

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

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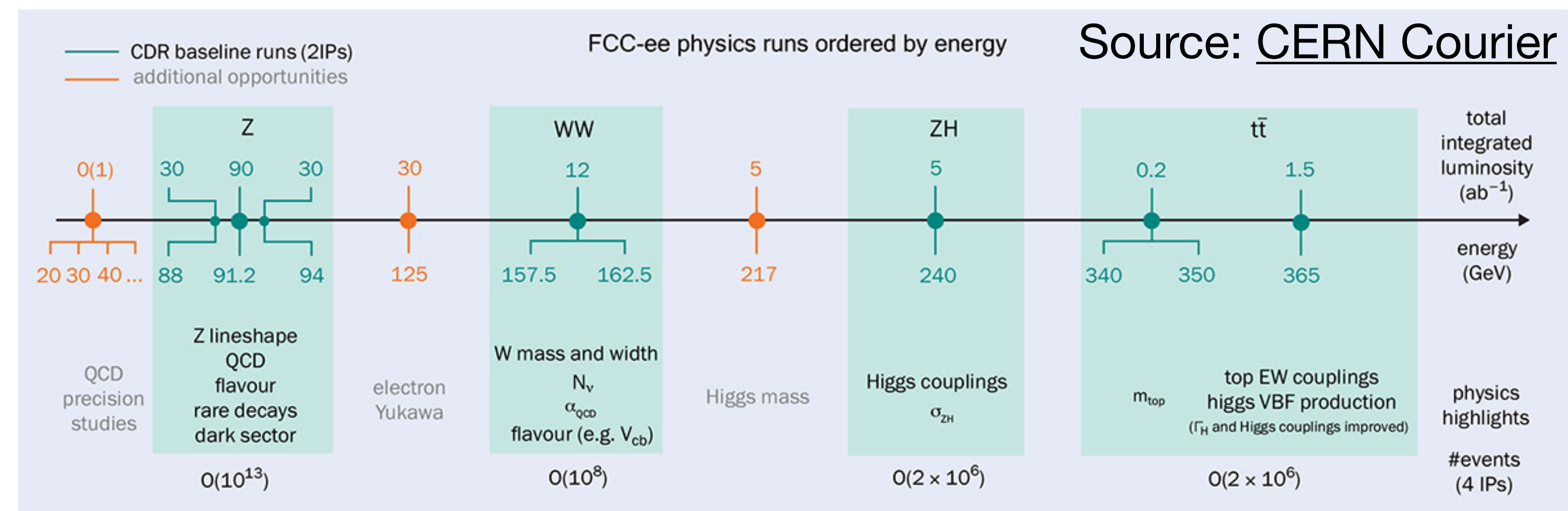
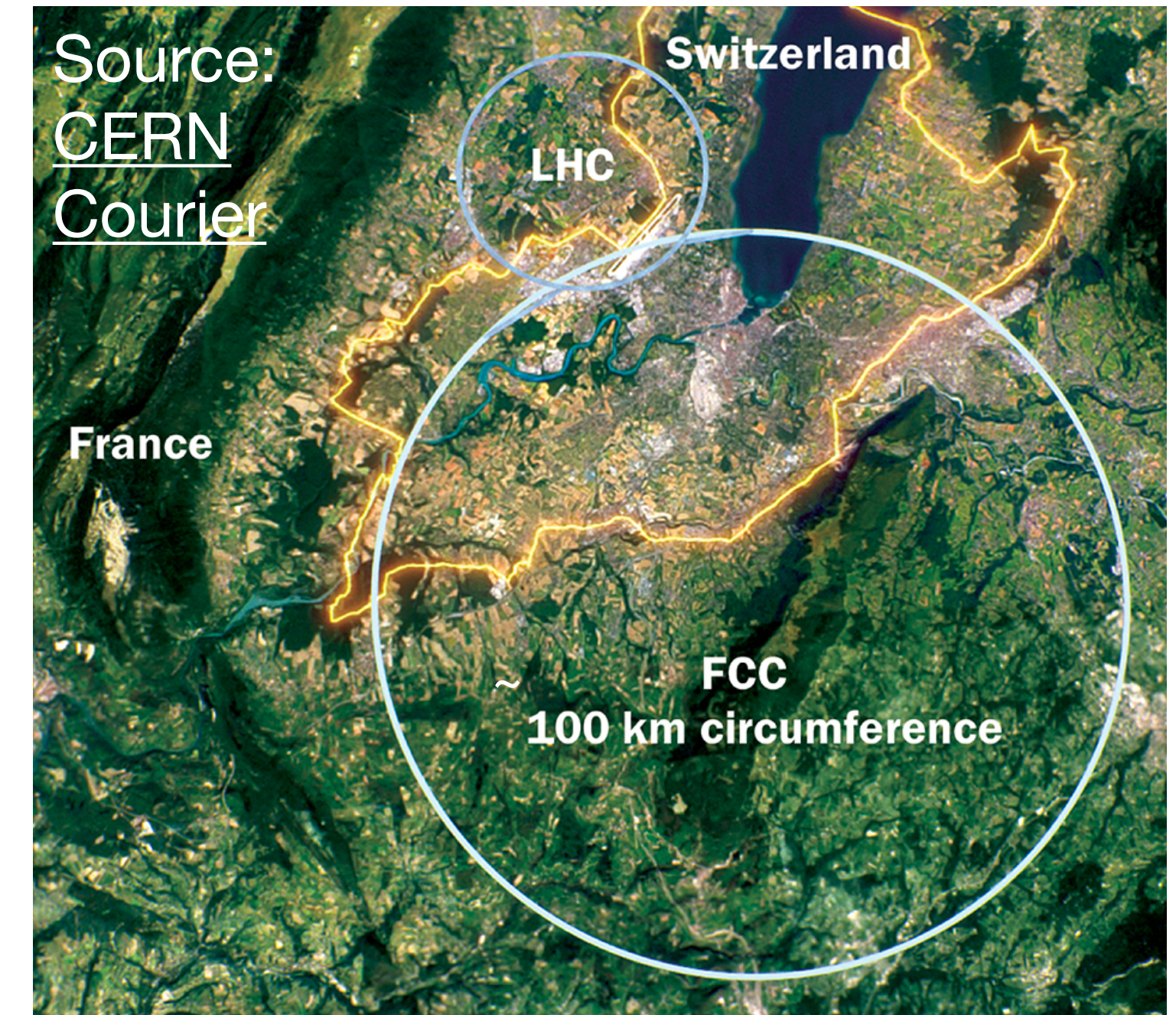
September 9, 2026



Motivation — why ALPs at the FCC-ee?

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

- The next flagship collider at CERN preferred by the German particle physics community
 - 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)



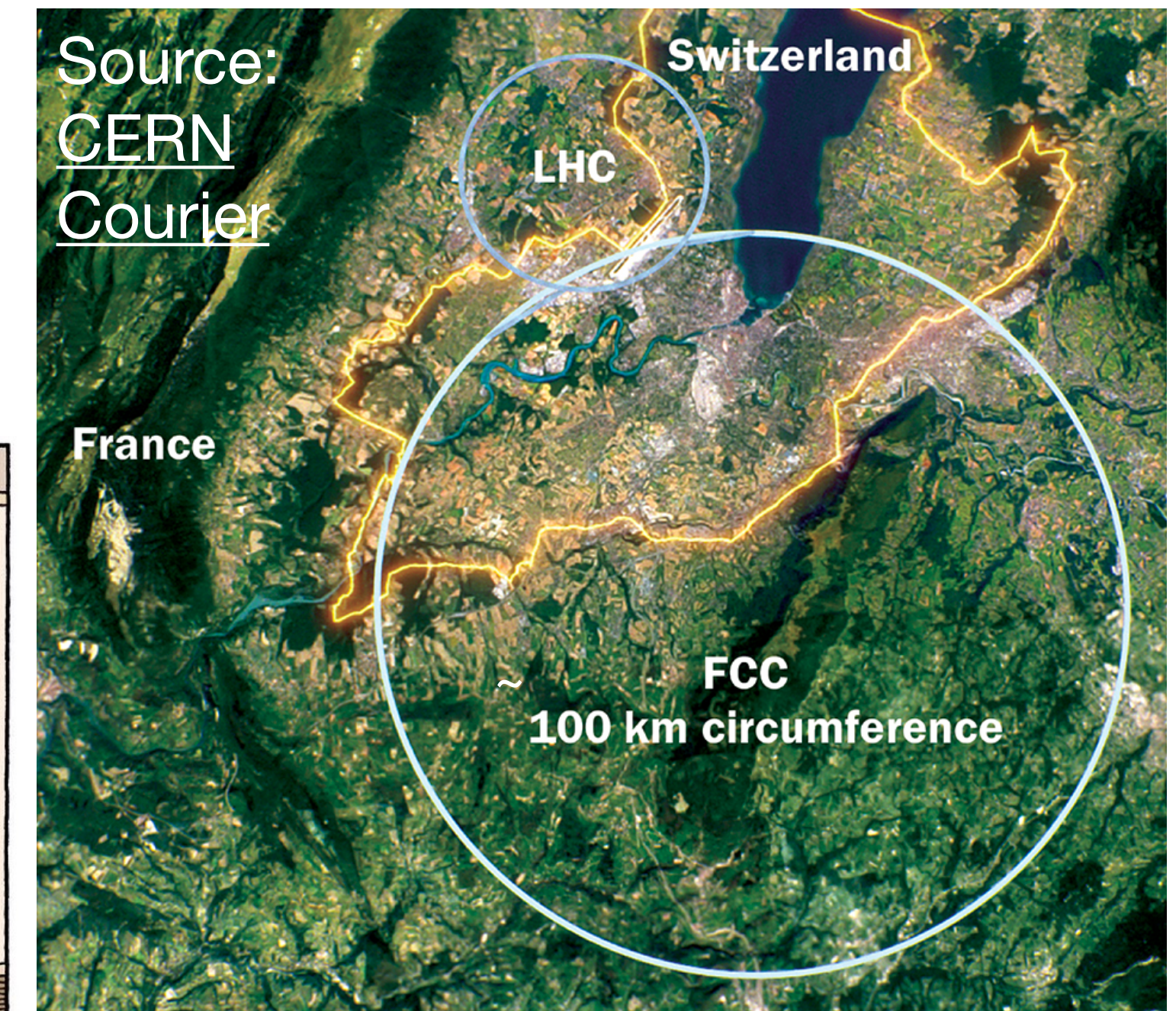
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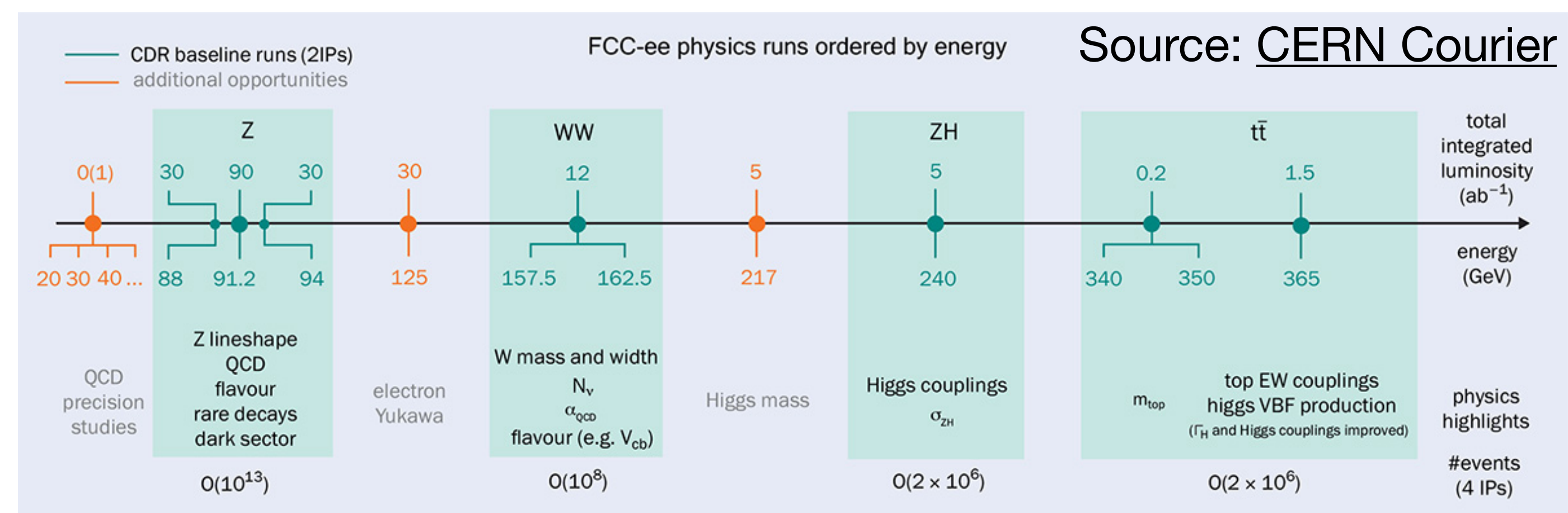


Source: New Scientist



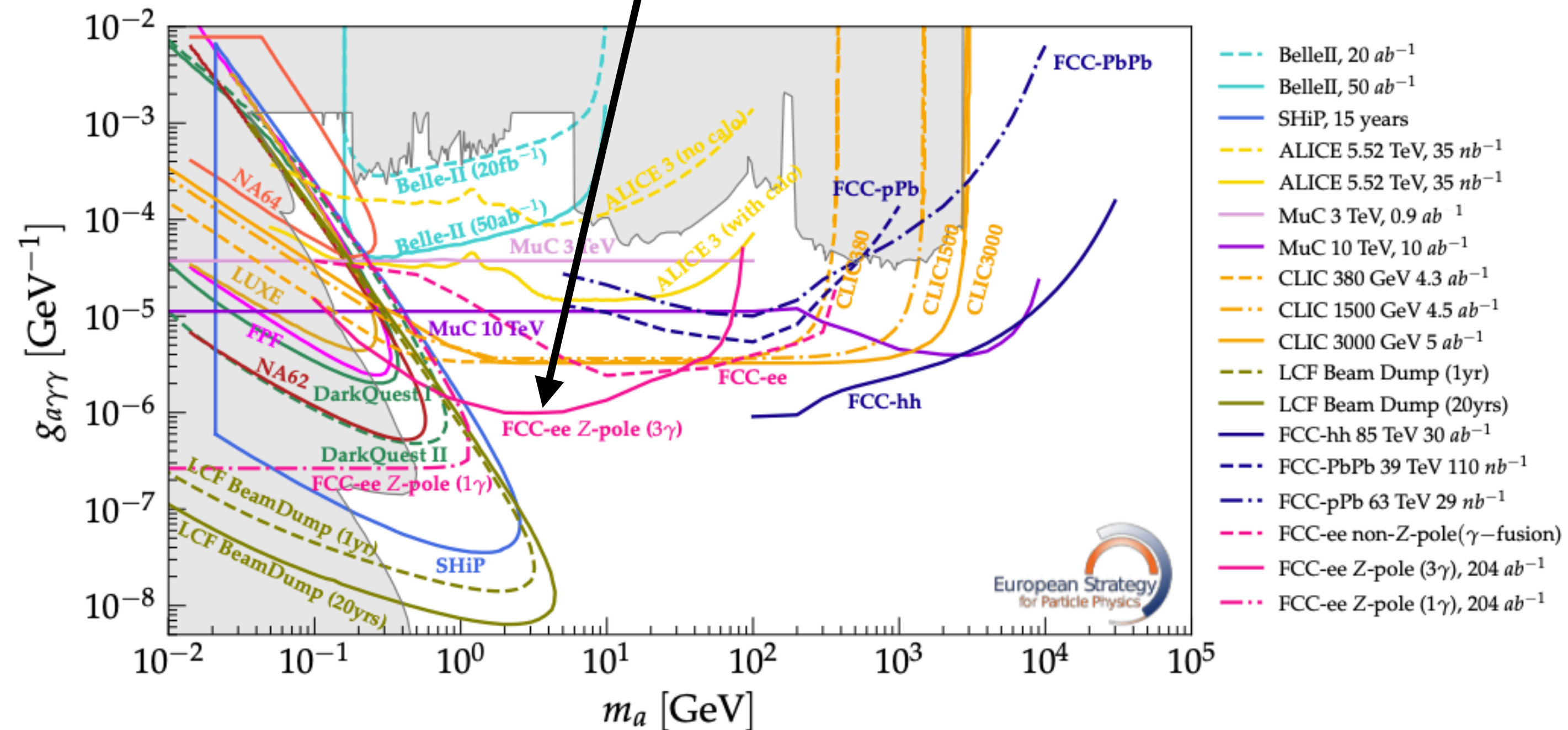
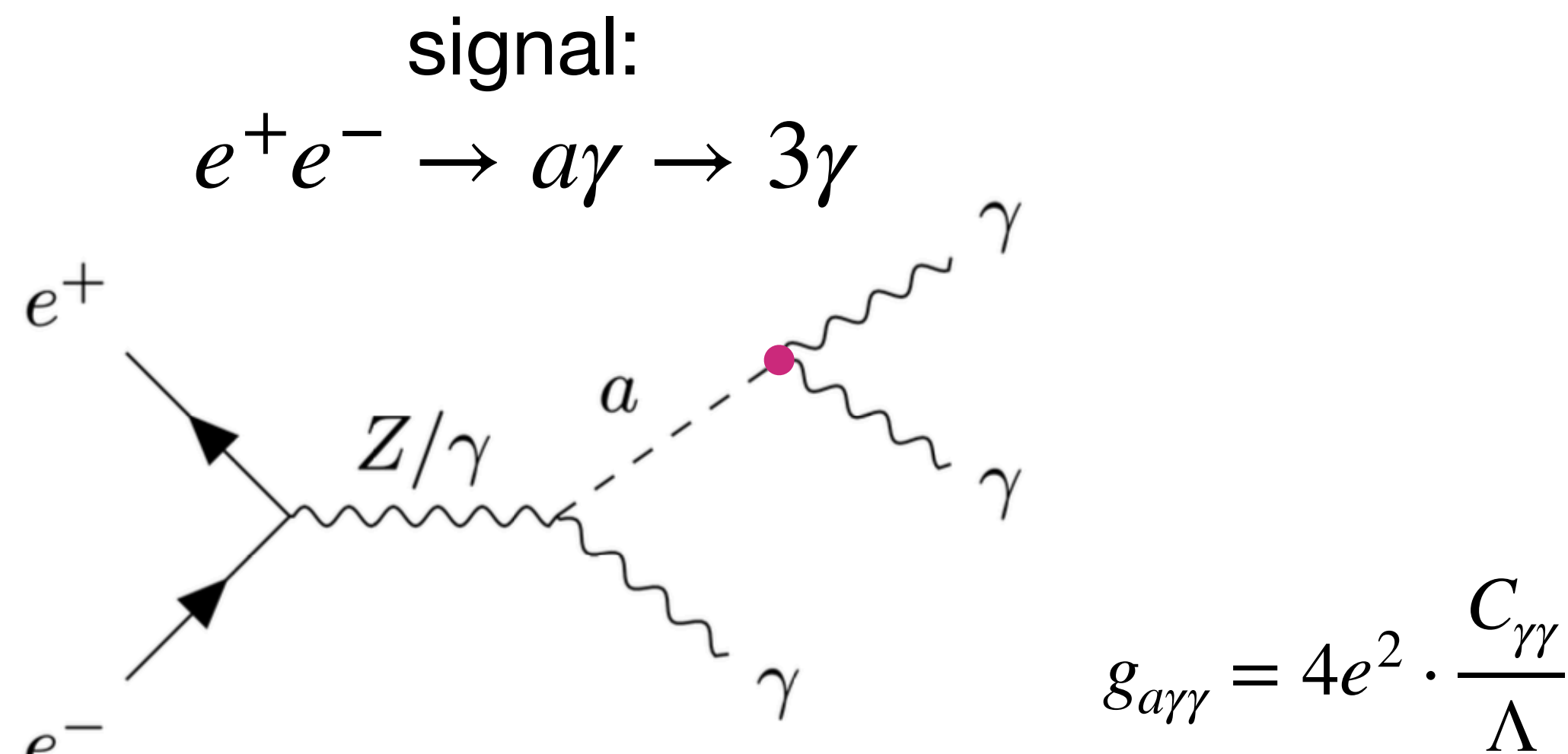
Axion-Like Particles (ALPs)

- Hypothetical pseudo-scalars that appear naturally in many SM extensions
- Dark Matter mediators/candidates



Existing limits and sensitivity projections

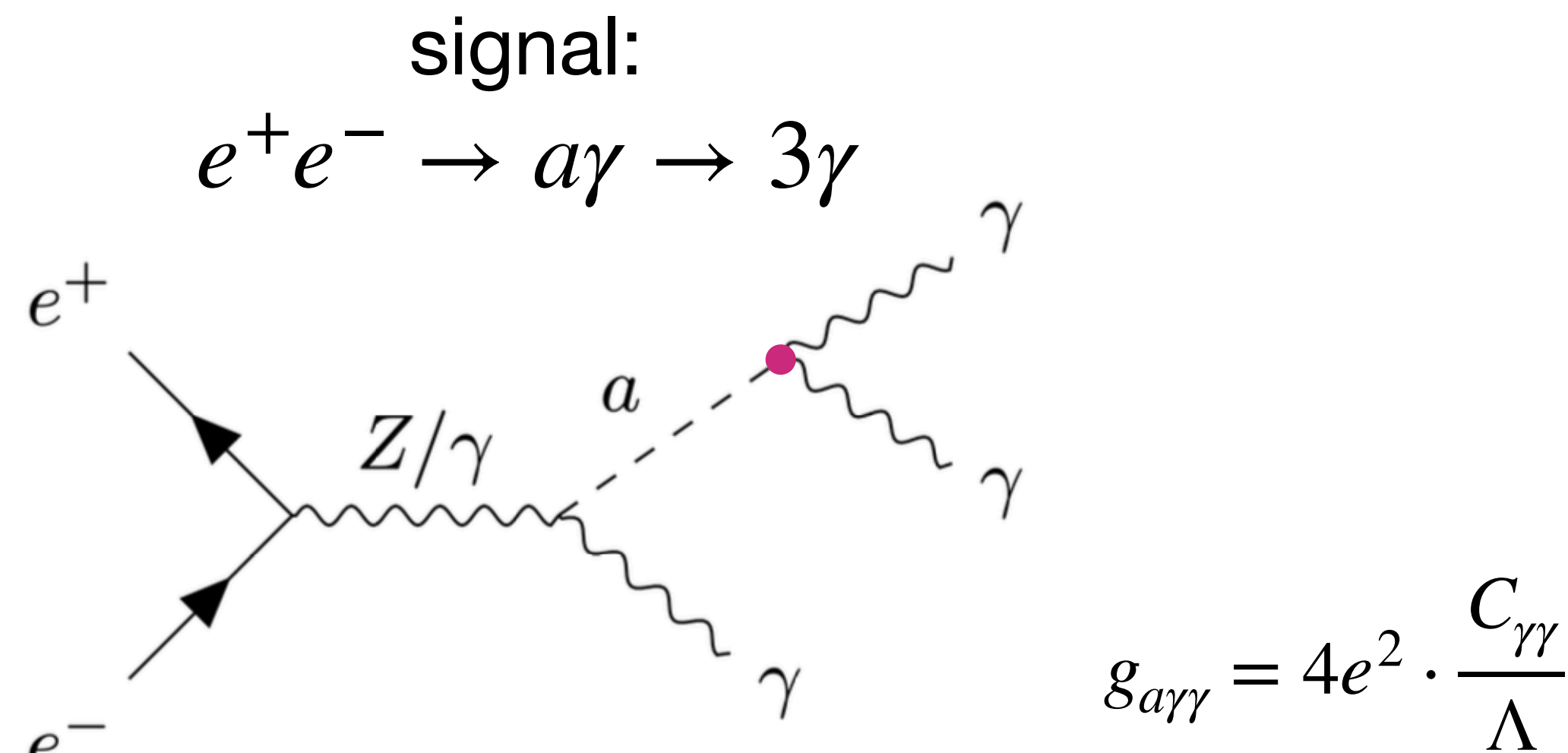
- Existing limits (in MeV-TeV ALP mass range) come from collider searches, beam dump and fixed-target experiments, and astrophysical bounds
- At the FCC-ee, high luminosity at Z pole means that we can probe **small couplings** for $m_a < 90$ GeV (Polesello:[arXiv:2502.08411](https://arxiv.org/abs/2502.08411))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



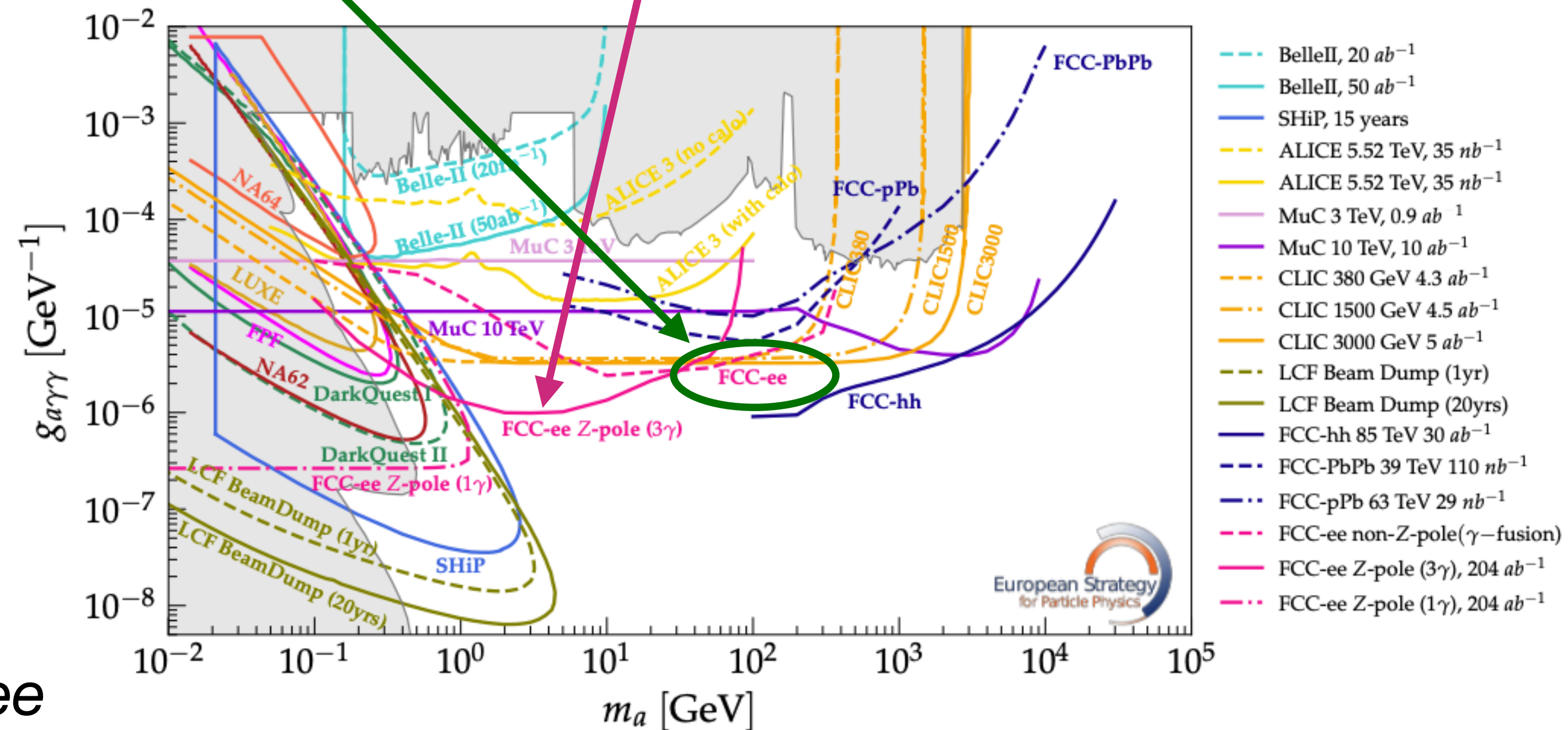
Sensitivity projections for ALPs coupling to photons as a function of ALP mass, figure from [arXiv:2511.03883](https://arxiv.org/abs/2511.03883)

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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](https://arxiv.org/abs/2511.03883)

Outline of the study

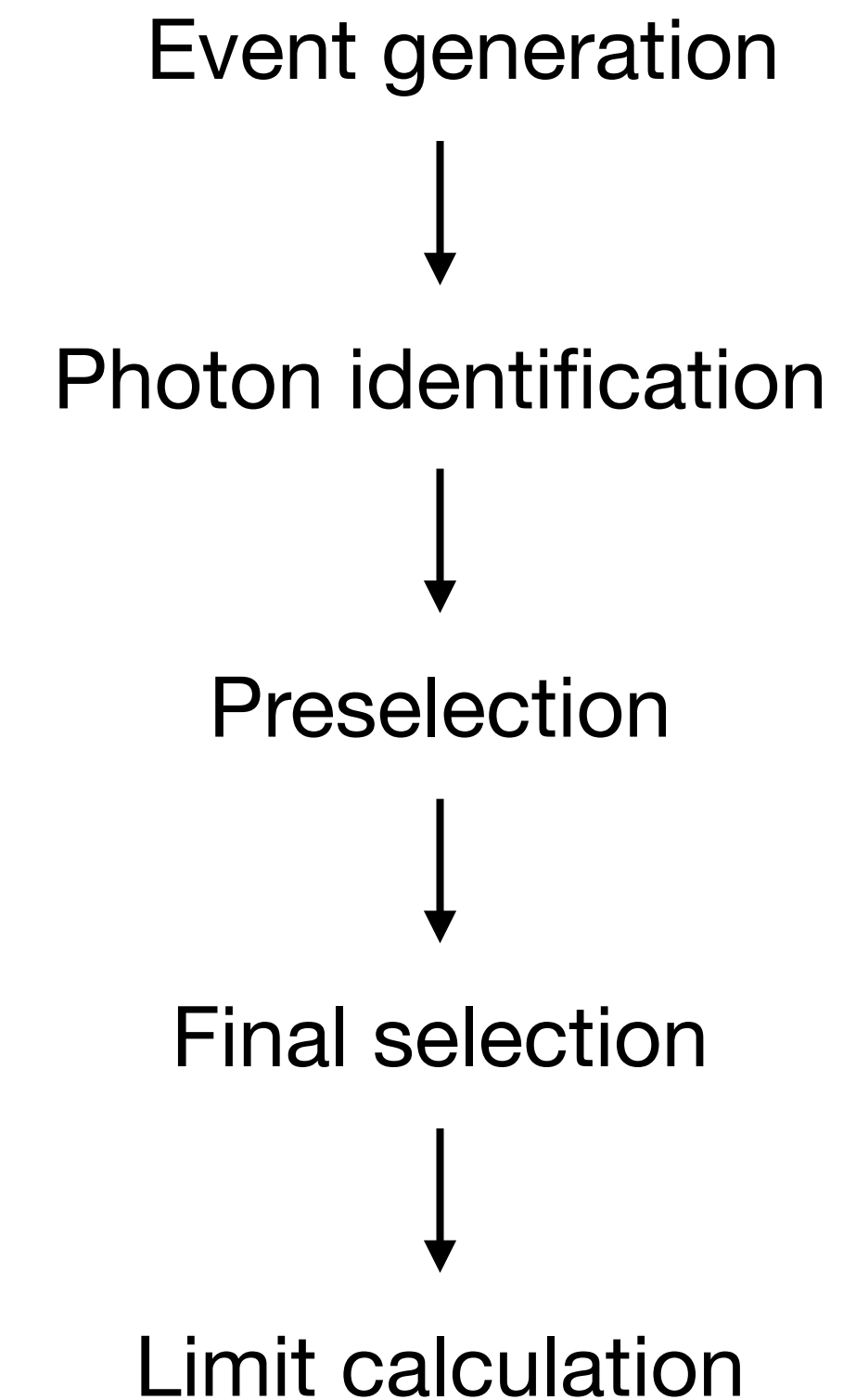
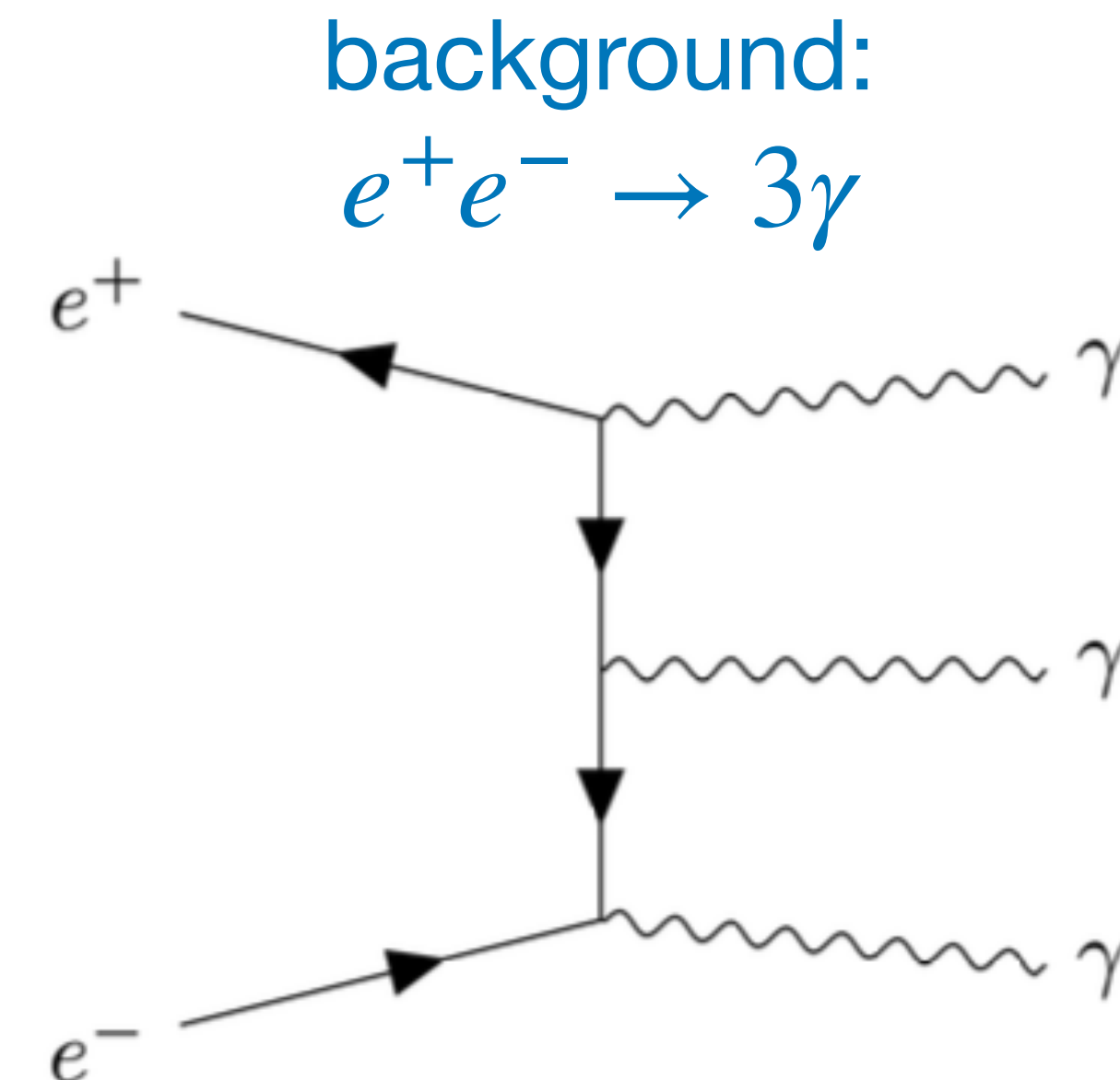
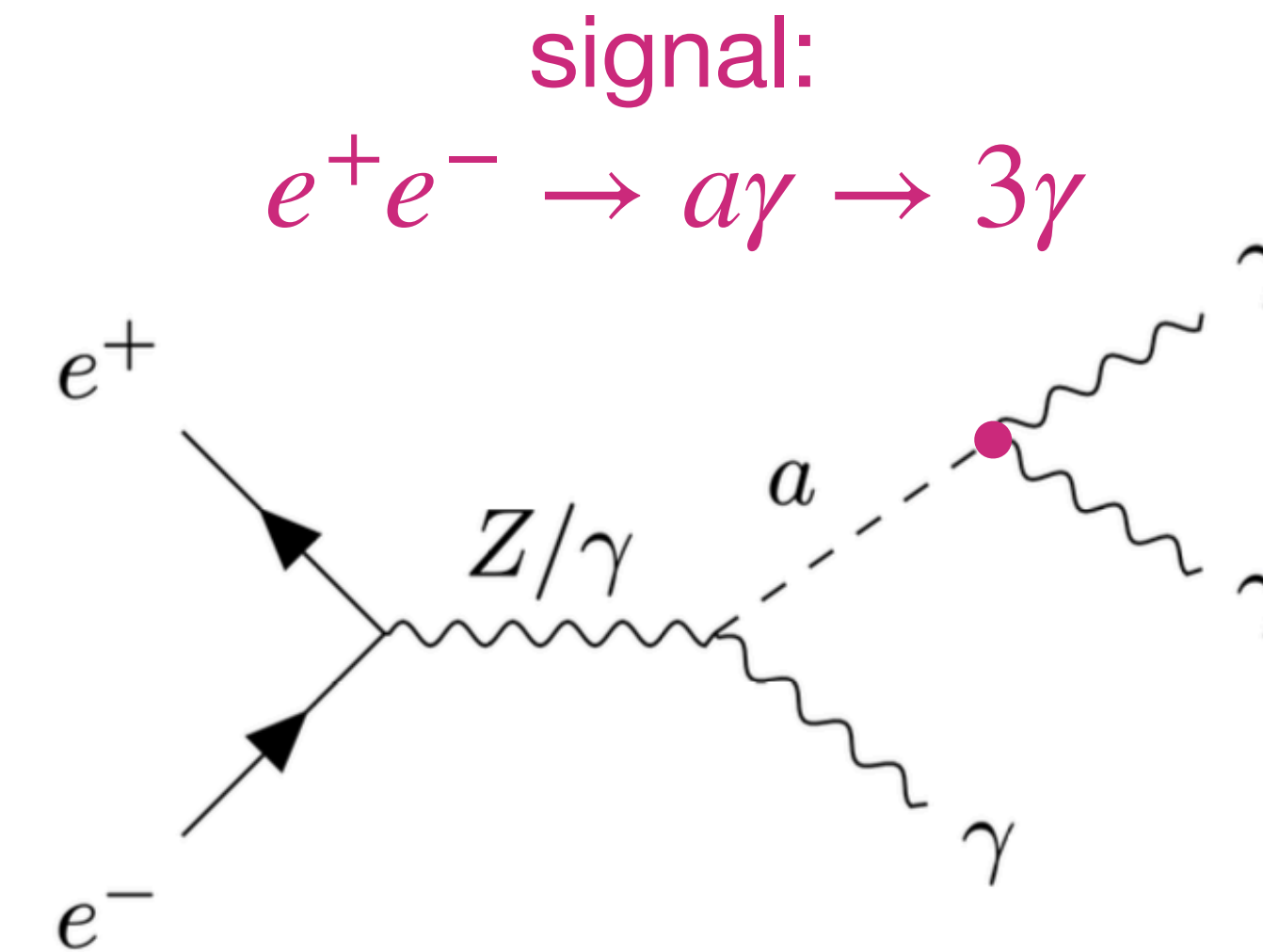
- In our model benchmark, we assume the ALP couples only to U(1) gauge fields
- We set $C_{BB} = 1$ and $C_{WW} = 0$, and that means:

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

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 and background generation

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

- 1M events generated
- $\Lambda = 1 \text{ TeV}$
- Used ALP UFO model of Bauer et al ([arxiv:1708.00443](https://arxiv.org/abs/1708.00443))
- Couplings set to $C_{\gamma\gamma} = 1$, $C_{\gamma Z} = -0.223$
- IDEA detector card used
- Photons required to have $E_\gamma > 0.1 \text{ GeV}$, 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)

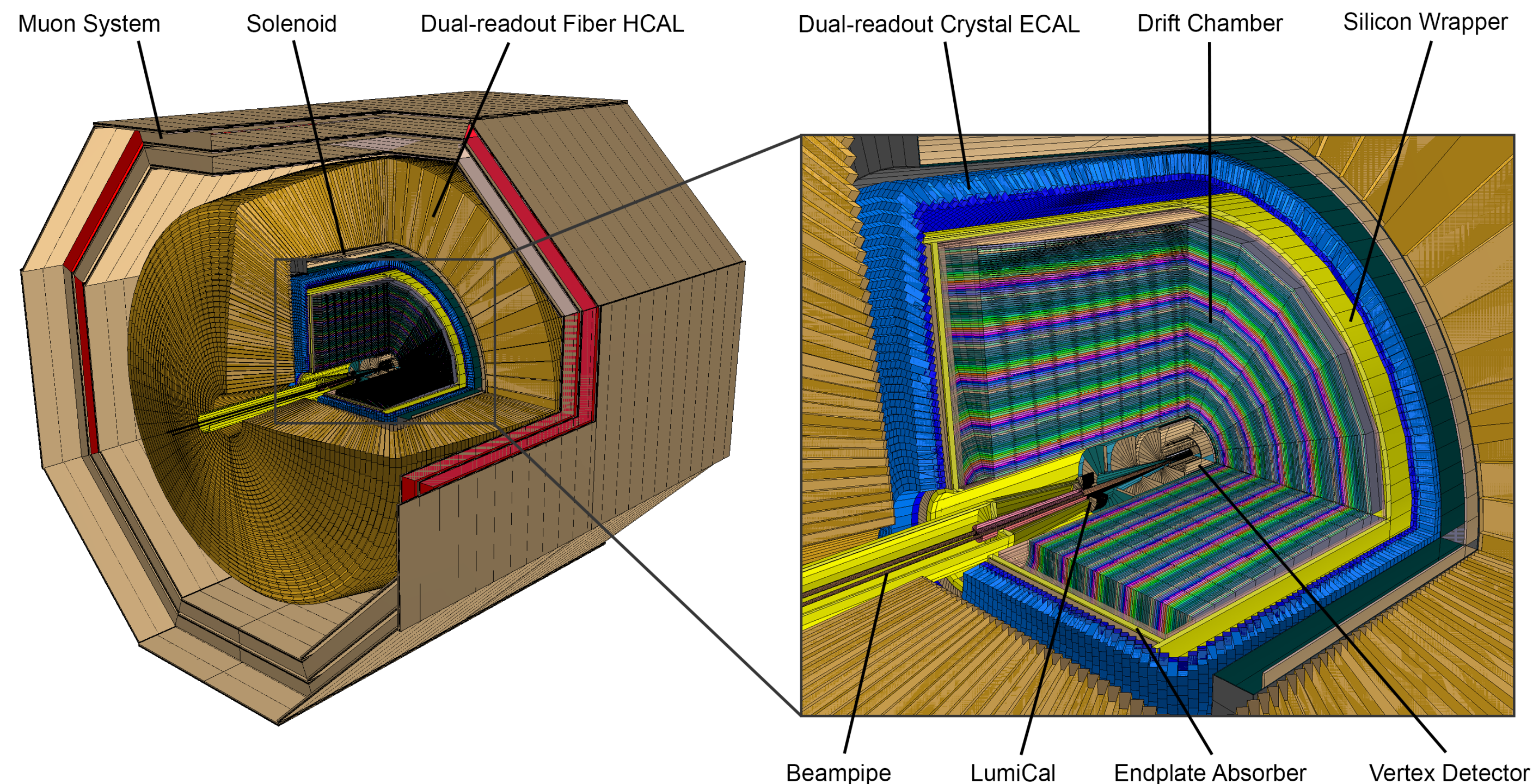


Analysis (FCCAnalyses
framework, Combine)

*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](https://arxiv.org/abs/2502.21223v4)

Photon assignment

- We have one recoil photon (γ_r) and two photons from ALP decay (γ_1, γ_2)
- It is difficult to identify which photons come from ALP!
- We therefore introduce variable M_{cut} :

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

ALP mass
reconstructed from
final state photons

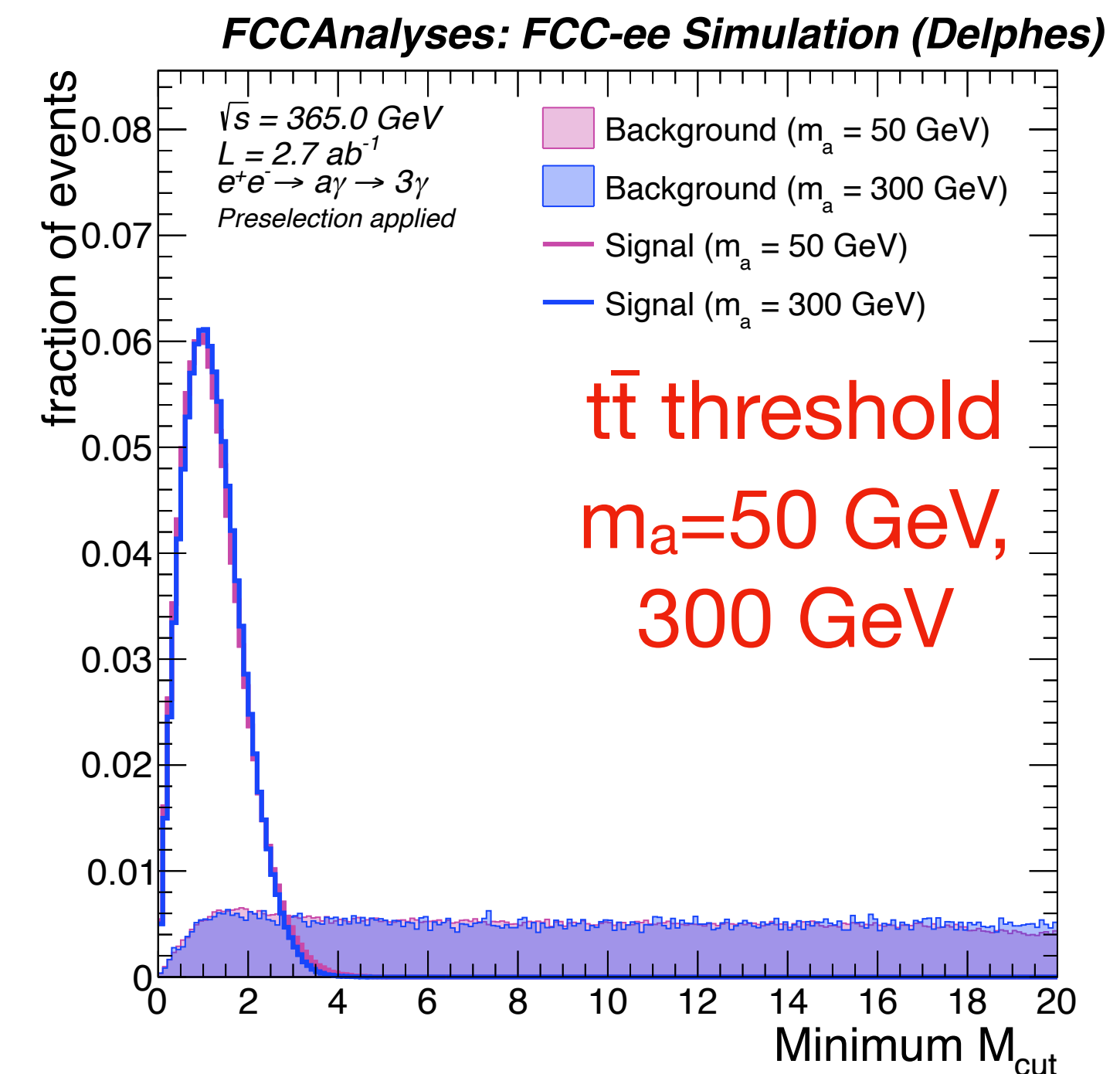
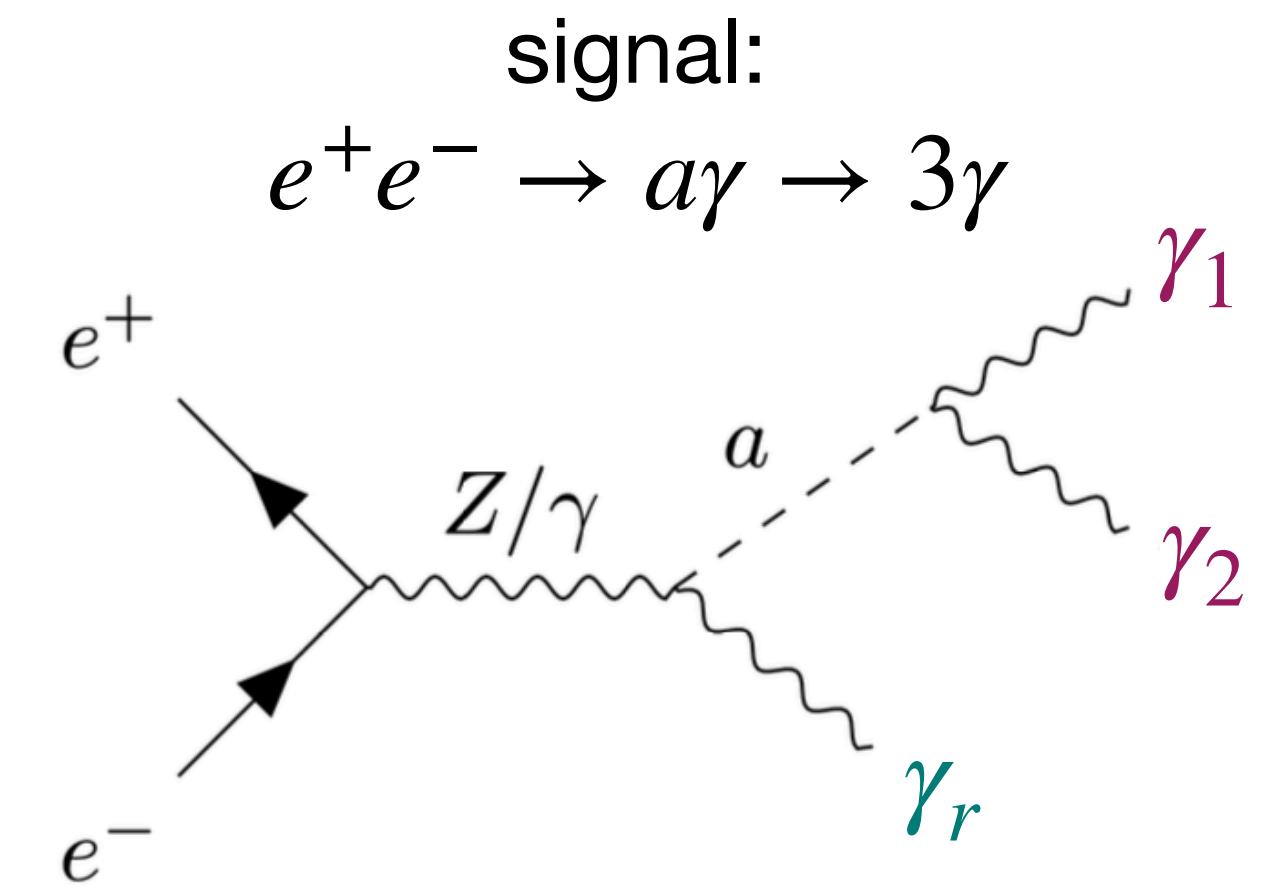
Recoil photon
energy

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

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

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

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

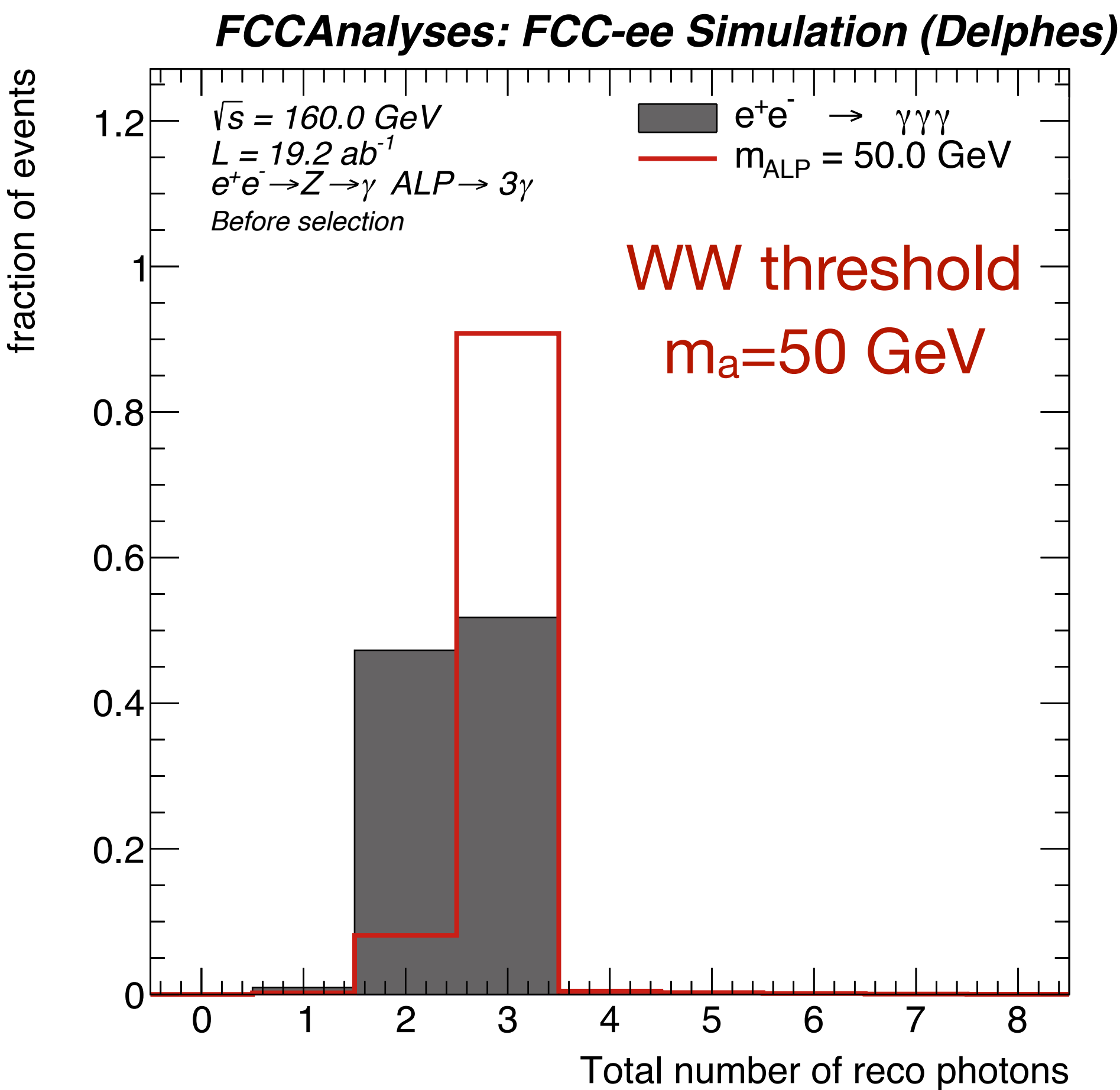


Preselection

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 $E_{\text{CM}} \pm \text{resolution}$ (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



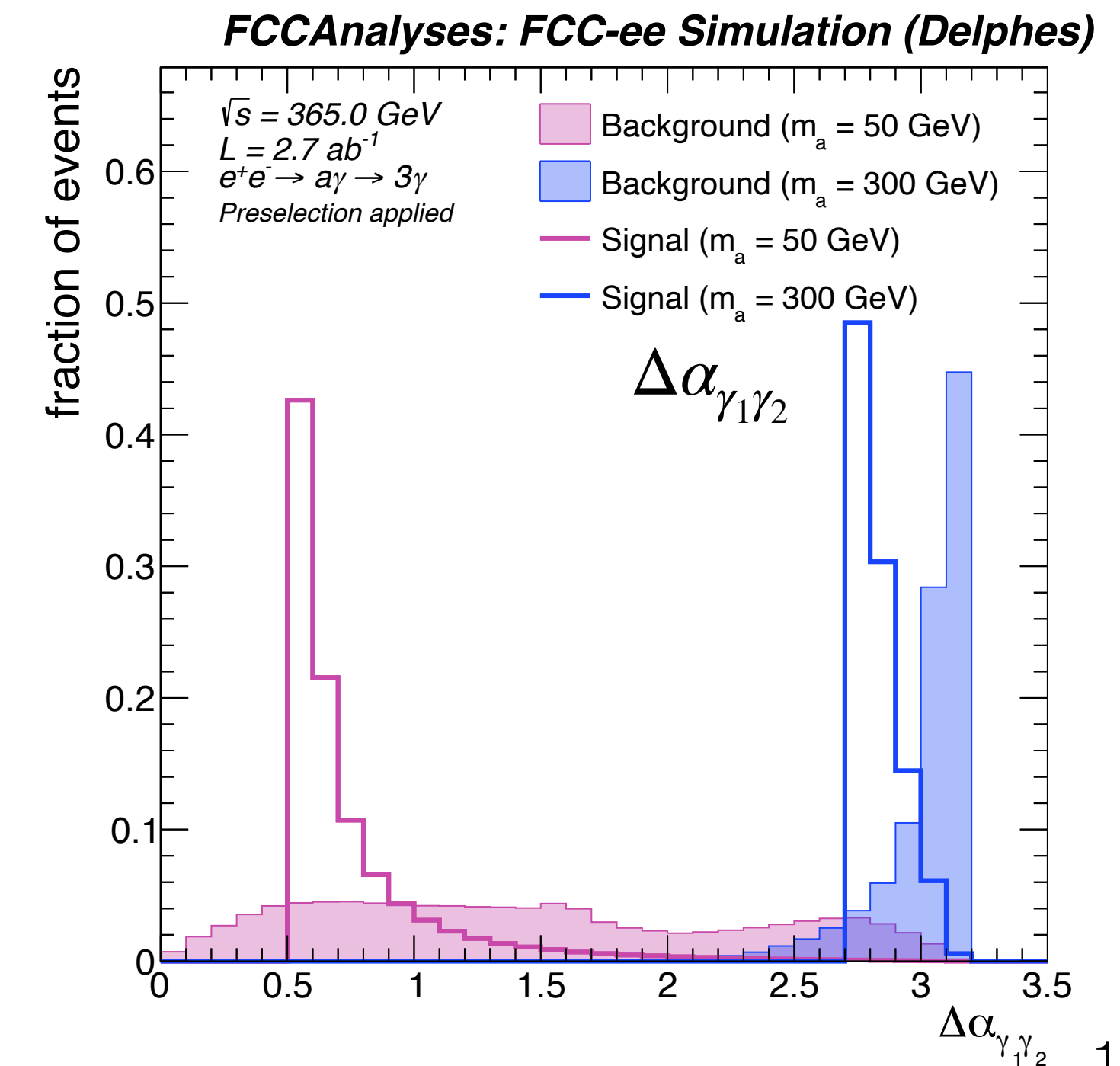
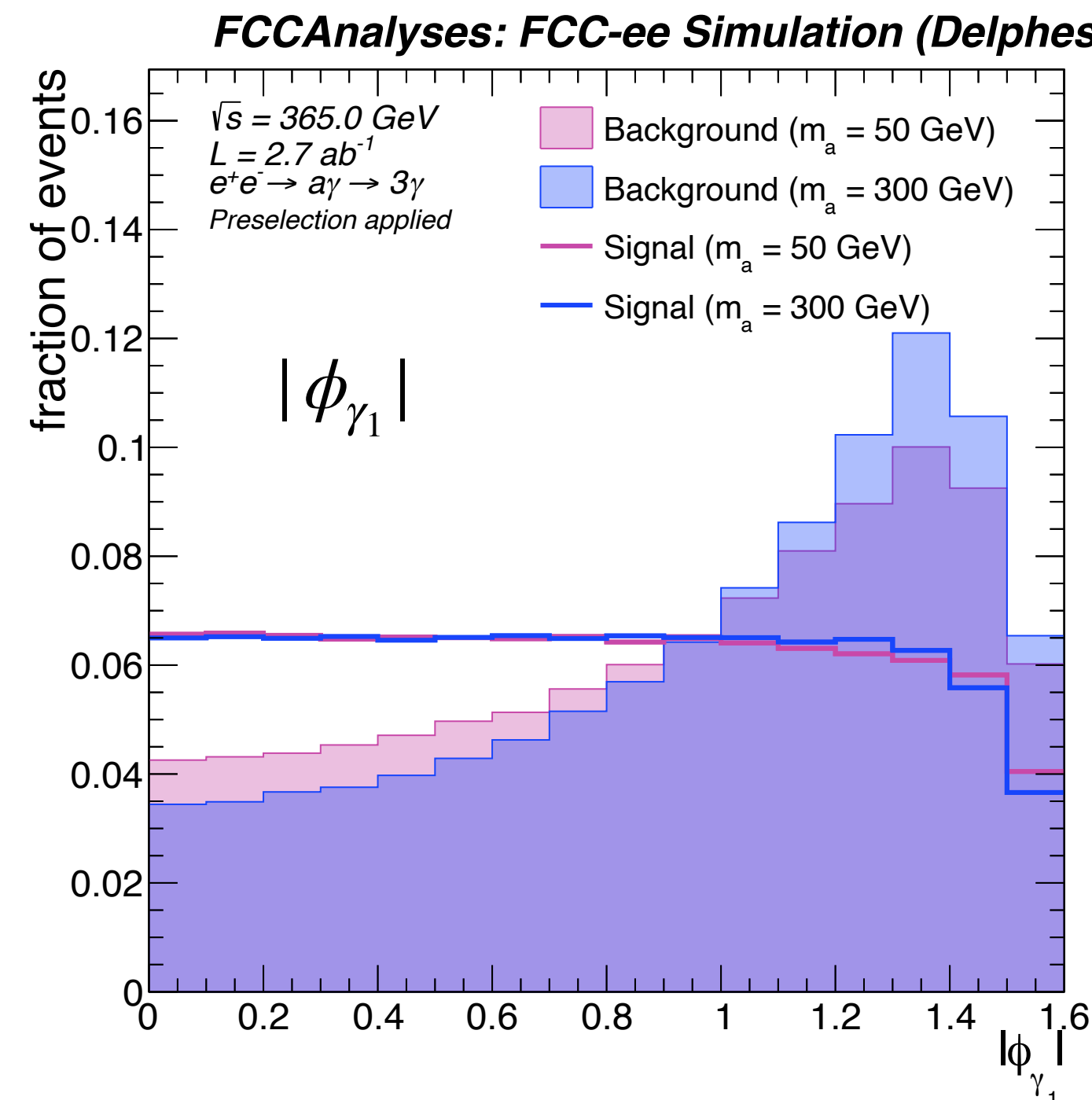
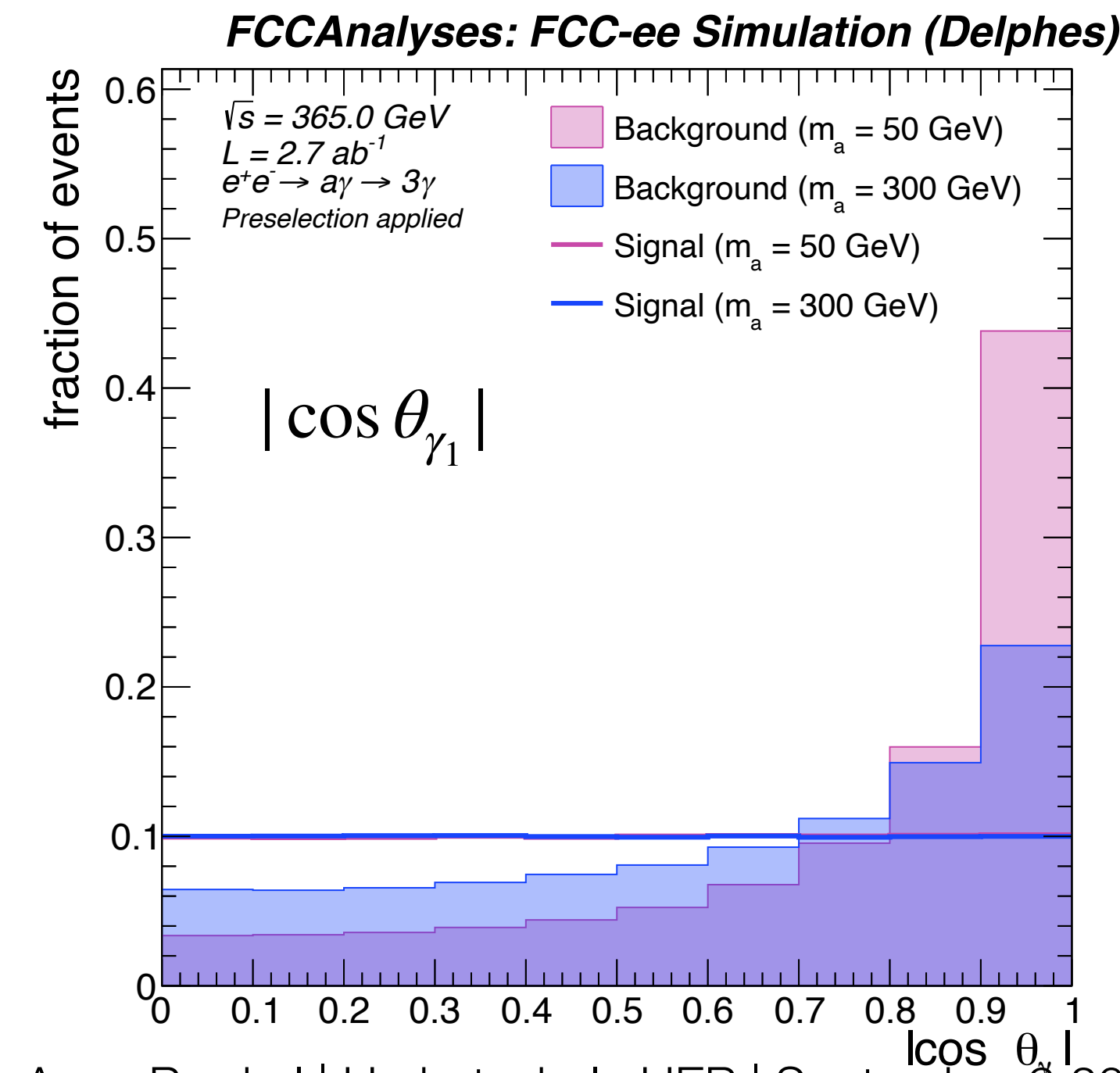
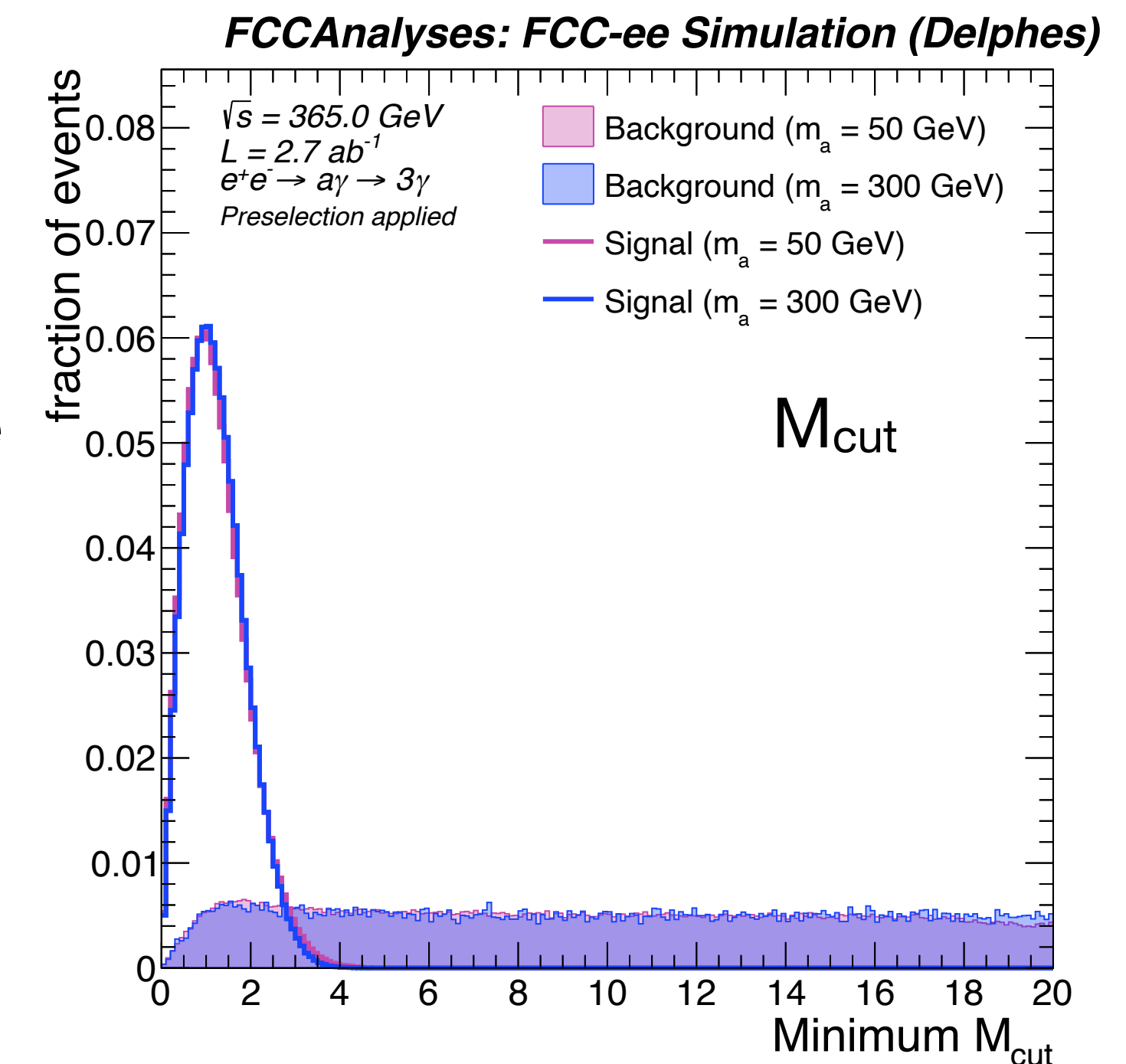
→ Averaged across all mass points

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

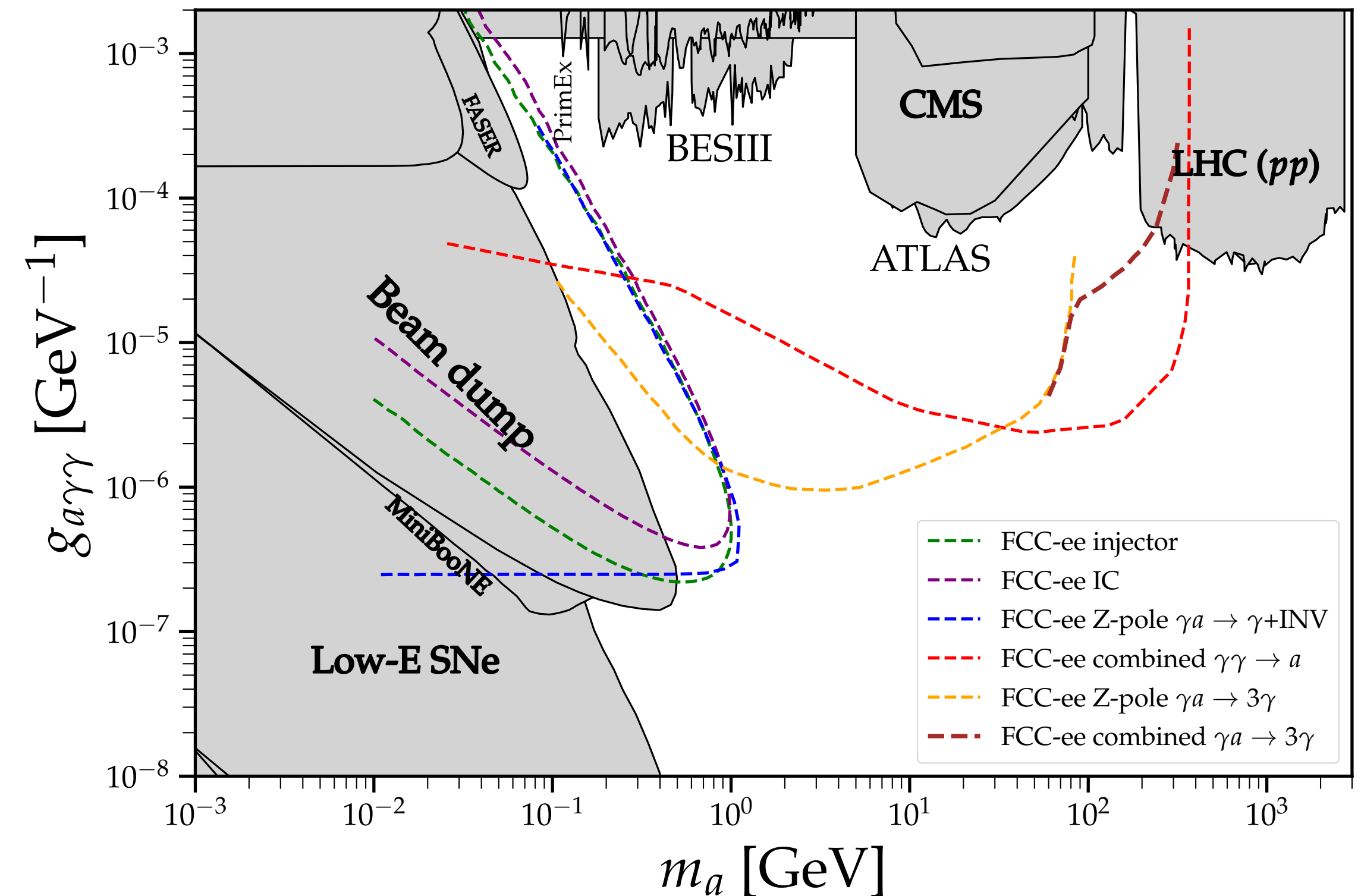
Signal strength parameter μ obtained from a shape analysis done using Combine (CMS statistical tool) for each mass point separately, assuming a background only observation

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

- Many studies have been conducted to find the sensitivity of ALPs at the FCC-ee

- **Blue**: ALP decay outside of the detector ($\gamma a \rightarrow \gamma + \text{INV}$) ([arXiv:2502.08411](#))
- **Orange**: our final state ($\gamma a \rightarrow 3\gamma$) 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 ($\gamma\gamma \rightarrow a$) ([arXiv:2310.17270v2](#))

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



In this study, we successfully extended the sensitivity of the 3γ final state to higher masses (**brown**), but $\gamma\gamma$ fusion is still better...is there anything more we can learn? **YES!**

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

- 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}

For $\gamma\gamma \rightarrow \gamma\gamma$:

- Production depends only on $C_{\gamma\gamma}$
- BR = 1 was assumed
- *Additional VBF (not just $\gamma\gamma$) could contribute, hasn't been studied

$$C_{\gamma\gamma} = C_{WW} + C_{BB}$$

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Two interesting scenarios:

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

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

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

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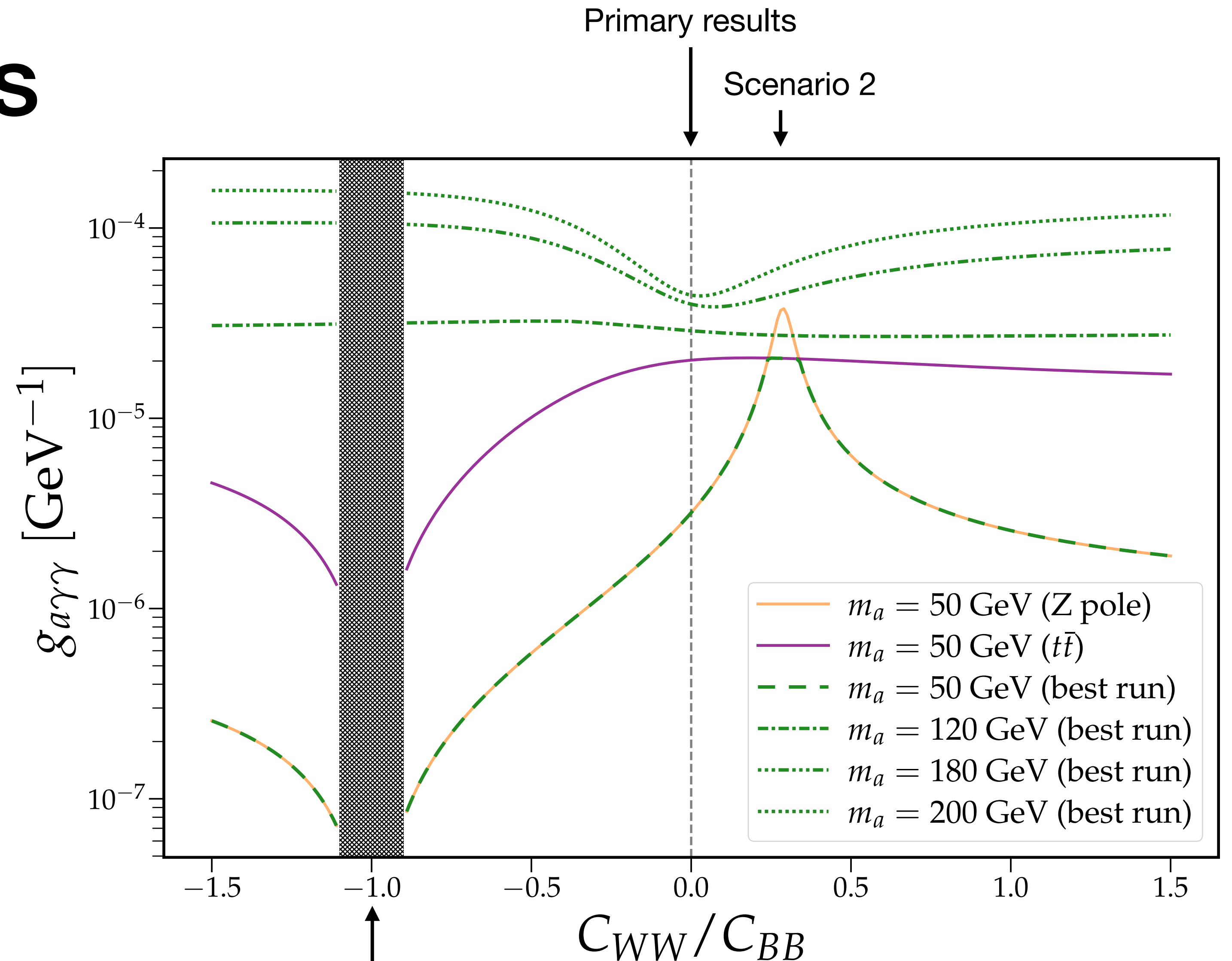
****How does varying C_{WW}/C_{BB} affect 3γ sensitivity?**

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

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

Recasting results

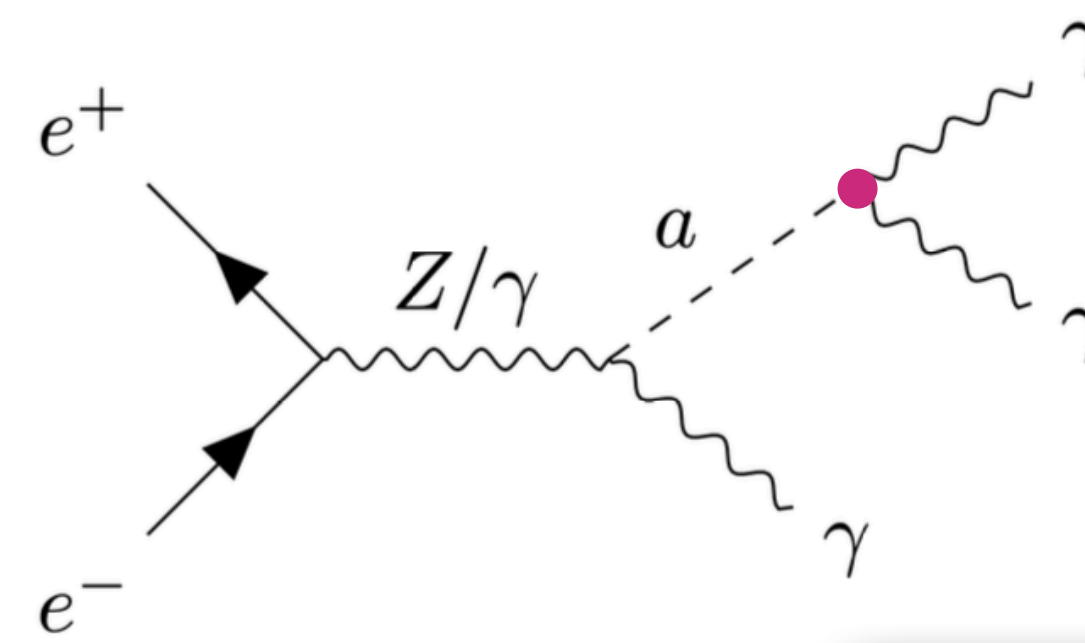
- The change in sensitivity is shown as a function of C_{WW}/C_{BB} for four different ALP masses
- For $m_a > m_Z$, the variation in reach is at most a factor of ≈ 3.5
- For $m_a < m_Z$, the variation in reach spans many orders of magnitude
 - Z pole run results are more drastic than $t\bar{t}$ threshold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



Conclusion

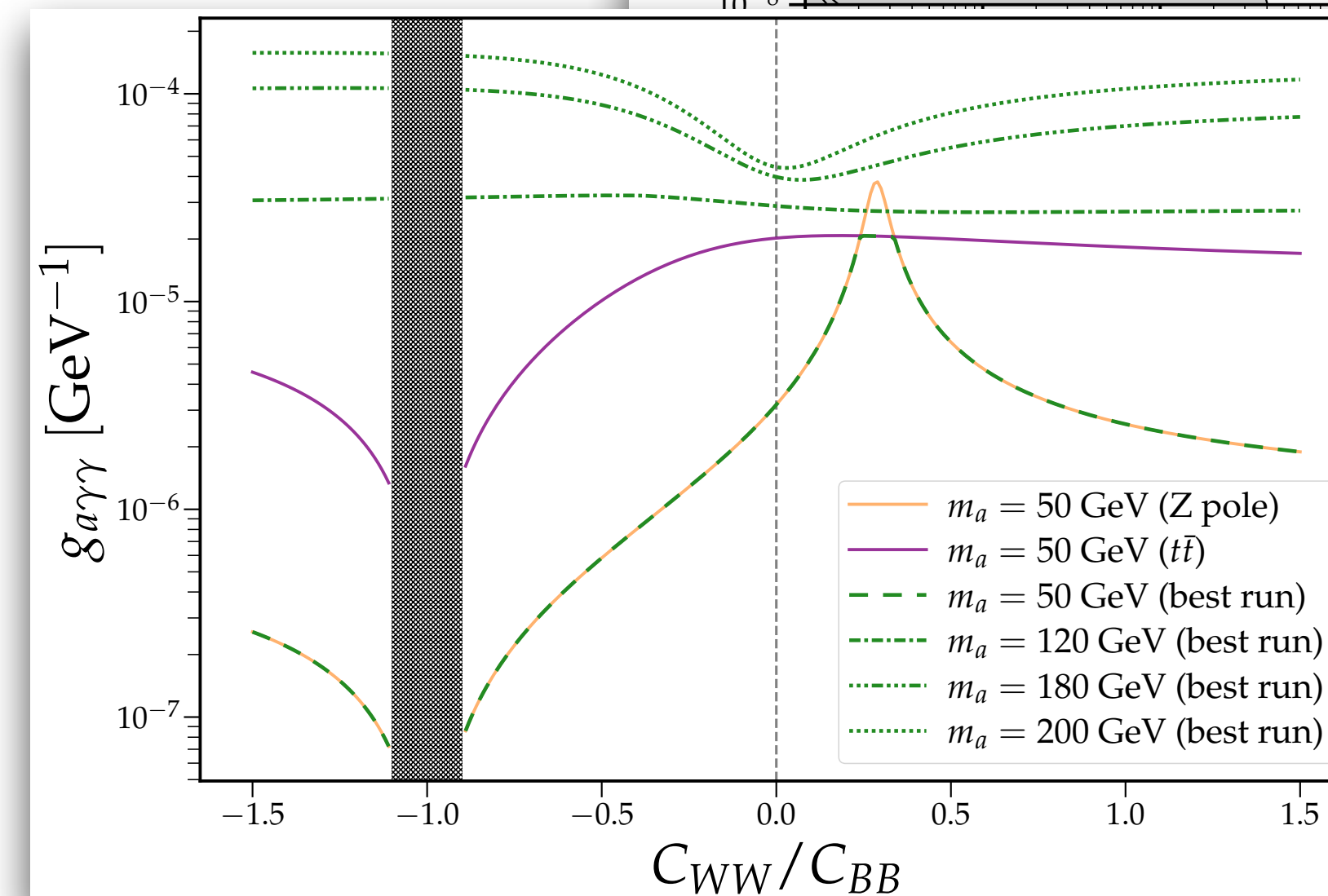
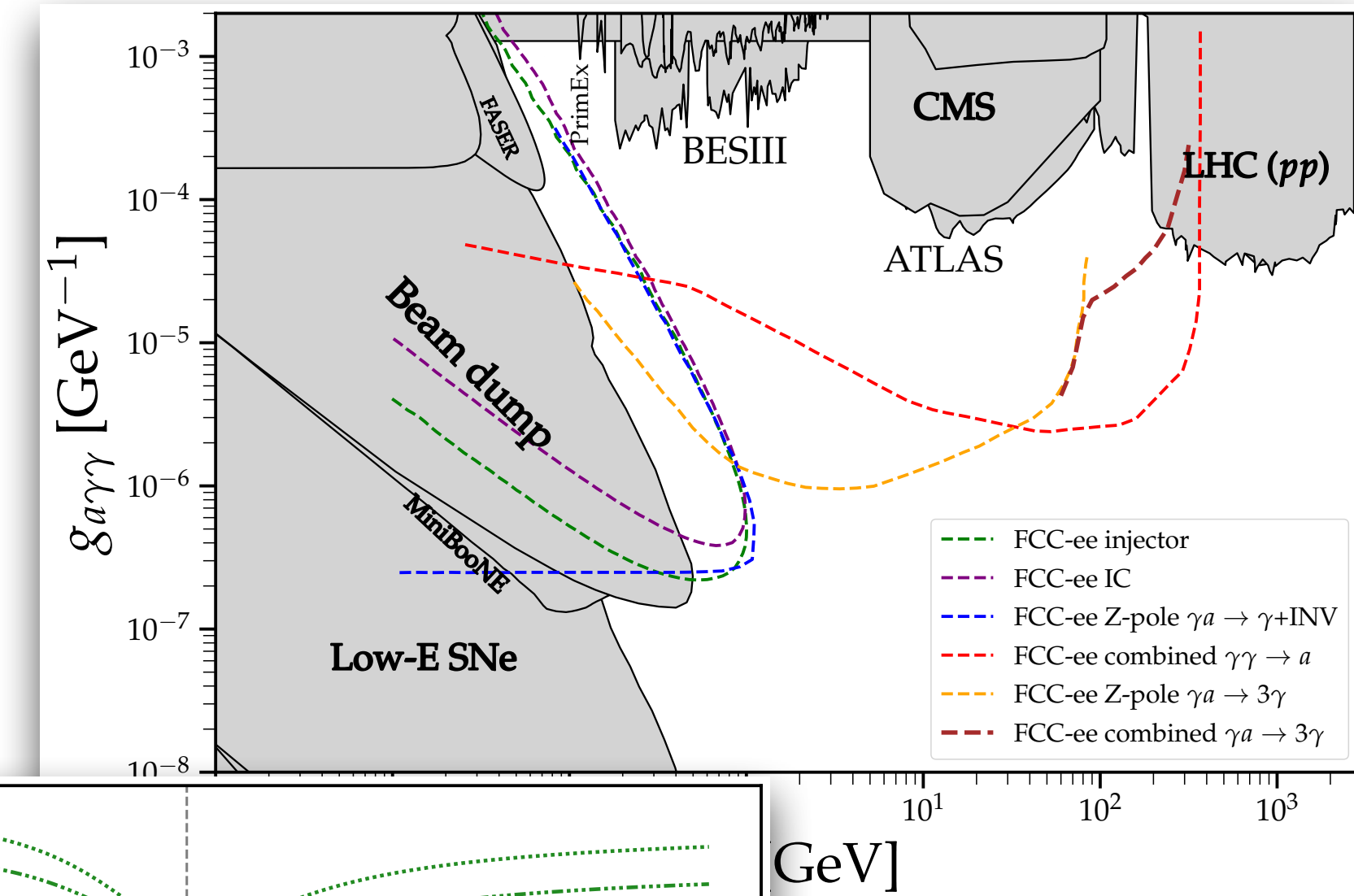
- The FCC-ee will be sensitive to ALPs produced in $e^+e^- \rightarrow \gamma a \rightarrow 3\gamma$
- This process is sensitive to **both** $C_{\gamma\gamma}$ and $C_{\gamma Z}$ → therefore it is sensitive to the relationship between C_{WW} and C_{BB}
 - This channel is important to consider in addition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

The paper has been submitted to arXiv ([arXiv:2605.21452](https://arxiv.org/abs/2605.21452)) and EPJC, and is currently under review!



$$C_{\gamma\gamma} = C_{WW} + C_{BB}$$

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



Thank you!

Backup slides

The theory

Leading interactions of ALP to SM particles is described by:

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

$\uparrow$
 ALP = a

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

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

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

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

The model benchmark

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

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

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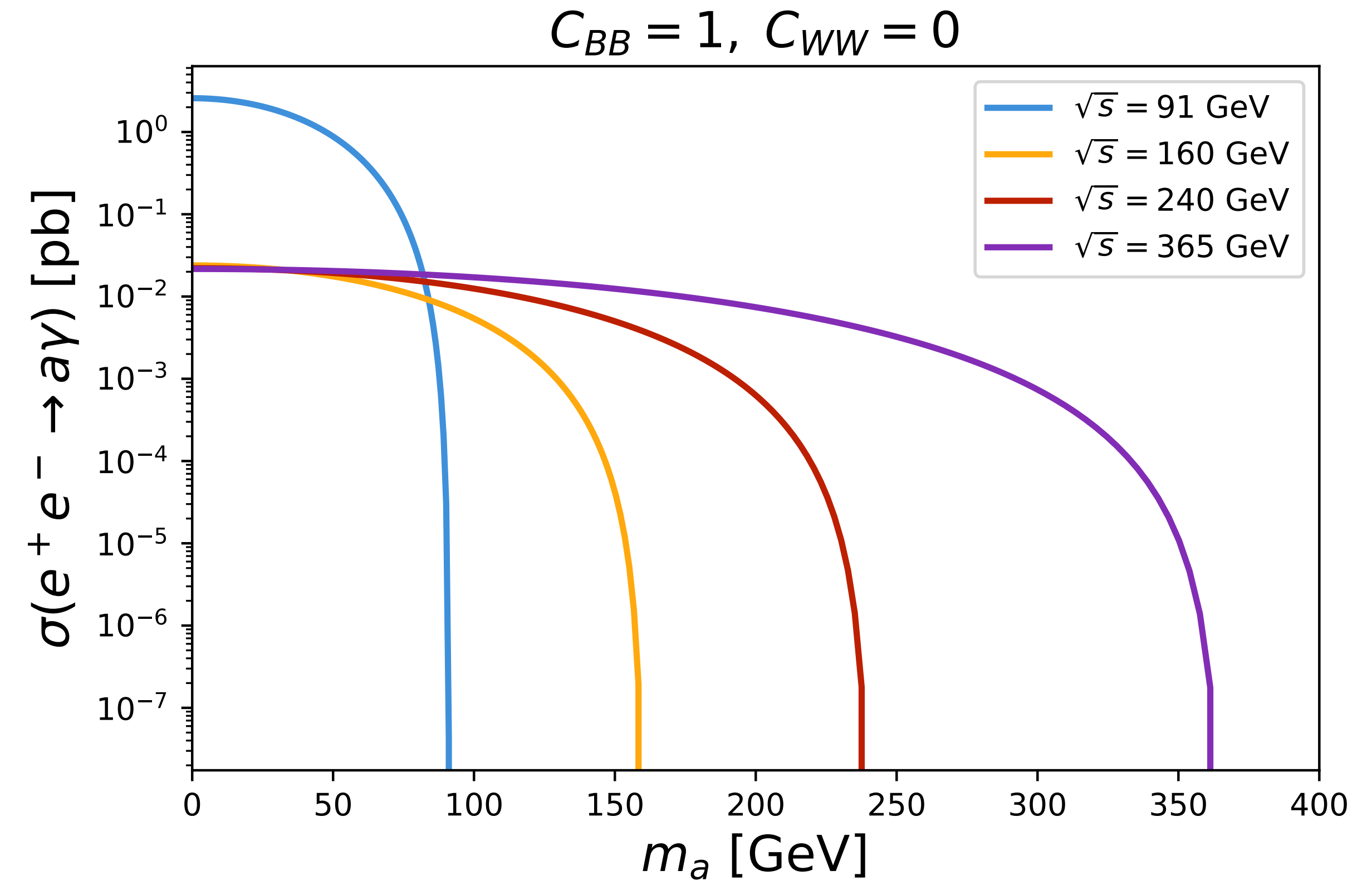


$$C_{\gamma Z} = -s_w^2 C_{\gamma\gamma}$$

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:

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

WW, ZH, tt:

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

Production cross section

The differential cross section is

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

where

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

$g_V = 2s_w^2 - 1/2$, $g_A = -1/2$, 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} :

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

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

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

ALP mass resolution Energy resolution

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:

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

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

ALP decay:

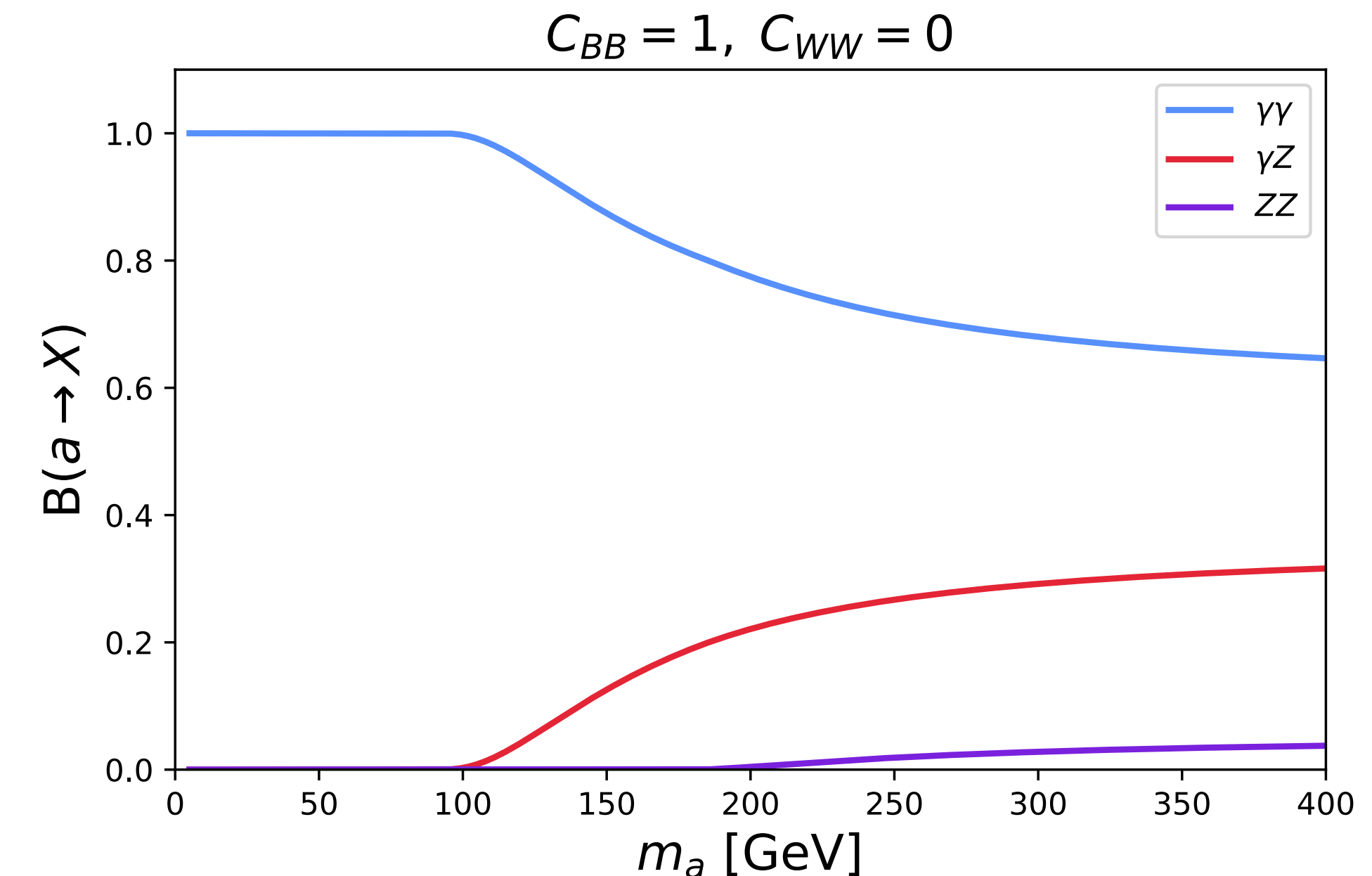
- Normalized to BR of $a \rightarrow \gamma\gamma$
- In our model benchmark,

$$\Gamma_{tot} = \Gamma(a \rightarrow \gamma\gamma) + \Gamma(a \rightarrow \gamma Z) + \Gamma(a \rightarrow ZZ)$$

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

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

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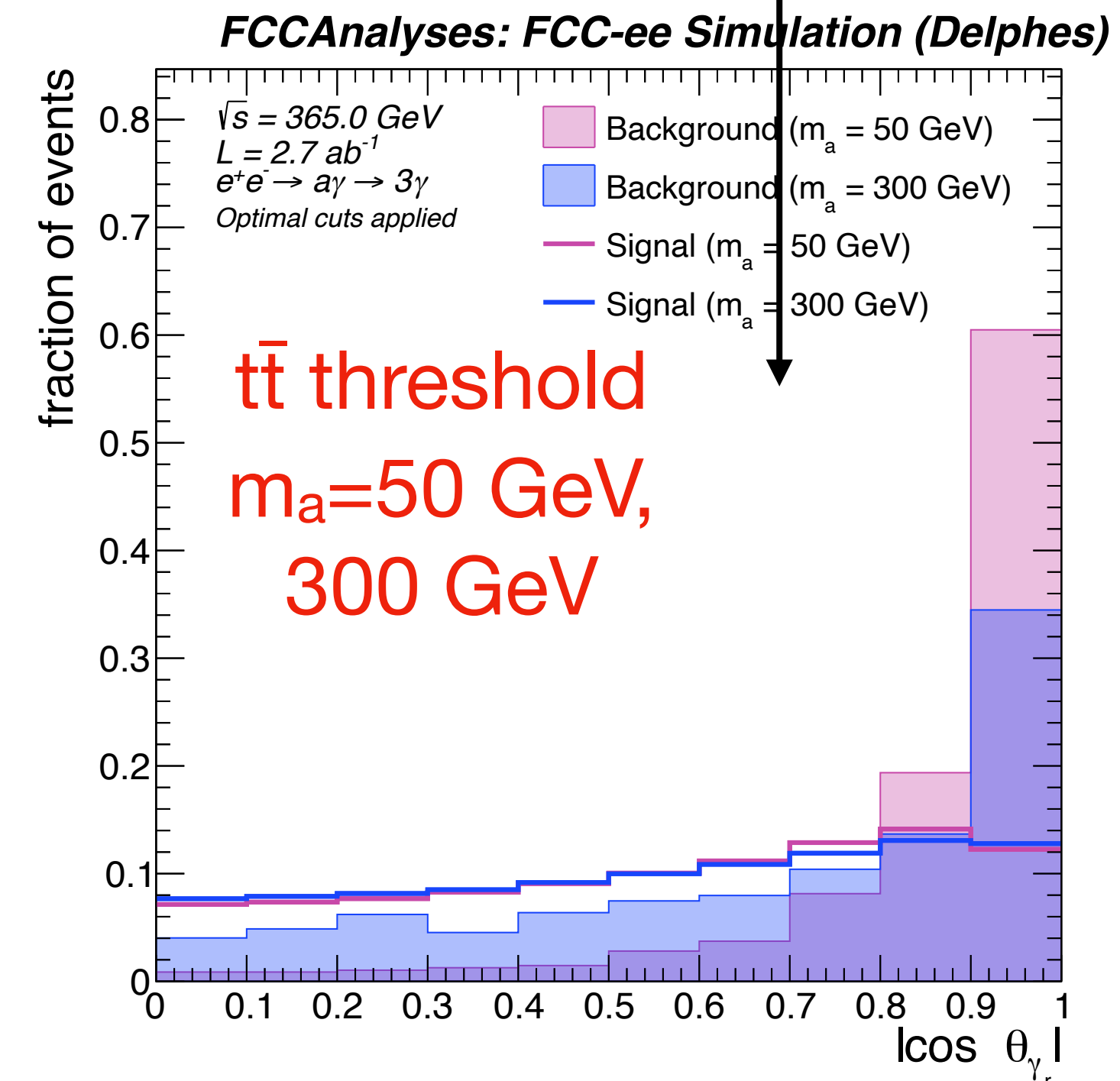
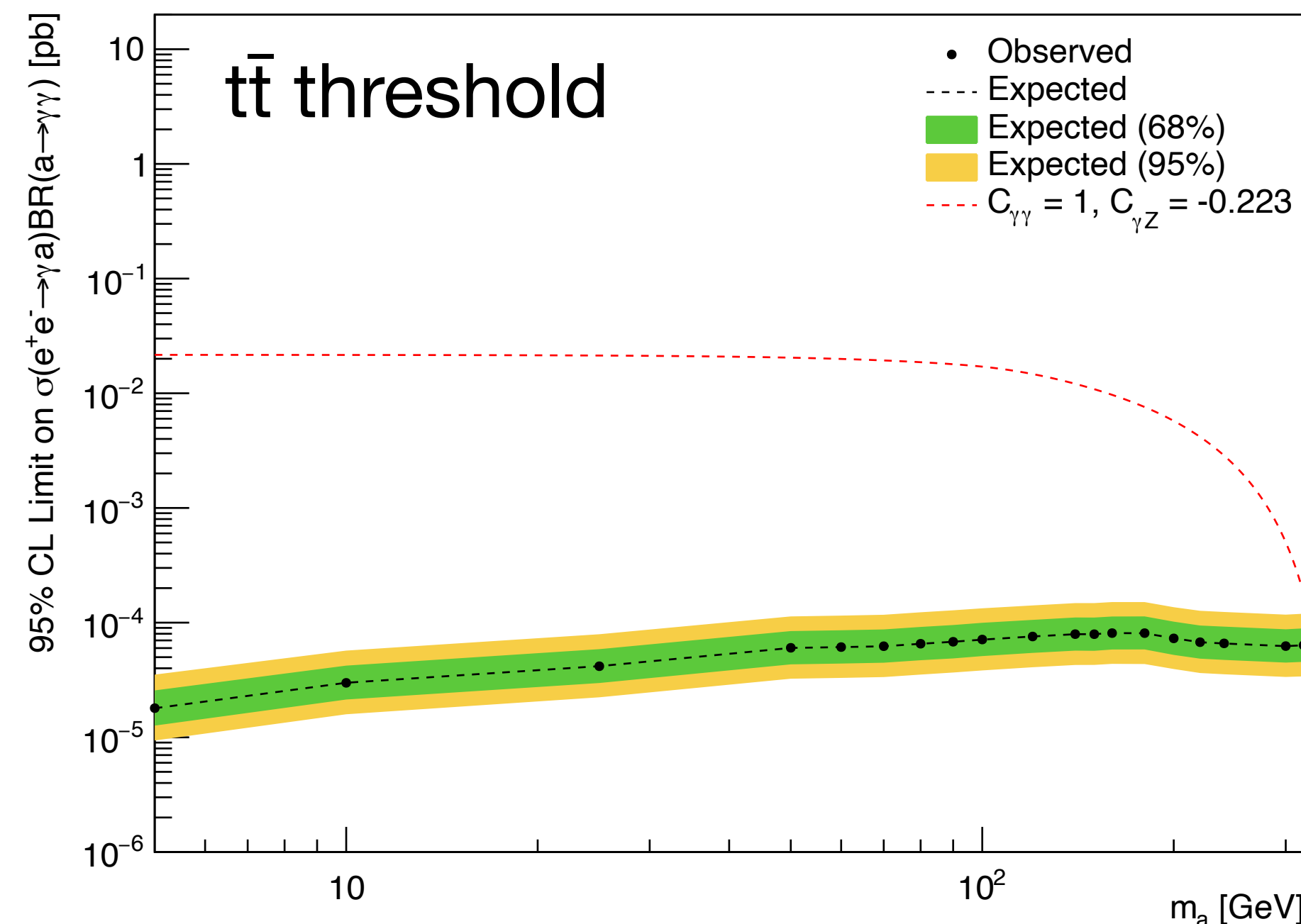
Cross section limits

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:

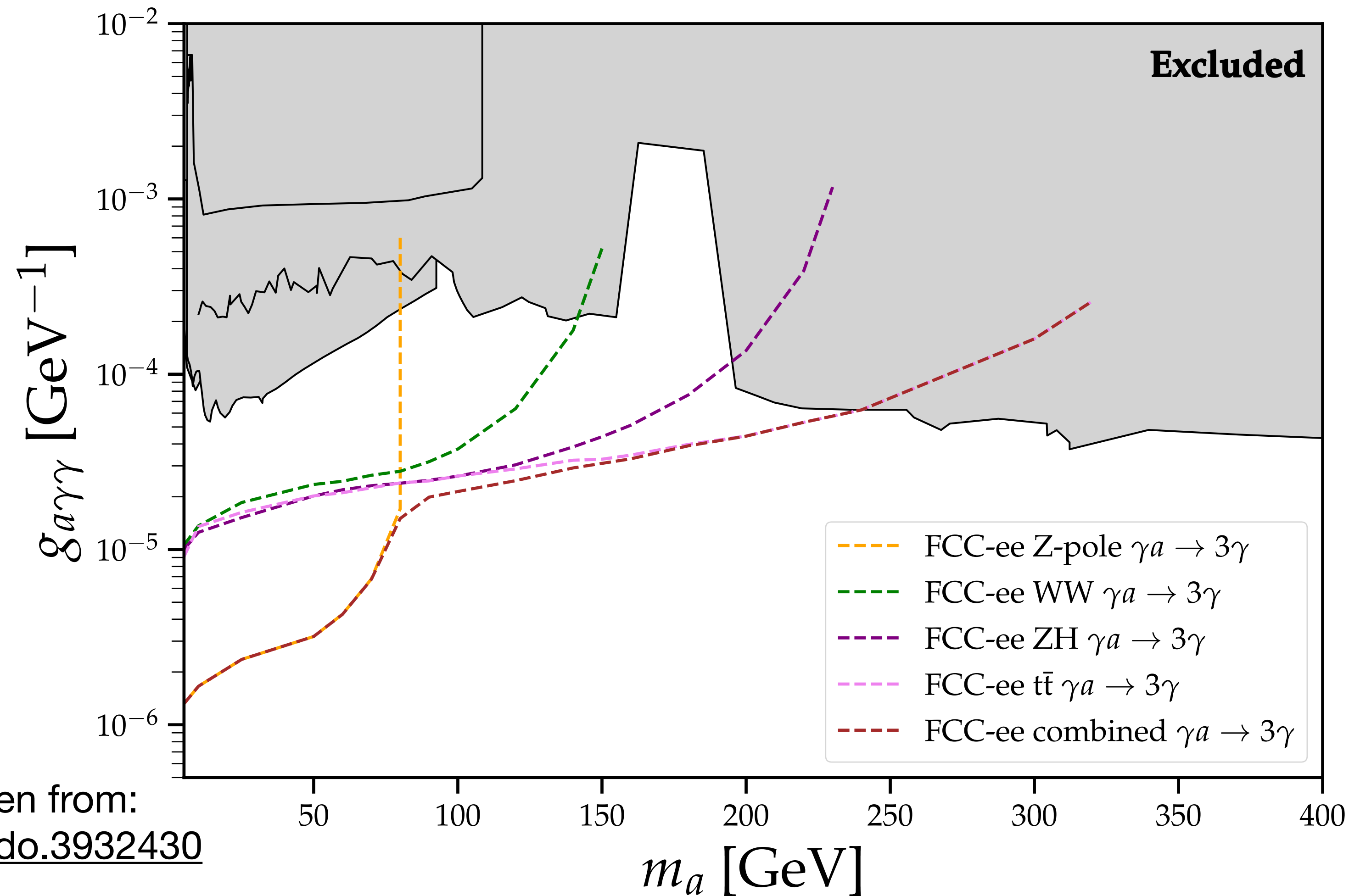
$$\sigma_{lim} = \mu \cdot \sigma_{theory}$$

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



Method of recasting limits

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

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

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

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

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

$$\text{Find } C_{BB}^r \text{ such that}$$

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

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

$$\rightarrow \text{convert to } g_{a\gamma\gamma}^r$$

$$\gamma\gamma \rightarrow \gamma\gamma:$$

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

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

Find C_{WW} , C_{BB} from $C_{\gamma\gamma}^{lim}$, and calculate
 $BR(m_a, C_{BB}, C_{WW})$

$$\text{Find the recasted limit } C_{\gamma\gamma}^r = \frac{C_{\gamma\gamma}^{lim}}{\sqrt{BR(m_a, C_{BB}, C_{WW})}}$$

$$\rightarrow \text{convert to } g_{a\gamma\gamma}^r$$

*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} :

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

$$C_{\gamma\gamma} = C_{WW} + C_{BB}$$

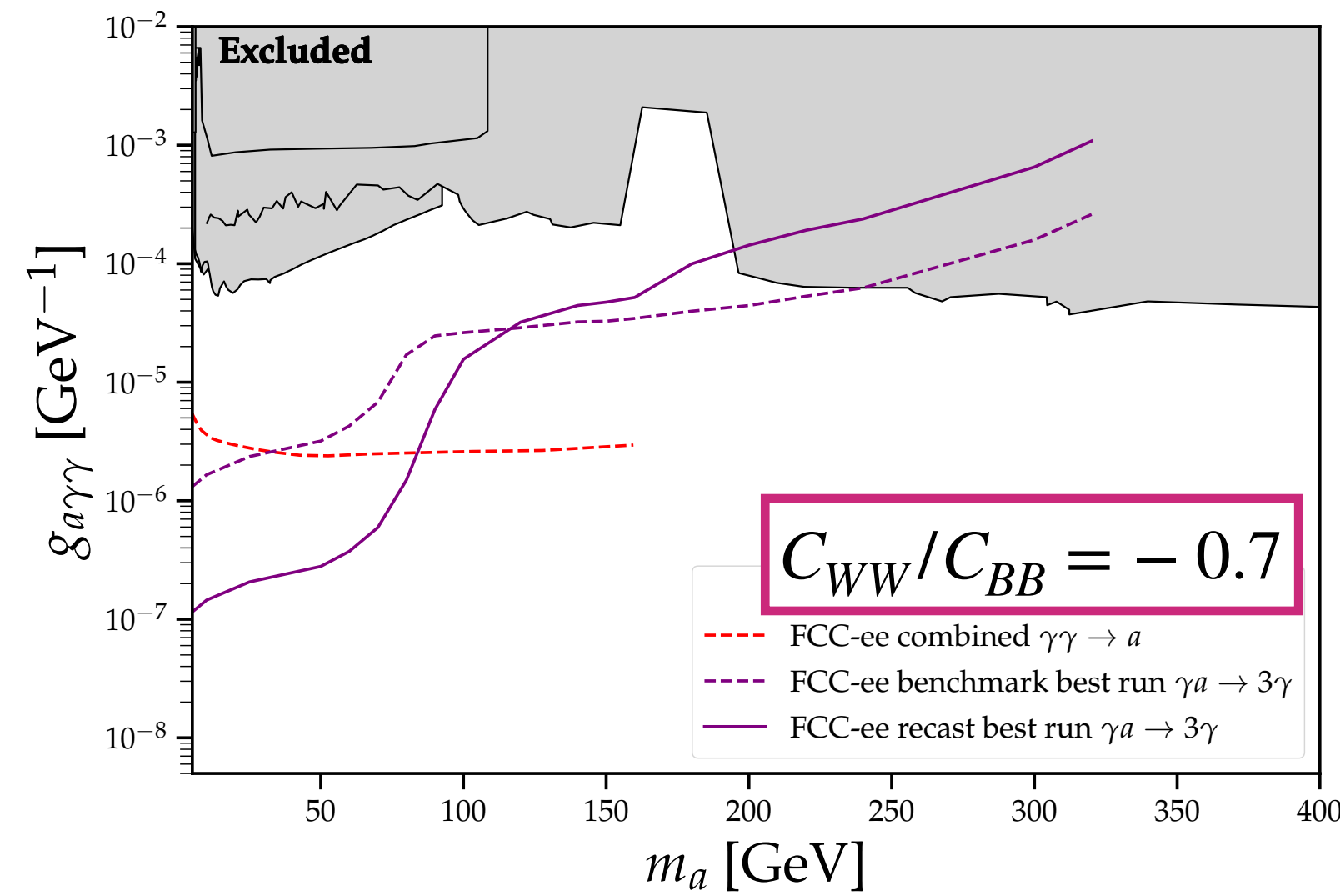
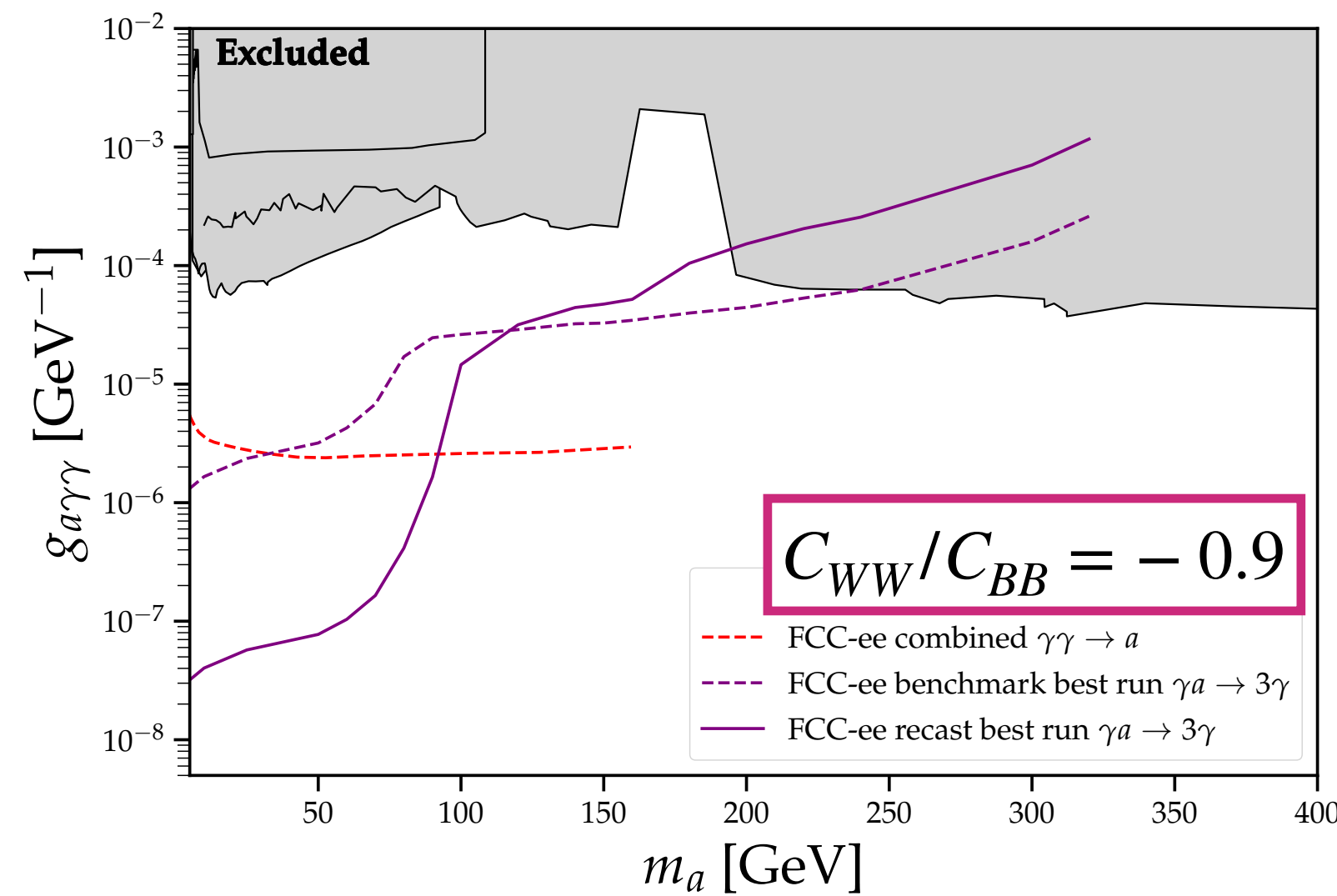
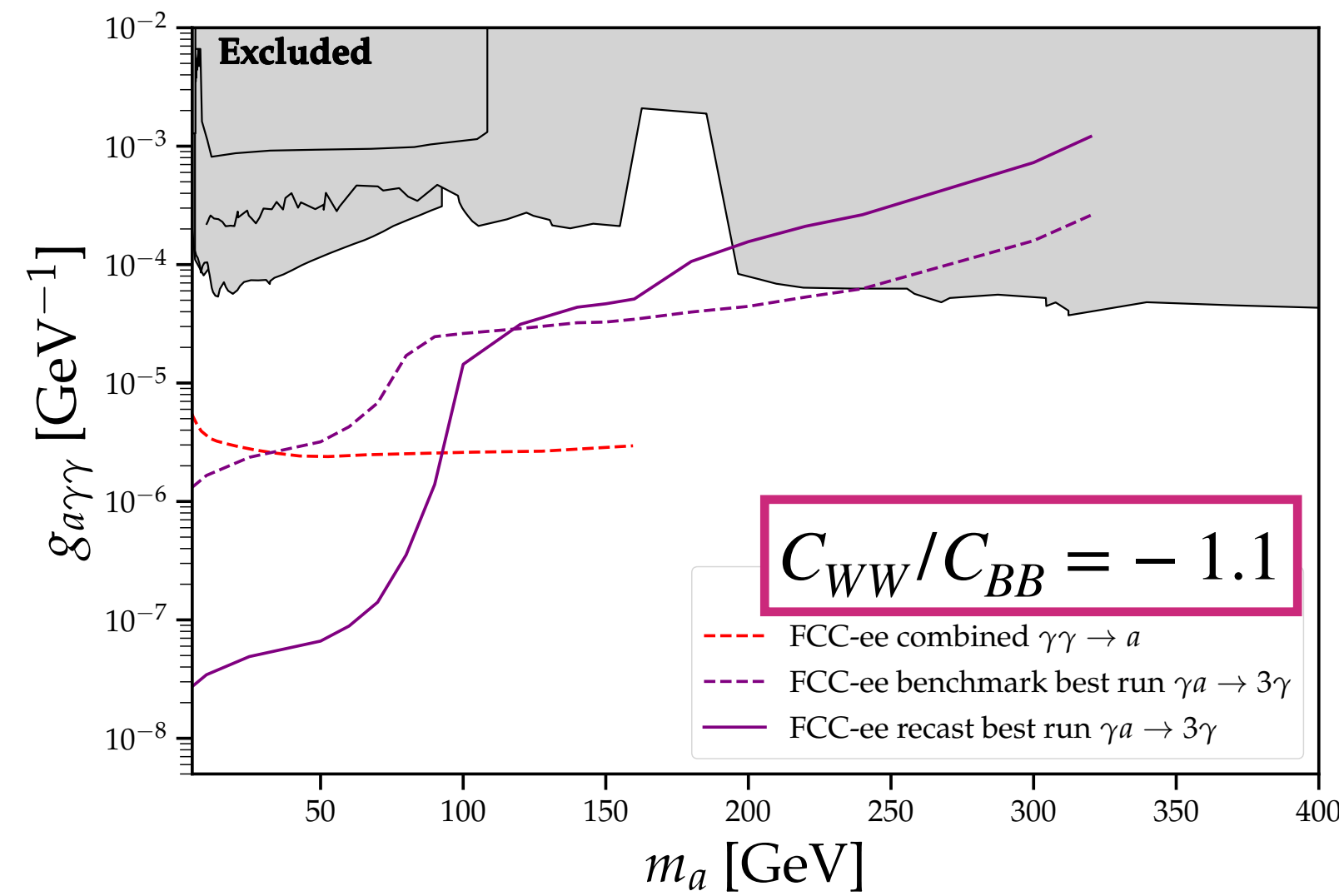
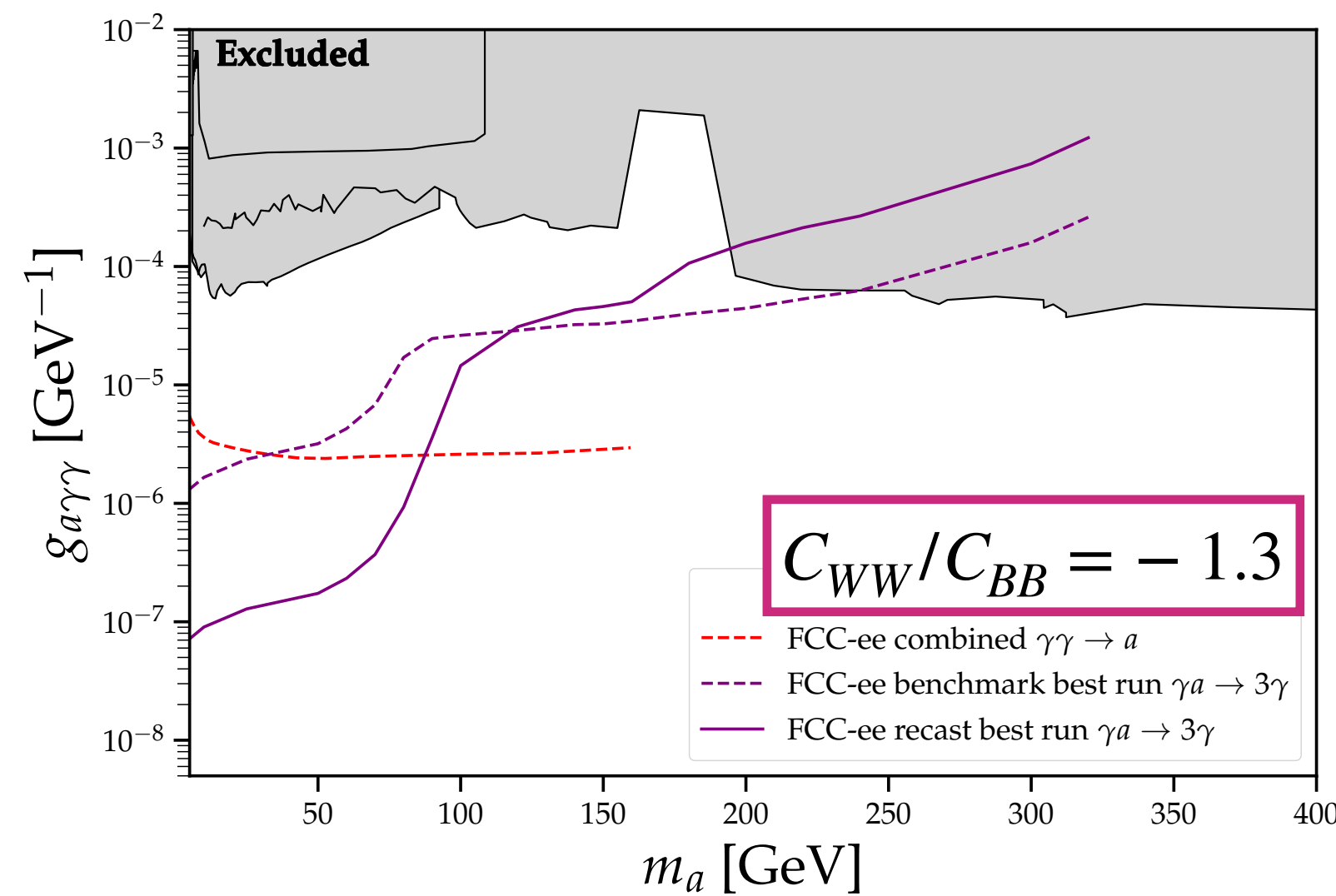
$$C_{\gamma Z} = c_w^2 C_{WW} - s_w^2 C_{BB}$$

$$C_{ZZ} = c_w^4 C_{WW} + s_w^4 C_{BB}$$

Scenario 1

$$C_{\gamma\gamma} = C_{WW} + C_{BB}$$

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



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

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

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

For $m_a < m_Z$, the sensitivity gets better

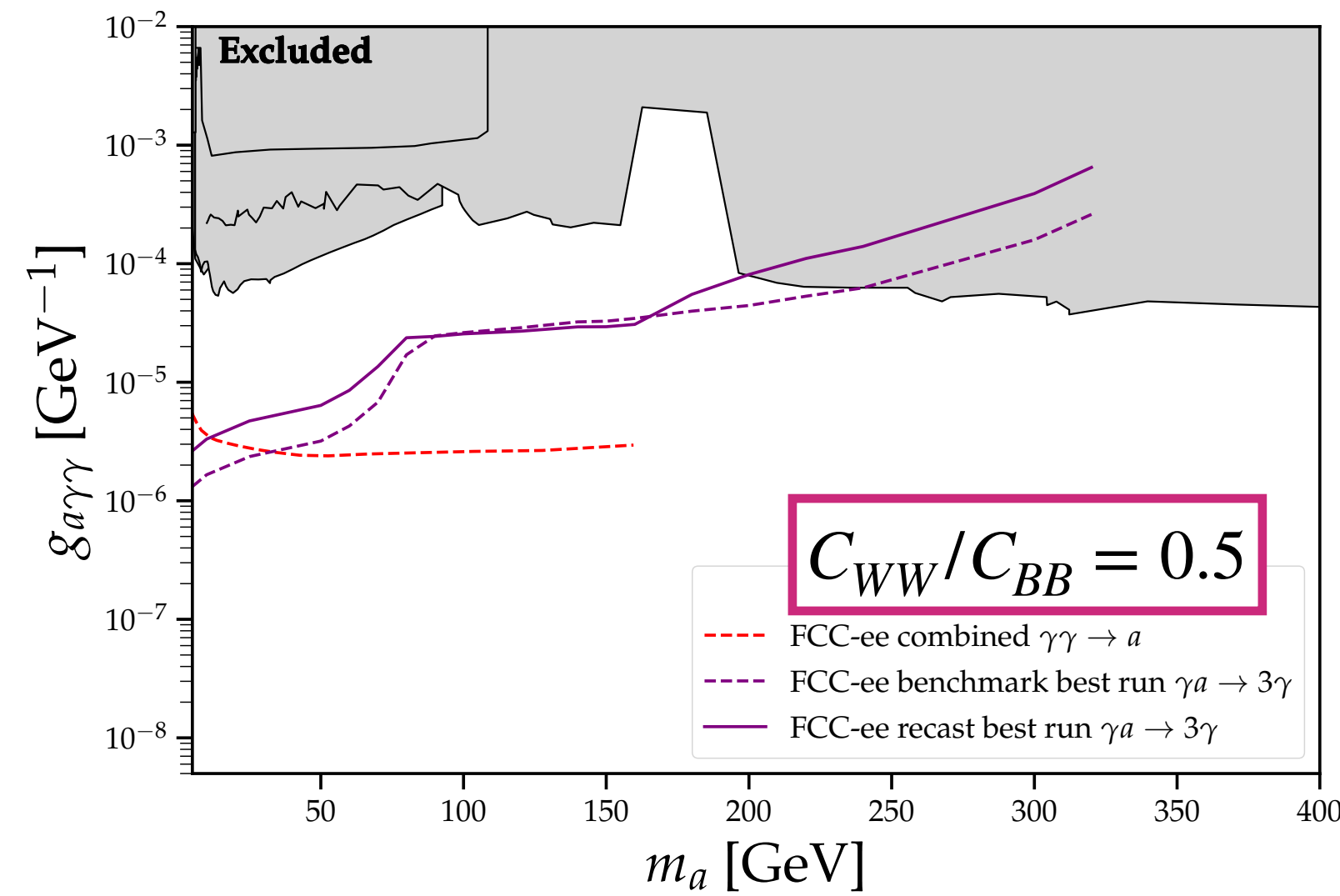
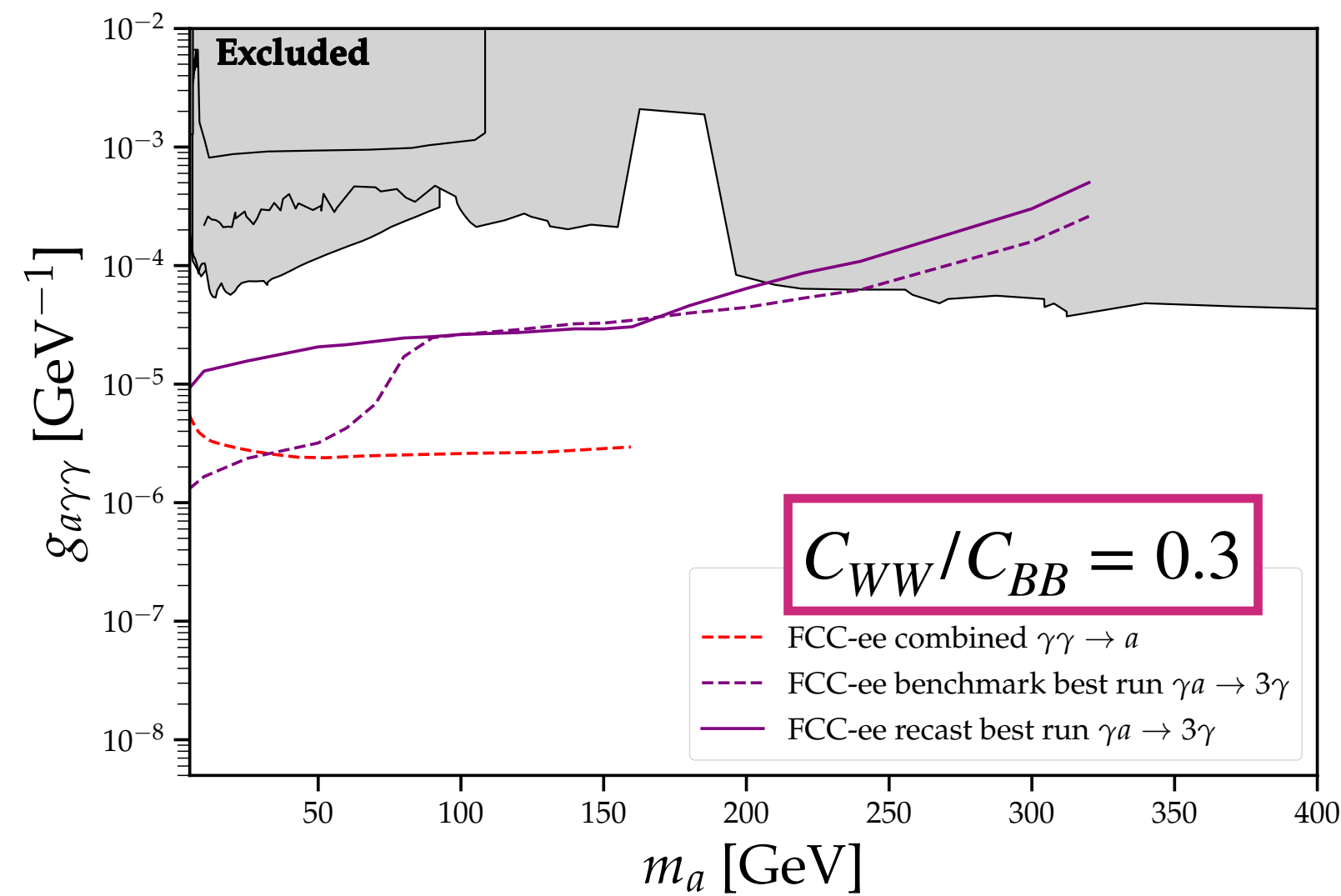
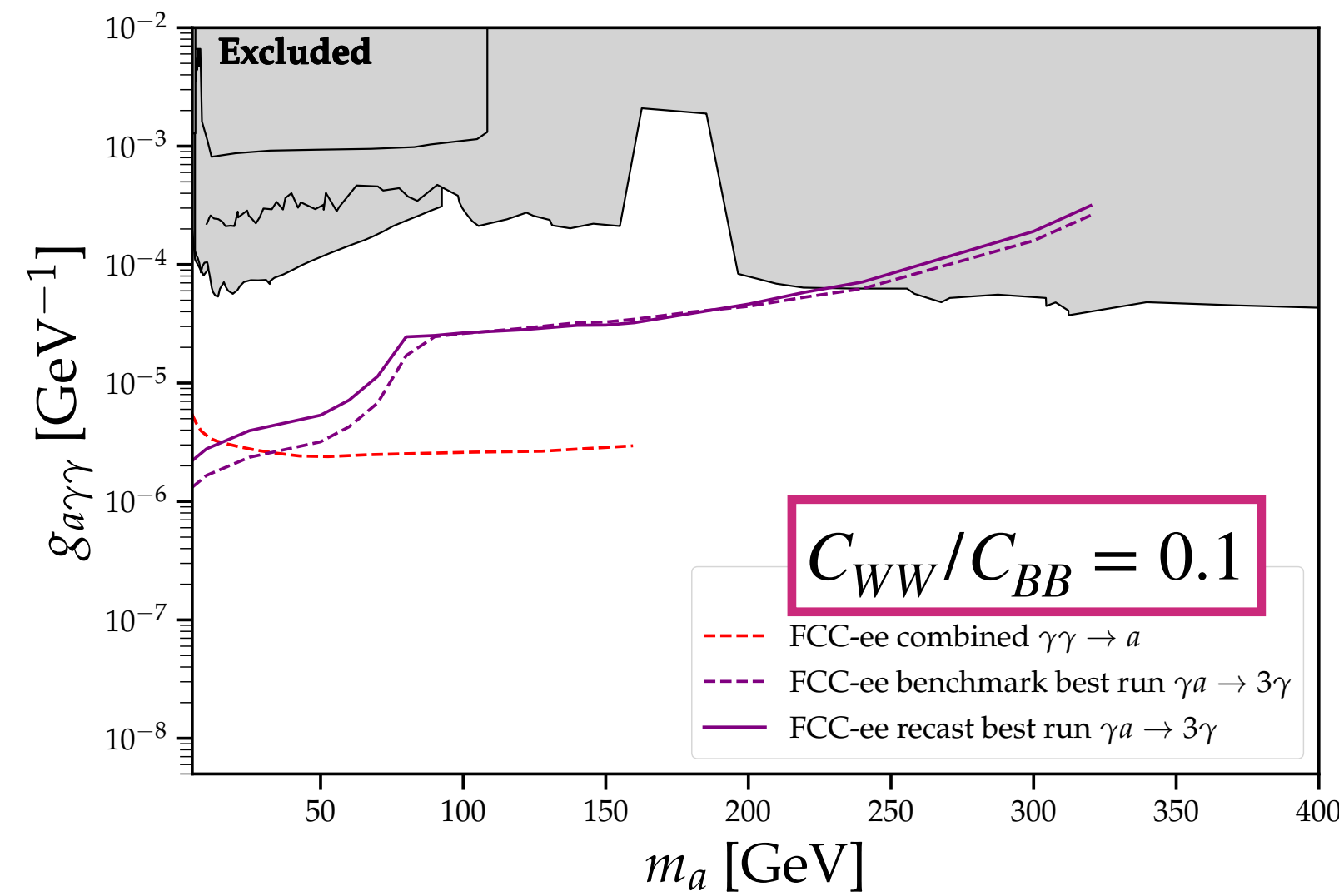
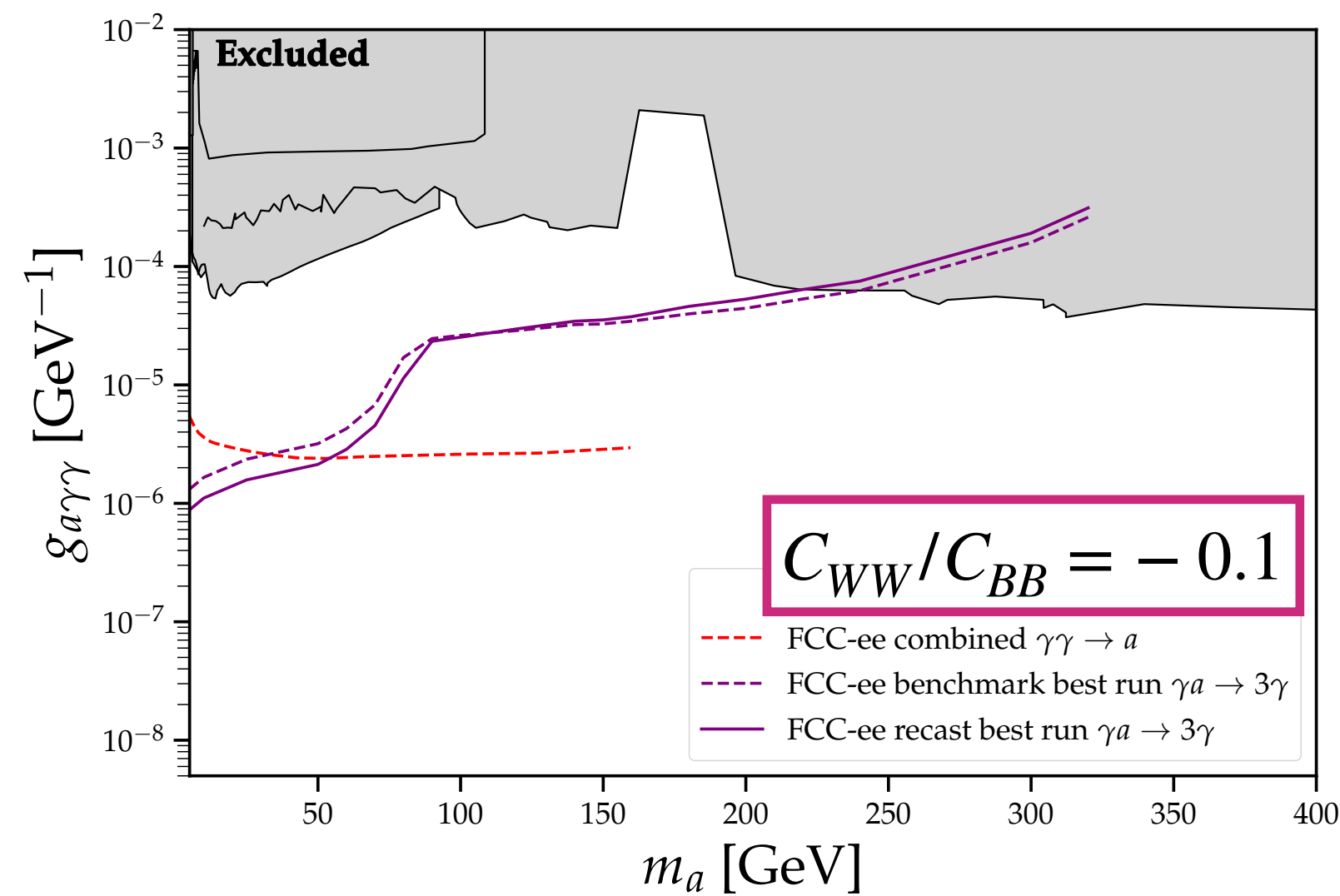
For $m_a > m_Z$, the sensitivity gets a bit worse

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

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

$C_{\gamma Z} \rightarrow 0$, $C_{\gamma\gamma}$ 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