Updating cuts for the FCC-ee Higgs CP Study

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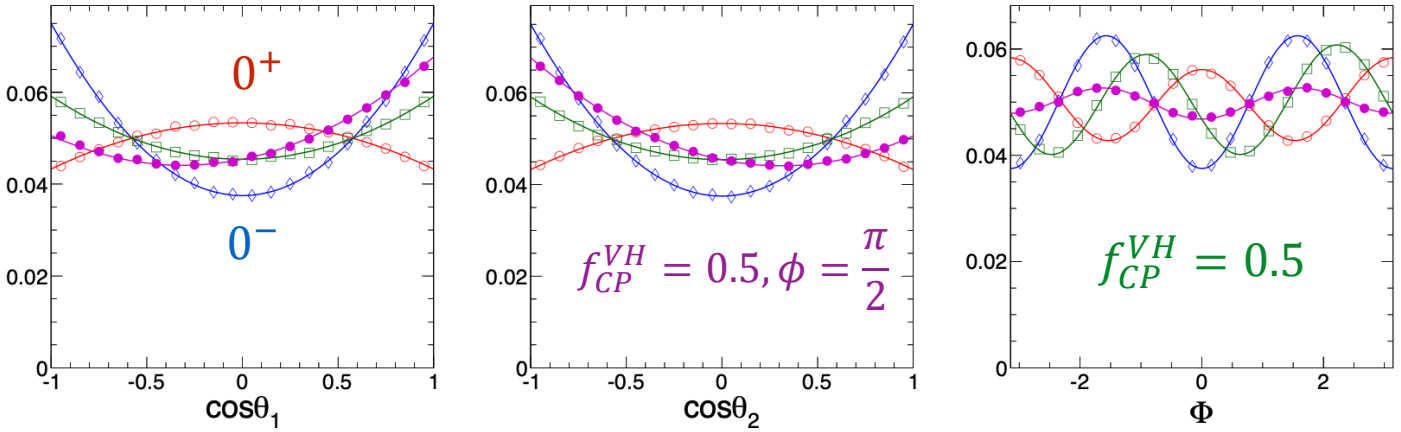
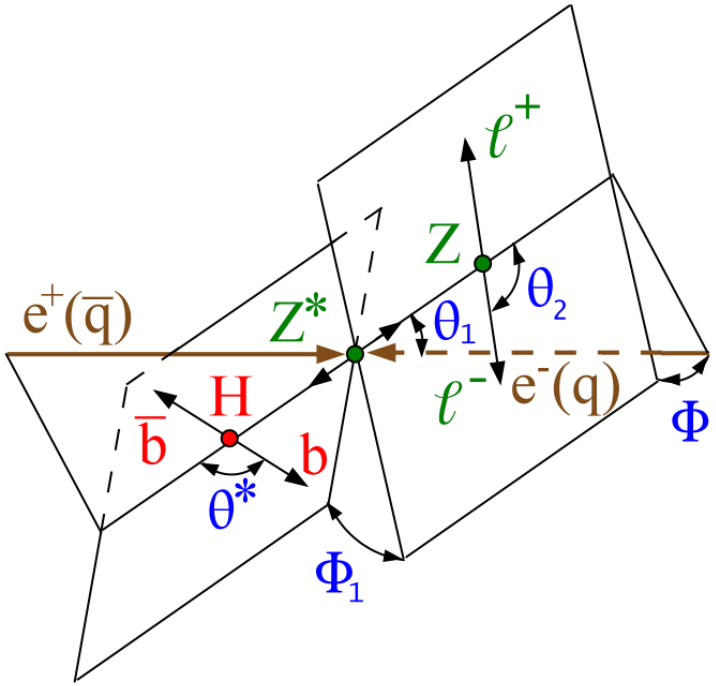
ECFA meeting on e+e- → ZH angular measurements

18 March 2024

Past Studies: Snowmass 2013

arXiv:1309.4819

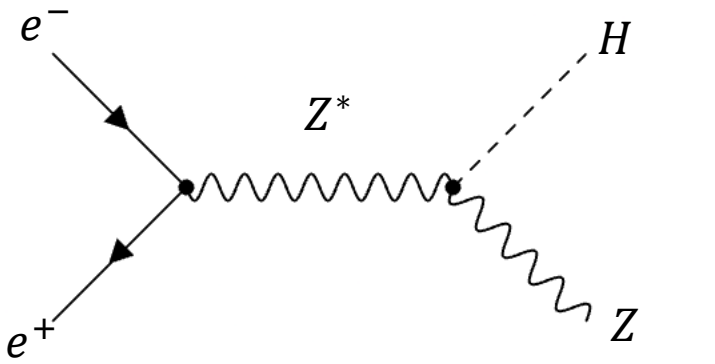




$$A(H \to V_1 V_2) = v^{-1}\left(a_1^{HVV} m_V^2 \epsilon_1^* \epsilon_2^* + a_2^{HVV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{HVV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

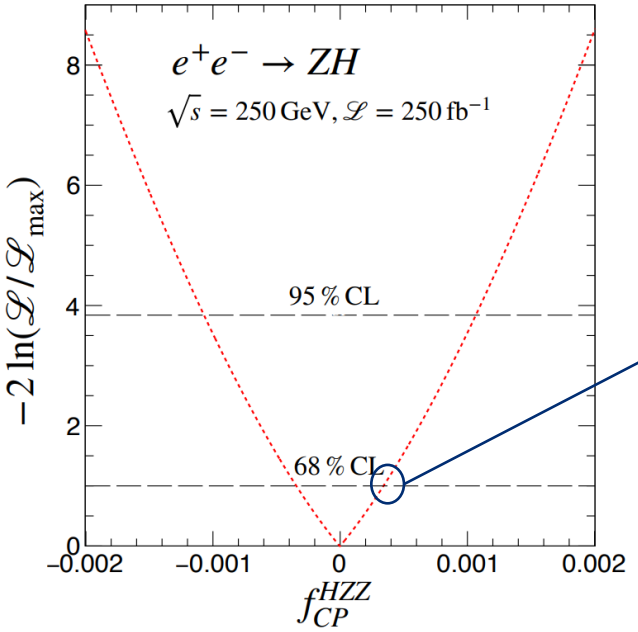
$$f_{\rm CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{\rm CP\ odd}}{\Gamma_{H\to X}^{\rm CP\ odd} + \Gamma_{H\to X}^{\rm CP\ even}}$$

$$f_{CP}^{HVV} = \frac{|a_3^{HVV}|^2}{\sum |a_i^{HVV}|^2 (\sigma_i^{HVV}/\sigma_3^{HVV})},$$



Past Studies: Snowmass 2022

arXiv:2205.07715



E (GeV)	$\mathcal{L}$ (fb^{-1})	f_{CP}^{HVV}
250	250	$\pm 3.4 \cdot 10^{-4}$
250	2,500	$\pm 3.9 \cdot 10^{-5}$
350	350	$\pm 1.2 \cdot 10^{-4}$
350	3,500	$\pm 2.9 \cdot 10^{-5}$
500	500	$\pm 4.3 \cdot 10^{-5}$
500	5,000	$\pm 1.3 \cdot 10^{-5}$
1,000	1,000	$\pm 1.0 \cdot 10^{-5}$
1,000	10,000	$\pm 3.0 \cdot 10^{-6}$

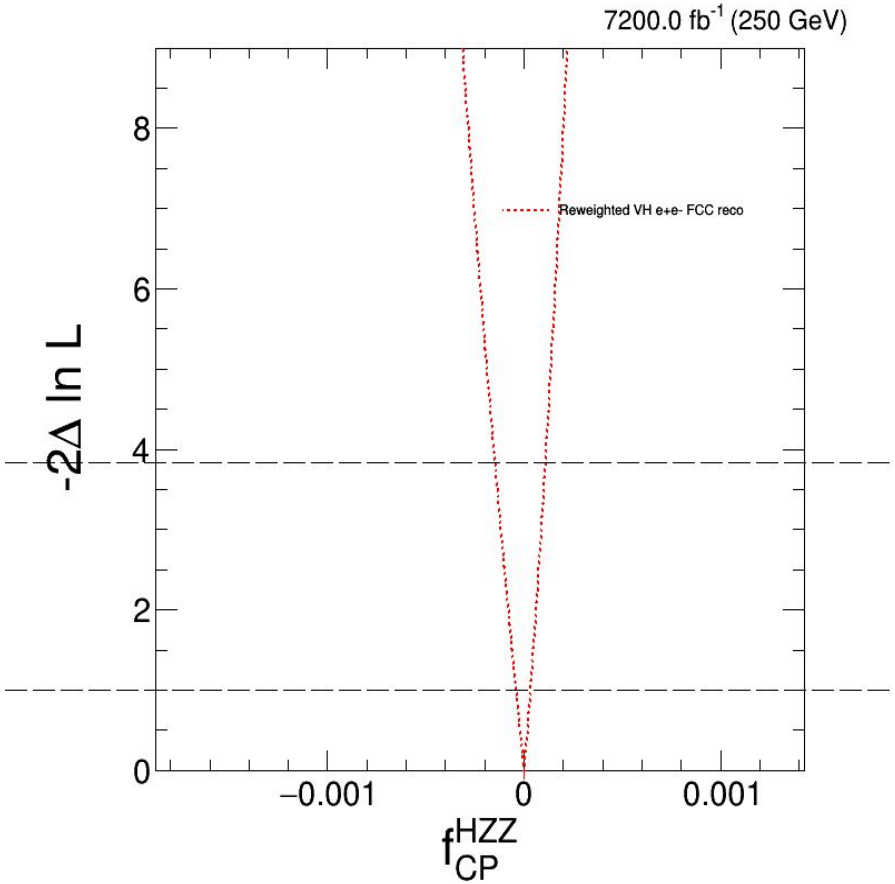
collider	energy	$\int \mathcal{L}dt$ (fb^{-1})	production	σ (fb)	decay	$\sigma \times \mathcal{B}$ (fb)	N_{prod}	N_{reco}	f_{jet}
pp	14 TeV	3000	$gg \to H$	49850	$H \to ZZ^* \to 4\ell$	6.23	18694	5608	0.1
pp	14 TeV	3000	$V^*V^* \to H$	4180	$H \to ZZ^* \to 4\ell$	0.52	1568	470	0.6
pp	14 TeV	3000	$W^* \to WH$	1504	$H \to ZZ^* \to 4\ell$	0.19	564	169	0.5
pp	14 TeV	3000	$Z^* \to ZH$	883	$H \to ZZ^* \to 4\ell$	0.11	331	99	0.5
pp	14 TeV	3000	$t\bar{t} \to t\bar{t}H$	611	$H \to ZZ^* \to 4\ell$	0.08	229	69	1.0
pp	14 TeV	3000	$V^*V^* \to H$	4180	$H \to \gamma\gamma$	9.53	28591	8577	0.6
pp	14 TeV	3000	$Z^* \to ZH$	883	$H \to b\bar{b}$, $Z \to \ell\ell$	34.3	102891	690	–
e^+e^-	250 GeV	250	$Z^* \to ZH$	240	$H \to b\bar{b}$, $Z \to \ell\ell$	9.35	2337	1870	–
e^+e^-	350 GeV	350	$Z^* \to ZH$	129	$H \to b\bar{b}$, $Z \to \ell\ell$	5.03	1760	1408	–
e^+e^-	500 GeV	500	$Z^* \to ZH$	57	$H \to b\bar{b}$, $Z \to \ell\ell$	2.22	1110	888	–
e^+e^-	1 TeV	1000	$Z^* \to ZH$	13	$H \to b\bar{b}$, $Z \to \ell\ell$	0.51	505	404	–
e^+e^-	250 GeV	250	$Z^*Z^* \to H$	0.7	$H \to b\bar{b}$	0.4	108	86	–
e^+e^-	350 GeV	350	$Z^*Z^* \to H$	3	$H \to b\bar{b}$	1.7	587	470	–
e^+e^-	500 GeV	500	$Z^*Z^* \to H$	7	$H \to b\bar{b}$	4.1	2059	1647	–
e^+e^-	1 TeV	1000	$Z^*Z^* \to H$	21	$H \to b\bar{b}$	12.2	12244	9795	–

Signal: $e^+e^- \to ZH, Z \to ll$ (7.7%), $H \to b\bar{b}$ (58%). Background: $e^+e^- \to ZZ \to ll\, b\bar{b}$, $N_{reco,Background}$ ~ 1/10$^{\text{th}}$ of signal, Z mass, angles input to combine (template fit), f_{CP}^{HVV} returned at 68% CL.

4+ different samples (SM Signal, BSM Signal, Background, SM/BSM Interference) used to produce fits.

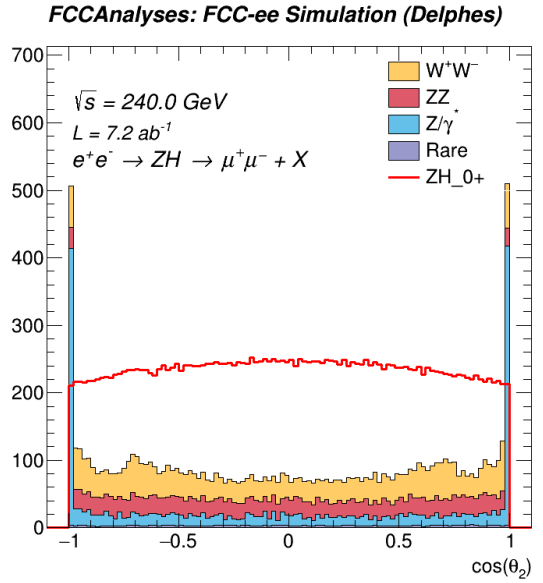
Previous Results:

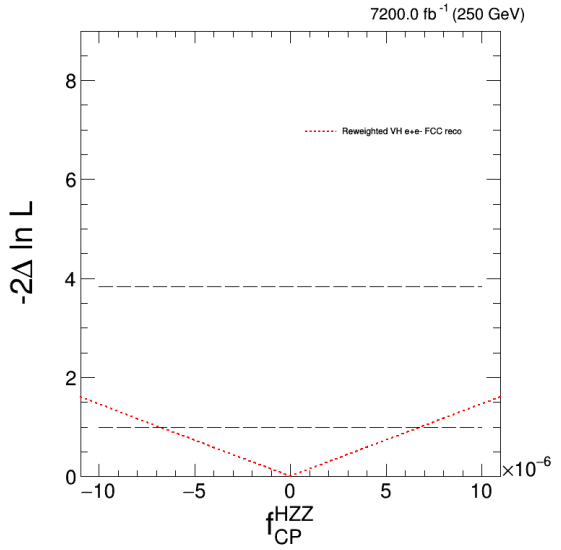
- Target: ee ⟶ ZH, H ⟶ X (recoil), Z ⟶ $\mu\mu$ (3.4%):
- Selection and samples from a Higgs recoil analysis.
- Detector simulation uses DELPHES fast sim.
- Template fit made from angular distributions.
- Uses Reco data, FCC signal yield and luminosity.
- Considers Snowmass background
  - ZZ background ~10% of signal
- 68% CL $f_{CP}^{HZZ} \approx \pm 3.7 * 10^{-5}$
- ECFA Report 12 December 2023



Updates for Today:

- Examine behavior of spikes at the extrema of the cosine plots.
- Update cuts to reduce background. Include a new cut on the cosine parameter.
- Produce updated likelihood fits with all background samples and yields reflective of updated cuts.

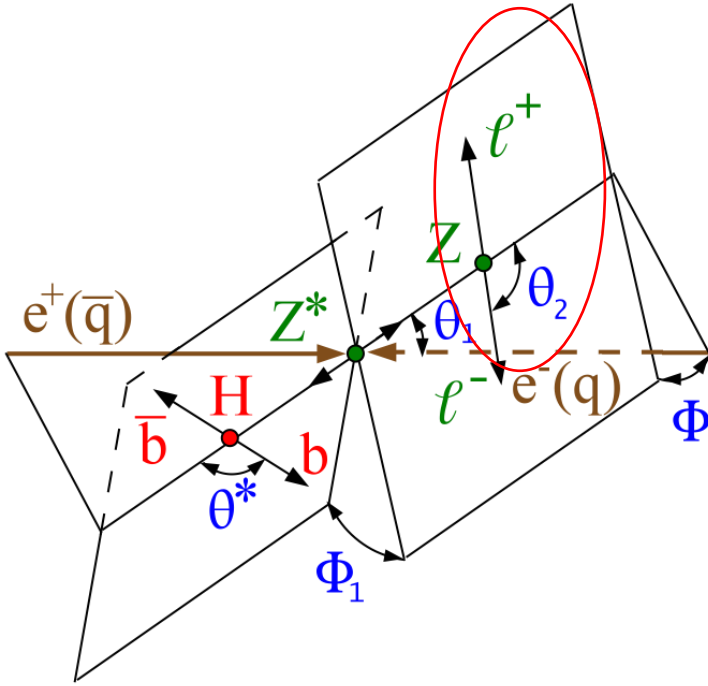




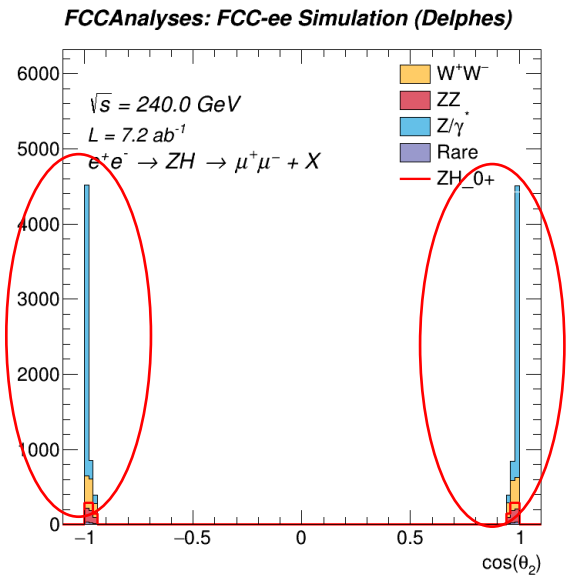
Behavior of Cos θ_2 Endpoints

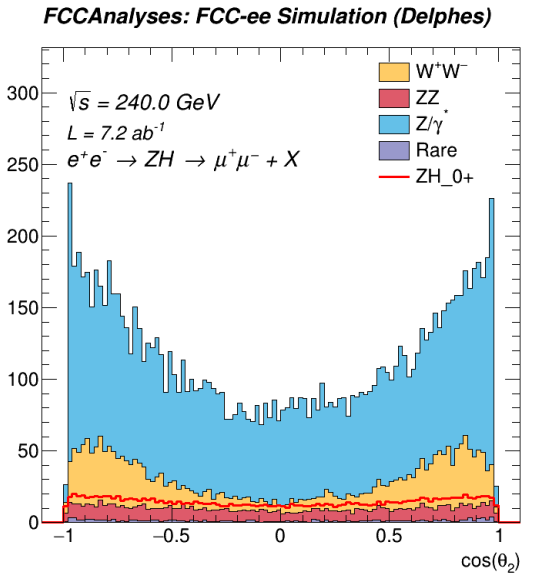
- Cos θ_2 is the angle between muon and recoil direction.

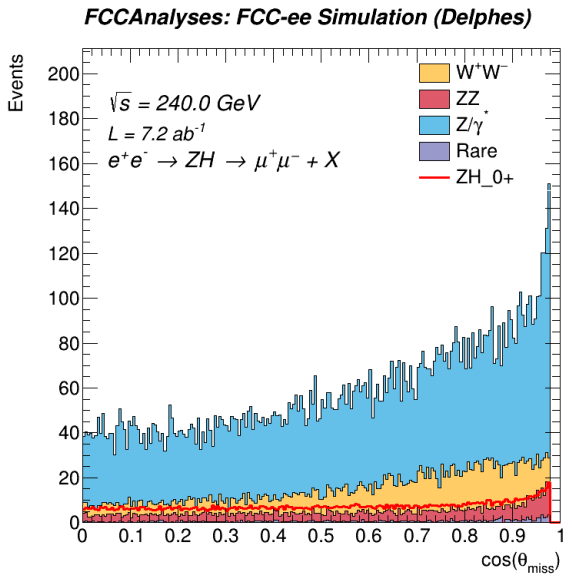
Behavior of Cos θ_2 Endpoints

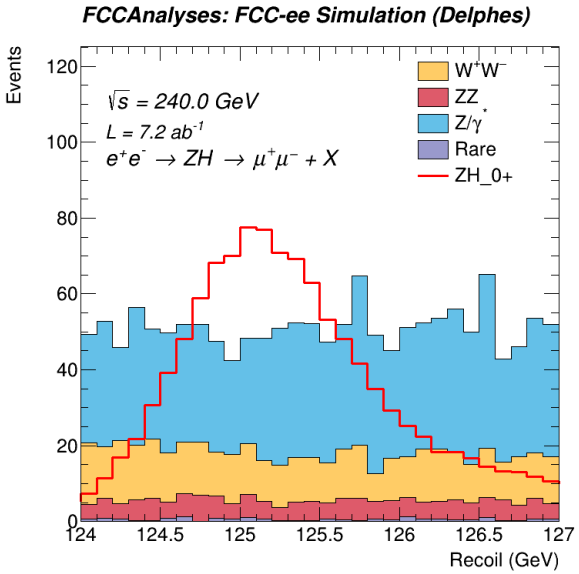


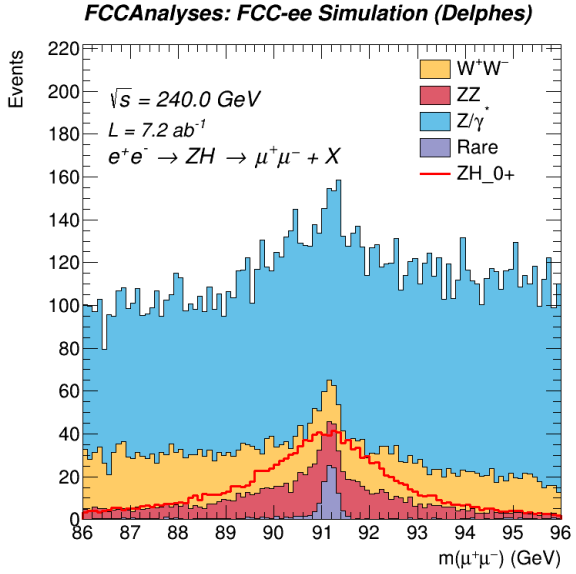
Events at Cos θ_2 Endpoints and Correlations to Other Observables:

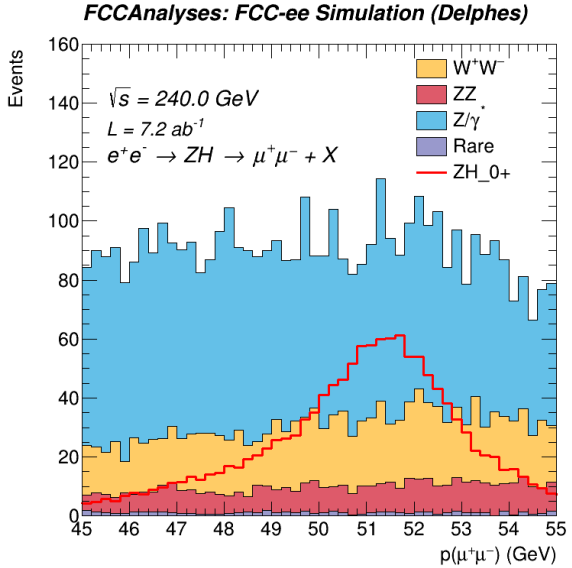




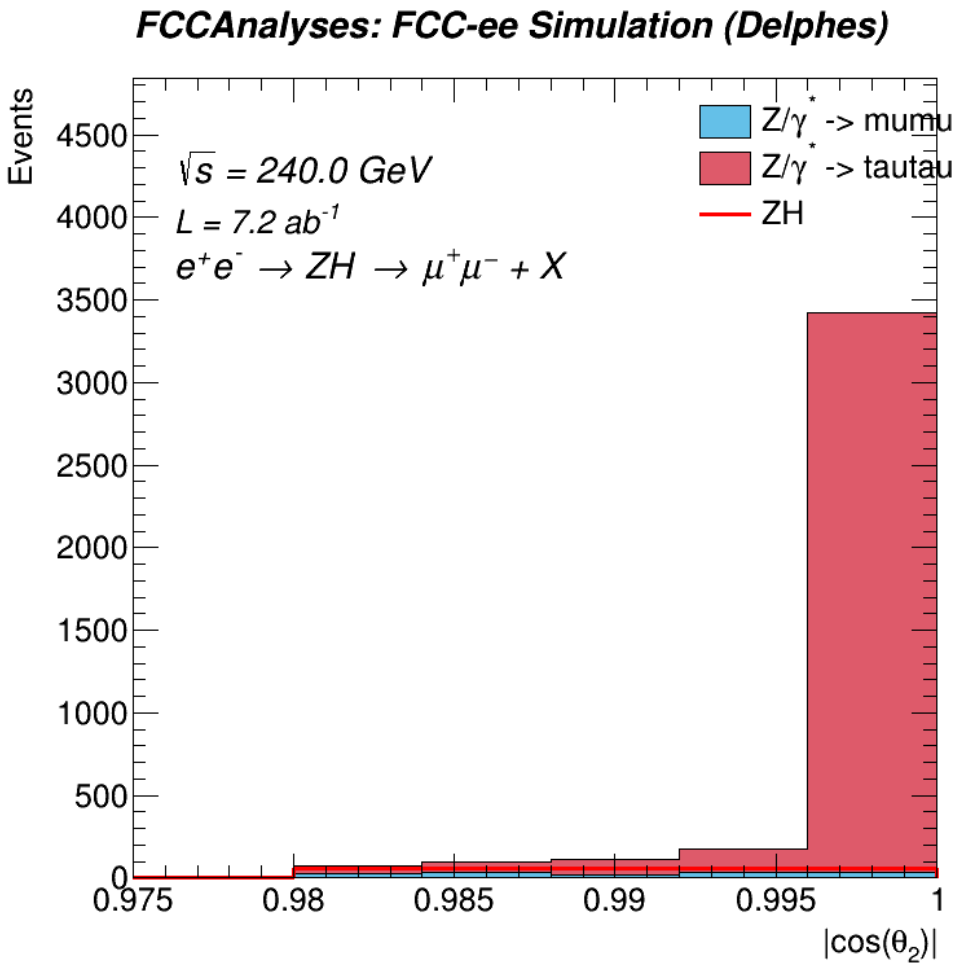


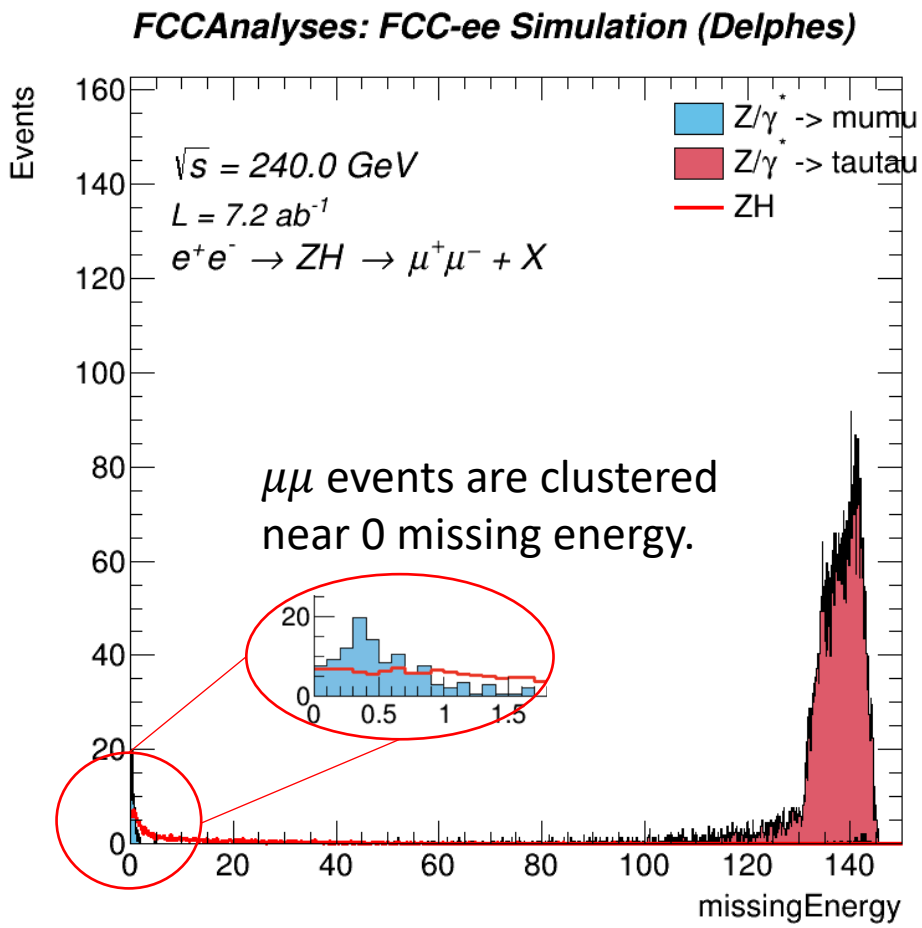






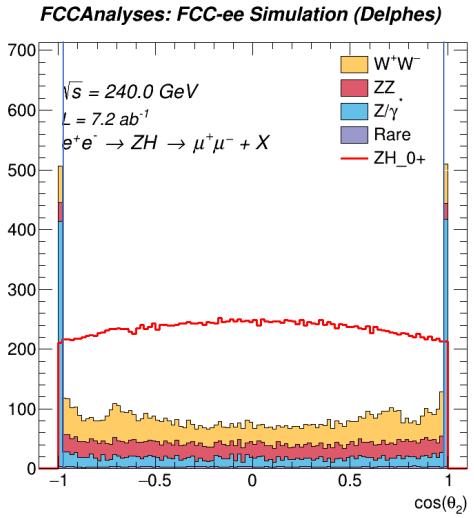
Cos θ_2 of Z/γ* $\longrightarrow$ $\mu\mu$ and $\tau\tau$:

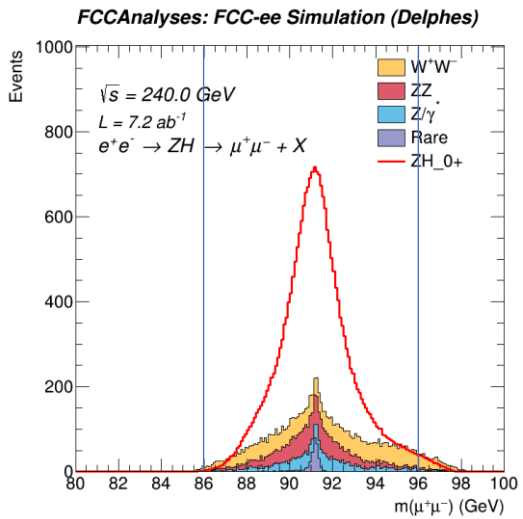


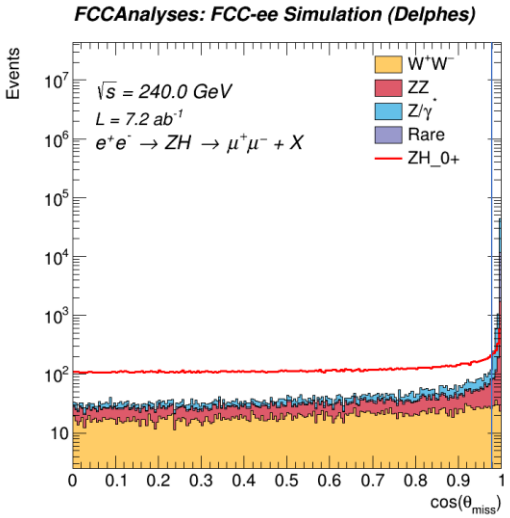


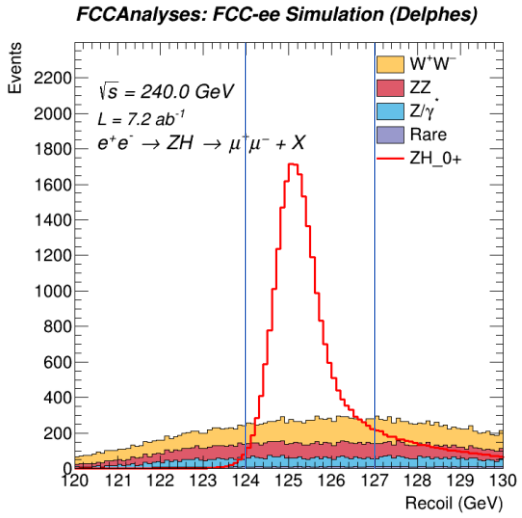
Horns are nearly all from $\tau\tau$ events. No events in the bins below 0.98.

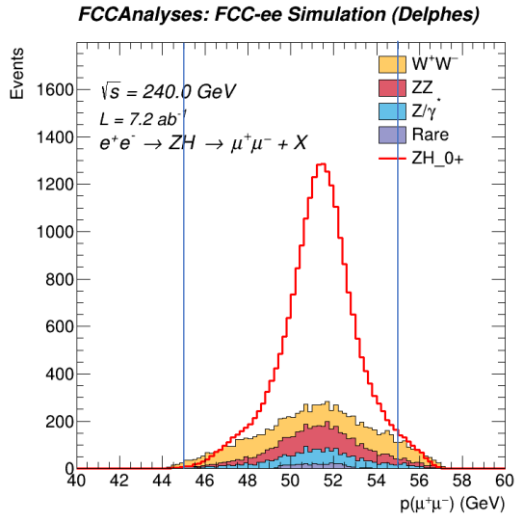
New Cuts Being Made: N-1 Plots



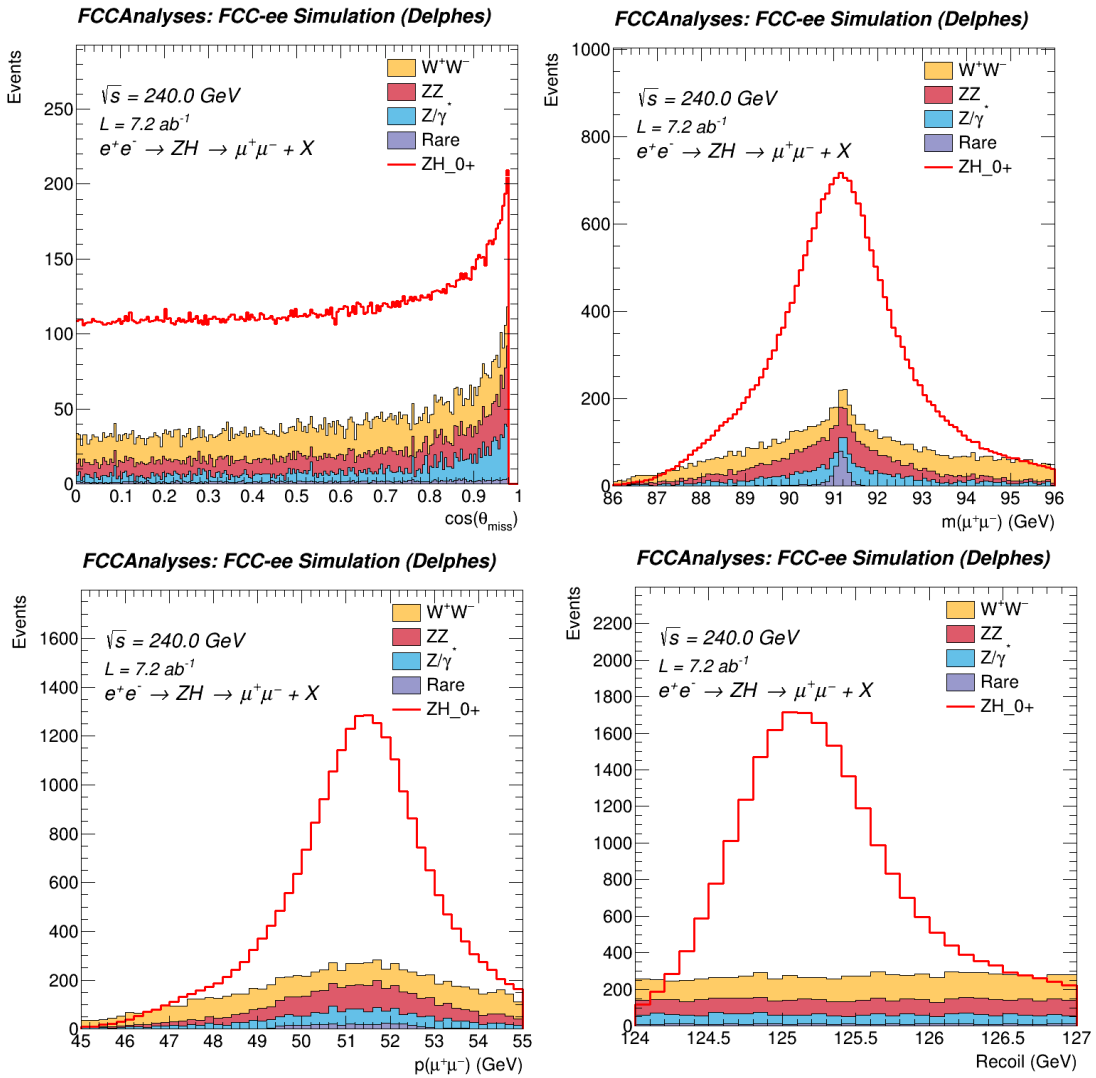




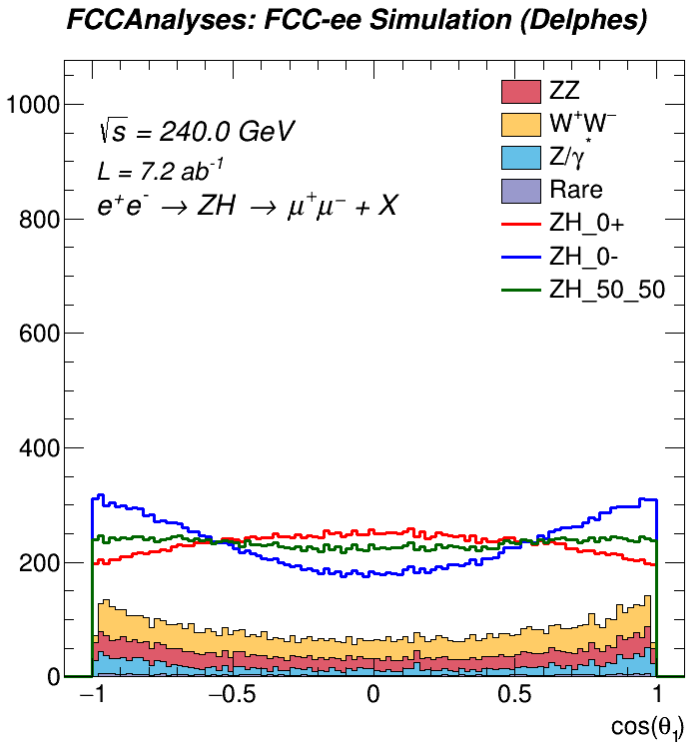


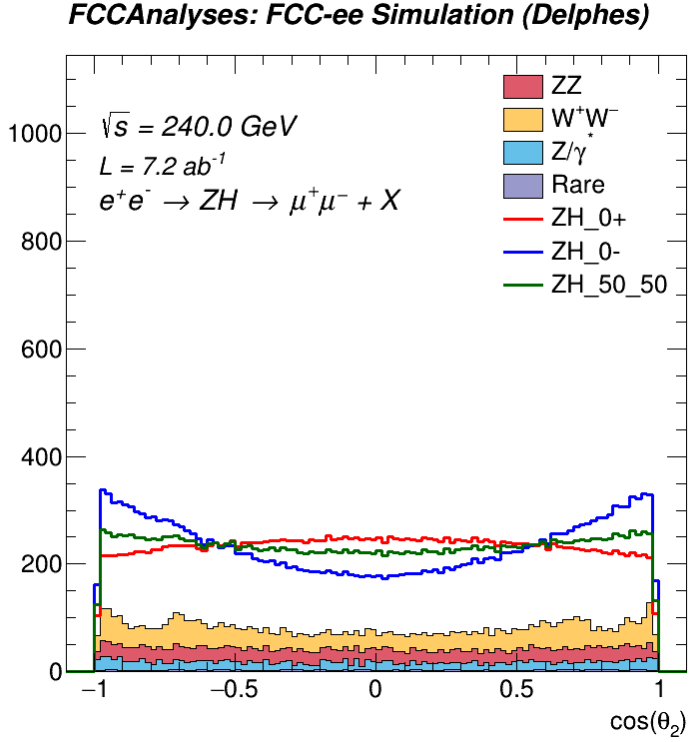


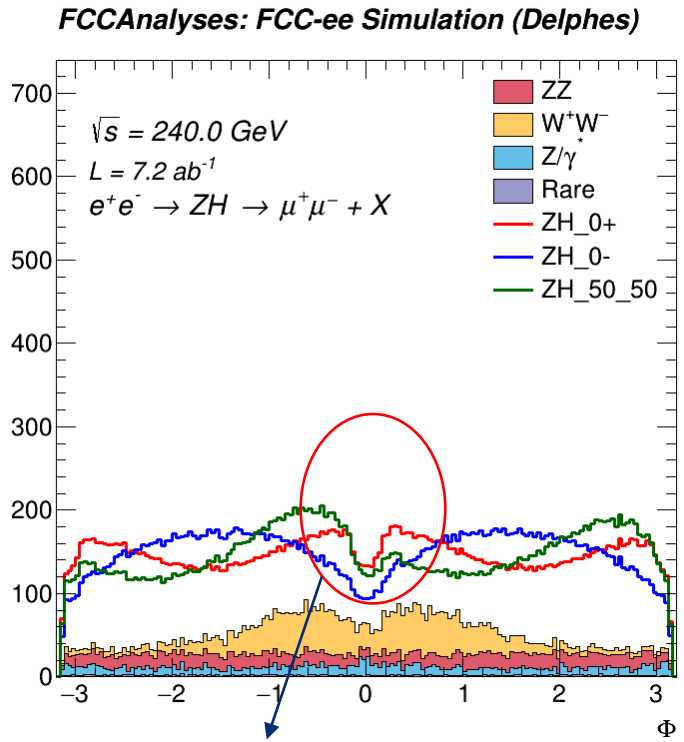
All Cuts Made



All Cuts Made: Angular Distributions

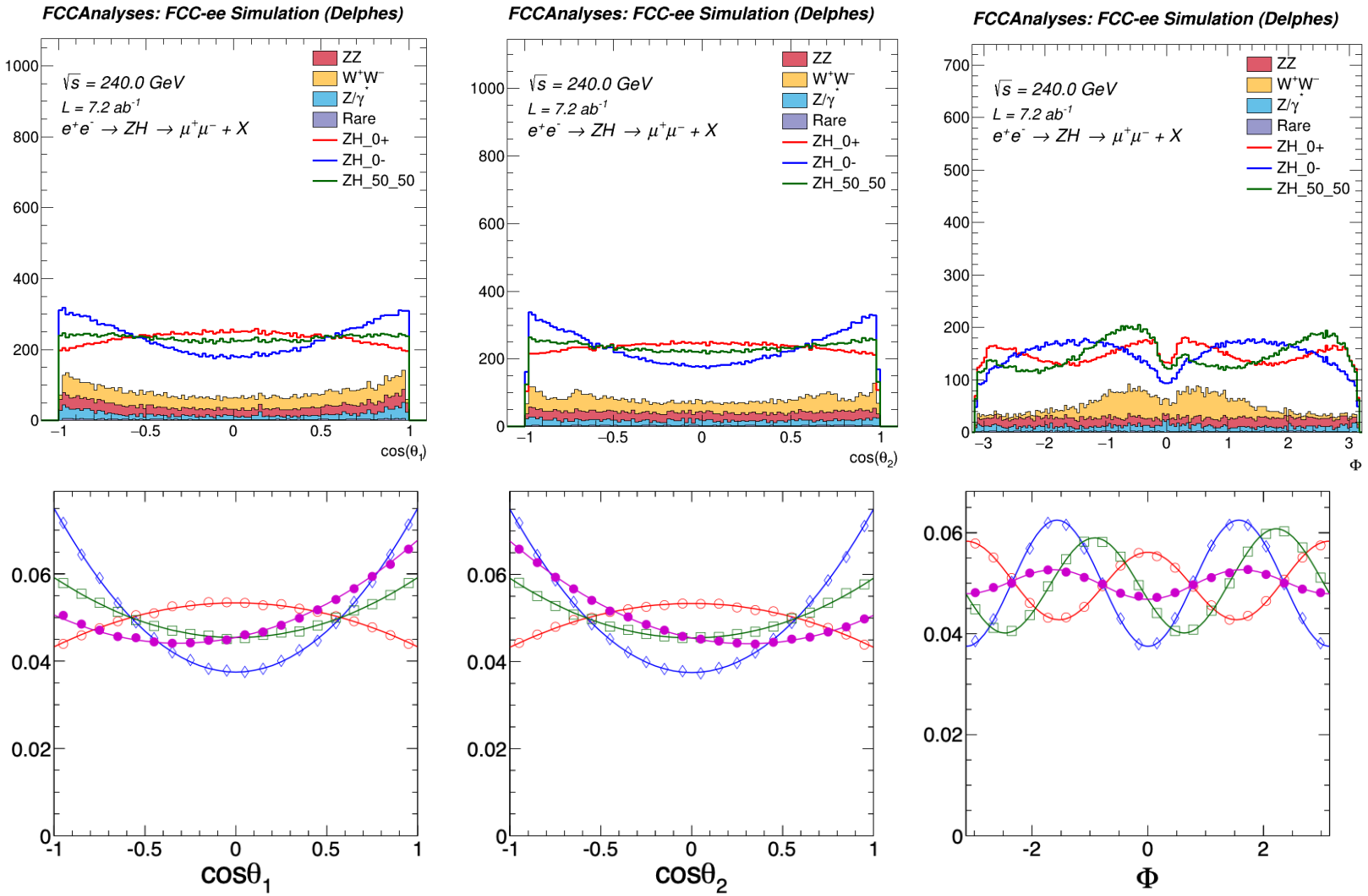






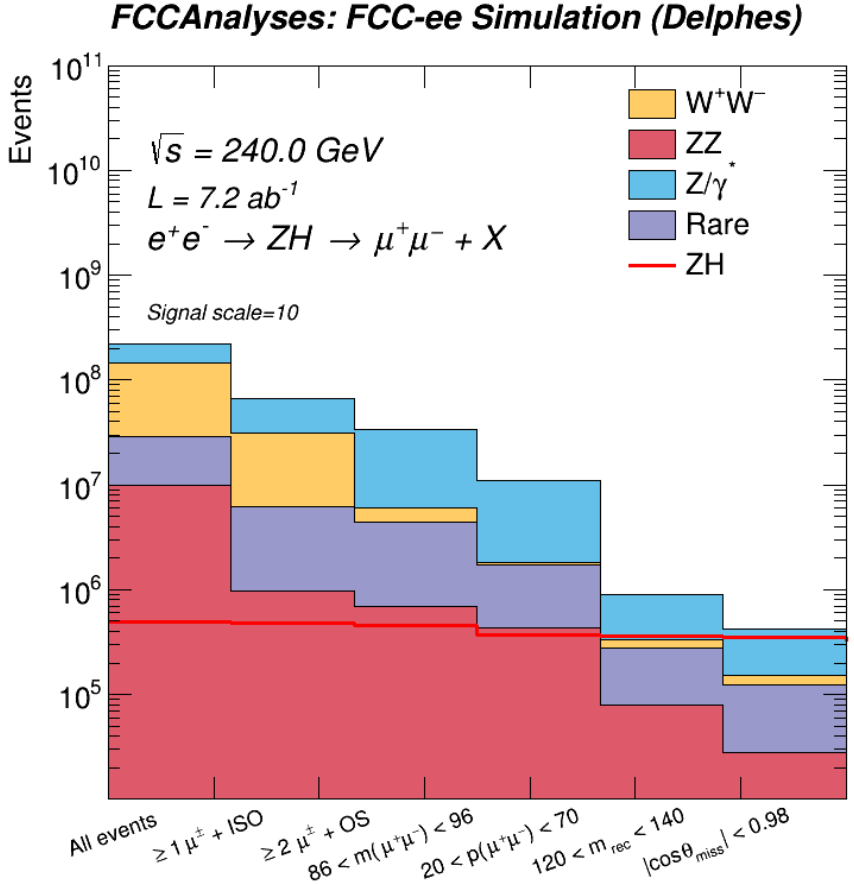
Selection effect occurs around $\Phi = 0$.

Comparing Angular Distributions to Snowmass Study

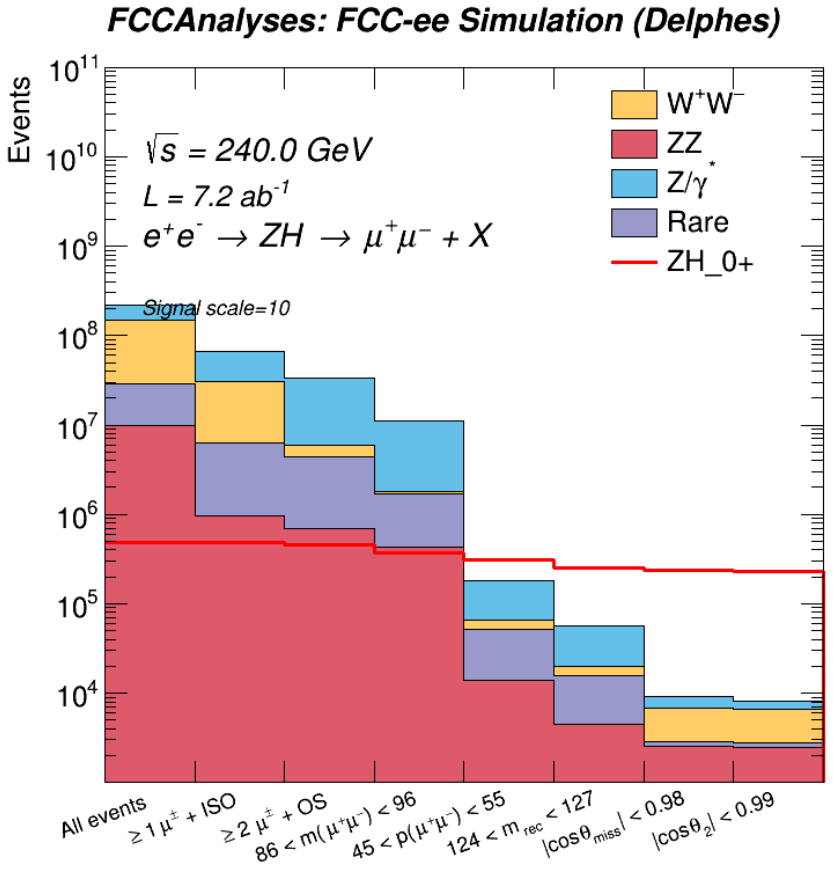


Comparing Cut Flows: Old vs New Cuts

Original Selection:
Signal Selection Efficiency ~ 68%
Signal : Background ~ 0.1

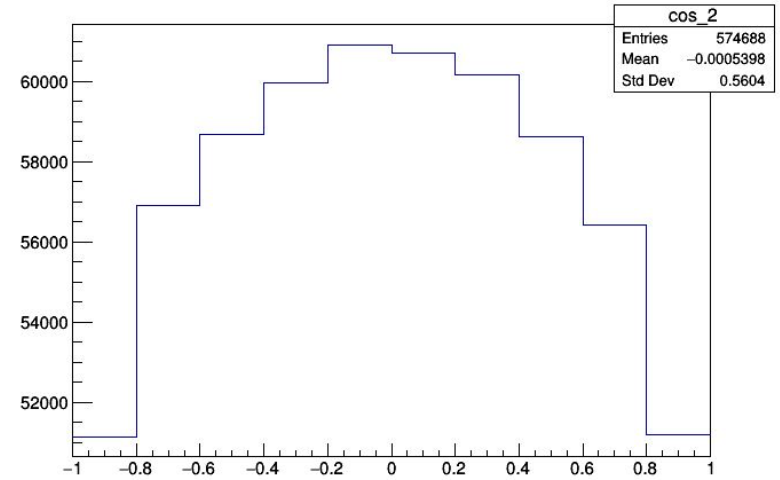


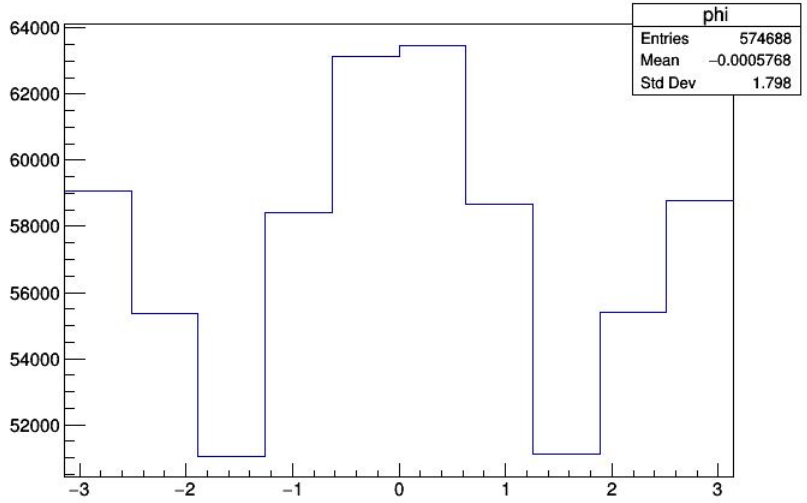
Updated Selection:
Signal Selection Efficiency ~ 47.9%
Signal : Background ~2.5



How Template Fits are Made

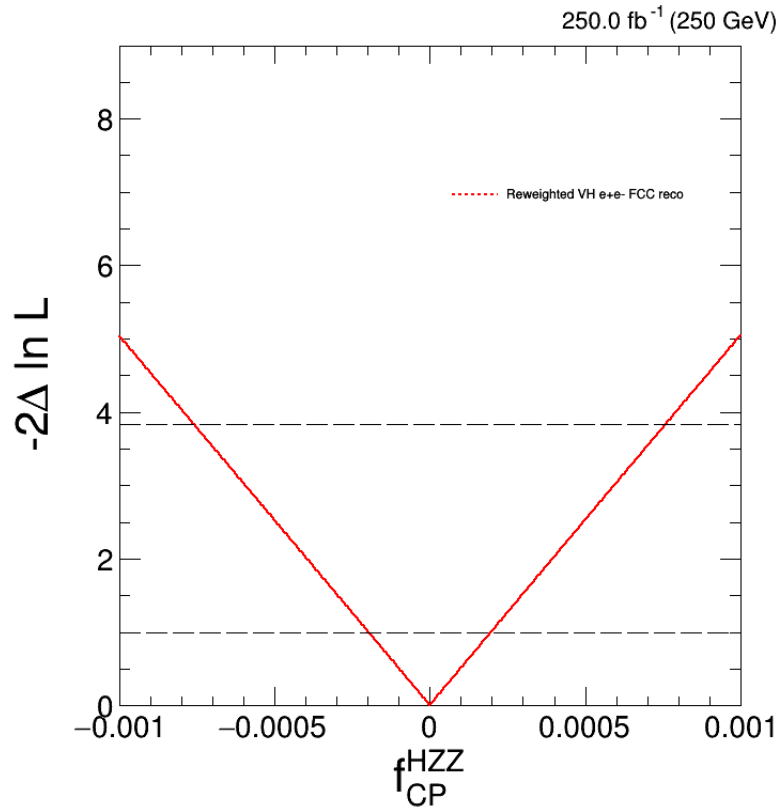
- 3D histogram filled with 1 angle on each axis.
- 10 bins/axis
- ~55000 entries/bin on average.
- Examples for 0^+ hypothesis shown on the right.





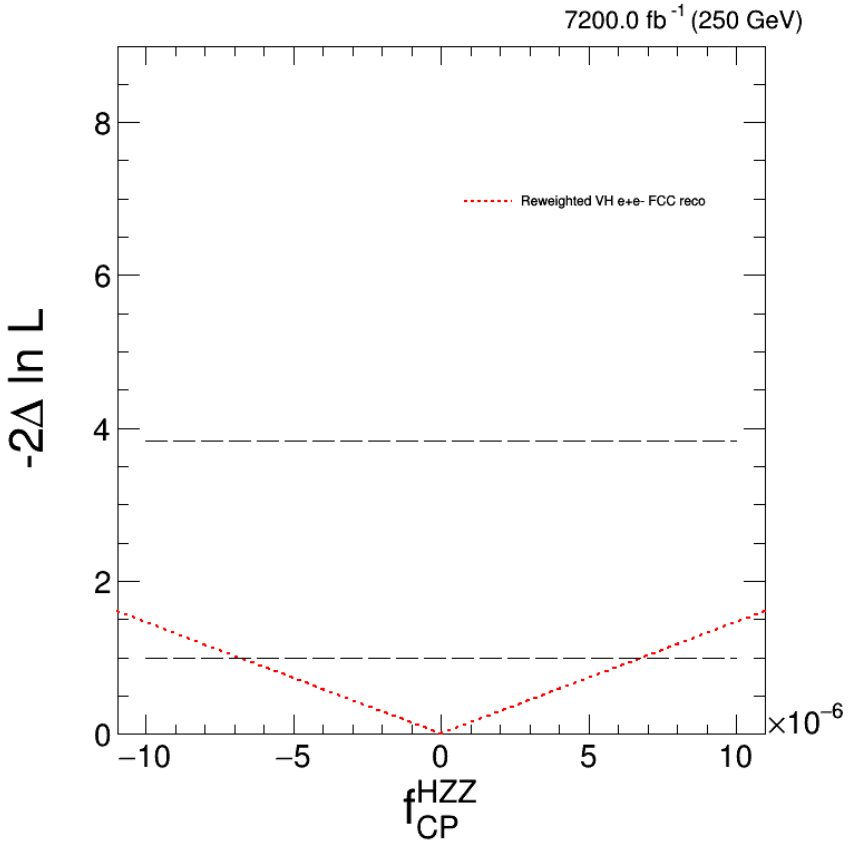
Progression of fits with Reconstructed Signal H ⟶ X, Z ⟶ $\mu\mu$:

Updated selection @
250 fb^-1

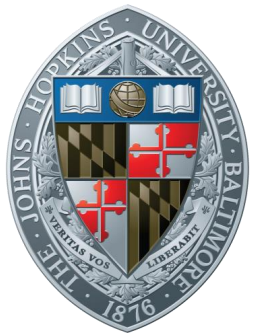


68% CL ≈ +/- 2.0 E-4

Updated selection @
7200 fb^-1



68% CL ≈ +/- 0.7 E-5



Expected yields:

- 0^+ and 0^- signal fixed to same cross section.

Updated selection @ 250 fb^-1

$\int Ldt(fb^{-1})$	production	$Yield$
250	ee→ZH(0^+)	809.2
250	ee→ZH(0^-)	809.3
250	ee→ZH(Positive int)	388.7
250	ee→ZH(Negative int)	389.5
250	ee→WW	133.7
250	ee→ZZ	86.1
250	ee→ $\mu\mu$	48.2
250	ee→ $\nu\nu$Z	11.1
250	ee→ $\tau\tau$Z	11.1
250	eγ →eZ	0.0
250	γe →eZ	0.0
250	$\gamma\gamma \rightarrow \tau\tau$	0.0
250	$\gamma\gamma \rightarrow \mu\mu$	0.0

Updated selection @ 7200 fb^-1

$\int Ldt(fb^{-1})$	production	$Yield$
7200	ee→ZH(0^+)	23303.9
7200	ee→ZH(0^-)	23306.6
7200	ee→ZH(Positive int)	11200.7
7200	ee→ZH(Negative int)	11238.5
7200	ee→WW	3849.9
7200	ee→ZZ	2480.4
7200	ee→ $\mu\mu$	1388.2
7200	ee→ $\nu\nu$Z	319.3
7200	ee→ $\tau\tau$Z	145.0
7200	eγ →eZ	1.1
7200	γe →eZ	2.1
7200	$\gamma\gamma \rightarrow \tau\tau$	1.4

Conclusions

- Updated likelihood fits incorporate all backgrounds considered in the cross-sectional study and now represent more realistic constraints on f_{CP}^{Hzz}.
- The techniques of this analysis can be extended to other channels / couplings.
- Can extend improve this study by optimizing binning.