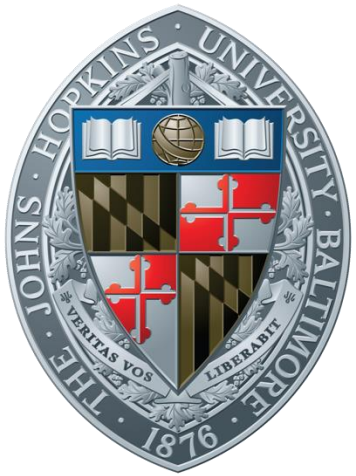
Update to the Hadronic Channel of the FCC-ee Higgs CP Study

Jan Eysermans (MIT), Andrei Gritsan (JHU), Lucas Mandacaru Guerra (Princeton), **Nicholas Pinto** (JHU), Valdis Slokenbergs (Texas Tech)



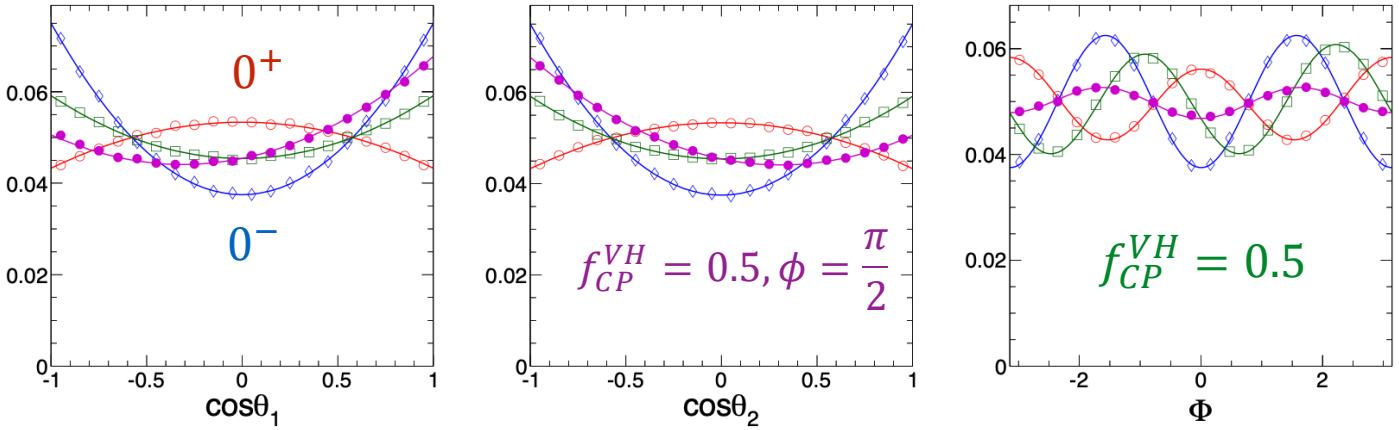
Higgs/Top Performance Meeting

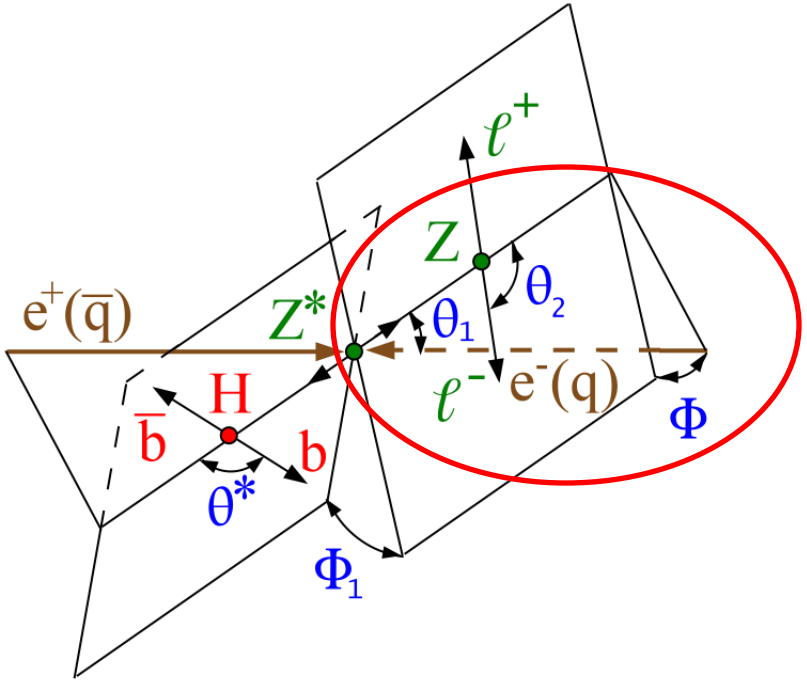
12 Nov 2024

Massachusetts Institute of Technology

Parameters of Interest:

arXiv:1309.4819

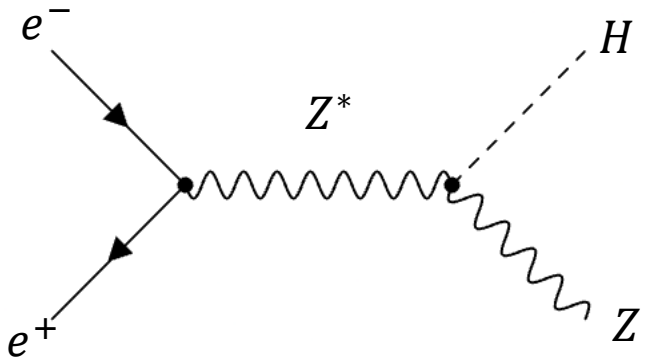




$$A(H \to V_1 V_2) = v^{-1}\left(a_1^{HVV} m_V^2 \epsilon_1^* \epsilon_2^* + a_2^{HVV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{HVV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

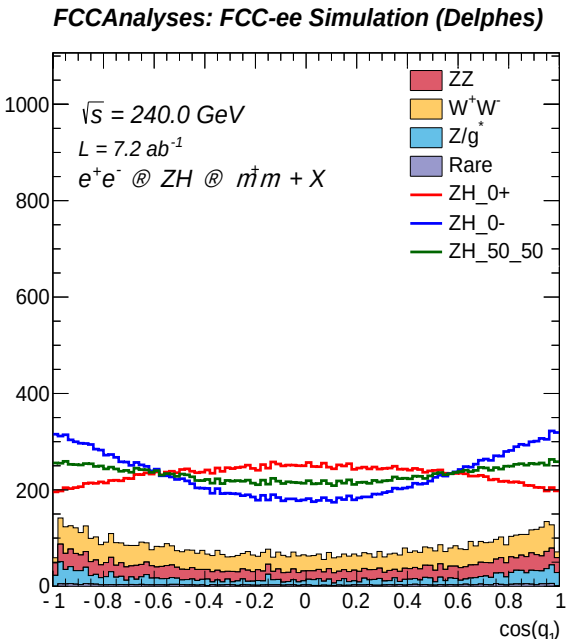
$$f_{\rm CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{\rm CP\ odd}}{\Gamma_{H\to X}^{\rm CP\ odd} + \Gamma_{H\to X}^{\rm CP\ even}}$$

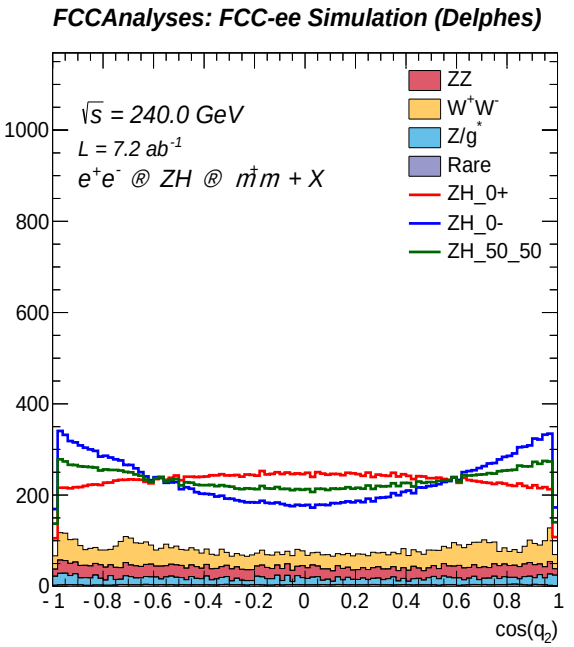
$$f_{CP}^{HVV} = \frac{|a_3^{HVV}|^2}{\sum |a_i^{HVV}|^2 (\sigma_i^{HVV}/\sigma_3^{HVV})},$$

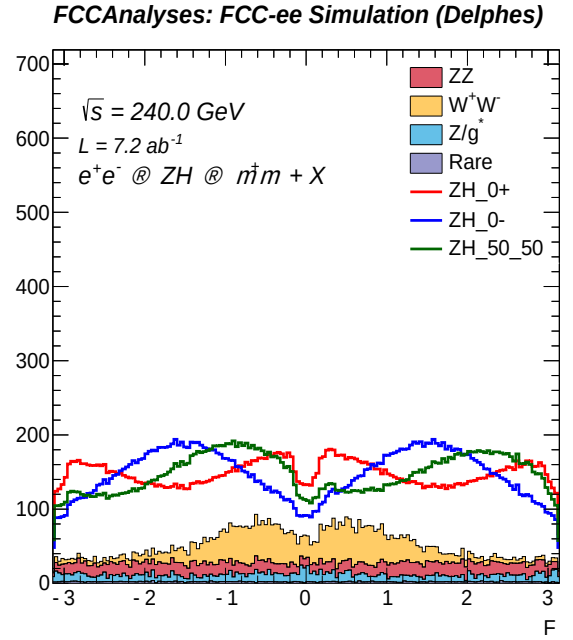


Previous Results:

- Last presented on 23 January 2024.
- Target: ee ⟶ ZH, H ⟶ X (recoil),
  Z ⟶ $\mu\mu$ (3.4%):
- Detector simulation uses DELPHES fast sim.
- Template fit made from angular distributions.
- Uses samples from the Winter2023 campaign.
- Yields determined at integrated luminosity of $\underline{7200\ fb^{-1}}$.

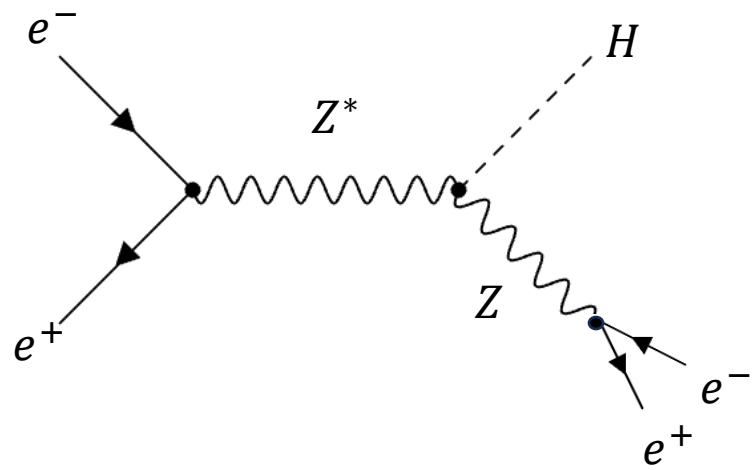


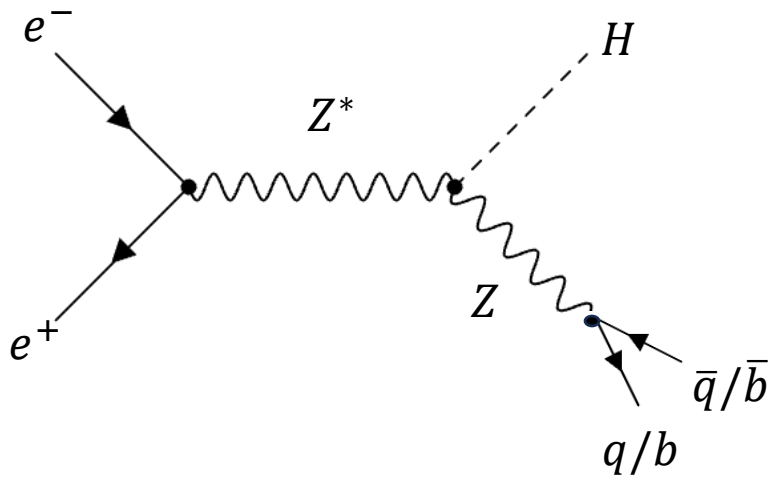




Updates for Today:

- Include $H \to X\ , Z \to ee, Z \to q\bar{q}$ $(u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c})$ and $Z \to b\bar{b}$.
  - Separation is done for background rejection
- Showcase optimal observables in leptonic final state.
- Describe selection for electronic final state.
- Describe selection for hadronic final state.
- Present combined likelihood fit for $Z \to q\bar{q}, bb, ee, \mu\mu$ (~76%).



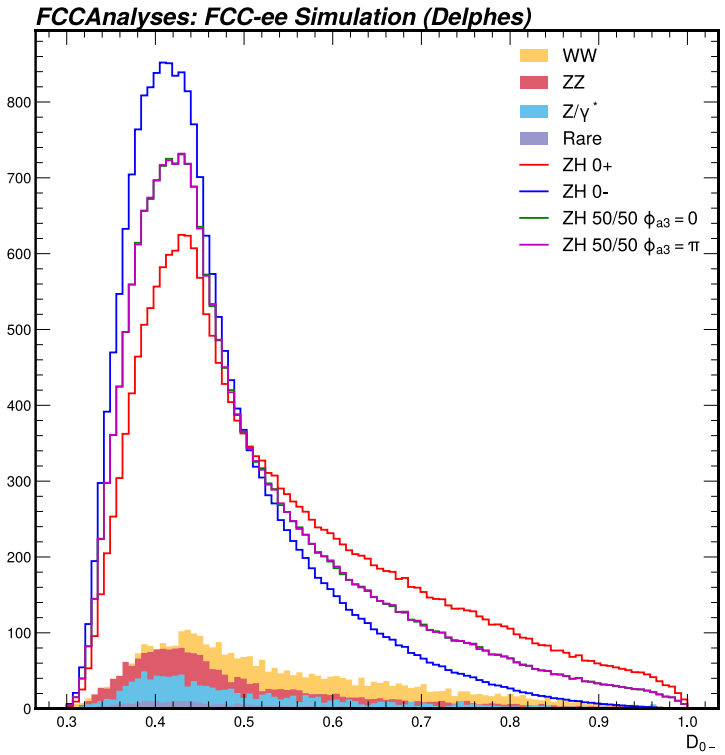


Using Optimal Observables:

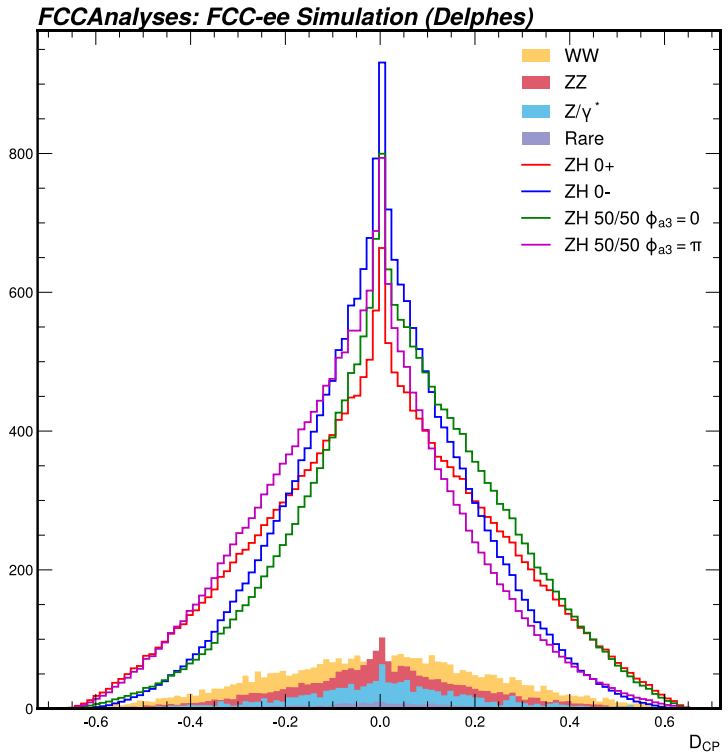
Neyman-Pearson Lemma: A likelihood ratio is optimal for separating two hypotheses.

$$D_{0^-} = \frac{P(0^-)}{P(0^+)+P(0^-)}$$

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



D_{0^-}



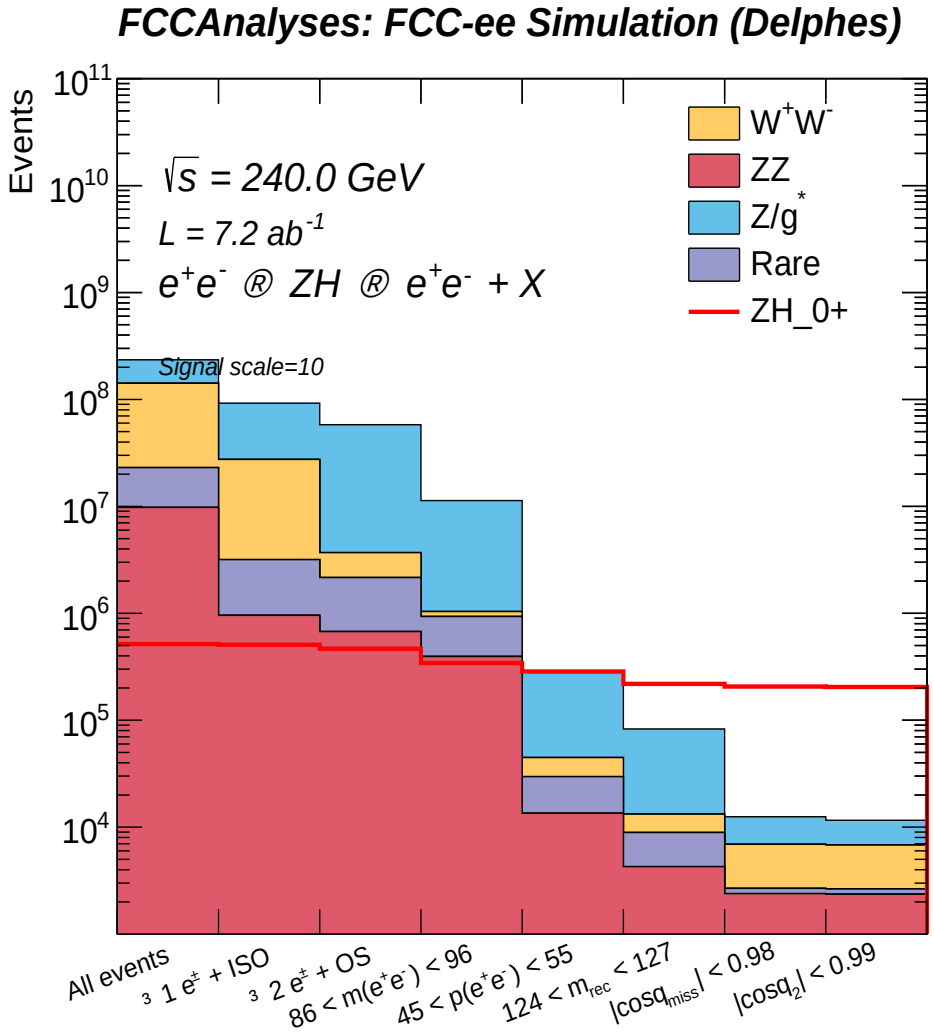
D_{CP}

- D_{0^-}: Separate CP-even distribution from CP-odd.
- D_{CP} : Separate two equal mixtures of CP-even and CP-odd with different phases of the CP-odd coupling.
- Probabilities calculated by MELA.

$Z \rightarrow ee$ channel:

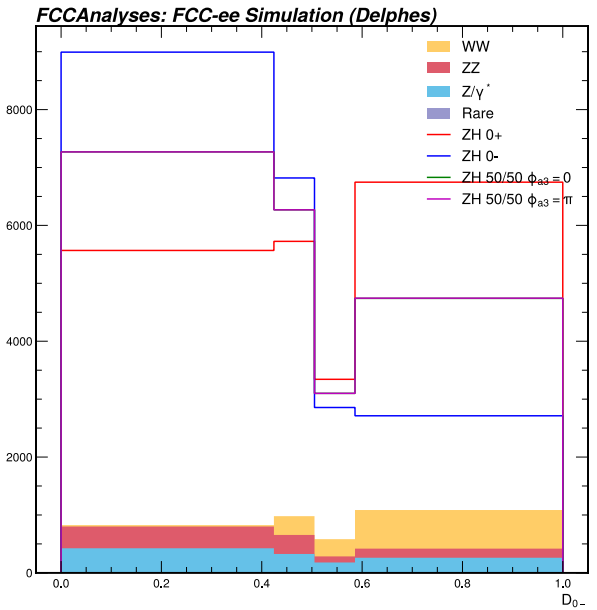
- Same selection as $Z \rightarrow \mu\mu$ channel.
- Uses optimal observables.
- Signal : Background slightly worse than muonic channel (~2.5 vs ~2.0)
- Selection is discussed more in depth here.

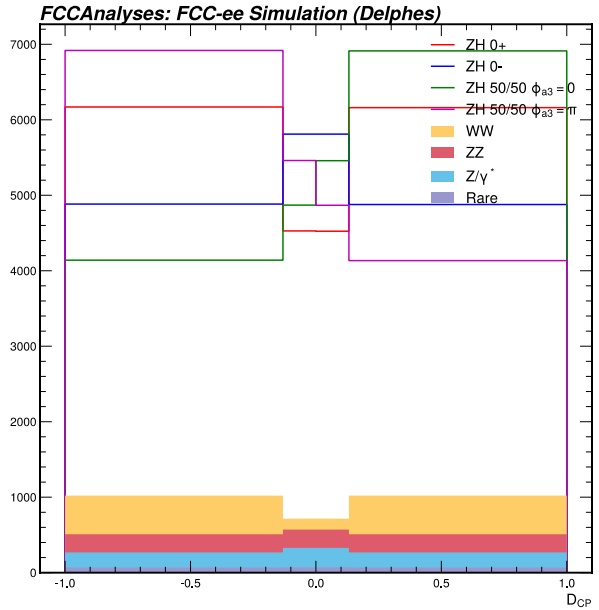
- Signal Selection Efficiency ~ 40.0%
- Signal : Background ~2.0

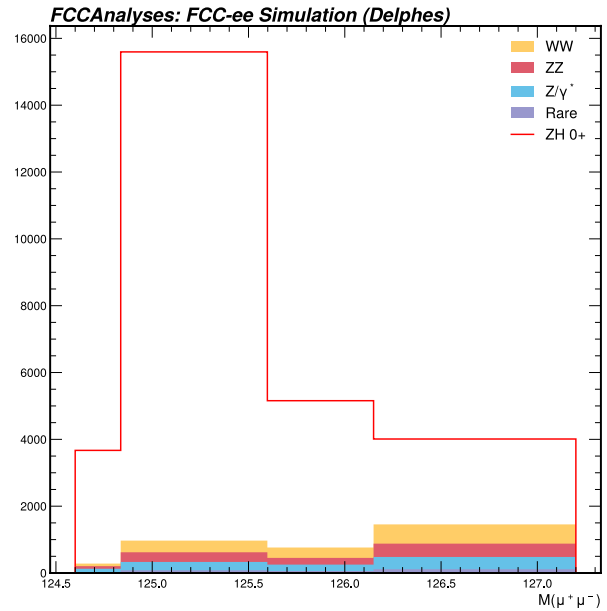


$Z \to ll$ Templates:

- 3D Histogram formed from D_0-, D_{CP} , and M_{Recoil}
- 4 bins per axis.
- Bin edges optimize differences between desired hypotheses.
- Example projections shown for $Z \to \mu\mu$.



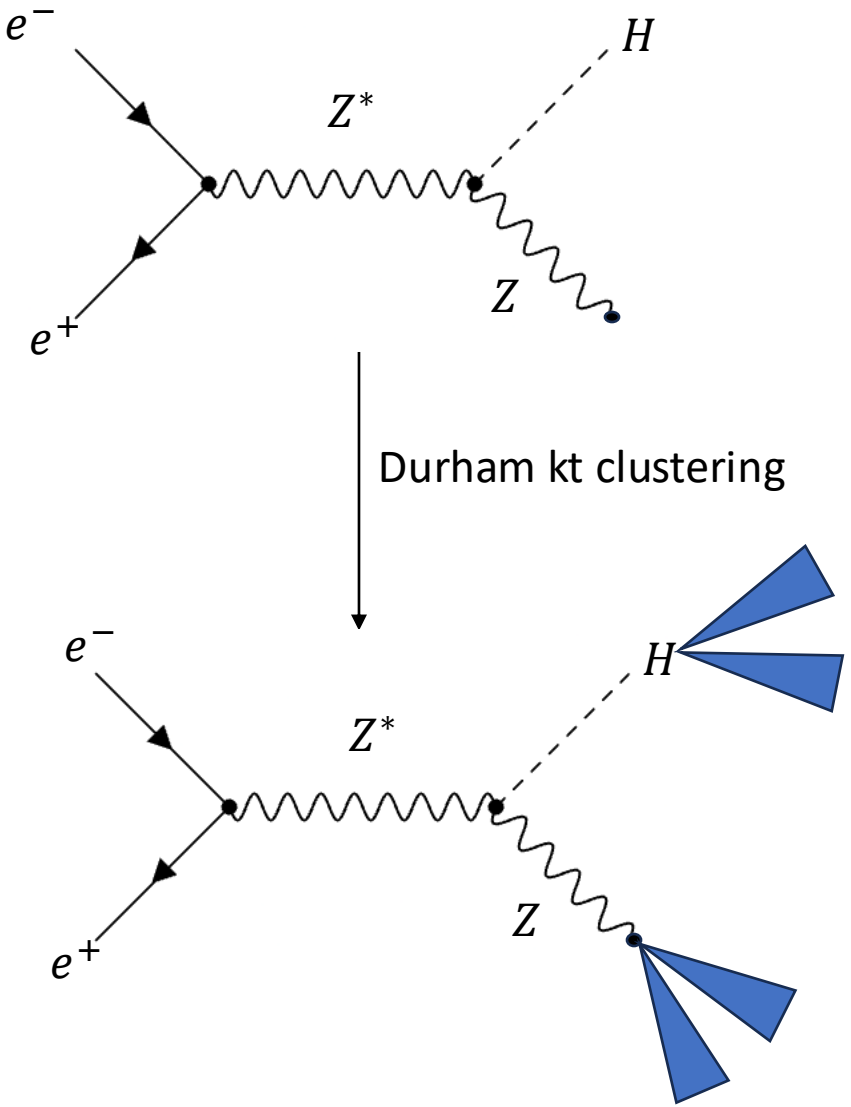




Hadronic Event Selection:

- Cut 1 and Cut 2:
  - Reject events with > 2 $e^{\pm}$ and > 2 $\mu^{\pm}$.

- Reconstruct Z from dijet system
  - (jet clustering performed by FastJet):
  - Durham kt clustering to exclusive 4 jets.
  - From all combinations of jets, select dijet candidate that minimizes:
    - $\chi^2 = 0.8(M_{Dijet} - M_Z)^2 + 0.2(M_{Recoil} - M_H)^2$
  - Enforce flavor(q) = flavor($\bar{q}$)

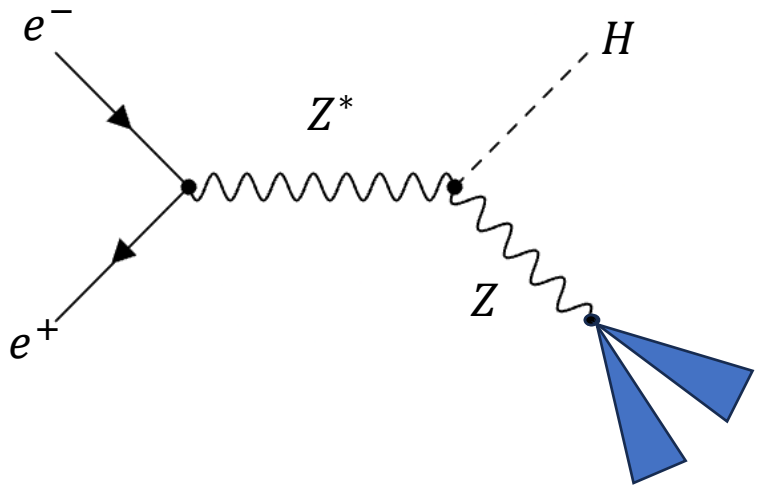


Reconstruct Z as dijet system that minimizes χ^2

Overview of $Z \rightarrow q\bar{q}$ Analysis:

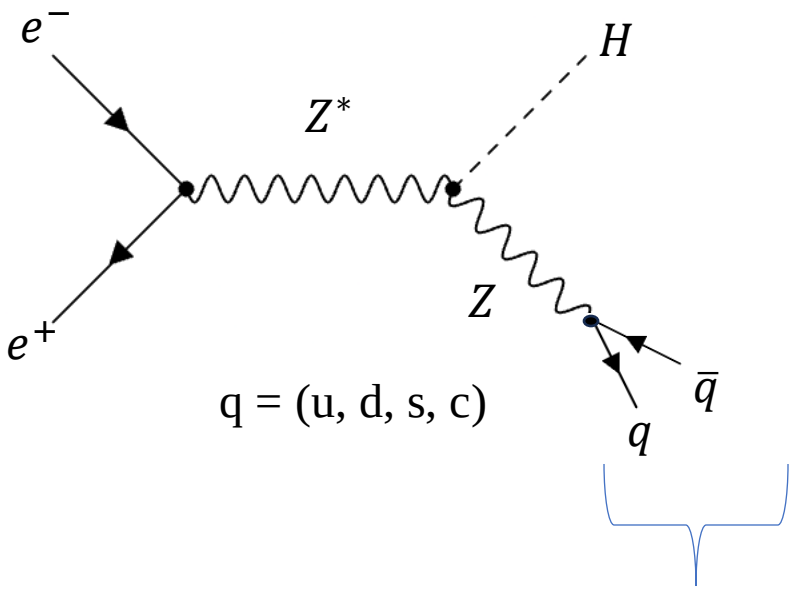
- Selection is determined by scores assigned by ParticleNet (arXiv:1902.08570)

- Each jet assigned a score for each flavor.
  - Flavors = Q (u or d), S, C, B, and G.
- Scores range from [0, 1].



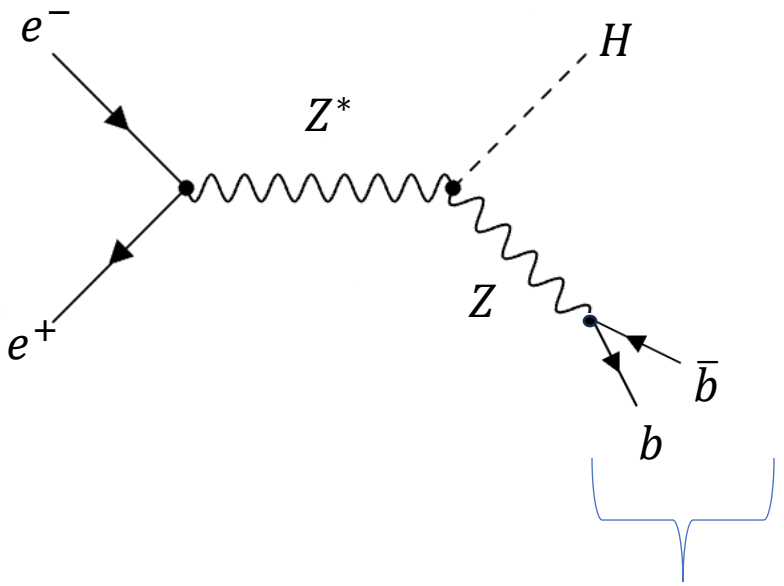
Overview of $Z \rightarrow q\bar{q}$ Analysis:

Split analysis into two channels based on the sum of the B-scores:



q = (u, d, s, c)

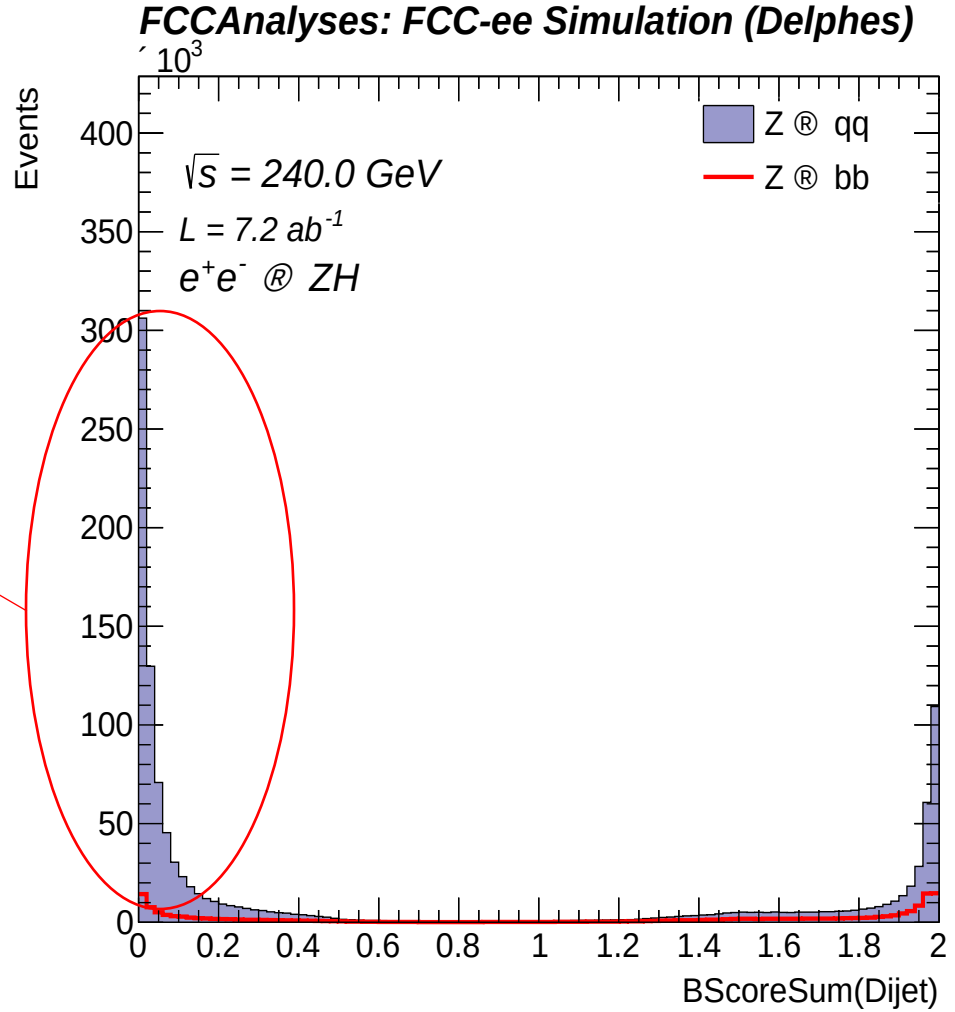
Sum of B-Scores < 1.7



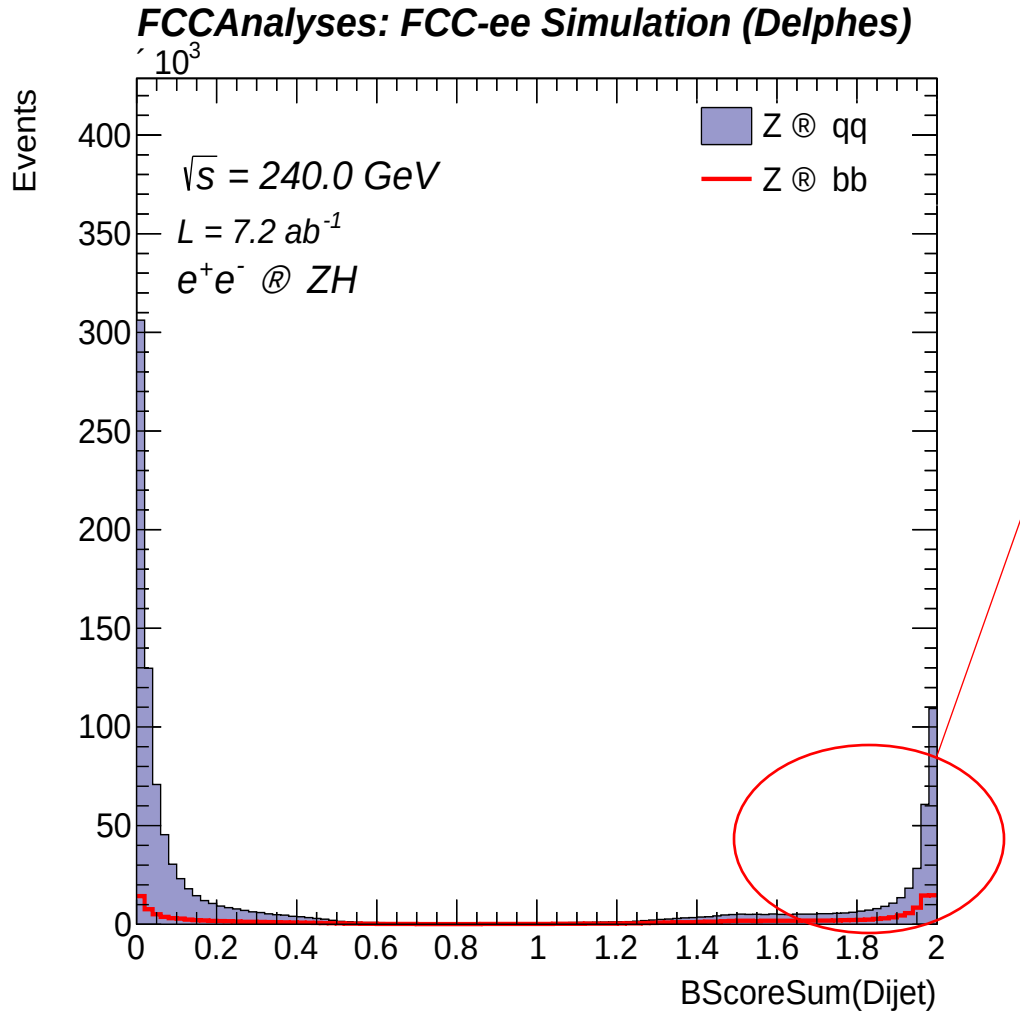
Sum of B-Scores ≥ 1.7

Overview of $Z \to q\bar{q}$ Analysis:

qq Analysis



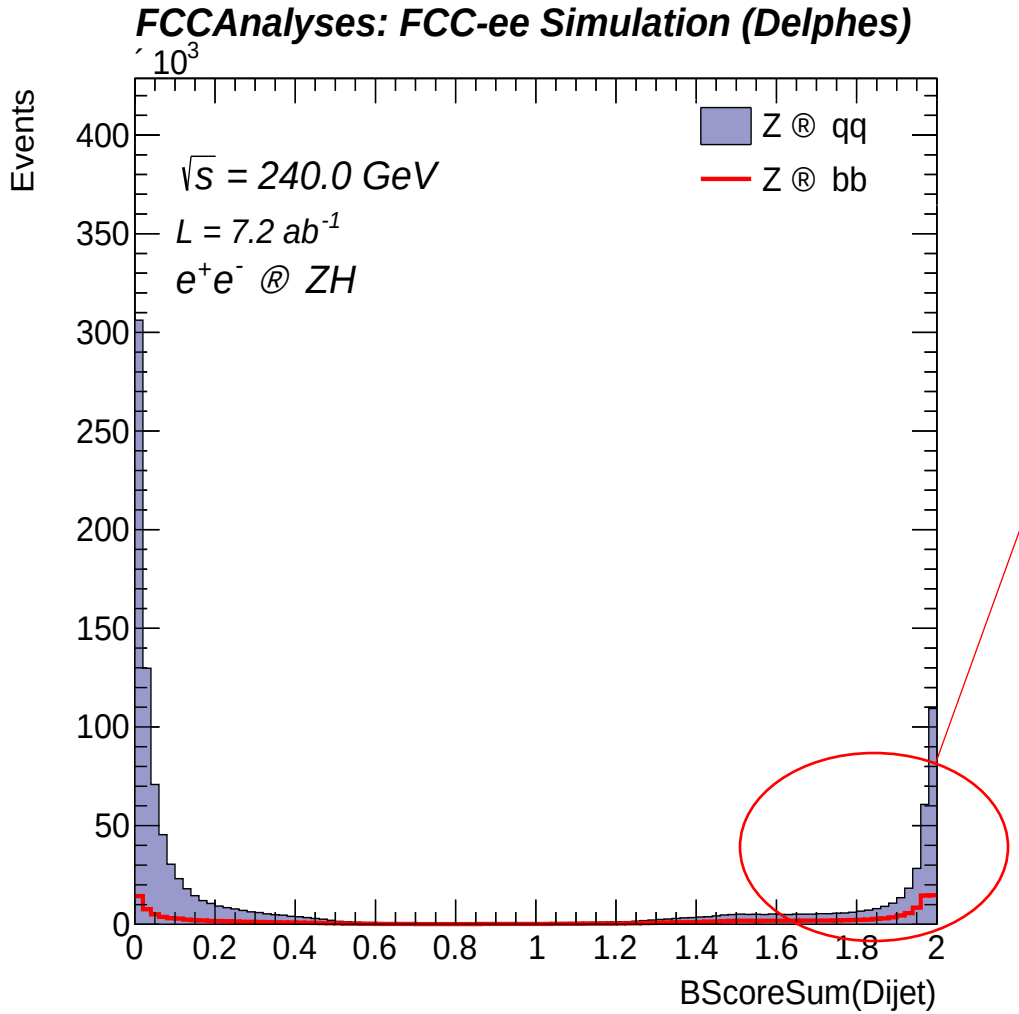
Overview of $Z \rightarrow q\bar{q}$ Analysis:



bb Analysis

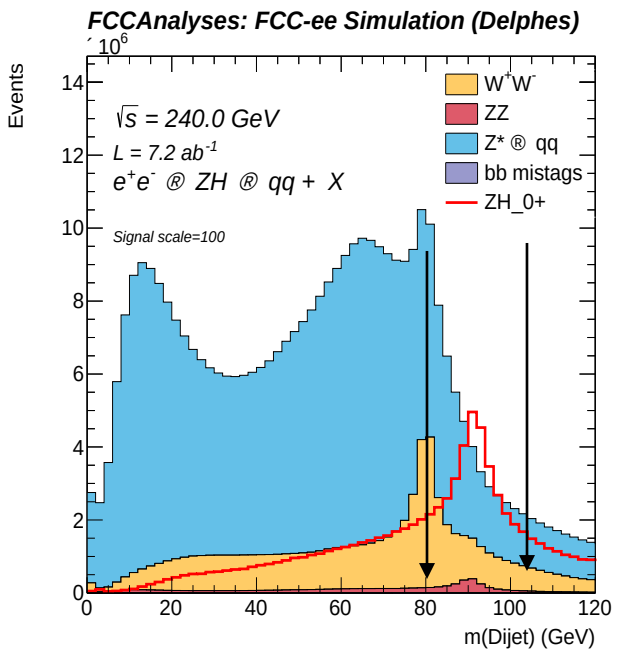
Note: No cuts have been applied yet besides lepton filter and dijet flavor enforcement.

Overview of $Z \rightarrow q\bar{q}$ Analysis:

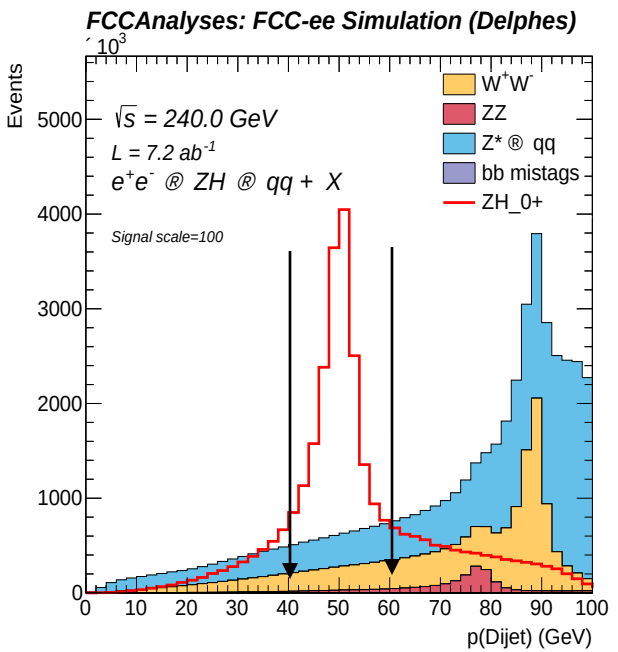


qq on the right mostly come from Higgs->bb.

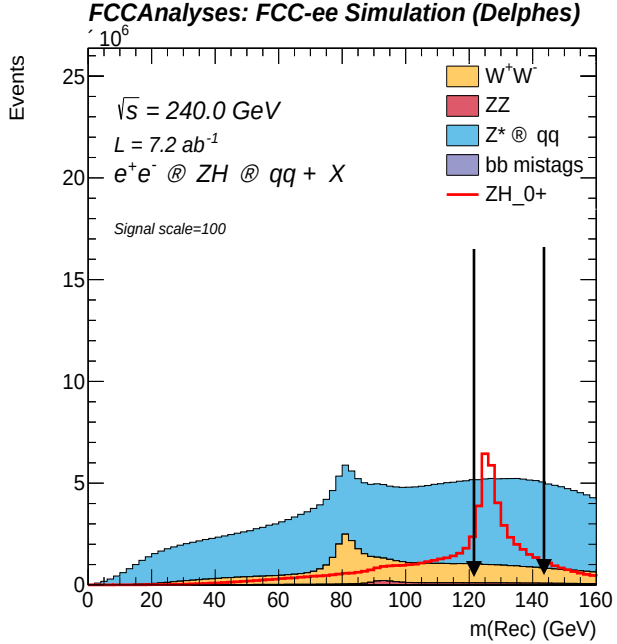
qq Event Selection (N-1 Plots):



$80 < M_{dijet} < 100$

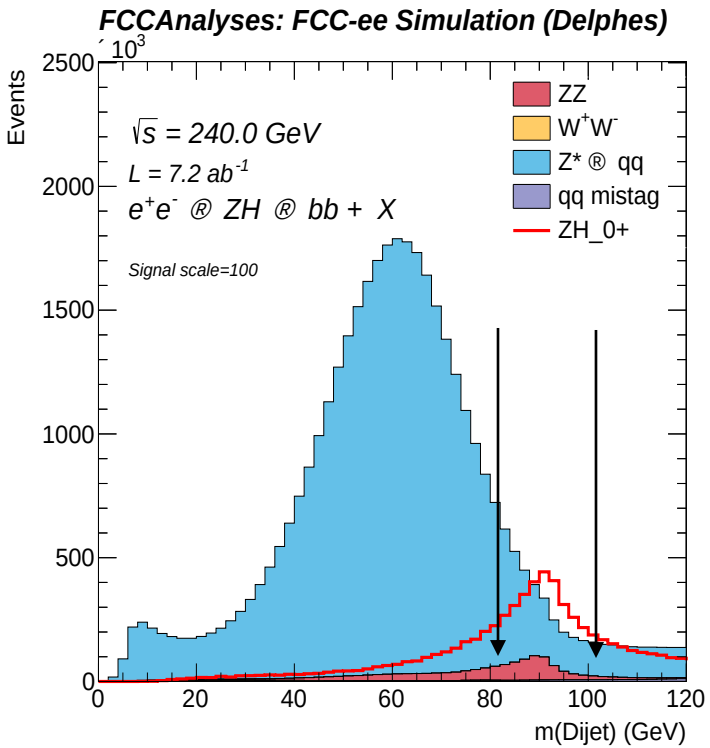


$40 < P_{dijet} < 60$

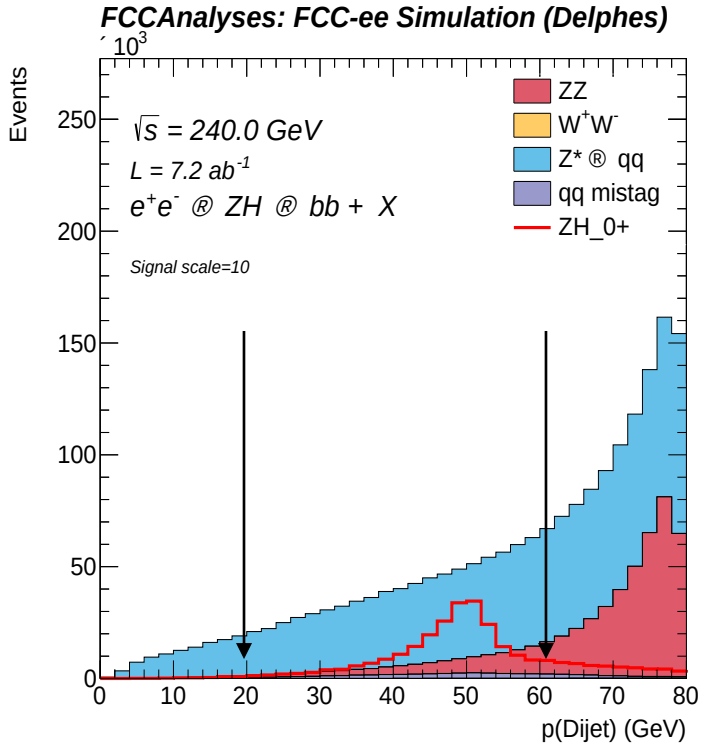


$120 < M_{recoil} < 140$

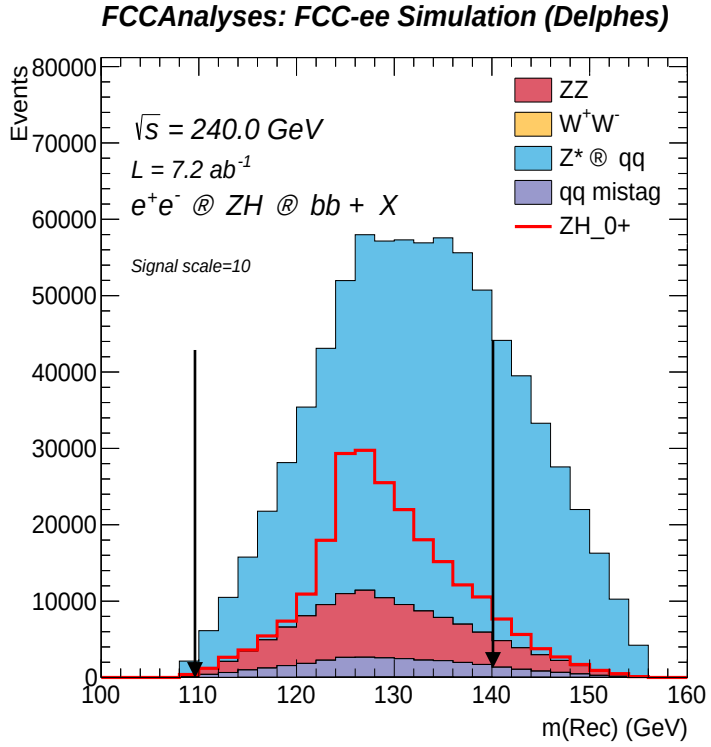
bb Event Selection (N-1 Plots):



$80 < M_{dijet} < 100$



$20 < P_{dijet} < 60$

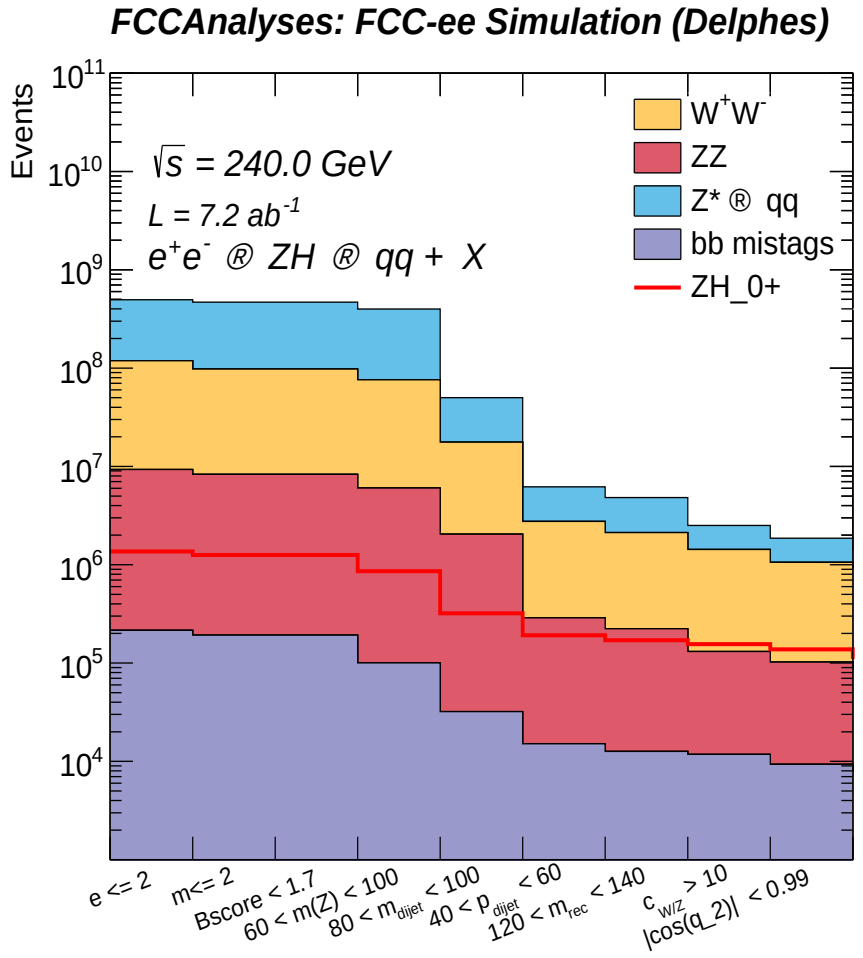


$110 < M_{recoil} < 140$

Analysis Cutflow:

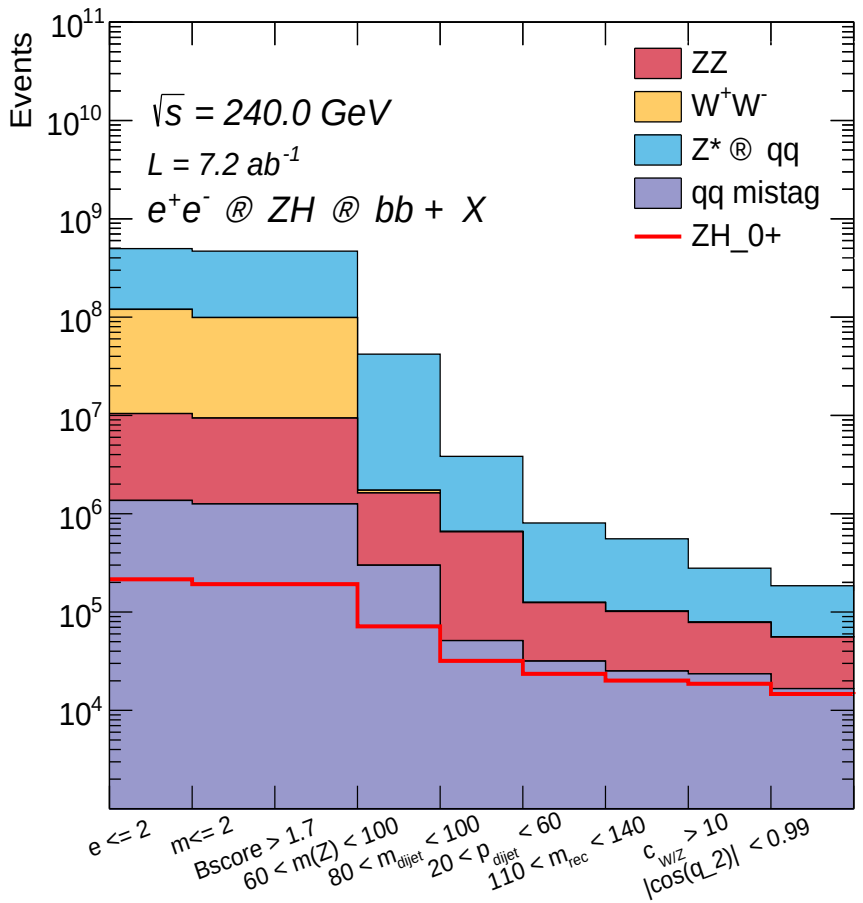
qq:

- Sig:Bkg ~ 0.08
- Selection Efficiency: ~8.1%



bb:

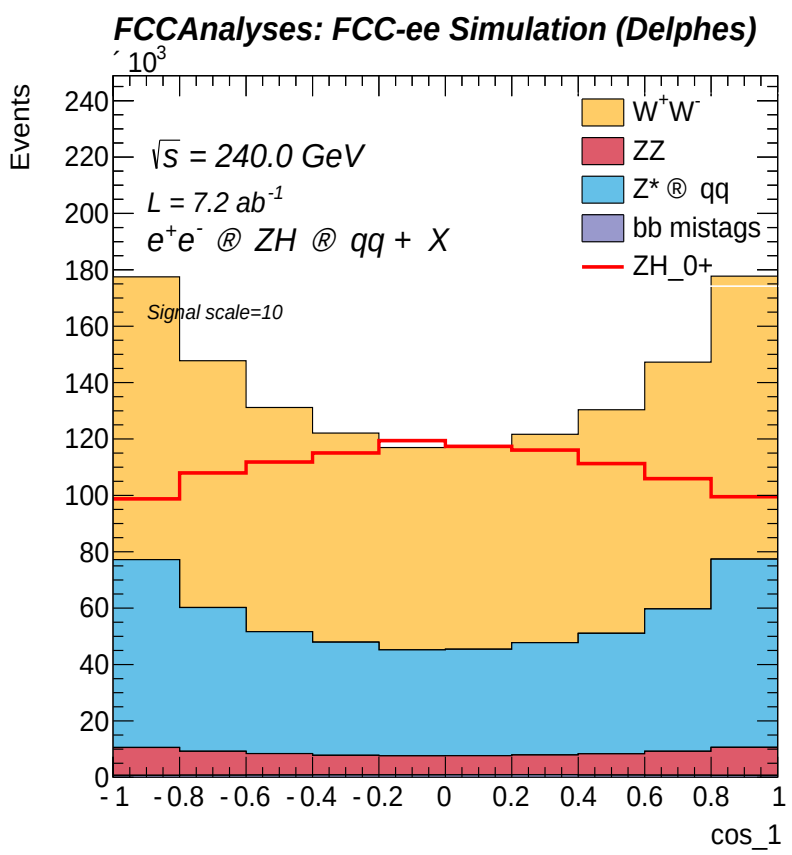
- Sig:Bkg ~ 0.09
- Selection Efficiency: ~6.79%

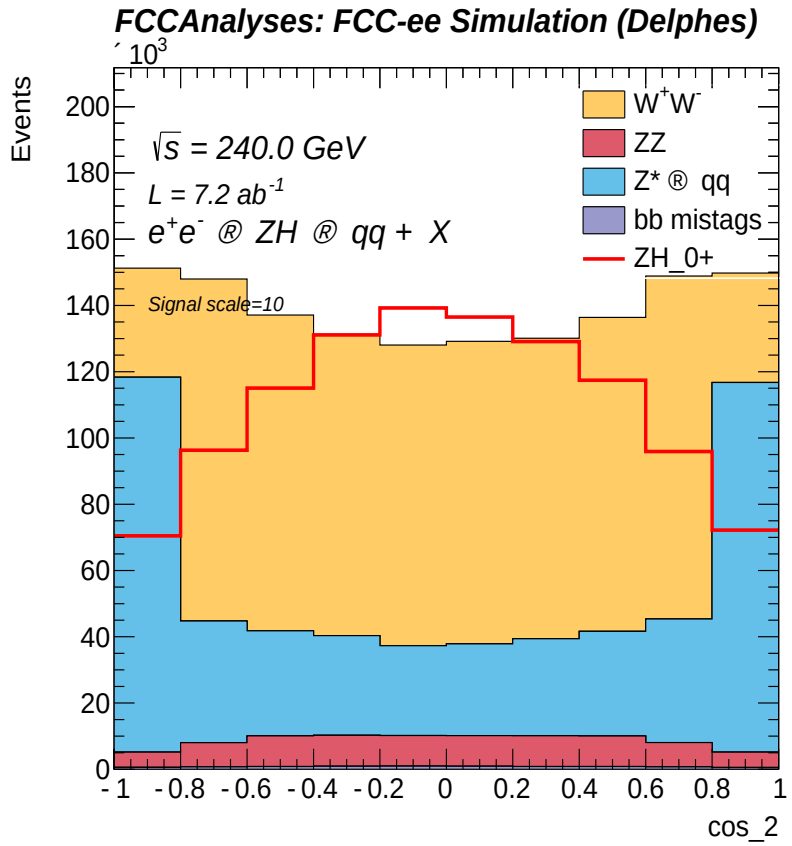


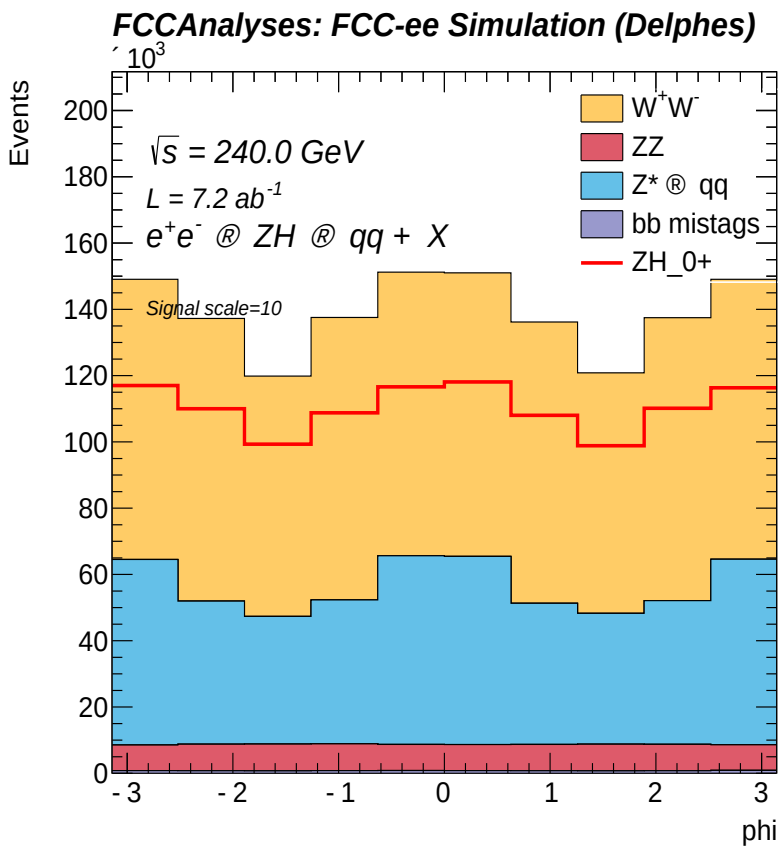
Hadronic Template Fits:

- 3D Histogram filled with $\cos\theta_1, \cos\theta_2, \Phi$ on each axis.
- 10 bins/ axis, 1000 bins total.
- $0^+, 0^-$, and interference templates created with signal.

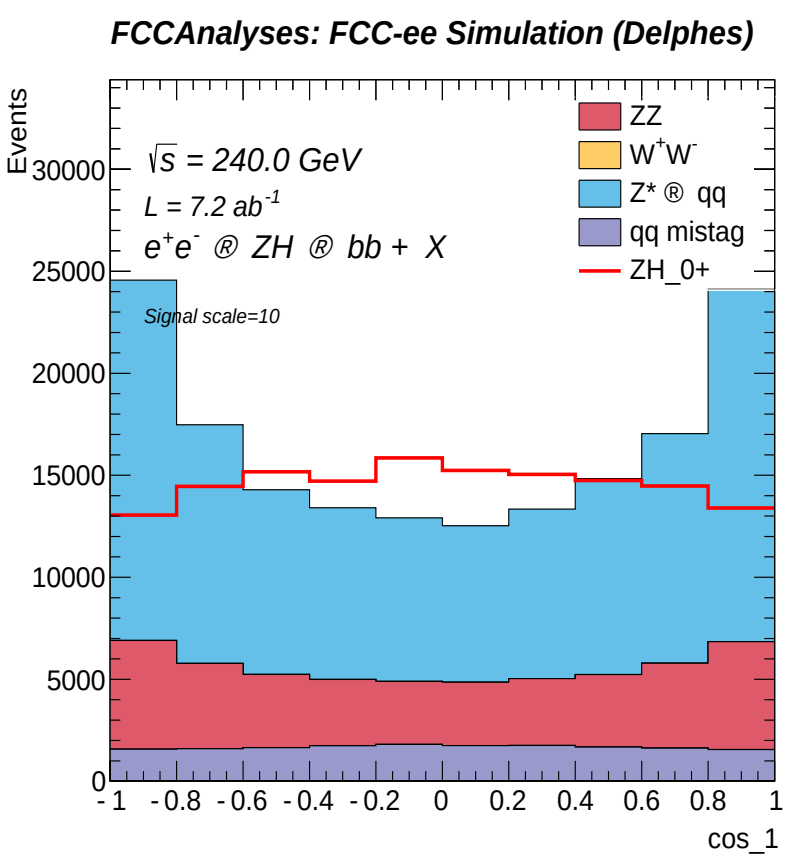
qq-Template Observables:

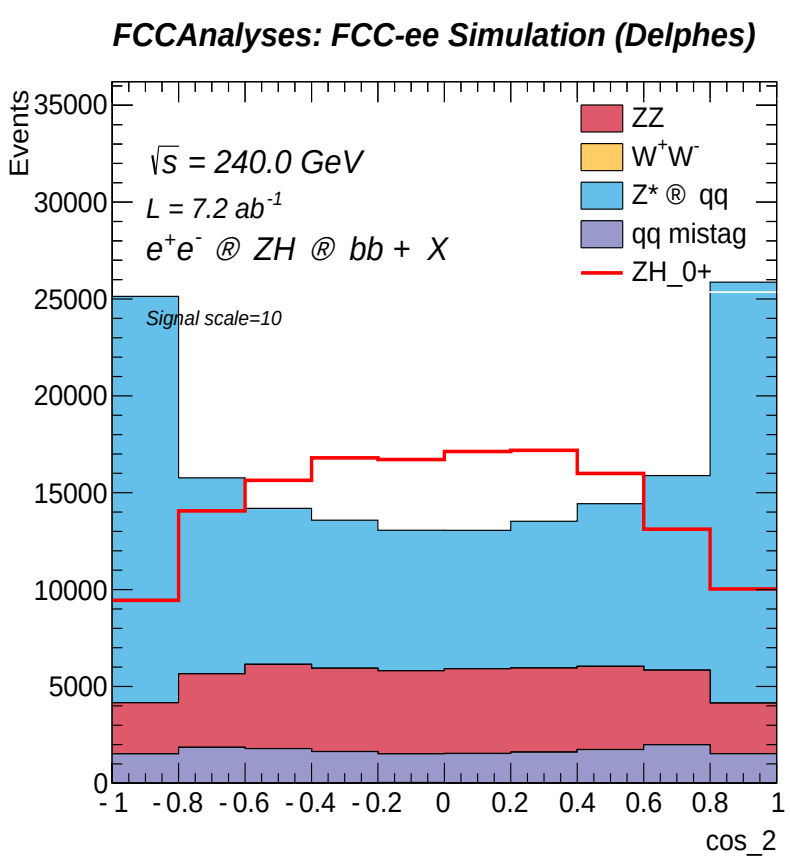


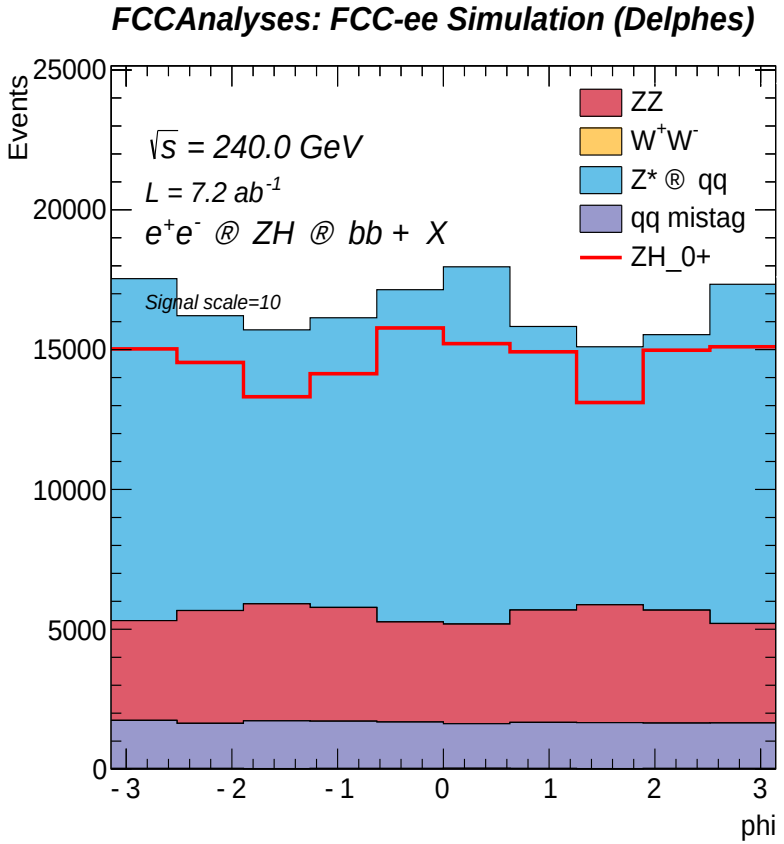




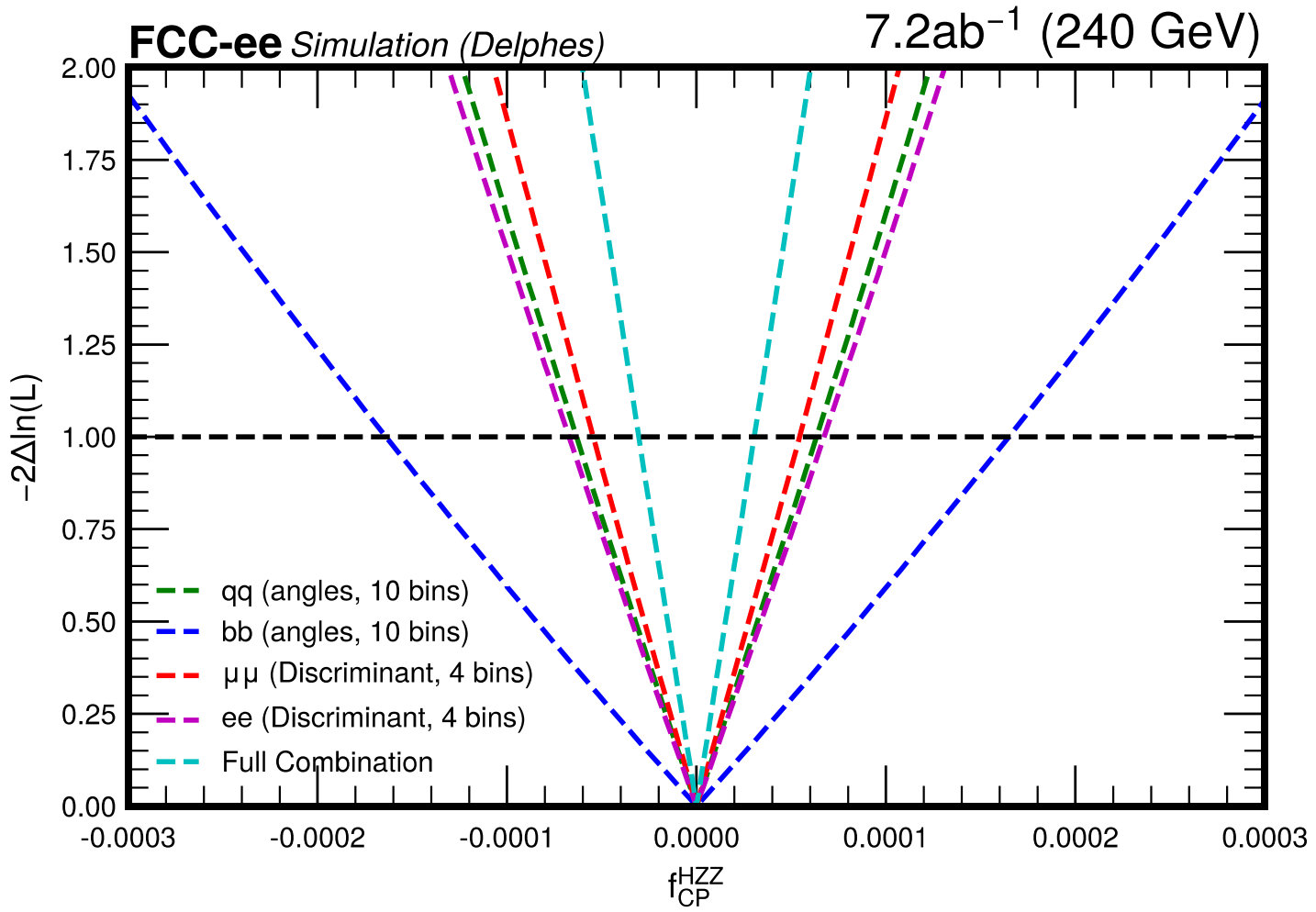
bb-Template Observables:







Progression of fits with Reconstructed Signal, $Z \longrightarrow q\bar{q}, b\bar{b}, ee, \mu\mu$:

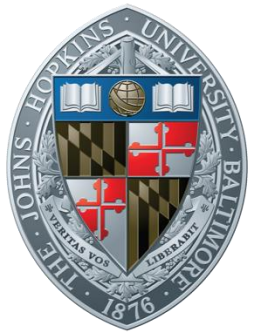


At 68% Confidence Level

- $qq \sim \pm 6.3 * 10^{-5}$
- $bb \sim \pm 1.6 * 10^{-4}$
- $\mu\mu \sim \pm 5.5 * 10^{-5}$
- $ee \sim \pm 6.7 * 10^{-5}$
- Combined$\sim \pm 3.0 * 10^{-5}$

Conclusions

- Combined $f_{CP}^{ZZ} \sim \pm 3 * 10^{-5}$
- Combined result represents ~79% of Z decays.
- Can include $Z \rightarrow \tau\tau$ final state.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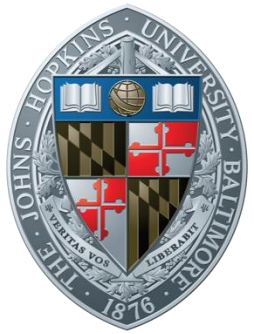
1876

Questions?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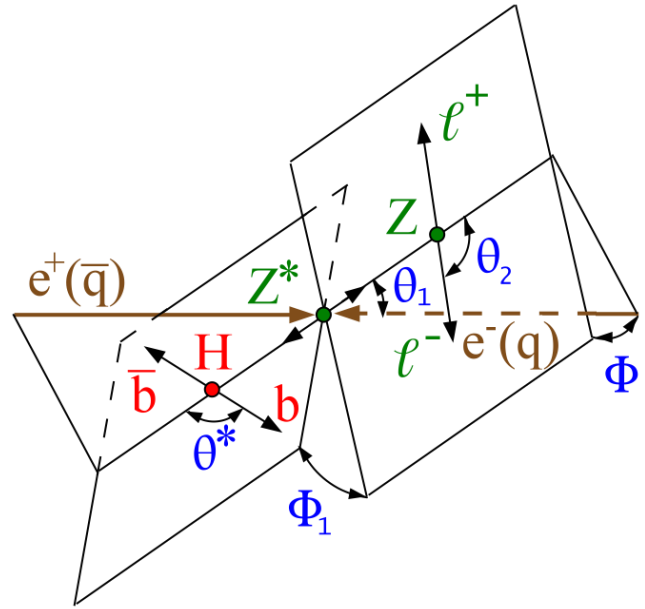
BACKUP

A Word on MELA:



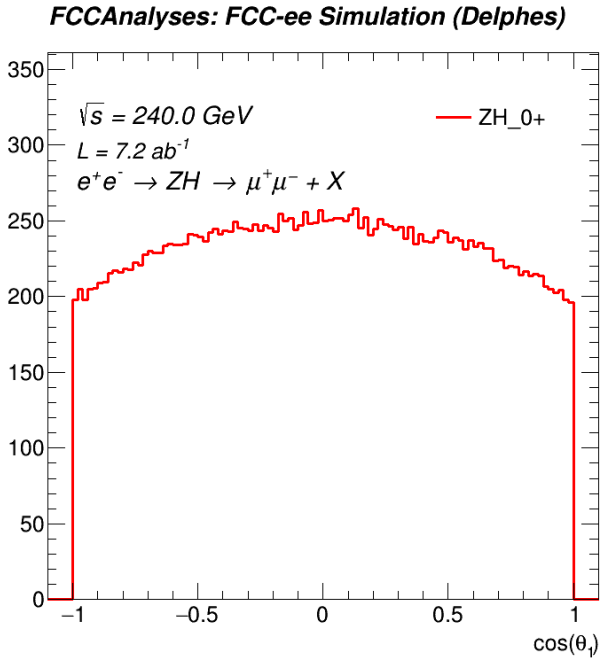
- Matrix Element Likelihood Approach.

- From event kinematics, calculates transition probability from a given initial state to a desired final state.
  - Transition from $a_1 = 1, a_{i\neq 1} = 0$ to $a_3 = 1, a_{i\neq 3} = 0$, etc.

- Interfaced to FCCAnalyses.
  - Code not yet publicly shared.

Reweighting:

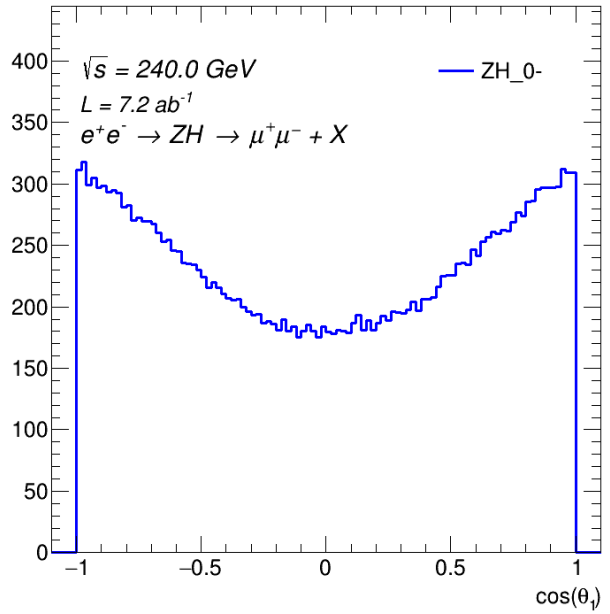
Simulated (Standard Model):

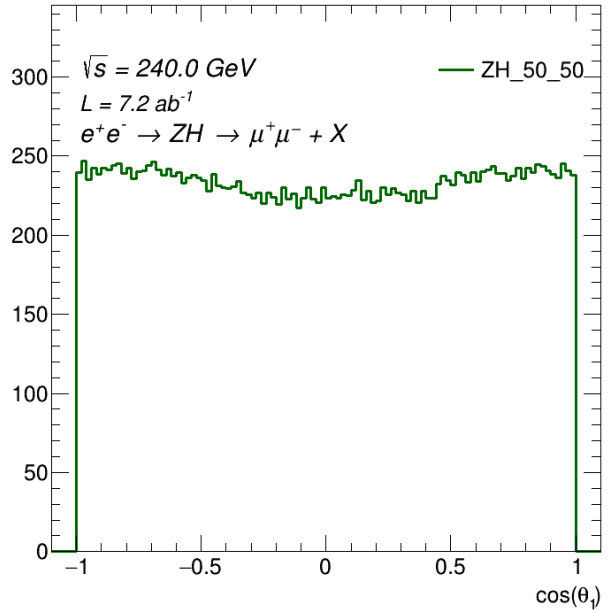


Reweighting:

$P(0^-)$

$P(50/50)$





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

Event Selection: