Institute of Experimental Particle Physics

Karlsruher Institut für Technologie

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

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Higgs/top performance meeting
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Targets and news

- Relative uncertainty of $ZH, H \to \tau\tau$ **cross-section** at $\sqrt{s} = 240$ GeV at FCC-ee
  ➜ final updates in this presentation
  - **Explicit** (from Maria Cepeda) vs. **ML-based** tau reconstruction (FCC PNet jet tagger)
  - **Inclusive** vs. **exclusive** jet algorithm
  - **Cut-based** vs. **BDT** event selection

- Further studies (just begun):
  - We will also repeat the same analysis with ZH and VFB signals at $\sqrt{s} = 365$ GeV
  - CP violation in the same channel

General workflow

- We excluded all isolated electrons and muons ($p_T > 20$ GeV and iso<0.25) from jets
  - **Inclusive e^+e^- generalized kt algorithm** with R=0.5 and $p_{T,j} > 2$ GeV
  - **Exclusive e^+e^- Durham algorithm** with n_{jets} depending on the category

- We define **nine categories** based on the Z and tau decays ($\ell = e, \mu$)
  - $Z \to \ell\ell$
  - $Z \to qq$
  - $Z \to \nu\nu$
  - $H \to \tau_\ell\tau_\ell$
  - $H \to \tau_\ell\tau_h$
  - $H \to \tau_h\tau_h$
- Basic selection requires exactly the objects in each category to be reconstructed

- Leptonic taus are always handled “manually” by selecting the isolated leptons
- Quark jets are differentiated from hadronic tau jets depending on the reconstruction method ➜ next slide

Tau reconstruction

- Both methods are based on jet clustering

Explicit

- Only jets with no electrons or muons
- Gets the leading π
- Adds constituents to it if pt>1 GeV and $\Delta\theta<0.2$
- Defines a tau ID based on decay modes

ParticleNet

- Trained on di-jets events
- Assigns quark/tau score for each jet
- We select jets with tau score > 0.5

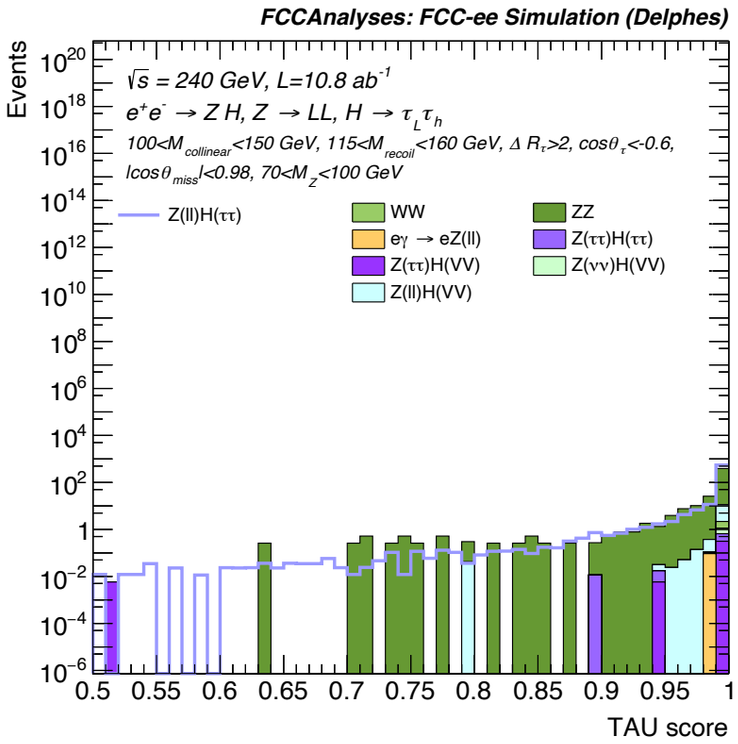
Efficiency compared to true taus

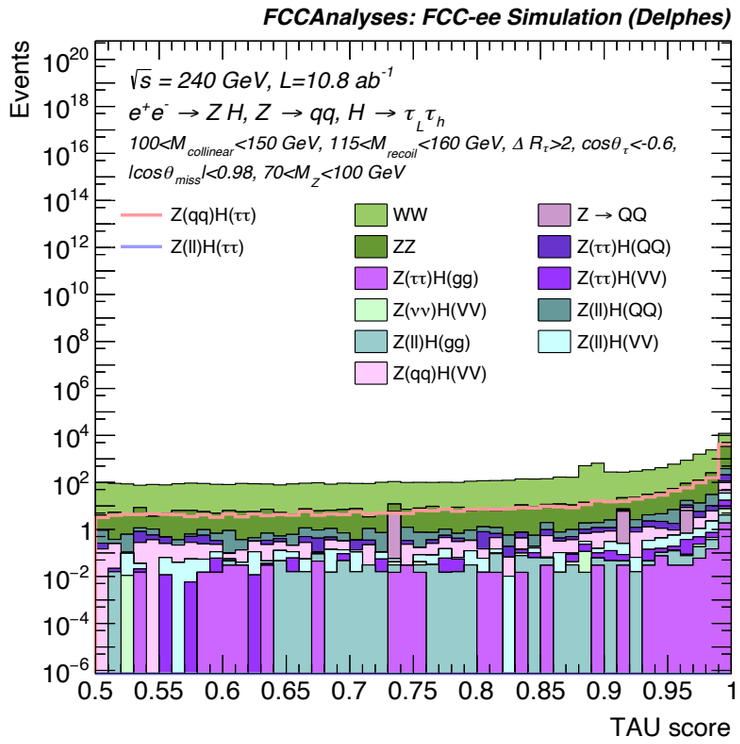
	Explicit tau reconstruction		ParticleNet tau reconstruction	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
$Z \to \nu\nu,\ H \to \tau\tau$	90.34%	87.09%	97.60%	94.20%
$Z \to ee,\ H \to \tau\tau$	84.96%	78.07 %	95.15%	83.21 %
$Z \to \mu\mu,\ H \to \tau\tau$	84.96%	79.94%	95.15%	83.21%
$Z \to bb,\ H \to \tau\tau$	77.69%	77.31%	76.23%	65.72%
$Z \to cc,\ H \to \tau\tau$	78.45%	78.07%	76.58%	65.72%
$Z \to ss,\ H \to \tau\tau$	78.82%	78.07%	76.15%	65.50%
$Z \to qq,\ H \to \tau\tau$	78.78%	77.95%	76.57%	65.50%

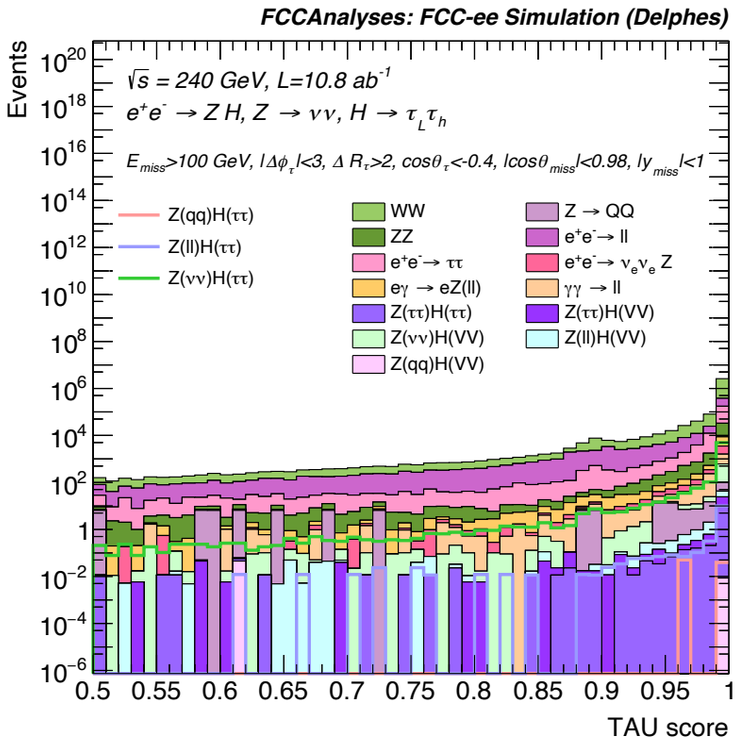
CUT-BASED ANALYSIS

Selection

- Event selection only differs between visible and invisible Z decays
  - Consistent physics picture between the combinations of tau reconstructions and jet clustering
  - Detailed optimization of $\sqrt{S}/B$ only marginally improves the precision
- Example plots show the inclusive jets with explicit tau reconstruction and ParticleNet reconstruction in the case of the tau score (this slide)

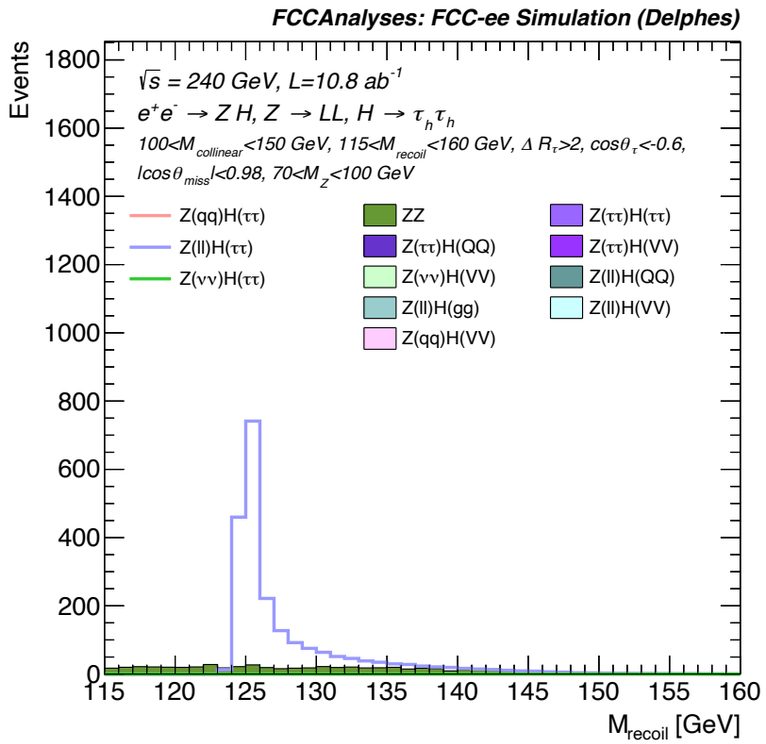


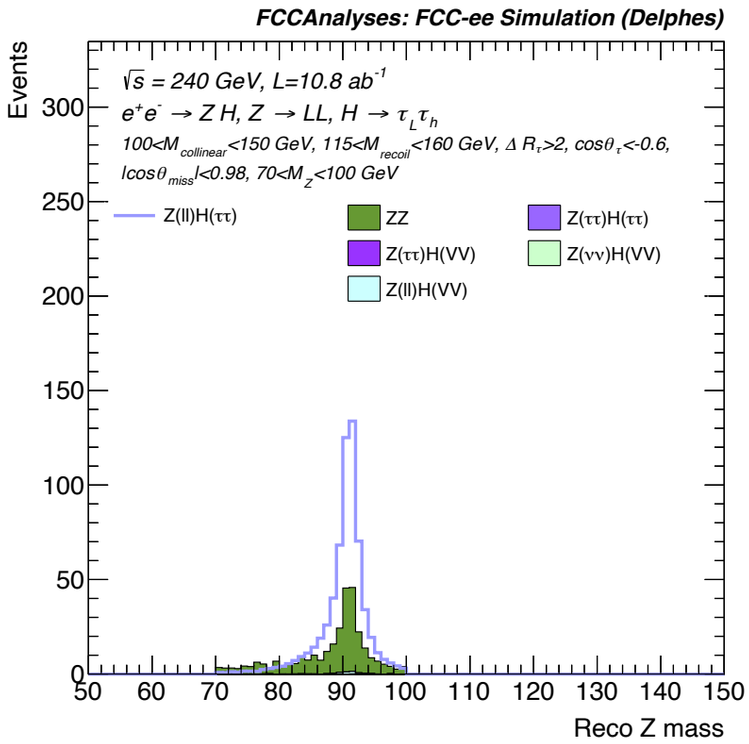


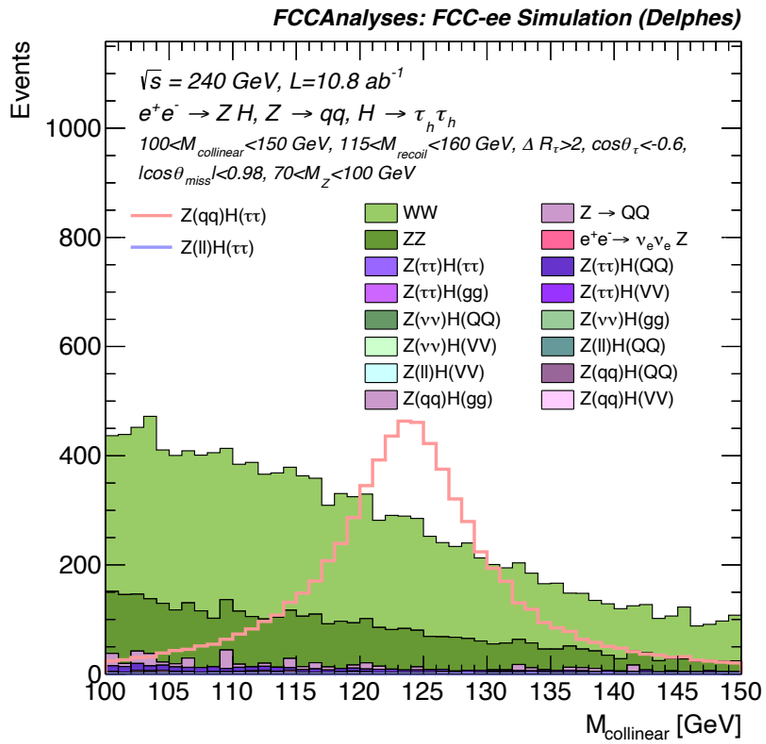


$Z \to \ell\ell$ and $Z \to qq$

Cut description for $Z \to \ell\ell$ and $Z \to qq$	Values
1. Selection for $Z \to \ell\ell$	Two leptons with same flavor and opposite charges, two taus with opposite charges
1. Selection for $Z \to qq$	Two jets and two taus with opposite charges
2. Collinear mass	$100 < M_{collinear} < 150$ GeV
3. Recoil mass	$115 < M_{recoil} < 160$ GeV
4. Reconstructed Z mass	$70 < M_Z < 100$ GeV
5. Angular distance between taus	$\Delta R_{\tau\tau} > 2$
6. Cosine of the angle between taus	$\cos\theta_{\tau\tau} < -0.6$
7. Cosine of missing theta	$\lvert\cos\not{\theta}\rvert < 0.98$

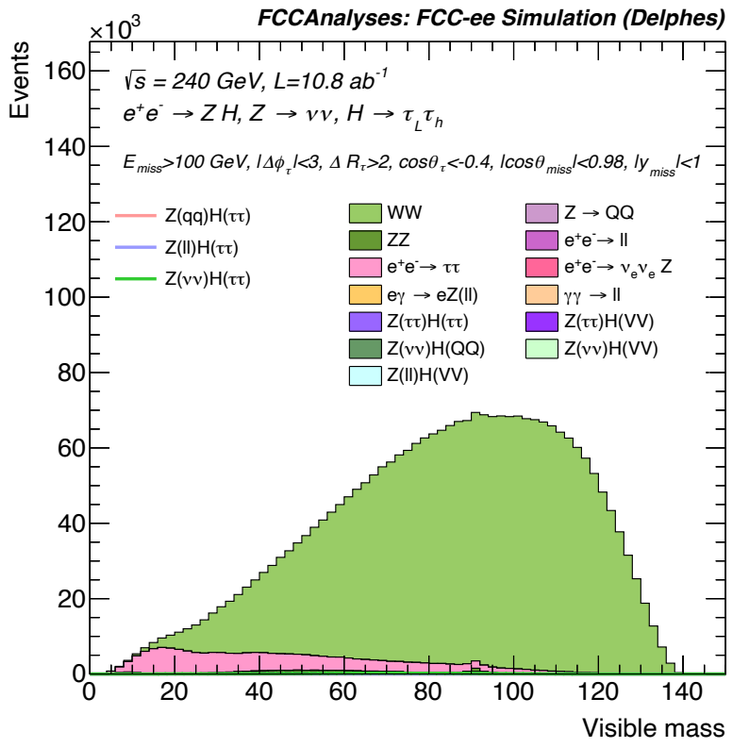


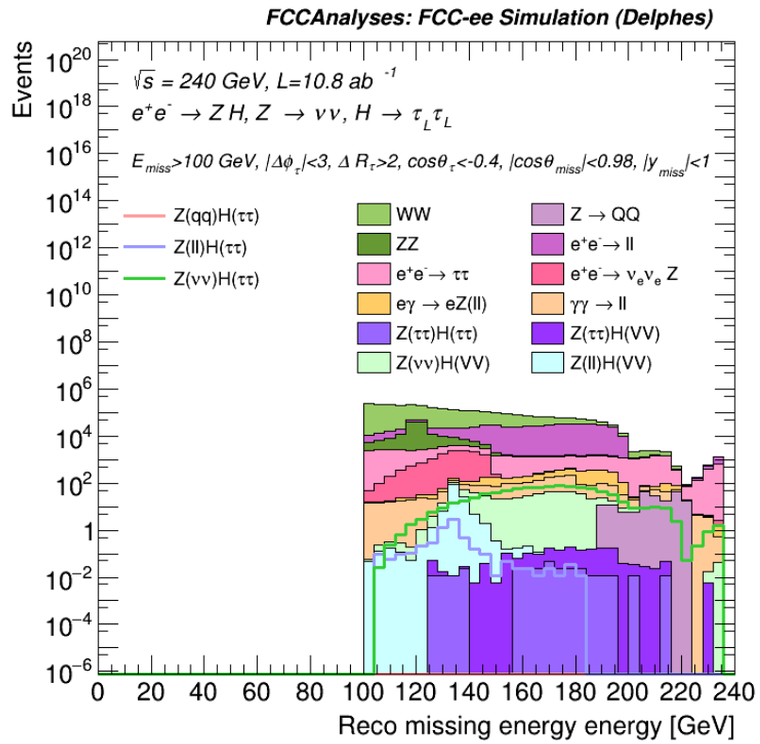


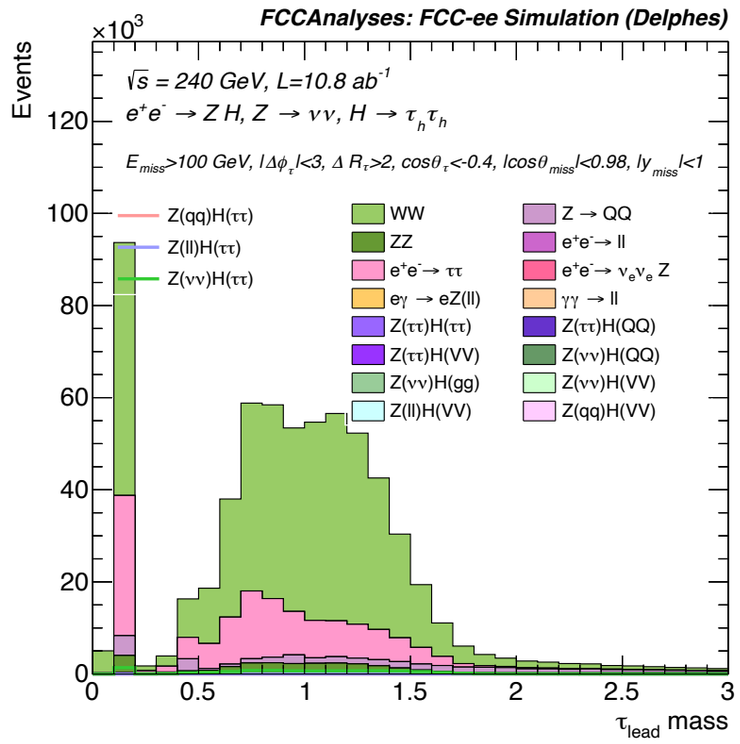


$Z \to \nu\nu$

Cut description for $Z \to \nu\nu$	Values
1. Selection	Two taus with opposite charges
2. Missing energy	$\not{E} > 100$ GeV
3. Missing rapidity	$\lvert\not{y}\rvert < 1$
4. taus azimuthal angle	$\lvert\Delta\phi_{\tau\tau}\rvert < 3$
5. Angular distance between taus	$\Delta R_{\tau\tau} > 2$
6. Cosine of the angle between taus	$\cos\theta_{\tau\tau} < -0.4$
7. Cosine of missing theta	$\lvert\cos\not{\theta}\rvert < 0.98$



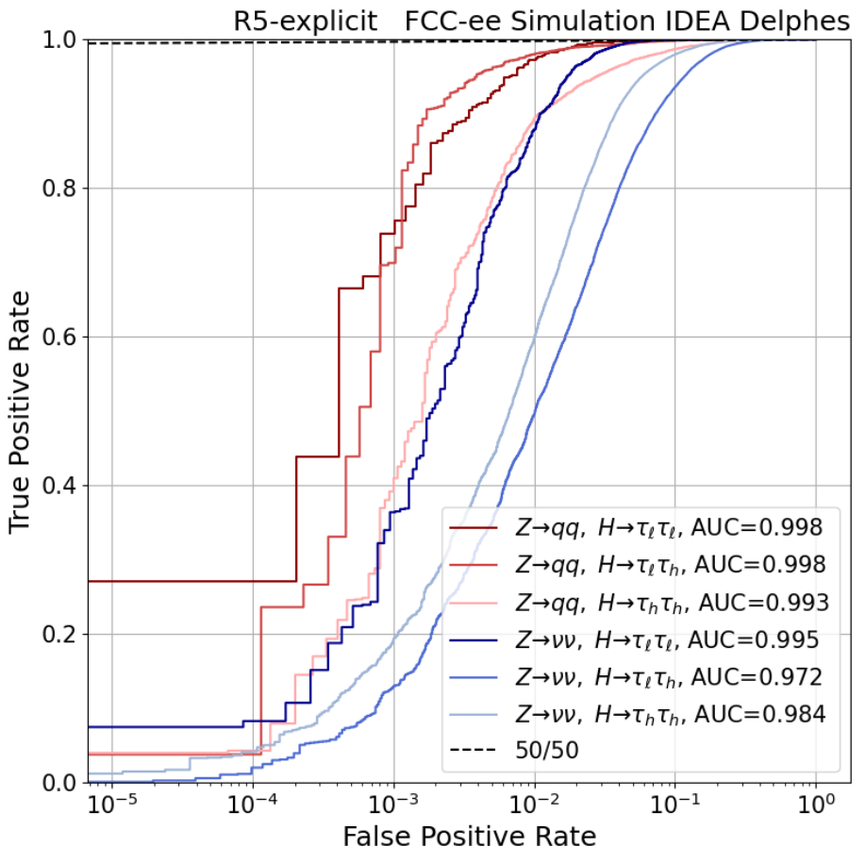


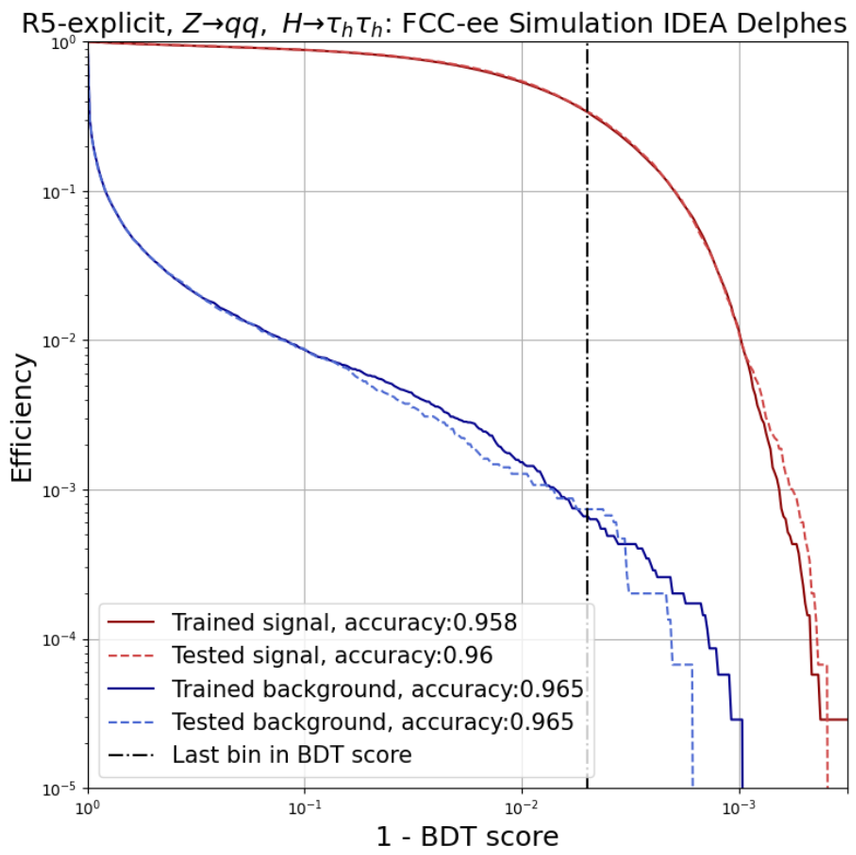


BDT ANALYSIS

BDT training

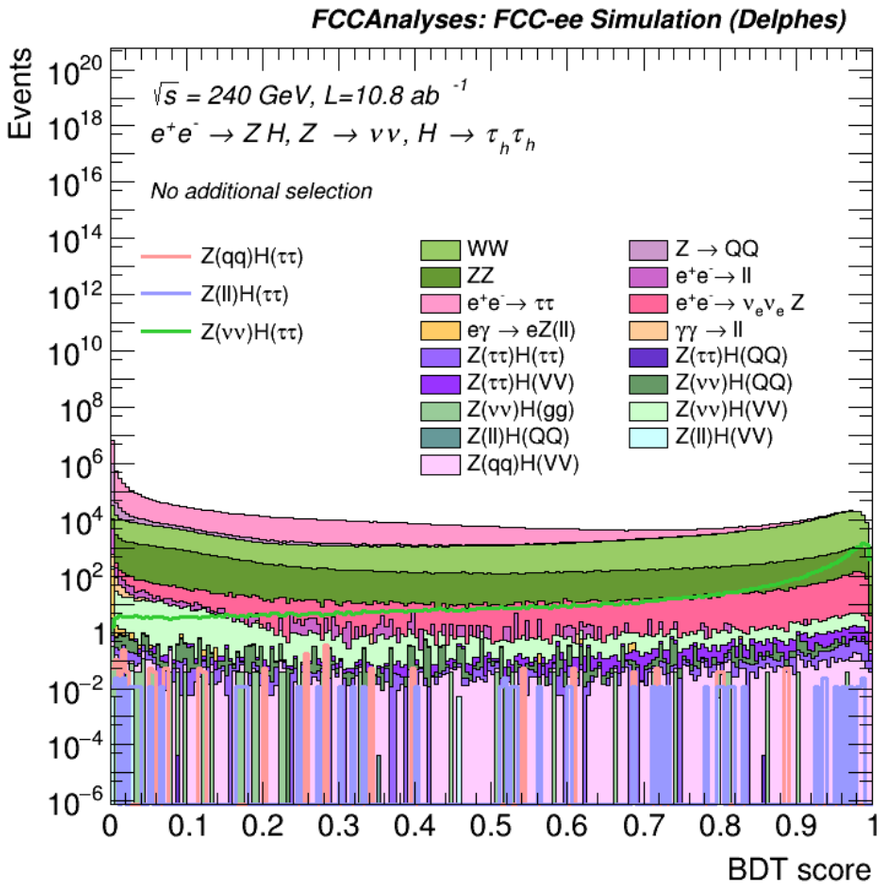
- We trained a different BDT in each category for $Z \to qq$ and $Z \to \nu\nu$
- No significant overtraining was observed for BDT of 200 trees and depth of 2
- Samples split into 70/30 for training and testing, both used in the analysis

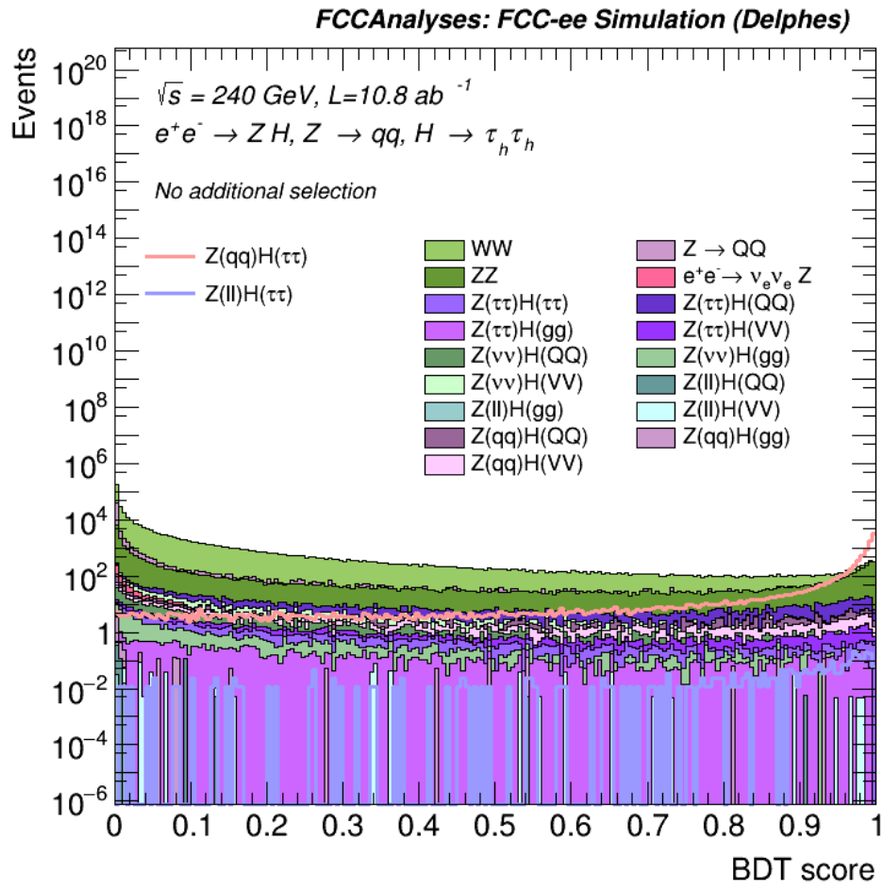




BDT selection

- The training is very effective in separating signal from background in all categories
- But $Z \to \nu\nu$ is still background-dominated
- We selected events with the BDT score above 0.5 in all cases





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RESULTS

Results

- **Combine shape-based fit** arXiv:2404.06614 with 20% lnN background uncertainty and MC statistical uncertainties
  - Cut-based analysis: M_{recoil} for $Z \to \ell\ell$ and $Z \to qq$, M_{vis} for $Z \to \nu\nu$
  - BDT analysis: M_{recoil} for $Z \to \ell\ell$, BDT score for $Z \to qq$ and $Z \to \nu\nu$

- Final numbers for the relative uncertainty (68% CL) of $H \to \tau\tau$ cross section at $\sqrt{s}$=240 GeV, $\mathscr{L}$=10.8 ab^{-1}
- Best result from ParticleNet tau reconstruction using exclusive jets and applying the BDT selection

	Explicit tau reconstruction		ParticleNet tau reconstruction	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
Cut-based analysis	-1.28 %, +1.30%	±1.54%	±0.95%	±1.15%
BDT analysis	±1.02%	±0.88	±0.79%	±0.74%

Background uncertainty

- We also varied the background uncertainty from 0 to 20 % only in the case of the BDT analysis
- We think 20% uncertainty is too conservative, we propose to use 2% instead ➜ open to suggestions/discussion

	Explicit tau reconstruction		ParticleNet tau reconstruction	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
BDT analysis - 20%	±1.02%	±0.88%	±0.79%	±0.74%
BDT analysis - 5%	±1.00%	±0.86%	±0.78%	±0.72%
BDT analysis - 2%	±0.98%	±0.83%	±0.76%	±0.69%
BDT analysis - 0%	±0.92%	±0.77%	±0.70%	±0.63%

Next steps

- Analysis at 240 GeV is now complete and documented
- Updated analysis note on CDS soon

- We began to look into ZH and VBF $H \rightarrow \tau\tau$ at 365 GeV
- We plan to publish this work later on (240+365 cross-section)

- Ongoing efforts to study CPV with EFT signal in the same channel at 240 GeV
- This will be a separate work/paper, unfortunately not in time for the European strategy

BACKUP

Detailed results

	Explicit tau reconstruction			
	Cut-based analysis		BDT analysis	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
$Z \to qq,\ H \to \tau_\ell\tau_\ell$	-29.50%, +29.38%	-29.04%, +28.60%	-5.37%, +5.49%	-4.24%, +4.30%
$Z \to qq,\ H \to \tau_\ell\tau_h$	-4.00%, +3.94%	-4.15%, +4.04%	±2.94%	±2.46%
$Z \to qq,\ H \to \tau_h\tau_h$	-3.07%, +3.04%	-9.30%, +8.84%	±2.15%	±1.88%
$Z \to qq$	-1.89%, +1.89%	-2.60%, +2.64%	±1.64%	±1.44%
$Z \to \ell\ell,\ H \to \tau_\ell\tau_\ell$	-17.96%, +18.42%		-	
$Z \to \ell\ell,\ H \to \tau_\ell\tau_h$	-4.65%, +4.83%	-5.41%, +5.55%	-	
$Z \to \ell\ell,\ H \to \tau_h\tau_h$	-2.46%, +2.50%	-2.55%, +2.58%	-	
$Z \to \ell\ell$	-2.08%, +2.10%	-2.18%, +2.22%	-	
$Z \to \nu\nu,\ H \to \tau_\ell\tau_\ell$	-610.46%, +605.58%		-226.24%, +229.13%	
$Z \to \nu\nu,\ H \to \tau_\ell\tau_h$	-61.66%, +61.44%	-61.98%, +61.83%	-15.15%, 15.19%	-17.31%, =17.36%
$Z \to \nu\nu,\ H \to \tau_h\tau_h$	-29.63%, +29.42%	-29.53%, +29.44%	-6.54%, +6.59%	-6.77%, +6.79%
$Z \to \nu\nu$	-11.06%, +11.12%	-11.68%, +11.72%	-5.78%, +5.85%	6.07%, +6.09%
combined	-1.30%, +1.28%	-1.54%, +1.54%	±1.02%	±0.88%

Detailed results

	ParticleNet tau reconstruction			
	Cut-based analysis		BDT analysis	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
$Z \to qq,\ H \to \tau_\ell\tau_\ell$	-25.57%, +25.43%	-22.99%, +22.50%	-4.67%, +4.79%	-3.39%, +3.43%
$Z \to qq,\ H \to \tau_\ell\tau_h$	-3.88%, +3.80%	-3.87%, +3.84%	±2.26%	±1.87%
$Z \to qq,\ H \to \tau_h\tau_h$	-2.12%, +2.08%	-2.98%, +2.88%	±1.52%	±1.44%
$Z \to qq$	-1.23%, +1.24%	-1.50%, +1.49%	±1.20%	±1.11
$Z \to \ell\ell,\ H \to \tau_\ell\tau_\ell$	-18.36%, +18.81%		-	
$Z \to \ell\ell,\ H \to \tau_\ell\tau_h$	-4.38%, +4.50%	-5.67%, +5.85%	-	
$Z \to \ell\ell,\ H \to \tau_h\tau_h$	-1.90%, +1.91%	-2.24%, +2.24%	-	
$Z \to \ell\ell$	-1.68%, +1.69%	-2.07%, +2.08%	-	
$Z \to \nu\nu,\ H \to \tau_\ell\tau_\ell$	-610.46%, +605.58%		-226.24%, +229.13%	
$Z \to \nu\nu,\ H \to \tau_\ell\tau_h$	-81.42%, +81.57%	-71.37%, +71.40%	-16.17%, +16.11%	-22.23%, +22.12%
$Z \to \nu\nu,\ H \to \tau_h\tau_h$	-32.23%, +32.10%	-43.73%, +43.59%	-6.00%, +6.04%	±7.07%
$Z \to \nu\nu$	-13.01%, +13.04%	-16.81%, +16.81%	±6.00%	±6.37%
combined	-0.95%, +0.95%	-1.15%, +1.15%	±0.79%	±0.74%