Karlsruher Institut für Technologie

$H \to \tau\tau$ MEASUREMENTS AT FCC-ee IN THE ZH CHANNEL AT 240 GeV

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TARGETS

- Our initial target was to do a **CP study** of the H→$\tau\tau$ coupling in ZH processes
- Recently expanded to include also the **cross-section measurement** in this channel
  - Work started by Maria Cepeda who kindly shared her code to get us started
- All fundamental targets for the FCC/ECFA reports coming up

- Since the last presentation in the Higgs/top meeting, we migrated the analysis to the FCCAnalyses software
  - We are now using the full list of centrally produced signal and background events
- The full workflow is now in place for both analyses

WORKFLOW

- We use the **generalized kt algorithm for all jets** with R=0.5 and $p_{T,j} > 2$ GeV, excluding isolated electrons and muons ($p_T > 20$ GeV and iso<0.25)

- The **tau reconstruction** comes from Maria's study:
  - Looks at jets with no electrons or muons (leptonic tau decays are selected from the lepton class "manually")
  - Gets the leading constituent (π+ or π−)
  - Adds constituents to the reconstructed tau 4-momentum vector (selection on pt>1 GeV or Δθ<0.2 from the leading)
  - Keeps track of the number of photons to define a tau ID (negative for non-tau-like jets)

BACKGROUNDS:

$e^+e^- \to Z \to qq$ (Pythia8)

$e^+e^- \to$ WW (Pythia8)

$e^+e^- \to$ ZZ (Pythia8)

$e^+e^- \to \ell\ell$ *new*

$e^+e^- \to \nu_e\bar{\nu}_e Z$ *new*

$e\gamma \to eZ, Z \to ee/\mu\mu$ *new*

$\gamma\gamma \to \ell\ell$ *new*

$Z \to \nu\nu, \ell\ell, qq$:

ZH, H→bb

ZH, H→cc

ZH, H→ss

ZH, H→WW *new*

ZH, H→ZZ *new*

ZH, H→gg *new*

CATEGORIES

- We have nine categories based on the Z and taus decays, also requiring the Z products and tauons to have opposite charges

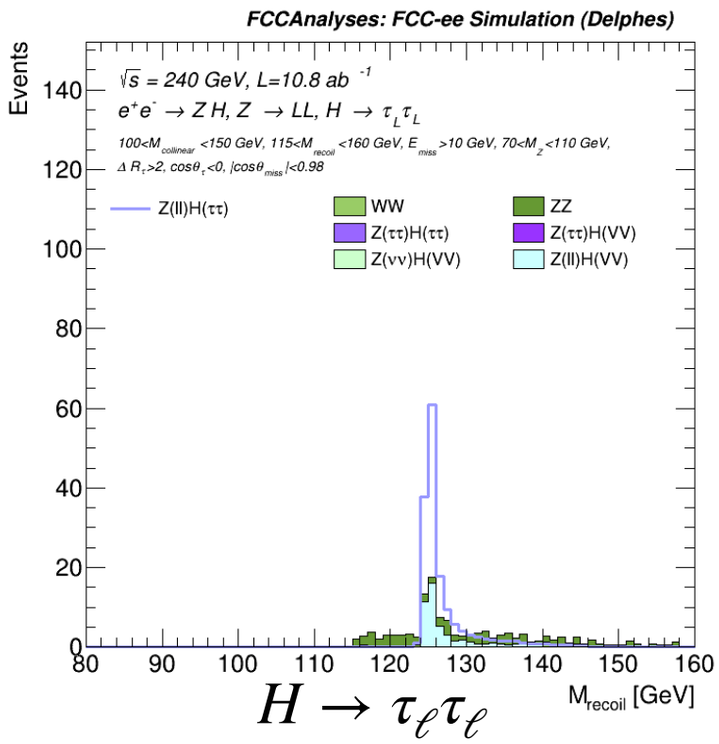
  - $Z \to \ell\ell$
  - $Z \to qq$
  - $Z \to \nu\nu$
  - $H \to \tau_\ell \tau_\ell$
  - $H \to \tau_\ell \tau_h$
  - $H \to \tau_h \tau_h$

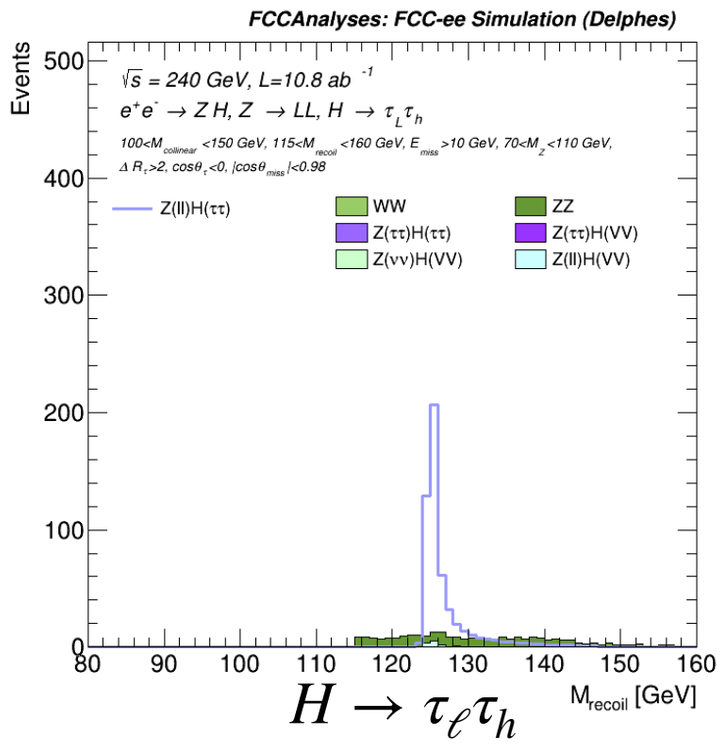
- Basic selection requires exactly the objects in each category to be reconstructed with opposite charges (decay products on Z and H)
  - The leptons in $Z \to qq$ are the isolated ones that have been excluded from the jets, otherwise they have no additional selection
  - Quark jets are differentiated from tau jets by the tau ID

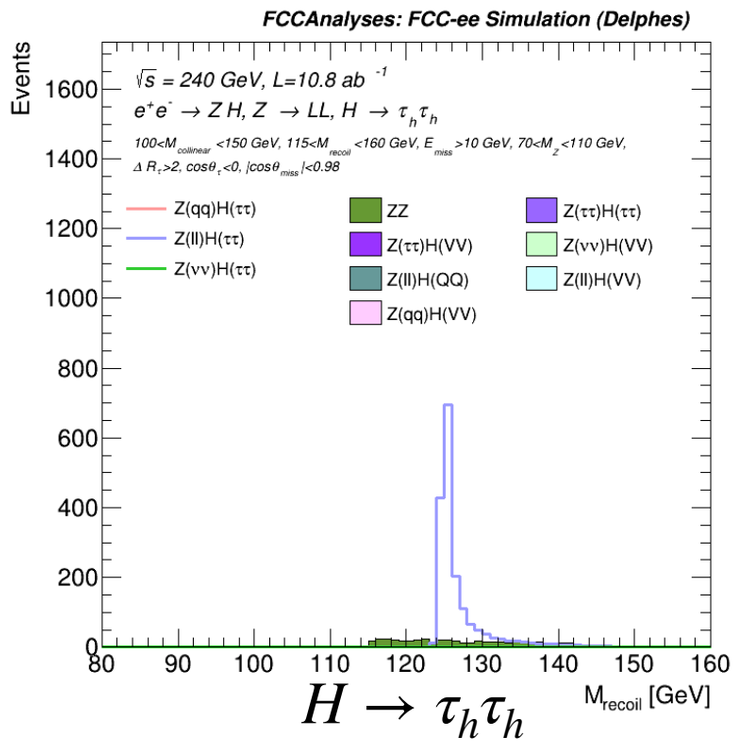
- We then proceeded to optimize a few cuts for each of the Z decay categories

$Z \to \ell\ell$ SELECTION

1. $Z \to \ell\ell$ Selection	Two leptons with same flavor and opposite charges, two tauons with opposite charges
2. Collinear mass	$100 < M_{collinear} < 150$ GeV
3. Recoil mass	$115 < M_{recoil} < 160$ GeV
4. Missing energy	$\not{E} > 10$ GeV
5. Reconstructed Z mass	$70 < M_Z < 100$ GeV
6. Angular distance between tauons	$\Delta R_\tau > 2$
7. Cosine of the angle between tauons	$\cos\theta_\tau < 0$
8. Cosine of missing theta	$\lvert\cos\not{\theta}\rvert < 0.98$



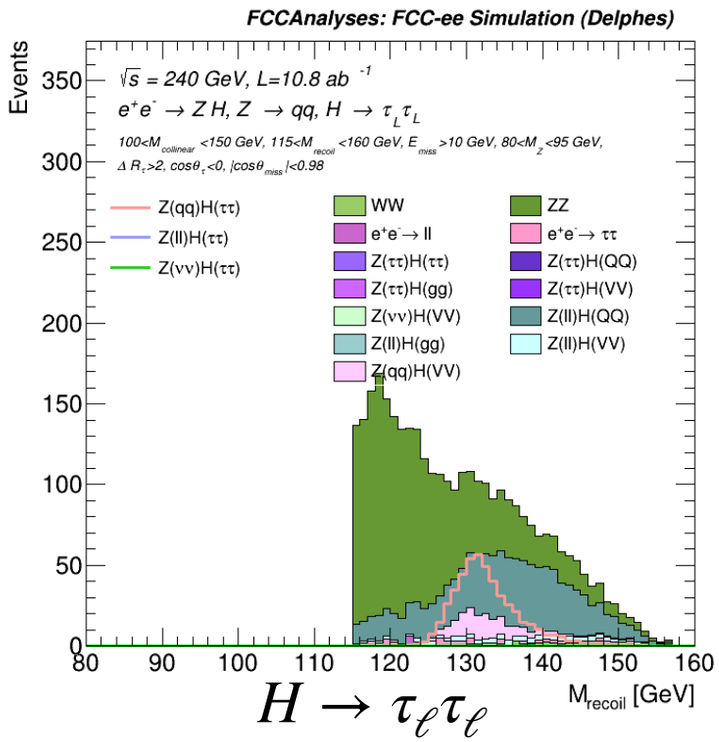




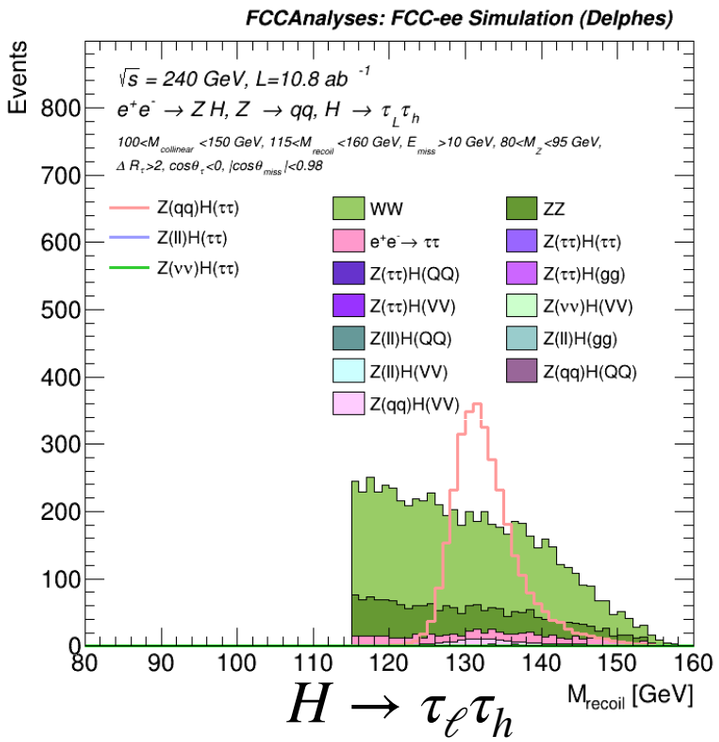
$Z \to qq$ SELECTION

1. $Z \to qq$ Selection	Two jets, two tauons with opposite charges
2. Collinear mass	$100 < M_{collinear} < 150$ GeV
3. Recoil mass	$115 < M_{recoil} < 160$ GeV
4. Missing energy	$\not{E} > 10$ GeV
5. Reconstructed Z mass	$80 < M_Z < 95$ GeV
6. Angular distance between tauons	$\Delta R_\tau > 2$
7. Cosine of the angle between tauons	$\cos\theta_\tau < 0$
8. Cosine of missing theta	$\lvert\cos\not{\theta}\rvert < 0.98$

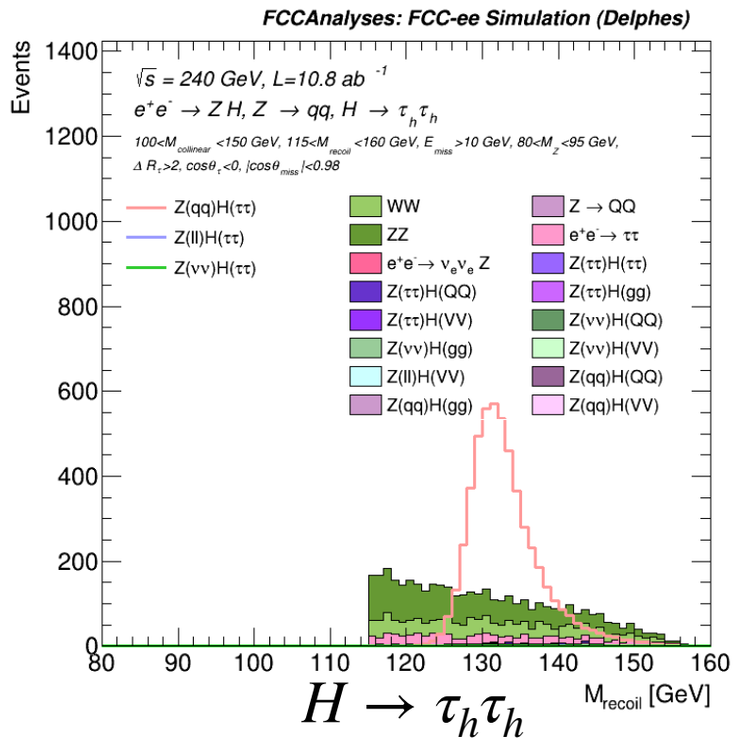
→ needs to be more constrained than $Z \to \ell\ell$ to reject backgrounds



$H \to \tau_\ell \tau_\ell$



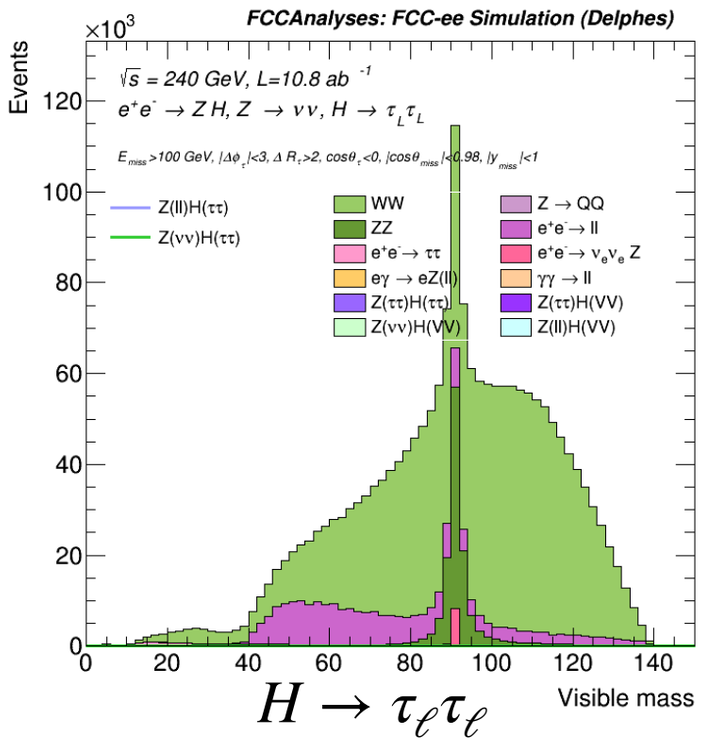
$H \to \tau_\ell \tau_h$

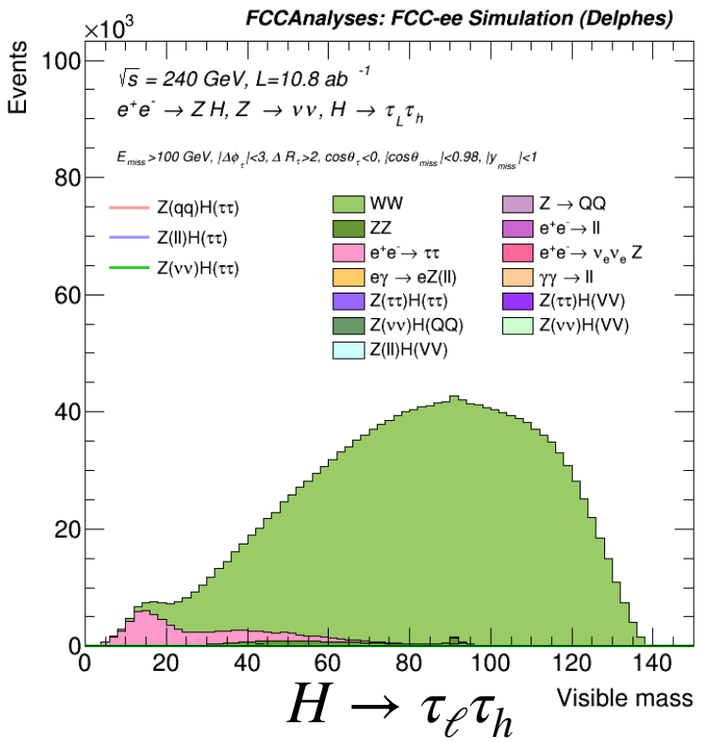


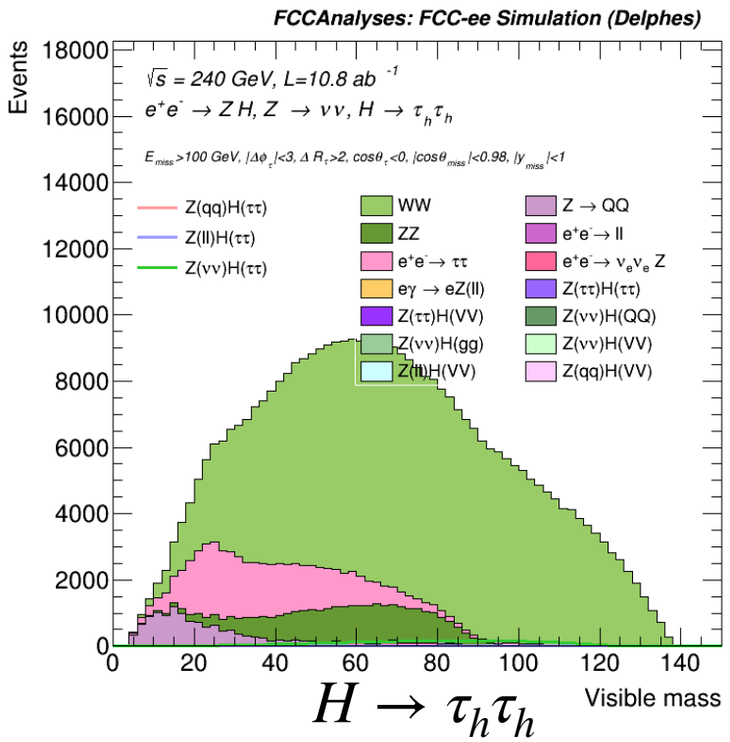
$H \to \tau_h \tau_h$

$Z \to \nu\nu$ SELECTION

1. $Z \to \nu\nu$ Selection	Two tauons with opposite charges
2. Missing energy	$\not{E} > 100$ GeV
3. Tauons azimuthal angle	$\lvert\Delta\phi_\tau\rvert < 3$
4. Angular distance between tauons	$\Delta R_\tau > 2$
5. Cosine of the angle between tauons	$\cos\theta_\tau < 0$
6. Cosine of missing theta	$\lvert\cos\not{\theta}\rvert < 0.98$

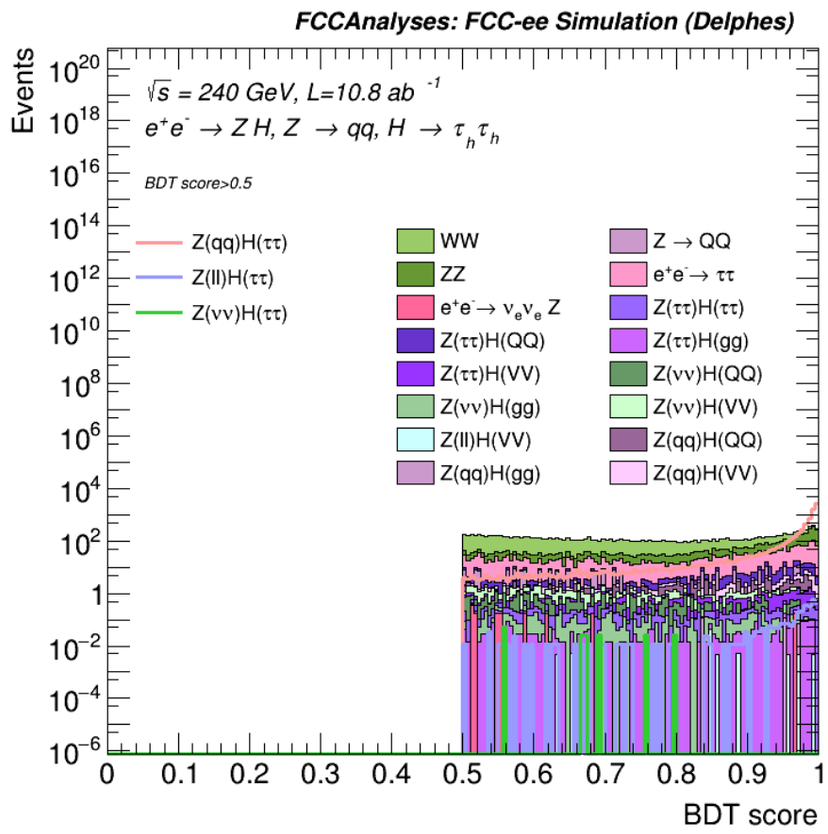






BDT TRAINING

- We're also training a BDT classifier for the categories where the events are not so clean after the final state selection (everything but $Z \to \ell\ell$) to achieve better separation between signal and background
- Currently only applied to $Z \to qq, H \to \tau_h\tau_h$:
  - **200 trees and depth of two** on 23 variables (missing energy, Z, Higgs, tau angular variables, recoil and collinear mass, …)
  - We use about 70% of our signal samples for training and don't exclude those events when we apply the BDT in the analysis
  - We don't expect much overtraining with the current size of the BDT but we're planning to study this and adjust the training and analysis dataset consequently



CROSS-SECTION RESULTS

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- Previous FCC-ee estimate of ±0.6% relative statistical uncertainty on the measurement of $\sigma_{ZH} \times \mathscr{B}(H \to \tau\tau)$ at √s=240 GeV, $\mathscr{L}_{int}$=10.8 ab^{-1} (FCC CDR, based on LEP3)
- We are using the Combine tool arXiv:2404.06614 fitting the recoil mass ($Z \to \ell\ell$, $Z \to qq$) or visible mass ($Z \to \nu\nu$) with freely floating processes
- Our current result, based purely on the cuts illustrated before and combined for the nine categories, is **±1.2% relative uncertainty (68% CL) at √s=240 GeV, $\mathscr{L}_{int}$=10.8 ab^{-1}**

DETAILS OF EACH CATEGORY:

$Z \to qq, H \to \tau_\ell\tau_\ell$: 1.00002 -0.137676/+0.143218

$Z \to qq, H \to \tau_\ell\tau_h$: 1.00004 -0.0476389/+0.04891

$Z \to qq, H \to \tau_h\tau_h$: 1.00003 -0.0397673/+0.0410996 ⇒ with BDT (preliminary) 1.00003 -0.0228522/+0.023222

$Z \to \ell\ell, H \to \tau_\ell\tau_\ell$: 1.00001 -0.219315/+0.271913

$Z \to \ell\ell, H \to \tau_\ell\tau_h$: 1.00001 -0.10732/+0.121276

$Z \to \ell\ell, H \to \tau_h\tau_h$: 1 -0.076209/+0.0836675

$Z \to \nu\nu, H \to \tau_\ell\tau_\ell$: 1.00077 -3.00077/+3.20104

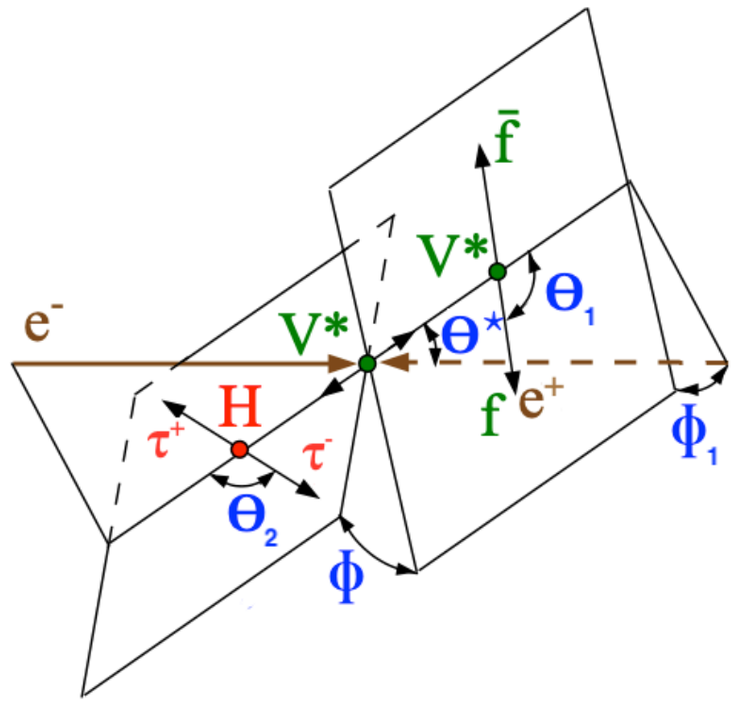
$Z \to \nu\nu, H \to \tau_\ell\tau_h$: 0.999502 -0.803933/+0.806547

$Z \to \nu\nu, H \to \tau_h\tau_h$: 1.00002 -0.261827/+0.26312

CP UPDATE

- In the previous meeting, we have reported a difference in cross-sections between the ZH events being produced in Whizard or Madgrap
- Now solved: the default SM MG card has a lower Higgs width

- We have generated a few EFT samples for $Z \to ee$ and $Z \to \mu\mu, H \to \tau\tau$ with CPC and CPV Yukawa operators $\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}_L \tilde{H} e_R) + \text{h.c.}$
- We are not observing any difference in the shape of the variables as expected due to limited statistics, but we do see the expected difference in the cross-section between the SM and EFT
  - We will generate more events
  - It may also be due to too small Wilson coefficients
  - We also plan to include dipole operators $\mathcal{O}_{eW} = (\bar{L}_L \sigma^{\mu\nu} e_R)\tau^I H W^I_{\mu\nu}$, $\mathcal{O}_{eB} = (\bar{L}_L \sigma^{\mu\nu} e_R) H B_{\mu\nu}$



NEXT STEPS

- For future updates, we plan to:
  - Keep developing the BDT classifier for more categories and do tests on the training
  - Study different CP hypotheses
    - Depending on the timeline and developments, we could also have some comparison between EFT and SM

- We are writing the analysis note with the updates discussed today
  - Cross-section result from the selection analysis
  - Developments on the BDT selection and results
  - EFT signal discussion

- All further updates will be documented in the note in the next few months before the final report