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European Strategy for Particle Physics

PPG BSM: ALPs

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Axion Like Particles (ALPs)

Pseudo-scalar Portal

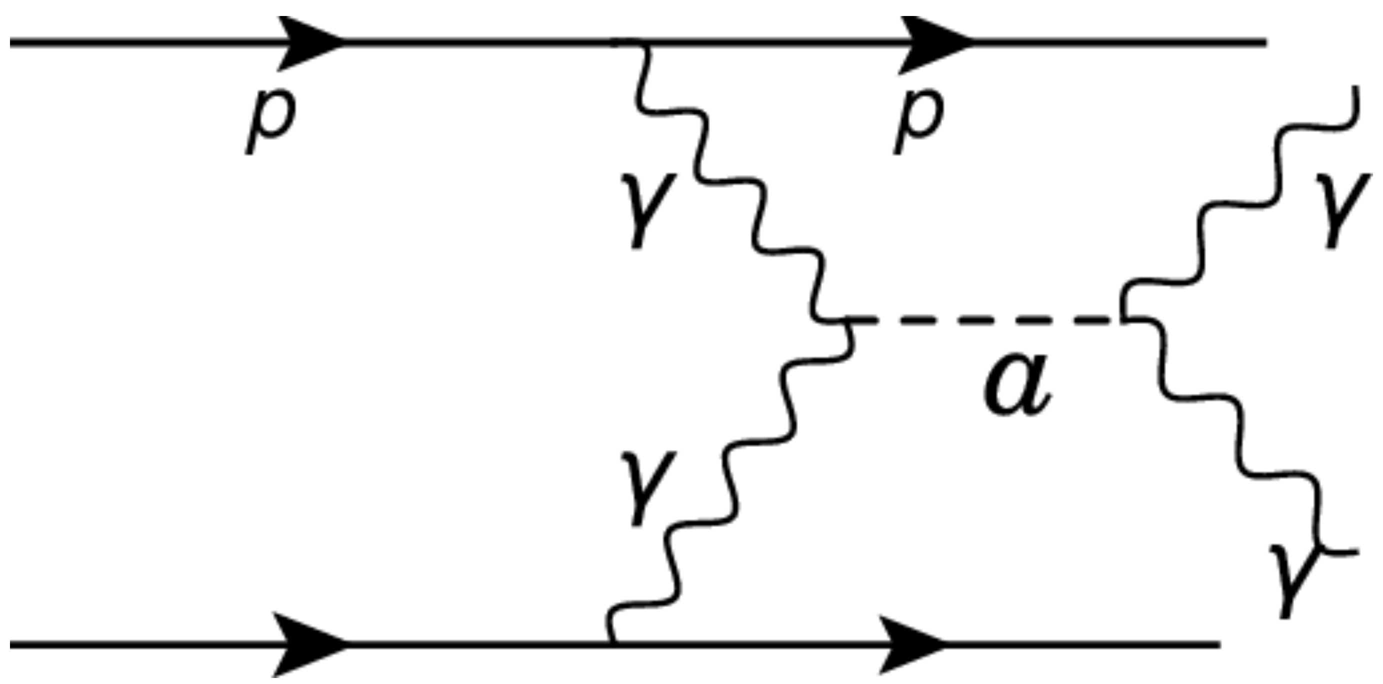
- ALPs are inspired by the solution to the CP-strong problem

- **ALPs are massive pseudo scalar particles from an extra dark U(1)** symmetry which can be valid candidates for DM or mediate DM-SM particles interactions.

  - With Lagrangian: $\mathscr{L} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

- Sensitivity curves are plotted in the plane $m_a[\mathrm{GeV}]$ - $g_{a\gamma\gamma}[\mathrm{GeV}^{-1}]$

  - **BC9, photon dominance***

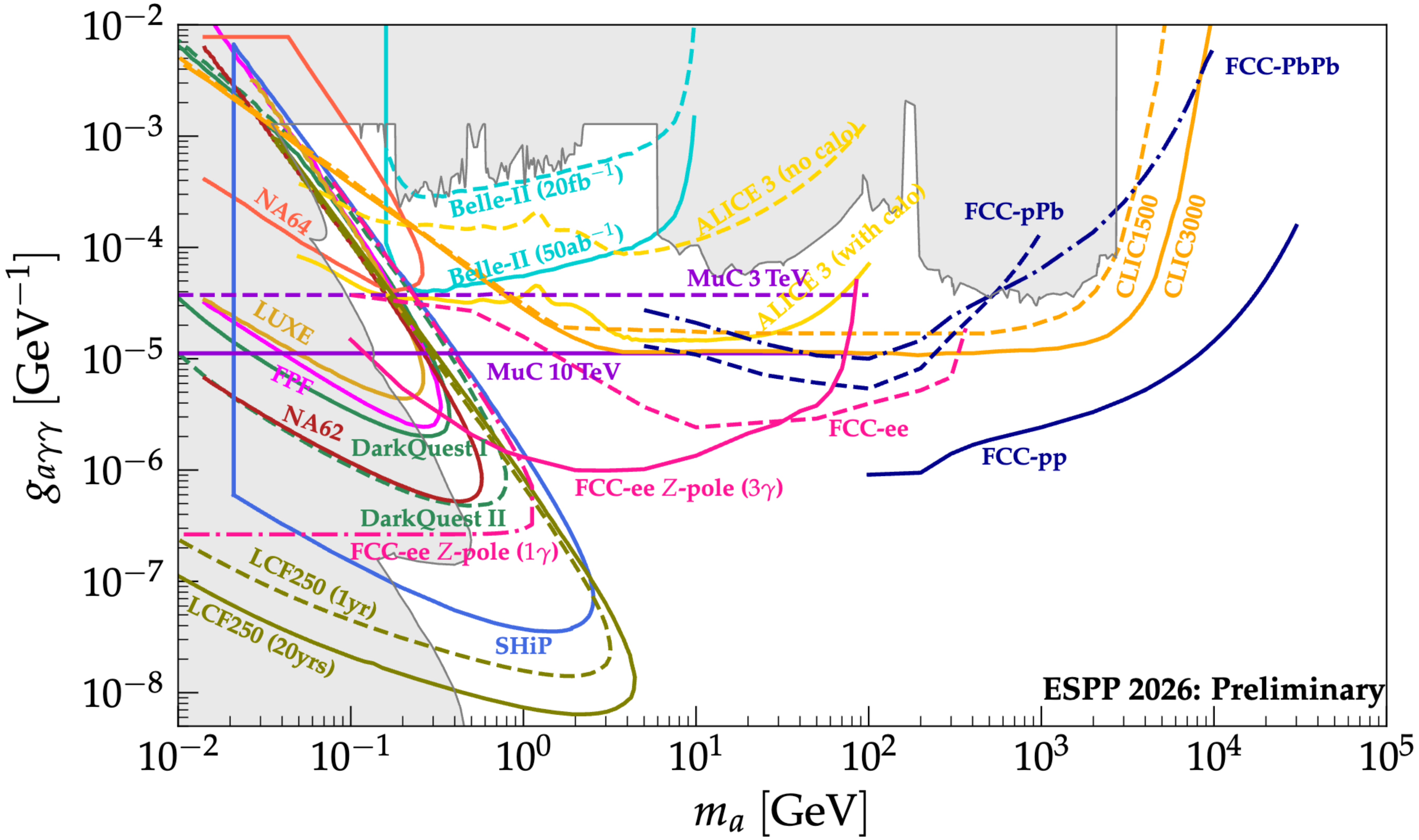


* fermion and gluon couplings not considered here as corresponding sensitivity curves have been evaluated only in a few cases

Sensitivity projections

Nice complementarity between colliders and beam-dump experiments

- $m_a < 1$ GeV: dominated by **beam-dump experiments** in very low coupling regime
  - ALPs have very long lifetime, sufficient to escape detectors at future colliders (missing energy)
- 1 GeV $< m_a < 90$ GeV: **future e^+e^- colliders** offer best sensitivity at the Z pole
- $m_a > 90$ GeV up to a few TeV: optimally explored by **linear colliders and future pp colliders**

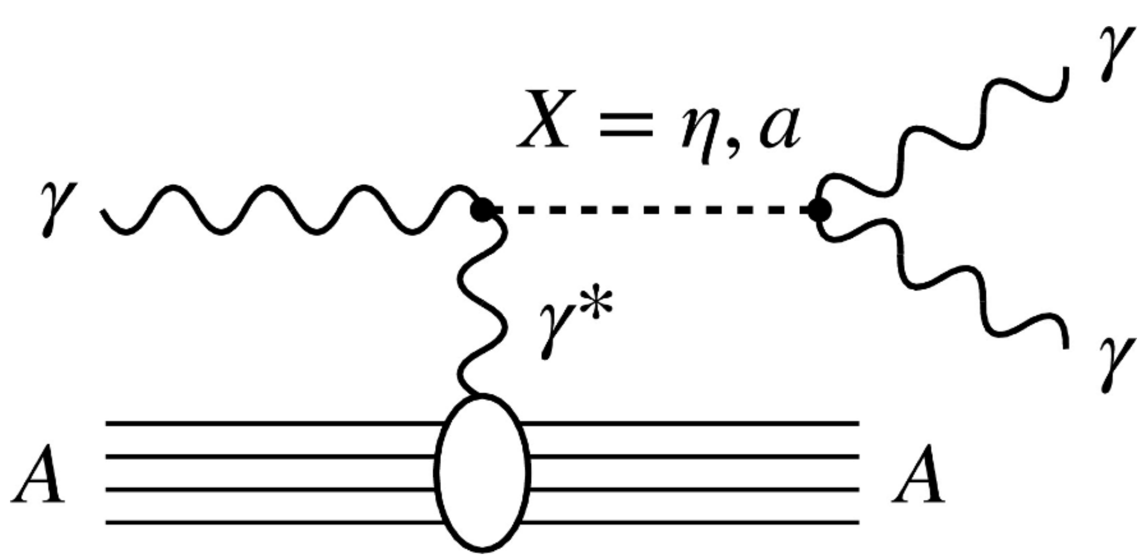


Exclusion limits on ALPs coupling to photons as a function of the ALP mass. All curves correspond to 90% CL exclusion limits, except for FCC-ee, FCC-hh and ILC(95% CL exclusion limits). See text for details.

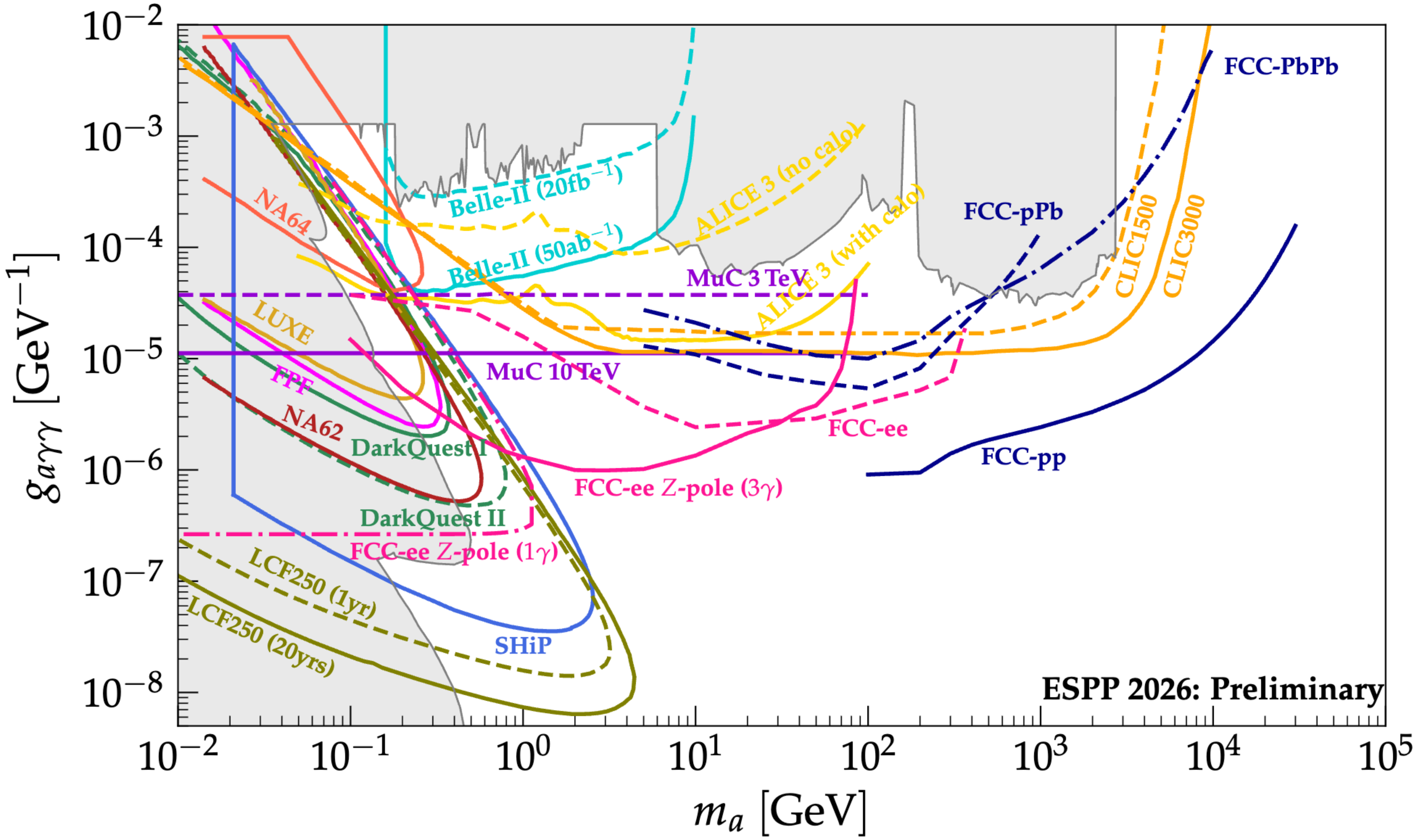
Beam Dump experiments

ALP production

- **Primakoff effect and π^0/η decays**:
    - $e^- Z \to e^- Z\gamma, Z\gamma \to Za, a \to \gamma\gamma$
- a observed through its decay to photons, or via missing energy if sufficiently long-lived



Primakoff production of a



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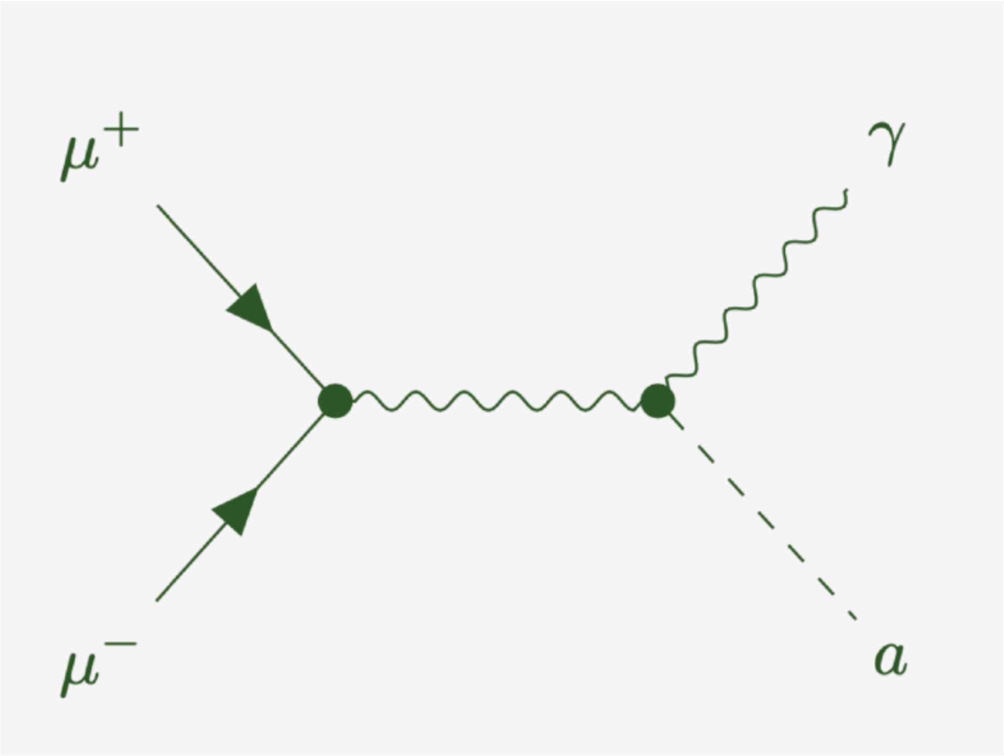
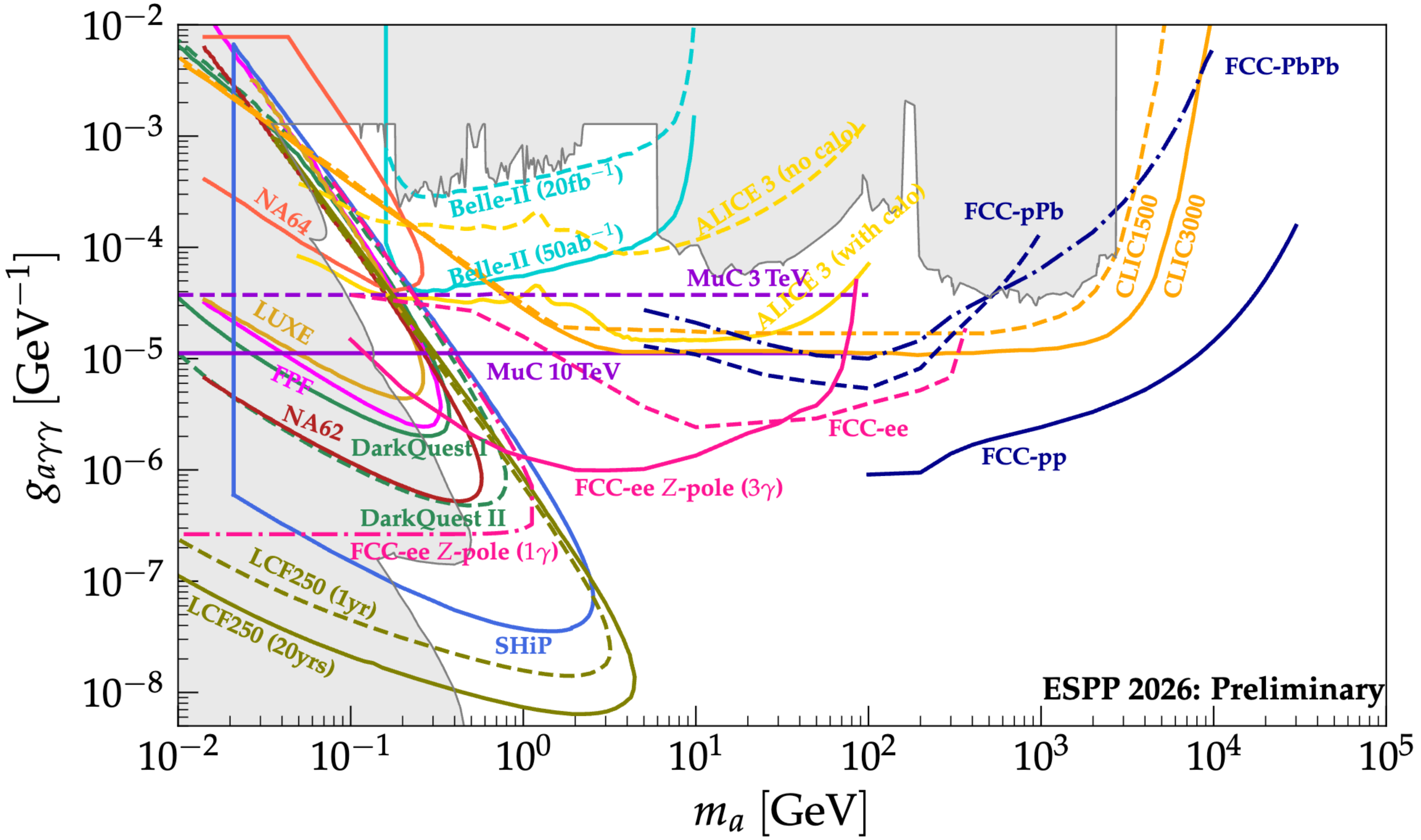
μ-collider experiments

ALP production

- **Associated production** $a\gamma$ dominates in the high-energy regime
- **Mainly ALP decays to dark sector**: invisible ALP
- Limits are mass independent up to 100 GeV





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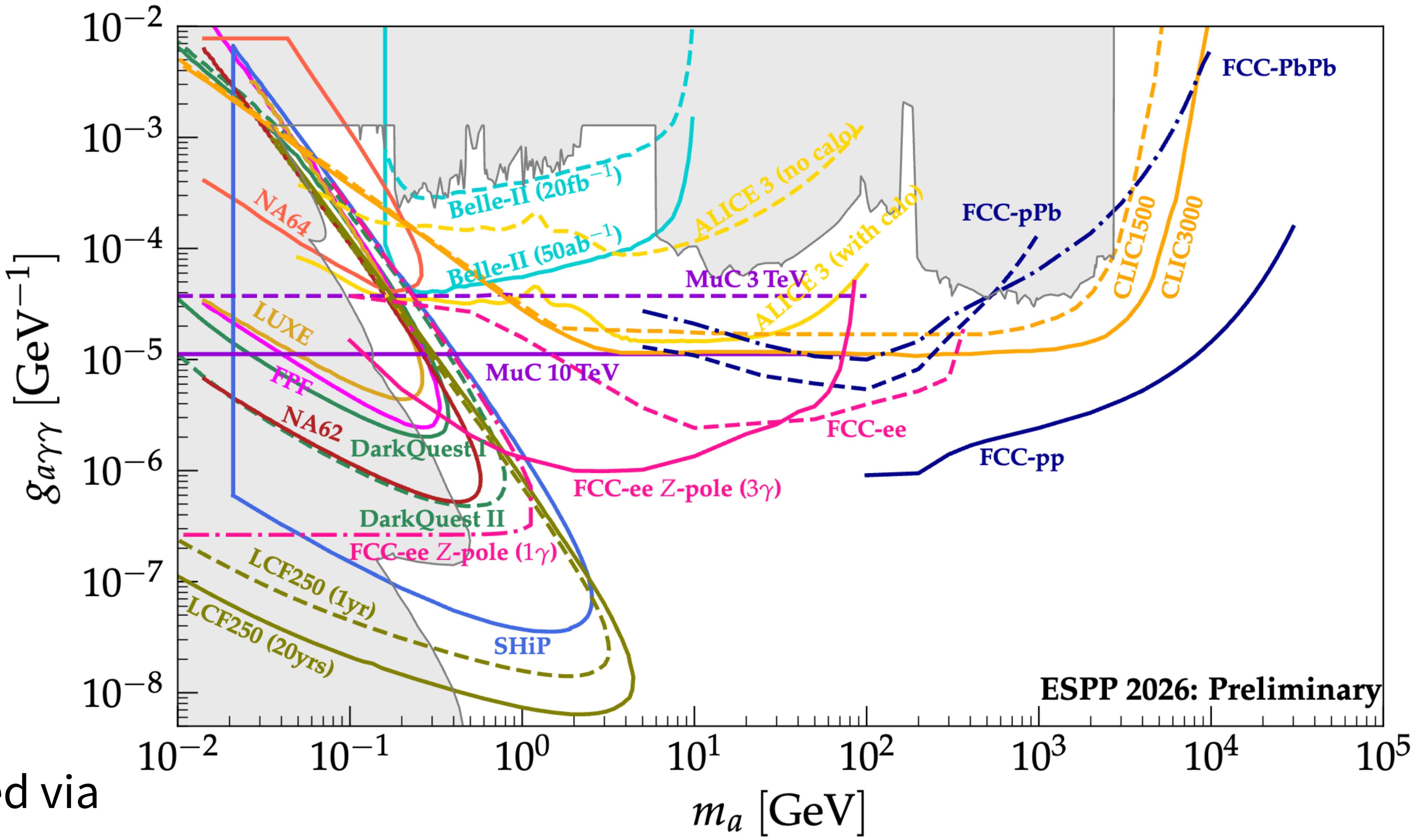
Lepton and Hadron Colliders

ALP Production

- **Belle II looks into 3γ events** $(e^+e^- \to a\gamma, a \to \gamma\gamma)$ or missing energy + 1γ if ALPs are LL
  - 3γ gives sensitivity in region not covered by beam-dump experiments
- **ALICE exploits light-by-light scattering** $(\gamma\gamma \to a \to \gamma\gamma)$ reaching nice sensitivity in the intermediate mass range
- **LCF in beam dump mode** exploits photons produced via Bremsstrahlung in the beam dump. The method leverage photon interactions via the Primakoff production mechanism



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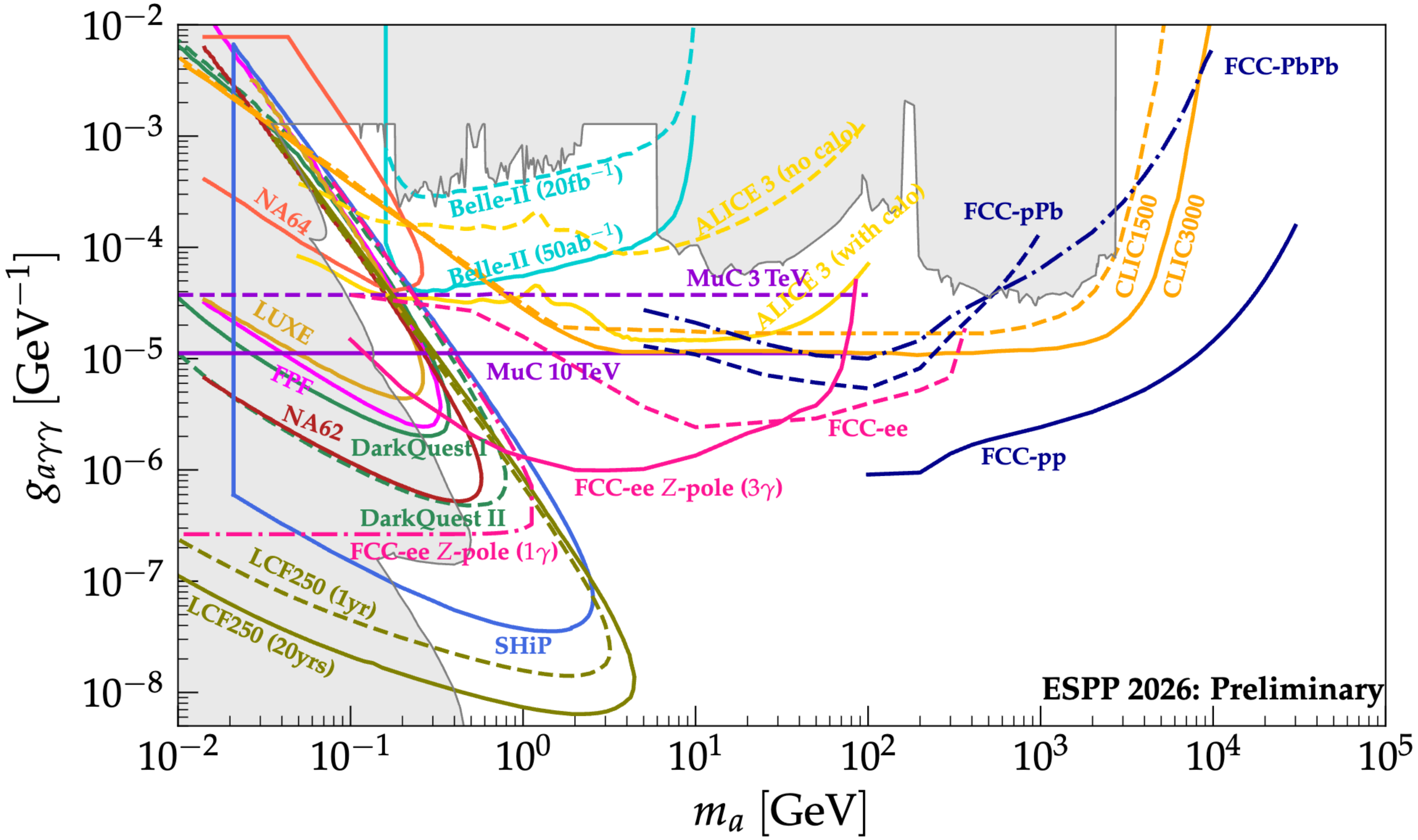
FCC-ee experiments

ALP production

- Assume different lagrangian:
  - $\mathscr{L} = \frac{e^2}{\Lambda} C_{\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
- DY production: $e^+e^- \to Z \to a\gamma$, with $a \to \gamma\gamma$
- The FCC-ee Z pole regions assume that $C_{WW} = 0$
- Original limits on $\frac{C_{\gamma\gamma}}{\Lambda}[\mathrm{TeV}^{-1}]$.
  - Conversion is: $g_{a\gamma\gamma}[\mathrm{GeV}^{-1}] = 10^{-3} \times 4e^2 \frac{C_{\gamma\gamma}}{\Lambda}[\mathrm{TeV}^{-1}]$.



Exclusion limits on ALPs coupling to photons as a function of the ALP mass. All curves correspond to 90% CL exclusion limits, except for FCC-ee, FCC-hh and ILC(95% CL exclusion limits). See text for details.

Contributions considered

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Summary

ALPs search require complementary approaches to cover a wide range of possibilities

- Beam-dump/fixed target facilities can probe very low mass (down to **10^{-2} GeV**)and low couplings
  - with **SHIP** and **ILC**-beam dump probing photon coupling down to **10^{-8}**
    and **NA64** probing larger couplings
- Intermediate mass ranges are potentially covered by **lepton colliders,**
  as well as by **ALICE** experiment, with **FCC-ee** bringing down the reach to much lower couplings
- Extension to high masses require going to the **energy frontier** with **linear and hadron colliders beyond 10^4 GeV**:
  - **FCC-hh** is particularly promising as can probe large to medium couplings.

Additional material

Details on inputs

- NA62-dump, LUXE-Nprod, FPF, DarkQuest - taken from 2310.17726, Fig. 27
- NA64: Fig 3 of the NA64 input to ESPP - 2.84x10e11 EoT
- SHiP: Fig.50 in https://cds.cern.ch/record/2878604/ 6x10e20 PoT 15 years
- ALICE: From Figure 76 (p126) of https://arxiv.org/pdf/2211.02491, which cites https://arxiv.org/pdf/1607.06083 for the procedure. Received from Andrea Dainese (andrea.dainese@pd.infn.it). “ideal” is the case with calorimeter and “eff” is the case with 5% photon efficiency without calorimeter (conversion reconstruction in the tracker).
- Belle II:: this is the projection region from Fig 10 (p34) of https://arxiv.org/pdf/2207.06307, originally taken from https://arxiv.org/abs/1709.00009.
- ILC and CLIC. Many of these are taken from the previous briefing book, which had regions for ILC-500, CLIC-380, CLIC-1500 and CLIC-300. New in this year's update is a projection for an ILC-250 beam dump mode - this is in Figure 44 of the Linear Collider Vision input, and comes from Fig 2 of https://arxiv.org/pdf/2009.13790.

Details on inputs

- FCC-ee:

  - fcc_ee_alp_3pho and fcc_ee_alp_monopho, this is the region labelled "FCCee Z-pole" from the FCC feasibility study fig 30 (p43) https://arxiv.org/pdf/2505.00272. Original ref https://arxiv.org/pdf/2502.08411. File received from Giacomo Polesello (giacomo.polesello@cern.ch).

  - Limits on $\frac{C_{\gamma\gamma}}{\Lambda}[\mathrm{TeV}^{-1}]$. So the conversion to our conventions is: $g_{a\gamma\gamma}[\mathrm{GeV}^{-1}] = 10^{-3} \times 4e^2 \frac{C_{\gamma\gamma}}{\Lambda}[\mathrm{TeV}^{-1}]$.

  - Fcc-ee-pp_and_fcc-pb-pb: from the FCC feasibility study fig 30 (p43). The FCC-ee constraints here come from the original ref 2310.17270, while the FCC-hh and heavy ion constraints refer to a paper "in preparation". File received from Patricia Rebello Teles (patricia.rebello.teles@cern.ch). The definition of the coupling is as in https://superchic.hepforge.org/superchic4.2.pdf process (68) page 19 (i.e same as our conventions).

- Muon Collider: Bounds given here:* Figure 20.3.2 of https://arxiv.org/abs/2504.21417, which originally comes from https://arxiv.org/pdf/2111.13220. Digitising these, we find: $g_{a\gamma\gamma} < 1.06 \times 10^{-2}\mathrm{TeV}^{-1}$ (95%CL, 10TeV muon collider), and $g_{a\gamma\gamma} < 3.60 \times 10^{-2}\mathrm{TeV}^{-1}$ (95%CL, 3TeV muon collider), for the mass range $2.5\mathrm{MeV} < m_a < 100\mathrm{GeV}$.

Available constraints - from PPG DMDS

- SN and GW bounds: taken from 2503.13653.
- Taken from https://cajohare.github.io/AxionLimits/ repository.