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Searching for axionlike particles at future electron-positron colliders

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based on

H.-Y. Zhang,C.-X. Yue, Y.-C. Guo and **SY**, PRD 104 (2021) 9, 096008
C.-X. Yue, **SY**, H. Wang and N. Zhang, arXiv:2204.04702 accepted by PRD

Joint Workshop of the CEPC Physics, Software and New Detector Concept in 2022, May 23-25, 2022

Outline

1. Introduction to axion-like particles (ALPs).
2. ALPs searches at colliders
3. Searching for ALPs at future e^+e^- colliders via light-by-light scattering
4. Searching for ALPs via decay $Z \to af\bar{f}$ at Z factories
5. Summary

Introduction to axion-like particles

- The discovery of Higgs bring us into new territory of spin-0 particles.
- Axion have been postulated to address the strong CP problem,which is the pNGB associated to Peccei-Quinn symmetry, a global U(1). $m_a \sim m_\pi f_\pi / f_a$
- Many extensions of the SM feature one or several spontaneously broken global U(1) symmetries, thus predicting axion-like particles (ALPs).
- ALPs：No direct relation between coupling and mass.

General effective Lagrangian of ALPs

bottom-up view

SMEFT $$\mathcal{L} = \mathcal{L}_0 + \sum_i \frac{c_i}{\Lambda^{d-4}} \mathbf{O}_i$$

Building Blocks：

SM fields： $B_{\mu\nu},\, W_{\mu\nu},\, G_{\mu\nu}$

EW scalar doublet: $\Phi(x) = \frac{v + h(x)}{\sqrt{2}} e^{i\vec{\pi}\vec{\sigma}/v}$

New pseduscalar (GB): $\frac{\partial_\mu a}{f_a}$

General effective Lagrangian of ALPs

Linear Effective Lagrangian

NLO bosonic operators

$$\mathbf{O}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{\tilde{G}} = -G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}$$

$$\mathbf{O}_{\tilde{W}} = -W_{\mu\nu}\tilde{W}^{\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{a\Phi} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\frac{\partial^\mu a}{f_a}$$

$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{M_a^2}{2}a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F C_F \gamma_\mu \psi_F$$
$$+ g_s^2 C_{GG}\frac{a}{\Lambda}G^A_{\mu\nu}\tilde{G}^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

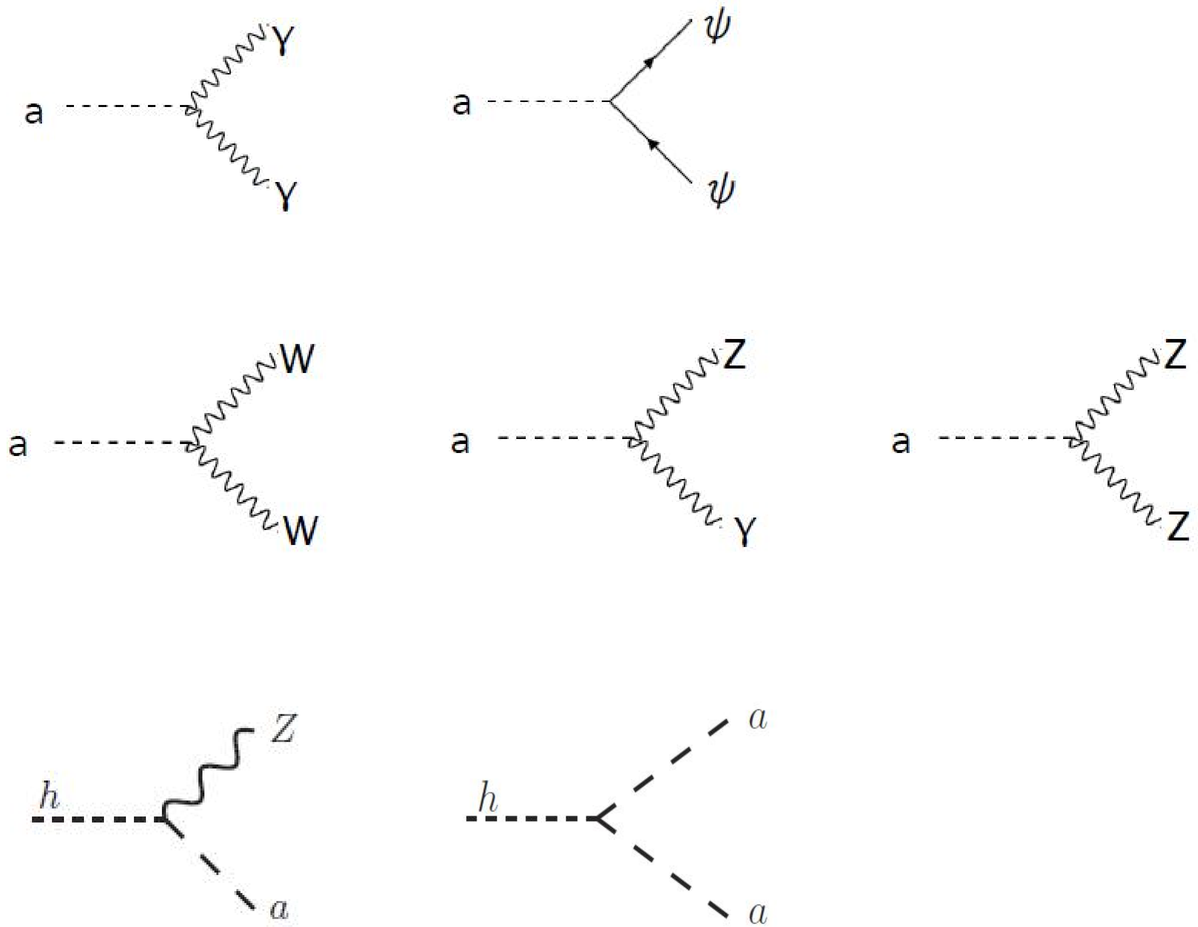
$$\mathcal{L}_{\rm eff}^{D\geq 6} = \frac{c_{ah}}{f^2}(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{c_{Zh}}{f^3}(\partial^\mu a)\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \ldots$$

H.Georgi,D.B.Kaplan& L.Randall, PLB169(1986)73-78

M.Bauer et al., JHEP12(2017),044

I.Brivio et al., EPJC77(2017),8,572 (including Noliner Effective Lagrangian)

Vertices



ALPs searches at colliders

Prodcution modes

- Resonant production

$gg \to a \quad \gamma\gamma \to a$

$e^+e^- \to a$ strongly suppresed

- Associated production

$pp \to a\,W^{\pm} \quad pp \to aZ(\gamma)$

$pp \to a\,h \quad pp \to t\bar{t}a \quad pp \to aW^{\pm}\gamma$

$e^+e^- \to aZ(\gamma) \quad e^+e^- \to ah$

$e^+e^- \to e^+e^-a \quad e^+e^- \to \nu\bar{\nu}a$

- Exotic SM decays

$h \to Za \quad h \to aa \quad Z \to a\gamma$

- Other modes

Decay channels

- Stable ALPs ~ $\not{E}$
- Long-Lived ALPs with a Displaced-Vertex
- Short lived ALP

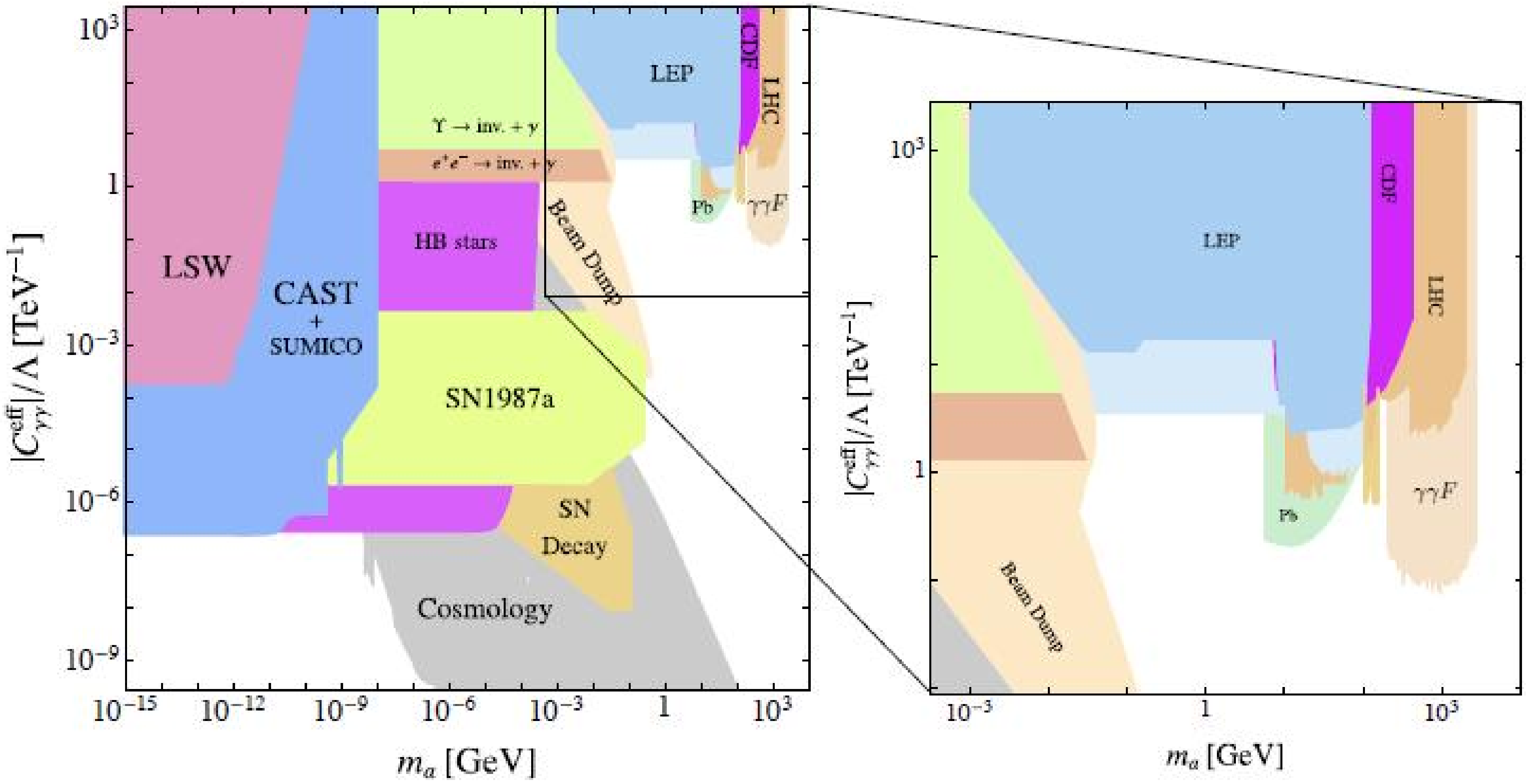
$a \to \gamma\gamma \quad a \to \ell^+\ell^- \quad a \to jj$

$a \to b\bar{b} \quad a \to VV \quad a \to t\bar{t}$

I.Brivio et al., EPJC77(2017),8,572
M.Bauer et al., EPJC79(2019),1,74
CERN Yellow Rep. Monogr. Vol. 3 (2018)

Constraints: di-photon coupling

M.Bauer et al., JHEP12(2017),044



1.For light ALPs (<<MeV), cosmological and astrophysical measurements place very tight bounds on the coupling to photons.
2. For heavier ALPs, the limits are less stringent.

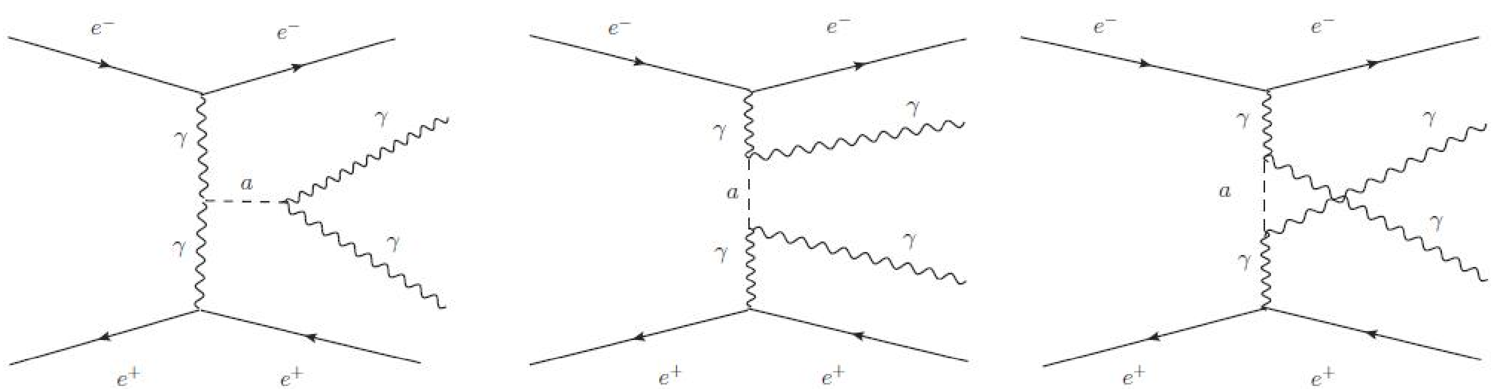
Searching for ALPs at future e+e- colliders via light-by-light scattering

H-Y Zhang，C-X Yue, Y-C Guo and ***SY***
PRD 104 (2021) 9, 096008

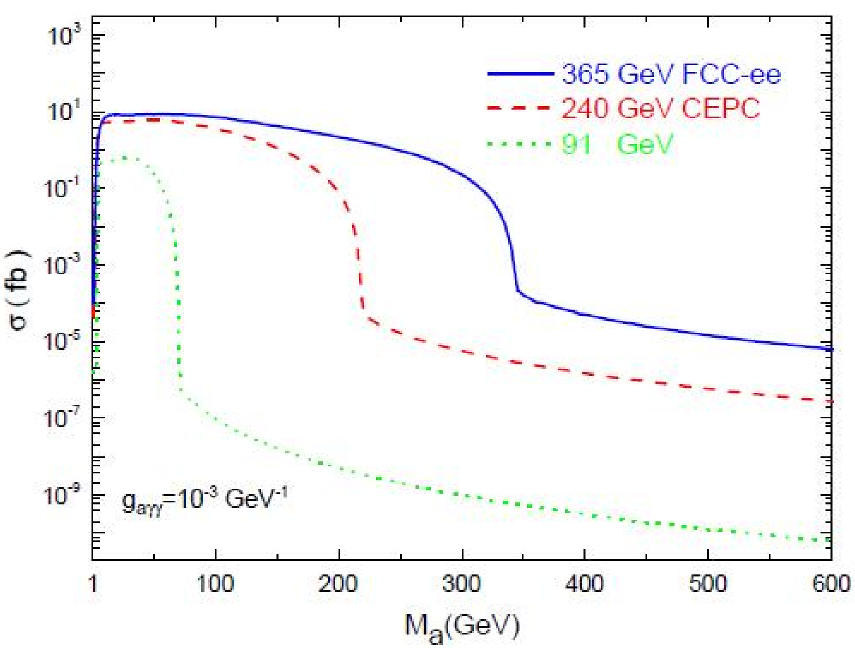
- The LHC generally is more sensitive to the heavy ALP searches by LBL scattering. The CLIC studies obtain a stonger bounds for TeV ALPs.

C.Baldenegro et al., JHEP06,(2018)131 (LHC LBL)
S.C. Inan and A.V. Kisselev, JHEP06(2020)183;
Chin.Phys.C 45 (2021) 4, 043109 (CLIC LBL)

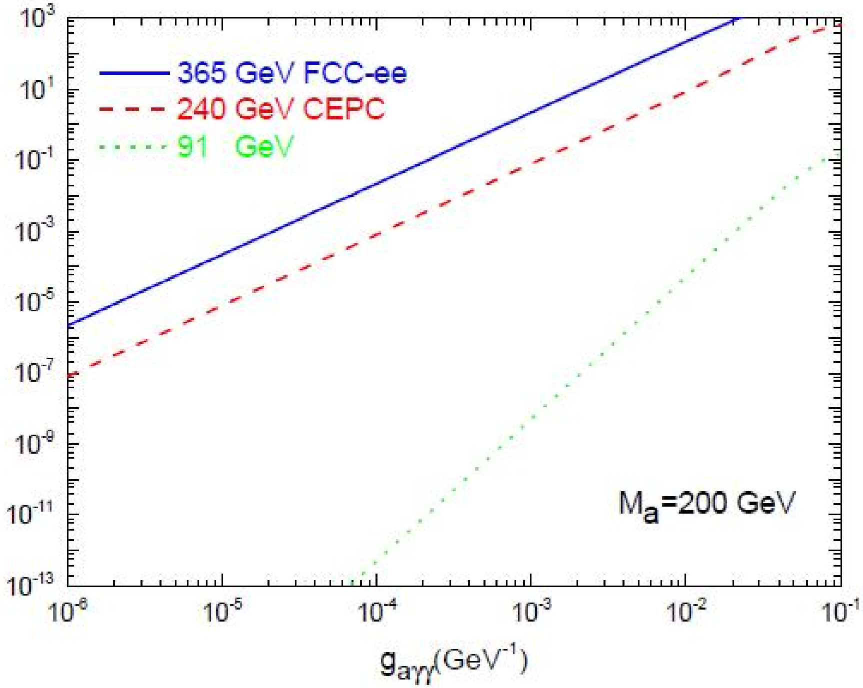
- It is interesting to study LBL at the CEPC and FCC-ee.



Searching for ALPs at future e+e- colliders via light-by-light scattering



(a)



(b)

The cross section for LBL scattering

Backgound for the LBL signal

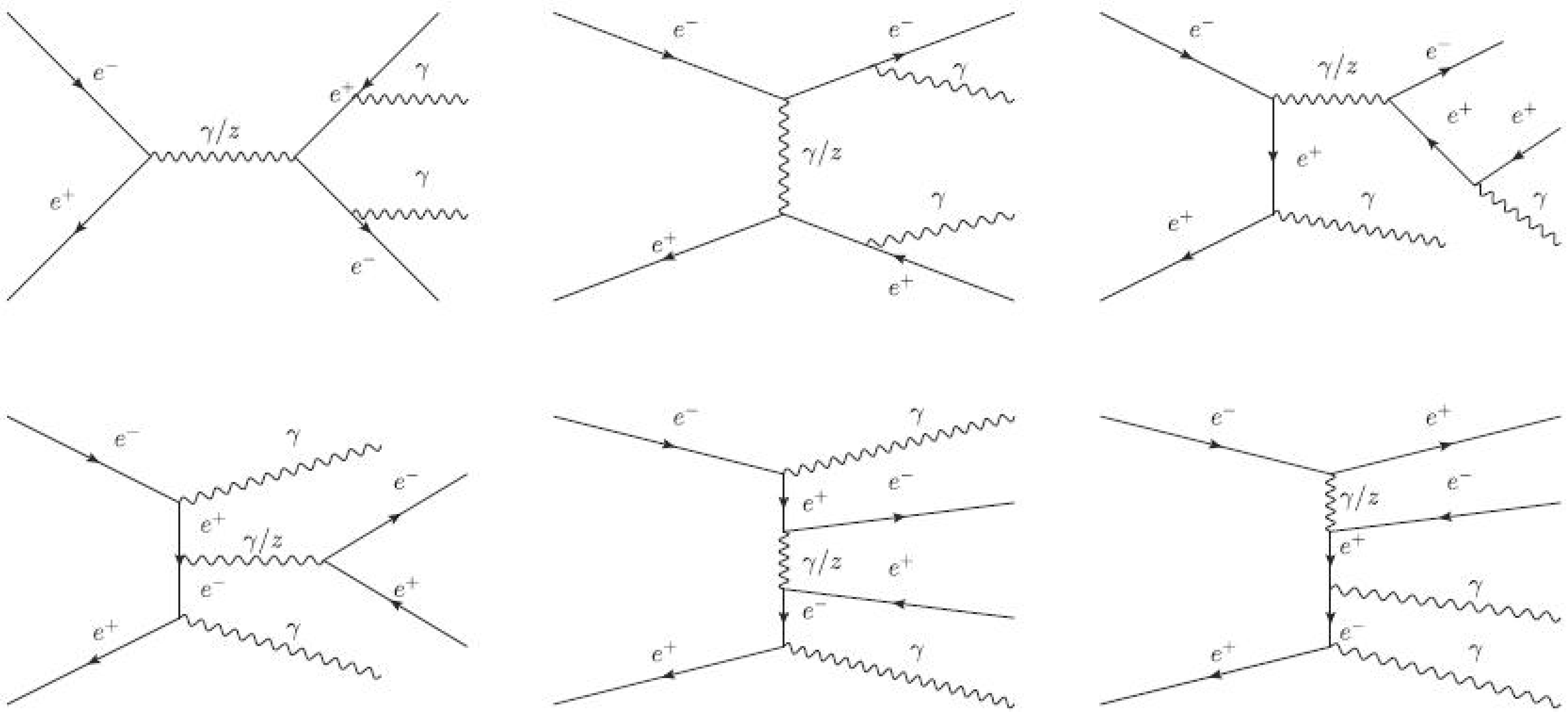


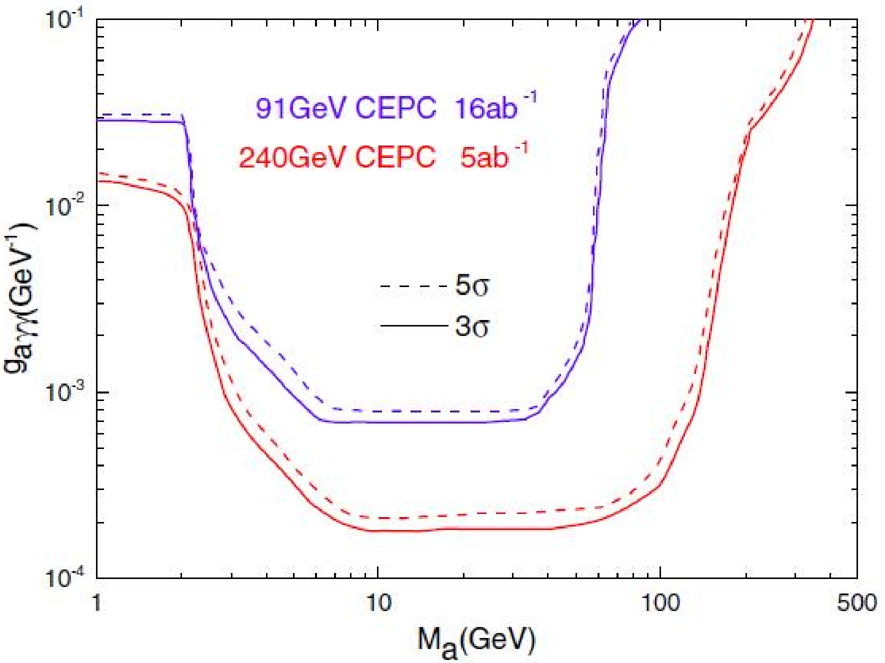
FIG. 3. The typical diagrams for the background of the process $e^+e^- \to \gamma\gamma e^+e^-$.

Detecting ALPs at the CEPC

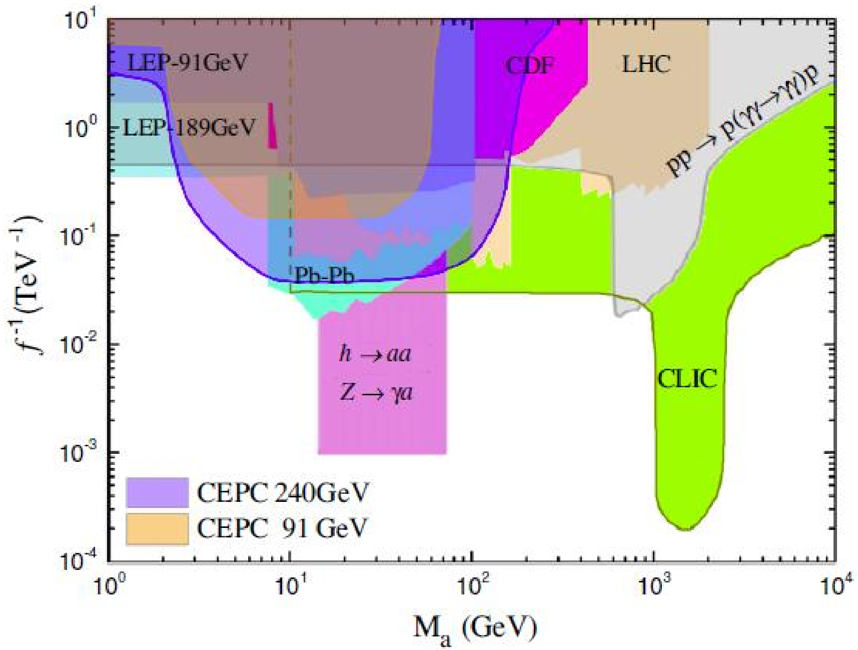
Cuts	$\sqrt{s} = 240$ GeV	$\sqrt{s} = 91$ GeV
Cut-1: Electron and positron pseudo-rapidity	$0.4 < \eta(e^+) < 2.4$ $-2.4 < \eta(e^-) < -0.4$	$-0.3 < \eta(e^+) < 0.9$ $-0.9 < \eta(e^-) < 0.3$
Cut-2: Angle between the ALP and the beam axis	$0.7 < \theta(\gamma\gamma) < 2.4$	$0.7 < \theta(\gamma\gamma) < 2.4$
Cut-3: Angular separation between electron-positron	$\Delta\theta(e^+e^-) < 2.9$	$\Delta\theta(e^+e^-) < 2.4$
Cut-4: Transverse momentum of reconstructed diphotons	$p_T(\gamma\gamma) > 45$ GeV	$p_T(\gamma\gamma) > 20$ GeV

CEPC @ $\sqrt{s} = 240$ (91) GeV							
Cuts	Signal (fb)						Background (fb)
	$M_a = 6$ GeV	$M_a = 8$ GeV	$M_a = 10$ GeV	$M_a = 50$ GeV	$M_a = 100$ GeV	$M_a = 160$ GeV	$\gamma\gamma e^+e^-$
Basic cuts	3.4378(0.249)	4.8088(0.4796)	5.2928(0.5003)	5.9064(0.2432)	3.585	0.8021	67.0614(98.8986)
Cut 1	2.9865(0.0316)	3.932(0.1267)	4.138(0.1417)	4.5336(0.0977)	2.4778	0.4436	33.7026(40.928)
Cut 2	2.1714(0.0309)	3.0176(0.1264)	3.2819(0.1411)	3.1262(0.0904)	1.6993	0.3145	12.628(34.93)
Cut 3	2.1368(0.0226)	3.0383(0.1156)	3.2422(0.1297)	3.0238(0.0717)	1.6497	0.3052	9.042(8.396)
Cut 4	1.4(0.0226)	2.2984(0.1156)	2.5065(0.1297)	2.0519(0.0501)	0.8747	0.0392	3.3614(6.1921)

Prospects for detecting ALP at CEPC



The 3σ and 5σ discovery curves in the $M_a - g_{a\gamma\gamma}$ plane at the CEPC.



The 95% C.L exclusion regions in the $M_a - g_{a\gamma\gamma}$ plane at the CEPC and other colliders

ALPs at the CEPC & FCC-ee

CEPC @ $\sqrt{s} = 240$ (91) GeV							
Cuts	Signal (fb)						Background (fb)
	M_a = 6 GeV	M_a = 8 GeV	M_a = 10 GeV	M_a = 50 GeV	M_a = 100 GeV	M_a = 160 GeV	$\gamma\gamma e^+e^-$
Basic cuts	3.4378(0.249)	4.8088(0.4796)	5.2928(0.5003)	5.9064(0.2432)	3.585	0.8021	67.0614(98.8986)
Cut 1	2.9865(0.0316)	3.932(0.1267)	4.138(0.1417)	4.5336(0.0977)	2.4778	0.4436	33.7026(40.928)
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Cut 3	2.1368(0.0226)	3.0383(0.1156)	3.2422(0.1297)	3.0238(0.0717)	1.6497	0.3052	9.042(8.396)
Cut 4	1.4(0.0226)	2.2984(0.1156)	2.5065(0.1297)	2.0519(0.0501)	0.8747	0.0392	3.3614(6.1921)

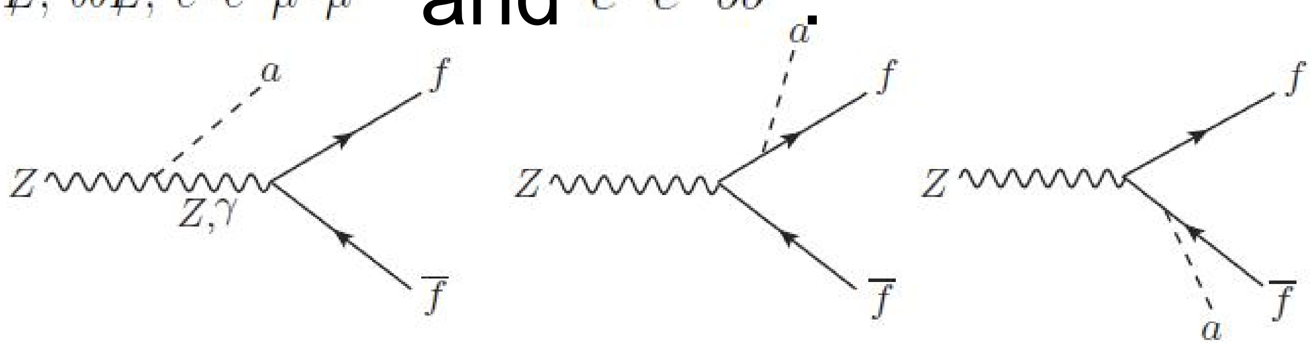
FCC-ee @ $\sqrt{s} = 365$ (91) GeV							
Cuts	Signal (fb)						Background (fb)
	M_a = 6 GeV	M_a = 8 GeV	M_a= 10 GeV	M_a= 50 GeV	M_a= 100 GeV	M_a= 200 GeV	$\gamma\gamma e^+e^-$
Basic cuts	2.9092(0.2483)	5.0074(0.4786)	6.5272(0.5001)	8.4206(0.2432)	7.1235	2.1737	54.203(98.8188)
Cut 1	2.1634(0.0311)	4.2978(0.1265)	5.3419(0.142)	4.5123(0.0977)	4.9093	1.2593	29.233(41.0505)
Cut 2	1.3962(0.0307)	2.6956(0.1261)	3.6755(0.1416)	2.9963(0.0904)	3.1011	0.7942	8.3373(35.0206)
Cut 3	1.2374(0.0223)	2.5417(0.1152)	3.5173(0.1304)	2.8482 (0.0717)	2.9926	0.768	4.8137(8.4019)
Cut 4	0.9014(0.0222)	2.2243(0.115)	3.1819(0.1303)	2.5198(0.05)	2.5458	0.453	2.6445(6.1842)

Searching for ALPs via exotic decay $Z \to a f \bar{f}$ at CEPC

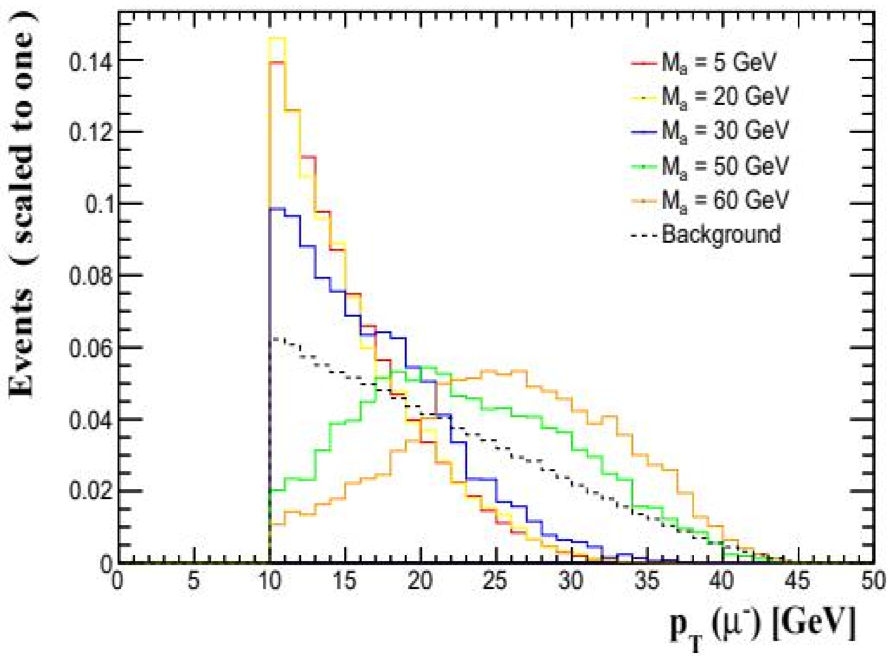
C.-X. Yue, **SY**, H. Wang and N. Zhang, arXiv:2204.04702 accepted by PRD

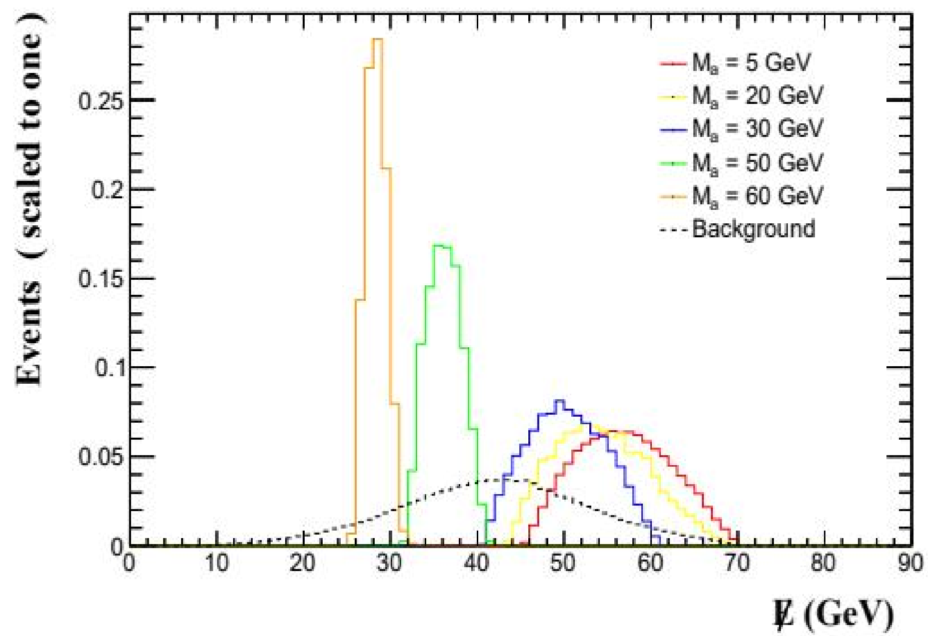
- CEPC and FCC-ee can produce up to 10^{12} Z bosons.
- It is possible for the observations of rare decay of Z.
- Future Z factories is powerful for detecing dark sector models via exotic Z decay. J.Liu, *et al.*， PRD97,095044,2018.
- We foucus on four types of exotic Z-decay signals

$Z \to \mu^+\mu^-\not{E}, b b\not{E}, e^+e^-\mu^+\mu^-$ and e^+e^-bb .



$Z \to \mu^+\mu^-\not{E}$ and $Z \to bb\not{E}$





The normalized distribution for kinematic variables for signal $\mu^+\mu^-\not{E}$ and BG.

$Z \to \mu^+\mu^- \not{E}$ and $Z \to bb\not{E}$

Cut1-A

$|m_{\mu^+\mu^-} - m_a| < 3$ GeV

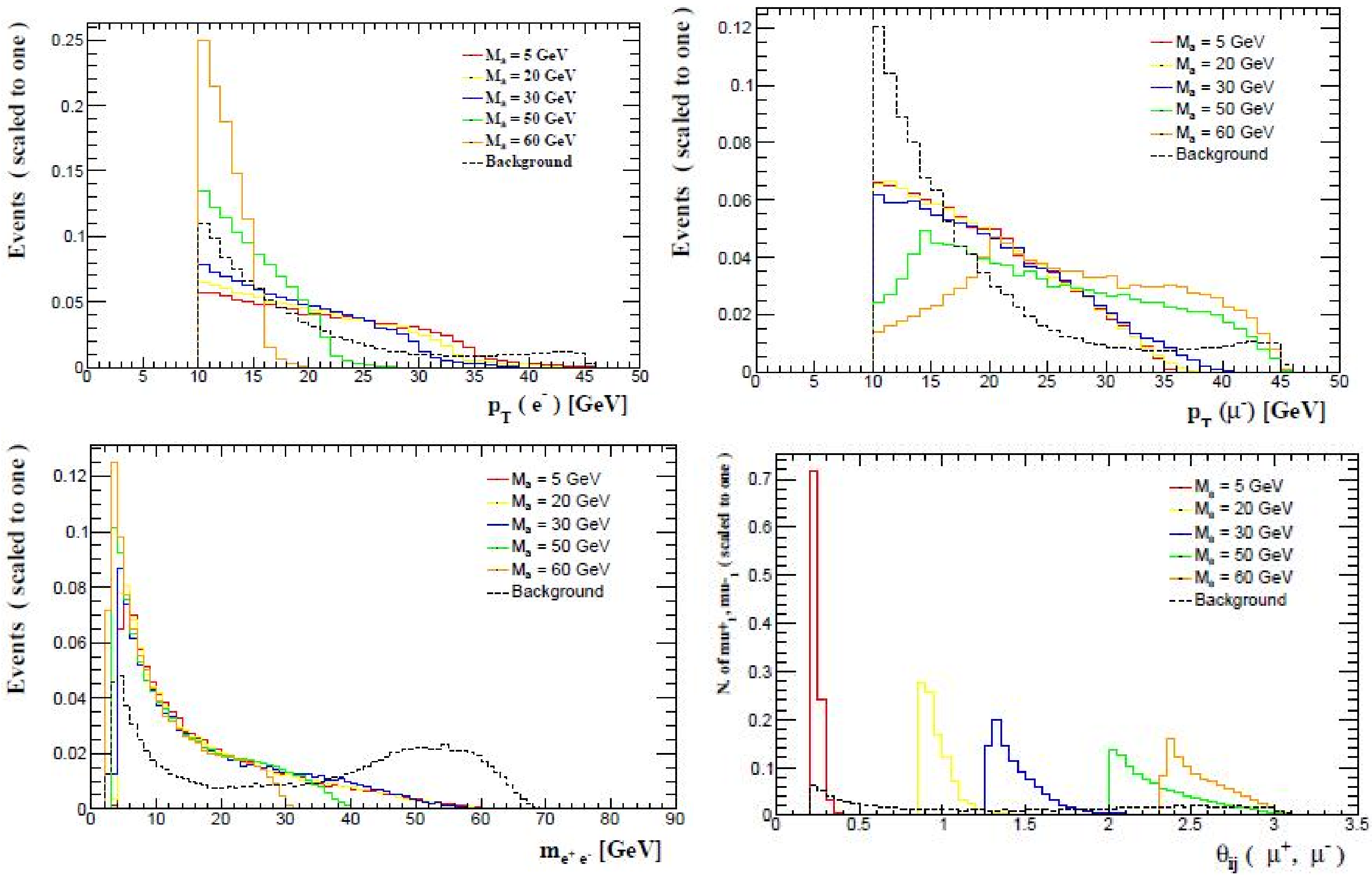
Cuts	Cross sections for signal(background) (fb)				
	m_a = 5GeV	m_a = 10GeV	m_a = 30GeV	m_a= 50GeV	m_a= 60GeV
Basic cuts	0.3406(0.2602)	0.3177(0.2602)	0.2368(0.2602)	0.0358(0.2602)	0.0062(0.2602)
Cut 1-A	0.3404(0.0059)	0.3175(0.0072)	0.2335(0.0300)	0.0343(0.0342)	0.0058(0.0195)
$S/\sqrt{S+B}$	18.29	17.62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

Cut1-B

$|m_{bb} - m_a| < 5$ GeV

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

$Z \to e^+e^-\mu^+\mu^-$ and $Z \to e^+e^-bb$



The normalized distribution for kinematic variables for signa $e^+e^-\mu^+\mu^-$ and BG.

$Z \to e^+e^-\mu^+\mu^-$ and $Z \to e^+e^-bb$

Cuts	Cross sections for signal(background) (fb)				
	m_a = 5GeV	m_a = 10GeV	m_a = 30GeV	m_a = 50GeV	m_a = 60GeV
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

Cut-C

$m_{e^+e^-} < 30$ GeV

$|m_{\mu^+\mu^-} - m_a| < 3$ GeV

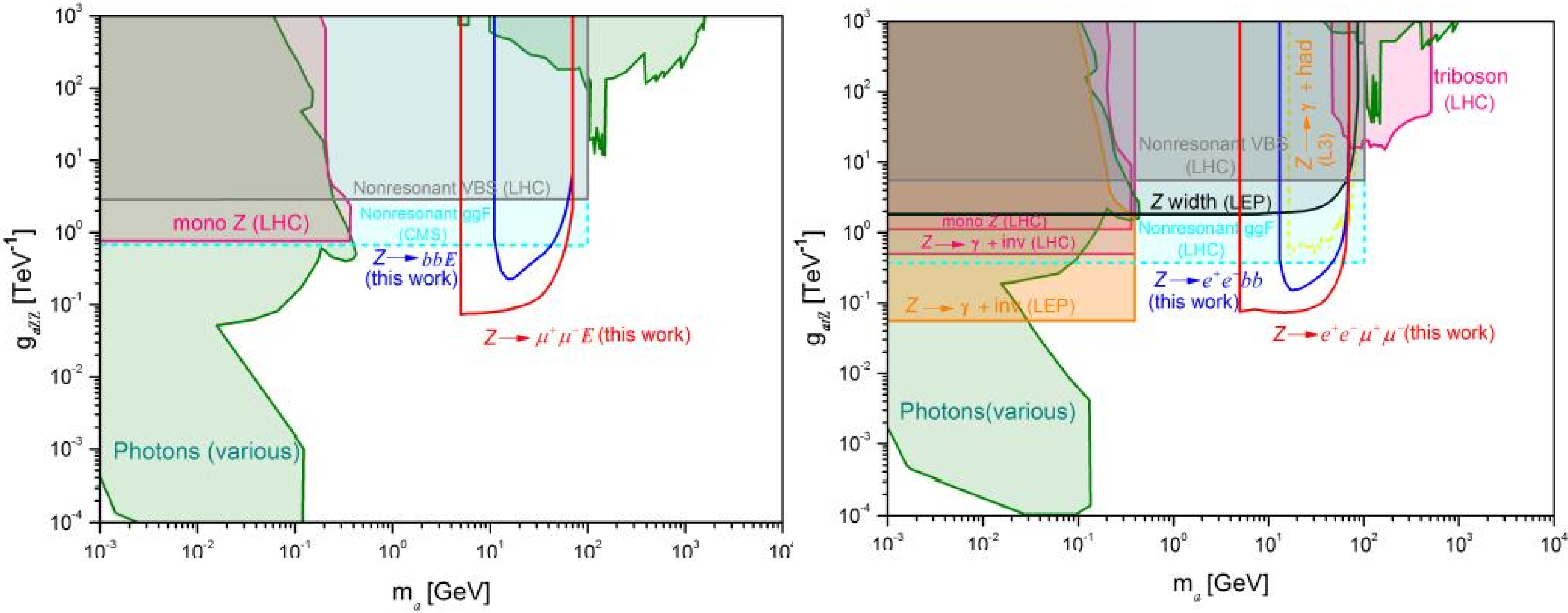
Cuts	Cross sections for signal(background) (fb)				
	m_a = 15GeV	m_a = 30GeV	m_a = 40GeV	m_a = 50GeV	m_a = 60GeV
Basic cuts	0.2058(2.7076)	0.2497(2.7076)	0.1874(2.7076)	0.1191(2.7076)	0.0354(2.7076)
Cut 1-D	0.1711(1.8332)	0.2251(1.8332)	0.1658(1.8332)	0.1103(1.8332)	0.0353(1.8332)
Cut 2-D	0.1694(0.1417)	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

Cut-D

$m_{e^+e^-} < 30$ GeV

$|m_{bb} - m_a| < 5$ GeV

Sensitivity bounds



Sensitivity bounds on and at 95% C.L. from exotic Z decays and other current exclusion regions.

Summary

- ALPs have a much wider parameter space and hence generate rich phenomenology at colliders.
- CEPC and FCC-ee can provide a good environment to exploring ALPs.
- The studies on LBL scattering and exotic decay $Z \to af\bar{f}$ found that CEPC and FCC-ee might be more sensitive to the ALPs in light mass range than LHC. It is expected that the future e^+e^- colliders could discovery or exclude ALPs.


Thank You!