Constraining Dark Photon Kinetic Mixing in Heavy-Ion Collisions from SIS to LHC energies

A. W. Romero Jorge[1,2,3], **E. Bratkovskaya**[2,3,4] **T. Song**[4], **Laura Sagunski**[2]

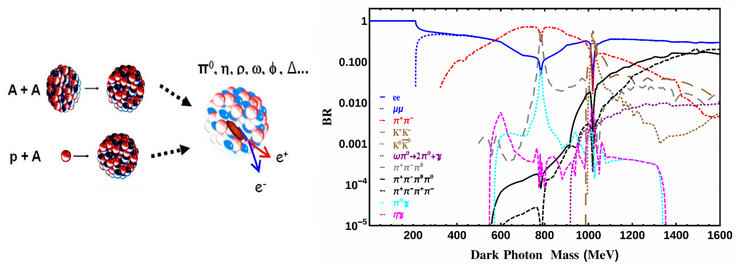
[1]Frankfurt Institute for Advanced Studies (FIAS), [2]Institute for Theoretical Physics, Goethe University, [3]Helmholtz Research Academy Hessen for FAIR (HFHF), [4]GSI Helmholtzzentrum für Schwerionenforschung.

1. Motivation

- Explore for a possible dark photon (U-boson) observation by dilepton experiments in heavy-ion collisions from SIS to LHC energies.
- Estimate the upper limit for the kinetic mixing parameter $\varepsilon^2(M_U)$ of the U-boson from the theoretically calculated in dilepton spectra using the PHSD approach.

2. U-boson in dilepton experiments

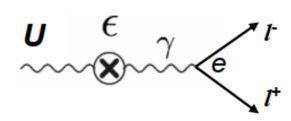
- Dilepton spectra from SM sources in $p+p, p+A, A+A$ collisions are well studied by experiments from SIS to LHC energies.
- Dark photon production by hadronic decays ($\pi^0, \eta, \Delta, \omega, \phi, K$, ...) and partonic decays.
- Possibility for an experimental observation of U-bosons by electromagnetic decays $U \rightarrow e^+e^-$ in heavy-ion experiments.



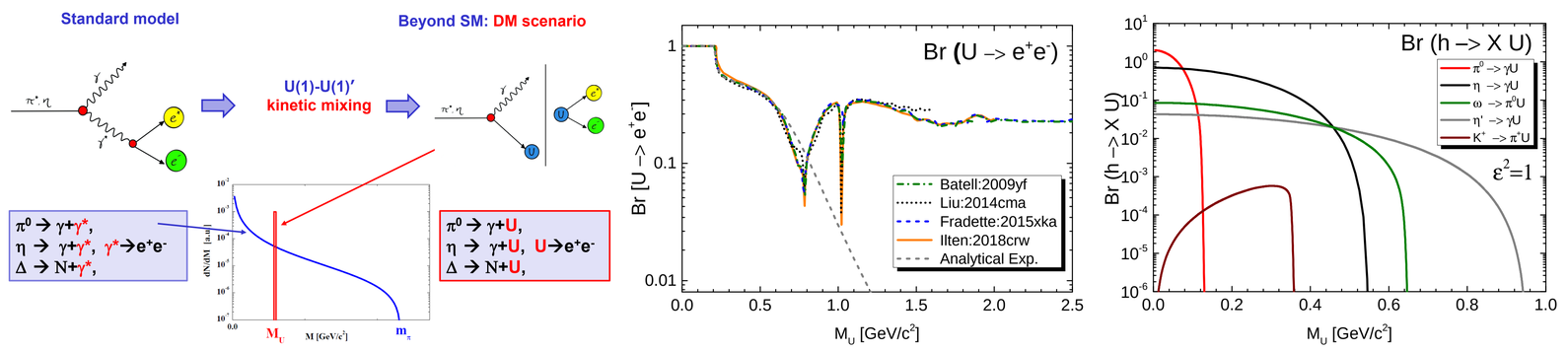
3. Dark Photon in the Vector Portal

- The 'vector' portal assumes the mixing of SM and DM via $U(1) - U(1)'$ gauge symmetry group mixing

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

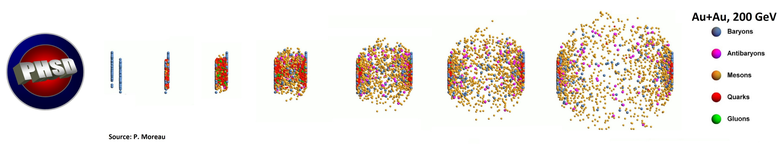


- Due to kinetic mixing, the dark photon couples to the electromagnetic current with strength $\varepsilon\, e$ and effective fine structure constant $\alpha' = \varepsilon^2 \alpha$.



4. PHSD Transport Approach

Parton-Hadron-String Dynamics (PHSD) is a non-equilibrium microscopic transport approach that describes the full evolution of heavy-ion collisions—from initial nucleon-nucleon interactions, through QGP formation (described in terms of the DQPM model) and interactions, to hadronization and final-state interactions—using generalized off-shell transport equations based on the Kadanoff-Baym theory [1].



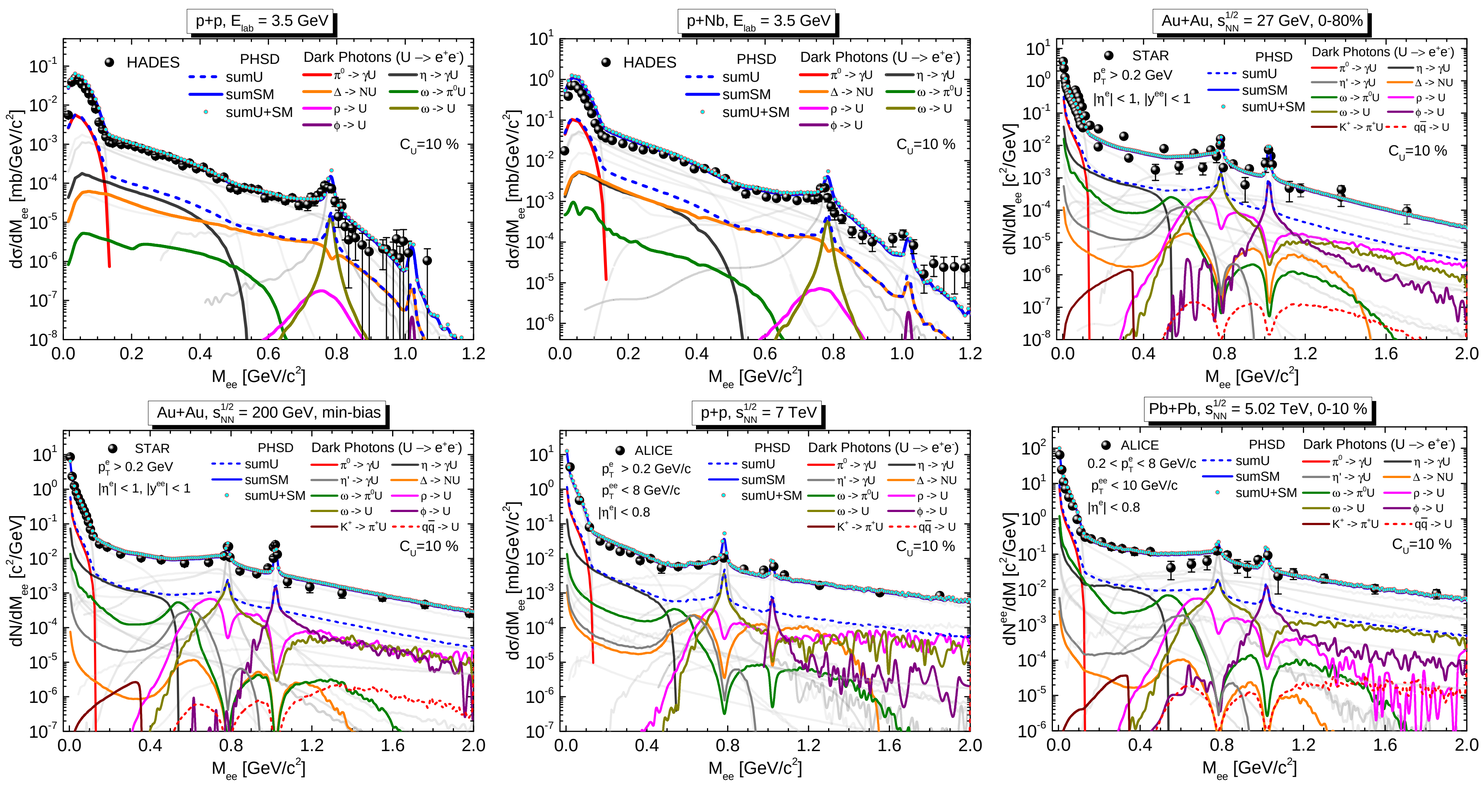
5. Dark photon production channels

We consider the next production channels for dark photons [2, 5, 6]:

- $\pi^0, \eta, \eta' \rightarrow \gamma\, U$
- $\Delta \rightarrow N\, U$
- $\omega \rightarrow \pi^0\, U$
- $K^+ \rightarrow \pi^+\, U$
- $\omega, \rho, \phi \rightarrow U$
- $q\bar{q} \rightarrow U$

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

6. Dilepton spectra from U-boson decays from SIS to LHC energies



- Standard Model (SM) contributions are well described by the PHSD transport model [3, 4].
- The contributions from $U \rightarrow e^+e^-$ are added with an allowed surplus C_U of the total SM yield, the total sum is still in good agreement with experimental data.
- Increasing collisional energy enhances the contribution of dark photon channels

7. Theoretical constraints on $\varepsilon^2(M_U)$

The total yield from all possible dilepton sources,

$$\frac{dN}{dM}^{total} = \frac{dN}{dM}^{sumSM} + \frac{dN}{dM}^{sumU},$$

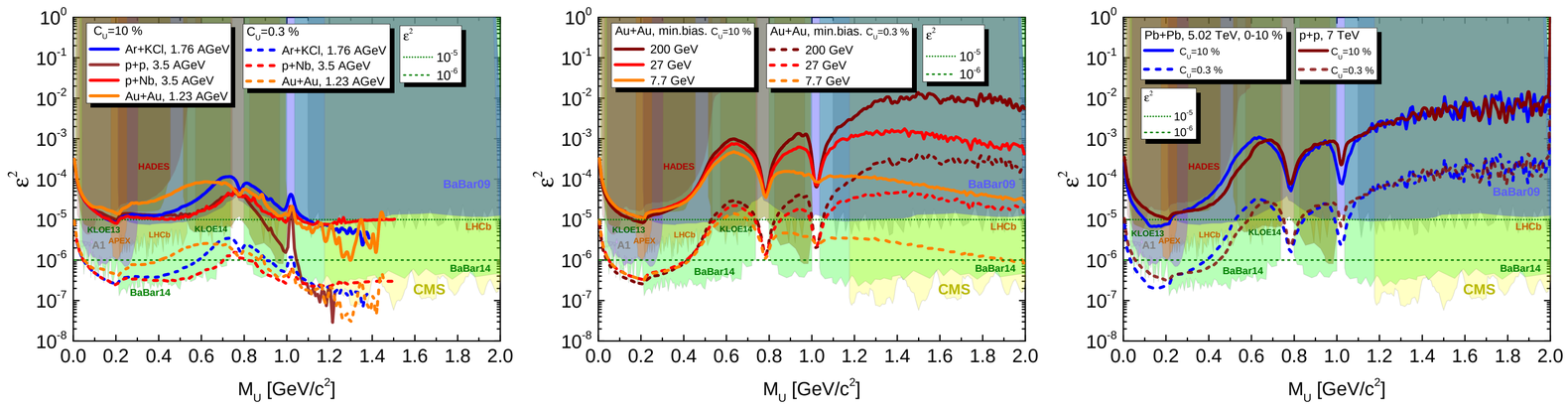
$$\frac{dN}{dM}^{sumU} = \varepsilon^2 \frac{dN^{sumU}_{\varepsilon^2=1}}{dM}.$$

Requesting that the total sum cannot surplus the sum of SM channels by more than a fraction C_U in each bin dM

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

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

8. Kinetic Mixing Parameter $\varepsilon^2(M_U)$



- $\varepsilon^2(M_U)$ calculated within PHSD is consistent with the experimental results of the HADES, A1 and BaBar for $M_U < 1.2$ GeV for differents C_U and $\sqrt{s_{NN}}$.
- Experimental data of high precision is needed to reduce the upper limit for ε^2.

9. Summary

- We presented first microscopic transport calculations, based on the PHSD approach, for the dilepton yield from the decay of U-bosons from $p + p$, $p + A$ and $A + A$ collisions from SIS up to RHIC energies.
- 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.
- Using $C_U = 0.3\%$, the extracted limits also match BaBar14 results in $0.2 < M_U < 1.5$,GeV, indicating a possible 0.3 % dark-photon contribution to the SM dilepton yield, consistent with global experimental compilations.

KEY REFERENCES

[1] W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919

[2] I. Schmidt, E. Bratkovskaya, et al., PRD 104 (2021) 015008

[3] Romero Jorge et al. (2025), arXiv:2503.05253.

[4] Song et al. (2018), PRC 97, 6, 064907.

[5] J. Alexander, et al., Dark Sectors Workshop: Community Rep. (2016)

[6] B. Battel, M. Pospelov, et al., PRD 80 (2009) 095024

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