Axion-Like Particles at the Electron-Ion collider

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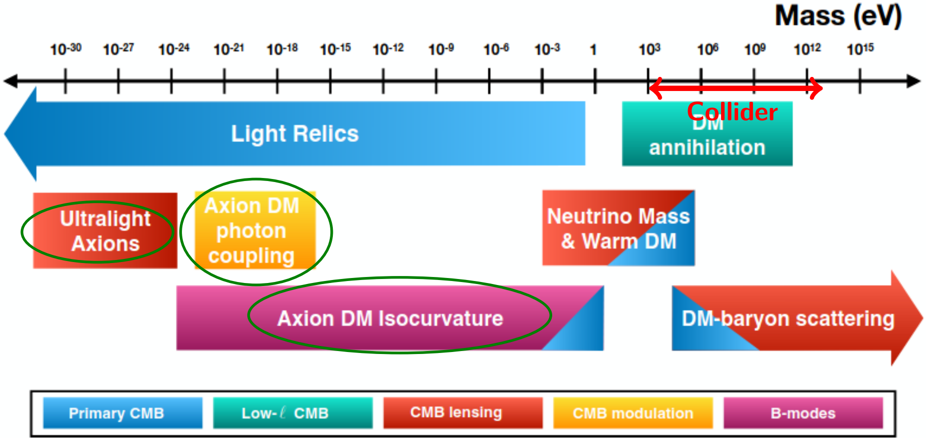
Based on work
w/ Brian Batell, Monica Leys (PITT) [2608.xxxxx]

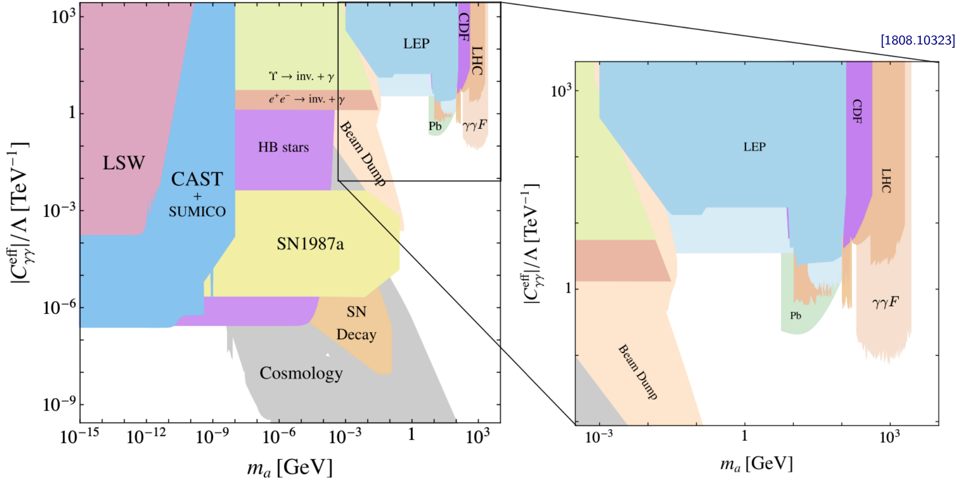
Outline

Axion and Axion-like particles

- Axion is introduced to address the strong CP problem: $aG\tilde{G}$ [Peccei & Quinn, Weinberg, Wilczek, '77-78].
- Generalization to Axion-Like particles (ALPs): CP odd $aF\tilde{F}$, $aW\tilde{W}$.
- Pseudo-Nambu Goldstone bosons (pNGB) of the spontaneous breaking of a global U(1) symmetry
- Compactified extra dimensions, including string theory [PDG]
- The ALP mass can spread in many magnitudes [1907.04473]



Many existing searches



- Colliders: Electron (LEP, B-factories), Hadron and Ion (CDF, LHC), Beam Dump
- Astro & Cosmo: red giant stars, Supernova, helioscopes, also DM DD
- Cavity & Laser: ADMX, light-shining-through-walls (LSW), etc

Parameterization of the ALP interactions

- EW gauge bosons [See 2505.10023 and references therein]

$$-\mathcal{L}_{aVV} = \frac{a}{f}\left(C_B B_{\mu\nu}\tilde{B}^{\mu\nu} + C_W W_{\mu\nu}\tilde{W}^{\mu\nu}\right)$$

$$\Longrightarrow \frac{1}{4}a\left(g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{a\gamma Z}F_{\mu\nu}\tilde{Z}^{\mu\nu} + g_{aZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + g_{aWW}W_{\mu\nu}\tilde{W}^{\mu\nu}\right)$$

The relation

$$g_{a\gamma\gamma} = \frac{4}{f_a}(s_W^2 C_W + c_W^2 C_B), \qquad g_{a\gamma Z} = \frac{8}{f_a}s_W c_W (C_W - C_B),$$

$$g_{aZZ} = \frac{4}{f_a}(c_W^2 C_W + s_W^2 C_B), \quad g_{aWW} = \frac{4}{f_a}C_W.$$

- Fermion

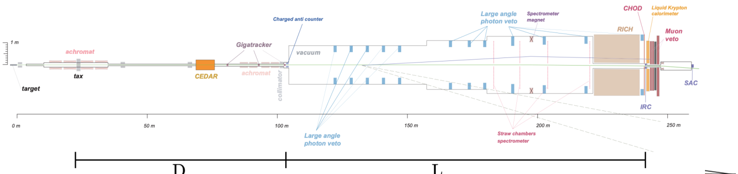
$$-\mathcal{L}_{aff} = \frac{1}{f_a}\partial_\mu a \bar{f}\gamma^\mu\gamma_5 f \xrightarrow{\text{IBP}} i g_f m_f a \bar{f}\gamma_5 f,\ g_f = \frac{C_f}{f_a}$$

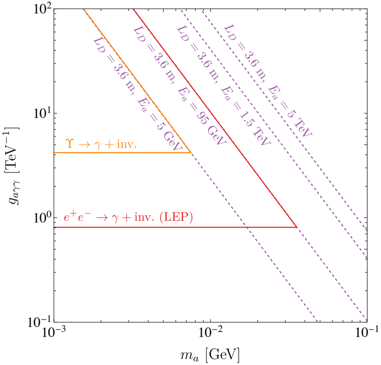
- At low energy, we can focus on the $a\gamma\gamma$ and aff interactions alone

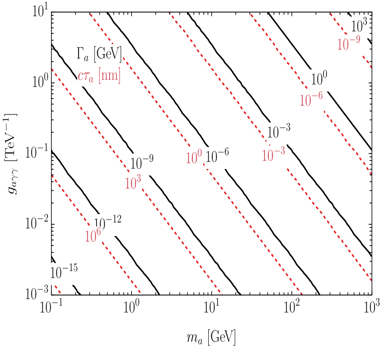
$$\Gamma(a\to\gamma\gamma) = \frac{g_{\gamma\gamma}^2 m_a^3}{64\pi},\ \Gamma(a\to f\bar{f}) = \frac{g_f^2 m_f^2 m_a}{8\pi}\sqrt{1-\frac{4m_f^2}{m_a^2}}$$

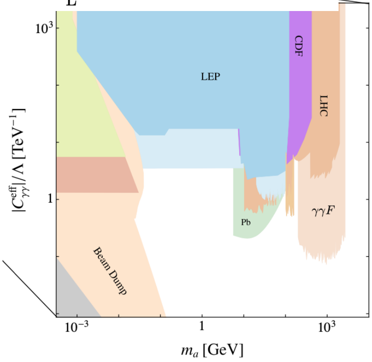
Collider searches

$$\Gamma(a \to \gamma\gamma) = g_{a\gamma\gamma}^2 m_a^3/(64\pi)$$



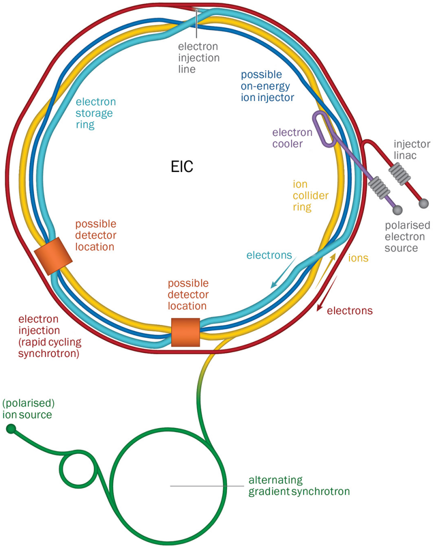






- Decay width crosses short- and long-lived regimes.
- Many resonance searches: $ee \to \gamma/Z + (a \to \gamma\gamma)$, $\gamma\gamma \to a \to \gamma\gamma$, $Z \to \gamma a$, $h \to Za$
- Long-lived searches (Beam Dump): $\mathcal{P} = \exp\{-D/\ell_a\} - \exp\{-(D+L)/\ell_a\}$, $\ell_a = \beta\gamma c\tau$
- How about ultra-long lived and non-resonant? See work [Bao, Ma, Wu, KX, and Zhang, 2505.10023]

Electron-Ion Collider



[1212.1701, 2103.05419]

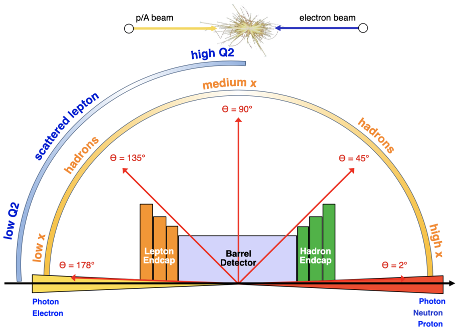
General purposes

- The Electron-Ion Collider (EIC) is approved by the U.S. DOE with an estimated cost of $1.6 to $2.6 billion, to be located at Brookhaven National Laboratory.
- The EIC features [1212.1701 and Yellow Report, 2103.05419].
  - Highly polarized (70%) electron and nucleon beams
  - Ions: proton, deuteron to uranium or lead
  - C.o.M energies: 20–100 GeV, upgradable to 140 GeV
  - high luminosity: 10^{33-34} cm^{-2}s^{-1} (10-1000 times HERA)
- The EIC goals: (designed as a QCD machine)
  - The proton spin
  - The motion of quarks and gluons in the proton
  - the tomographic images of the proton
  - QCD matter at the extreme gluon density
  - Quark hadronization
- Other physics opportunities: EW and BSM [Snowmass whitepaper, 2203.13199].
  - Heavy Neutral Lepton (HNL) is explored in Ref. [Batell, Gosh, Han, KX, 2210.09287].
  - We explore Axion-Like Particle (ALP) in this work.

Collider configuration

- We want to maximize the machine reachability
$$e(10/18\ \text{GeV}) + p(100/275\ \text{GeV})\ \text{or}\ A(110A).$$
- We assume the integrated luminosity to be $\mathcal{L} = 100\ \text{fb}^{-1}$.
- Primary physics goals require a multi-purpose Hermitic detector with excellent tracking resolution and particle ID capabilities over a broad momentum range.
- Detector still under design; see EIC Detector Requirements R&D Handbook

[EIC CDR 2021]

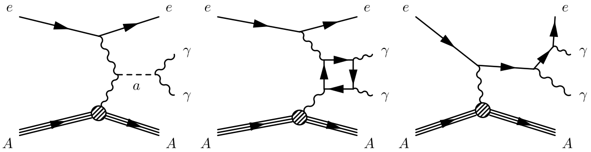


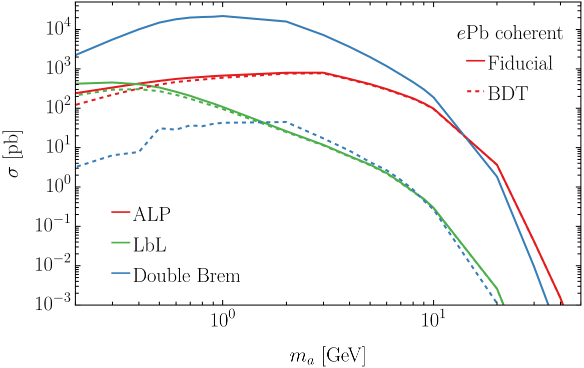
η	Resolution
Tracking (σ_p/p)	
$2.5 < \|\eta\| \leq 3.5$	$0.1\% \times p \oplus 2\%$
$1.0 < \|\eta\| \leq 2.5$	$0.05\% \times p \oplus 1\%$
$\|\eta\| \leq 1.0$	$0.05\% \times p \oplus 0.5\%$
Electromagnetic calorimeter (σ_E/E)	
$-3.5 \leq \eta < -2.0$	$2\%/\sqrt{E}$
$-2.0 \leq \eta < -1.0$	$7\%/\sqrt{E}$
$-1.0 \leq \eta \leq 3.5$	$12\%/\sqrt{E}$
Hadronic calorimeter (σ_E/E)	
$1.0 < \|\eta\| \leq 3.5$	$50\%/\sqrt{E}$
$\|\eta\| \leq 1.0$	$100\%/\sqrt{E}$

Coherent production of Axion-Like Particle at EIC

Signal and backgrounds

- Signal: $eA \to eA(a \to \gamma\gamma)$
- Light-by-light $\gamma\gamma \xrightarrow{\text{box}} \gamma\gamma$
- Double-bremsstrahlung: $e \to e\gamma\gamma$



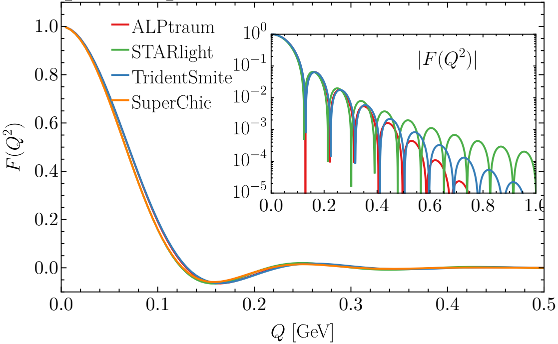


Technical challenges: multiple scales:

- Beam energies: $E_e = 18$ GeV, $E_{\text{Pb}} = AE_N \simeq 23$ TeV
- Coherent photon momentum: $|q| \sim 1/R_A \lesssim 30$ MeV
- Axion mass: $0.1 < m_a < 100$ GeV

Heavy-ion (A, Z) form factors

- Electric and magnetic form factors
$$G_E \sim ZF(Q^2),\ G_M \sim \mu_N F_N(Q^2) \approx 0.$$
- Woods-Saxon (`SuperChic` [1810.06567])
$$F(Q^2 = |\vec{q}|^2) = \int \mathrm{d}^3 r e^{i\vec{q}\cdot\vec{r}} \rho_p(r),\ \rho_p(r) = \frac{\rho_0}{1 + \exp[(r - R)/d]}$$
- Helm (`ALPtraum` [1512.03069]), `STARlight` [1607.03838], `TridentSmite` [1807.10973], and `gamma-UPC` [2207.03012]
$$F(Q^2) = \frac{3 j_1(QR_1)}{QR_1} \exp\left[-\frac{(Qs)^2}{2}\right],\ F(Q^2) = \frac{4\pi\rho_0}{ZQ^3}\left[\sin(QR_A) - QR_A\cos(QR_A)\right]\frac{1}{1 + a^2 Q^2}.$$



Monte-Carlo Integration with Form Factors (MC4FFs)

4-body scattering

$$A(p_1,m_1)+e(p_2,m_2)\to A(p_3,m_3)+e(p_4,m_4)+\gamma(p_5,0)+\gamma(p_6,0)$$

- Nuclear-photon interaction is take as scalar form

$$iV^\mu(p,p')=iZeF(Q^2)(p+p')^\mu$$

- The cross section

$$\sigma=\int \mathrm{d}\Phi^{(4)}|\mathcal{M}(Ae\to Ae\gamma\gamma)F(Q^2)|^2$$

- Kinematic variable

$$p_1=(E_1,0,0,p),\ p_2=(E_2,0,0,-p),\ p_3=(E_3,p_3\sin\theta\cos\phi,p_3\sin\theta\sin\phi,p_3\cos\theta),$$

  which gives

$$Q^2=-(p_1-p_3)^2=-m_1^2-m_3^2+2(E_1E_3-pp_3\cos\theta)\implies \mathrm{d}\cos\theta=\mathrm{d}Q^2/(2pp_3)$$

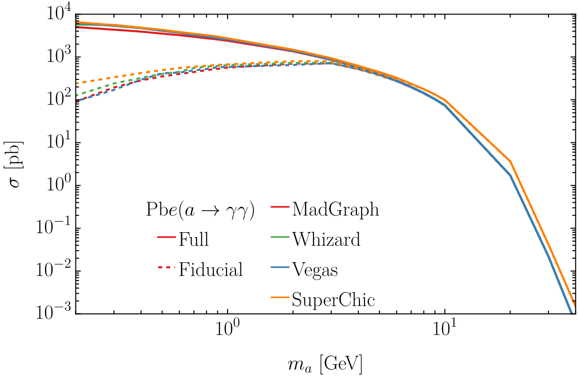
- Considering the $F(Q^2)\sim\exp\big(-Q^2\rho^2/2\big)$, we take the replacement

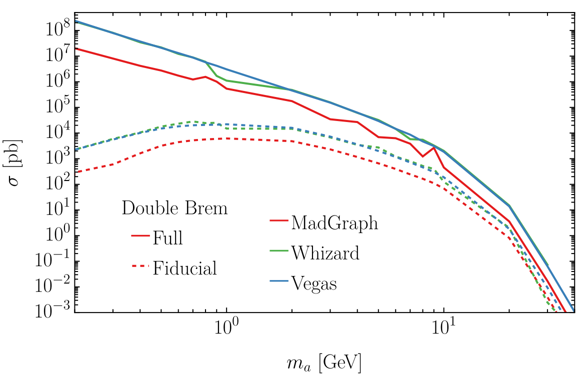
$$y=\exp\big(-Q^2\rho^2\big)\implies \mathrm{d}Q^2=e^{Q^2\rho^2}\mathrm{d}y/\rho^2$$

  which absorb the exponential into a Jacobian

$$\big|F(Q^2)\big|^2\mathrm{d}\cos\theta\sim\frac{1}{2pp_3}\frac{\mathrm{d}y}{\rho^2}.$$

Numerical performance





- SuperChic: a dedicate MC generators for ALP and LbL
- Implement FFs into MadGraph and Whizard, good enough for the ALP signal, but not enough for double-bremsstrahlung
- MC4FFs: our generators, good for both (Available on GitHub)

Collinear photon approximation

- LUXqed formulism [Manohar+, PRL'16, JHEP'17]

$$xf_\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{\mathrm{d}z}{z}\Bigg\{\int_{x^2m_p^2/(1-z)}^{\mu^2/(1-z)} \frac{\mathrm{d}Q^2}{Q^2}\alpha_{\mathsf{ph}}(-Q^2)\Bigg[\left(zp_{\gamma q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2\left(\frac{x}{z},Q^2\right)$$

$$-z^2F_L\left(\frac{x}{z},Q^2\right)\Bigg] - \alpha(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\Bigg\} + \mathcal{O}(\alpha^2,\alpha\alpha_s)$$

- Proton and Neutron's Form Factors (A1 [1307.6227] and Ye et al. [1707.09063])

$$F_2\left(x,Q^2\right) = \frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau}\delta(1-x),\ \ F_L\left(x,Q^2\right) = \frac{G_E^2(Q^2)}{\tau}\delta(1-x)$$

where $\tau = Q^2/(4m_p^2)$ and $G_M(0) = \mu_p \approx 2.793$

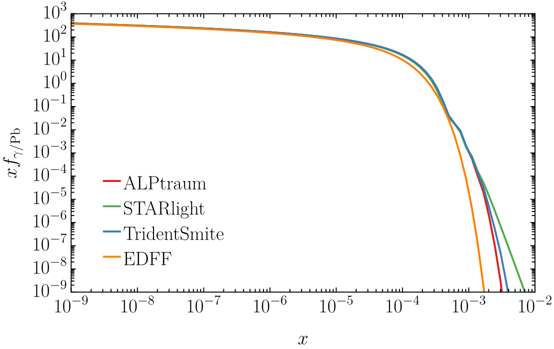
- Elastic photon PDF [Xie+, 2106.10299, 2305.10497]

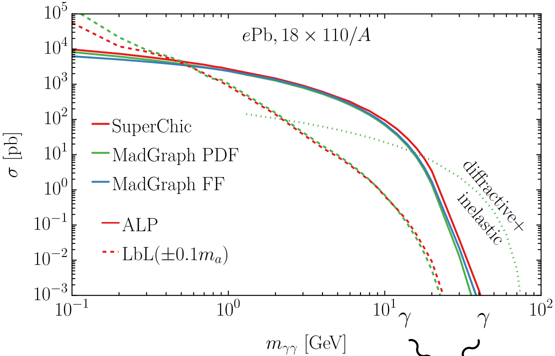
$$xf_\gamma^{\mathrm{el}}(x,\mu^2) = \frac{1}{2\pi\alpha\left(\mu^2\right)}\int_{\frac{x^2m_p^2}{1-x}}^{\infty}\frac{\mathrm{d}Q^2}{Q^2}\alpha^2\left(Q^2\right)\left[\left(1-\frac{x^2m_p^2}{Q^2(1-x)}\right)\frac{2(1-x)G_E^2\left(Q^2\right)}{1+\tau}\right.$$

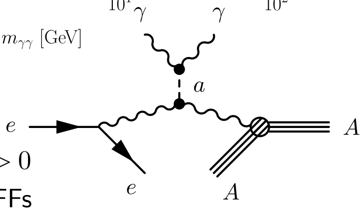
$$\left.+\left(2-2x+x^2+\frac{2x^2m_p^2}{Q^2}\right)\frac{G_M^2\left(Q^2\right)\tau}{1+\tau}\right]$$

- Coherent photon PDF can be determined in a similar way

Applications and limitations



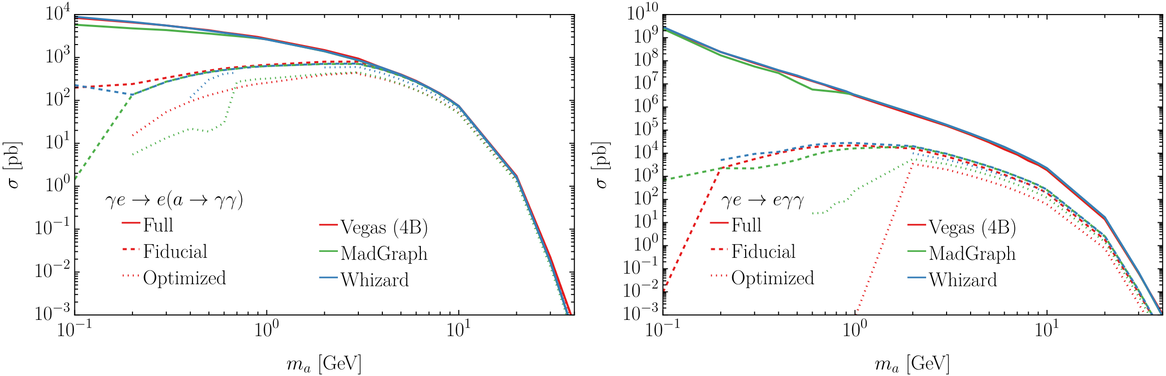




- The photon PDF corresponds to the collinear approximation, $p_T^{\gamma\gamma} \sim 0$
- It applies to the inclusive cross section
- It fails in the off-beam-axis kinematics with recoiling boost, e.g. $p_T^{\gamma\gamma} > 0$
- Recoiling boost requires a N-body $(N \geq 3)$ phase space, with SFs or FFs
- The collinear photon PDF is available on HEPForge

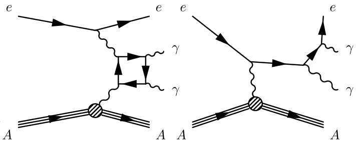
Reconcile: 2-to-3 scattering

- $p_T^{\gamma\gamma} \sim 0$ corresponds to 2 collinear photons on both electron and ion sides
- We can take a $2 \to 3$ scattering $e\gamma_{\mathrm{Pb}} \to e\gamma\gamma$ (ion-side collinear photon)
- It applies both to the ALP and the double-bremsstrahlung



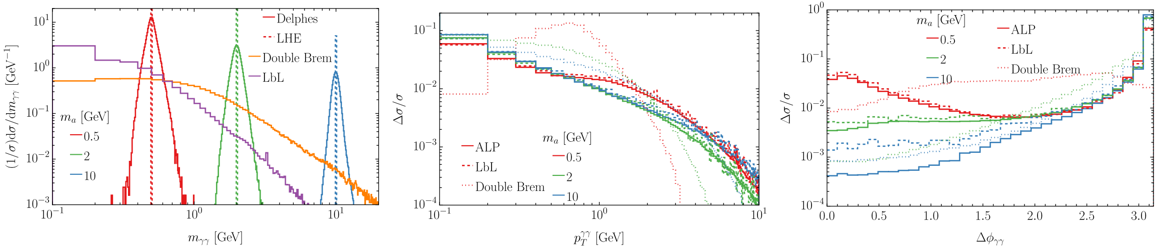
Our analysis [w/ Batell, Leys, 2608.xxxxx]

- Detector simulation: `Delphes` + ECCE/EICmatrixv2(YR): Critical for $m_{\gamma\gamma}$ resolution
- Light-by-light (LbL) scattering: full kinematics with `SuperChic`
- Double Bremstralung: `Vegas` with Form Factors



Pre-selection cuts:

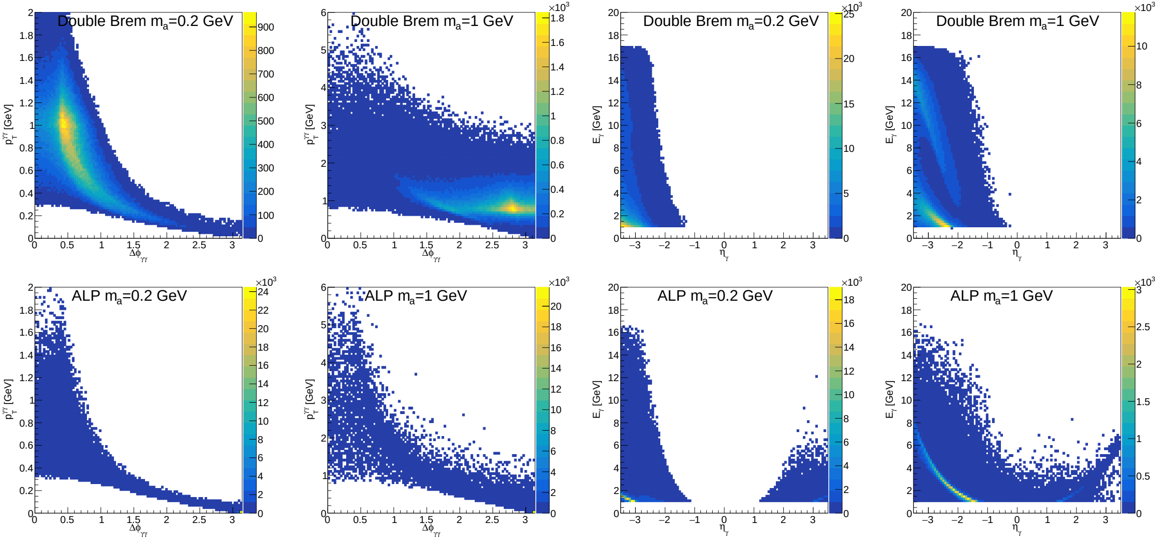
$$E_\gamma > 1\ \text{GeV},\ |\eta_\gamma| < 3.5\ , \Delta R_{\gamma\gamma,\gamma\ell,\gamma j} > 0.4$$



Motivate for optimization (fiducial) cuts (motivated by LHC)

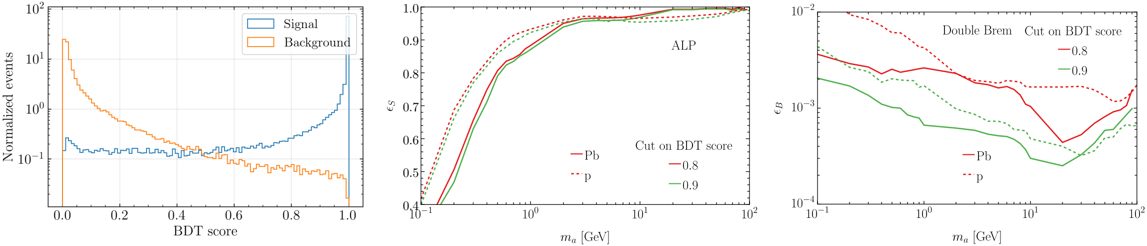
$$p_T^{\gamma\gamma} < \max(0.5\ \text{GeV}, m_a/10),\ A_\phi = 1 - \Delta\phi_{\gamma\gamma}/\pi < 0.01$$

Kinematical correlations



Transition from a boosted $a \to \gamma\gamma$ region to a spherical decay

Boost Decision Tree (BDT) or Machine Learning (ML)



- To perform a multidimensional correlated cuts, suitable for BDT/ML.
- Signal and background can be well separated based on the BDT score
- The efficiency for the signal can be kept up to order 1
- The background is suppressed up to 10^{-3}

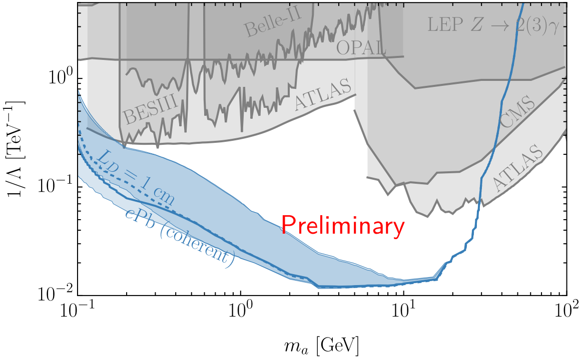
The elastic scattering at the EIC

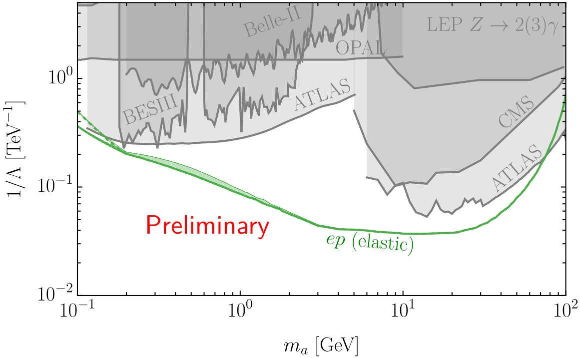
A figure of merite measure:

$$\mathcal{S} = \frac{N_s}{\sqrt{N_s + N_b + \delta_s^2 N_b^2 + \delta_s^2 N_s^2}} = 2, \;\; N_{s(b)} = \epsilon_{s(b)} \mathcal{L} \sigma_{s(b)}$$

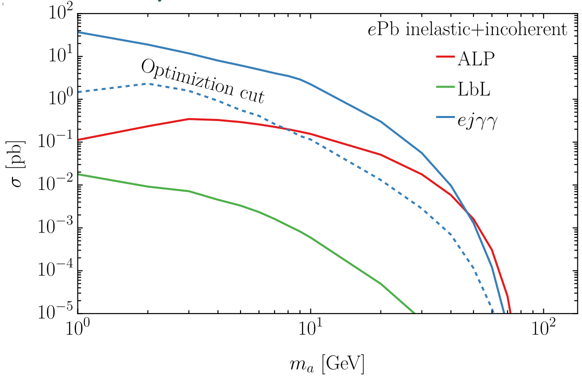
where systematics $\delta_s = \delta_b = 0, 0.1\%, 1\%$, and reconstruction efficiency $\epsilon_{s(b)} = 70\%(100\%)$

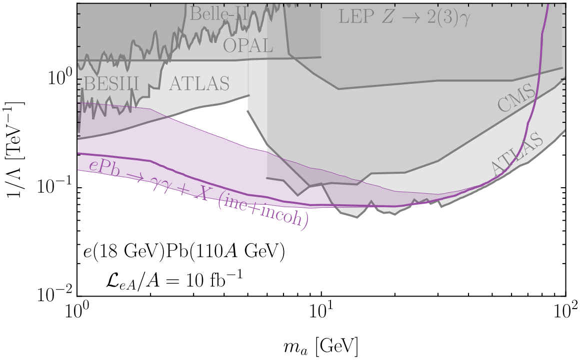
- At a low ALP mass, the coherent scattering dominates
- At a high ALP mass, the inelastic scattering takes over





Inelastic/incoherent scattering





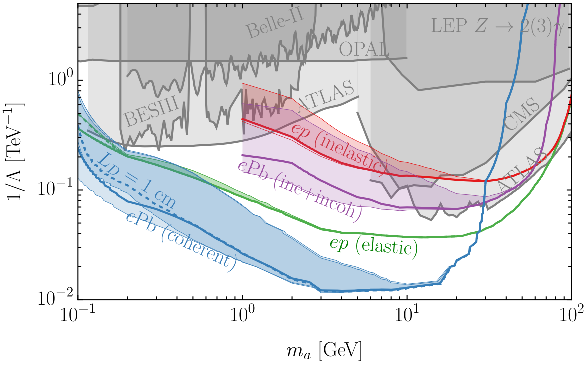
- Inelastic quark/gluon and Incoherent nucleon p/n
- We take the photon PDF approach, with optimized cuts

$$p_T^{\gamma\gamma} < \max(0.5 \text{ GeV}, m_a/10),\ A_\phi - 1 - \Delta\phi/\pi < 0.01$$

- Complementary with coherent at large m_a
- A similar scenario for proton inelastic

Summary

- The photon-coupled ALP production at the EIC is carefully examined, for both signal (coherent and inelastic scattering) and backgrounds (LbL and Double Brem) [w/ Batell, Leys, 2608.xxxxx]
- The detector simulation: `Delphes` with ECCE/EICmatrix2(YR)
- The full background kinematics: ALP/LbL by `SuperChic`; Double Bremstralung by `MC4FFs`
- With the LUXqed formalism, the nucleon and ion's photon PDF can be precise determined through the Structure Functions and Form Factors [Available on HEPForge]
- Ongoing for fermion-coupled ALP, long-lived analysis, etc [Ongoing with Tricoli, Wheeler (experimentalists), Liu et al.]



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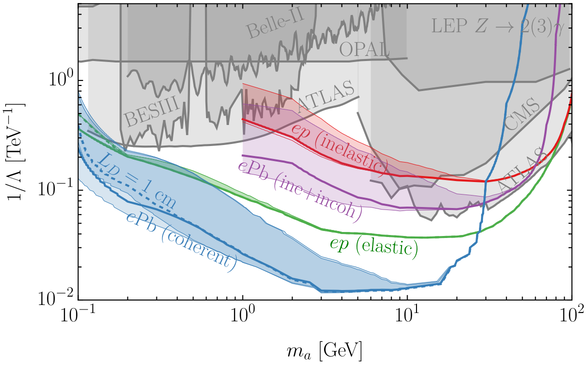
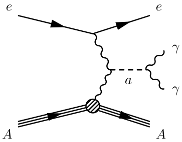
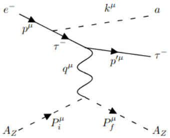


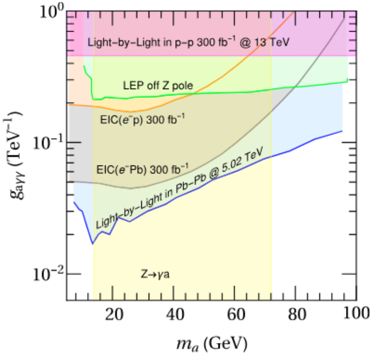
Thanks for your attention!

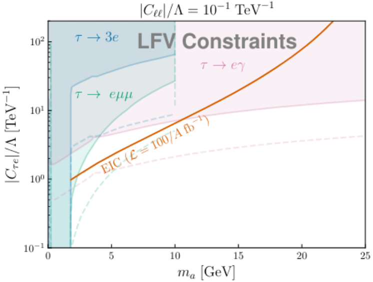
Existing searches for ALPs at the EIC

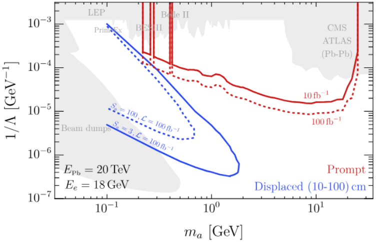
- Liu, Yan: Inelastic scattering [2112.02477]
- Balkin, Hen, Li, Liu, Ma, Soreq, Williams: Coherent scattering [2310.08827]
- Davoudiasl, Marcarelli, Neil: Lepton-Flavor-Violating ALPs [2112.04513]











Lepton(Fermion)-coupled ALP production

Ongoing work with Alessandro Tricoli, Alyssa Wheeler, Hongkai Liu, et al.

- Production through Compton-like scattering, similar as the LFV ALP [2112.04513]
- We currently simplify it with coherent photon PDF (not perfect but can be improved later)
- Incorporate with `MadGraph` (or other generators) for the simulation
- Can have a long-lived decay signal (displaced vertex) at a low ALP mass and coupling
- See Alyssa's talk for many details