Axion-Like Particles at the Electron Ion Collider

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Overview

- Motivation
- Theoretical Background
- Phenomenology
- Simulation
- Analysis
- Results
- Outlook

Motivation (ALPs)

- Axion-like particles (ALPs) pop up in many theories
  - Strong CP problem in quantum chromodynamics (QCD) can be solved via the existence of the axion [1]
  - Spontaneous approximate global symmetry breaking → light pseudo-Nambu Goldstone boson (pNGB) [2,3]
  - Compact dimensions, string theory [4]
- ALPs are the subject of many ongoing searches
  - Collider searches at ATLAS/CMS at CERN [5,6] plus many others
  - Astroparticle and table-top precision searches

Motivation (EIC)

- Future Electron-Ion Collider (EIC) in the works at Brookhaven National Lab (BNL)
  - Will be capable of colliding electron, proton and lead ion beams
  - Good environment for studying a multitude of beyond the Standard Model (BSM) particles
    - Axion-like particles (ALPs) [7-10]
    - Heavy neutral leptons (HNLs) [11]
    - Dark photons [12]
    - Leptoquarks [13]
- Past EIC ALP searches considered flavor violating ALPs, photon coupled ALPs produced in coherent nuclear scattering
- Our searches focus on higher mass, promptly decaying photon coupled ALPs produced mainly through both elastic/coherent and inelastic scattering

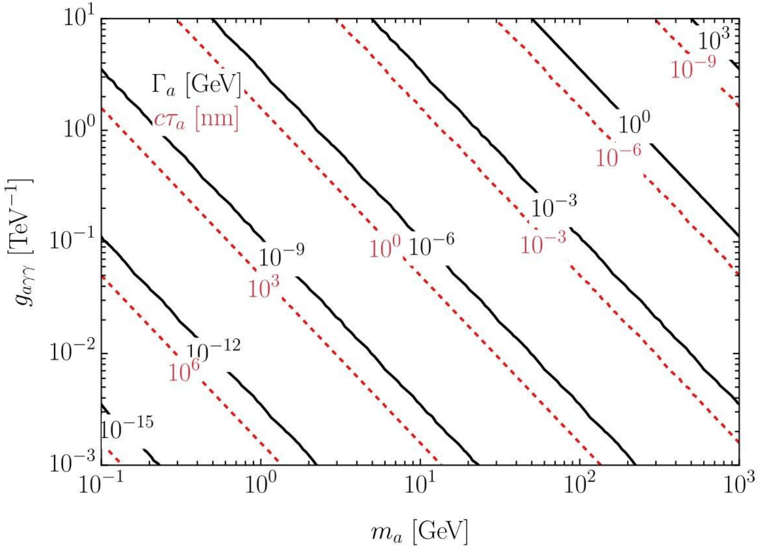
Theoretical Background

- ➢ Photon-coupled ALP benchmark model:

$$\Delta\mathcal{L} = \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{1}{2}m_a^2 a^2 - g_{a\gamma\gamma}\,aF_{\mu\nu}\widetilde{F}^{\mu\nu}$$

- ➢ Conventionally swap $g_{a\gamma\gamma}$ for energy scale $1/4\Lambda$
- ➢ ALP decay width:

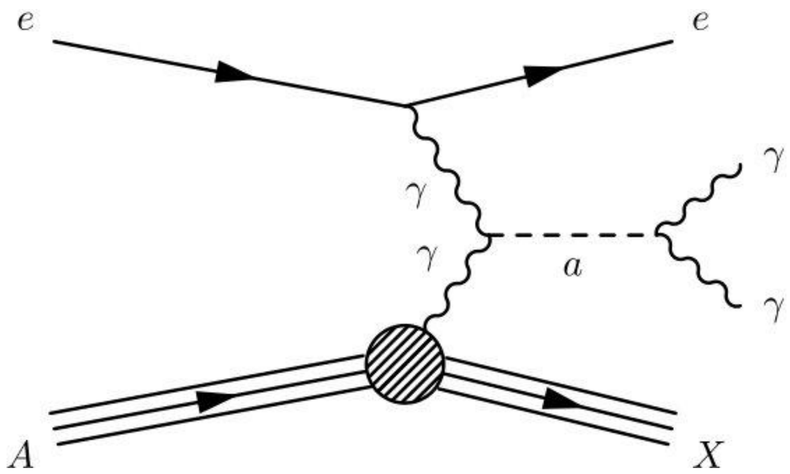
$$\Gamma(a \to \gamma\gamma) = \frac{m_a^3}{4\pi}g_{a\gamma\gamma}^2$$



- ➢ Focus only on short-lived ALPs:
  - ○ $m_a \in [1\text{-}10^2]$ GeV
  - ○ $g_{a\gamma\gamma} \in [10^{-2}\text{-}1]$ TeV^{-1}
- ➢ Manifests as narrow width ($m_a >> \Gamma_a$)

Phenomenology (Signal)

- Focus on e^-p and e^-Pb collisions (need PDFs)
- Main ALP production through photon fusion, s-channel dominates
- Narrow diphoton resonance ($m_{\gamma\gamma} \sim m_a$)
- Both elastic and inelastic processes
  - Elastic: X = p / Pb
  - Inelastic: X = j / jj
- Elastic refers to coherent scattering in the Pb case



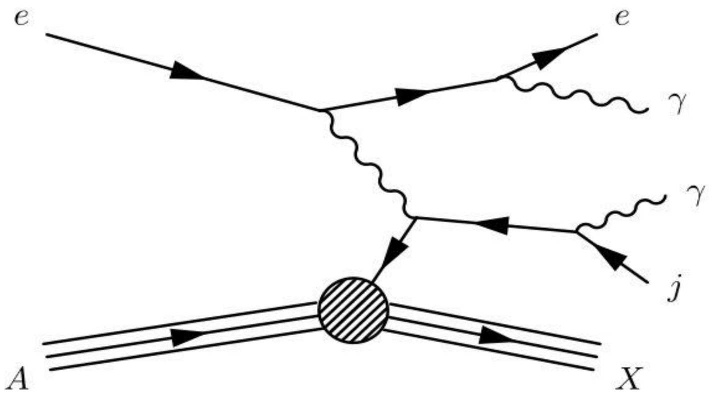
Phenomenology (PDFs)

- Proton PDF:
  - Photon: CT18qed [14,15]
  - Quark/Gluon: CT18qed inherited from CT18 NNLO QCD [16]
- Lead Ion PDF:
  - Elastic/inelastic parts taken from proton/neutron PDFs
  - Ion’s coherent photon PDF developed by Keping Xie
- Electron PDF:
  - Improved Weizsäcker-Williams approximation [17]

Phenomenology (Search Strategies)

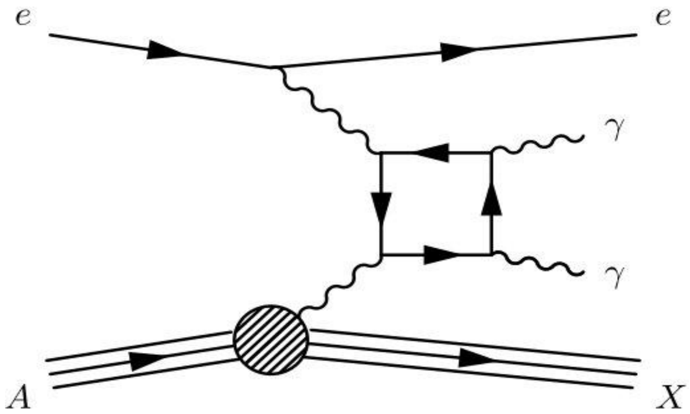
- ➢ Inclusive diphoton: final state includes two photons + anything
- ➢ Exclusive diphoton: final state includes two photons ONLY
- ➢ Elastic/Coherent diphoton: final state includes two photons + intact proton/Pb nucleus
    - ○ Past searches carried out at ATLAS and CMS [5,6]
    - ○ Most lucrative strategy
- ➢ Associated production: final state includes 2 photons + electron + jet(s)
    - ○ Previously proposed EIC search strategy [8]

Phenomenology (Background)



➢ Standard Model (SM) Inelastic
  - Inclusive, exclusive and associated searches

➢ Meson decays from hadronic activity cloud diphoton spectrum at particular masses



➢ Light-by-light (LbL) scattering
  - Subleading background
  - Inclusive, exclusive and elastic/coherent searches

Phenomenology (Beams and Detector, Fiducial Cuts)

- Electron-Proton collisions:

$$E_e = 18 \text{ GeV}, \; E_p = 275 \text{ GeV}, \; \mathcal{L}_{ep} = 100 \text{ fb}^{-1}$$

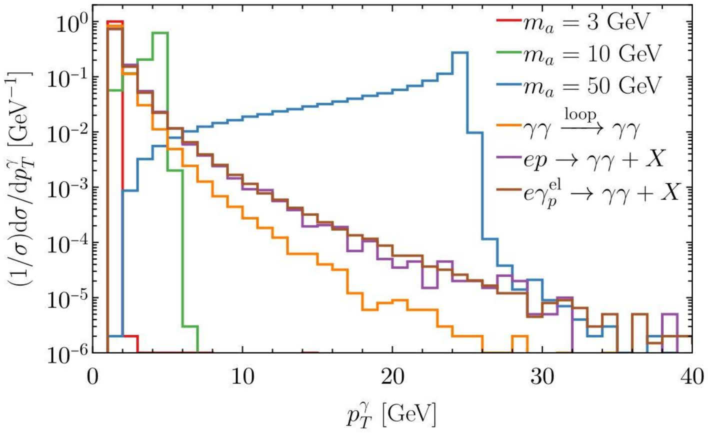
- Electron-Lead Ion collisions:

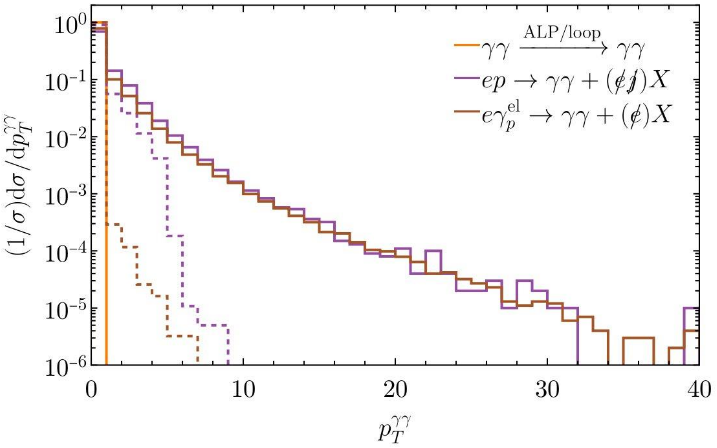
$$E_e = 18 \text{ GeV}, \; E_A/A = 110 \text{ GeV}, \; \mathcal{L}_{eA}/A = 10 \text{ fb}^{-1}$$

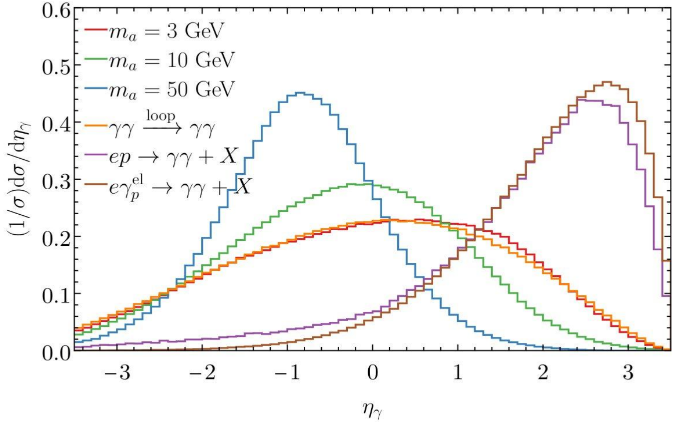
- Energy and angular fiducial cuts [18]:

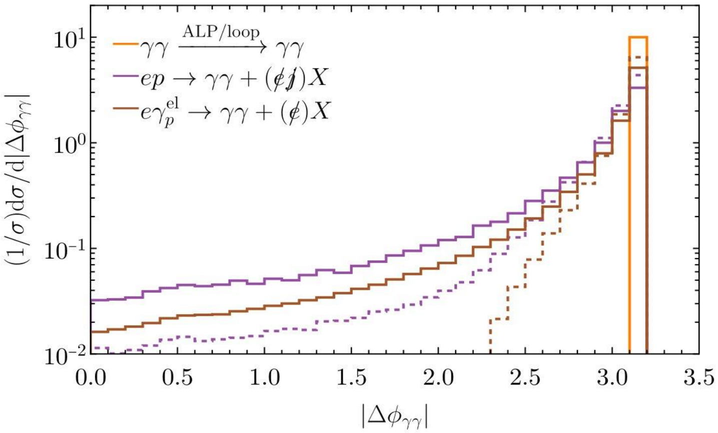
$$p_T^\gamma > 1 \text{ GeV}, \; |\eta_\gamma| < 3.5, \; \Delta R_{\gamma\gamma,\gamma\ell,\gamma j} > 0.4 \quad \Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Simulation (Electron-Proton)









Simulation (Electron-Proton)

- Inclusive search:
  - background peaks as diphoton transverse momentum → 0 and diphoton acoplanarity → π (2-2 kinematics)
  - Implement cuts similar to ATLAS/CMS treatment [5,6]:

$$p_T^{\gamma\gamma} < 1 \text{ GeV}, \; A_\phi = 1 - |\Delta\phi_{\gamma\gamma}|/\pi < 0.01$$

    - Efficiencies: inelastic (35%), elastic (48%)
  - Invariant mass window cut: $|\Delta m| = |m_{\gamma\gamma} - m_a| < 1 \text{ GeV}$
    - Efficiencies: m_a = 3/10/50 GeV (57%/2%/2x10^{-5})
  - Inelastic background dominates, LbL negligible in comparison

Simulation (Electron-Proton)

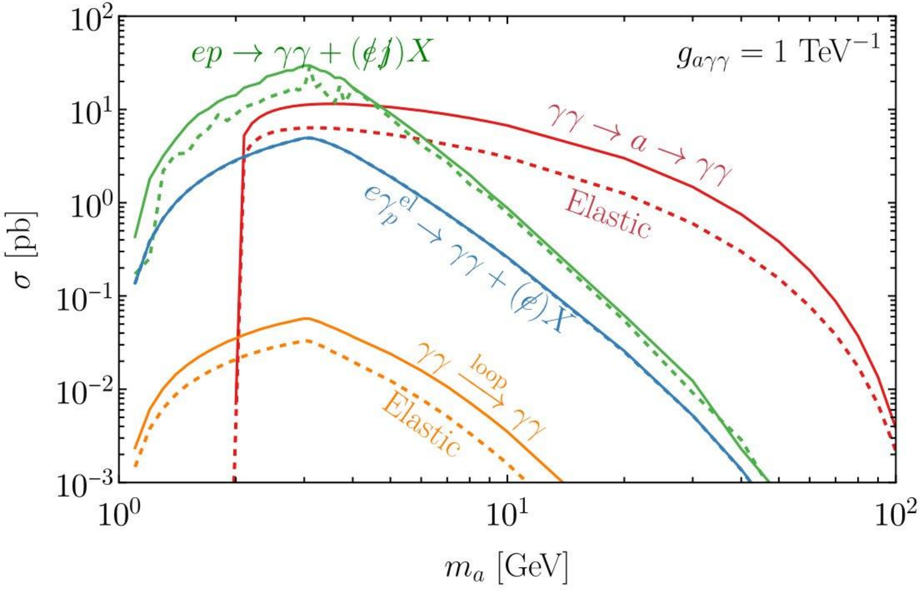
- Exclusive search:
  - Same as inclusive with reversed fiducial cuts:

$$p_T^{\gamma} < 1 \text{ GeV}, \ |\eta_{\gamma}| > 3.5, \ \Delta R_{\gamma\gamma,\gamma\ell,\gamma j} < 0.4$$

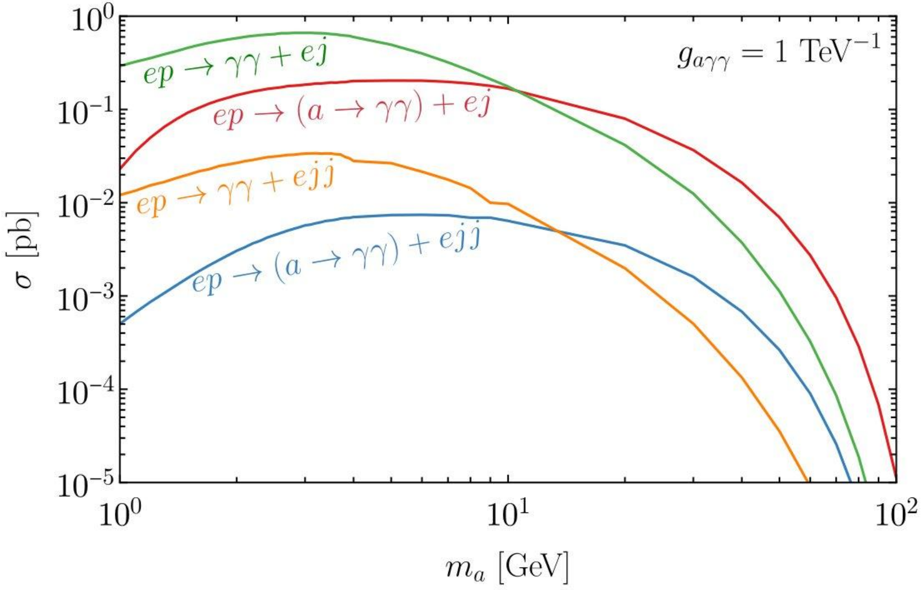
  - Additional cut efficiency negligible compared to inclusive search
- Elastic search:
  - Same cuts as inclusive, slight reduction in both signal/background
- Associated search:
  - Fiducial cuts: $p_T^{e} > 1 \text{ GeV}, \ p_T^{j} > 5 \text{ GeV}, \ |\eta_{e,j}| < 3.5, \ \Delta R_{ij} > 0.4$
  - New phase space available (2-4 kinematics)

Simulation (Electron-Proton)

Inclusive, Exclusive and Elastic

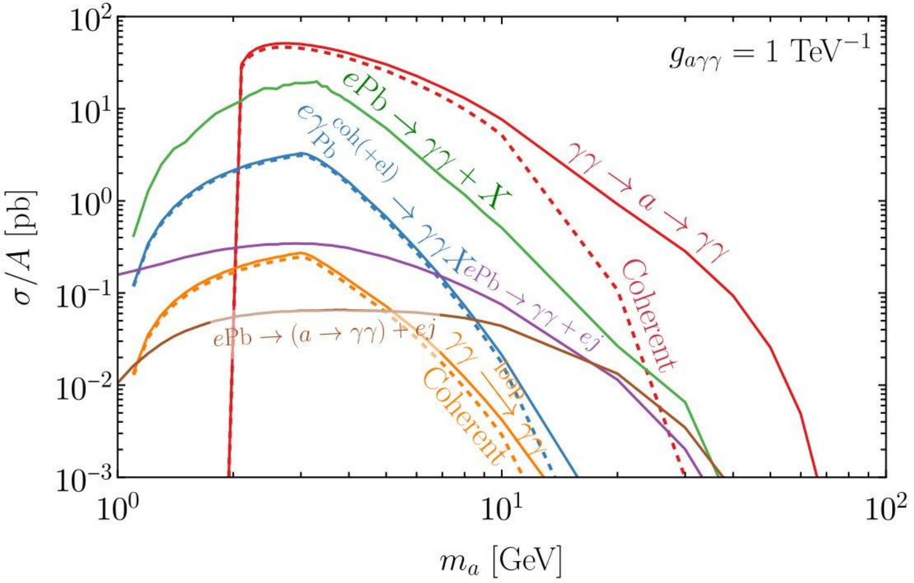


Associated



Simulation (Electron-Lead Ion)

➢ Inclusive/Associated searches:
  ○ Same cuts with similar efficiencies as proton case
➢ Exclusive search:
  ○ Neglected completely
➢ Coherent search:
  ○ Same cuts with similar efficiencies as proton case
  ○ Z^2 enhancement improves signal compared to proton case



Analysis

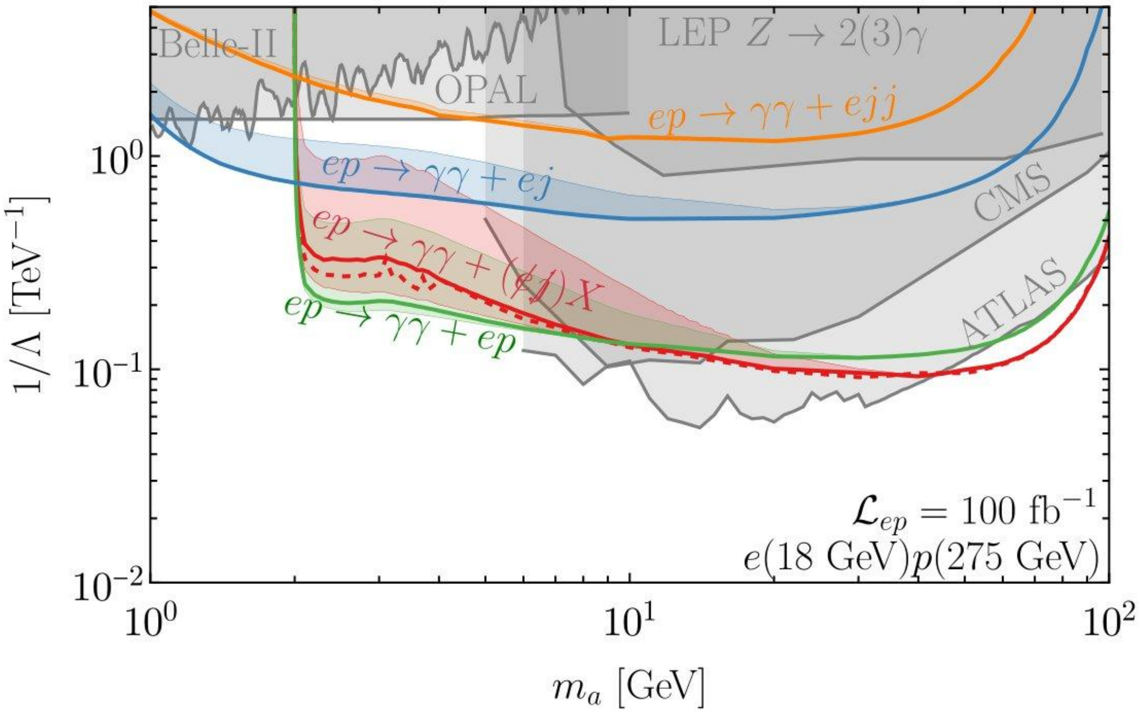
- Plot sensitivity in parameter space of the model (m_a - 1/Λ plane)
- Narrow width cross section decomposition:

$$\sigma(m_a, g_{a\gamma\gamma}) = g_{a\gamma\gamma}^2 \sigma(m_a) \mathcal{B}(a \to \gamma\gamma)$$

- Sensitivity [19]: $$\mathcal{S} = \frac{s}{\sqrt{s + b + \varepsilon^2 (s+b)^2}} = 2,$$
  - S = 2 equivalent to 2σ confidence level
  - the systematic uncertainty ε taken to be 0.1% (0-1% range)

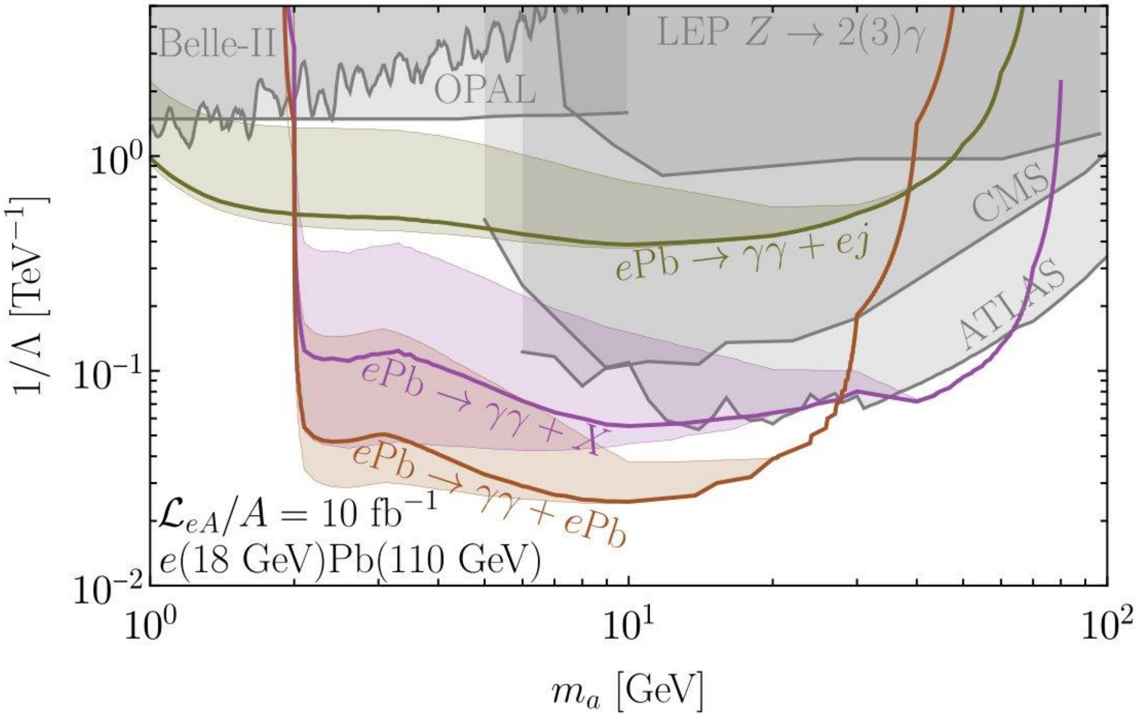
Analysis (Electron-Proton)

- All search strategies probe new parameter space
  - Elastic search yields best results, almost 10x reach improvement for low mass
  - Associated search improves lowest mass reach



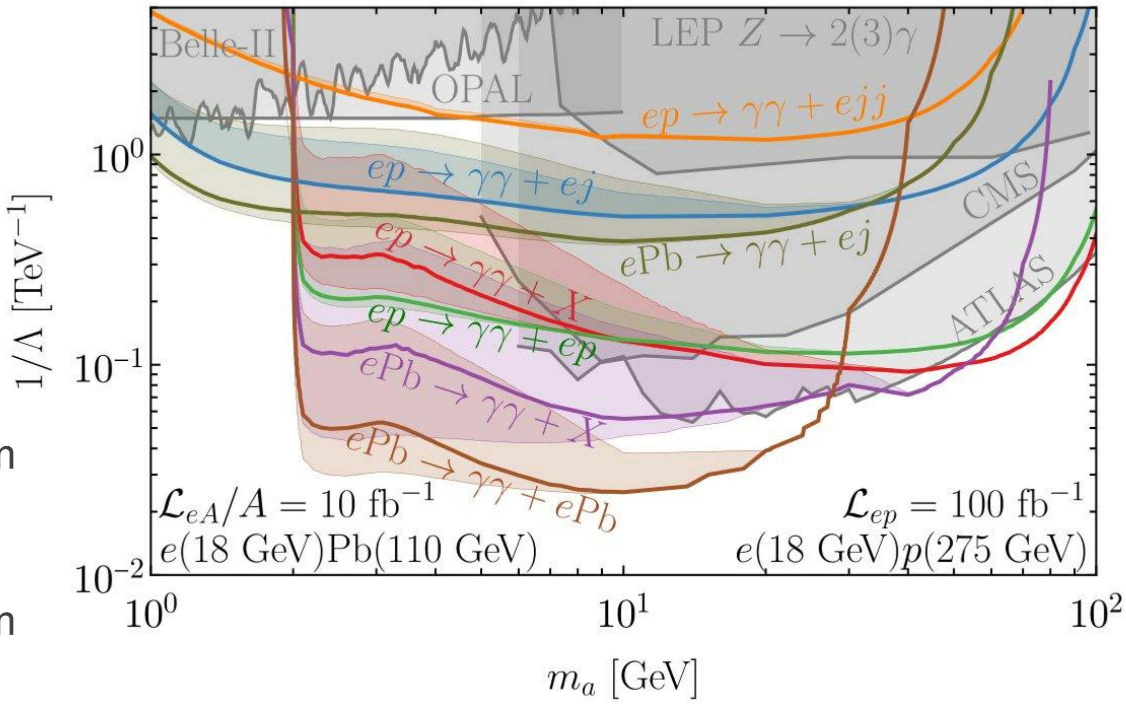
Analysis (Electron-Lead Ion)

- ➢ Overall improvement from proton case
  - ○ Most improvement from coherent search, extends reach for low mass + some larger masses



Results

- ➢ Coherent ion search:
  - ○ 10^2 better from $2\text{ GeV} < m_a < 5\text{ GeV}$
  - ○ factor of a few better from $5\text{ GeV} < m_a < 30\text{ GeV}$
- ➢ Associated ion search:
  - ○ factor of a few better from $1\text{ GeV} < m_a < 2\text{ GeV}$
- ➢ Inclusive proton/inclusive ion searches:
  - ○ mild improvement in region $40\text{ GeV} < m_a < 100\text{ GeV}$



Outlook

- ALPs are well motivated extension of SM
- EIC can probe uncharted parameter space for photon-coupled ALPs in the few - 100 GeV mass range
- Future work to search for other ALP signals at the EIC
  - Other SM-ALP couplings
  - Long lived/displaced vertex
  - Invisible ALP decays/missing energy

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