Combined constraints on dark photons from high-energy collisions, cosmology, and astrophysics

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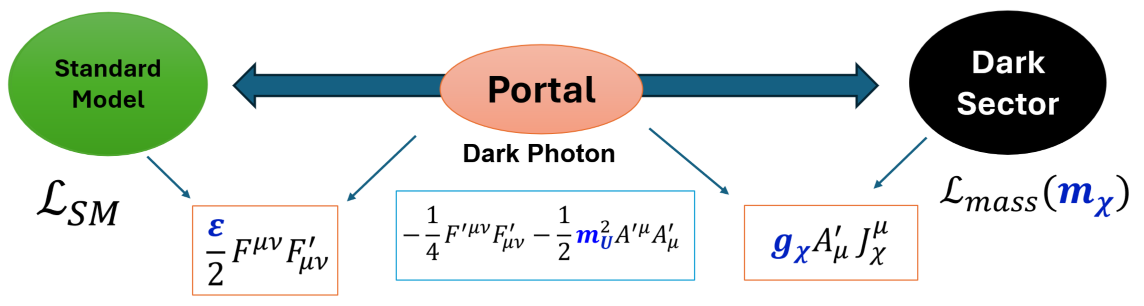
1. Motivation

- Goal: Constrain vector portal dark photons by combining dilepton spectra with dark matter (DM) relic density and self-interacting DM (SIDM) constraints.

2. Vector portal with Dark Matter

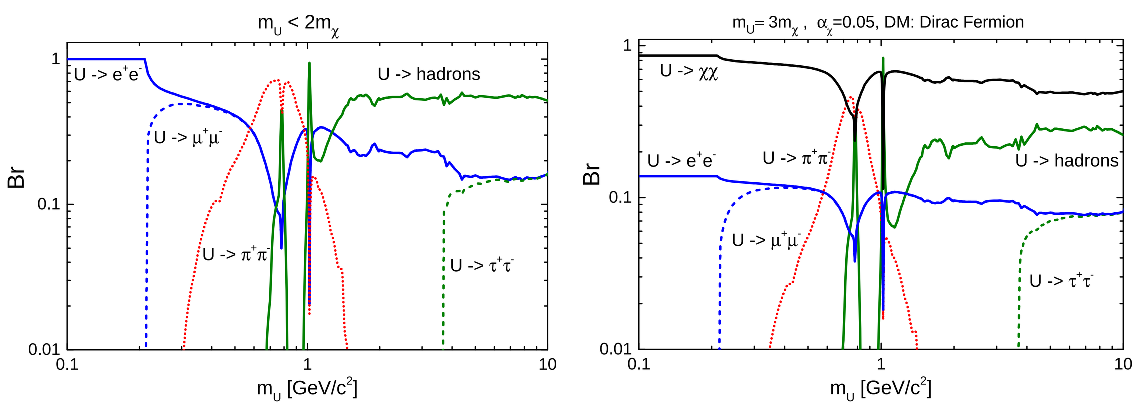
The dark photon lagrangian with dark matter is [1]



At low energies, the mediator couples as $\varepsilon e A'_\mu J^\mu_{\rm EM}$. The dark current J^μ_χ reads as:

$$J^\mu_\chi = \begin{cases} \bar{\chi}\gamma^\mu\chi, & \text{Dirac fermion,} \\ \frac{1}{2}\bar{\chi}\gamma^\mu\gamma^5\chi, & \text{Majorana fermion,} \\ i\left(\varphi^\dagger\partial^\mu\varphi-(\partial^\mu\varphi^\dagger)\varphi\right). & \text{complex scalar,} \end{cases}$$

Visible $(m_U < 2m_\chi)$ and **Invisible** $(m_U > 2m_\chi)$ width



- For $m_U < 2m_\chi$, the dilepton branching ratio $(U \to e^+e^-)$ remains unsuppressed. For $m_U > 2m_\chi$, invisible decays reduce the observable $U \to e^+e^-$ signal.

3. Dark photon production in PHSD

The Parton-Hadron-String Dynamics (**PHSD**) is a non-equilibrium off-shell transport approach for relativistic hadronic and heavy-ion collisions. It describes the full space-time evolution of the collision, from the initial nucleon–nucleon interactions and string excitation, through the QGP phase, to hadronization and final-state hadronic rescattering and decays. [3]

Dark-photon production channels in PHSD [2]

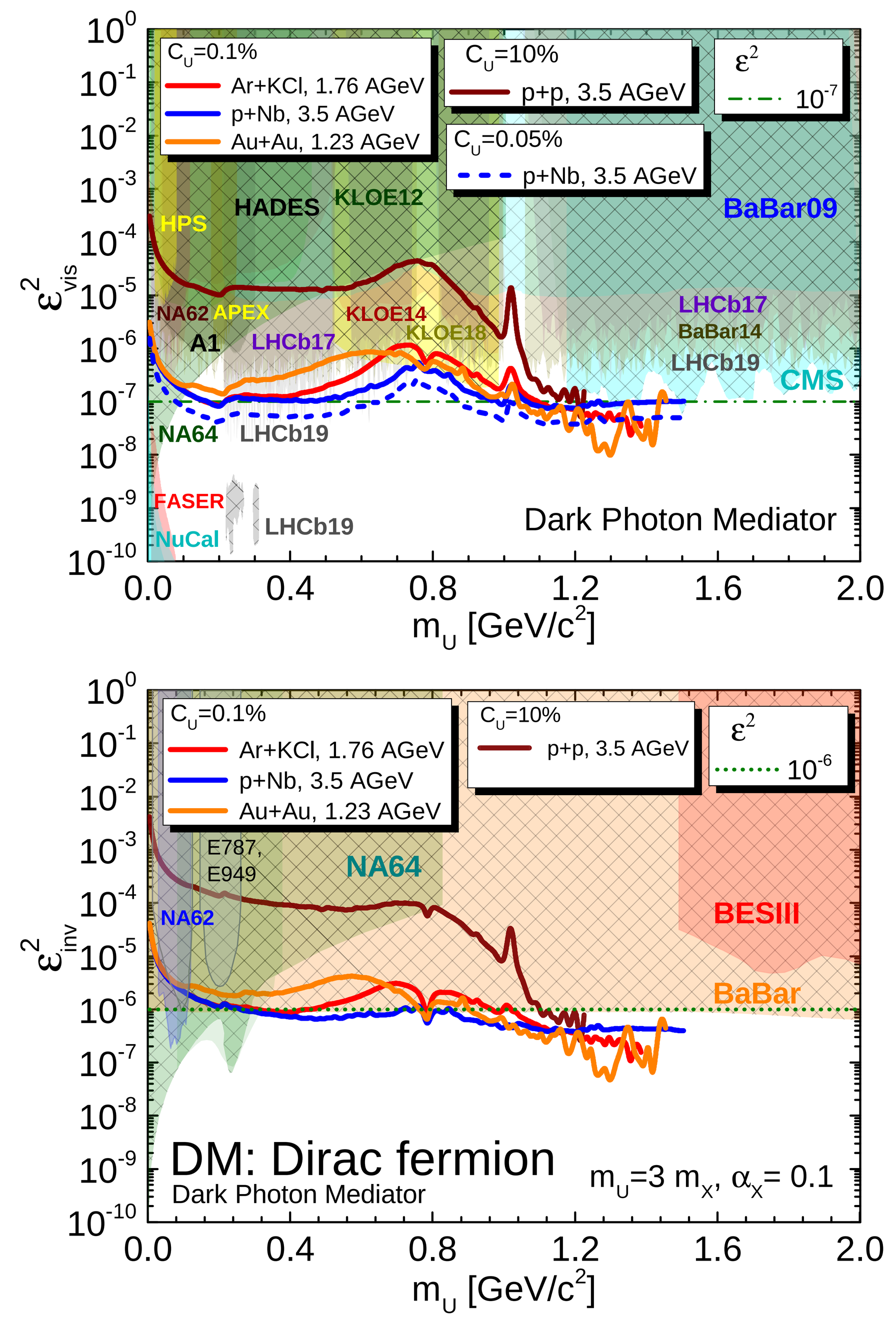
$$\pi^0,\eta,\eta' \to \gamma U, \qquad \rho,\omega,\phi \to U,$$
$$\omega \to \pi^0 U, \qquad K^+ \to \pi^+ U,$$
$$\Delta \to NU, \qquad q\bar{q} \to U.$$

The total dilepton yield from dark photons is

$$N^{U\to e^+e^-} = \mathrm{Br}(U \to e^+e^-)\sum_h N_{h\to UX}$$

- Hadronic sources are implemented explicitly in PHSD [2].
- The partonic contribution is obtained by rescaling the PHSD quark-gluon plasma dilepton yield.

4. From dilepton excess to a limit on ε^2



For each invariant-mass bin dM, the dark-photon yield scales linearly with kinetic mixing square,

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

We require the dark photon contribution not to exceed a small surplus over the SM yield,

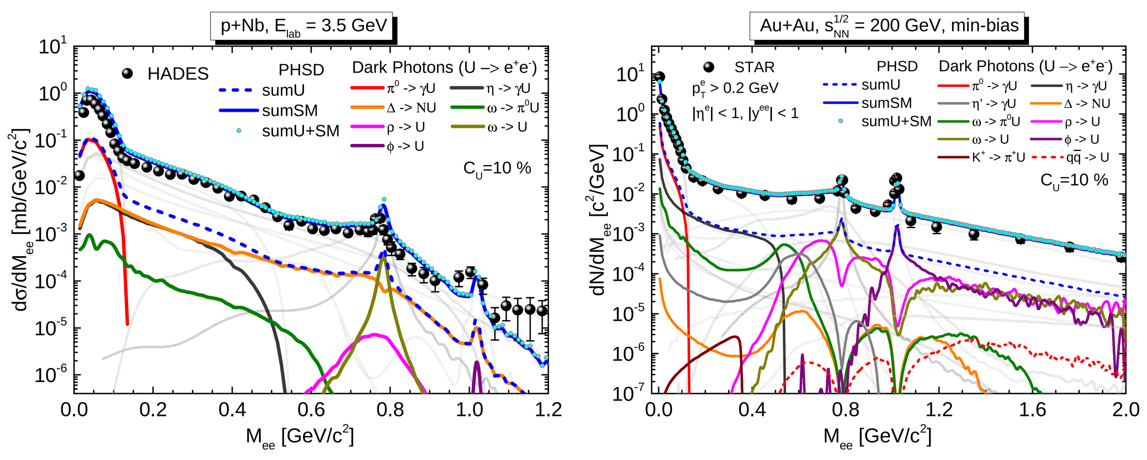
$$\frac{dN^{\rm sumU}}{dM} \le C_U\frac{dN^{\rm sumSM}}{dM}.$$

This yields the upper bound for the kinetic mixing [2]

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

- Heavy-ion dilepton data probe both visible and invisible dark-photon regimes.

5. PHSD dilepton spectra with dark photons

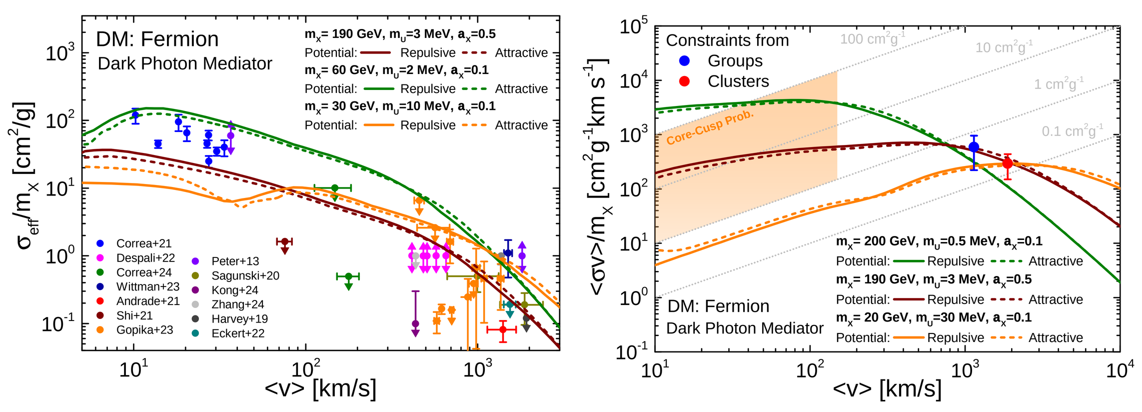


- PHSD reproduces the Standard Model dilepton background from SIS to LHC energies. [1–3]
- Dark photons appear as narrow structures in the invariant-mass spectra.
- Improved experimental precision translates directly into stronger limits on ε^2 through smaller C_U.

6. Self-interacting dark matter constraints

We compute Yukawa-mediated DM self-scattering with CLASSICS, and use transport cross-sections [4, 6]

$$\sigma_T(v) = \int d\Omega\,(1-\cos\theta)\frac{d\sigma}{d\Omega}, \qquad \sigma_{\rm eff} = \frac{3}{2}\frac{\langle\sigma(v)v^5\rangle}{\langle v^5\rangle}.$$

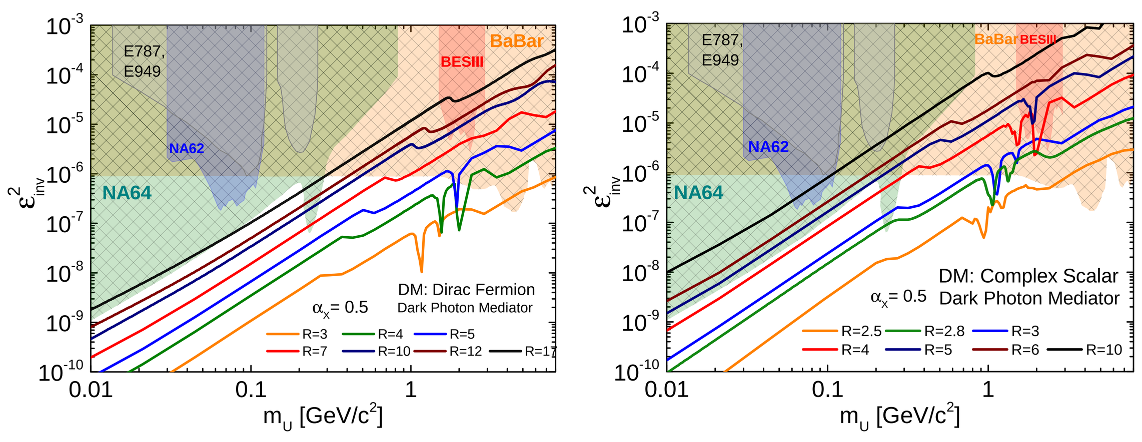


- Viable SIDM scenarios require large self-interactions at dwarf velocities and suppressed scattering at group and cluster scales.
- This typically favors light mediators and comparatively heavy dark matter.

7. Thermal relic target

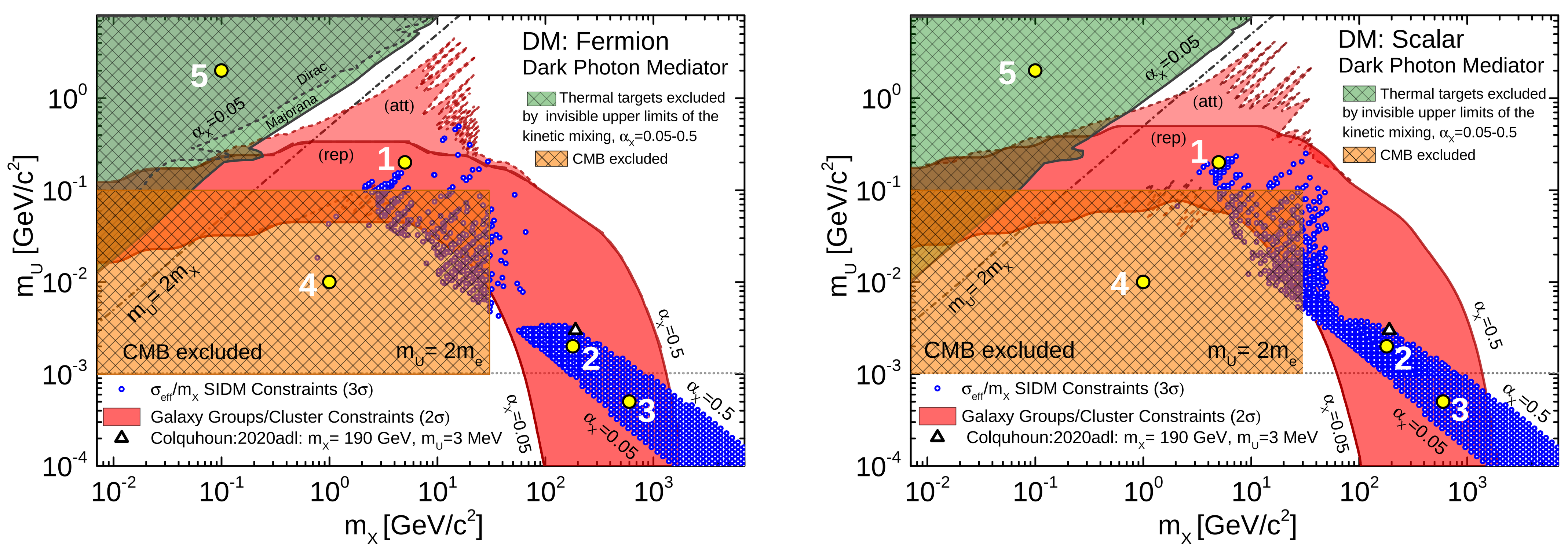
Using ReD-DeLiVeR, we solve the freeze-out dynamics and require the observed DM relic abundance [5],

$$\Omega_{\rm DM}h^2 \simeq 0.120 \pm 0.001.$$



- Dirac, Majorana, and complex scalar DM lead to distinct thermal target curves.
- Local dips originate from hadronic thresholds and resonance effects in the mediator width.

8. Combined parameter-space constraints



- **Blue/red:** Regions compatible with SIDM (effective cross-section and Groups/Cluster constraints) from dwarfs, galaxies, groups, and clusters.
- **Orange:** CMB-excluded DM low-mass region.
- **Green:** Thermal target points excluded by invisible kinetic mixing limits on ε^2.
- $m_U = 2m_\chi$ Separates the visible and invisible regimes.
- **BP1:** visible sub-GeV mediator and intermediate-mass DM, it satisfies SIDM constraints.
- **BP2:** MeV mediator with heavy DM, typical of SIDM-favored scenarios.
- **BP3:** Ultra-light long-lived mediator with $m_U < 2m_e$: stable dark photon.
- **BP4/BP5:** Representative CMB and PHSD excluded benchmarks (see orange and green regions).

9. Summary

- We have studied a dark sector in which a kinetically mixed dark photon U is constrained through dilepton production within the PHSD transport approach.
- Combining the kinetic mixing limits with thermal relic targets and self-interaction constraints, we found that large regions of the parameter space are excluded.
- The combined analysis favors light mediators in the MeV-sub-GeV range and comparatively heavy dark matter (DM),

KEY REFERENCES

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