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Prospects for detecting axion-like particles at future electron-positron colliders

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Based on Phys. Rev. D 105, 115027 (2022), 2204.04702 with C.-X. Yue, S. Yang and N. Zhang
Another paper is accepted by J. Phys. G with C.-X. Yue and Y.-C. Guo

Outline

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1. Introduction
2. Detecting axion-like particles via the decay $Z \to a f \bar{f}$ at future Z factories
3. Searching for axion-like particles at the CEPC
4. Conclusions

1.1 Properties of axion-like particles

- Many new physics scenarios beyond the standard model (SM) predict the existence of axion-like particles (ALPs), which are generalizations of QCD axions proposed as a solution to the strong CP problem.

- The ALP is a CP-odd neutral pseudoscalar particle of the broken global symmetry at high scale and a singlet under the SM gauge group.

- The masses of ALPs and couplings to the SM particles are considered to be independent parameters.

1.2 Effective interactions of ALP

The effective interactions of ALP with the SM particles:

$$\mathcal{L}_{eff}=\frac{1}{2}(\partial^{\mu}a)(\partial_{\mu}a)-\frac{1}{2}m_a^2a^2+\frac{\partial^{\mu}a}{f_a}\sum_{\substack{\psi=Q_L,Q_R,\\ L_L,L_R}}\bar{\psi}\gamma_{\mu}X_{\psi}\psi-C_{\tilde{B}}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu}-C_{\tilde{W}}\frac{a}{f_a}W_{\mu\nu}^{i}\tilde{W}^{i\mu\nu}$$

m_a : the mass of ALP

f_a : the characteristic scale

$W_{\mu\nu}^{i}$ *and* $B_{\mu\nu}$: the field strength tensors of $SU(2)_L$ *and* $U(1)_Y$

$C_{\tilde{W}}$ *and* $C_{\tilde{B}}$: the coupling constants

X_{ψ} : Hermitian matrices in flavour space

After electroweak symmetry breaking:

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial^{\mu} a)(\partial_{\mu} a) - \frac{1}{2} m_a^2 a^2 + i g_{a\psi} a \sum_{\psi = Q, L} m_{\psi}^{diag} \bar{\psi} \gamma_5 \psi$$
$$- \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{1}{4} g_{aZZ} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{1}{4} g_{a\gamma Z} a F_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{1}{4} g_{aWW} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

m_{ψ}^{diag} : the diagonalizable fermion mass matrix

$F_{\mu\nu}$: the photon field strength tensor

$Z_{\mu\nu}$: the Z boson field strength tensor

$W_{\mu\nu}$: the W boson field strength tensor all the couplings $g_{a\gamma\gamma}$, g_{aZZ}, $g_{aZ\gamma}$, g_{aWW} *and* $g_{a\psi}$ are governed by f_a

where

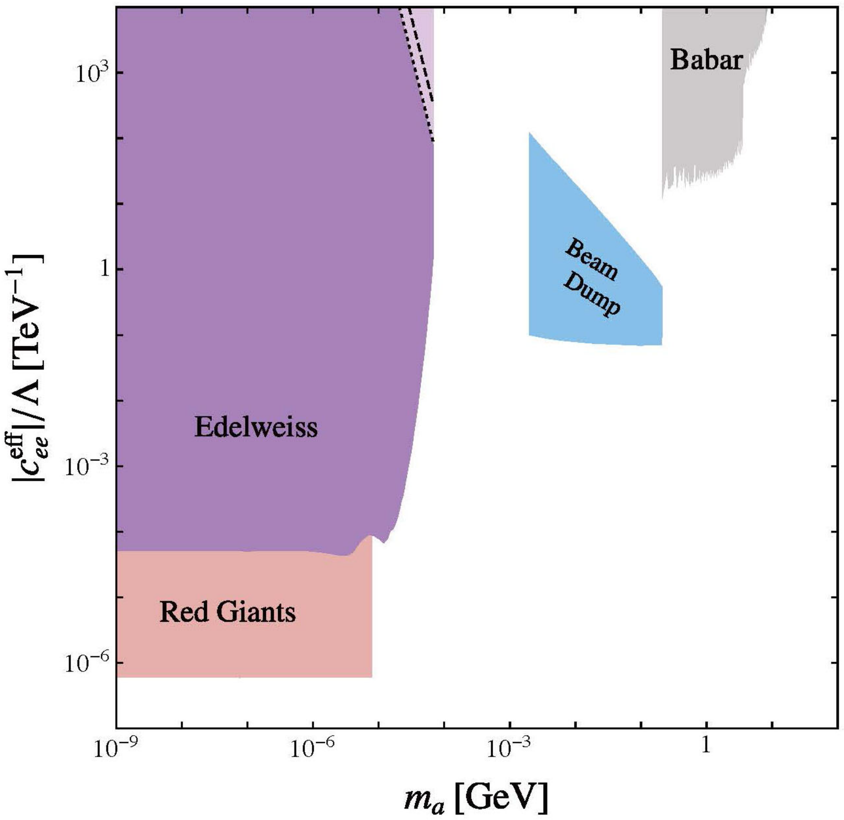
$$g_{a\gamma\gamma} = \frac{4}{f_a}(c_W^2 C_{\tilde{B}} + s_W^2 C_{\tilde{W}}), \quad g_{aZZ} = \frac{4}{f_a}(s_W^2 C_{\tilde{B}} + c_W^2 C_{\tilde{W}}),$$

$$g_{a\gamma Z} = \frac{8}{f_a} s_W c_W (C_{\tilde{W}} - C_{\tilde{B}}), \quad g_{aWW} = \frac{4}{f_a} C_{\tilde{W}}$$

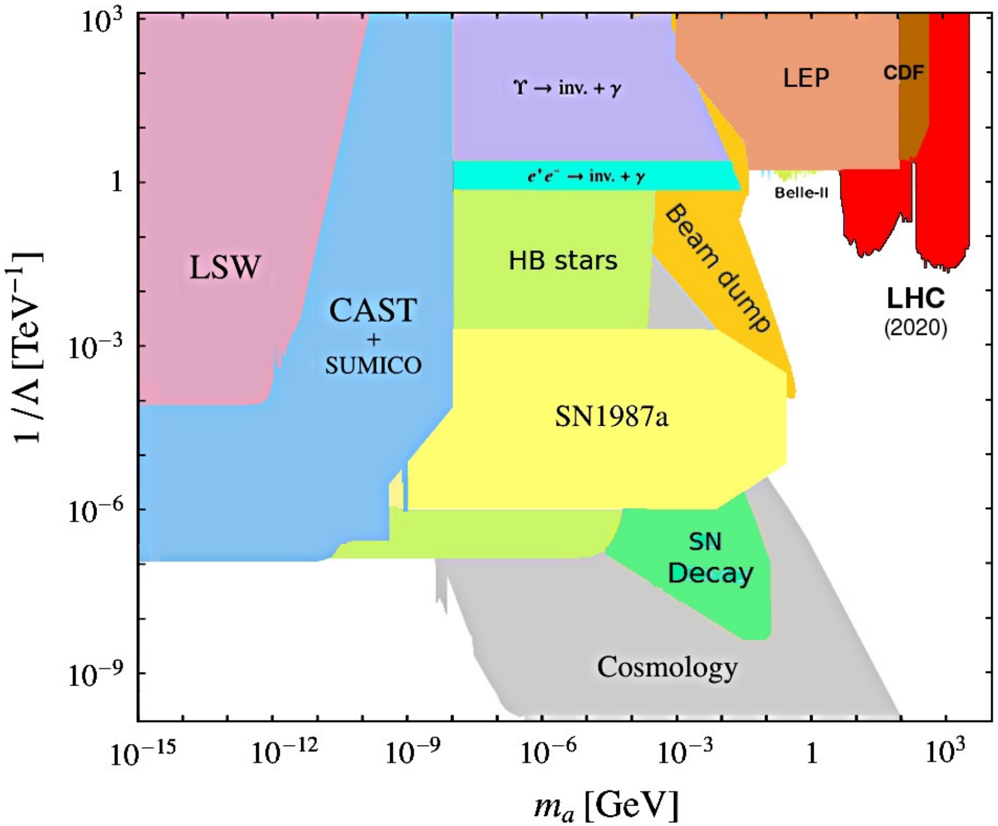
s_W *and* c_W : the sine and cosine of the weak mixing angle

1.3 The constraints on the effective couplings of ALP to the SM electrons or bosons

M. Bauer, M. Neubert, and A. Thamm, JHEP **12**, 044 (2017), 1708.00443



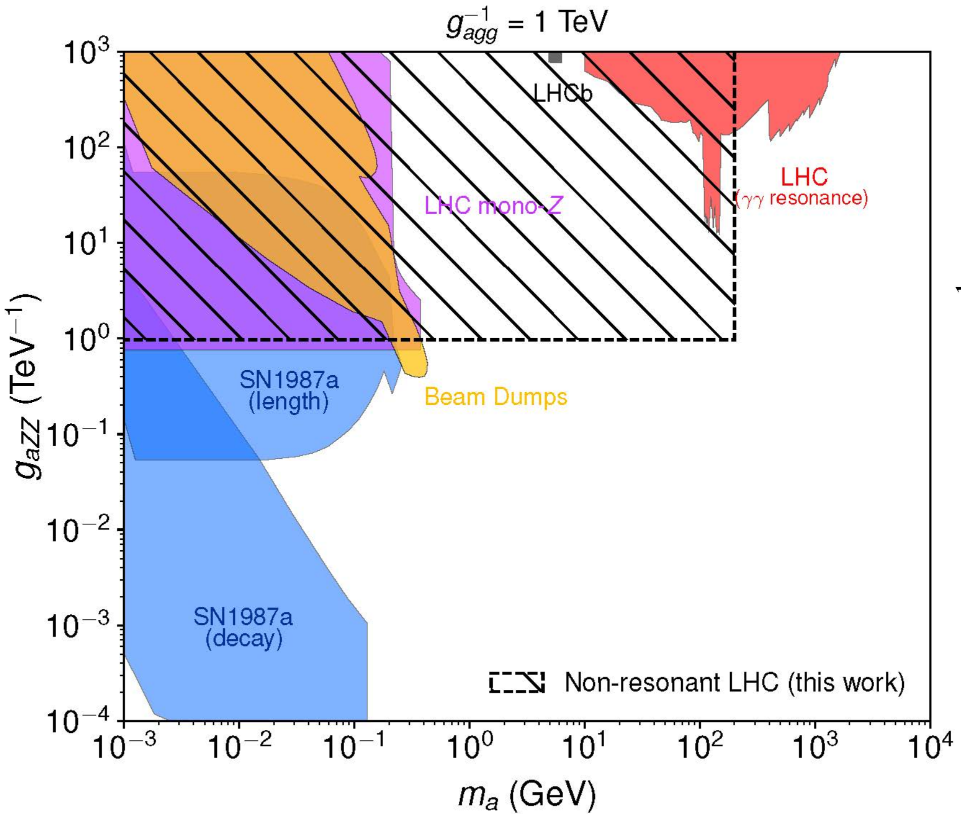
D. d'Enterria, in *Workshop on Feebly Interacting Particles* (2021), 2102.08971

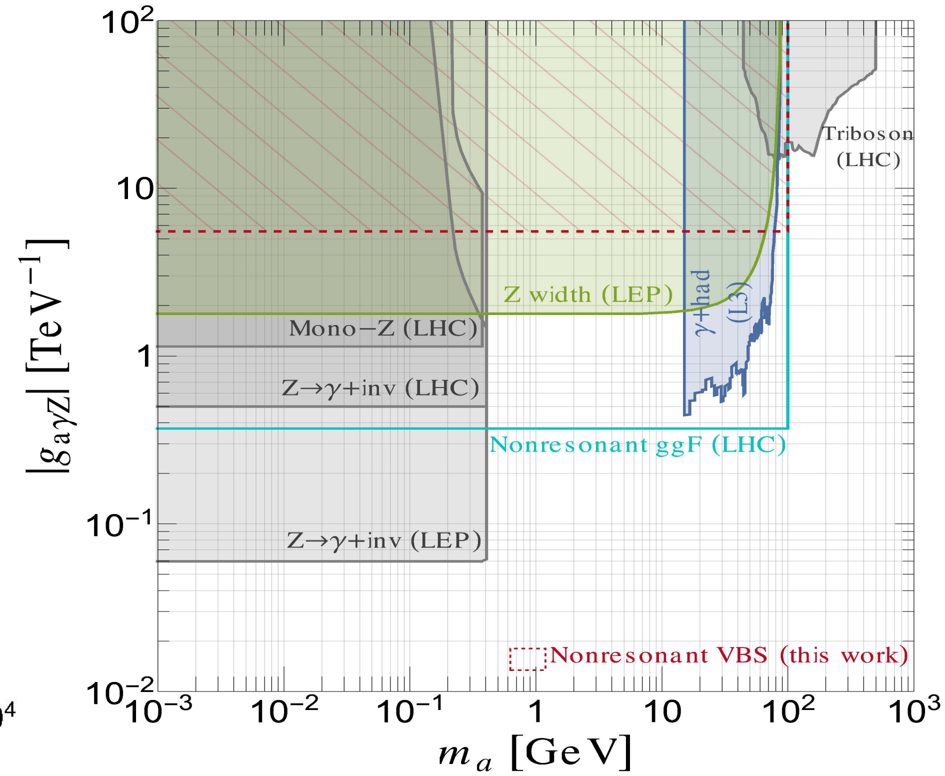


Existing constraints on the ALP–electron coupling (left) and ALP–photon coupling (right) from cosmological, astrophysical, and accelerator searches.

M. B. Gavela, J. M. No, V. Sanz, and J. F. de Trocóniz, Phys. Rev. Lett. **124**, 051802 (2020), 1905.12953

J. Bonilla, I. Brivio, J. Machado-Rodríguez, and J. F. de Trocóniz, JHEP **06**, 113 (2022), 2202.03450





Bounds on the ALP coupling g_{aZZ} (left) and ALP coupling $g_{a\gamma Z}$ (right).

2.1 Future circular e^+e^- colliders

Run plan for the Future Circular Collider (FCC-ee)

Phase	Run duration (years)	Centre-of-mass energies (GeV)	Integrated luminosity (ab^{-1})	Event statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt(1)	1	340–350	0.2	$t\bar{t}$ threshold scan
FCC-ee-tt(2)	4	365	1.5	10^6 $t\bar{t}$ events

Run plan for the Circular Electron-Positron Collider (CEPC)

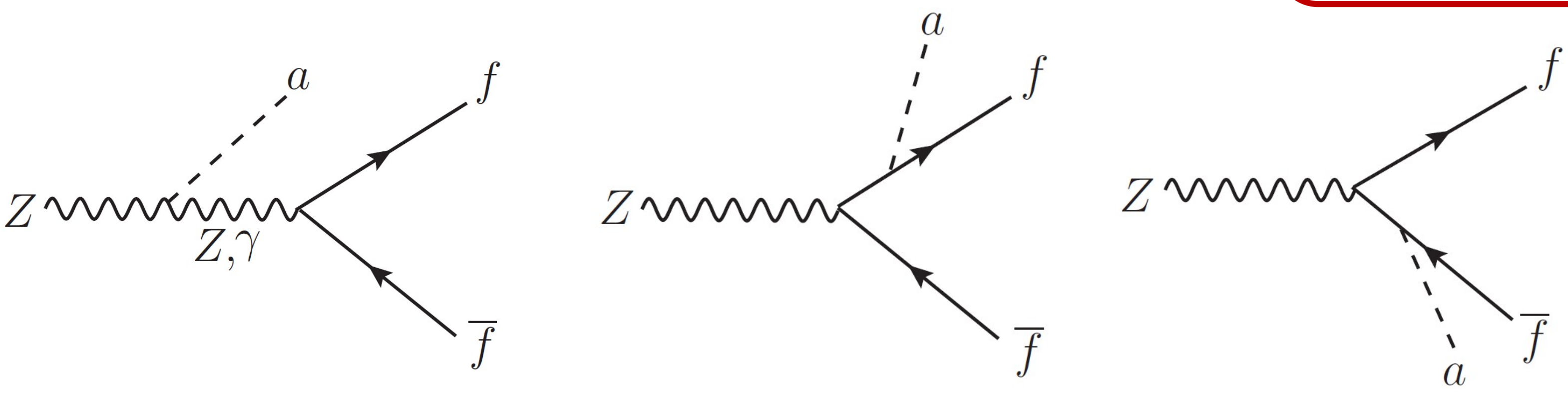
Particle	$E_{c.m.}$ (GeV)	L per IP (10^{34} $cm^{-2}s^{-1}$)	Integrated L per year (ab^{-1}, 2 IPs)	Years	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of particles
H	240	3	0.8	7	5.6	1×10^6
Z	91	32 (*)	8	2	16	7×10^{11}
W^+W^-	160	10	2.6	1	2.6	1.5×10^7

(*) Assuming detector solenoid field of 2 Tesla during Z operation

2.2 Searching for ALP via exotic Z decay

Phys. Rev. D 105, 115027 (2022), 2204.04702

The Feynman diagrams:



- For $m_a < m_Z$, there exits rare decay channel $Z \to a f \bar{f}$.
  The mass of ALP : $5\,\text{GeV} \le m_a \le 70\,\text{GeV}$.
- The relevant measurements of the channel $Z \to a\nu\bar{\nu}$ could be used to extract the aZZ coupling directly.
- The channel $Z \to a f \bar{f}$ with f being charged leptons or quarks is more sensitive to the coupling $a\gamma Z$.

- Focusing on the decay channels $a \to \mu^+\mu^-$ and $a \to b\bar{b}$.
- Four types of exotic Z decay signals $Z \to \mu^+\mu^- \not{E}$, $b\bar{b}\not{E}$, $e^+e^-\mu^+\mu^-$ *and* $e^+e^-b\bar{b}$ are studied.

Tools used:

FeynRules

MadGraph5_aMC@NLO

PYTHIA 8

DELPHES

MadAnalysis 5

- $E_{CM} = 91.2$ GeV

- Basic cuts:

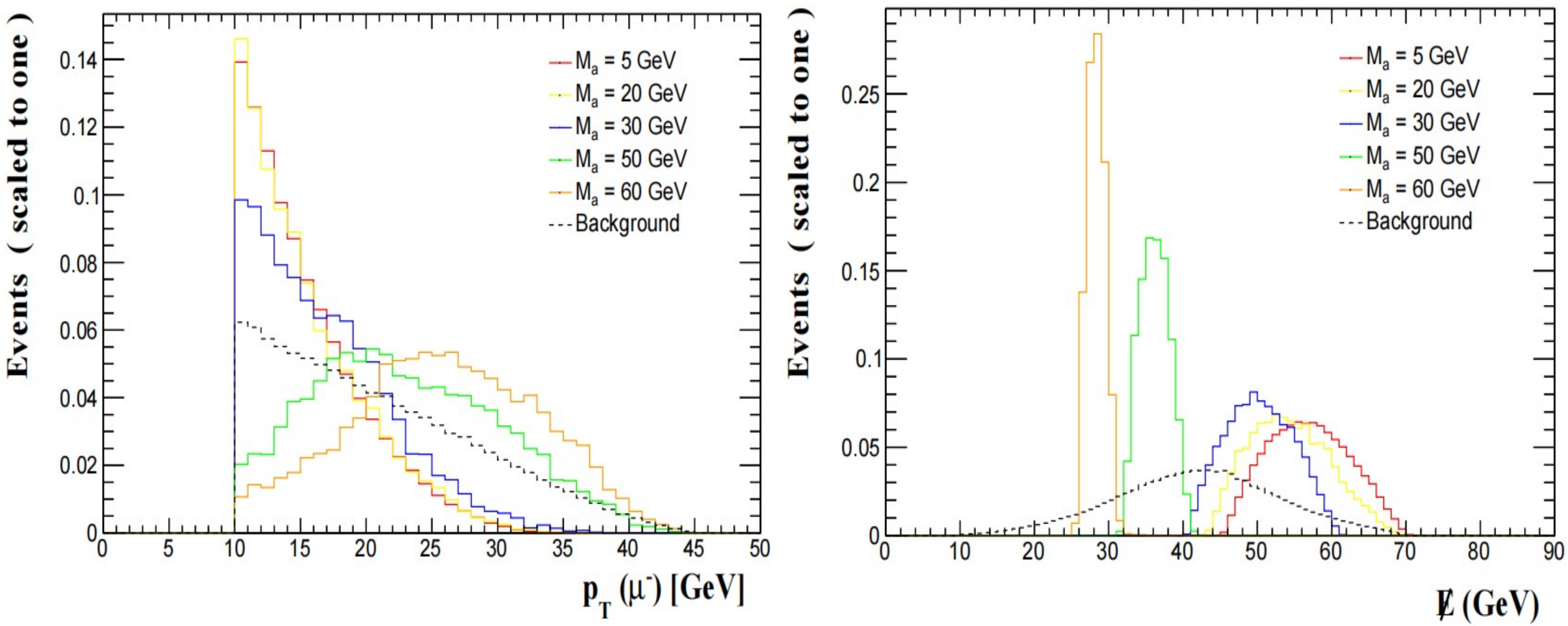
$$P_T(l, j) > 10 \text{ GeV}$$

$$\not{E} > 10 \text{ GeV}$$

$$|\eta(l, j)| < 2.5$$

$$\theta_{ij}(l, l) > 0.2, \theta_{ij}(j, j) > 0.4$$

A. $Z \to \mu^+ \mu^- \not{E}$ the exotic decay $Z \to a \nu \bar{\nu}$ followed by $a \to \mu^+ \mu^-$



A. $Z \to \mu^+\mu^- \not{E}$ the exotic decay $Z \to a\nu\bar{\nu}$ followed by $a \to \mu^+\mu^-$

- $\left| m_{\mu^+\mu^-} - m_a \right| < 3\ \text{GeV}$ (Cut 1-A)

Cuts	Cross sections for signal(background) (fb)				
	m_a = 5GeV	m_a = 10GeV	m_a = 30GeV	m_a= 50GeV	m_a= 60GeV
Basic cuts	0.3406(0.2602)	0.3177(0.2602)	0.2368(0.2602)	0.0358(0.2602)	0.0062(0.2602)
Cut 1-A	0.3404(0.0059)	0.3175(0.0072)	0.2335(0.0300)	0.0343(0.0342)	0.0058(0.0195)
$S/\sqrt{S+B}$	18.29	17.62	14.38	5.59	1.16

- $g_{aZZ} = 0.5\ \text{TeV}^{-1}$
- $\mathcal{L} = 1\ \text{ab}^{-1}$

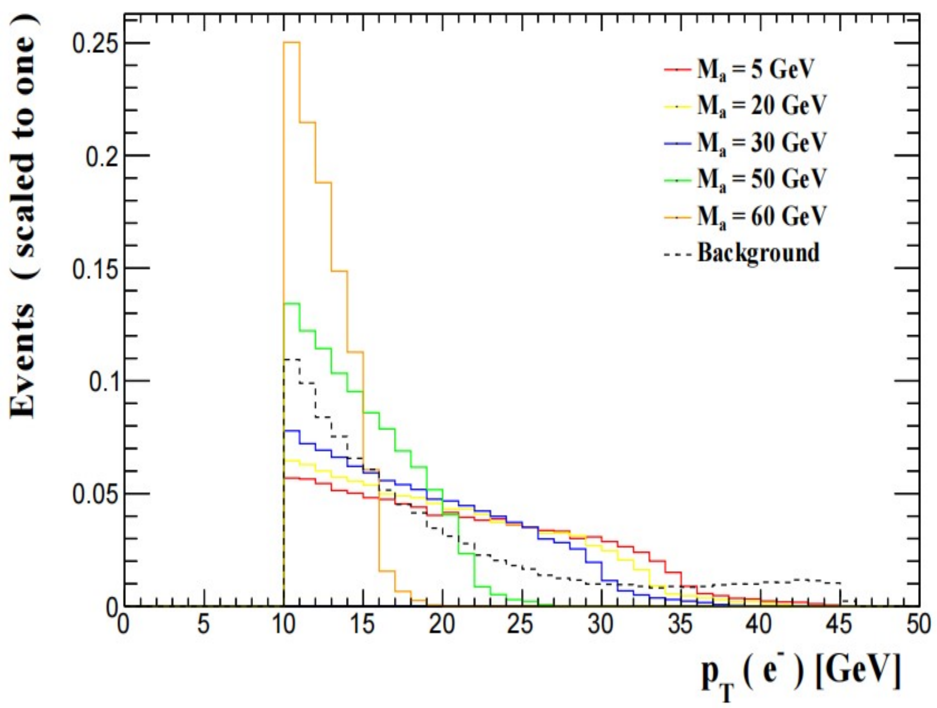
B. $Z \to b\bar{b}\not{E}$ the exotic decay $Z \to a\nu\bar{\nu}$ followed by $a \to b\bar{b}$

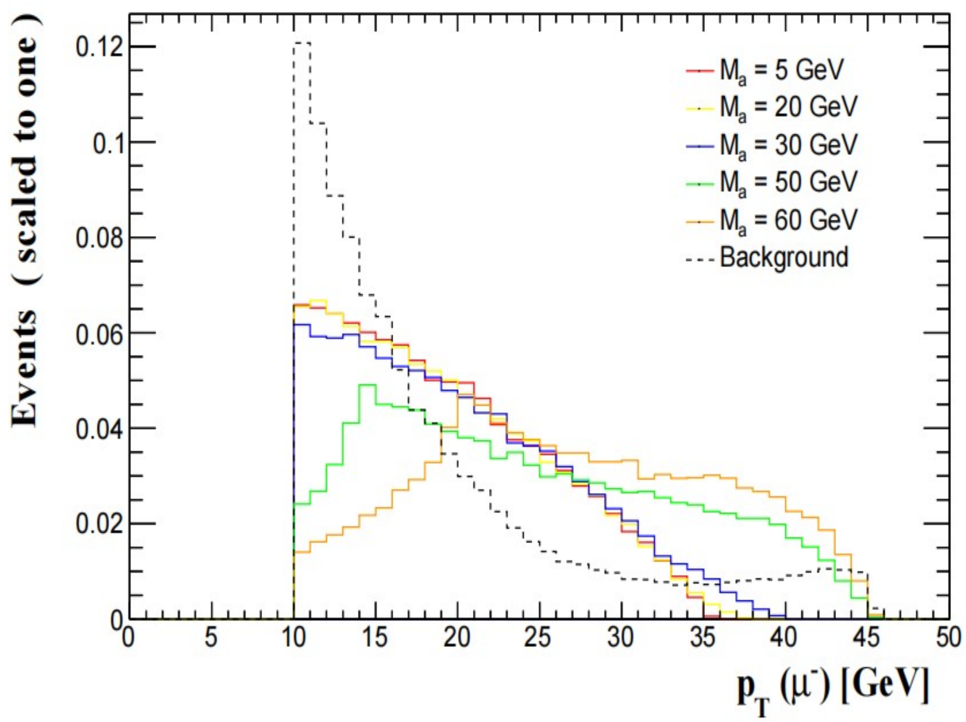
- $|m_{bb} - m_a| < 5\ \text{GeV}$ (Cut 1-B)

Cuts	Cross sections for signal(background) (fb)				
	m_a = 15GeV	m_a = 30GeV	m_a= 40GeV	m_a= 50GeV	m_a=60GeV
Basic cuts	0.0460(0.7172)	0.03345(0.7172)	0.0284(0.7172)	0.0142(0.7172)	0.0134(0.7172)
Cut 1-B	0.0449(0.0126)	0.0279(0.08387)	0.0199(0.1832)	0.0078(0.2115)	0.0015(0.1364)
$S/\sqrt{S+B}$	5.92	2.64	1.39	0.53	0.12

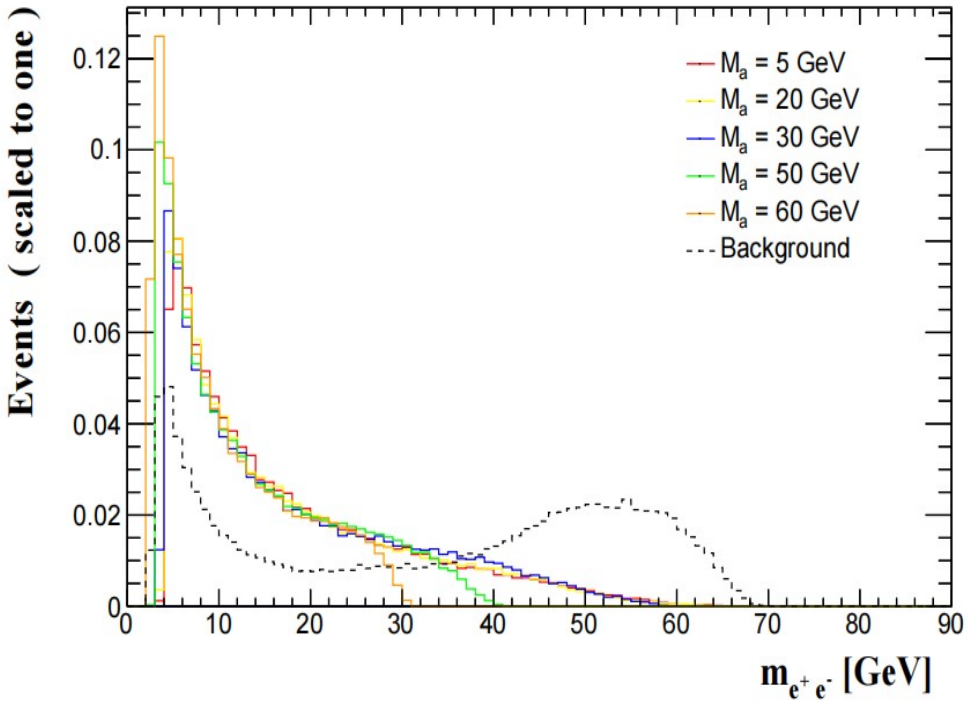
- $g_{aZZ} = 0.5\ \text{TeV}^{-1}$
- $\mathcal{L} = 1\ \text{ab}^{-1}$

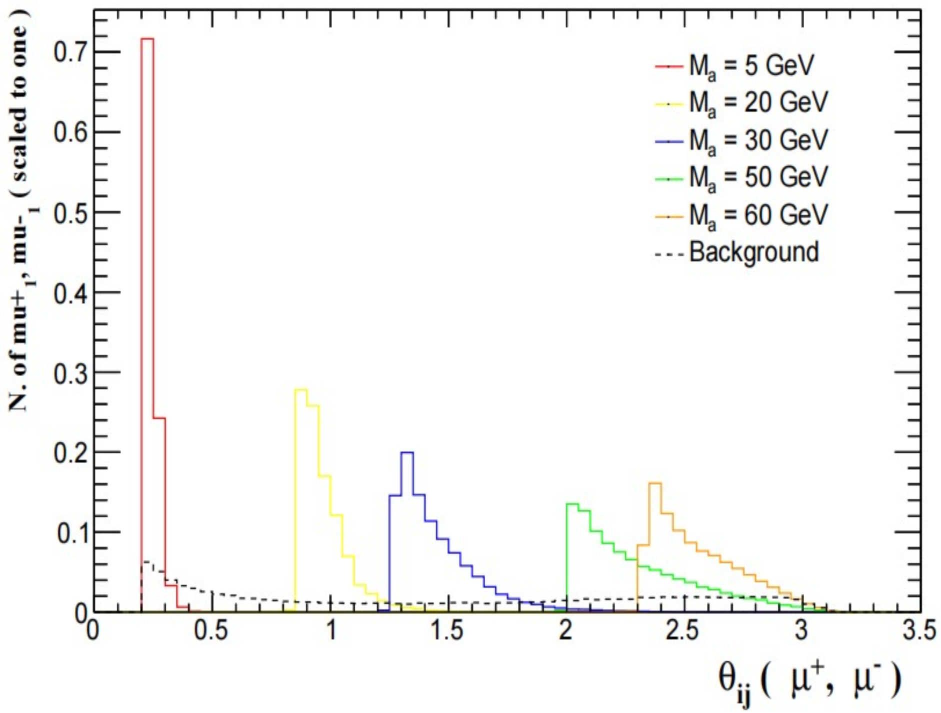
C. $Z \to e^+e^-\mu^+\mu^-$ the exotic decay $Z \to a\, e^+e^-$ followed by $a \to \mu^+\mu^-$





C. $Z \to e^+ e^- \mu^+ \mu^-$ the exotic decay $Z \to a\, e^+ e^-$ followed by $a \to \mu^+ \mu^-$





C. $Z \to e^+e^-\mu^+\mu^-$ the exotic decay $Z \to a\, e^+e^-$ followed by $a \to \mu^+\mu^-$

- $m_{e^+e^-} < 30$ GeV (Cut 1-C)
- $|m_{\mu^+\mu^-} - m_a| < 3$ GeV (Cut 2-C)

Cuts	Cross sections for signal(background) (fb)				
	$m_a = 5$GeV	$m_a = 10$GeV	$m_a = 30$GeV	$m_a = 50$GeV	$m_a = 60$GeV
Basic cuts	1.5314(8.0284)	1.4735(8.0284)	1.1559(8.0284)	0.4615(8.0284)	0.1067(8.0284)
Cut 1-C	1.2659(3.4300)	1.2231(3.4300)	0.9318(3.4300)	0.4258(3.4300)	0.1065(3.4300)
Cut 2-C	1.2659(0.1743)	1.2215(0.1623)	0.9143(0.1689)	0.4066(0.6499)	0.1005(0.5635)
$S/\sqrt{S+B}$	33.36	32.83	27.78	12.51	3.90

- $g_{a\gamma Z} = 0.5\ \text{TeV}^{-1}$
- $\mathcal{L} = 1\ \text{ab}^{-1}$

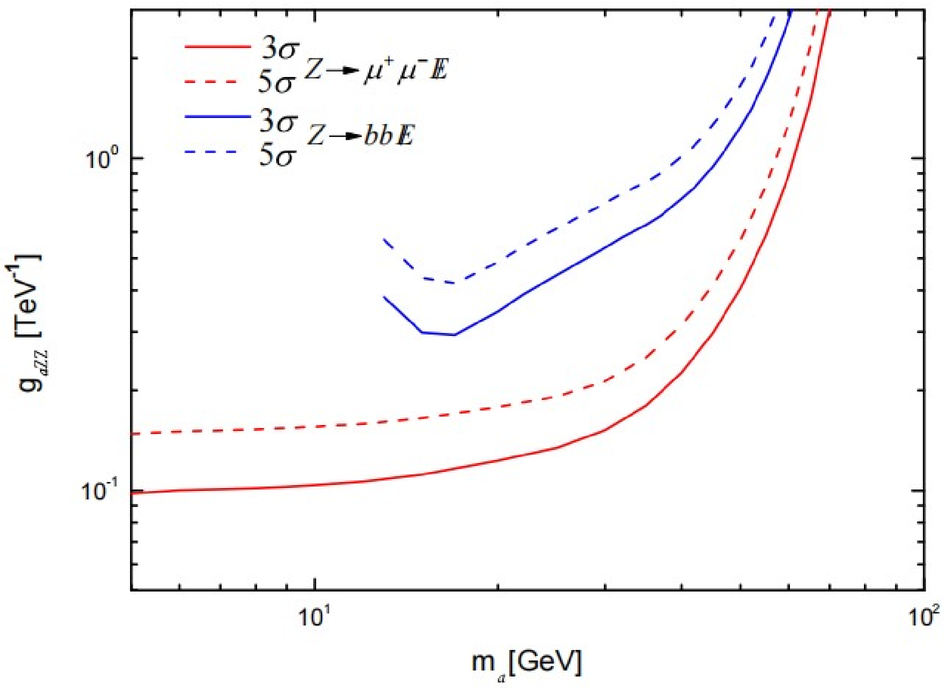
D. $Z \to e^+e^- b\bar{b}$ the exotic decay $Z \to a\, e^+e^-$ followed by $a \to b\bar{b}$

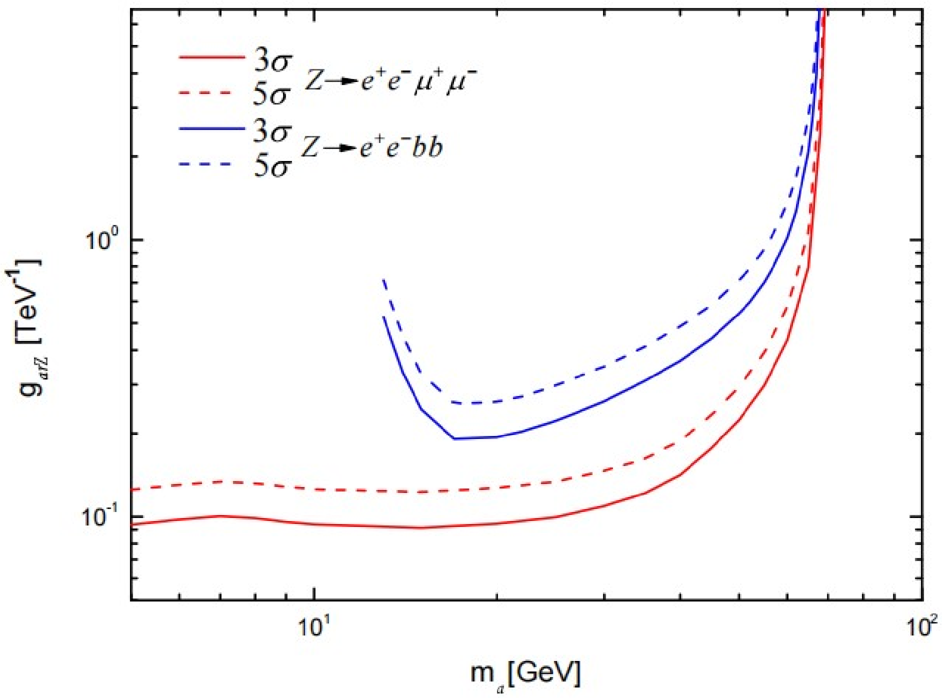
- $m_{e^+e^-} < 30$ GeV (Cut 1-D)
- $|m_{bb} - m_a| < 5$ GeV (Cut 2-D)

Cuts	Cross sections for signal(background) (fb)				
	$m_a = 15$GeV	$m_a = 30$GeV	$m_a = 40$GeV	$m_a = 50$GeV	$m_a = 60$GeV
Basic cuts	0.2058(2.7076)	0.2497(2.7076)	0.1874(2.7076)	0.1191(2.7076)	0.0354(2.7076)
Cut 1-D	0.1711(1.8332)	0.2251(1.8332)	0.1658(1.8332)	0.1103(1.8332)	0.0353(1.8332)
Cut 2-D	0.1694(0.1417)	0.1763(0.2081)	0.1106(0.3301)	0.0617(0.5102)	0.0160(0.4212)
$S/\sqrt{S+B}$	9.61	8.99	5.27	2.58	0.76

- $g_{a\gamma Z} = 0.5\ \text{TeV}^{-1}$
- $\mathcal{L} = 1\ \text{ab}^{-1}$

- 3σ and 5σ discovery curves in the planes (m_a, g_{aZZ}) and $(m_a, g_{a\gamma Z})$:

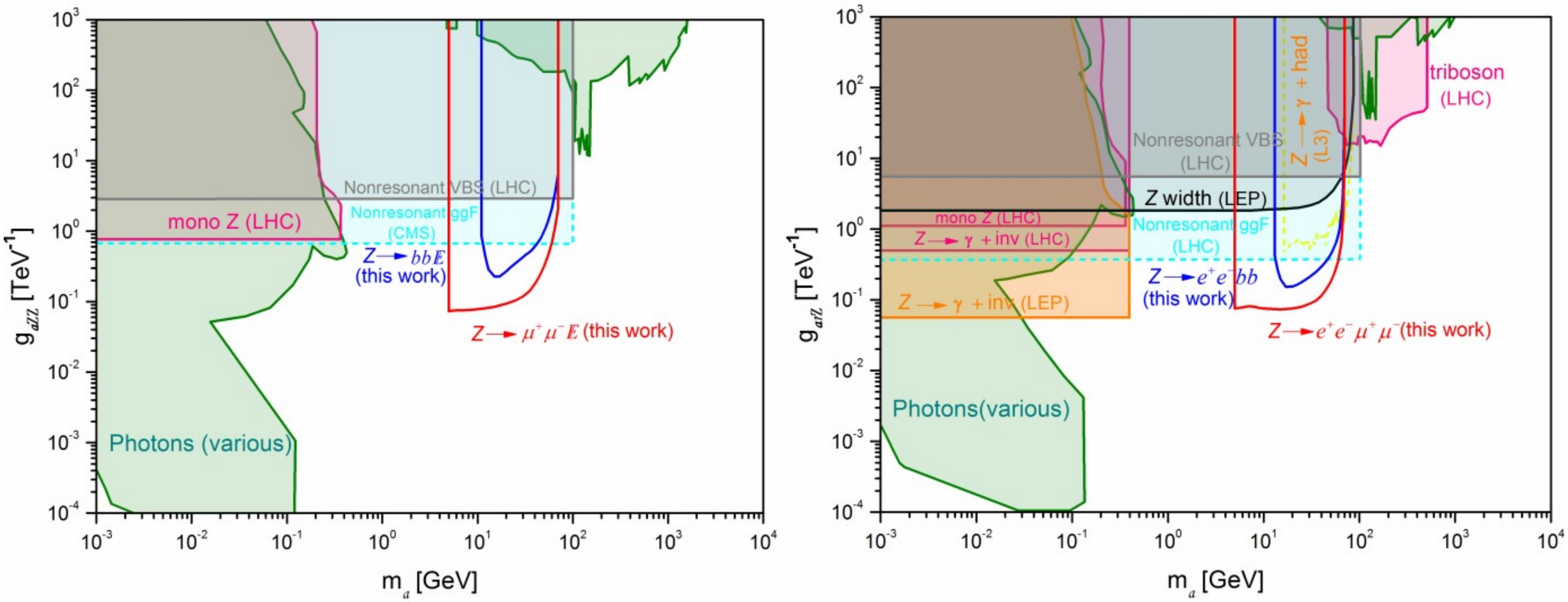




- For $5\ \text{GeV} \le m_a \le 20\ \text{GeV}$, the $\mu^+\mu^-\not{E}$ and $e^+e^-\mu^+\mu^-$ signals can probe the couplings g_{aZZ} and $g_{a\gamma Z}$ down to $0.1\ \text{TeV}^{-1}$.

2.3 Results

Sensitivity bounds on g_{aZZ} (left) and $g_{a\gamma Z}$ (right) at 95% C.L. from exotic Z decays and other current exclusion regions.

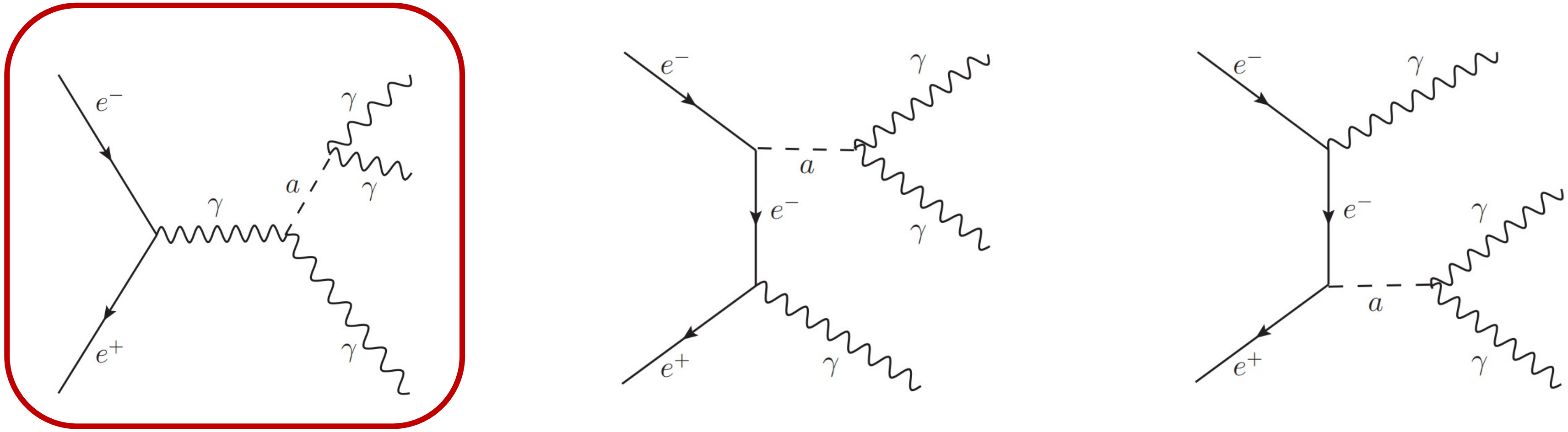


- Compared to the LHC, the future Z factories are more sensitive to g_{aZZ} and $g_{a\gamma Z}$ via these four channels for m_a in the range from 5GeV to tens GeV.

3.1 Searching for ALP via the triphoton production at the 240 GeV CEPC

Accepted by J. Phys. G

- Assuming $C_{\tilde{W}} = C_{\tilde{B}}$ and there are $g_{a\gamma\gamma} = g_{aZZ} = g_{aWW}$ *and* $g_{a\gamma Z} = 0$.
- The Feynman diagrams for the process of $e^+e^- \to a\gamma \to 3\gamma$:

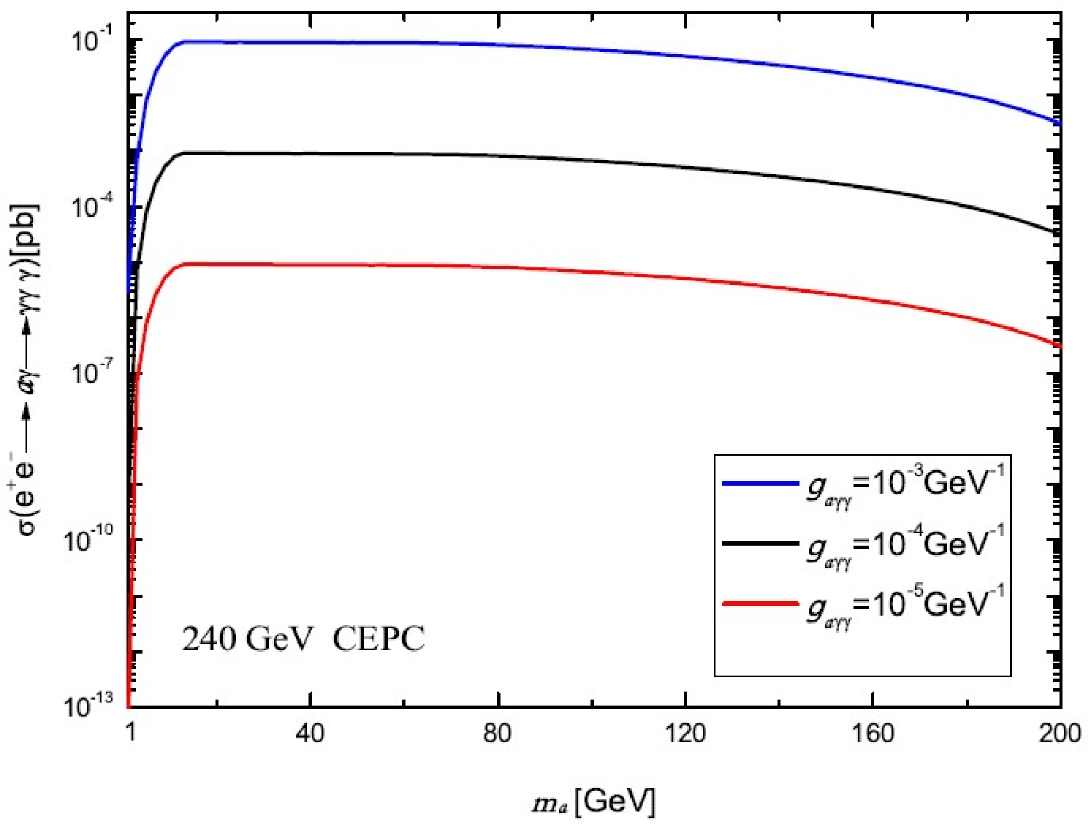


(a) (b) (c)

dominant

- The mass of ALP : $1\,\mathrm{GeV} < m_a \le 200\,\mathrm{GeV}$

- The cross section of the process $e^+e^- \to a\gamma \to 3\gamma$ as a function of the ALP mass m_a :



- Basic cuts:

$$p_T^{\gamma} > 10\ \text{GeV}$$

$$|\eta_{\gamma}| < 2.5$$

$$\Delta R_{\gamma\gamma} > 0.2 \qquad (\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2})$$

Tools added:

CutExperiment https://github.com/NBAlexis/CutExperiment

- The angular separation of the two photons from ALP decay strongly depends on the ALP mass.

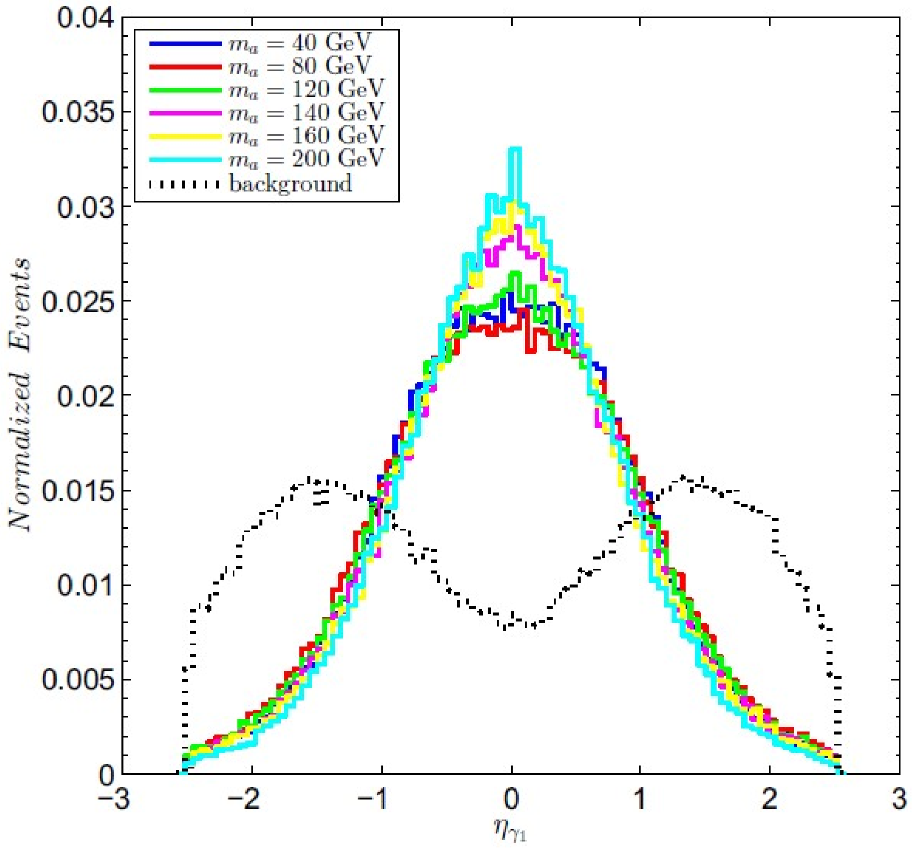
  - The ALP mass less than 20 GeV ⟶ $N_\gamma \geq 1$

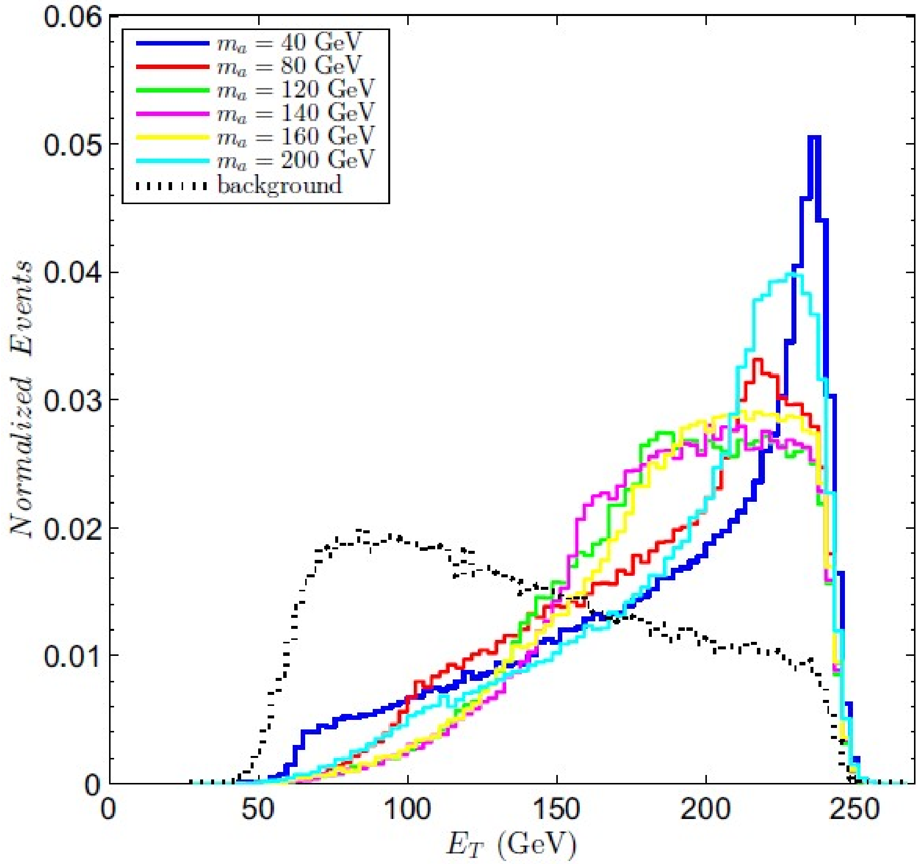
    the invariant mass of all final state photons m_γ

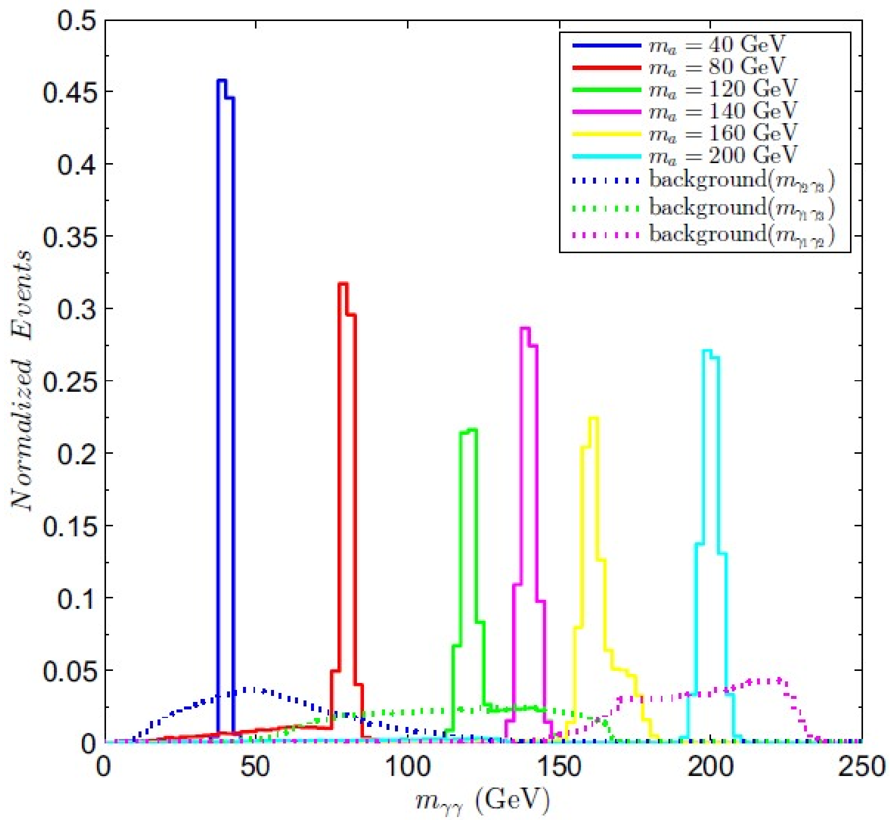
    the transverse momentum of the hardest photon in the final states $p_T^{\gamma_1}$

    } observables

  - The ALP mass is higher than 20 GeV ⟶ $N_\gamma \geq 3$


$m_a = 40$ GeV
$m_a = 80$ GeV
$m_a = 120$ GeV
$m_a = 140$ GeV
$m_a = 160$ GeV
$m_a = 200$ GeV
background
Normalized Events
η_{γ_1}


$m_a = 40$ GeV
$m_a = 80$ GeV
$m_a = 120$ GeV
$m_a = 140$ GeV
$m_a = 160$ GeV
$m_a = 200$ GeV
background
Normalized Events
E_T (GeV)



- The symbols γ_1, γ_2 *and* γ_3 :
  The photons with the largest, intermediate and smallest momentum.

- For the ALP with high (low) mass, the ALP tends to decay into $\gamma_1\gamma_2$ ($\gamma_2\gamma_3$).

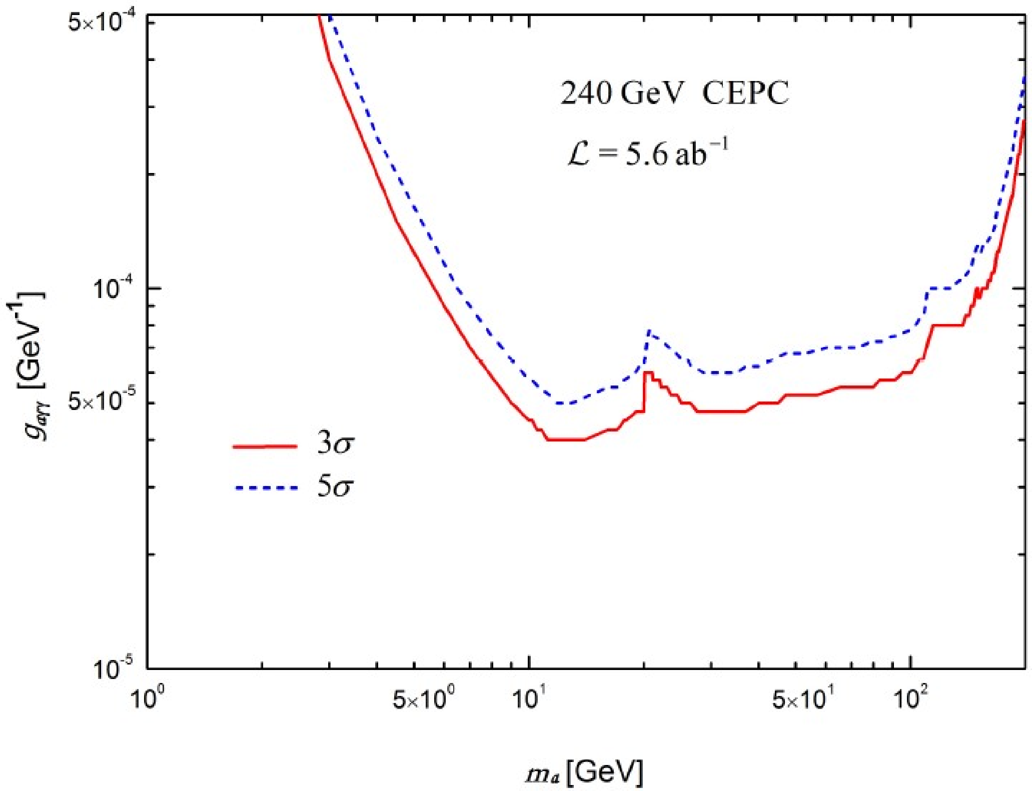
- The improved cuts:

Cut \ mass	1 GeV$< m_a \leq 20$ GeV	20 GeV$< m_a \leq 200$ GeV
Cut1	$N_\gamma \geq 1$	$N_\gamma \geq 3$
Cut2	$m_\gamma \leq 20$ GeV	$\|\eta_{\gamma_1}\| < 1.7$
Cut3	$p_T^{\gamma_1} \geq 20$ GeV	$E_T \geq 100$ GeV
Cut4	–	$\|m_{\gamma\gamma} - m_a\| \leq 5$ GeV

m_a [GeV]	cross sections for signal(background)[pb]					SS
	Basic Cuts	Cut1	Cut2	Cut3	Cut4	
10	6.5893×10^{-4}(0.2851)	6.5303×10^{-4}(0.2850)	5.8278×10^{-4}(0.0087)	5.8259×10^{-4}(0.0086)	–	14.38
20	9.0768×10^{-4}(0.2851)	9.0260×10^{-4}(0.2850)	4.9382×10^{-4}(0.0087)	4.9369×10^{-4}(0.0086)	–	12.24
40	8.9170×10^{-4}(0.2851)	8.1998×10^{-4}(0.2679)	7.7072×10^{-4}(0.1842)	7.5997×10^{-4}(0.1739)	7.5569×10^{-4}(0.0202)	12.35
80	8.0760×10^{-4}(0.2851)	7.3533×10^{-4}(0.2679)	6.8321×10^{-4}(0.1842)	6.7924×10^{-4}(0.1739)	5.4713×10^{-4}(0.0178)	9.56
120	5.0300×10^{-4}(0.2851)	4.5322×10^{-4}(0.2679)	4.2267×10^{-4}(0.1842)	4.2141×10^{-4}(0.1739)	2.8405×10^{-4}(0.0189)	4.85
140	3.4438×10^{-4}(0.2851)	3.0861×10^{-4}(0.2679)	2.8993×10^{-4}(0.1842)	2.8918×10^{-4}(0.1739)	2.5867×10^{-4}(0.0204)	4.26
160	2.0613×10^{-4}(0.2851)	1.8364×10^{-4}(0.2679)	1.7283×10^{-4}(0.1842)	1.7234×10^{-4}(0.1739)	1.2056×10^{-4}(0.0103)	2.80
200	3.0873×10^{-5}(0.2851)	2.7060×10^{-5}(0.2679)	2.5737×10^{-5}(0.1842)	2.5585×10^{-5}(0.1739)	2.3273×10^{-5}(0.0251)	0.35

- $g_{a\gamma\gamma} = 10^{-4}\ \mathrm{GeV}^{-1}$
- $\mathcal{L} = 5.6\ \mathrm{ab}^{-1}$

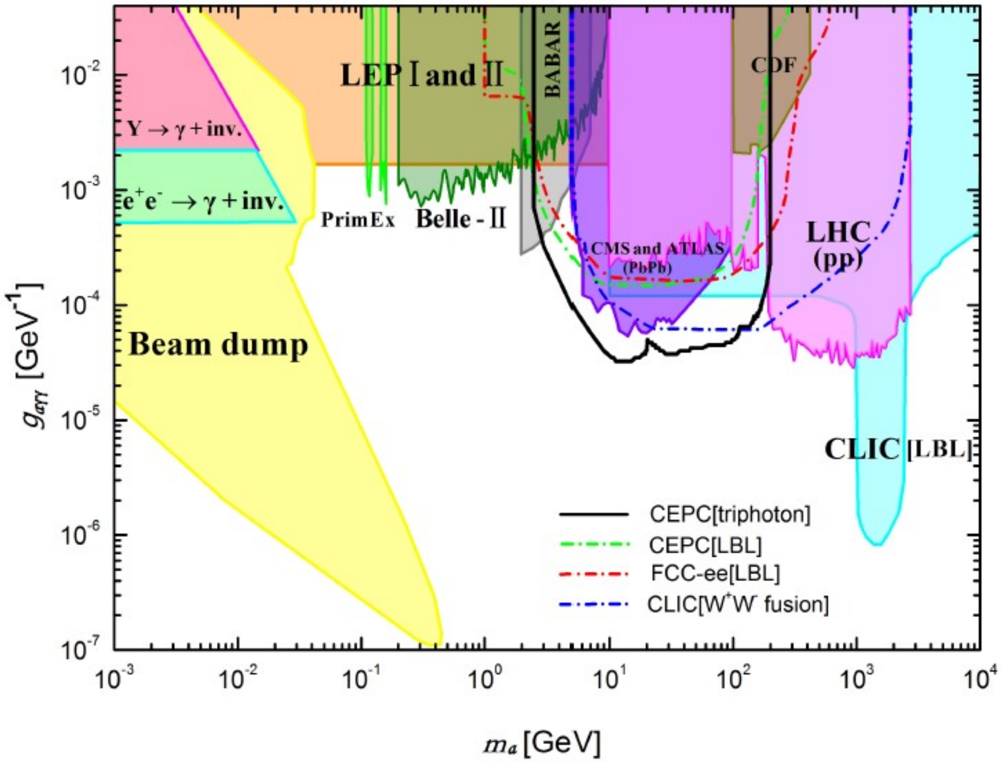
- The 3σ and 5σ curves for the process $e^+e^- \to a\gamma \to 3\gamma$ in the $(m_a,\ g_{a\gamma\gamma})$ plane:



- The expected bounds on $g_{a\gamma\gamma}$ can reach $4\times10^{-5}\ \mathrm{GeV}^{-1}$ $(5\times10^{-5}\ \mathrm{GeV}^{-1})$ at 3σ (5σ) levels.

3.2 Results

The projected CEPC sensitivity region for the process $e^+e^- \to a\gamma \to 3\gamma$ as well as other current and prospective limits on $g_{a\gamma\gamma}$.



- The promising sensitivities as $g_{a\gamma\gamma} \in [3.25\times10^{-5}, 3.7\times10^{-4}]\,\mathrm{GeV}^{-1}$ with $m_a \in [2.9, 190]$ GeV at 2σ level .

- ALPs appear naturally in broad extensions of the SM, which have various beneficial properties to search by many experiments.

- The exotic decay channel $Z \to a f \bar{f}$ is promising for probing ALPs.

  It is expected that the future Z factories could discover or exclude ALPs with m_a in the range of 5 GeV - 70 GeV.

- The promising sensitivities of the CEPC to the coupling $g_{a\gamma\gamma}$ are in the range of $3.25\times10^{-5}\,\mathrm{GeV}^{-1}$ to $3.7\times10^{-4}\,\mathrm{GeV}^{-1}$ with m_a from 2.9 GeV to 190 GeV.

Thanks