ALPs @ FCC-ee

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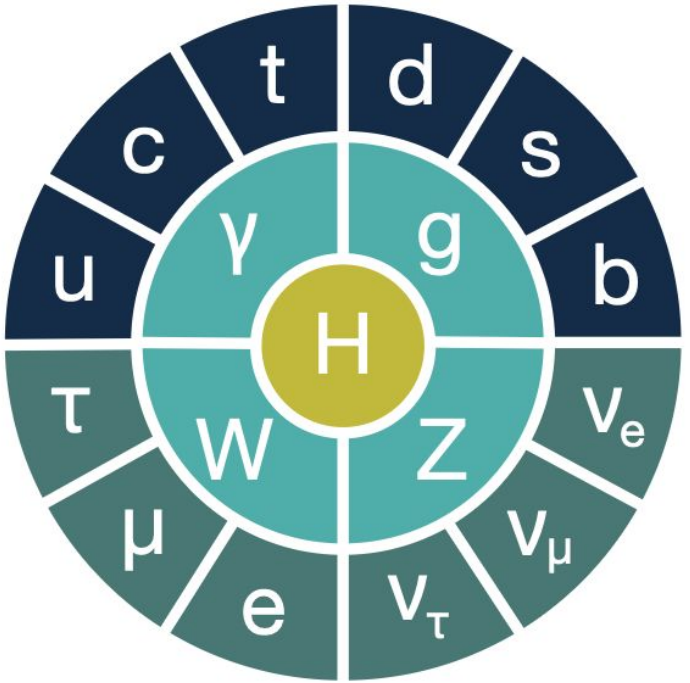
Supervised by Juliette Alimena, Jeremi Niedziela, Lovisa Rygaard
10 September 2025

DESY.

The Standard Model (SM)

- Fundamental particles that constitute matter
- Fundamental forces of nature:
  - Electromagnetic force
  - Weak force
  - Strong force



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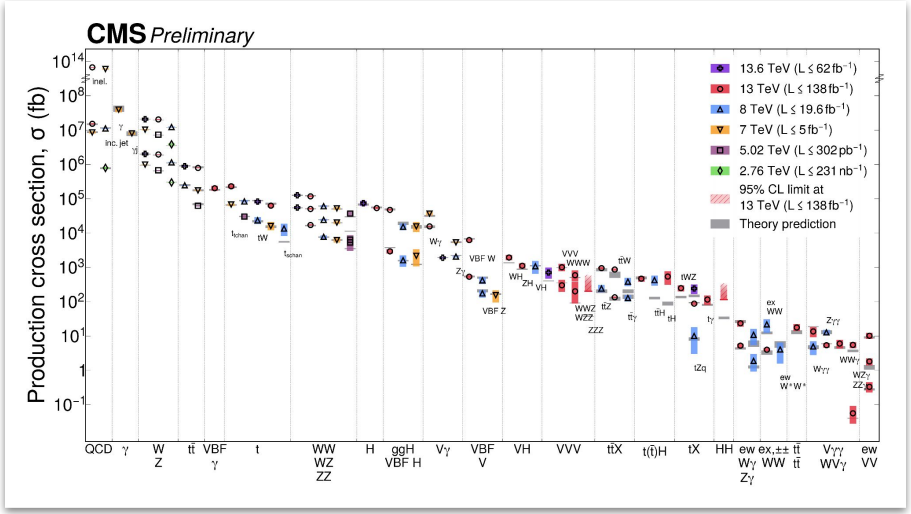

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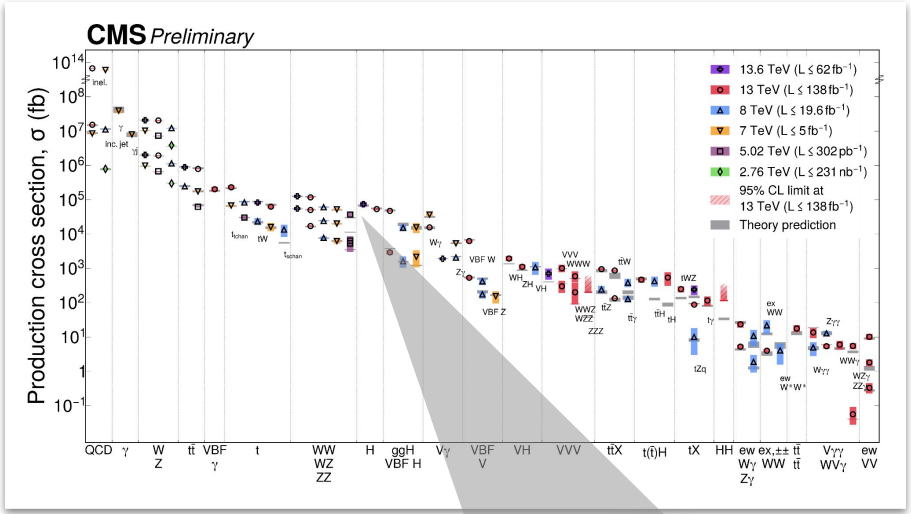

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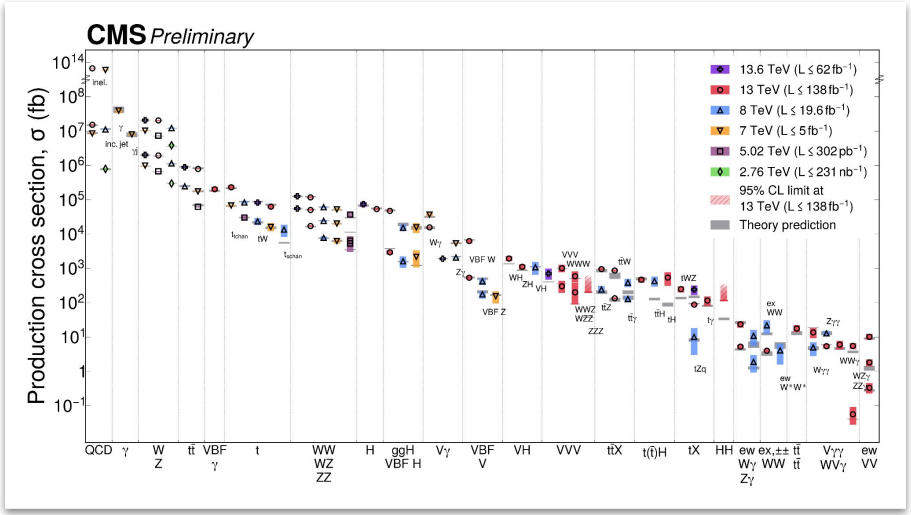
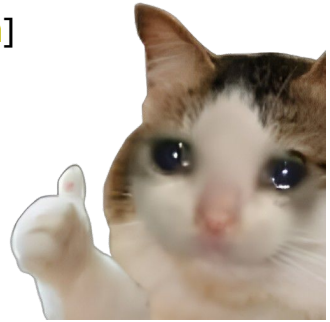


"Physics would be far more interesting if [the **Higgs boson**] had not been found"

- Stephen Hawking



Beyond the Standard Model (BSM)

Despite its remarkable success in many respects, still fails to explain:

Why is there more **matter** than **antimatter** in the Universe?

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Why is the **Higgs mass** so small compared to the Planck scale?

Why is the **CP-violating** θ parameter in QCD so small (or zero)?

What originates the **neutrino mass**?

Why are there **three generations** of quarks and leptons?

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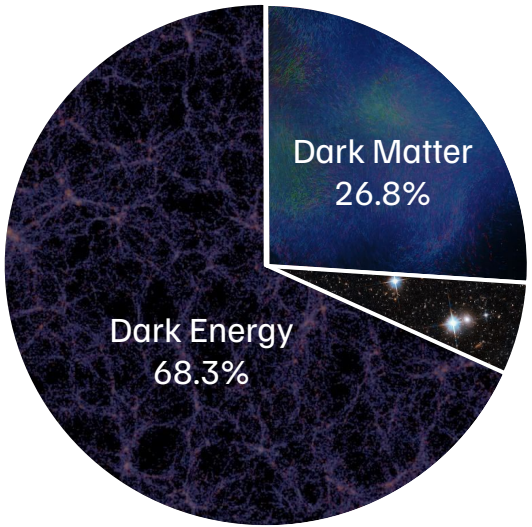


What is dark matter?

Why is the **Higgs mass** so small compared to the Planck scale?

Why is the **CP-violating** θ parameter in QCD so small (or zero)?

What is dark energy?

What originates the **neutrino mass**?

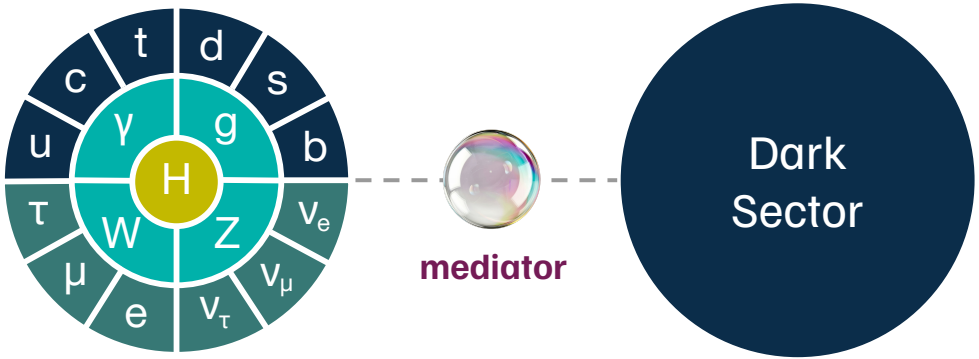
Why are there **three generations** of quarks and leptons?

Where should we look next and what might we discover?

Axion-Like Particles (ALPs)

One of the best motivated candidates for new particles beyond the SM

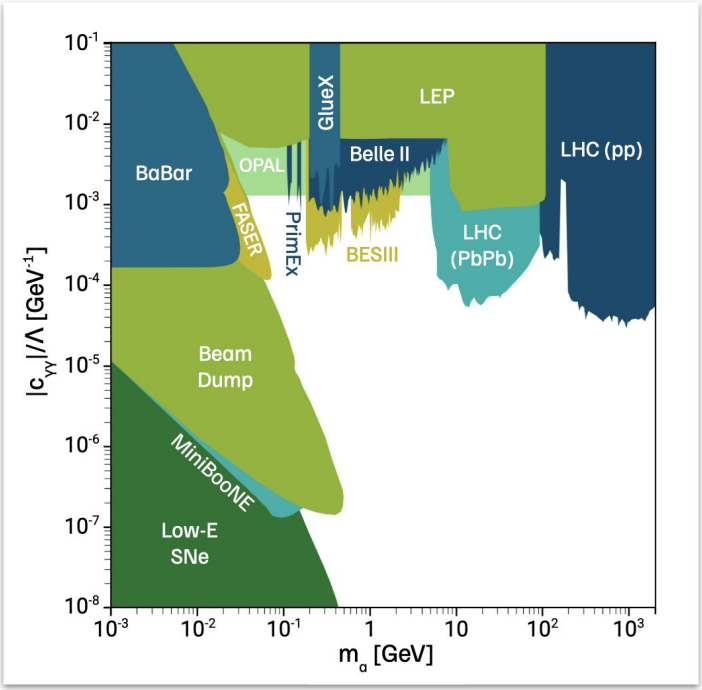
- **Could be mediator to the dark sector (axion portal)**
- Generic feature of supersymmetry and string theory
- Could explain why electroweak scale ≪ Planck scale



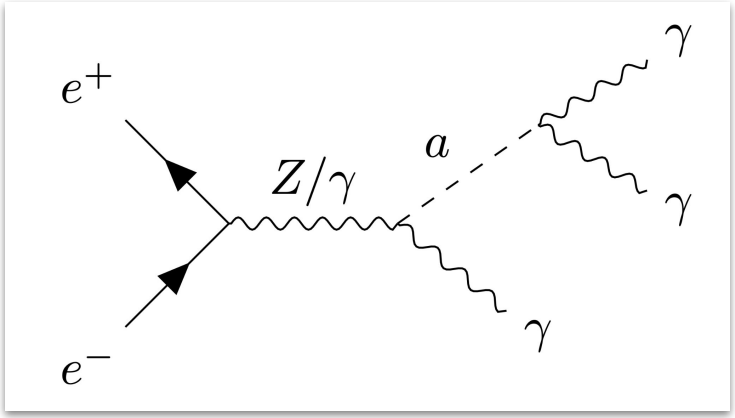
Axion-Like Particles (ALPs)

doi:10.5281/zenodo.3932430

Wide phenomenological parameter space and **diverse possibilities for experimental searches**



- ALPs can be radiated of a photon (γ) or a Z boson and be produced in association with a γ
- Relevant coupling for this process is $C_{\gamma\gamma}$



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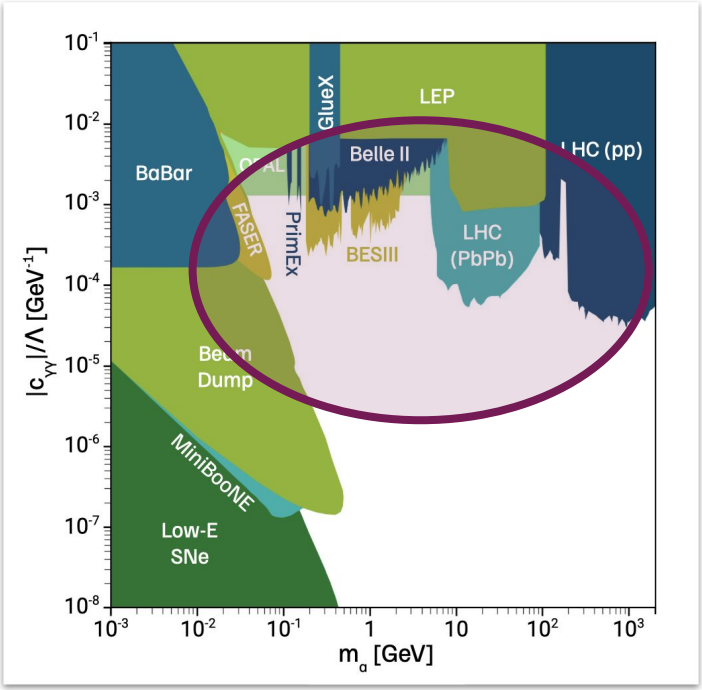

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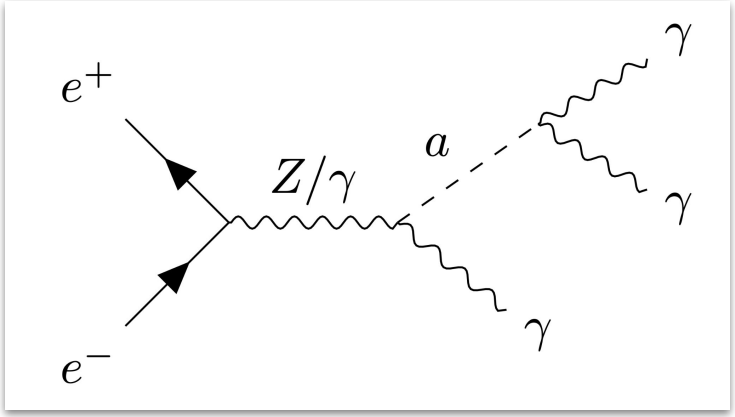
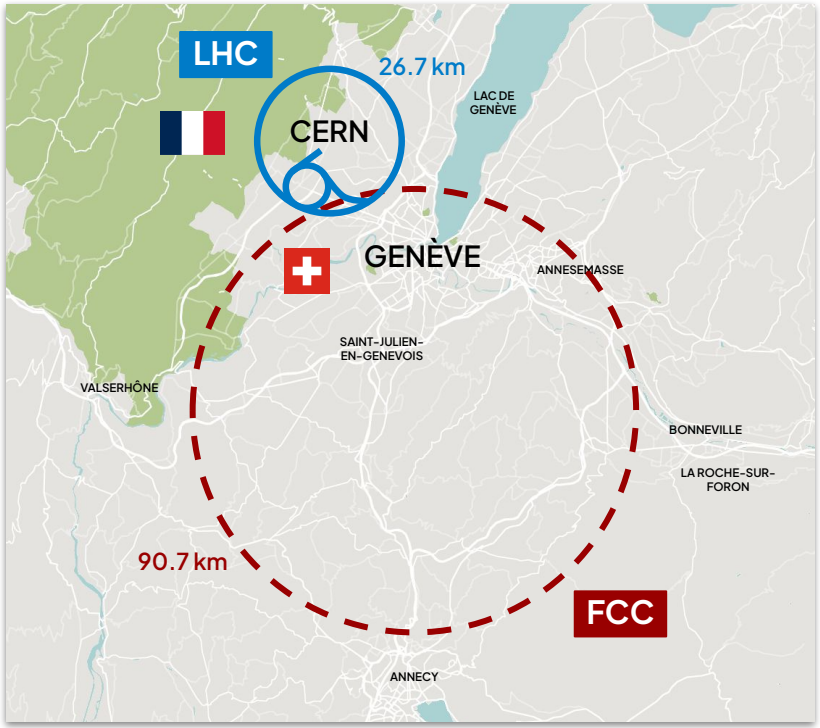


Future Circular Electron-Positron Collider (FCC-ee)

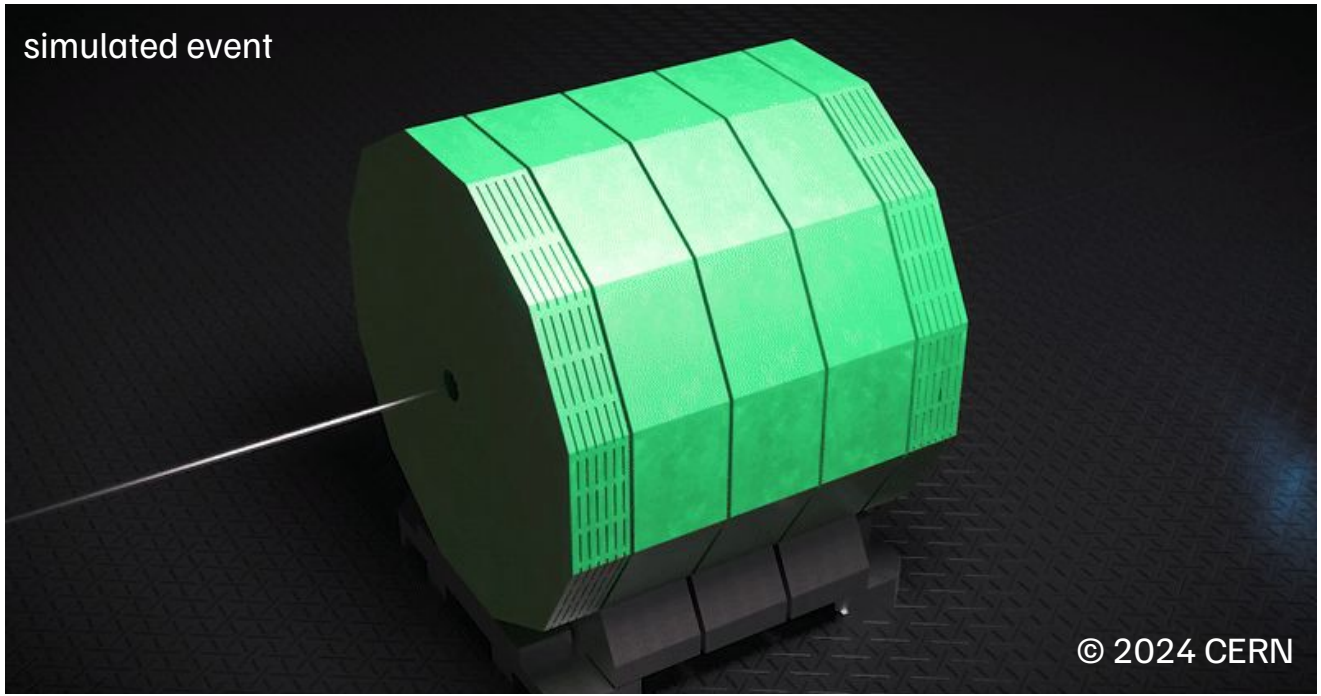
- Proposed next-generation collider at CERN as part of integrated FCC project
- Electron-positron machine in 91 km tunnel
- Run at 4 different centre-of-mass energies

Working Point	Z pole	WW thres.	ZH	$t\bar{t}$
√s [GeV]	91.2	160	240	365
Integrated Lumi (L) [ab^{-1}]	205	19.2	10.8	2.7



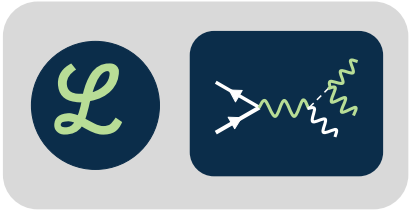
IDEA Detector

- **IDEA**: **I**nnovative **D**etector for **E**lectron-positron **A**ccelerators

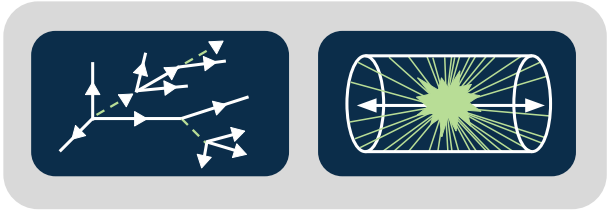


Analysis Workflow

Event Generation



Detector Simulation



FCCAnalyses

Statistical Framework

- Generate physics process involving ALP in MadGraph
- Set mass, coupling, etc.

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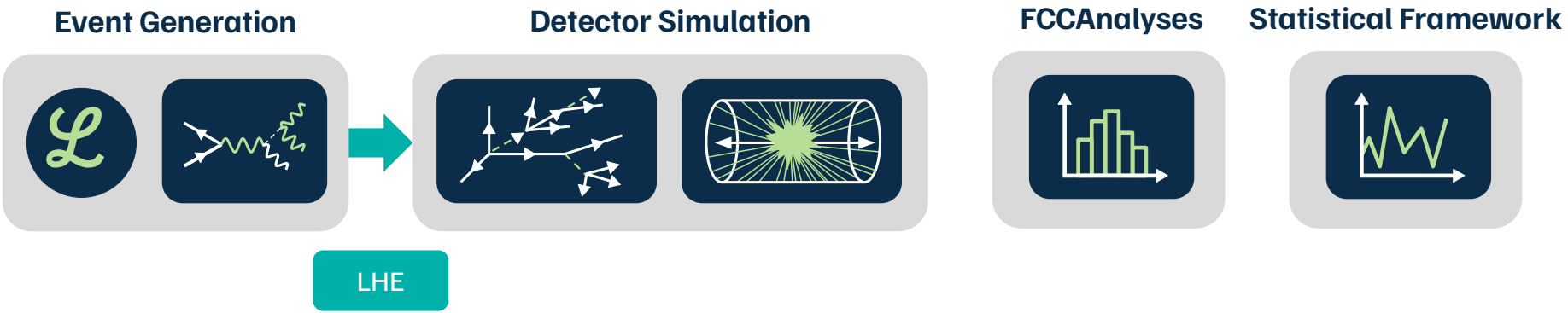

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- Reconstruct the event and imitate what it would look like in the detector

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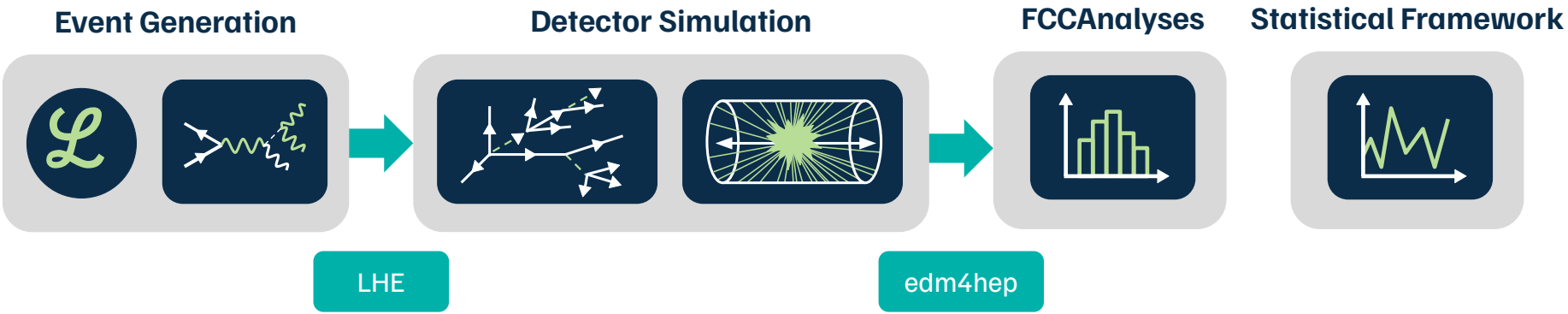

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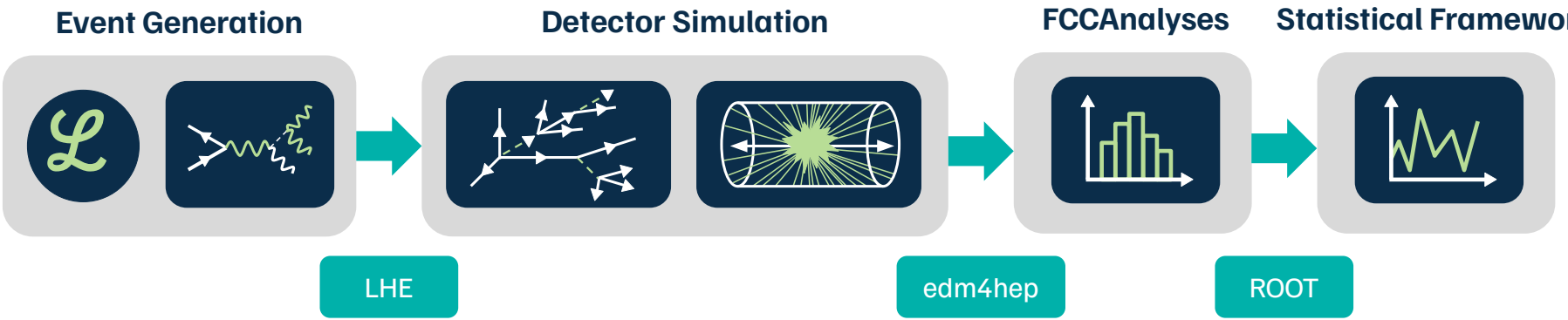

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- Determine expected sensitivity to ALPs given the background

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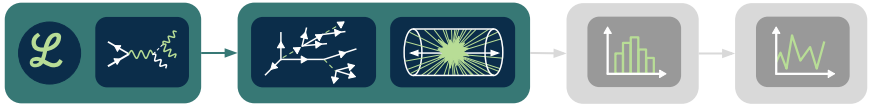
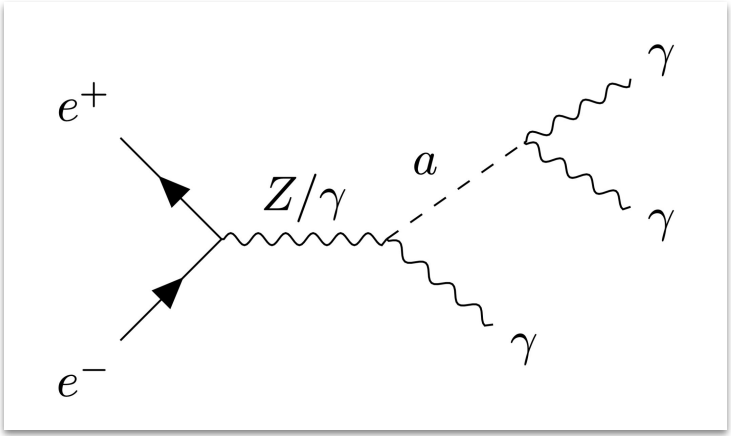


- MadGraph5_aMC@NLO:
  - Machine parameters: √s and *L* corresponding to physics run
  - ALP mass ranging from 0.01 GeV to 360 GeV
  - Model parameters: $C_{\gamma\gamma} = 1$, $\Lambda = 1$ TeV, BR(a→γγ) = 100%
  - ~1 million events per signal point, ~1 million per background

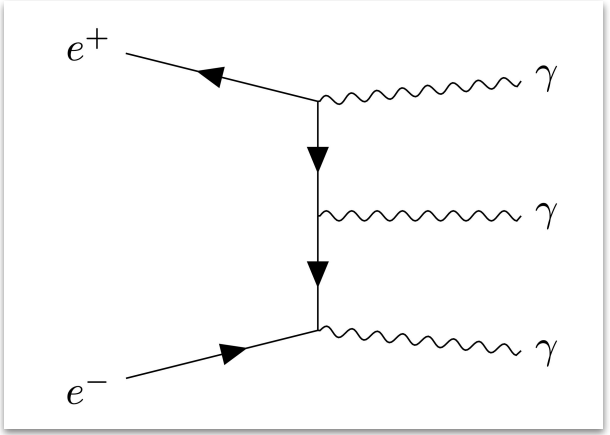
Photon Constraints

E ≥ 0.1 GeV
pT ≥ 0 GeV
η ≤ 2.6
ΔR ≥ 0

Signal



Background



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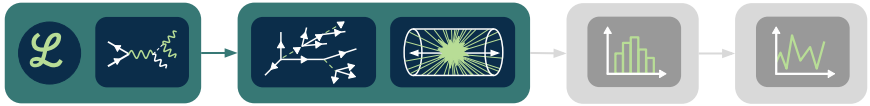

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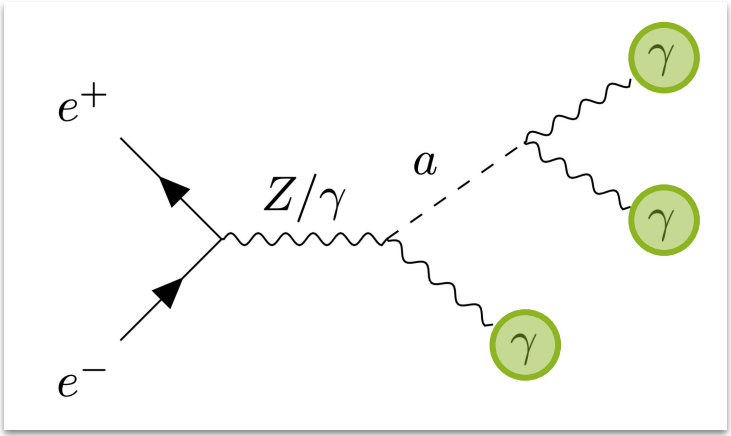

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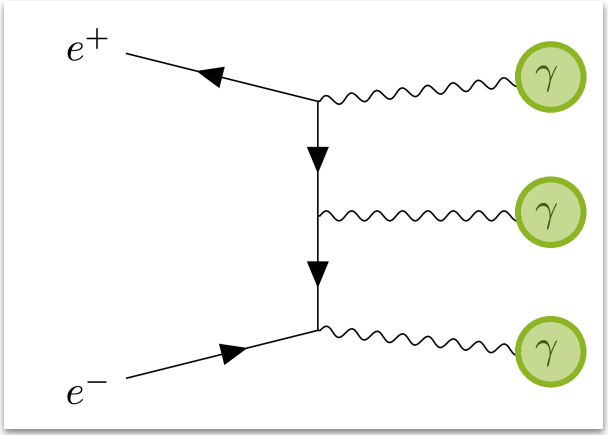
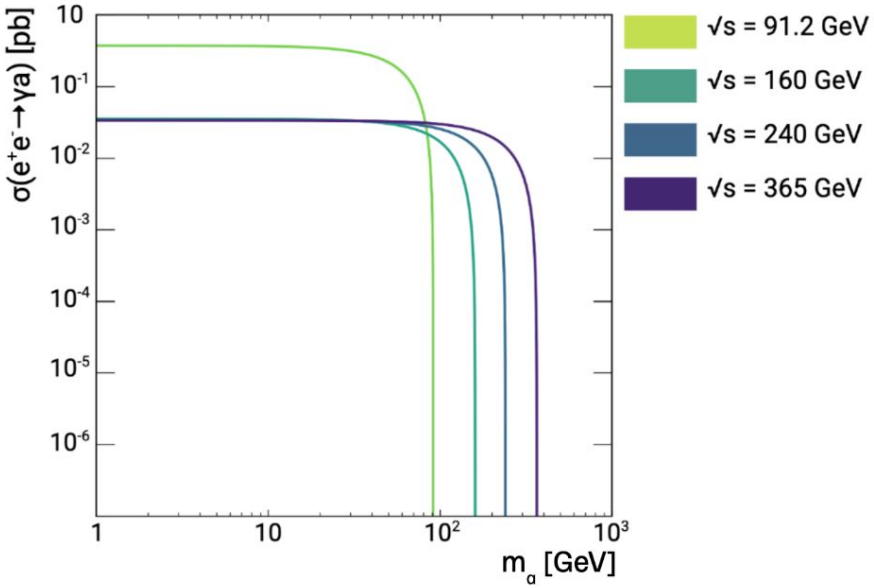
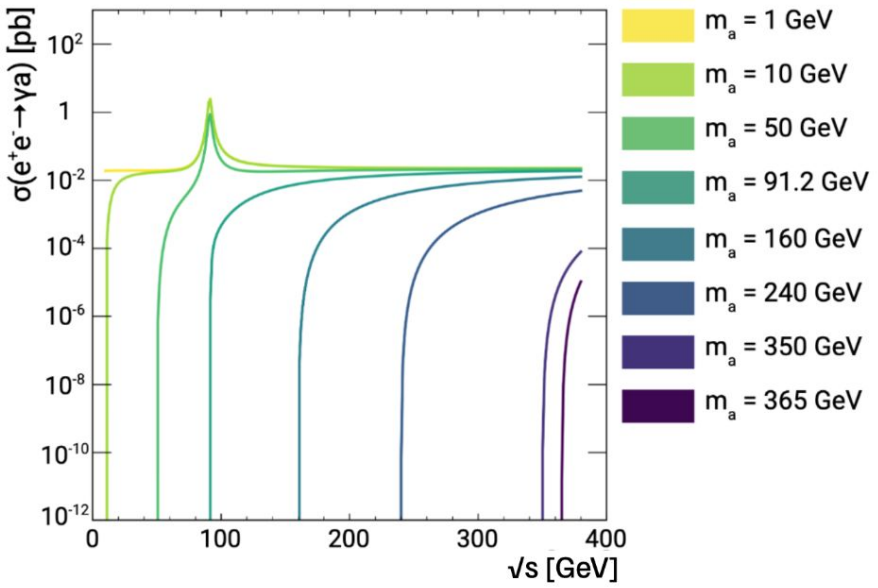


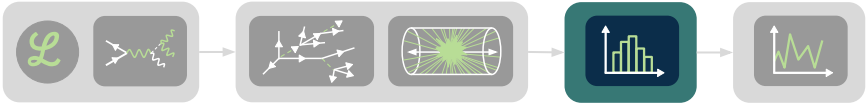
√s Comparison

- At higher centre-of-mass energies we can explore heavier ALPs, though Z pole provides unique opportunity for ALP studies

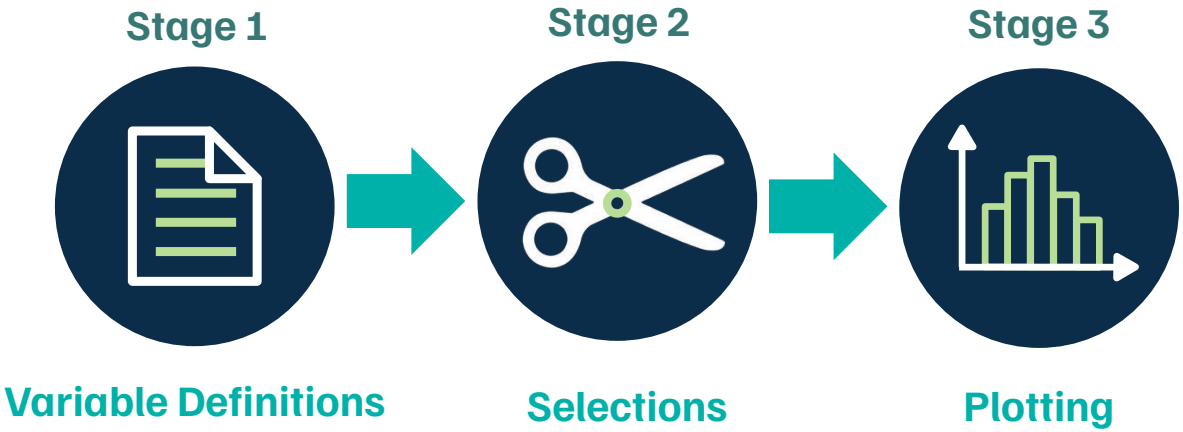




FCCAnalyses



A framework developed within the FCC project to perform physics analysis on simulated data



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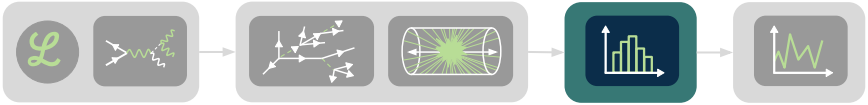

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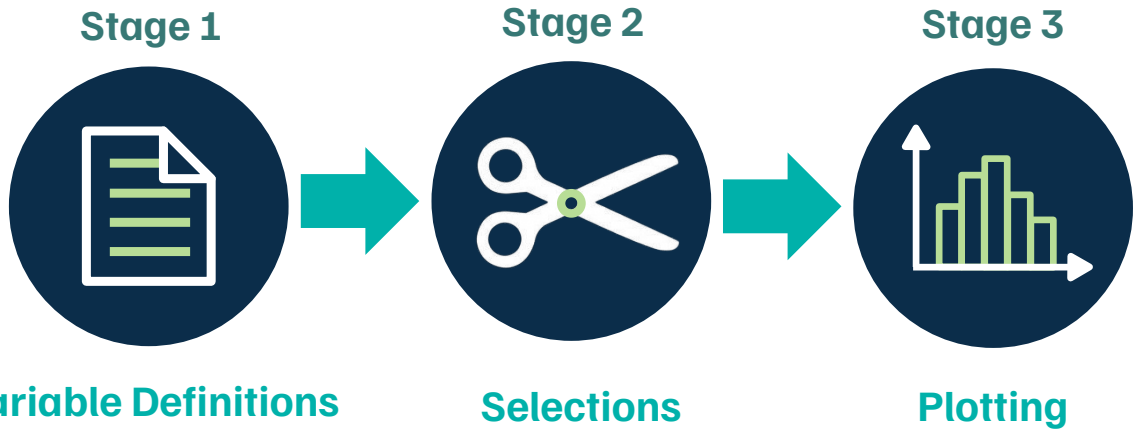

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- Defines new physics variables

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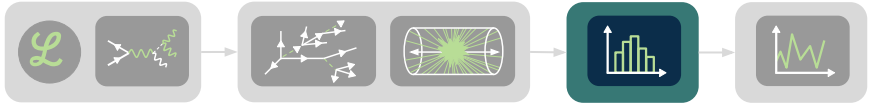

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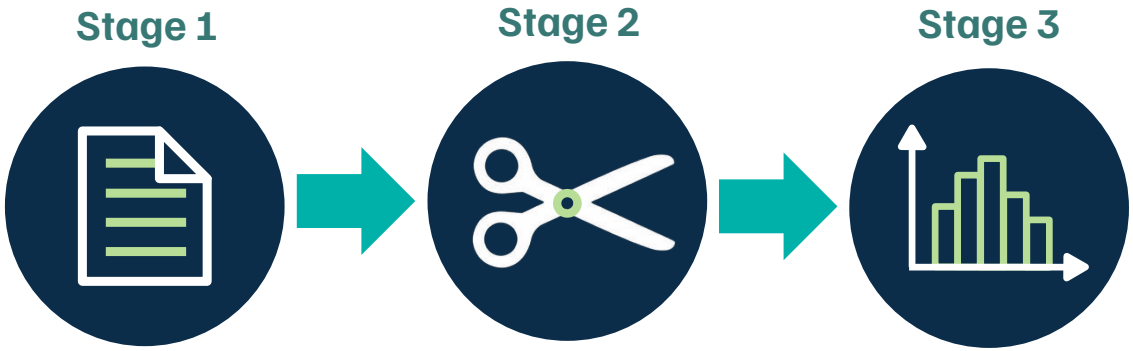

Variable Definitions

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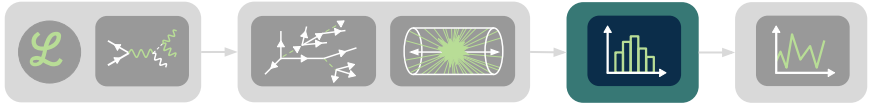
Selections

- Applies event selections (cuts)
- Defines plot parameters

Plotting

FCCAnalyses



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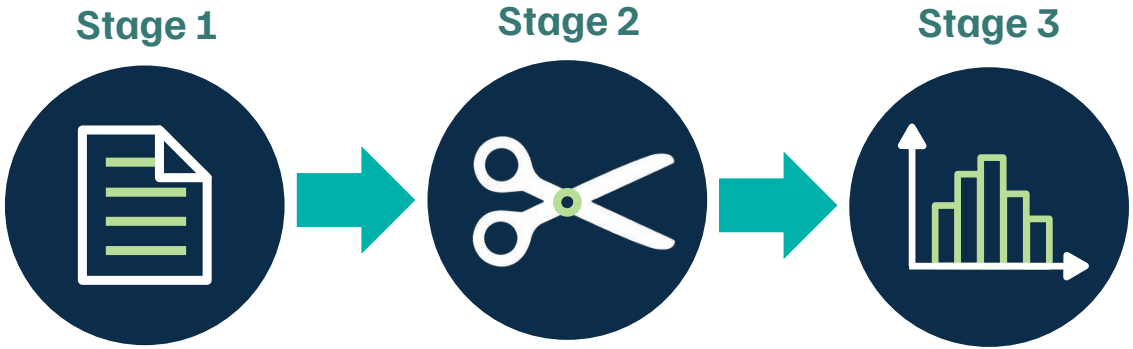

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- Produces histograms

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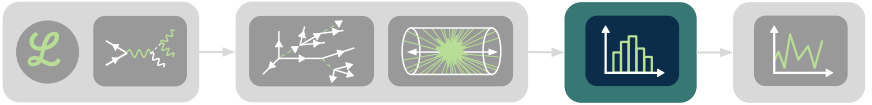

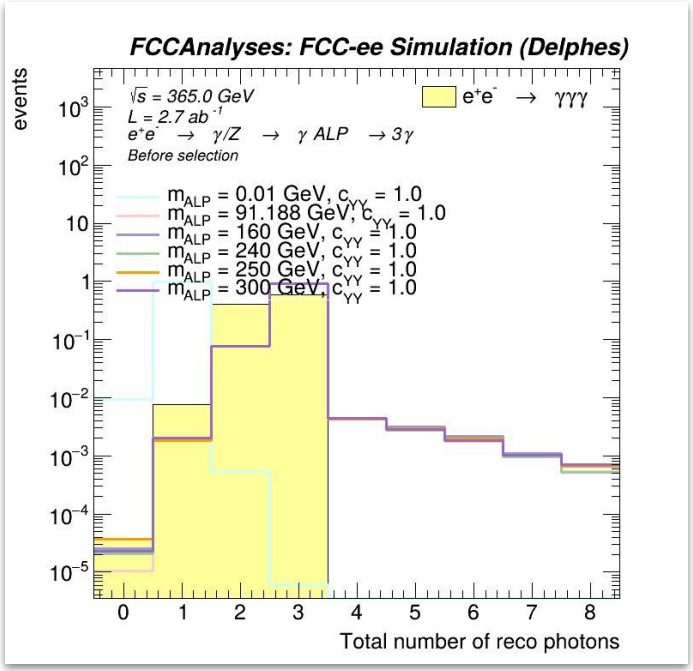

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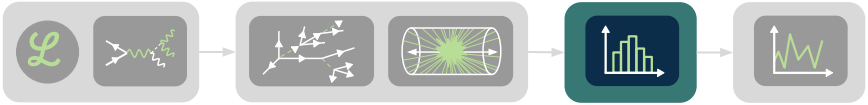

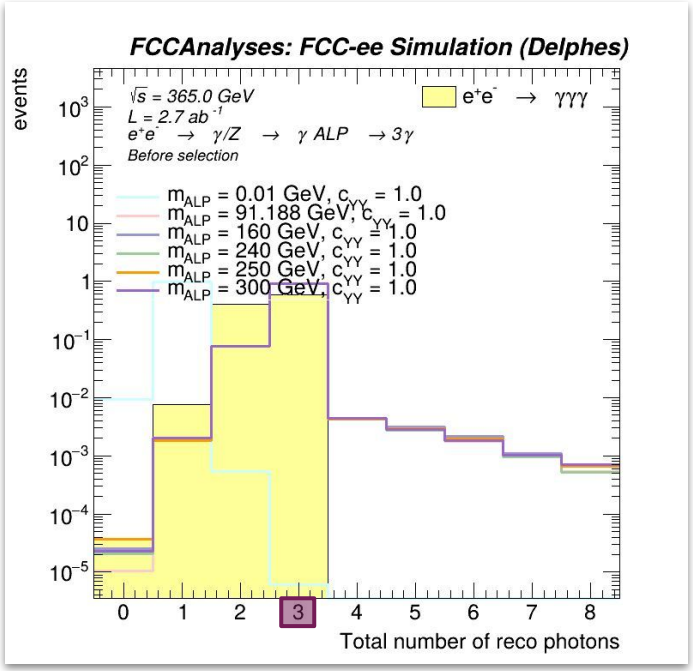

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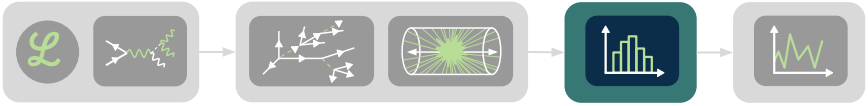
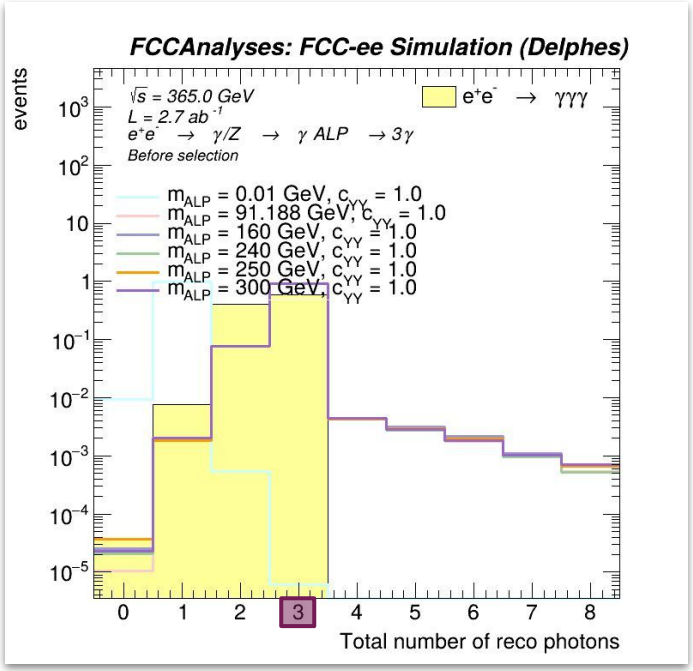
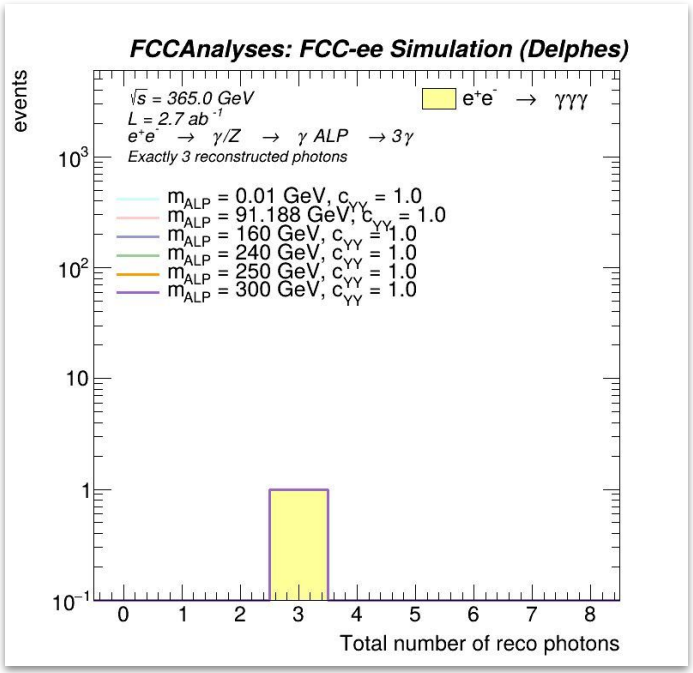
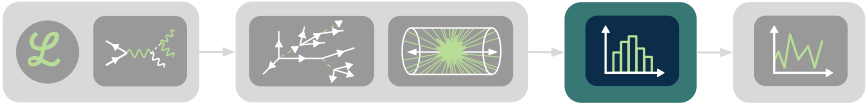






Selection efficiency at √s = 365 GeV



Reduces background and maintains signal

Sample	No selections	3 reconstructed photons
Signal		
m_a = 0.01 Gev	1	6.16×10^{-6}
m_a = 91.188	1	0.909
m_a = 160 GeV	1	0.909
m_a = 240 GeV	1	0.910
m_a = 360 GeV	1	0.914
Background		
$e^+e^- \rightarrow \gamma\gamma\gamma$	1	0.583

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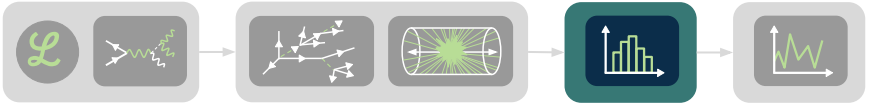

Reduces background and maintains signal, but..

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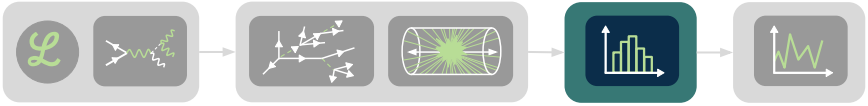
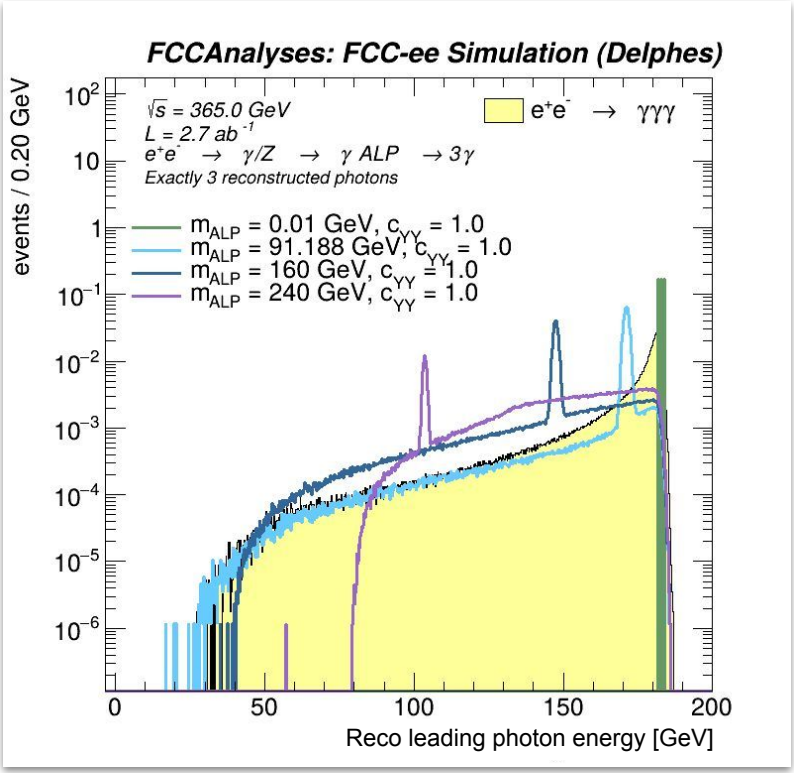
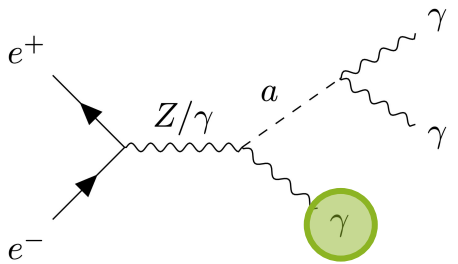


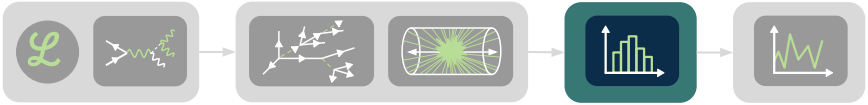


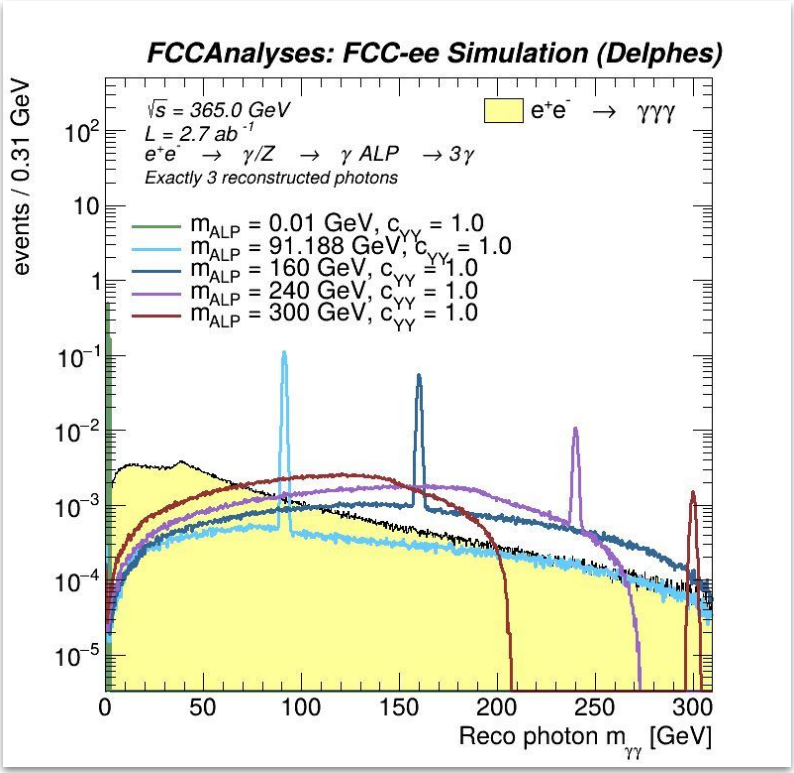


The energy of the **photon** from the γ/Z decay has a fixed value E, determined by the **recoil formula**

$$E = \frac{s - m_a^2}{2\sqrt{s}}$$

FCCAnalyses





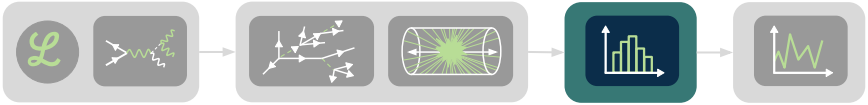
The **invariant mass** of the diphoton system:

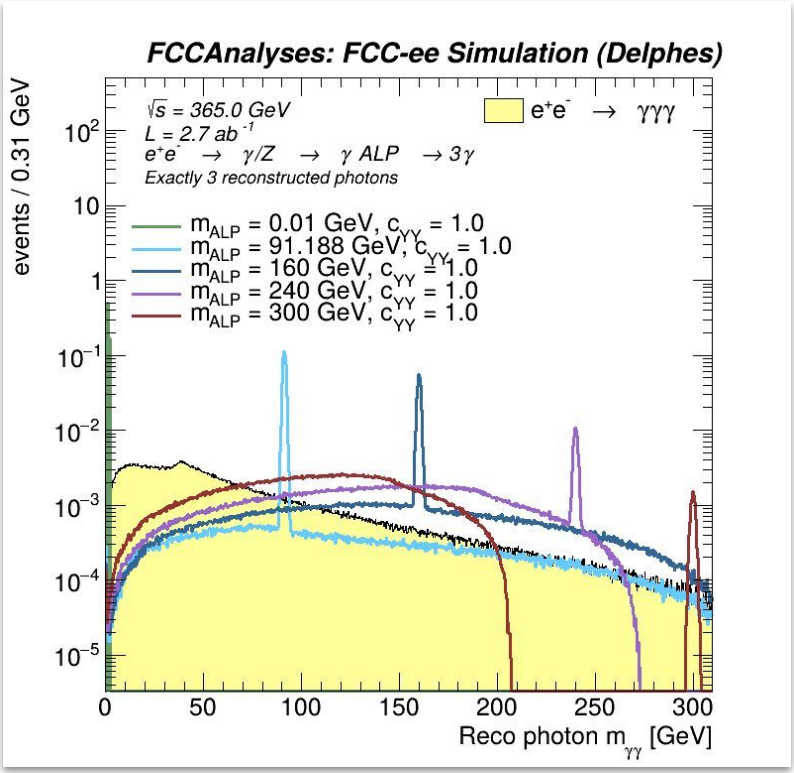
$$m_{\gamma\gamma}^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$

where p_i is the 3-momentum for photon i, i = 1,2

photon **0** = highest-energy photon,
photon **1** = second-highest-energy photon,
photon **2** = lowest-energy photon

FCCAnalyses





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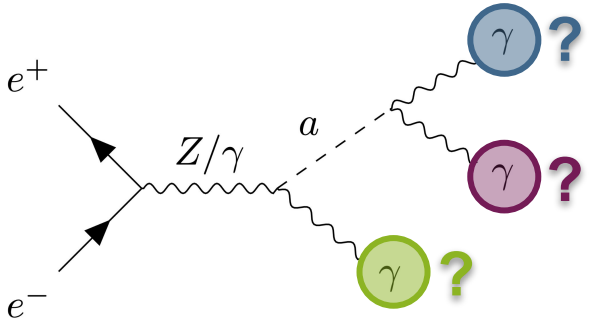
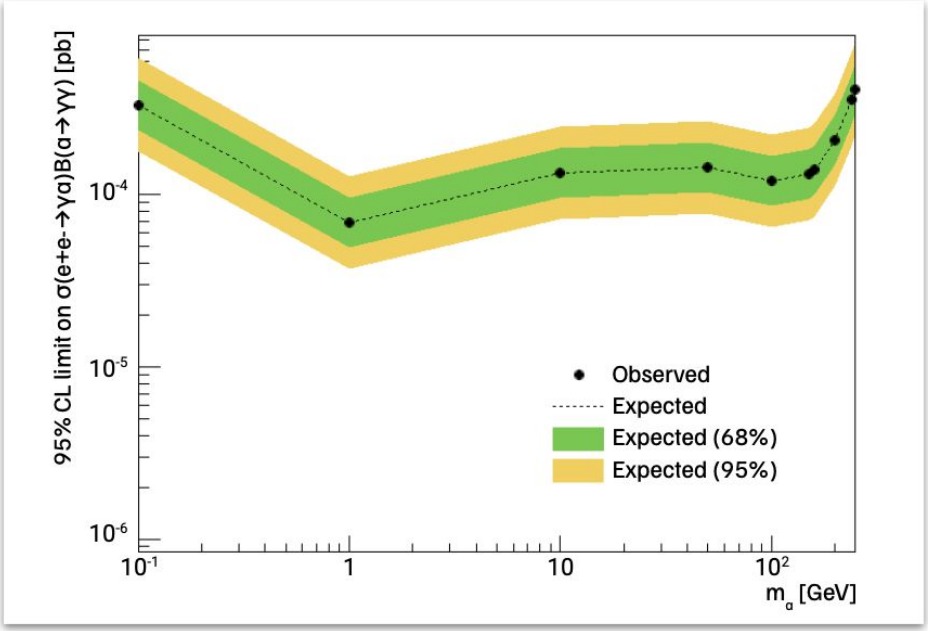
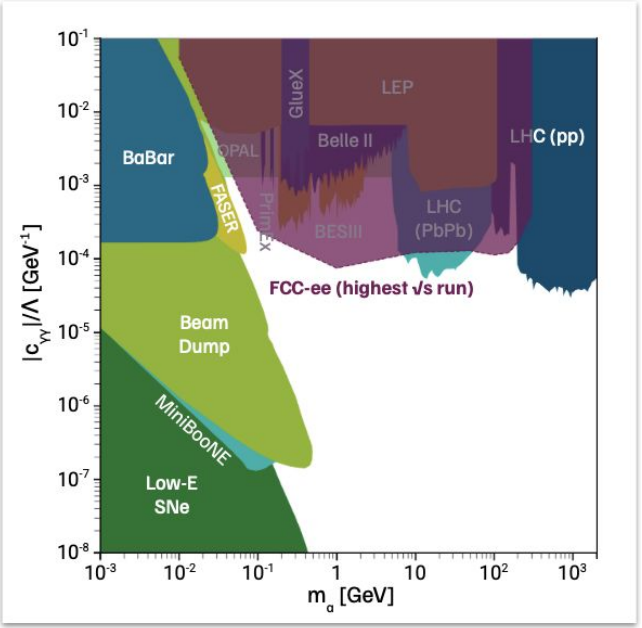


Combine

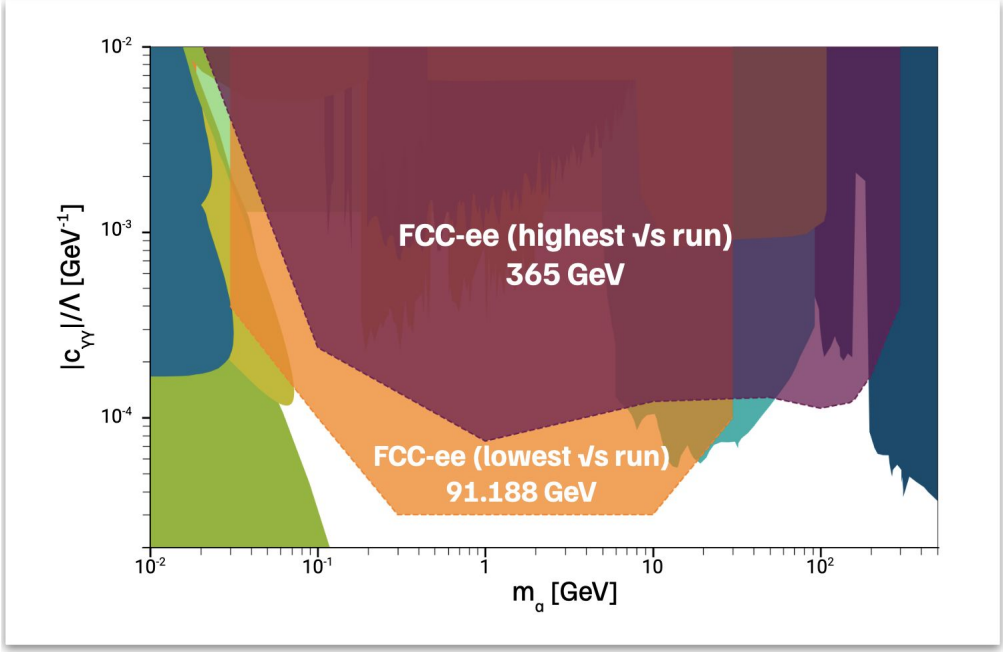
- Limit on cross section for three photon ALP signature at √s = 365 GeV
- Background only expectation represented by median (dashed line)





Results

- Compare sensitivity between Z-Pole and $t\bar{t}$ threshold runs
- Lower √s → lower couplings, higher √s → **higher masses**!



Summary

- Strong theoretical motivation to look for Axion-Like Particles
- We developed a full analysis workflow from event generation to limits
- Explored different ALP processes and couplings
- Analyzed process behavior and explored different selections
- Showed that FCC-ee would provide unique sensitivity and reach into previously unexplored parameter space

Outlook

- Further steps: discriminating variables, mass-dependent cuts
- Even further steps: different signatures (mono-photon), different couplings (Higgs)
- **The future looks promising!**

Thank you!

Special thanks to Juliette Alimena, Jeremi Niedziela, Lovisa Rygaard
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DESY Summer Student Programme Organizers
DESY Staff, Secretariat, and IT Support
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and thank ***you*** for your kind attention!

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Backup

ALP Lagrangian

- ALP (a) couplings to the SM arise at dimension-5, described by the effective Lagrangian in the unbroken electroweak phase with new physics scale Λ

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{\Lambda}\bar{f}\gamma_\mu\gamma_5 f + g_s^2 C_{GG}\frac{a}{\Lambda}G^A_{\mu\nu}\tilde{G}^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

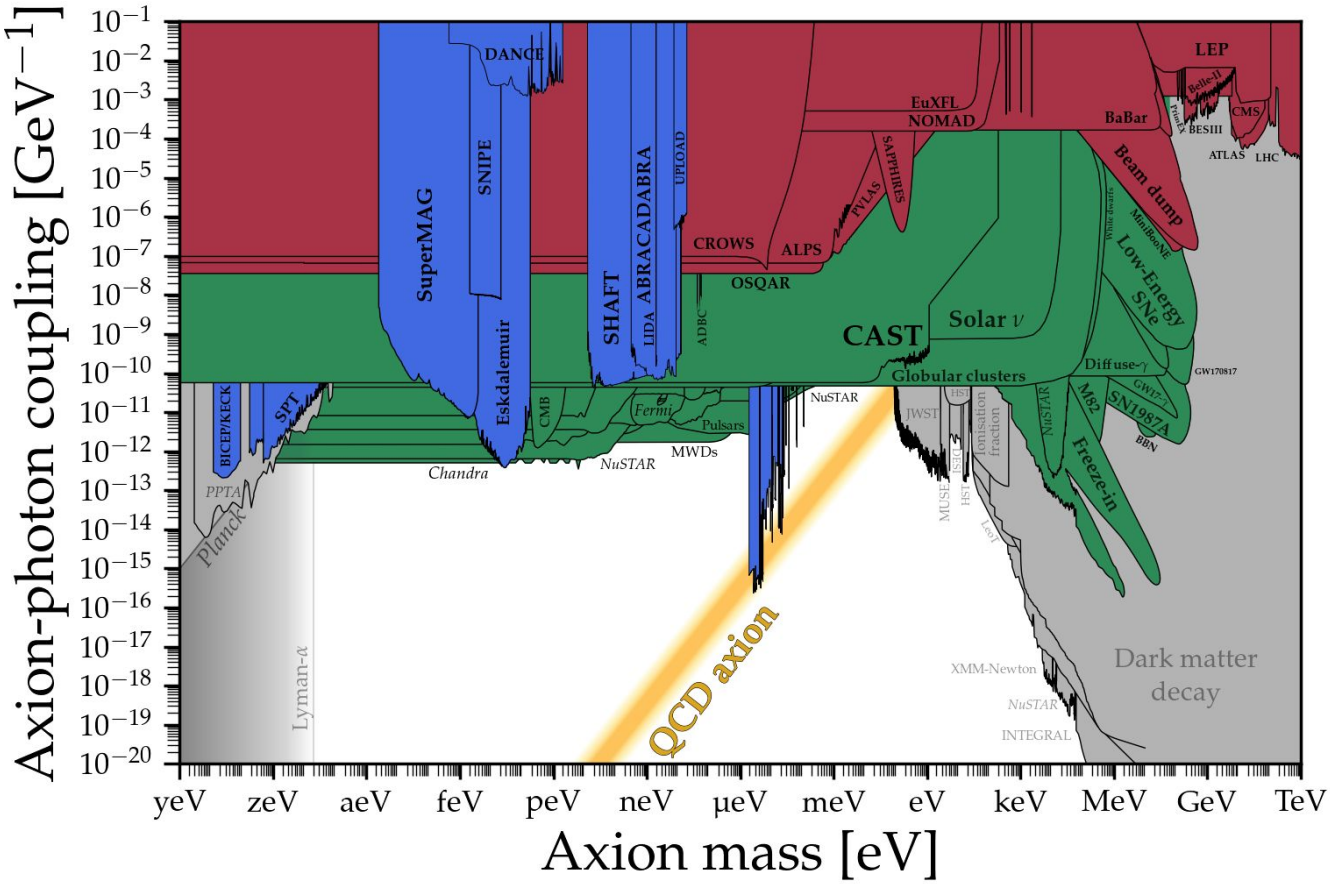
kinetic term | mass term | derivative couplings to fermions | $SU(3)_C$ gluons | $SU(2)_L$ W gauge bosons | $U(1)_Y$ hypercharge gauge bosons

- Additional interactions (Higgs) arise at dimension-6 order and higher

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

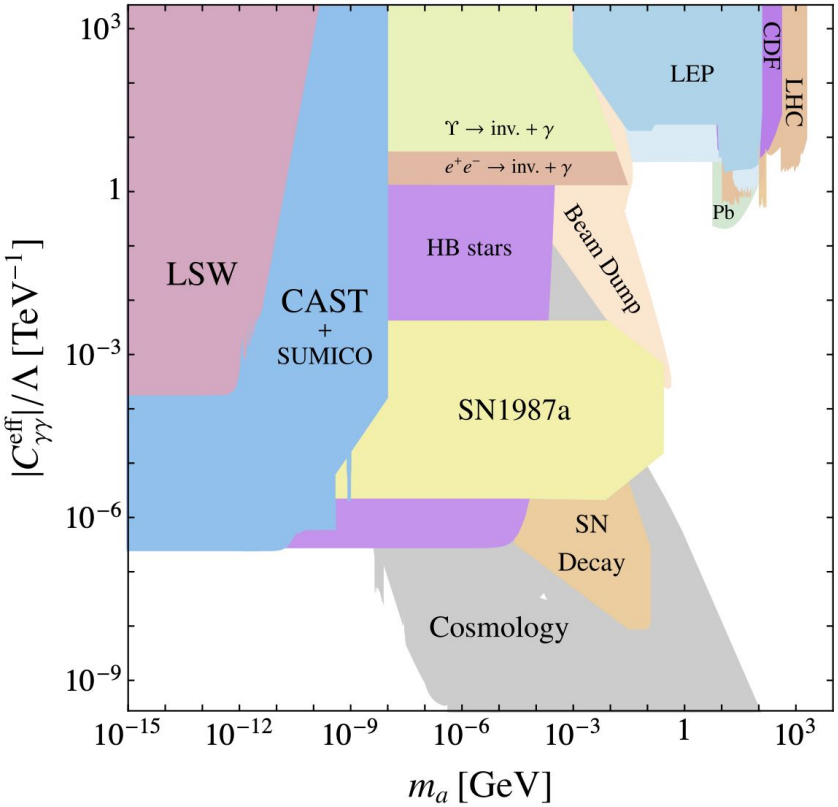
h → aa | h → Za

ALP Parameter Space



ALP Parameter Space

Adapted from Thamm



ALP Parameter Space

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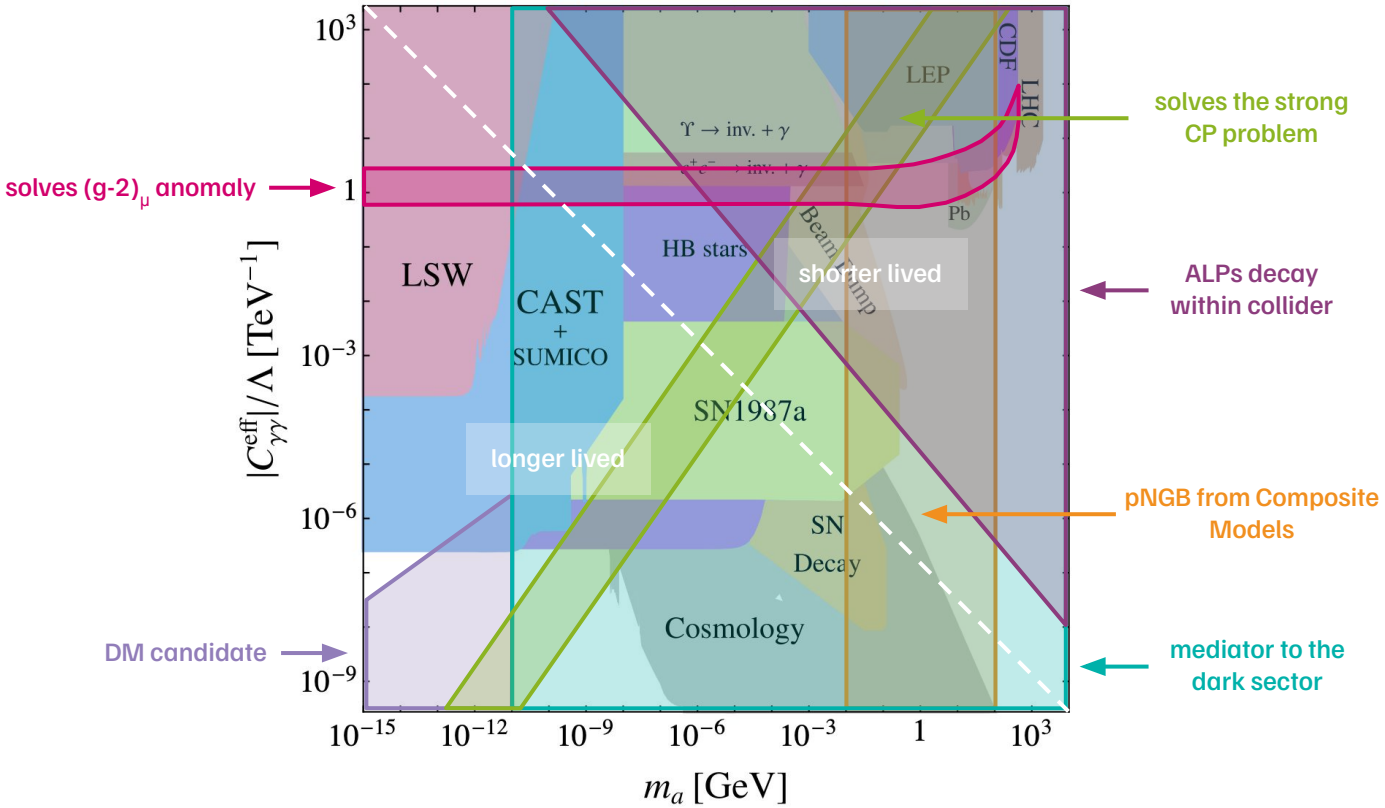


Axions and Axion-Like Particles (ALPs)

Axion

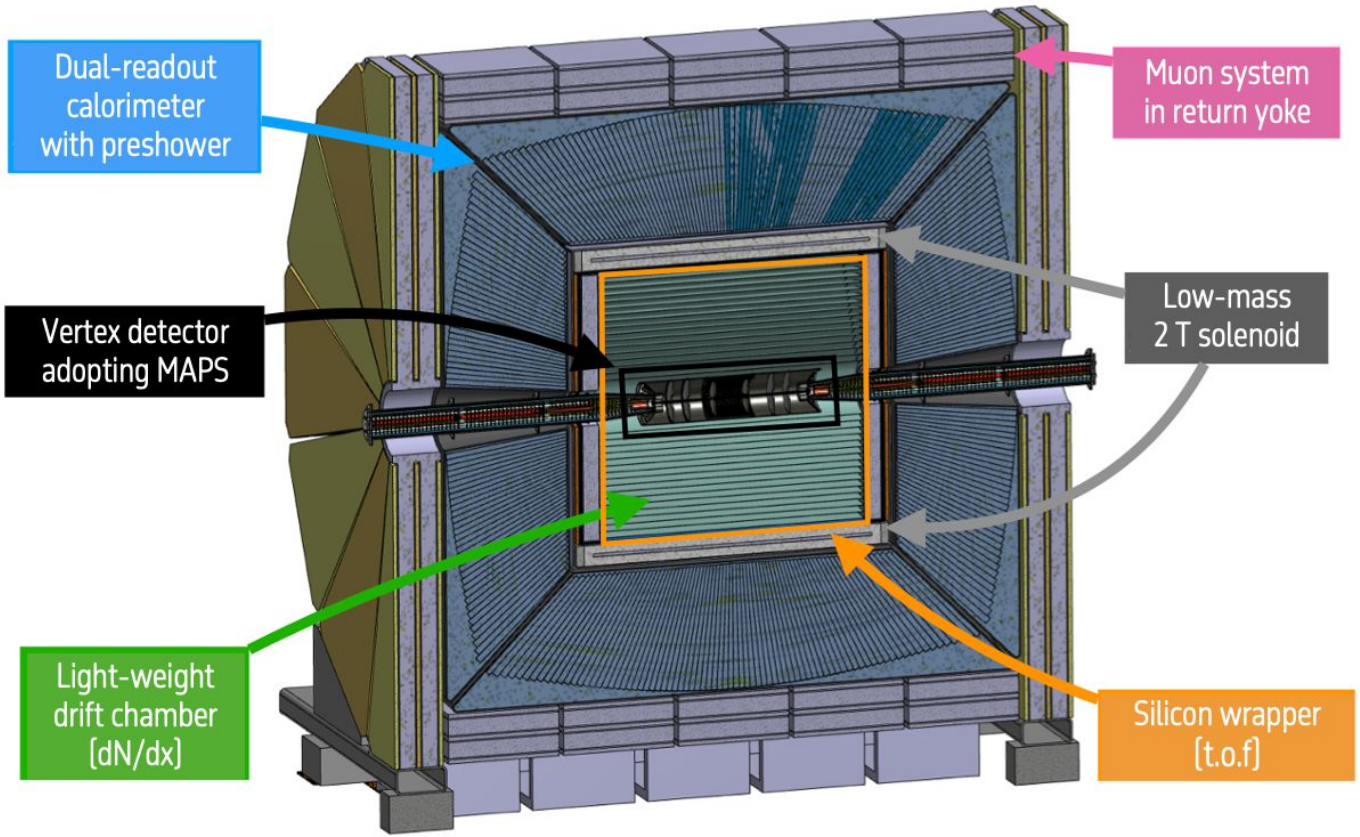
- Introduced to solve strong CP problem in QCD
- Compelling candidate for DM

Axion-like Particle

- Need not satisfy strict relationship between mass and coupling
- Wider phenomenological parameter space

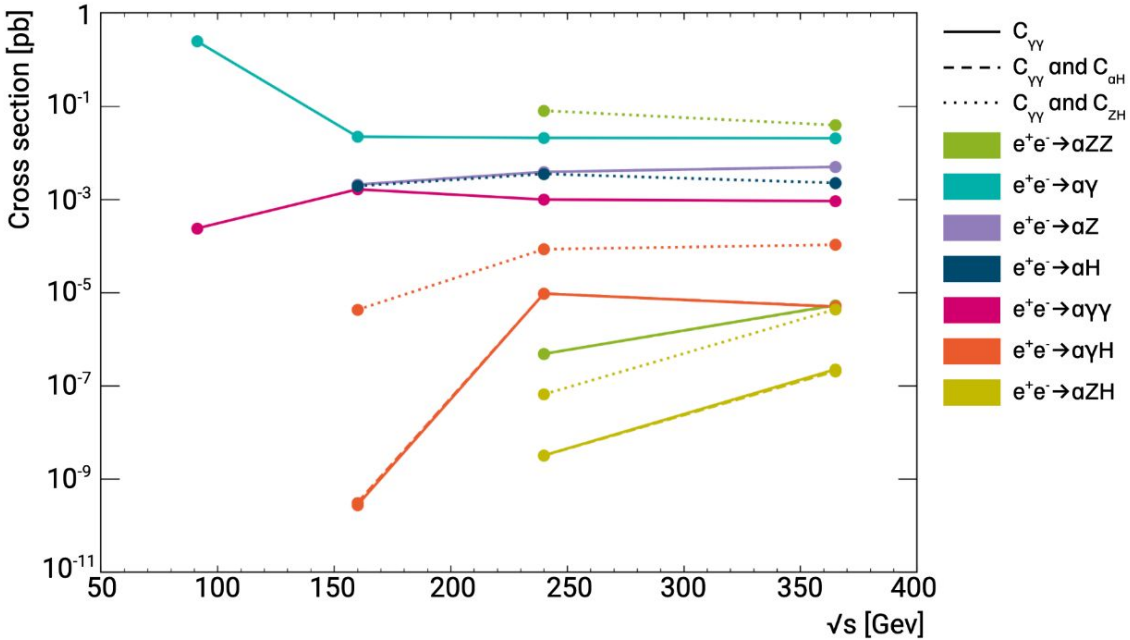
Diverse possibilities for experimental searches

IDEA Detector



Process Comparison

- αZZ has highest cross section but is not accessible at lower √s, assumes more couplings



Process Comparison

- aZZ has highest cross section but is not accessible at lower √s, assumes more couplings
- **aγ** is the selected final state for this analysis (and previous work)