FCC-ee Higgs CP Studies:

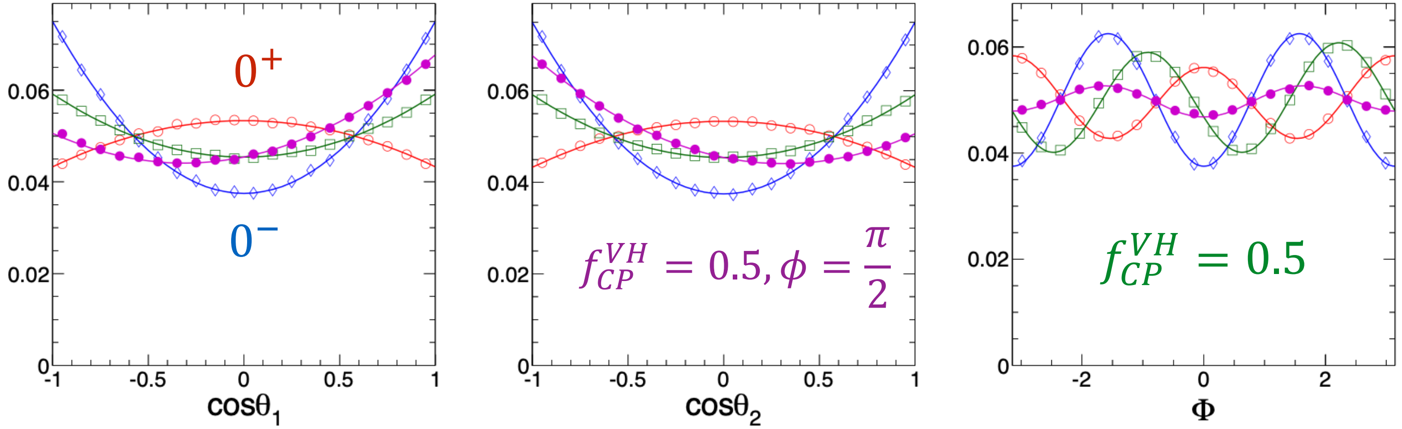
Nicholas Pinto (JHU), Andrei Gritsan (JHU), Jan Eysermans (MIT), Valdis Slokenbergs (JHU)

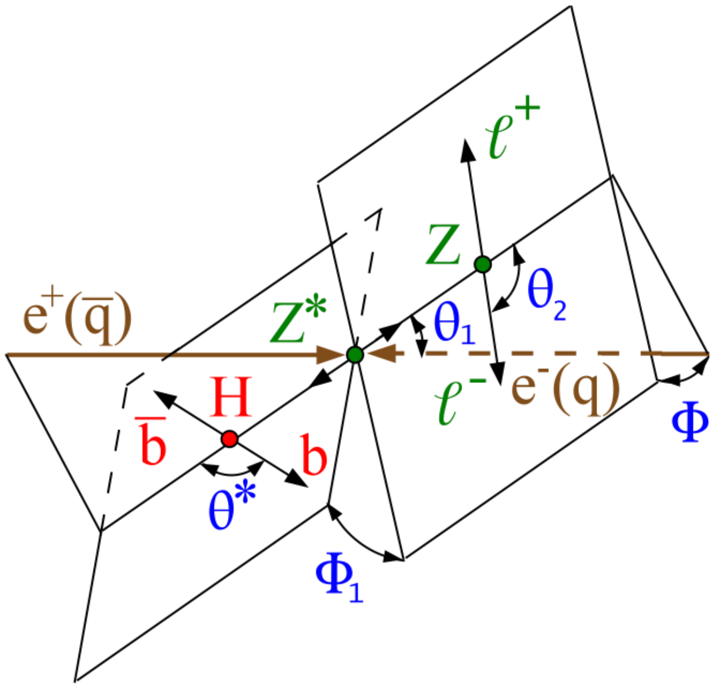
ECFA meeting on e+e- to ZH angular measurements

12 December 2023

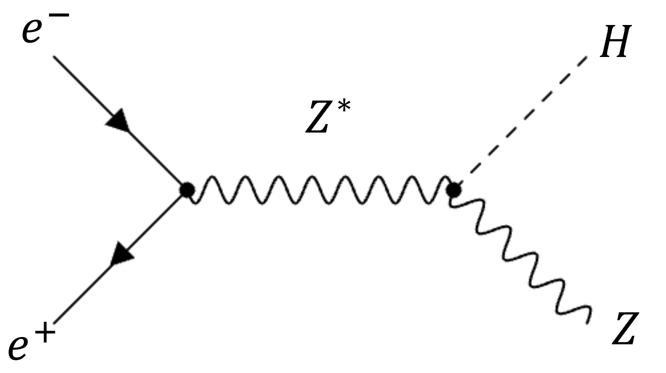
Past Studies: Snowmass 2013

arXiv:1309.4819





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

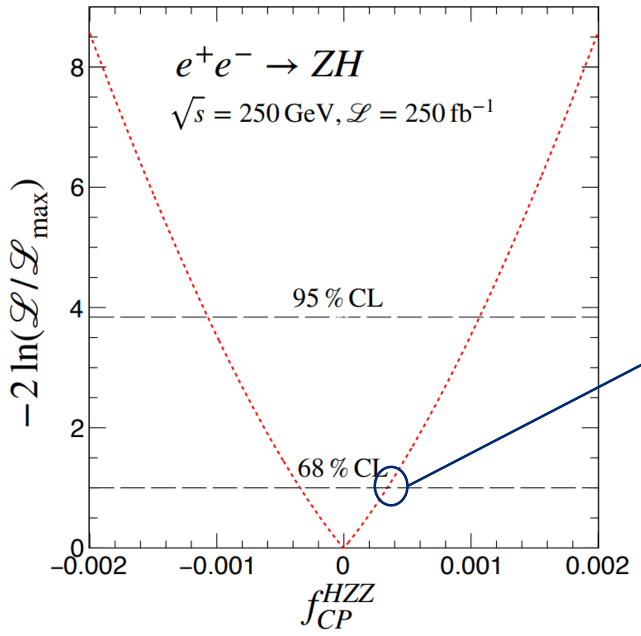


$$f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{\text{CP odd}}}{\Gamma_{H\to X}^{\text{CP odd}} + \Gamma_{H\to X}^{\text{CP even}}}$$

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

Past Studies: Snowmass 2022

arXiv:2205.07715



E (GeV)	$\mathcal{L}$ (fb^{-1})	f_{CP}^{HVV}
250	250	$\pm3.4\cdot10^{-4}$
250	2,500	$\pm3.9\cdot10^{-5}$
350	350	$\pm1.2\cdot10^{-4}$
350	3,500	$\pm2.9\cdot10^{-5}$
500	500	$\pm4.3\cdot10^{-5}$
500	5,000	$\pm1.3\cdot10^{-5}$
1,000	1,000	$\pm1.0\cdot10^{-5}$
1,000	10,000	$\pm3.0\cdot10^{-6}$

collider	energy	$\int\mathcal{L}dt$ (fb^{-1})	production	σ (fb)	decay	$\sigma\times\mathcal{B}$ (fb)	$N_{\rm prod}$	$N_{\rm reco}$	$f_{\rm jet}$
pp	14 TeV	3000	$gg\to H$	49850	$H\to ZZ^*\to4\ell$	6.23	18694	5608	0.1
pp	14 TeV	3000	$V^*V^*\to H$	4180	$H\to ZZ^*\to4\ell$	0.52	1568	470	0.6
pp	14 TeV	3000	$W^*\to WH$	1504	$H\to ZZ^*\to4\ell$	0.19	564	169	0.5
pp	14 TeV	3000	$Z^*\to ZH$	883	$H\to ZZ^*\to4\ell$	0.11	331	99	0.5
pp	14 TeV	3000	$t\bar{t}\to t\bar{t}H$	611	$H\to ZZ^*\to4\ell$	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	$H\to bb,\ Z\to\ell\ell$	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: $e^+e^- \to ZH \to ll\, b\bar{b}$. Background: $e^+e^- \to ZZ \to ll\, b\bar{b},\ N_{reco,Background}$ ~ 1/10th of signal,
Z mass, angles input to combine, f_{CP}^{HVV} returned at 68% CL.
4+ different samples (SM Signal, BSM Signal, Background, SM/BSM Interference) used to produce fits.

Current Study

Goals:

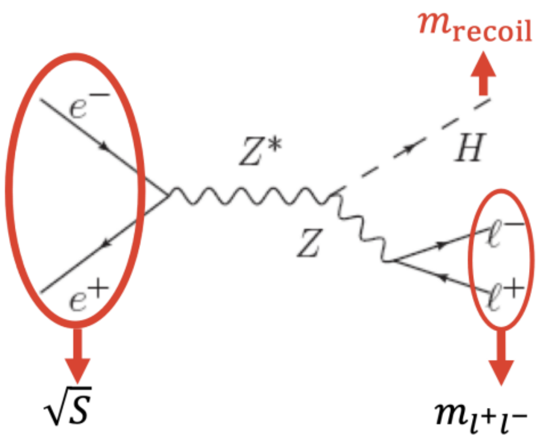
- ***Within FCC Framework***, reproduce past study fits using templates from FCC Reco-level simulation and yields from past LHE-level study.

- Reproduce fits but with the yields re-calculated based on luminosity, cross sections, and selection of the FCC samples.

- Generate 1 sample instead of many, use Matrix Element Likelihood Approach (MELA) to reweight to other samples.

Current Study

- This study shares selection with Jan Eysermans' and Ang Li's cross-sectional analysis.
- This analysis does not fully reconstruct the Higgs, it decays inclusively.
- Only manipulating a_3^{HVV}
- The study is run over the Winter2023 Campaign.



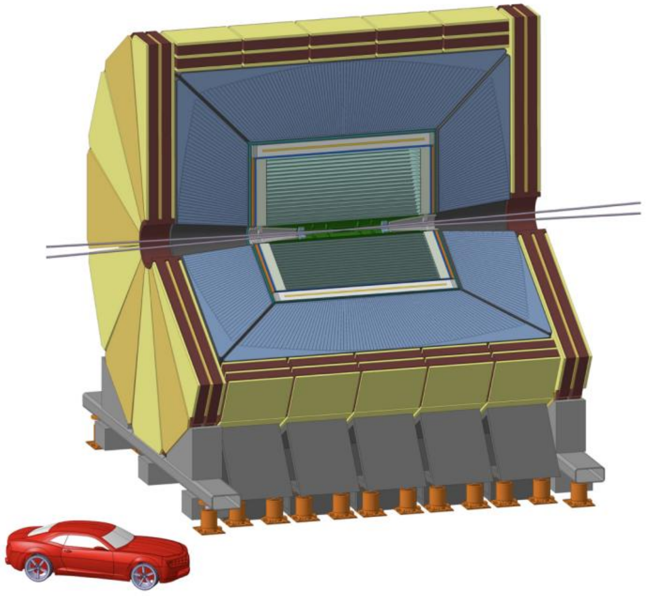
Sample Name	Processes	Generator	# of events	x-section(pb)
Higgs Processes				
wzp6_ee_mumuH	$e^+e^- \to \mu^+\mu^- H$	WHIZARD + PYTHIA6	1,200,000	0.0067643
wzp6_ee_eeH	$e^+e^- \to e^+e^- H$	WHIZARD + PYTHIA6	1,200,000	0.0071611
Diboson Processes				
p8_ee_ZZ_ecm240	$e^+e^- \to ZZ$	PYTHIA8	56,162,093	1.35899
p8_ee_WW_ecm240	$e^+e^- \to WW$	PYTHIA8	373,375,386	16.4385
Dilepton Processes				
wzp6_ee_mumu	$e^+e^- \to \mu^+\mu^-$	WHIZARD + PYTHIA6	53,400,000	5.288
wzp6_ee_ee_Mee_30_150	$e^+e^- \to e^+e^-$	WHIZARD + PYTHIA6	85,400,000	8.305
wzp6_ee_tautau	$e^+e^- \to \tau^+\tau^-$	WHIZARD + PYTHIA6	52,400,000	4.668
Electron Photon Processes				
wzp6_egamma_eZ_Zmumu	$e^-\gamma \to e^- Z(\mu^+\mu^-)$	WHIZARD + PYTHIA6	6,000,000	0.10368
wzp6_gammae_eZ_Zmumu	$e^+\gamma \to e^+ Z(\mu^+\mu^+)$	WHIZARD + PYTHIA6	5,600,000	0.10368
wzp6_egamma_eZ_Zee	$e^-\gamma \to e^- Z(e^+e^-)$	WHIZARD + PYTHIA6	6,000,000	0.05198
wzp6_gammae_eZ_Zee	$e^+\gamma \to e^+ Z(e^+e^-)$	WHIZARD + PYTHIA6	6,000,000	0.05198
Photon Photon Processes				
wzp6_gaga_mumu_60	$\gamma\gamma \to \mu^+\mu^-$	WHIZARD + PYTHIA6	33,900,000	1.5523
wzp6_gaga_ee_60	$\gamma\gamma \to e^+e^-$	WHIZARD + PYTHIA6	22,500,000	0.873
wzp6_gaga_tautau_60	$\gamma\gamma \to \tau^+\tau^-$	WHIZARD + PYTHIA6	33,700,000	0.836
Other Processes				
wzp6_ee_nuenueZ	$e^+e^- \to \nu_e\bar{\nu}_e Z$	WHIZARD + PYTHIA6	2,000,000	0.033274

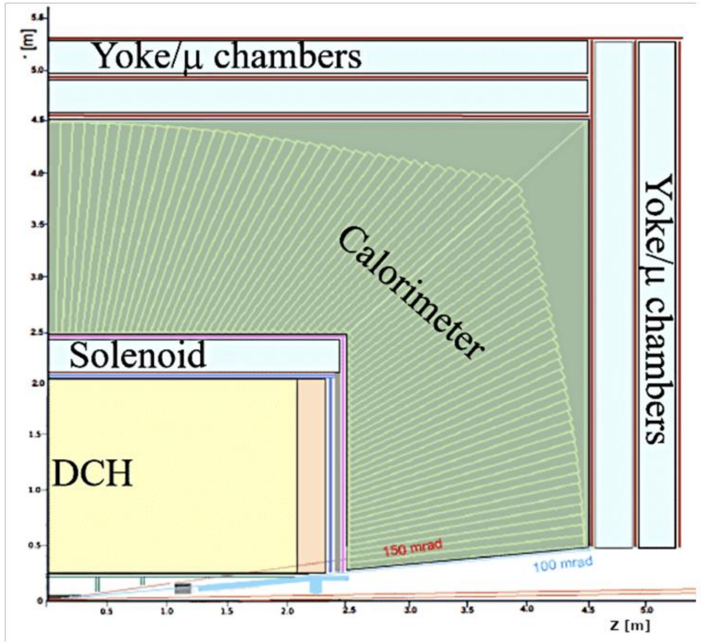
These come from Jan's and Ang's study.

FCC-IDEA Detector

Detector simulation is done in the DELPHES framework.

The IDEA detector concept for FCC-ee





Current Cuts Made

≥ 1 isolated lepton.

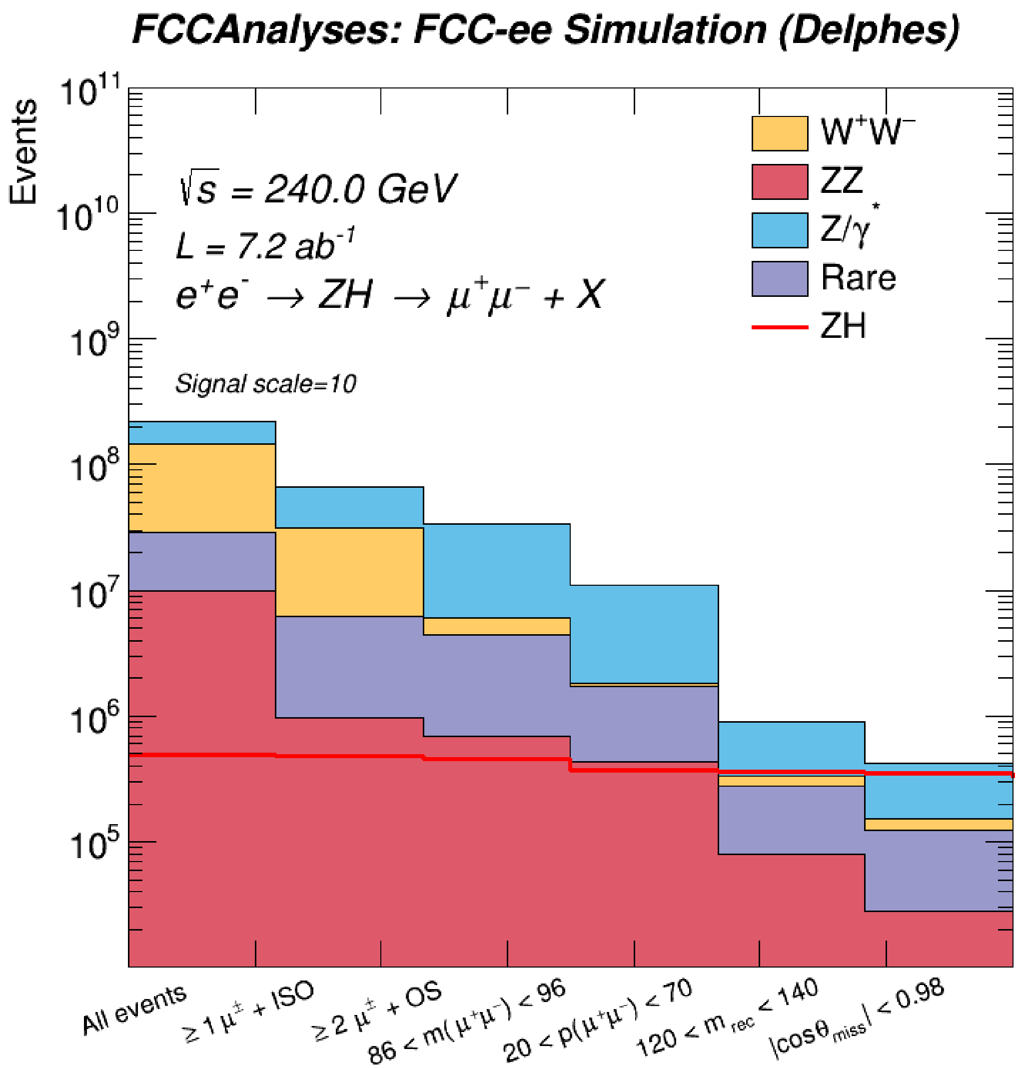
≥ 2 charge conj. leptons.

86 < dilepton inv. mass < 96

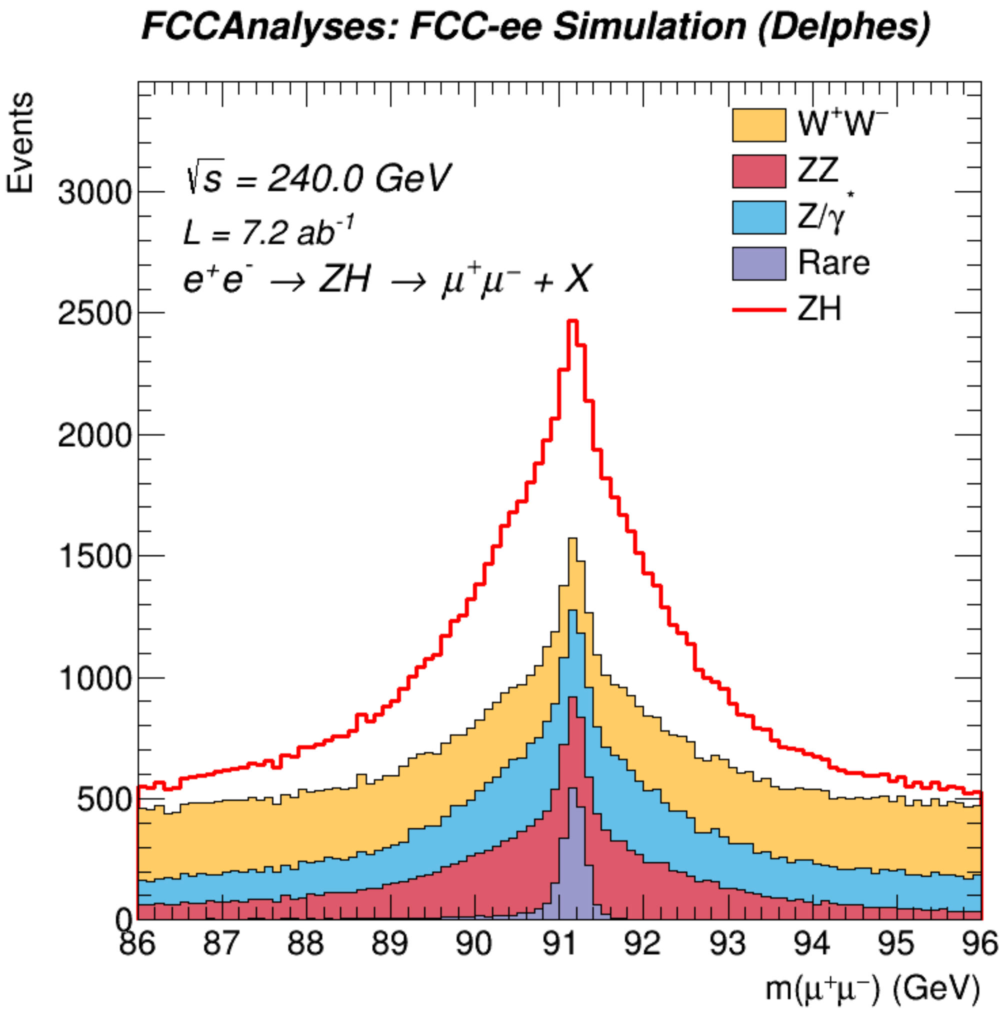
20 < dilepton system momentum < 70

120 < Recoil mass < 140

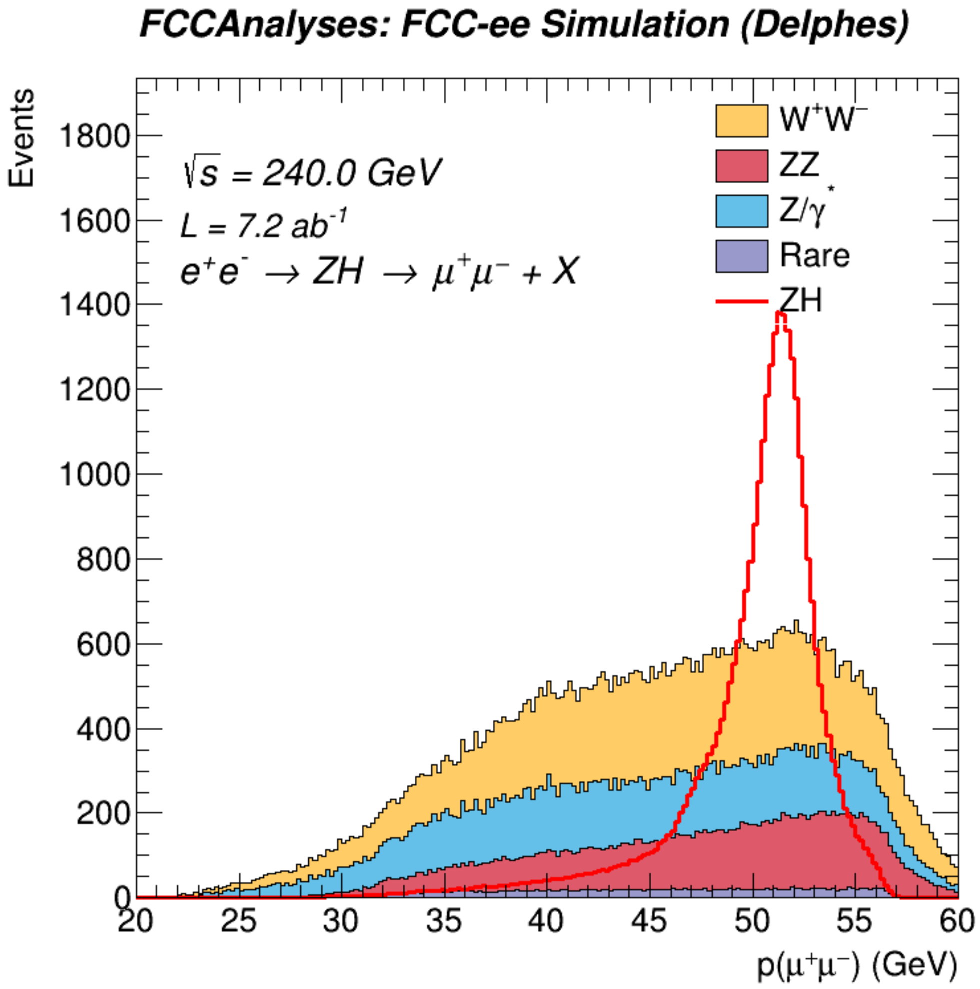
|Cos(t)_miss| < 0.98



$86 < m(\mu^+ \mu^-) < 96$

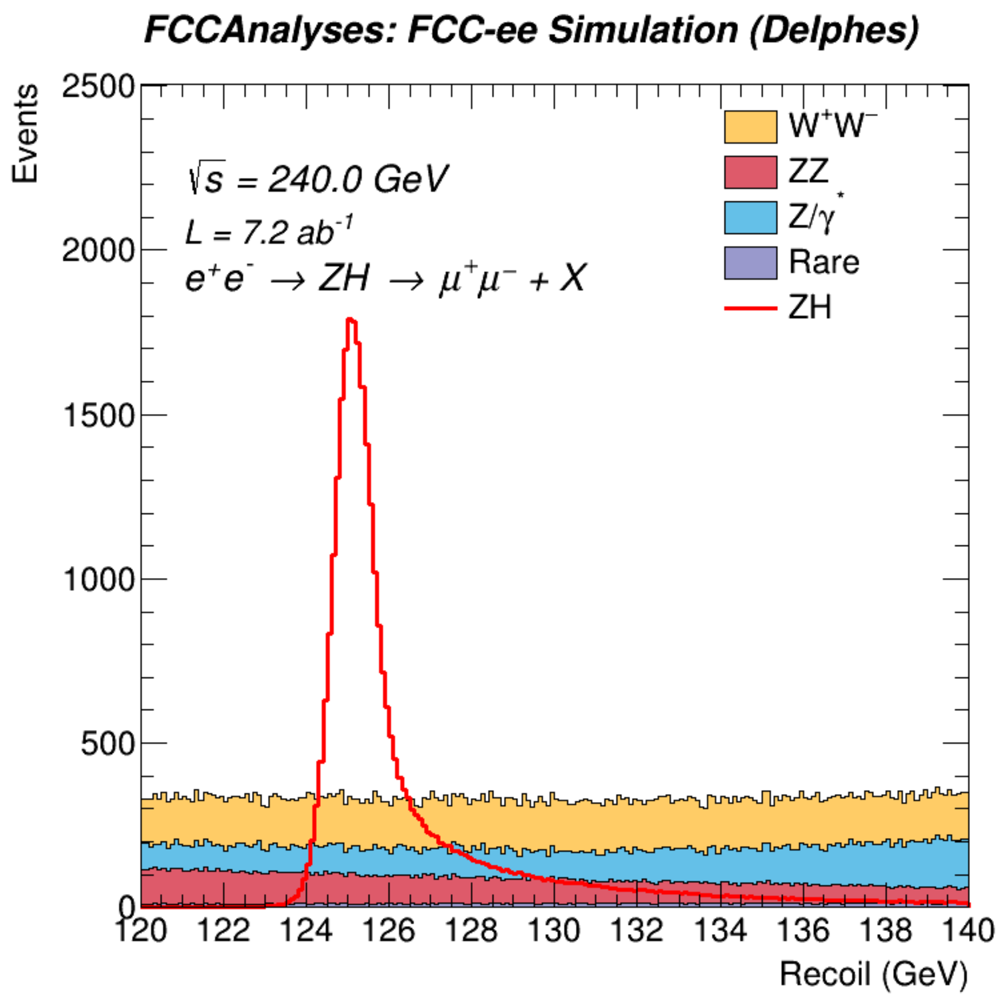

FCCAnalyses: FCC-ee Simulation (Delphes)
Events
3000
2500
2000
1500
1000
500
0
86
87
88
89
90
91
92
93
94
95
96
m(μ⁺μ⁻) (GeV)
√s = 240.0 GeV
L = 7.2 ab⁻¹
e⁺e⁻ → ZH → μ⁺μ⁻ + X
W⁺W⁻
ZZ
Z/γ*
Rare
ZH

$20 < p(\mu^+ \mu^-) < 60$



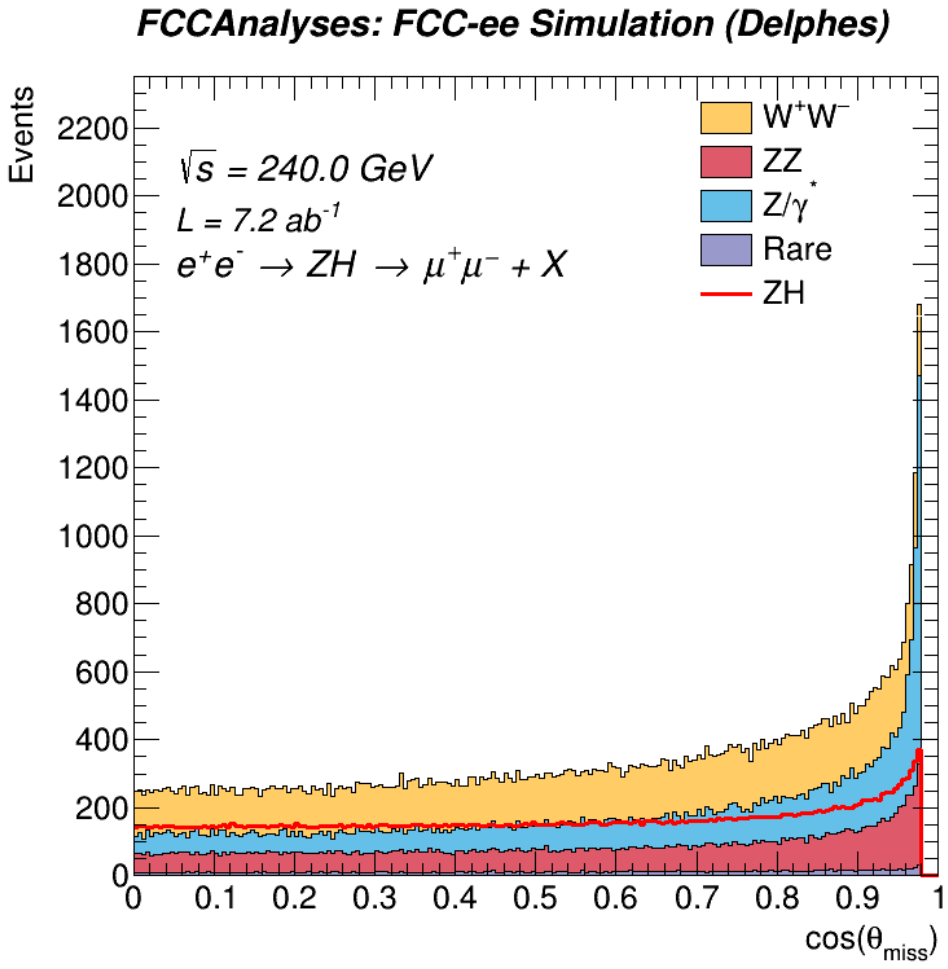
FCCAnalyses: FCC-ee Simulation (Delphes)
√s = 240.0 GeV
L = 7.2 ab⁻¹
e⁺e⁻ → ZH → μ⁺μ⁻ + X
W⁺W⁻
ZZ
Z/γ*
Rare
ZH
Events
p(μ⁺μ⁻) (GeV)

$120 < m_{rec} < 140$



FCCAnalyses: FCC-ee Simulation (Delphes)
Events
$\sqrt{s}$ = 240.0 GeV
L = 7.2 ab^{-1}
$e^+e^- \to ZH \to \mu^+\mu^- + X$
W^+W^-
ZZ
Z/γ^*
Rare
ZH
0
500
1000
1500
2000
2500
120
122
124
126
128
130
132
134
136
138
140
Recoil (GeV)

$|\cos\theta_{miss}| < 0.98$



What is MELA?

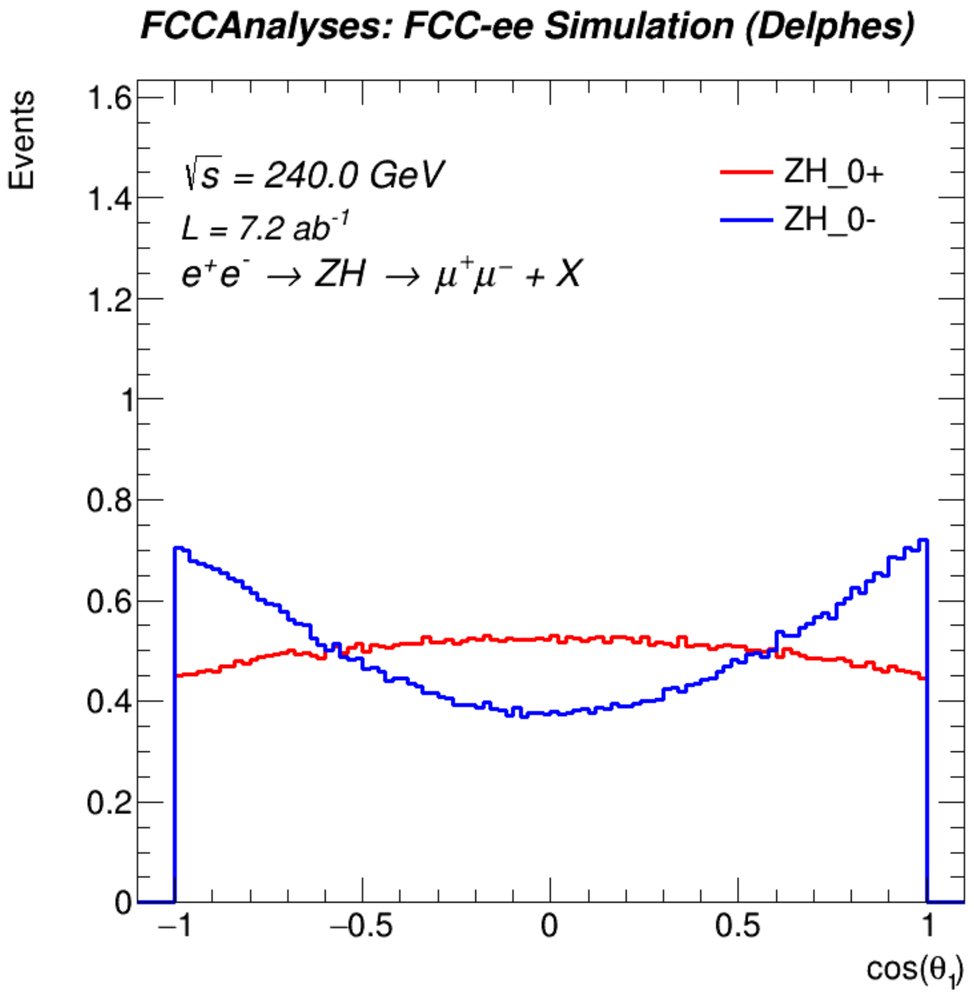
- Use event kinematics to reweight from SM hypothesis to BSM hypothesis.

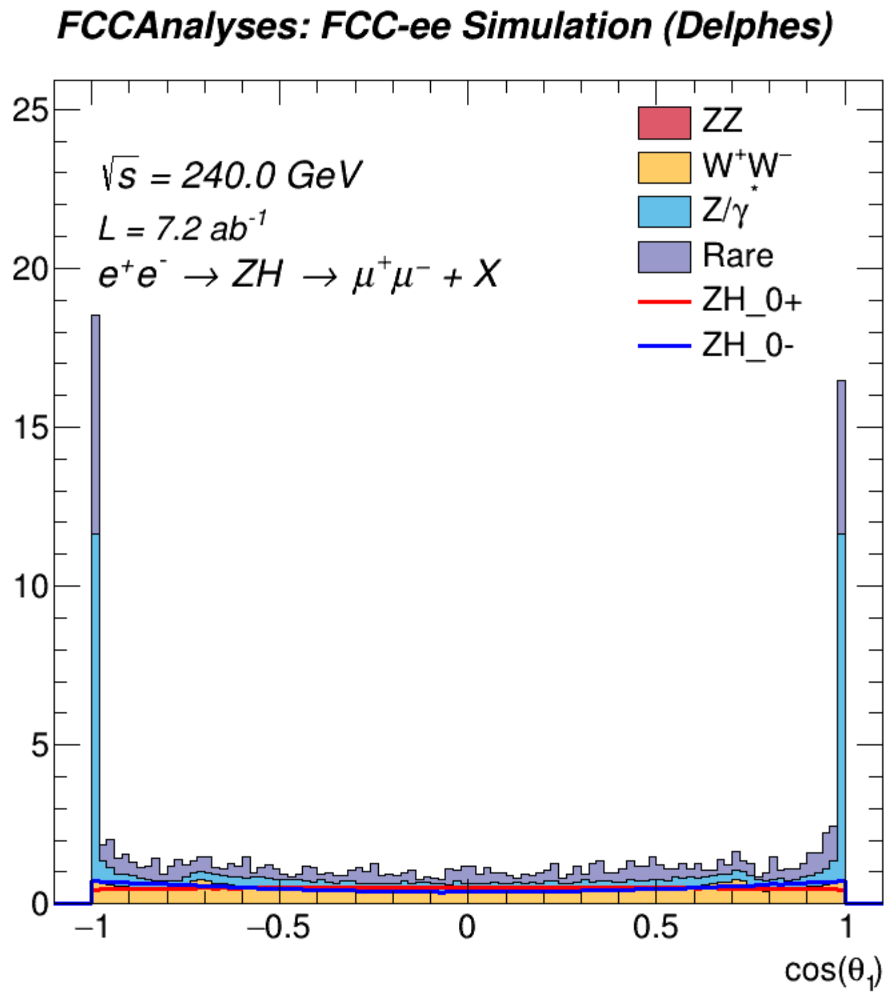
$$R = \frac{P_{BSM}}{P_{SM}}$$

- Also reweight from SM hypothesis to mixed states.

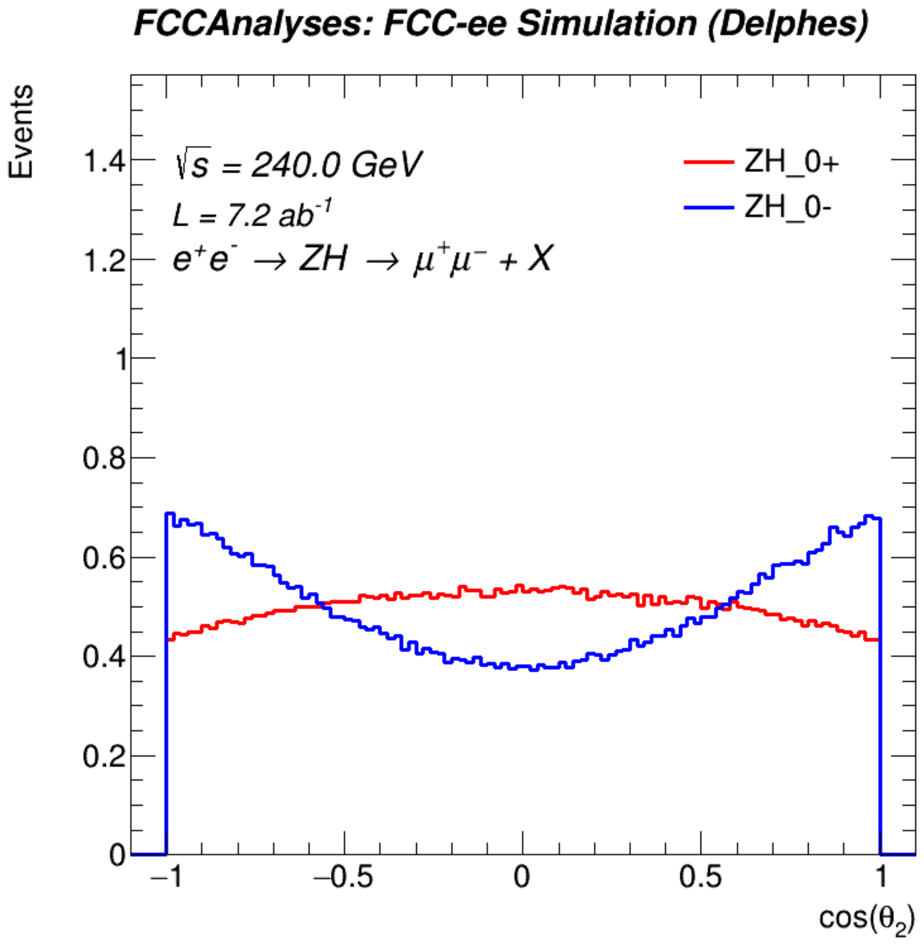
$$R = \frac{aP_{SM} + bP_{BSM}}{P_{SM}}$$

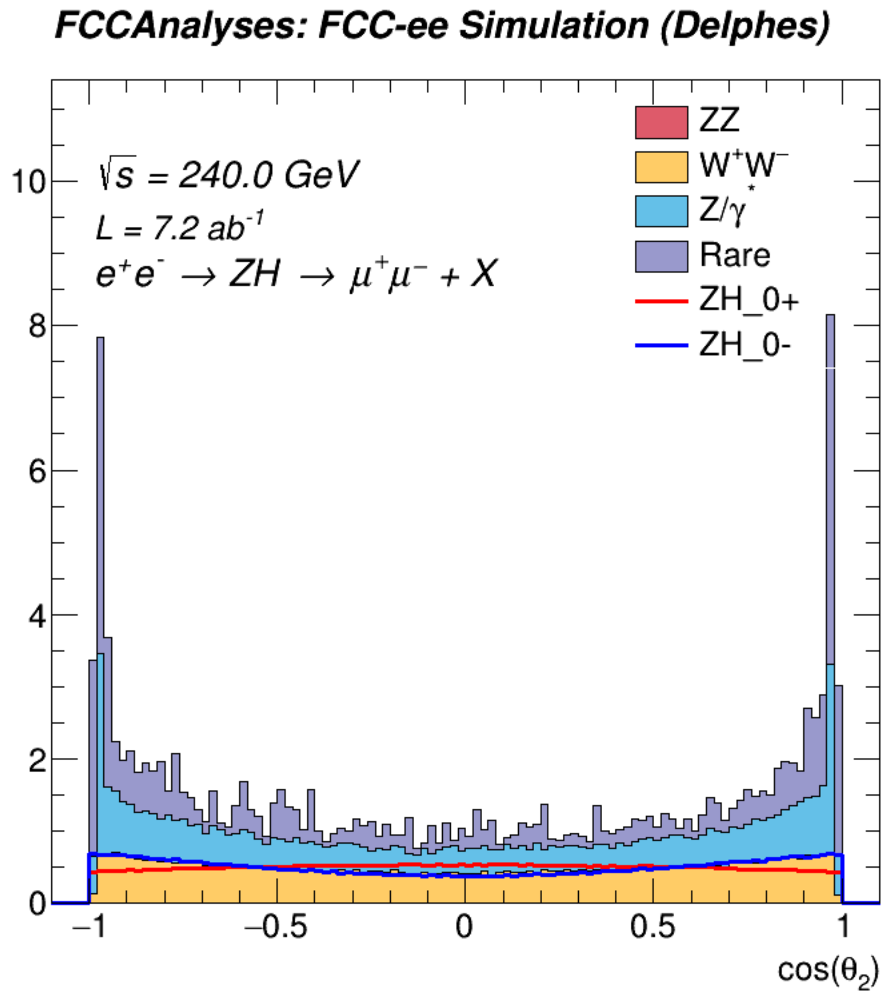
Reco-Level Angular Distributions



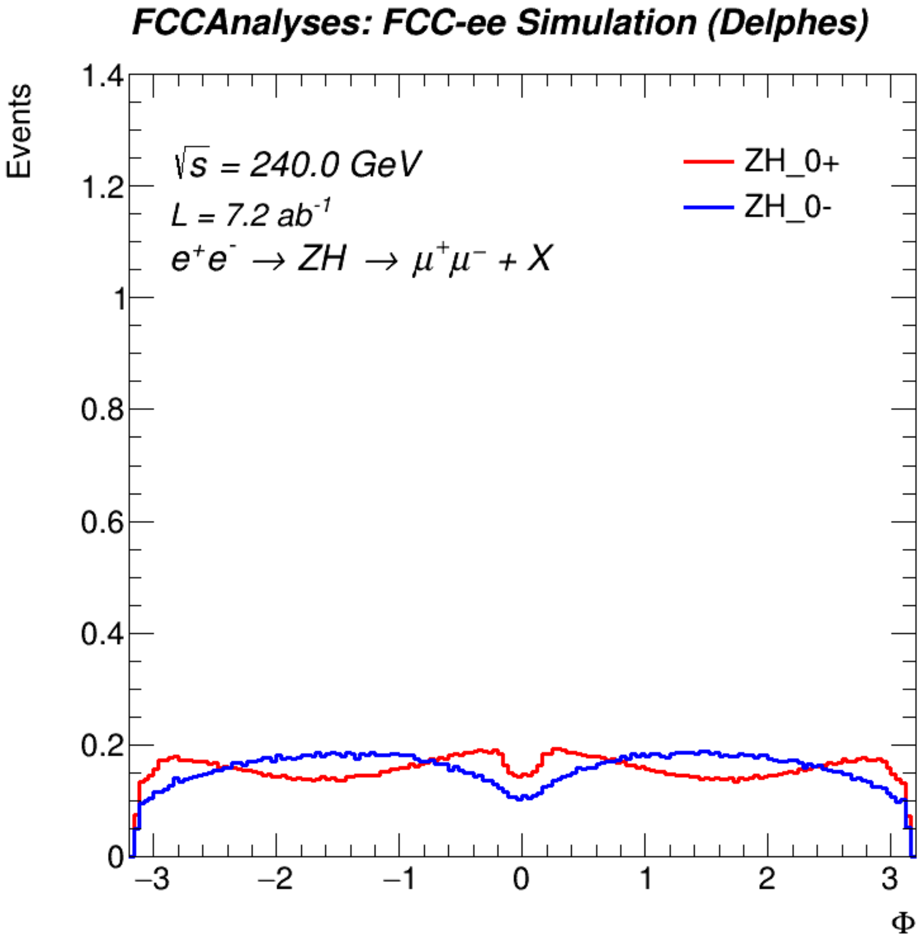


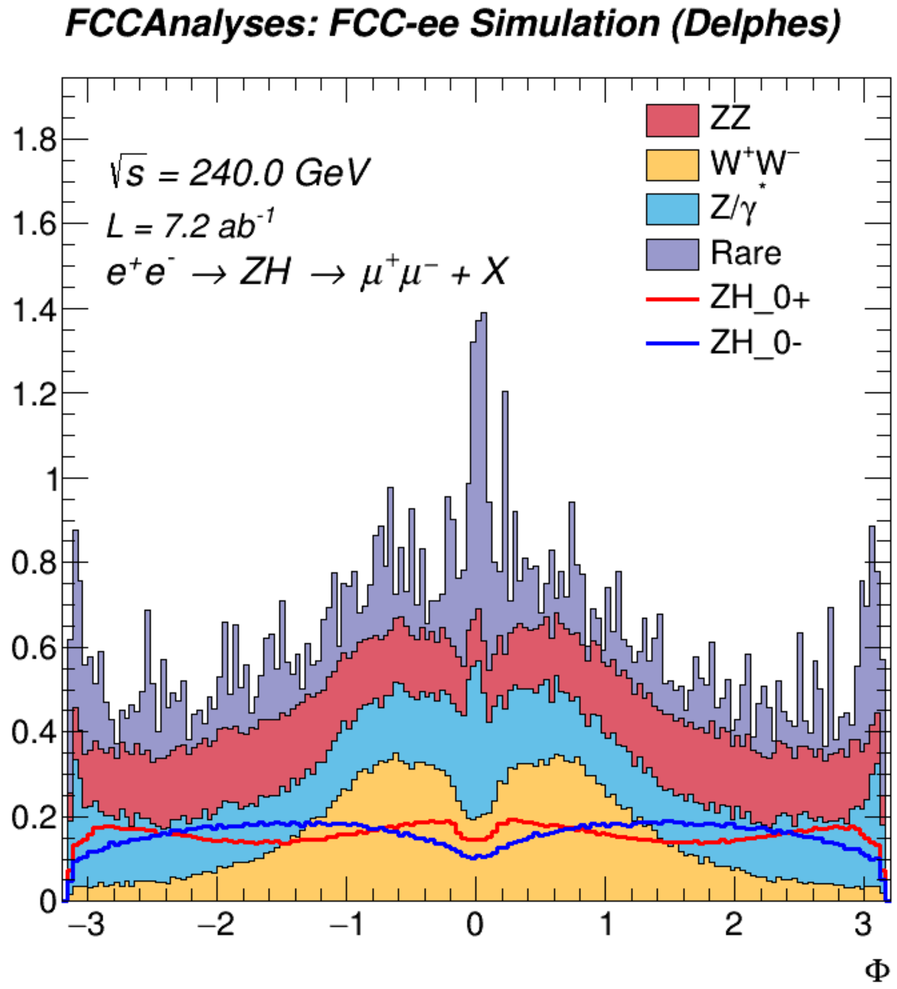
Reco-Level Angular Distributions





Reco-Level Angular Distributions





Yields

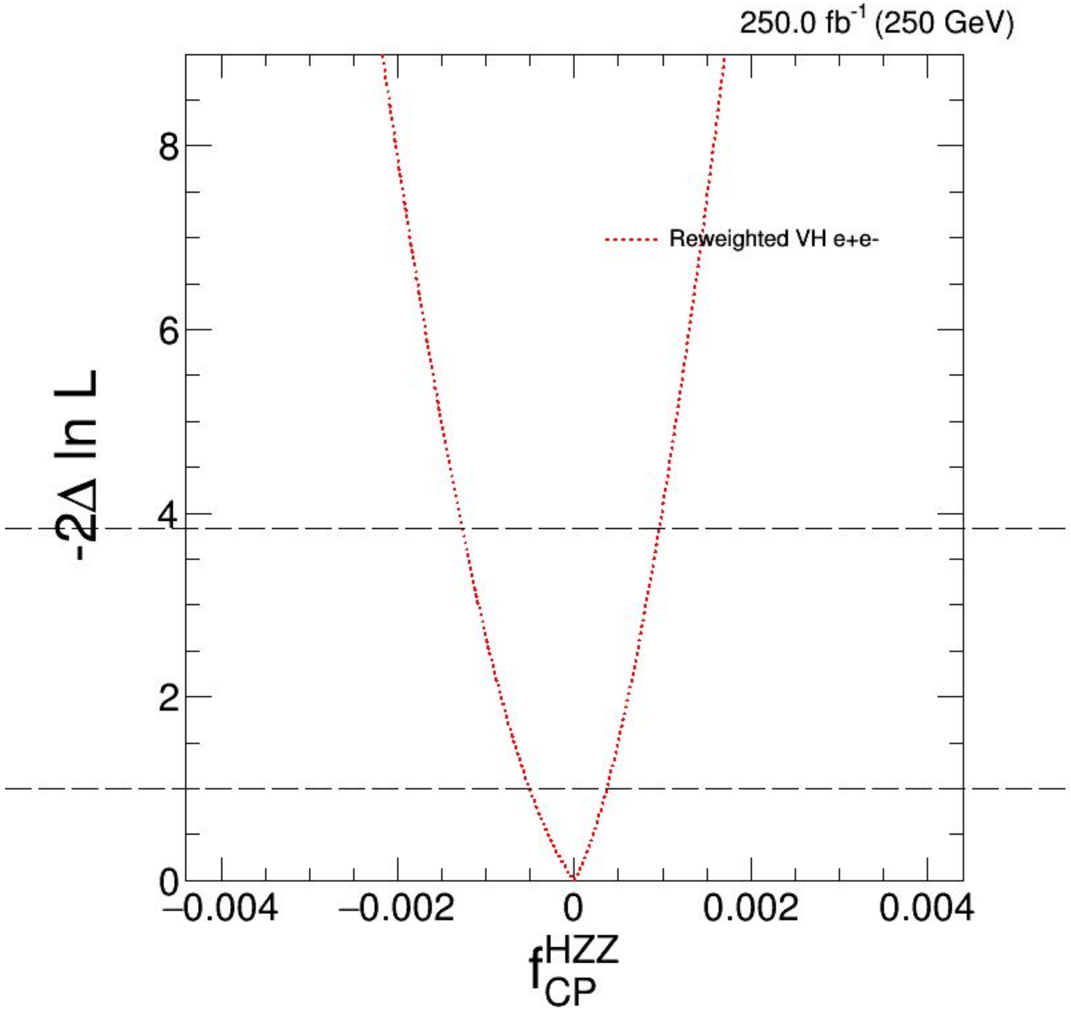
Snowmass 2022

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	–

Energy (GeV)	$\int Ldt(fb^{-1})$	production	decay	$\sigma * B$ (fb)	N_{prod}	N_{reco}
250	250	ee→Z* → ZH	H→X, Z→ $\mu\mu$	8.08	2019	1615
240	250	ee→Z* → ZH	H→X, Z→ $\mu\mu$	6.76	1690	1115
240	7200	ee→Z* → ZH	H→X, Z→ $\mu\mu$	6.76	48672	32123
250	250	ee→ZZ	Z→ $llbb$	–	–	184
240	7200	ee→ZZ	Z→ X	1360	$9.78 * 10^6$	15039
240	7200	ee→WW	W→X	$1.64 * 10^4$	$1.18 * 10^8$	29610
240	7200	ee→ Z/γ	$Z/\gamma \to l^+l^-$	9596	$6.91 * 10^7$	18861

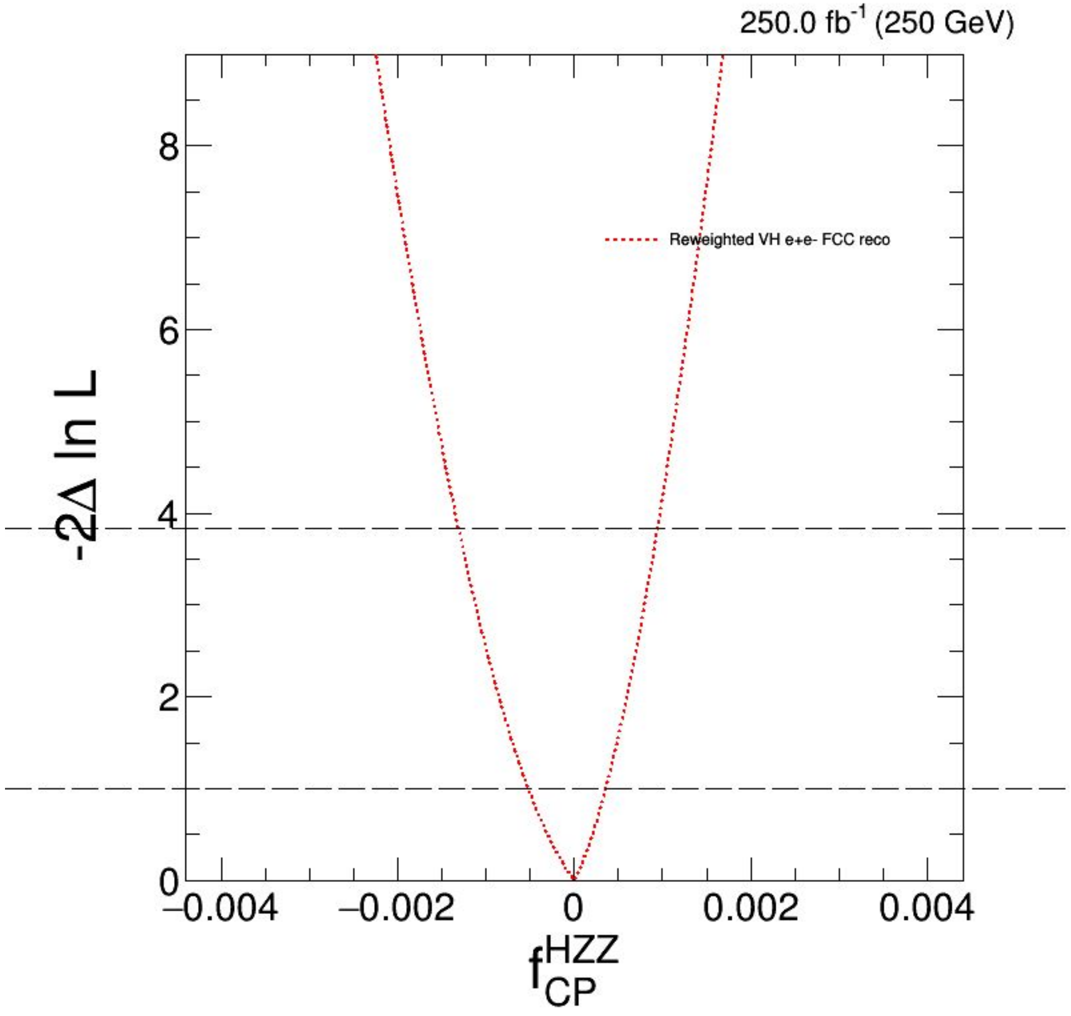
Combine Fits: FCC LHE-Level Data, Snowmass Yields

- FCC LHE-level data used as input.
- Yields use values from Snowmass.
- 68% CL $f_{CP}^{HZZ} \approx \pm 4.4 * 10^{-4}$
- Verify that f_{CP}^{HZZ} values are comparable to Snowmass 2022.



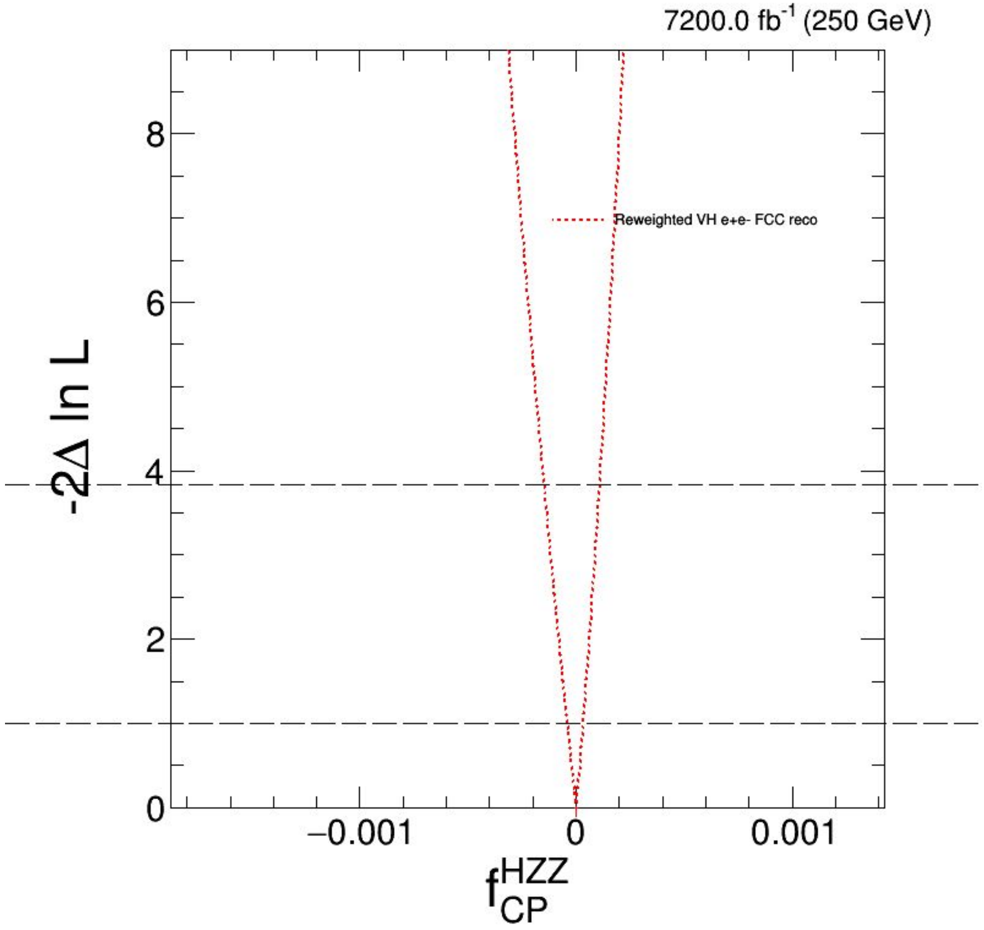
Combine Fits: FCC Reco-Level Data, Snowmass Yields

- FCC Reco-level data used as input.
- Yields use values from Snowmass.
- 68% CL $f_{CP}^{HZZ} \approx \pm 4.1 * 10^{-4}$



Combine Fits: FCC Reco-Level Data, FCC Yields, Snowmass Background

- FCC Reco-level data used as input.
- Yields use values from FCC.
- 68% CL $f_{CP}^{HZZ} \approx \pm 3.7 * 10^{-5}$
- Aligns with Snowmass projection for increased luminosity, even with detector effects.



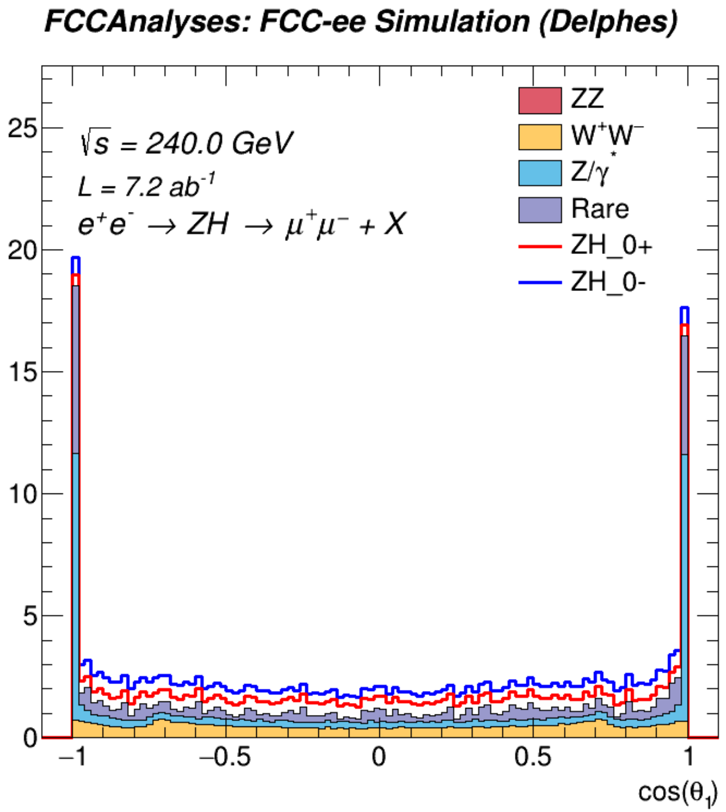
Conclusions

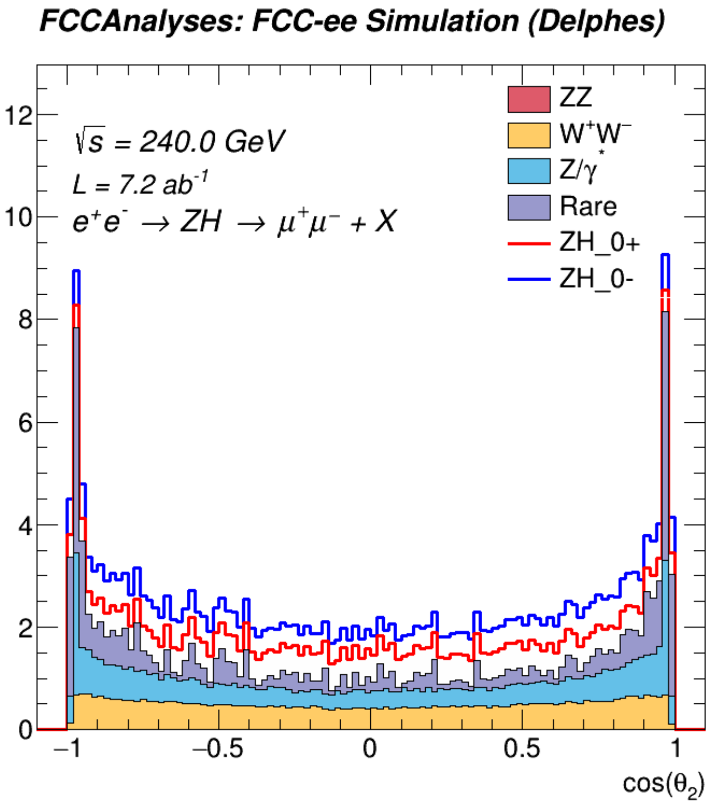
- Fits with yields from FCC parameters and templates have been created.
  - We seem to agree with Snowmass.
- Next steps: Incorporate full backgrounds, optimize cuts.

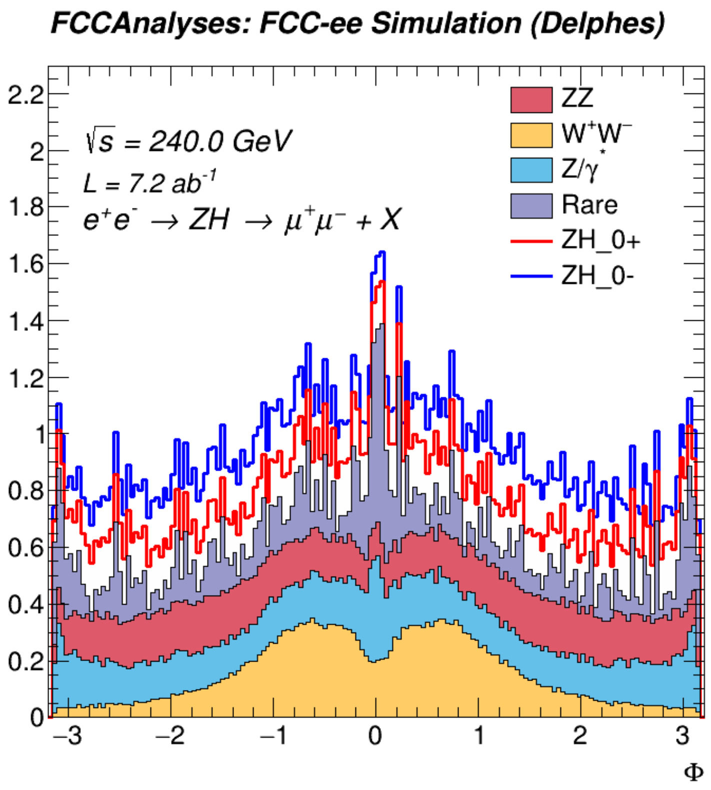
References

- IDEA Detector: https://inspirehep.net/files/64b3c8108ce781ee7a215284970eec70
- Snowmass 2013: https://arxiv.org/pdf/1309.4819.pdf
- Snowmass 2022: https://arxiv.org/pdf/2205.07715.pdf

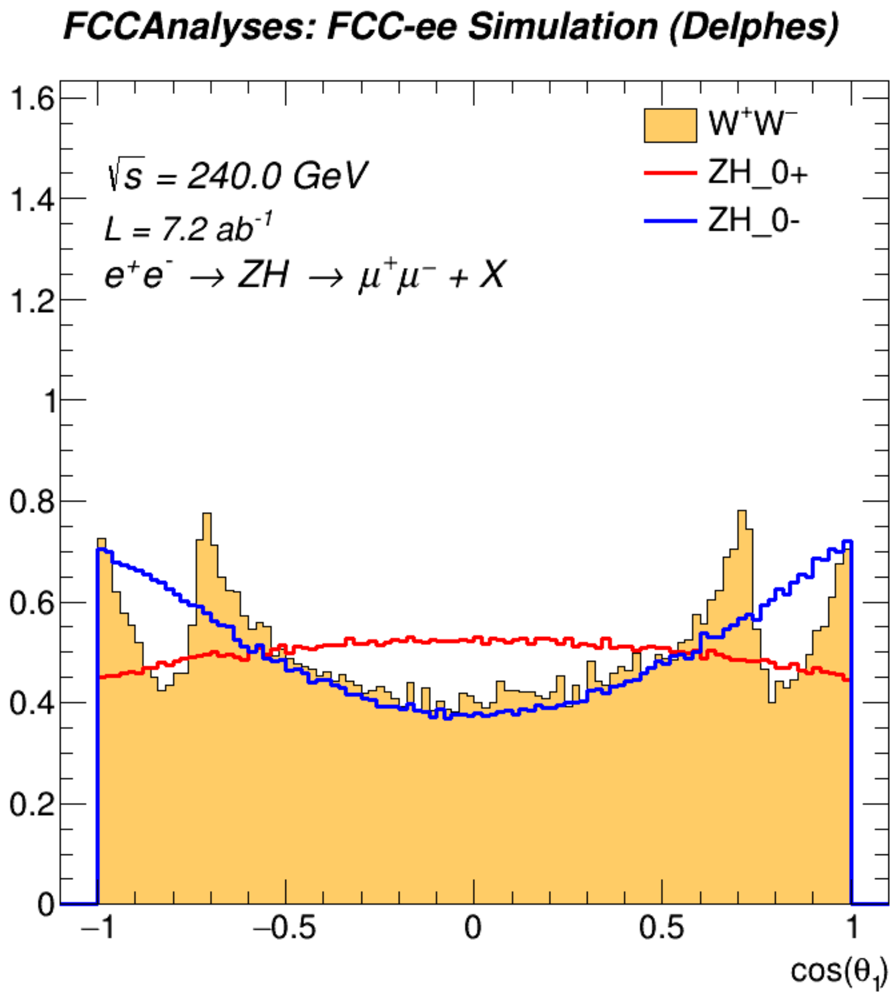
Backup Plots: Stacked Histograms

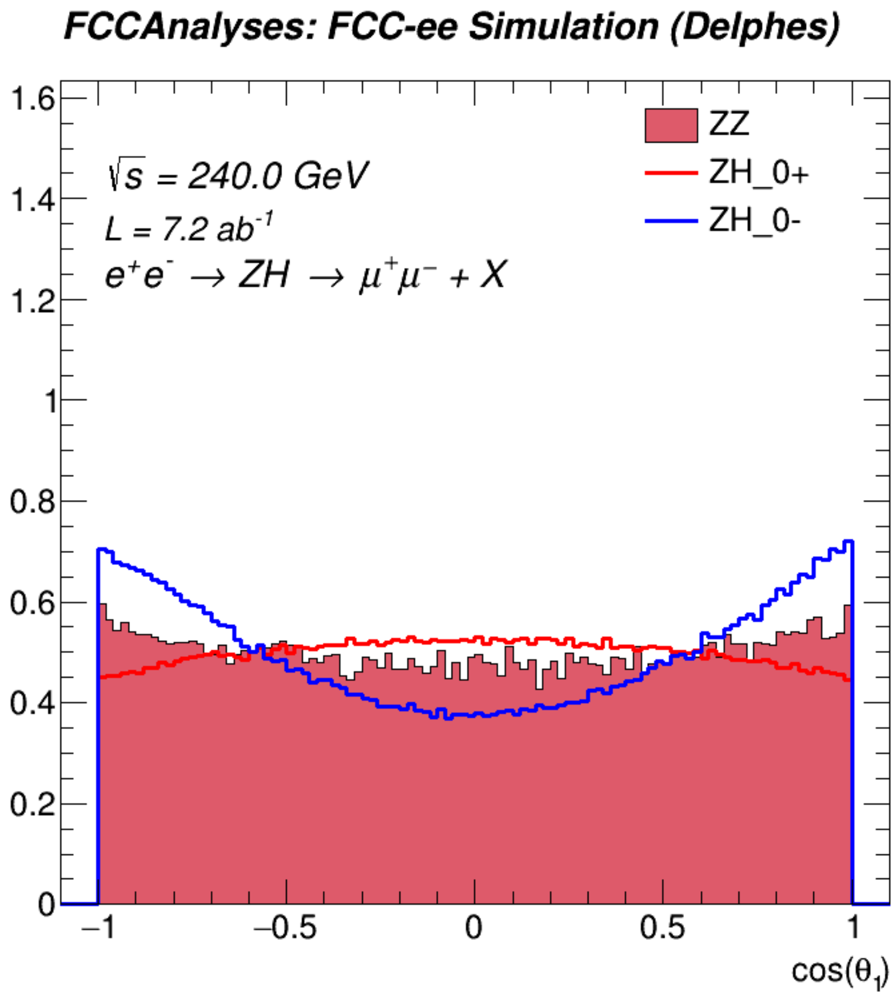




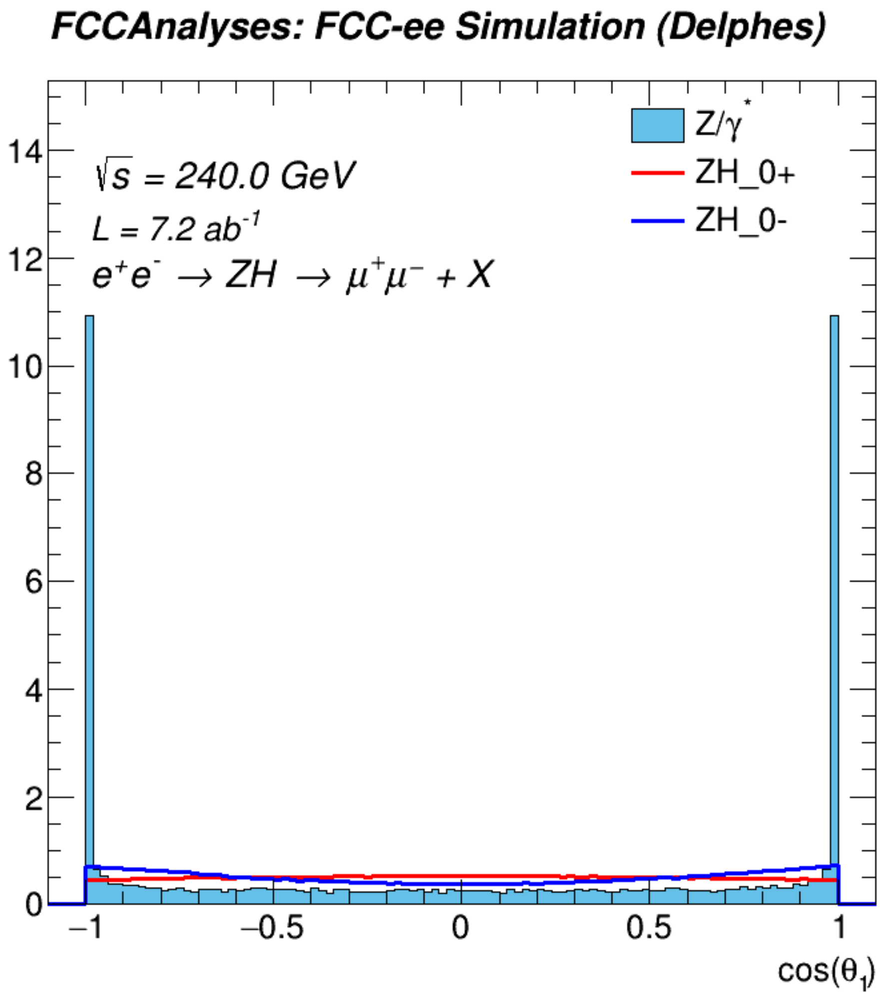


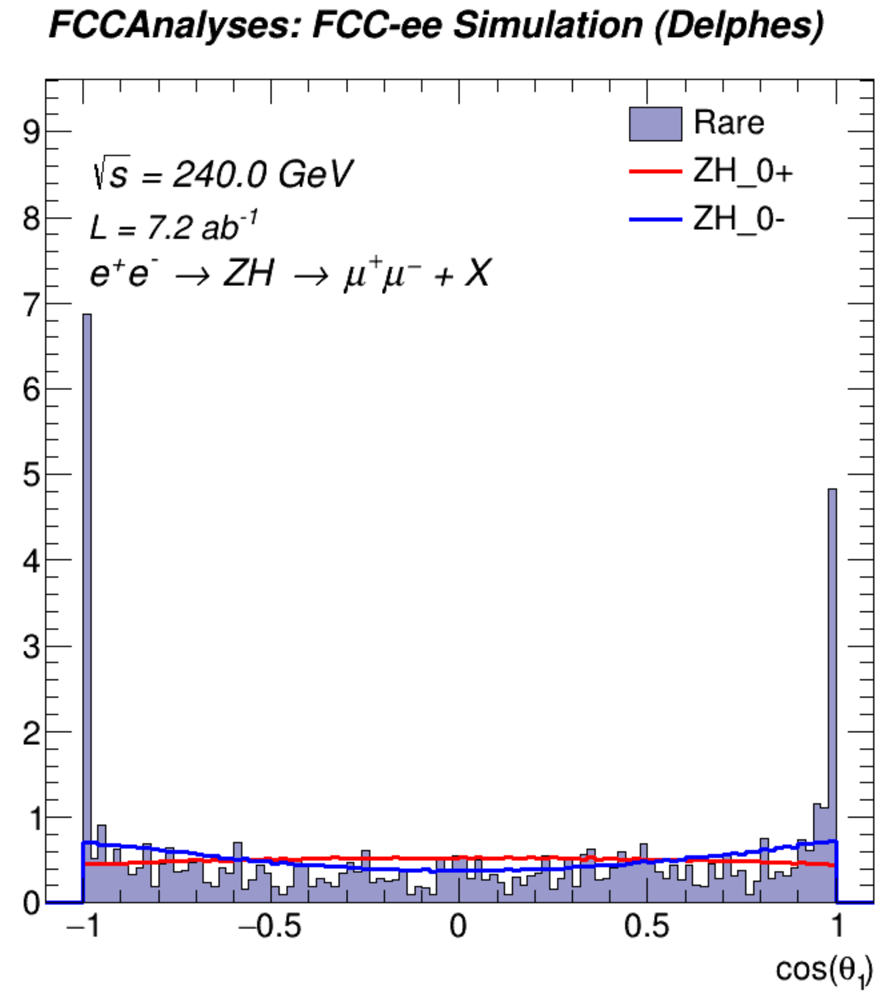
Backup Plots: $\cos\theta_1$



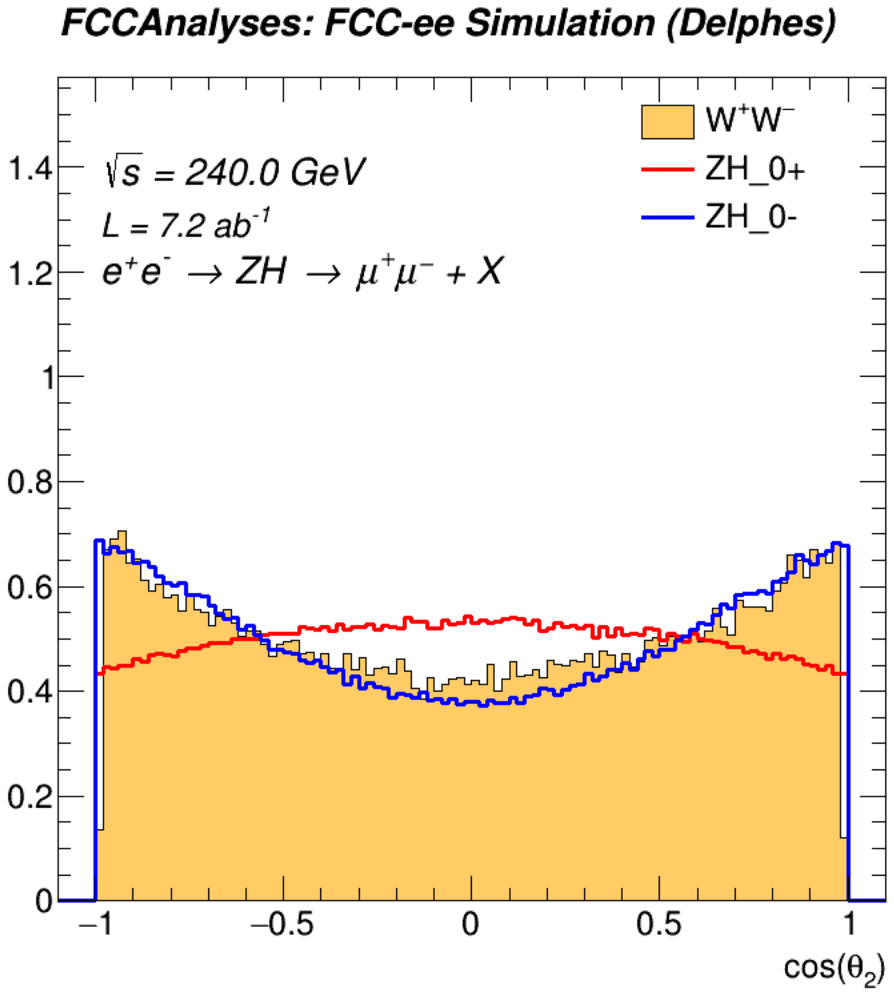


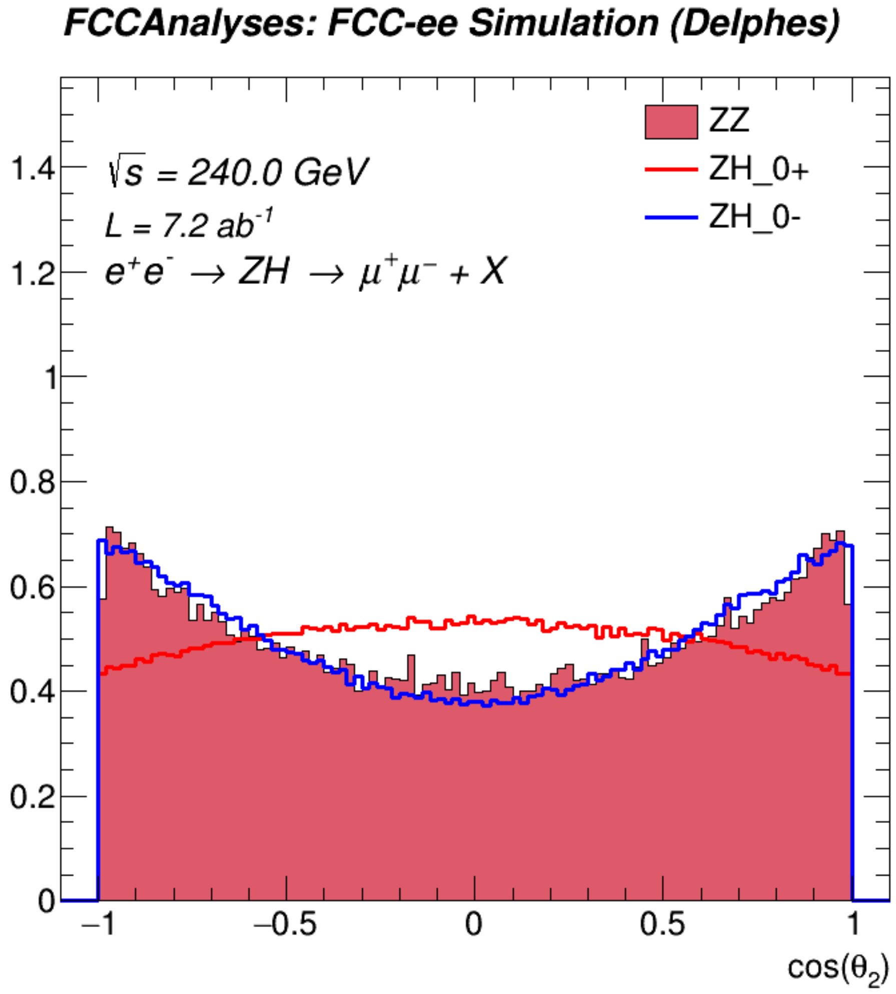
Backup Plots: $\cos\theta_1$



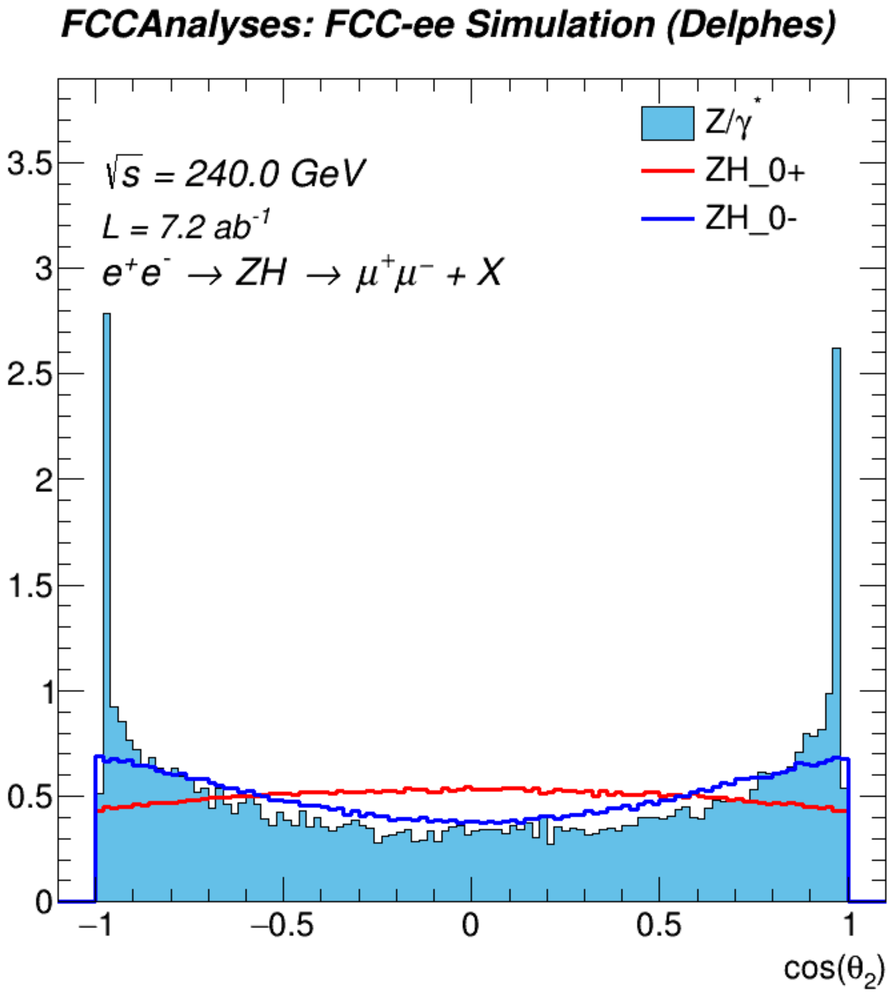


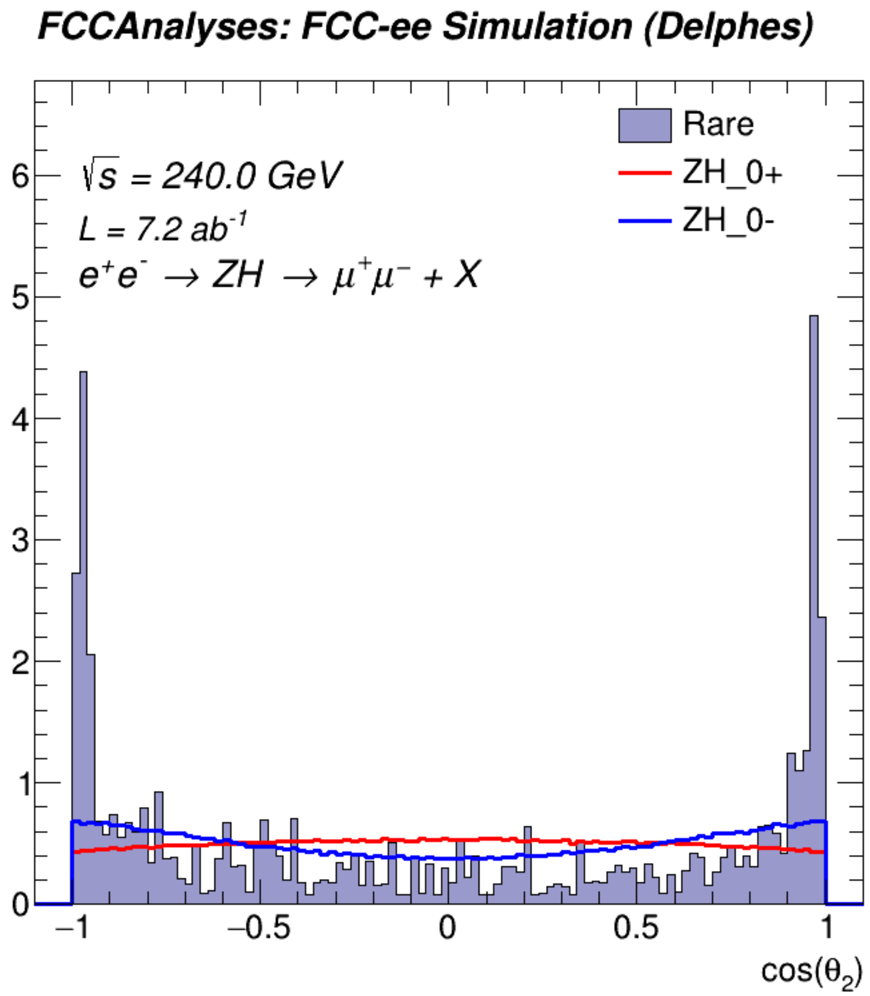
Backup Plots: $\cos\theta_2$



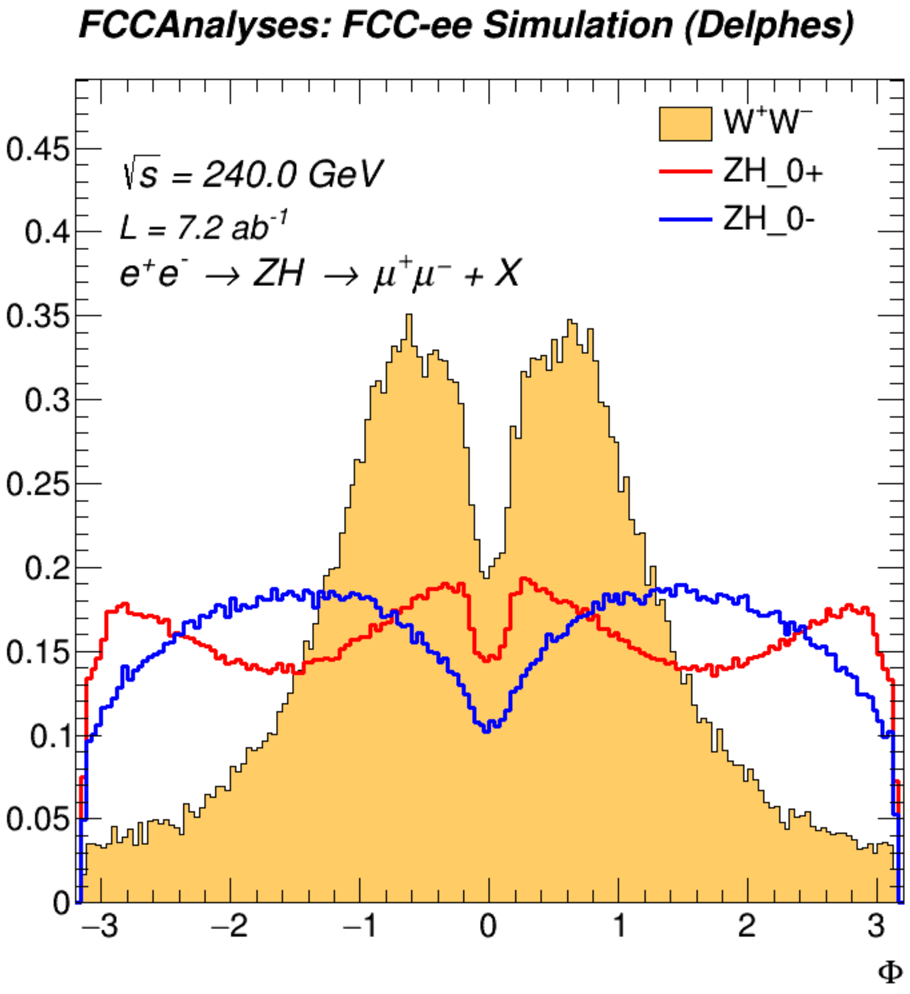


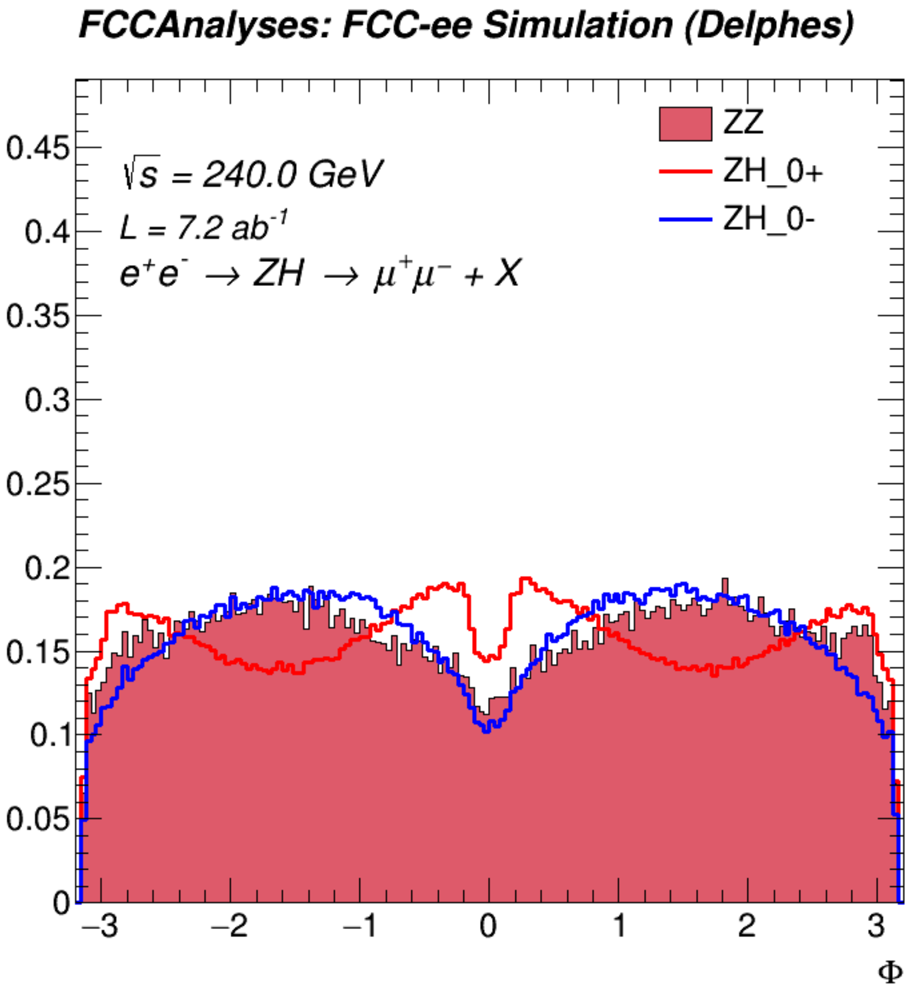
Backup Plots: $\cos\theta_2$





Backup Plots: Φ





Backup Plots: Φ