Lighting Electroweak-Violating ALP-Lepton Interactions at CEPC

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The Second International Conference on Axion Physics and Experiment (Axion 2023)

Content

1. Motivation
2. ALP-lepton interactions
3. Energy enhancement behaviors in $e^+e^- \to \nu_e a \overline{\nu_e}$
4. The signal-to-background analysis at CEPC
5. Conclusion

Content

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4 W + 1 H questions for axion-like particles (ALPs)

1. **What** does an ALP come from ?

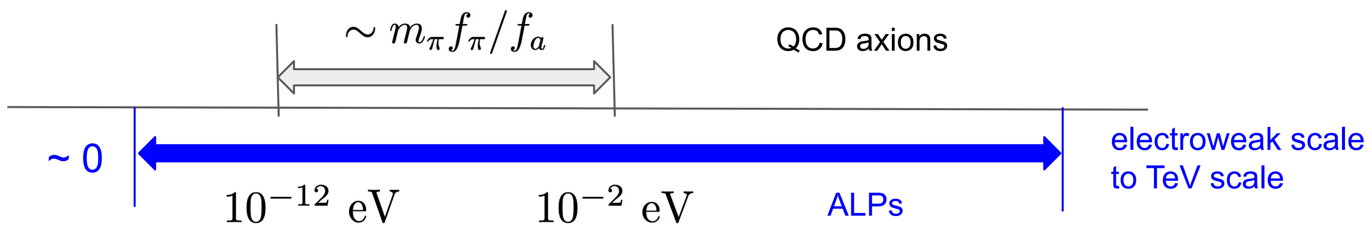
   → An ALP is a light pseudoscalar with approximate shift symmetry.

2. **Why** we need ALPs ?

   → (1) Strong CP problem, (2) DM candidates, (3) Hierarchy problem of the Higgs boson mass, (4) A hint of some string theories, … etc.

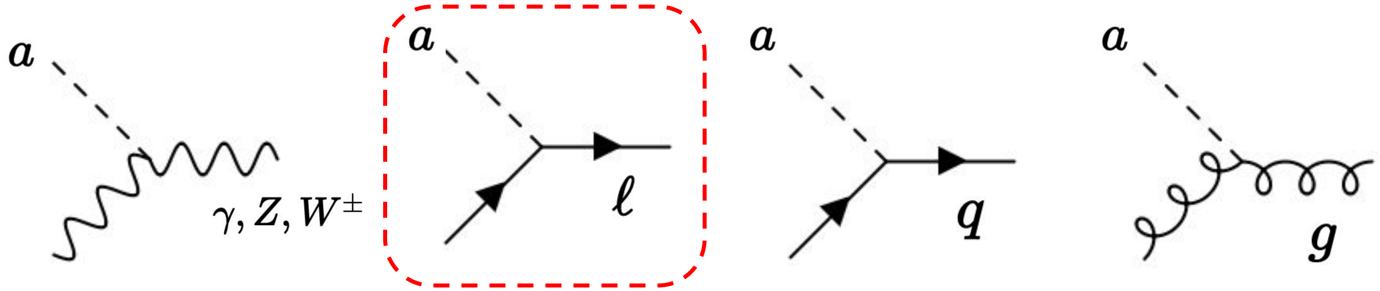
3. **Which** is the mass range of ALPs ?

   →

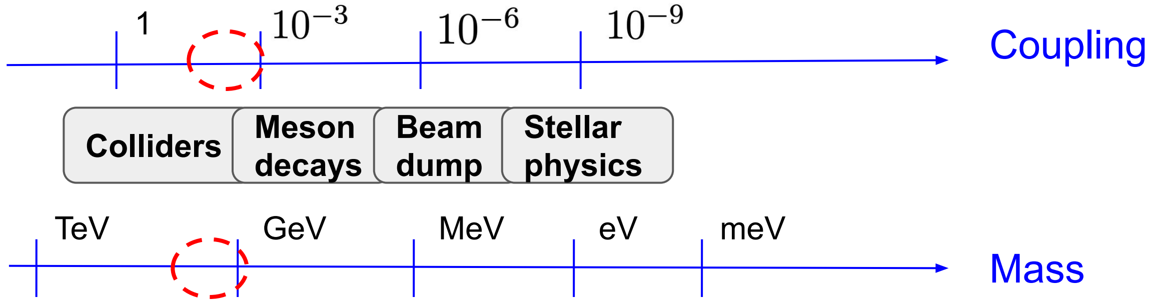


4 W + 1 H questions for axion-like particles (ALPs)

4. **Who** can interact with ALPs (SM particles only) ?



5. **How** to search for ALPs ?



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ALP-lepton interactions

The global $\cancel{U(1)_{\rm PQ}}$ ⟹ pseudo Nambu-Goldstone bosons

(ALPs)

⇓ shift symmetry

$$a(x) \to a(x) + \text{const.}$$

⇓

$$\mathcal{L}_{\ell \rm ALP} = \partial_\mu a \; J^\mu_{\rm PQ,\ell}$$

ALP-lepton interactions

$$\mathcal{L}_{\ell \rm ALP} = \partial_\mu a \, J^\mu_{\rm PQ,\ell}$$

dimensionless coupling

$$J^\mu_{\rm PQ,\ell} = \frac{c_\ell^V}{2\Lambda}\bar{\ell}\gamma^\mu \ell + \frac{c_\ell^A}{2\Lambda}\bar{\ell}\gamma^\mu\gamma_5 \ell + \frac{c_\nu}{2\Lambda}\overline{\nu_\ell}\gamma^\mu P_L \nu_\ell$$

~~$U(1)_{\rm PQ}$~~ new physics scale

ALP-lepton interactions

$$\mathcal{L}_{\ell \mathrm{ALP}} = \partial_\mu a \, J^\mu_{\mathrm{PQ},\ell}$$

Are the previous statements in the literature correct ?

"The neutrino coupling is suppressed by its mass"

$$J^\mu_{\mathrm{PQ},\ell} = \frac{c^V_\ell}{2\Lambda} \bar{\ell} \gamma^\mu \ell + \frac{c^A_\ell}{2\Lambda} \bar{\ell} \gamma^\mu \gamma_5 \ell + \frac{c_\nu}{2\Lambda} \overline{\nu_\ell} \gamma^\mu P_L \nu_\ell$$

"The vector coupling is unphysical"

$$\text{"} \; \tfrac{1}{2} \partial_\mu a \bar{\ell} \gamma^\mu \gamma_5 \ell = m_\ell a \bar{\ell} i \gamma_5 \ell \; \text{"}$$

ALP-lepton interactions

$$J^{\mu}_{\mathrm{PQ},\ell} = \frac{c^V_\ell}{2\Lambda}\bar{\ell}\gamma^\mu \ell + \frac{c^A_\ell}{2\Lambda}\bar{\ell}\gamma^\mu\gamma_5 \ell + \frac{c_\nu}{2\Lambda}\overline{\nu_\ell}\gamma^\mu P_L \nu_\ell$$

More generally, each lepton coupling term in the above can arise independently in a electroweak invariant theory by including the following currents,

$$\overline{(HL)}\gamma_\mu(HL)\,, \bar{e}_R\gamma_\mu e_R\,, \text{ and } \overline{(H^\dagger L)}\gamma_\mu(H^\dagger L)\,,$$

Phys. Rev. Lett. 130, 241801 [arXiv: 2209.00665]

New Opportunities for Detecting Axion-Lepton Interactions

Wolfgang Altmannshofer, Jeff A. Dror, and Stefania Gori
Phys. Rev. Lett. **130**, 241801 – Published 13 June 2023

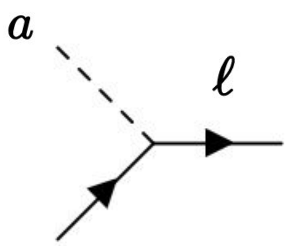
ABSTRACT

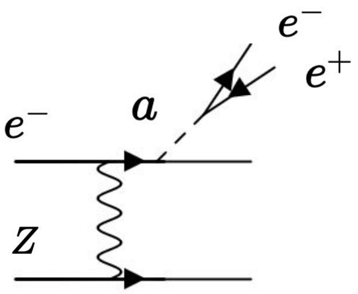
We revisit the theory and constraints on axionlike particles (ALPs) interacting with leptons. We clarify some subtleties in the constraints on ALP parameter space and find several new opportunities for ALP detection. We identify a qualitative difference between weak-violating and weak-preserving ALPs, which dramatically change the current constraints due to possible "energy enhancements" in various processes. This new understanding leads to additional opportunities for ALP detection through charged meson decays (e.g., $\pi^+ \to e^+ \nu a$, $K^+ \to e^+ \nu a$) and W boson decays. The new bounds impact both weak-preserving and weak-violating ALPs and have implications for the QCD axion and addressing experimental anomalies using ALPs.

ALP-lepton interactions

After integration by parts of $\partial_\mu a \, J^\mu_{\mathrm{PQ},\ell}$, the $\mathcal{L}_{\ell \mathrm{ALP}}$ can be represented as

$$
\begin{aligned}
a\,\partial_\mu J^\mu_{\mathrm{PQ},\ell} = & \; i c_\ell^A \frac{m_\ell}{\Lambda} \, a \bar{\ell}\gamma_5 \ell \\
& + \frac{\alpha_{\mathrm{em}}}{4\pi\Lambda}\Bigg[\frac{c_\ell^V - c_\ell^A + c_\nu}{4 s_W^2} \, a W^+_{\mu\nu}\tilde{W}^{-,\mu\nu} \\
& + \frac{c_\ell^V - c_\ell^A(1-4s_W^2)}{2 s_W c_W} \, a F_{\mu\nu}\tilde{Z}^{\mu\nu} - c_\ell^A \, a F_{\mu\nu}\tilde{F}^{\mu\nu} + \\
& \frac{c_\ell^V(1-4s_W^2) - c_\ell^A(1-4s_W^2+8s_W^4) + c_\nu}{8 s_W^2 c_W^2} \, a Z_{\mu\nu}\tilde{Z}^{\mu\nu} \Bigg] \\
& + \frac{i g_W}{2\sqrt{2}\Lambda}(c_\ell^A - c_\ell^V + c_\nu) \, a(\bar{\ell}\gamma^\mu P_L \nu) W^-_\mu \; + \; \mathrm{h.c.} \, ,
\end{aligned}
$$





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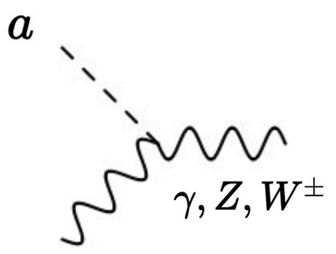
$$a\,\partial_\mu J^\mu_{\mathrm{PQ},\ell} = i c_\ell^A \frac{m_\ell}{\Lambda}\, a\bar{\ell}\gamma_5\ell$$

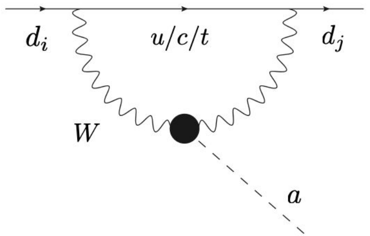
$$+ \frac{\alpha_{\mathrm{em}}}{4\pi\Lambda}\left[\frac{c_\ell^V - c_\ell^A + c_\nu}{4s_W^2}\, aW^+_{\mu\nu}\tilde{W}^{-,\mu\nu}\right.$$

$$+ \frac{c_\ell^V - c_\ell^A(1-4s_W^2)}{2s_W c_W}\, aF_{\mu\nu}\tilde{Z}^{\mu\nu} - c_\ell^A\, aF_{\mu\nu}\tilde{F}^{\mu\nu} +$$

$$\left.\frac{c_\ell^V(1-4s_W^2) - c_\ell^A(1-4s_W^2+8s_W^4) + c_\nu}{8s_W^2 c_W^2}\, aZ_{\mu\nu}\tilde{Z}^{\mu\nu}\right]$$

$$+ \frac{i g_W}{2\sqrt{2}\Lambda}(c_\ell^A - c_\ell^V + c_\nu)\, a(\bar{\ell}\gamma^\mu P_L \nu)W^-_\mu \; + \; \mathrm{h.c.}\,,$$





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& + \frac{\alpha_{\mathrm{em}}}{4\pi\Lambda}\Bigg[\frac{c_\ell^V - c_\ell^A + c_\nu}{4 s_W^2}\, aW^+_{\mu\nu}\tilde{W}^{-,\mu\nu} \\
& + \frac{c_\ell^V - c_\ell^A(1-4s_W^2)}{2 s_W c_W}\, aF_{\mu\nu}\tilde{Z}^{\mu\nu} - c_\ell^A\, aF_{\mu\nu}\tilde{F}^{\mu\nu} + \\
& \frac{c_\ell^V(1-4s_W^2) - c_\ell^A(1-4s_W^2+8s_W^4) + c_\nu}{8 s_W^2 c_W^2}\, aZ_{\mu\nu}\tilde{Z}^{\mu\nu}\Bigg] \\
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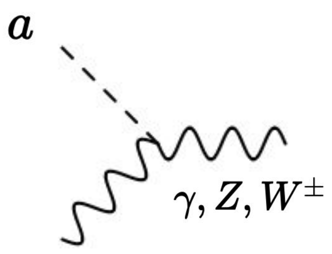

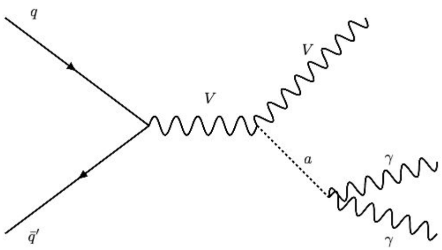

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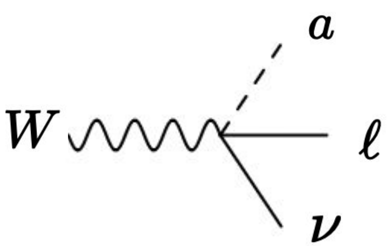
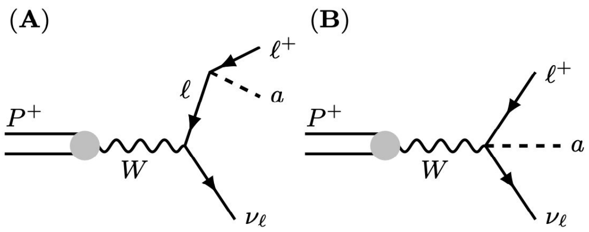
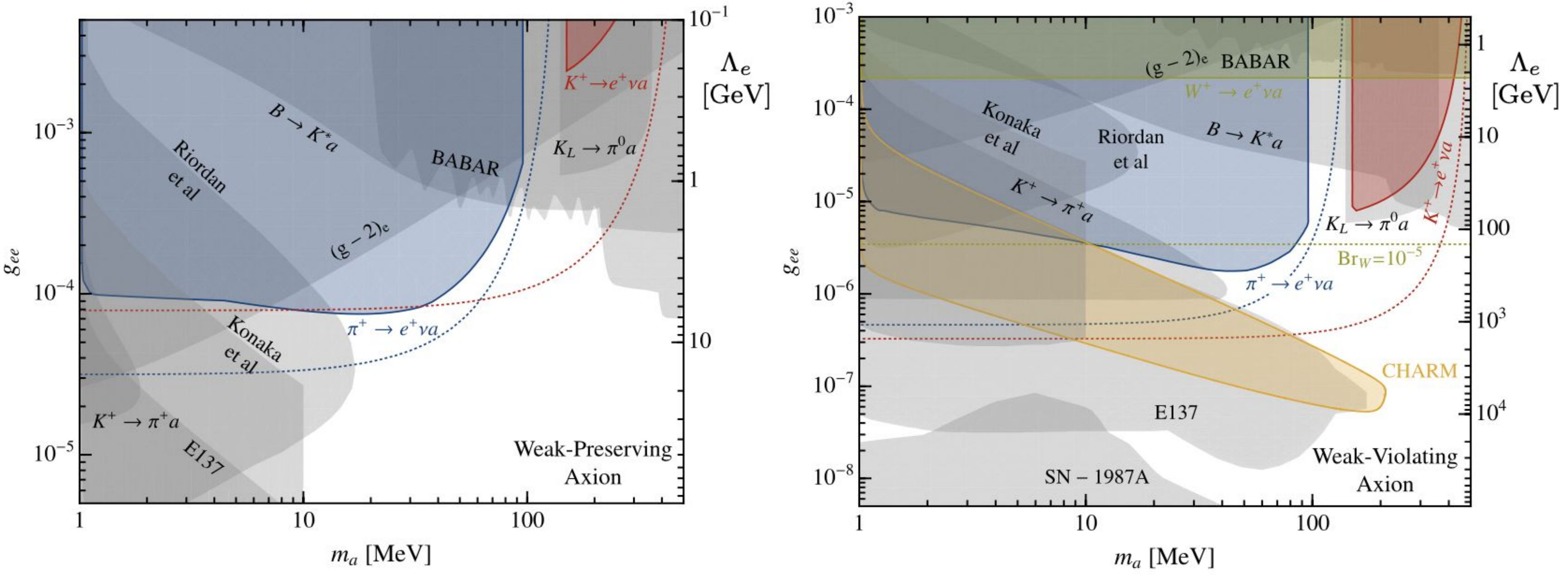
\begin{aligned}
a\,\partial_\mu J^\mu_{\mathrm{PQ},\ell} &= i c_\ell^A \frac{m_\ell}{\Lambda}\, a\bar{\ell}\gamma_5\ell \\
&+ \frac{\alpha_{\mathrm{em}}}{4\pi\Lambda}\left[\frac{c_\ell^V - c_\ell^A + c_\nu}{4s_W^2}\, aW^+_{\mu\nu}\tilde{W}^{-,\mu\nu}\right. \\
&+ \frac{c_\ell^V - c_\ell^A(1-4s_W^2)}{2s_W c_W}\, aF_{\mu\nu}\tilde{Z}^{\mu\nu} - c_\ell^A\, aF_{\mu\nu}\tilde{F}^{\mu\nu} + \\
&\left.\frac{c_\ell^V(1-4s_W^2) - c_\ell^A(1-4s_W^2+8s_W^4) + c_\nu}{8s_W^2 c_W^2}\, aZ_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\
&+ \frac{ig_W}{2\sqrt{2}\Lambda}(c_\ell^A - c_\ell^V + c_\nu)\, a(\bar{\ell}\gamma^\mu P_L\nu)W^-_\mu \; + \; \mathrm{h.c.},
\end{aligned}
$$







$$j^{\mu}_{\mathrm{PQ}} = \frac{\bar{g}_{\ell\ell}}{2m_\ell}\bar{\ell}\gamma^\mu \ell + \frac{g_{\ell\ell}}{2m_\ell}\bar{\ell}\gamma^\mu\gamma_5\ell + \frac{g_{\nu_\ell}}{2m_\ell}\bar{\nu}_\ell\gamma^\mu P_L \nu_\ell \,.$$

$$\Lambda_e \equiv m_e/g_{ee}$$

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$$a\,\partial_\mu J^\mu_{\mathrm{PQ},\ell} = i c_\ell^A \frac{m_\ell}{\Lambda}\, a\bar{\ell}\gamma_5\ell$$
$$+\frac{\alpha_{\mathrm{em}}}{4\pi\Lambda}\Bigg[\frac{c_\ell^V - c_\ell^A + c_\nu}{4s_W^2}\, aW^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$
$$+\frac{c_\ell^V - c_\ell^A(1-4s_W^2)}{2s_W c_W}\, aF_{\mu\nu}\tilde{Z}^{\mu\nu} - c_\ell^A\, aF_{\mu\nu}\tilde{F}^{\mu\nu} +$$
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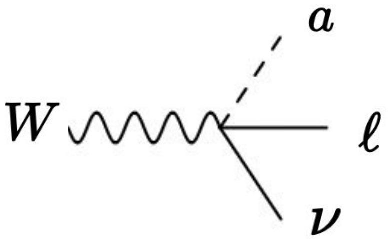
$$+\frac{i g_W}{2\sqrt{2}\Lambda}(c_\ell^A - c_\ell^V + c_\nu)\, a(\bar{\ell}\gamma^\mu P_L \nu)W^-_\mu \;+\; \mathrm{h.c.},$$



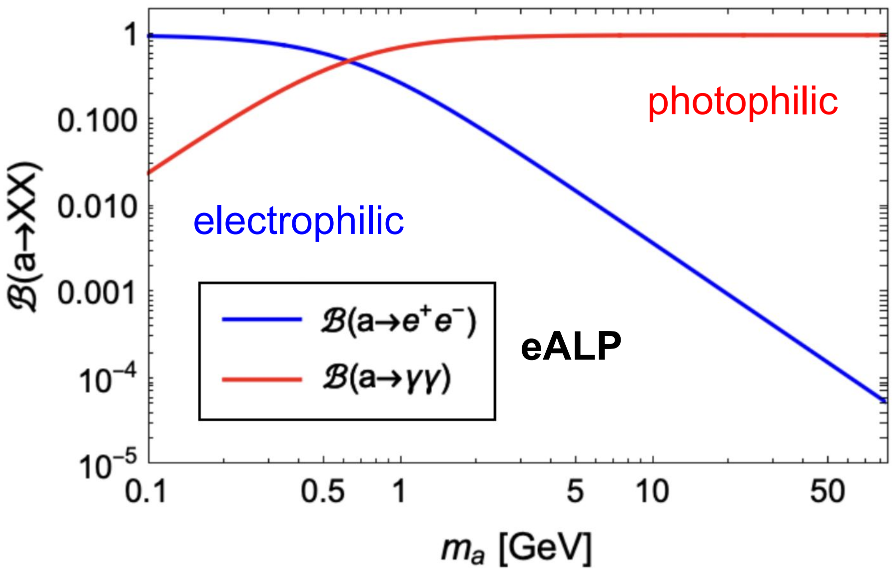
How about the scenario for heavy leptophilic ALPs ?

Leptophilic ALP decay modes

$$\Gamma_{a\to\ell^+\ell^-} = \frac{(c_\ell^A)^2 m_\ell^2 m_a}{8\pi\Lambda^2}\sqrt{1-\frac{4m_\ell^2}{m_a^2}}\,, \quad \Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}\,,$$

$$g_{a\gamma\gamma} = \frac{\alpha_{\rm em}}{\pi}\frac{c_\ell^A}{\Lambda}\left|1-\mathcal{F}\left(\frac{m_a^2}{4m_\ell^2}\right)\right|$$

$$\mathcal{F}(z>1) = \frac{1}{z}\arctan^2\left(\frac{1}{\sqrt{1/z-1}}\right)$$



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Electroweak Violating and Electroweak Preserving scenarios

$$\text{Electroweak Violating } (\mathbf{EWV}) : c_\ell^V = c_\nu = 0, c_\ell^A \neq 0,$$

$$\text{Electroweak Preserving } (\mathbf{EWP}) : c_\nu = 0, c_\ell^V = c_\ell^A \neq 0$$

$$J^\mu_{\mathrm{PQ},\ell} = \frac{c_\ell^V}{2\Lambda}\bar{\ell}\gamma^\mu\ell + \frac{c_\ell^A}{2\Lambda}\bar{\ell}\gamma^\mu\gamma_5\ell + \frac{c_\nu}{2\Lambda}\overline{\nu_\ell}\gamma^\mu P_L\nu_\ell$$

EWP :

1. PQ charges are electroweak symmetric
2. The lepton current is pure right-handed coupling current

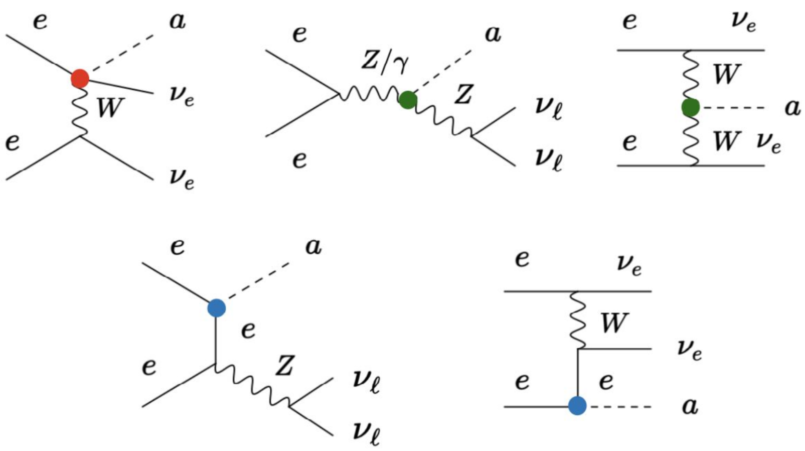
$$J^\mu_{\mathrm{PQ},\ell} = \frac{c_\ell^A}{\Lambda}\bar{\ell}\gamma_\mu P_R\ell$$

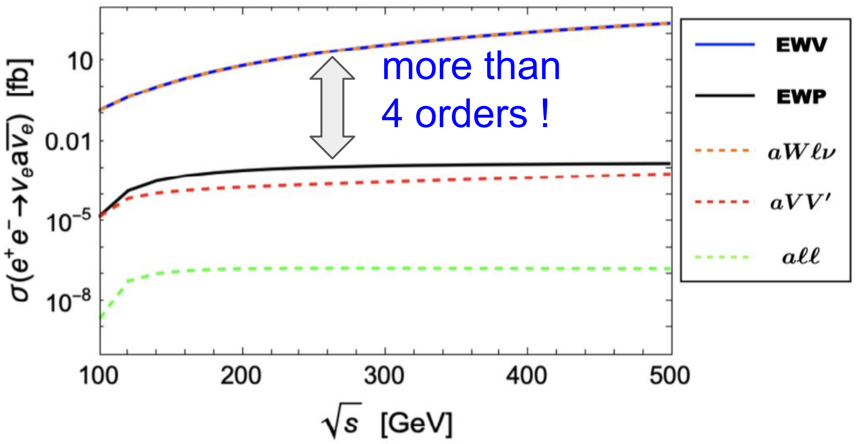
EWV :

1. Generated through RG flow
2. Also by $\overline{(HL)}\gamma_\mu(HL)$
3. The lepton current is pure axial-vector current

$$J^\mu_{\mathrm{PQ},\ell} = \frac{c_\ell^A}{2\Lambda}\bar{\ell}\gamma_\mu\gamma_5\ell$$

$$e^+e^- \to \nu_e a \overline{\nu_e}$$

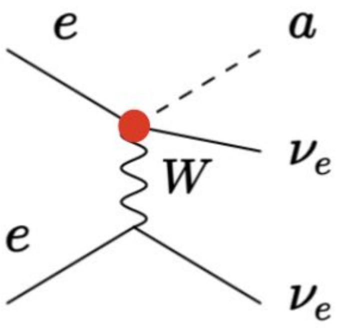




$c_e^A/\Lambda = 0.01\ \mathrm{GeV}^{-1}$

$$e^+e^- \to \nu_e a \overline{\nu_e}$$

$$e^-(p_1)e^+(p_2) \to \nu_e(q_1)a(q_2)\overline{\nu_e}(q_3),$$



$$\overline{|\mathcal{M}|^2} = \frac{g_W^4\left(c_\ell^A - c_\ell^V + c_\nu\right)^2}{32\Lambda^2}\left(\frac{1}{k^2 - M_W^2} + \frac{1}{k'^2 - M_W^2}\right)^2 \times \left(s - 2m_e^2\right)\left[s - m_a^2 - 2q_2\cdot(q_1+q_3)\right], \tag{3.1}$$

where $s = (p_1+p_2)^2 = (q_1+q_2+q_3)^2$, $k = p_2 - q_3$ and $k' = p_1 - q_1$. It's clear to see this amplitude square can be enhanced when the momentum transferring in this t-channel process is large enough and it is estimated to be smaller than

$$\overline{|\mathcal{M}|^2} < \frac{g_W^4\left(c_\ell^A - c_\ell^V + c_\nu\right)^2}{16\Lambda^2\left(s - M_W^2\right)^2}\left(s - 2m_e^2\right)\left(\sqrt{s} - m_a\right)^2.$$

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Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC

1. We choose the CEPC with $\sqrt{s} = 240$ GeV
2. Benchmark point : $m_a = 50$ GeV with $c_e^A/\Lambda = 1$ TeV^{-1}.
3. The signal process $e^+e^- \to \nu_e a \overline{\nu_e}$, $a \to \gamma\gamma$

   signature : 2 isolated photons plus missing energy

4. Possible SM backgrounds :

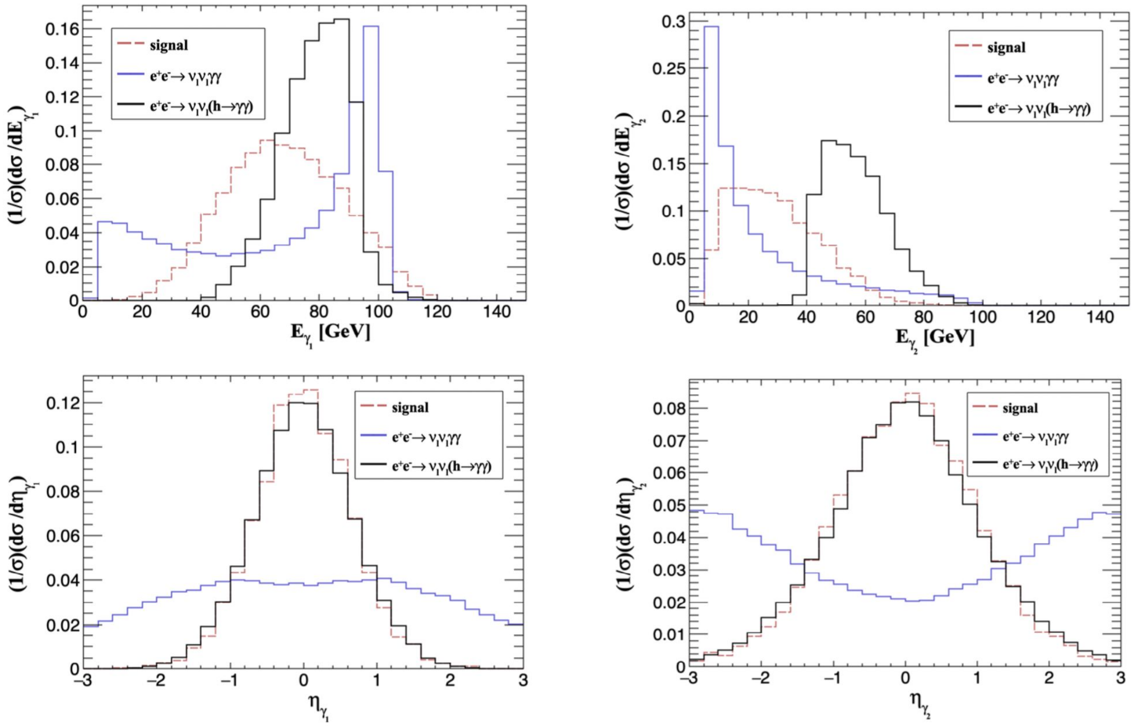
$$e^+e^- \to \gamma\gamma\nu_\ell\overline{\nu_\ell}$$

$$e^+e^- \to \nu_\ell\overline{\nu_\ell}h \to \nu_\ell\overline{\nu_\ell}(\gamma\gamma)$$

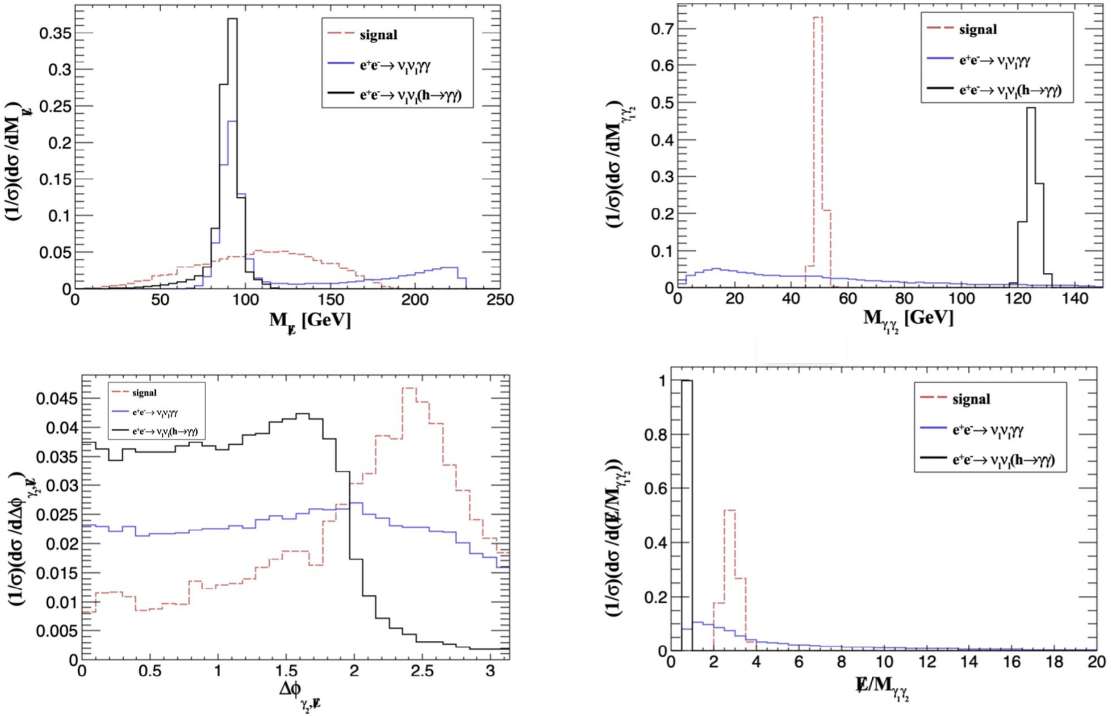
Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC

- (1) $N(\gamma) \geqslant 2$ with $30 < E_{\gamma_1} < 90$ GeV, $E_{\gamma_2} > 15$ GeV, $|\eta_{\gamma_1}| < 1.5$ and $|\eta_{\gamma_2}| < 2.0$,
- (2) $\not{E} > 120$ GeV and $|\eta_{\not{E}}| < 2.0$,
- (3) Veto $85 < M_{\not{E}} < 95$ GeV,
- (4) $|M_{\gamma_1\gamma_2} - m_a| < 3$ GeV,
- (5) $\Delta\phi_{\gamma_1,\not{E}} > 2.5$ and $\Delta\phi_{\gamma_2,\not{E}} > 1.8$,
- (6) $2.2 < \not{E}/M_{\gamma_1\gamma_2} < 3.6$,

Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC



Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC



Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC

cut flow in σ [fb]	signal	$\nu_\ell \overline{\nu_\ell} \gamma\gamma$	$\nu_\ell \overline{\nu_\ell} (h \to \gamma\gamma)$
Generator	0.11	263.60	7.67×10^{-2}
cut-(1)	7.10×10^{-2}	32.23	5.47×10^{-2}
cut-(2)	6.62×10^{-2}	21.85	3.84×10^{-5}
cut-(3)	6.02×10^{-2}	12.62	3.84×10^{-5}
cut-(4)	5.96×10^{-2}	1.17	7.67×10^{-7}
cut-(5)	5.01×10^{-2}	0.68	0
cut-(6)	4.99×10^{-2}	0.64	0

pre-selection cuts ($E_\gamma > 5$ GeV and $|\eta_\gamma| < 3.0$)

Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC

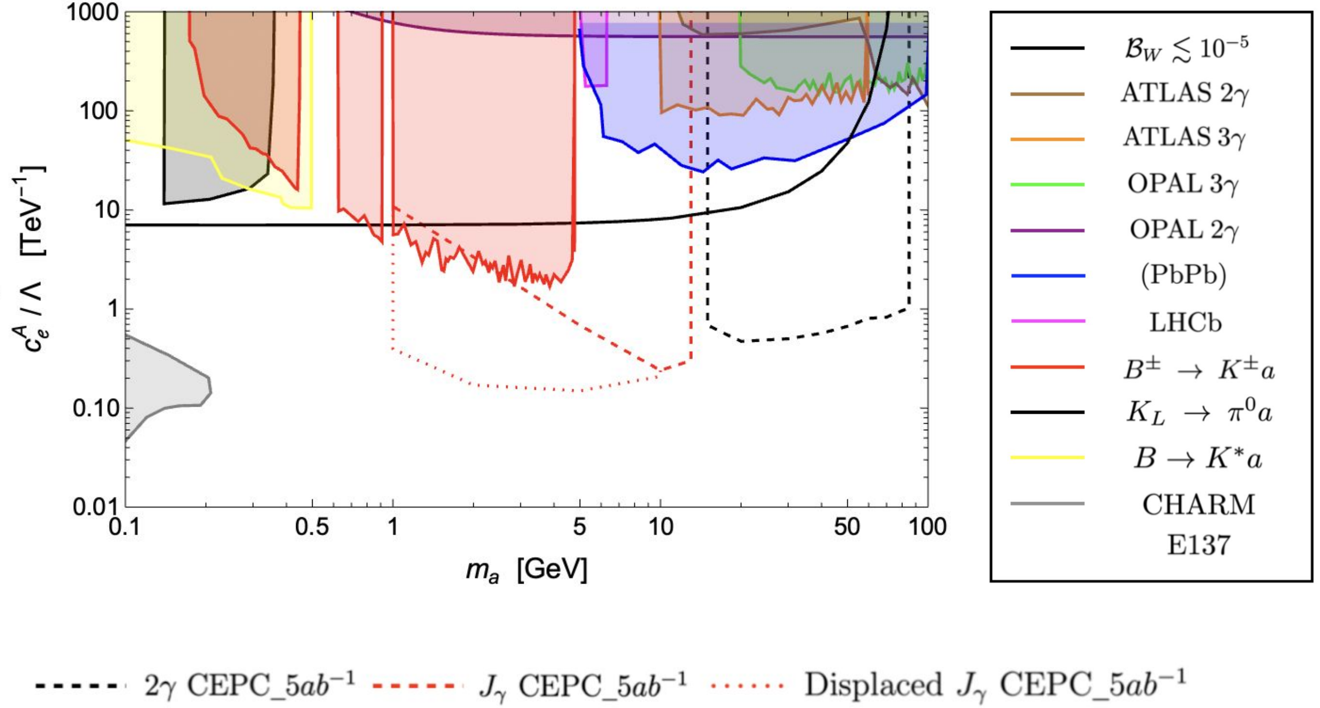
When the ALP is light, it will be highly boosted, generating two photons in the final state that are too collimated to pass the photon isolation criteria, resulting in a novel 'photon-jet' signature. Additionally, the light ALP can become a long-lived particle (LLP). Further details on these studies can be found in my paper.

Lighting Electroweak-Violating ALP-Lepton Interactions at e^+e^- and ep Colliders

Chih-Ting Lu (Nanjing Normal U.) (Oct 27, 2022)

e-Print: 2210.15648 [hep-ph]

Main results and existing bounds



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Conclusion

1. The less discussed four-point interaction, W-l-v-a, in electroweak-violating (EWV) scenario plays an important role to explore leptophilic ALPs :

   Light eALPs : charged mesons and W boson exotic decays.

   Heavy eALPs : t-channel ALP production modes : $e^+e^- \to \nu_e a \overline{\nu_e}$

2. Taking CEPC with $\mathcal{L} = 5ab^{-1}$ as an examples, we find the possible future bounds of c_e^A/Λ can be lower than about $0.1-1.0\ \mathrm{TeV}^{-1}$ for $1\ \mathrm{GeV} \leqslant m_a \lesssim M_W$ which is much stronger than existing bounds.

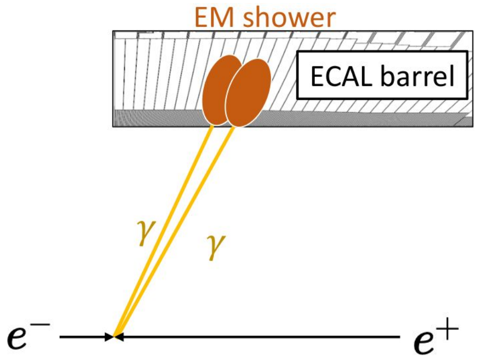
Thank you
for your attention

Back-up

Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC

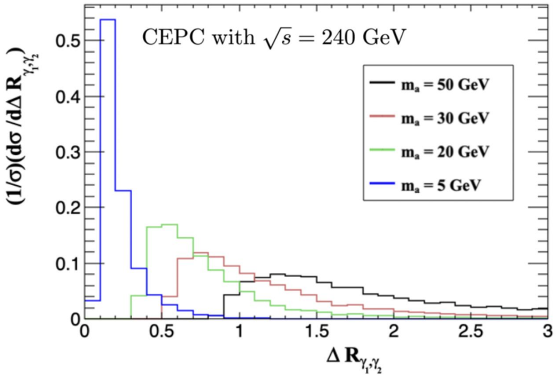
1. We choose the CEPC with $\sqrt{s} = 240\ \mathrm{GeV}$
2. Benchmark point : $m_a = 5\ \mathrm{GeV}$ with $c_e^A/\Lambda = 1\ \mathrm{TeV}^{-1}$
3. The signal process $e^+e^- \to \nu_e a \overline{\nu_e}$, $a \to \gamma\gamma$

   signature : A photon-jet plus missing energy



4. Possible SM backgrounds :

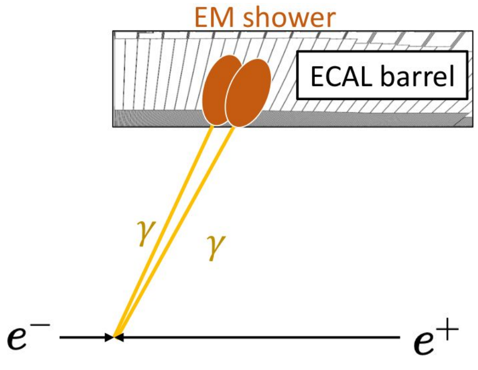
$$e^+e^- \to \nu_\ell \overline{\nu_\ell} \gamma$$

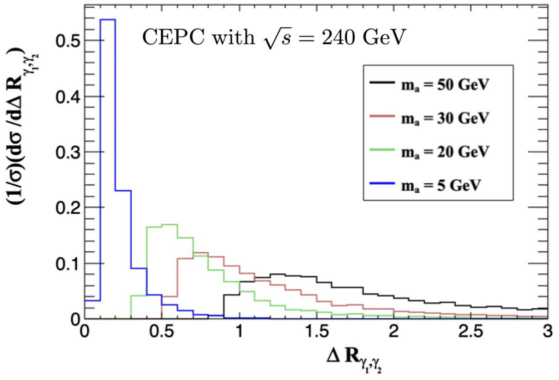


Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC

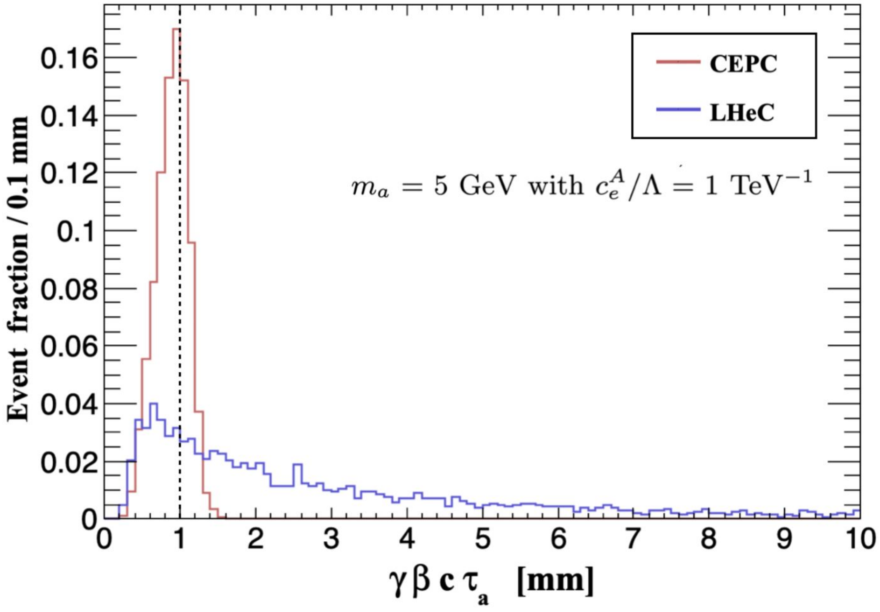
1. We apply the C/A jet clustering algorithm with a cone size R = 0.4 for a photon-jet candidate.
2. Then the hadronic energy fraction is required to satisfy $log\theta_J < -2$

$$\theta_J = \frac{E_{J,\mathrm{HCAL}}}{E_J},$$

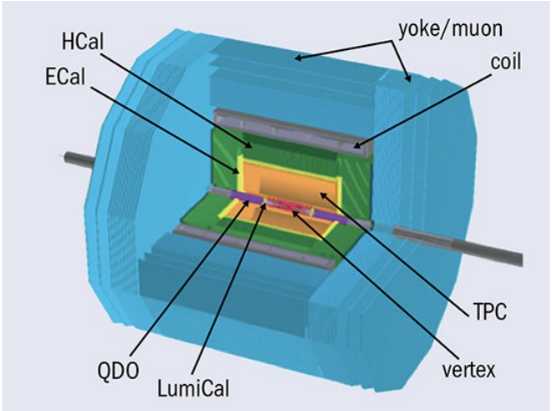




Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC



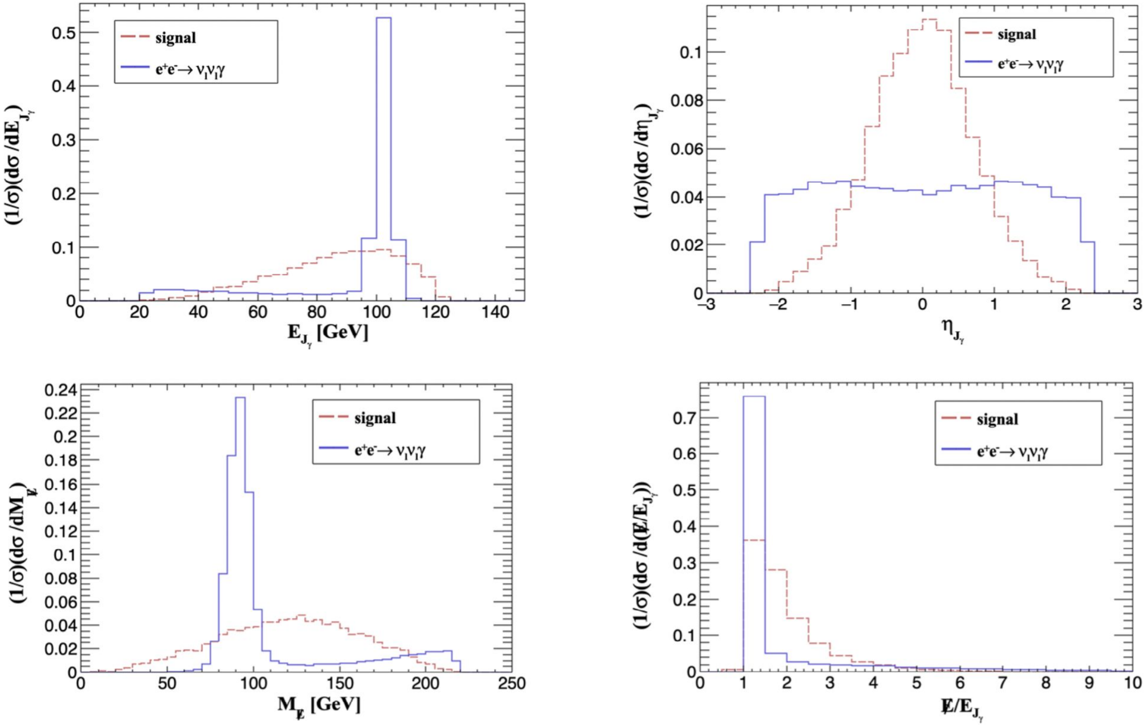
1. $16 \leqslant R_{\text{vertex}} \leqslant 60$ mm,
2. $0.15 \leqslant R_{\text{ECAL}} \leqslant 1.81$ m,
3. $2.30 \leqslant R_{\text{HCAL}} \leqslant 3.34$ m,
4. $2.30 \leqslant R_{\text{muon}} \leqslant 3.34$ m



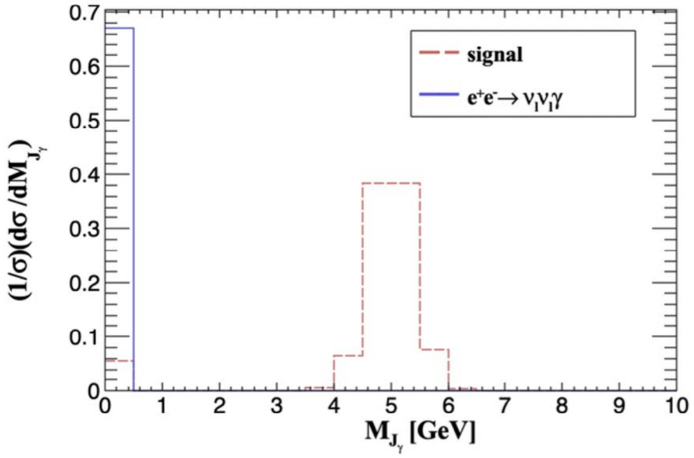
Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC

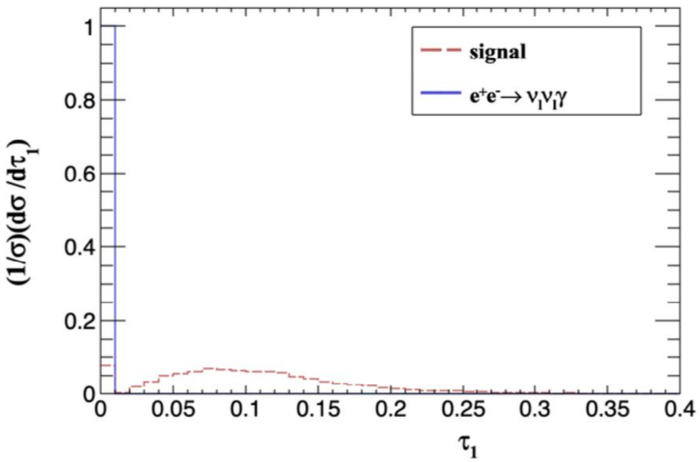
- (1) $N(J_\gamma) \geqslant 1$ with $log\theta_J < -2$, $30 < E_{J_\gamma} < 100$ GeV, and $|\eta_{J_\gamma}| < 1.5$,
- (2) $\not{E} > 140$ GeV and $|\eta_{\not{E}}| < 1.5$,
- (3) Veto $75 < M_{\not{E}} < 105$ GeV,
- (4) $\not{E}/E_{J_\gamma} > 1.5$,
- (5) $|M_{J_\gamma} - m_a| < 1$ GeV,
- (6) $\tau_1(J_\gamma) > 0.03$.

Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC



Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC





Exploring $e^+e^- \to \nu_e a \overline{\nu_e}$ at CEPC

cut flow in σ [fb]	signal	$\nu_\ell \overline{\nu_\ell} \gamma$
Generator	0.16	4266.80
$\gamma\beta c\tau_a < 1$ mm	0.10	–
cut-(1)	8.49×10^{-2}	520.29
cut-(2)	8.49×10^{-2}	520.29
cut-(3)	8.10×10^{-2}	387.77
cut-(4)	7.92×10^{-2}	373.39
cut-(5)	7.76×10^{-2}	0
cut-(6)	7.67×10^{-2}	0

The pre-selection cuts in parton-level are similar as before, except for $E_\gamma > 1$ GeV ($E_\gamma > 10$ GeV) for the signal (background).