Sensitivity of the FCC-ee to axion-like particles

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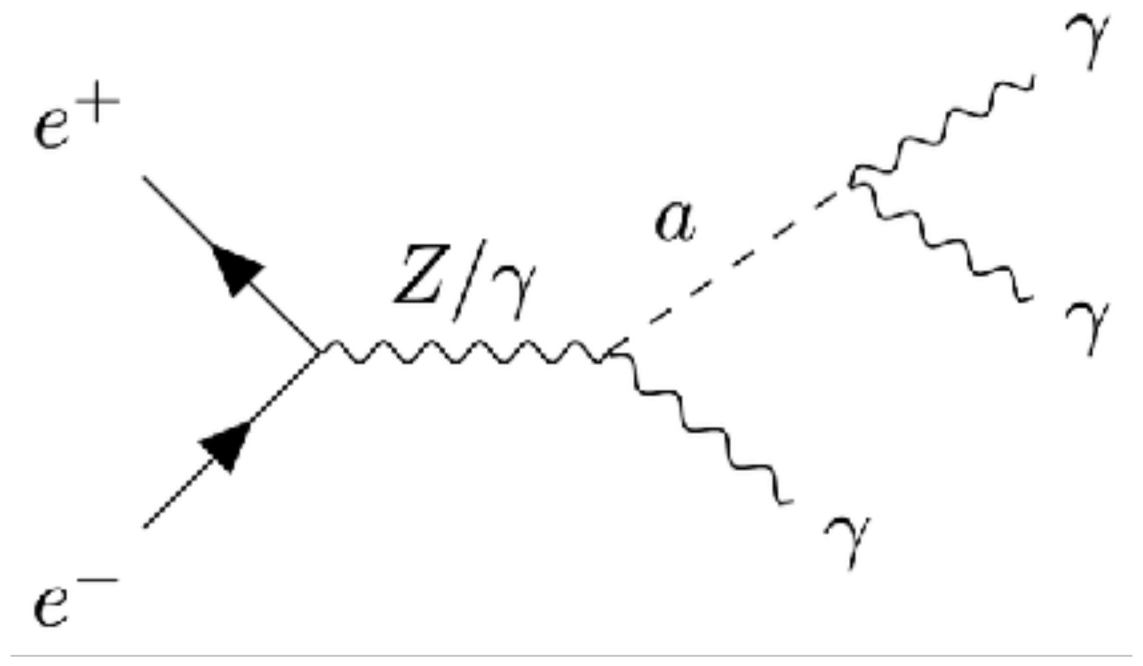
ALP signature at the FCC-ee

process: $e^+e^- \rightarrow a\gamma; \quad a \rightarrow \gamma\gamma$



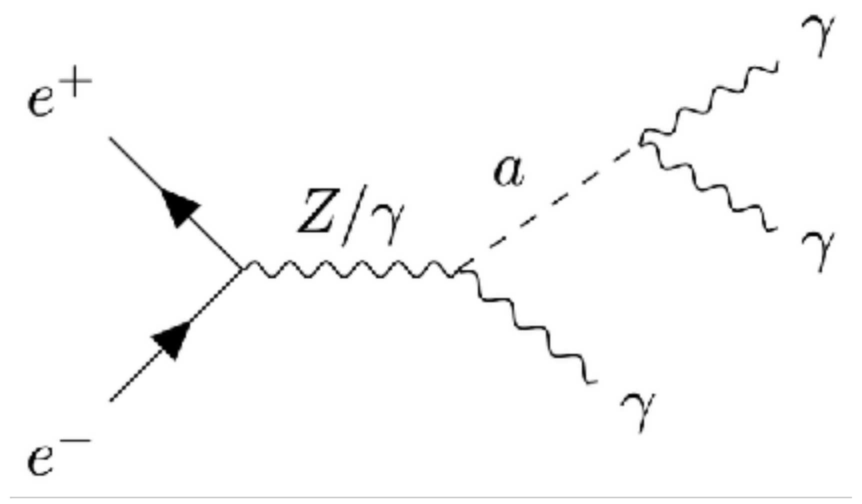
Currently:

- Recoil photon is defined by leading pT photon
- We select events with exactly 3 reconstructed photons

Current project status

process: $e^+e^- \to a\gamma; \quad a \to \gamma\gamma$

- Events were generated over the summer for all center-of-mass energies (Z pole, WW threshold, ZH production maximum, tt threshold)
    - MadGraph → Pythia → Delphes (IDEA detector card)
- FCCAnalyses framework was used to analyze Z pole, and Combine was used to calculate limits
- I have reproduced previous work, updated limit (and other) scripts, and generated kinematic distributions for higher center-of-mass energies



Efficiencies

Recoil photon: defined by leading pT photon

Selection: exactly 3 reconstructed photons

zpole	m_ALP = 0.1 GeV	m_ALP = 1.0 GeV	m_ALP = 10 GeV	m_ALP = 50 GeV	m_ALP = 80 GeV	Background
Before selection	1	1	1	1	1	1
Exactly 3 photons	0,382	0,845	0,837	0,885	0,887	0,465

ww	m_ALP = 0.1 GeV	m_ALP = 1.0 GeV	m_ALP = 10 GeV	m_ALP = 50 GeV	m_ALP = 80 GeV	m_ALP = 140 GeV	Background
Before selection	1	1	1	1	1	1	1
Exactly 3 photons	0,252	0,904	0,885	0,908	0,909	0,908	0,518

zh	m_ALP = 0.1 GeV	m_ALP = 1.0 GeV	m_ALP = 10 GeV	m_ALP = 50 GeV	m_ALP = 80 GeV	m_ALP = 140 GeV	m_ALP = 200 GeV	m_ALP = 220 GeV	Background
Before selection	1	1	1	1	1	1	1	1	1
Exactly 3 photons	0,175	0,897	0,899	0,908	0,908	0,909	0,909	0,91	0,549

tt	m_ALP = 0.1 GeV	m_ALP = 1.0 GeV	m_ALP = 10 GeV	m_ALP = 50 GeV	m_ALP = 80 GeV	m_ALP = 140 GeV	m_ALP = 200 GeV	m_ALP = 320 GeV	Background
Before selection	1	1	1	1	1	1	1	1	1
Exactly 3 photons	0,114	0,797	0,909	0,908	0,908	0,908	0,908	0,909	0,578

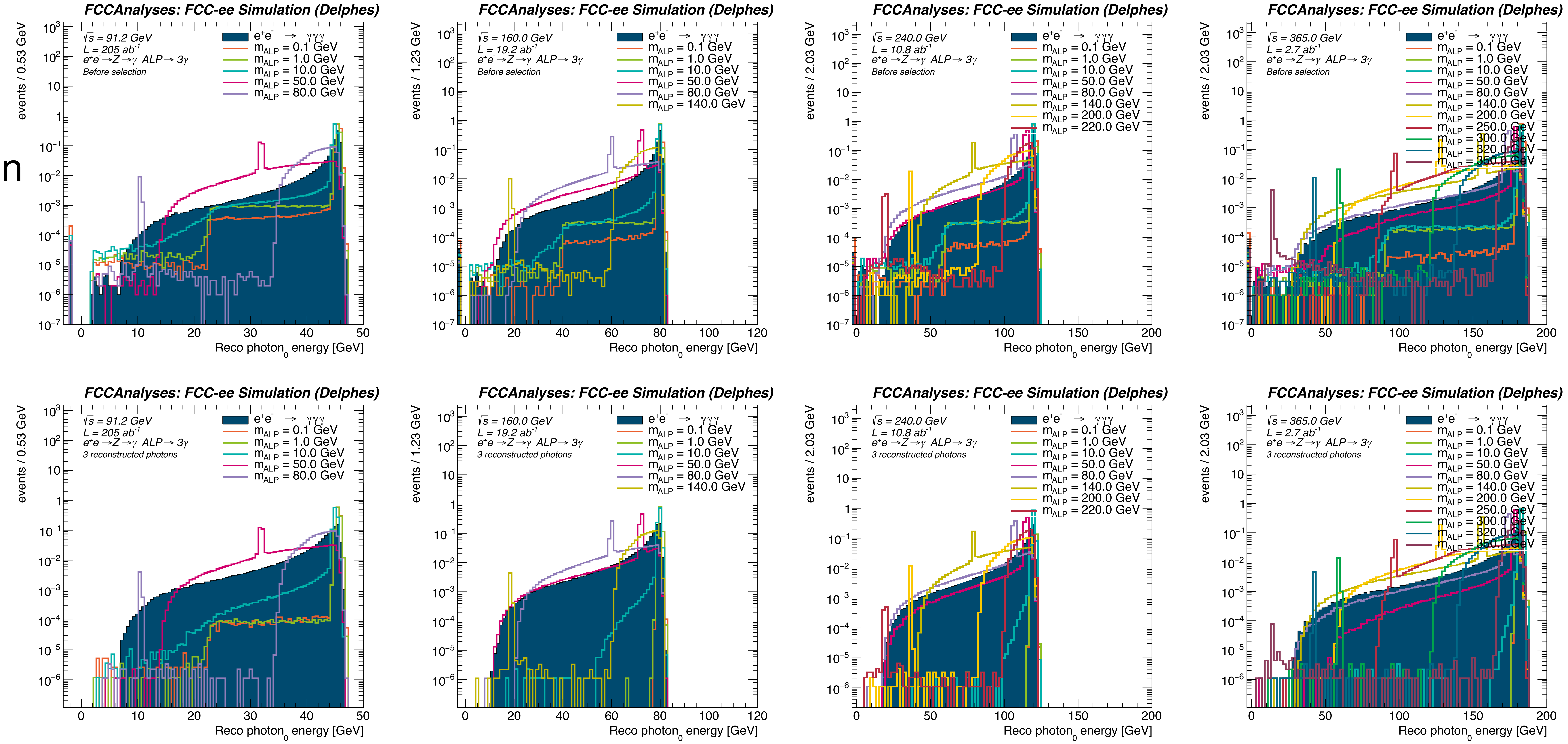
Photon merging

Recoil photon energy

- Peaks in the right spots, but events decrease with mALP (see next slide)

Before selection

After selection

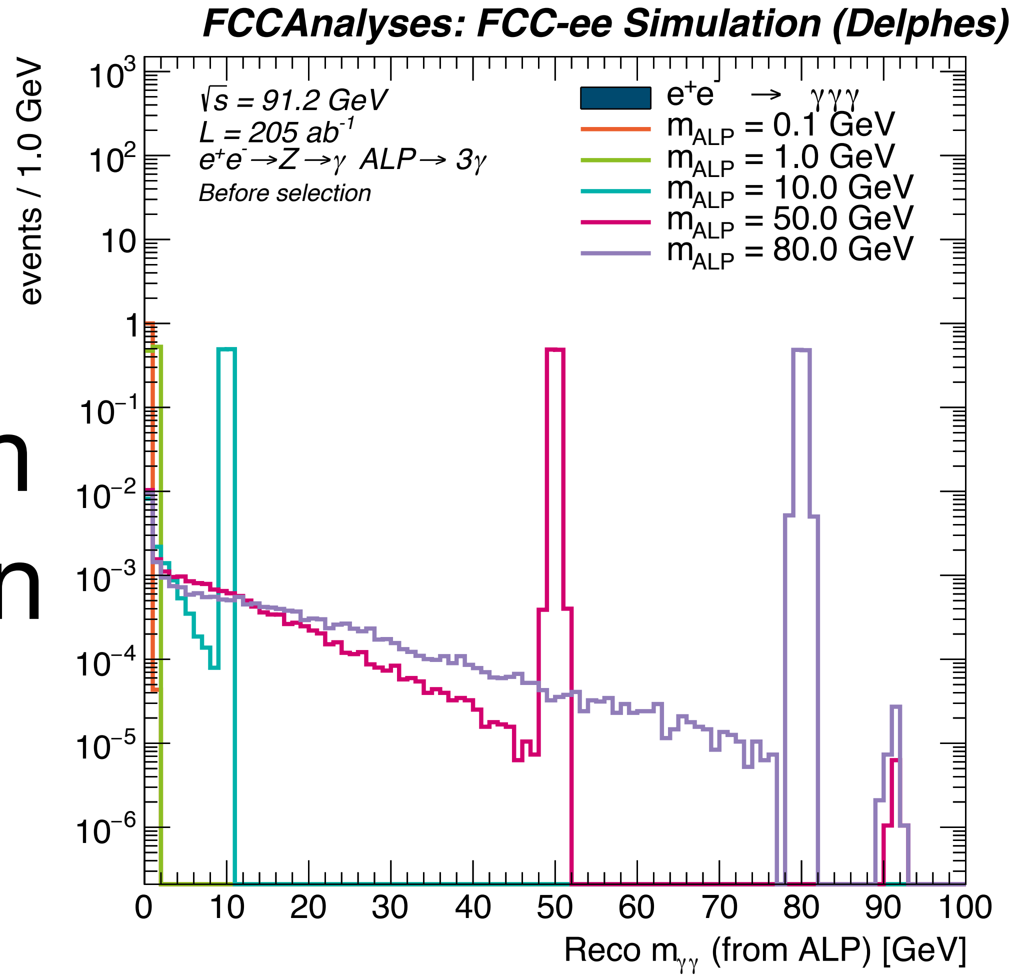


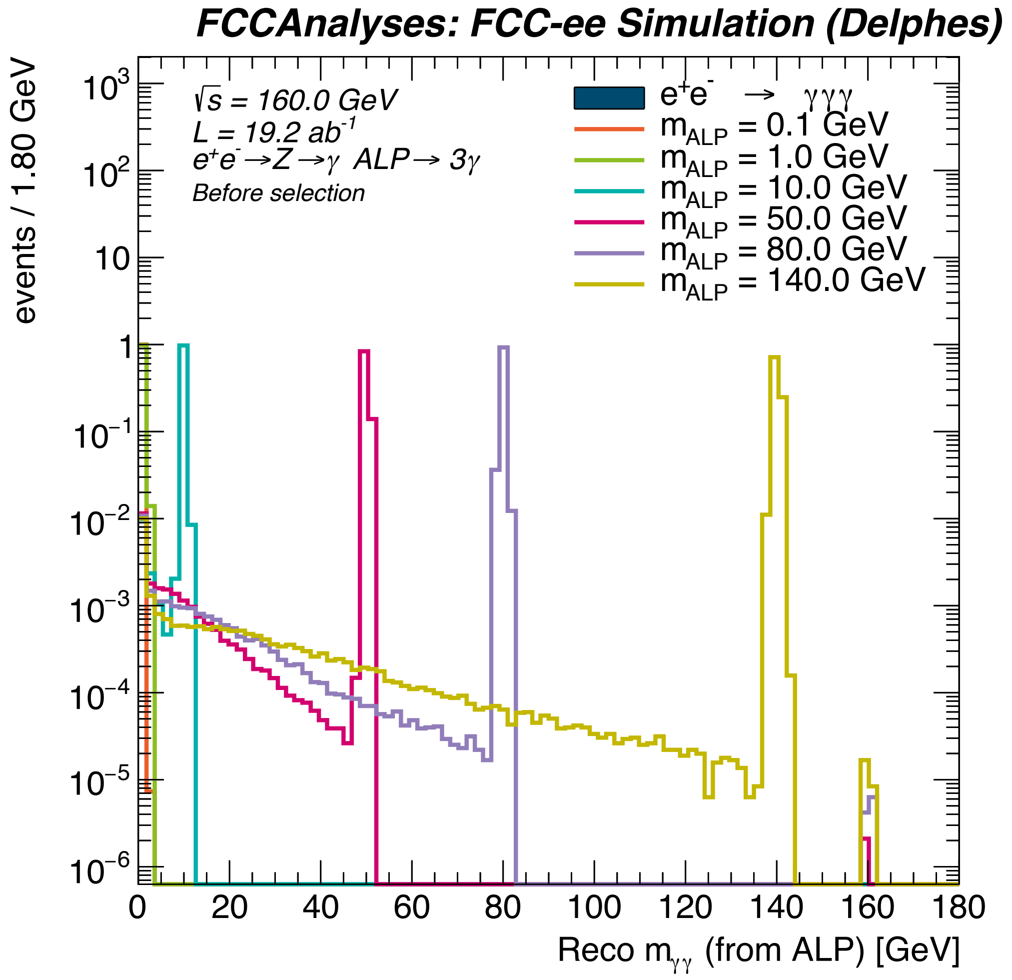
Z pole WW ZH tt

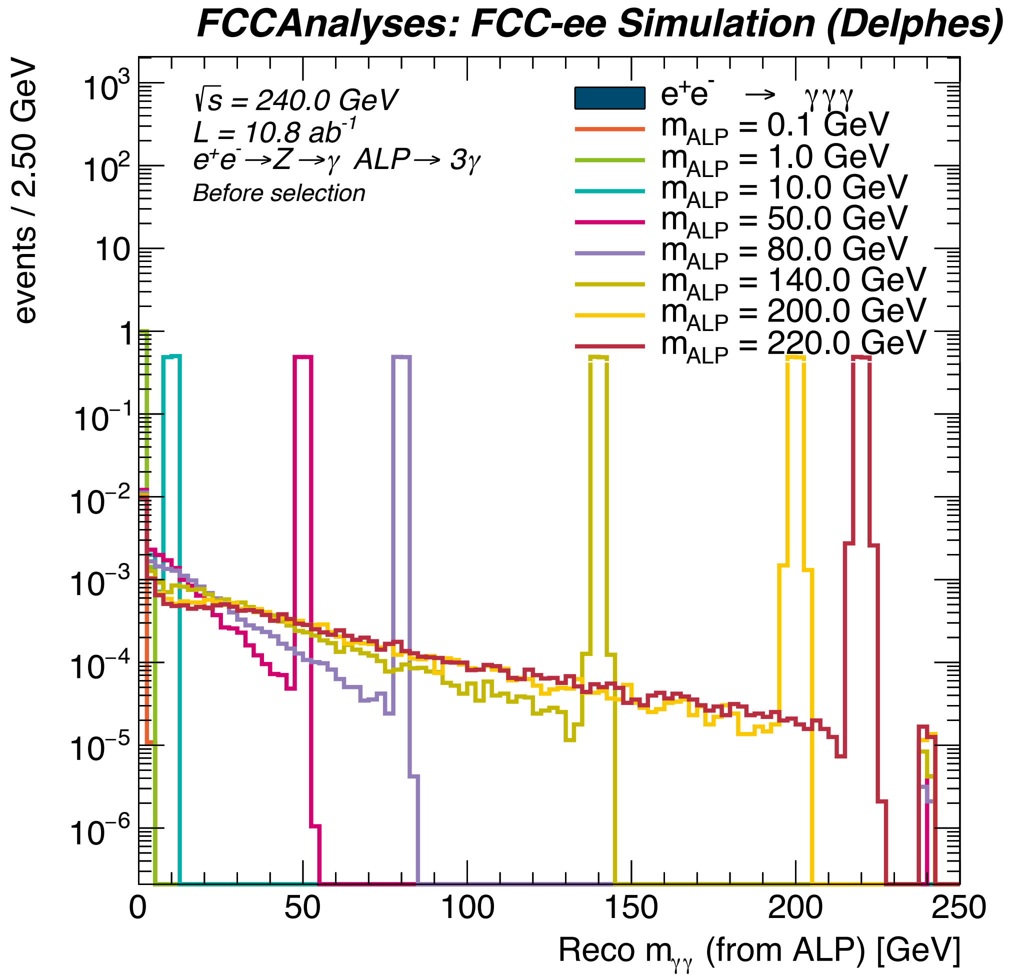
Reconstructed ALP mass — before selection

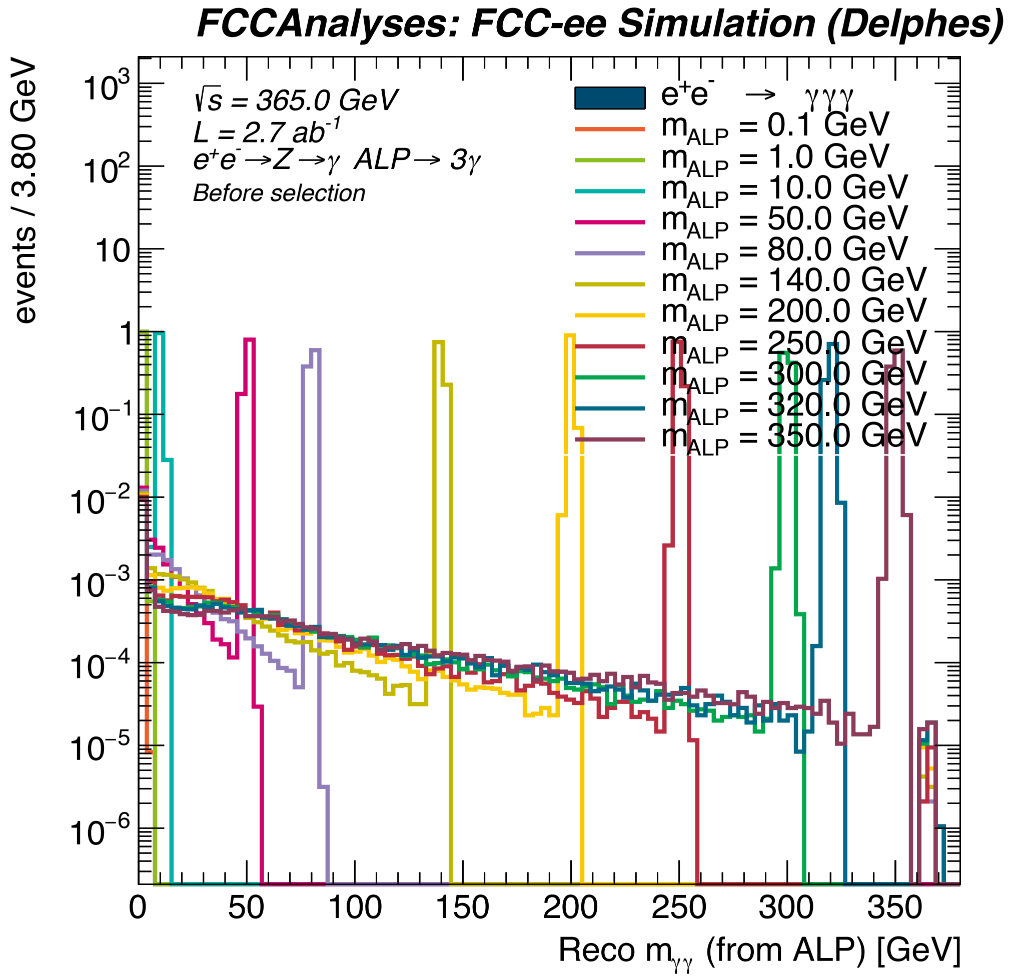
- As mALP increases, ALP less likely to be reconstructed at correct mass

Reco photons matched to Gen level information

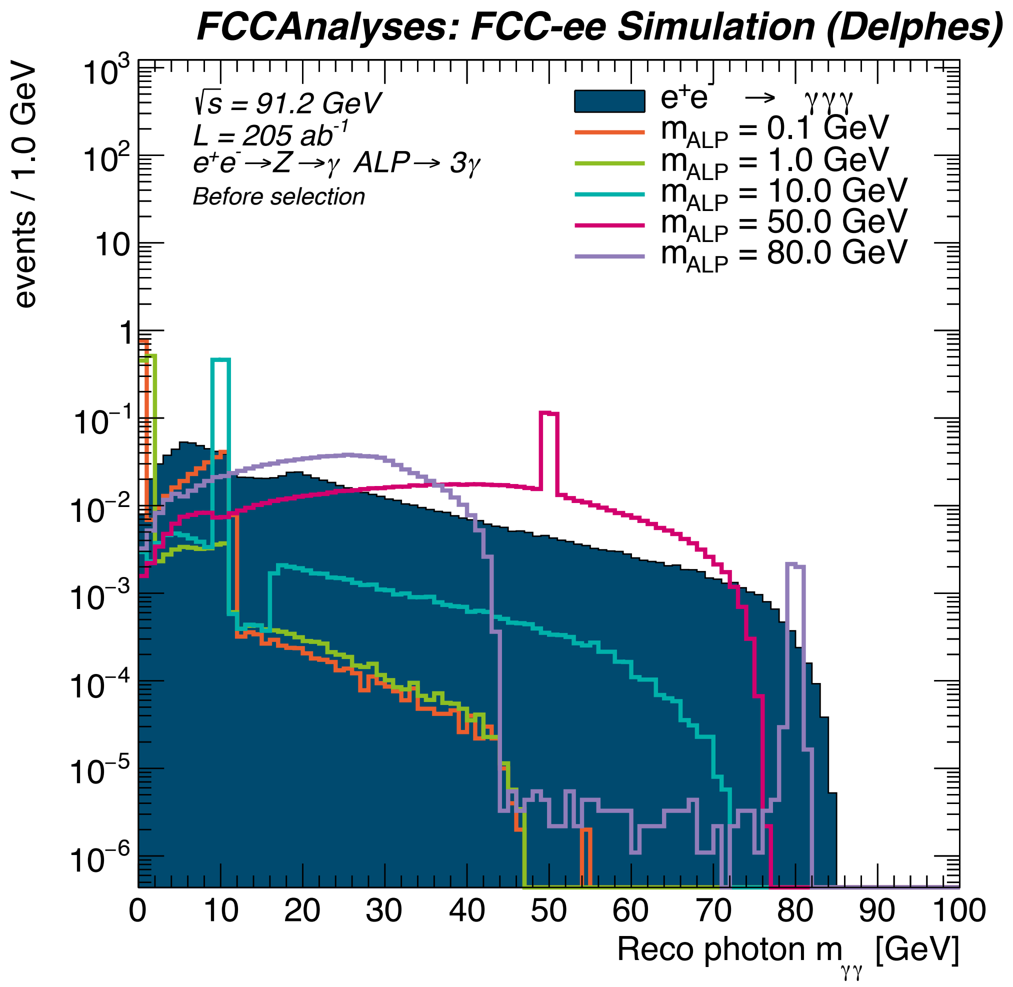


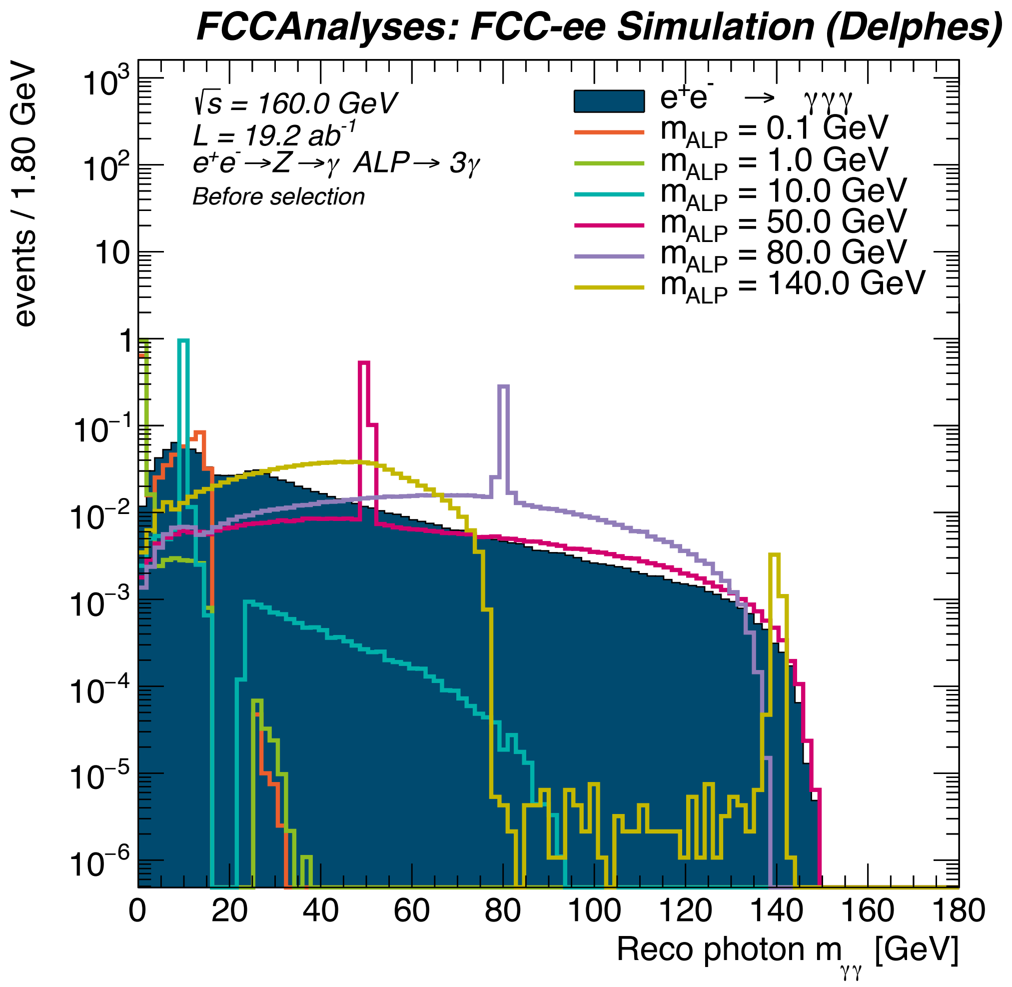


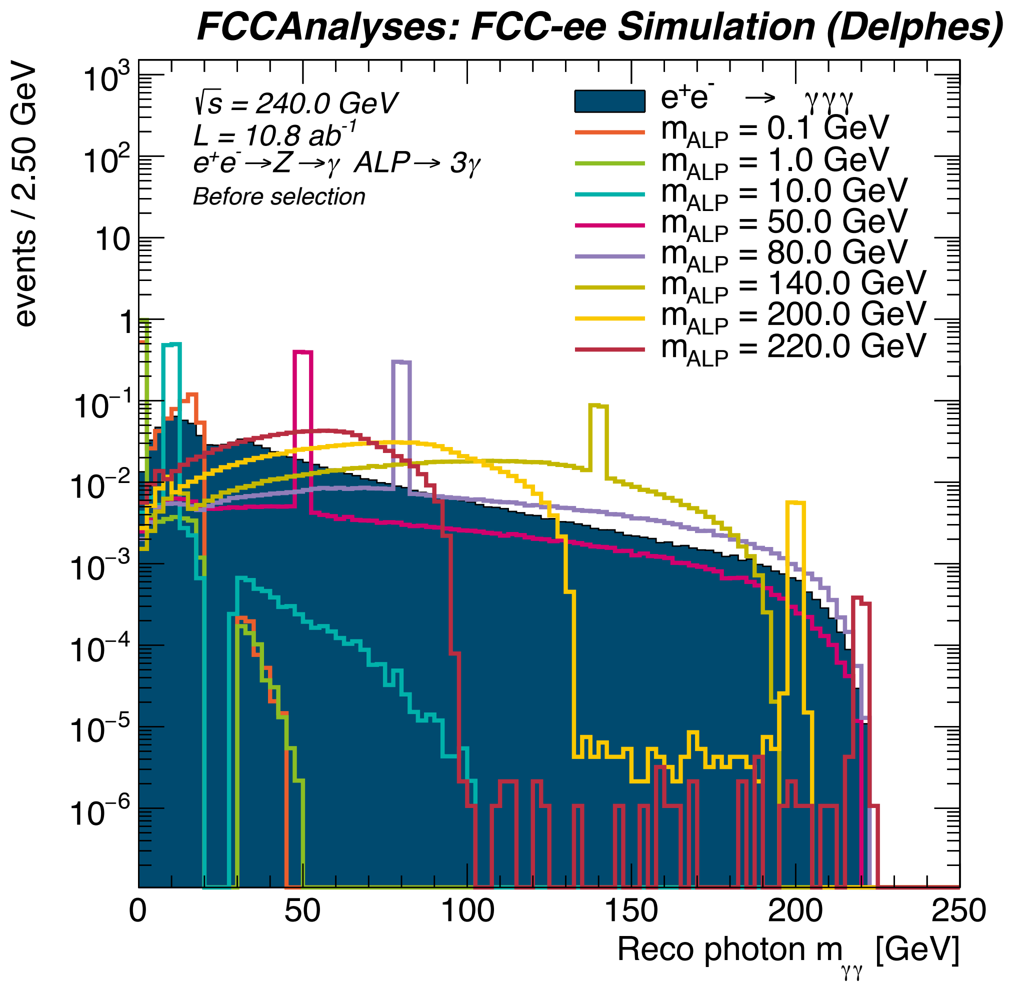


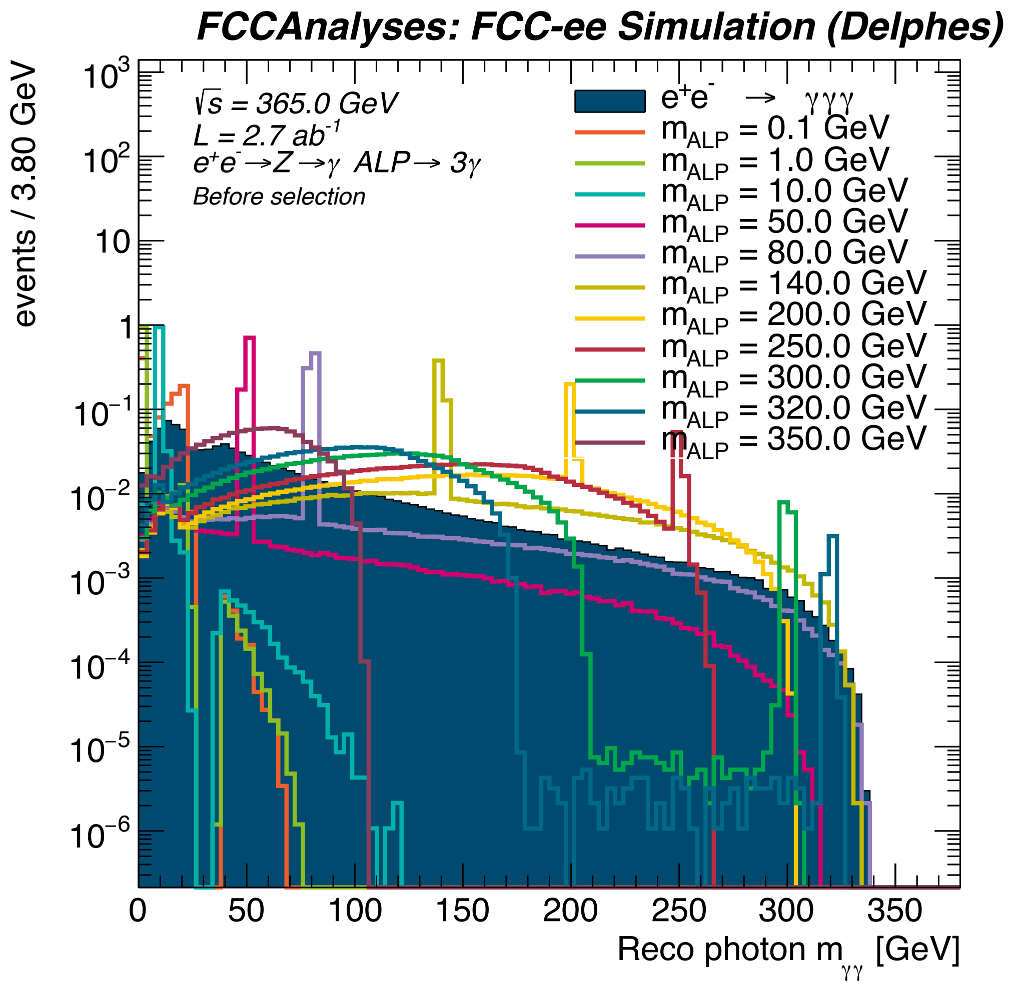


Reco photons (recoil photon defined by leading pT)









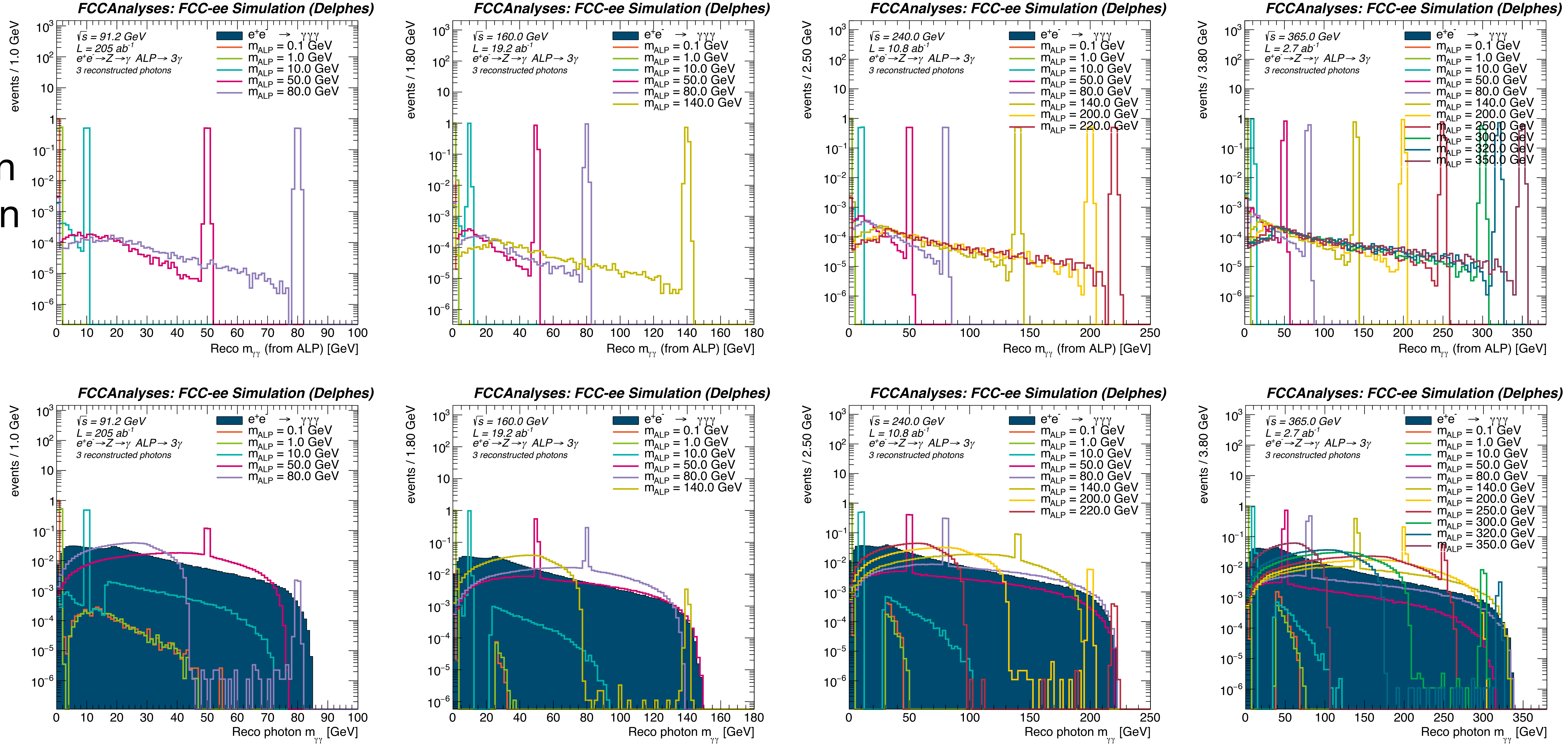
Z pole WW ZH tt

Reconstructed ALP mass — after selection

- As mALP increases, ALP still less likely to be reconstructed at correct mass

Reco photons matched to Gen level information

Reco photons (recoil photon defined by leading pT)



Z pole WW ZH tt

Mass efficiencies

$$\frac{\text{number of events in mALP reco peak}}{\text{number of events in mALP recoALP peak}}$$

zpole	m_ALP = 0.1 GeV	m_ALP = 1.0 GeV	m_ALP = 10 GeV	m_ALP = 50 GeV	m_ALP = 80 GeV
Before selection	0,504	0,862	0,856	0,278	0,004
Exactly 3 photons	0,998	0,997	0,961	0,295	0,004

Recoil photon: leading pT photon

Selection: exactly 3 photons

ww	m_ALP = 0.1 GeV	m_ALP = 1.0 GeV	m_ALP = 10 GeV	m_ALP = 50 GeV	m_ALP = 80 GeV	m_ALP = 140 GeV
Before selection	0,372	0,924	0,929	0,648	0,354	0,004
Exactly 3 photons	0,999	0,999	0,989	0,677	0,364	0,005

zh	m_ALP = 0.1 GeV	m_ALP = 1.0 GeV	m_ALP = 10 GeV	m_ALP = 50 GeV	m_ALP = 80 GeV	m_ALP = 140 GeV	m_ALP = 200 GeV	m_ALP = 220 GeV
Before selection	0,275	0,924	0,944	0,8	0,613	0,199	0,011	0,0007
Exactly 3 photons	0,999	0,999	0,995	0,825	0,631	0,205	0,012	0,0007

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Before selection	0,195	0,869	0,955	0,884	0,776	0,53	0,267	0,058
Exactly 3 photons	0,997	0,999	0,997	0,911	0,799	0,546	0,275	0,013

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Conclusion: this definition/selection does well for lower ALP masses (only after selection for 0.1 GeV), but begins deteriorating relatively quickly…

Next steps?

- We could come up with additional cuts for the current analysis

- Another option is to redefine the recoil photon, I would like to introduce:

delta_e $= \dfrac{E_{CM}^2 - m_a^2}{2E_{CM}} - E_r = \dfrac{E_{CM}^2 - m_{\gamma_1\gamma_2}^2}{2E_{CM}} - E_{\gamma_3}$

  - Iterate over all γ combinations and define the recoil photon as the configuration with minimum delta_e (work in progress)

- Introduce categories (for example, include a 2 photon final state — this would require generating background but should be relatively easy overall)

Backup — Introduction

Leading interactions of ALP to SM particles are described by:

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

ALP coupling to photon and Z is described by:

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

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

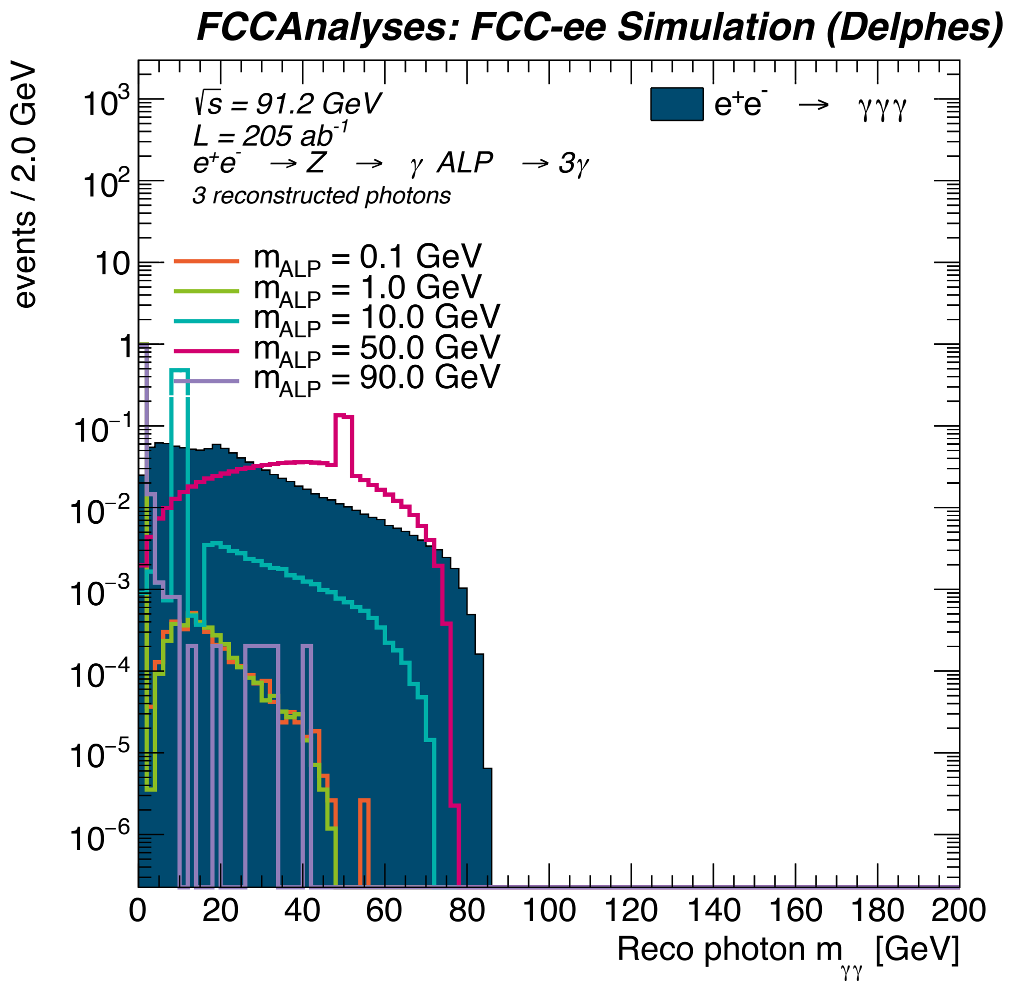
$$C_{\gamma Z} = c_w^2 C_{WW} - s_w^2 C_{BB} \xrightarrow{C_{WW} = 0} C_{\gamma Z} = -s_w^2 C_{\gamma\gamma}$$

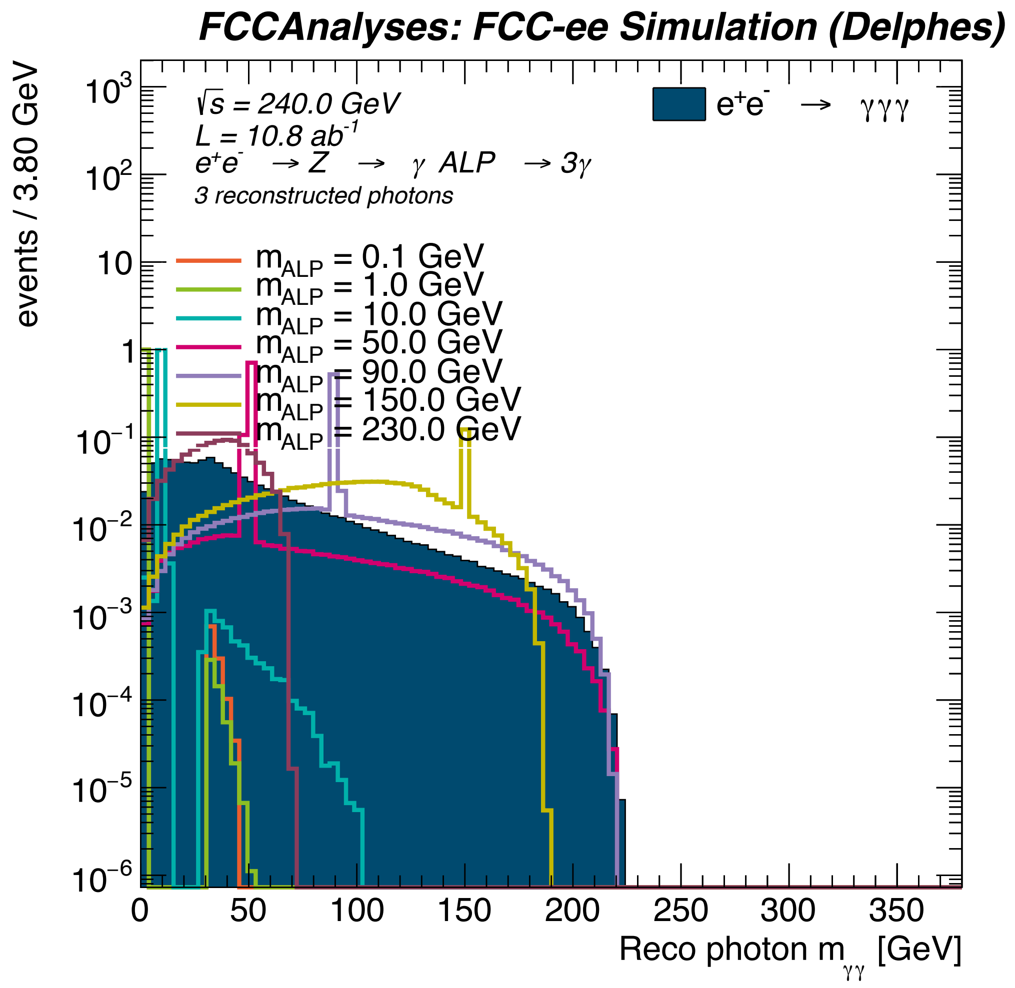
$$C_{ZZ} = c_w^4 C_{WW} + s_w^4 C_{BB}$$

Backup — Reproduced results

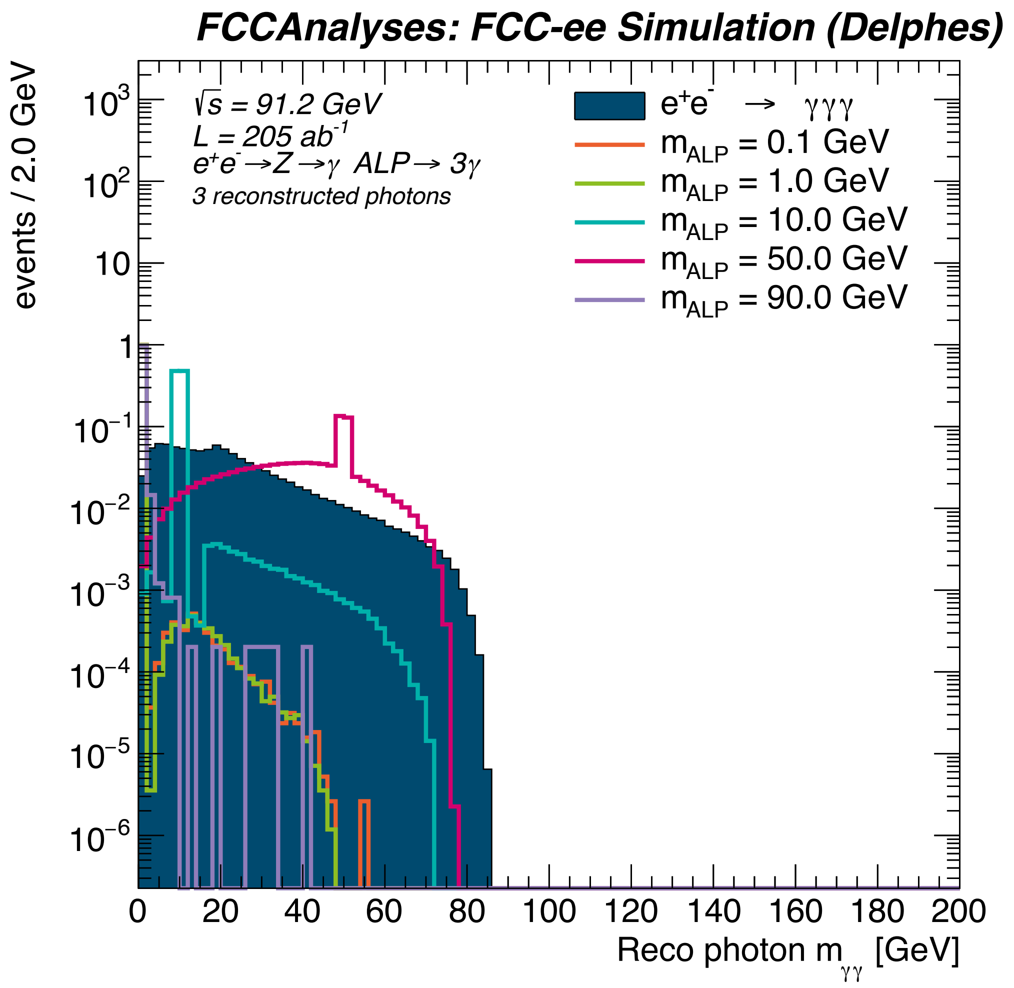
- Everything matches!

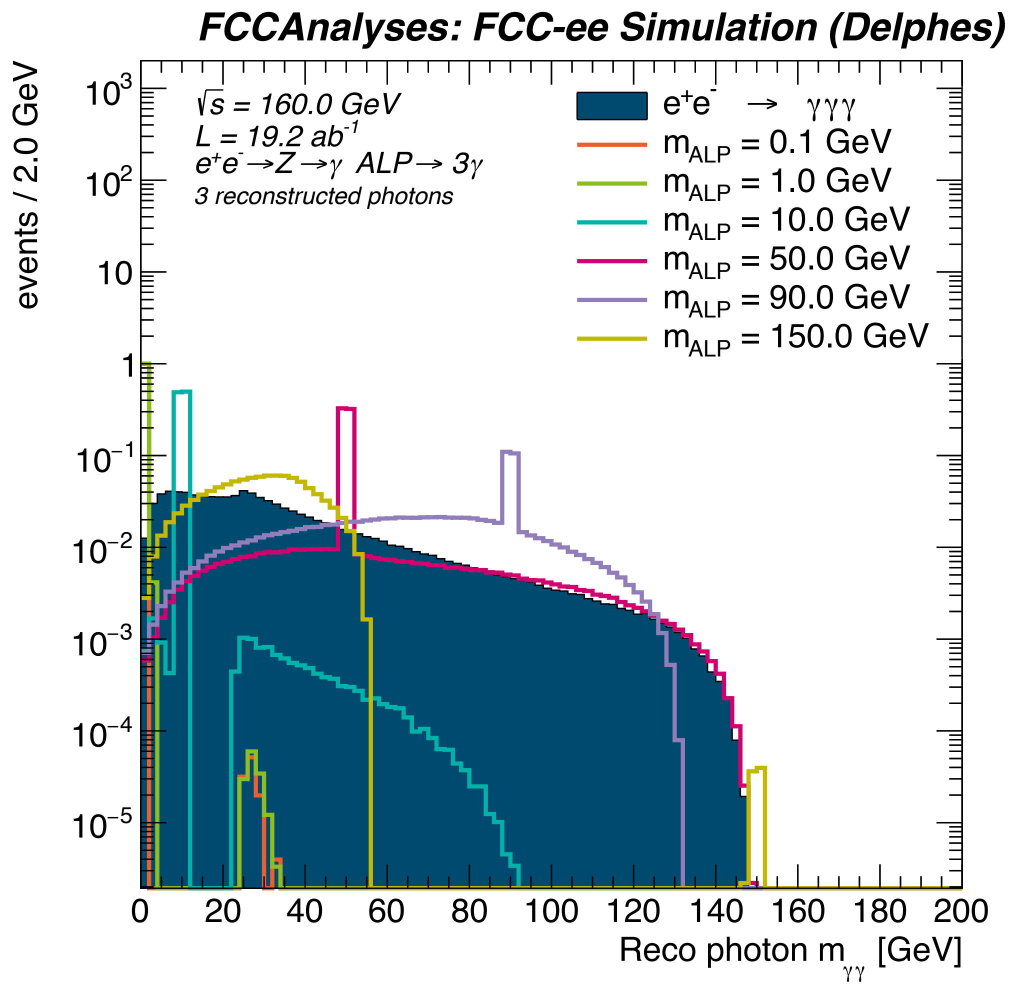
Christina's results

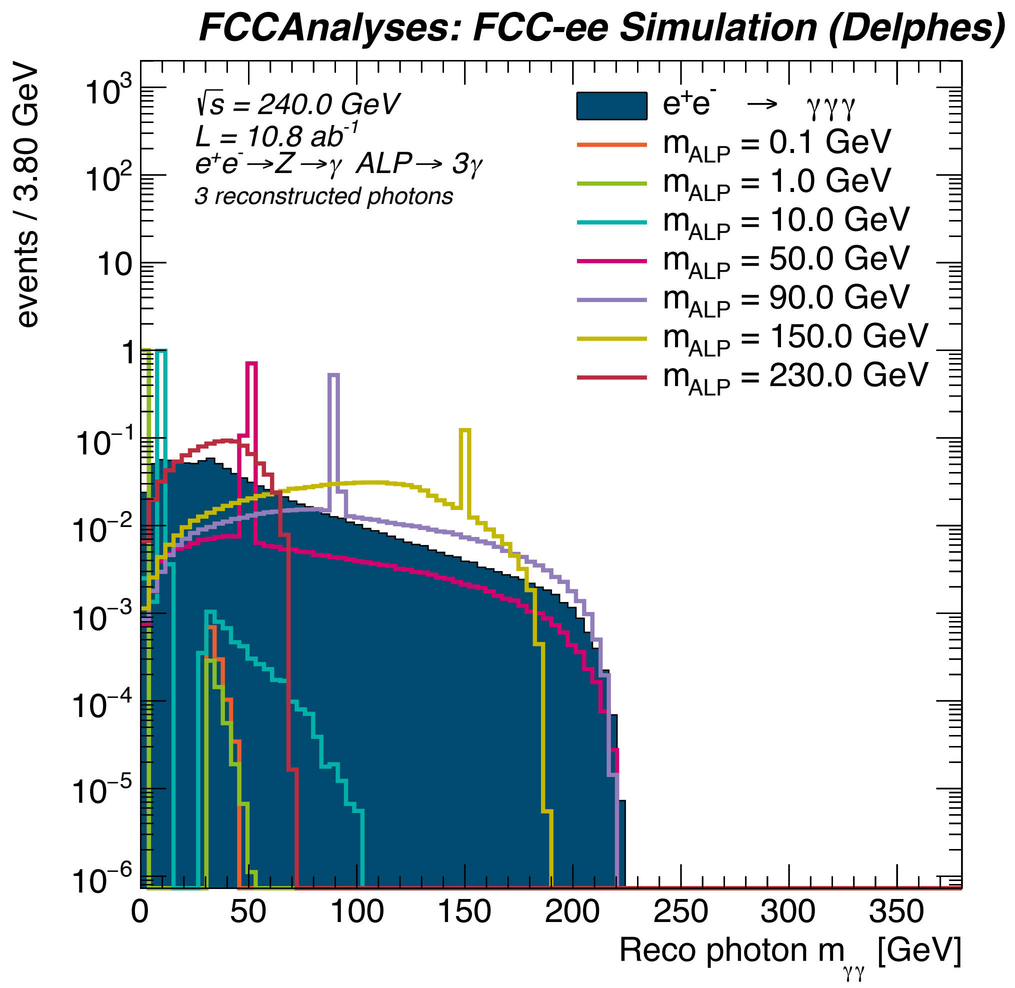


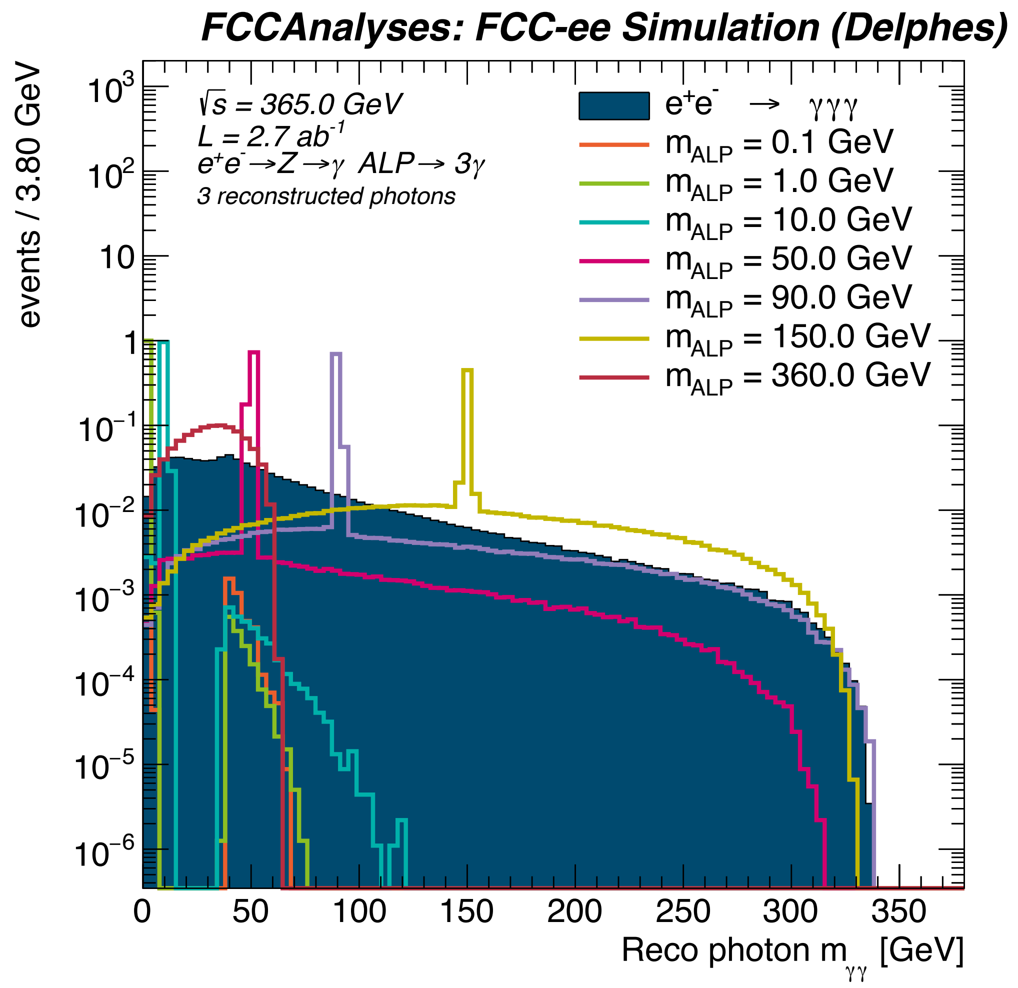


My results





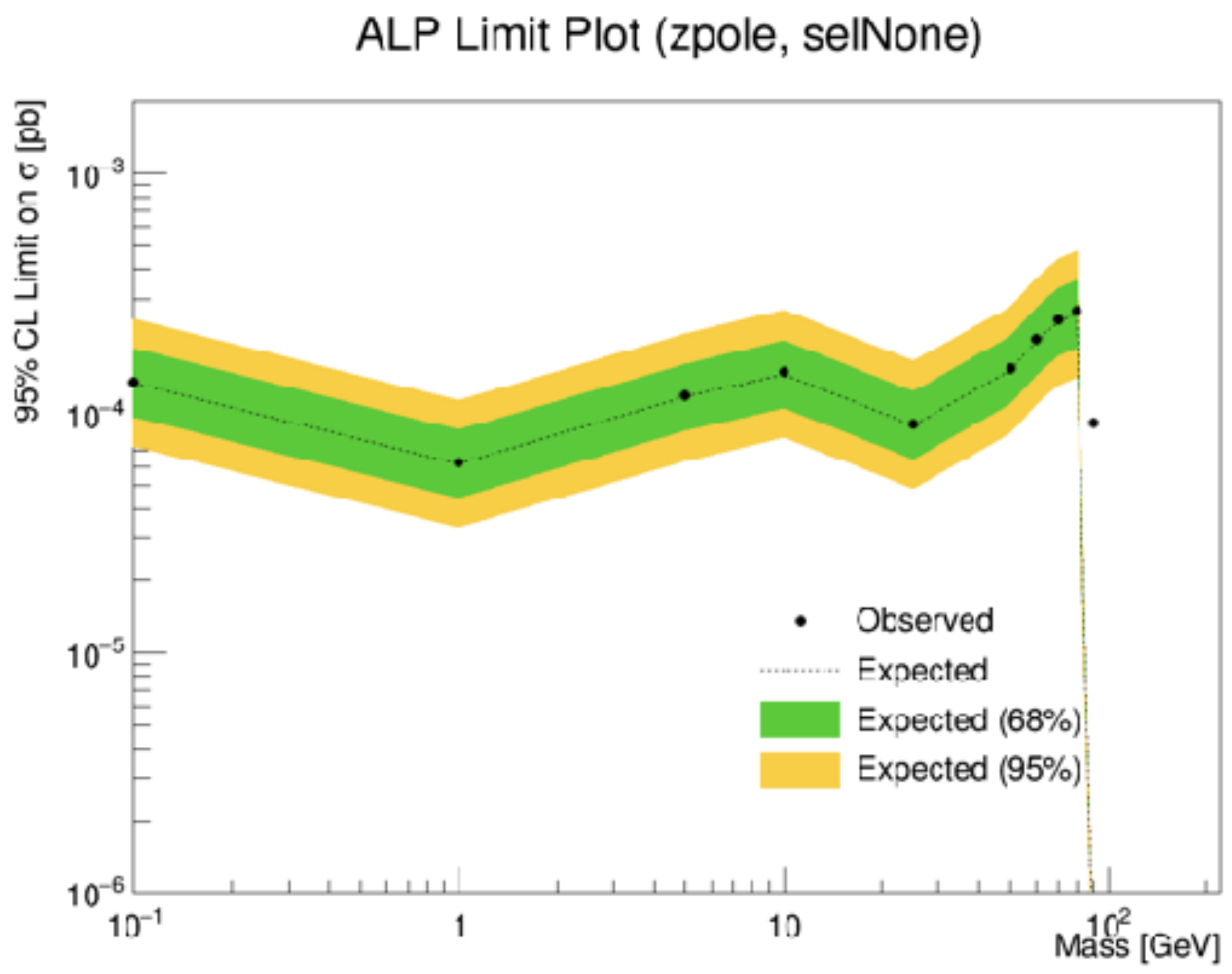




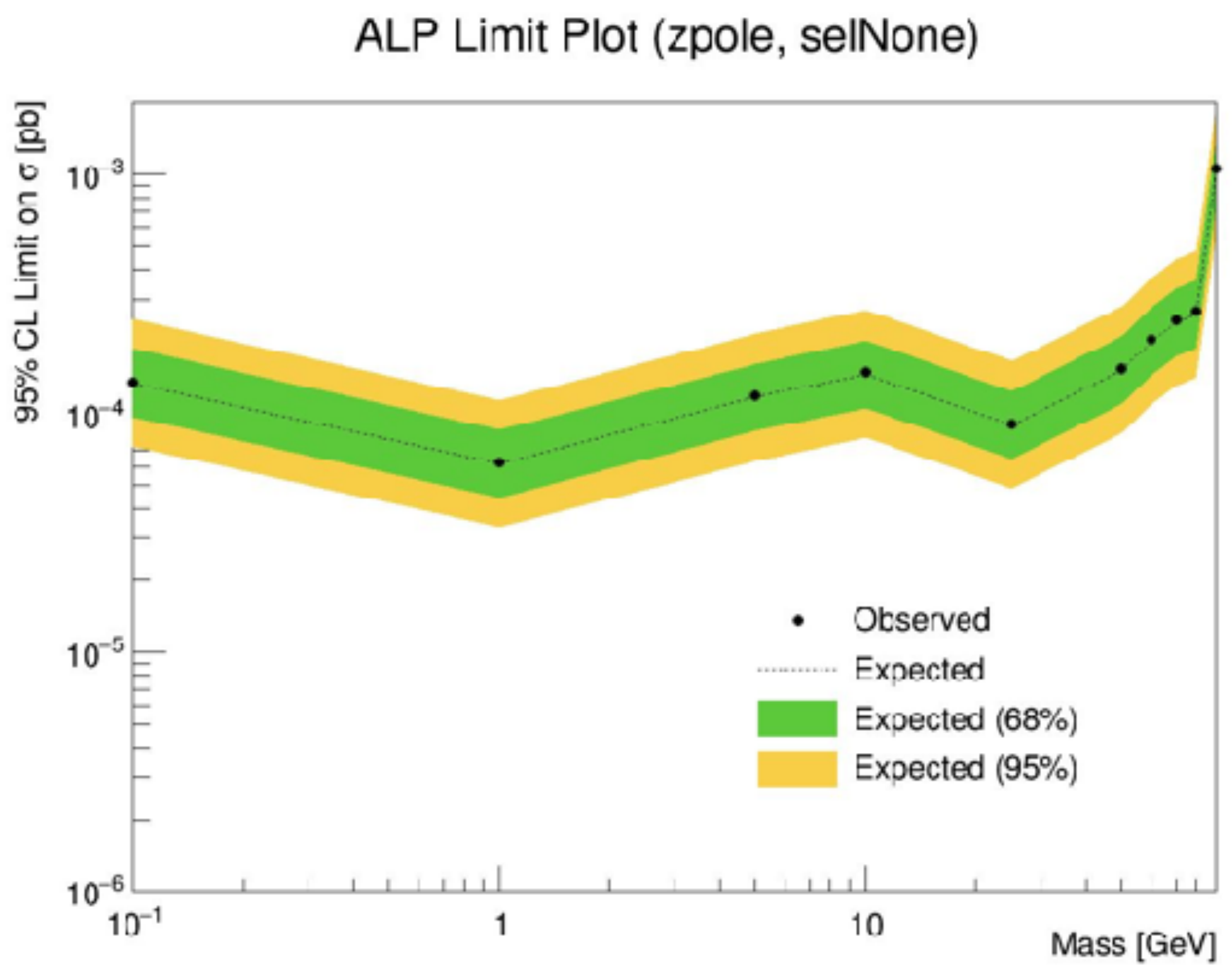
Z pole WW ZH tt

Backup — Reproduced results (cont.)

Christina's results



My results



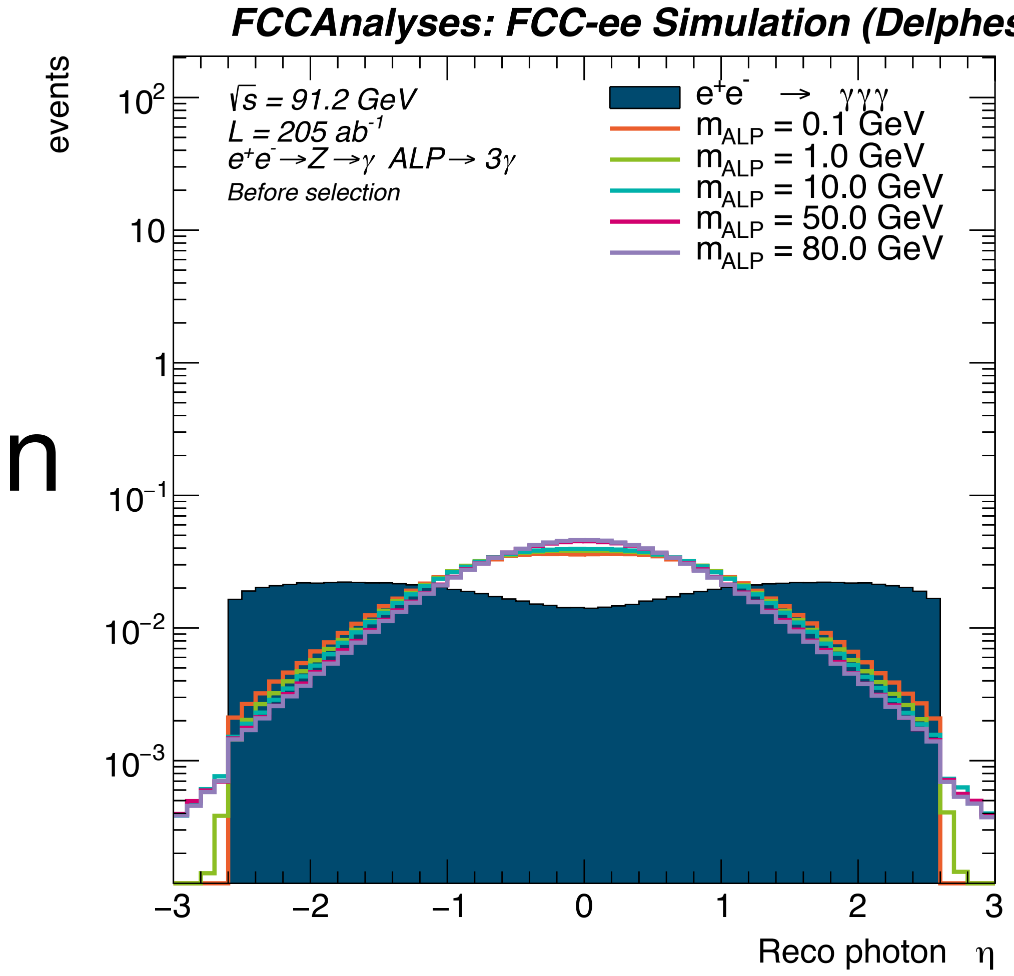
Z pole

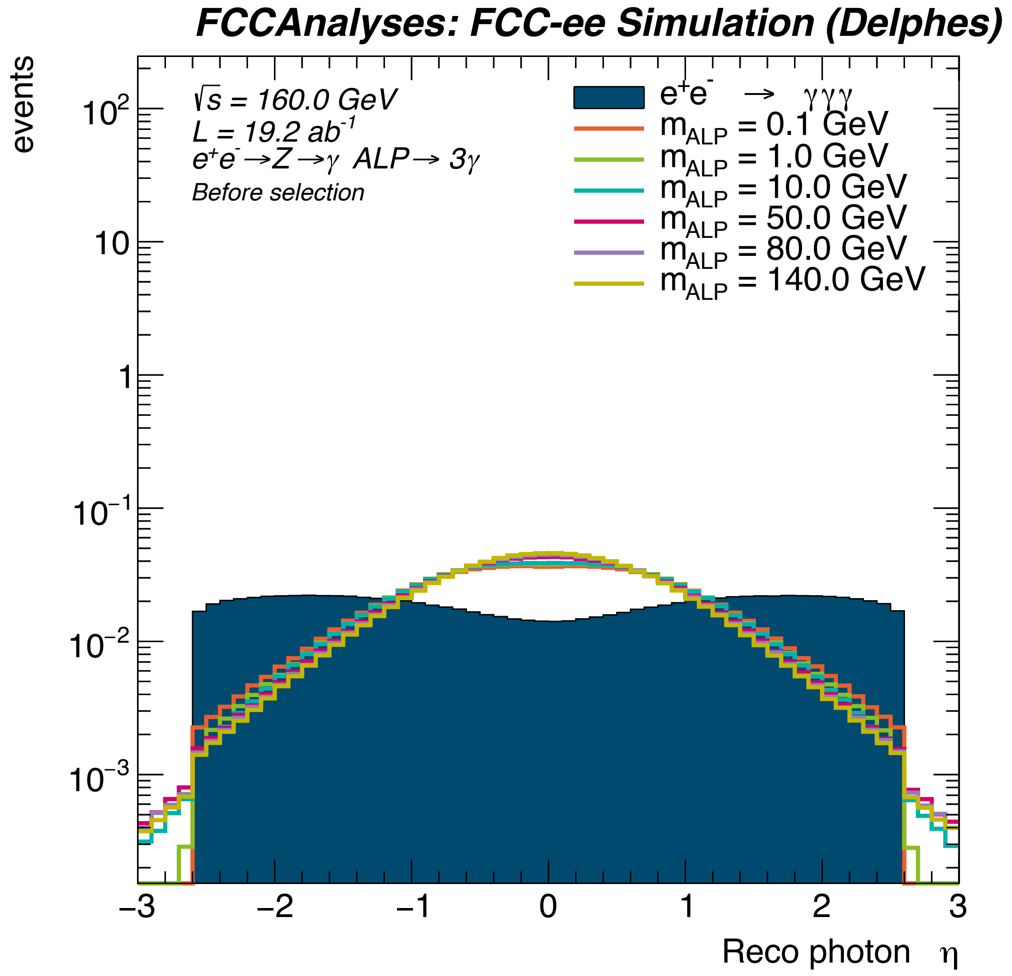
- Limit results are (essentially) the same!
- Combine runs into numerical errors at ALP masses near center-of-mass energy, this is fixed in current script

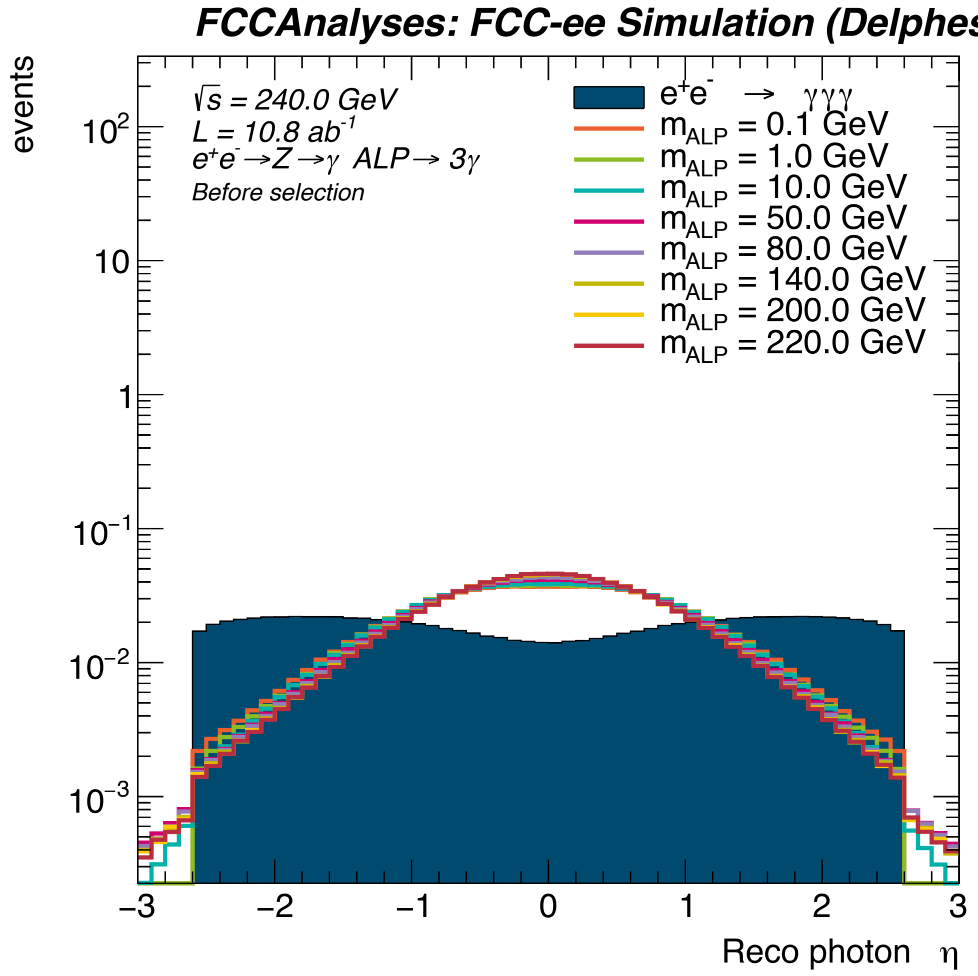
Backup — Recoil photon η

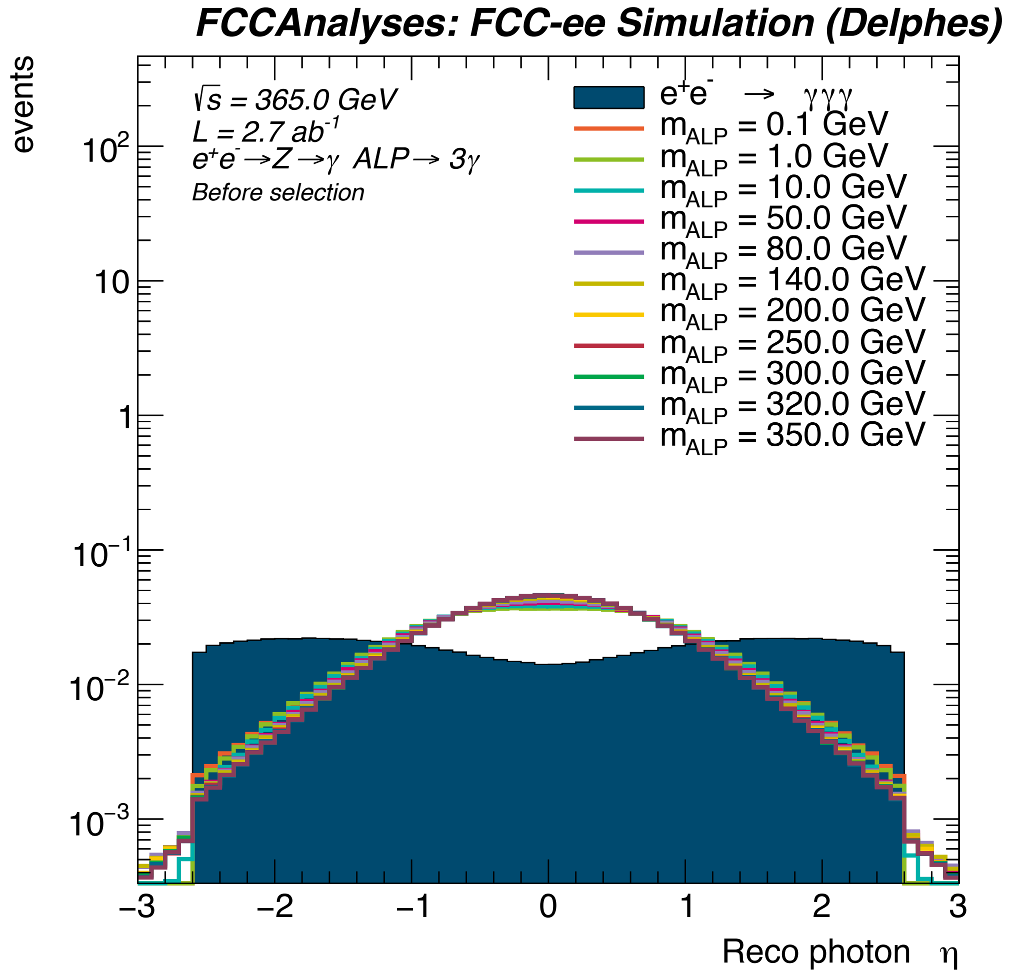
- In principle we could cut here, but it probably wouldn't be super helpful

Before selection

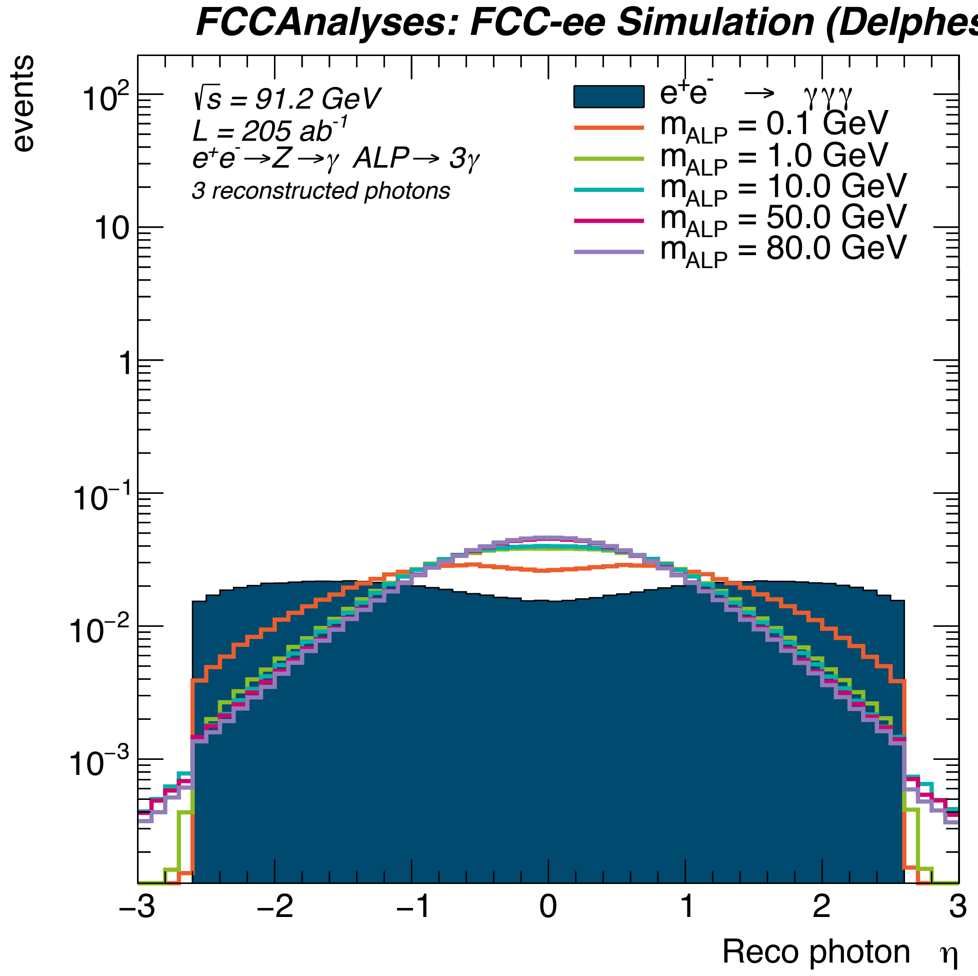


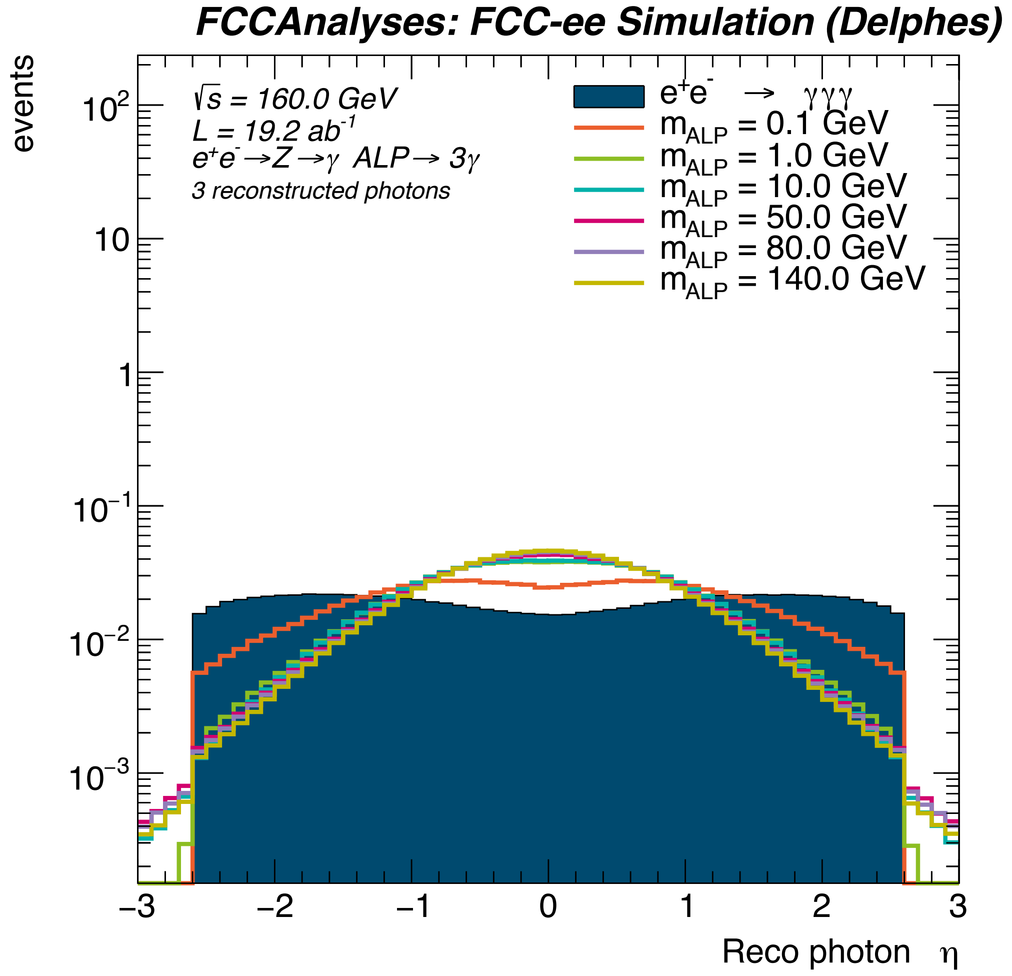


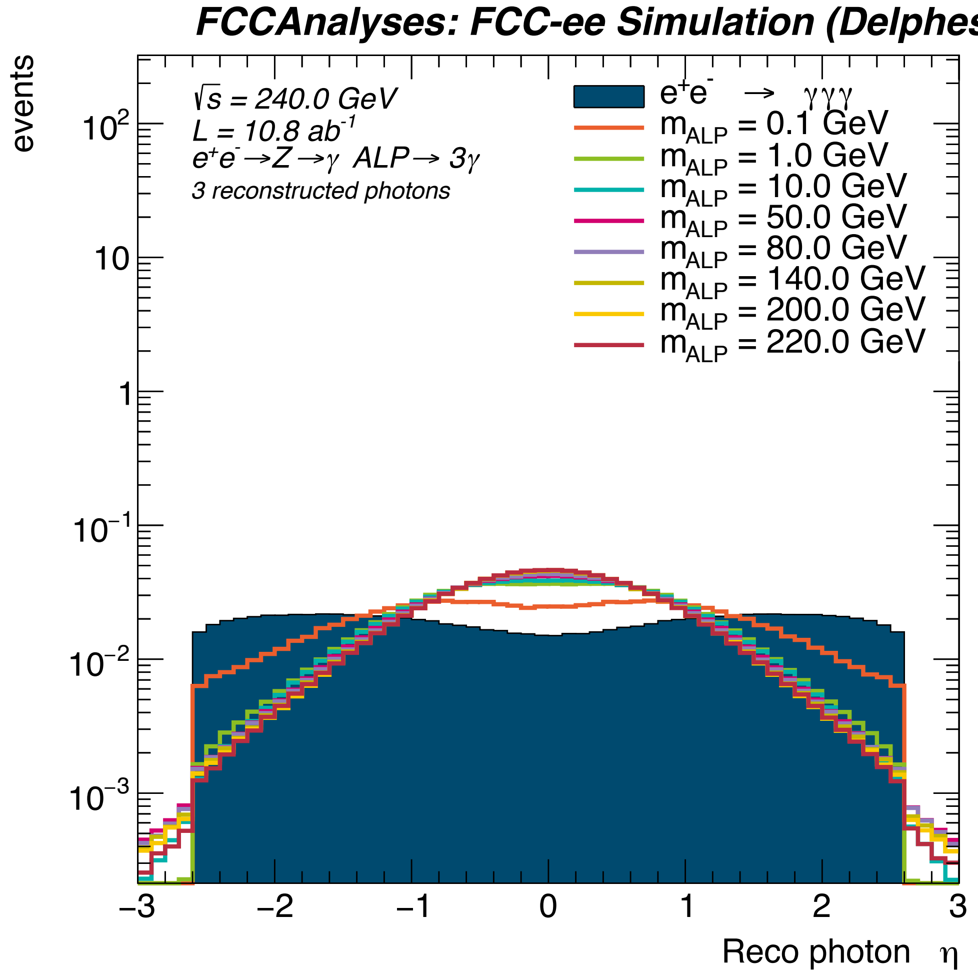


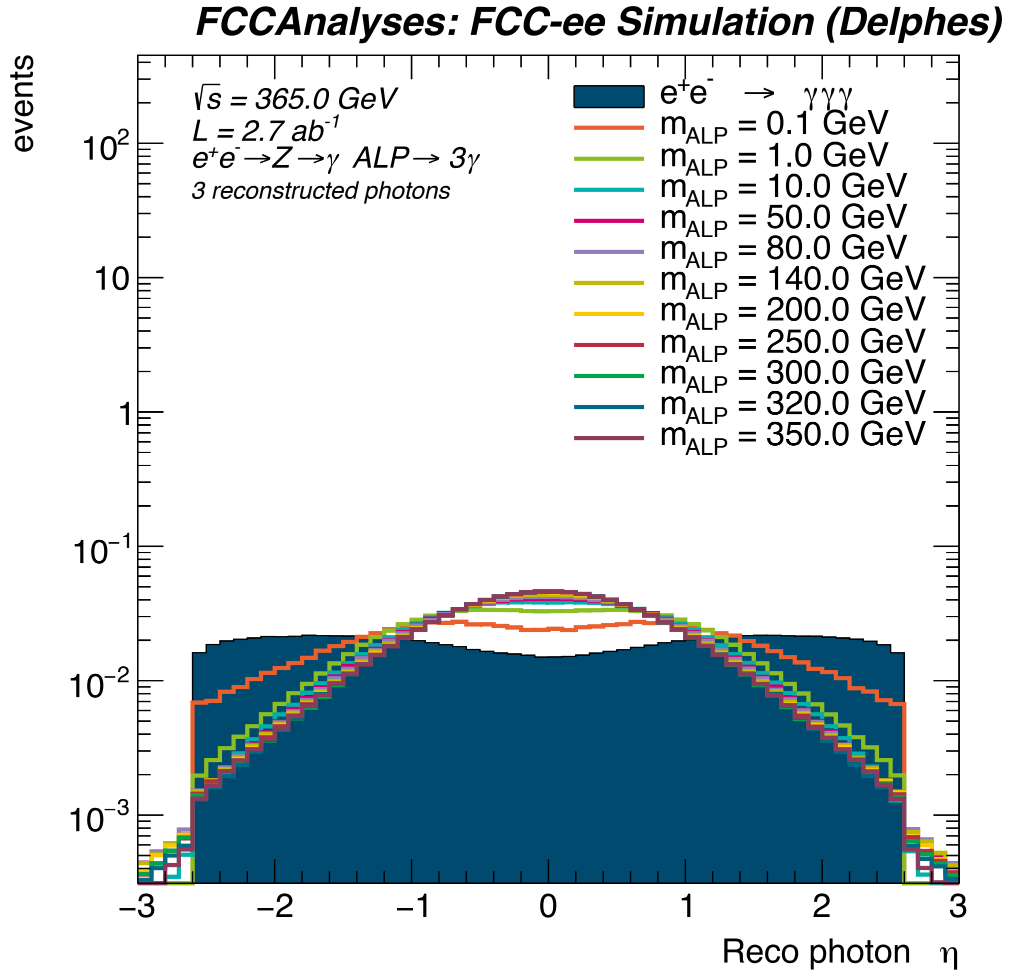


After selection









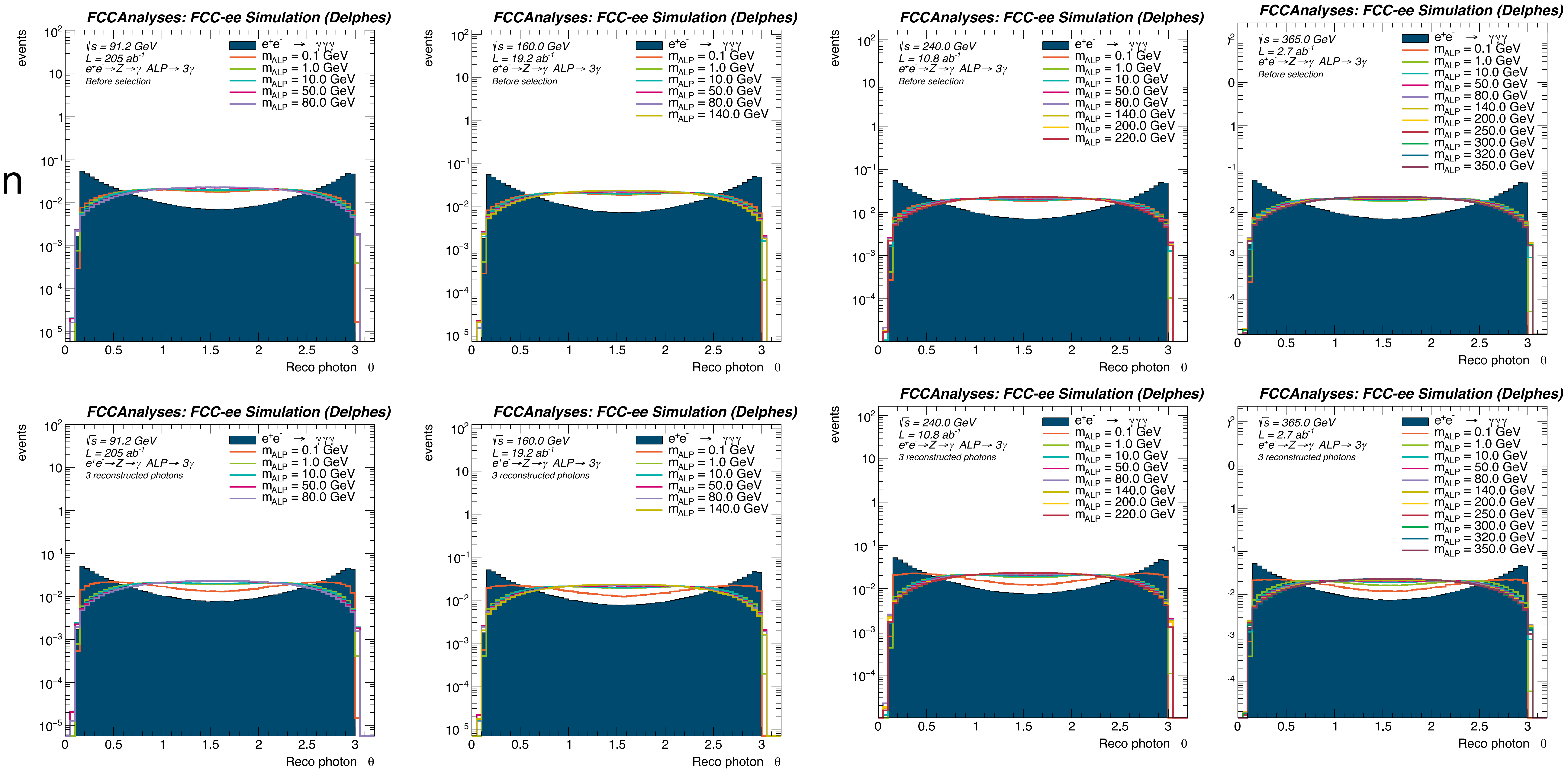
Z pole WW ZH tt

Backup – Recoil photon θ

- In principle we could cut here, but it probably wouldn't be super helpful

Before selection

After selection



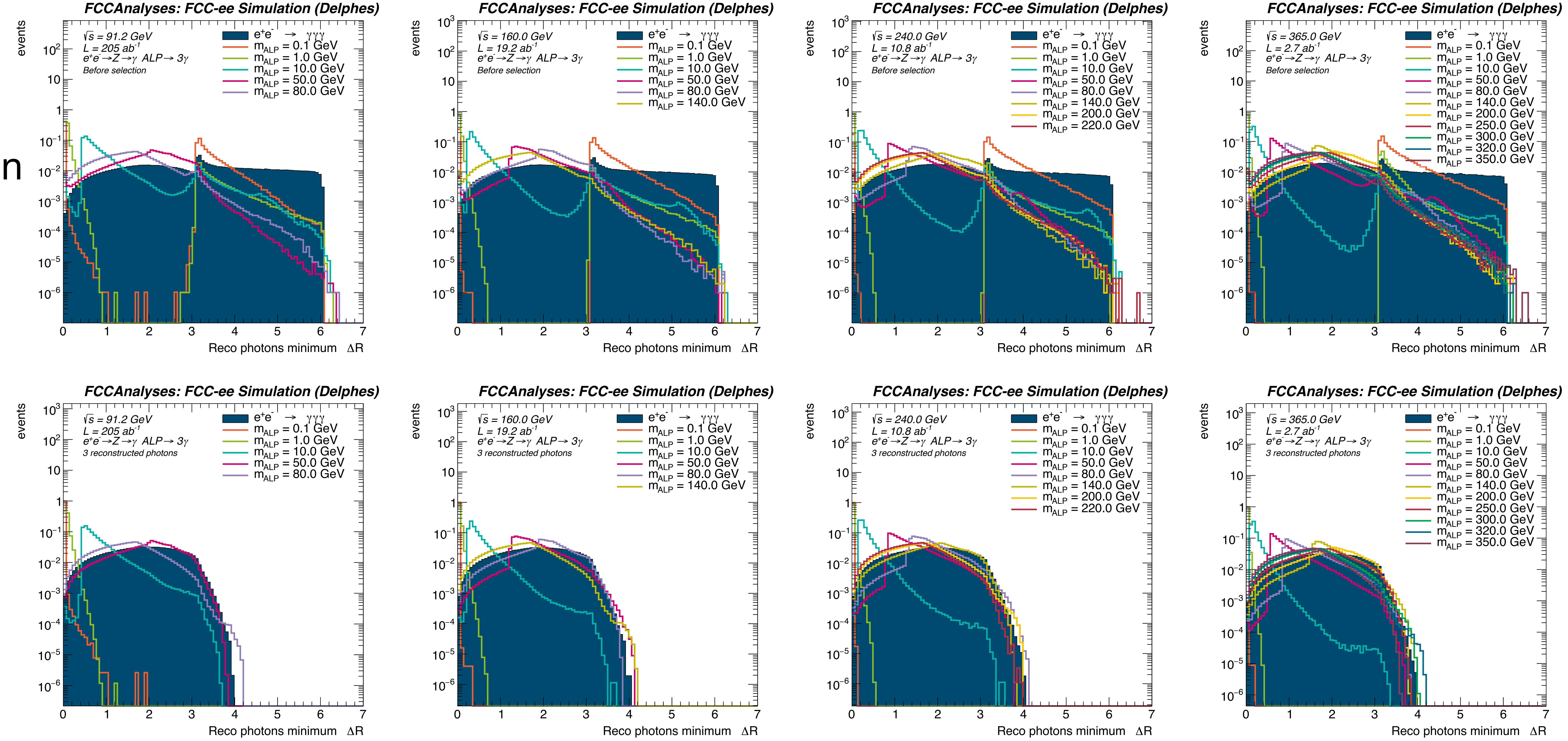
Z pole WW ZH tt

Backup – Minimum ΔR

Iterates over all photon combinations and finds the minimum ΔR, originally there was an idea to define the ALP photons from this but it did not work

Before selection

After selection



Z pole WW ZH tt