Light axion-like particles at high-energy muon colliders

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In collaboration with
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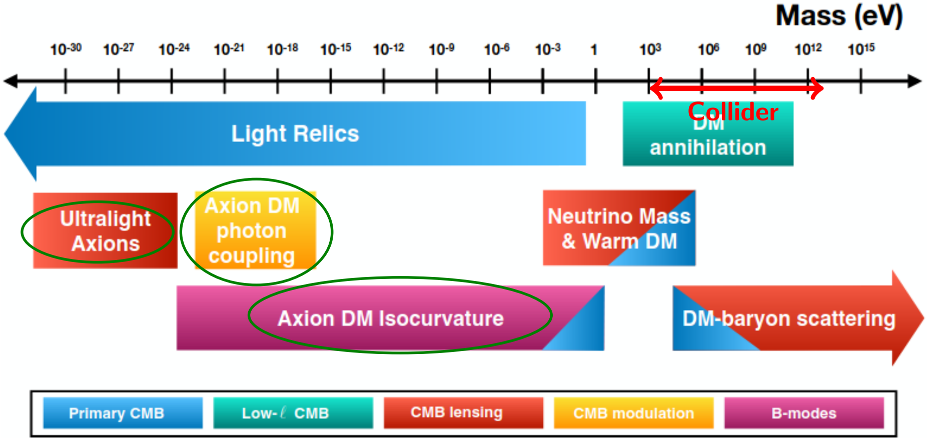
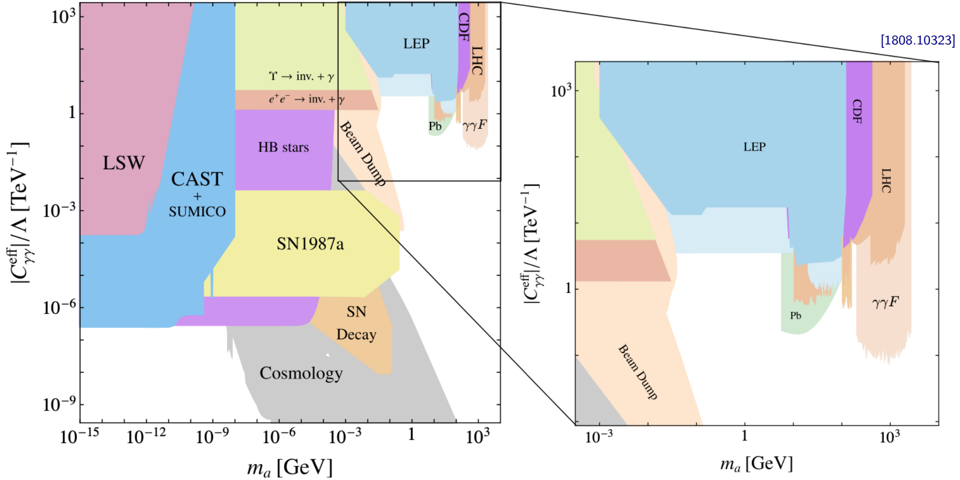
Axion and Axion-like particles

- 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
- The ALP mass can spread in many magnitudes!



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

A EFT formulation: dimensional-5 operators

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

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

The relation

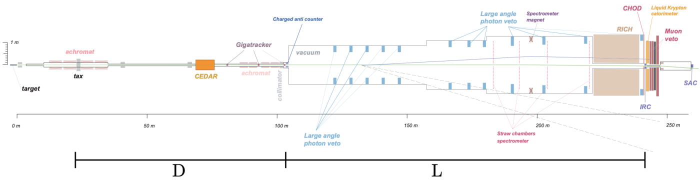
$$g_{a\gamma\gamma} = \frac{4}{f_a}(s_W^2 C_W + c_W^2 C_B), \qquad g_{a\gamma Z} = \frac{8}{f_a}s_W c_W(C_W - C_B),$$

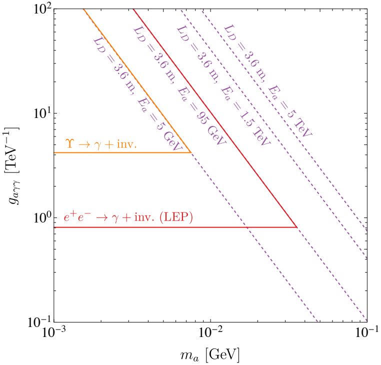
$$g_{aZZ} = \frac{4}{f_a}(c_W^2 C_W + s_W^2 C_B), \quad g_{aWW} = \frac{4}{f_a}C_W.$$

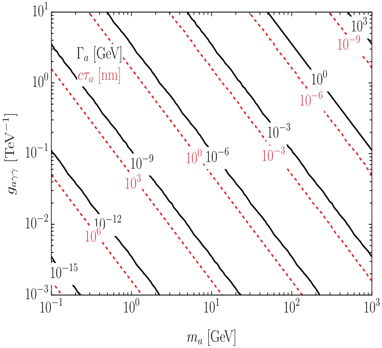
- We will stay with (C_B, C_W) and this matching in this work.
- See Peiran Li's talk for a heavy axion.

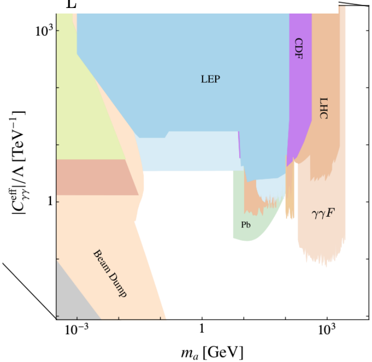
Collider searches

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



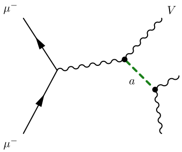


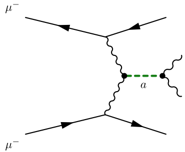


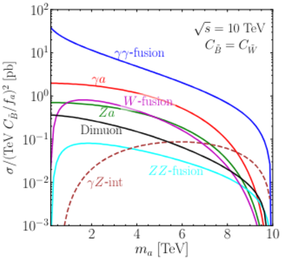


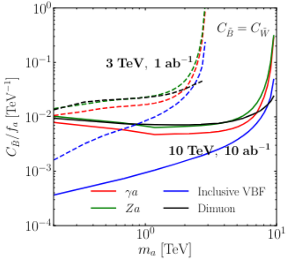
- Decay width crosses short- and long-lived regimes.
- Many resonance searches: $ee \to \gamma/Z + (a \to \gamma\gamma)$, $\gamma\gamma \to a \to \gamma\gamma$, $Z \to \gamma a$, $h \to Za$
- Long-lived searches (Beam Dump): $\mathscr{P} = \exp\{-D/\ell_a\} - \exp\{-(D+L)/\ell_a\}$, $\ell_a = \beta\gamma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

Direct search for heavy ALP resonance

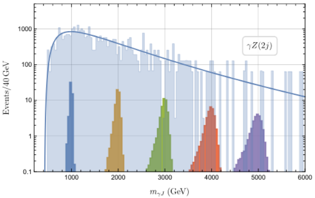


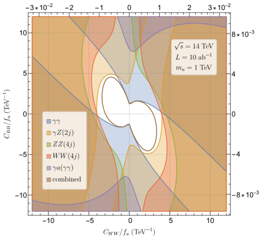






[Han, Li, Wang, 2203.05484]





[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

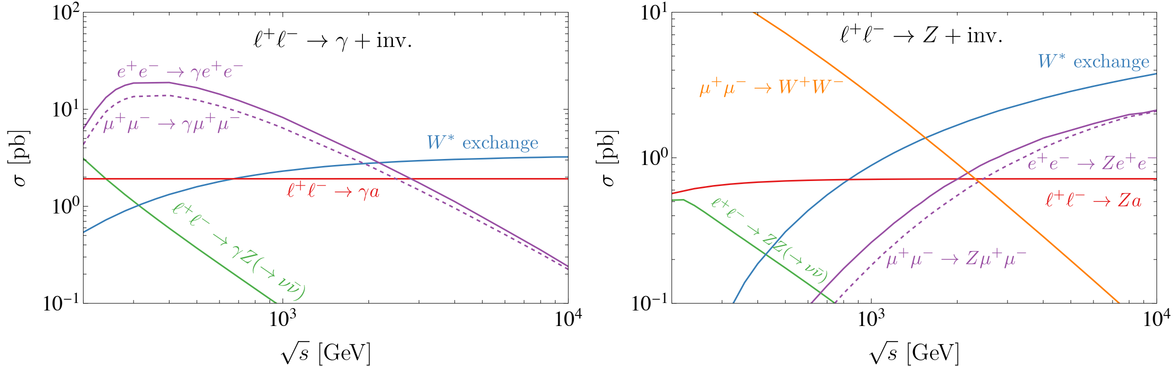
- Multiple bosons to reconstruct a resonance
- (C_{WW}, C_{BB}) contour probe with $m_a \sim \mathcal{O}(\text{TeV})$

Also see talk by Peiran Li

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

Light ALP production at lepton colliders

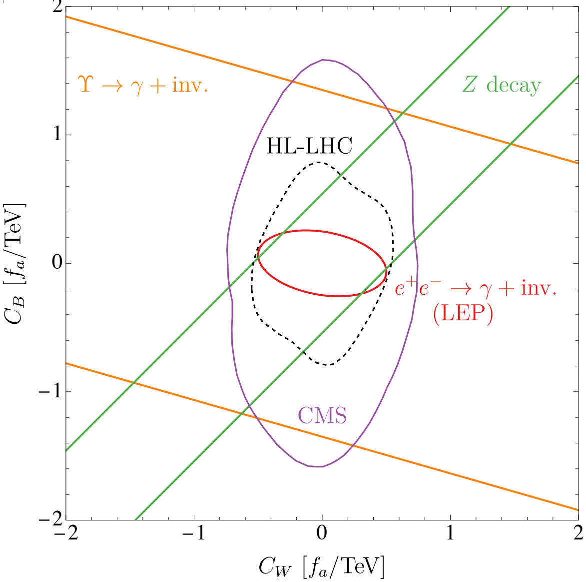
- Ultra-long lived $\ell_a > D + L$, ALPs fly out of the detector and leave the missing energy signal.
- Mono-V: $a + \gamma$ gives mono-γ, and $a + Z$ gives mono-Z



- 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).

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

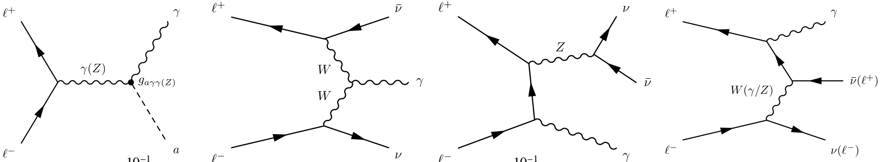
Recast of the existing constraints: (C_B, C_W) plane

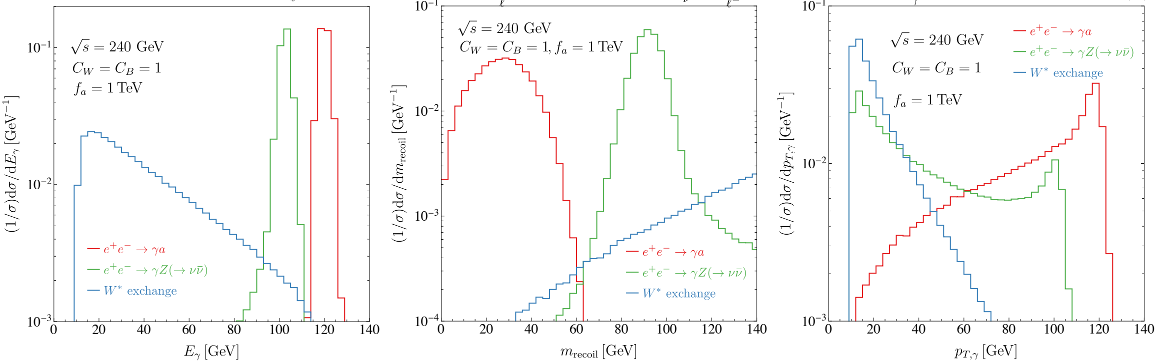


- LEP OPAL189 $\gamma + \text{inv.}$: $4.35 \pm 0.15 \pm 0.09$ pb
  $\sigma(e^+e^- \to \gamma + a) \sim g_{a\gamma\gamma}^2, g_{a\gamma\gamma} g_{a\gamma Z}, g_{a\gamma Z}^2.$
- Crystal Ball $\Upsilon \to \gamma + \text{inv.}$:
  $\mathscr{B}(\Upsilon \to \gamma + a) = g_{a\gamma\gamma} m_b^2 / (8\pi\alpha) \mathscr{B}(\Upsilon \to e^+e^-)$
- $Z \to \gamma + \text{inv.}$: $\Gamma(Z \to \text{BSM}) \lesssim 2$ 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



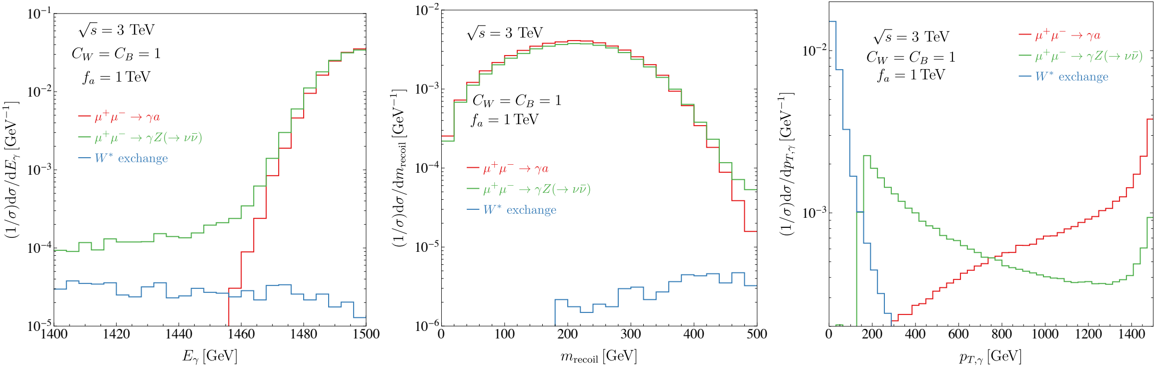


- Monochromatic kinematics subject to detector effects (Delphes simulation)

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

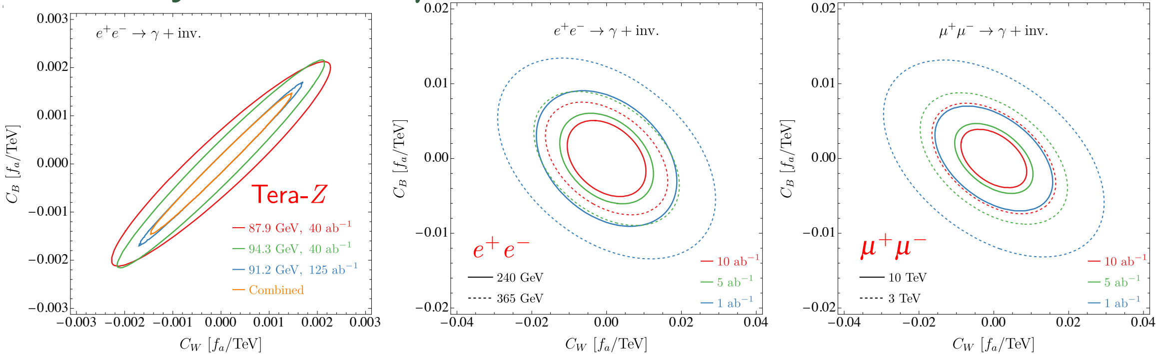
- W^* exchange can be removed with E_γ (equivalent to m_{recoil}) and p_T^γ cuts

Mono-photon at muon colliders



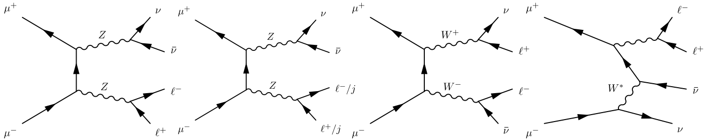
- W^* exchange can be excluded as well
- The detector smearing for $Z \to \bar{\nu}\nu$ looks identical as ALP signal
- Z boson mass is relative negligible with respective collider energy $(M_Z \ll \sqrt{s})$: no difference from light ALP $a \to$invisible.

Sensitivity from mono-γ measurements



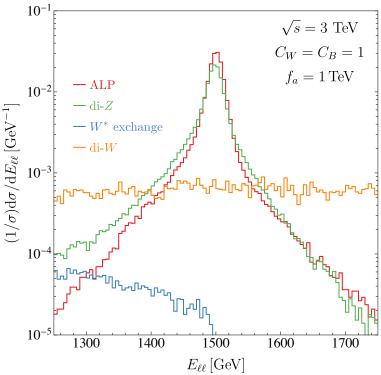
- Tera-Z factory gives the best bound due to the large luminosity and a small background
- Electron collider 240 GeV is better than 365 GeV, due to the better cut efficiency
- Muon collider, 10 TeV gives better bound than 3 TeV, due to the smaller background ($1/s$ behavior for $\gamma + (Z \to \nu\bar{\nu})$)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

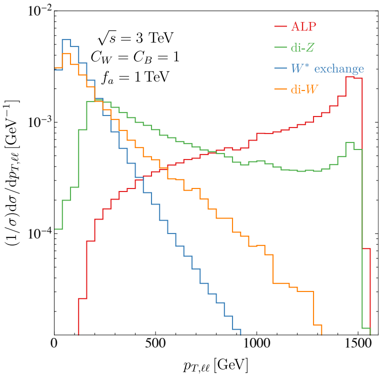
Mono-Z with $Z \to \ell^+\ell^- / jj$

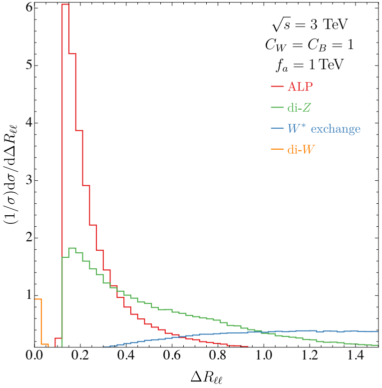


$a + (Z \to \ell^+\ell^-)$

- 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



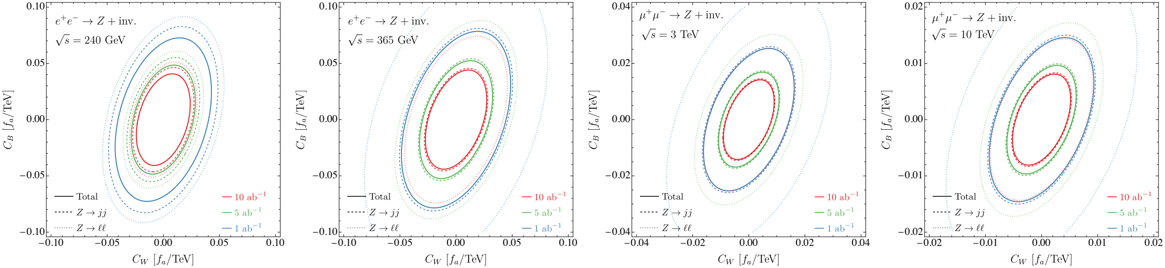




- We optimize the cuts in addition to $|M_{\ell\ell} - M_Z| < 10$ GeV, while a 20-GeV window for $Z \to jj$

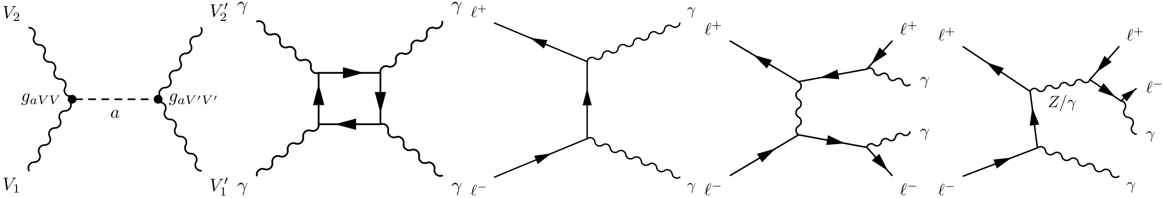
Sensitivity from mono-Z measurements

Electron colliders　　　　Muon colliders

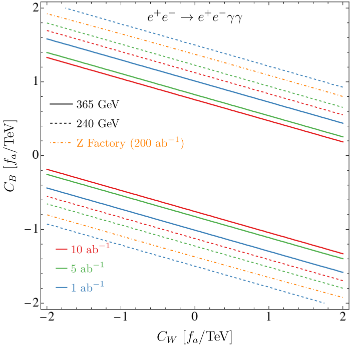


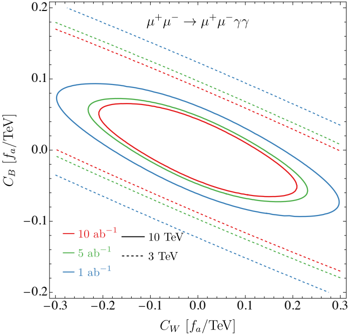
- Electron collider 250 GeV is better than 365 GeV due to the better cut efficiency, while muon collider 10 TeV is stronger than 3 TeV
- At TeV muon colliders, the hadronic Z decay as one Z-jet due to the collimated boost
- Hadronic channel gives better bounds than leptonic one due to the larger branch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

Nonresonant vector-boson scattering: light-by-light

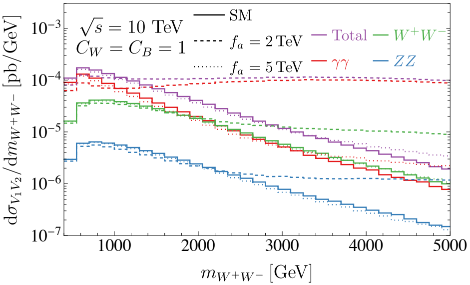


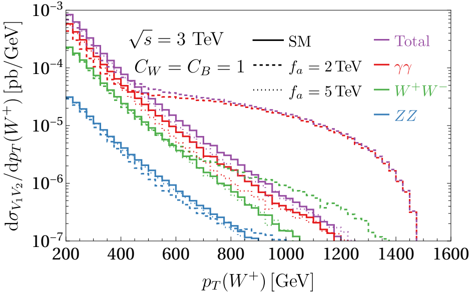
- Light-by-light scattering: s, t, u channels
- Loop induced background
- Annihilation can be removed with a $m_{\gamma\gamma}$ cut
- Other di-photon backgrounds

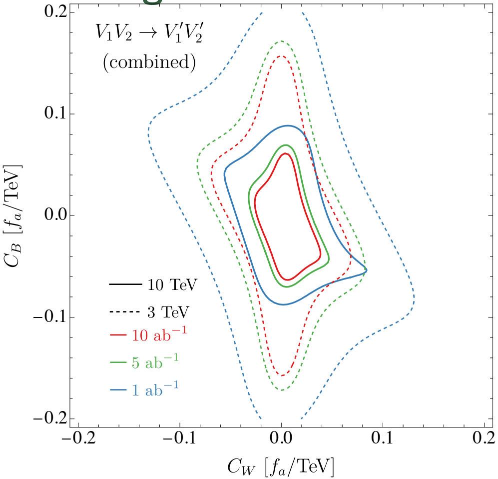


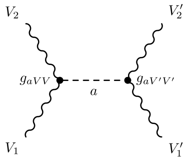


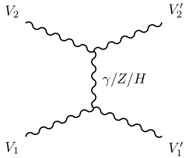
Electroweak vector boson scattering







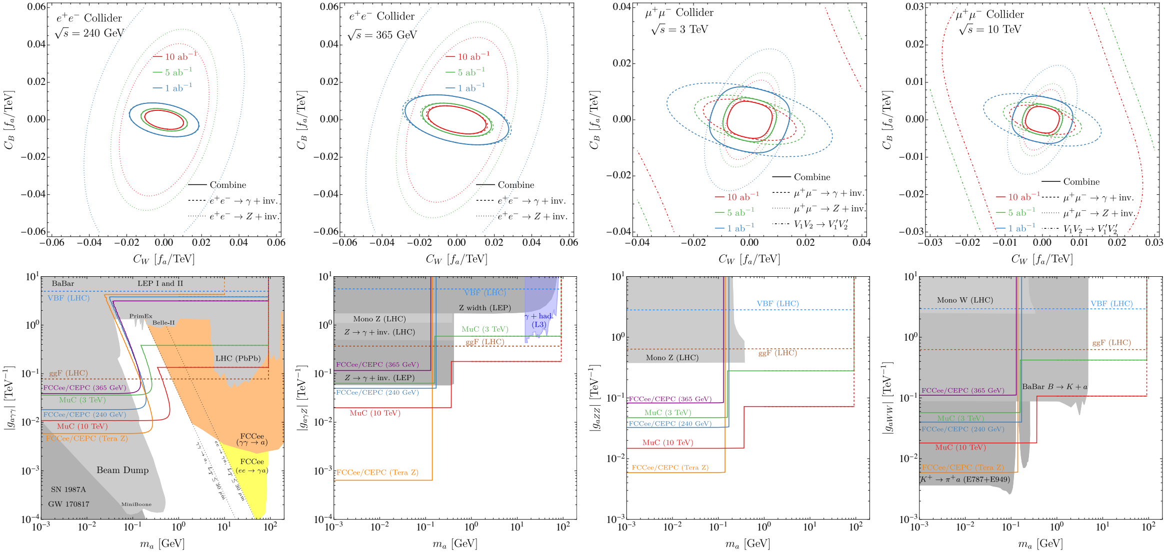




- Signal: flat tails (m_a independent)
- SM backgrounds die out
- Directly probe $g_{a\gamma Z}, g_{aZZ}, g_{aWW}$

Combination

Electron colliders Muon colliders

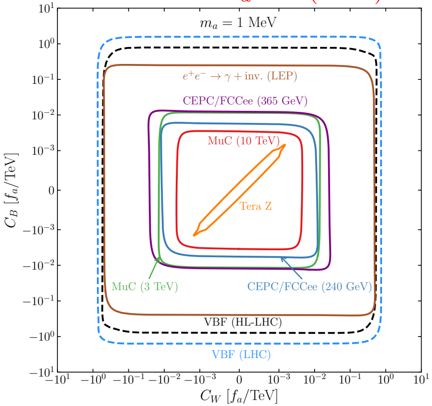


$g_{a\gamma\gamma}$ $g_{a\gamma Z}$ g_{aZZ} g_{aWW}

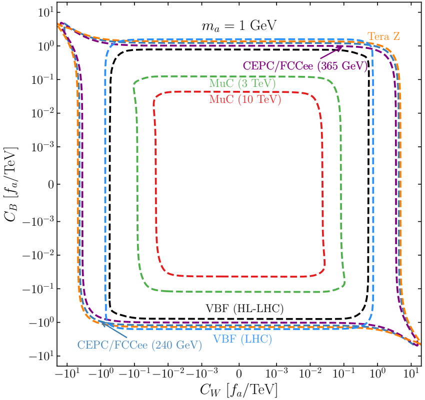
Summary

More details in arXiv:2505.10023

Mono-V : $m_a \sim \mathcal{O}(\text{MeV})$



VBS: $m_a \sim \mathcal{O}(\text{GeV})$



- 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 (TeV) [See Peiran Li's talk]