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Searching for axion-like particles at future electron-positron colliders

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in collaboration with
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arXiv：2103.05218, accepted by PRD

The 2021 International Workshop on the High Energy Circular Electron Positron Collider
November 8-12, 2021, Nanjing

Outline

- 1. Introduction to axion and axion-like particles.
- 2. General effective Lagrangian of ALPs
- 3. ALPs searches at colliders
- 4. Searching for ALPs at future e+e- colliders via light-by-light scattering
- 5. Summary

Introduction to axion and 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 SM feature one or several spontaneously broken global U(1) symmetries, thus predicting the existence of 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

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

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

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{M_a^2}{2}a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F C_F \gamma_\mu \psi_F$$

$$+ g_s^2 C_{GG}\frac{a}{\Lambda}G^A_{\mu\nu}\tilde{G}^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

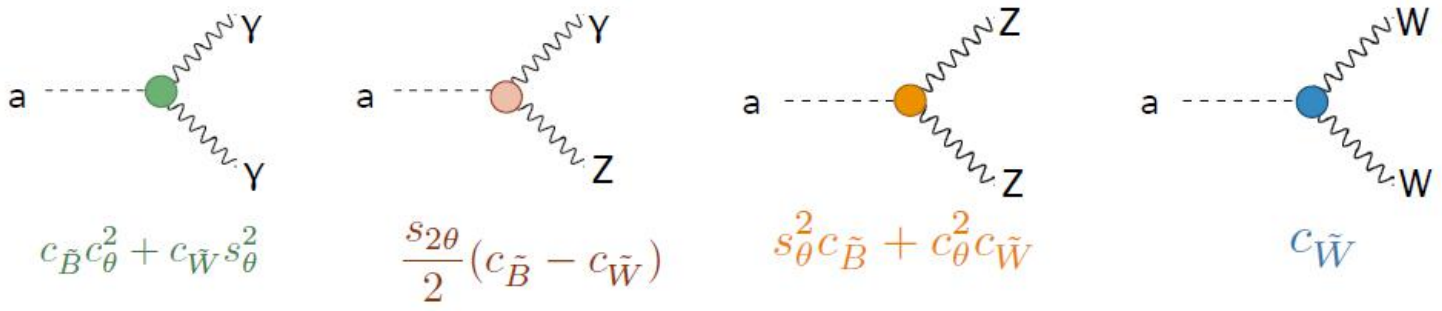
$$\mathcal{L}_{\text{eff}}^{D\geq 6} = \frac{c_{ah}}{f^2}(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{c_{Zh}}{f^3}(\partial^\mu a)\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \ldots$$

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

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

General effective Lagrangian of ALPs

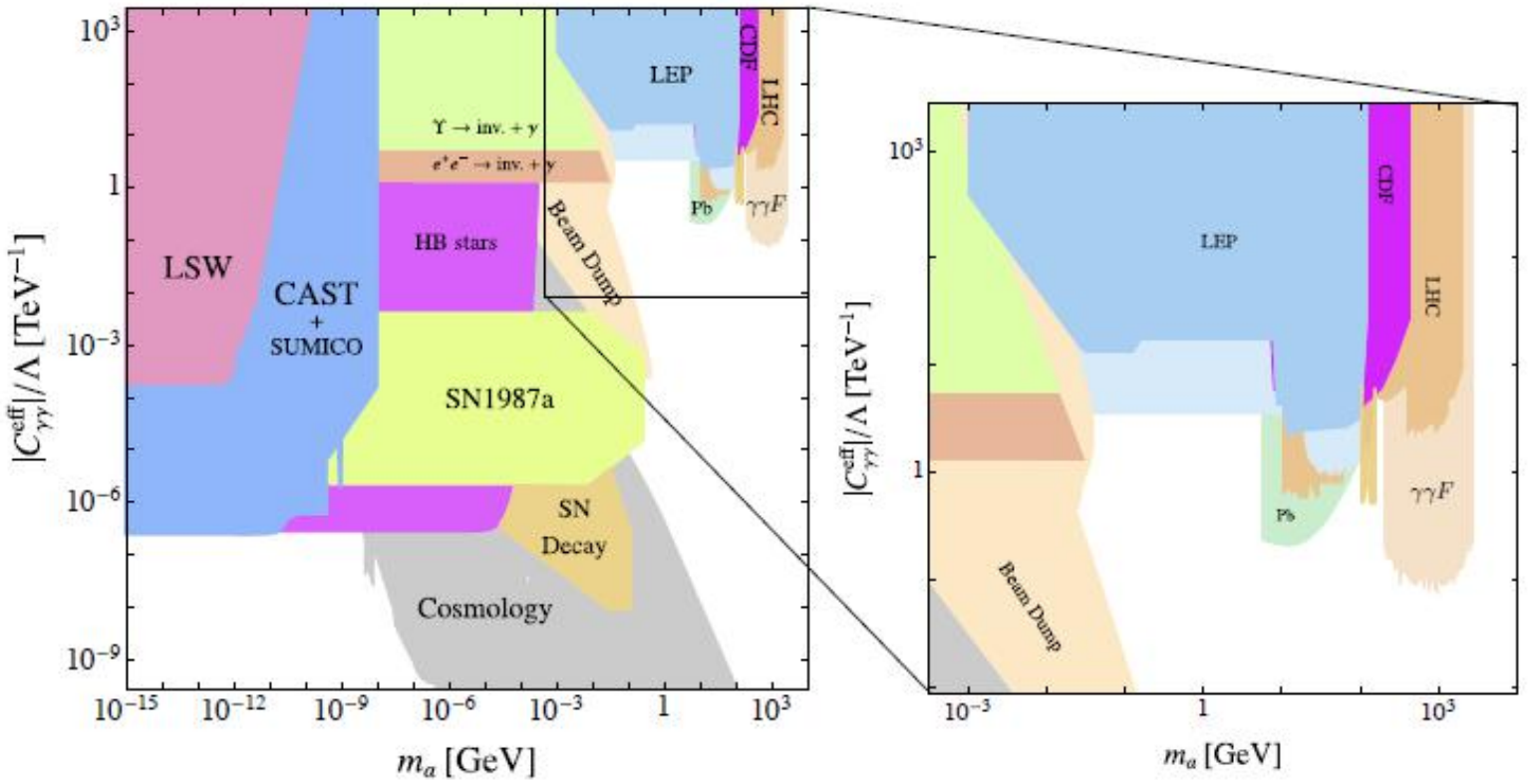
$$\frac{a}{f_a}\left(c_{\tilde{B}} B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{\tilde{W}} W_{\mu\nu}\tilde{W}^{\mu\nu}\right)$$



stolen from R.del Rey's talk

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.

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

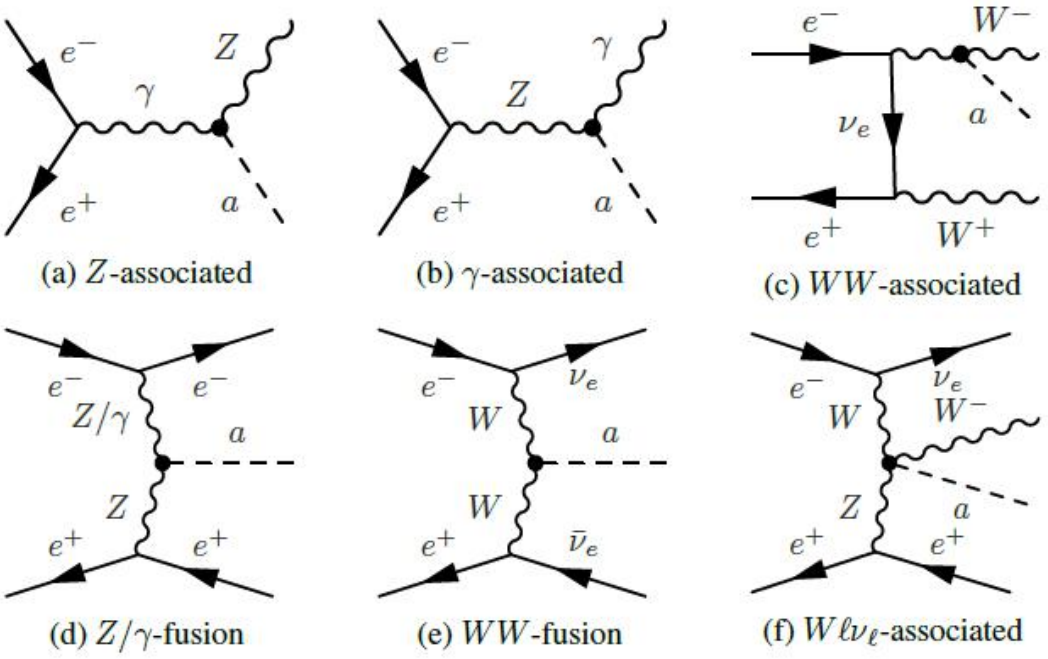
- Stable ALPs ~ $\not{E}$
- Long-Lived ALPs with a Displaced-Vertex
- Short lived ALP

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

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

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

ALPs searches at e+e-colliders

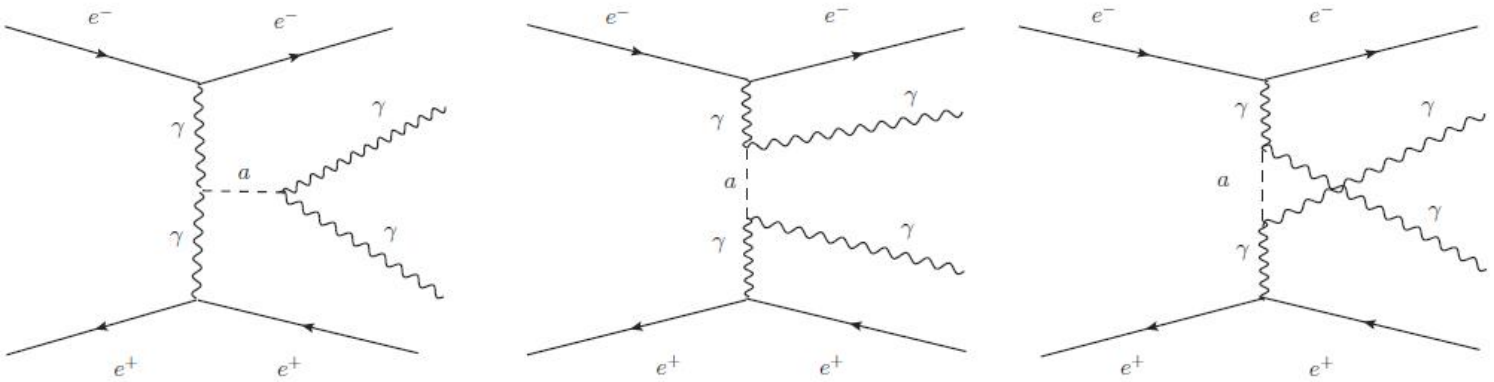


Respective Feynman diagrams for ALP production processed at e+e- colliders

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

*H-Y Zhang，C-X Yue, Y-C Guo and **SY***
arXiv: 2021.05218,accepted by PRD

- Using proton tagging technique，the LHC generally is more sensitive to the heavy ALP searched by LBL scattering that othe processes. The CLIC studies obtain a stonger bounds for TeV ALPs.
- It is interesting to study LBL at the CEPC and FCC-ee.



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 (CLC LBL)

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

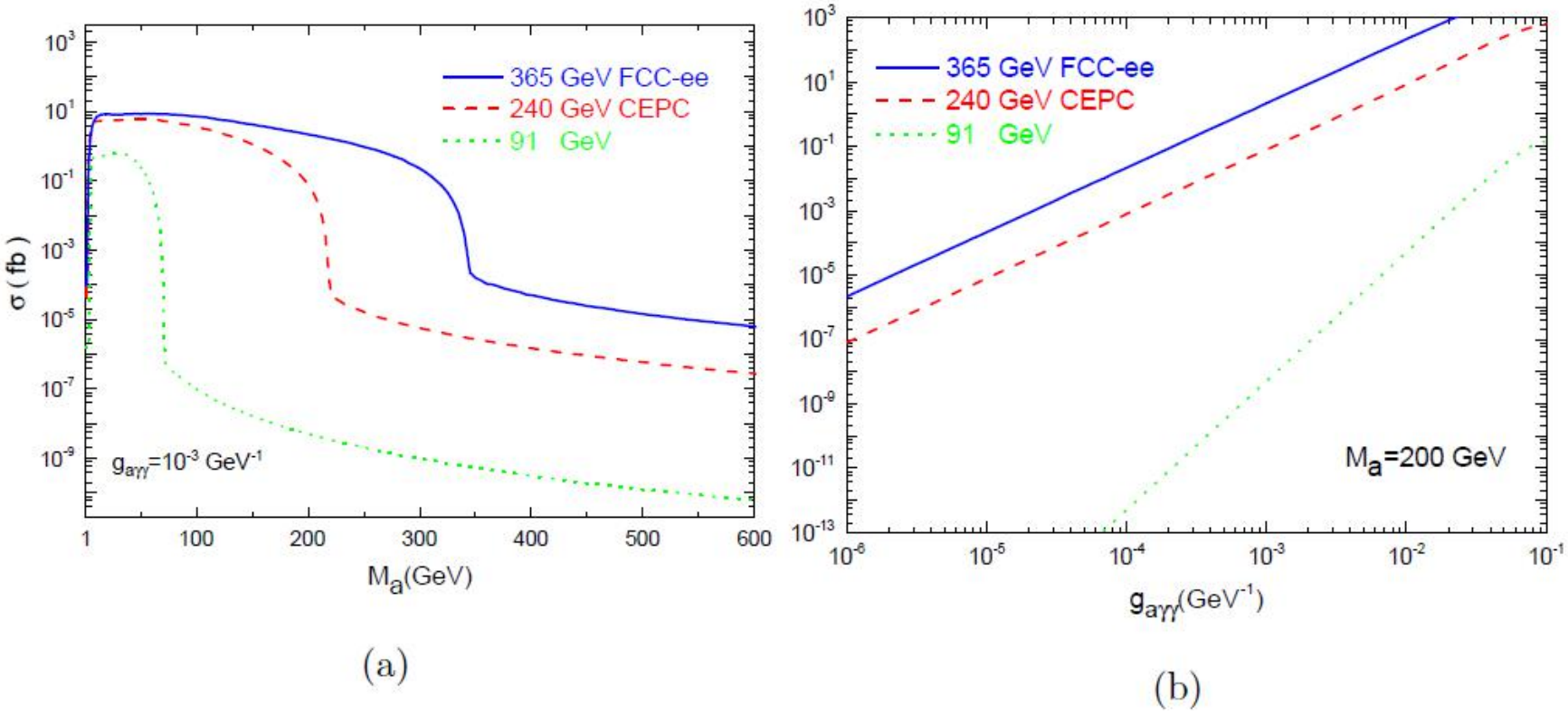


FIG. 2: The production cross section σ of the LBL scattering process induced by ALP as a function of the parameter M_a or $g_{a\gamma\gamma}$ at 365 GeV FCC-ee (blue), 240 GeV CEPC (red) and 91 GeV (green).

Backgound for the LBL signal

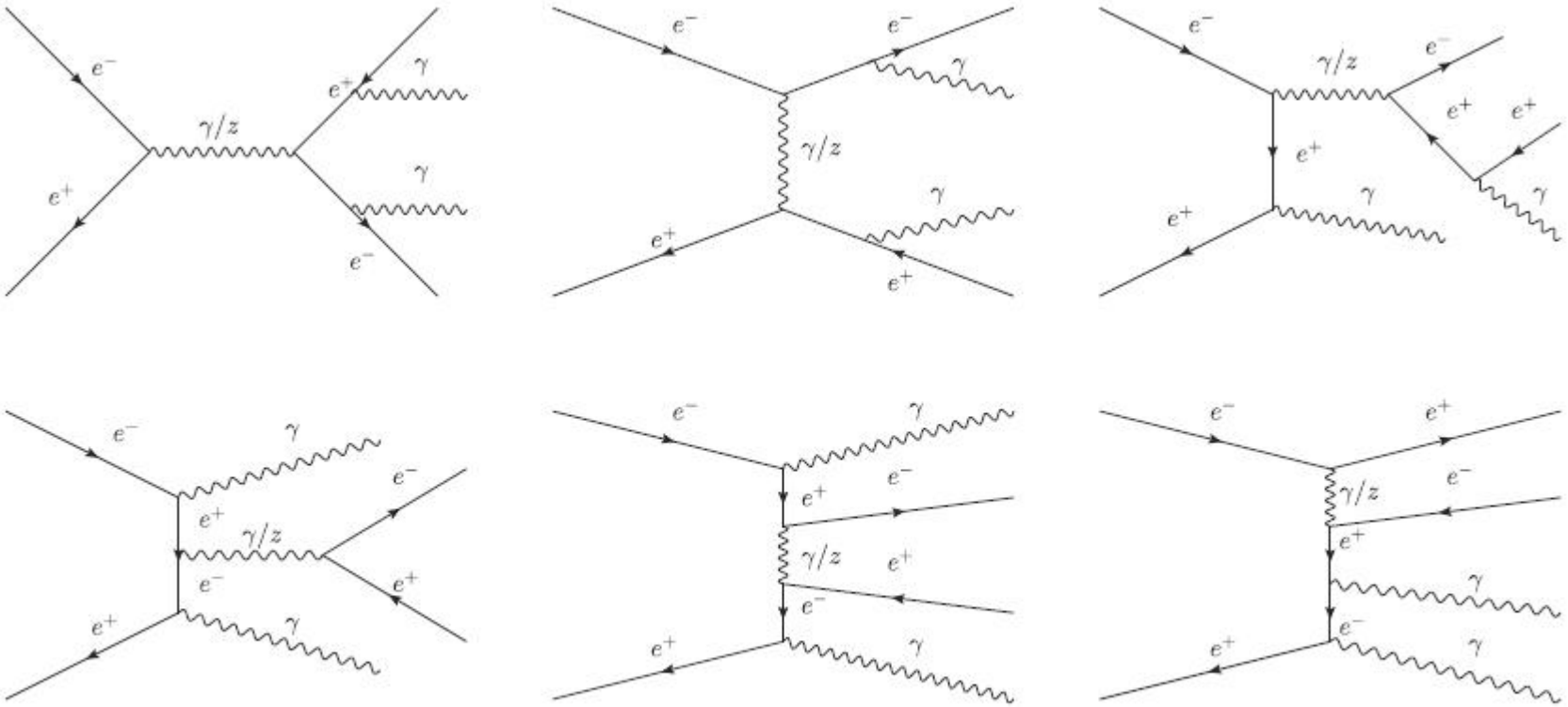


FIG. 3. The typical diagrams for the background of the process $e^+e^- \to \gamma\gamma e^+e^-$.

Detecting ALPs at the FCC-ee

Cuts	$\sqrt{s} = 365$ GeV	$\sqrt{s} = 91$ GeV
Cut-1: Electron and positron pseudo-rapidity	$0.6 < \eta(e^+) < 2.5$	$-0.3 < \eta(e^+) < 0.9$
	$-2.5 < \eta(e^-) < -0.6$	$-0.9 < \eta(e^-) < 0.3$
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 ALP	$p_T(\gamma\gamma) > 50$ GeV	$p_T(\gamma\gamma) > 20$ GeV

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)

Detecting ALPs at the FCC-ee

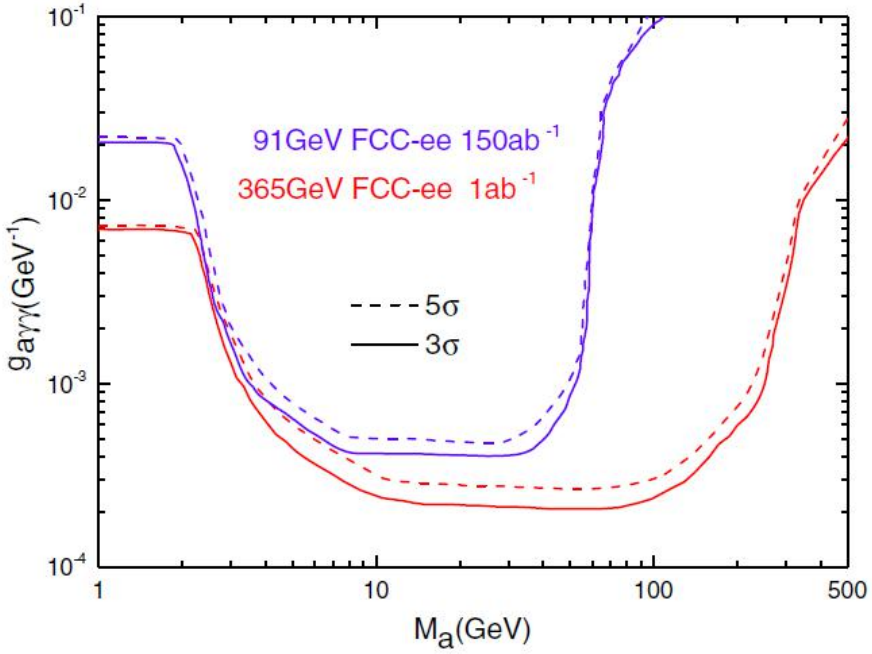


FIG. 5. The 3σ and 5σ curves in the $M_a - g_{a\gamma\gamma}$ plane for $e^+e^- \to \gamma\gamma e^+e^-$ induced by ALP at 365 GeV and 91 GeV FCC-ee with the designed luminosities.

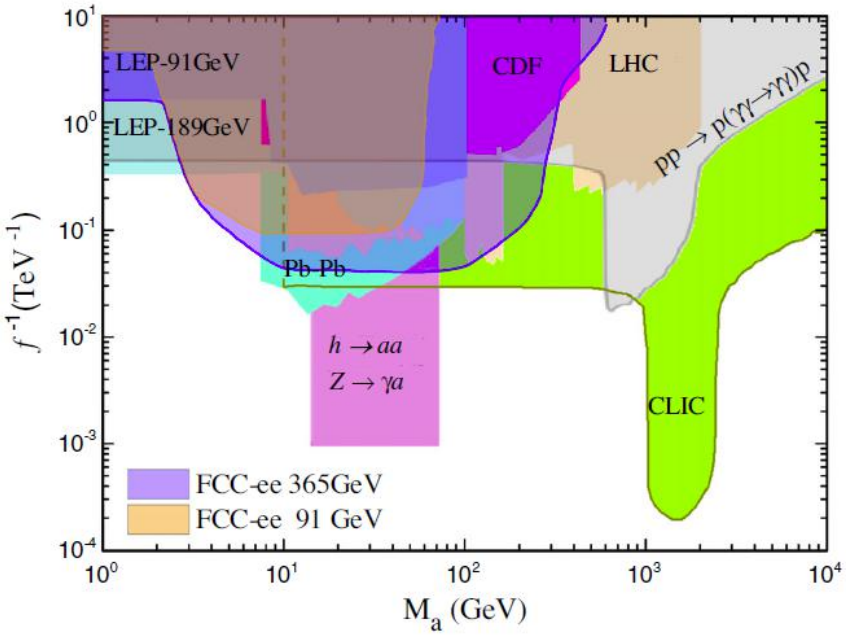


FIG. 6. The 95% C.L. exclusion regions on the ALP couplings $g_{a\gamma\gamma}$ as function of M_a from the process $e^+e^- \to \gamma\gamma e^+e^-$ at FCC-ee and other current exclusion regions.

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 ALP	$p_T(\gamma\gamma) > 45$ 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)

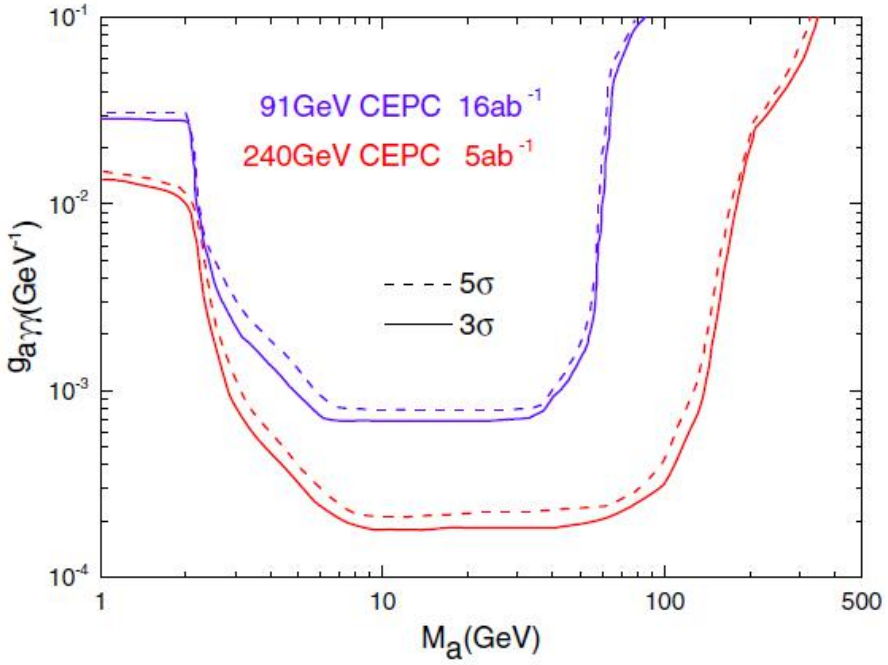


FIG. 8. The 3σ and 5σ curves in the $M_a - g_{a\gamma\gamma}$ plane for $e^+e^- \to \gamma\gamma e^+e^-$ induced by ALP at 240 GeV and 91 GeV CEPC with designed luminosities.

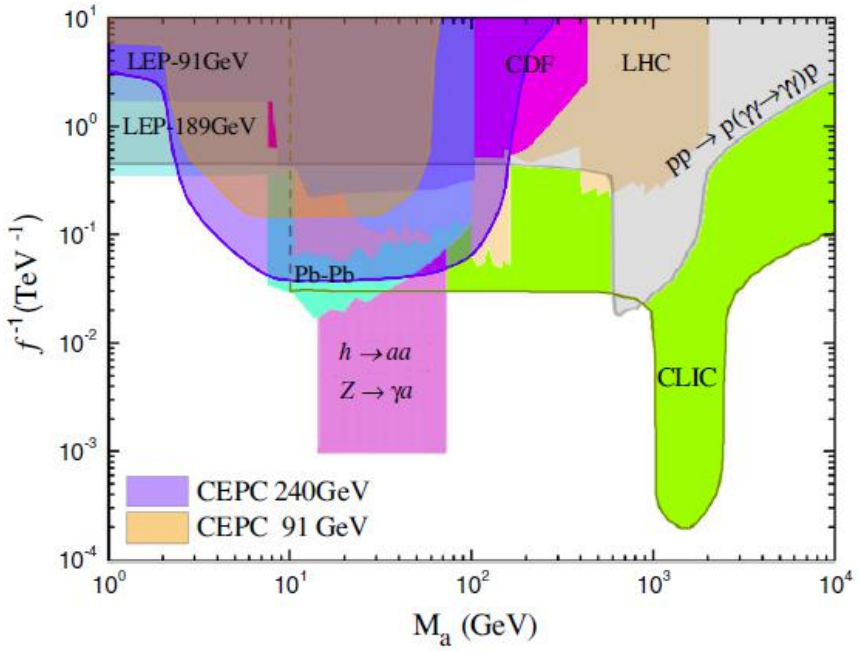


FIG. 9. The 95% C.L. exclusion regions on the ALP couplings $g_{a\gamma\gamma}$ as function of M_a from the process $e^+e^- \to \gamma\gamma e^+e^-$ at the CEPC and other current exclusion regions.

Summary

- Unlike the QCD axion, the mass and the couplings of ALPs might be independent free parameters. ALPs have a much wider parameter space and hen generate rich phenomenology at colliders.
- We have investigated the observabitlity of the ALP diphoton signal through the light-by-light process at the FCC-ee and CEPC.
- Although the detectable mass ranges of the FCC-ee and CEPC are small, it is found that the bounds are stronger than thoese given by the LBL scattering at the LHC in the mass range 2~8 GeV.