Improvements in ZH cross section measurement

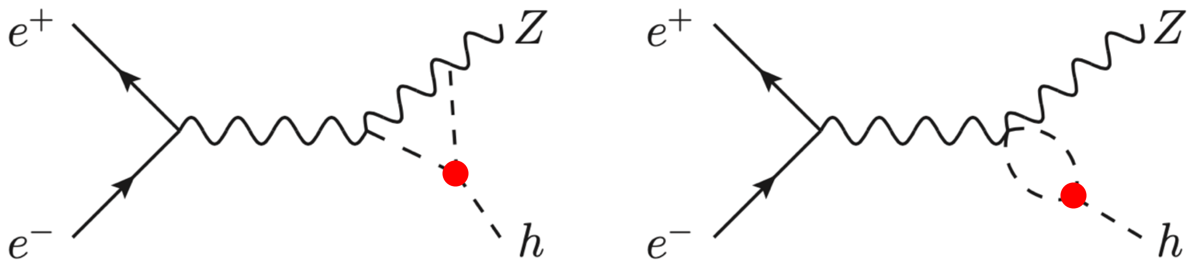
Tom Fournier

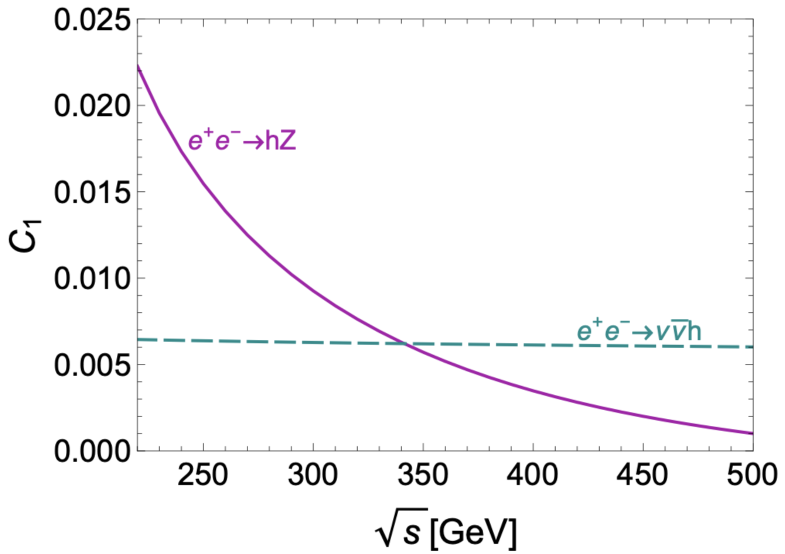
Supervised by Gregorio Bernardi

5th FCC/DRD France Workshop, November 2025

Motivations

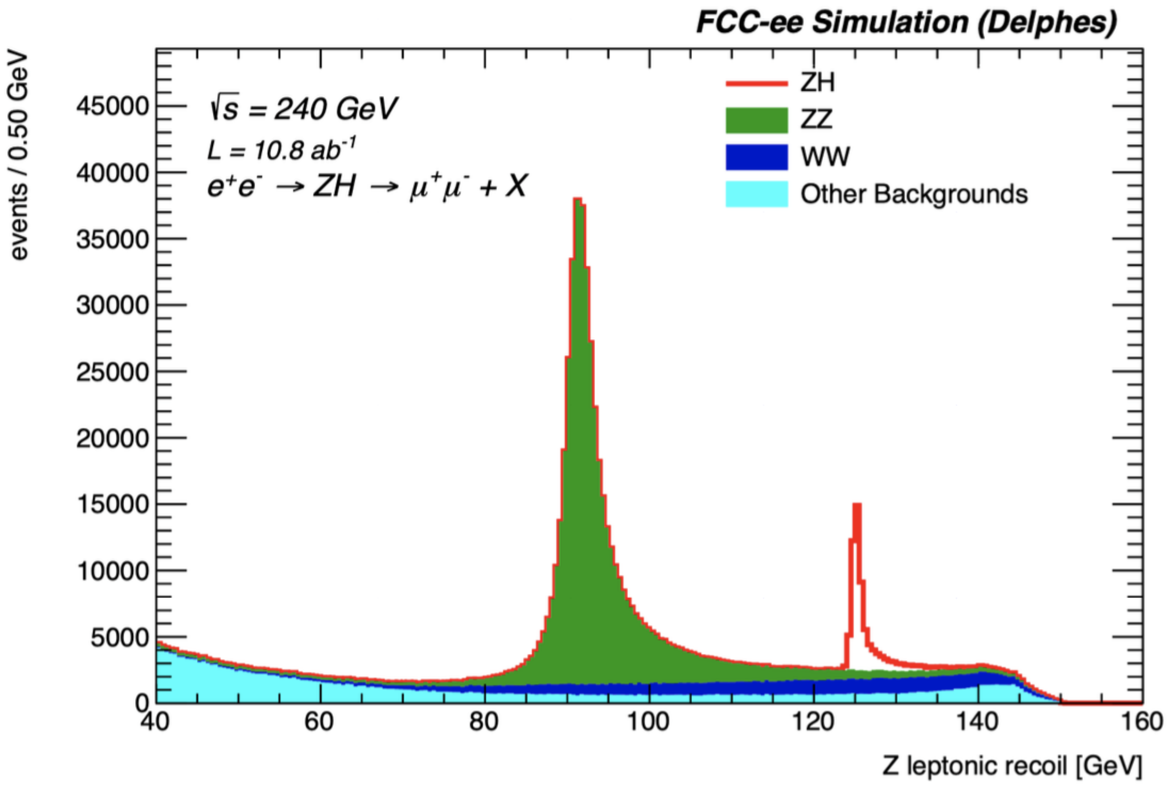
- Measuring σ_{ZH} permit us to access g_{ZZ^*} in a model-independent way through
  - $\sigma_{ZH} \times \mathcal{B}(H \to X\bar{X}) \propto \frac{g_{HZZ}^2 \times g_{HXX}^2}{\Gamma_H} \to \sigma_{ZH} \times \mathcal{B}(H \to ZZ^*) \propto \frac{g_{HZZ}^4}{\Gamma_H}$
- Once known, g_{ZZ^*} used as a standard candle to determines g_{XX} in a model-independent way
- Recoil mass shape distribution analysis to extract the Higgs mass with great precision
- We can also acces the Higgs width Γ_H through
  - $\Gamma_H \propto \frac{\sigma(e^+e^- \to ZH, H \to ZZ)^2}{\sigma(e^+e^- \to ZH)}$
- Allow us to access Higgs self-coupling through NLO correction to ZH cross section
  - $\Sigma_{NLO} = Z_H \Sigma_{LO}(1 + \kappa_\lambda C_1)$
  - With C_1 dependent on $\sqrt{s}$ → can measure σ_{ZH} at $\sqrt{s} = 240\ GeV$ and $\sqrt{s} = 365\ GeV$ to access κ_λ
  - Complementary measurement to the one made at HL-LHC

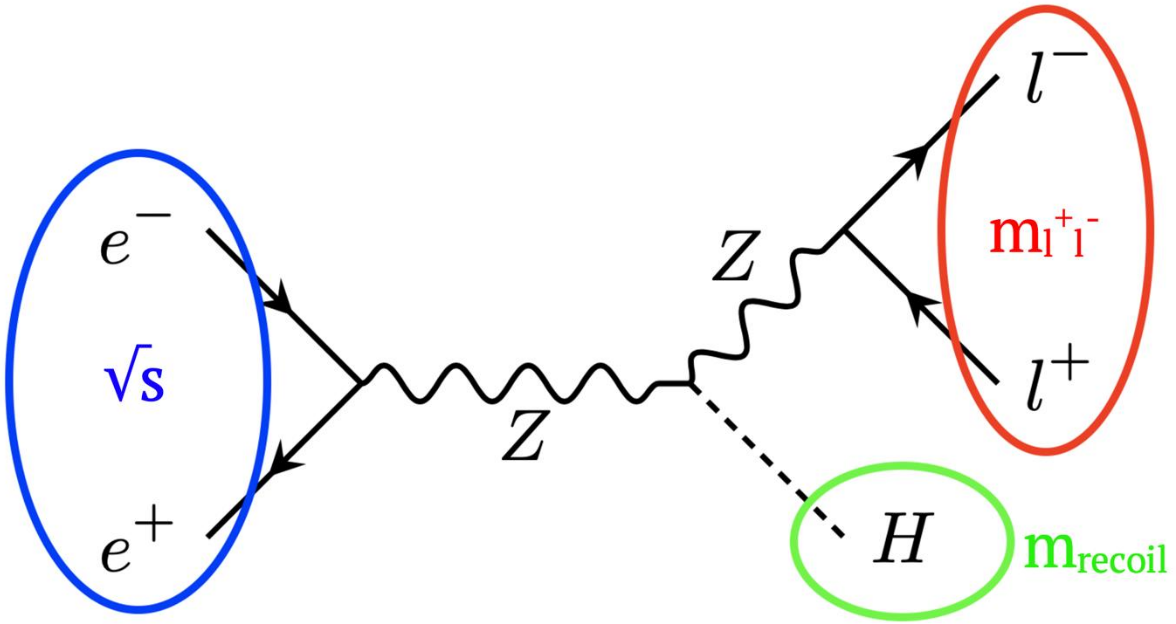




Recoil mass method

e^+e^- collisions → initial state known → can use the recoil mass method to measure σ_{ZH} in a model-independent way



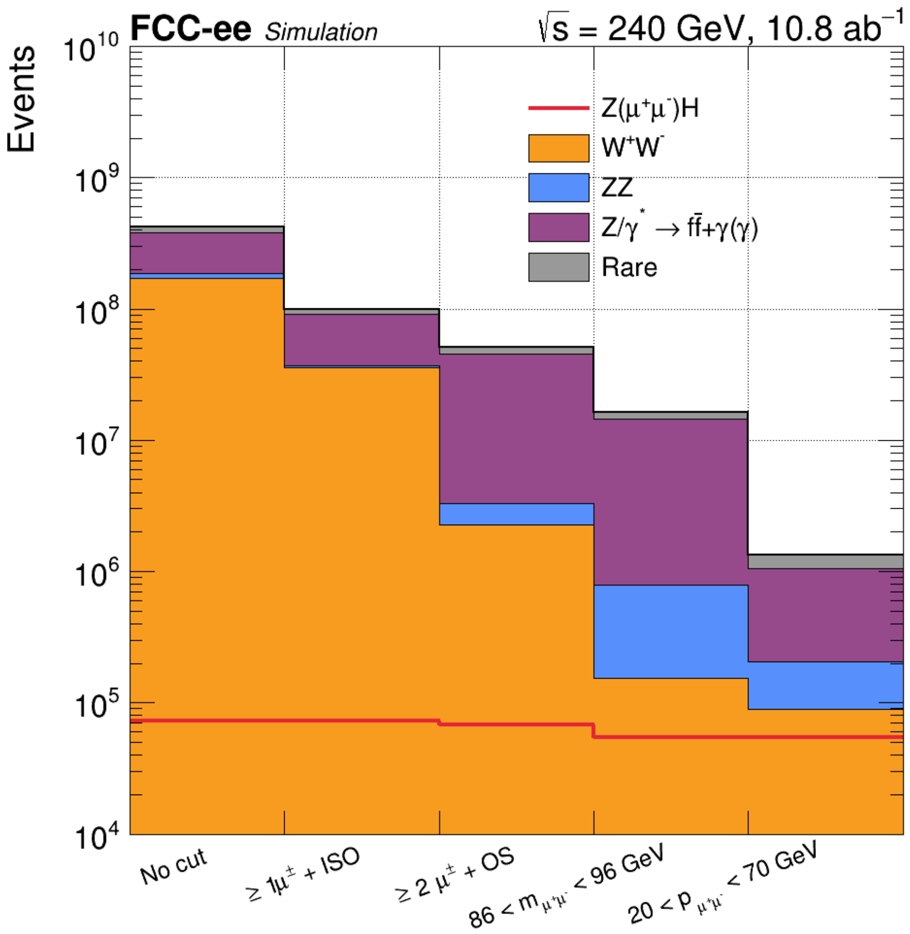


$$m_{recoil}^2 = (E_{\ell^+\ell^-} - \sqrt{s})^2 - p_{\ell^+\ell^-}^2 = s - 2\sqrt{s}E_{\ell^+\ell^-} + m_{\ell^+\ell^-}^2$$

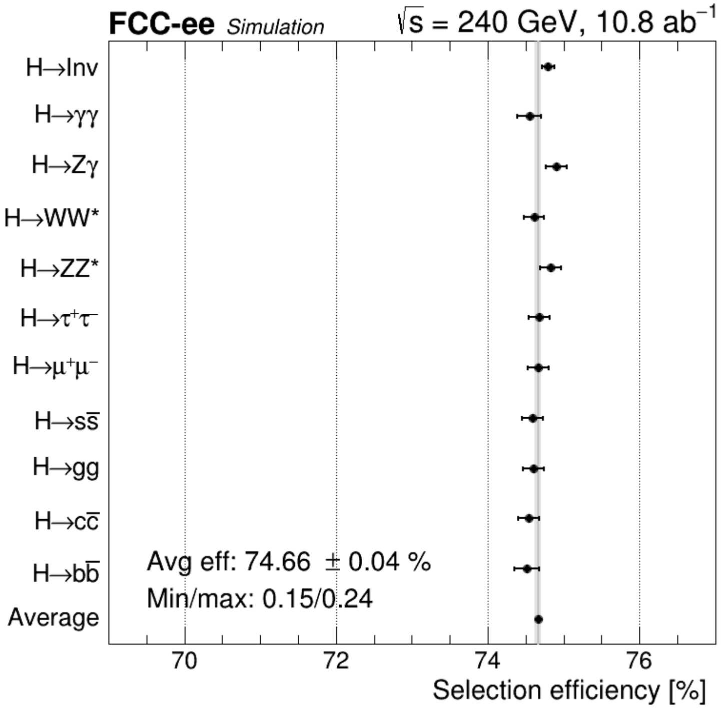
- Focus only on the Z and its daughter particles variable to reconstruct m_{recoil}
- Analysis done in three channels
  - $Z(\rightarrow e^+e^-)H$
  - $Z(\rightarrow \mu^+\mu^-)H$
  - $Z(\rightarrow q\bar{q})H$
- Only presenting the leptonic channel (e^+e^- and $\mu^+\mu^-$)

Event Selection

- Lepton momentum $p > 20\ GeV$
- At least one lepton isolated ($I_{rel} < 0.25$)
- At least two leptons with opposite charge
- If more than 2 leptons, select the pair that minimizes:
  - $\chi^2 = 0.6 \times (m_{\ell^+\ell^-} - 91.2\ GeV)^2 + 0.4 \times (m_{recoil} - 125\ GeV)^2$
- $86\ GeV < m_{\ell^+\ell^-} < 96\ GeV$
- $20\ GeV < p_{\ell^+\ell^-} < 70\ GeV$

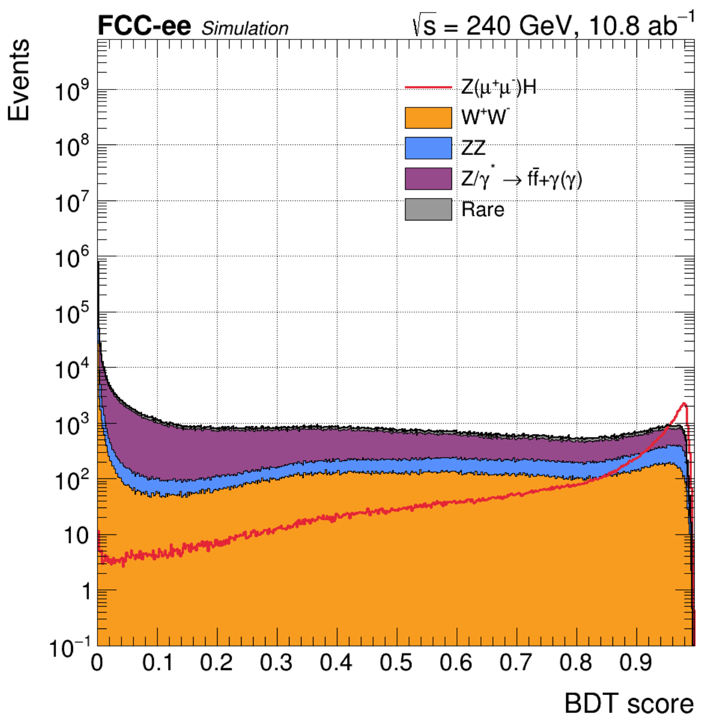


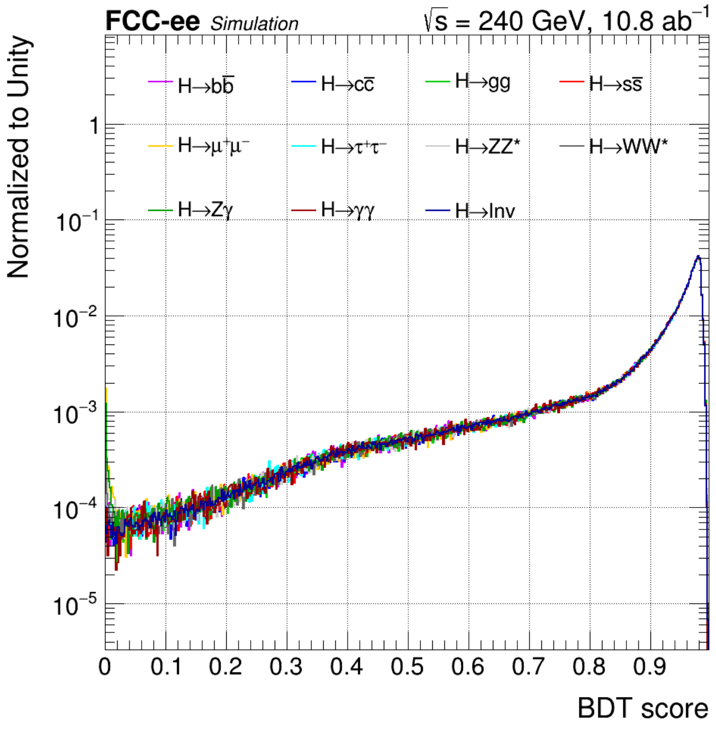
Cutflow



- Cutflow and selection efficiency shown for $\mu^+\mu^-$
- Selection efficiency independent of Higgs decay

MVA Discriminant

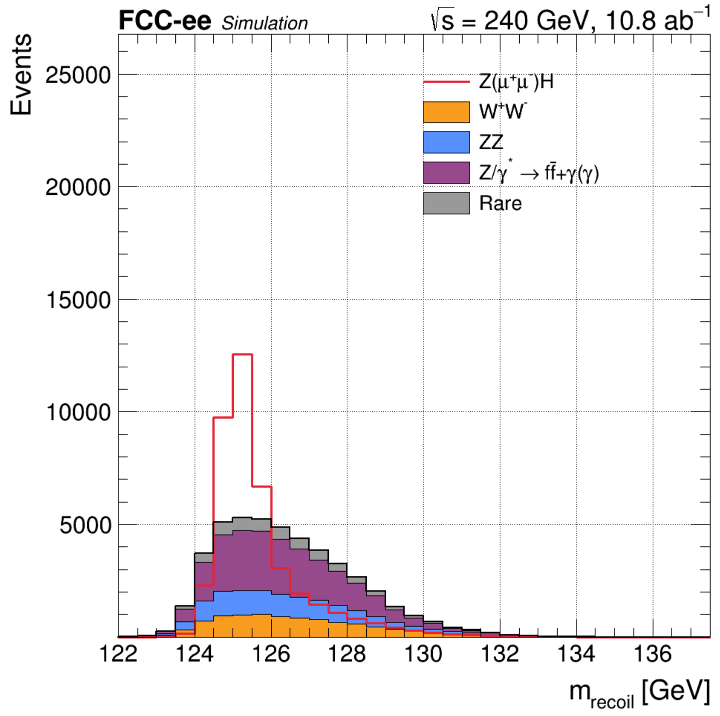


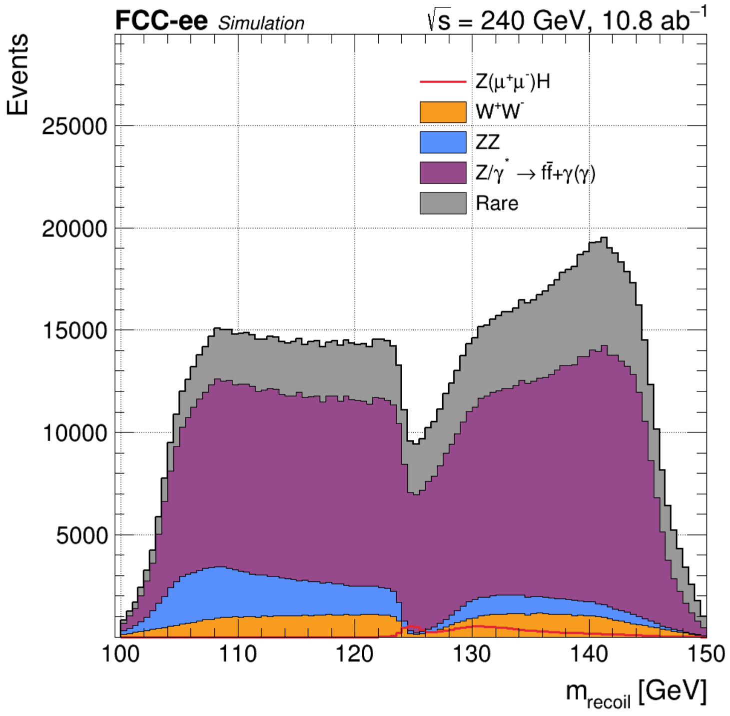


Variable	Description
$p_{leading}$	Leading lepton momentum
$\theta_{leading}$	Leading lepton polar angle
$p_{subleading}$	Subleading lepton momentum
$\theta_{subleading}$	Subleading lepton polar angle
$m_{\ell^+\ell^-}$	Lepton pair invariant mass
$p_{\ell^+\ell^-}$	Lepton pair momentum
$\theta_{\ell^+\ell^-}$	Lepton pair polar angle
$\Delta\theta_{\ell^+\ell^-}$	Acolinearity
$\pi - \Delta\phi_{\ell^+\ell^-}$	Acoplanarity

- Train a BDT to further discriminate signal from background
- BDT distribution independent of the Higgs decay

Uncertainty Extraction





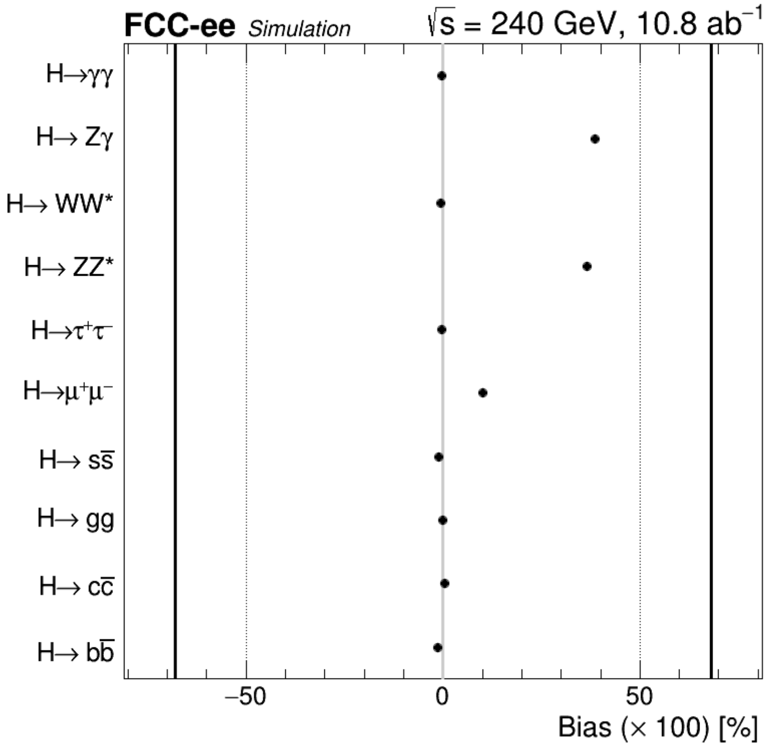
- Separate events into:
  - High score region: BDT score > 0.86(0.84) for $\mu^+\mu^-(e^+e^-)$
  - Low score region: BDT score < 0.86(0.84) for $\mu^+\mu^-(e^+e^-)$
- Concatenate the histograms and fits on the resulting distribution to extract the total σ_{ZH}
- Take into account the contributions from $Z(q\bar{q})H$ and $Z(\nu\bar{\nu})H$ in the fit
- 1% normalization for all background processes (uncorrelated)

Channel	ZH uncertainty
$Z(e^+e^-)H$	**0.81%**
$Z(\mu^+\mu^-)H$	**0.68%**
$Z(\ell^+\ell^-)H$	**0.52%**

Bias Test

We use a bias test to determine the degree of independence of the selection:

- We modify the Br of each Higgs decays individually so that $\frac{\delta\sigma_{ZH}}{\sigma_{ZH}} = X\%$
- We construct pseudo-data from these modified Br's
- Extract the bias by fitting the pseudo-data
  - $b = 100 \times (\mu_{fit} - 1 - X/100)$ with X in %
- Compare it with the measurement uncertainty



$X = 5\%$ prior taken for all the bias test

- If the bias is within the quoted uncertainty, the test is successful
- Shown here for $\mu^+\mu^-$, bias for e^+e^- and combined fit are in back-up slides

For the Baseline

- Slighty high bias for $H \rightarrow \mu^+\mu^-$
- High bias observed for $H \rightarrow ZZ^*$ and $H \rightarrow Z\gamma$
  - Due to ambiguity in the selection at the χ^2 step
- But still under ZH uncertainty → test successful

Channel	Baseline [%]
$H \rightarrow b\bar{b}$	-0.01
$H \rightarrow c\bar{c}$	+0.00
$H \rightarrow gg$	-0.00
$H \rightarrow s\bar{s}$	-0.01
$H \rightarrow \mu^+\mu^-$	+0.10
$H \rightarrow \tau^+\tau^-$	-0.00
$H \rightarrow ZZ^*$	+0.37
$H \rightarrow WW^*$	-0.01
$H \rightarrow Z\gamma$	+0.38
$H \rightarrow \gamma\gamma$	-0.00

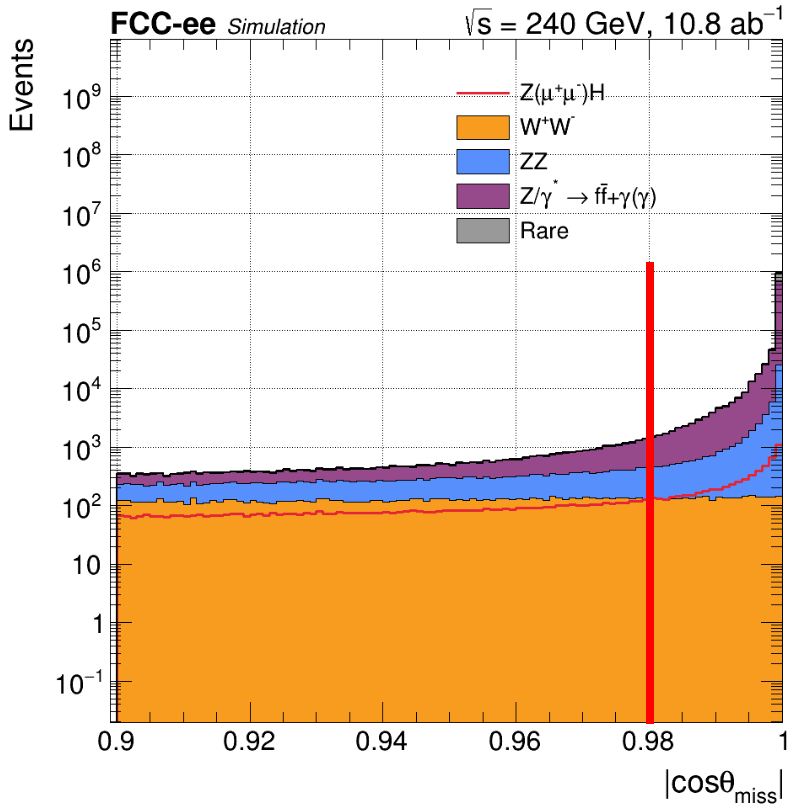
Comparison with ILC

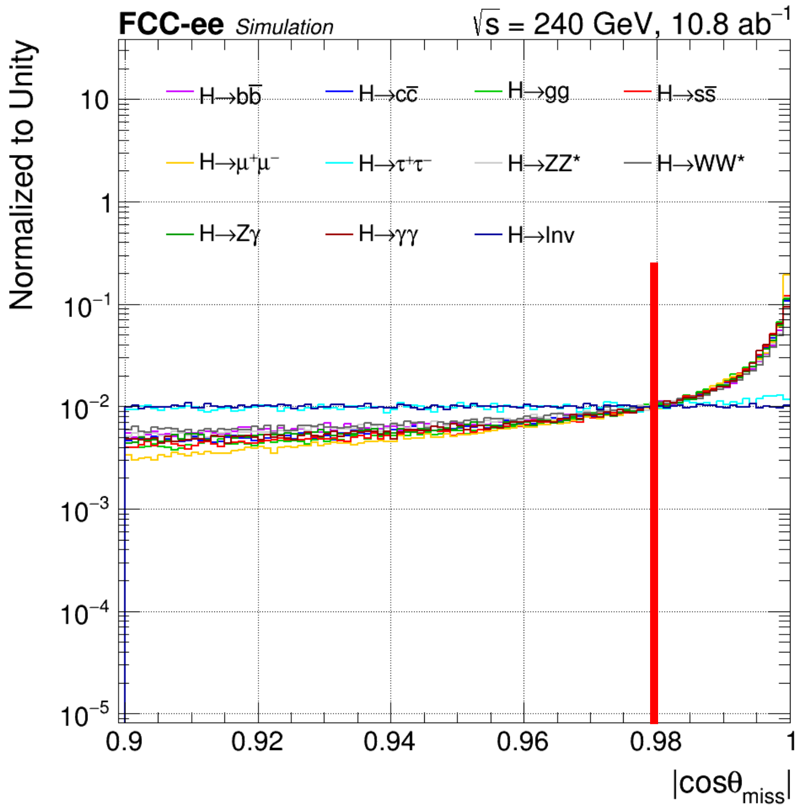
(+/-) indicates the beam polarization: $(Pe^{-}, Pe^{+}) = (-80\%, +30\%)/(+80\%, -30\%)$

Selection	$Z(e^{+}e^{-})H$	$Z(\mu^{+}\mu^{-})H$	$Z(\ell^{+}\ell^{-})H$
ILC (+/-)	**4.0%/4.7%**	**3.2%/3.6%**	**2.5% / 2.9%**
FCC (Baseline)	**0.81%**	**0.68%**	**0.52%**
ILC scaled to FCC luminosity (+/-)	**0.61% / 0.71%**	**0.48% / 0.54%**	**0.38% / 0.44%**
FCC (Baseline) scaled to ILC cross section (+/-)	**0.63% / 0.75%**	**0.54% / 0.63%**	**0.41% / 0.48%**

- With the same cross sections and the same luminosity, ILC is better than FCC
- Particulary on the $Z(\mu^{+}\mu^{-})H$ channel
  - Due to the different $\sqrt{s}$ and the polarization of the beam that leads to better signal to background ratio
    - Still better performance if taken into account
      - Because of the separation of the events in two samples
      - The use of $cos\theta_{miss}$ cut in their selection

Adding a cut on $\cos\theta_{miss}$





- $cos\theta_{miss}$ is a good variable to remove ZZ and Z/γ background but break invariance in selection efficiency
- Already used in Higgs mass measurement
  - Don't require model-independence
- Try to implement it in cross-section analysis
  - $cos\theta_{miss} < 0.98$

Comparing with Baseline Selection

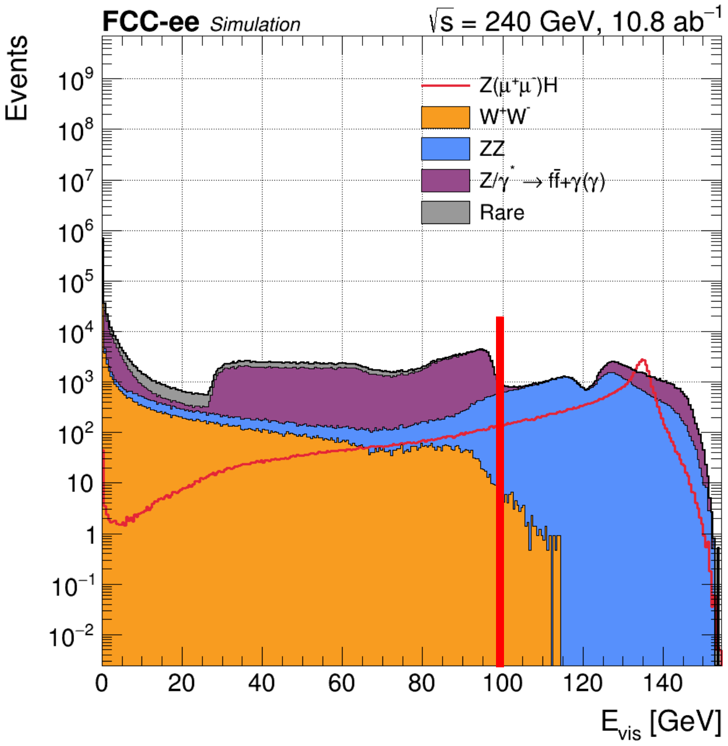
Selection	$Z(e^+e^-)H$	$Z(\mu^+\mu^-)H$	$Z(\ell^+\ell^-)H$
Baseline	**0.81%**	**0.68%**	**0.52%**
Baseline + $cos\theta_{miss}$ cut	**0.67%**	**0.60%**	**0.45%**

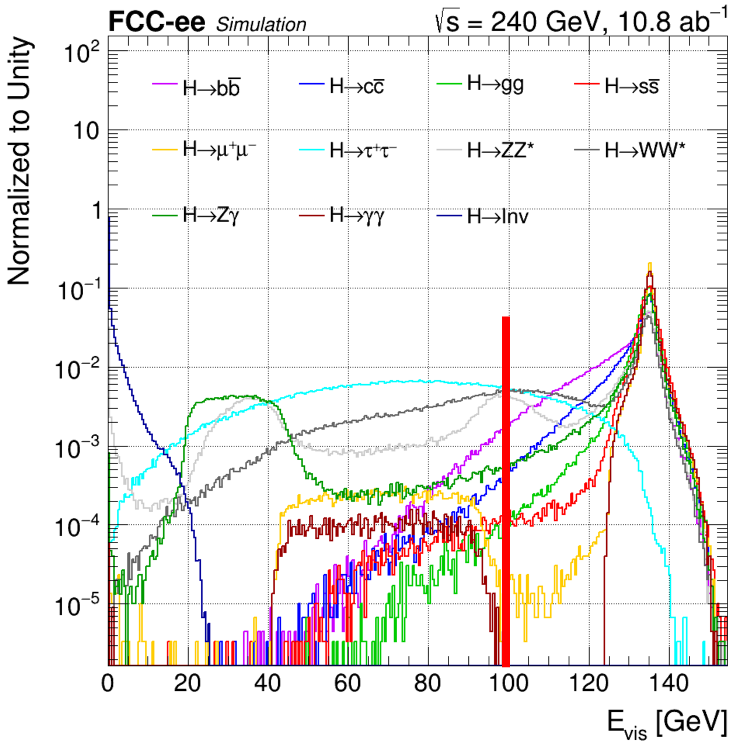
- $cos\theta_{miss}$ cut selection improves the precision on σ_{ZH}
- But gives a too high bias for $H \to \mu^+\mu^-$
  - Bias test is not successful
- Can't use this cut to measure σ_{ZH}

The goal is to try to include $cos\theta_{miss}$ cut to improve the precision on σ_{ZH} while keeping the bias low

Channel	Baseline [%]	Baseline + $cos\theta_{miss}$ cut [%]
$H \to b\bar{b}$	**-0.01**	**-0.02**
$H \to c\bar{c}$	**+0.00**	**-0.09**
$H \to gg$	**-0.00**	**-0.21**
$H \to s\bar{s}$	**-0.01**	**-0.17**
$H \to \mu^+\mu^-$	**+0.10**	**-0.69**
$H \to \tau^+\tau^-$	**-0.00**	**+0.21**
$H \to ZZ^*$	**+0.37**	**+0.29**
$H \to WW^*$	**-0.01**	**+0.03**
$H \to Z\gamma$	**+0.38**	**+0.20**
$H \to \gamma\gamma$	**-0.00**	**+0.03**

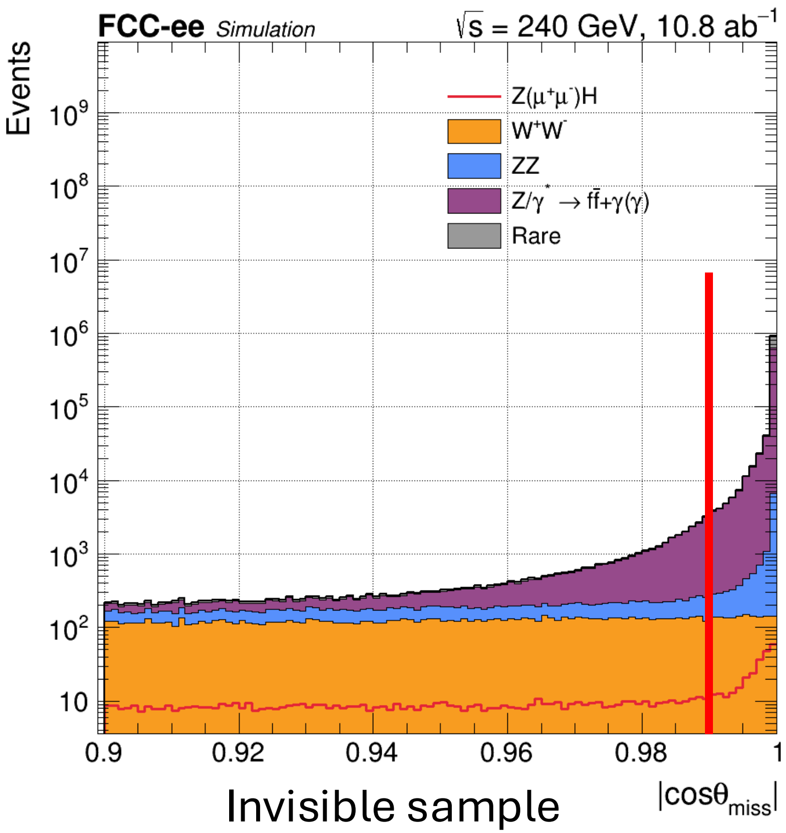
Separating Events



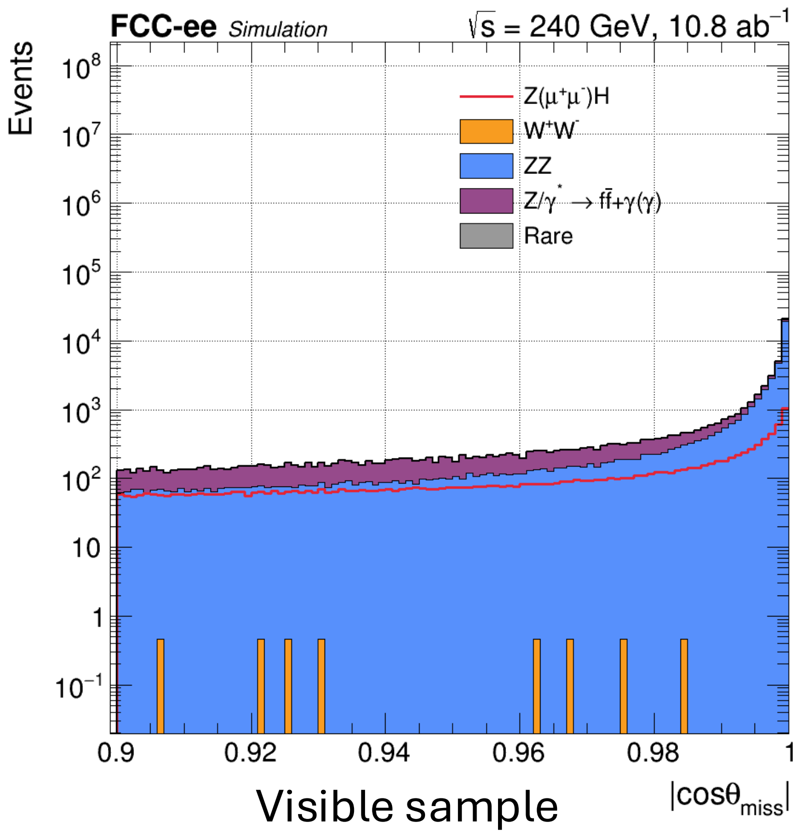


- Visible energy E_{vis} is a good variable to discriminate signal from background but is a very model-dependent variable
- Could use it on the Higgs mass measurement
- Can't use it to select events but can use it to separate events
  - Visible sample ($E_{vis} > 100\ GeV$)
  - Invisible sample ($E_{vis} < 100\ GeV$)
- Inspired from ILC selection, they also separate the analysis into visible and invisible sample

Adding the $cos\theta_{miss}$ cut in the « Invisible » Sample



Invisible sample



Visible sample

- Z/γ events are in the invisible sample
  - Applying $cos\theta_{miss} < 0.99$ cut on the invisible sample
  - No cut on the visible sample to avoid bias
- No other cut applied
  - Other cuts were tested but do not affect the precision or increase the bias

Comparing to other Selection

Selection	$Z(e^+e^-)H$	$Z(\mu^+\mu^-)H$	$Z(\ell^+\ell^-)H$
Baseline	**0.81%**	**0.68%**	**0.52%**
Baseline + $cos\theta_{miss}$ cut	**0.67%**	**0.60%**	**0.45%**
Baseline + E_{vis} splitting	**0.67%**	**0.59%**	**0.45%**

- E_{vis} sep and $cos\theta_{miss}$ cut selections give same precision on σ_{ZH}
- E_{vis} sep has better bias than $cos\theta_{miss}$ cut selection and reduce bias on $H \rightarrow \mu^+\mu^-$ channel
- Slighty better bias on $H \rightarrow ZZ^*$ and $H \rightarrow Z\gamma$ but still a bit high

→ Bias test successful for E_{vis} sep

Channel	Baseline [%]	Baseline + $cos\theta_{miss}$ cut [%]	Baseline + E_{vis} splitting [%]
$H \rightarrow b\bar{b}$	**-0.01**	**-0.02**	**-0.01**
$H \rightarrow c\bar{c}$	**+0.00**	**-0.09**	**+0.00**
$H \rightarrow gg$	**-0.00**	**-0.21**	**+0.01**
$H \rightarrow s\bar{s}$	**-0.01**	**-0.17**	**-0.01**
$H \rightarrow \mu^+\mu^-$	**+0.10**	**-0.69**	**+0.01**
$H \rightarrow \tau^+\tau^-$	**-0.00**	**+0.21**	**-0.02**
$H \rightarrow ZZ^*$	**+0.37**	**+0.29**	**+0.33**
$H \rightarrow WW^*$	**-0.01**	**+0.03**	**-0.00**
$H \rightarrow Z\gamma$	**+0.38**	**+0.20**	**+0.30**
$H \rightarrow \gamma\gamma$	**-0.00**	**+0.03**	**-0.03**

Comparison with ILC

Selection	$Z(e^+e^-)H$	$Z(\mu^+\mu^-)H$	$Z(\ell^+\ell^-)H$
ILC (+/-)	**4.0%/4.7%**	**3.2%/3.6%**	**2.5% / 2.9%**
FCC (Baseline)	**0.81%**	**0.68%**	**0.52%**
FCC (Baseline + E_{vis} splitting)	**0.67%**	**0.59%**	**0.45%**
ILC scaled to FCC luminosity (+/-)	**0.61% / 0.71%**	**0.48% / 0.54%**	**0.38% / 0.44%**
FCC (Baseline + E_{vis} splitting) scaled to ILC cross section (+/-)	**0.54% / 0.62%**	**0.48% / 0.54%**	**0.36% / 0.41%**

- Now assuming the same cross sections and luminosity
  - $Z(\mu^+\mu^-)H$ has the same precision for FCC and ILC
  - $Z(\mathrm{e}^+e^-)H$ is now better for FCC than ILC
- Which gives a better global precision
- Due to the successful addition of the $cos\theta_{miss}$ cut to the selection

Conclusion and Outlook

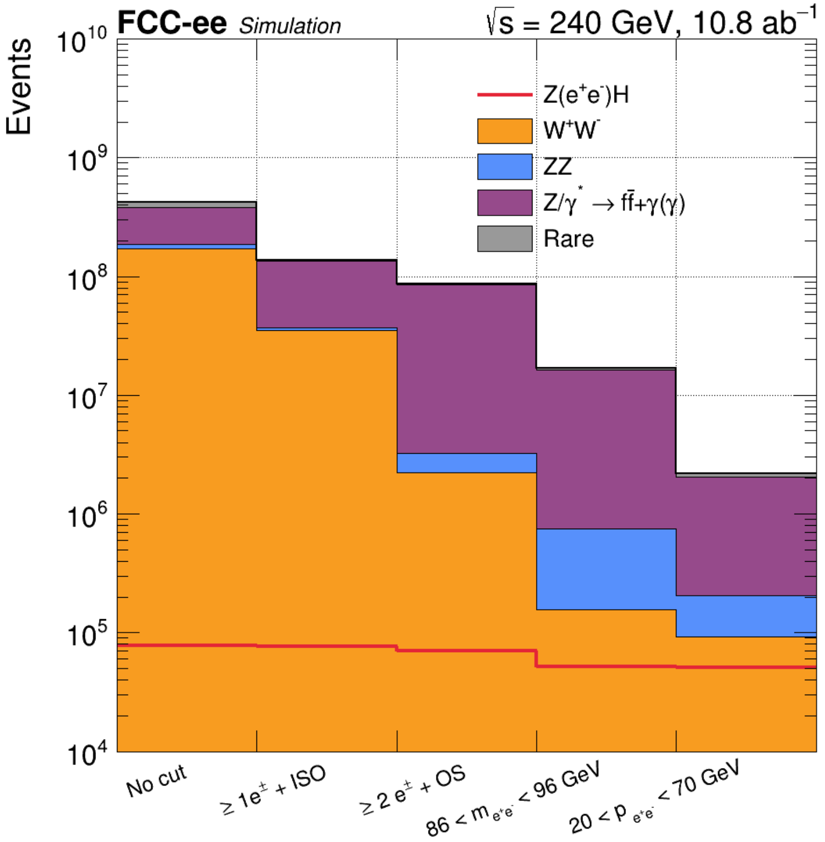
- Succeded in improving the precision on σ_{ZH} by adding a cut on $cos\theta_{miss}$ in the sub-sample
  - $Z(e^+e^-)H$: 0.81% → 0.67%, 17% improvement
  - $Z(\mu^+\mu^-)H$: 0.68% → 0.59%, 13% improvement
  - $Z(\ell^+\ell^-)H$: 0.52% → 0.45%, 16% improvement
- Kept model-independence while adding $cos\theta_{miss}$ cut
  - Bias test successful for all channels
- Preliminary results
  - Analysis still in progress to confirm the results
    - Have to include $H \to Inv$ to bias test to check the model-independence of the selection
    - Couldn't include it due to code problems

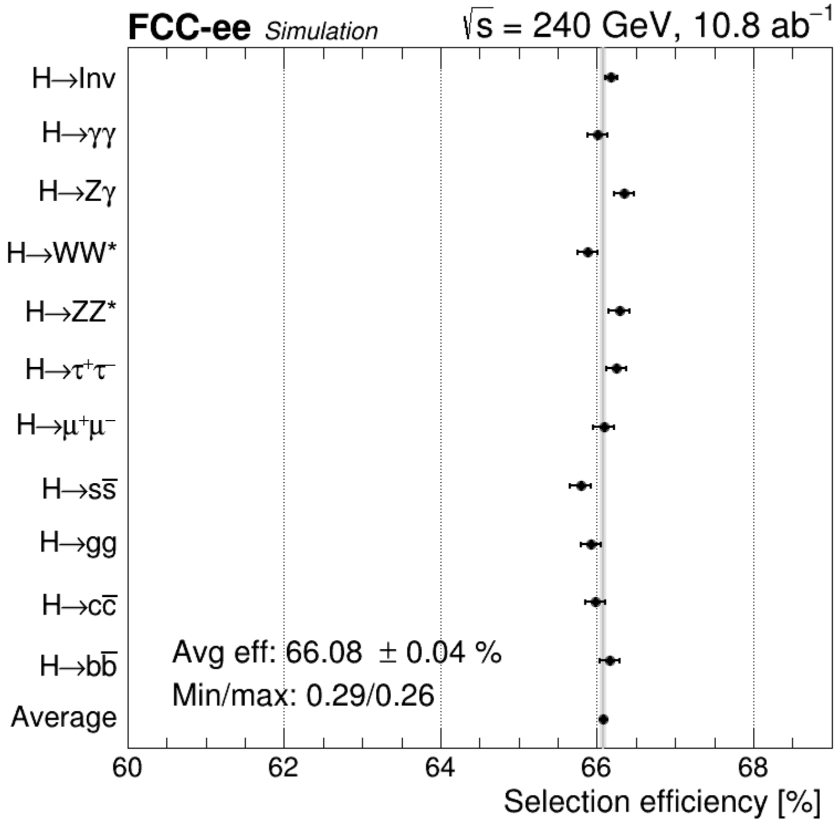
Outlook:
- Redo the analysis for $\sqrt{s} = 365\ GeV$
  - Will improve precision on κ_λ measurement
- Work on the hadronic channel of σ_{ZH} analysis

Thanks for listening

BACK UP

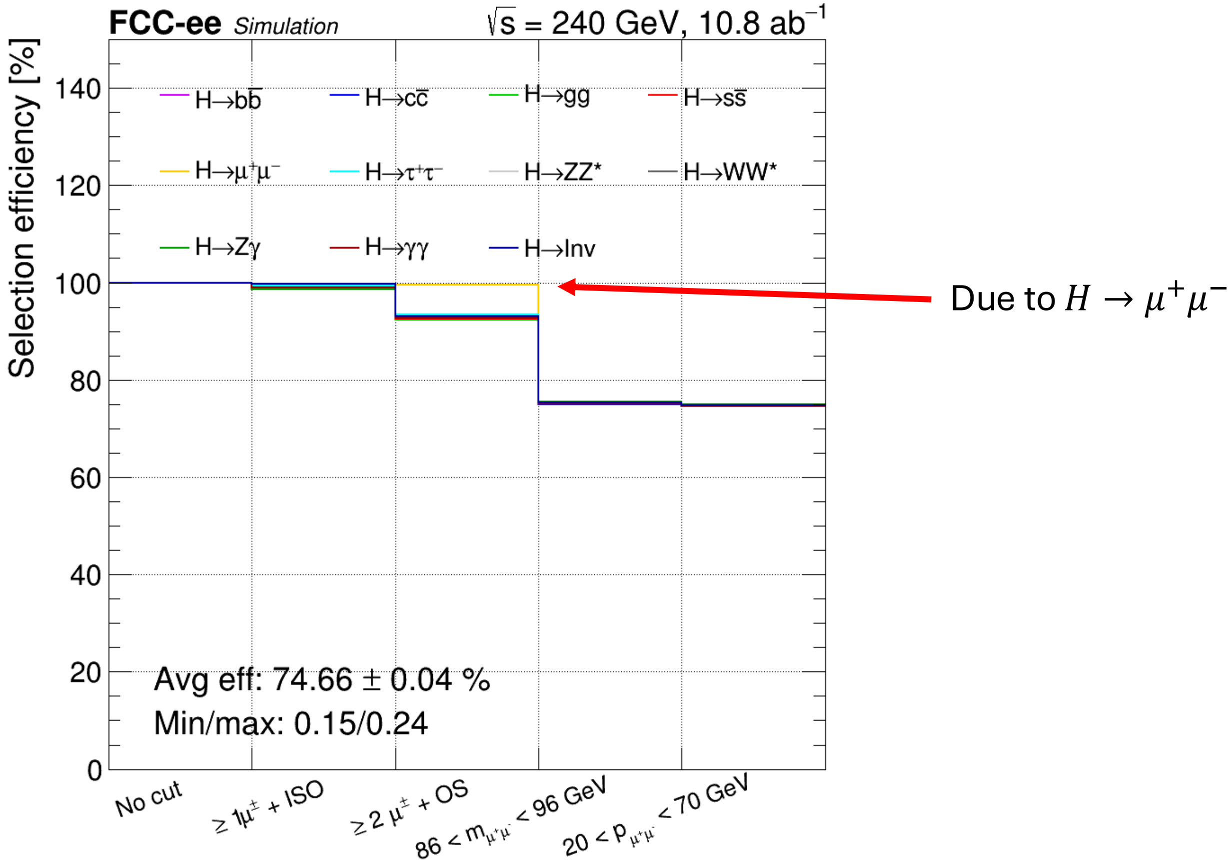
Events Selection



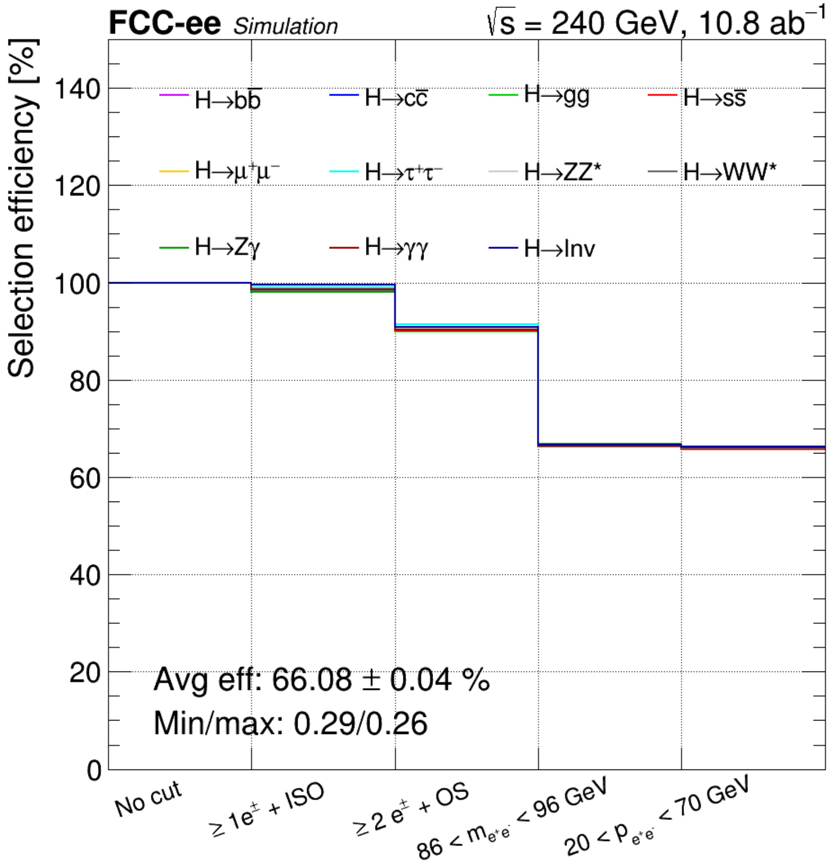


Cutflow and events selection for e^+e^- (Baseline)

Cutflow for each Higgs decay



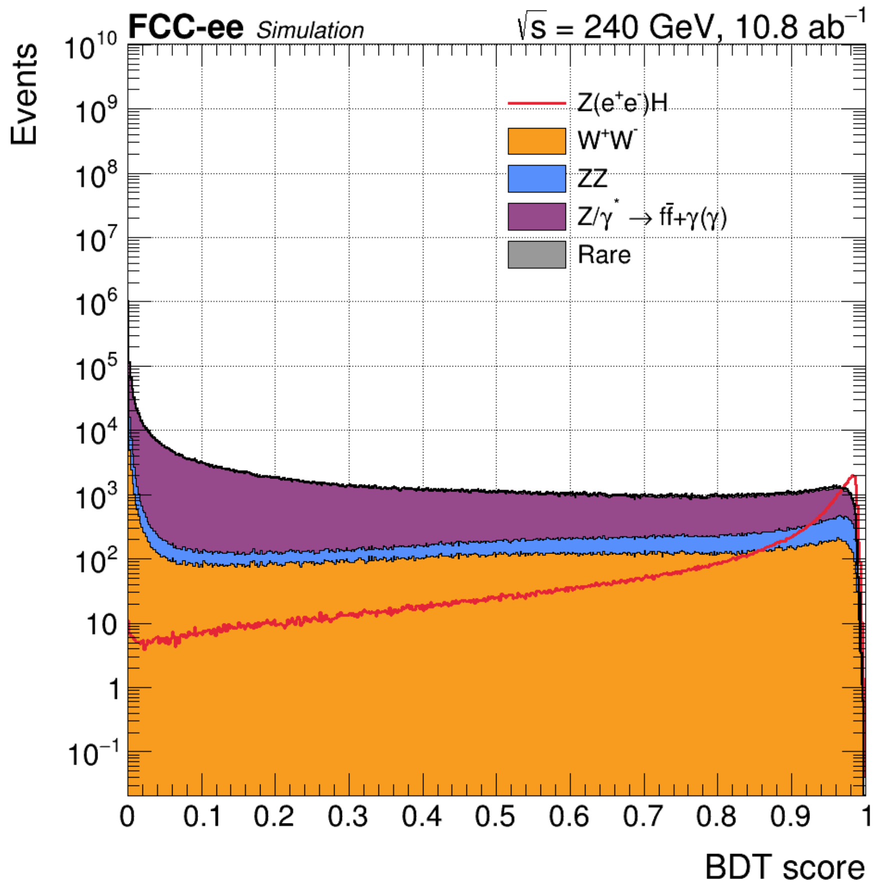
$Z(\mu^+\mu^-)H$

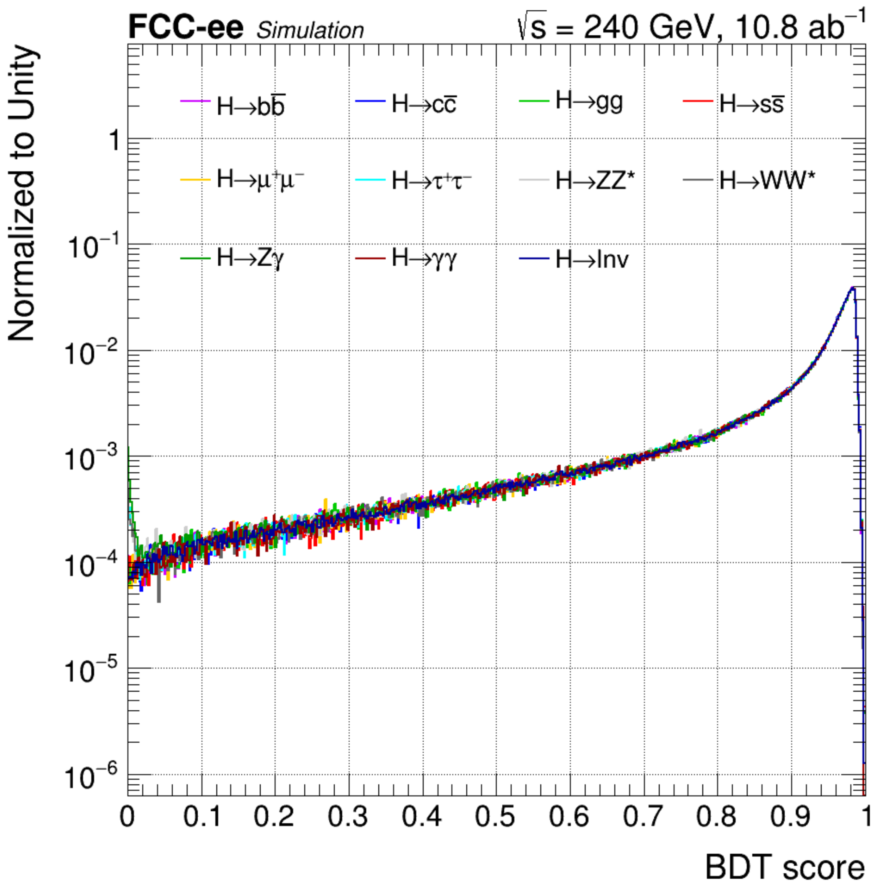


$Z(e^+e^-)H$

Cutflow independent of the Higgs decay

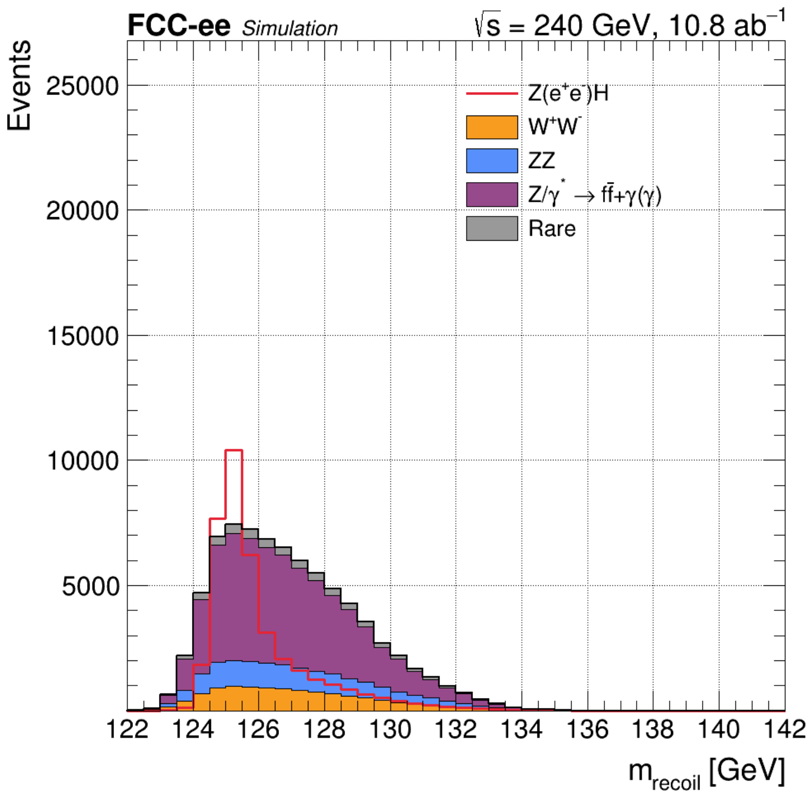
MVA Discriminant



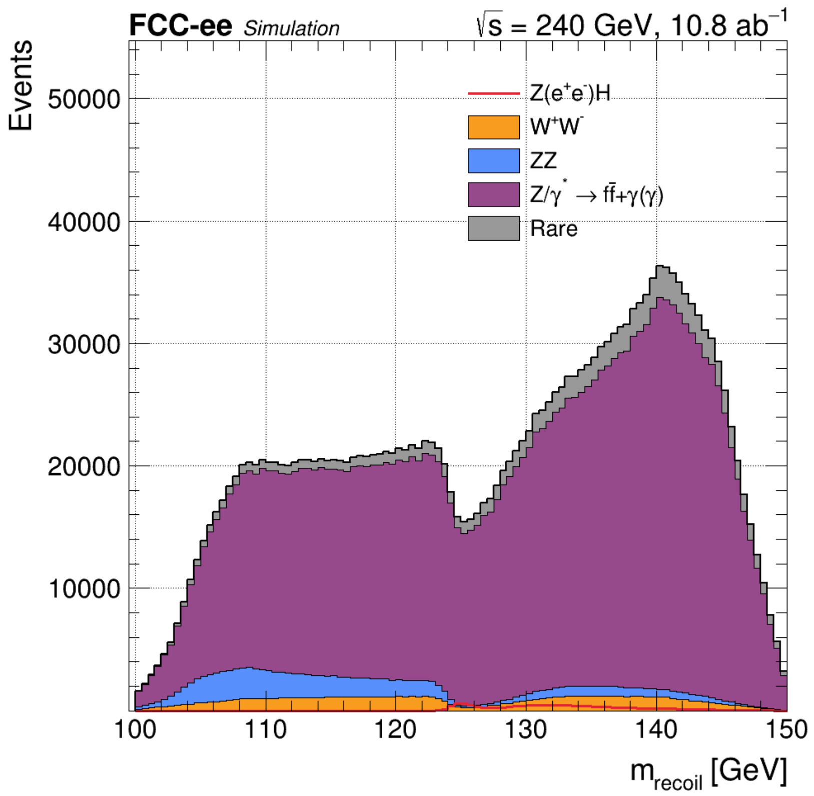


BDT score distribution for e^+e^-

Uncertainty Extraction



High score region



Low score region

Bias Test

Bias test for e^+e^-

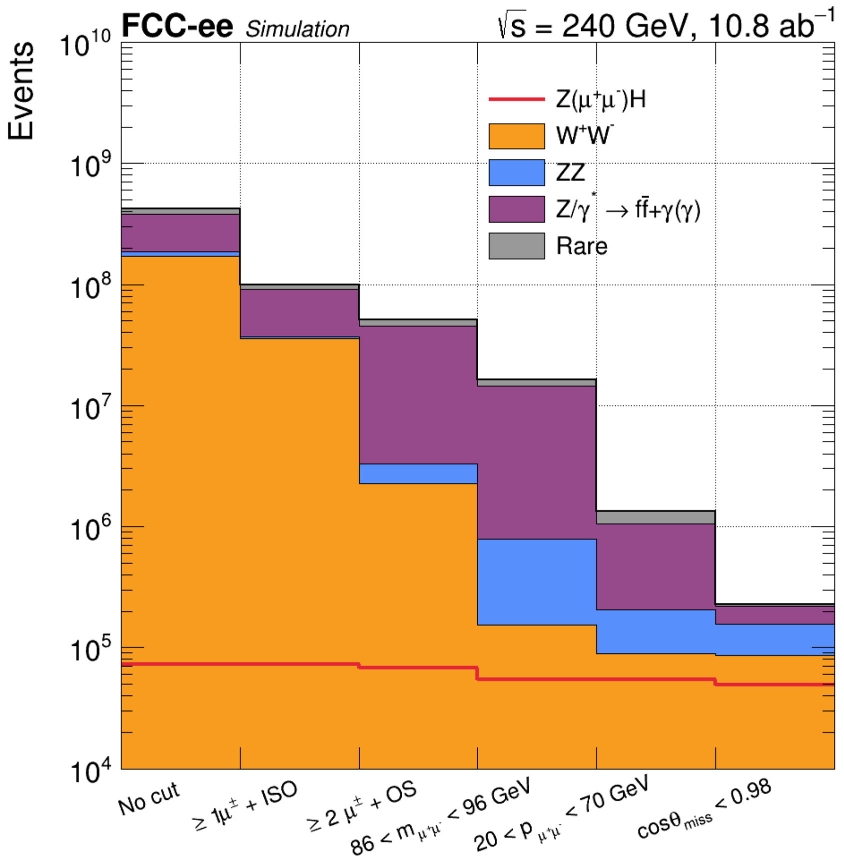
Channel	Baseline [%]	Baseline + $cos\theta_{miss}$ cut [%]	Baseline + E_{vis} splitting [%]
$H\to b\bar{b}$	+0.00	+0.00	+0.00
$H\to c\bar{c}$	-0.03	-0.11	-0.03
$H\to gg$	-0.03	-0.23	-0.02
$H\to s\bar{s}$	-0.03	-0.19	-0.03
$H\to \mu^+\mu^-$	-0.02	-0.70	-0.09
$H\to \tau^+\tau^-$	-0.02	+0.20	-0.03
$H\to ZZ^*$	+0.38	+0.31	+0.35
$H\to WW^*$	-0.04	-0.00	-0.04
$H\to Z\gamma$	+0.36	+0.18	+0.28
$H\to \gamma\gamma$	-0.02	+0.01	-0.04

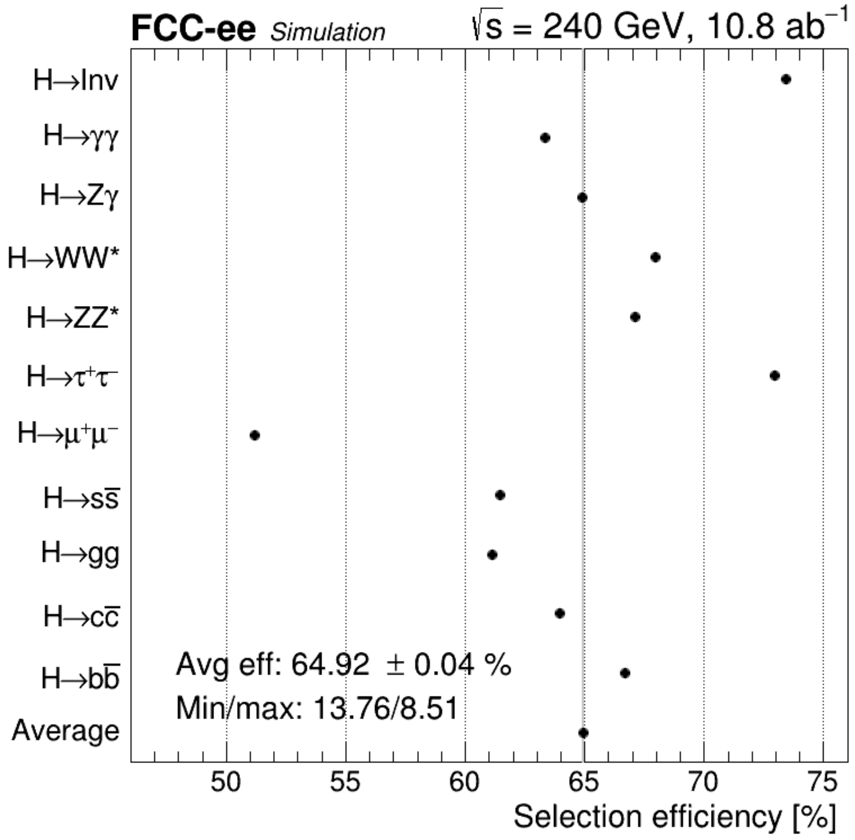
Bias Test

Bias test for $\ell^+\ell^-$

Channel	Baseline [%]	Baseline + $cos\theta_{miss}$ cut [%]	Baseline + E_{vis} splitting [%]
$H \to b\bar{b}$	**+0.00**	**+0.00**	**+0.00**
$H \to c\bar{c}$	**-0.03**	**-0.11**	**-0.03**
$H \to gg$	**-0.03**	**-0.23**	**-0.02**
$H \to s\bar{s}$	**-0.03**	**-0.19**	**-0.03**
$H \to \mu^+\mu^-$	**-0.02**	**-0.70**	**-0.09**
$H \to \tau^+\tau^-$	**-0.02**	**+0.20**	**-0.03**
$H \to ZZ^*$	**+0.38**	**+0.31**	**+0.35**
$H \to WW^*$	**-0.04**	**-0.00**	**-0.04**
$H \to Z\gamma$	**+0.36**	**+0.18**	**+0.28**
$H \to \gamma\gamma$	**-0.02**	**+0.01**	**-0.04**

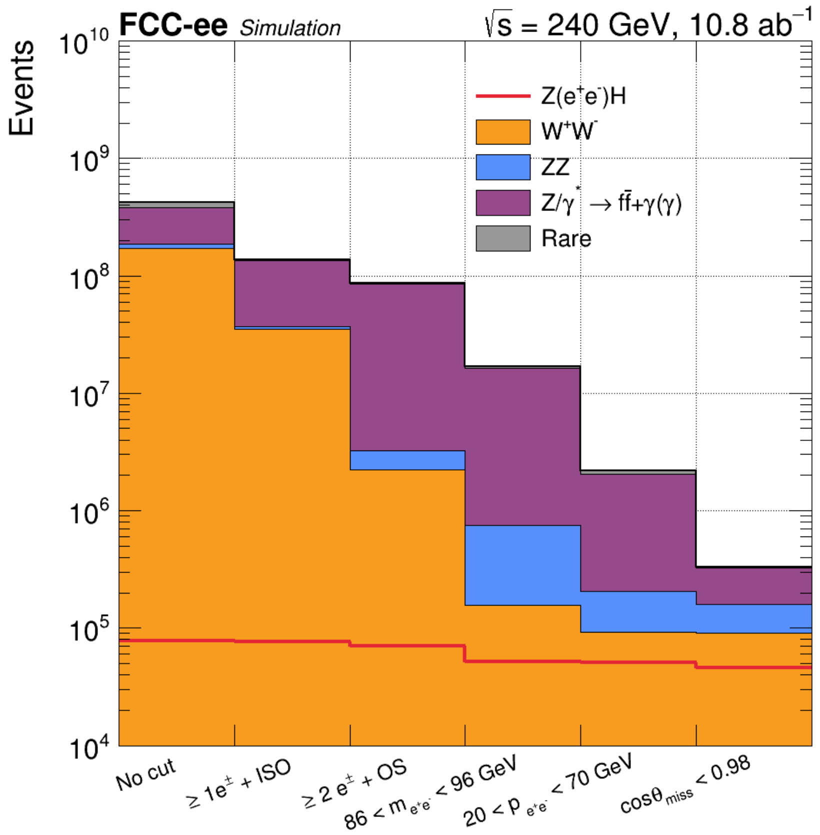
Events Selection

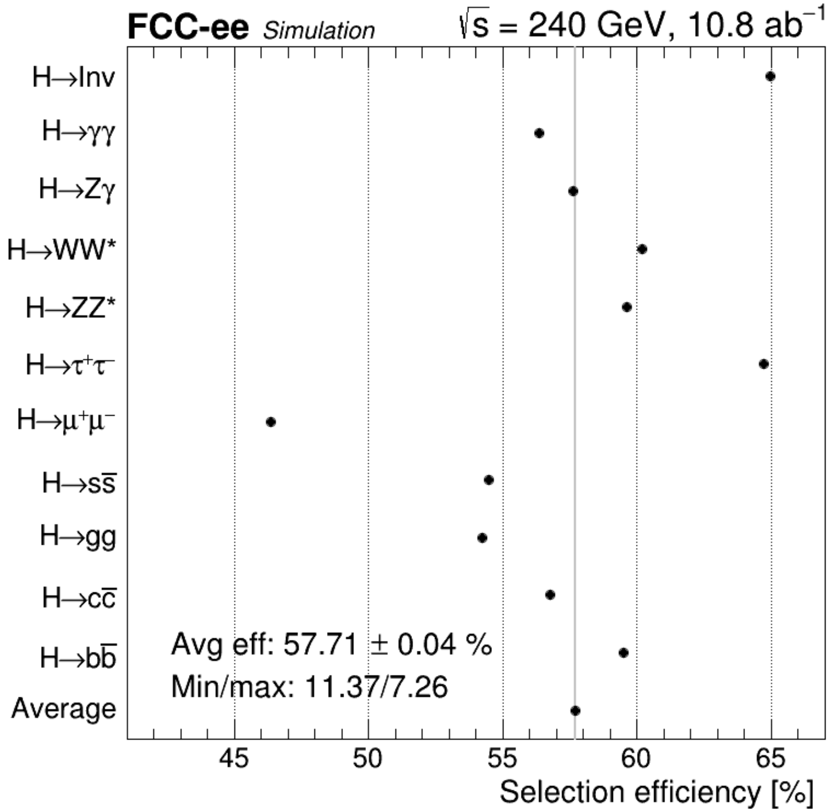




Cutflow and events selection for $\mu^+\mu^-$ (Baseline + $cos\theta_{miss}$ cut)

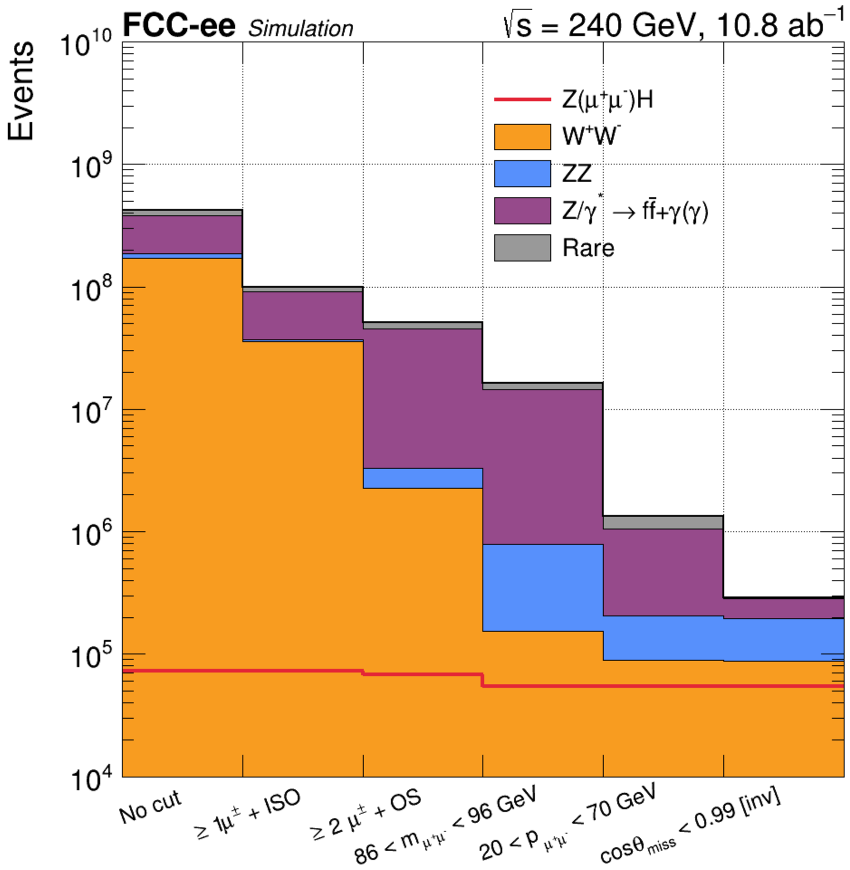
Events Selection

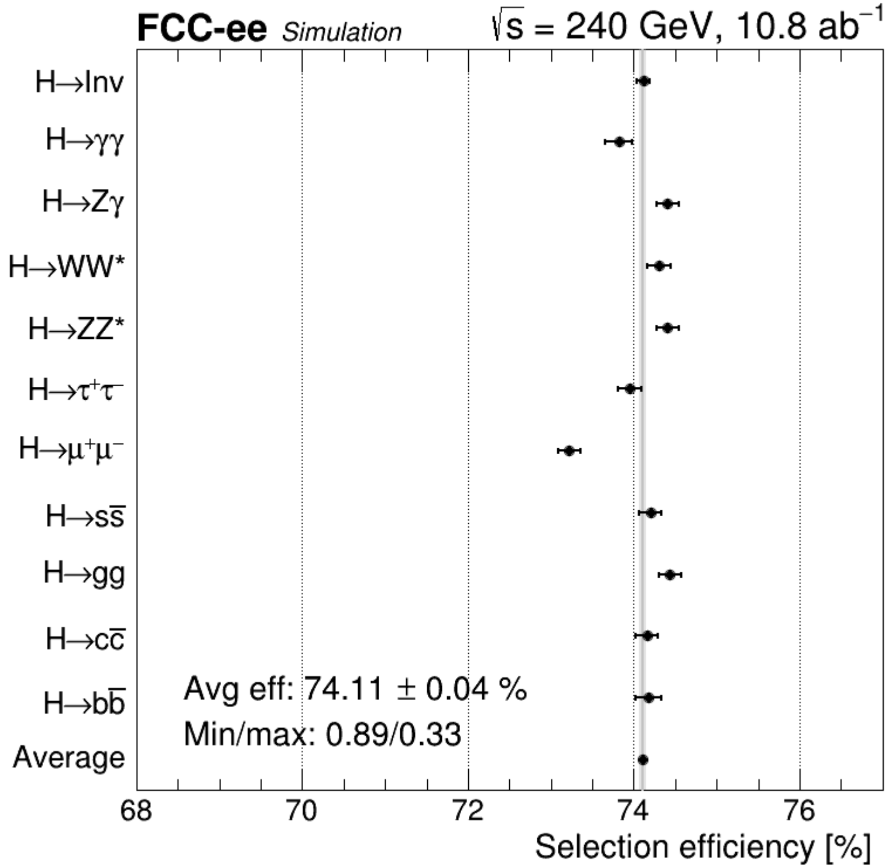




Cutflow and events selection for e^+e^- (Baseline + $cos\theta_{miss}$ cut)

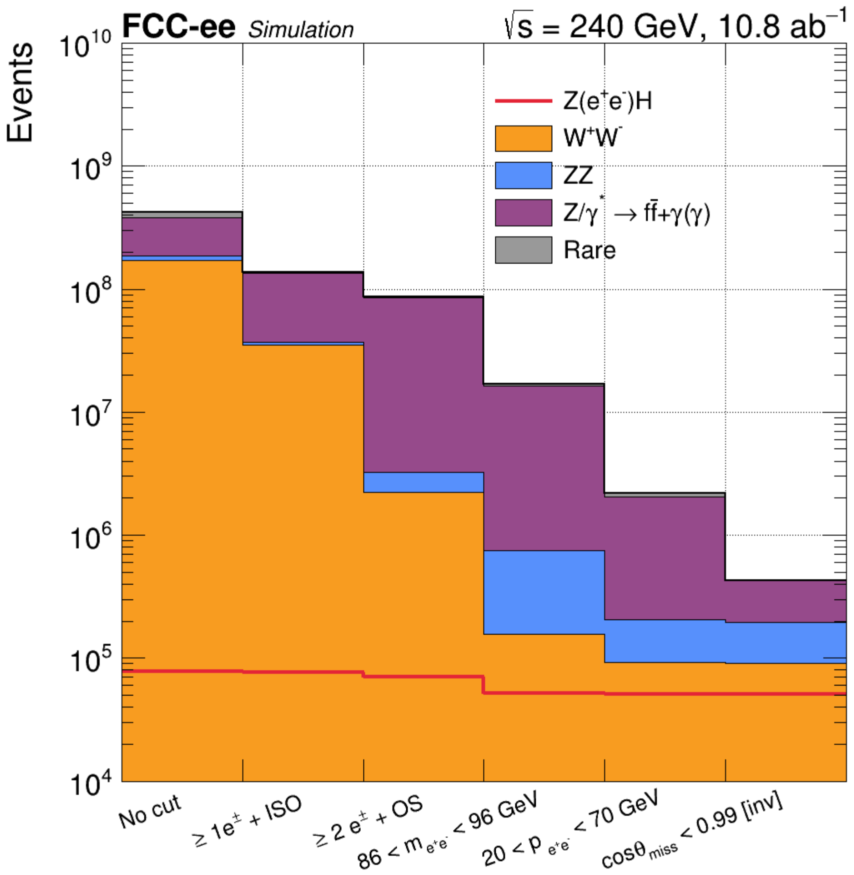
Events Selection

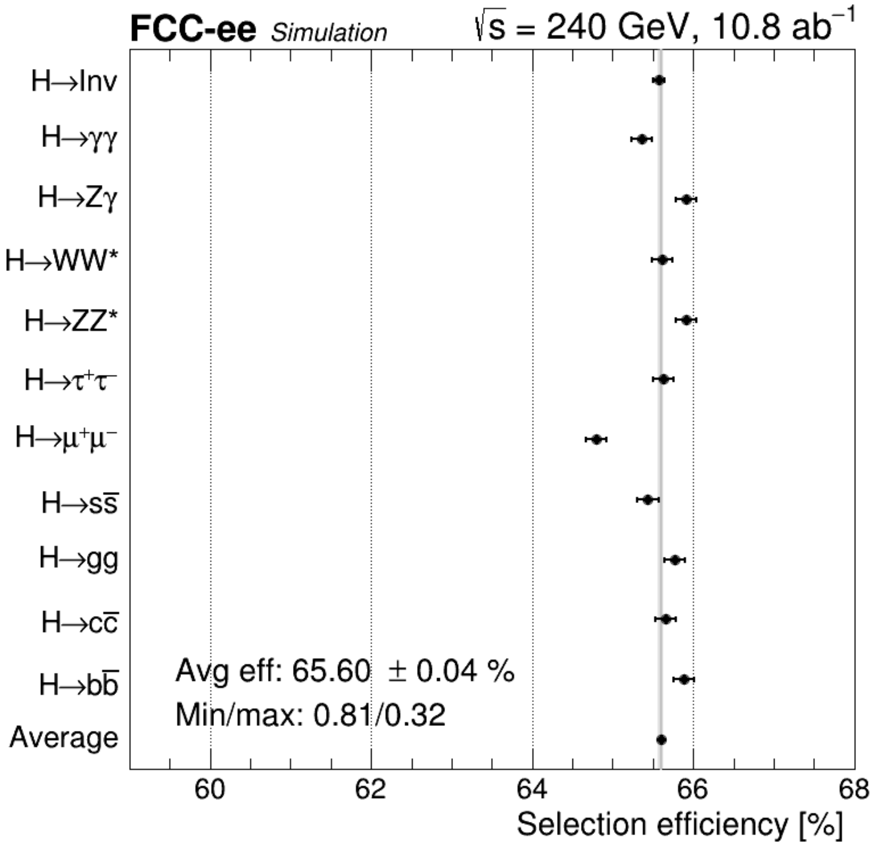




Cutflow and events selection for $\mu^+\mu^-$ (Baseline + E_{vis} splitting)

Events Selection





Cutflow and events selection for e^+e^- (Baseline + E_{vis} splitting)