Long-lived ALP Searches with Far Detectors at the Electron Positron Collider (FADEPC)

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Based on **Minglun Tian**, K. Wang, and Zeren Simon Wang
[hep-ph/2201.08960, PRD 101 (2020) 075046]

OUTLINE

FADEPC

→ geometry, shape, volume, position, ...

→ previous physics scenarios

Long-lived ALP Searches

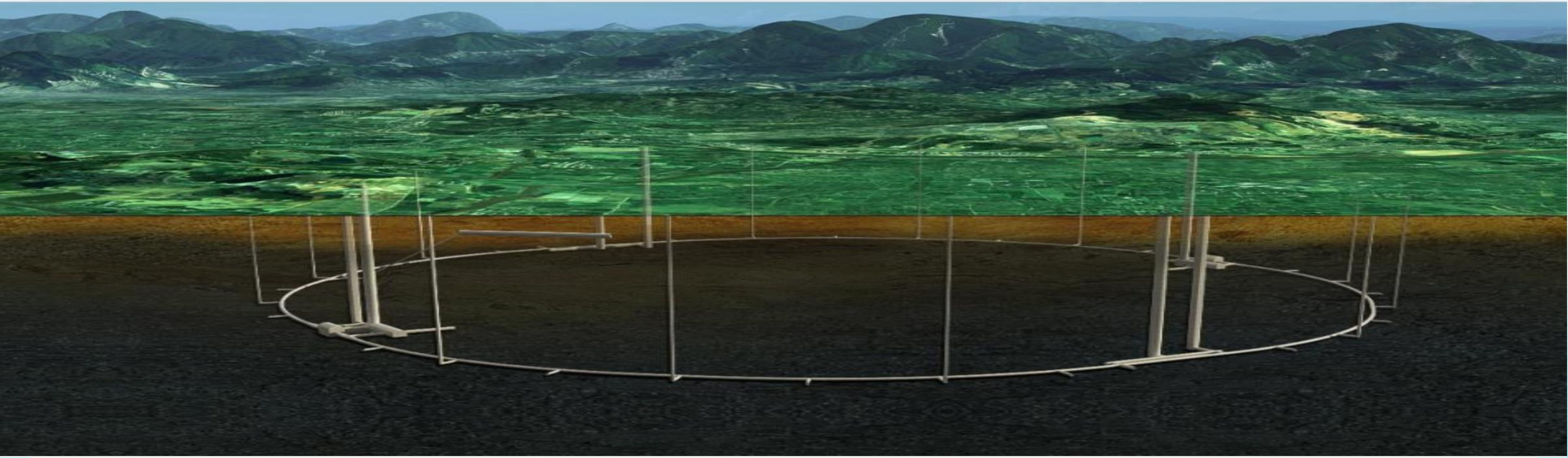
→ $C_{\gamma Z} = 0$

→ $C_{\gamma Z} = C_{\gamma\gamma}$

→ free $C_{\gamma Z}, C_{\gamma\gamma}$ parameters

Conclusion & Discussion

CEPC Civil Engineering



FDs can be placed on the ground above the IPs.

CEPC Civil Engineering

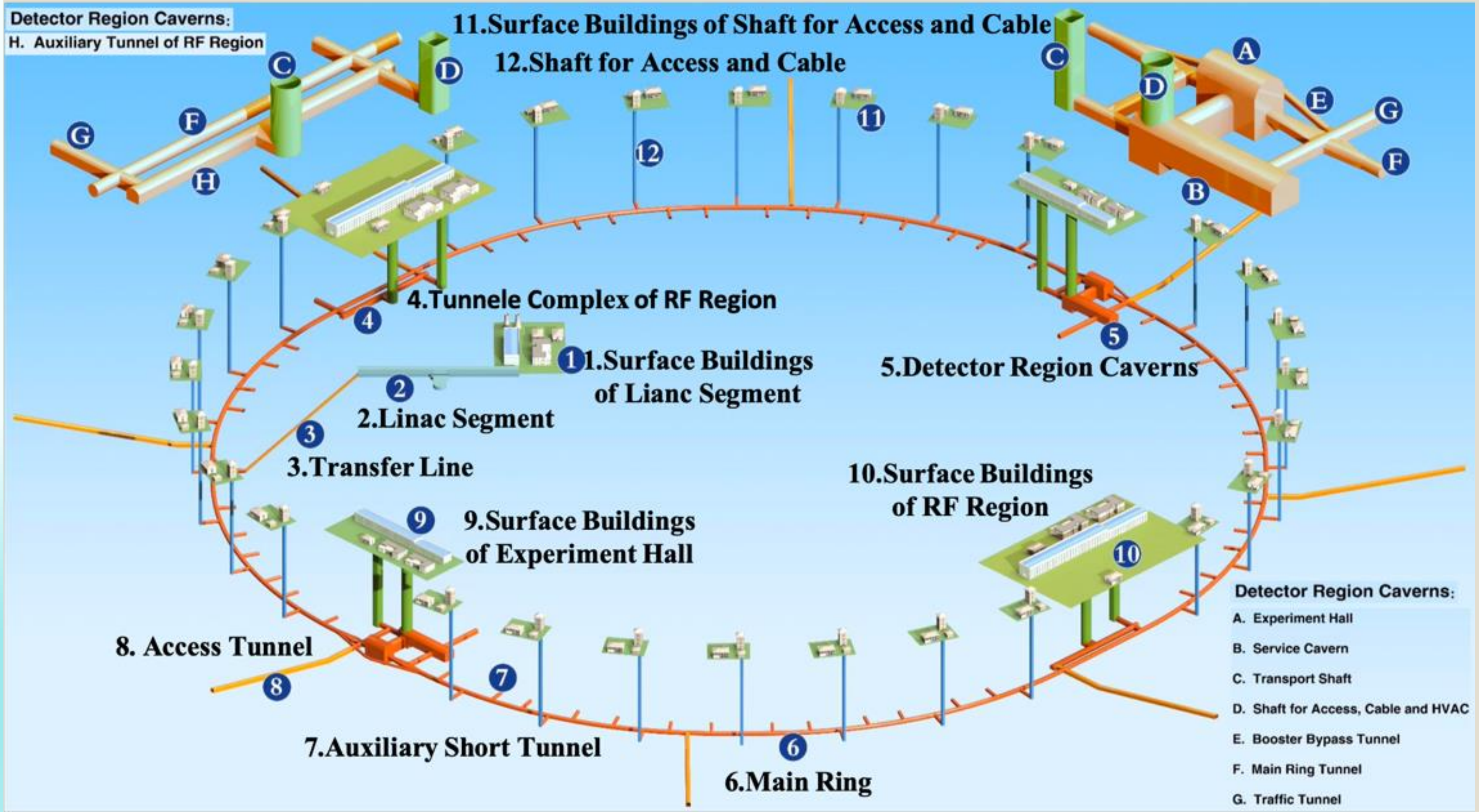


Figure based on [Lei Ye, Workshop on the Circular Electron-Positron Collider, Oxford, (2019)]

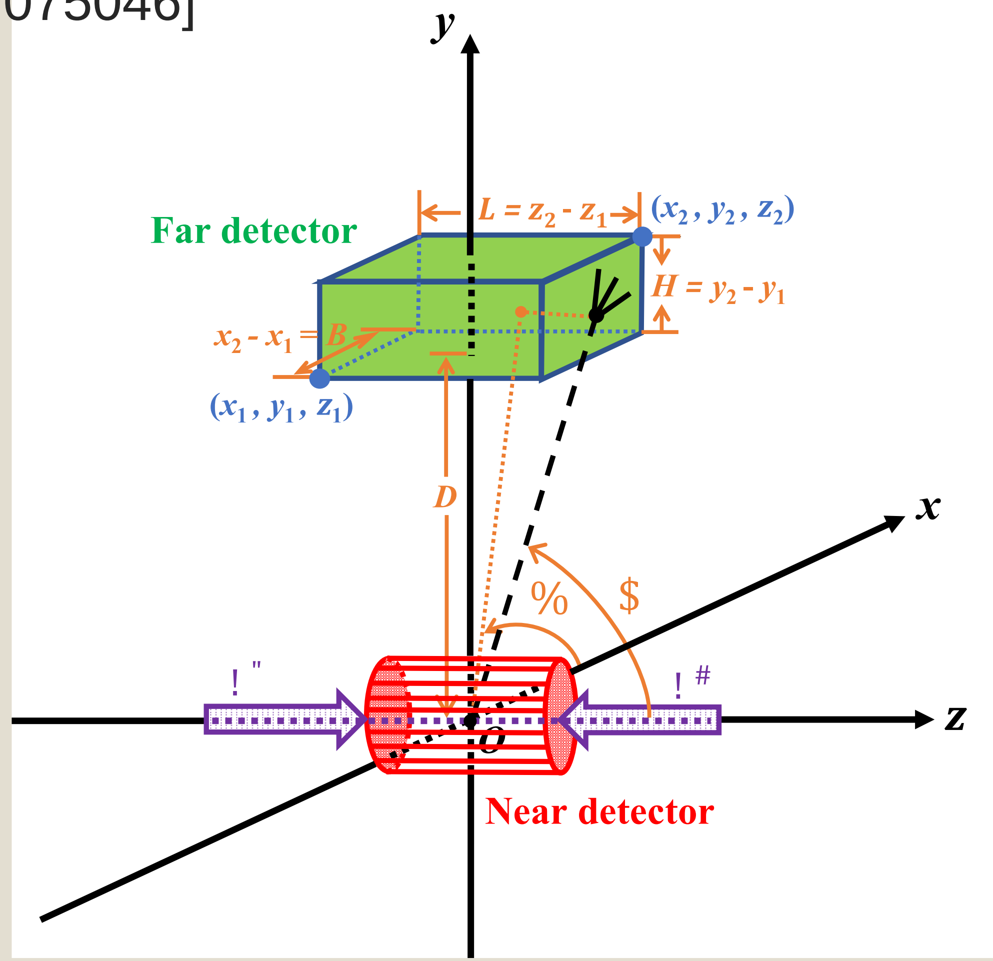
FDs can also be placed inside the experiment hall if the hall is big enough.

Or, placed in a cavern or shaft near the experiment hall.

Far Detectors at the Electron Positron Collider (FADEPC)

First proposed & different designs of FDs in [PRD 101 (2020) 075046]

	V [m^3]	B [m]	H [m]	L [m]	(x_1, y_1, z_1) [m]	(x_2, y_2, z_2) [m]	D [m]
FD1	5.0×10^3	10	10	50	(5, -5, -25)	(15, 5, 25)	5
					(10, -5, -25)	(20, 5, 25)	10
FD2	8.0×10^5	200	20	200	(-100, 50, 50)	(100, 70, 250)	50
					(-100, 100, 100)	(100, 120, 300)	100
FD3	8.0×10^5	200	20	200	(-100, 50, -100)	(100, 70, 100)	50
					(-100, 100, -100)	(100, 120, 100)	100
FD4	8.0×10^5	100	80	100	(-50, 50, -50)	(50, 130, 50)	50
					(-50, 100, -50)	(50, 180, 50)	100
FD5	3.2×10^6	200	80	200	(-100, 50, -100)	(100, 130, 100)	50
					(-100, 100, -100)	(100, 180, 100)	100
FD6	8.0×10^7	1000	80	1000	(-500, 50, -500)	(500, 130, 500)	50
					(-500, 100, -500)	(500, 180, 500)	100
FD7	8.0×10^5	2000	20	20	(-1000, 50, -10)	(1000, 70, 10)	50
					(-1000, 100, -10)	(1000, 120, 10)	100
FD8	8.0×10^5	20	20	2000	(-10, 50, -1000)	(10, 70, 1000)	50
					(-10, 100, -1000)	(10, 120, 1000)	100



Simple shape: cuboid, similar to MUTHUSLA
Varying: position & geometry size

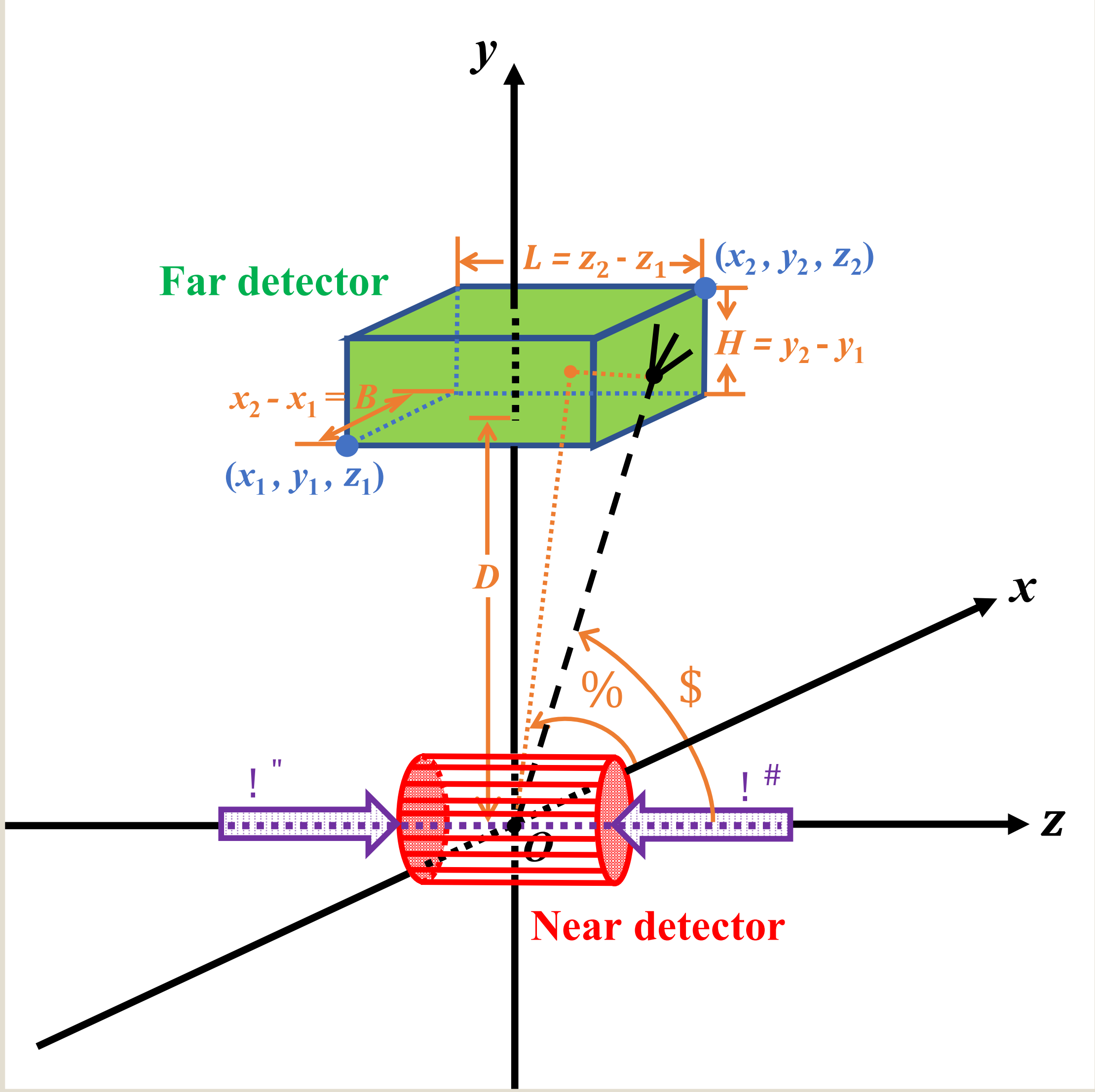
LLP Searches with FADEPC

When $\lambda \sim \mathcal{O}(100)$m,

Mainly travel through and acts as missing energy in the near detector.

Far detector is more likely to observe the decay process, and reconstruct the time, position, direction, momentum, mass, etc.

Far detector can enhance the discovery potential for LLPs with very long decay length.



Previous Physics Scenarios

		Exotic Higgs Decays	Heavy Neutral Leptons	Light Neutralinos in RPV SUSY	
scenario		$h \to XX$	$Z \to N\nu$	$Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$	
LLP		X light scalar	N	$\tilde{\chi}_1^0$ light fermion	
production $e^-e^+ \to$		Zh (main) $\nu\bar{\nu}h, e^-e^+h$ (VBF)	Z		
$\sqrt{s}$ [GeV]		240	91.2		
N_h	CEPC FCC-ee	1.14×10^6 [16] 5.6 ab^{-1}, 7 years, 2 IPs	-		
N_Z	CEPC	-	7.0×10^{11} [16]		**16 ab^{-1}**, 2 years, 2 IPs
	FCC-ee		5.0×10^{12} [20]		**150 ab^{-1}**, 4 years, 2 IPs

has been updated to 1.5×10^{12}

Results shown in [PRD 101 (2020) 075046]

ALP lagrangian

5 dimension ALP effective lagrangian

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + g^2 C_{WW}\frac{a}{\Lambda}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

electroweak symmetry breaking

$$\mathcal{L}_{\rm eff} \supset e^2 C_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}C_{\gamma Z}\frac{a}{\Lambda}F_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}C_{ZZ}\frac{a}{\Lambda}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\,.$$

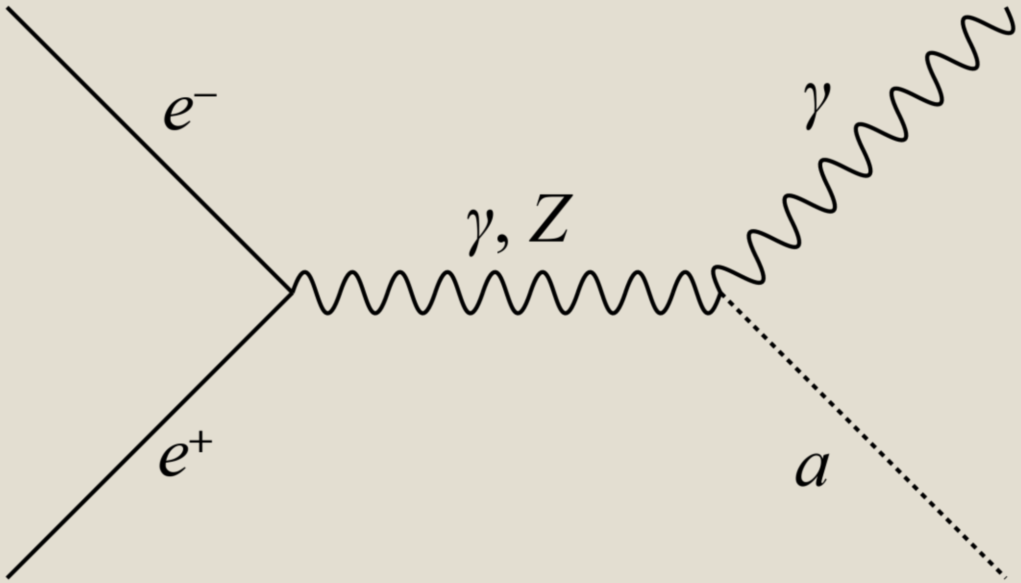
$$C_{\gamma\gamma} = C_{WW} + C_{BB}$$
$$C_{\gamma Z} = c_w^2 C_{WW} - s_w^2 C_{BB}$$
$$C_{ZZ} = c_w^4 C_{WW} + s_w^4 C_{BB}$$

arxiv:1808.10323

ALP Signal

$e^- e^+ \longrightarrow \gamma a, a \longrightarrow \gamma\gamma$

@ $\sqrt{s}$ = 91.2 GeV



import ALP model in Madgraph5 to simulate the event
arxiv:1701.05379

PYTHIA8: perform ALP decay

$$\Gamma(a \to \gamma\gamma) = 4\pi\alpha^2 m_a^3 \left|\frac{C_{\gamma\gamma}}{\Lambda}\right|^2$$

arxiv:1808.10323

ALP Signal

differential cross section

$$\frac{d\sigma(e^-e^+\to\gamma a)}{d\Omega}=2\pi\alpha\alpha^2(s)\frac{s^2}{\Lambda^2}\left(1-\frac{m_a^2}{s}\right)^3(1+\cos^2\theta)\times\left(|V_\gamma(s)|^2+|A_\gamma(s)|^2\right)$$

$$V_\gamma(s)=\frac{C_{\gamma\gamma}}{s}+\frac{g_V}{2c_w^2s_w^2}\frac{C_{\gamma Z}}{s-m_Z^2+im_Z\Gamma_Z}$$

$$A_\gamma(s)=\frac{g_A}{2c_w^2s_w^2}\frac{C_{\gamma Z}}{s-m_Z^2+im_Z\Gamma_Z}$$

$$g_V=2s_w^2-1/2 \text{ and } g_A=-1/2$$

arxiv:1808.10323

ALP Signal

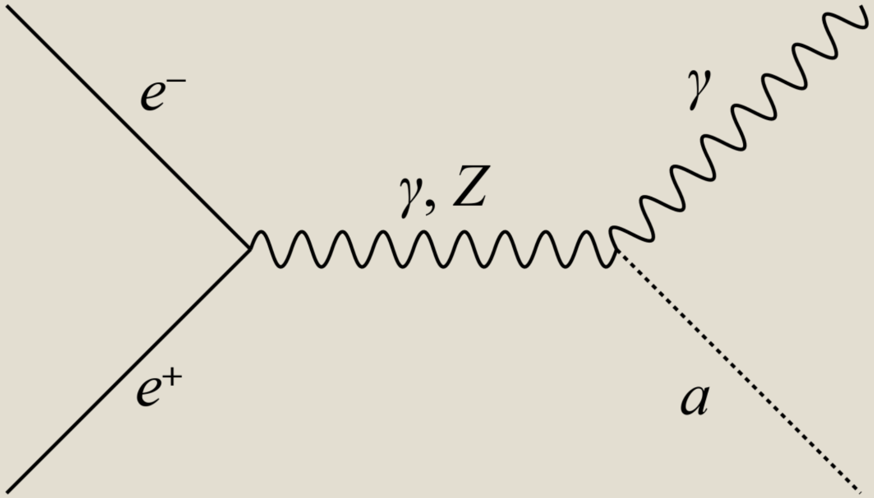
$$\mathcal{L}_{\rm eff} \supset e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}\,.$$

$$\sigma(e^-e^+ \to \gamma\, a) \approx 16\,\text{fb} \times \left(\frac{\text{TeV}}{\Lambda}\right)^2 \left(1 - \frac{m_a^2}{s}\right)^3 \left(|C_{\gamma\gamma}|^2 + 2680\,|C_{\gamma Z}|^2 - 0.082\,|C_{\gamma\gamma} C_{\gamma Z}|\right)$$

$$\Gamma(a \to \gamma\gamma) = 4\pi\alpha^2 m_a^3 \left|\frac{C_{\gamma\gamma}}{\Lambda}\right|^2$$

$e^-e^+ \longrightarrow \gamma a,\, a \longrightarrow \gamma\gamma$

@ $\sqrt{s} = 91.2$ GeV



Number of Signal Events

$$N_{\rm LLP}^{\rm obs} = N_{\rm LLP}^{\rm prod} \cdot \langle P[\text{LLP in f.v.}]\rangle \cdot \text{Br}(\text{LLP} \to \text{visible})$$

average decay probabilities in FD

$$P[(\text{ALP})_i \text{ in f.d.}] = e^{\left(-D_i^{\rm first}/\lambda_i\right)} - e^{\left(-D_i^{\rm last}/\lambda_i\right)}$$

probability of decaying inside the FD

in the lab. frame:

$$\lambda = \beta c\,\gamma\tau = \frac{p}{E}\frac{E}{m}c\tau = \frac{p}{m}c\tau$$

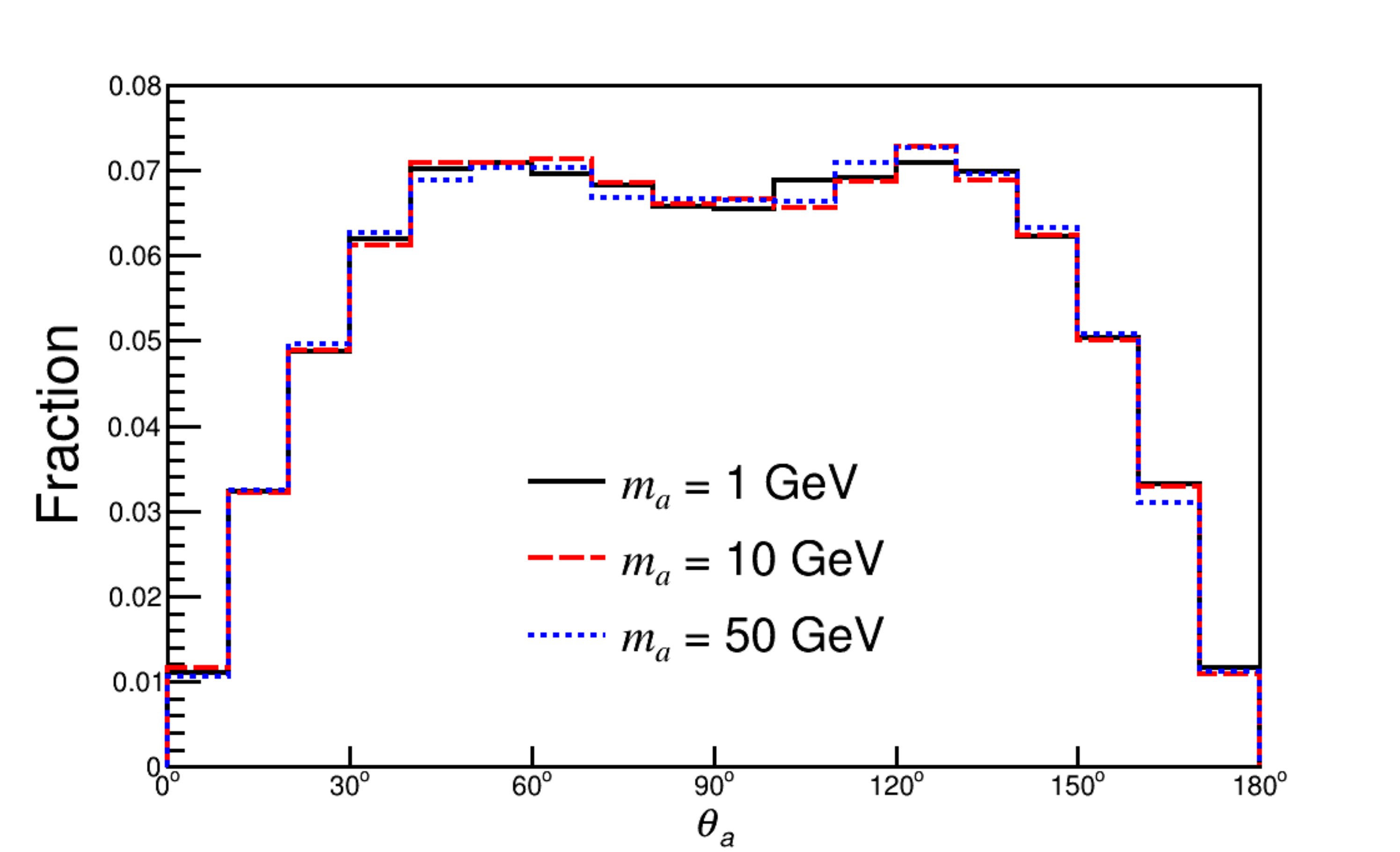
$$\lambda_i \approx 15\,\text{m}\left(\frac{s - m_a^2}{m_a\sqrt{s}}\right)\left(\frac{\text{GeV}}{m_a}\right)^3\left(\frac{\Lambda}{\text{TeV}}\right)^2\left(\frac{10^{-4}}{C_{\gamma\gamma}}\right)^2$$

# of signal events

In general, depends on theory models (kinematics, parameters) & geometry of FD

For fixed FD & ALP model: a complicated function of model parameters: $C_{\gamma\gamma}/\Lambda$, $C_{\gamma Z}/\Lambda$ & m_a

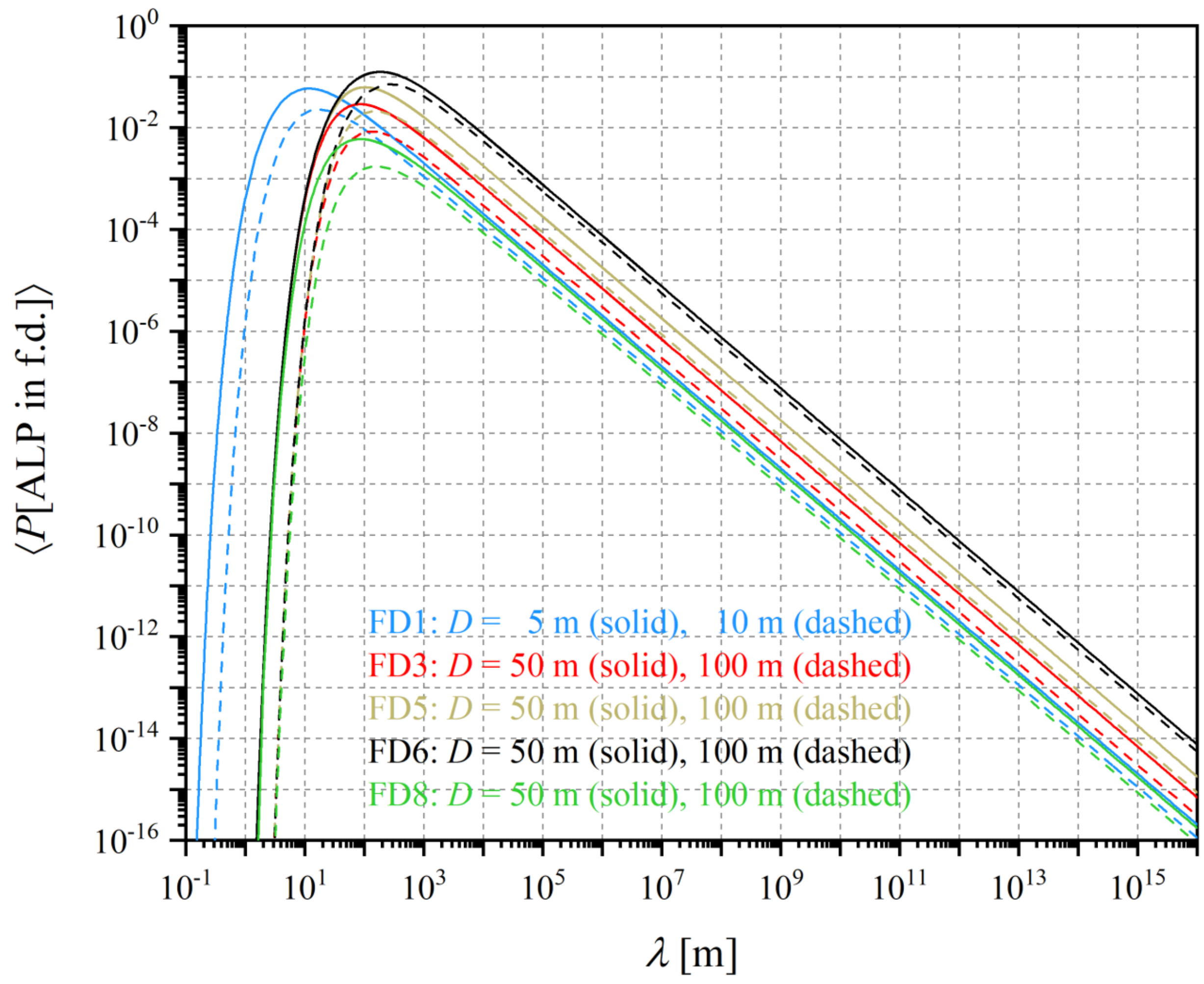
Kinematical Distributions



Two peaks around $90^\circ \pm 40^\circ$

FDs in the very forward direction like FASER may not work at ee colliders.
Better to be installed in the central region.

Average Decay Probabilities

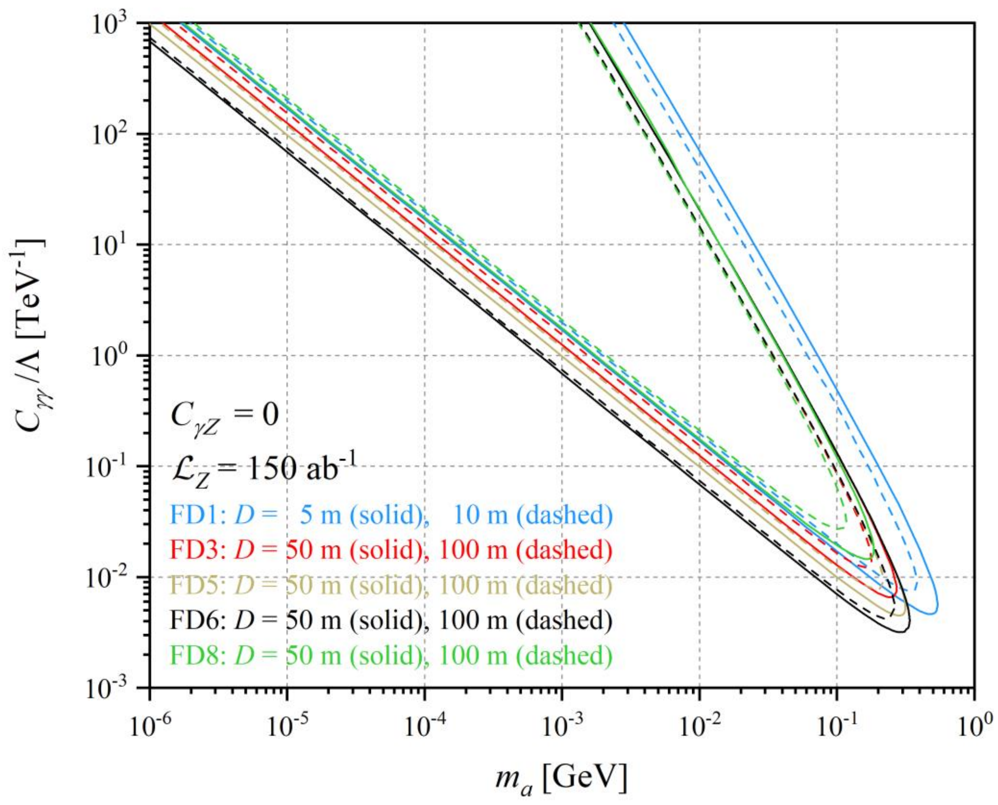


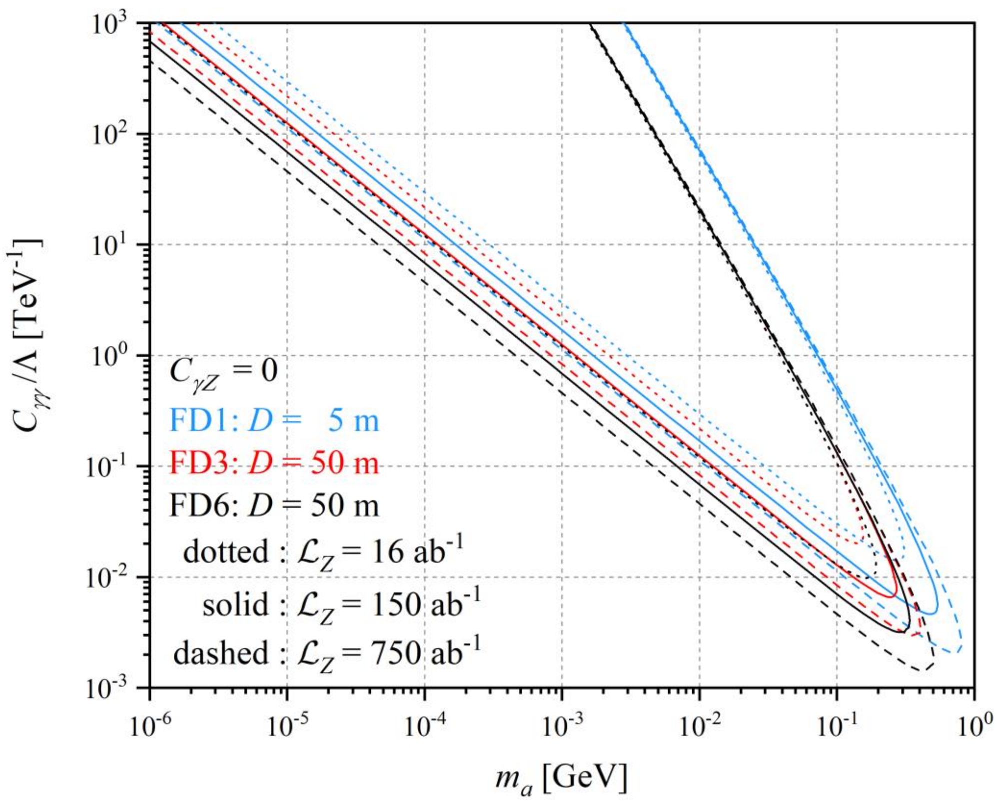
FDs with smaller distance from the IP have higher probabilities

⇒ Closer distance is helpful to improve the discovery potentials.

The decay lengths λ corresponding to peak values are slightly higher than D.

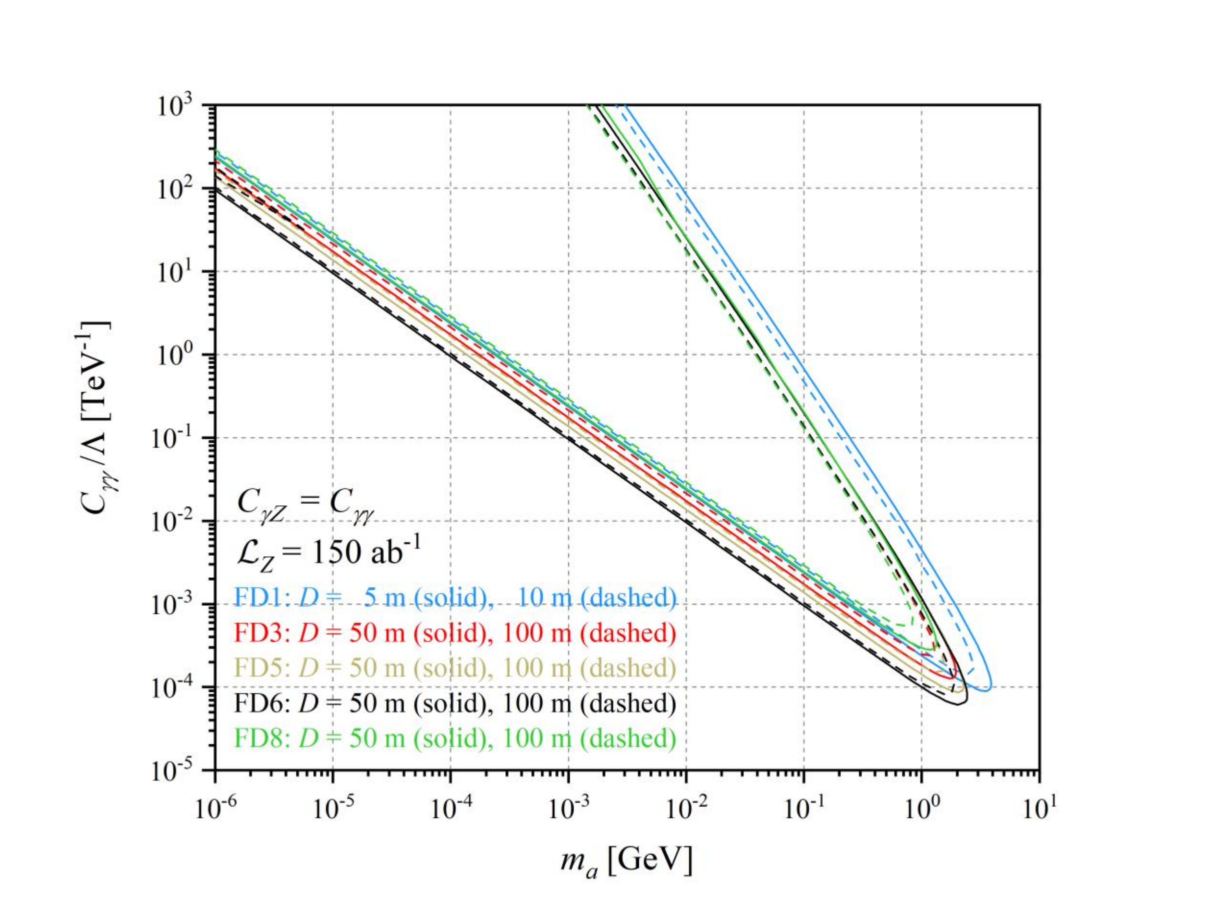
Limits for $C_{\gamma Z} = 0$

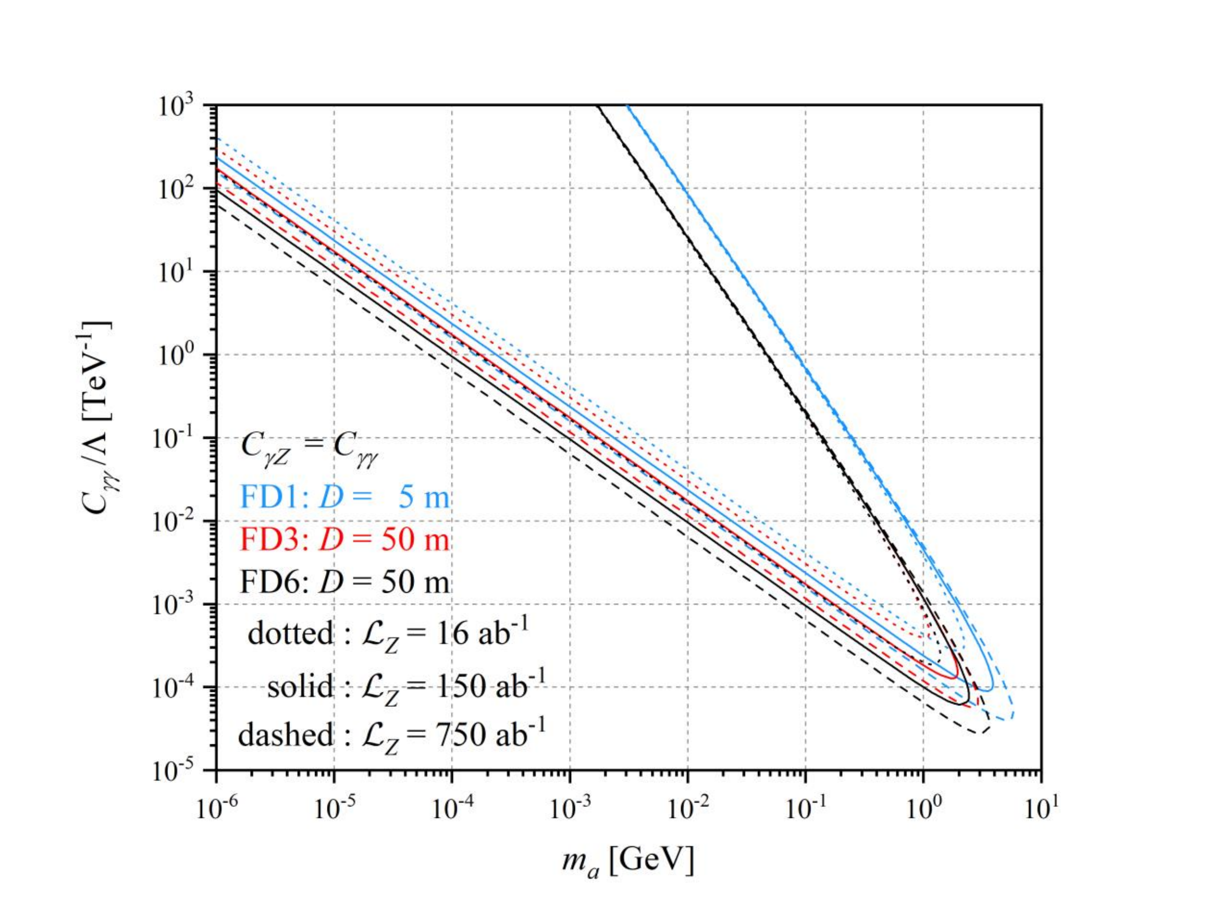




smaller D , bigger V , perpendicular location → stronger discovery limits

Limits for $C_{\gamma Z} = C_{\gamma\gamma}$

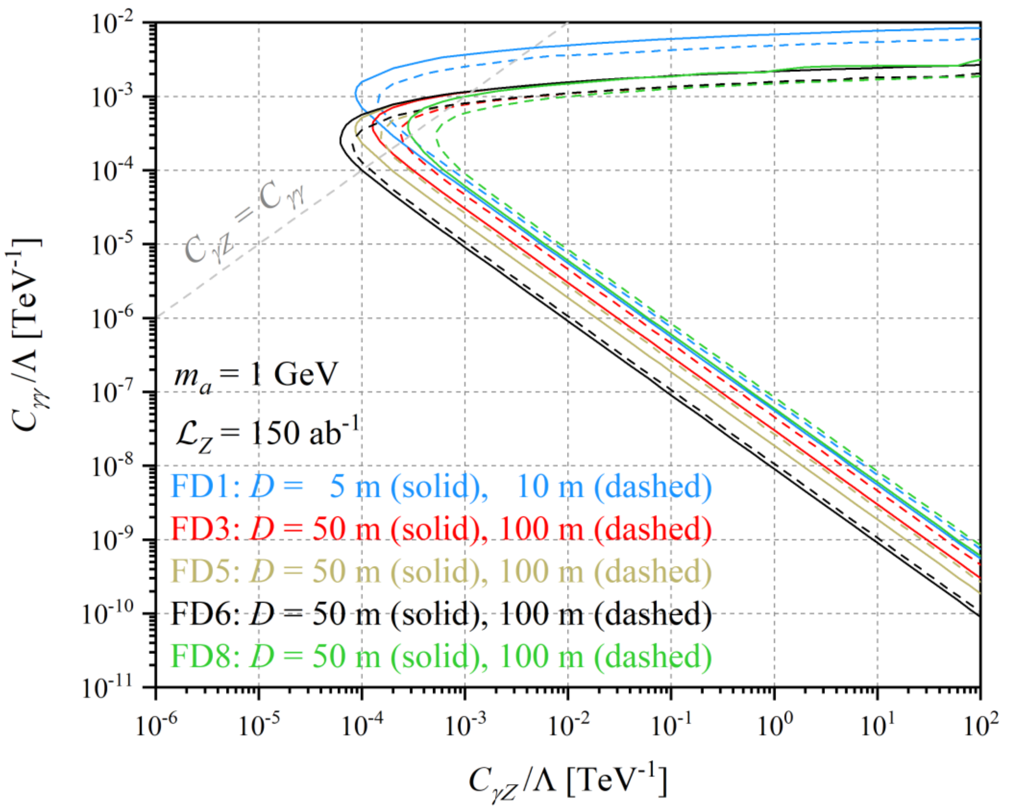


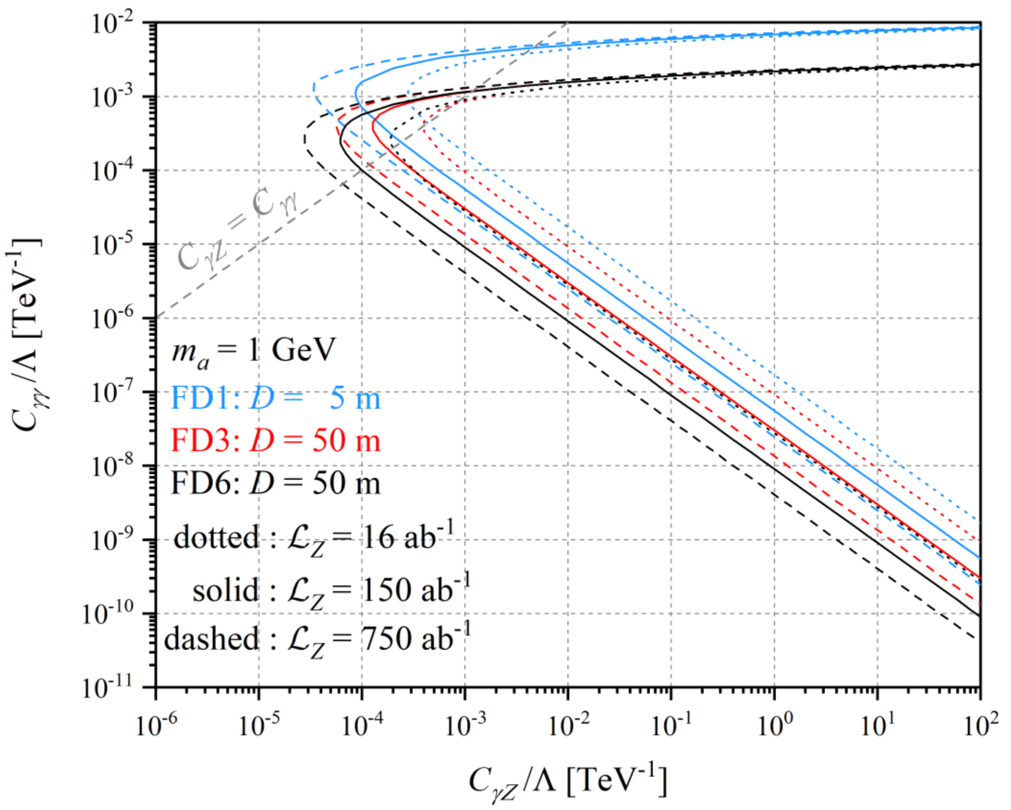


→ Lower $C_{\gamma\gamma}/\Lambda$, slightly larger m_a reaches

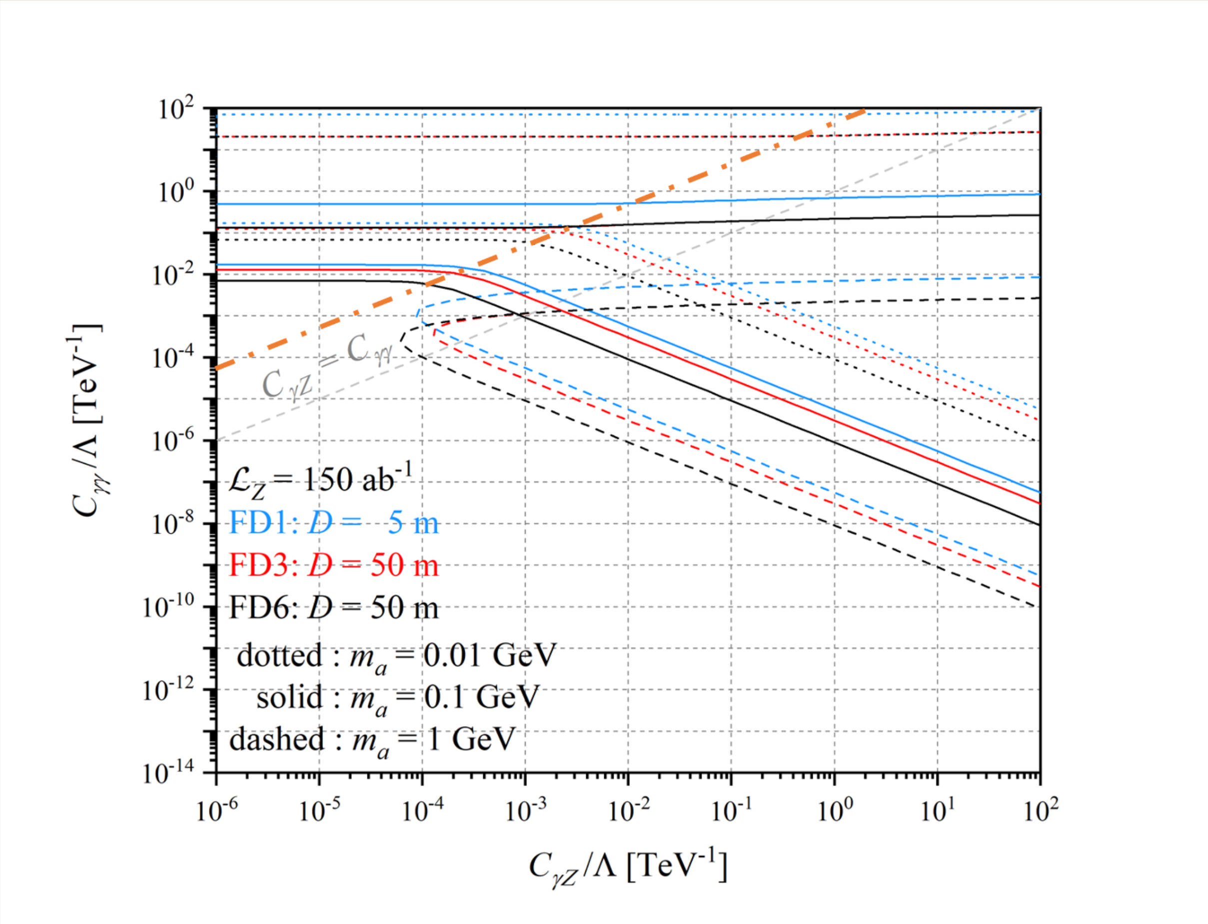
→ Larger luminosity is helpful to probe more parameter space with lower $C_{\gamma\gamma}/\Lambda$

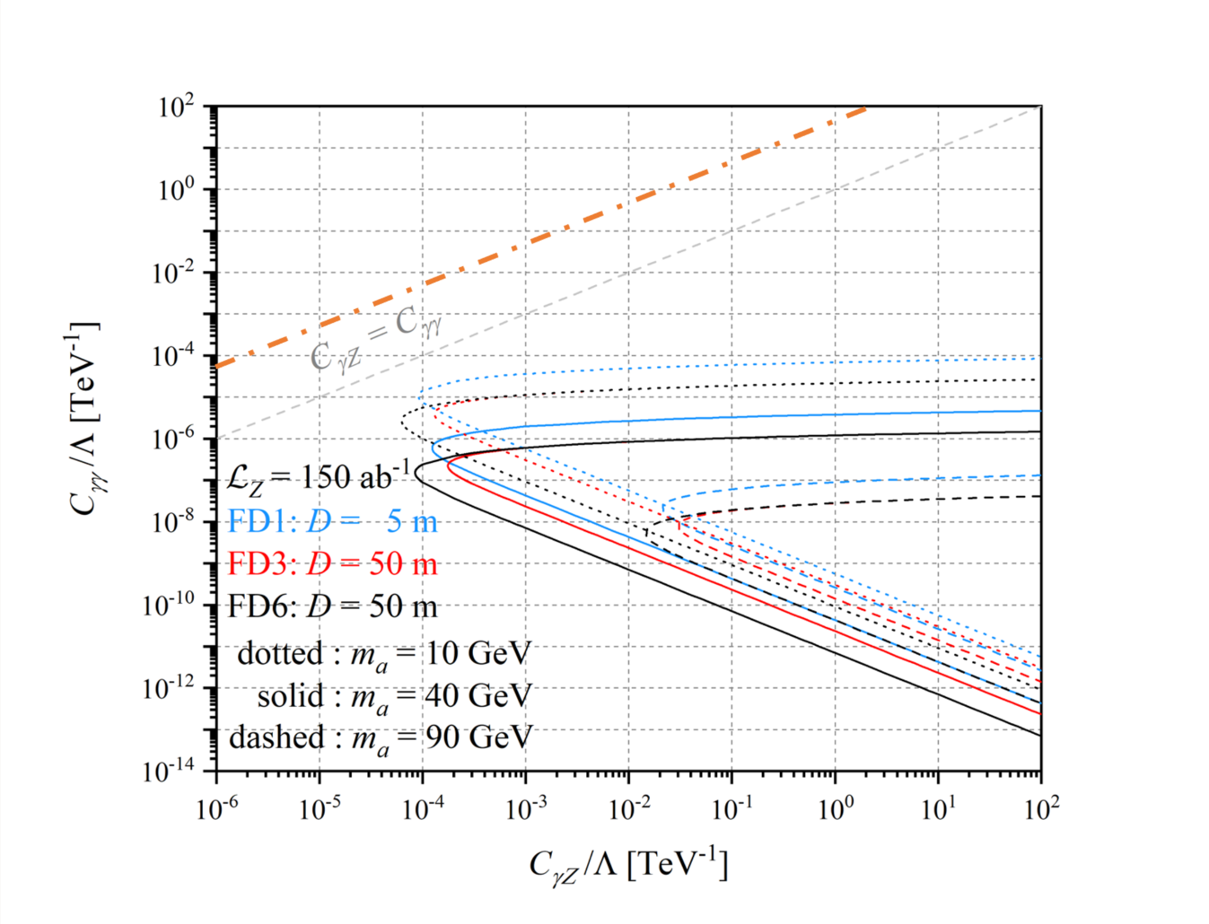
Limits for Free $C_{\gamma Z}, C_{\gamma\gamma}$ Parameters





Free $C_{\gamma Z}, C_{\gamma\gamma}$ Parameters





→ Discoverable regions shift downward with increasing m_a

→ Discovery regions shift rightward when m_a > 40 GeV

Conclusion

Proposed to install Far Detectors at the Electron Positron Collider (FADEPC), such as at CEPC & developed 8 basic designs

Previous LLP searches for $Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, $Z \to \nu N$, $h \to XX$ physics scenarios.

ALP signal from $e^- e^+ \longrightarrow \gamma a, a \longrightarrow \gamma\gamma$ @ $\sqrt{s}$ = 91.2 GeV

Forecast limits for 3 cases: $C_{\gamma Z} = 0$; $C_{\gamma Z} = C_{\gamma\gamma}$; free $C_{\gamma Z}$,$C_{\gamma\gamma}$ parameters

Smaller D , bigger V , perpendicular location → stronger discovery limits

Larger luminosity is helpful to probe more parameter space with lower $C_{\gamma\gamma}/\Lambda$.......

Discussion

Long-lived ALP searches with ND @ CEPC

To realize such FDs, more pre-studies are needed.

For example:

More designs.

Investigate the physics potential and optimize the designs in the context of more physics scenarios, different center-of-mass energies, background analysis.

Take into account more realistic factors, including the availability of the space, the technology, cost and shielding of the detectors, the reusing possibility at the SppC/FCC-hh.

Consider other applications: probing neutrinos, cosmic rays, etc.

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