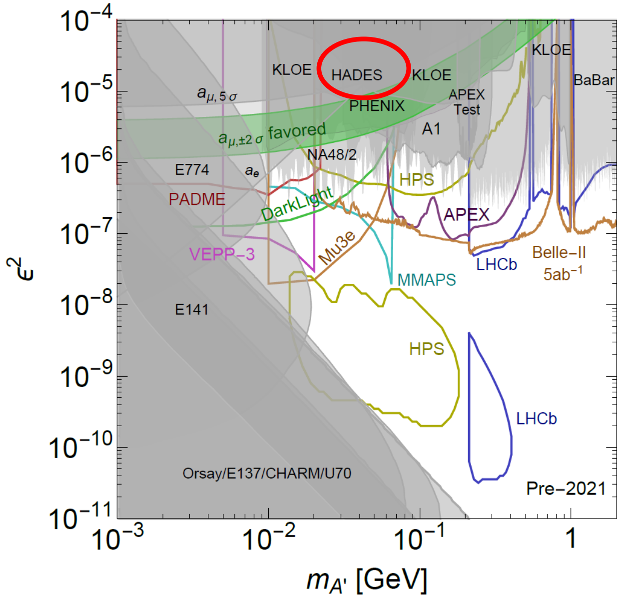
HADES 2014

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



J. Alexander et al. (2016), 1608.08632

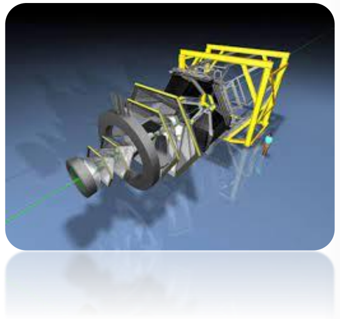
World wide exp. data 2016



HADES coverage : 0.02 < M_U < 0.6 GeV

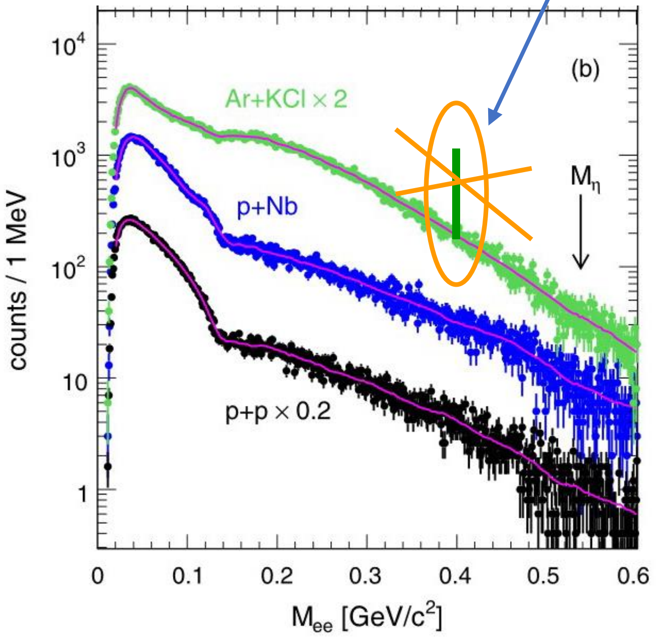
Dark photons are not observed so far!

Search for dark photons with HADES (GSI)

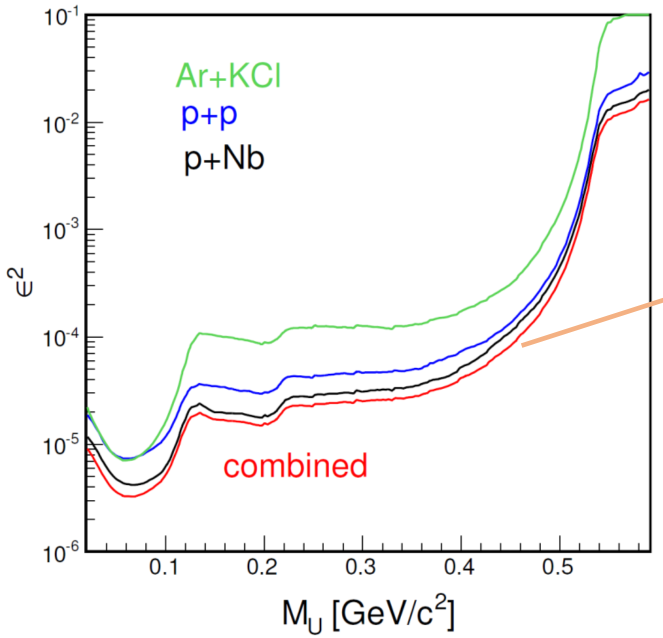


HADES data:
p+p, p+Nb at 3.5 GeV, Ar+KCl at 1.76 A GeV

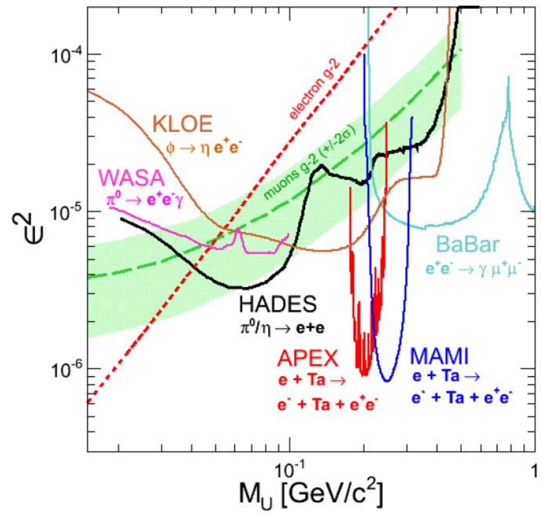
1) **Search for a peak structure** in the raw dN/dM spectrum taking into account mass resolution
2) If no peak found, get an UL (upper limit) on peak



Upper limit on the mixing parameter ε^2



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



HADES coverage : $0.02 < M_U < 0.6$ GeV

Dark photons are not observed so far!

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))

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

Dark photon production in PHSD

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

$\Delta \rightarrow NU$

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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:

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

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

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

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

The yield of U-bosons of mass M_U:

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

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

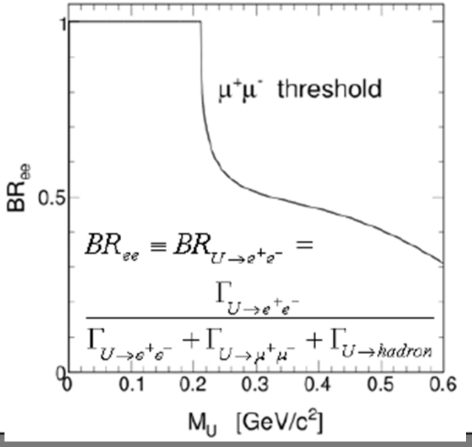
$$\frac{\Gamma_{i\to\gamma U}}{\Gamma_{i\to\gamma\gamma}} = 2\epsilon^2 |F_i(q^2 = M_U^2)| \frac{\lambda^{3/2}(m_i^2, m_\gamma^2, M_U^2)}{\lambda^{3/2}(m_i^2, m_\gamma^2, m_\gamma^2)} \qquad i = \pi^0, \eta$$

Formfactor

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

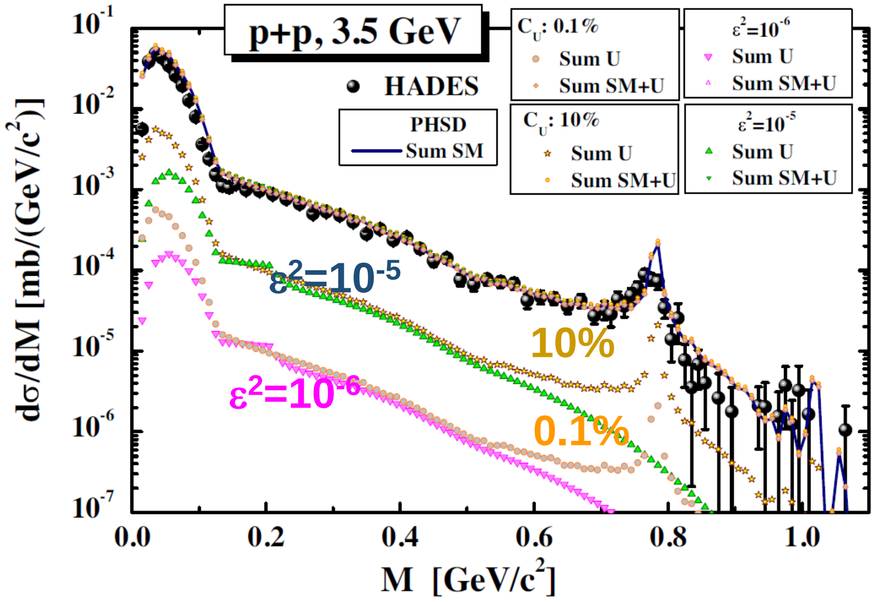
$$Br^{U\to ee} = \frac{\Gamma_{U\to e^+e^-}}{\Gamma_{tot}^U} = \frac{1}{1 + \sqrt{1 - \frac{4m_\mu^2}{M_U^2}}\left(1 + \frac{2m_\mu^2}{M_U}\right)(1 + R(M_U))}$$

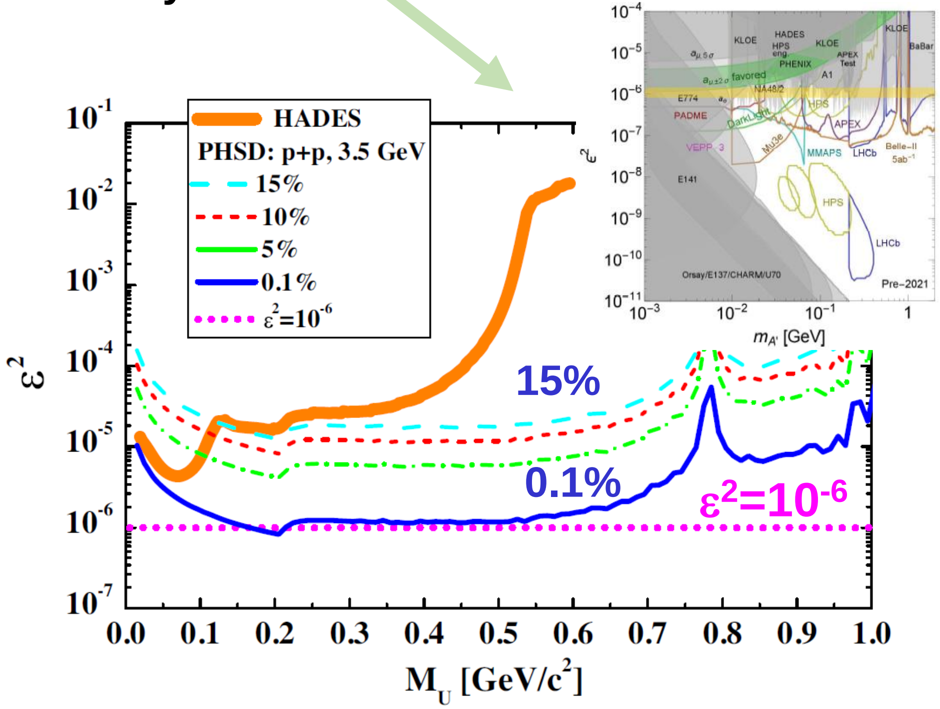
$$R(\sqrt{s}) = \sigma_{e^+e^-\to hadrons}/\sigma_{e^+e^-\to\mu^+\mu^-}$$



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 $\varepsilon^2(M_U)$

Helmholtz Forschungsakademie Hessen für FAIR

Deutsche Forschungsgemeinschaft

Search for dark photons in heavy-ion collisions

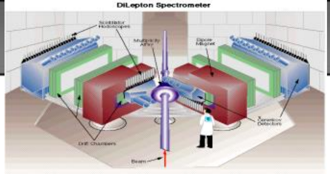
Elena Bratkovskaya

(GSI, Darmstadt & Uni. Frankfurt)

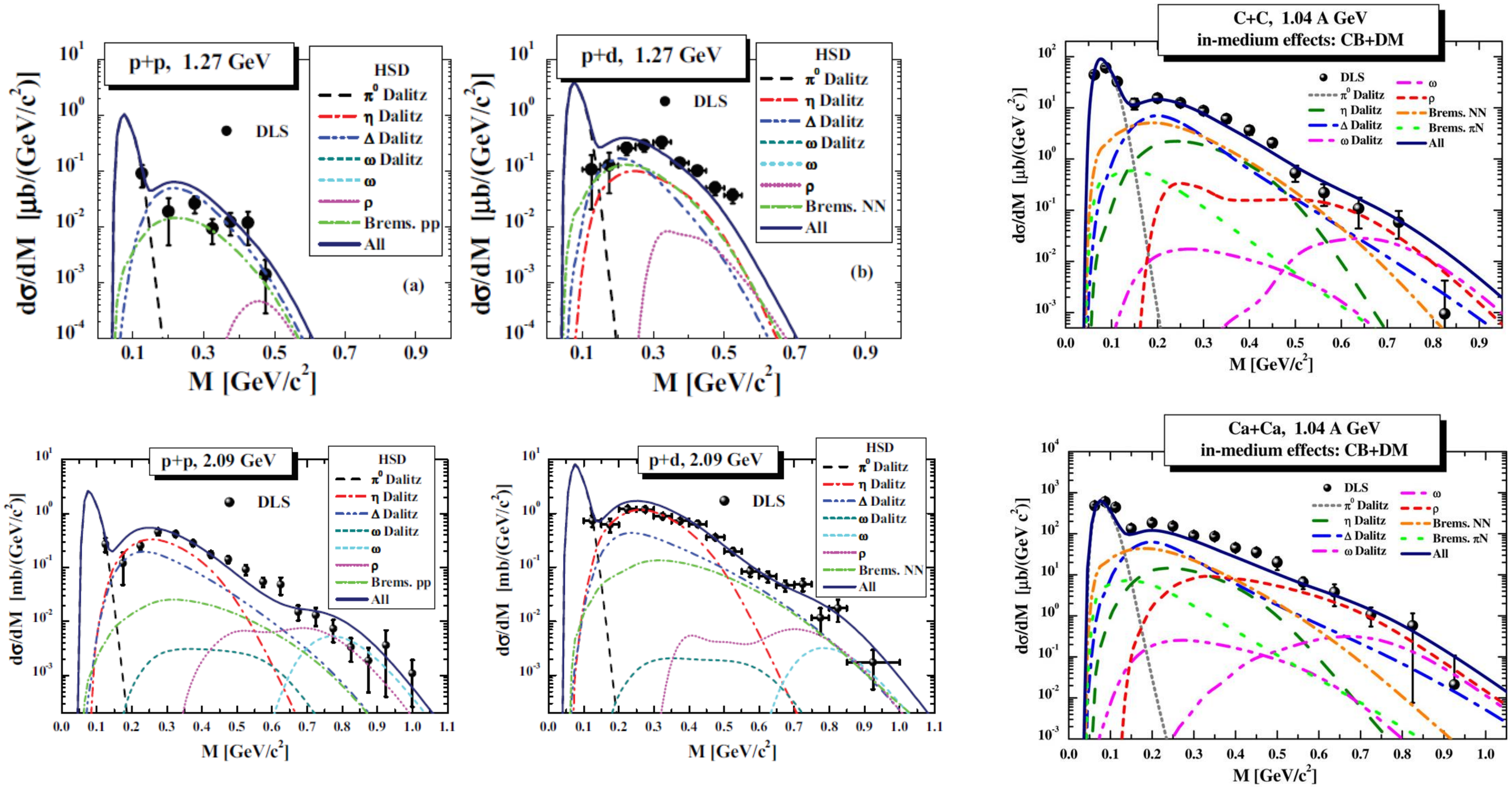

Kazimir Malevich, “Black Square” (1915)

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

9-13 January 2023, Valparaíso, Chile



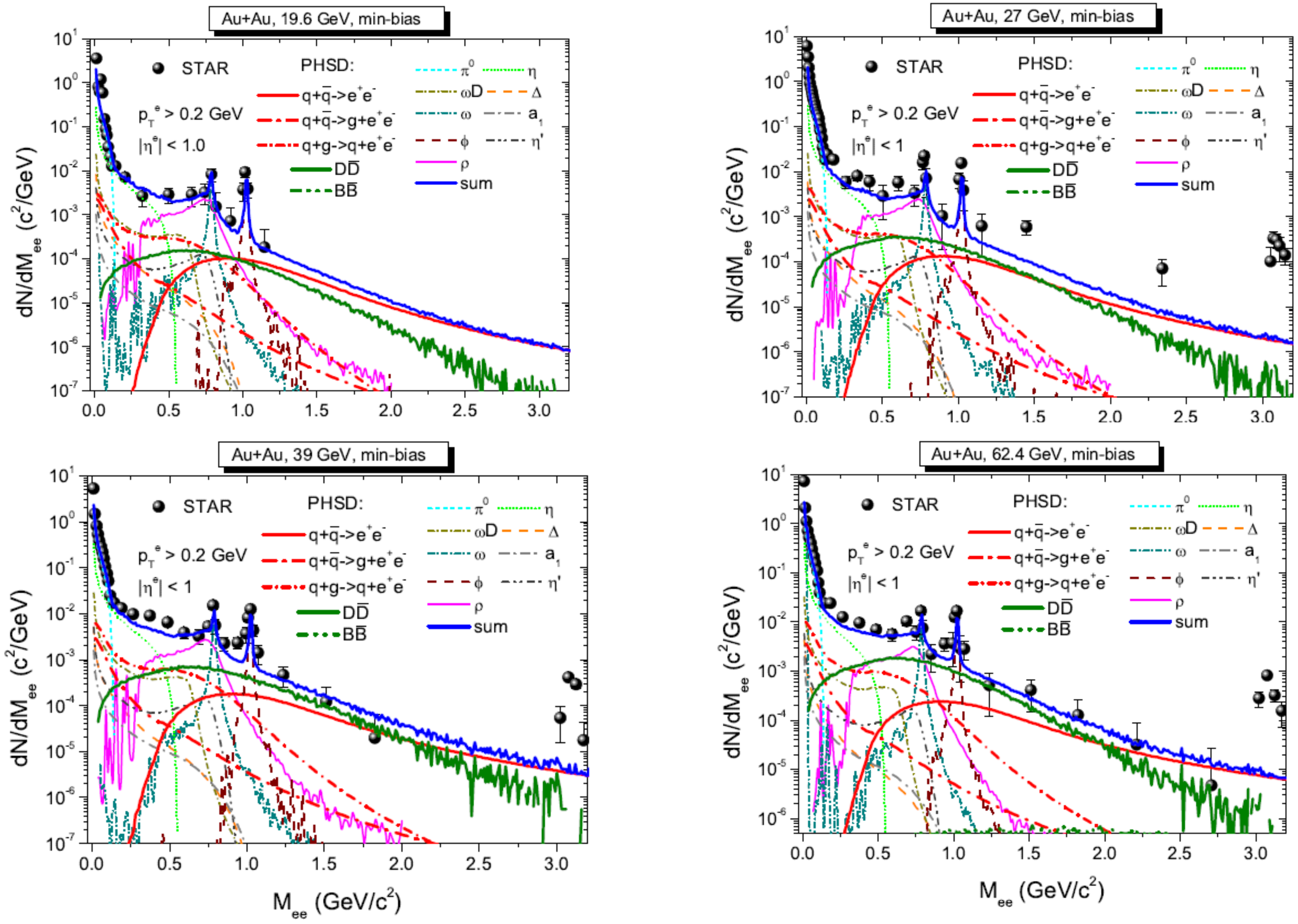
PHSD: Dileptons from p+p, p+d, A+A - DLS



- **bremsstrahlung** and **Δ-Dalitz decay** are the dominant contributions in low energy p+p, p+d and A+A collisions for 0.15 < M < 0.55 GeV

E.B., W. Cassing, Nucl.Phys.A 807 (2008) 214

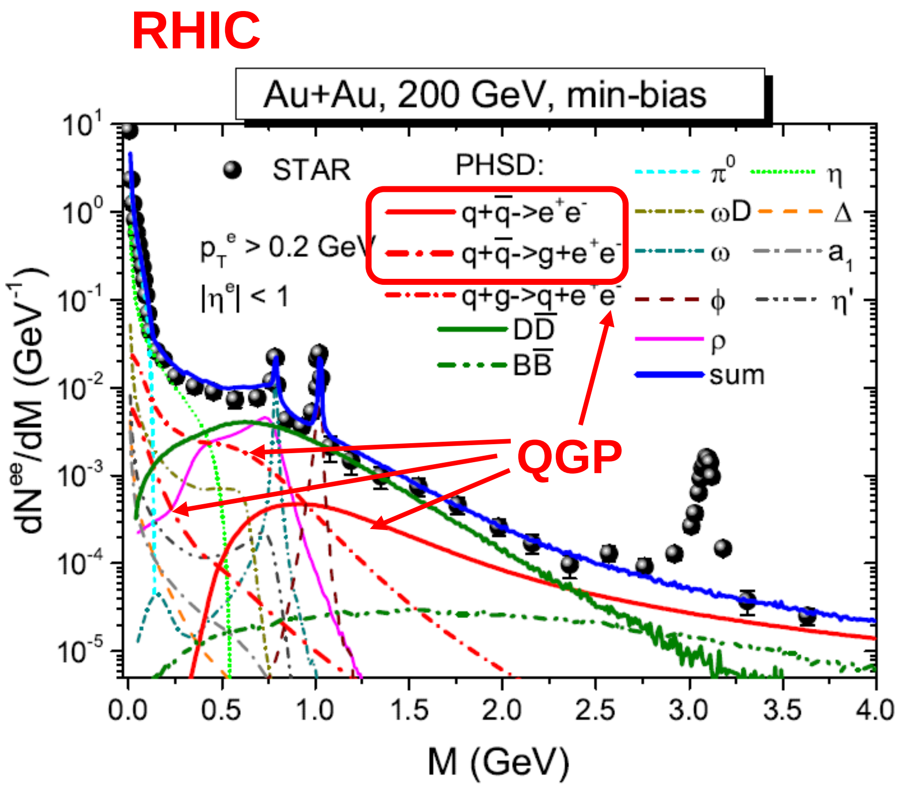
Dileptons from RHIC BES: STAR

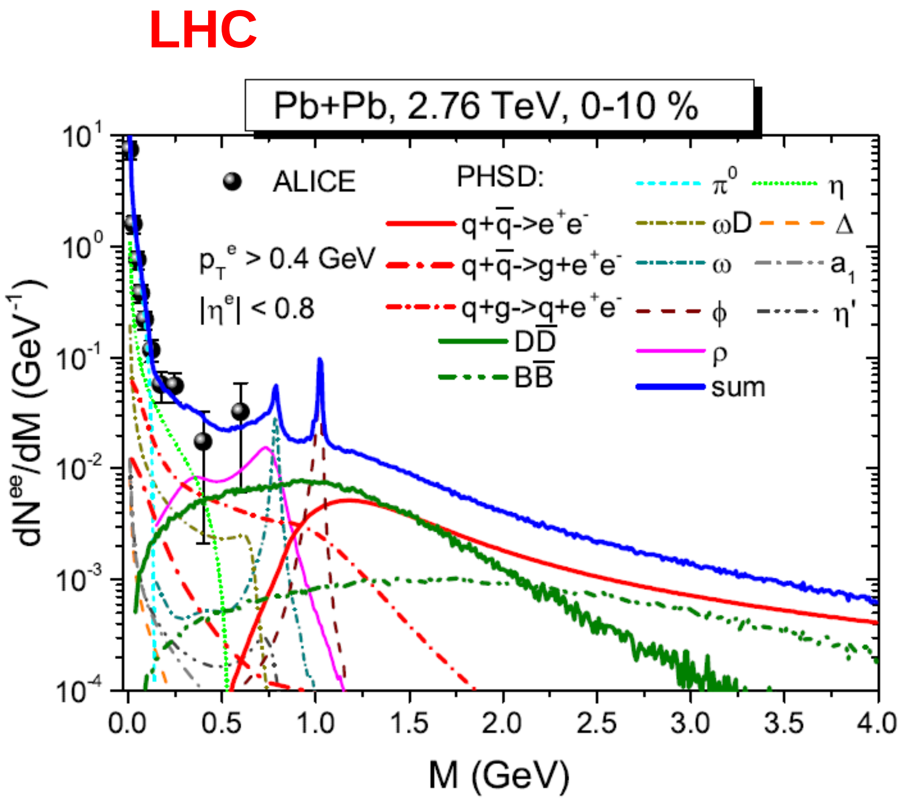


- Low M: a collisional broadening scenario for the vector meson spectral functions
- QGP and charm are dominant contributions for intermediate masses at BES-RHIC

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907

Dileptons at RHIC and LHC





STAR data at 200 GeV and the ALICE data at 2.76 TeV are described by PHSD within

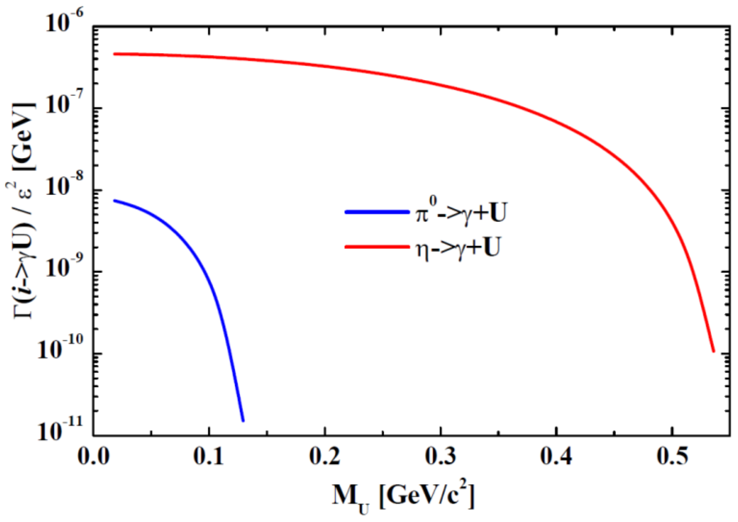
1) a collisional broadening scenario for the vector meson spectral functions
+ QGP + correlated charm

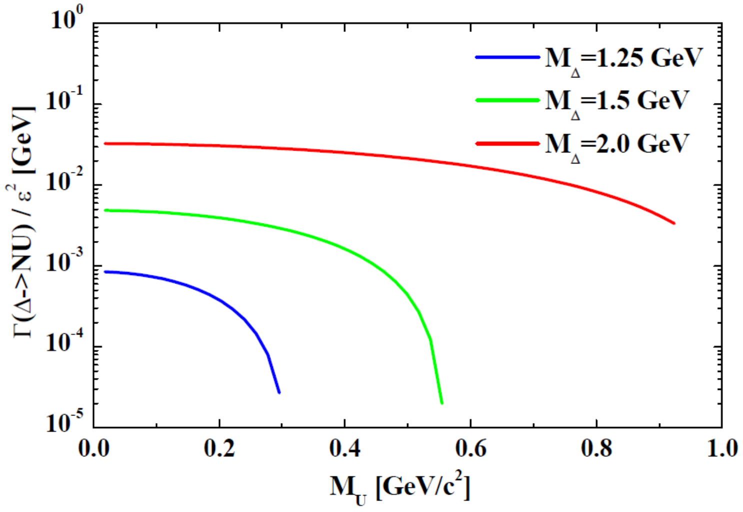
2) Charm contribution is dominant for 1.2 < M < 2.5 GeV

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907

Dalitz decays of π^0,η and Δ to U-bosons and e+e-

- Dalitz decay width of π^0,η mesons and Δ-resonance to U-bosons normalized to ε^2



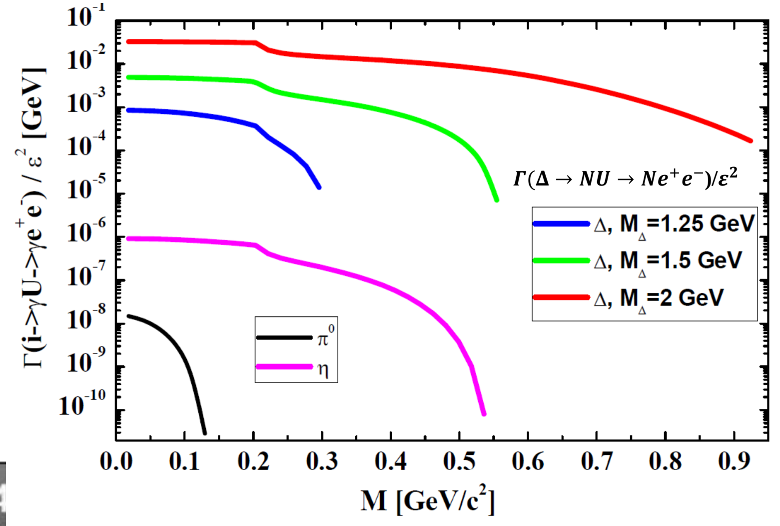


- Decay width of π^0,η mesons and Δ-resonances to dileptons (via U-bosons) normalized to ε^2

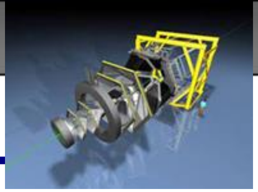
$\pi^0 \rightarrow \gamma + U$,
$\eta \rightarrow \gamma + U$, $U \rightarrow e^+e^-$
$\Delta \rightarrow N + U$,

$$\Gamma(i \to \gamma U \to \gamma e^+ e^-)/\varepsilon^2$$
$$\Gamma(\Delta \to NU \to Ne^+ e^-)/\varepsilon^2$$

➔ to PHSD calculations

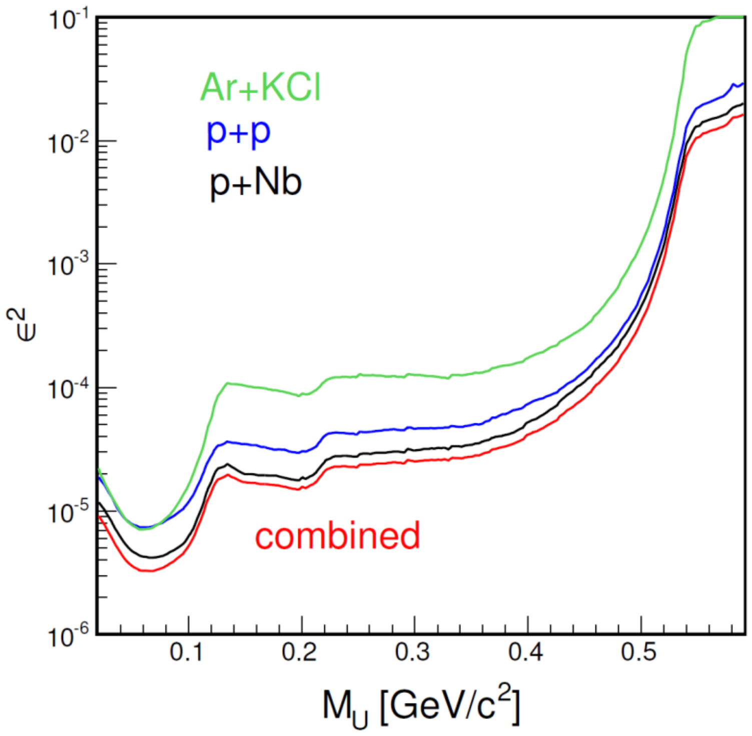


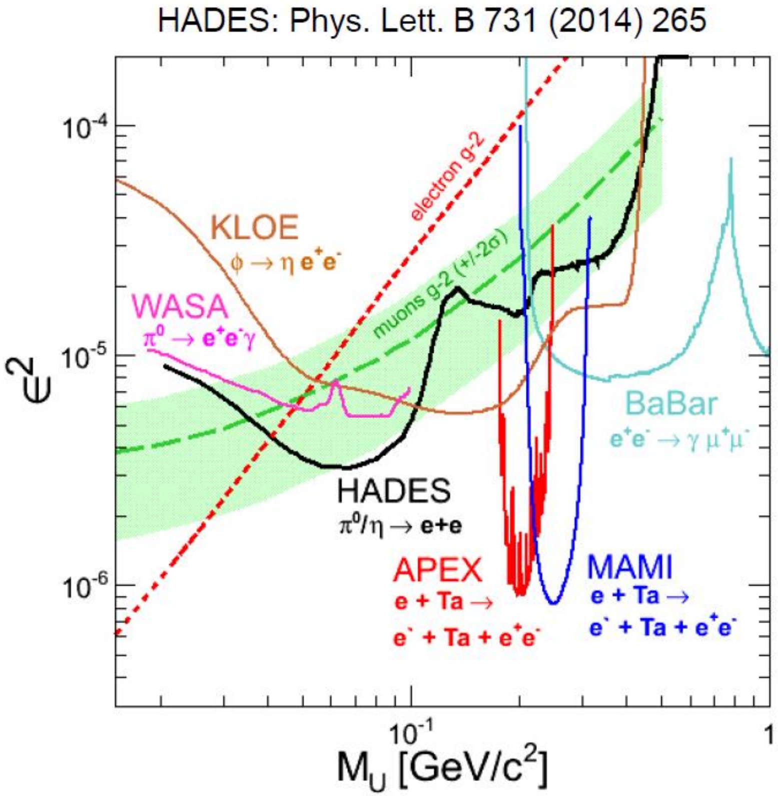
Search for dark photons with HADES



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

Upper limit on the mixing parameter ε^2



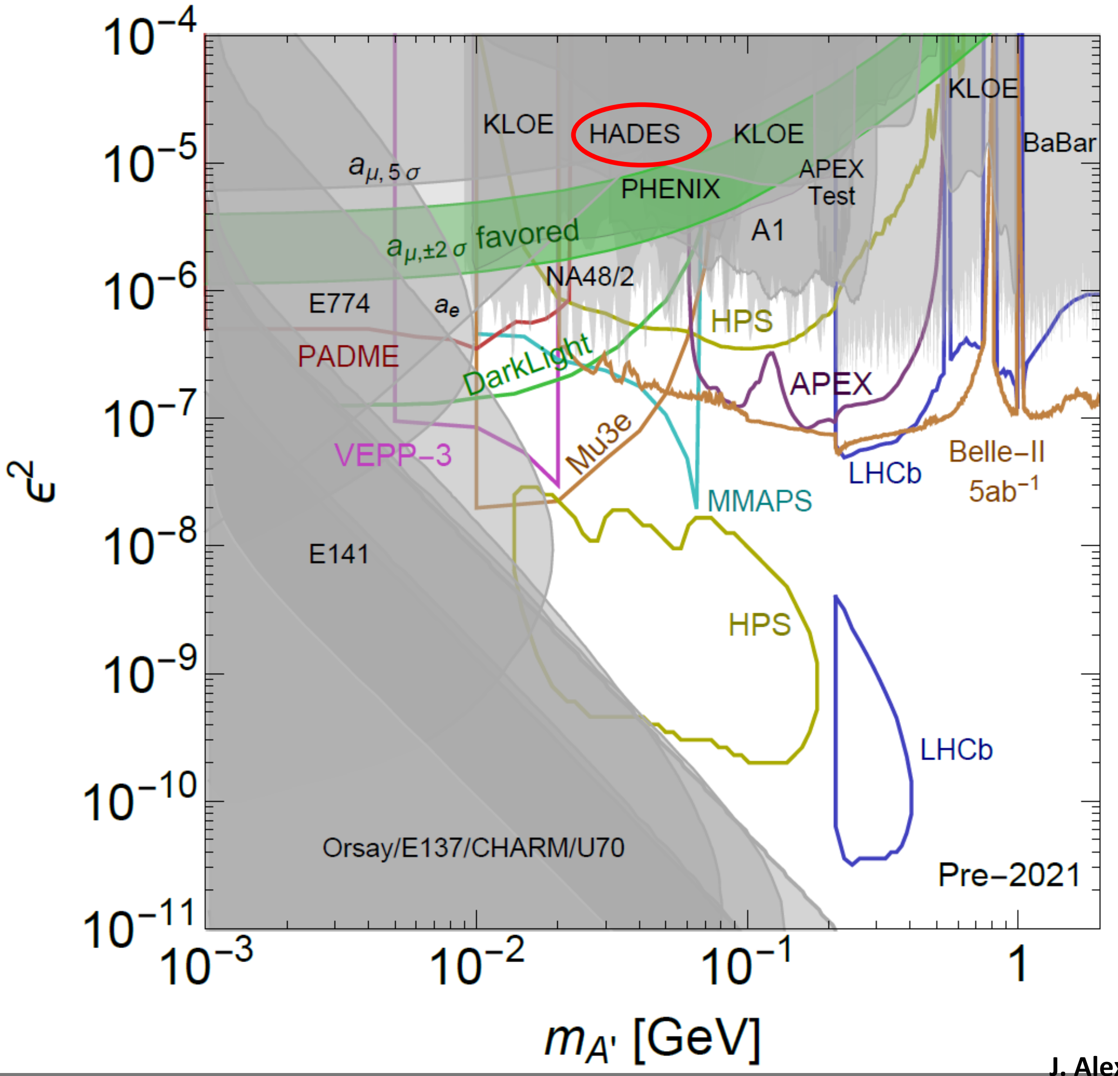


HADES coverage : $0.02 < M_U < 0.6$ GeV

Dark photons are not observed so far!

Mixing parameter ε^2

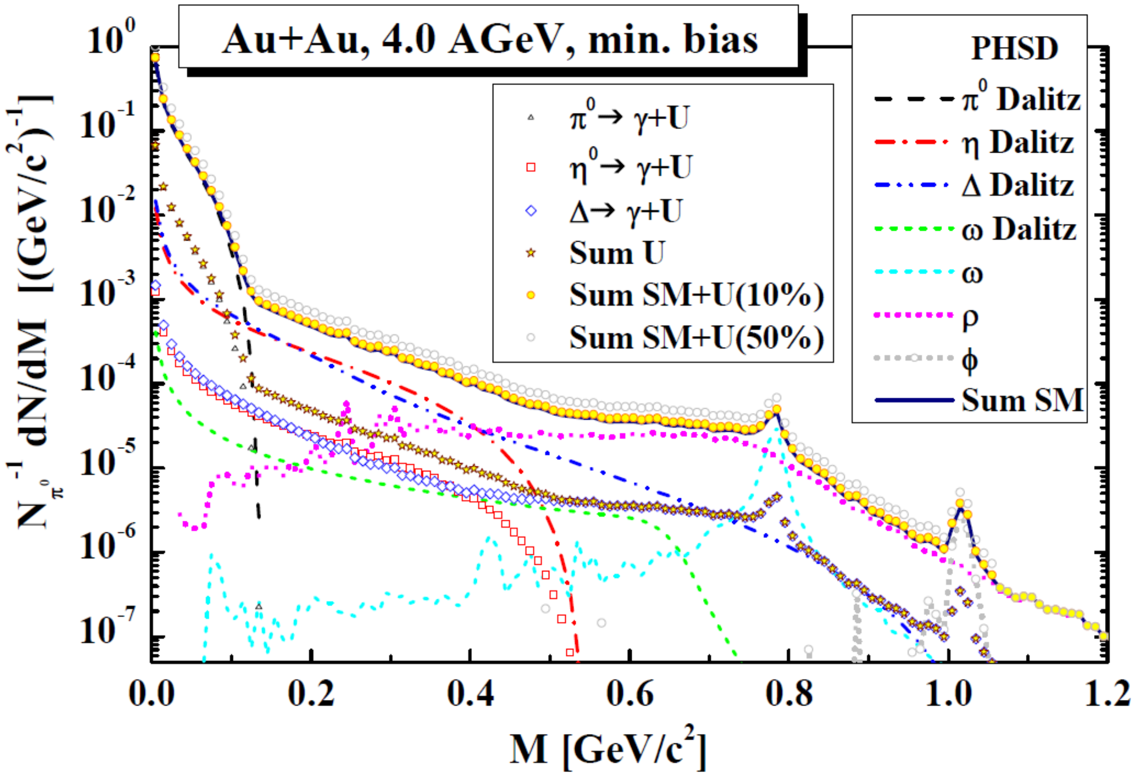
Compilation of world wide exp. data on the upper limit of the mixing parameter ε^2



J. Alexander et al. (2016), 1608.08632

Dileptons yields including dark photons

- The PHSD **predictions** for Au+Au at 4.0 A GeV - **without exp. acceptance**



- The contributions from U→e+e- are added with C_U=10% and alternatively 50% allowed surplus of the total SM yield

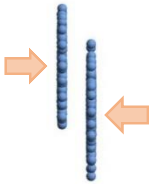
- With increasing beam energy other channels are getting important at M > 0.5 GeV

Parton-Hadron-String-Dynamics (PHSD)

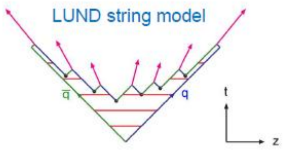
PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

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

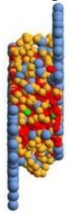
Initial A+A collision



- **Initial A+A collisions** :
  N+N → string formation → decay to pre-hadrons + leading hadrons

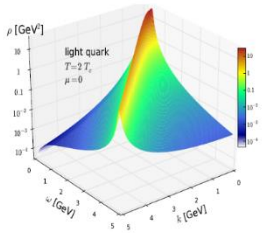


Partonic phase

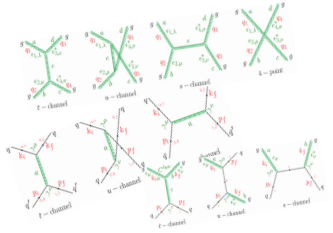


- **Formation of QGP stage** if local $\varepsilon > \varepsilon_{critical}$:
  dissolution of pre-hadrons → partons

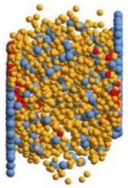
- **Partonic phase - QGP:**
  QGP is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD EoS for finite T and μ_B (crossover)



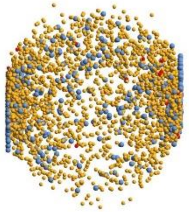
  - Degrees-of-freedom: strongly interacting quasiparticles: massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in a self-generated mean-field potential
  - Interactions: (quasi-)elastic and inelastic collisions of partons



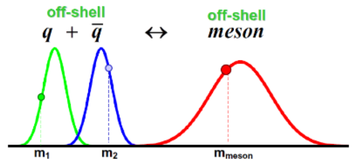
Hadronization



Hadronic phase



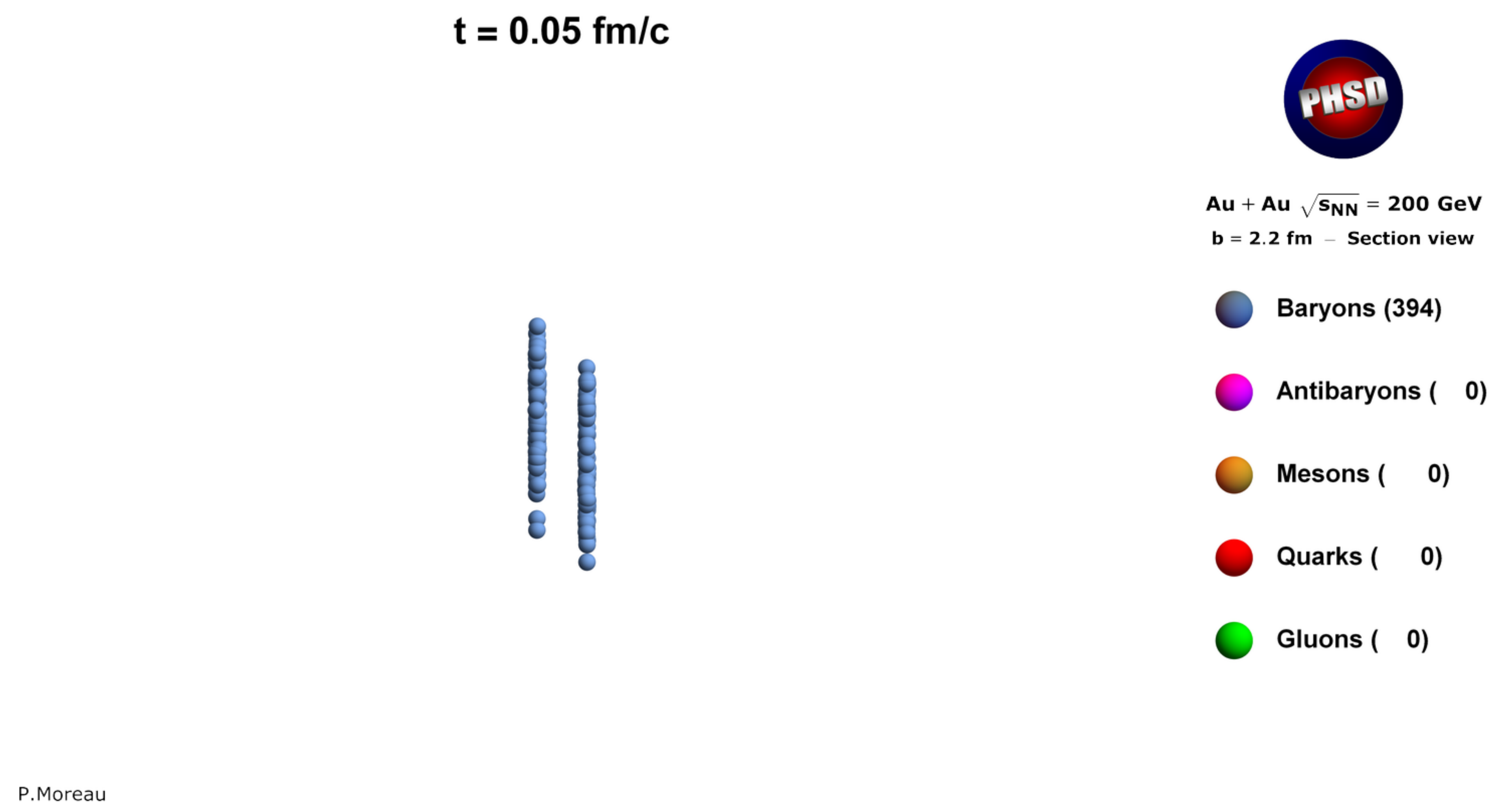
- **Hadronization** to colorless off-shell mesons and baryons:
  Strict 4-momentum and quantum number conservation



- **Hadronic phase:** hadron-hadron interactions – off-shell HSD

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

Stages of a collision in PHSD



Stages of a collision in PHSD

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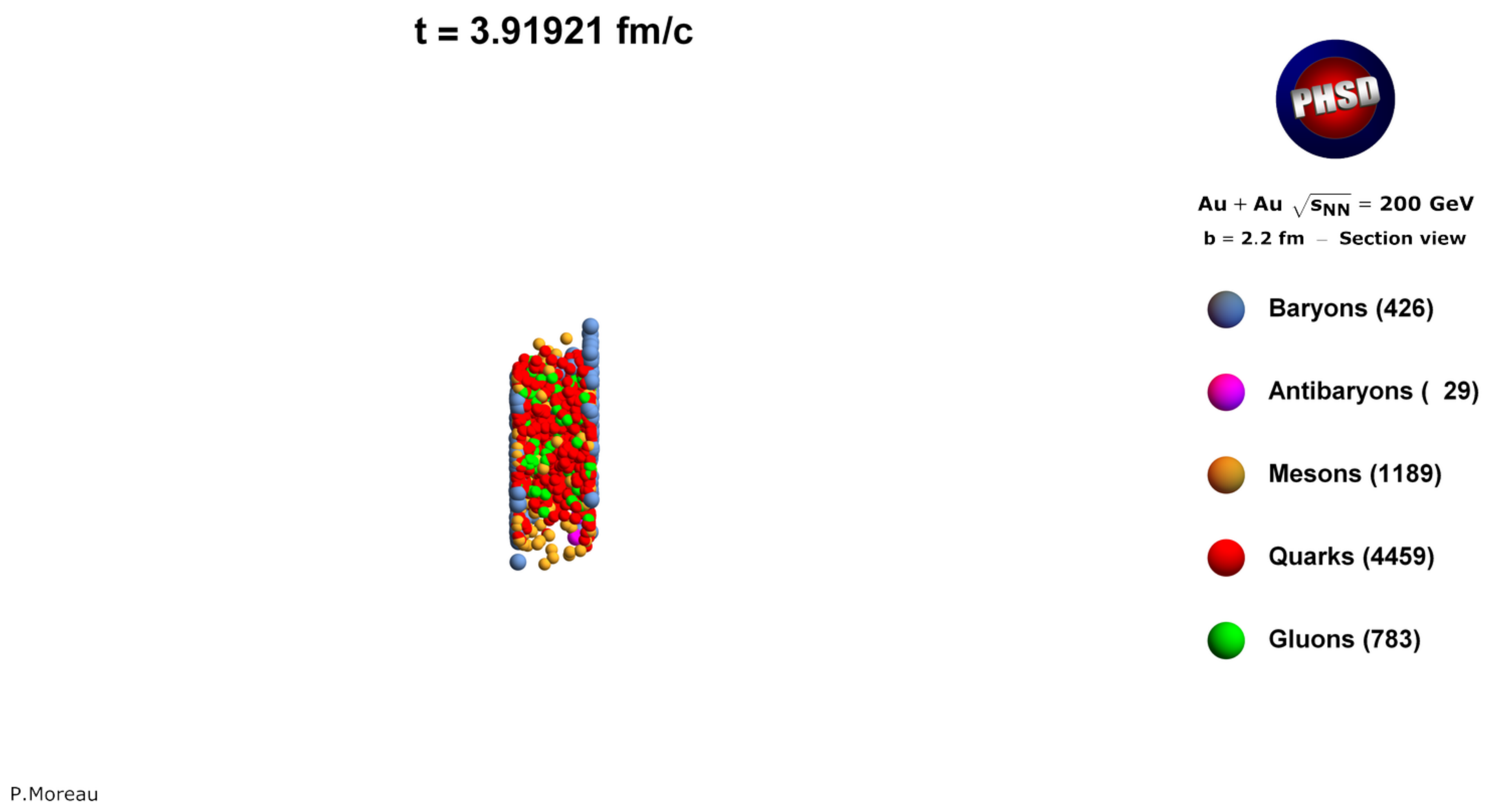
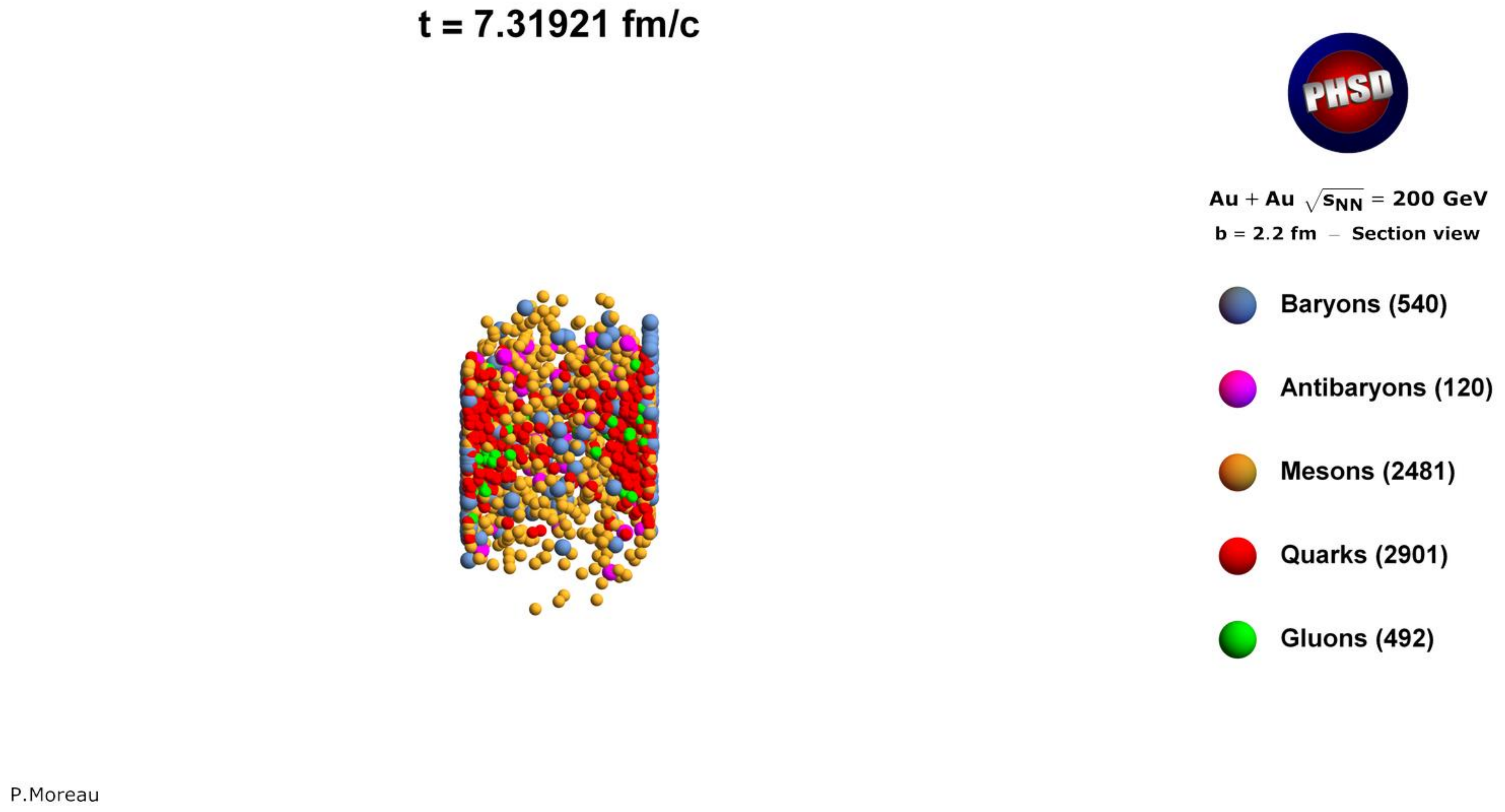
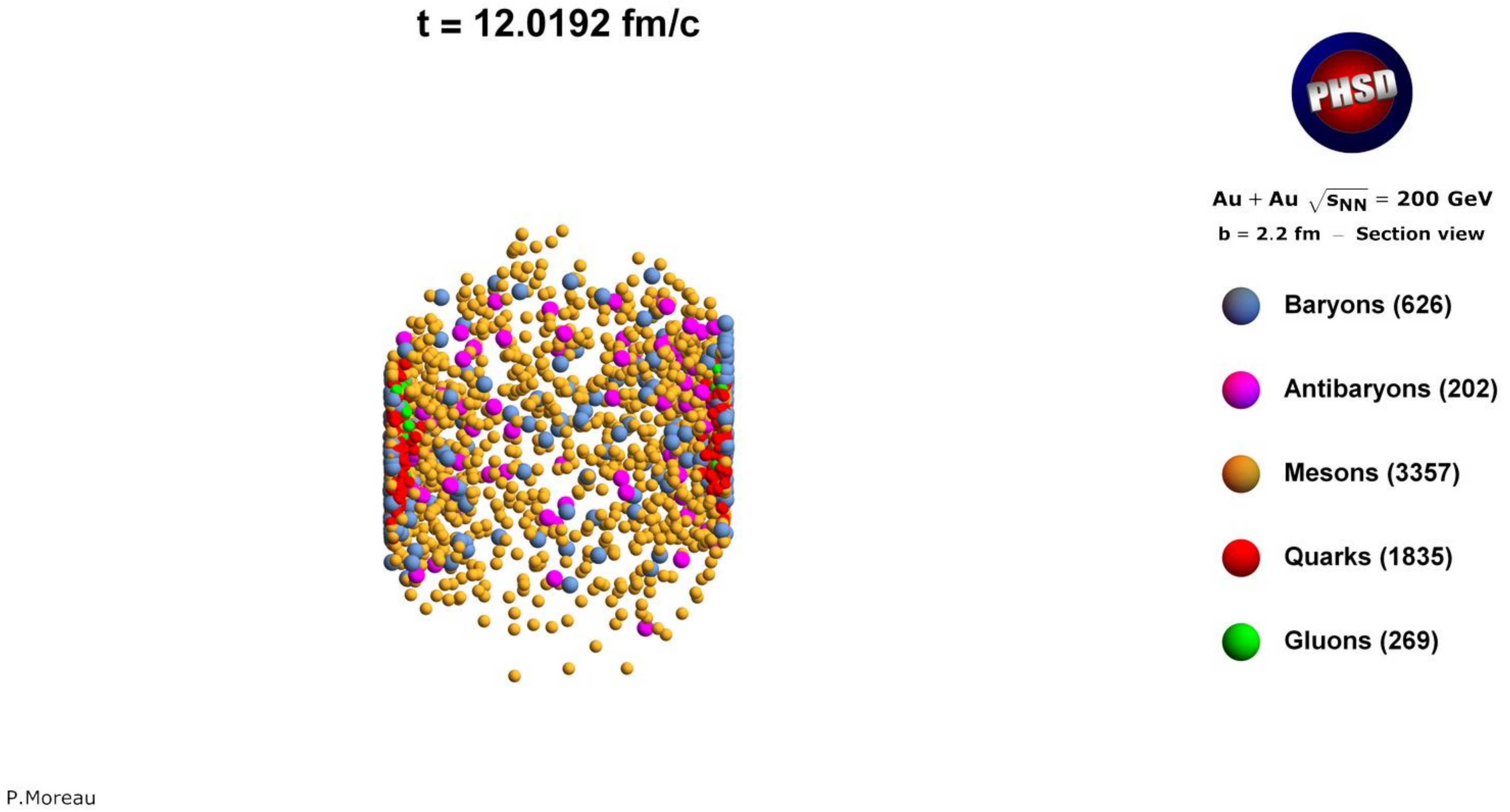


Stages of a collision in PHSD



Stages of a collision in PHSD



Stages of a collision in PHSD