Long-Lived Axion-Like Particles at the Future Circular Electron-Positron Collider

Elnura Bakhishova[1]

Supervised by: Prof. Freya Blekman[1,2], Dr. Juliette Alimena[2], Lovisa Rygaard[1,2]

➢ Link to thesis: https://bib-pubdb1.desy.de/record/625748

GraSPA 2025
Annecy

[1] University of Hamburg
[2] Deutsches Elektronen-Synchrotron (DESY)

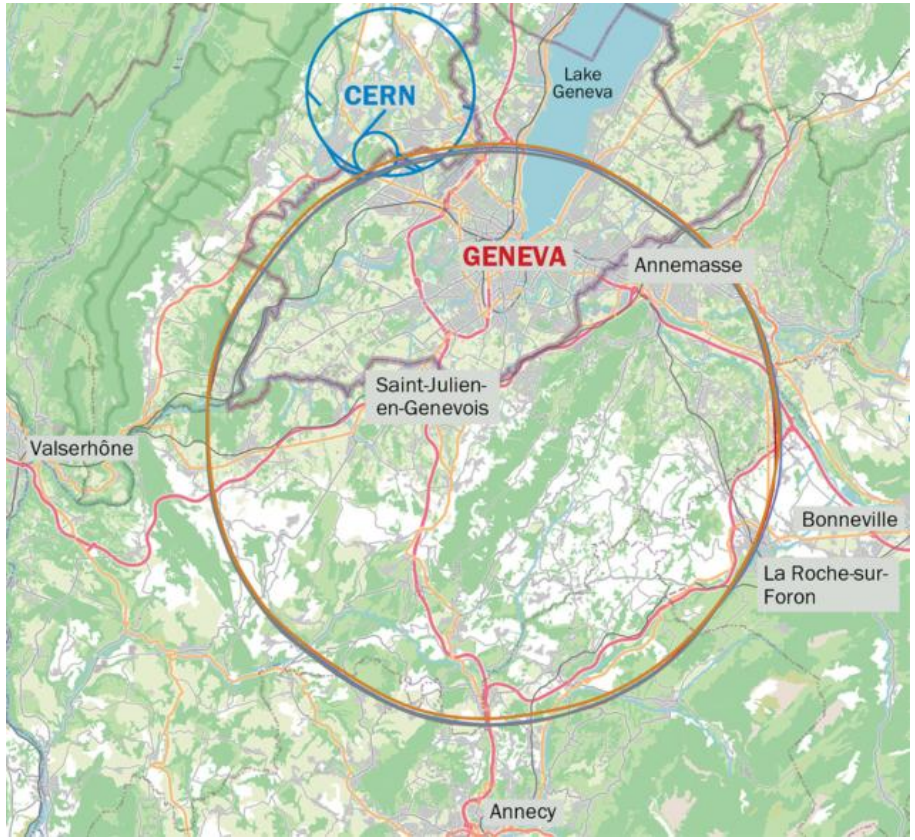
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

FUTURE CIRCULAR COLLIDER

DESY.

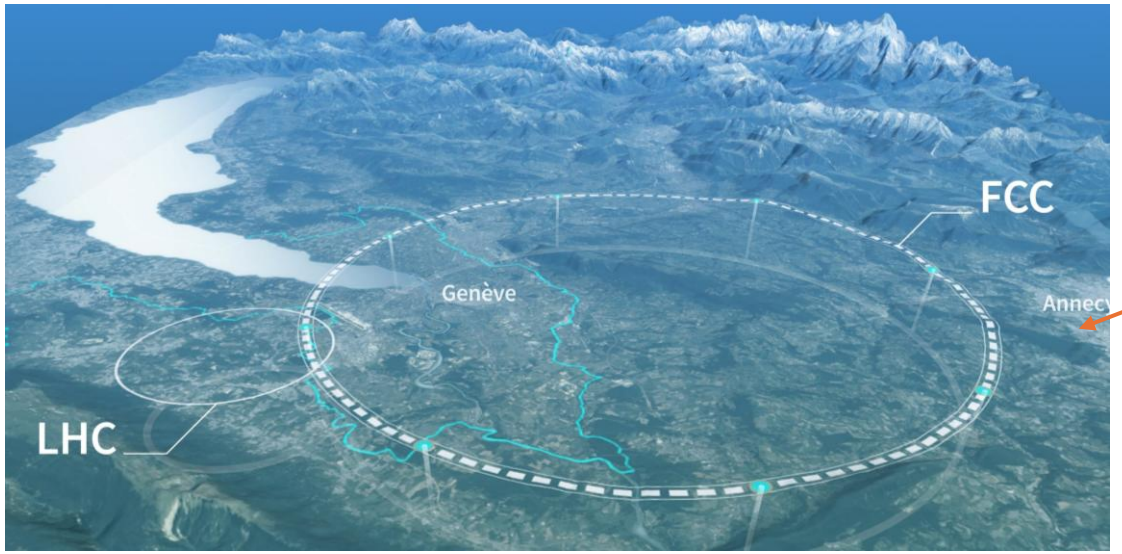
Future Circular Collider (FCC)

- Proposed to be built at CERN with a circumference of 90.7 km (~3x LHC)



1st stage of FCC: e+e- collisions (FCC-ee)
→Z-pole run ($\sqrt{s} = 91\ GeV$)

! enormous data set → ALPs could be produced in large quantities at FCC-ee



Bernardi et al., FCC

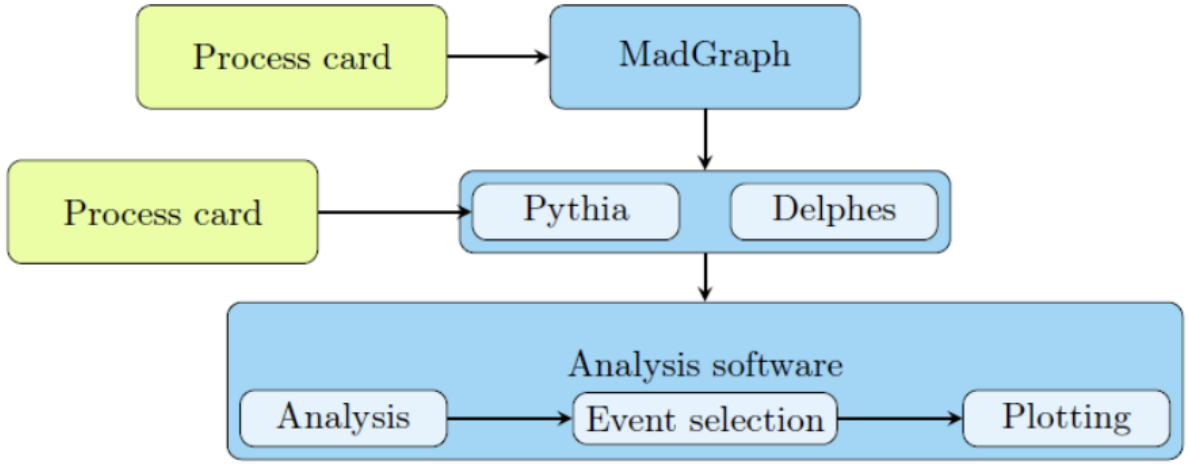
Overview

Machine parameters:
$\sqrt{s} = 91\ GeV$
$\mathcal{L} = 205 ab^{-1}$

Goal: Studying the sensitivity of the FCC-ee to an ALP signature during the Z-pole run

How?

- Using simulation and analysis software to produce samples of defined ALP signal event & background events
- Making event selections



The Common analysis framework for the FCC ,
MadGraph, Pythia, Delphes, L. Rygaard

Axion-Like Particle (ALP)

- ALP = BSM, hypothetical, pseudoscalar particle
- ALP is a generalization of axion with **independent mass and coupling strength**
- Long-lived due to weak coupling to SM particles

Bauer et al.

Axion-Like Particle (ALP)

- ALP = BSM, hypothetical, pseudoscalar particle
- ALP is a generalization of axion with **independent mass and coupling strength**
- Long-lived due to weak coupling to SM particles

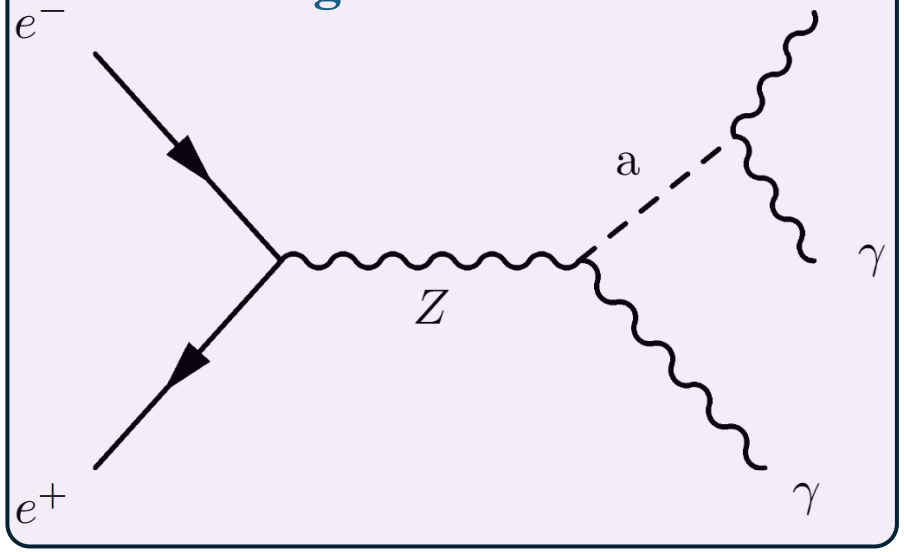
Signal event $e^+e^- \to Z \to a\gamma \to \gamma\gamma\gamma$

- 3 final state photons
- 1M events produced for various ALP parameter settings

Varied in analysis: ALP mass & ALP-photon coupling $c_{\gamma\gamma}$

→ Influences cross-section and lifetime

Signal event

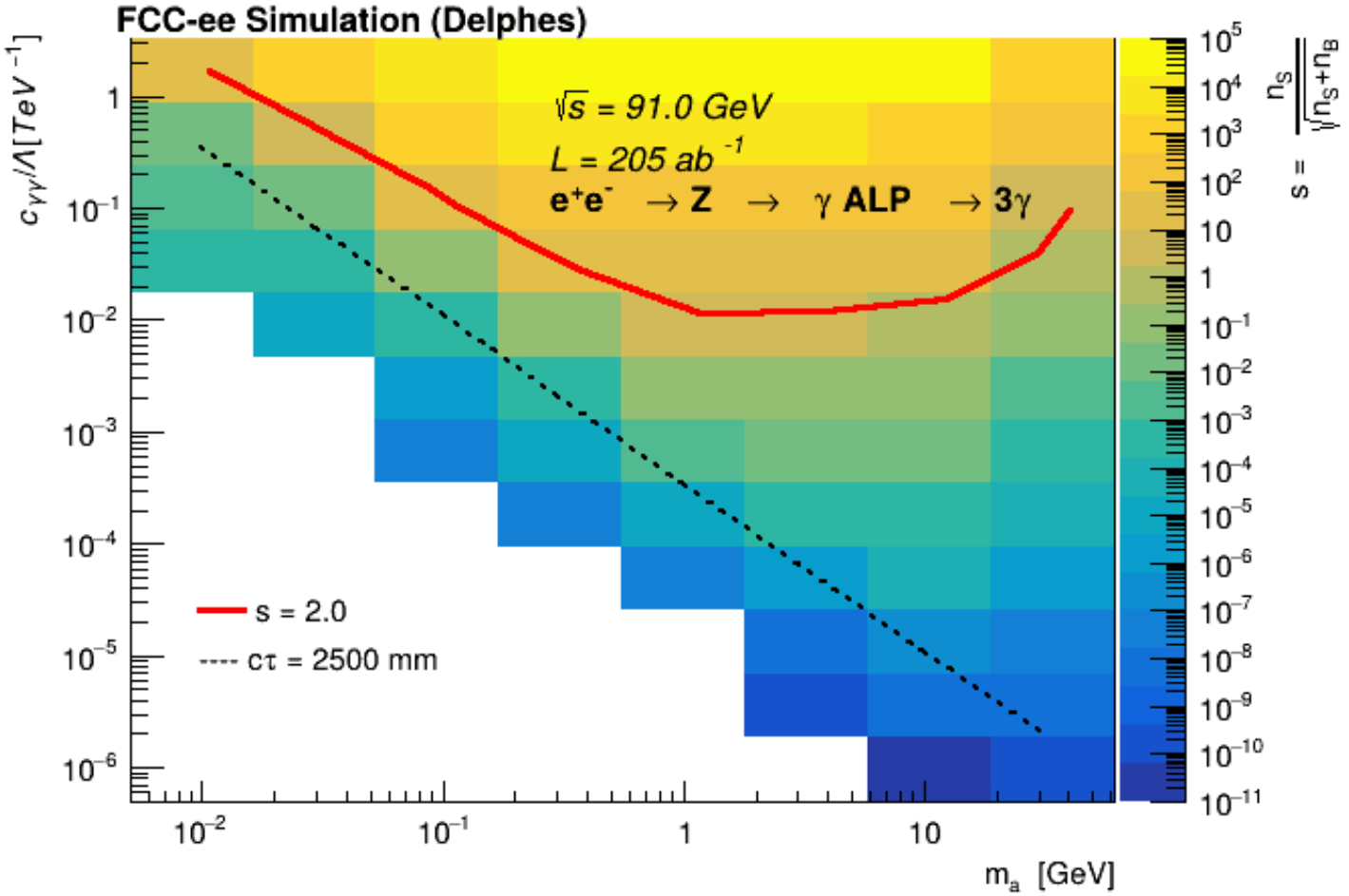


Bauer et al.

Projected sensitivity for ALP at the FCC-ee

Sensitivity for ALP signal detection at FCC-ee is determined with the expected number of signal events (n_S) and background events (n_B) during the complete Z-pole run:

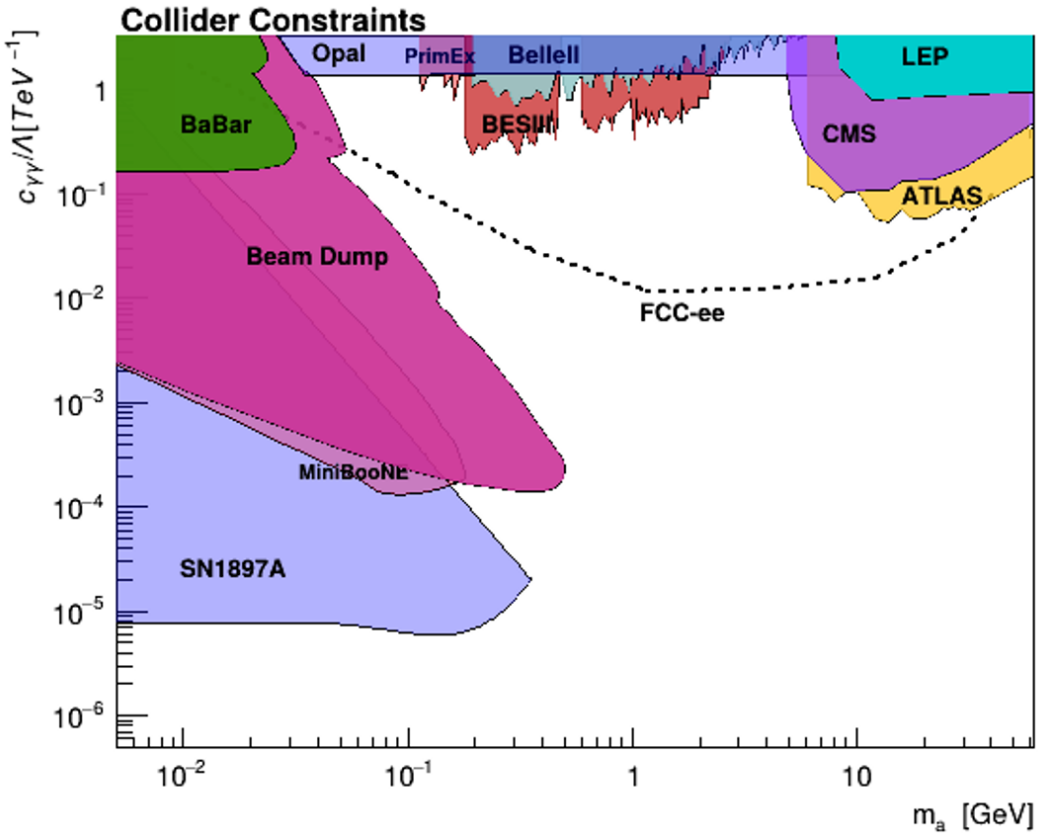
$$s = \frac{n_S}{\sqrt{n_S + n_B}}$$



The red line corresponds to ~95% CL

Comparison to existing collider constraints

Constraints from other collider searches on the ALP parameter space indicate that FCC-ee would reach so far uncovered parameter space!



Projected sensitivity of FCC-ee to the ALP signal process at 95% confidence level limit (black dashed line) in the ALP-photon coupling versus ALP mass plane

Backup

Background events

= processes that could mimic the ALP signal event

1M events produced for each sample

$$Diphoton : e^+e^- \to \gamma\gamma$$

$$Triphoton : e^+e^- \to \gamma\gamma\gamma$$

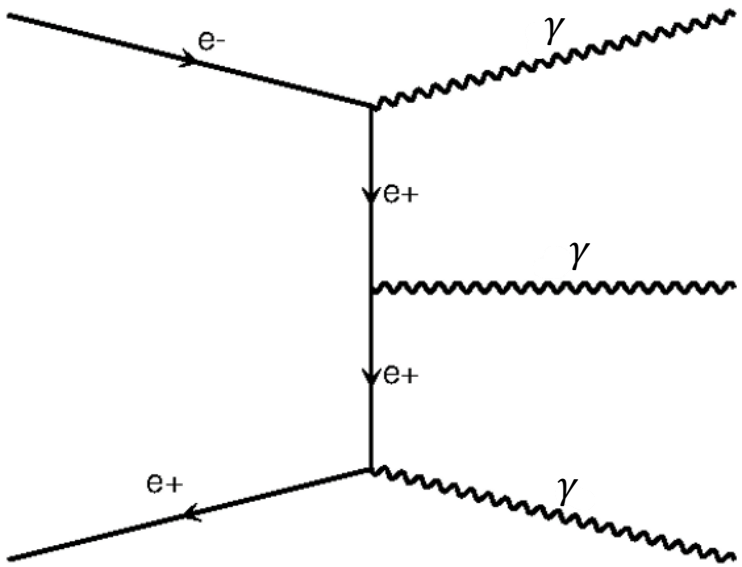
$$Quadphoton : e^+e^- \to \gamma\gamma\gamma\gamma$$

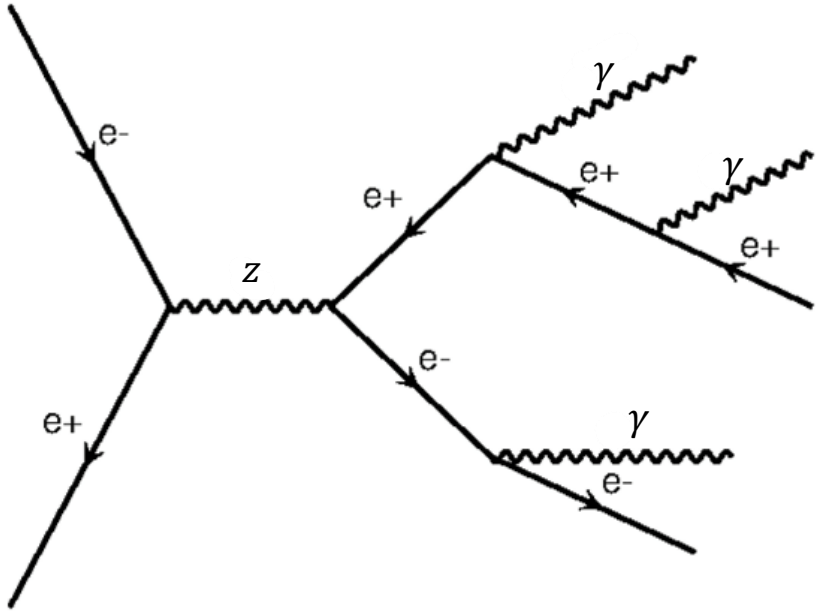
$$e^+e^- \to e^+e^-$$

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

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

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





Event selections

Total number of background events for Z-pole run: ~10^{11}
Total number of signal events for Z-pole run depends on ALP parameters: 10^{-4} - 10^{8}

Increase signal-to-background ratio by applying event selection criteria to the collision events, thereby increasing the sensitivity for ALP signal detection at FCC-ee

Selections on final state particles, angular separation between particles, momentum…

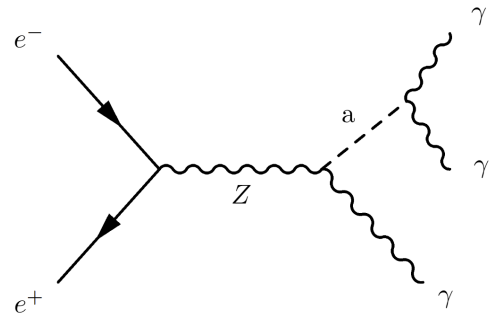
Event selections

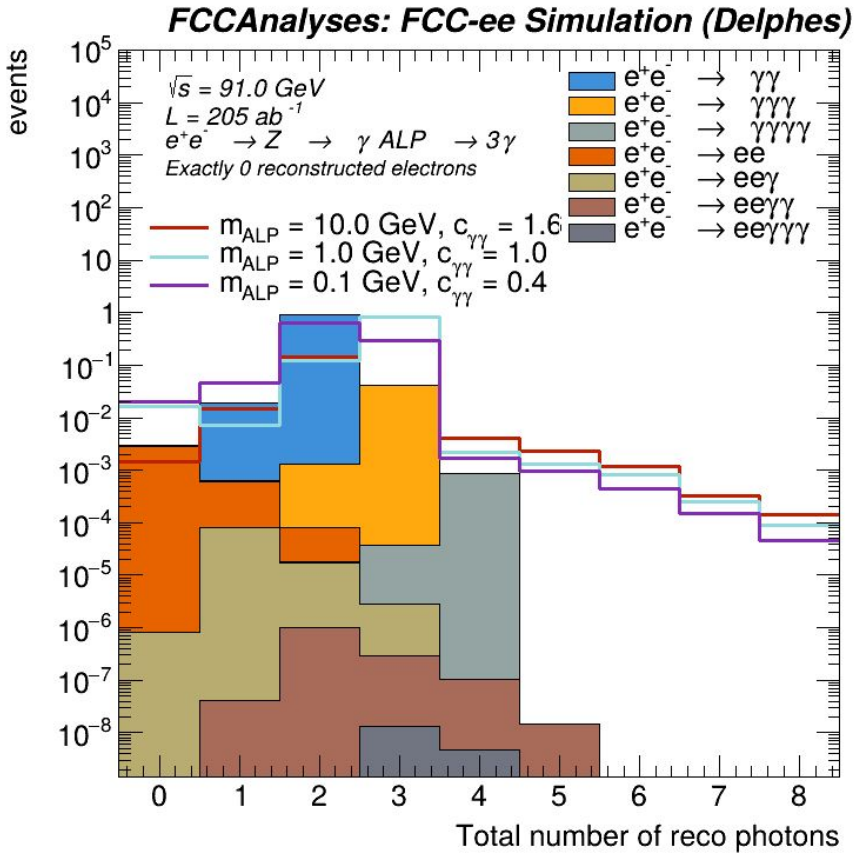
Total number of background events for Z-pole run: ~10^{11}
Total number of signal events for Z-pole run depends on ALP parameters: 10^{-4} - 10^{8}

		Selection Criteria
Selection 1	**Vetoes**	No reconstructed electrons
Selection 2	**Final State**	Exactly 3 reconstructed photons
Selection 3	**Angles**	$\min \Delta R < 1$
Selection 4	**Momentum**	$p > 42$ GeV for leading photon ($photon_0$)

Table 3: Summary of the event selections.

Final state: 3 photons

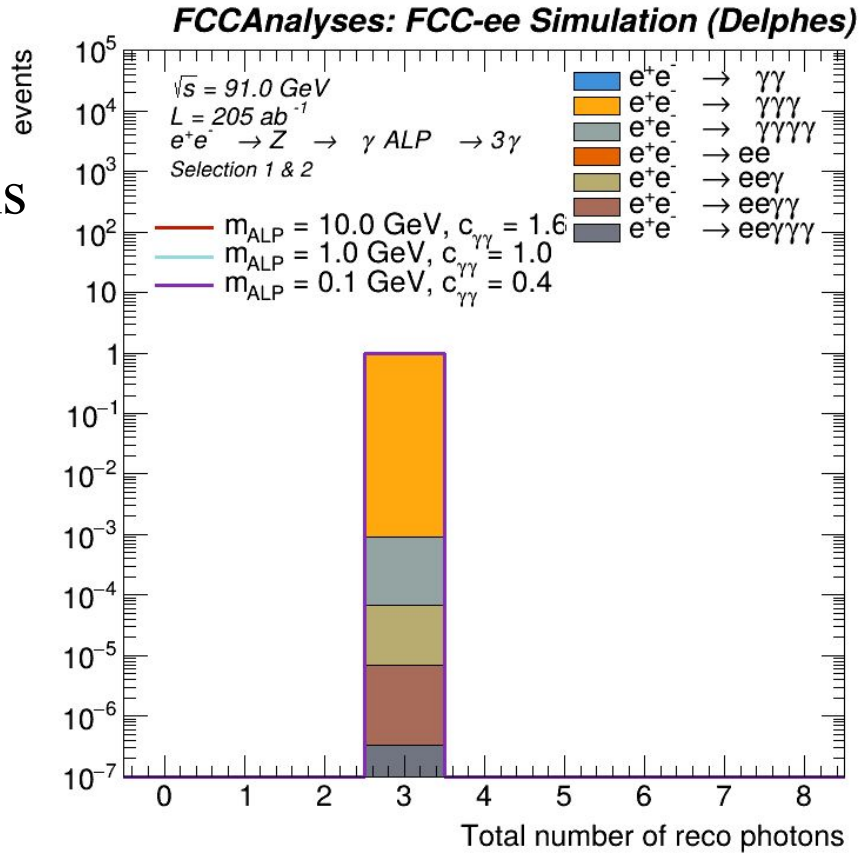




Selection2:

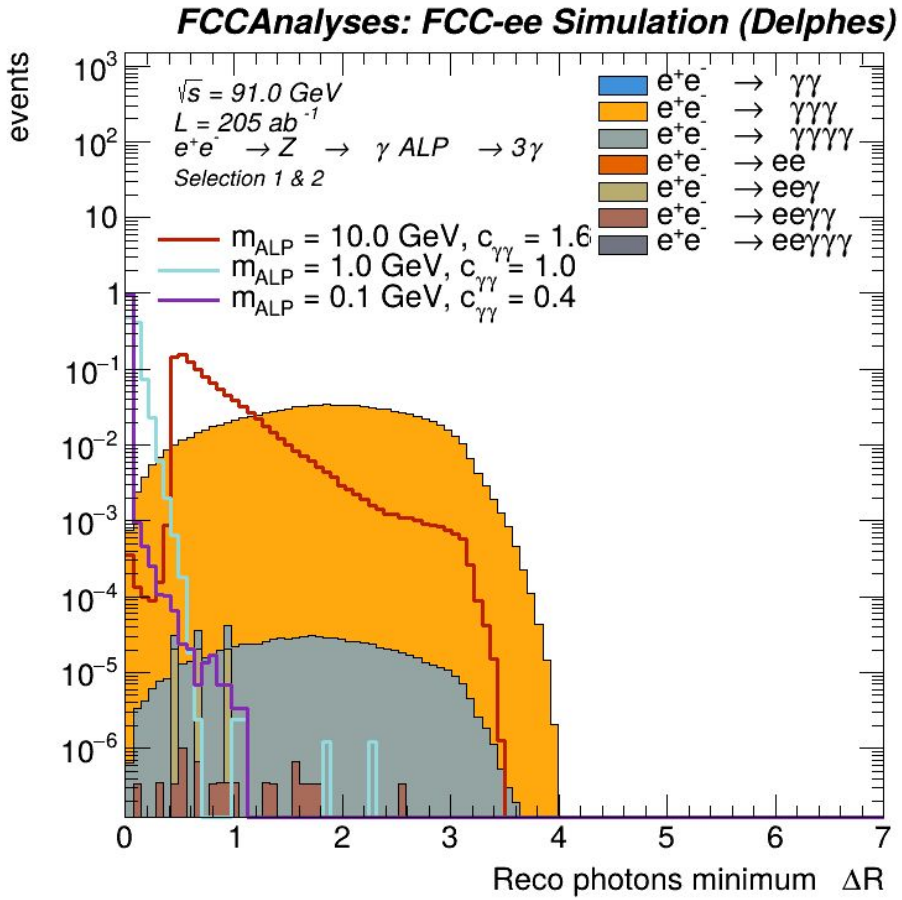
Require exactly 3 reco photons

Signal events		% *
m_a[GeV]	$c_{\gamma\gamma}$	
1	1	82
3	0.4	81
0.1	0.4	30
10	1.6	80
10	0.002	81
Background events		%
$e^+e^- \to \gamma\gamma$		0
$e^+e^- \to \gamma\gamma\gamma$		97
$e^+e^- \to \gamma\gamma\gamma\gamma$		3.9
$e^+e^- \to e^+e^-$		0
$e^+e^- \to e^+e^-\gamma$		0.0003
$e^+e^- \to e^+e^-\gamma\gamma$		0.003
$e^+e^- \to e^+e^-\gamma\gamma\gamma$		0.0082



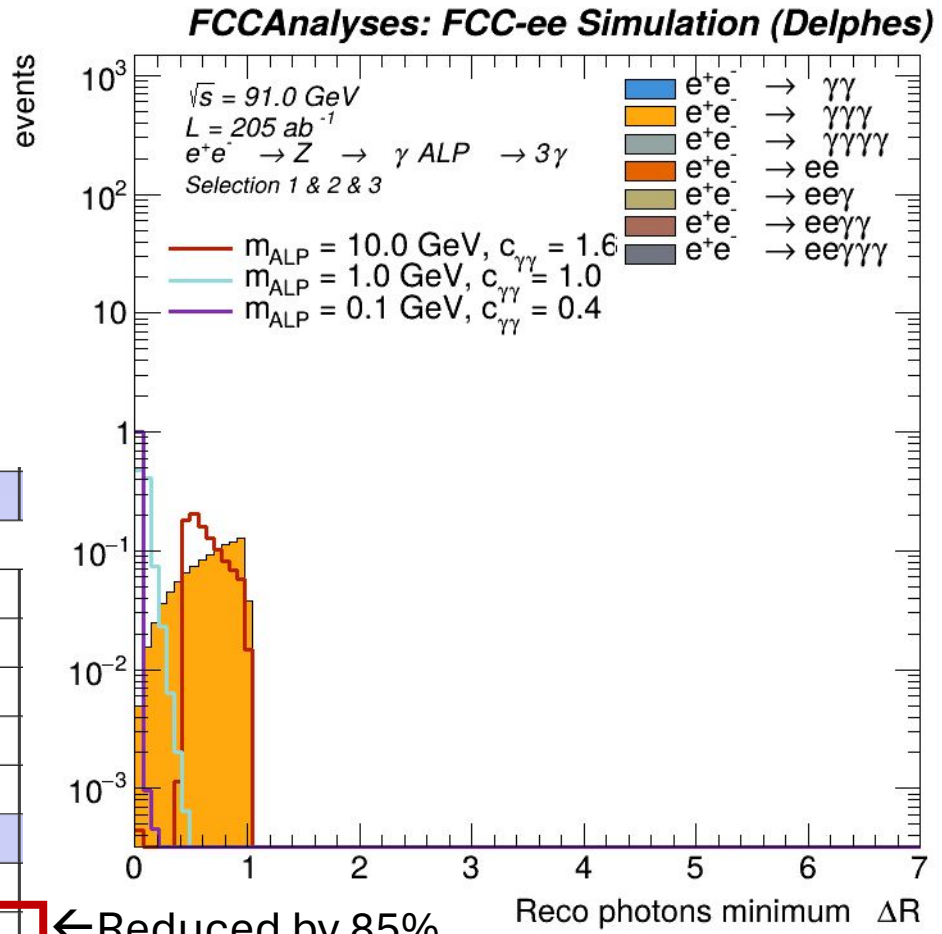
*Values and plots already include prior selection requirements

Angles: Require min$\Delta R < 1$



Selection3:
Require min$\Delta R < 1$
for reco photons

Signal events		% *
m_a[GeV]	$c_{\gamma\gamma}$	
1	1	82
3	0.4	81
0.1	0.4	30
10	1.6	63
10	0.002	63
Background events		%
$e^+e^- \to \gamma\gamma$		0
$e^+e^- \to \gamma\gamma\gamma$		15
$e^+e^- \to \gamma\gamma\gamma\gamma$		0.75
$e^+e^- \to e^+e^-$		0
$e^+e^- \to e^+e^-\gamma$		0.0003
$e^+e^- \to e^+e^-\gamma\gamma$		0.0011
$e^+e^- \to e^+e^-\gamma\gamma\gamma$		0.003



←Reduced by 85%
←Reduced by 80%

*Values and plots already include prior selection requirements

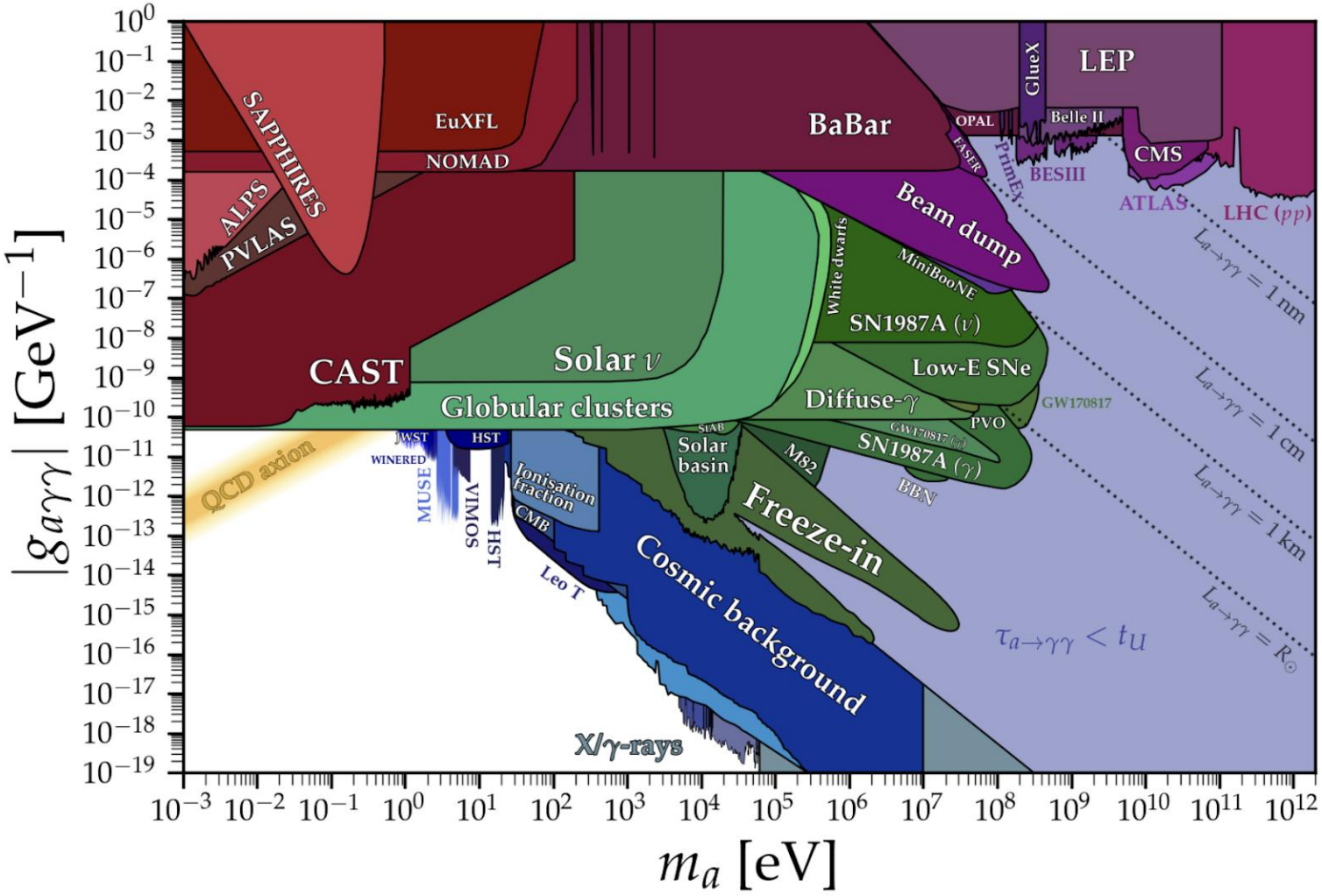
Cut flow table

		Before selections		After all selections	
Signal events		N_{exp}	%	N_{exp}	%
m_a[GeV]	$c_{\gamma\gamma}$				
1	1	2.75e+08	100	2.26e+08	82
3	0.4	4.39e+07	100	3.54e+07	81
0.1	0.4	4.40e+07	100	1.29e+07	29
10	1.6	6.79e+08	100	4.25e+08	63
10	0.002	1.06e+03	100	6.65e+02	63
Background events		N_{exp}	%	N_{exp}	%
$e^+e^- \to \gamma\gamma$		1.38e+10	100	0.	0
$e^+e^- \to \gamma\gamma\gamma$		6.14e+08	100	9.16e+07	15
$e^+e^- \to \gamma\gamma\gamma\gamma$		1.29e+07	100	2.16e+04	0.17
$e^+e^- \to e^+e^-$		4.52e+11	100	0.	0
$e^+e^- \to e^+e^-\gamma$		1.19e+10	100	1.19e+04	0.0001
$e^+e^- \to e^+e^-\gamma\gamma$		2.00e+08	100	2.00e+02	0.0001
$e^+e^- \to e^+e^-\gamma\gamma\gamma$		2.38e+06	100	0.	0

→Background events have been significantly reduced while maintaining as much of the signal events as possible

Table : Cut flow table of the sequential application of the four event selections. The table displays the ALP mass and coupling strength of selected signal samples and all background events. N_exp is the expected number of events that remain at each stage of the applied selection for the Z-pole run at the FCC-ee. The % columns show what percentage of the initial number of events (prior to any selections) remain after the specified selections.

ALP constraints – zoomed out



ALP limits

ALP couplings and Wilson coefficients

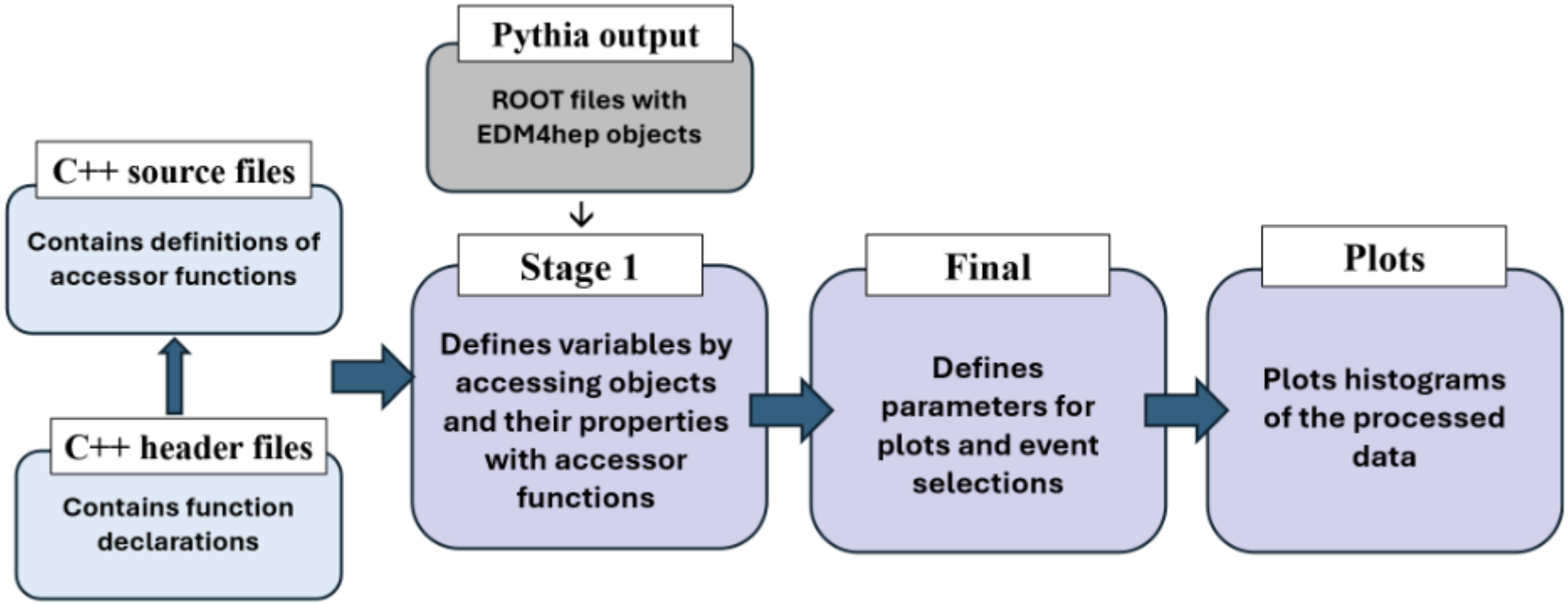
After EW symmetry breaking the U(1) gauge boson mixes with the neutral SU(2) gauge bosons to produce a photon (mediator of EM interaction) & Z boson (neutral mediator of weak force)

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

- Coupling to SU(2) gauge boson (C_WW) set to 0, we assume ALP only couples to U(1) gauge bosons (C_BB)
- Parameters fixed at zero allow analysis of simulations with direct dependencies on C_yy

$$C_{\gamma\gamma}^{\text{eff}}\,(m_a \gg \Lambda_{QCD}) = C_{\gamma\gamma} + \sum_f \frac{N_c^f Q_f^2}{16\pi^2} c_{ff} B_1(\tau_f) + \frac{2\alpha}{\pi}\frac{C_{WW}}{s_w^2} B_2(\tau_W)$$

Methodology



Standard Model

- Developed in 1970s
- Successfully verified by many experiments
- Includes 3 of the 4 fundamental forces

Unexplained:

- Dark matter, dark energy
- Baryon asymmetry
- Neutrino mass
- Gravity not incorporated