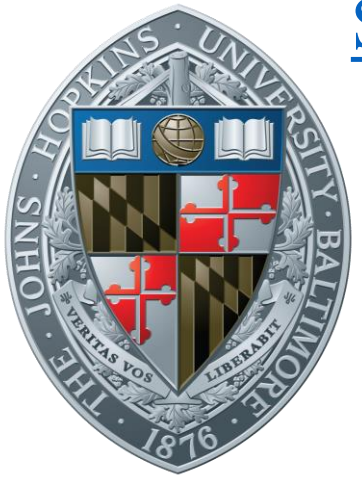
FCC-ee Higgs CP Study

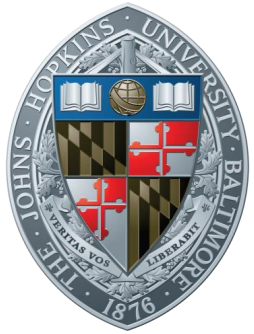
Nicholas Pinto (JHU), Andrei Gritsan (JHU), Jan Eysermans (MIT), Valdis Slokenbergs (JHU)



Second Annual U.S. Future Circular Collider (FCC) Workshop

26 March 2024

Massachusetts Institute of Technology

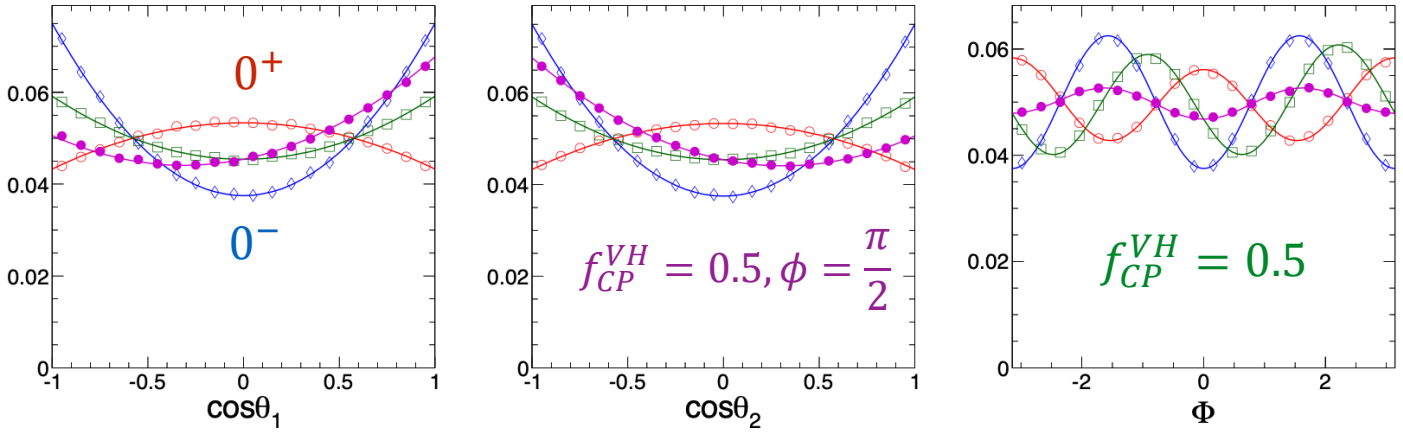


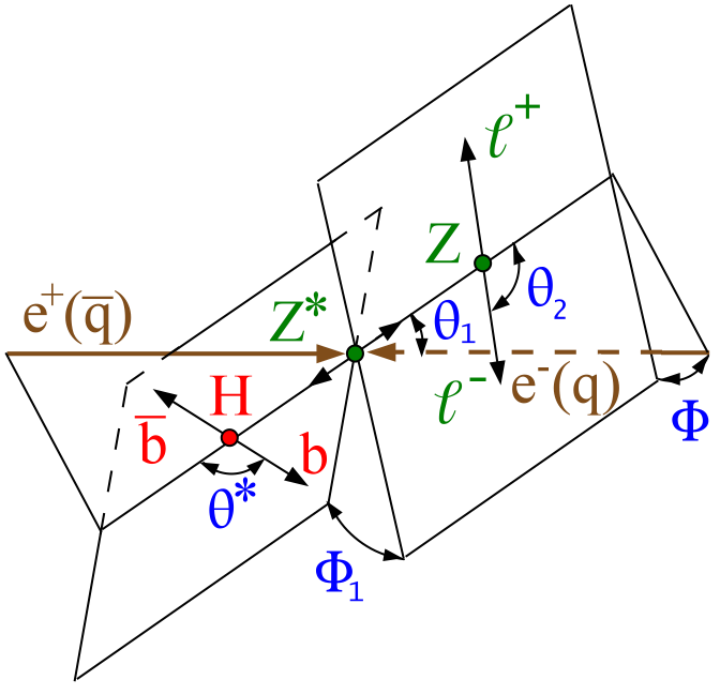
Outline:

- Overview of Past Studies
- Current Study:
  - Selection and Efficiency
  - Results
- MELA
  - Reweighting in the FCC Framework
  - Future Avenues

Past Studies: Snowmass 2013

arXiv:1309.4819

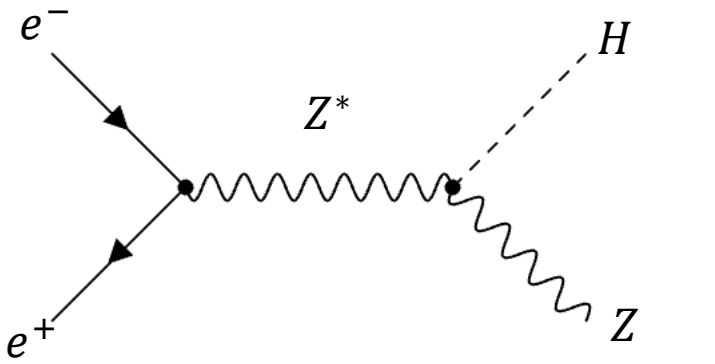




$$A(H \to V_1V_2) = v^{-1}\left(a_1^{HVV} m_V^2 \epsilon_1^* \epsilon_2^* + a_2^{HVV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{HVV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

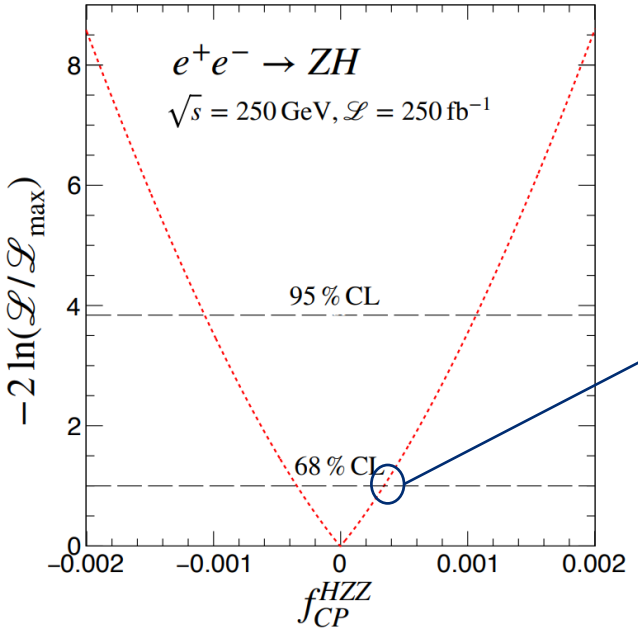
$$f_{\rm CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{\rm CP\ odd}}{\Gamma_{H\to X}^{\rm CP\ odd} + \Gamma_{H\to X}^{\rm CP\ even}}$$

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



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	$\pm 3.0 \cdot 10^{-6}$

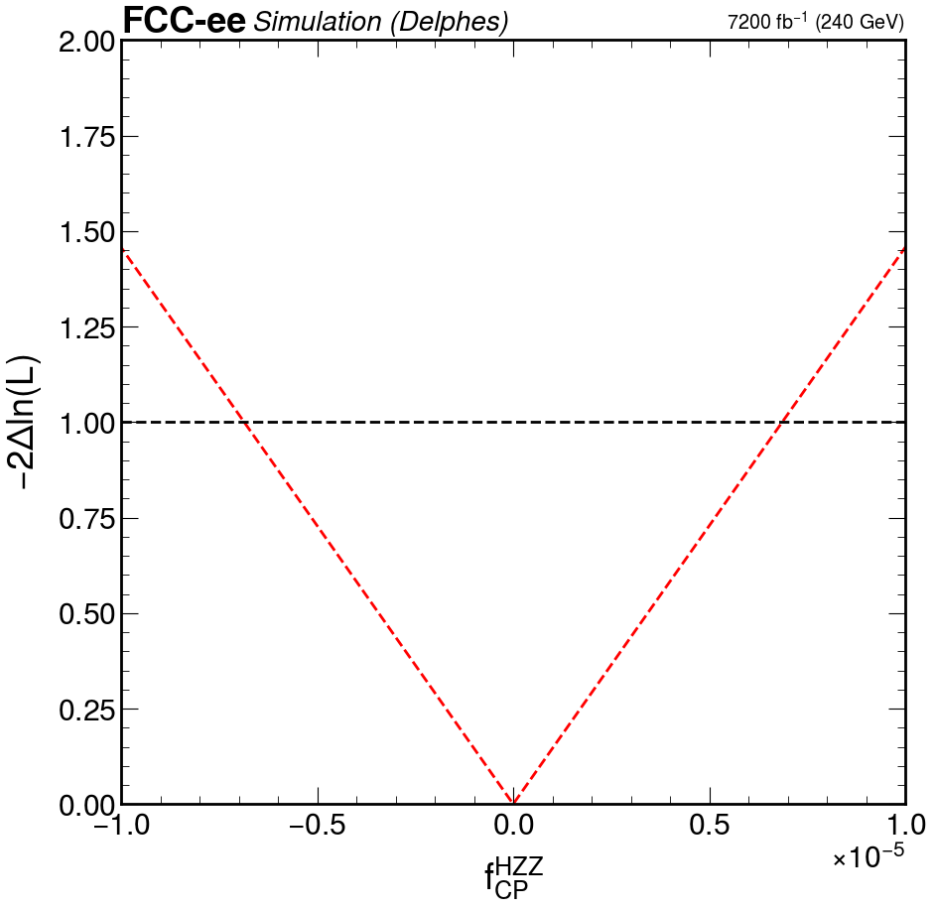
collider	energy	$\int \mathcal{L}dt$ (fb^{-1})	production	σ (fb)	decay	$\sigma \times \mathcal{B}$ (fb)	N_{prod}	N_{reco}	f_{jet}
pp	14 TeV	3000	$gg \to H$	49850	$H \to ZZ^* \to 4\ell$	6.23	18694	5608	0.1
pp	14 TeV	3000	$V^*V^* \to H$	4180	$H \to ZZ^* \to 4\ell$	0.52	1568	470	0.6
pp	14 TeV	3000	$W^* \to WH$	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.

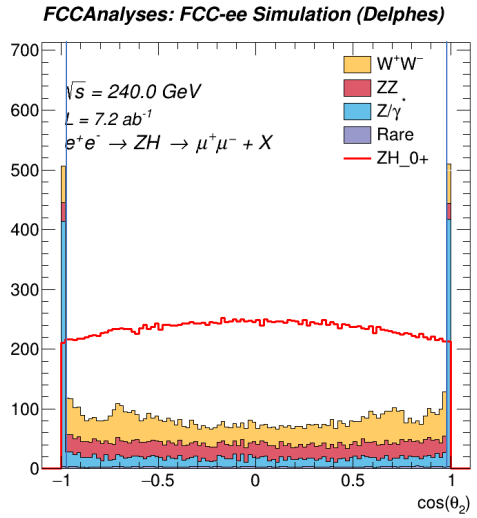
4+ different samples (SM Signal, BSM Signal, Background, SM/BSM Interference) used to produce fits.

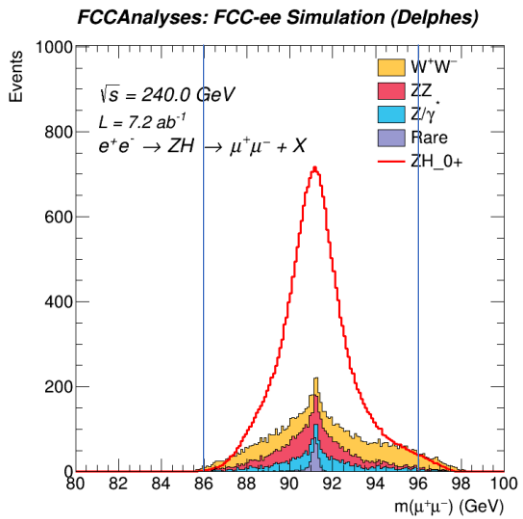
Overview of Current Study:

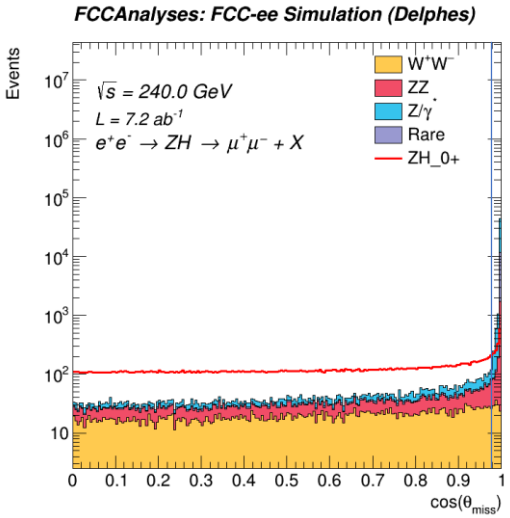
- Target: ee ⟶ ZH, H ⟶ X (recoil), Z ⟶ $\mu\mu$ (3.4%)
- Detector simulation uses DELPHES fast sim.
- Template fit made from angular distributions.
- Uses Reco data, FCC signal yield and luminosity.
  - Additional fit w/ Snowmass luminosity used as a comparison.
- Broader range of backgrounds used:
  - Primarily WW, ZZ, Z/γ^*

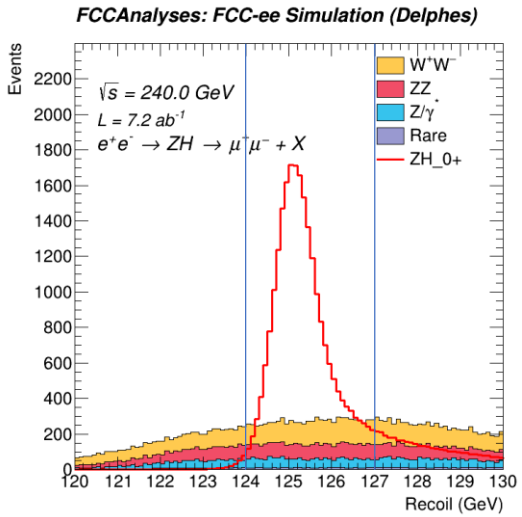


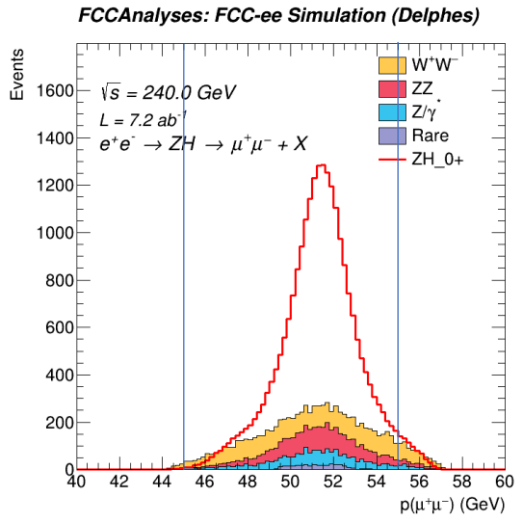
Current Selection: N-1 Plots:





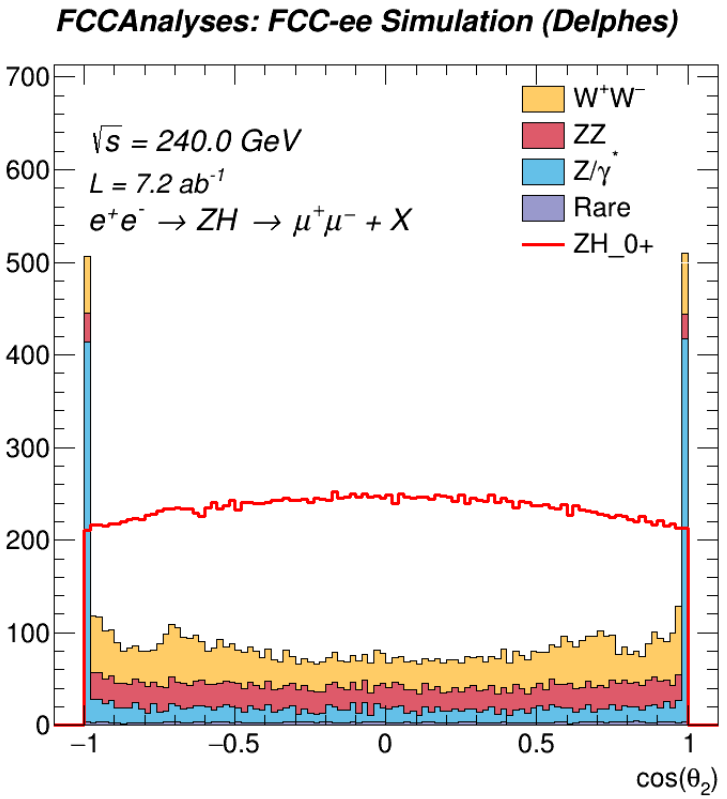


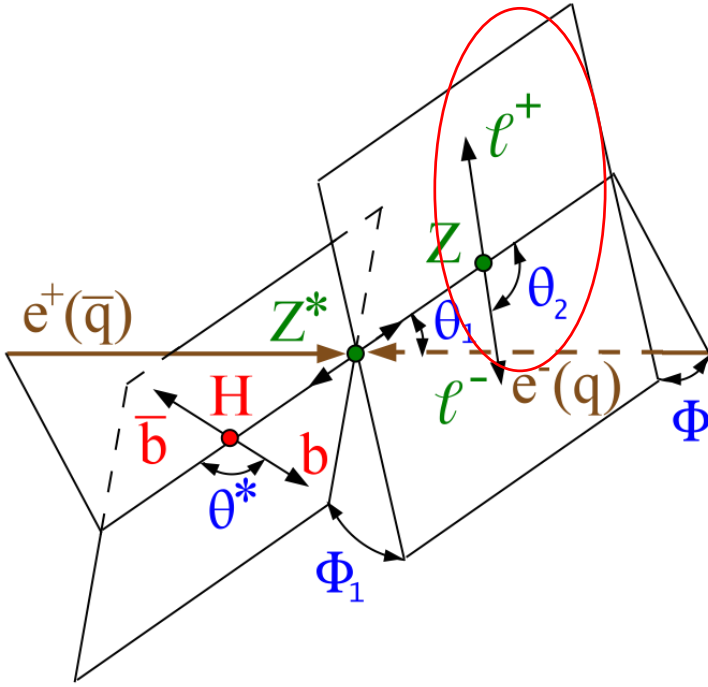




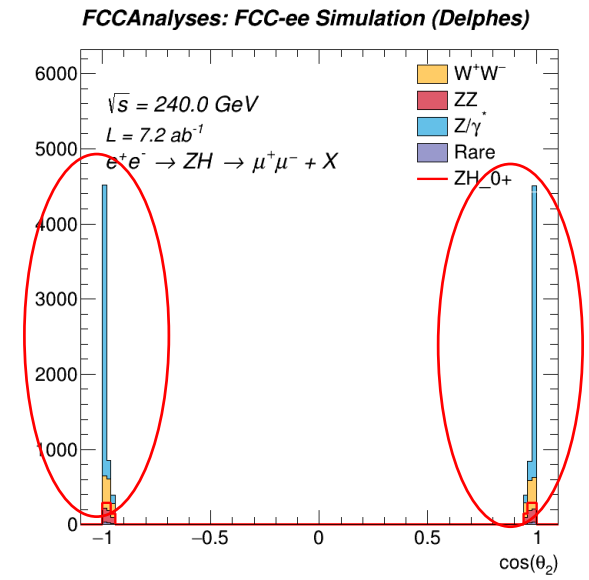
Selection: Behavior of Cos θ_2 Endpoints:

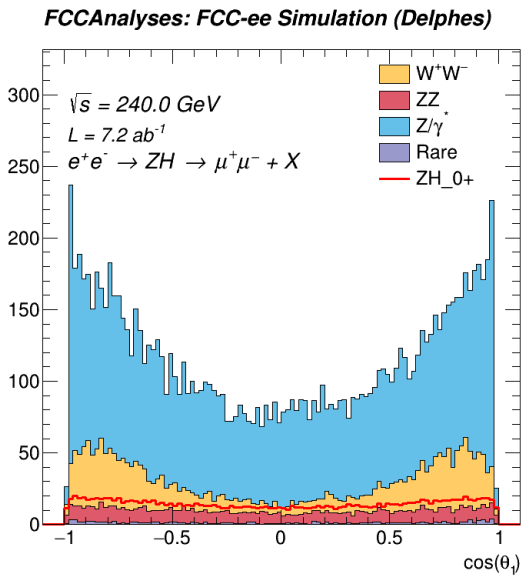
- Cos θ_2 is the angle between muon and recoil direction.
- ”Bullhorns” appear at the extrema of Cos θ_2 in $e^+e^- \rightarrow \tau^+\tau^-$

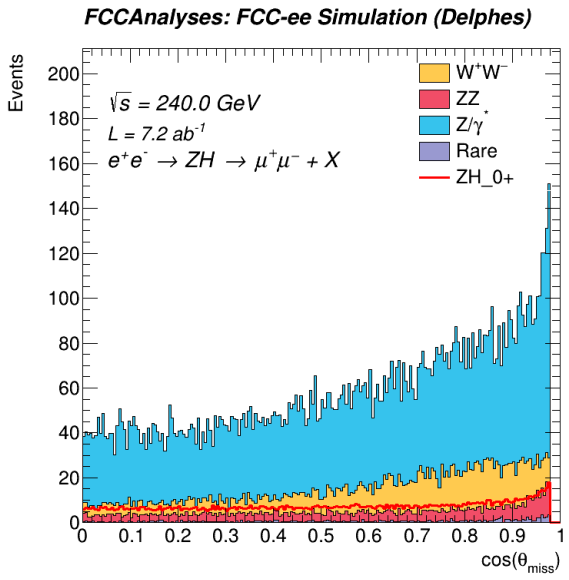


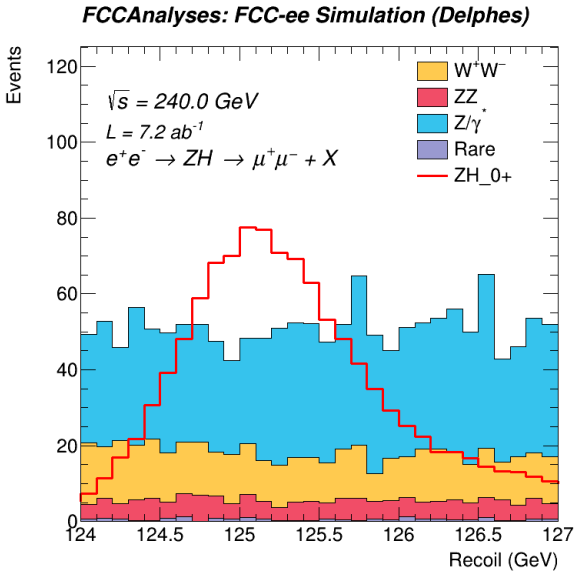


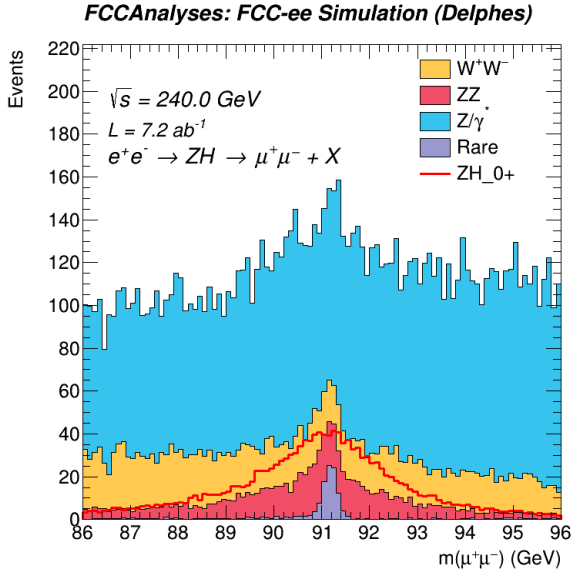
Events at Cos θ_2 Endpoints and Correlations to Other Observables:

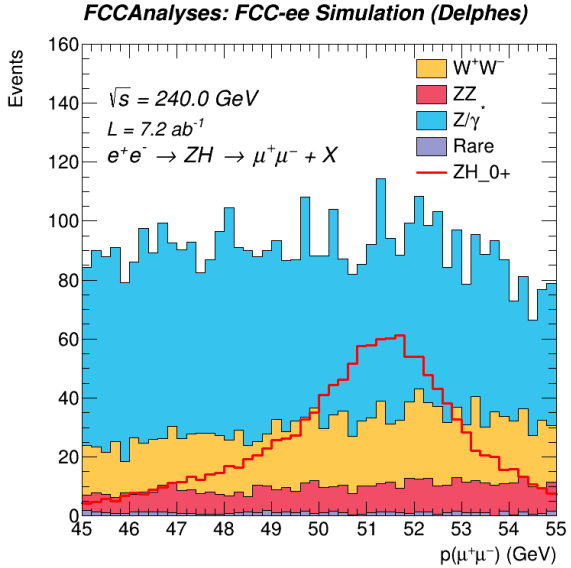




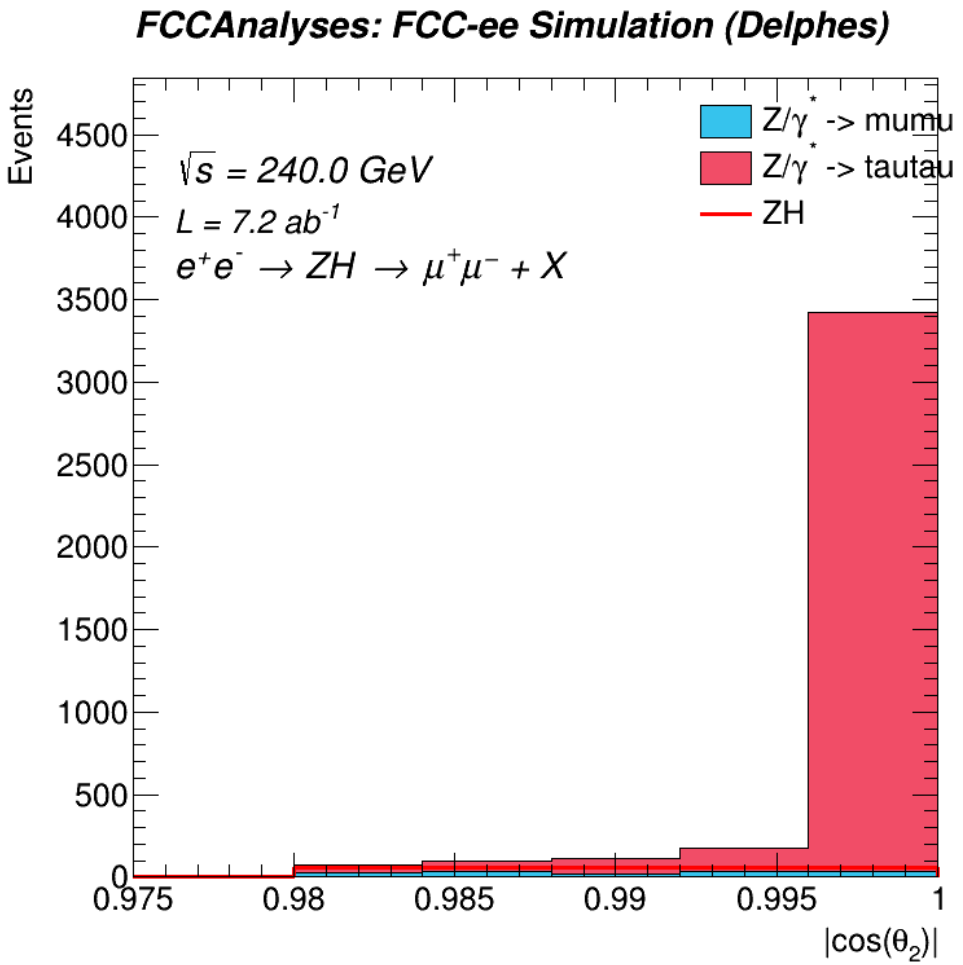


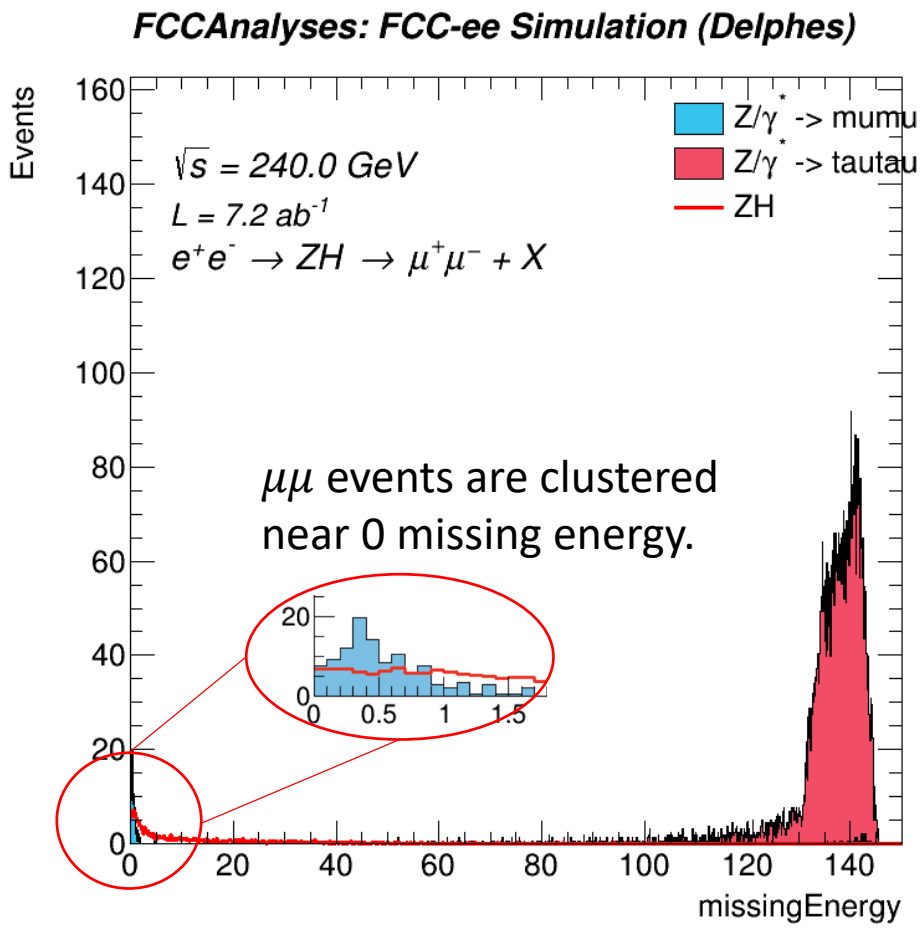






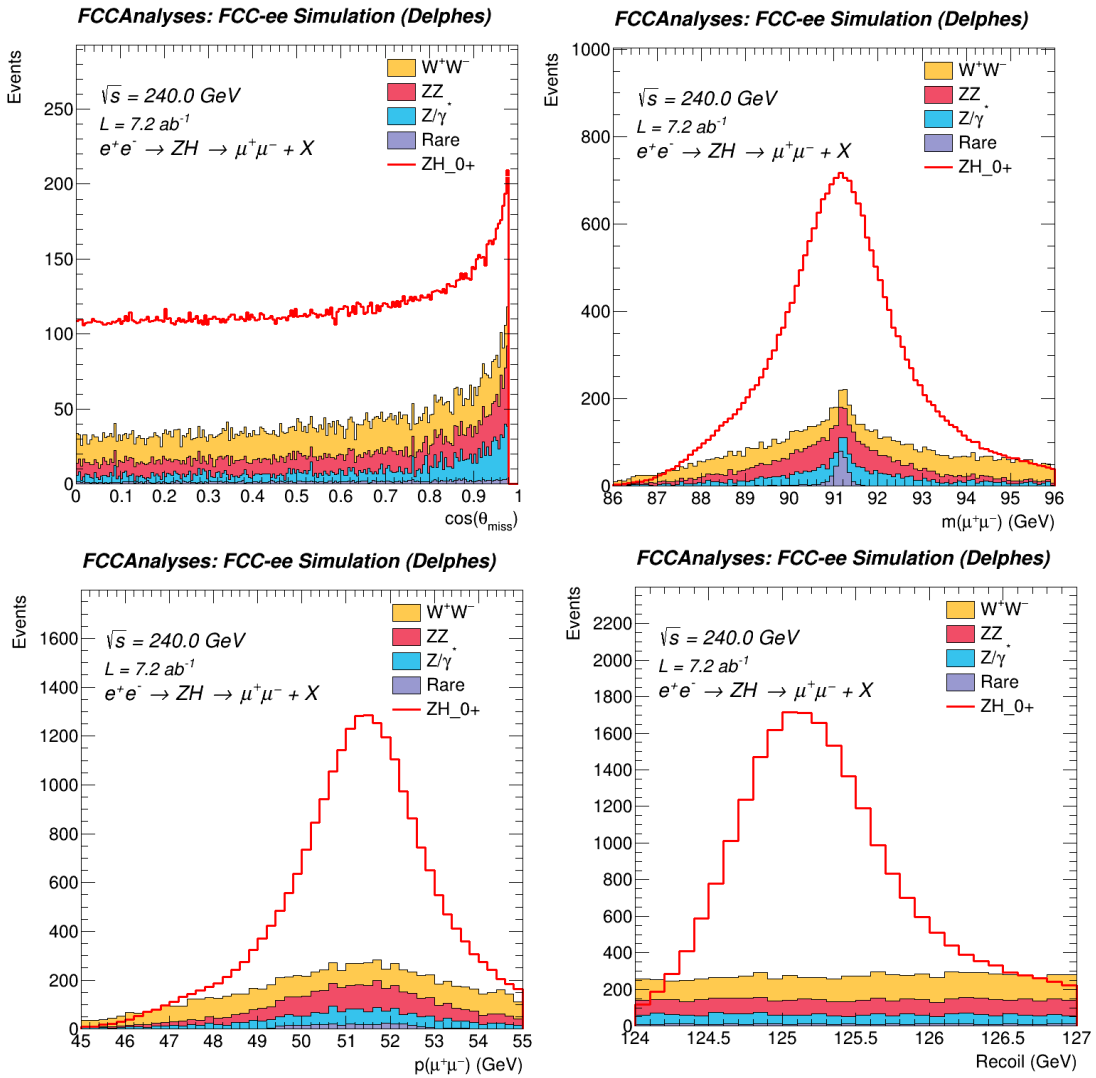
Cos θ_2 of $Z/\gamma^* \longrightarrow \mu\mu$ and $\tau\tau$:



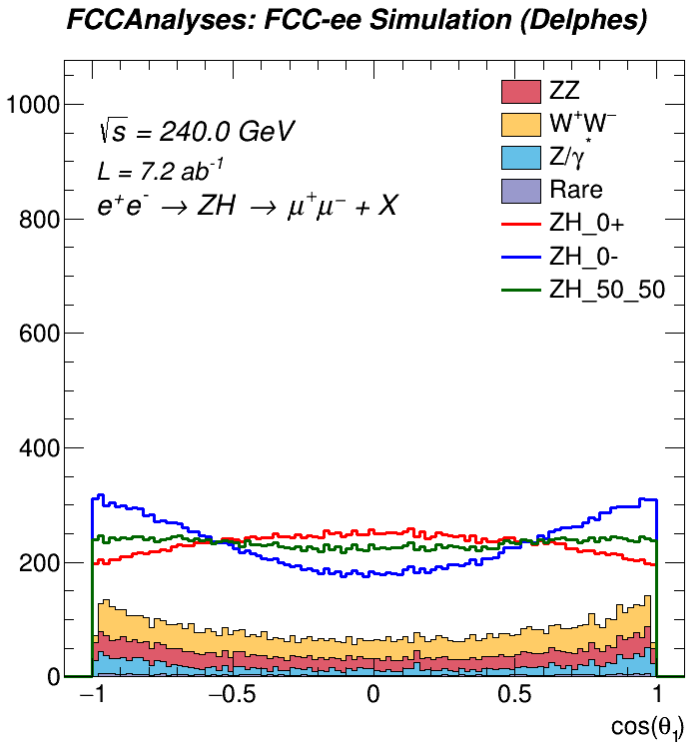


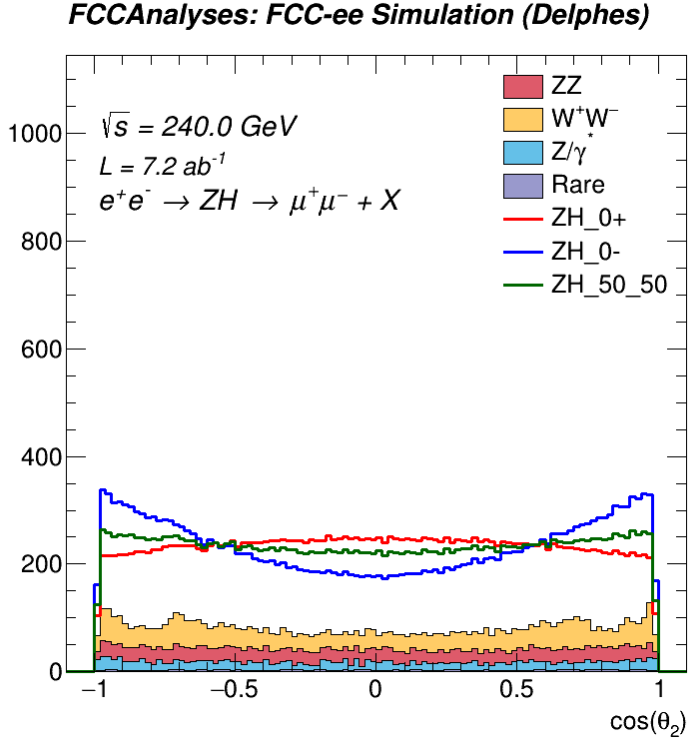
Horns are nearly all from $\tau\tau$ events. No events in the bins below 0.98.
Missing energy from τ decays into neutrinos.

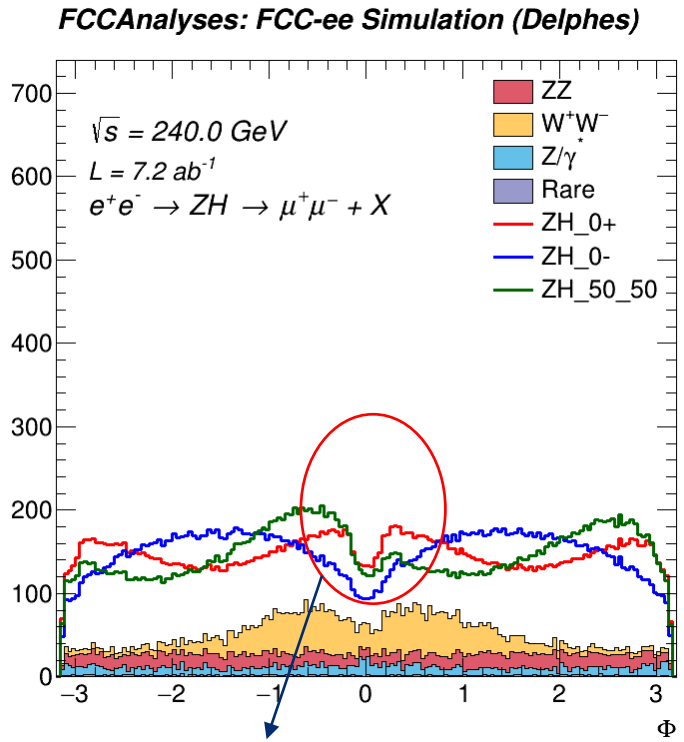
All Cuts Made:



All Cuts Made: Angular Distributions:

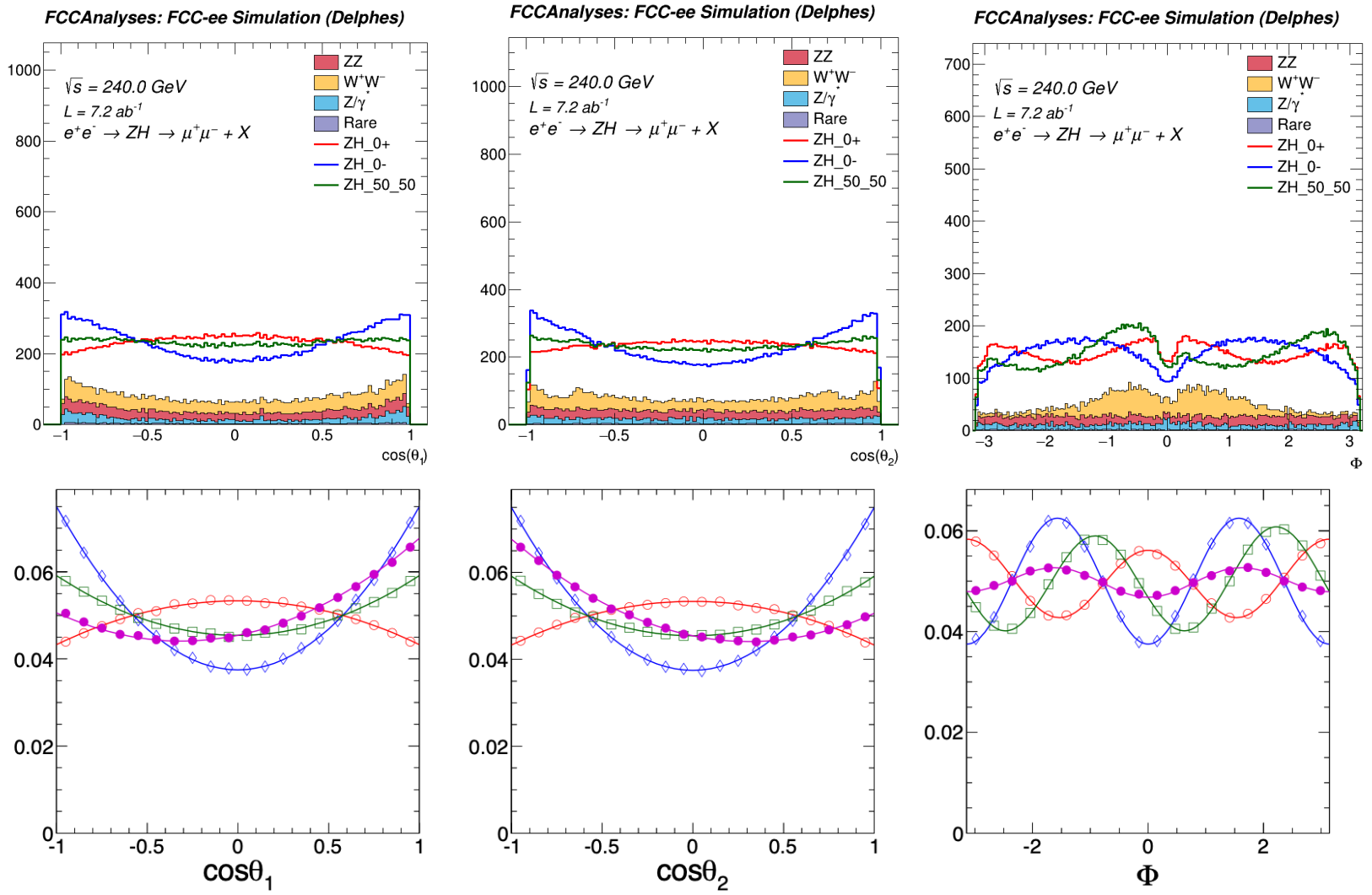






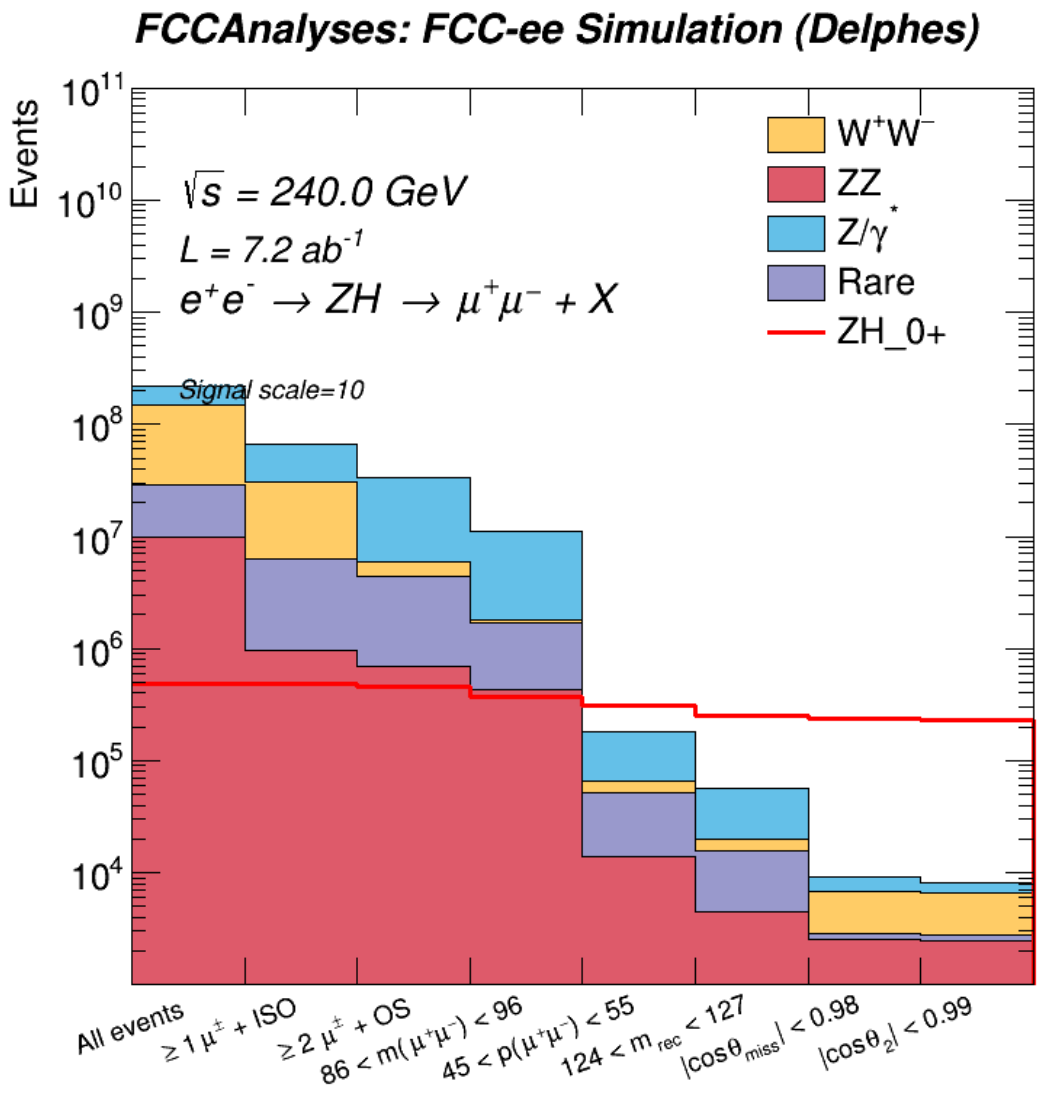
Selection effect occurs around $\Phi = 0$.

Comparing Angular Distributions to Snowmass Study:



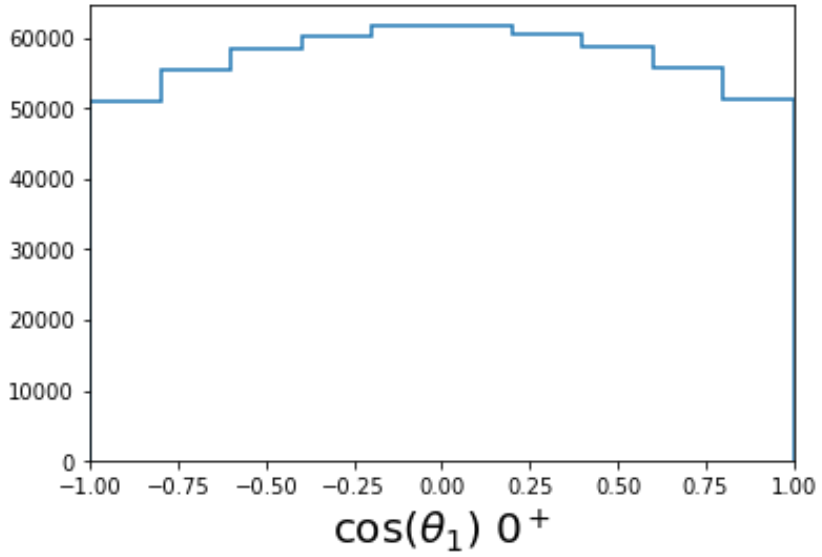
Cut Flow:

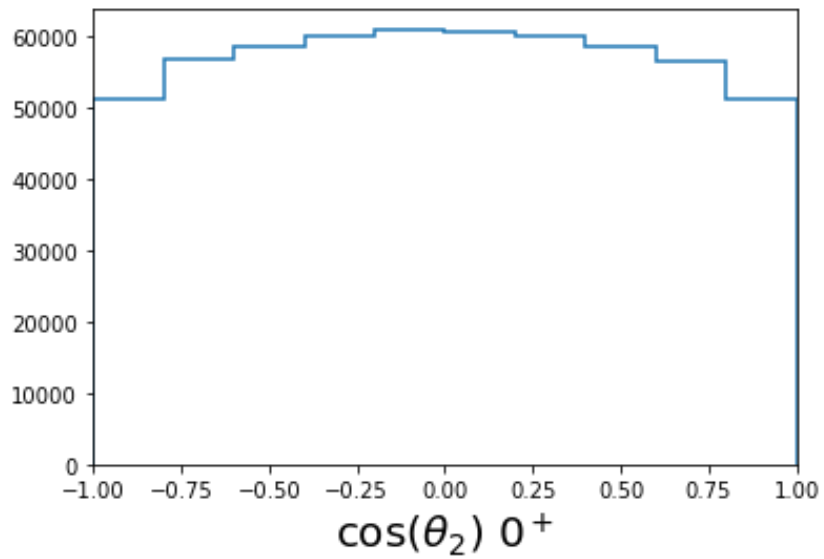
- Signal Selection Efficiency ~ 47.9%
- Signal : Background ~2.5

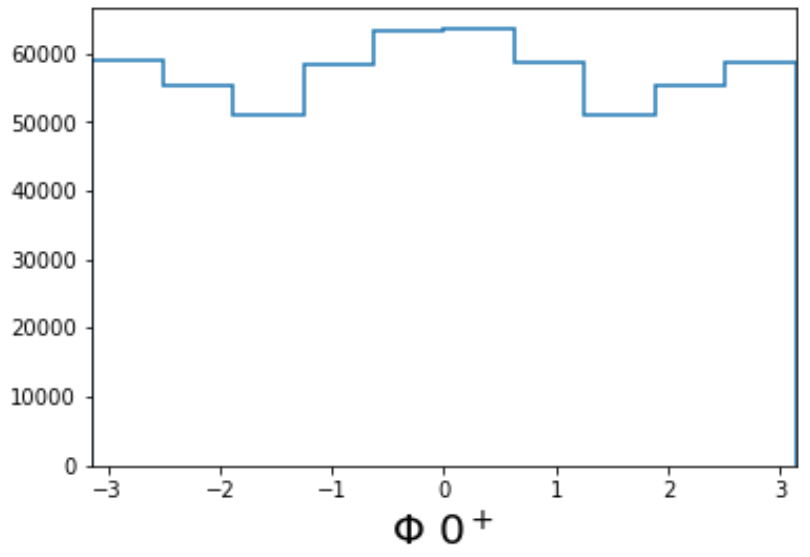


Template Fit Details:

- 3D histogram filled with 1 angle on each axis. ~55000 entries/bin on average.
- 10 bins/axis
- Example projections for 0^+hypothesis:







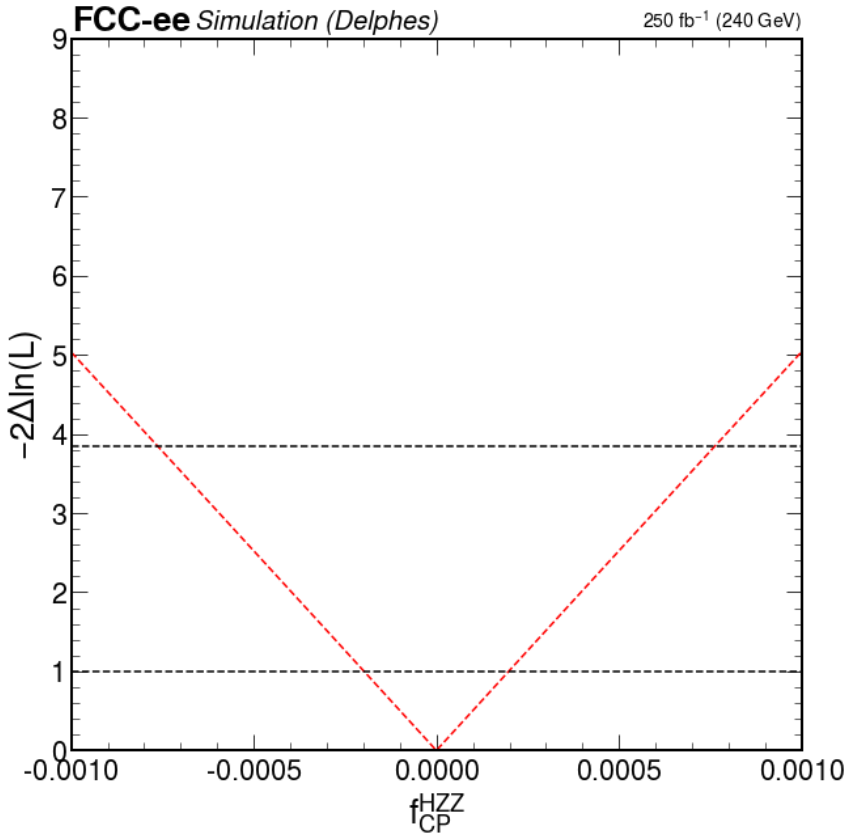
Expected Yields After Reco. + Selection:

(Red box = signal yields)

$\int Ldt(fb^{-1})$	production	$Yield$	$\int Ldt(fb^{-1})$	production	$Yield$
250	ee→ZH(0^+)	809.2	7200	ee→ZH(0^+)	23303.9
250	ee→ZH(0^-)	809.3	7200	ee→ZH(0^-)	23306.6
250	ee→ZH(Positive int)	388.7	7200	ee→ZH(Positive int)	11200.7
250	ee→ZH(Negative int)	389.5	7200	ee→ZH(Negative int)	11238.5
250	ee→WW	133.7	7200	ee→WW	3849.9
250	ee→ZZ	86.1	7200	ee→ZZ	2480.4
250	ee→ $\mu\mu$	48.2	7200	ee→ $\mu\mu$	1388.2
250	ee→ $\nu\nu$Z	11.1	7200	ee→ $\nu\nu$Z	319.3
250	ee→ $\tau\tau$Z	5.0	7200	ee→ $\tau\tau$Z	145.0
250	eγ →eZ	0.0	7200	eγ →eZ	1.1
250	γe →eZ	0.0	7200	γe →eZ	2.1
250	$\gamma\gamma \to \tau\tau$	0.0	7200	$\gamma\gamma \to \tau\tau$	1.4

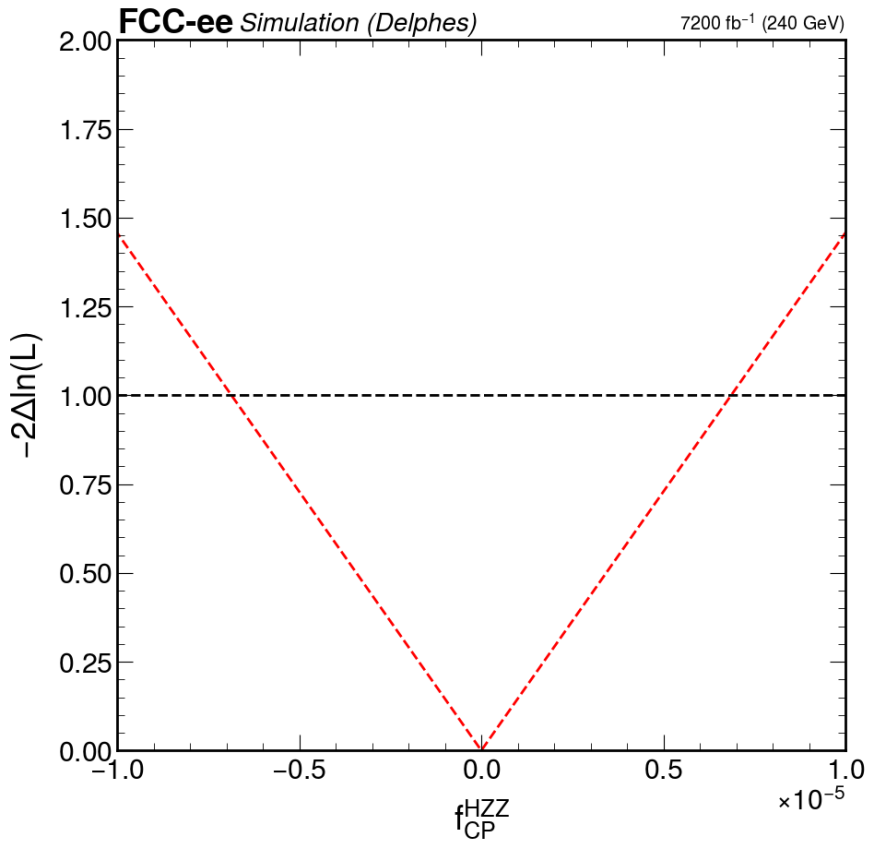
Fits with Reconstructed Signal H ⟶ X, Z ⟶ $\mu\mu$:

$@\ 250 fb^{-1}$

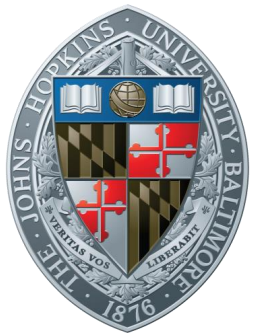


68% CL ≈ +/- 2.0 E-4

$@7200\ fb^{-1}$



68% CL ≈ +/- 0.7 E-5

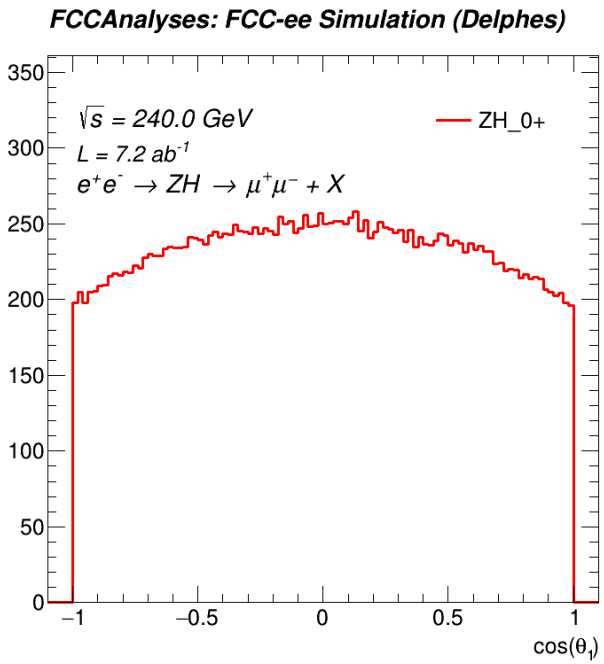


MELA:

- “Matrix Element Likelihood Approach”
- Calculates transition probability from one hypothesis to another using event kinematics.
  - Used to reweight a distribution in one sample to an alternative hypothesis.
- Calculates angular distributions.
- Currently interfaced to the FCC framework!

MELA in this study:

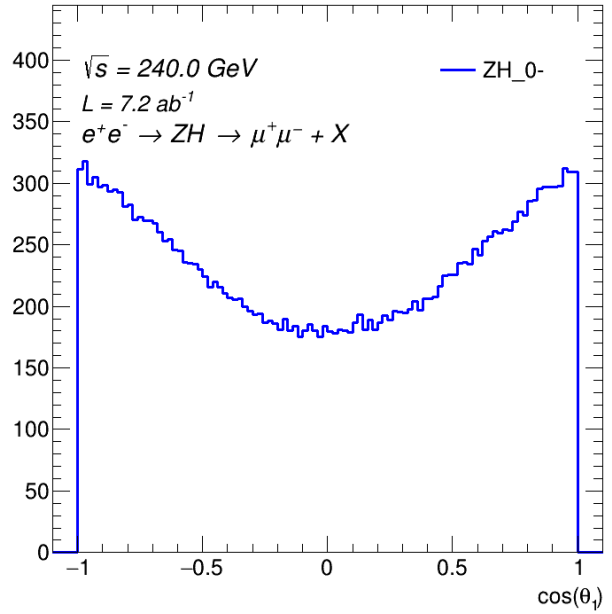
Simulated:

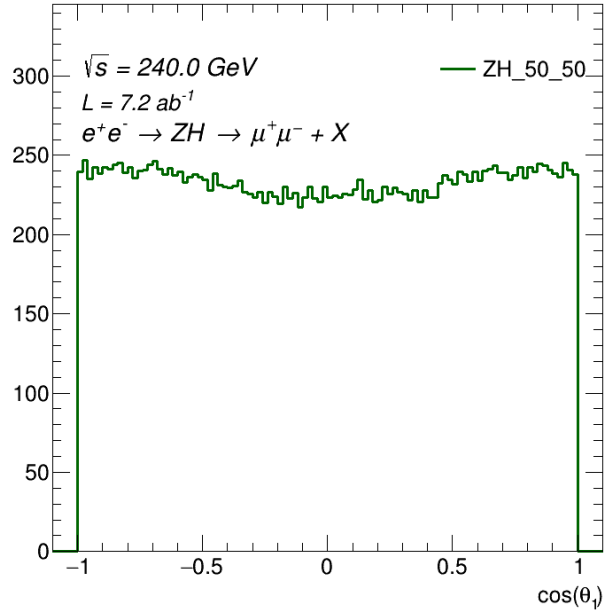


Reweighting:

$P(0^-)$

$P(50/50)$



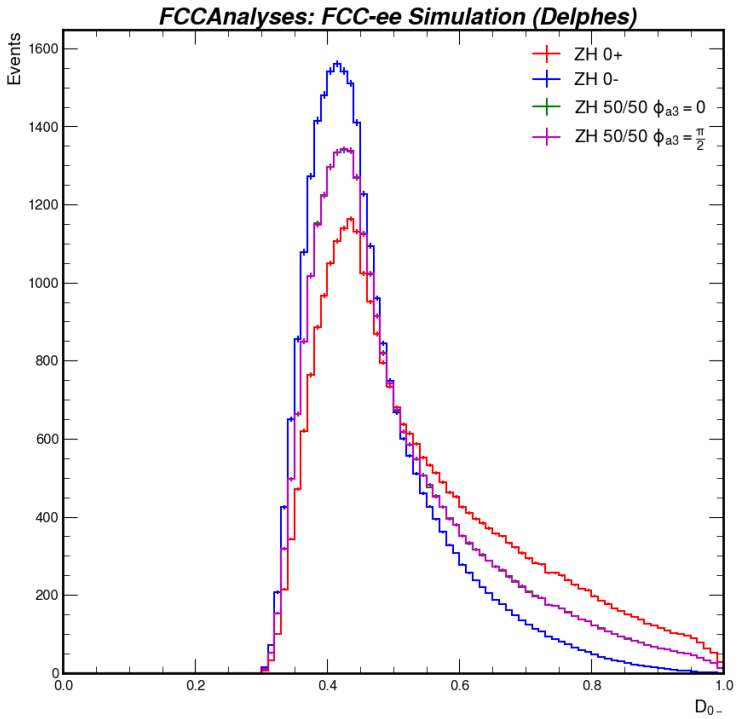


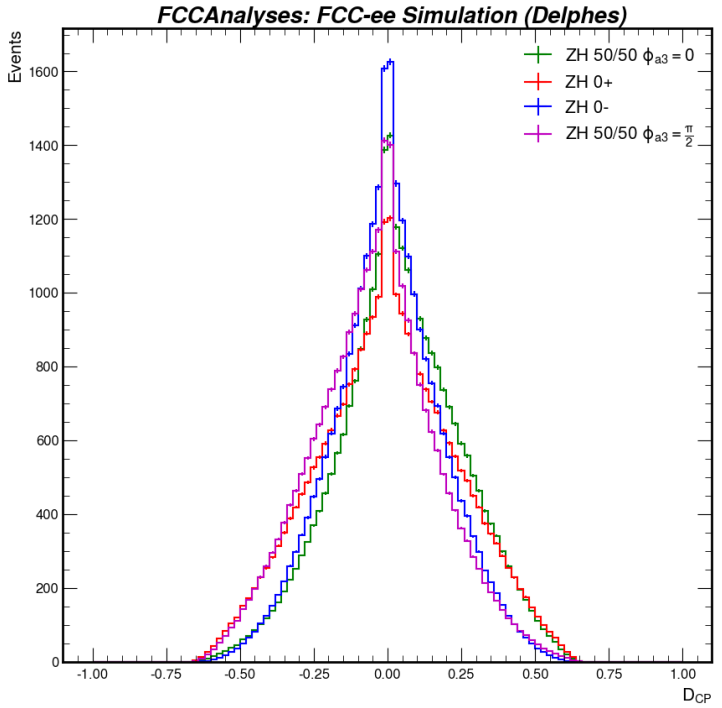
- Angular distributions and probabilities calculated by MELA.
- Reweights 0^+ distribution to 0^- and 50/50 mixture distributions.

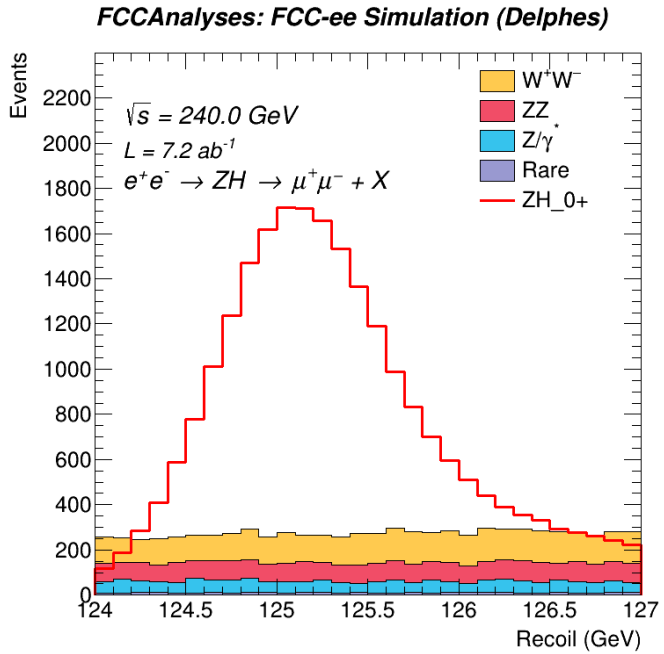
Improving this study with MELA:

$$D_{0^-} = \frac{P(0^-)}{P(0^+)+P(0^-)}$$
$$D_{CP} = \frac{P(int)}{2\sqrt{P(0^+)*P(0^-)}}$$

- Discriminants = Optimal observables from MELA probabilities.
- Determine optimal binning, create likelihood fit with D_{0^-}, D_{CP}, and m_{rec}.

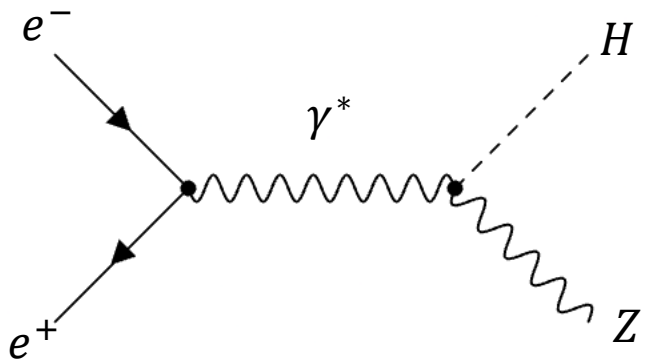


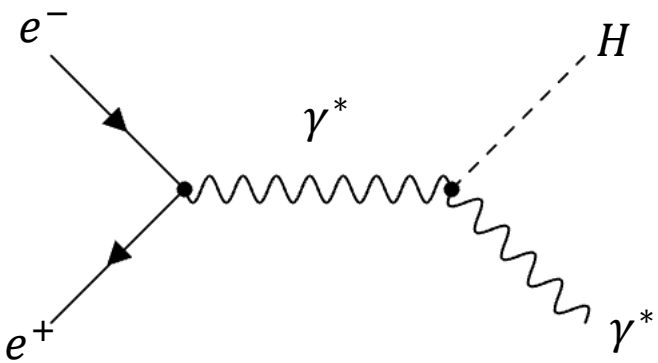


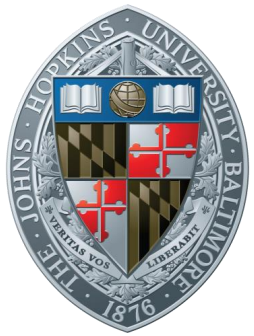


MELA in future studies:

- MELA can probe couplings besides f_{CP}^{HZZ}.
  - $f_{CP}^{HZ\gamma*}$, $f_{CP}^{H\gamma*\gamma*}$ studies also possible within FCC framework.







Conclusions:

- Likelihood fit from angular distributions represents a realistic constraints on f_{CP}^{HZZ}.
- MELA functional within FCC framework.
  - Pending review to be officially incorporated.
- Update to this study using discriminants in the works!
- Plans to extend this study:
  - $Z \rightarrow e^{+}e^{-}$ final state
  - Alternative couplings: $f_{CP}^{HZ\gamma*}$, $f_{CP}^{H\gamma*\gamma*}$