Axion-Like Particles at Future Colliders

Lepton Colliders and Electron-Ion Collider

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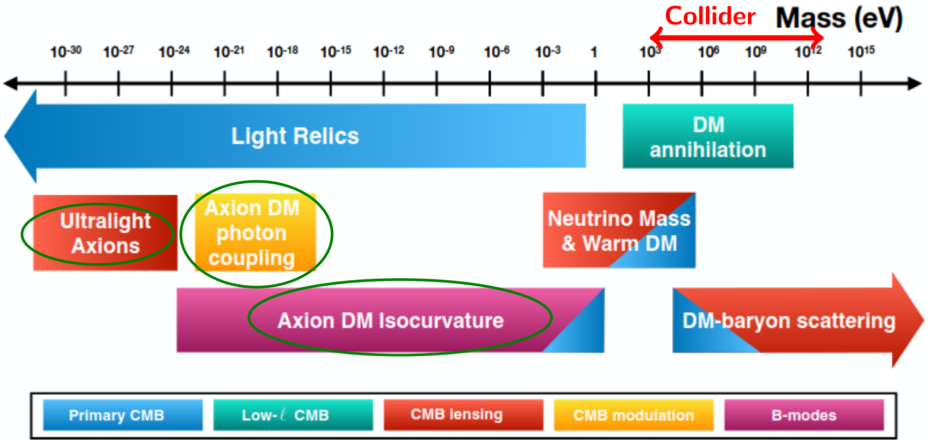
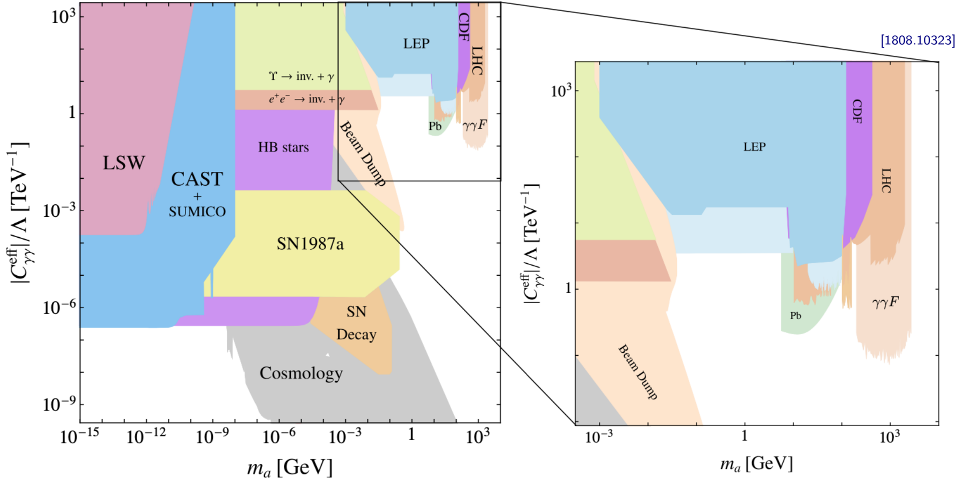
Based on work
w/ Shou-shan Bao, Yang Ma, Yongcheng Wu, and Hong Zhang, 2505.10023
w/ Brian Batell, Monica Leys (PITT) [2606.xxxxx]

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]

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

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

  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

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

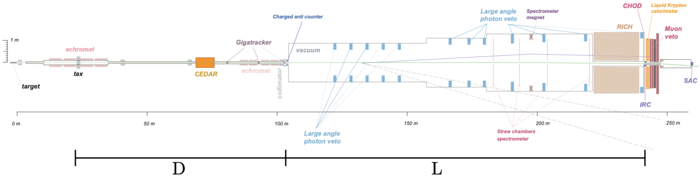
- At low energy, we can focus on the $a\gamma\gamma$ and aff interactions alone

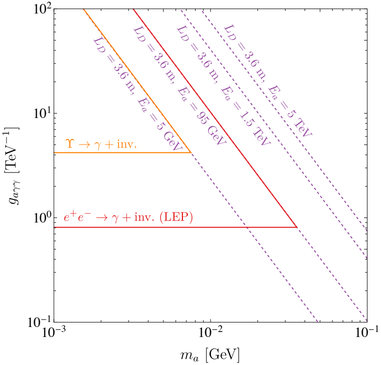
$$\Gamma(a\to\gamma\gamma) = \frac{g_{\gamma\gamma}^2 m_a^3}{64\pi},\ \Gamma(a\to f\bar{f}) = \frac{g_f^2\, m_f^2\, m_a}{8\pi}\sqrt{1-\frac{4m_f^2}{m_a^2}}$$

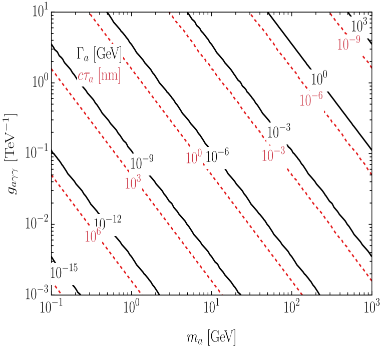
Outline

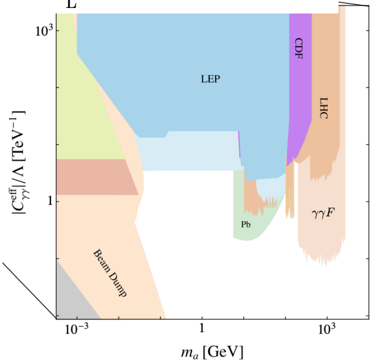
Collider searches

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



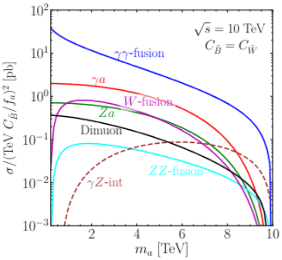


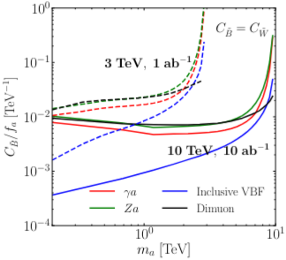




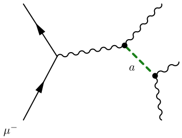
- Decay width crosses short- and long-lived regimes.
- Many resonance searches: $ee \to \gamma/Z + (a \to \gamma\gamma)$, $\gamma\gamma \to a \to \gamma\gamma$, $Z \to \gamma a$, $h \to Za$
- Long-lived searches (Beam Dump): $\mathscr{P} = \exp\{-D/\ell_a\} - \exp\{-(D+L)/\ell_a\}$, $\ell_a = \beta\gamma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

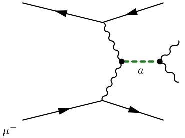
Direct search for heavy ALP resonance

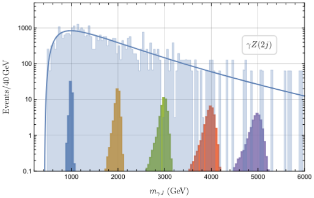


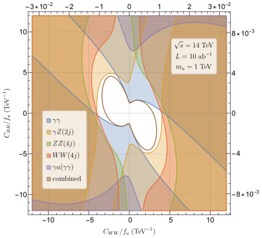


[Han, Li, Wang, 2203.05484]









[Bao, Fan Li, 2203.04328]

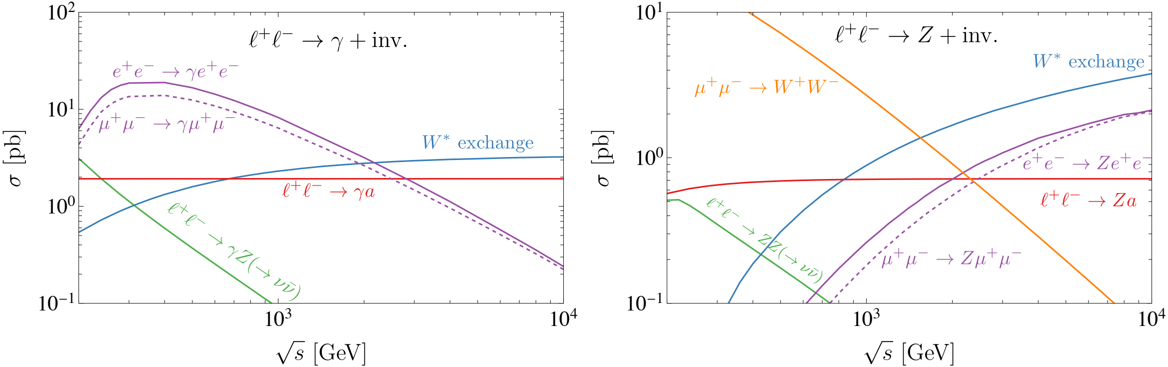
- ALP on-shell production through the associated production (Va) and vector-boson fusion
- Prompt decay into vector bosons: reconstruction of the ALP resonance
- Energy frontier: TeV ALP

- Multiple bosons to reconstruct a resonance
- (C_{WW}, C_{BB}) contour probe with $m_a \sim \mathcal{O}(\text{TeV})$

How about a light (sub-GeV), especially for a long-lived ALP?

Light ALP production at lepton colliders

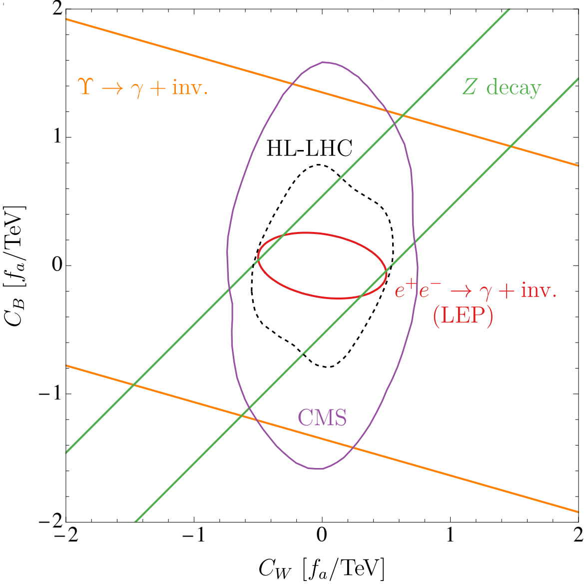
- Ultra-long lived $\ell_a > D + L$, ALPs fly out of the detector and leave the missing energy signal.
- Mono-V: $a+\gamma$ gives mono-γ, and $a+Z$ gives mono-Z



- Light ALP cross sections are almost independent on $\sqrt{s}$ and m_a
- The annihilation backgrounds decrease with $\sqrt{s}$.
- Mono-γ cuts: $p_{T,\gamma} > 10$ GeV and $|\eta_\gamma| < 2.5$. while no cuts for mono-Z here (detailed later).

$$\sigma_{\ell^+\ell^-\to\gamma a} = \frac{\alpha}{768}\left[32g_{a\gamma\gamma}^2 + \frac{8g_{a\gamma\gamma}g_{a\gamma Z}(c_W^2 - 3s_W^2)s}{s_W c_W (s - M_Z^2)} + \frac{g_{a\gamma Z}^2(6s_W^4 + 2c_W^4 - 1)s^2}{s_W^2 c_W^2 (s - M_Z^2)^2}\right]$$

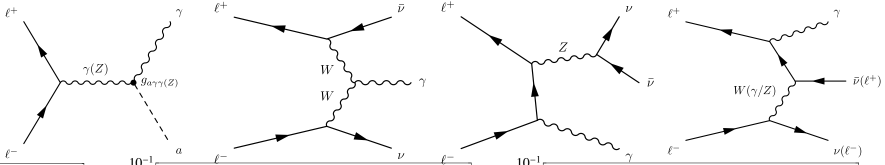
Recast of the existing constraints: (C_B, C_W) plane

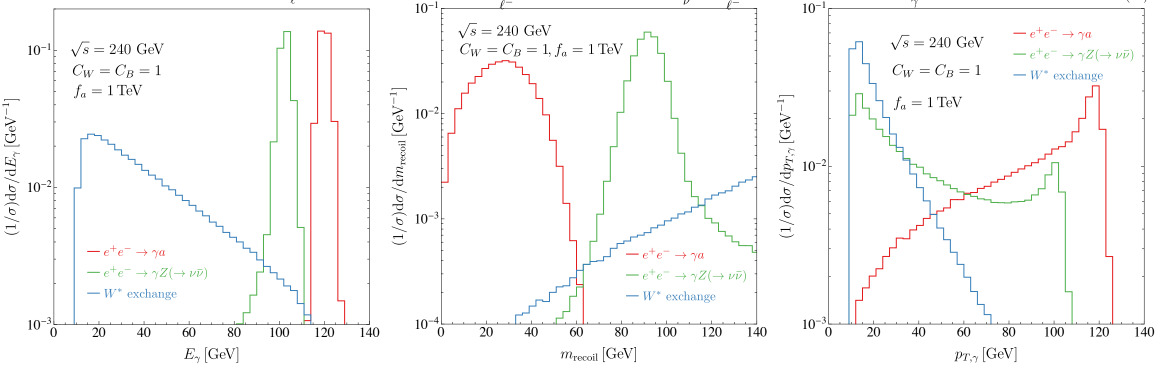


- LEP OPAL189 $\gamma + \text{inv.}$: $4.35 \pm 0.15 \pm 0.09$ pb
  $$\sigma(e^+e^- \to \gamma + a) \sim g_{a\gamma\gamma}^2, g_{a\gamma\gamma} g_{a\gamma Z}, g_{a\gamma Z}^2.$$
- Crystal Ball $\Upsilon \to \gamma + \text{inv.}$:
  $$\mathscr{B}(\Upsilon \to \gamma + a) = g_{a\gamma\gamma} m_b^2 / (8\pi\alpha) \mathscr{B}(\Upsilon \to e^+e^-)$$
- $Z \to \gamma + \text{inv.}$: $\Gamma(Z \to \text{BSM}) \lesssim 2$ MeV
  $$\Gamma(Z \to a\gamma) = \frac{M_Z^3}{384\pi} g_{aZ\gamma}^2 \left(1 - \frac{m_a^2}{M_Z^2}\right)^3$$
- $Z \to 3\gamma \sim g_{a\gamma\gamma} g_{aZ\gamma}$: constraint is weaker
- CMS and HL-LHC [2202.03450]
  $$W^\pm\gamma, Z\gamma, ZZ, W^+W^-, W^\pm Z$$

Mono-photon

Electron colliders:
FCC-ee/CEPC/Tera-Z



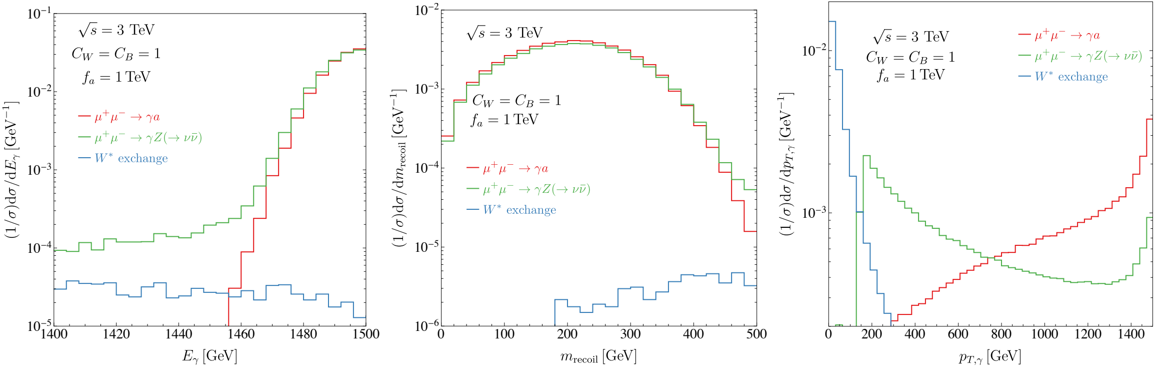


- Monochromatic kinematics subject to detector effects (Delphes simulation)

$$E_\gamma \sim \frac{s - m_{\mathrm{inv.}}^2}{2\sqrt{s}}, \;\; m_{\mathrm{recoil}} = s - 2\sqrt{s}E_\gamma \sim m_{\mathrm{inv.}}^2, \;\; m_{\mathrm{inv.}} = m_a, M_Z\,.$$

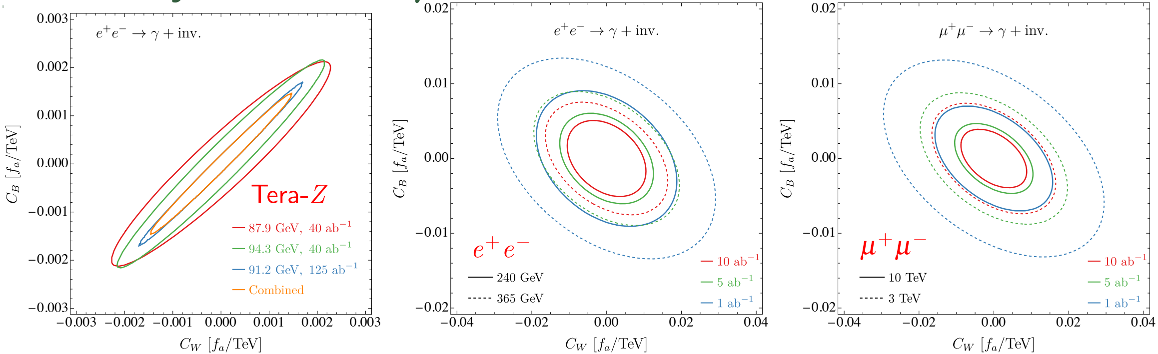
- W^* exchange can be removed with E_γ (equivalent to m_{recoil}) and p_T^γ cuts

Mono-photon at muon colliders



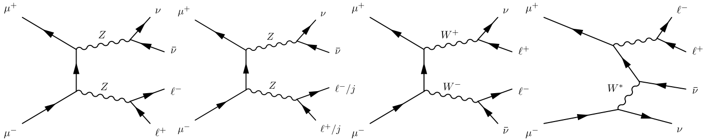
- W^* exchange can be excluded as well
- The detector smearing for $Z \to \bar{\nu}\nu$ looks identical as ALP signal
- Z boson mass is relative negligible with respective collider energy $(M_Z \ll \sqrt{s})$: no difference from light ALP $a \to$invisible.

Sensitivity from mono-γ measurements



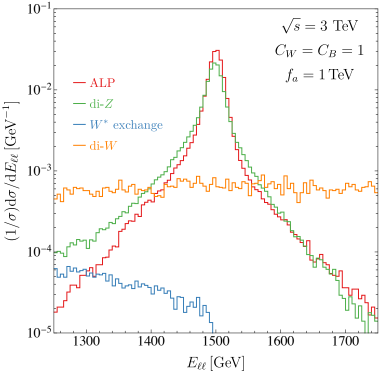
- Tera-Z factory gives the best bound due to the large luminosity and a small background
- Electron collider 240 GeV is better than 365 GeV, due to the better cut efficiency
- Muon collider, 10 TeV gives better bound than 3 TeV, due to the smaller background ($1/s$ behavior for $\gamma + (Z \to \nu\bar{\nu})$)
- The compensation between background and cut efficiency: 240 $\text{GeV}\,ee \sim$10 $\text{TeV}\,\mu\mu$

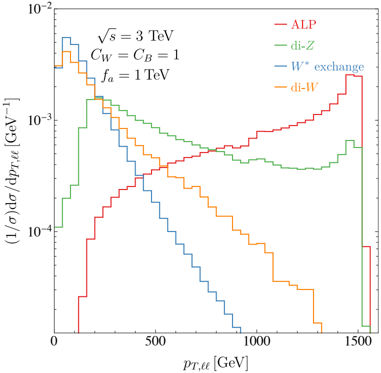
Mono-Z with $Z \to \ell^+\ell^- / jj$

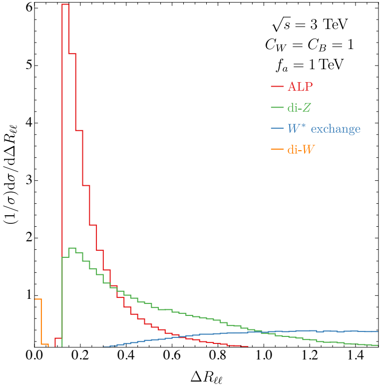


$a + (Z \to \ell^+\ell^-)$

- di-Z: $(Z \to \ell^+\ell^-) + (Z \to \nu\bar{\nu})$
- di-W: $(W^+ \to \ell^+\nu) + (W^- \to \ell^-\bar{\nu})$
- $t-$channel W^* and γ/Z exchange



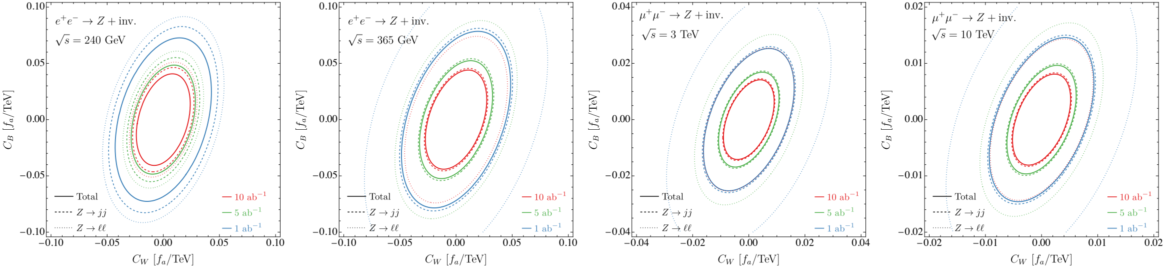




- We optimize the cuts in addition to $|M_{\ell\ell} - M_Z| < 10$ GeV, while a 20-GeV window for $Z \to jj$

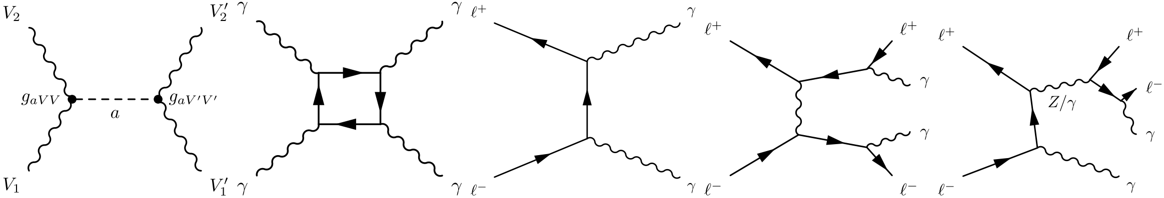
Sensitivity from mono-Z measurements

Electron colliders   Muon colliders

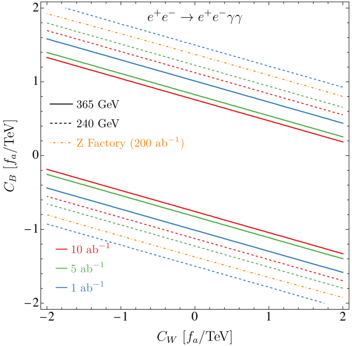


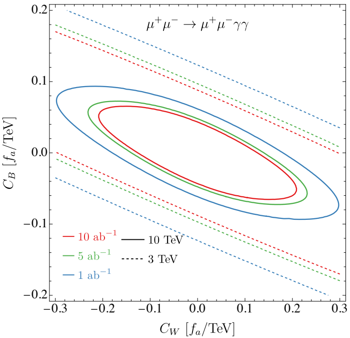
- Electron collider 250 GeV is better than 365 GeV due to the better cut efficiency, while muon collider 10 TeV is stronger than 3 TeV
- At TeV muon colliders, the hadronic Z decay as one Z-jet due to the collimated boost
- Hadronic channel gives better bounds than leptonic one due to the larger branch fraction

Nonresonant vector-boson scattering: light-by-light

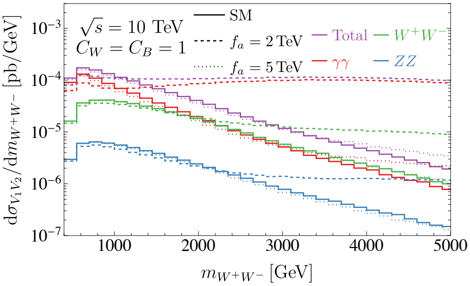


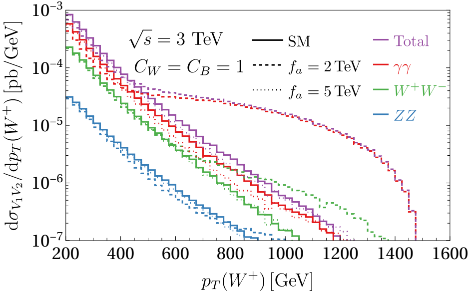
- Light-by-light scattering: s, t, u channels
- Loop induced background
- Annihilation can be removed with a $m_{\gamma\gamma}$ cut
- Other di-photon backgrounds

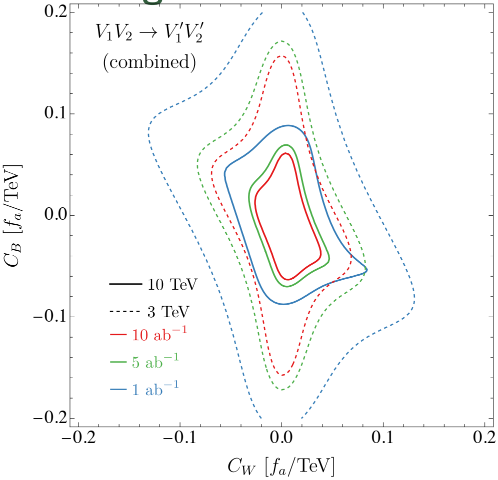


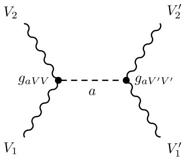


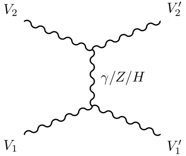
Electroweak vector boson scattering







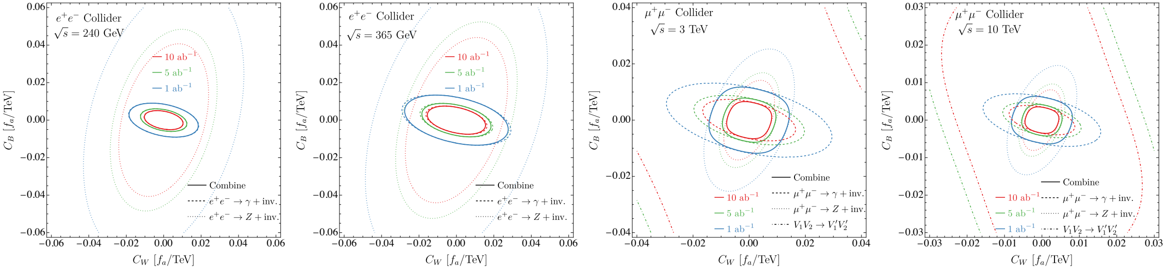


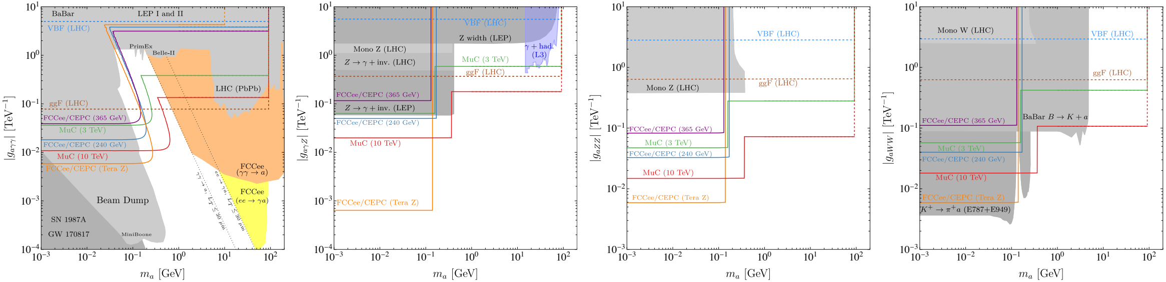


- Signal: flat tails (m_a independent)
- SM backgrounds die out
- Directly probe $g_{a\gamma Z}, g_{aZZ}, g_{aWW}$

Combination

Electron colliders | Muon colliders



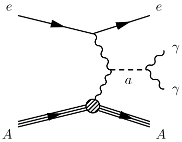


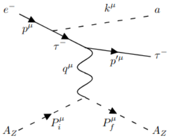
$g_{a\gamma\gamma}$ $g_{a\gamma Z}$ g_{aZZ} g_{aWW}

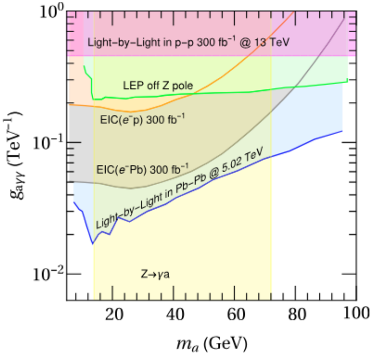
Outline

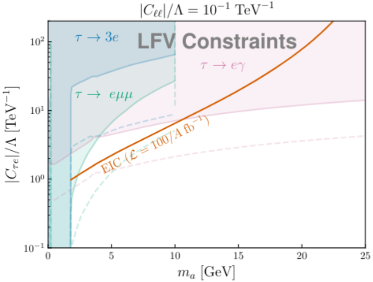
Existing searches for ALPs at the EIC

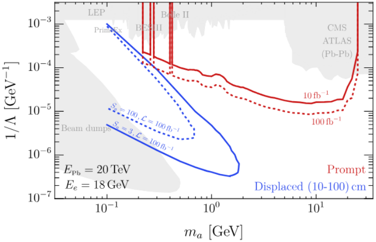
- Liu, Yan: Inelastic scattering [2112.02477]
- Balkin, Hen, Li, Liu, Ma, Soreq, Williams: Coherent scattering [2310.08827]
- Davoudiasl, Marcarelli, Neil: Lepton-Flavor-Violating ALPs [2112.04513]





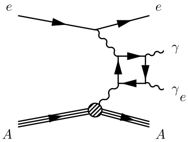






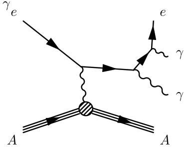
Our analysis [w/ Batell, Leys, 2606.xxxxx]

- 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



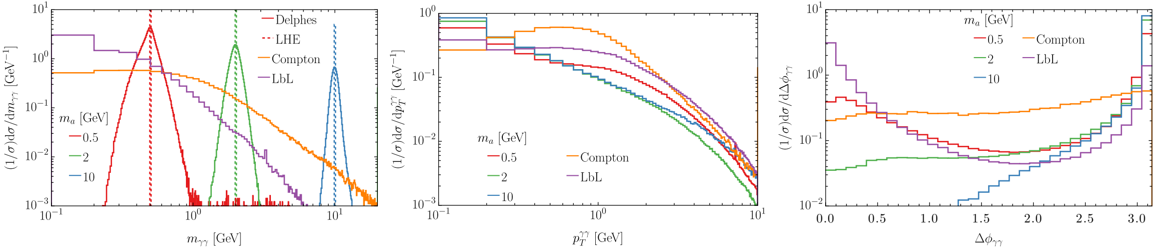
Pre-selection (fiducial) cuts:

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

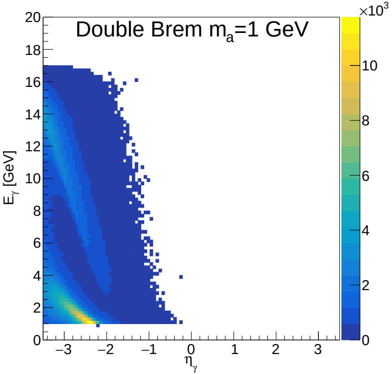


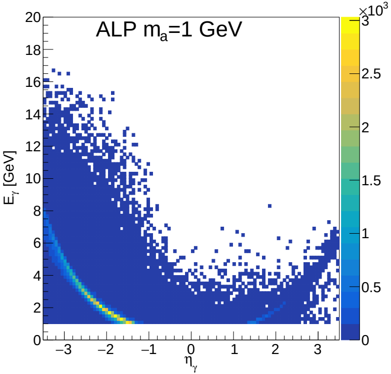
Optimization cuts (similar to LHC)

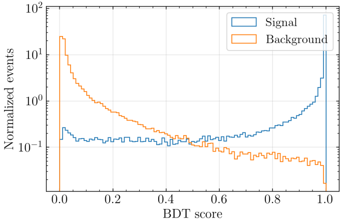
$$p_T^{\gamma\gamma} < \max(0.5 \text{ GeV}, m_a/10),\ A_\phi = 1 - \Delta\phi_{\gamma\gamma}/\pi < 0.01$$

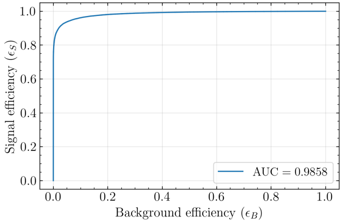


Correlations and Boost Decision Tree (BDT)









- Correlations between various kinematics are significant different.
- We can take BDT to distinguish the signal and backgrounds
- Signal remains the same magnitudes, while backgrounds can be suppressed down to $10^{-3} \sim 10^{-2}$

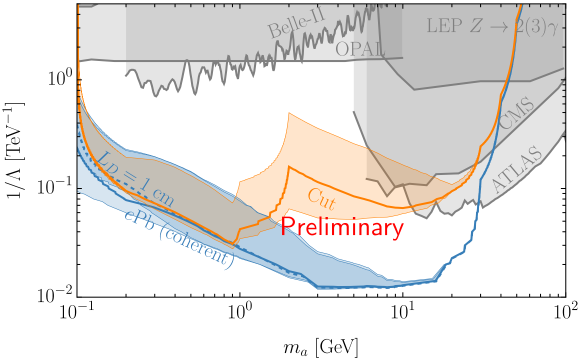
The elastic scattering at the EIC

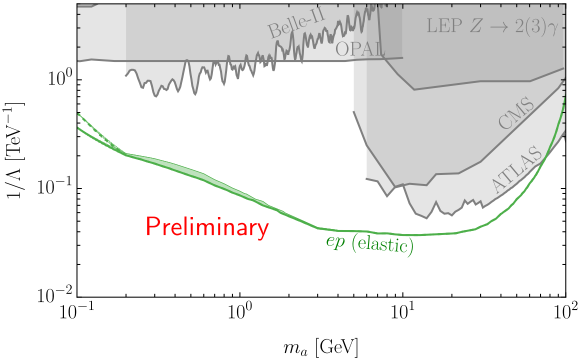
A figure of merite measure:

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

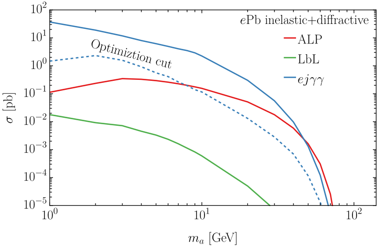
where systematics $\delta_s = \delta_b = 0, 0.1\%, 1\%$, and reconstruction efficiency $\varepsilon_{s(b)} = 70\%(100\%)$

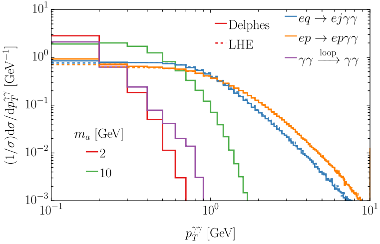
- At a low ALP mass, the coherent scattering dominates
- At a high ALP mass, the inelastic scattering takes over

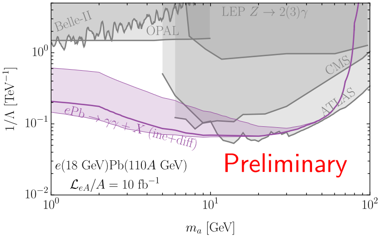




Inelastic/diffractive scattering







- We also have the inelastic and diffractive (incoherent) components
- The backgrounds come from LbL and the inelastic $eq \to ej\gamma\gamma$
- We just perform a cut based optimization

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

Summary

- At Lepton Colliders
  - Mono-V production give very good constraints on ultra long-lived ALP couplings
  - Non-resonant vector boson scatterings give a good probe to EW couplings $g_{a\gamma Z}, g_{aZZ}, g_{aWW}$
  - Resonant searches will take over at a higher ALP mass
- At the EIC
  - The photon-coupled ALP production at the EIC is carefully examined, for both signal (coherent and inelastic scattering) and backgrounds (LbL and Double Brem)
  - The detector simulation: `Delphes` with ECCE/EICmatrix2(YR)
  - With the LUXqed formalism, the nucleon and ion's photon PDF can be precise determined through the Structure Functions and Form Factors