Sensitivity of the FCC-ee to axion-like particles at different center-of-mass energies

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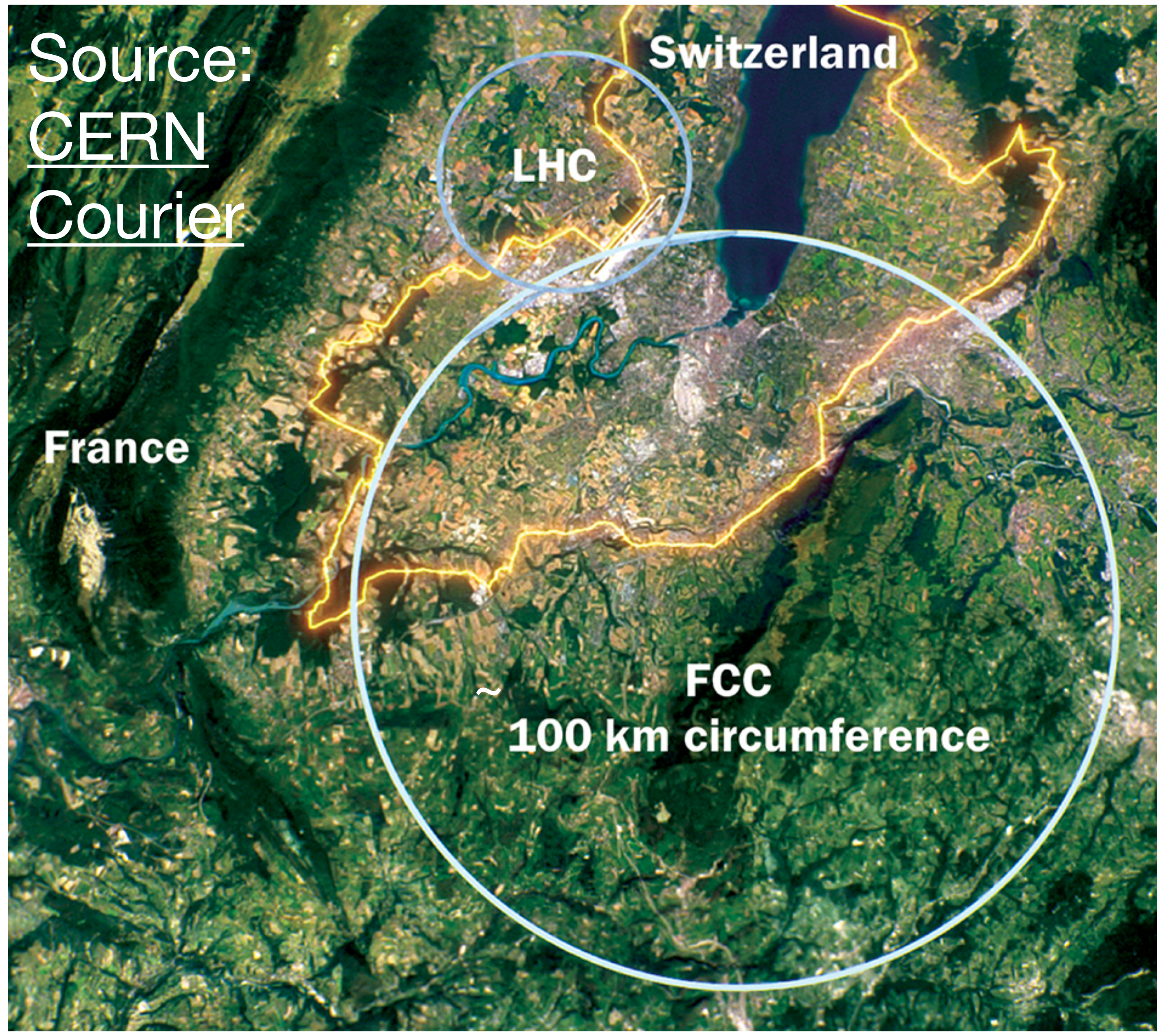
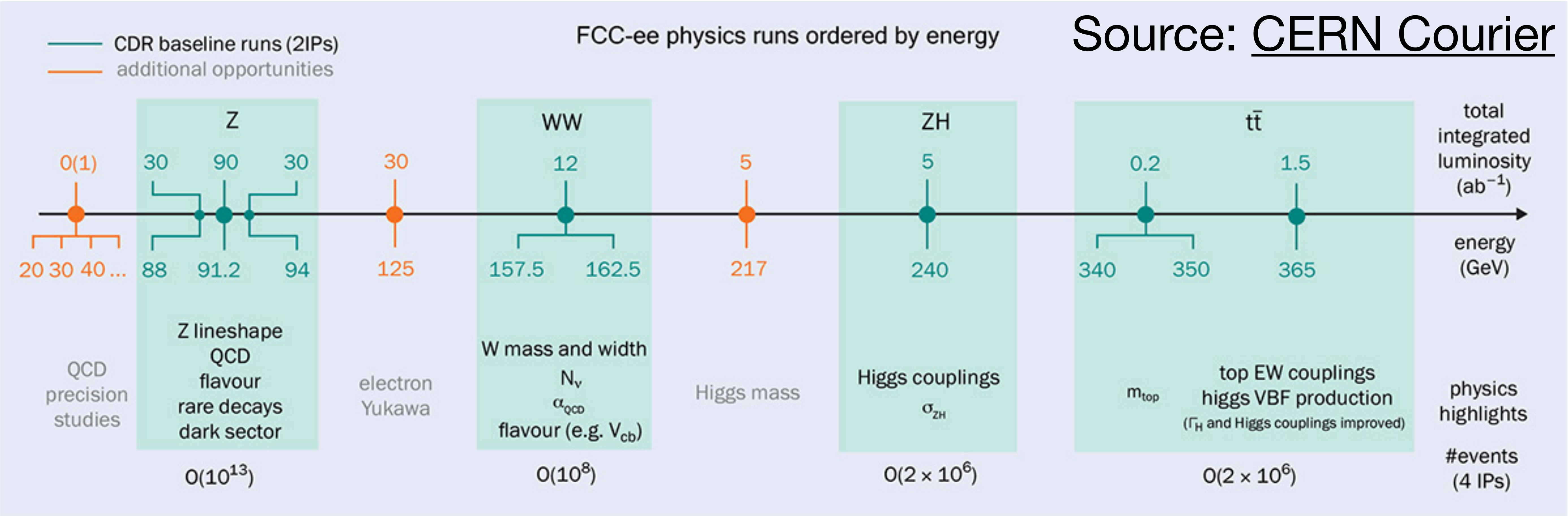
Motivation — why ALPs at the FCC-ee?

Future Circular Collider electron-positron collider (FCC-ee)

- The next flagship collider at CERN preferred by the CERN council
  - Has incredible potential for both new physics searches and precision measurements
- It is planned to operate at four center-of-mass energies:
  - Z pole (~91 GeV)
  - WW threshold (160 GeV)
  - ZH threshold (240 GeV)
  - $t\bar{t}$ threshold (365 GeV)





Motivation — why ALPs at the FCC-ee?

Axion-Like Particles (ALPs)

- Hypothetical pseudoscalars that arise from theories with spontaneously broken approximate global symmetries
  - Generalization of the QCD axion, but the masses and couplings are independent
  - Occur in many extensions of the Standard Model
- Well-motivated, generic new physics scenario → potential dark matter mediators/candidates
- Broad phenomenology → huge range of masses and couplings
  - Depending on the mass and coupling, they can be prompt or long-lived
  - Complementary search strategies: colliders, beam dumps, helioscopes, light-shining through a wall (ALPs II), astrophysics

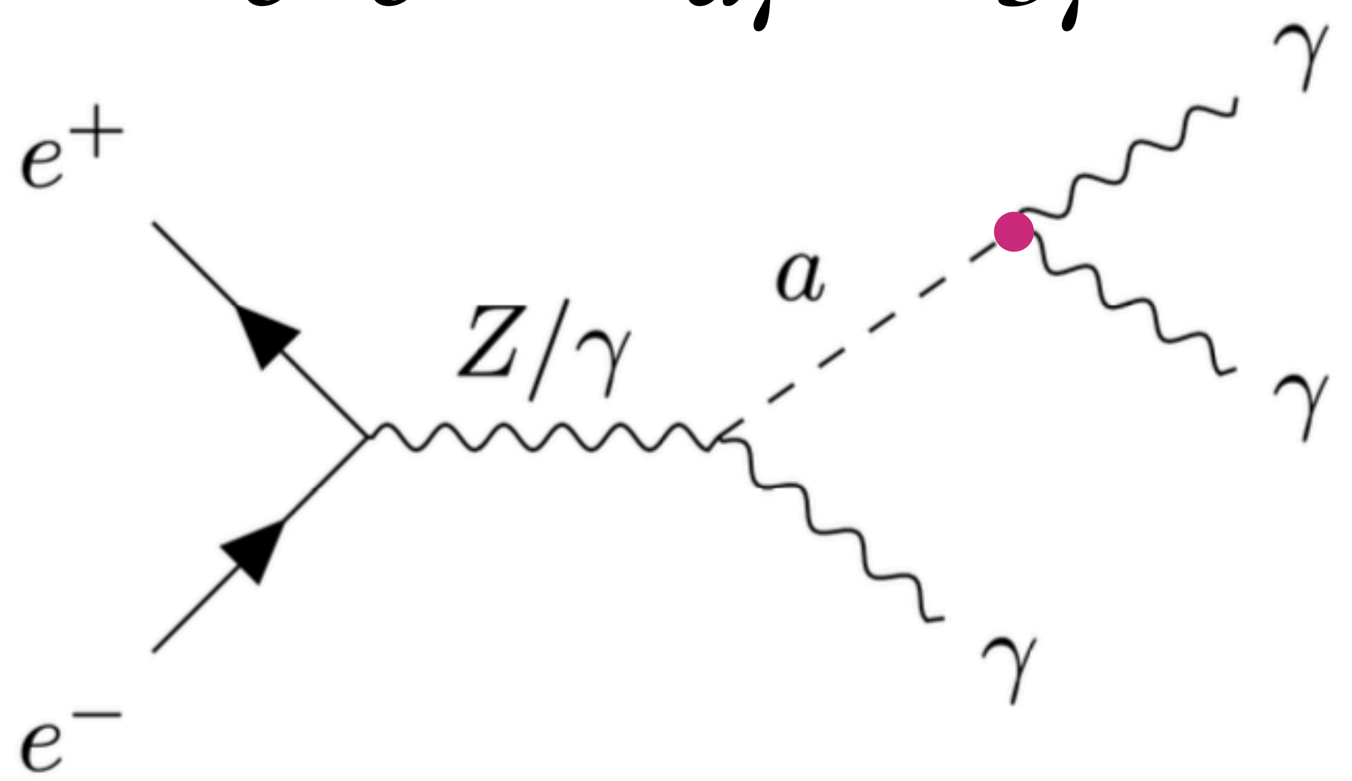
Source: New Scientist

Existing limits and sensitivity projections

- Existing limits (in MeV-TeV ALP mass range) come from collider searches, beam dump and fixed-target experiments, and astrophysical bounds
- At the FCC-ee, high luminosity at Z pole means that we can probe small couplings for $m_a < 90$ GeV (Polesello:arXiv:2502.08411)
- At higher center-of-mass energies, we can probe higher masses

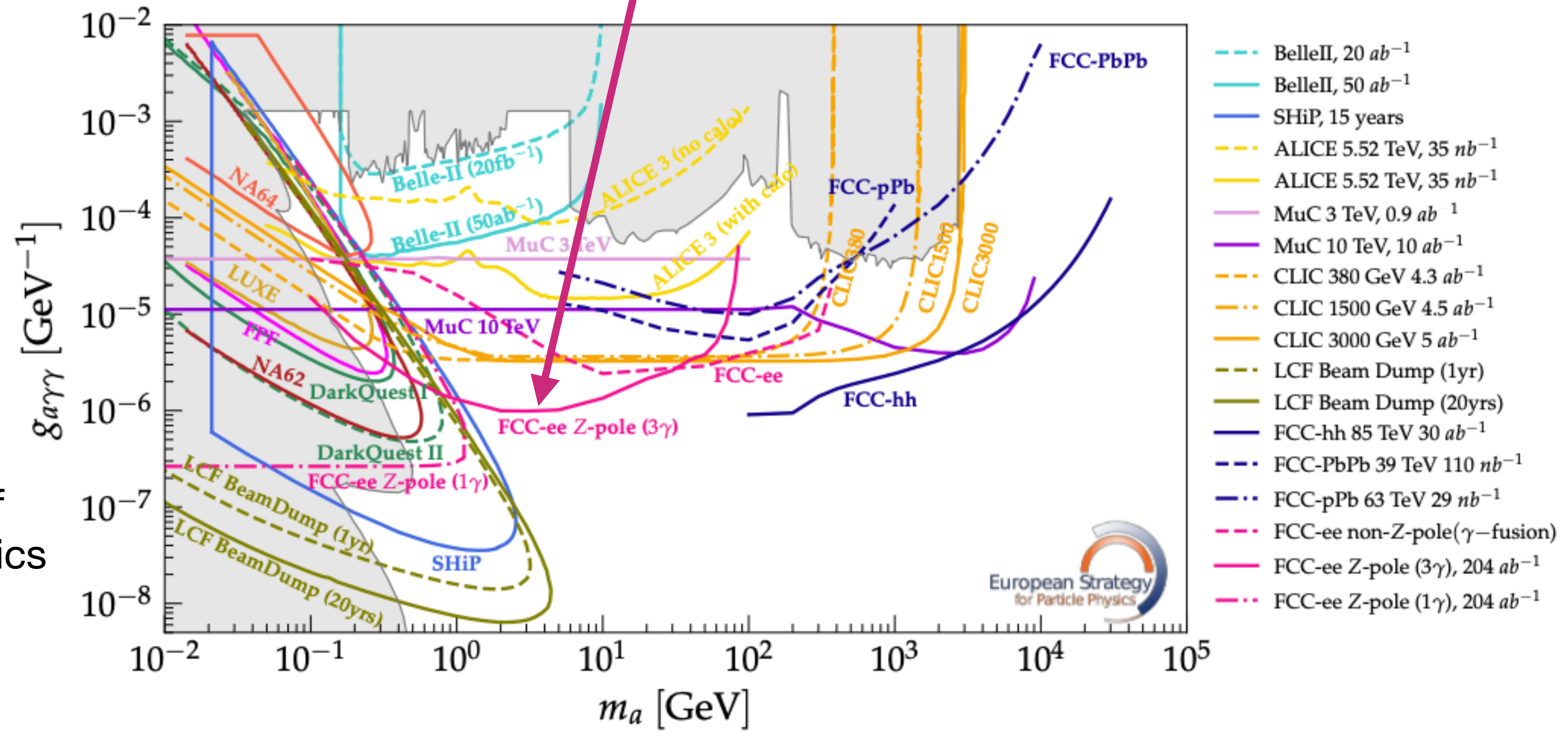
signal:

$$e^+e^- \to a\gamma \to 3\gamma$$



$$g_{a\gamma\gamma} = 4e^2 \cdot \frac{C_{\gamma\gamma}}{\Lambda}$$

scale of new physics



Sensitivity projections for ALPs coupling to photons as a function of ALP mass, figure from arXiv:2511.03883

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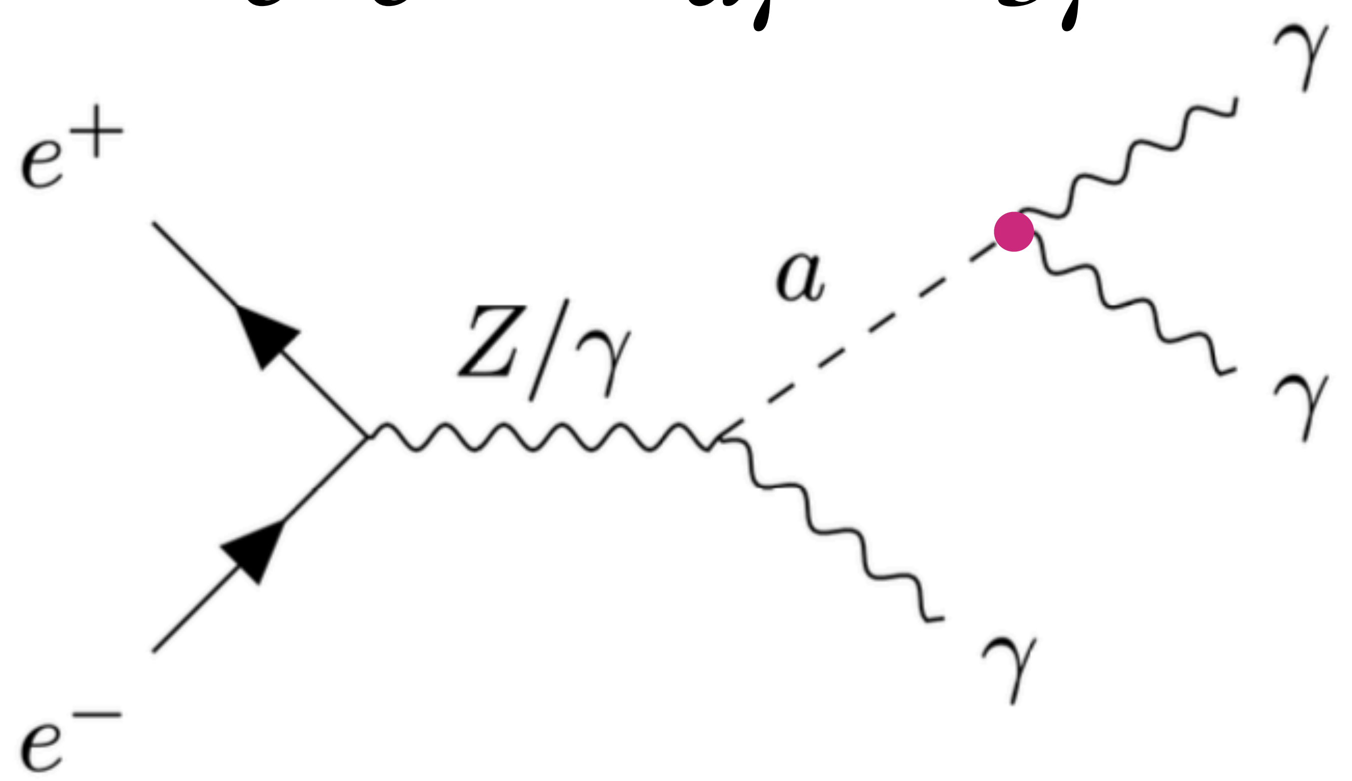

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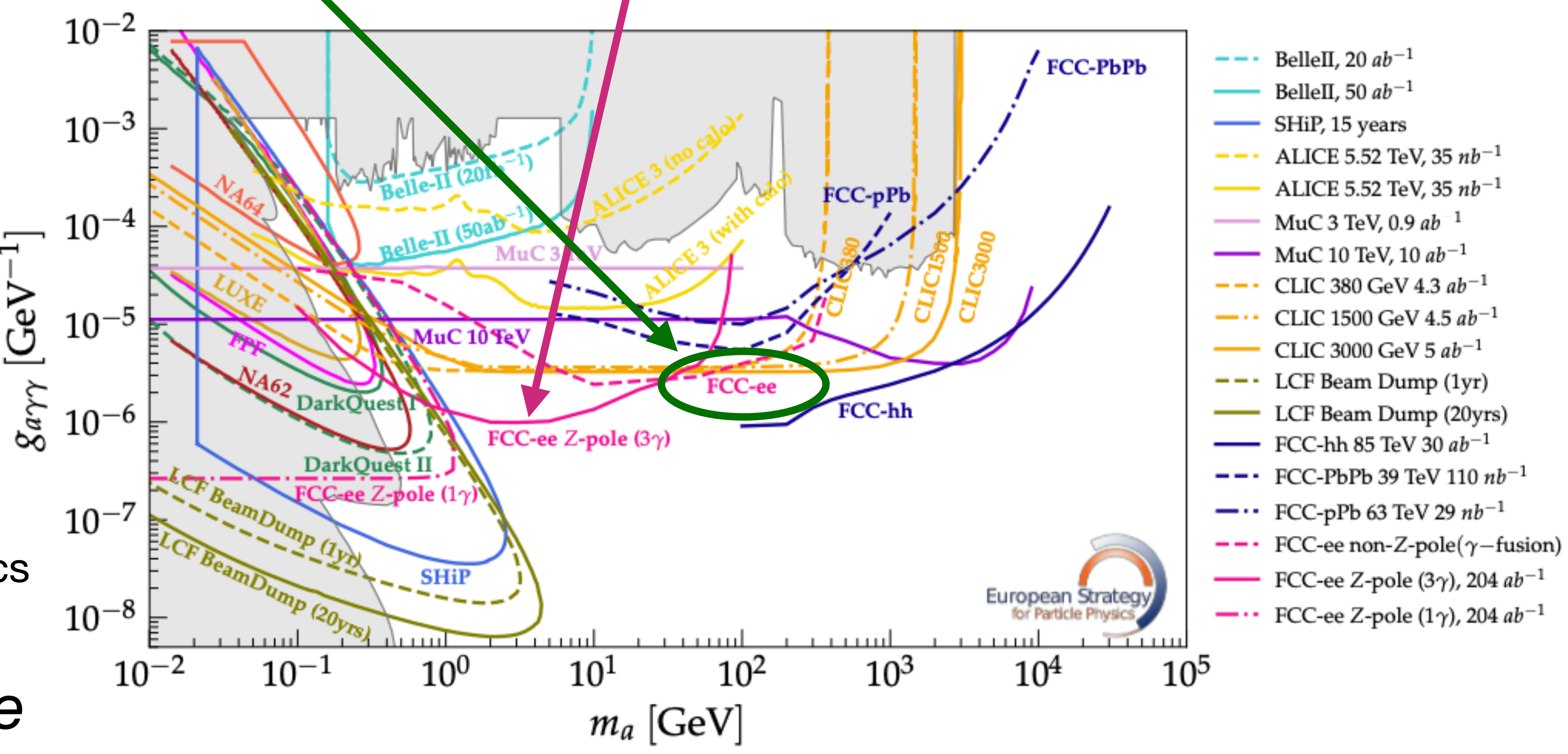


Can we extend the sensitivity of the FCC-ee to ALPs to higher center-of-mass energies?

Sensitivity projections for ALPs coupling to photons as a function of ALP mass, figure from arXiv:2511.03883

Outline of the study

- In our model benchmark, we assume the ALP couples only to U(1) gauge fields
- We set $C_{BB} = 1$ and $C_{WW} = 0$, and that means:

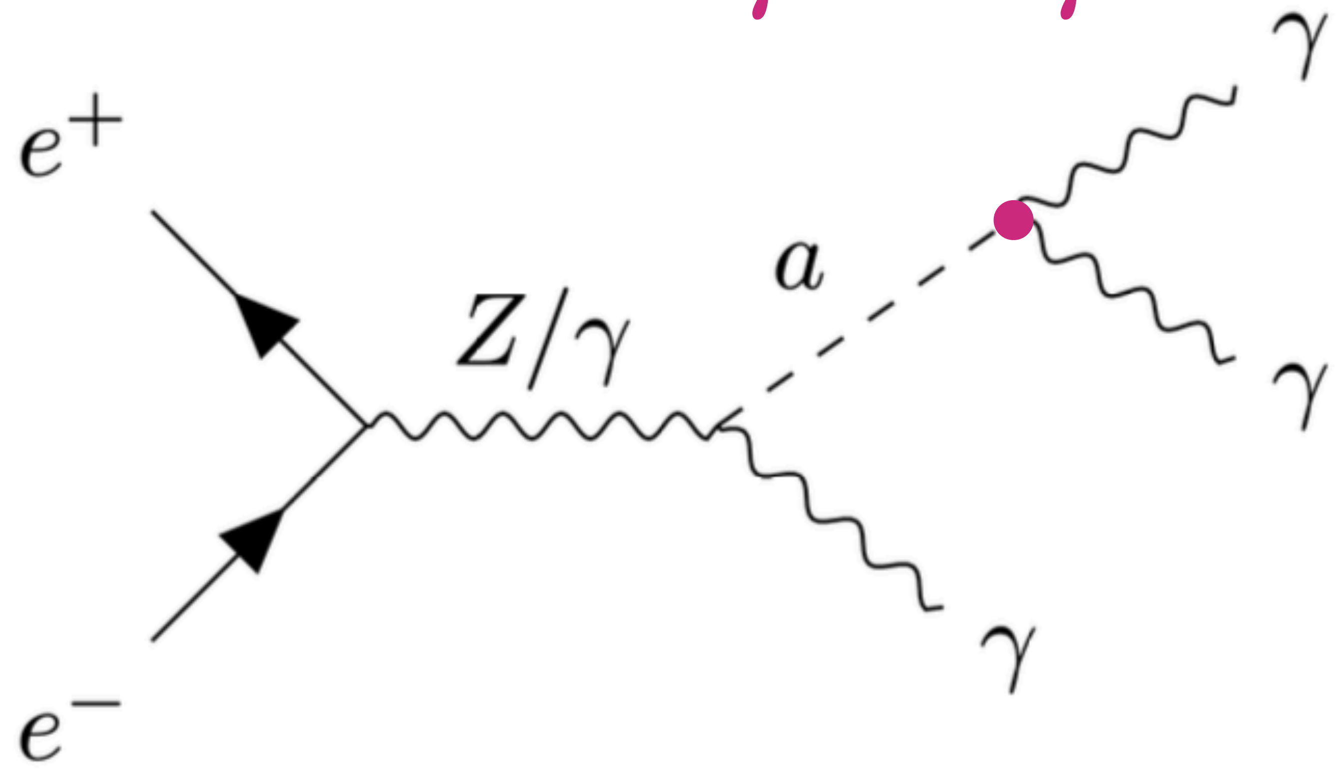
$$\begin{aligned} C_{\gamma\gamma} &= C_{WW} + C_{BB} \\ C_{\gamma Z} &= c_w^2 C_{WW} - s_w^2 C_{BB} \end{aligned} \longrightarrow \quad C_{\gamma Z} = -\, s_w^2 C_{\gamma\gamma}$$

Signal: ALP produced in association with a γ via either a Z boson or a γ, decays to $\gamma\gamma$

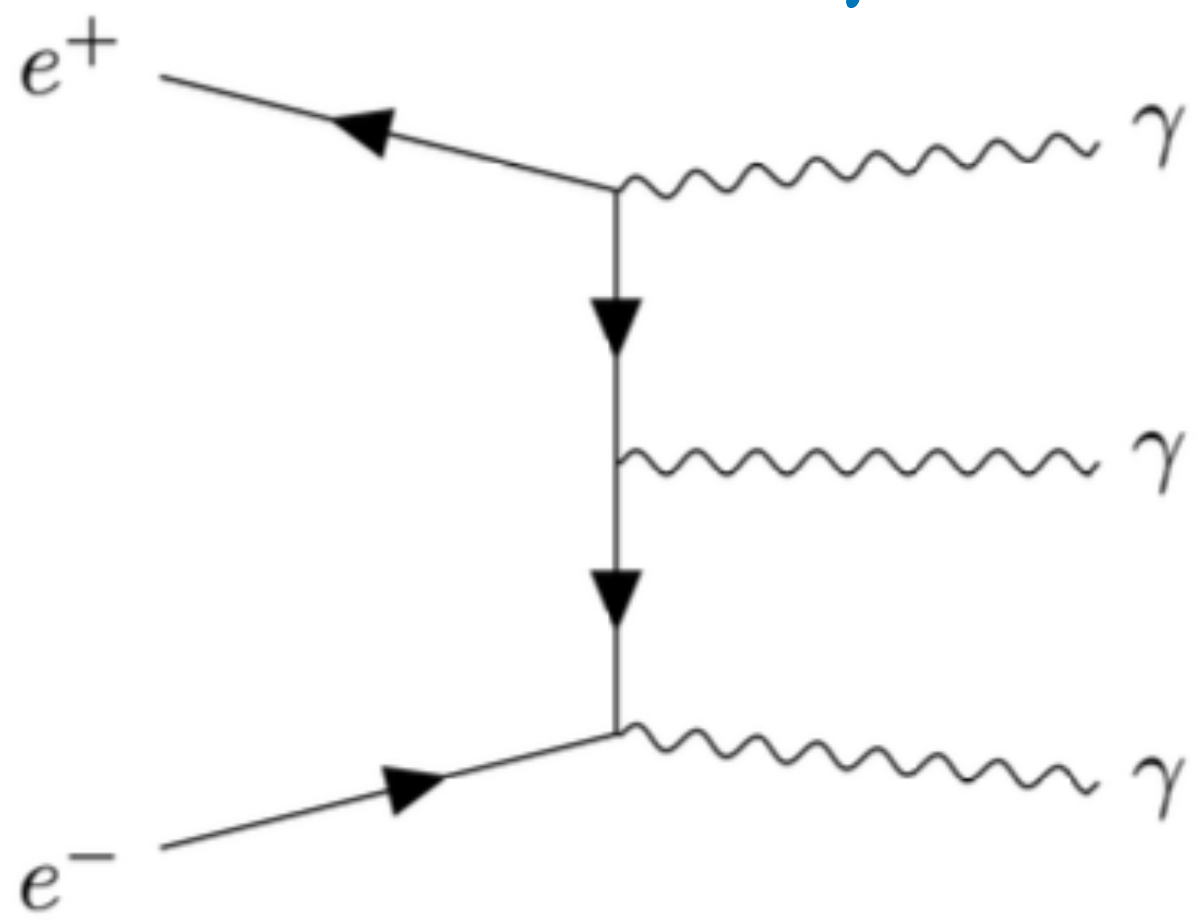
- Other decay modes possible (γZ, ZZ) when $m_a \geq m_Z$

Background: $\gamma\gamma\gamma$ produced in e^+e^- collision

signal:
$e^+e^- \to a\gamma \to 3\gamma$



background:
$e^+e^- \to 3\gamma$



Event generation
↓
Photon identification
↓
Preselection
↓
Final selection
↓
Limit calculation

Signal and background generation

For each E_{CM} and ALP mass point (see ALP mass range in table):

- 1M events generated
- Λ = 1 TeV
- Used ALP UFO model of Bauer et al (arxiv:1708.00443)
- Couplings set to $C_{\gamma\gamma} = 1,\ C_{\gamma Z} = -0.223$
- IDEA detector card used
- Photons required to have $E_\gamma > 0.1$ GeV, and $|\eta| < 2.6$

Pole/ threshold	E_{CM} (GeV)	ALP mass range (GeV)	Integrated luminosity (ab^{-1})
Z	91	5 - 80	205
WW	160	5 - 150	19.2
ZH	240	5 - 220	10.8
$t\bar{t}$	365	5 - 320	2.7

MC event generation (MadGraph5)

↓

Showering simulation (PYTHIA8)

↓

Detector simulation (Delphes)

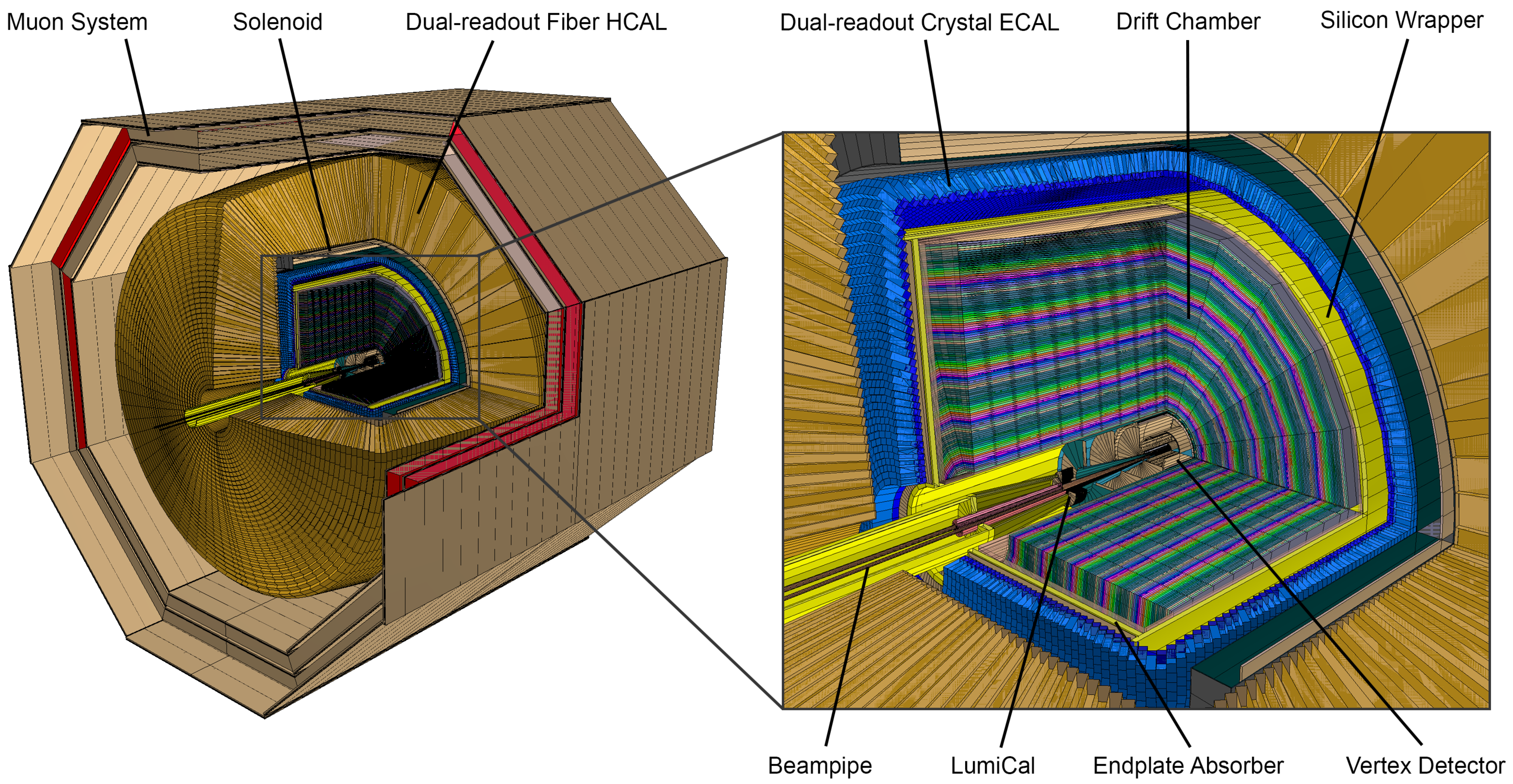
↓

Analysis (FCCAnalyses framework, Combine)

*in this region, the ALP is dominantly prompt

FCC-ee: the IDEA detector

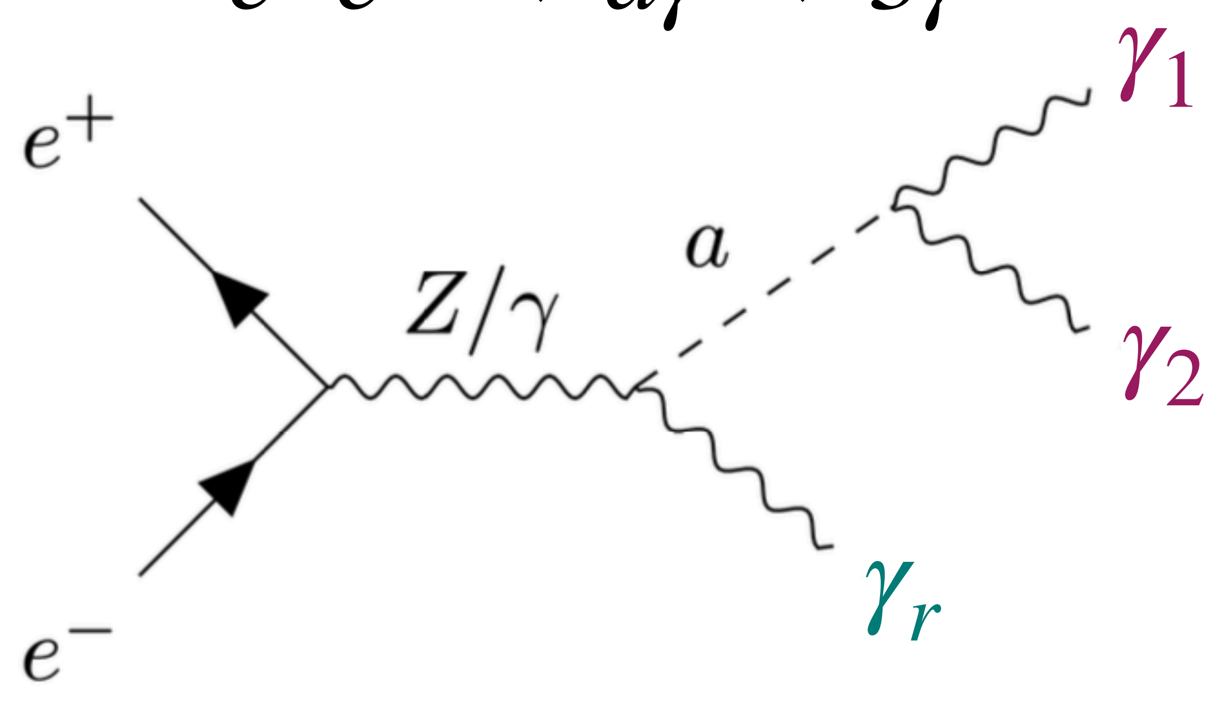
- Many detector concepts have been proposed for FCC-ee, among them the general purpose Innovative Detector for Electron-positron Accelerators (IDEA)
  - High-precision vertex detector combined with high-granularity calorimeter → high resolution energy measurements
  - Excellent particle identification



Source: arXiv:2502.21223v4

Photon assignment

signal:
$e^+e^- \to a\gamma \to 3\gamma$



- We have one recoil photon (γ_r) and two photons from ALP decay (γ_1, γ_2)

$E_{\gamma_1} > E_{\gamma_2}$

- It is difficult to identify which photons come from ALP!
- We therefore introduce variable M_{cut}:

$$M_{cut}^2 = \boxed{\frac{(m_{\gamma_1\gamma_2} - m_a)^2}{\sigma(m_a)^2}} + \boxed{\frac{(E_{\gamma_3} - E_r)^2}{\sigma(E_r)^2}}$$

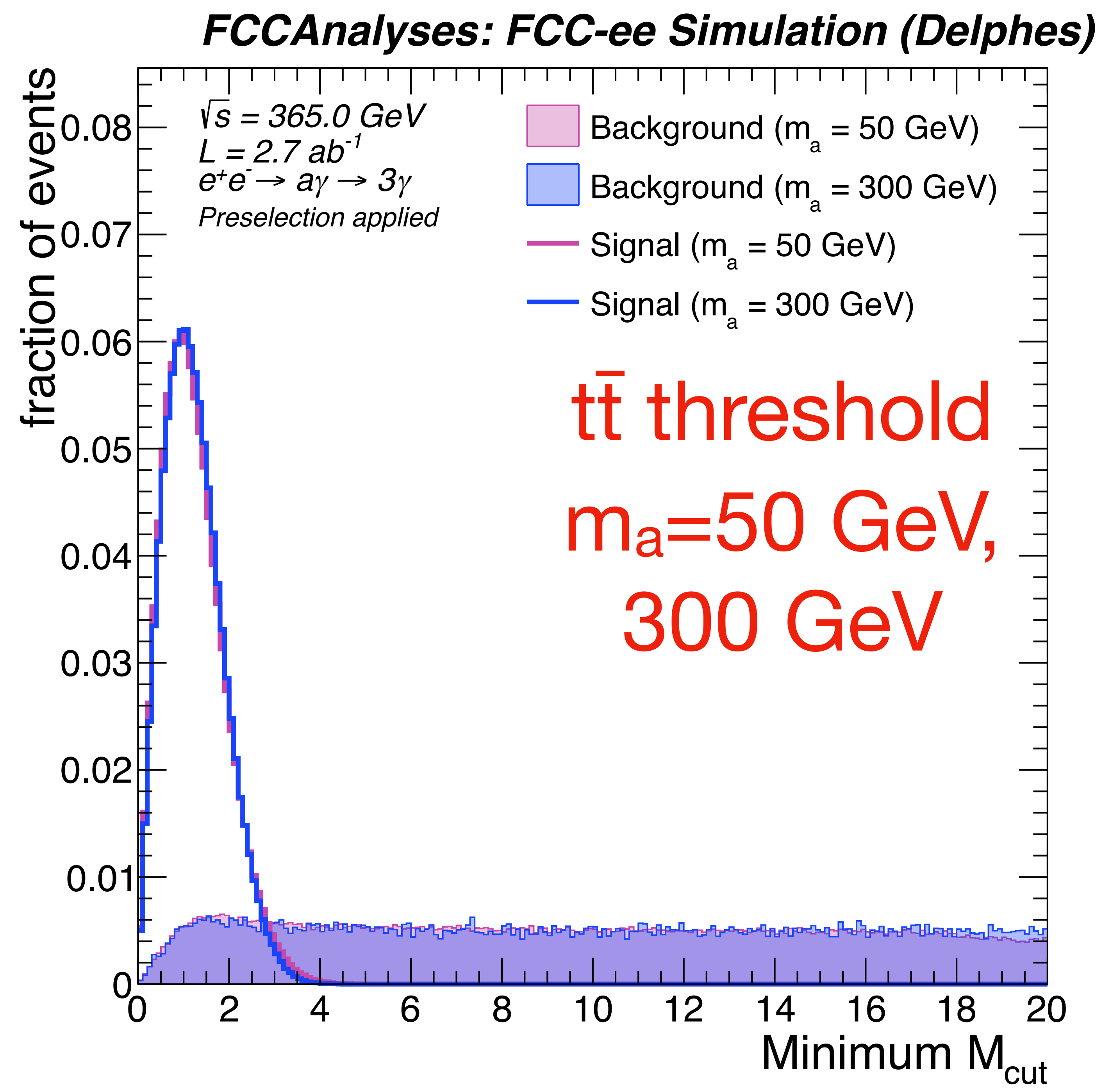
ALP mass reconstructed from final state photons

Recoil photon energy

For each m_a, the photon produced in association with the ALP (recoil photon) has:

$$E_r = \frac{E_{CM}^2 - m_a^2}{2E_{CM}}$$

Iterate over all possible photon assignments, choose the one that gives the smallest value of M_{cut}: finds most compatible option given expected kinematics!



Preselection

Preselection applied

- We require exactly 3 reconstructed photons (to remove possible backgrounds) with $E_\gamma \geq$ 2 GeV and $|\eta| < 2.6$

- We require that $m_{\gamma\gamma\gamma}$ is within $E_{CM} \pm$ resolution (to correct for photon mis-reconstruction)

- We require that the 3D opening angle $\Delta\alpha_{\gamma_1\gamma_2} > 0.02$ (to correct the spatial smearing)

	Z pole run	WW threshold	ZH threshold	$t\bar{t}$ threshold
Signal efficiency	0,86	0,90	0,90	0,90
Background rejection	0,54	0,48	0,45	0,42

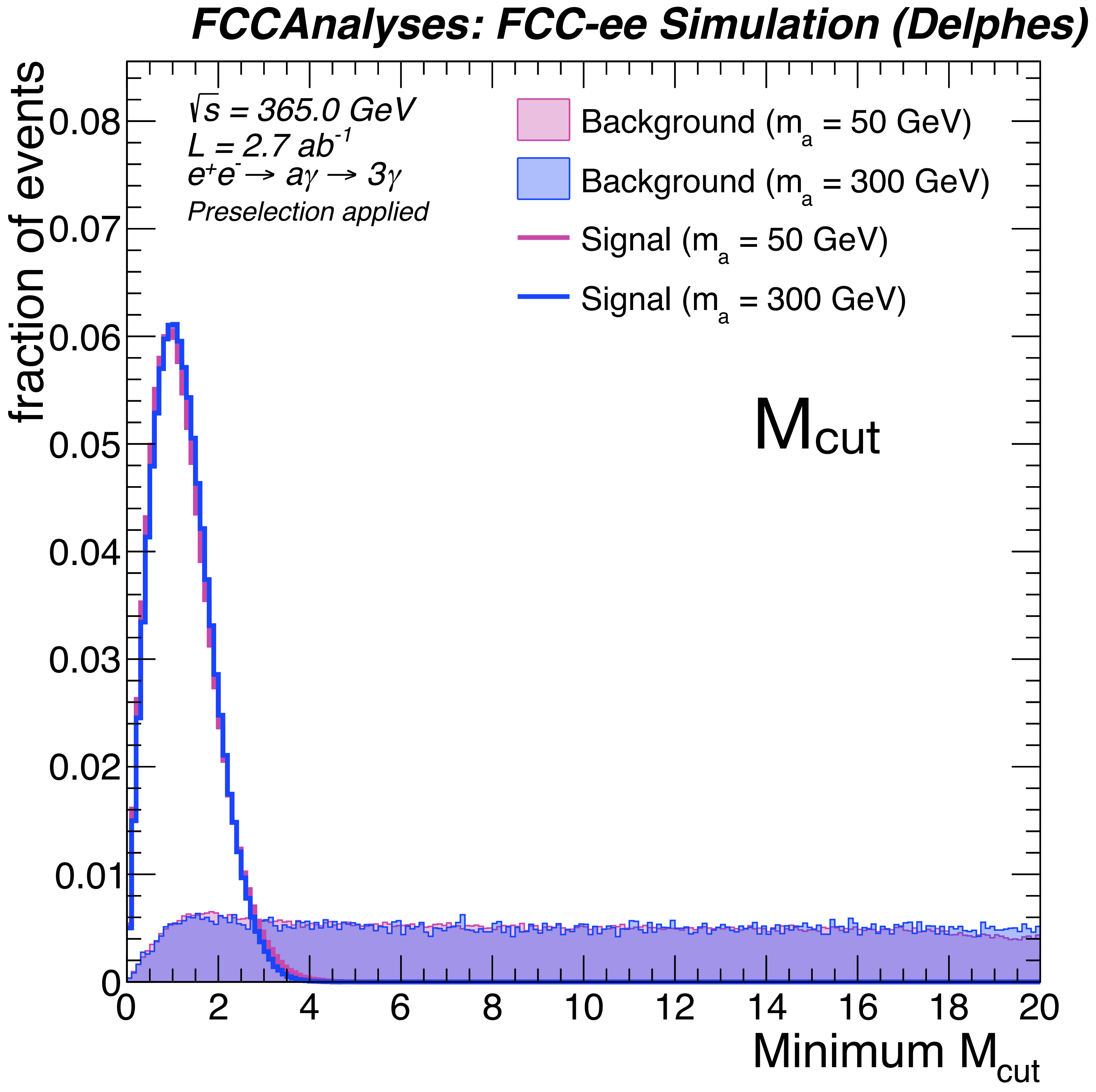
*averaged across all mass points

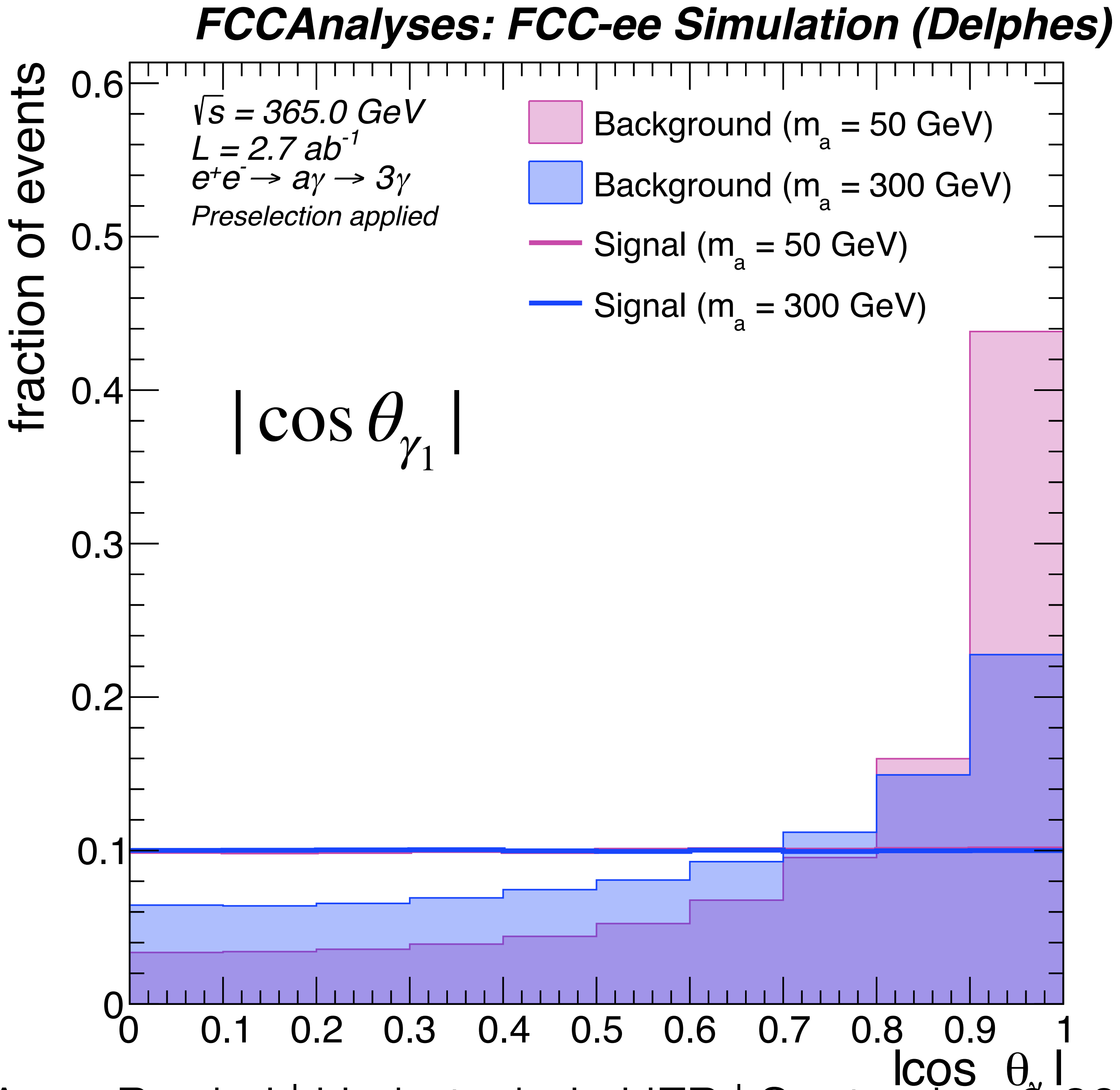
Final selection

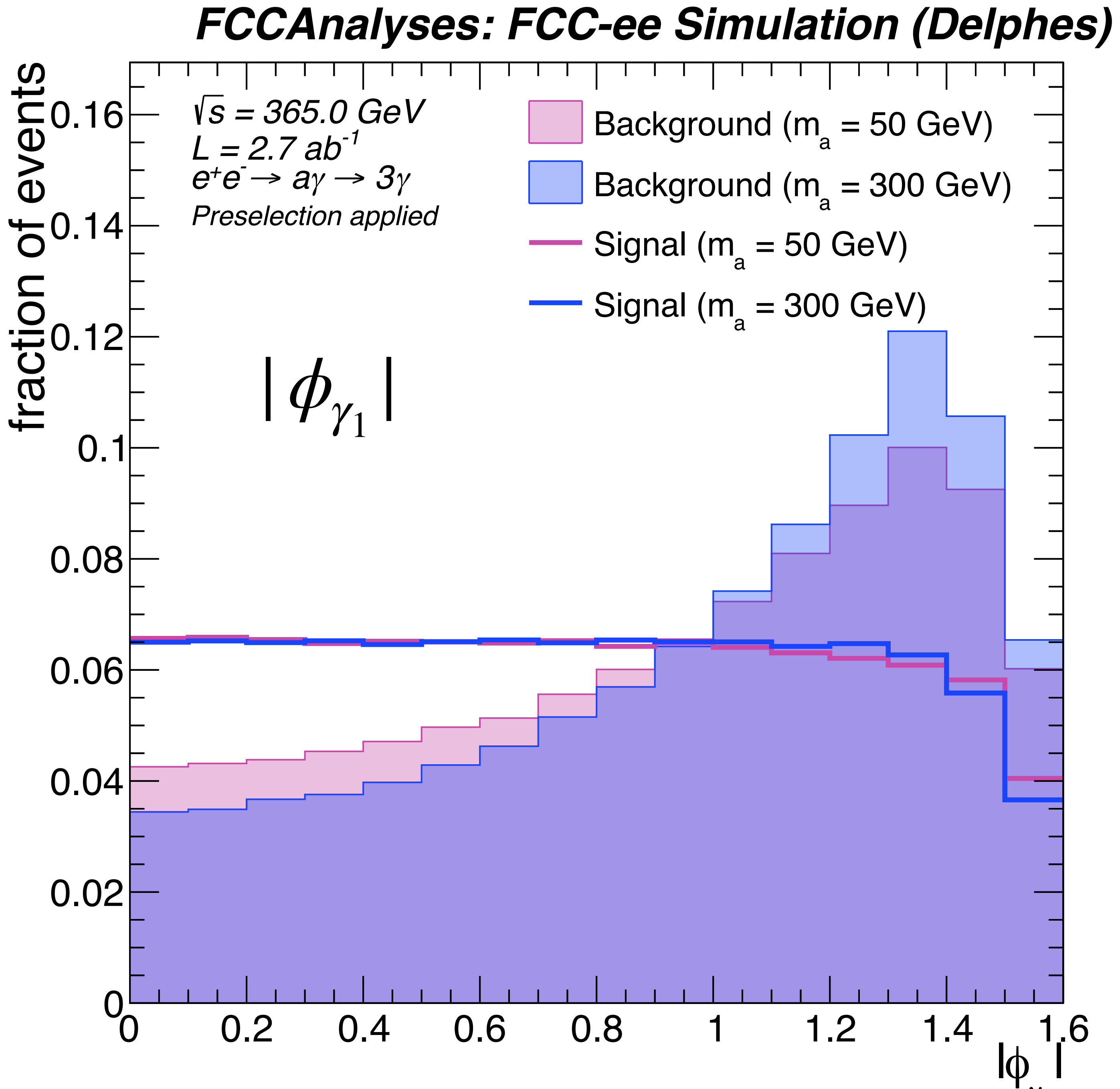
Selection cuts applied simultaneously to discriminant variables (looped over the variables for each mass point, optimized cuts to Punzi significance)

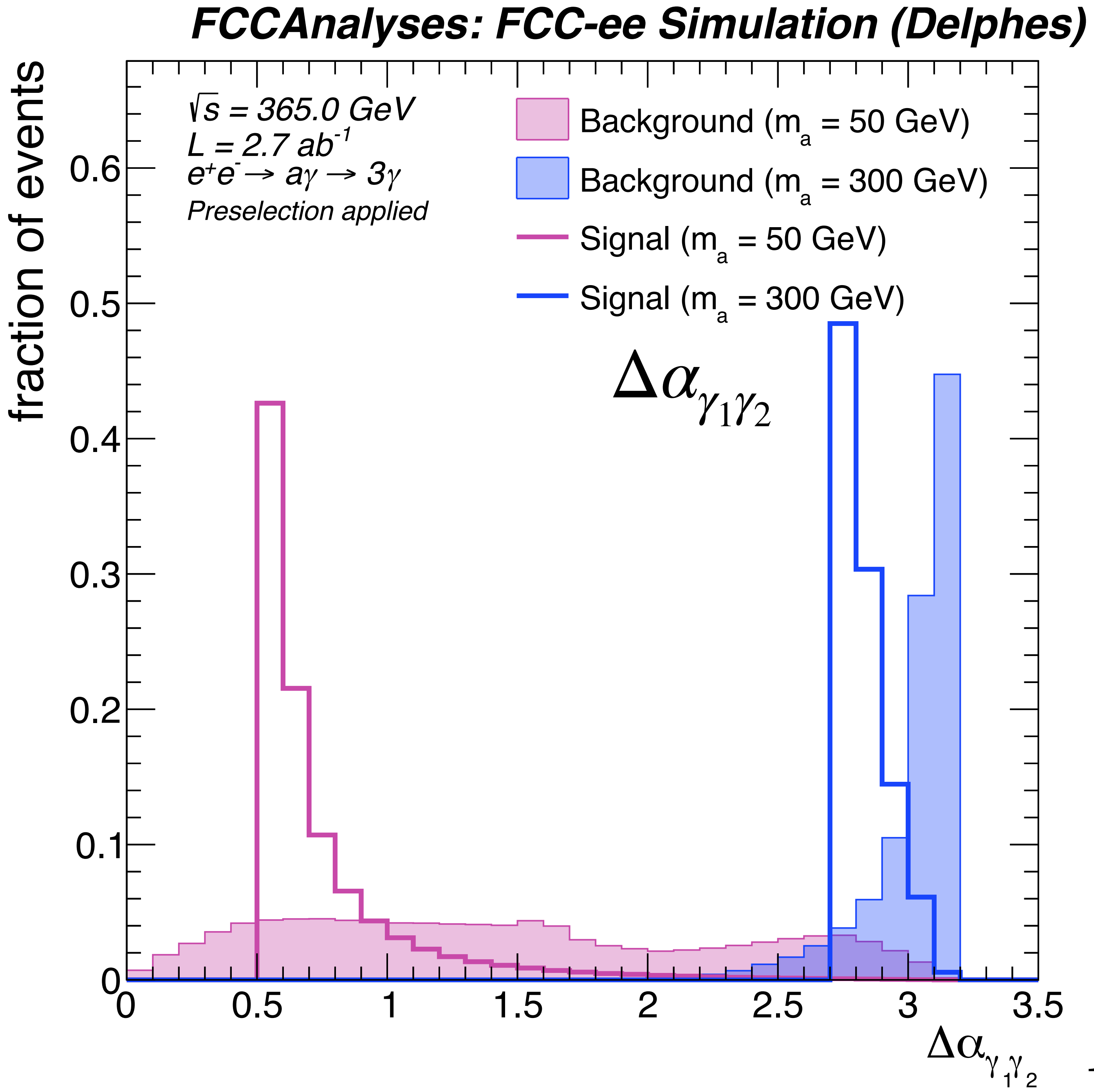
- M_{cut}
- Polar angle of γ_1 in ALP rest frame: $|\cos\theta_{\gamma_1}|$
- Azimuthal angle of γ_1 in ALP rest frame: $|\phi_{\gamma_1}|$
- 3D opening angle between γ_1 and γ_2: $\Delta\alpha_{\gamma_1\gamma_2}$

$t\bar{t}$ threshold
m_a=50 GeV, 300 GeV









FCC-ee sensitivity projections

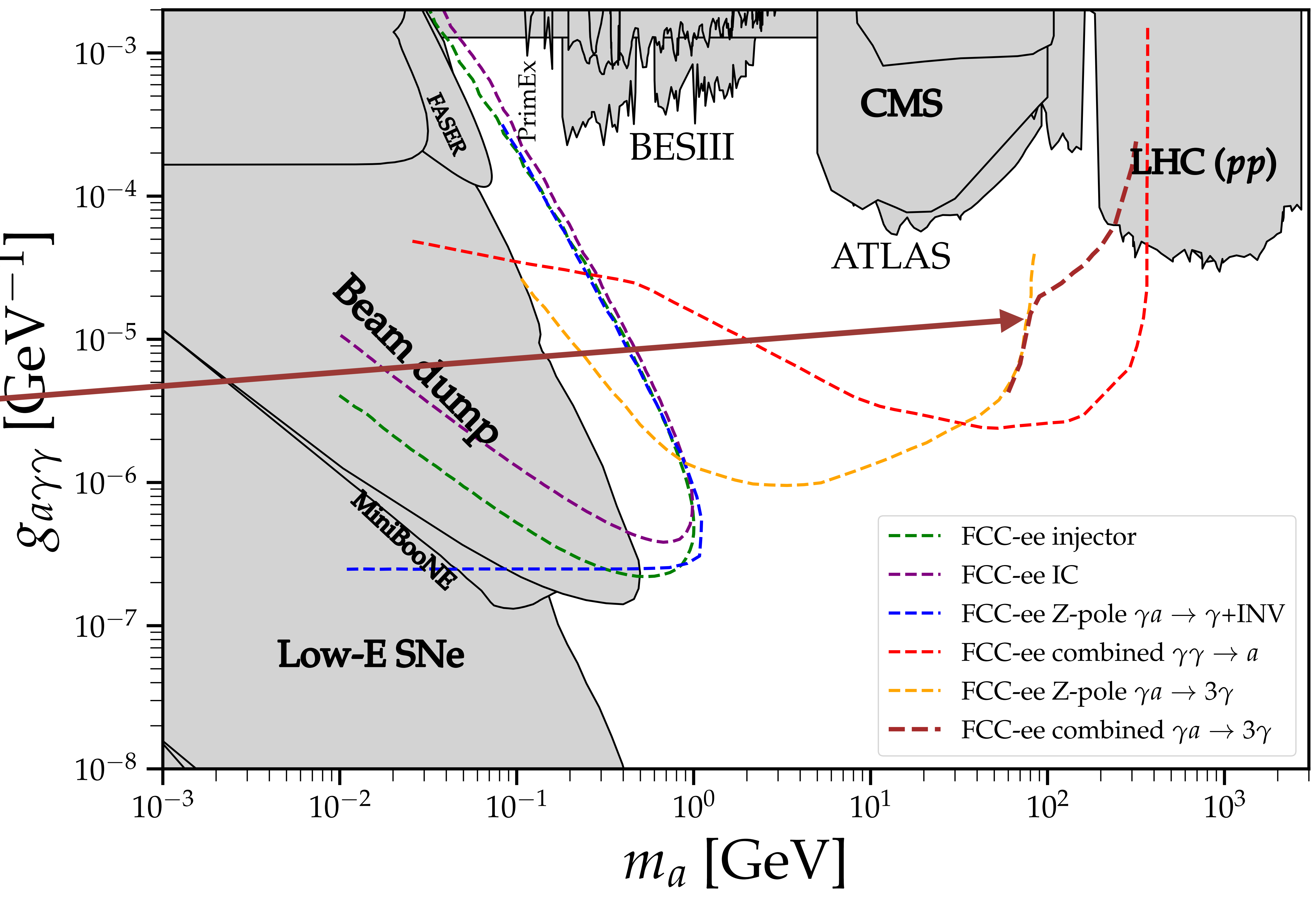
Existing limits taken from:
doi:10.5281/zenodo.3932430

Signal strength parameter μ obtained from a shape analysis done using Combine (CMS statistical tool) for each mass point separately, assuming a background only observation

$$C_{\gamma\gamma,lim} = \sqrt{\mu} = \sqrt{\frac{\sigma_{lim}}{\sigma_{theory}}}; \quad g_{a\gamma\gamma} = \frac{4e^2 C_{\gamma\gamma}}{\Lambda}$$

Overall, the FCC-ee will be sensitive to a large range of ALP masses and $g_{a\gamma\gamma}$ couplings

- Brown: this study, combined for all projected FCC-ee runs ($\gamma a \rightarrow 3\gamma$)
- Orange: our final state ($\gamma a \rightarrow 3\gamma$) at the Z pole, with special attention paid to low ALP masses (arXiv:2502.08411)



Is there anything more we can learn? *YES!*

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

Recasting limits

We also study the effect of C_{WW} and C_{BB}

- Varying the relationship between C_{WW} and C_{BB} changes the relative strength of $C_{\gamma\gamma}$ and $C_{\gamma Z}$

For $e^+e^- \to \gamma a \to 3\gamma$:

- Production depends on both $C_{\gamma\gamma}$ and $C_{\gamma Z}$
- Decay depends on C_{WW}, $C_{\gamma\gamma}$, $C_{\gamma Z}$, and C_{ZZ}

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Two interesting scenarios:

$C_{BB} = -C_{WW} \quad \to \quad C_{\gamma\gamma} = 0$ (scenario 1)

$c_w^2 C_{BB} = s_w^2 C_{WW} \quad \to \quad C_{\gamma Z} = 0$ (scenario 2)

**How does varying C_{WW}/C_{BB} affect 3γ sensitivity?

Recasting limits

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**How does varying C_{WW}/C_{BB} affect 3γ sensitivity?

In the following slide, we vary C_{WW}/C_{BB} from -1.5 to +1.5 and:

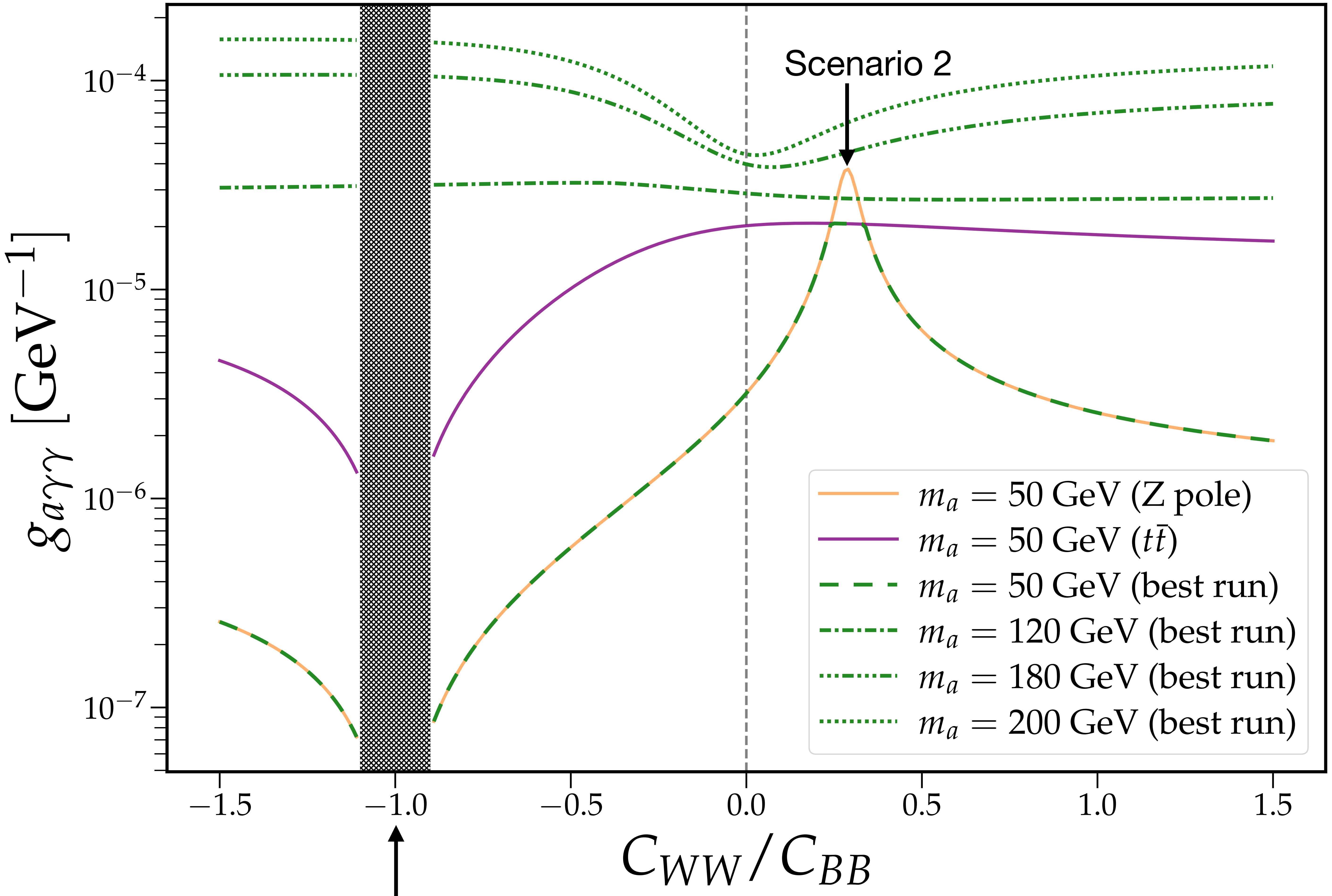
- Rescale our $\sigma(e^+e^- \to \gamma a) \cdot BR(a \to \gamma\gamma)$
- Compare to our primary results
- Observe how C_{WW}/C_{BB} changes

Recasting results

$e^+e^- \rightarrow \gamma a \rightarrow 3\gamma$

- The change in sensitivity is shown as a function of C_{WW}/C_{BB} for four different ALP masses
- For $m_a > m_Z$, the variation in reach is at most a factor of ≈ 3.5
- For $m_a < m_Z$, the variation in reach spans many orders of magnitude
  - Z pole run results are more drastic than $t\bar{t}$ threshold results → different production modes dominate
- The process *is* sensitive to changes in C_{WW}/C_{BB}!

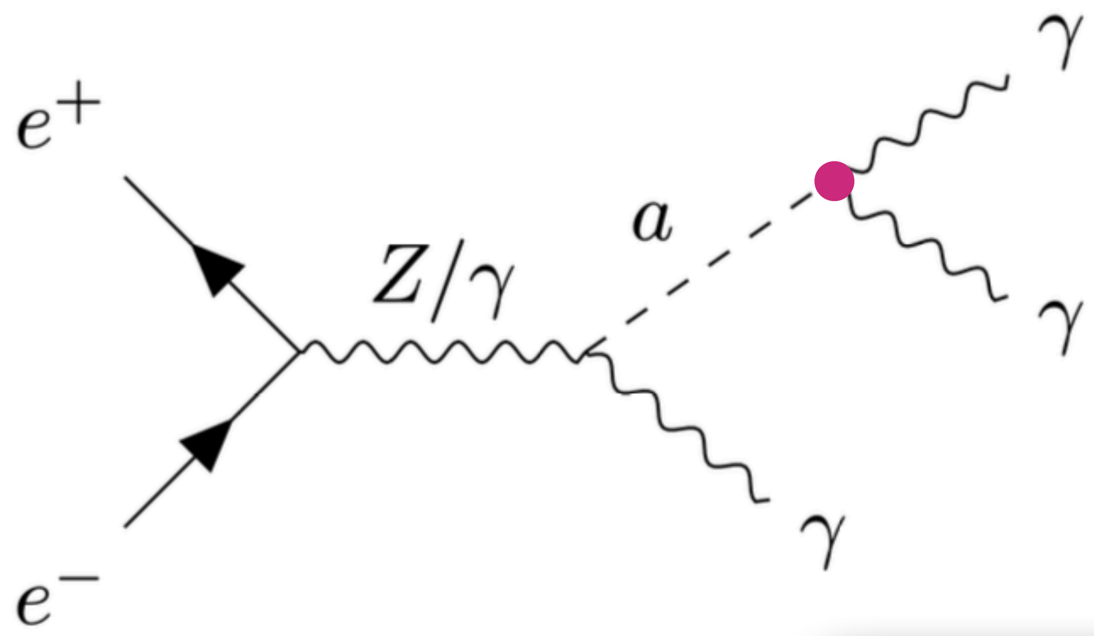
Primary results



Photophobic case (scenario 1), where radiative corrections become important. At -1.1 and -0.9 the corrections are negligible, so we didn't connect these points and shaded the region in between, to account for this.

Conclusion

- The FCC-ee will be sensitive to ALPs produced in $e^+e^- \to \gamma a \to 3\gamma$
- This process is sensitive to ***both*** $C_{\gamma\gamma}$ and $C_{\gamma Z}$ → therefore it is sensitive to the relationship between C_{WW} and C_{BB}
  - This channel is important to consider in addition to previous studies!



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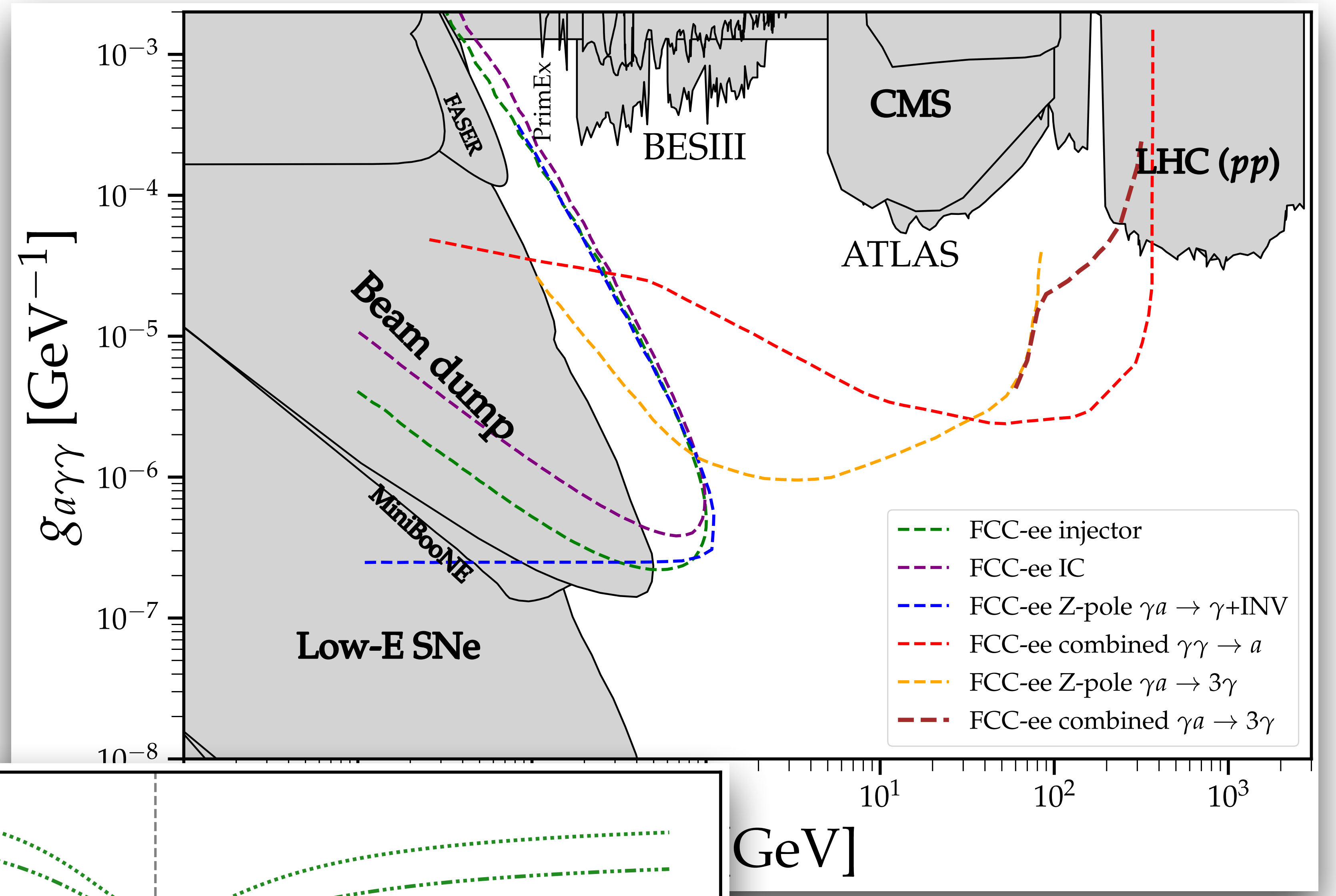

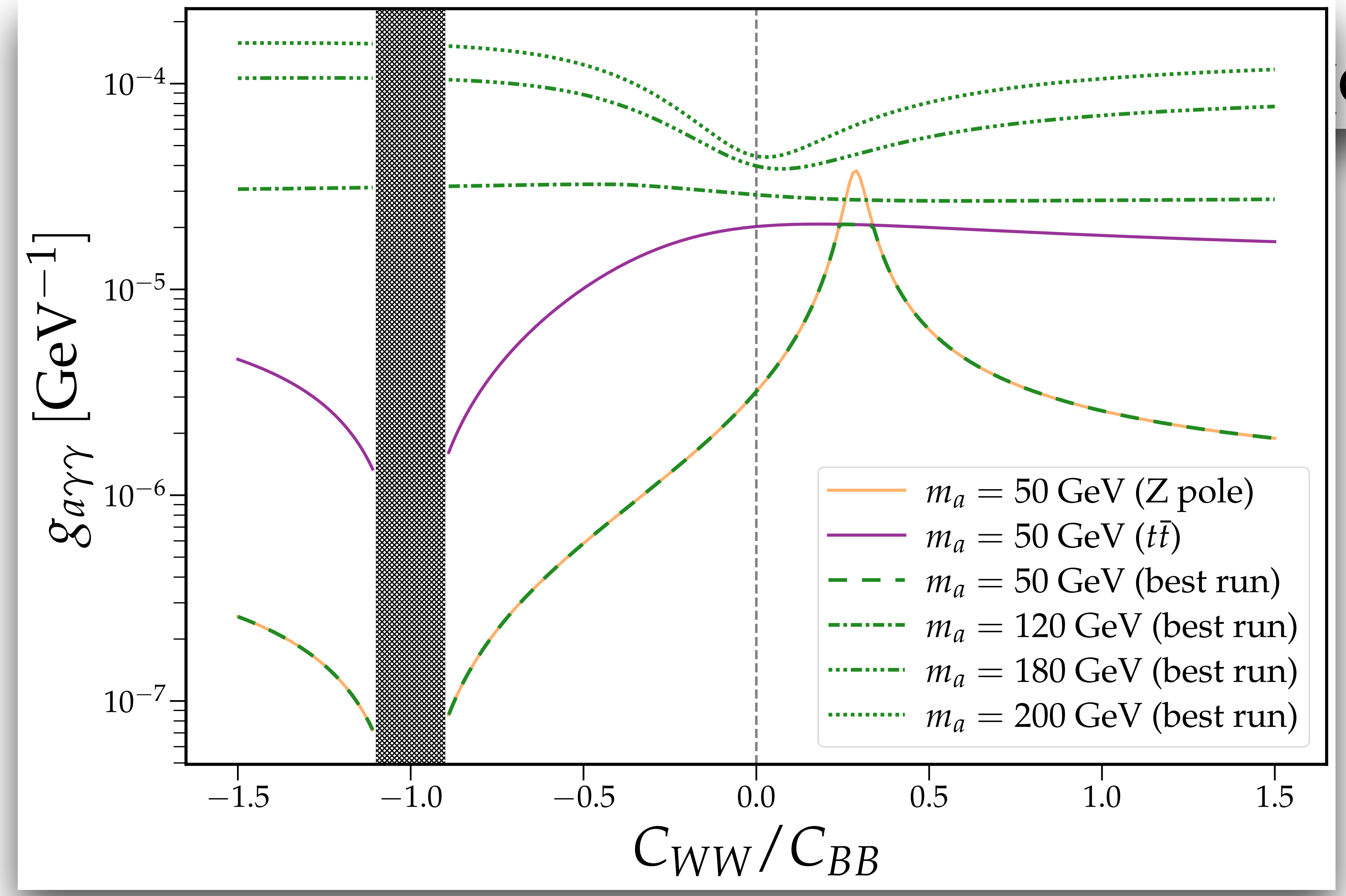

The paper has been submitted to arXiv (arXiv:2605.21452) and EPJC, and is currently under review!

Thank you!

Backup slides

The theory

Leading interactions of ALP to SM particles is described by:

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}\left(\partial_\mu a\right)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \underbrace{\sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{\Lambda}\bar{f}\gamma_\mu\gamma_5 f}_{\text{Fermions}} + \underbrace{g_s^2 C_{GG}\frac{a}{\Lambda}G^A_{\mu\nu}\tilde{G}^{\mu\nu,A}}_{\text{Gluons}} + \underbrace{g^2 C_{WW}\frac{a}{\Lambda}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu}}_{\text{Vector bosons}}$$

ALP = a

After EWSB, the ALP coupling to photons and Z boson is described by:

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

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

$$^* s_w^2 = \sin^2\theta_W; \quad c_w^2 = \cos^2\theta_W;$$

The model benchmark

- Tree level couplings of ALP to fermions and gluons are set to zero
- ALP couples only to U(1) gauge fields → $C_{WW} = 0$

$$\mathscr{L}_{eff} \ni e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w} C_{\gamma Z} \frac{a}{\Lambda} F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2} C_{ZZ} \frac{a}{\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

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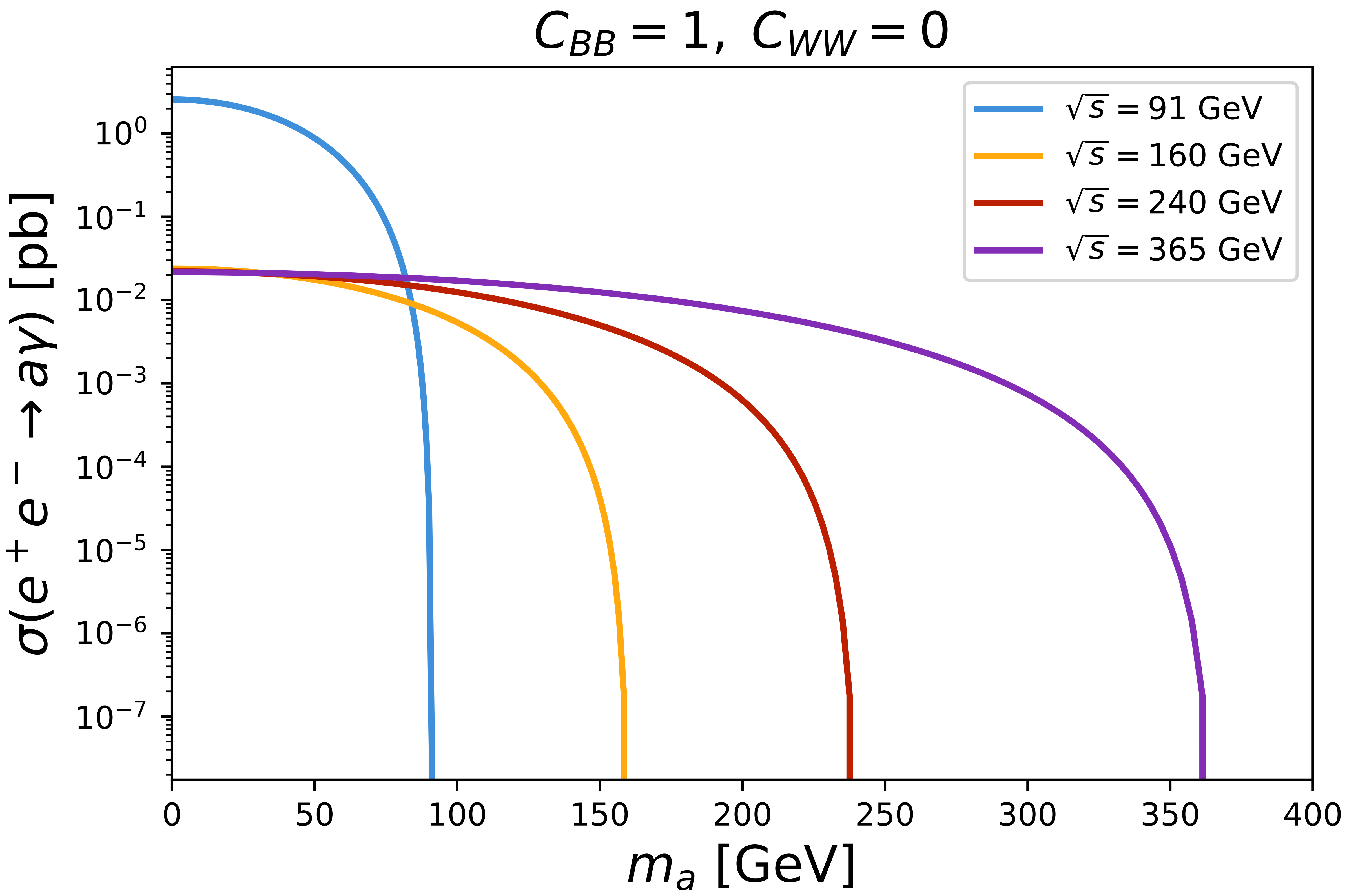
$$\downarrow$$

$$\boxed{C_{\gamma Z} = -\, s_w^2 C_{\gamma\gamma}}$$

ALP only couples to photon and Z!

ALP production

- Rapid decrease in cross section as m_a approaches $\sqrt{s}$
- Due to (m_Z^2/Γ_Z^2) factor, Z boson propagator is enhances by ~ 1336 at Z pole run



Z pole: $$\sigma(e^+e^- \to \gamma a)|_{s=m_Z^2} \approx \frac{32\pi^2\alpha}{3}\alpha^2(s)\left(1-\frac{m_a^2}{s}\right)\left[\frac{|C_{\gamma\gamma}|^2}{\Lambda^2} - \frac{m_Z^2}{\Gamma_Z^2}\frac{|C_{\gamma Z}|^2}{16 s_w^2 c_w^4 \Lambda^2}\right]$$

WW, ZH, tt: $$\sigma(e^+e^- \to \gamma a)|_{s\gg m_Z^2} \approx \frac{32\pi^2\alpha}{3}\alpha^2(s)\left(1-\frac{m_a^2}{s}\right)\left[\frac{|C_{\gamma\gamma}|^2}{\Lambda^2} + \frac{|C_{\gamma Z}|^2}{16 s_w^2 c_w^4 \Lambda^2}\right]$$

Production cross section

The differential cross section is

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

where

$$V_\lambda(s) = \frac{C_{\gamma\gamma}}{s} + \frac{g_V}{2c_w^2 s_w^2}\frac{C_{\gamma Z}}{s - m_Z^2 + i m_Z \Gamma_Z}, \quad \text{and} \quad A_\lambda(s) = \frac{g_A}{2c_w^2 s_w^2}\frac{C_{\gamma Z}}{s - m_Z^2 + i m_Z \Gamma_Z}\,.$$

$g_V = 2s_w^2 - 1/2, \quad g_A = -1/2$, and Γ_Z is the total width of the Z boson

Energy and mass resolutions

- We include an energy and mass resolution in M_{cut}:

$$M^2_{cut} = \frac{(m_{\gamma_1\gamma_2} - m_a)^2}{\sigma(m_a)^2} + \frac{(E_{\gamma_3} - E_r)^2}{\sigma(E_r)^2}$$

ALP mass resolution

Energy resolution

For each m_a, the photon produced in association with the ALP (recoil photon) has:

$$E_r = \frac{E^2_{CM} - m_a^2}{2E_{CM}}$$

Event by event, I found $\frac{m_{a,true} - m_{a,reco}}{m_{a,true}}$ and fit a Gaussian to find $\frac{\sigma(m_a)}{m_a}$

Can do the same for energy resolution, or take it from the IDEA detector card:

$$\sigma(E) = \sqrt{0.005^2E^2 + 0.03^3E + 0.002^2}$$

A quick note on normalization

ALP production:

- Events normalized to the cross section and number of Z bosons at the Z pole ($6 \cdot 10^{12}\ Z$ bosons)
- At higher center-of-mass energies, normalized to luminosity and cross section

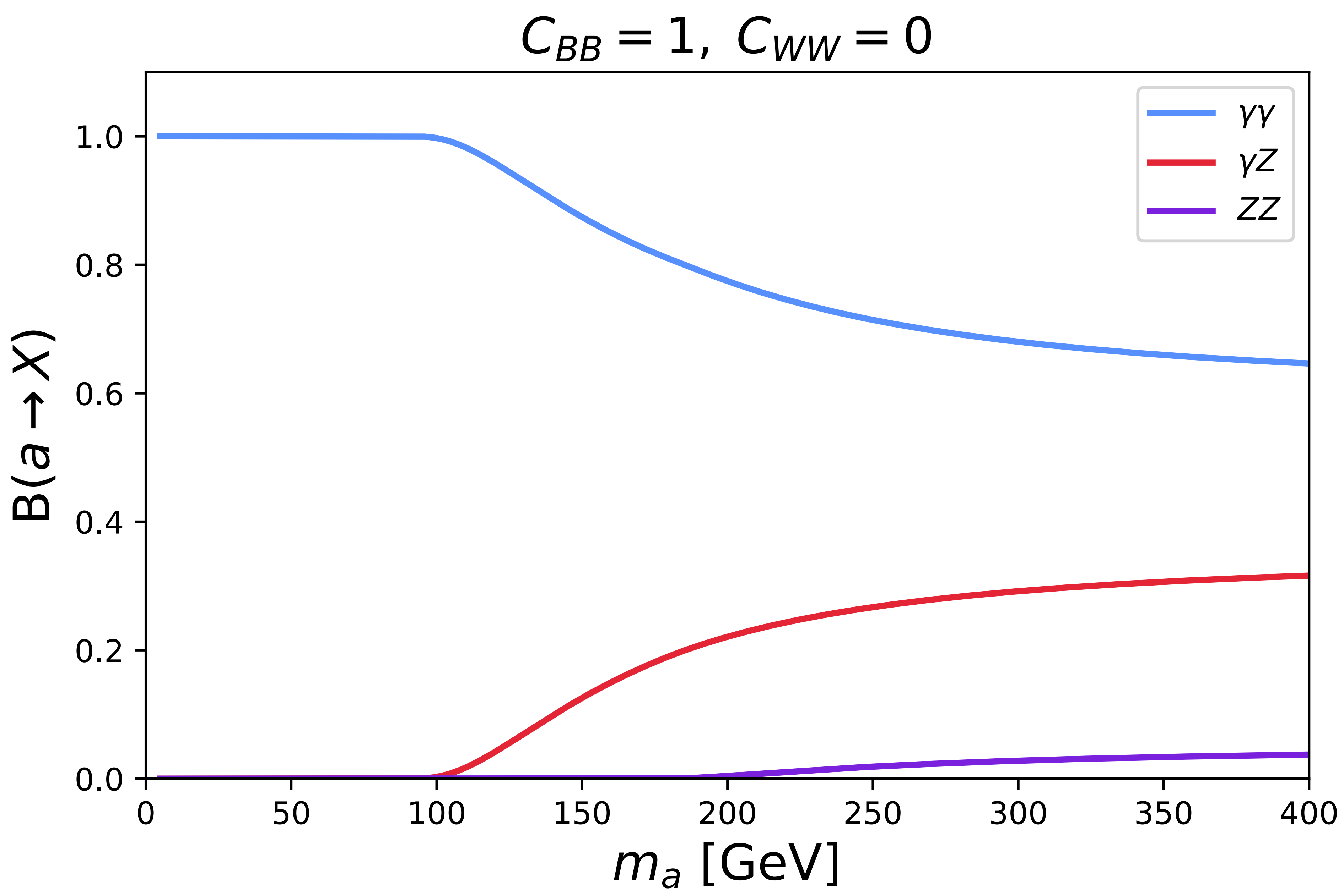
Pole/ threshold	E_{CM} (GeV)	ALP mass range (GeV)	Integrated luminosity (ab^{-1})
Z	91	5 - 80	205
WW	160	5 - 150	19.2
ZH	240	5 - 220	10.8
$t\bar{t}$	365	5 - 320	2.7

ALP decay:

- Normalized to BR of $a \to \gamma\gamma$
- In our model benchmark, $\Gamma_{tot} = \Gamma(a \to \gamma\gamma) + \Gamma(a \to \gamma Z) + \Gamma(a \to ZZ)$

$$\Gamma(a \to \gamma\gamma) = \frac{4\pi\alpha^2 m_a^3 \left|C_{\gamma\gamma}\right|^2}{\Lambda^2} \qquad \Gamma(a \to \gamma Z) = \frac{8\pi\alpha^2 m_a^3 \left|C_{\gamma Z}\right|^2}{s_w^2 c_w^2 \Lambda^2}\left(1 - \frac{m_Z^2}{m_a^2}\right)^3$$

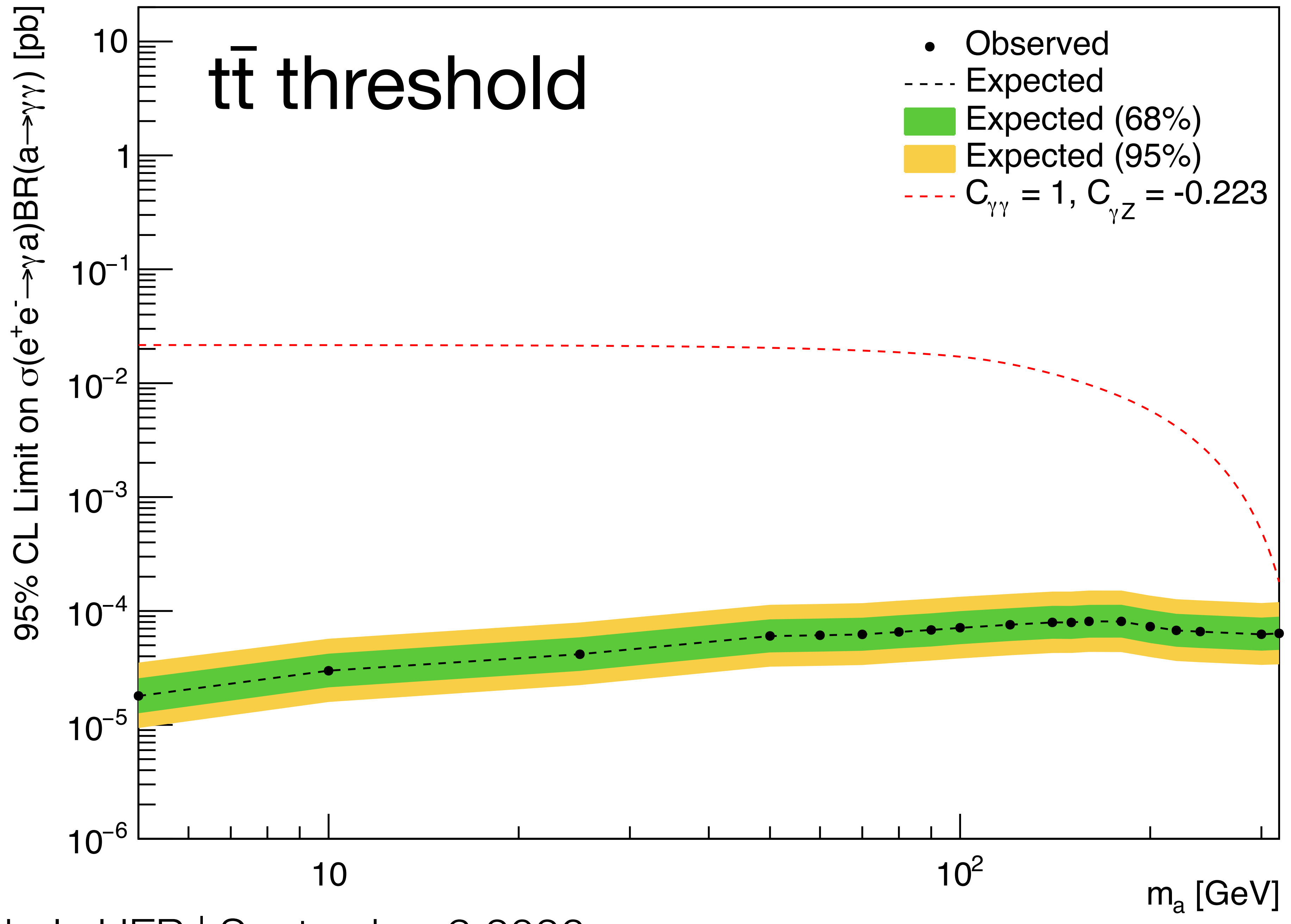
$$\Gamma(a \to ZZ) = \frac{4\pi\alpha^2 m_a^3 \left|C_{ZZ}\right|^2}{s_w^4 c_w^4 \Lambda^2}\left(1 - \frac{4m_Z^2}{m_a^2}\right)^{3/2}$$

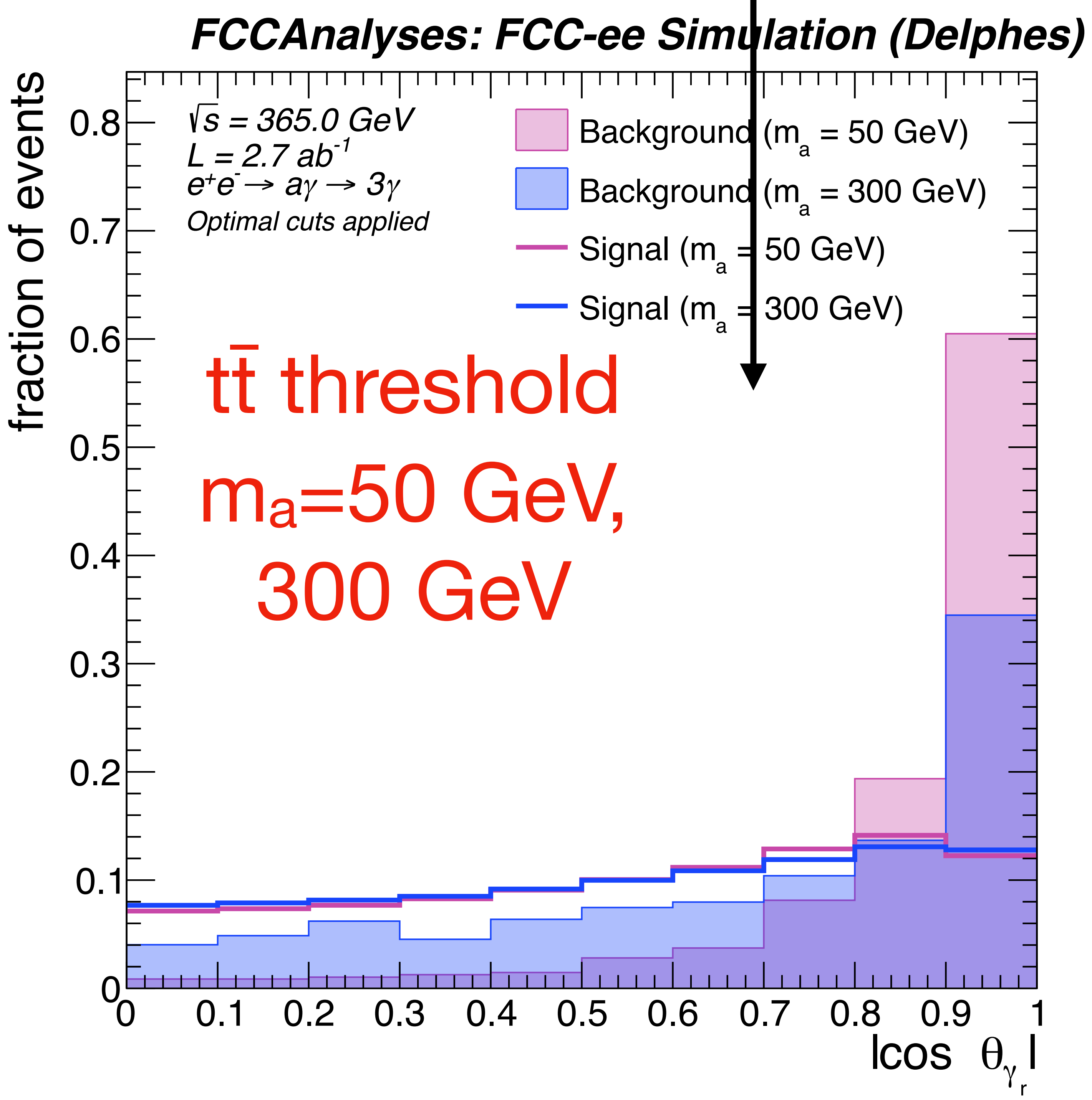


Cross section limits

Combine (CMS statistical tool) was used for a binned likelihood (shape analysis) on $|\cos\theta_{\gamma_r}|$ for each mass point separately, assuming a background only observation

- Combine finds signal strength parameter μ, to convert to cross section limit: $\sigma_{lim} = \mu \cdot \sigma_{theory}$
- The FCC-ee will be sensitive to the theoretical cross section at all ALP masses for the $t\bar{t}$ threshold for $C_{\gamma\gamma} = 1$



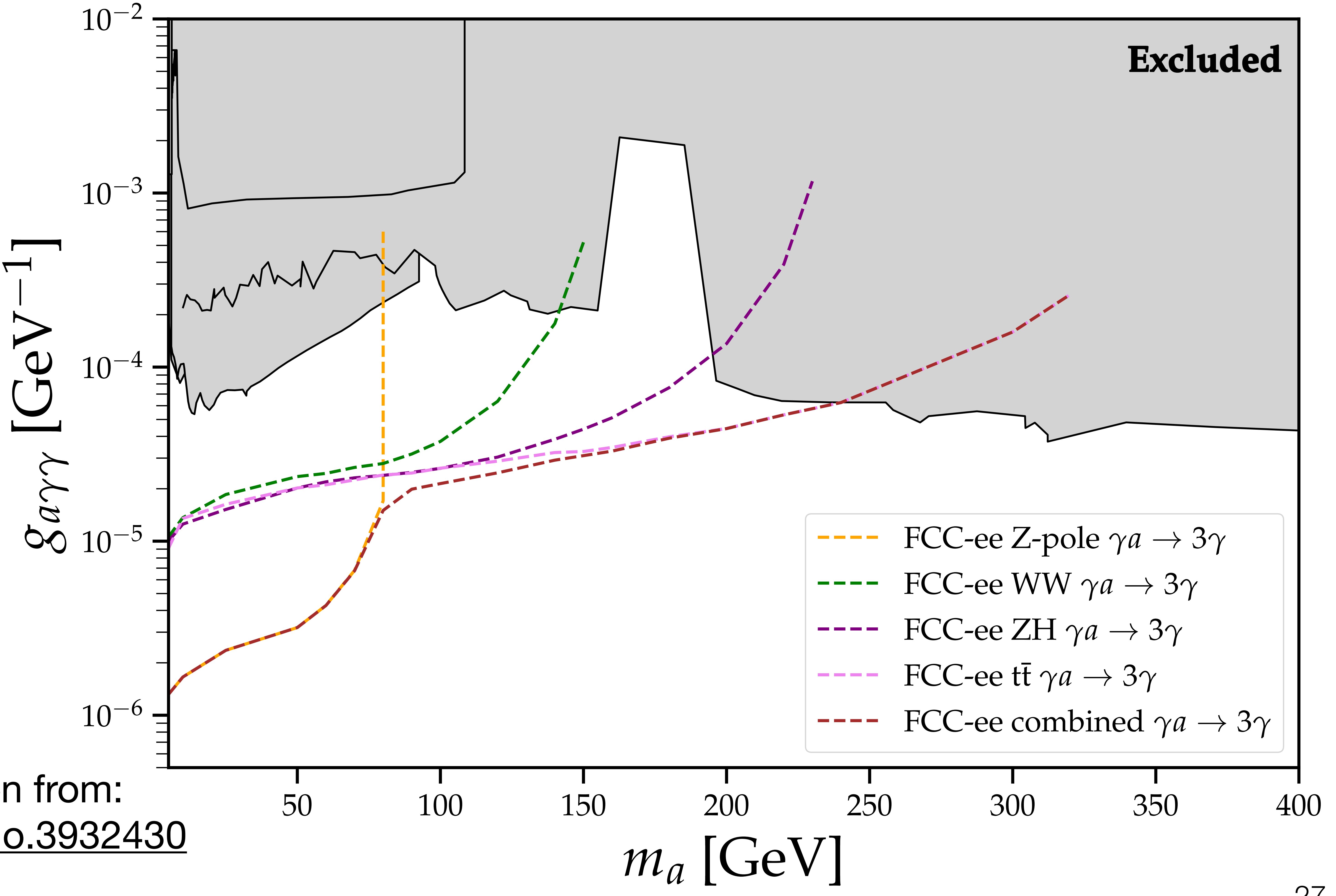


Primary results

- The conversion from cross section limit to experimental coupling limit is done via: $C_{\gamma\gamma,lim} = \sqrt{\frac{\sigma_{lim}}{\sigma_{theory}}}; \quad g_{a\gamma\gamma} = \frac{4e^2 C_{\gamma\gamma}}{\Lambda}$

- The FCC-ee will have sensitivity to ALPs in regions of parameter space that are not yet excluded!
  - As expected, Z pole is sensitive to very low couplings
  - Higher center-of-mass energy runs are less sensitive to low couplings but can probe higher masses

- Combined limit gains a bit of sensitivity from m_a = 100 GeV to m_a = 150 GeV, but follows Z pole and $t\bar{t}$ threshold otherwise

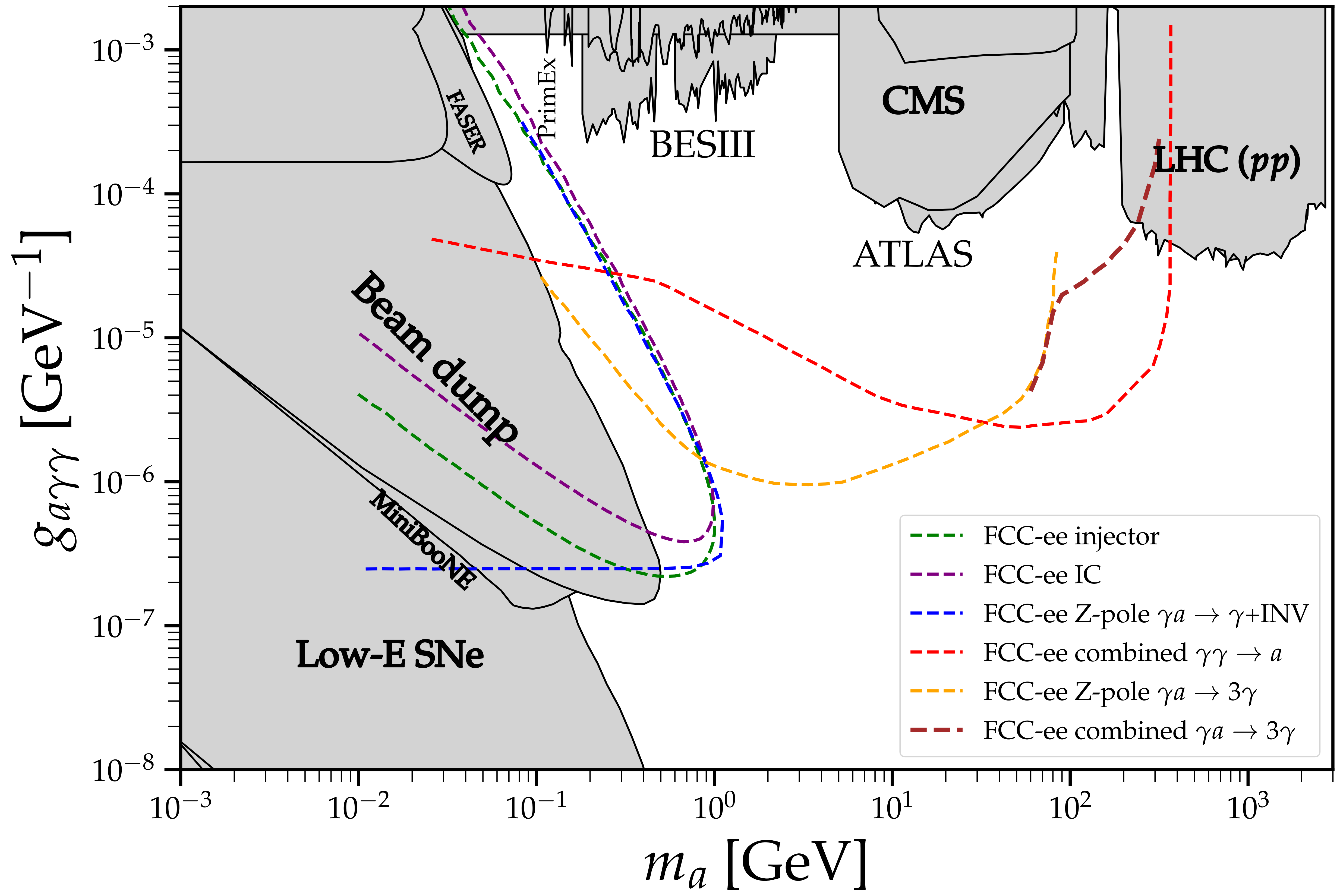


Existing limits taken from: doi:10.5281/zenodo.3932430

FCC-ee sensitivity projections — references

- Many studies have been conducted to find the sensitivity of ALPs at the FCC-ee
  - Brown: this study, combined for all projected FCC-ee runs ($\gamma a \to 3\gamma$) (arXiv:2605.21452)
  - Blue: ALP decay outside of the detector ($\gamma a \to \gamma + \text{INV}$) (arXiv:2502.08411)
  - Orange: our final state ($\gamma a \to 3\gamma$) at the Z pole, but special attention paid to low ALP masses (arXiv:2502.08411)
  - Green + purple: beam dump modes at the FCC-ee (arXiv:2503.20996)
  - Red: ALP production via $\gamma\gamma$ fusion ($\gamma\gamma \to a$) (arXiv:2310.17270v2)

Existing limits taken from:
doi:10.5281/zenodo.3932430



Method of recasting limits

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

$e^+e^- \to \gamma a \to 3\gamma$:

At each m_a, convert excluded $g_{a\gamma\gamma}$ back to $C_{\gamma\gamma}^{lim}$

Set $C_{BB} = C_{\gamma\gamma}^{lim},\ \ C_{WW} = 0$:

$\sigma \cdot BR(m_a, C_{\gamma\gamma}^{lim}, 0) = \ \sigma \cdot BR^{exc}$

Now for a $r = C_{WW}/C_{BB}$:

Find C_{BB}^r such that

$\sigma \cdot BR(m_a, C_{BB}^r, rC_{BB}^r) = \sigma \cdot BR^{exc}$

Find the recast limit $C_{\gamma\gamma}^r = C_{BB}^r + rC_{BB}^r$

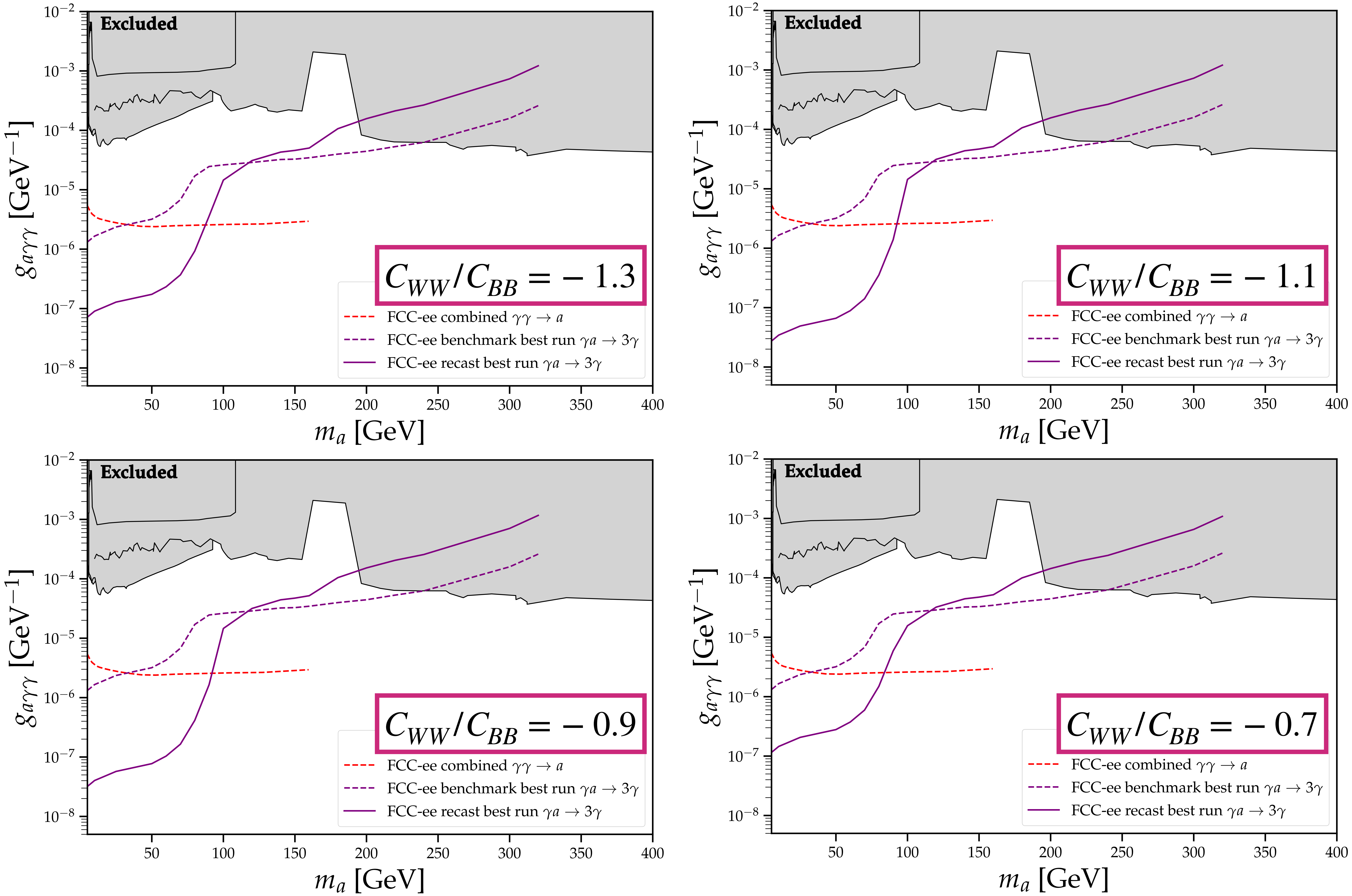
→ convert to $g_{a\gamma\gamma}^r$

*rewrite $\sigma(m_a, C_{\gamma\gamma}, C_{\gamma Z})$ and $BR(m_a, C_{\gamma\gamma}, C_{\gamma Z}, C_{ZZ})$ in terms of C_{WW}, C_{BB}:

$\sigma(m_a, C_{BB}, C_{WW}), BR(m_a, C_{BB}, C_{WW})$

Scenario 1

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



Around $C_{BB} = -C_{WW}$:

$C_{WW}/C_{BB} = -1$

$C_{\gamma\gamma} \to 0$ while $C_{\gamma Z}$ increases with respect to primary benchmark point

For $m_a < m_Z$, the sensitivity gets better

For $m_a > m_Z$, the sensitivity gets a bit worse

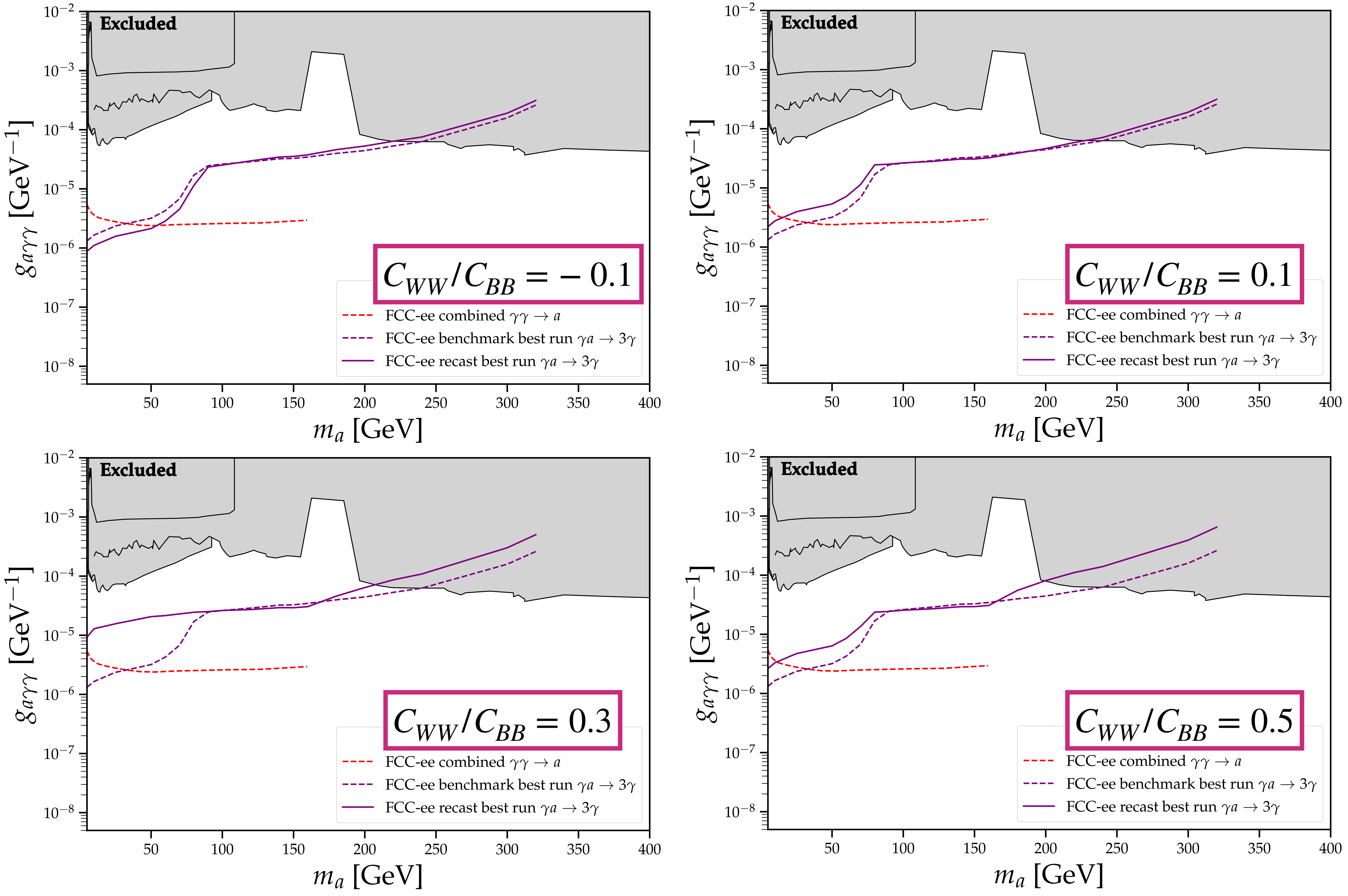
original published result

original benchmark result

scaled to new C_{WW}, C_{BB} values

Scenario 2

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



Around $c_w^2 C_{BB} = s_w^2 C_{WW}$:

$C_{WW}/C_{BB} \approx 0.3$

$C_{\gamma Z} \to 0$, $C_{\gamma\gamma}$ increases with respect to primary benchmark point

For $m_a < m_Z$, the sensitivity gets worse

For $m_a > m_Z$, the sensitivity doesn't change much

original published result

original benchmark result

scaled to new C_{WW}, C_{BB} values