

3rd Workshop on Heavy Ion Physics and Compact Stars

21-25 October 2024, Havana, Cuba



Hipstars

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)

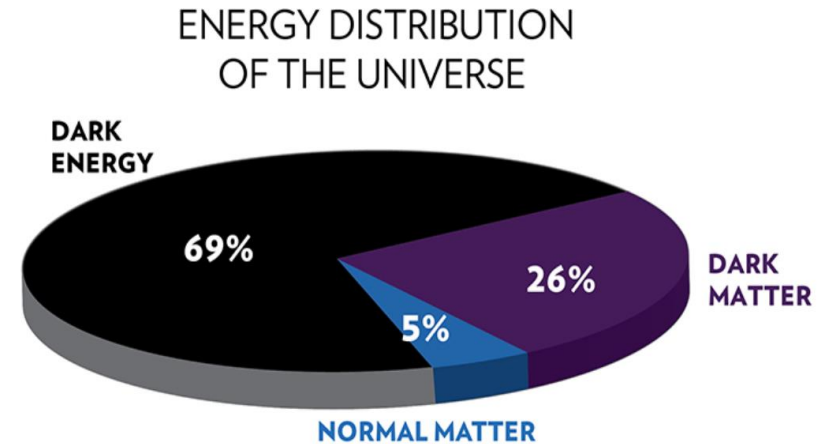
&

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:



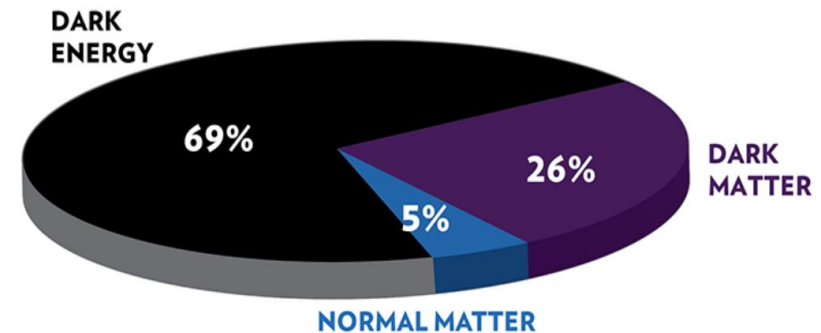
chandra.harvard.edu

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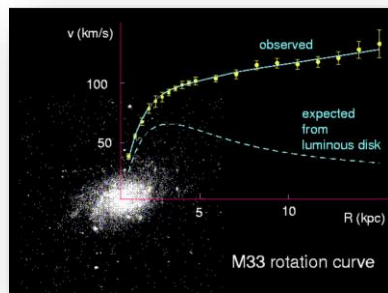
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ENERGY DISTRIBUTION OF THE UNIVERSE



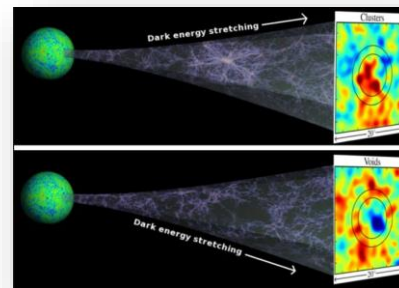
chandra.harvard.edu

Galaxy Rotation Curves



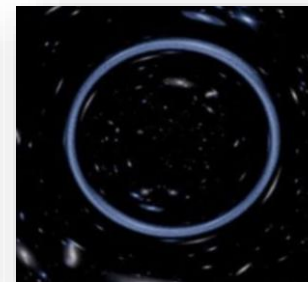
arxiv.org/abs/physics/0007025

Structure Formation



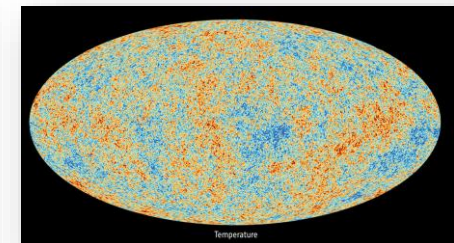
Granett, Neyrinck, Szapudi

Gravitational lensing



NASA

Cosmic Microwave Background (CMB)



ESA and the Planck Collaboration.

Dark Matter Detection

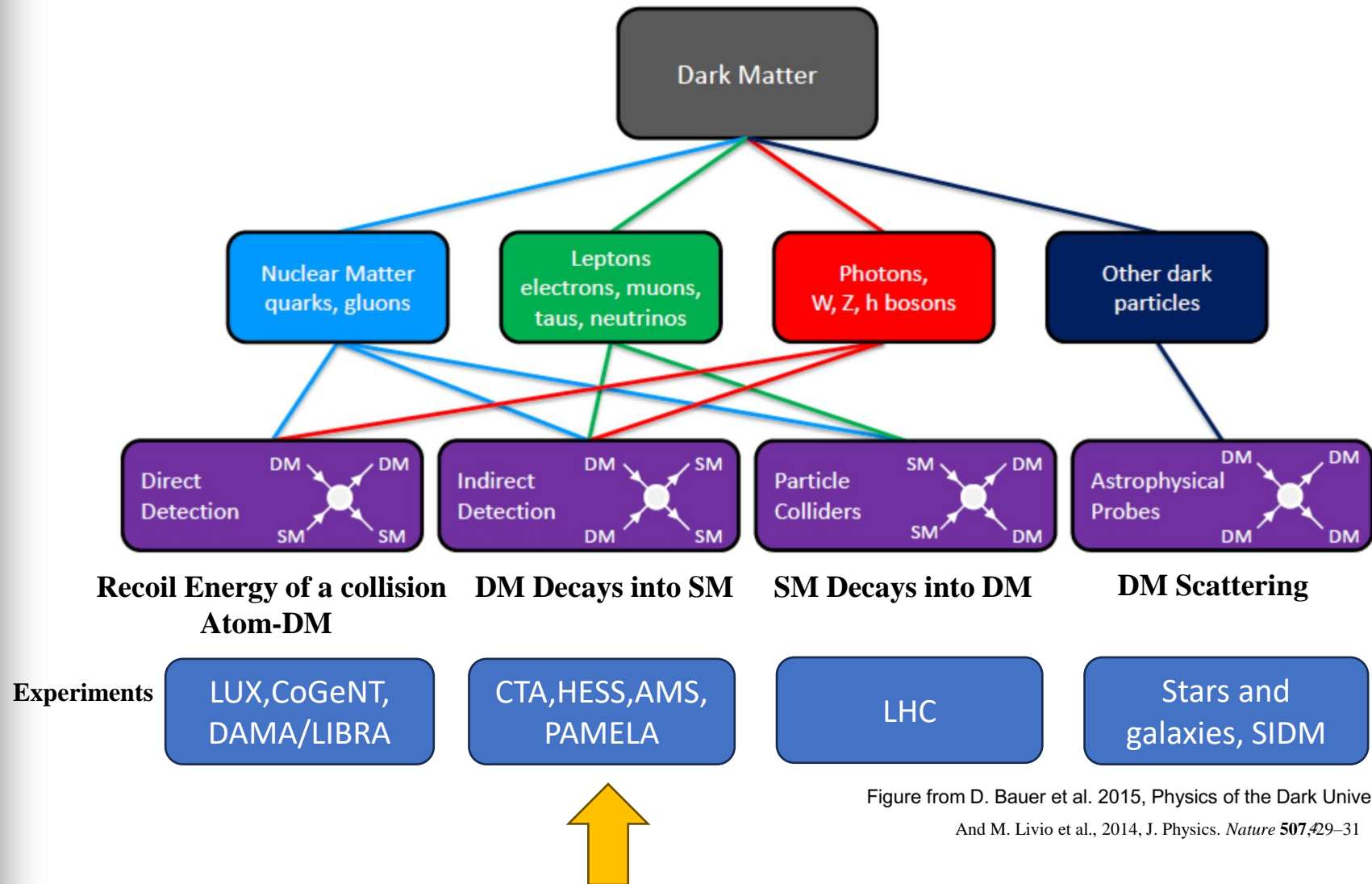
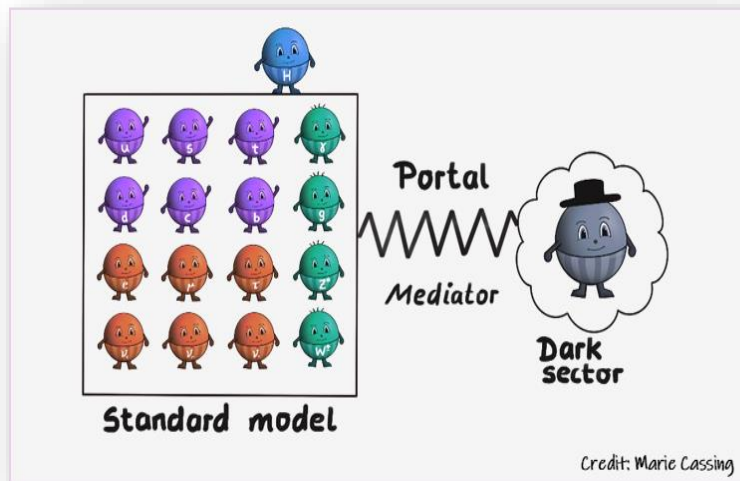
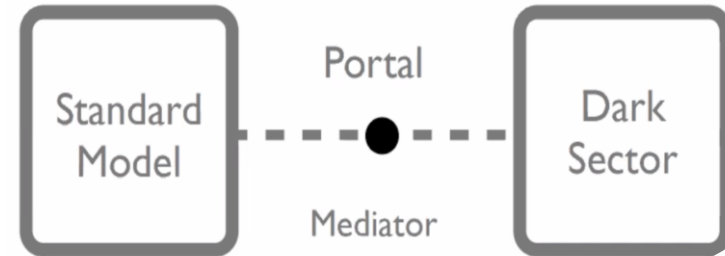


Figure from D. Bauer et al. 2015, Physics of the Dark Universe, 7, 16
 And M. Livio et al., 2014, J. Physics. *Nature* 507,429–31

Dark Matter Portals

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

Figure from Brian Battel



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

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

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

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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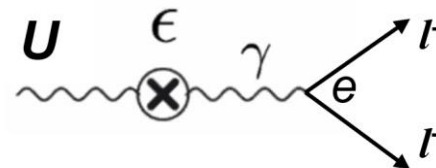
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SM hypercharge field strength:

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ϵ \rightarrow Kinetic mixing parameter

m_U \rightarrow Dark photon mass



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

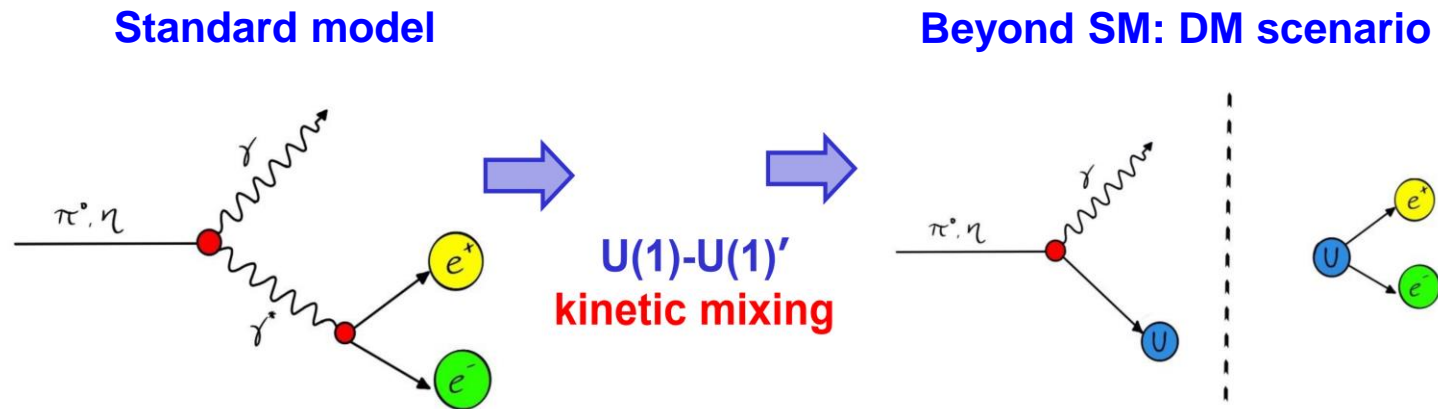
Due to the kinetic mixing the dark photon (U-boson) couples to the electromagnetic current with strength ϵe

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

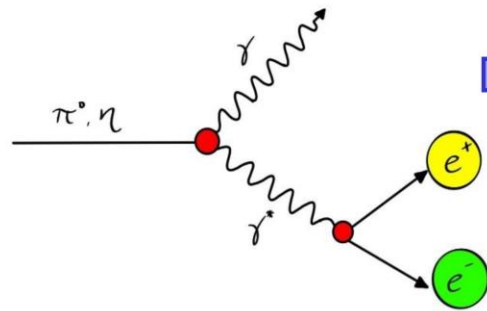
- Dalitz decays of pseudoscalar mesons π^0, η and Δ -resonances to dileptons via the U-boson mediator



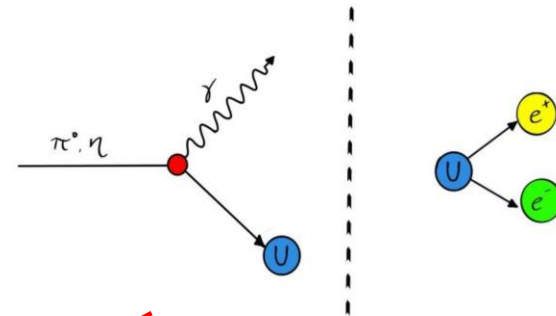
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Standard model

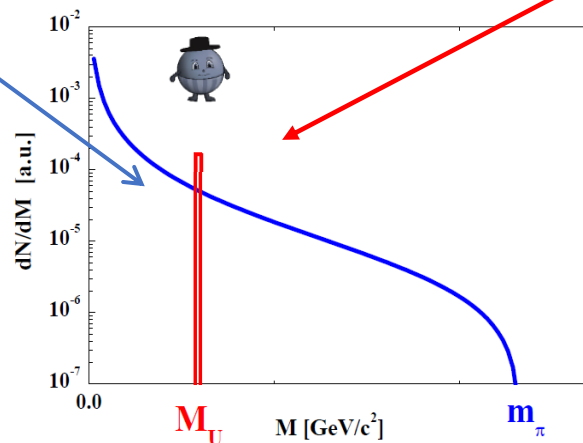


Beyond SM: DM scenario



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

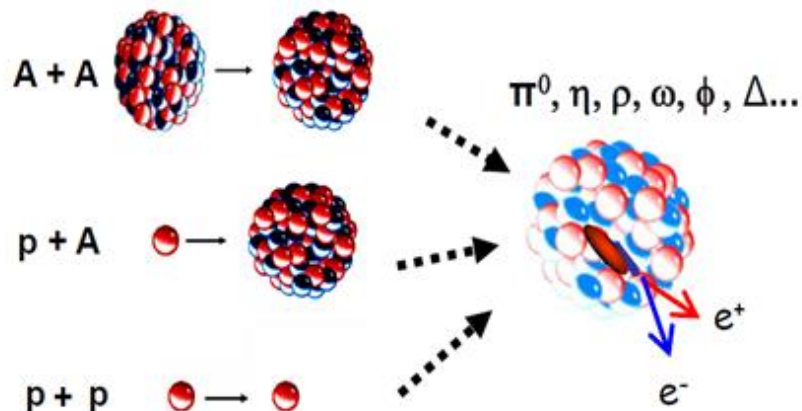
$\pi^0 \rightarrow \gamma + \gamma^*$,
 $\eta \rightarrow \gamma + \gamma^*$, $\gamma^* \rightarrow e^+e^-$
 $\Delta \rightarrow N + \gamma^*$,
 ...



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

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

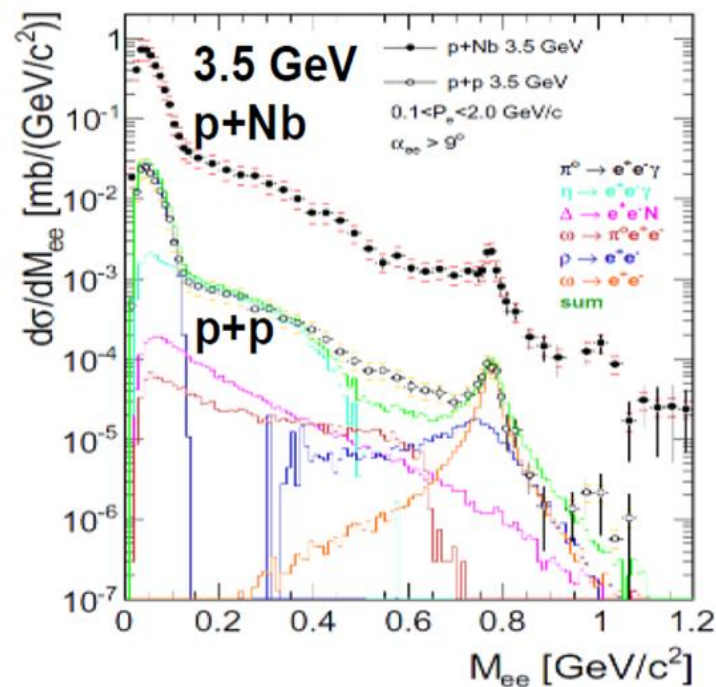
Possible dark photon observation by dilepton experiments



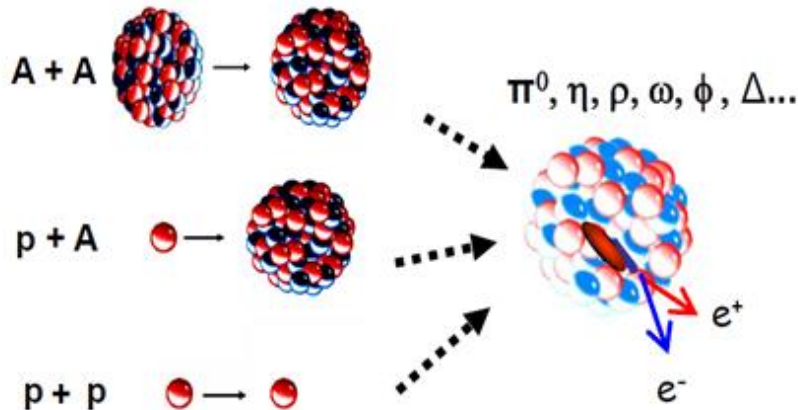
□ Dilepton spectra from SM sources are well studied by dilepton experiments from SIS to LHC energies (HADES, STAR,...)

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

Dilepton spectra at low M ('cocktail')



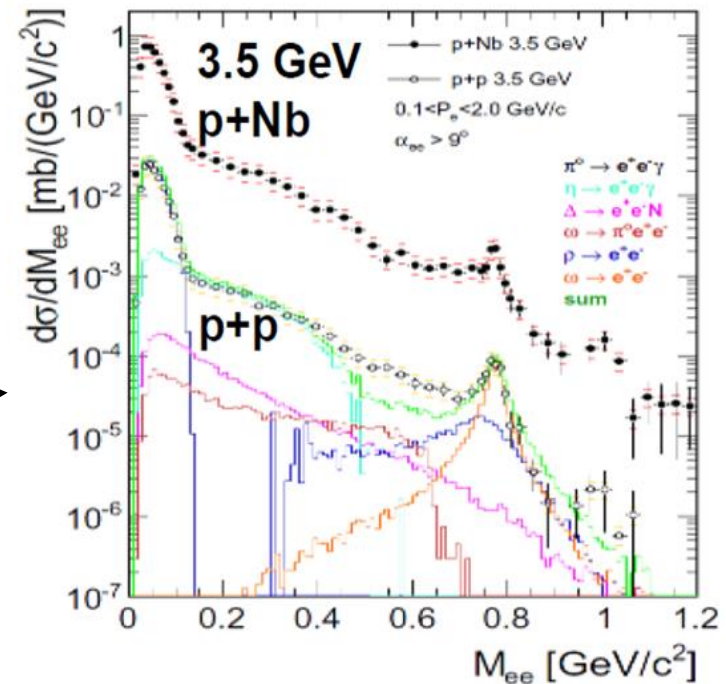
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 - Dalitz π^0, η and Δ decays are the **dominant dilepton sources at low M**
- Possibility for an **experimental observation** of dark photons by **electromagnetic decays** $U \rightarrow e^+ e^-$ in heavy-ion experiments

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



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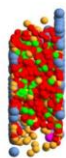
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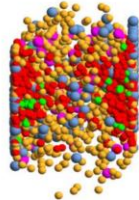
Initial State:
Au+Au
200 GeV, b=2 fm



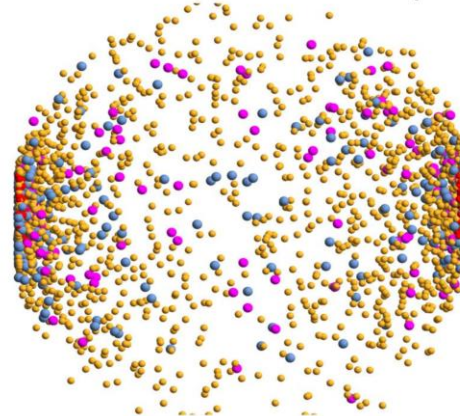
Quark Gluon Plasma: IQCD
EoS. Non-perturbative QCD
quasiparticles



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

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

$$\Delta \rightarrow N U$$

$$\omega \rightarrow \pi^0 U$$

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



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

Direct Decay

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

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Production of hadron \rightarrow decay to $U \rightarrow$ dilepton yield from U -
boson decay of mass m_U :

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

$$h \rightarrow X + U$$

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

$$= Br^{U \rightarrow e^+ e^-} \times$$

$$\sum_{h=1}^8 N_{h \rightarrow XU}$$

$$N_{h \rightarrow XU} = N_h Br^{h \rightarrow XU}$$

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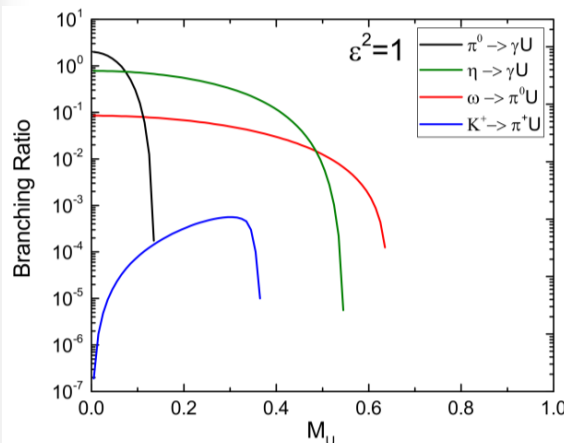
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$$Br(P \rightarrow \gamma U) = \epsilon^2 Br(P \rightarrow \gamma \gamma) \left(1 - \frac{m_U^2}{m_P^2}\right)^3 \quad P = \pi, \eta$$

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

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

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

$$Br(V \rightarrow U) = \frac{\alpha \epsilon^2 m_U}{3 \Gamma_T(V)}$$

$$V = \rho, \phi, \omega$$

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

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

new channels in PHSD

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

Dark photon production in PHSD

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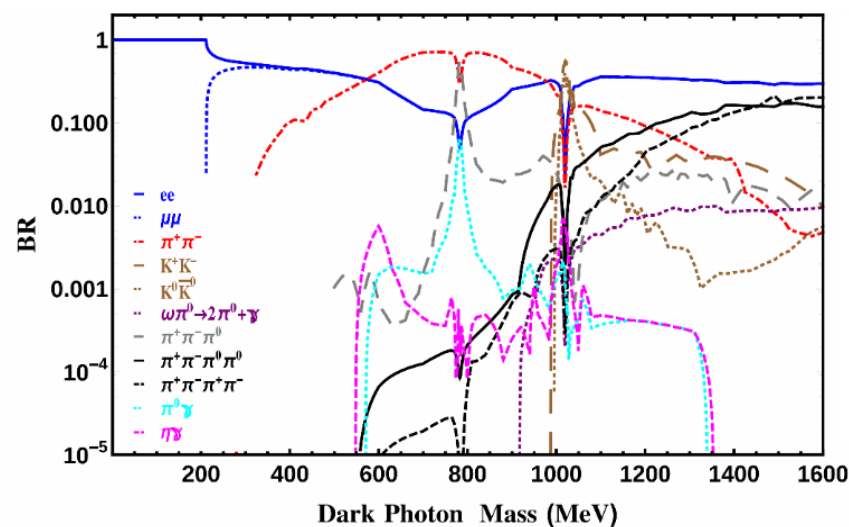
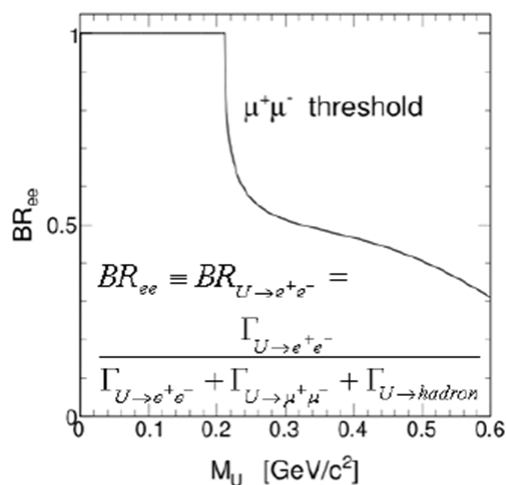
Direct Decay

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

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

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

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



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

Dark photon production in PHSD

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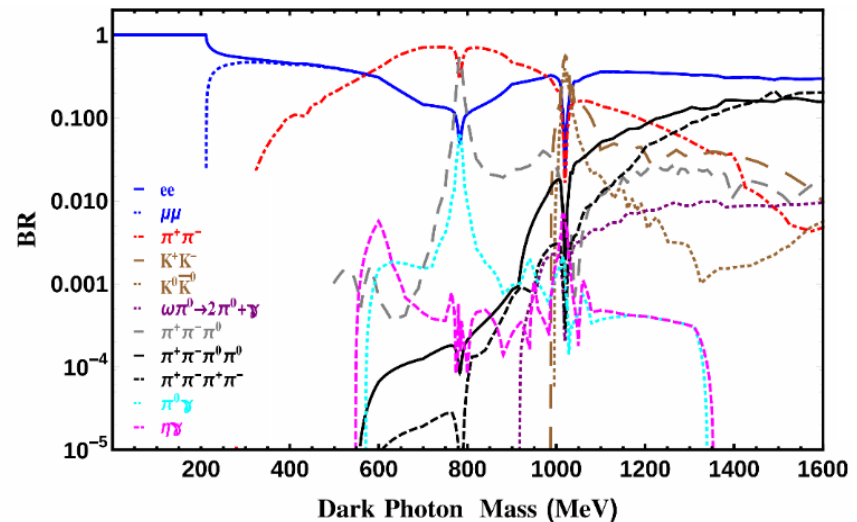
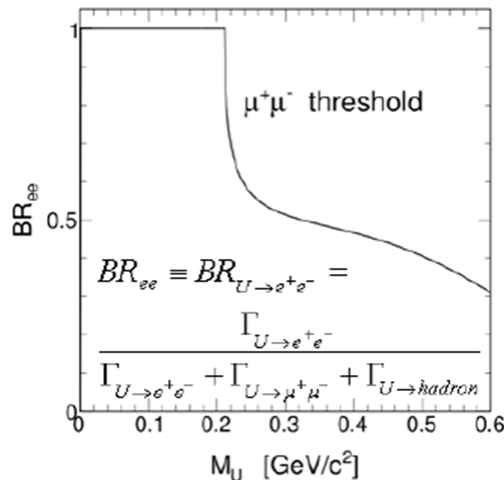
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J. Liu et al. JHEP 08, 050 (2015)

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

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

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 $U \rightarrow e^+e^-$ contributions** (kinematically possible in this mass bin)

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

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

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

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



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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.

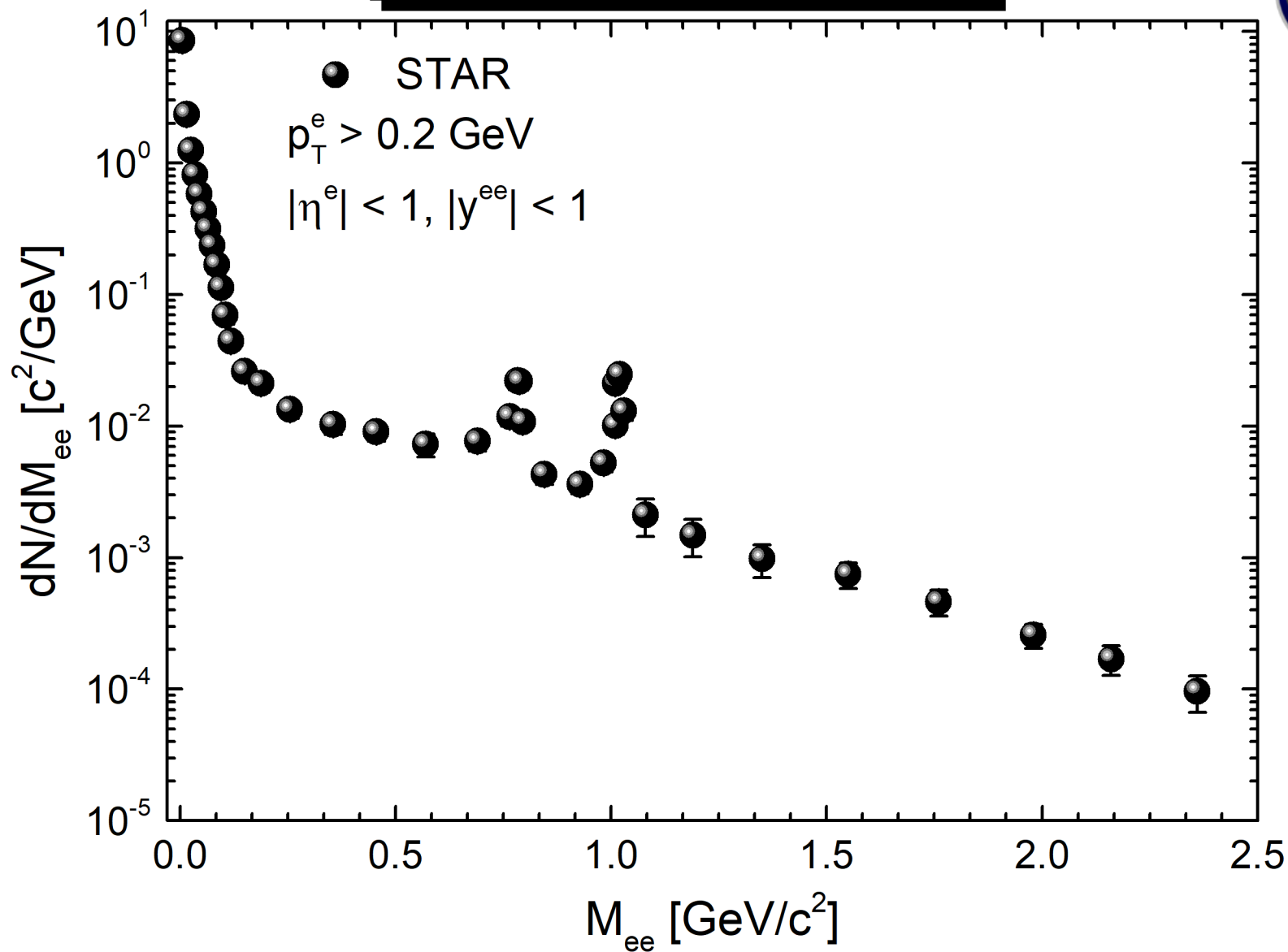
$$\frac{dN^{total}}{dM} = (1 + \boxed{C_U}) \frac{dN^{sumSM}}{dM} \quad \Rightarrow \quad C_U \text{ controls the allowed "surplus" dilepton yield resulting from dark photons on top of the total SM yield}$$

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

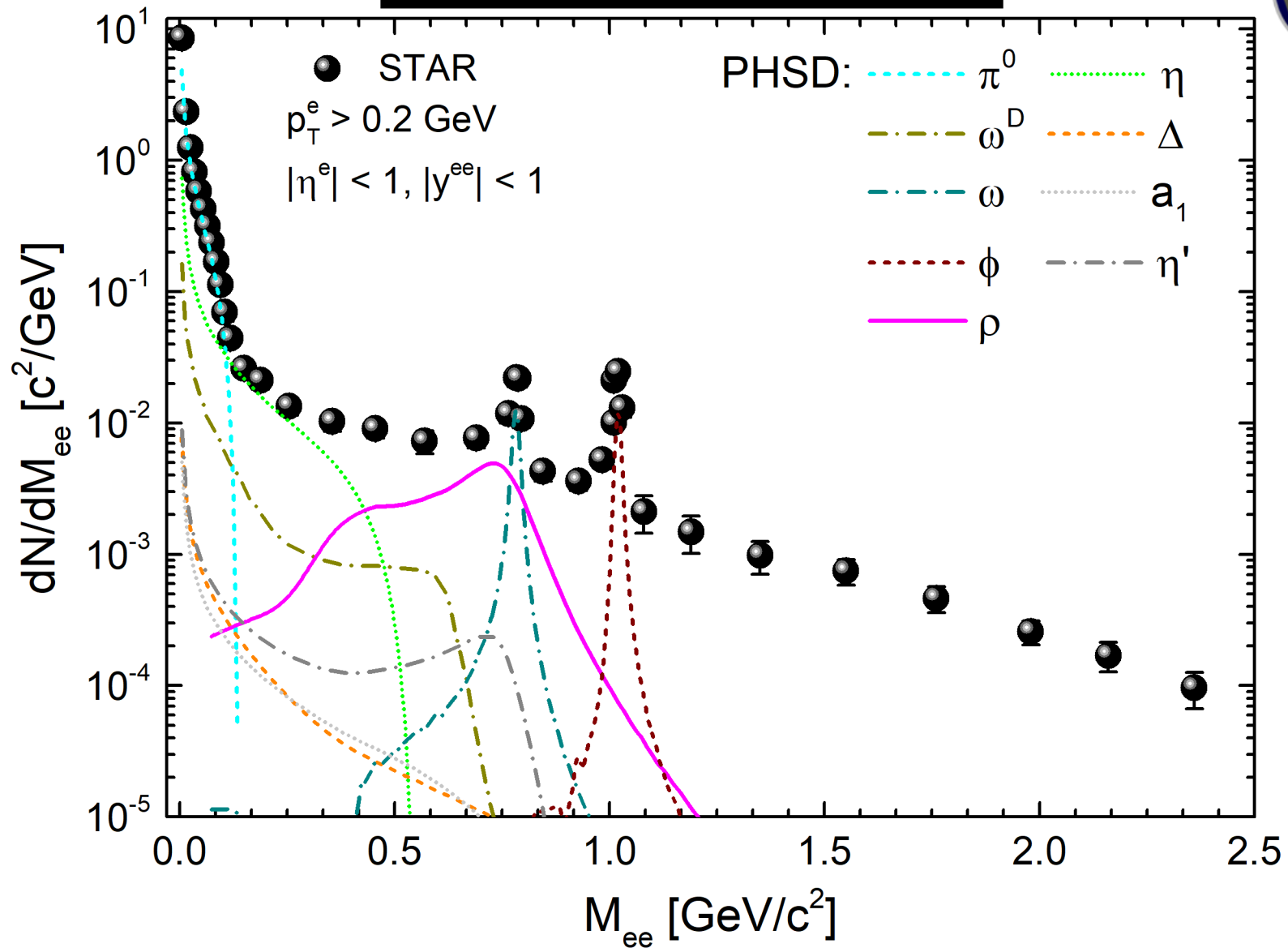
$$\varepsilon^2(m_U) = C_U \cdot \left(\frac{dN^{sumSM}}{dM} \right) / \left(\frac{dN_{\varepsilon^2=1}^{sumU}}{dM} \right)$$



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

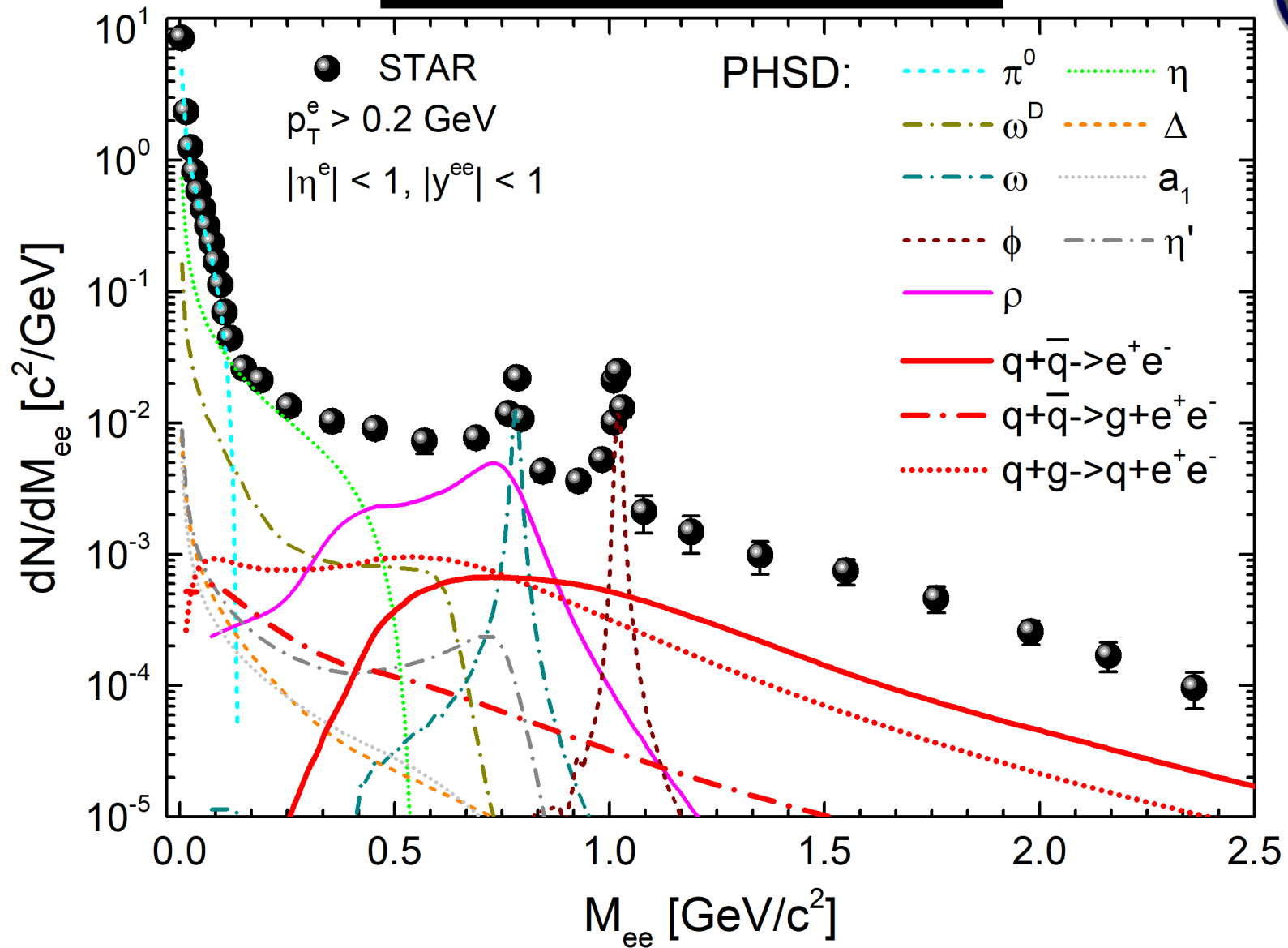


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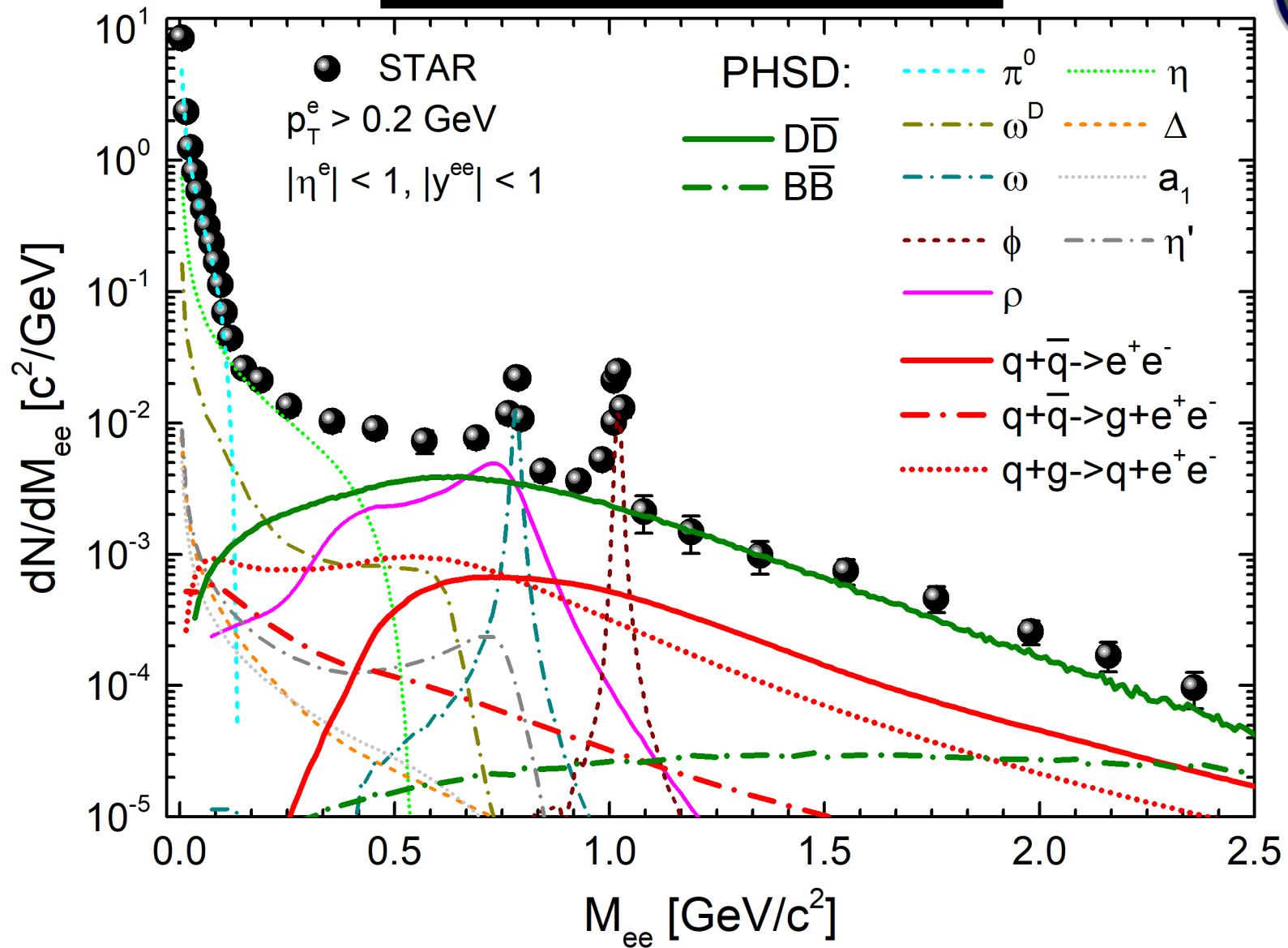


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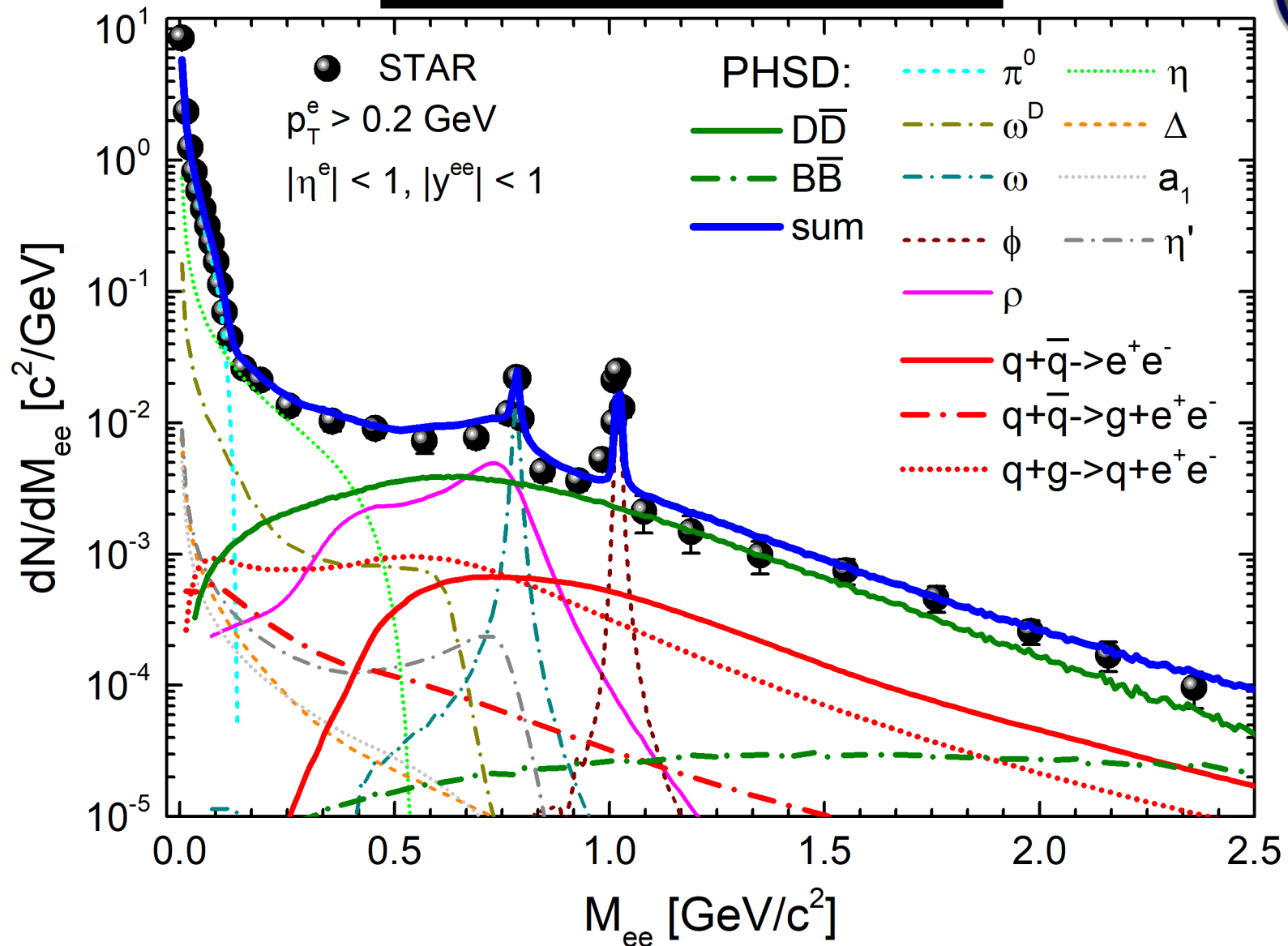


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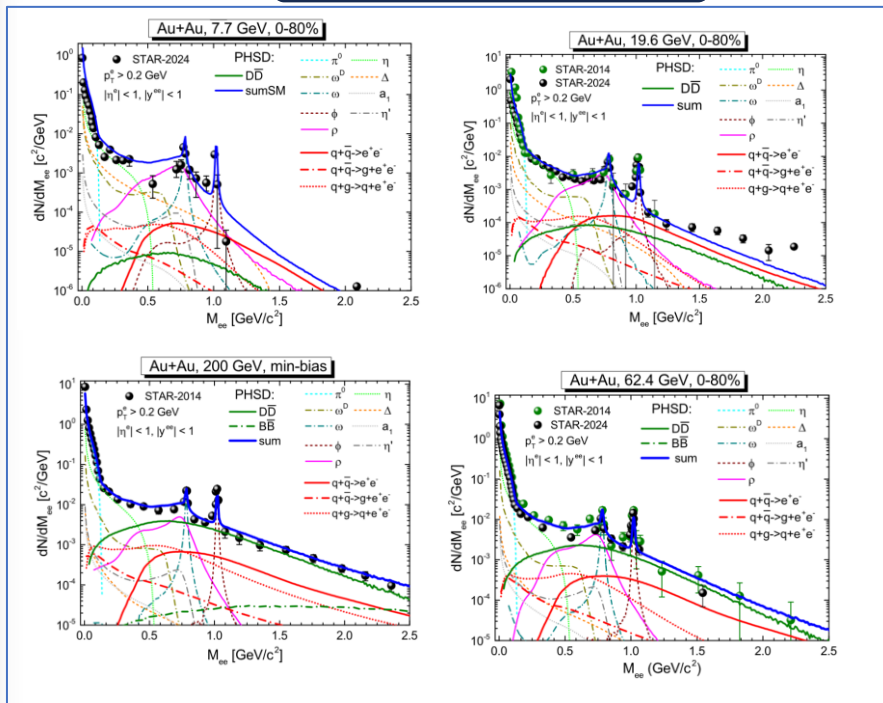


Dilepton mass spectra Au+Au, 200 GeV, min-bias

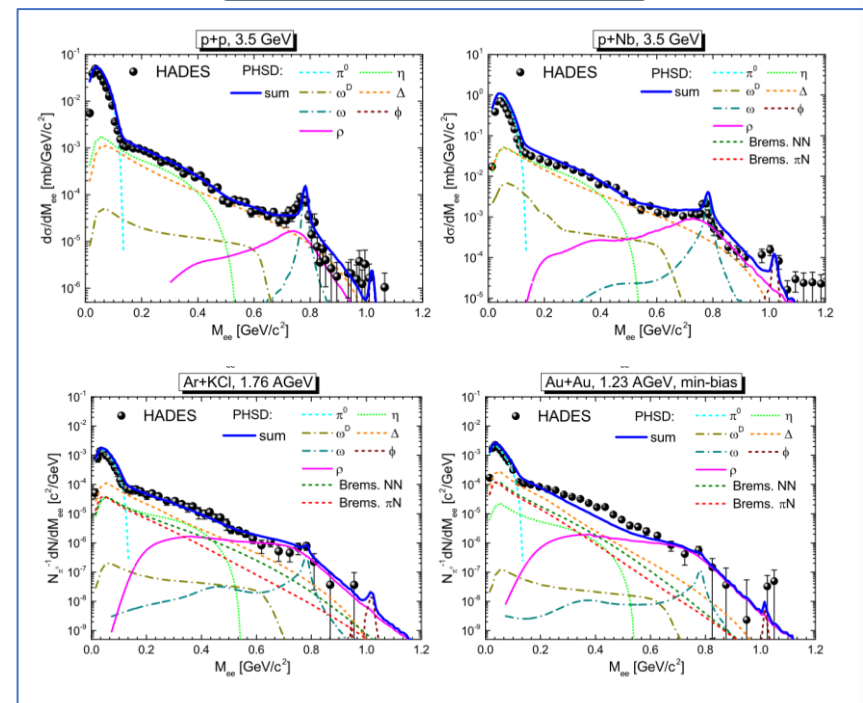


Dilepton spectra from PHSD from SIS18 to RHIC energies

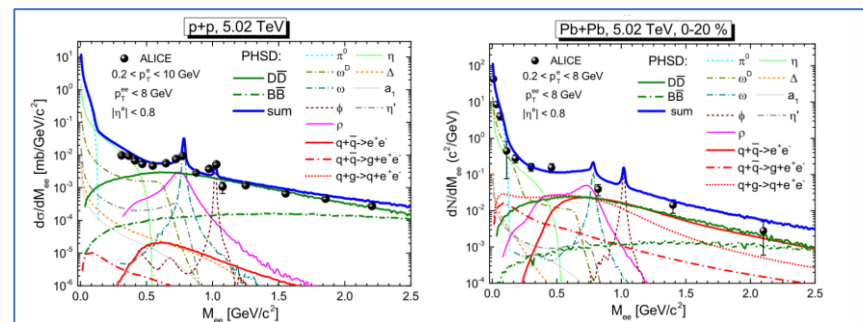
BES-LHC-STAR



SIS18-HADES



ALICE

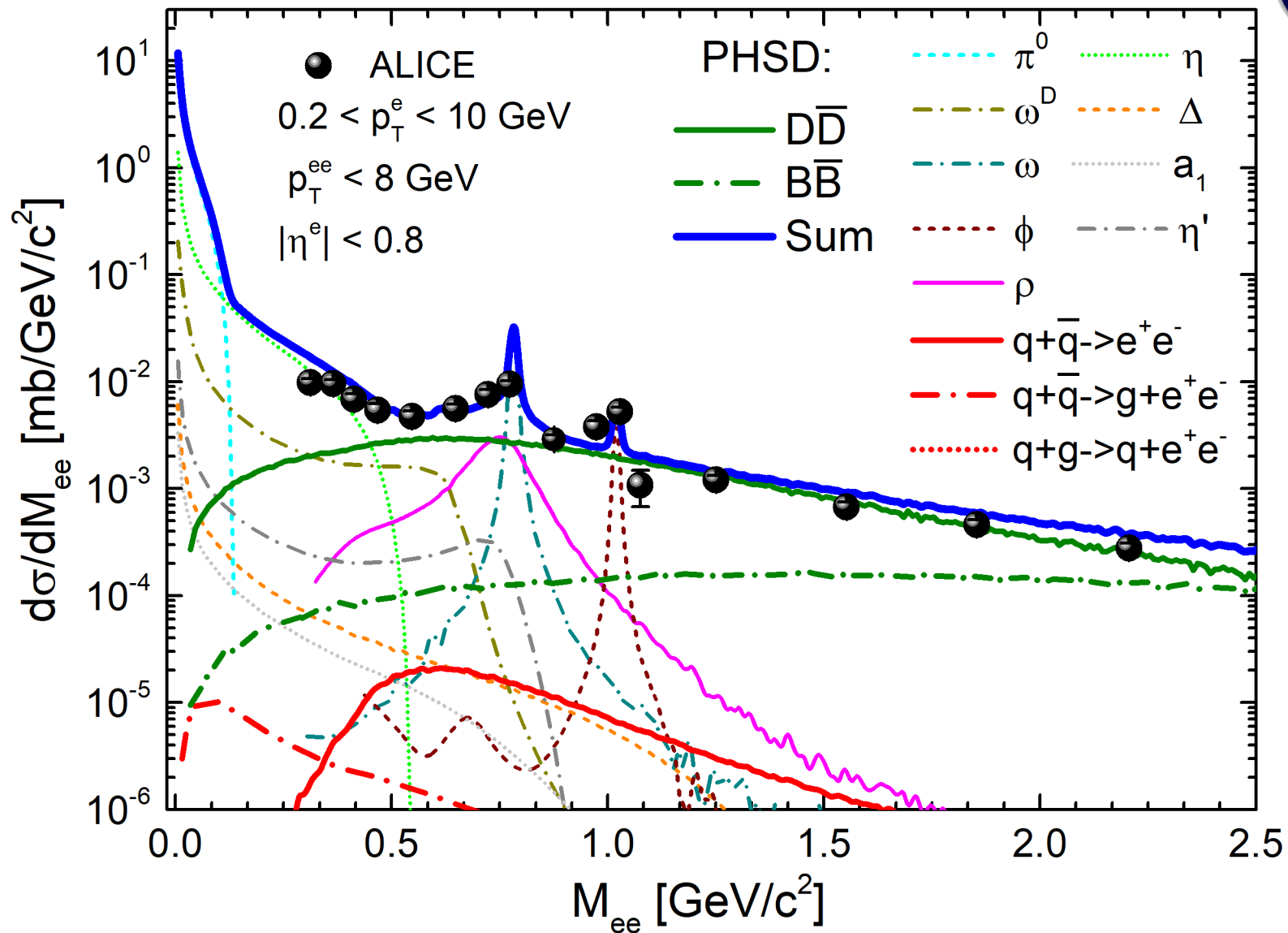


- The STAR/HADES/ALICE data, i.e. **SM contributions** (including exp. acceptance) are well described by the PHSD



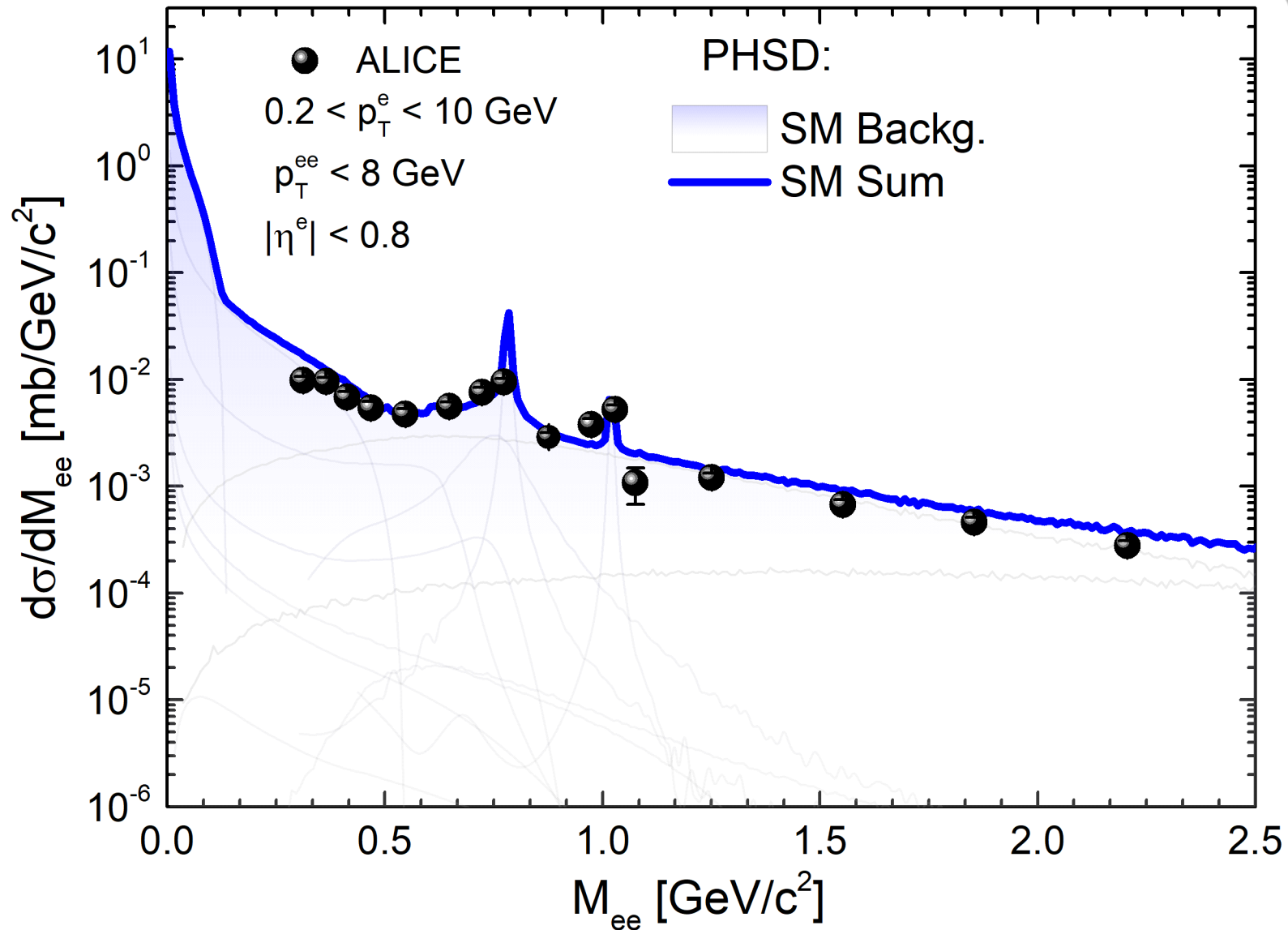
Dilepton mass spectra

p+p, 5.02 TeV

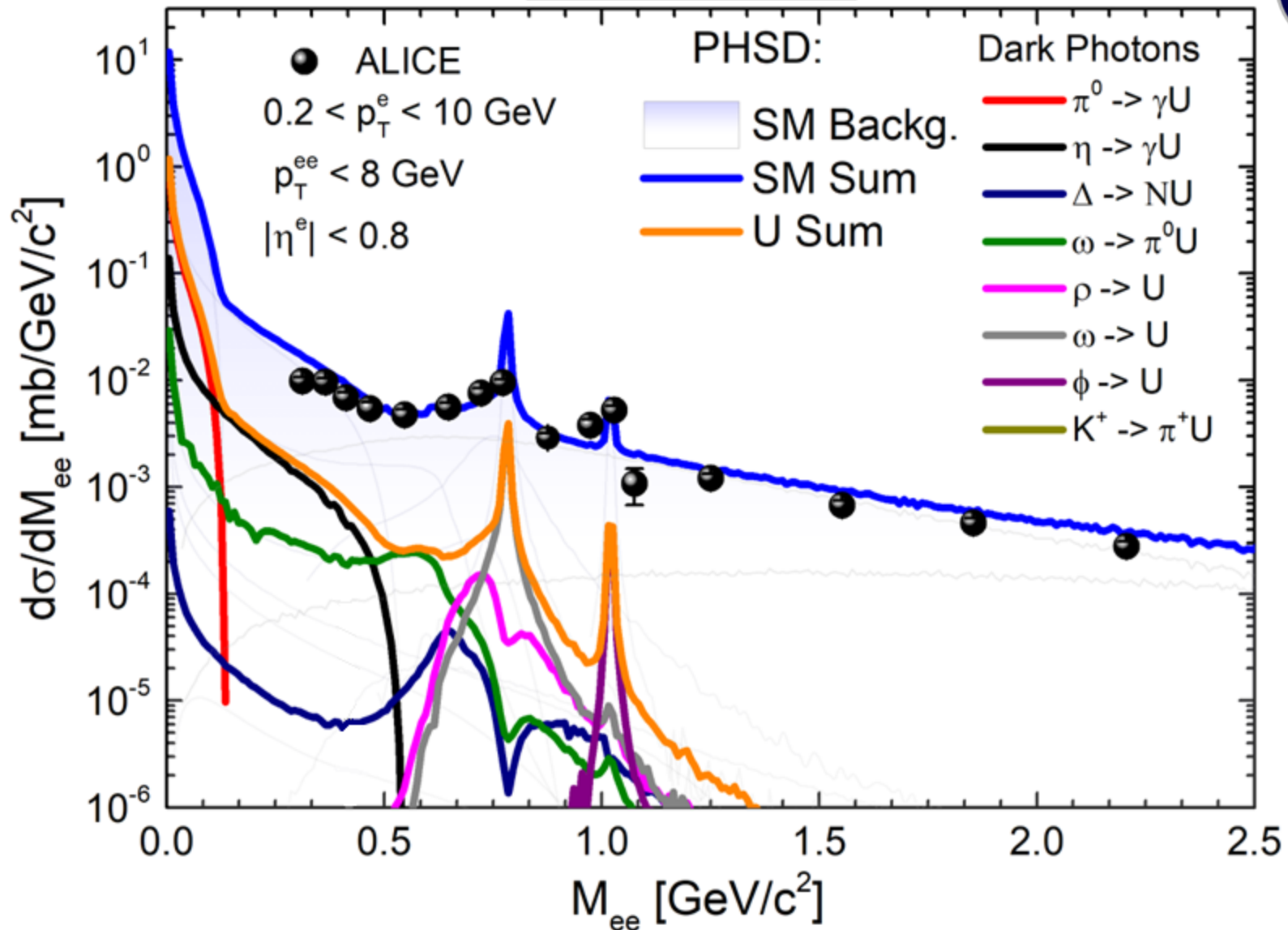


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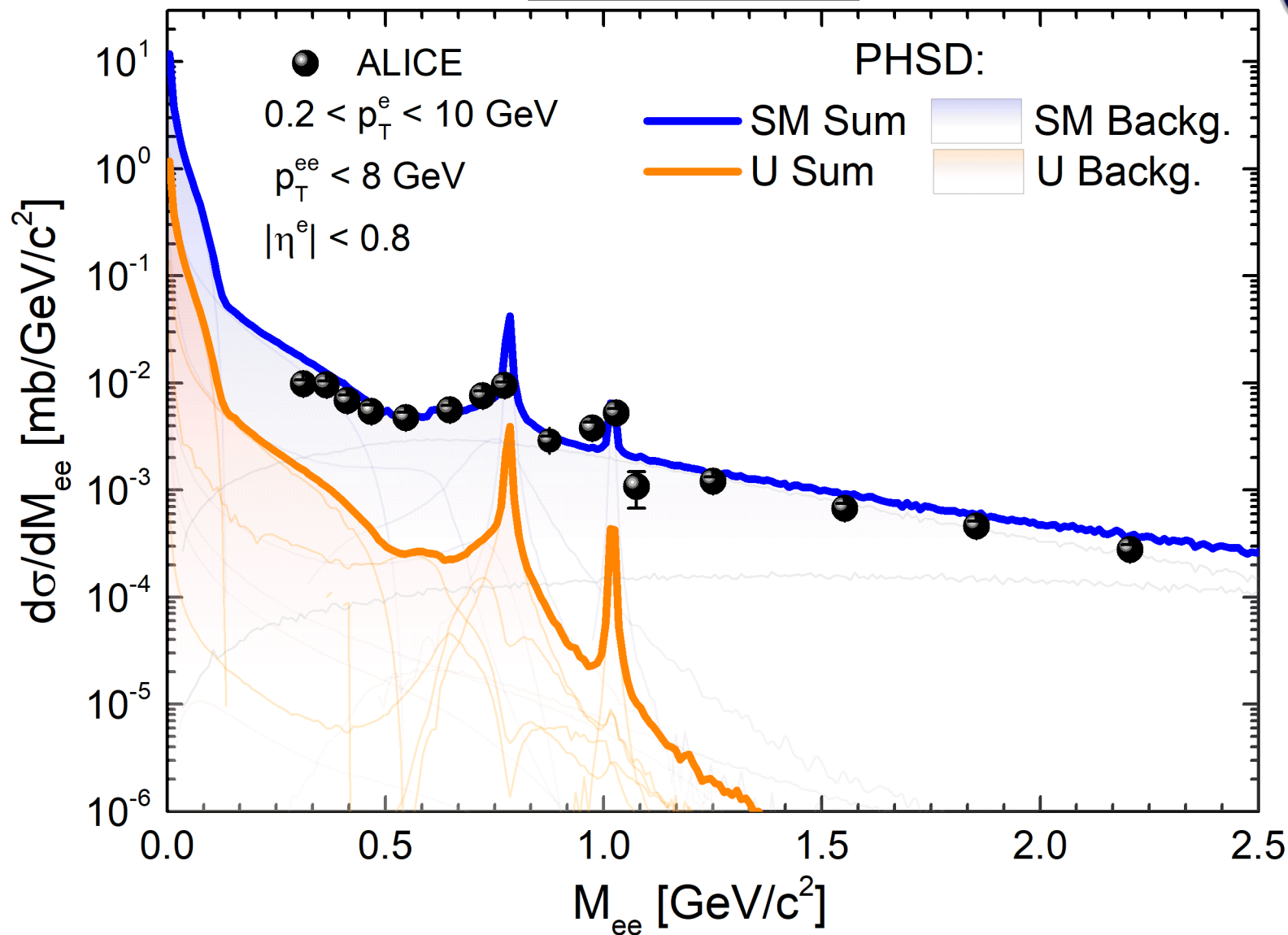


Dilepton mass spectra

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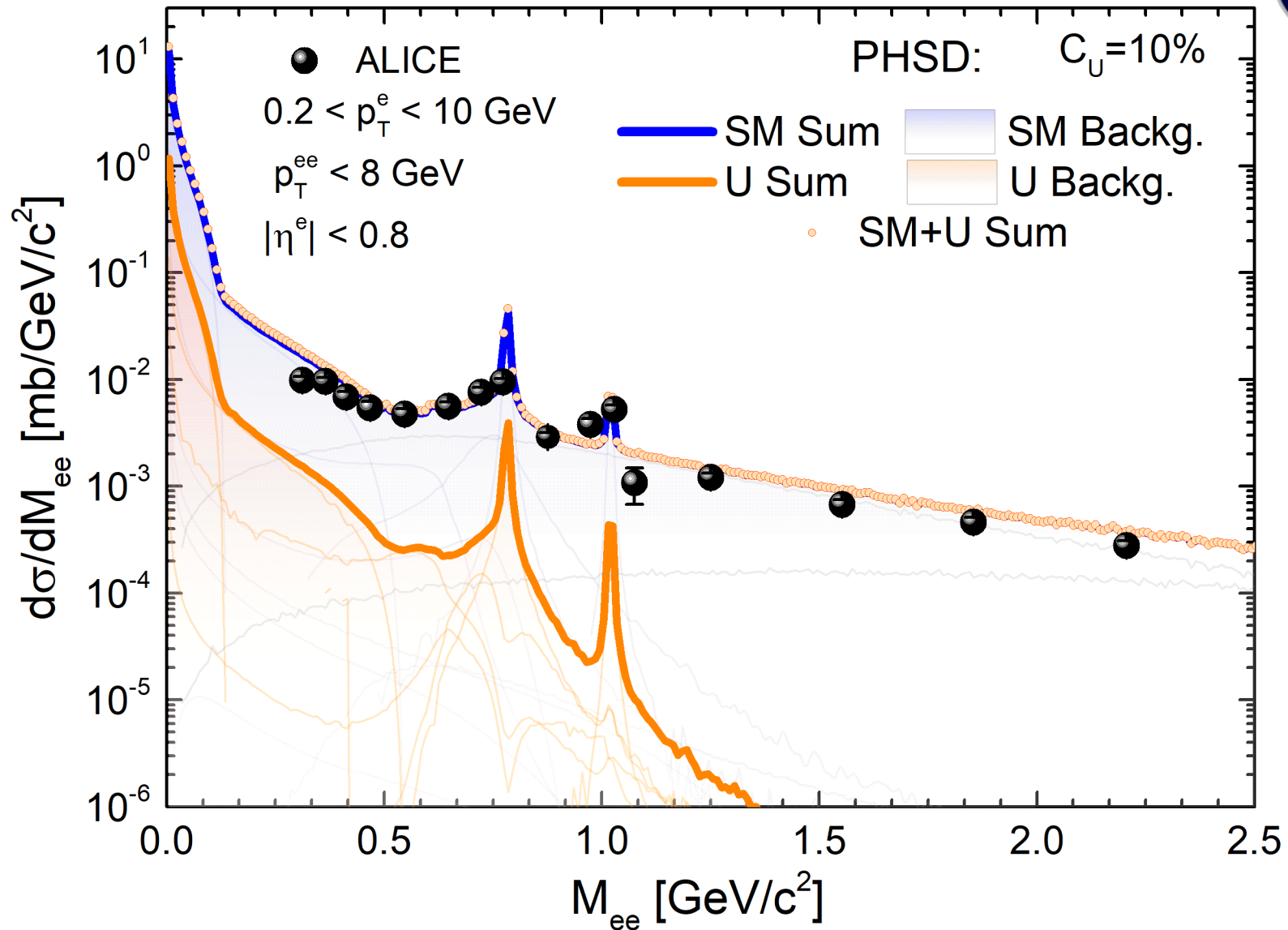
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Dilepton mass spectra

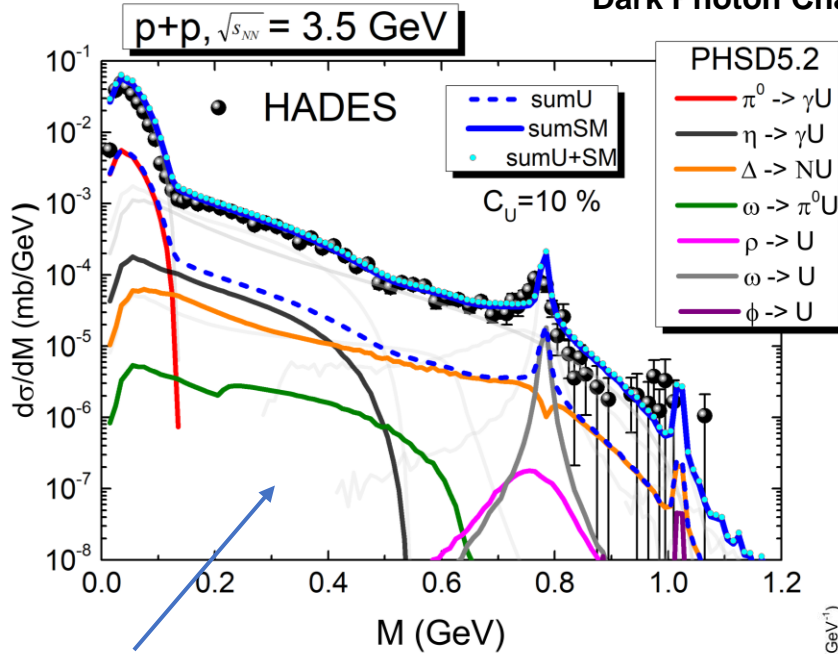
p+p, 5.02 TeV



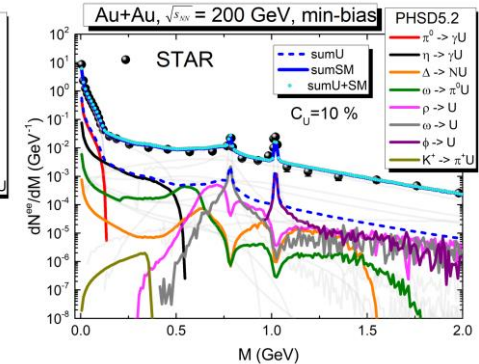
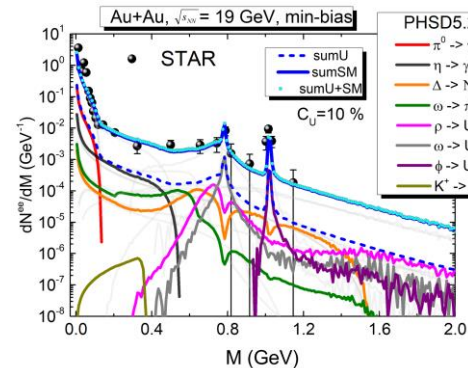
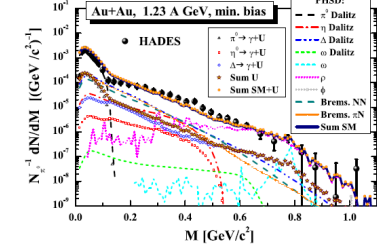
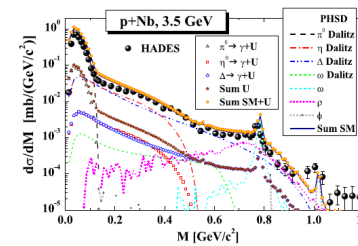
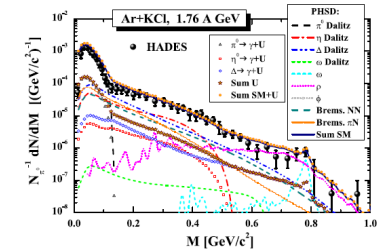
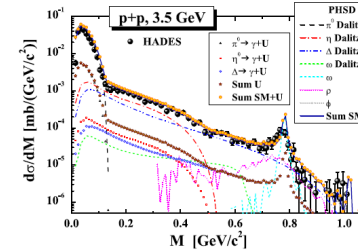


Dilepton spectra from U-boson decays

Dark Photon Channels



Gray lines
display SM
decay channels



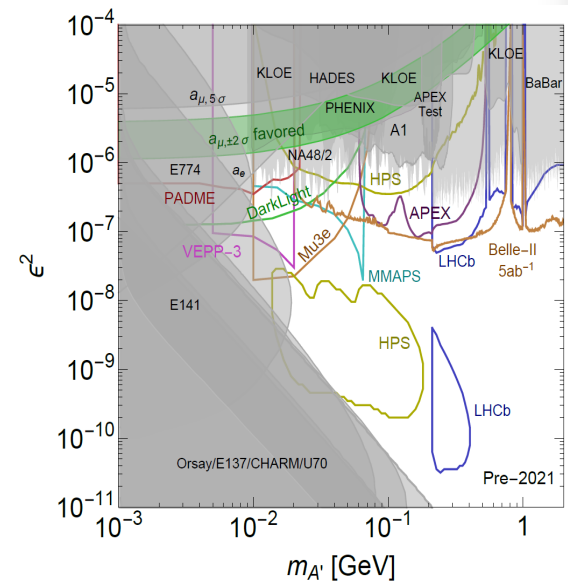
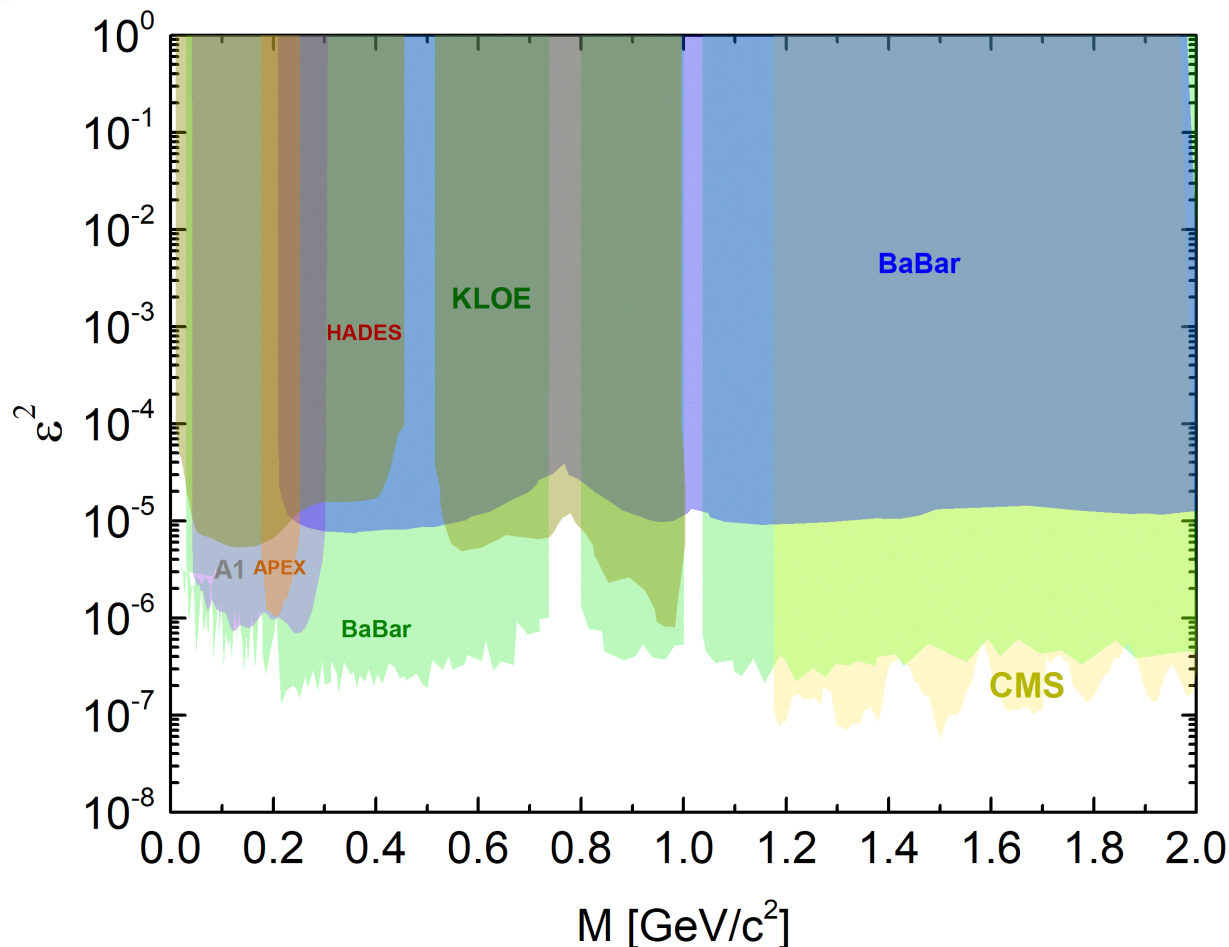
- The contributions from $U \rightarrow e^+e^-$ are added with $C_U=10\%$ allowed surplus of the total SM yield
- → the total sum is still in a good agreement with exp. data

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

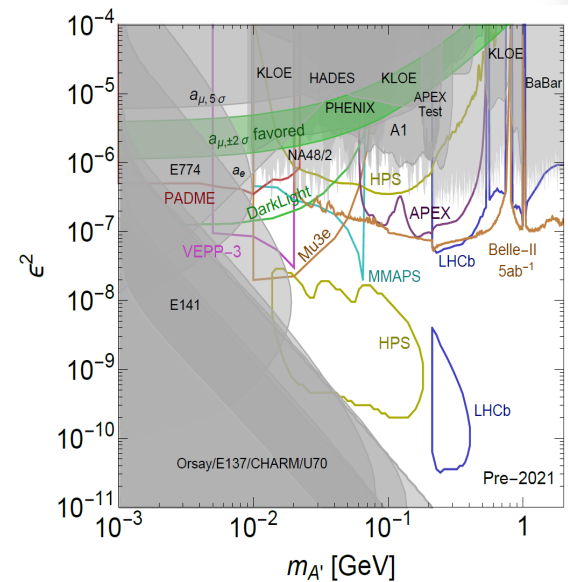
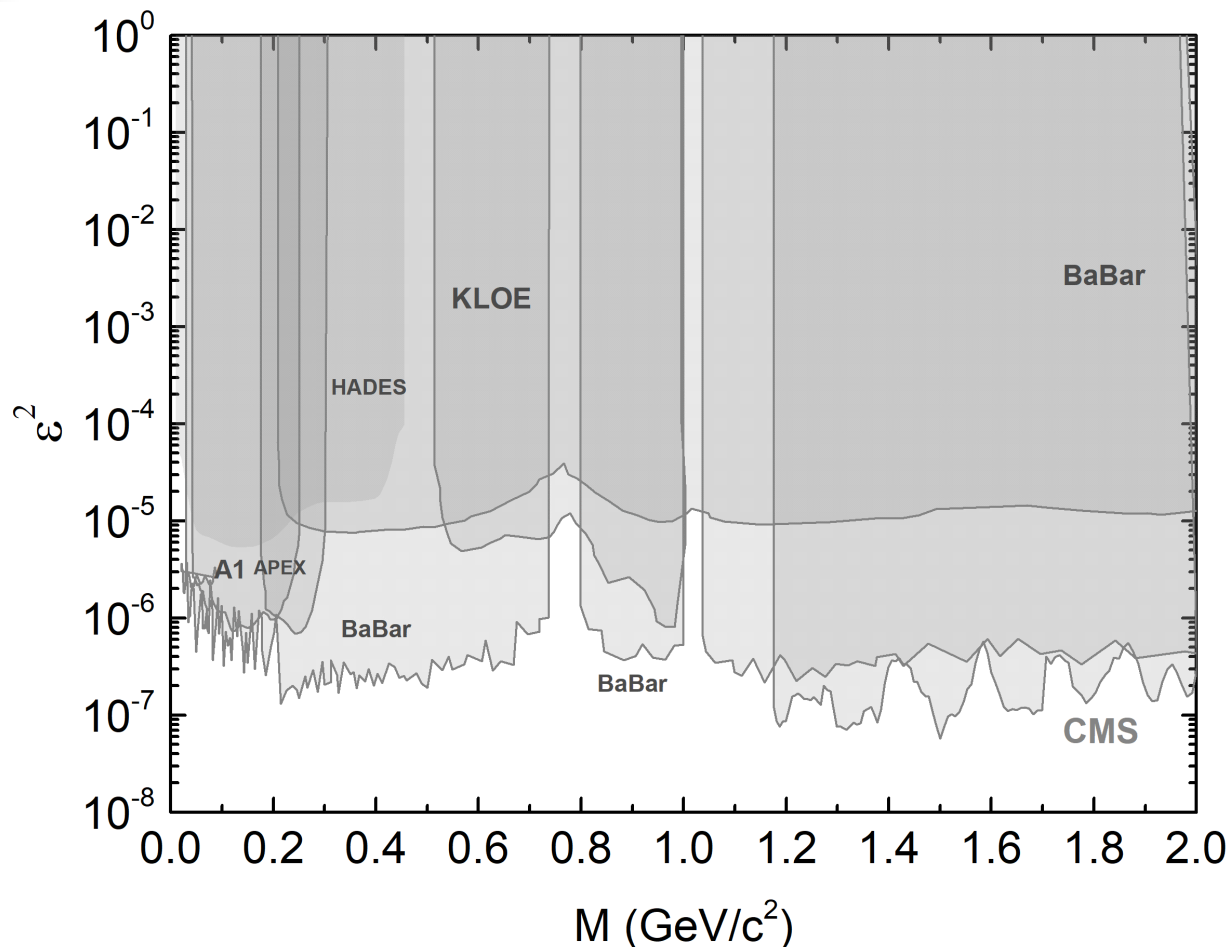


J. Alexander et al. (2016), 1608.08632



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

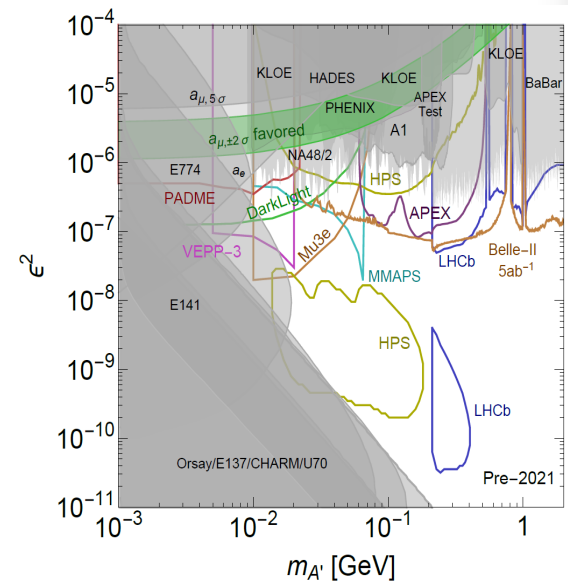
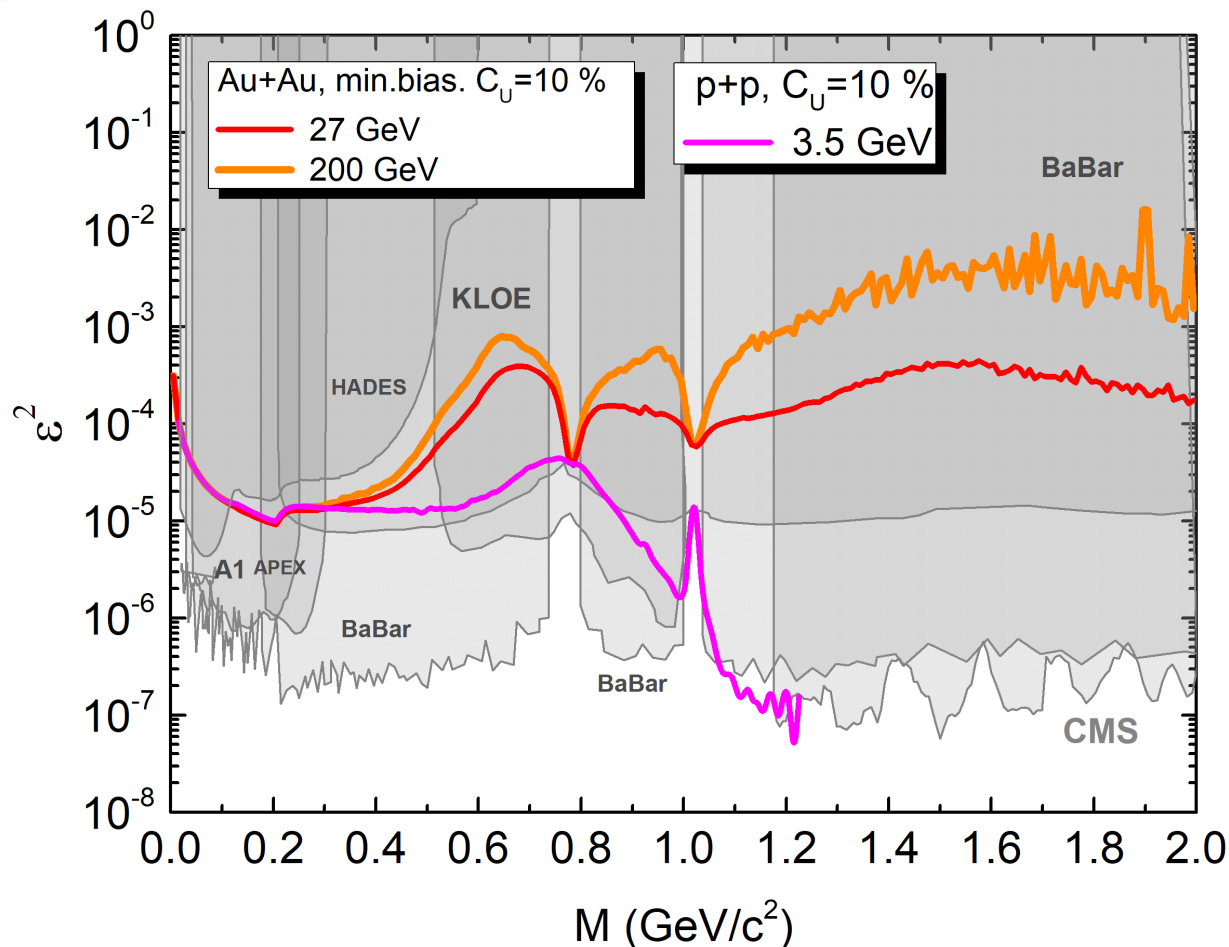


J. Alexander et al. (2016), 1608.08632



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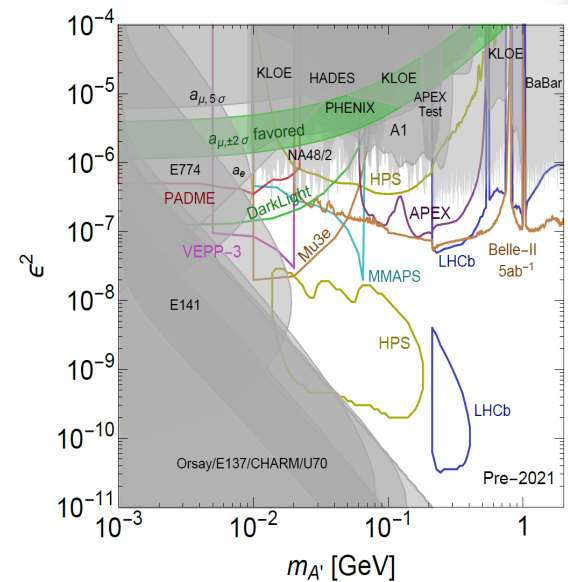
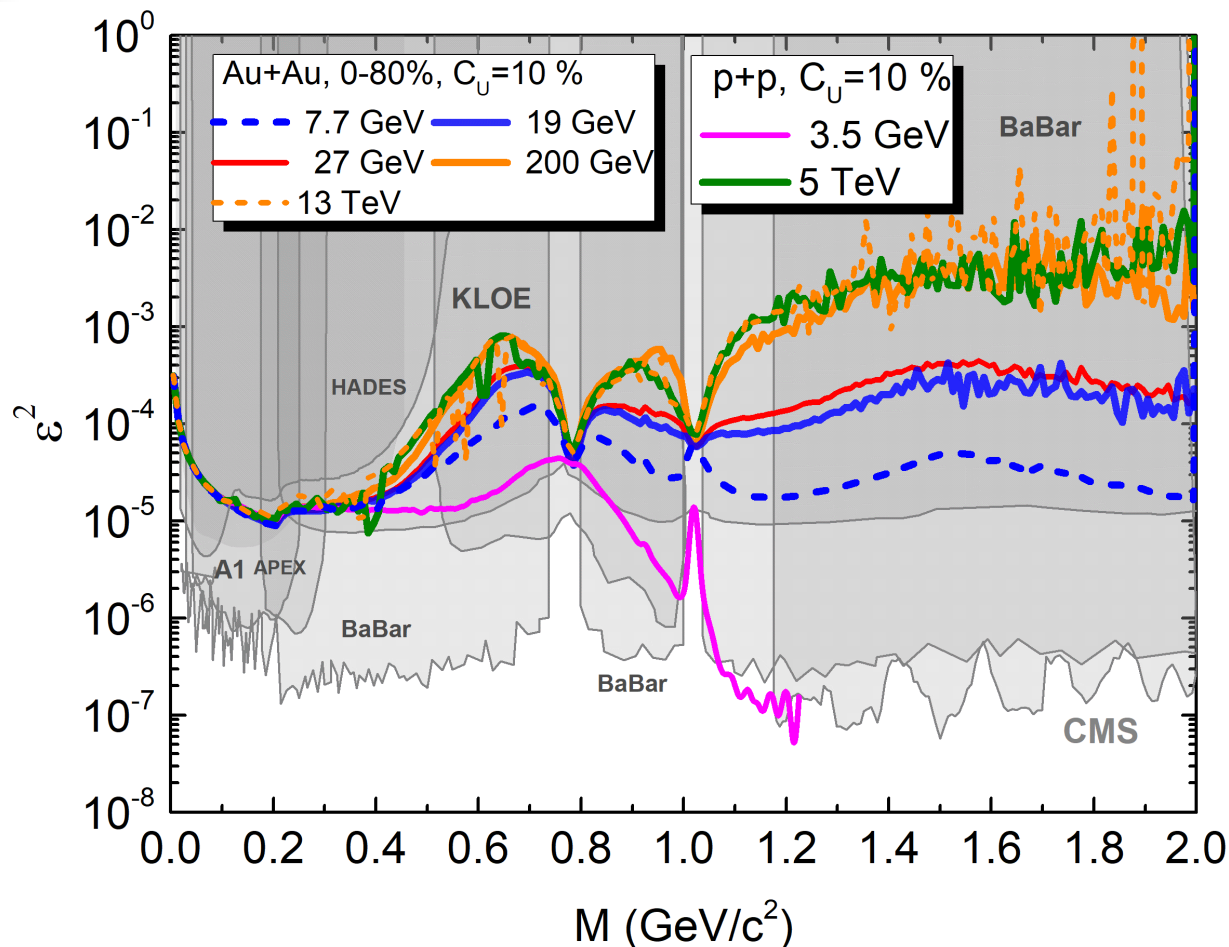


J. Alexander et al. (2016), 1608.08632



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

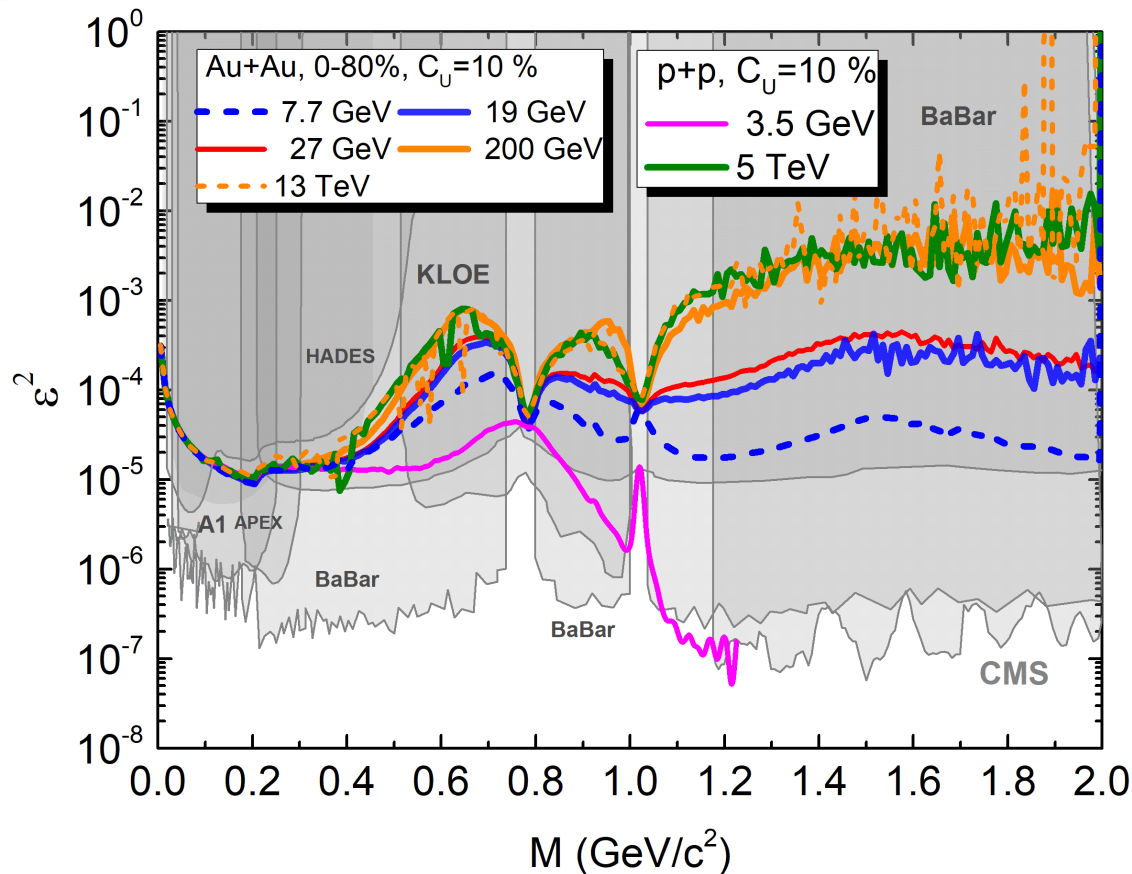


J. Alexander et al. (2016), 1608.08632



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



$\varepsilon^2(m_U)$ for $C_U = 10\%$ is consistent with the exp. data from

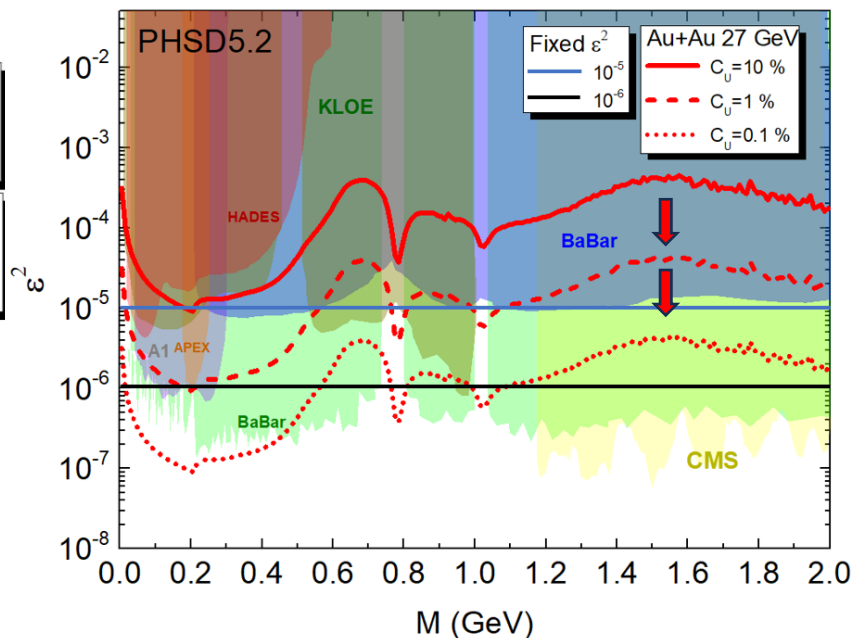
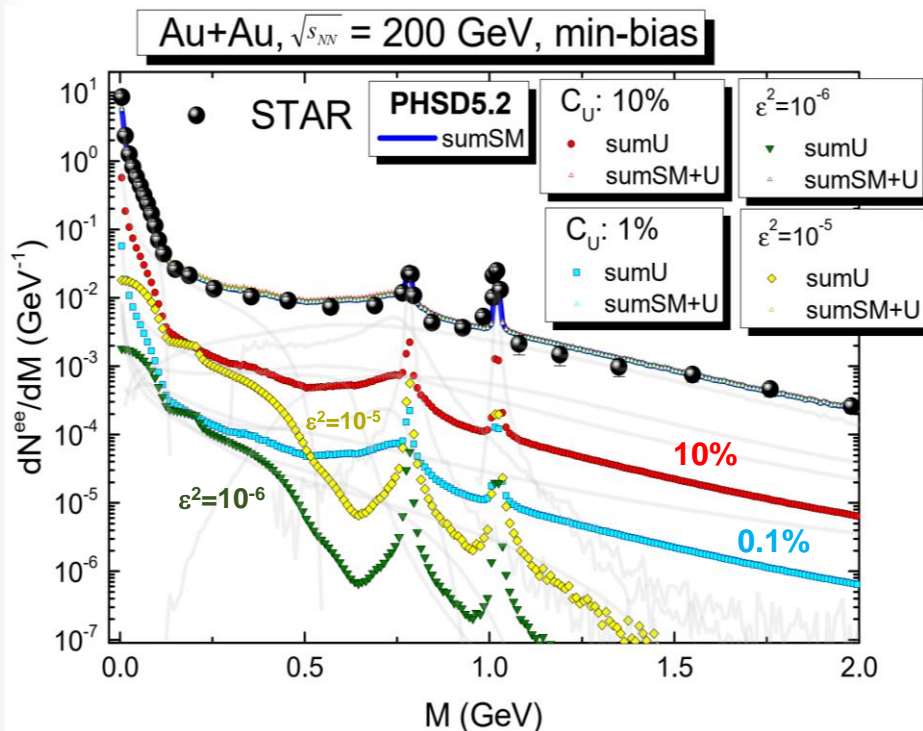
- BaBar ($0.2 < m_U < 0.9$ GeV)
- KLOE ($0.2 < m_U < 1$ GeV)

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

→ Perspectives:

- Include dark photon decays from other possible channels
- Explore the axion portal
- Look for constraints in astrophysics and cosmology



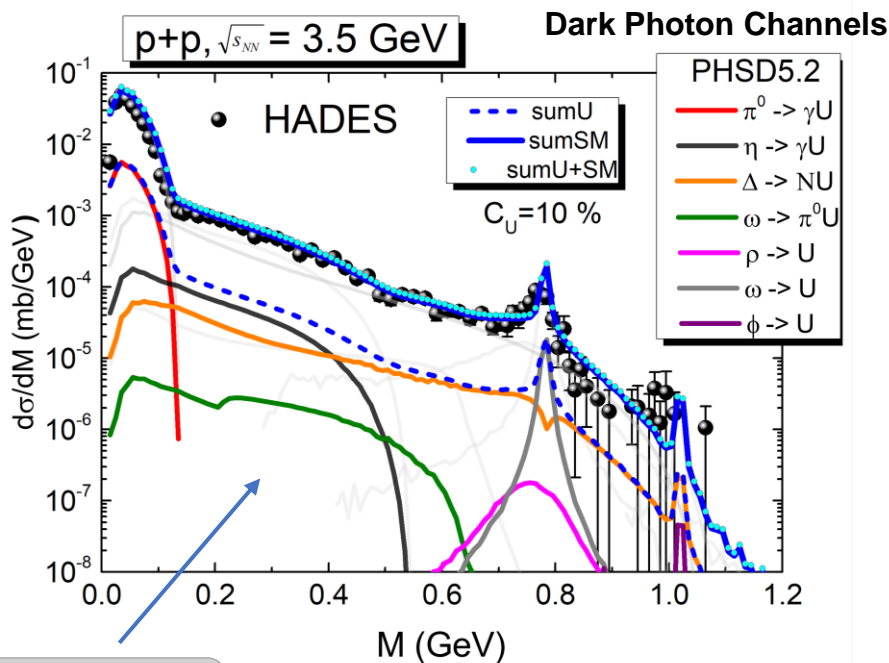
Thanks to the Organizers !

Thank you for your attention !

Extras

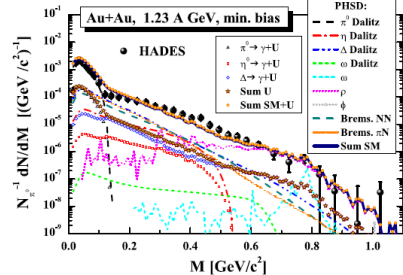
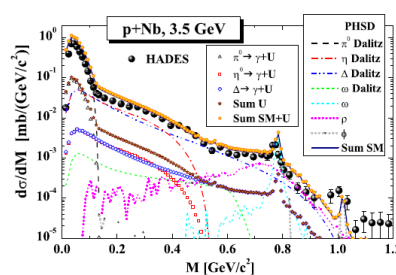
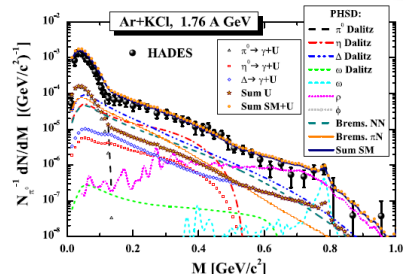
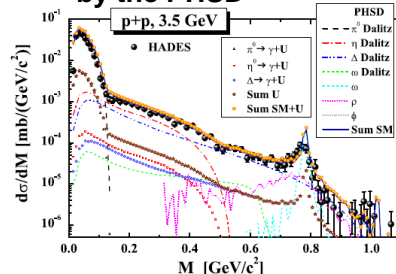


Dilepton spectra from U-boson decays at SIS18 energies vs. HADES data



Gray lines display SM decay channels

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

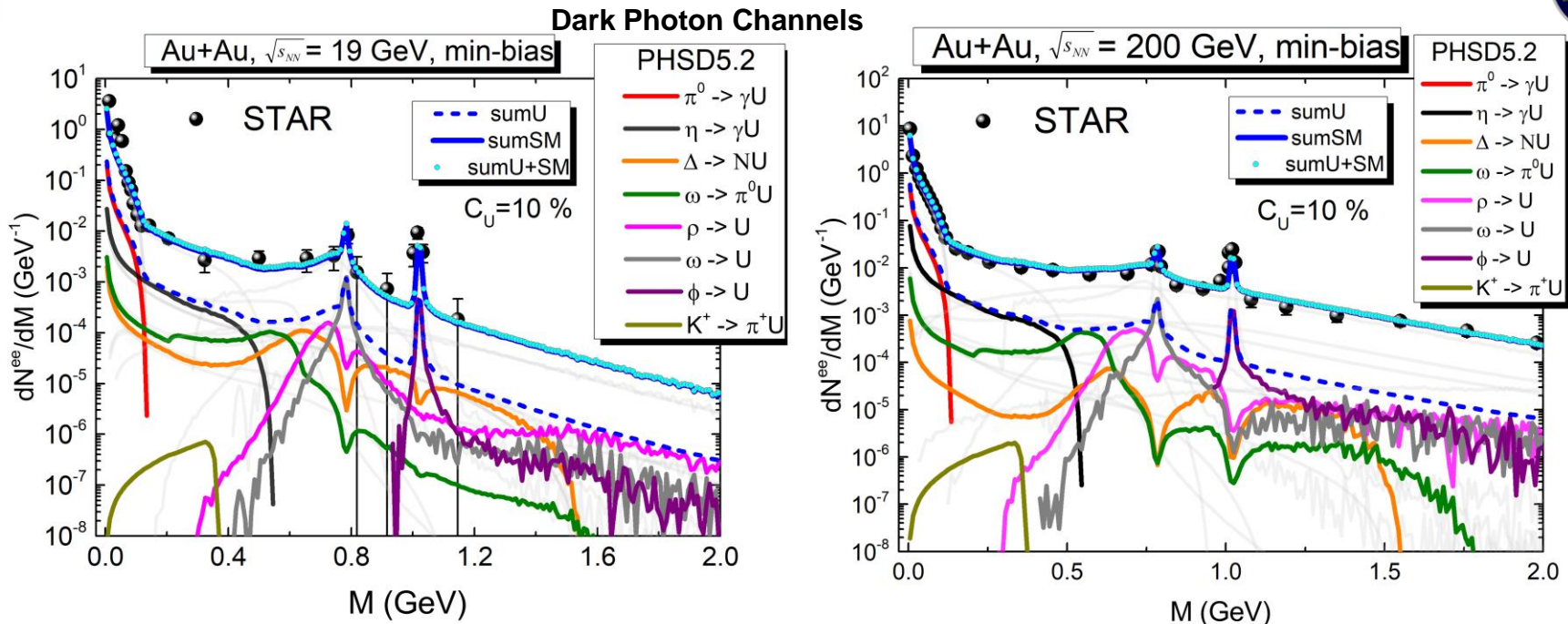


I. Schmidt et al., PRD 104 (2021) 015008

- 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



- 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 \rightarrow the **total sum** is still in a good agreement with exp. data



Dileptons at SIS energies - HADES

□ **HADES:** dilepton yield dN/dM scaled with the **number of pions N_{π^0}**

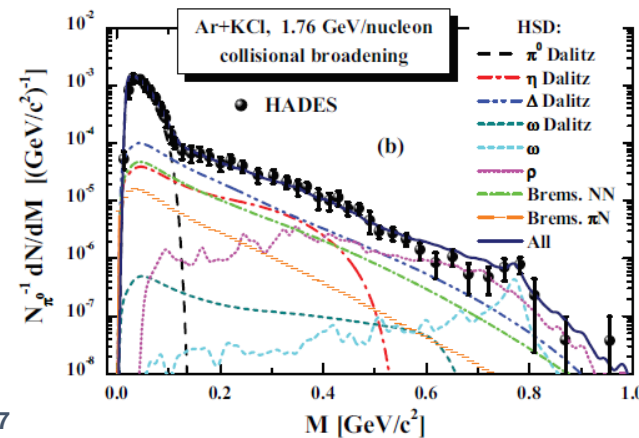
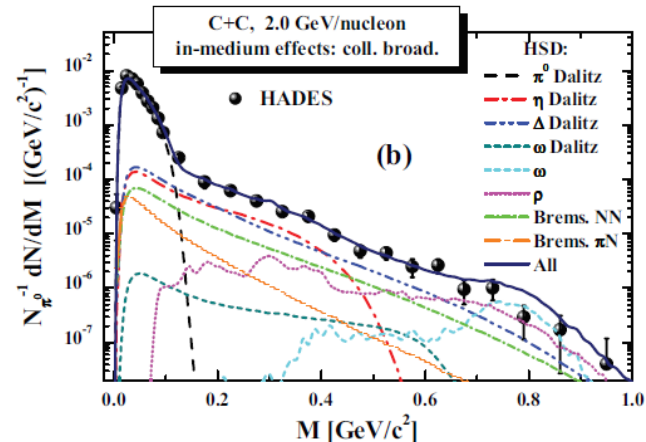
□ **Dominant hadronic sources for $M > m_{\pi^0}$:**

- 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 $M \sim 0.78$ GeV relates to ω/ρ mesons decaying in vacuum

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



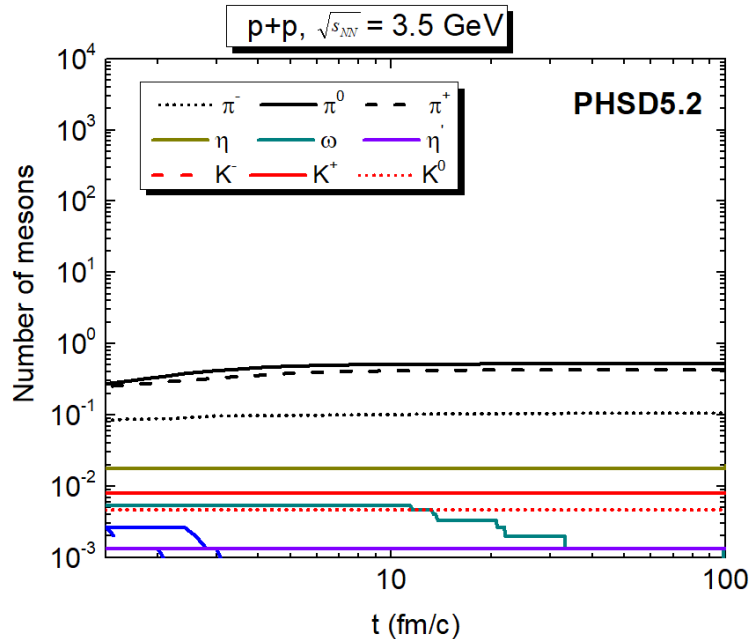
from the three data sets separately. Evidently, the $p + \text{Nb}$ data provide the strongest constraint. However, as the three data sets are of comparable statistical quality and result hence in upper limits of similar magnitude, it is natural to join them into a combined upper limit [49]. Since all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

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

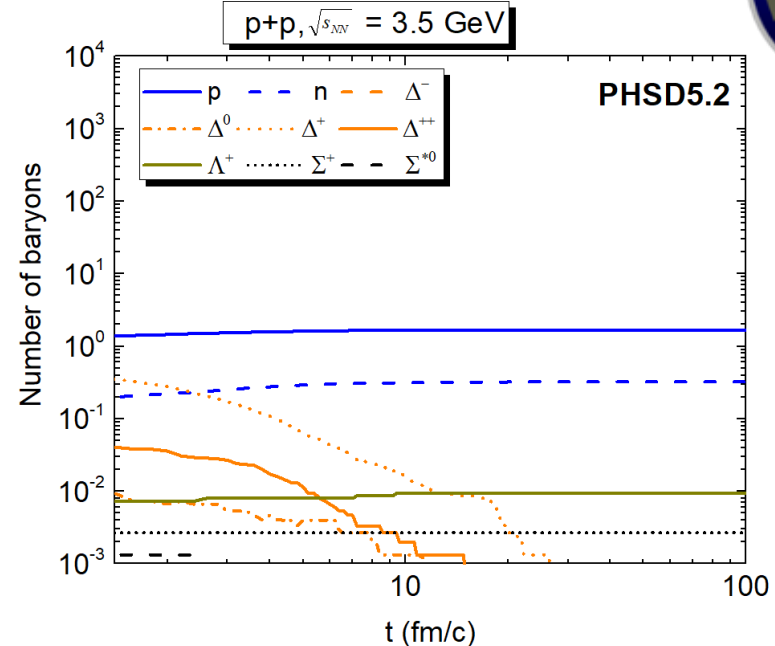
The combined upper limit $UL_{(1+2+3)}$ is overall about 10 to 20% lower than the $p + \text{Nb}$ value taken alone. This is indeed expected from the moderate increase in pair statistics achieved by cumulating the data from all experiments and is consistent with a $UL \propto 1/\sqrt{N}$ behavior.

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

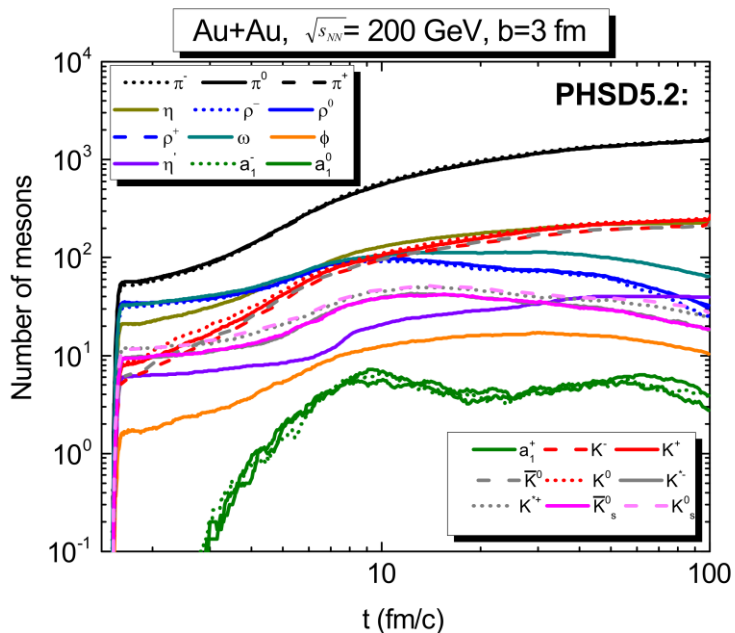


p, n and a small fraction of **Δ** are relevant at the beginning of the collision

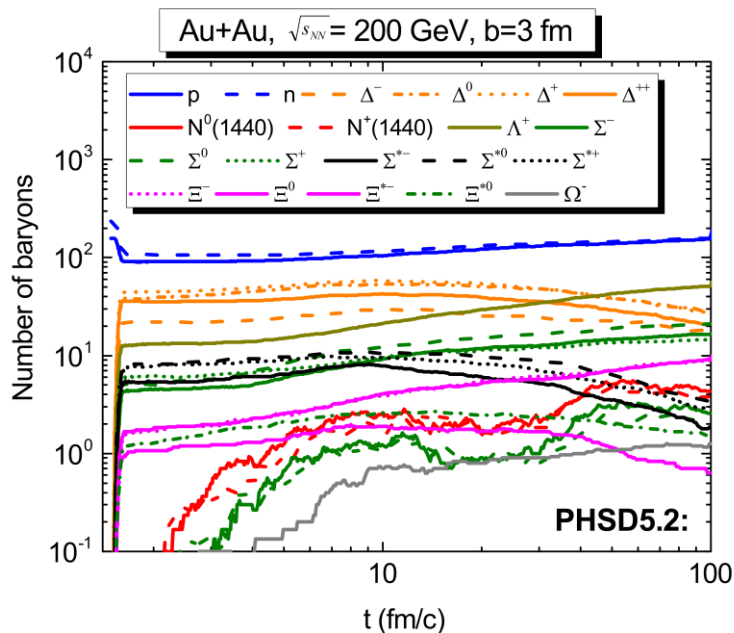


Number of particles in Au+Au collision

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

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

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

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

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

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

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

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

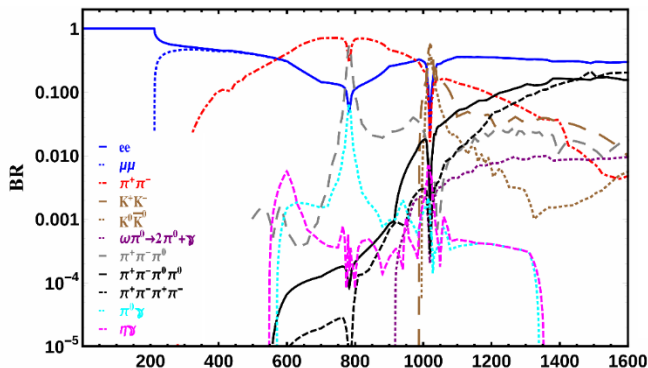
Based on the model

HADES Col. (2014) PLB, 731, 265

NICA Col. (2024) PLB, 852, 138599

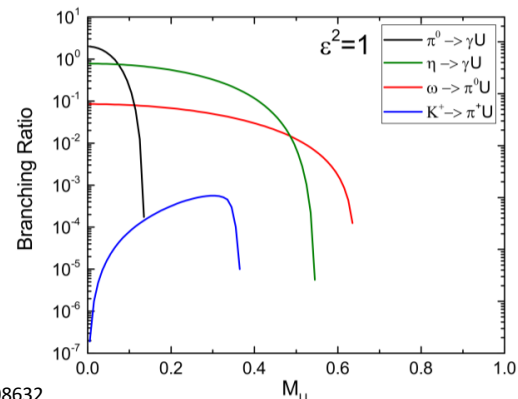
Pospelov (2009) PRD 80, 095002

Battel (2009) PRD 79, 115008



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

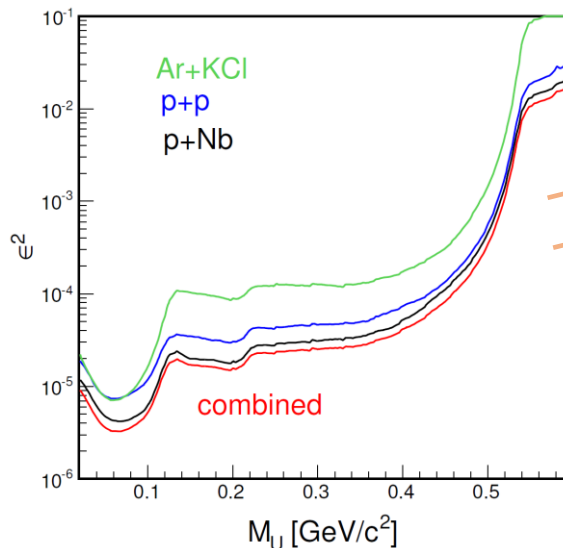
Dark Photon Mass (MeV) J. Alexander et al. (2016), 1608.08632



Search for dark photons with HADES

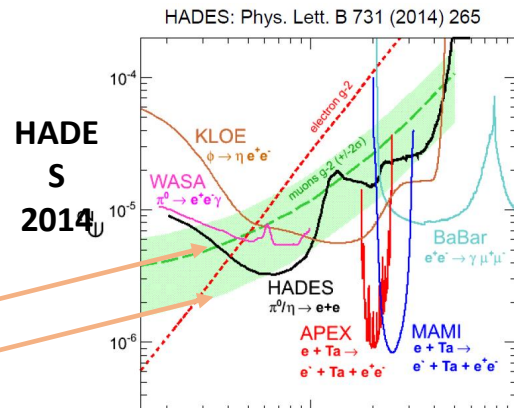
G. Agakishiev et al. (HADES), Phys. Lett. B 731, 265 (2014)

Upper limit on the mixing parameter ϵ^2

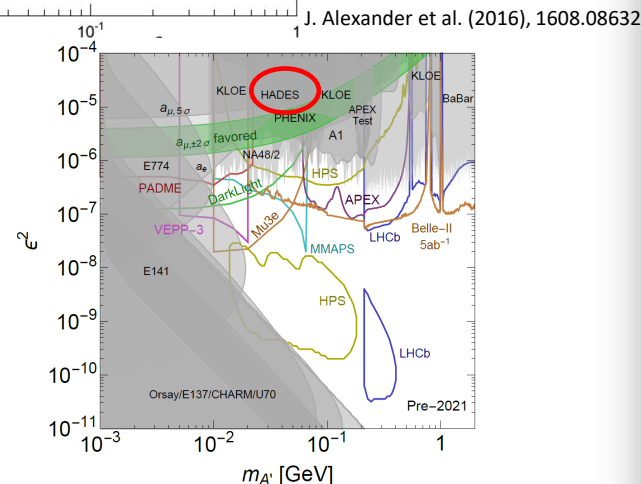


HADES coverage : $0.02 < M_U < 0.6$ GeV

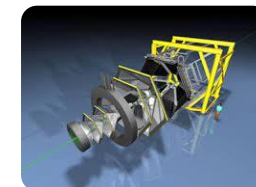
Dark photons are not observed so far!



World wide
exp. data
2016



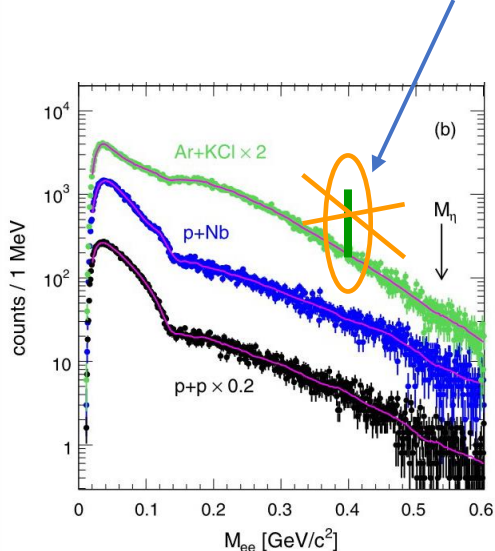
Search for dark photons with HADES (GSI)



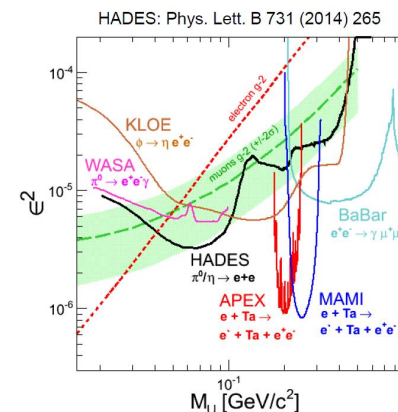
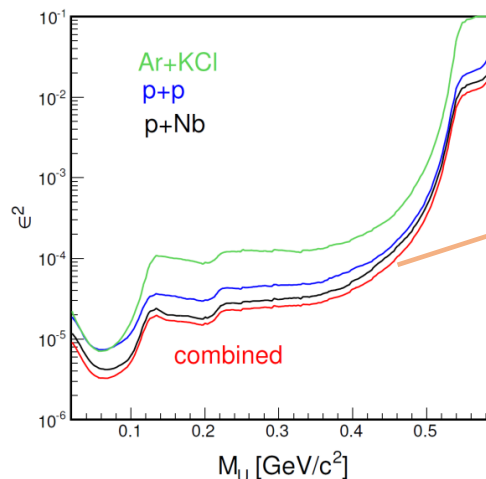
HADES data:

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 coverage : $0.02 < M_U < 0.6$ GeV

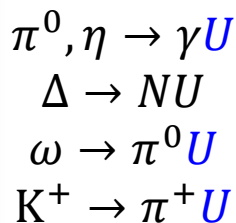
Dark photons are not observed so far!

- 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))

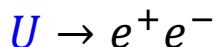
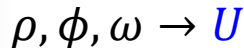
G. Agakishiev et al. (HADES), Phys. Lett. B 731, 265 (2014)

Dark photon production in PHSD

Dalitz Decay



Direct Decay



Production of hadron \rightarrow decay to U \rightarrow dilepton yield from U-boson decay of mass

M_U :

$$\begin{aligned} N^{U \rightarrow e^+ e^-} &= N_{\pi^0}^{U \rightarrow e^+ e^-} + N_{\eta}^{U \rightarrow e^+ e^-} + \dots + N_{\omega}^{U \rightarrow e^+ e^-} \\ &= Br^{U \rightarrow e^+ e^-} (N_{\pi^0 \rightarrow \gamma U} + N_{\eta \rightarrow \gamma U} + \dots + N_{\omega \rightarrow U}) \end{aligned}$$

$$(N_{\pi^0 \rightarrow \gamma U} + N_{\eta \rightarrow \gamma U} + N_{\Delta \rightarrow NU}) N_{i \rightarrow \gamma U} = N_i Br_{i \rightarrow \gamma \gamma} \cdot \frac{\Gamma_{i \rightarrow \gamma U}}{\Gamma_{i \rightarrow \gamma \gamma}}, \quad i = \pi^0, \eta \quad \leftarrow \epsilon^2 = \alpha'/\alpha$$

The yield of U-bosons of mass M_U : $N_{\Delta \rightarrow NU} = N_{\Delta} Br_{\Delta \rightarrow N \gamma} \cdot \frac{\Gamma_{\Delta \rightarrow NU}}{\Gamma_{\Delta \rightarrow N \gamma}}$

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

Based on the model: B. Batell, M. Pospelov, and A. Ritz, Phys. Rev. D 79, 115008 (2009);
(used in the HADES analysis) Phys. Rev. D 80,095024 (2009)

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

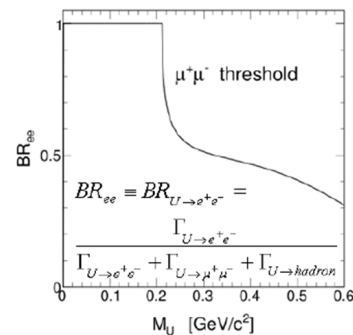
$$\frac{\Gamma_{i \rightarrow \gamma U}}{\Gamma_{i \rightarrow \gamma \gamma}} = 2\epsilon^2 |F_i(q^2 = M_U^2)| \frac{\lambda^{3/2}(m_i^2, m_\gamma^2, M_U^2)}{\lambda^{3/2}(m_i^2, m_\gamma^2, m_\gamma^2)} \quad i = \pi^0, \eta$$

Formfactor

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

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

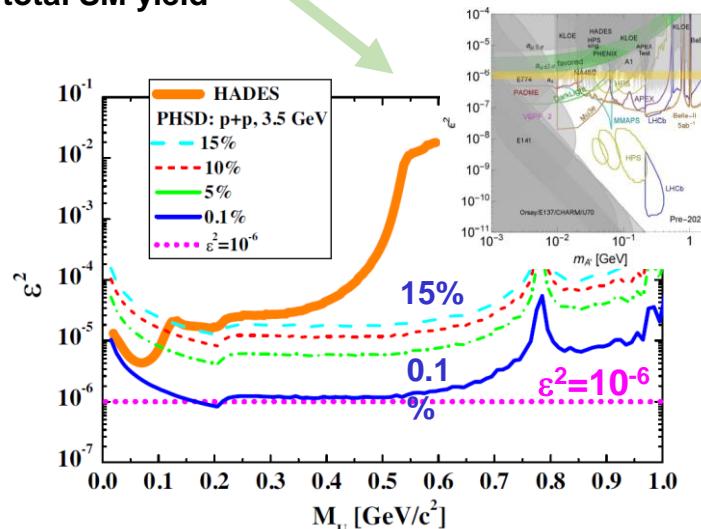
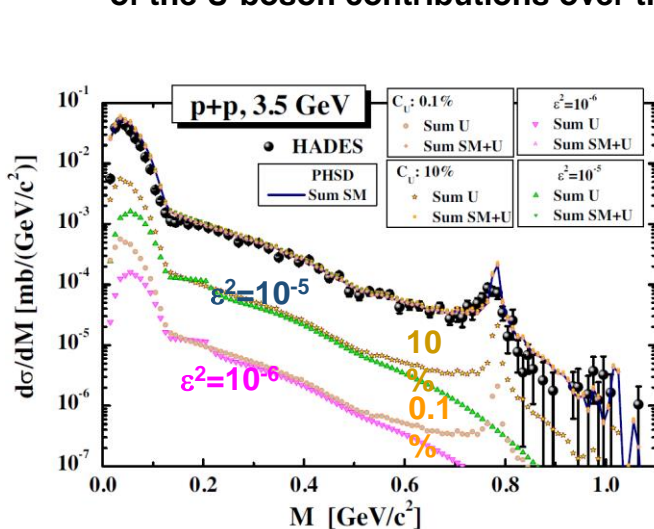
$$R(\sqrt{s}) = \sigma_{e^+ e^- \rightarrow hadrons} / \sigma_{e^+ e^- \rightarrow \mu^+ \mu^-}$$





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:

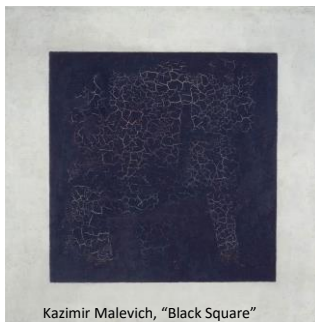
- strongly reduces by lowering the allowed 'surplus'
- exp. data of high precision is needed to reduce the upper limit for $\varepsilon^2(M_U)$



Search for dark photons in heavy-ion collisions

Elena Bratkovskaya

(GSI, Darmstadt & Uni. Frankfurt)

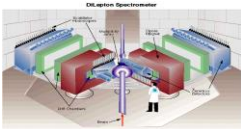


Kazimir Malevich, "Black Square"
(1915)

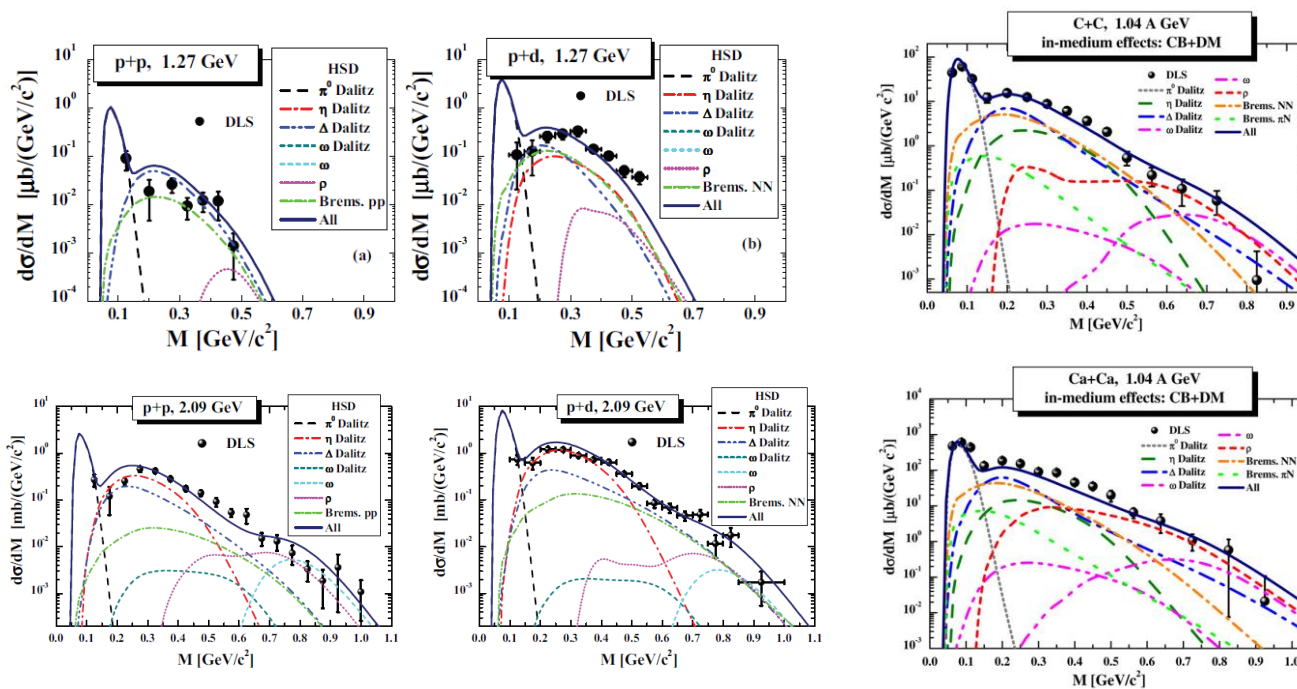
10th international conference on
High Energy Physics in the LHC Era
(HEP-2023)

9-13 January 2023, Valparaíso, Chile





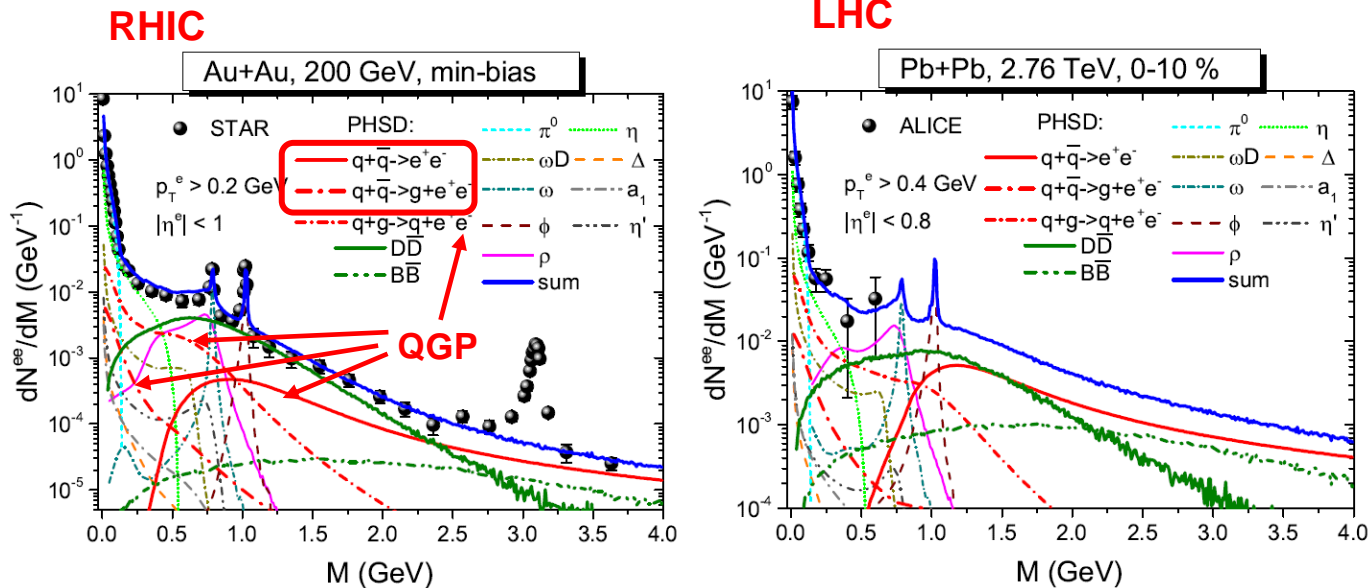
PHSD: Dileptons from p+p, p+d, A+A - DLS



- **bremstrahlung** 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



Dileptons at RHIC and LHC



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

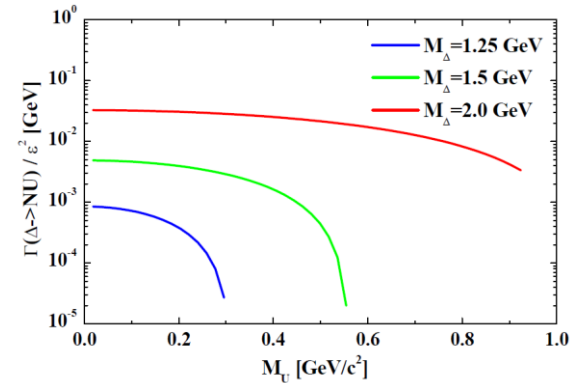
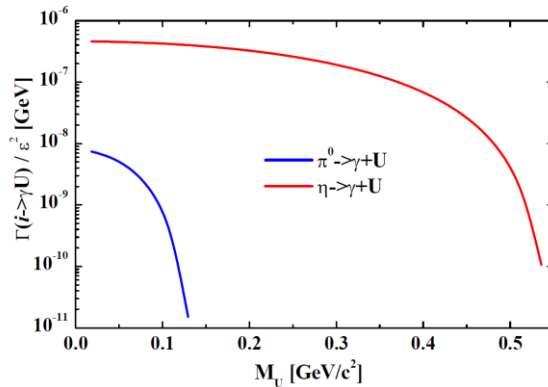
- 1) a **collisional broadening** scenario for the **vector meson** spectral functions
+ **QGP + correlated charm**
- 2) **Charm contribution** is dominant for $1.2 < M < 2.5$ GeV

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907 ⁵⁶

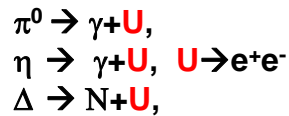


Dalitz decays of π^0, η and Δ to U-bosons and $e+e^-$

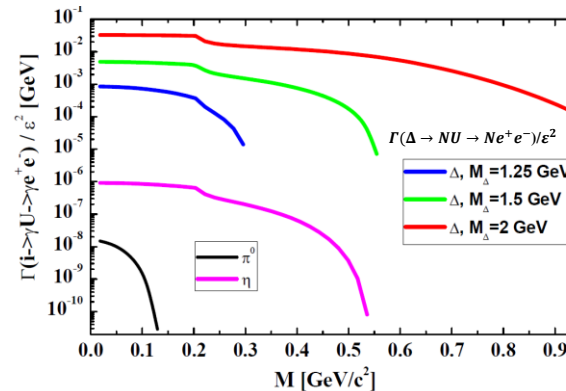
- Dalitz decay width of π^0, η mesons and Δ -resonance to U-bosons **normalized to ε^2**



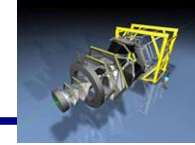
- Decay width of π^0, η mesons and Δ -resonances to dileptons (via U-bosons) **normalized to ε^2**



$$\begin{aligned} &\Gamma(i \rightarrow \gamma \mathbf{U} \rightarrow \gamma e^+ e^-) / \varepsilon^2 \\ &\Gamma(\Delta \rightarrow \mathbf{N} \mathbf{U} \rightarrow \mathbf{N} e^+ e^-) / \varepsilon^2 \\ &\rightarrow \text{to PHSD calculations} \end{aligned}$$

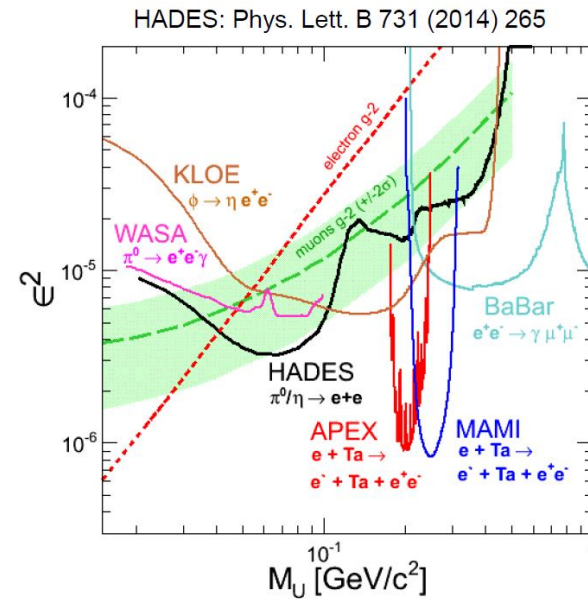
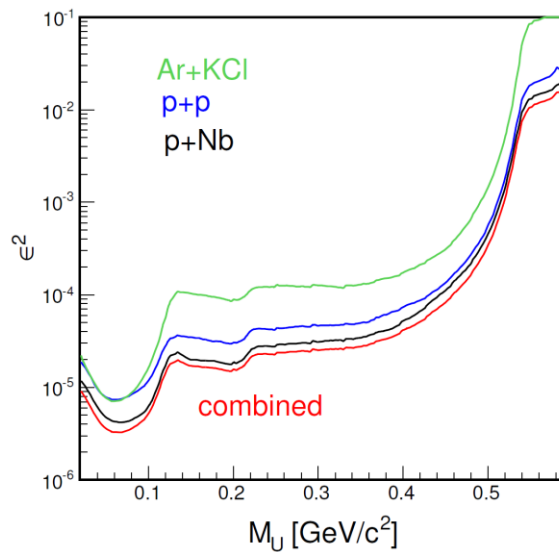


Search for dark photons with HADES



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

Upper limit on the mixing parameter ϵ^2

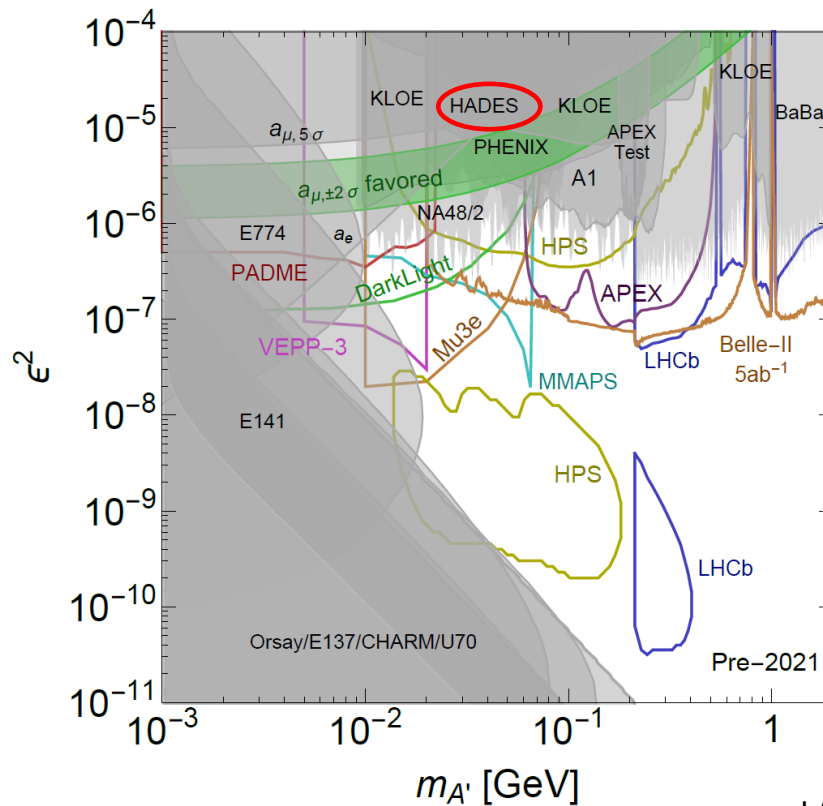


HADES coverage : $0.02 < M_U < 0.6 \text{ GeV}$

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



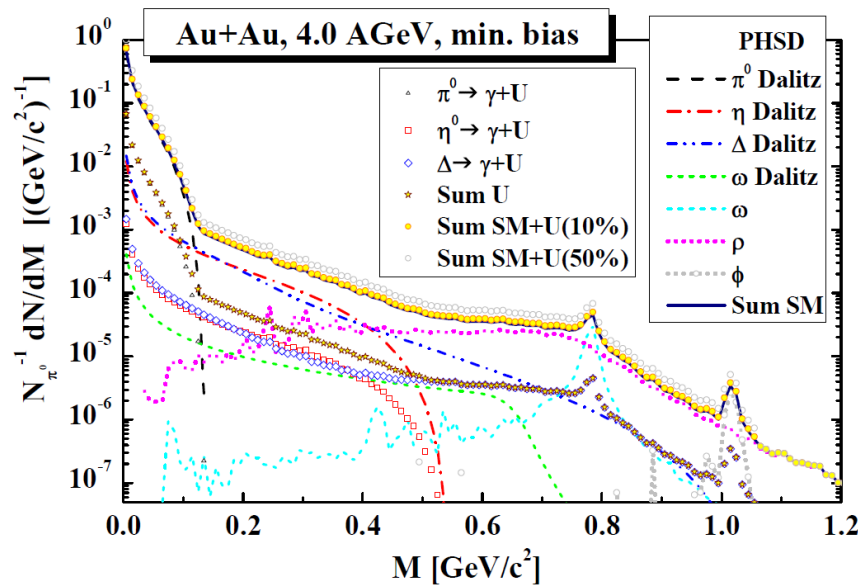
J. Alexander et al. (2016), 1608.08632

59



Dileptons yields including dark photons

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



- The contributions from $U \rightarrow e+e-$ 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

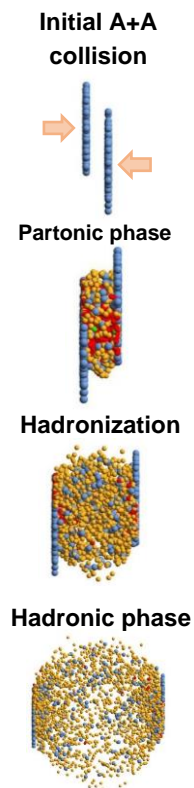


Parton-Hadron-String-Dynamics (PHSD)

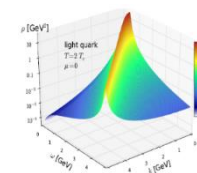
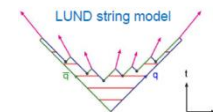


PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

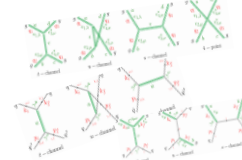
Dynamics: based on the solution of **generalized off-shell transport equations** derived from Kadanoff-Baym many-body theory



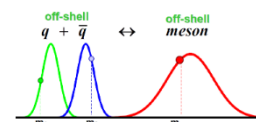
- **Initial A+A collisions :**
 $N+N \rightarrow$ **string formation** \rightarrow decay to pre-hadrons + leading hadrons
- **Formation of QGP stage** if local $\epsilon > \epsilon_{\text{critical}}$:
 dissolution of **pre-hadrons** \rightarrow partons
- **Partonic phase - QGP:**
 QGP is described by 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** to colorless **off-shell mesons and baryons:**
 Strict 4-momentum and quantum number conservation

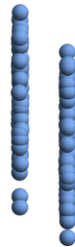


- **Hadronic phase:** **hadron-hadron interactions – off-shell HSD**

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3 61

Stages of a collision in PHSD

$t = 0.05 \text{ fm}/c$



$\text{Au} + \text{Au} \sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
 $b = 2.2 \text{ fm}$ – Section view

- Baryons (394)
- Antibaryons (0)
- Mesons (0)
- Quarks (0)
- Gluons (0)

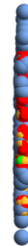
P.Moreau






Stages of a collision in PHSD

$t = 1.6512 \text{ fm}/c$



$\text{Au} + \text{Au} \sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
 $b = 2.2 \text{ fm}$ – Section view

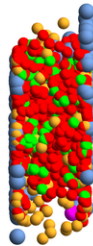


-  Baryons (394)
-  Antibaryons (0)
-  Mesons (1523)
-  Quarks (4553)
-  Gluons (368)

P.Moreau

Stages of a collision in PHSD

$t = 3.91921 \text{ fm}/c$



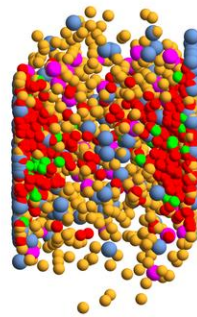
$\text{Au} + \text{Au} \sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
 $b = 2.2 \text{ fm}$ – Section view

-  Baryons (426)
-  Antibaryons (29)
-  Mesons (1189)
-  Quarks (4459)
-  Gluons (783)

P.Moreau

Stages of a collision in PHSD

$t = 7.31921 \text{ fm}/c$



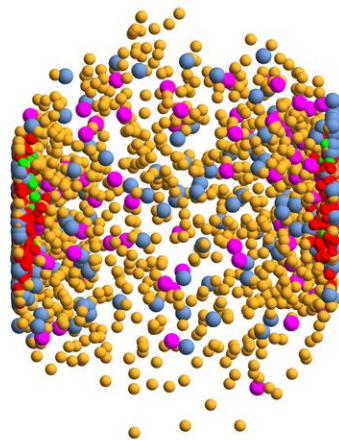
$\text{Au} + \text{Au} \sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
 $b = 2.2 \text{ fm}$ – Section view

- Baryons (540)
- Antibaryons (120)
- Mesons (2481)
- Quarks (2901)
- Gluons (492)


P. Moreau

Stages of a collision in PHSD

$t = 12.0192 \text{ fm}/c$



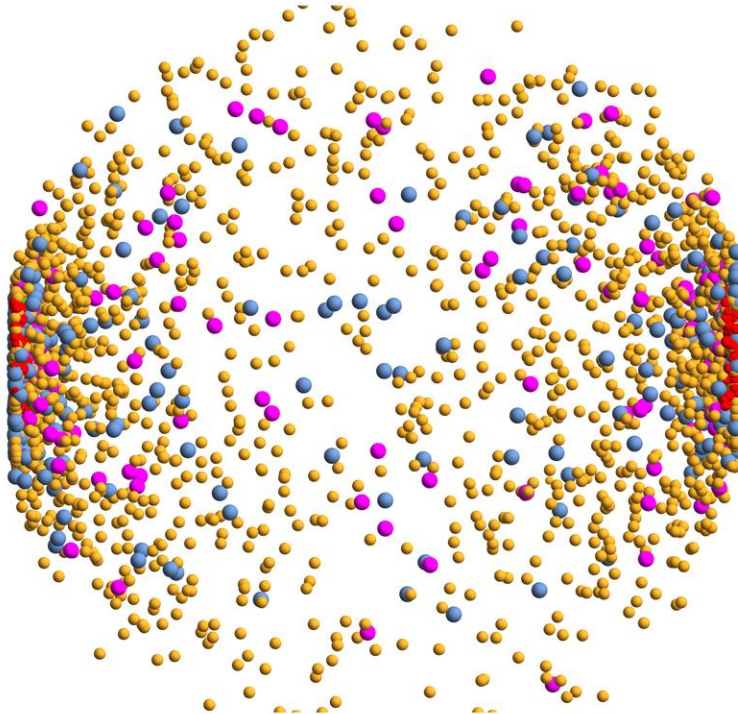
$\text{Au} + \text{Au} \sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
 $b = 2.2 \text{ fm}$ – Section view

-  Baryons (626)
-  Antibaryons (202)
-  Mesons (3357)
-  Quarks (1835)
-  Gluons (269)



P.Moreau

Stages of a collision in PHSD

$t = 25.5191 \text{ fm}/c$



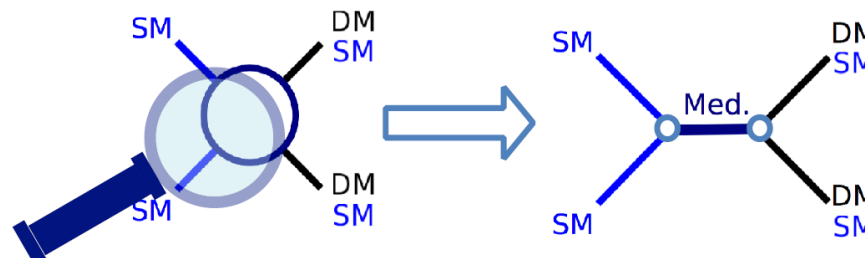
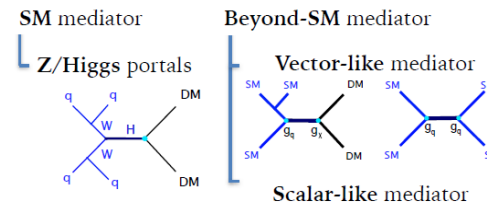
$\text{Au} + \text{Au} \sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
 $b = 2.2 \text{ fm}$ – Section view

-  Baryons (710)
-  Antibaryons (272)
-  Mesons (4343)
-  Quarks (899)
-  Gluons (46)

P.Moreau

Searching for U in electromagnetic processes

- $e^- + A \rightarrow e^- + X + U$ (APEX, MAMI)
- $\Phi \rightarrow \eta + U$ (KLOE-2)
- $\pi^0 \rightarrow \gamma + U$ (WASA, **HADES**)
- $\eta \rightarrow \gamma + U$ (**HADES**)
- $e^+ e^- \rightarrow \mu^+ \mu^-$ (BaBar, Belle, BES3)
- various beam-dump expts.



Dark photon time life

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

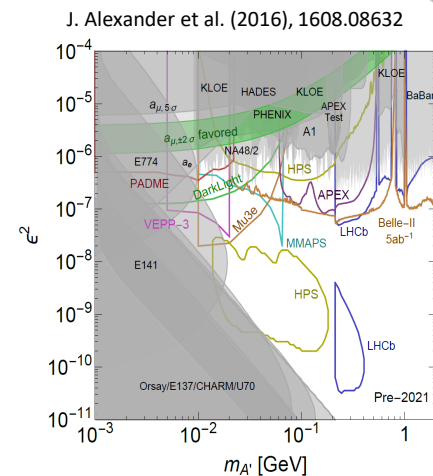
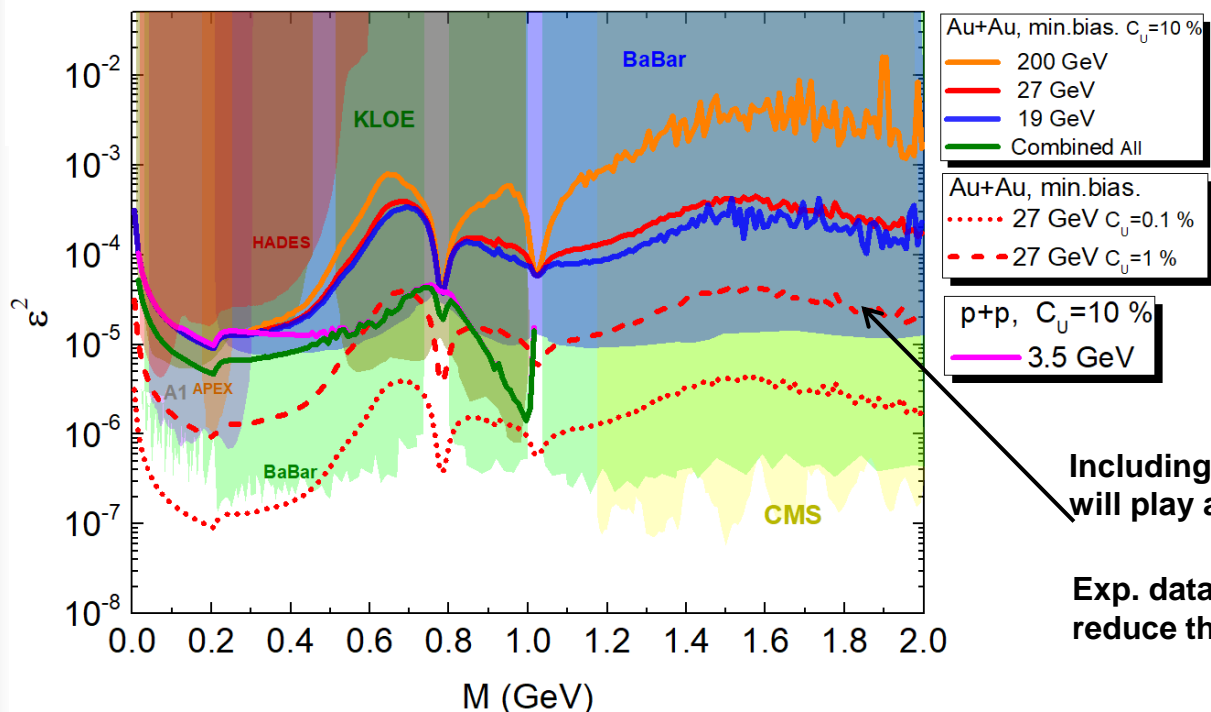
$$\tau \approx \frac{1}{\Gamma} \quad \Gamma(U \rightarrow \ell^+ \ell^-) \approx \frac{\alpha \epsilon^2}{3} m_U \quad \begin{array}{l} m_U = 1 \text{ GeV} \\ \epsilon^2 = 10^{-6} \end{array}$$

$$\Gamma(U \rightarrow \ell^+ \ell^-) \approx 2.43 \times 10^{-8} \text{ GeV}$$

$$\tau \approx 2.71 \times 10^{-17} \text{ s}$$

Mixing parameter $\epsilon^2(M_U)$

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



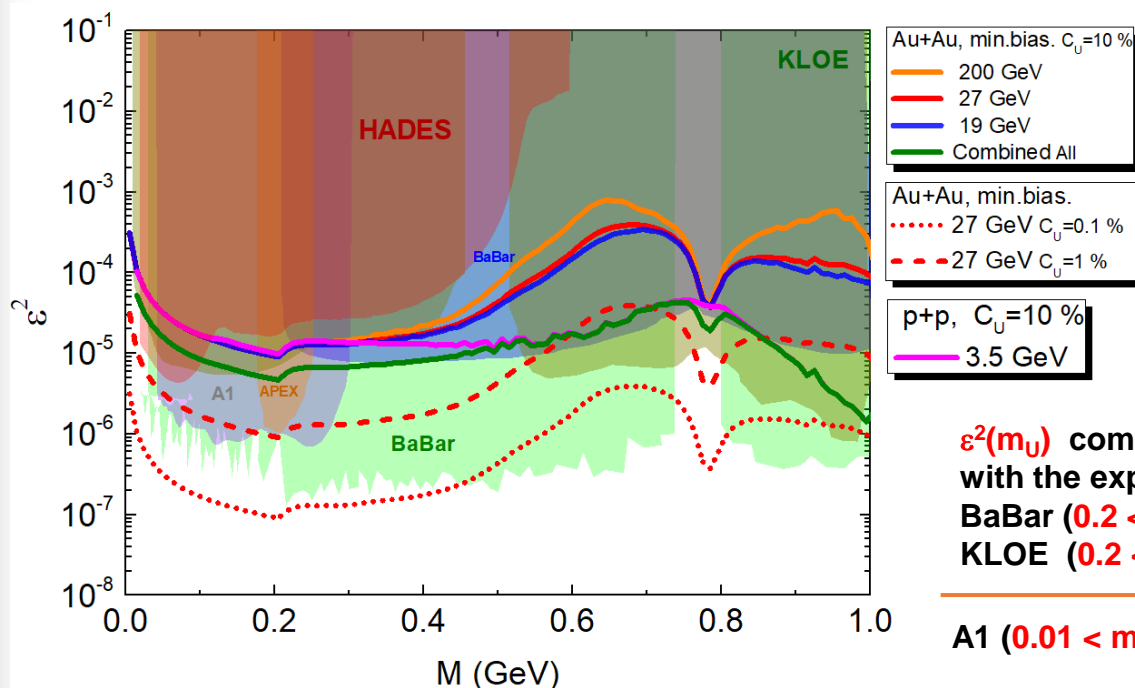
Including dark photon decays from QGP will play an important role at $m_U < 1$ GeV

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

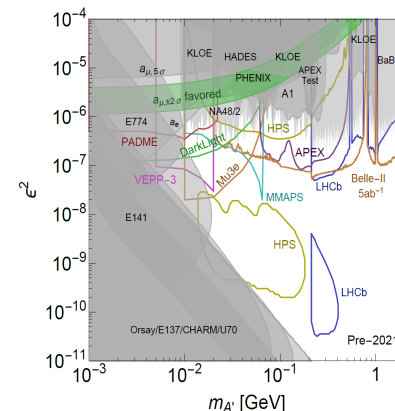


Mixing parameter $\varepsilon^2(M_U)$

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 ($0.2 < m_U < 1 \text{ GeV}$)
KLOE ($0.2 < m_U < 0.8 \text{ GeV}$)

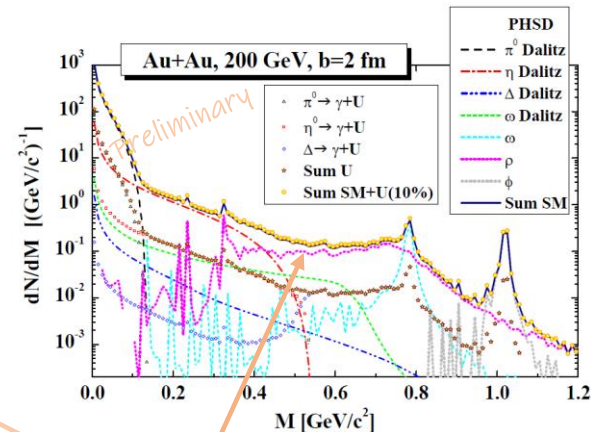
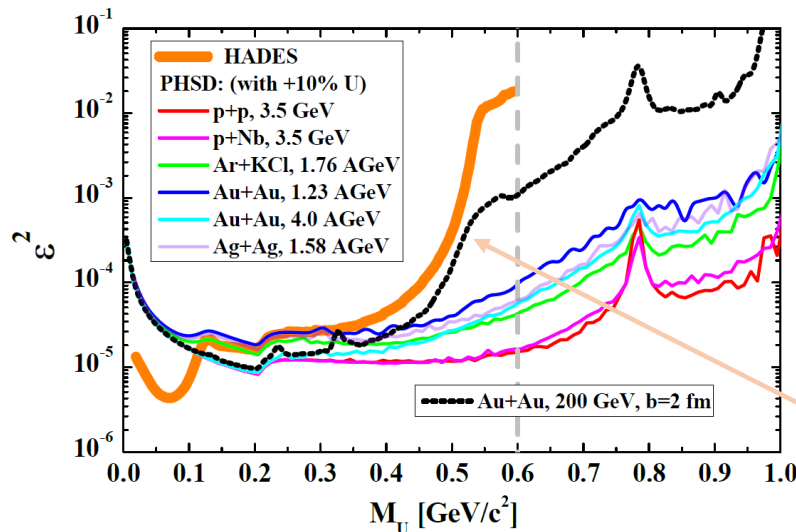
A1 ($0.01 < m_U < 0.3 \text{ GeV}$) Au+Au 27 GeV for $C_U = 1\%$

Validity range of extracted kinetic mixing parameter: **$0.01 < M_U < 0.8 \text{ GeV}$** based on low energy dilepton spectra



Mixing parameter $\varepsilon^2(M_U)$

- How sensitive is the extraction procedure of $\varepsilon^2(M_U)$ on acceptance, system size, beam energy?



With increasing beam energy the contribution of vector mesons are getting dominant for $M > 0.5$ GeV

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:

- only **very weakly depends** on the experimental **acceptance**
- is **more accurate (i.e. lower)** for **light systems and for low energies** since the Dalitz decays of π^0, η -mesons and Δ -resonances are the dominant channels

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

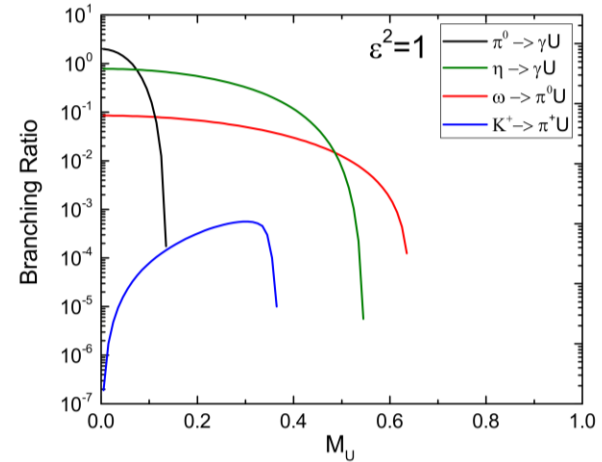
$$\rho, \phi, \omega \rightarrow U$$

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

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

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

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



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

$$P = \pi, \eta$$

Based on the model

HADES Col. (2014) PLB, 731, 265

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

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

NICA Col. (2024) PLB, 852, 138599

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

Pospelov (2009) PRD 80, 095002

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

Battel (2009) PRD 79, 115008

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

Dark photon production in PHSD



Dalitz Decay

Production of hadron \rightarrow decay to $U \rightarrow$ dilepton yield from U-boson decay of mass M_U :

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

$$\Delta \rightarrow NU$$

$$\omega \rightarrow \pi^0 U$$

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

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

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

Direct Decay

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

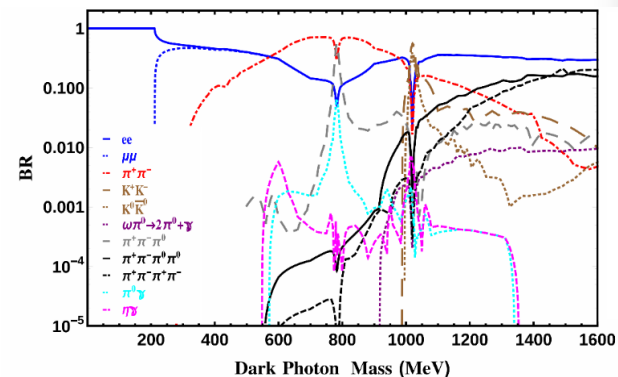
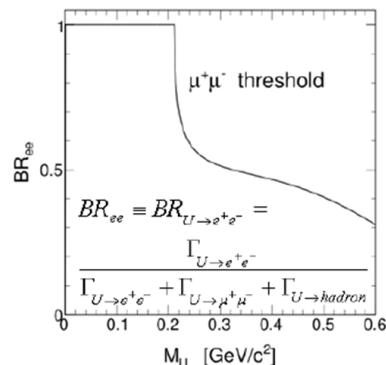
$$\rho, \phi, \omega \rightarrow U$$

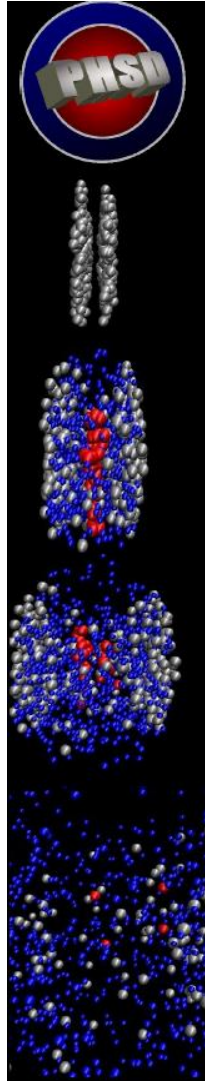
$$I. \quad Br^{U \rightarrow e^+ e^-} = \frac{\Gamma_{U \rightarrow e^+ e^-}}{\Gamma_T(U)} = \frac{\Gamma_{U \rightarrow e^+ e^-}}{\Gamma_{U \rightarrow e^+ e^-} + \Gamma_{U \rightarrow \mu^+ \mu^-} + \Gamma_{U \rightarrow hadrons}}$$

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

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

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





Parton-Hadron-String-Dynamics (PHSD)

PHSD is a **non-equilibrium transport approach** with

- explicit **phase transition** from hadronic to partonic degrees of freedom
- **IQCD EoS** for the partonic phase (‘crossover’ at low μ_q)
- explicit **parton-parton interactions** - between quarks and gluons
- dynamical **hadronization**

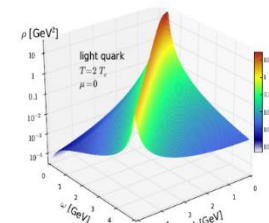
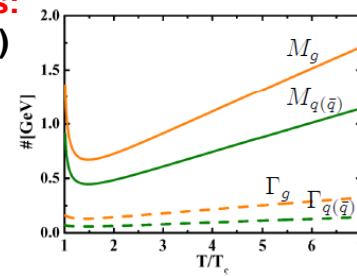
□ **QGP phase is** described by the **Dynamical QuasiParticle Model (DQPM)** matched to reproduce lattice QCD

- **strongly interacting quasi-particles:** massive quarks and gluons (g, q, q_{bar}) with sizeable collisional widths in a self-generated **mean-field potential**

- **Spectral functions:**

$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{(\omega^2 - \vec{p}^2 - M_i^2(T))^2 + 4\omega^2\Gamma_i^2(T)}$$

$(i = q, \bar{q}, g)$



A. Peshier, W. Cassing, PRL 94 (2005) 172301;
W. Cassing, NPA 791 (2007) 365; NPA 793 (2007)

- **Transport theory:** **generalized off-shell transport equations** based on the 1st order gradient expansion of Kadanoff-Baym equations (**applicable for strongly interacting systems!**)

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

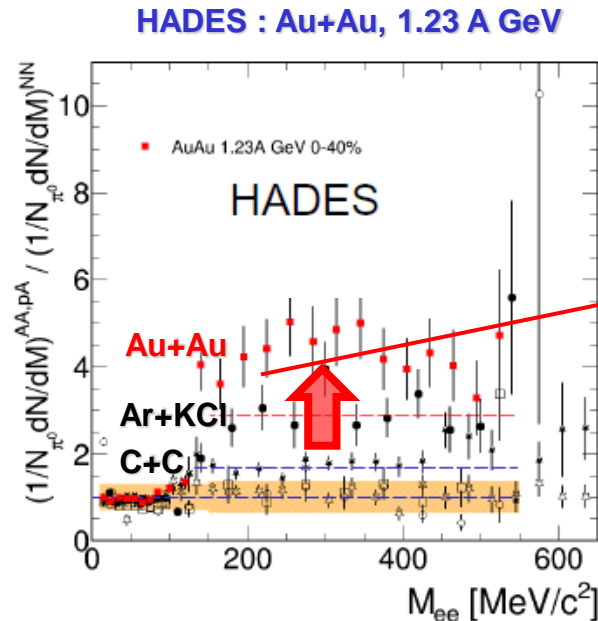
75



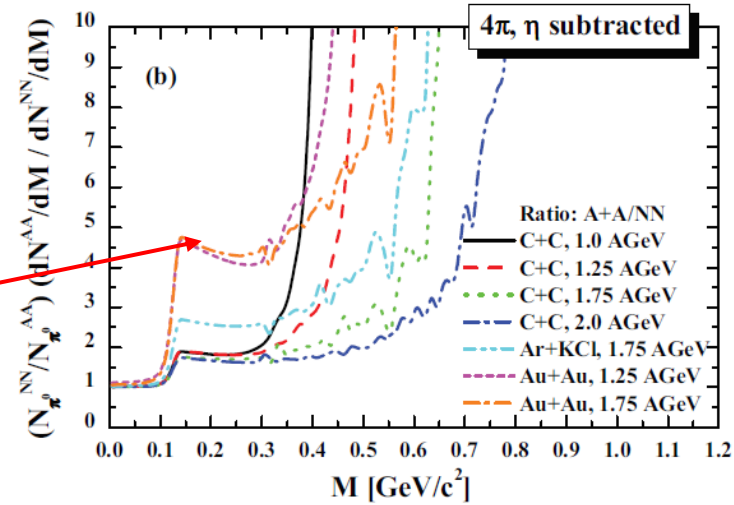
Dileptons at SIS (HADES): Au+Au

HADES, Nature Phys.15 (2019) 1040

▪ HSD predictions (2013)



- Strong in-medium enhancement of dilepton yield in Au+Au vs. NN
- Increases with the system size!

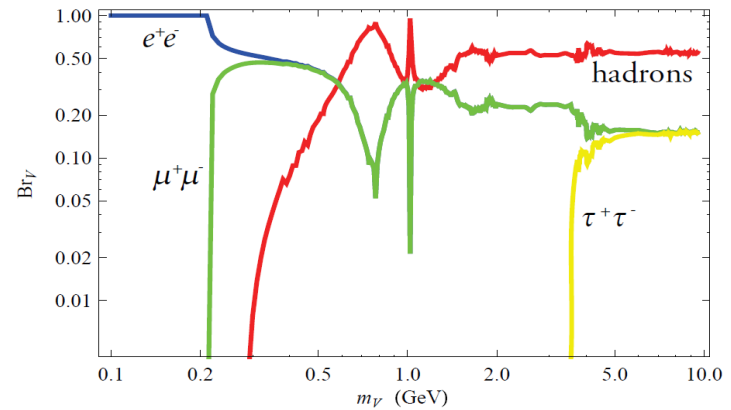
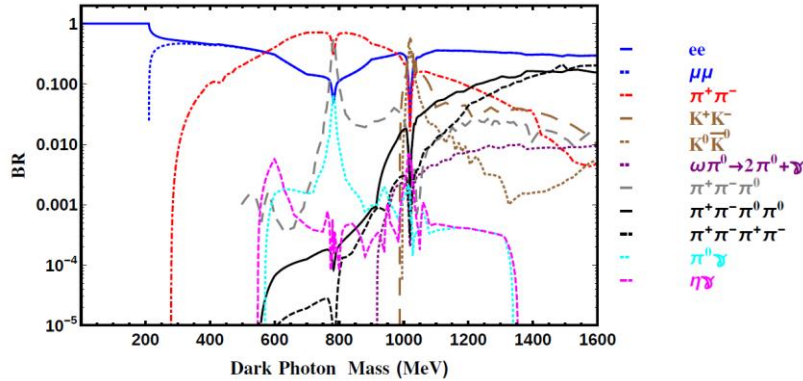


- 1) the **multiple Δ regeneration** – dilepton emission from intermediate Δ 's which are part of the reaction cycles $\Delta \rightarrow \pi N$; $\pi N \rightarrow \Delta$ and $NN \rightarrow N\Delta$; $N\Delta \rightarrow NN$
- 2) the **pN bremsstrahlung** which scales with N_{bin} and not with N_{part} , i.e. pions;

E.B., J. Aichelin, M. Thomeer, S. Vogel, M. Bleicher, PRC 87 (2013) 064907


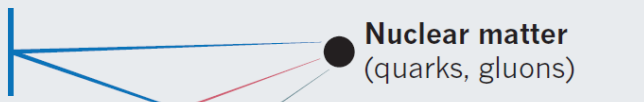





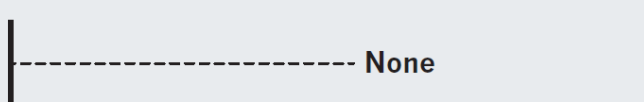


Heavy-ion collisions



Dark matter detection

D = dark-matter particle, **S** = standard-model particle

Method	Experiments	Interaction	Standard-model particles involved
Direct detection	LUX, CoGeNT, DAMA/LIBRA		
Indirect detection	CTA*, HESS, AMS, PAMELA		
Collisions	LHC, 100-TeV collider*		
Astrophysical observations	Star and galaxy surveys*, helioseismology*		



Livio, M., Silk, J. Physics: Broaden the search for dark matter. *Nature* **507**, 29–31 (2014) 78

Production of dark photons by SM particles

P. Fayet, Phys. Lett. B 95, 285 (1980)

M. Pospelov, A. Ritz, and M. B. Voloshin, Phys. Lett. B 662, 53 (2008)

L. Ackerman, M.R. Buckley, S.M. Carroll, M. Kamionkowski, Phys. Rev. D79, 023519 (2008)

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

...

- **The dominant production mechanisms of U-bosons (=‘V’=‘dark photons’) and h' - Higgs :**

Dalitz decays of pseudoscalar π^0, η mesons and Δ -resonance

$$m_{V,h'} \lesssim m_\pi$$

$$m_{V,h'} \lesssim 400 \text{ MeV}$$

$$m_{V,h'} \lesssim m_\rho$$

$$m_{V,h'} \gtrsim 1 \text{ GeV}$$

$$\pi^0 \rightarrow \gamma V, \gamma V h'$$

$$\eta \rightarrow \gamma V, \gamma V h'$$

$$\Delta \rightarrow NV$$

$$\rho^0, \omega, \phi \rightarrow V h', V \pi^0(\eta)$$

$$q + \bar{q} \rightarrow V, V h', \dots$$

$$q + g \rightarrow V h', qV, \dots$$

Possible dark photon observation by dileptons

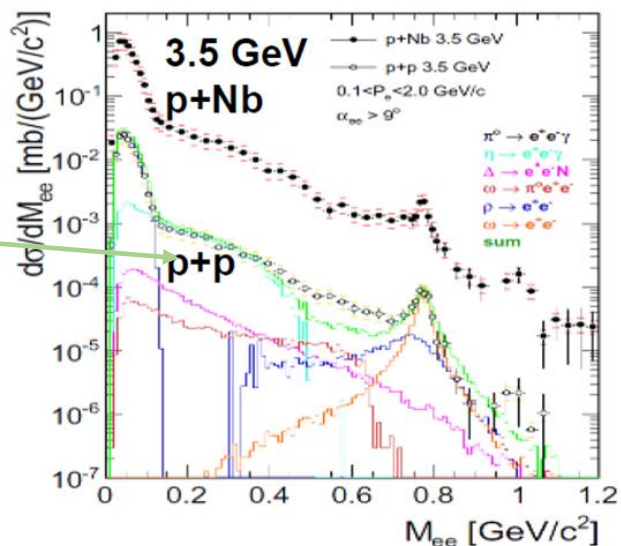
- Dalitz decays of pseudoscalar mesons π^0, η and Δ -resonances to **dileptons** via **U-boson mediator**



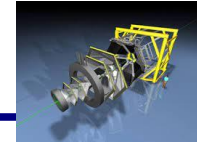
$$\begin{aligned} \pi^0 &\rightarrow \gamma + U, \\ \eta &\rightarrow \gamma + U, \quad U \rightarrow e^+e^- \\ \Delta &\rightarrow N + U, \end{aligned}$$

- 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



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 dN/dM spectrum taking into account mass resolution:
Fit inspected M-region using sum of a 5th-order polynomial and a Gauss peak of fixed M bin of 3 MeV

2) If no peak found, get an UL (upper limit) on peak

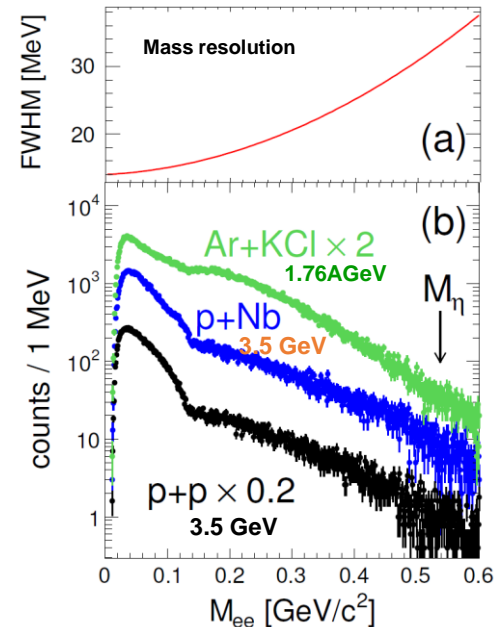
3) Transform this UL into an UL on the **mixing parameter ϵ^2** based on the modelling of U-boson production rate

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

* **Important requirements** for the exp. dark photon search:

1. Large e+e- data samples
(to reduce combinatorial background)
2. Very good mass resolution

Reaction	N_{LVLI}	N_{π^0}	N_{η}
p+p	3.0×10^9	2.5×10^9	1.5×10^8
p+Nb	7.7×10^9	5.9×10^9	3.0×10^8
Ar+KCl	2.2×10^9	7.7×10^9	1.9×10^8



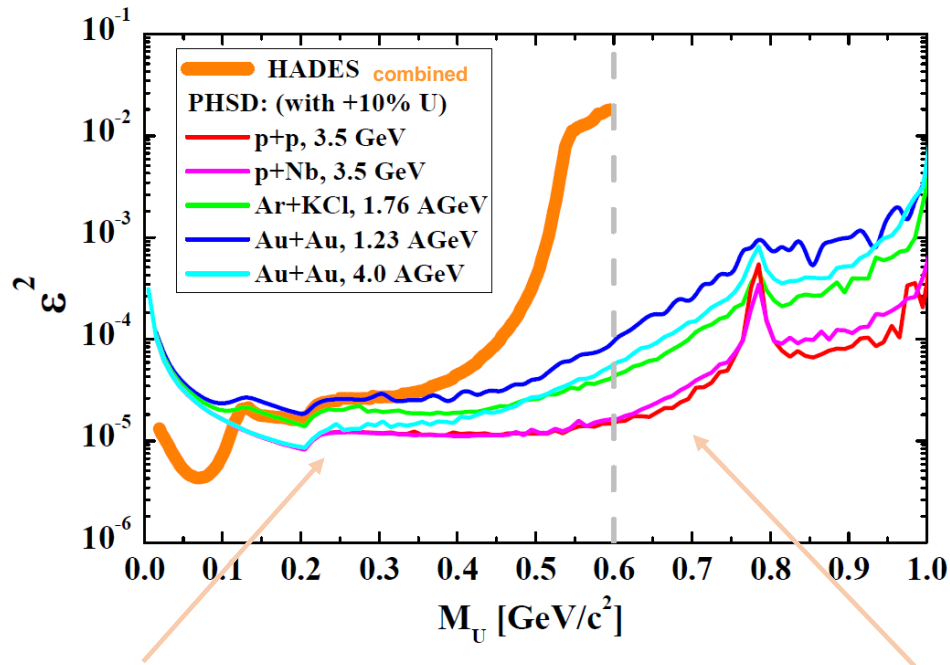
* based on presentation by Roman Holzmann at PANIC2014

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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

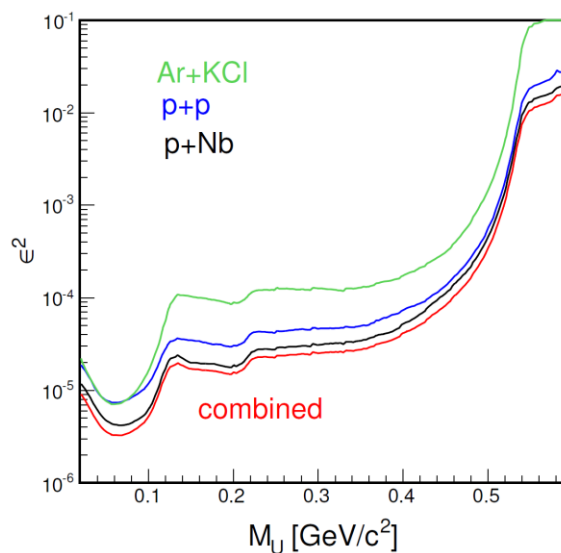
Possible contribution from other dark photon channels

Search for dark photons with HADES



Upper limit on the mixing parameter ϵ^2

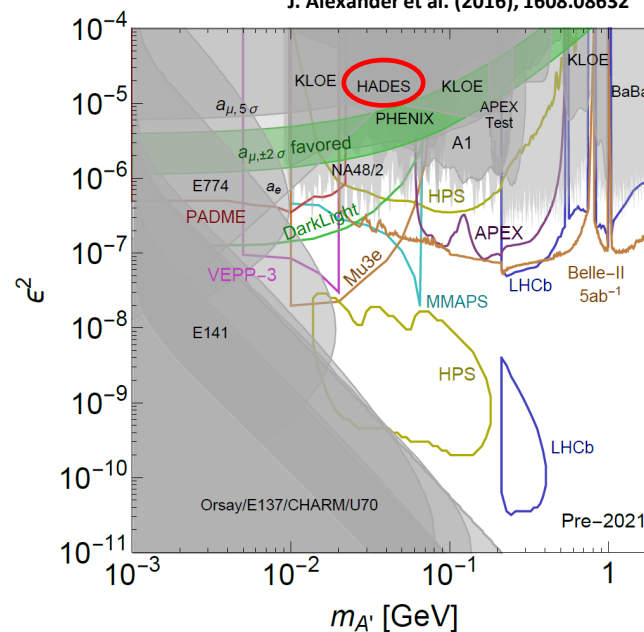
G. Agakishiev et al. (HADES), Phys. Lett. B 731, 265 (2014)



HADES coverage : $0.02 < M_U < 0.6 \text{ GeV}$

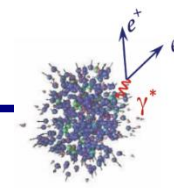
Compilation of world exp. data on the upper limit of the mixing parameter ϵ^2

J. Alexander et al. (2016), 1608.08632



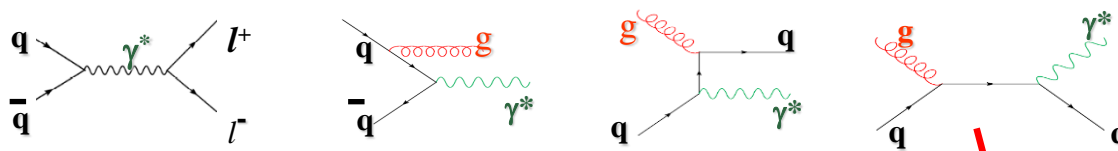
Dark photons are not observed so far!

I. Dilepton sources from SM



from the QGP via partonic (q,qbar, g) interactions:

PHSD: non-perturbative QGP → DQPM (Dynamical Quasiparticle Model)



from hadronic sources:

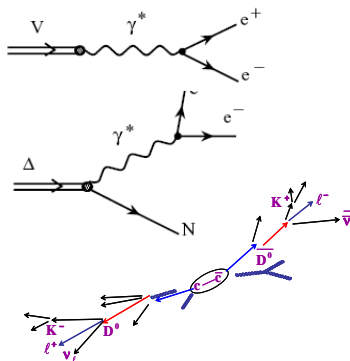
- direct decay of vector mesons ($\rho, \omega, \phi, J/\Psi, \Psi'$)

- Dalitz decay of mesons and baryons ($\pi^0, \eta, \Delta, \dots$)

- correlated D+Dbar pairs

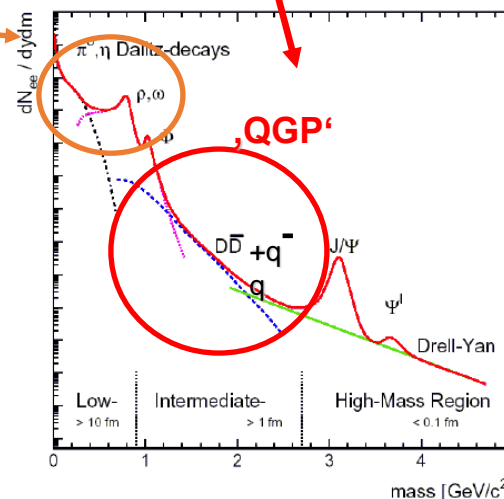
- radiation from multi-meson reactions

($\pi+\pi, \pi+\rho, \pi+\omega, \rho+\rho, \pi+a_1$) - , $4\pi^0$



in-medium effects

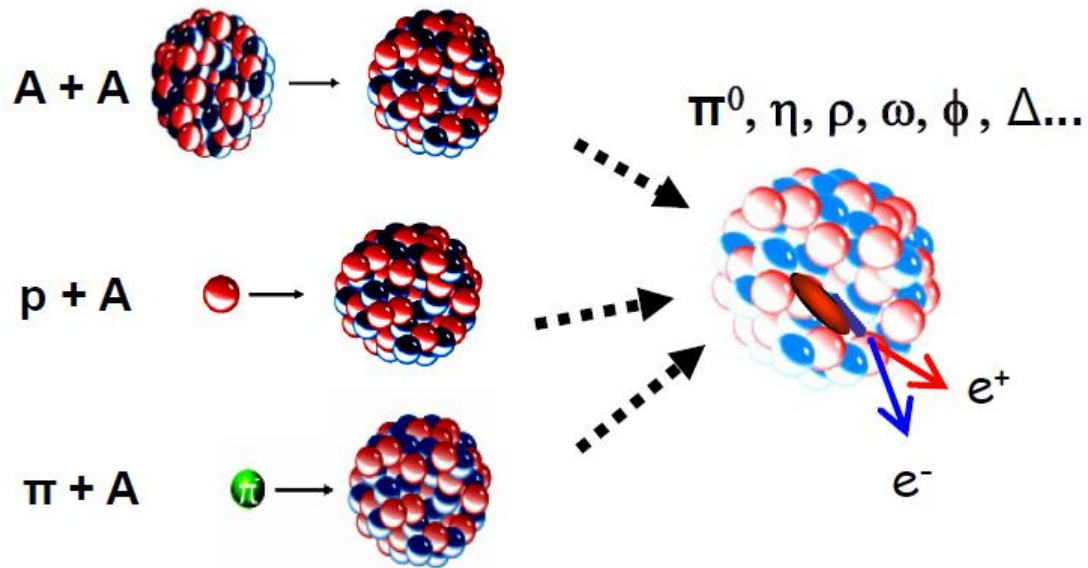
Plot from A. Drees



Cf. review: O. Linnyk, E. Bratkovskaya, W. Cassing, Prog. Part. Nucl. Phys. 87 (2016)
50



Light dark photon production in PHSD



Dark matter detection

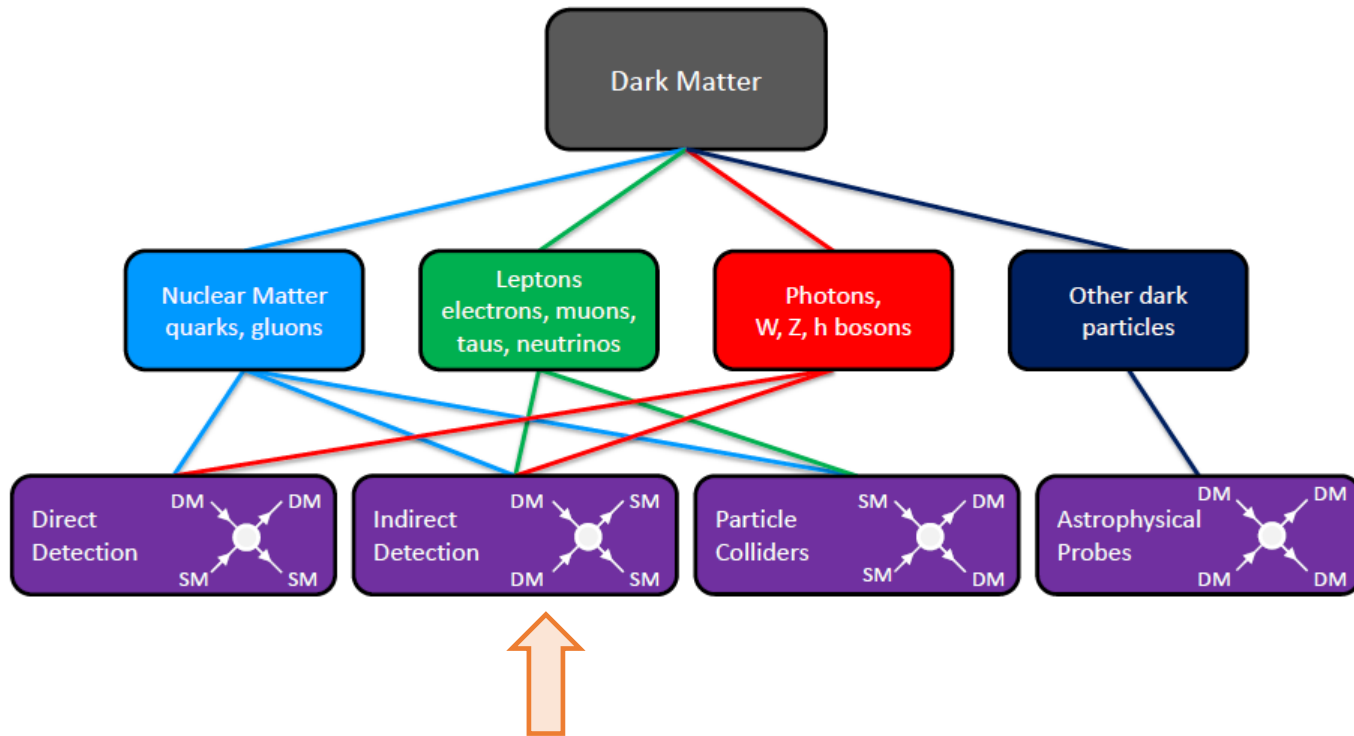


Figure from D. Bauer et al. 2015, Physics of the Dark Universe, 7, 16



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

Basic ideas:

- 1) There is **NO evidence for an experimental observation of dark photons** in dilepton experiments **so far**
- 2) Theoretical model (**PHSD**) provides a good description of exp. data on SM dileptons (from SIS to LHC energies)
- 3) Dark photon yield is proportional to $\varepsilon^2(M_U)$
- 4) **Use the theoretical spectra** – instead of exp. data – **to estimate an upper limit for $\varepsilon^2(M_U)$** from the **constraint** that an additional yield from dark photons **can not exceed the total yield** from standard sources by more than a small factor (for each M_U), which we can vary in our calculations
- 5) Variation of this **'surplus' factor** can provide the range of possible $\varepsilon^2(M_U)$ and can be related to **experimental accuracy** e.g. via error bars, mass resolution, acceptance etc.



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

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

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

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

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

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

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

$$\frac{dN^{total}}{dM} = (1 + C_U) \frac{dN^{sumSM}}{dM} \Rightarrow C_U \text{ controls the allowed "surplus" dilepton yield resulting from dark photons on top of the total SM yield}$$

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

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



Light dark photon production in PHSD

Production of hadron \rightarrow decay to U \rightarrow **dilepton yield from U-boson** decay of mass

M_U

$$\begin{aligned} \pi^0 &\rightarrow \gamma + \mathbf{U}, \\ \eta &\rightarrow \gamma + \mathbf{U}, \\ \mathbf{U} &\rightarrow e^+ e^- \\ \Delta &\rightarrow \mathbf{N} + \mathbf{U}, \end{aligned}$$

$$\begin{aligned} N^{U \rightarrow e^+ e^-} &= N_{\pi^0}^{U \rightarrow e^+ e^-} + N_{\eta}^{U \rightarrow e^+ e^-} + N_{\Delta}^{U \rightarrow e^+ e^-} \\ &= \boxed{Br^{U \rightarrow e^+ e^-}} \boxed{(N_{\pi^0 \rightarrow \gamma U} + N_{\eta \rightarrow \gamma U} + N_{\Delta \rightarrow NU})} \end{aligned}$$

- **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 $\pi^0(\eta) \rightarrow \gamma + \mathbf{U}$ and $\pi^0(\eta) \rightarrow \gamma + \gamma$:**

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

Formfactors:

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

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

$$\Lambda = 0.72 \text{ GeV}$$

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

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

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

Spectral function of Δ -resonance: $A_\Delta(M_\Delta) = C_1 \cdot \frac{2}{\pi} \frac{M_\Delta^2 \Gamma_\Delta^{tot}(M_\Delta)}{(M_\Delta^2 - M_{\Delta 0}^2)^2 + (M_\Delta \Gamma_\Delta^{tot}(M_\Delta))^2}$



Light dark photon production in PHSD

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

$$\begin{aligned} \pi^0 &\rightarrow \gamma + \mathbf{U}, \\ \eta &\rightarrow \gamma + \mathbf{U}, \\ \mathbf{U} &\rightarrow e^+ e^- \\ \Delta &\rightarrow \mathbf{N} + \mathbf{U}, \end{aligned}$$

$$\begin{aligned} N^{U \rightarrow e^+ e^-} &= N_{\pi^0}^{U \rightarrow e^+ e^-} + N_{\eta}^{U \rightarrow e^+ e^-} + N_{\Delta}^{U \rightarrow e^+ e^-} \\ &= Br^{U \rightarrow e^+ e^-} (N_{\pi^0 \rightarrow \gamma U} + N_{\eta \rightarrow \gamma U} + N_{\Delta \rightarrow NU}) \end{aligned}$$

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

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

The yield of U-bosons of mass M_U :

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

□ 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 $\pi^0(\eta) \rightarrow \gamma + \mathbf{U}$ and $\pi^0(\eta) \rightarrow \gamma + \gamma$:

$$\frac{\Gamma_{i \rightarrow \gamma U}}{\Gamma_{i \rightarrow \gamma \gamma}} = 2\epsilon^2 \underbrace{|F_i(q^2 = M_U^2)|}_{\text{Formfactor}} \frac{\lambda^{3/2}(m_i^2, m_\gamma^2, M_U^2)}{\lambda^{3/2}(m_i^2, m_\gamma^2, m_\gamma^2)} \quad i = \pi^0, \eta \quad \leftarrow \quad \epsilon^2 = \alpha'/\alpha$$

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

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

Spectral function of Δ -resonance:

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

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Light dark photon production in PHSD

Production of hadron \rightarrow decay to U \rightarrow **dilepton yield from U-boson** decay of mass

M_U :

$$\begin{aligned} \pi^0 &\rightarrow \gamma + \mathbf{U}, \\ \eta &\rightarrow \gamma + \mathbf{U}, \\ \mathbf{U} &\rightarrow e^+e^- \\ \Delta &\rightarrow \mathbf{N} + \mathbf{U}, \end{aligned}$$

$$\begin{aligned} N^{U \rightarrow e^+e^-} &= N_{\pi^0}^{U \rightarrow e^+e^-} + N_{\eta}^{U \rightarrow e^+e^-} + N_{\Delta}^{U \rightarrow e^+e^-} \\ &= \boxed{Br^{U \rightarrow e^+e^-}} \boxed{(N_{\pi^0 \rightarrow \gamma U} + N_{\eta \rightarrow \gamma U} + N_{\Delta \rightarrow NU})} \end{aligned}$$

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Formfactors:

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

Spectral function of Δ -resonance: $A_\Delta(M_\Delta) = C_1 \cdot \frac{2}{\pi} \frac{M_\Delta^2 \Gamma_\Delta^{tot}(M_\Delta)}{(M_\Delta^2 - M_{\Delta 0}^2)^2 + (M_\Delta \Gamma_\Delta^{tot}(M_\Delta))^2}$

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Dark photon production in PHSD

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

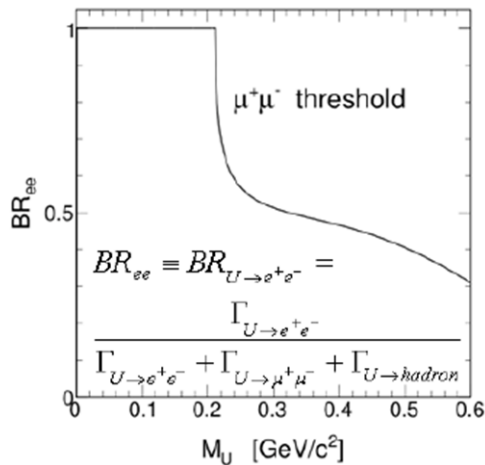
The **yield of U-bosons** of mass M_U :

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

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

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

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



$$\Gamma_{tot}^U = \Gamma_{U \rightarrow hadr} + \Gamma_{U \rightarrow e^+ e^-} + \Gamma_{U \rightarrow \mu^+ \mu^-}$$

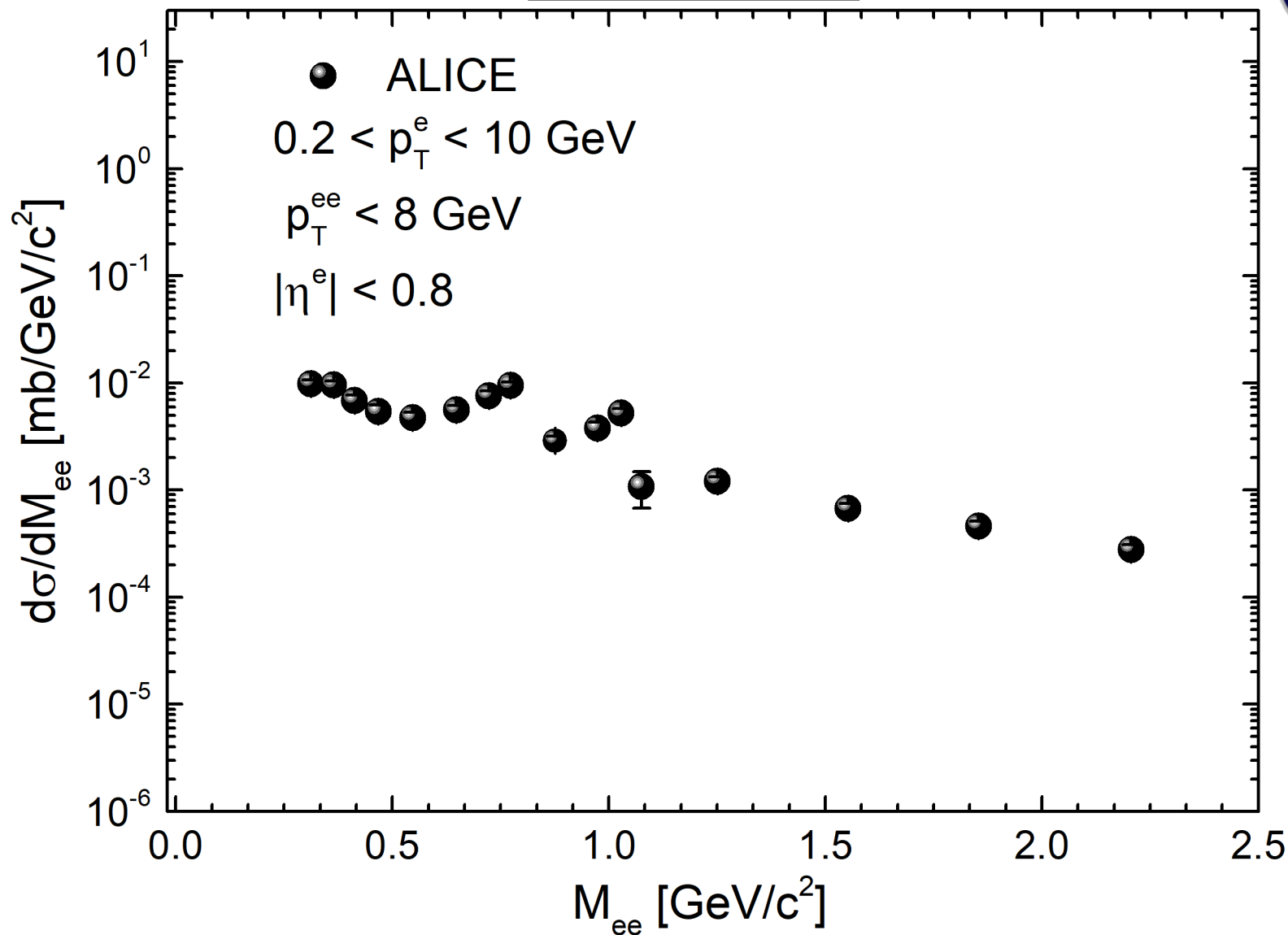
$$\Gamma_{U \rightarrow hadr} = R(\sqrt{s} = M_U) \Gamma_{U \rightarrow \mu^+ \mu^-}$$

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

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

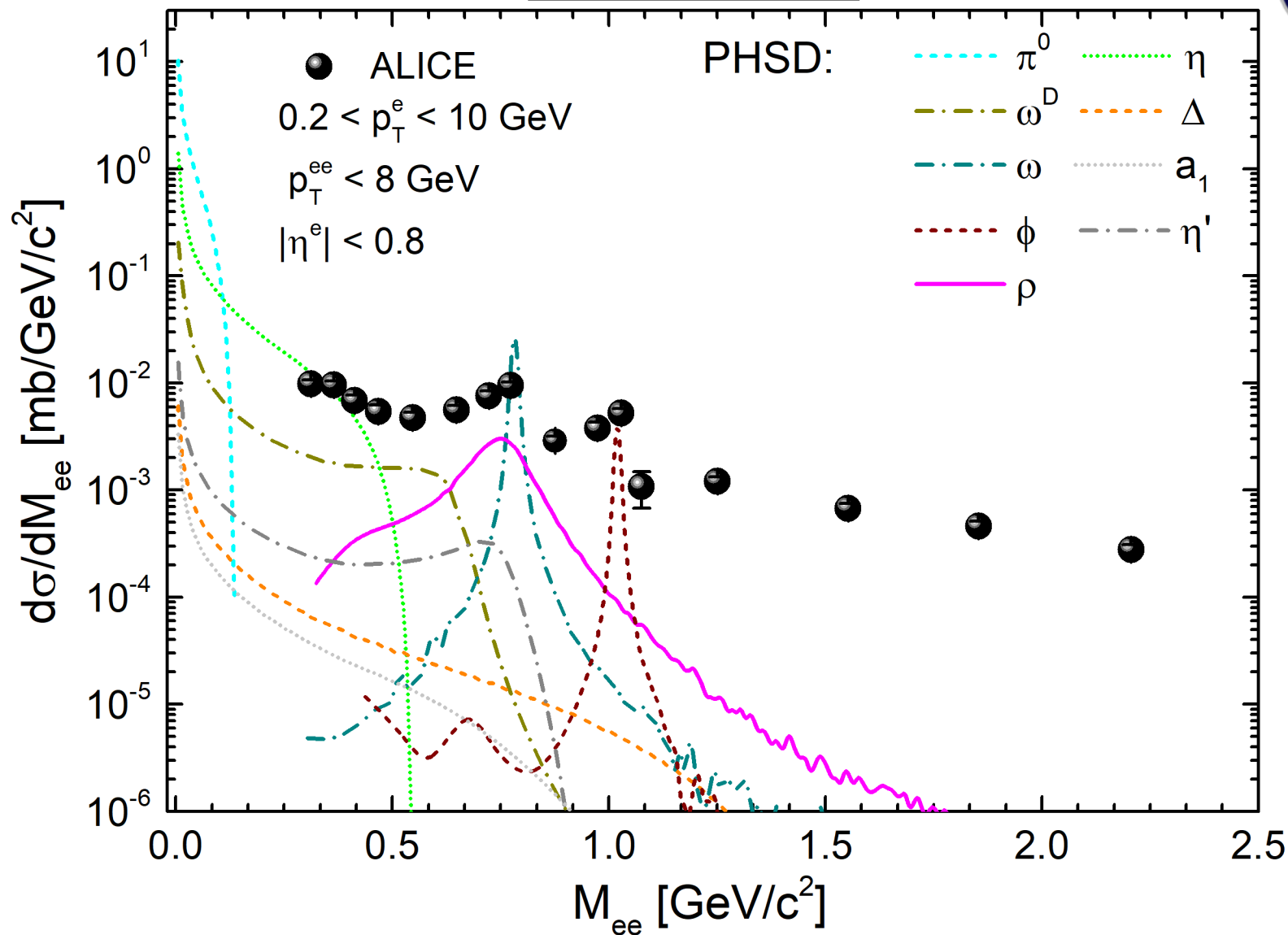
Dilepton mass spectra

p+p, 5.02 TeV



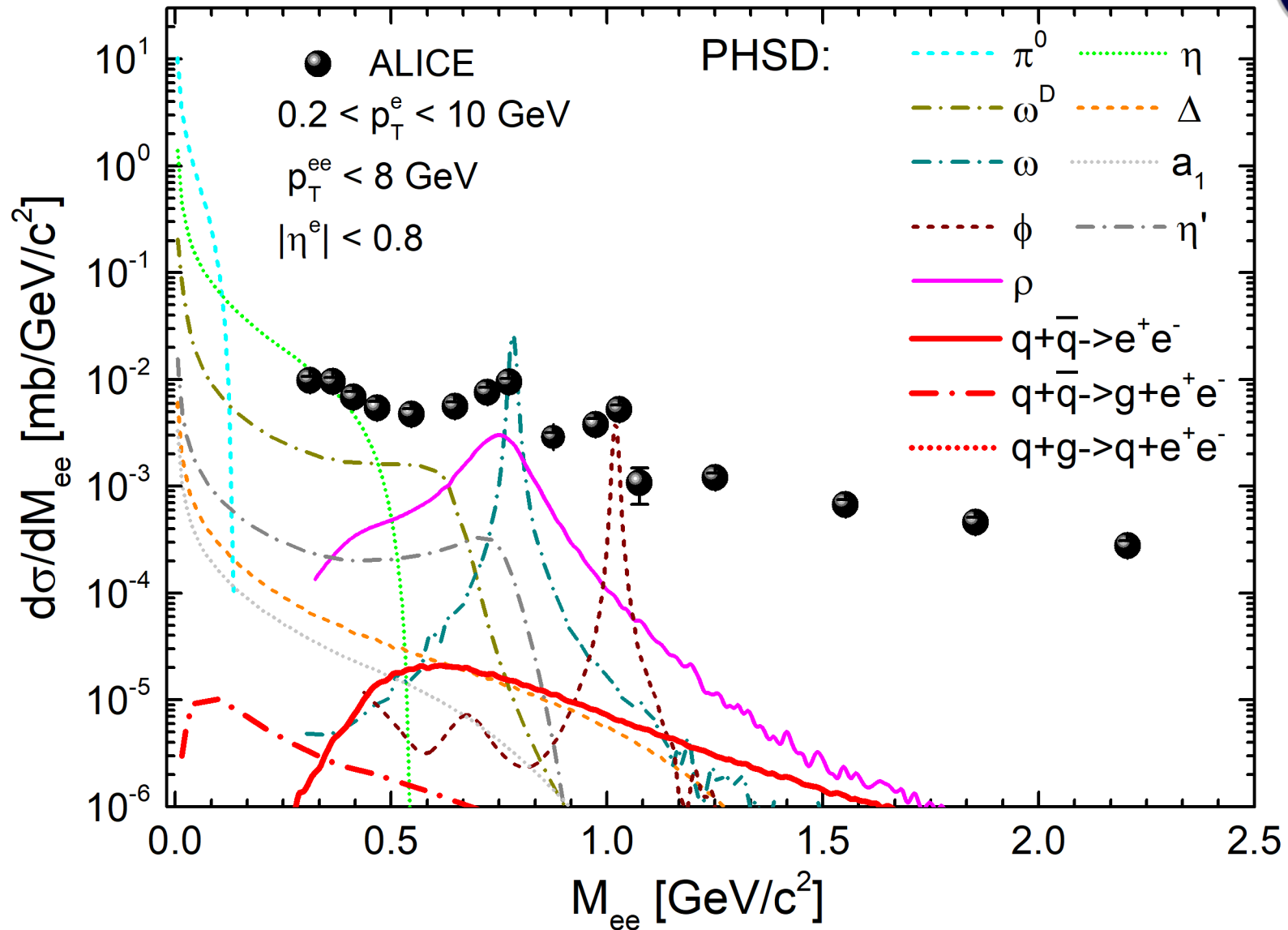
Dilepton mass spectra

p+p, 5.02 TeV



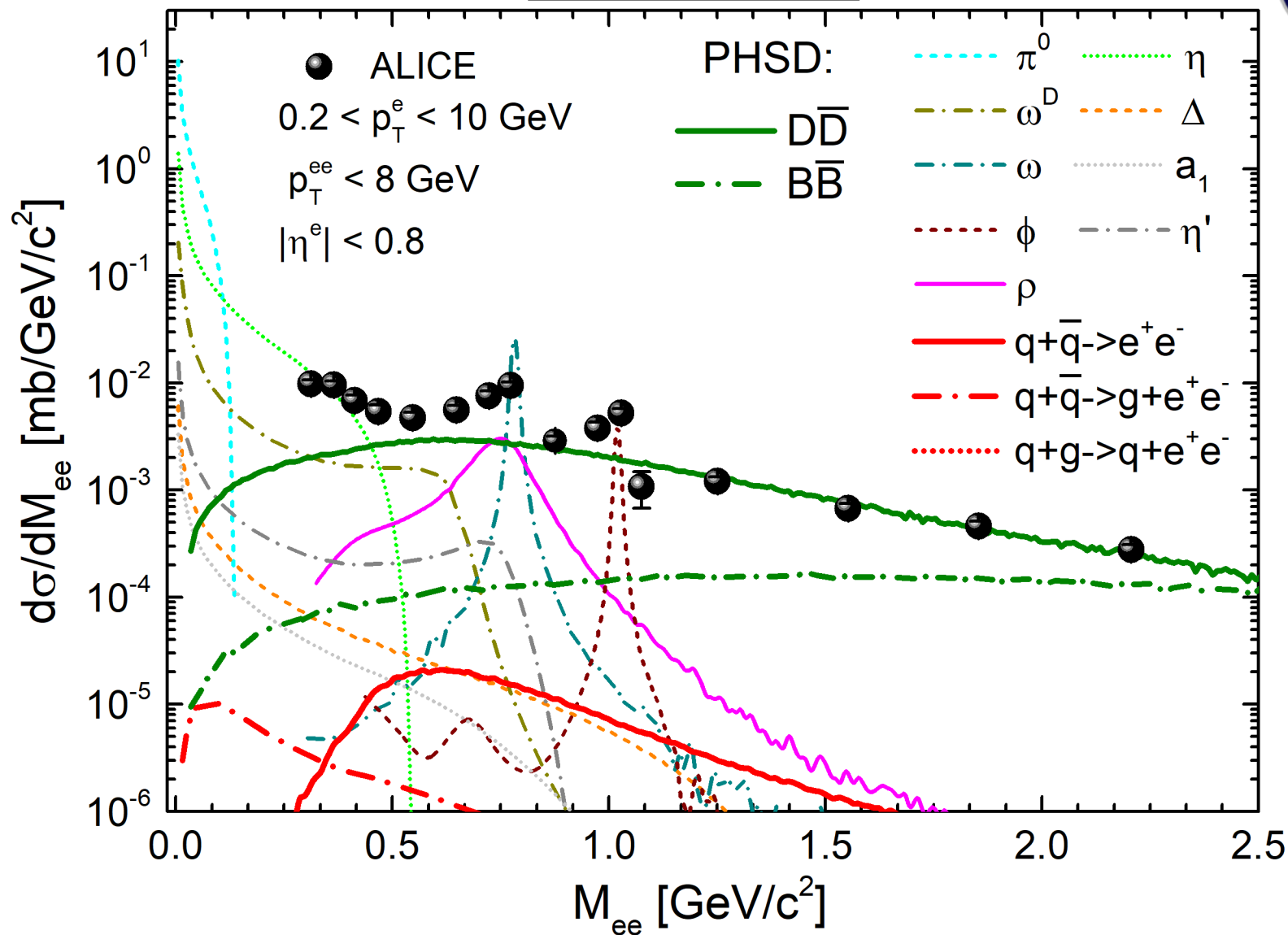
Dilepton mass spectra

p+p, 5.02 TeV



Dilepton mass spectra

p+p, 5.02 TeV



Dilepton mass spectra

p+p, 5.02 TeV

