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PPG BSM: Dark Photon

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Feebly Interacting Particles

A portal to an Hidden Sector

- **Feebly Interacting Particles (FIPs)** populating a new Hidden sector, might be responsible for phenomena such as Dark Matter

  - FIPs expected below EW scale (**MeV-GeV mass range**), **feebly coupling** with SM particles.

  - FIPs-SM interaction via portal operators

Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S+\lambda_{HS}S^2)H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N LHN$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$

Dark Photon Portal

Spin-1 fields with MeV-GeV mass

- Dark Photons A' : **massive vector particles** from an extra dark U(1) symmetry
  - With Lagrangian (BC1):

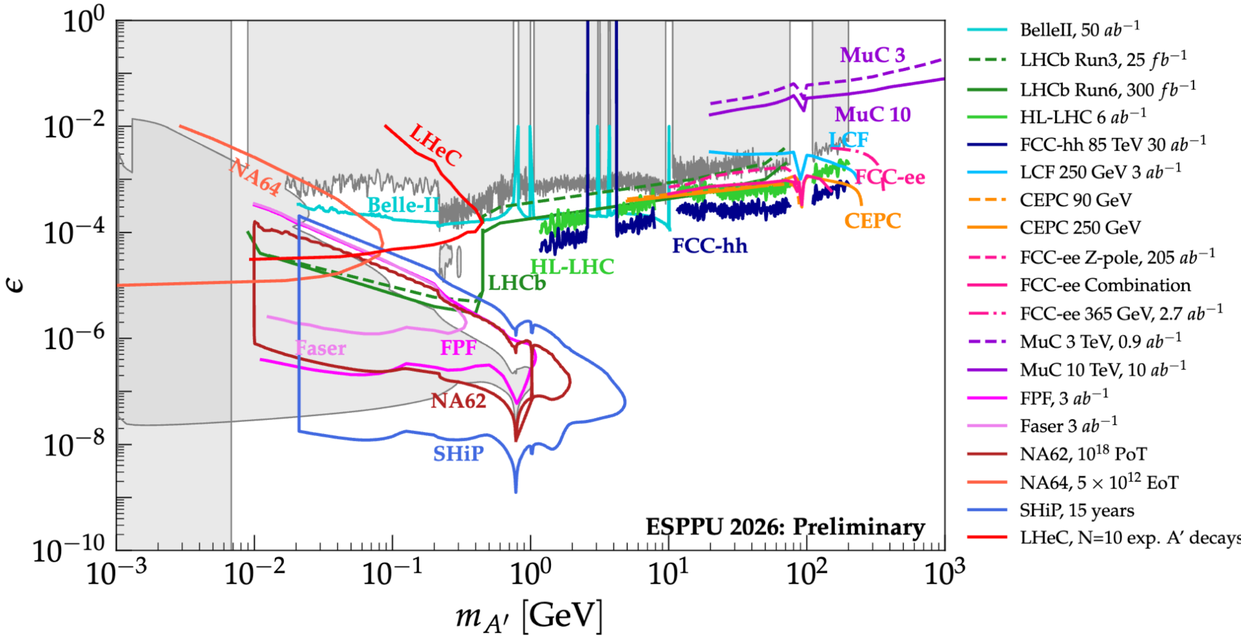
$$-\frac{\epsilon}{2cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

    - where $F'_{\mu\nu}$, the A' field, mixes with $B_{\mu\nu}$, the SM $U(1)_Y$ field, with **coupling suppressed by ϵ.**
- **Minimal Dark Photon** here → 1 new single state, A'
  - **DM assumed to be out of reach** (too heavy or belonging to a different sector)
    - DM coupling to SM, α_D, assumed to be negligible → **Visible A' decays**

Sensitivity projections

Nice complementarity between colliders and beam-dump experiments

- **Future collider exps** sensitivity covers large-mass large-coupling regime
- **Beam-dump exps** sensitive in the low-mass low-coupling region
  - LHCb upgrade and Belle II complement the medium-mass, high-coupling region

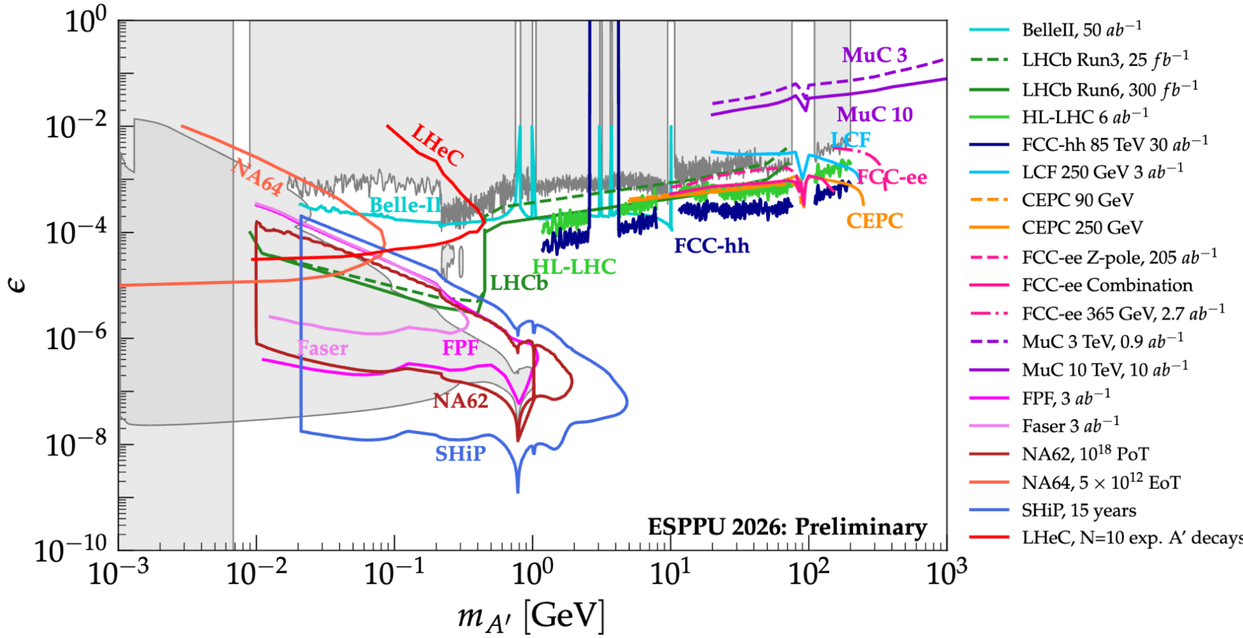


90% CL exclusion limits for Dark Photons in the plane mixing parameter ε versus Dark Photon mass. HL-LHC, CEPC, FCC-ee and FCC-hh curves correspond to 95% CL exclusion limits. LHeC curve correspond to N=10 expected A' decays and 0 background. The sensitivity of future colliders, mostly covers the large-mass, large-coupling range, and is fully complementary to the the low-mass, very low- coupling regime where beam-dump and fixed-target experiments are most sensitive. Belle II and LHCb upgrade provide additional coverage in the medium-mass, high-coupling region.

Beam Dump experiments

A’ production

- **Bremsstrahlung** $e^- Z \to e^- Z A'$ and $pZ \to pZA'$ (NA62, NA64, Faser, FPF, SHiP)
- **Light mesons decays** $M \to A'\gamma$ (NA62, Faser 2, SHiP)
- **Meson mixing** (NA62)



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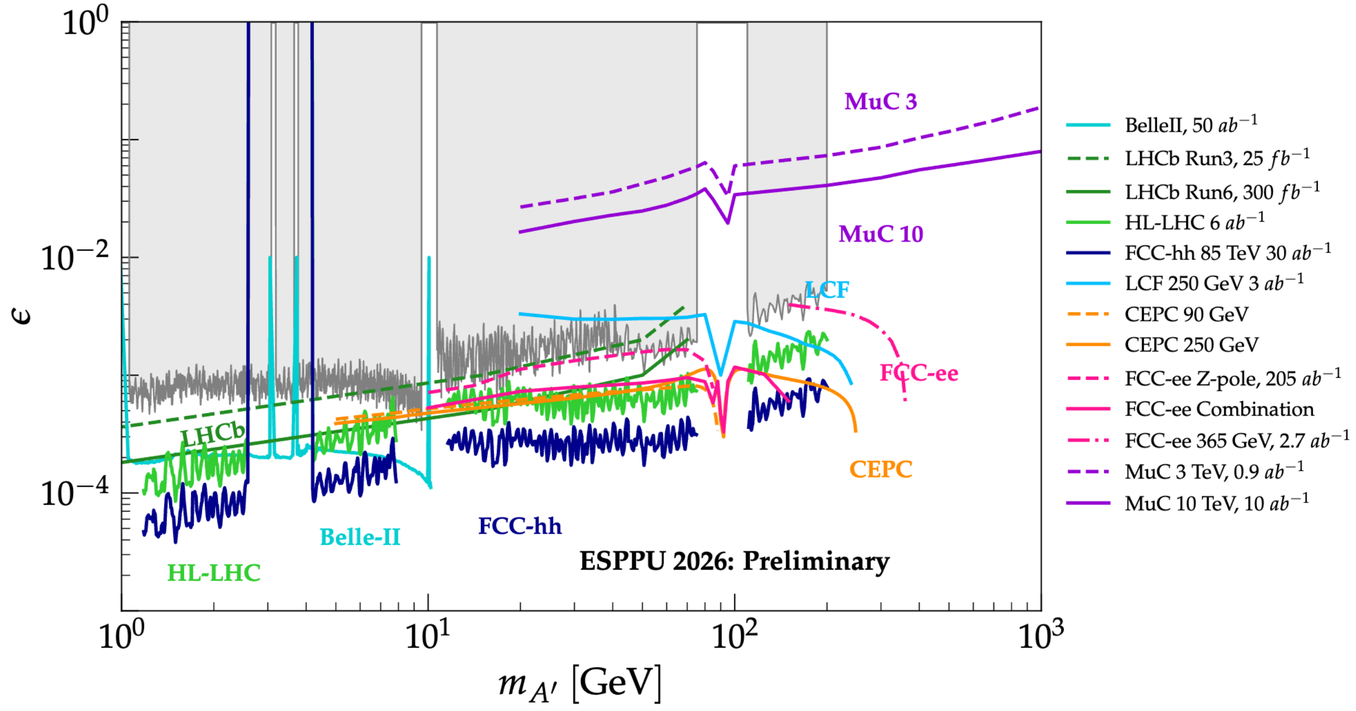
Theoretical Uncertainties: models in low-mass, low-coupling region affected by sizeable Th. Unc., which are treated in different ways by experiments

Collider experiments

A’ production

- **Radiative return**, $e^-e^+/\mu^-\mu^+ \to A'\gamma$ (MuC, FCC-ee, CEPC, ILC)
- **Drell-Yan**, $q\bar{q} \to A'$ (HL-LHC, LHCb, FCC-hh)
- **Associated production**, $\mu^+\mu^- \to A'\mu^+\mu^-$, (MuC
- **Z decays**, $Z \to A'\mu^+\mu^-$ (FCC-ee, CEPC)
- **Heavy meson decays**, $D^* \to DA'$ (LHCb)



High dark photon mass region: 90% CL exclusion limits for Dark Photons in the plane mixing parameter ε versus Dark Photon mass. HL-LHC, CEPC, FCC-ee and FCC-hh curves correspond to 95% CL exclusion limits. The sensitivity of future colliders mostly covers the large-mass, large-coupling range. Belle II and LHCb upgrade provide additional coverage in the medium-mass, high-coupling region.

Contributions considered

- 19 The Forward Physics Facility at the Large Hadron Collider
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- 140 A Linear Collider Vision for the Future of Particle Physics
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- 170 Highlights of the HL-LHC physics projections by ATLAS and CMS
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- 261 FCC Integrated Programme: Stages 1 + 2

Summary

The landscape of approved and proposed facilities provide a nice coverage of Dark Photon possibilities in a complementary way

- Beam-dump/fixed target facilities can probe very low to medium mass and low mixing
  - with **SHIP** probing mixing down to **10^{-9}** and **NA64** probing masses down to **10^{-3}** GeV
    with **LHCb** covering larger mixing
  - Intermediate to high mass ranges with large couplings are potentially covered by **colliders,**
    with HL-LHC and potentially **FCC-hh** bringing down the reach to lower couplings
    and **lepton colliders** further extending the reach, with **Muon Collider** extending it up to **1 TeV**

Additional material

Details on inputs

- NA62: $A' \to ll$ and $A' \to ll$ + hadrons. Production mode: Bremsstrahlung + meson mixing + light meson decays (without time-like form factor)
  - Projections based on Fig. 7 in arXiv:2502.04241, updated to 10^{18} PoT
- NA64: taken from https://arxiv.org/abs/2305.01715 (discussed with Paolo Crivelli), Bremsstrahlung production + visible A' decay Projections to 5×10^{12}EOT
- SHiP: Fig.1 in ESPPU Coll. input
- Faser 2: Fig.4.4 in arxiv:2203.05090
- SHIFT: taken from https://arxiv.org/abs/2406.08557
- DarkQuest: taken from https://arxiv.org/abs/2203.08322
- FASER@HL-LHC: provided by Roshan Mammen and Felix Kling
- LHeC: Fig. 5 top left (Pt(X)>5 GeV, N=10 expected dark photon decay. Zero background assumed.

Details on inputs

- ILC 250 GeV 3ab-1, inputs provided by Jenny List. The plot is an update from Figure 123 in the ECFA report: https://indico.cern.ch/event/1439855/contributions/6461549/attachments/3045922/5381868/ECFA_HETFactories_Backup_FullReport_indicov1.pdf. It includes updted luminosity and doing a likelihood ratio weighting of the two polarisations.
- LHCb: Run 3 and Run 4 projections for inclusive $A' \rightarrow e^+e-$ from Fig.1 in LHCb Snowmass projection
- Belle II: Fig.11 in arxiv:2207.06307
- Muon Collider: Fig. 6 in arxiv:2412.09681 (gZ' >>gD) Muon Collider production modes: associated production + Brem.
- FCC-ee inputs comes from Giacomo Polesello
- CEPC: Fig 8 in arxiv.org:1503.07209 Resonant production with ISR (radiative return)
- HL-LHC and FCC are rescaled from CMS dark photon results (scouting plus offline trigger strategies, JHEP 12 (2023) 070 and PRL 124 (2020) 131802) - Resonant production

Available constraints

Provided by PPG DMDS

- NuCal, CHARM: computed using the approach of https://arxiv.org/abs/2409.11096 ($m_{A'}$ [GeV] $-$ ϵ)
- LHCb, NA48, Orsay - taken from the FORESEE repository.
- SN+cosmo: taken from 2502.01731 + to cite the future overview papers ("The Heavy Dark Photon Handbook: Cosmological and Astrophysical Bounds", A. Caputo, F. D'Eramo, Jaeyoung Park, Seokhoon Yun, "The Dark Photon: a 2025 Perspective", A. Caputo & R. Essig, Encyclopedia for Particle Physics 2025)