

ZH CROSS SECTION, HIGGS MASS AND BRANCHING RATIO MEASUREMENTS IN ZH EVENTS AT FCC-EE, AT 240 AND 365 GEV

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on behalf on FCC collaboration
HIGGS HUNTING 2026



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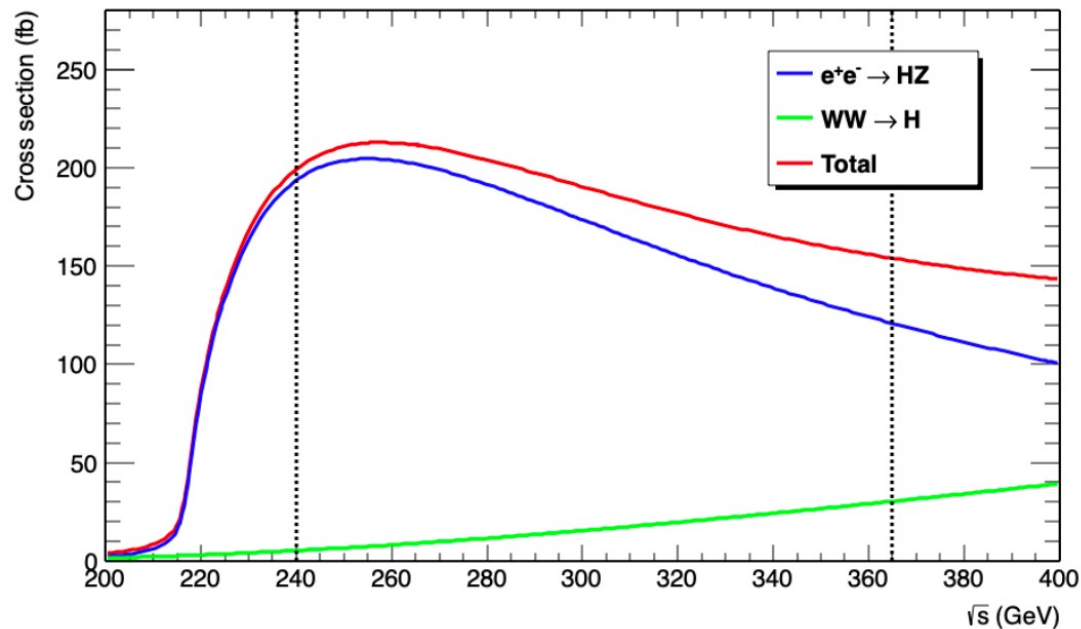


INTRODUCTION

FCC-ee has been selected as the next CERN's flagship collider to succeed HL-LHC

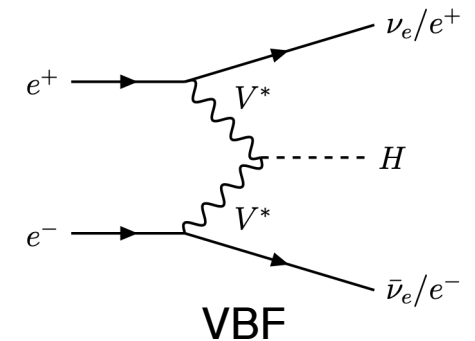
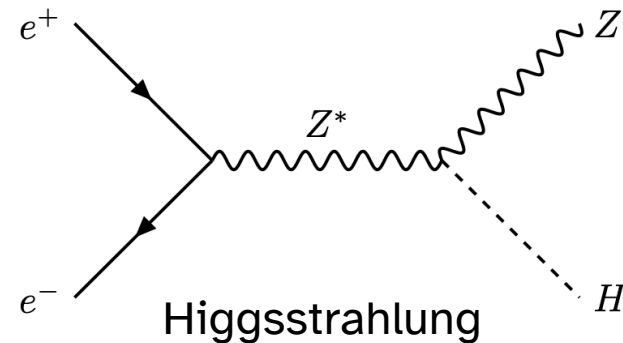
- FCC-ee (2045-2060) will run at different $\sqrt{s}$

Main Higgs productions cross-section



Working point	Z pole	WW thresh.	ZH	t $\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm $^{-2}$ s $^{-1}$)	140	20	7.5	1.8	1.4
Lumi/year (ab $^{-1}$)	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab $^{-1}$)	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH + 65k WW $\rightarrow$ H	2×10^6 t $\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

At FCC-ee, about 2.6 millions Higgs should be produced in a **clean environment** enabling **precision measurements** to test the Standard Model and to search for BSM



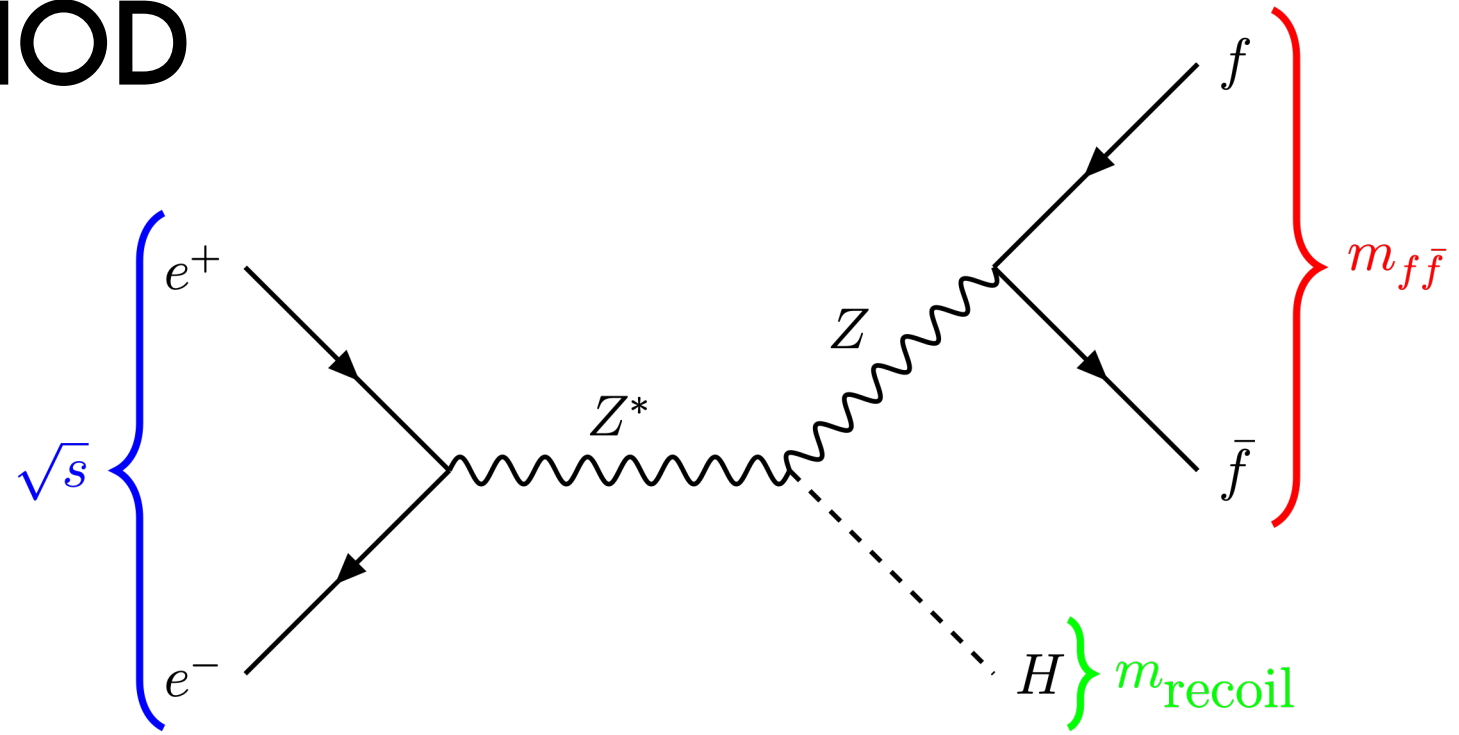
Several properties of the Higgs boson can be measured with precision in the ZH and $t\bar{t}$ run: its mass, width, branching ratios, CP properties, production cross-section, self-coupling

In this talk, we focus on the ZH production cross-section (σ_{ZH}), the Higgs mass (m_H) and the Higgs couplings (g_{HXX})

RECOIL MASS METHOD

At FCC-ee we do e^+e^- collisions $\rightarrow$ initial state known $\rightarrow$ can use the **recoil mass method**

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



In most of the analysis of this talk, we reconstruct the Z by asking the fermion pair to be compatible with m_Z and m_{recoil} with m_H , enabling a high selection efficiency.

The analysis are generally separated depending on the Z decay:

- $Z \rightarrow e^+e^-, \mu^+\mu^-$, together they make the leptonic channel ($Z \rightarrow \ell^+\ell^-$)
- $Z \rightarrow \nu\bar{\nu}$, for this channel VBF must be considered (especially at 365 GeV)
- $Z \rightarrow q\bar{q}$, is generally called the hadronic channel

ZH CROSS-SECTION

PHYSICS MOTIVATION

Measuring $\sigma_{ZH} \rightarrow$ gives access to g_{HZZ} in a model-independent way

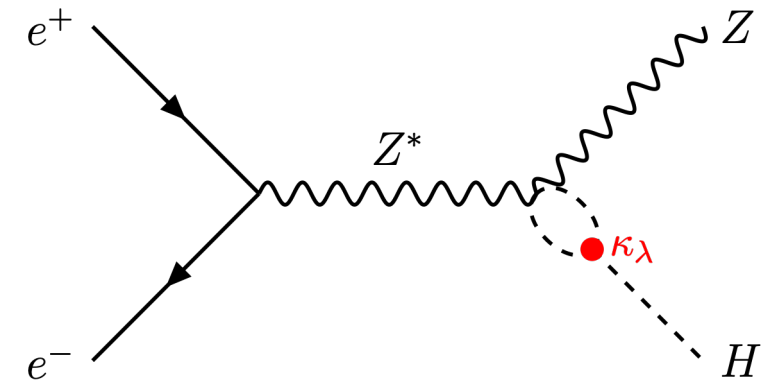
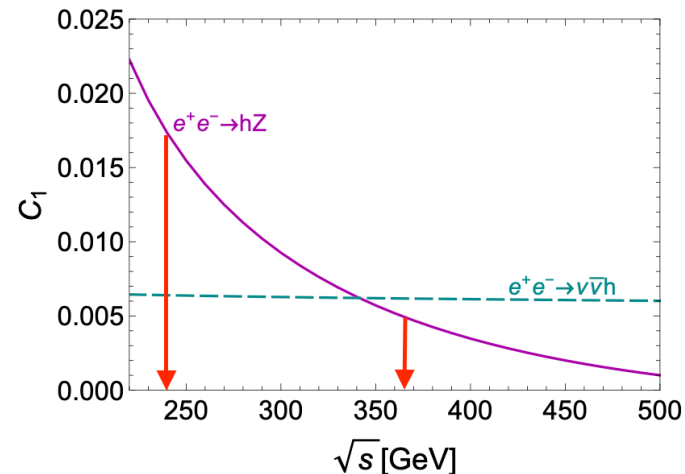
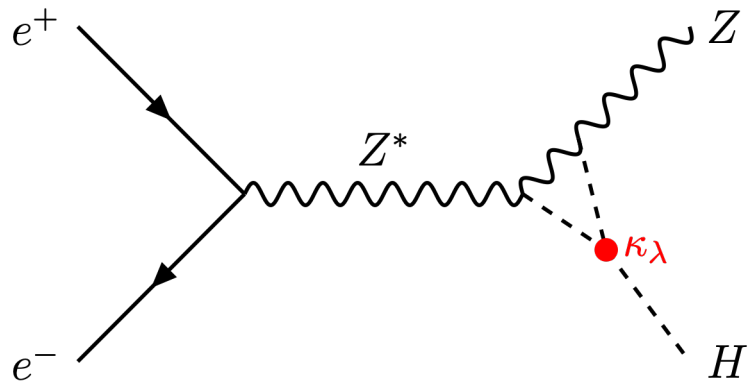
- $\sigma_{ZH} \times \mathcal{B}(H \rightarrow X\bar{X}) \propto g_{HZZ} \times g_{HXX} / \Gamma_H \rightarrow \sigma_{ZH} \times \mathcal{B}(H \rightarrow ZZ^*) \propto g_{HZZ}^4 / \Gamma_H$
- g_{HZZ} can be used as a standard candle to determine g_{HXX} in a model-independent way

The Higgs width Γ_H can also be measured

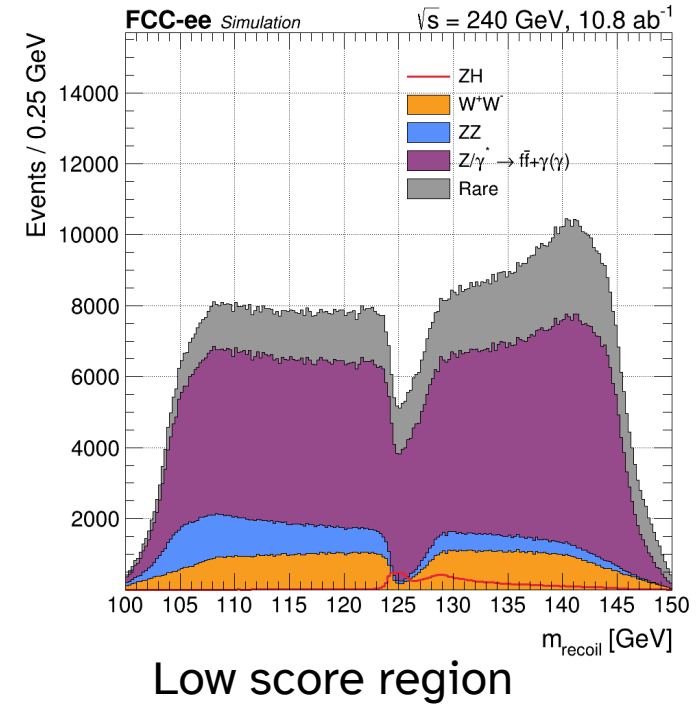
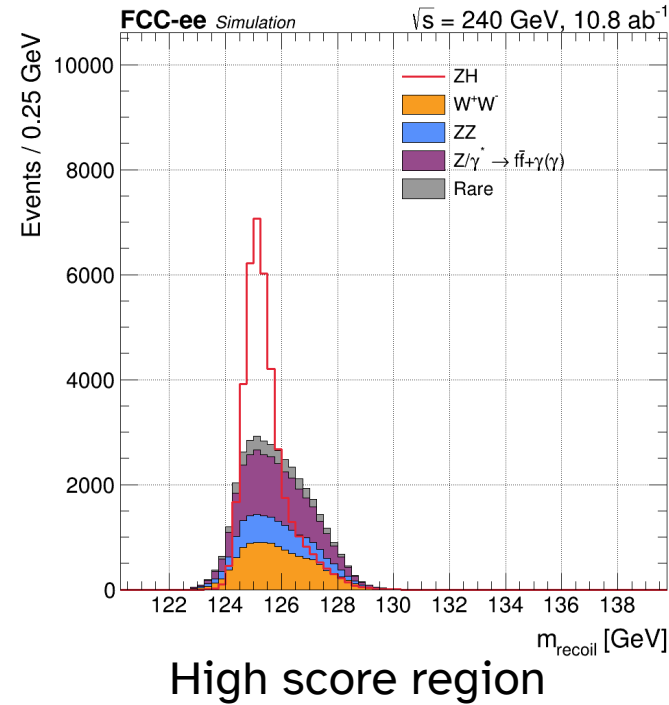
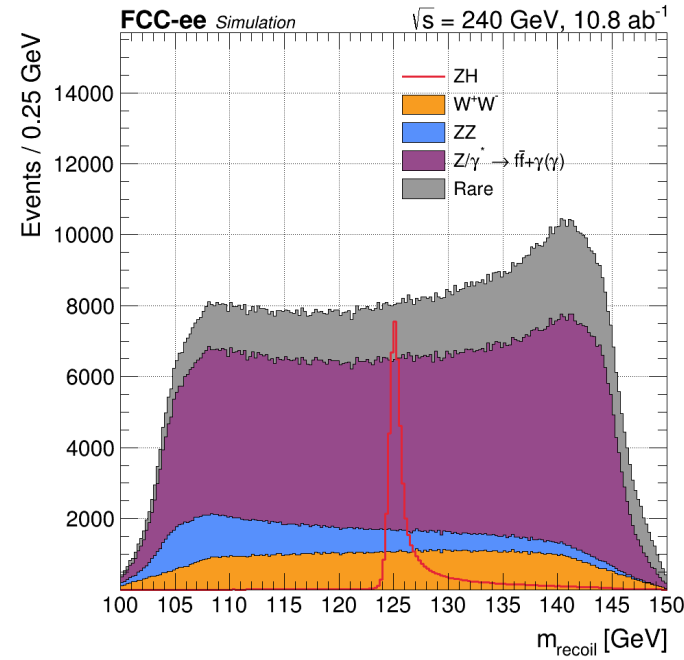
- $\Gamma_H \propto \sigma(e^+e^- \rightarrow ZH, H \rightarrow ZZ^*)^2 / \sigma_{ZH}$

Allows to indirectly measure the Higgs self-coupling through NLO correction

- Will be a complementary measurement to the one made directly at HL-LHC



ZH SELECTION (LEPTONIC CHANNEL)



Selection steps:

- Reconstruct the Z and the Higgs with the recoil mass method
- Apply kinematic cuts to remove background
- Use the BDT to categorize events into signal-like and background-like events
- Get ZH cross-section by fitting m_{recoil} in the 2 BDT regions
 - Reach sub-percent level precision at 240 GeV and %-level at 365 GeV

Channel	240 GeV	365 GeV
$Z(e^+e^-)H$	0.81%	1.89%
$Z(\mu^+\mu^-)H$	0.68%	1.77%
$Z(\ell^+\ell^-)H$	0.52%	1.31%

RECENT IMPROVEMENTS

Recently, two methods were used to improve the analysis (leptonic channel):

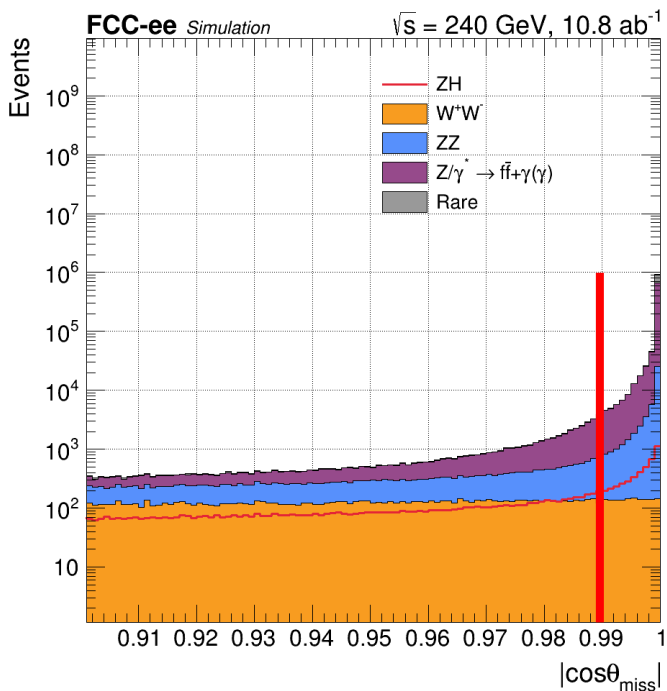
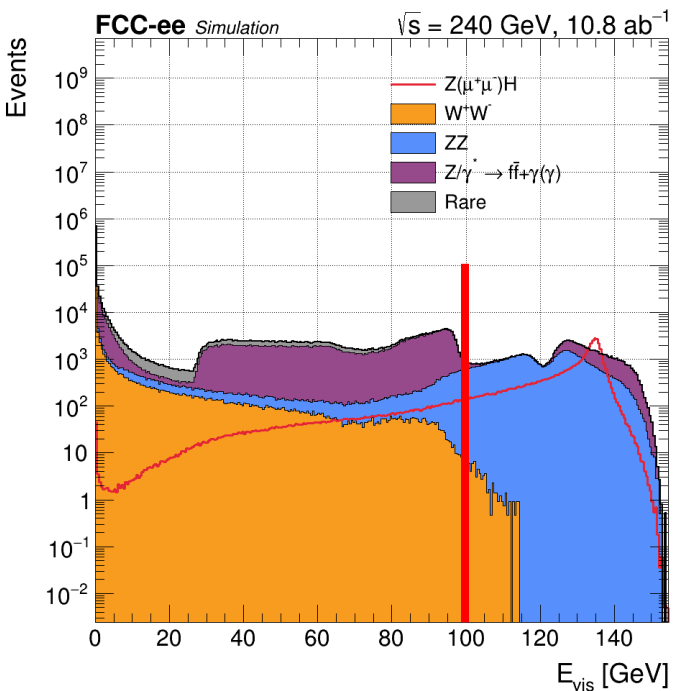
- To recover energy lost from FSR, lepton-photon pairs were merged if they are enough collinear
- Categorized events into sub-samples according to their visible energy (E_{vis})
 - Was used to remove background with $\cos \theta_{miss}$

This improve $\Delta\sigma_{ZH}$ by ~20% while keeping the selection model-independent

- Only done for $Z(\ell^+\ell^-)H$
- Work to improve $Z(q\bar{q})H$ is still ongoing

Difference between leptonic and hadronic selection

- Use looser selection due to worse energy resolution
- Fit on the $m_{jj} - m_{recoil}$ distributions to get ZH production cross-section



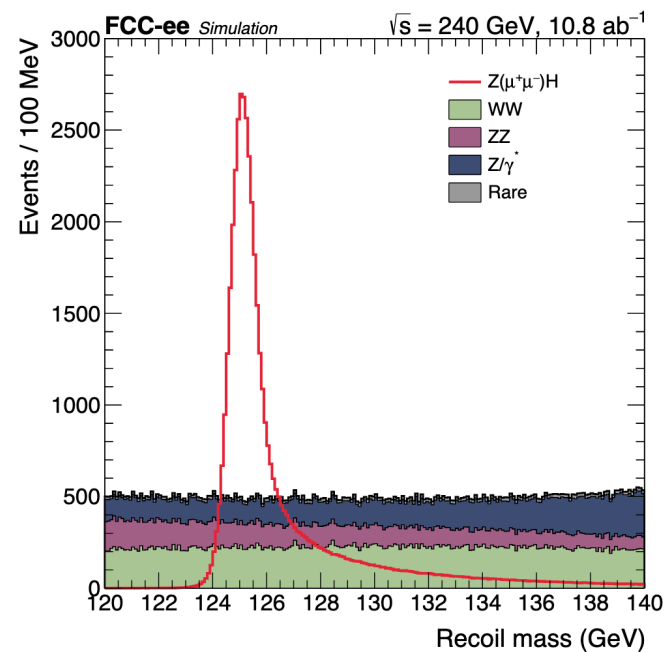
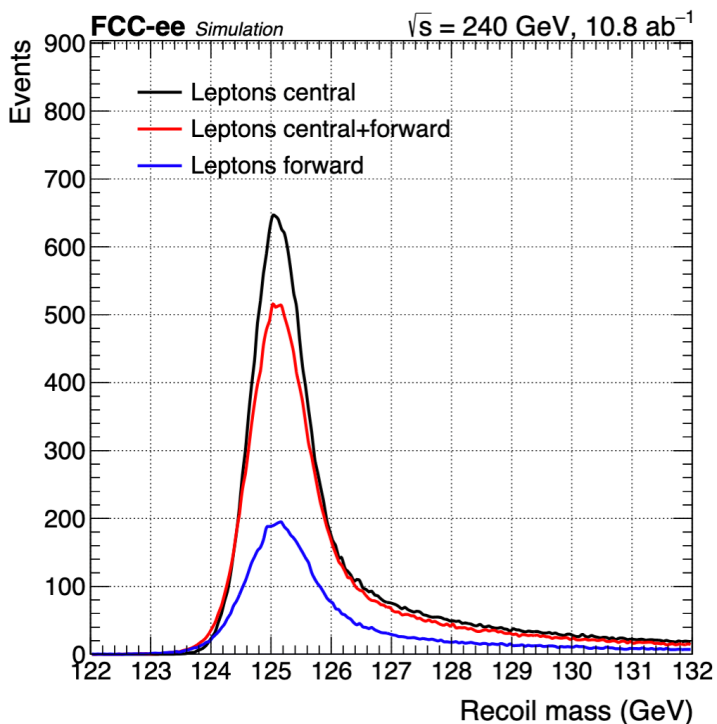
Channel	240 GeV	365 GeV
$Z(e^+e^-)H$	0.58%	1.47%
$Z(\mu^+\mu^-)H$	0.57%	1.46%
$Z(\ell^+\ell^-)H$	0.41%	1.05%
$Z(q\bar{q})H$	0.38%	0.56%
ZH	0.28%	0.49%

HIGGS MASS

HIGGS MASS SELECTION

Use mostly the same selection as σ_{ZH} leptonic analysis, but:

- Use $\cos \theta_{miss}$ in the selection without E_{vis} categorization
- Categorize events depending on if the lepton is central or forward
 - This separate regions with different m_{recoil} resolution
- Do a simultaneous fit on the different categories
- Use 2 Crystal Ball functions and a Gaussian to fit the signal
- Use Bernstein polynomials to fit the background



<https://repository.cern/records/c5dn3-c0s73>

stat(stat + syst)

Fit configuration	$Z(e^+e^-)H$	$Z(\mu^+\mu^-)H$	$Z(\ell^+\ell^-)H$
Nominal	4.95(5.68)	3.92(4.74)	3.07(3.97)
Electron resolution	5.79(6.33)	3.92(4.74)	3.24(4.12)
Magnetic field 3T	4.11(4.83)	3.22(4.14)	2.54(3.52)
Silicon tracker	5.89(6.42)	5.11(5.73)	3.86(4.55)
BES 6% uncertainty	4.95(5.92)	3.92(4.79)	3.07(3.98)
No BES	2.93(3.88)	2.11(3.31)	1.71(2.92)
Ideal resolution	3.58(4.52)	3.12(3.95)	2.42(3.40)

Get a nominal m_H precision of 3.97 MeV

- Δm_H is at the level of Γ_H
- Systematics dominated by BES (~ 2 MeV)
- Done for several detector configurations

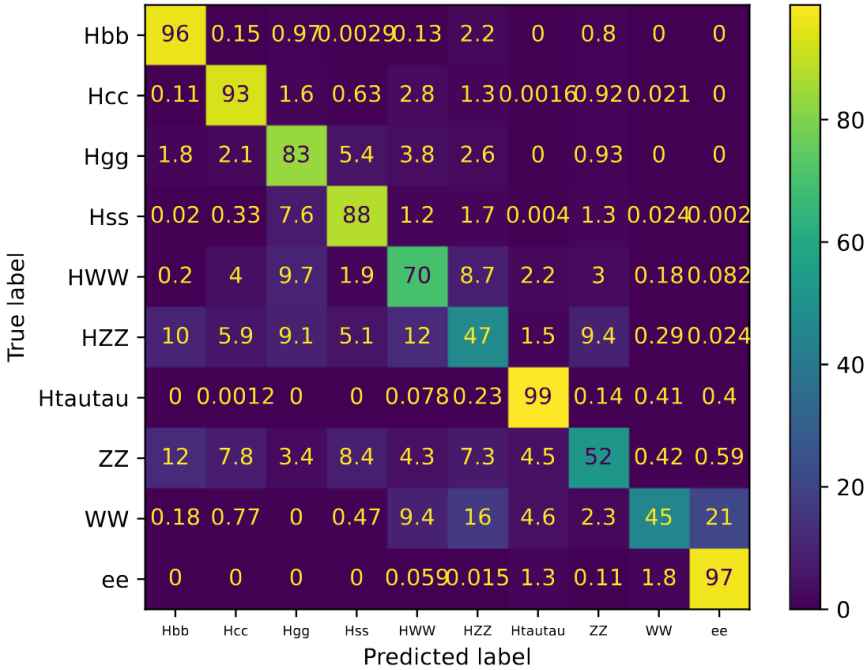
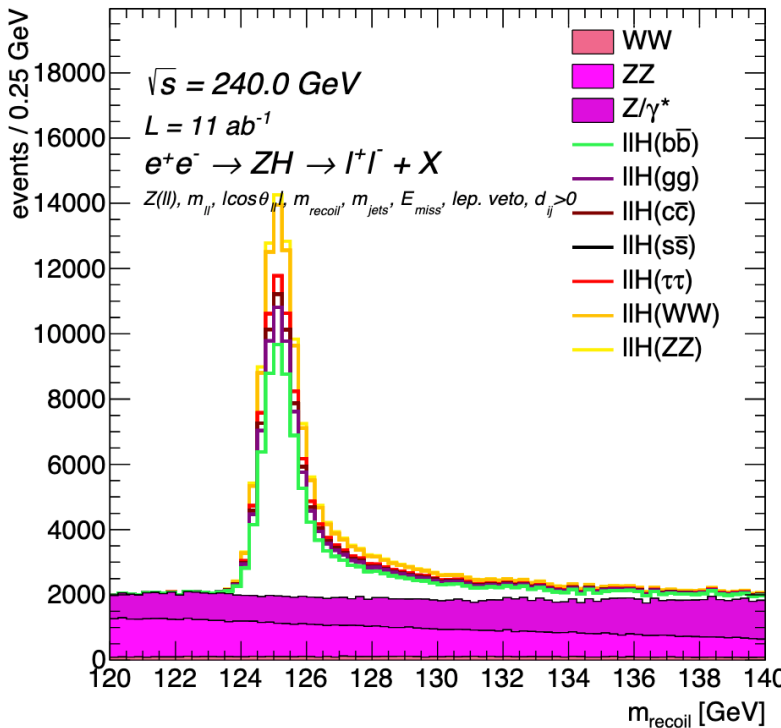
HIGGS BRANCHING RATIOS

HADRONIC COUPLINGS

Selection steps:

- Reconstruct the Z and H without distinguishing the Higgs hadronic decays by using the recoil mass method
- Separate ZH from VBF in the $Z(\nu\bar{\nu})H$ channel
- Use a neural network to classify the events into orthogonal categories enriched in the different Higgs decays
- Do a simultaneous fit to get the signal strength of each Higgs decay channel
 - Reach an impressive precision on $H \rightarrow s\bar{s}$

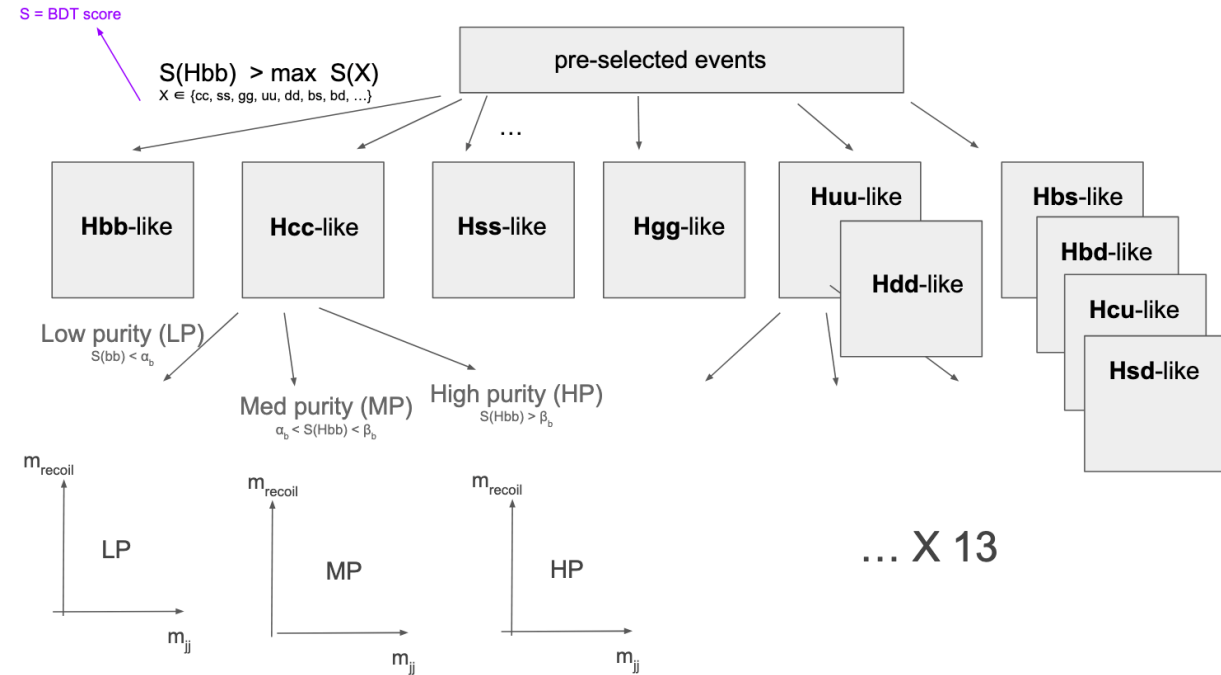
FCCAnalyses: FCC-ee Simulation (Delphes)



$\sqrt{s}$	240 GeV		365 GeV	
$\mathcal{L}$	10.8 ab ⁻¹		3.12 ab ⁻¹	
Channel	ZH	$\nu_e \bar{\nu}_e H$	ZH	$\nu_e \bar{\nu}_e H$
$H \rightarrow b \bar{b}$	0.21%	1.89%	0.41%	0.67%
$H \rightarrow c \bar{c}$	1.61%	19.4%	3.13%	3.49%
$H \rightarrow s \bar{s}$	120%	990%	360%	290%
$H \rightarrow g g$	0.80%	5.5%	2.21%	2.66%

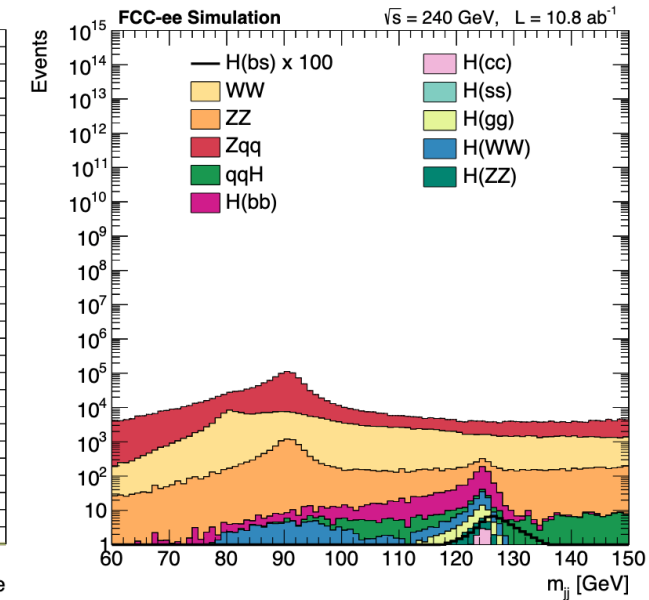
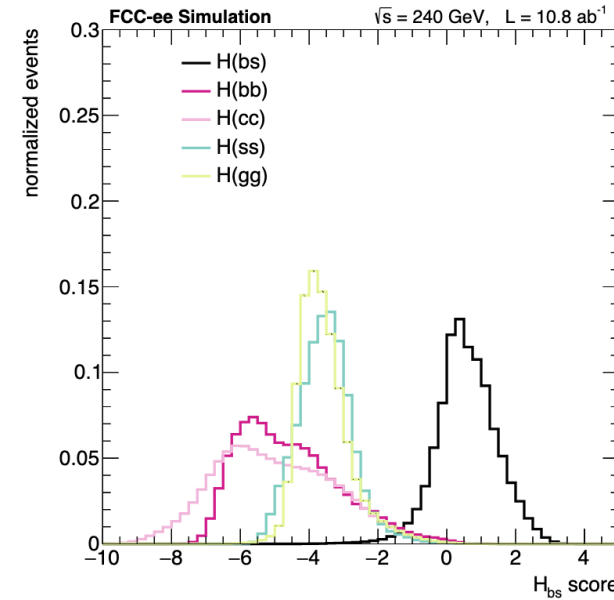
LIGHT YUKAWA COUPLING AND FCNC

Do the analysis only in $Z(\nu\bar{\nu})H$ channel
Selection steps:



- Do a simultaneous fit on the $m_{jj} - m_{recoil}$ distributions to extract upper limits on the processes

Work is ongoing for the $Z(\ell^+\ell^-)H$ channel to further improve the limits



Decay	SM Prediction	This work (95% CL)	Current constraints
$H \rightarrow u\bar{u}$	1.2×10^{-7}	$< 1.2 \times 10^{-3}$	3×10^{-2}
$H \rightarrow d\bar{d}$	5.5×10^{-7}	$< 1.2 \times 10^{-3}$	7×10^{-3}
$H \rightarrow bs$	9×10^{-8}	$< 3.1 \times 10^{-4}$	$< 1.6 \times 10^{-3}$
$H \rightarrow bd$	4×10^{-9}	$< 2.2 \times 10^{-4}$	$< 10^{-3}$
$H \rightarrow cu$	3×10^{-20}	$< 2.0 \times 10^{-4}$	$< 2 \times 10^{-3}$
$H \rightarrow sd$	2×10^{-15}	$< 6.5 \times 10^{-4}$	—

$H \rightarrow ZZ^*, WW^*$

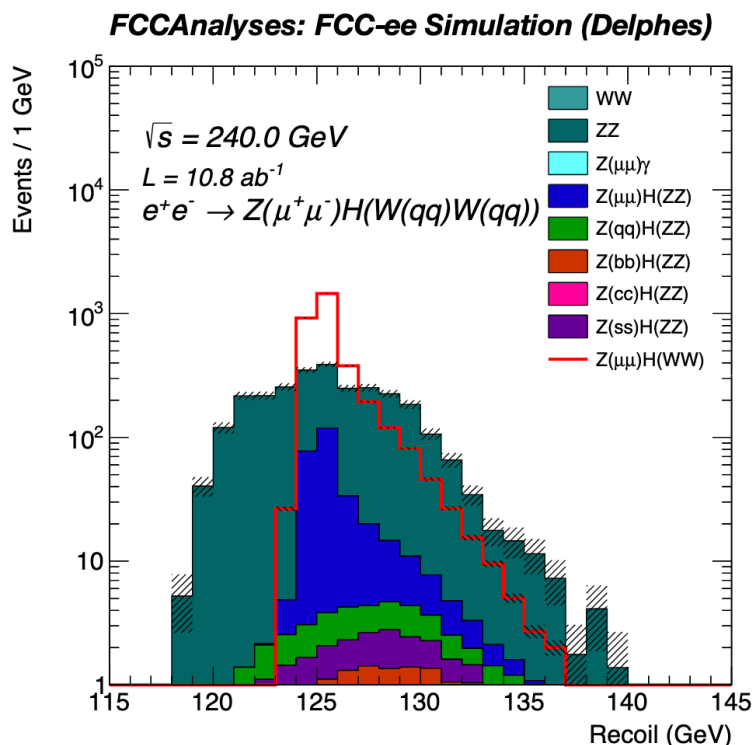
Analysis only done at 240 GeV

Consider all the possible final states

- $ZH \rightarrow VV^* \rightarrow 4j/6j$
- $ZH \rightarrow jj\ell^+\ell^-\nu\bar{\nu}$
- $ZH \rightarrow ZZ^* \rightarrow 4\ell/6\ell$

Need to use a BDT to separate $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ for channels with the same final state

- Also indirectly measured by the hadronic coupling analysis (slide 11)

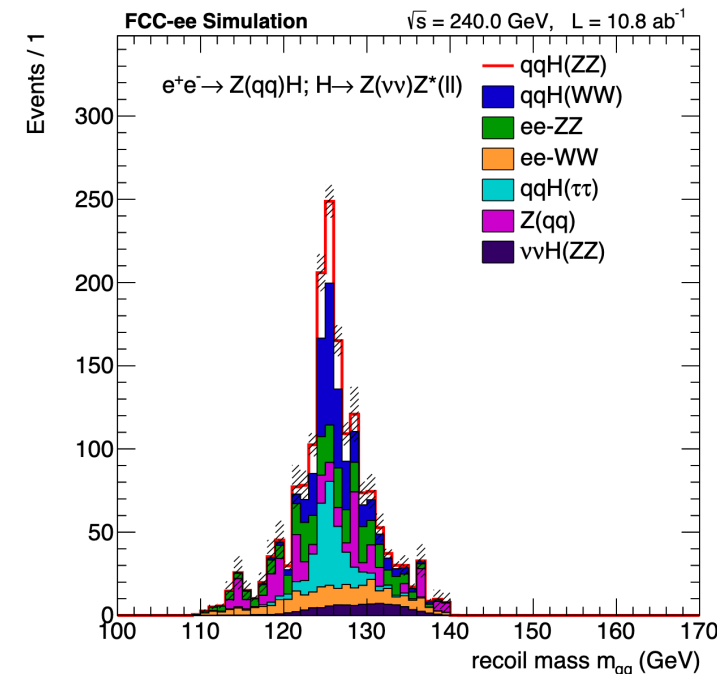


$H \rightarrow ZZ^*, WW^*$ are critical for the Higgs width measurement

- $\Gamma_H \propto \sigma_{ZH}^2 \times \sigma_{VBF}(H \rightarrow YY) / \sigma_{ZH}(H \rightarrow YY) \times \sigma_{ZH}(H \rightarrow WW^*)$
- $H \rightarrow ZZ^*$ important because $\sigma_{ZH} \times \mathcal{B}(H \rightarrow ZZ^*) \propto g_{HZZ}^4 / \Gamma_H$
 - Give absolute measurement of g_{HZZ}
 - Can also measure $\Gamma_H \propto \sigma_{ZH} / \sigma_{ZH}(H \rightarrow ZZ^*)$

Detailed contributions are in the back-up slides

$Z(\ell^+\ell^-)H(WW^* \rightarrow q\bar{q}q\bar{q})$: <https://repository.cern/records/1d9a2-qqm10>
 $Z(q\bar{q})H(ZZ^* \rightarrow \ell^+\ell^-\nu\bar{\nu})$: <https://repository.cern/records/fnwcp-qfs39>
 $Z(q\bar{q})H(VV^* \rightarrow q\bar{q}q\bar{q})$: <https://repository.cern/records/jxx9k-b9z97>
 $Z(\nu\bar{\nu}, q\bar{q})H(ZZ^* \rightarrow 4\ell)$: <https://repository.cern/records/jxx9k-b9z97>
 $Z(\ell^+\ell^-)H(ZZ^* \rightarrow 4\ell)$: <https://repository.cern/records/aaf59-q6v03>
Others: <https://repository.cern/records/ysabc-wm427>



Channel	240 GeV
$H \rightarrow WW^*$	0.8%
$H \rightarrow ZZ^*$	2.5%

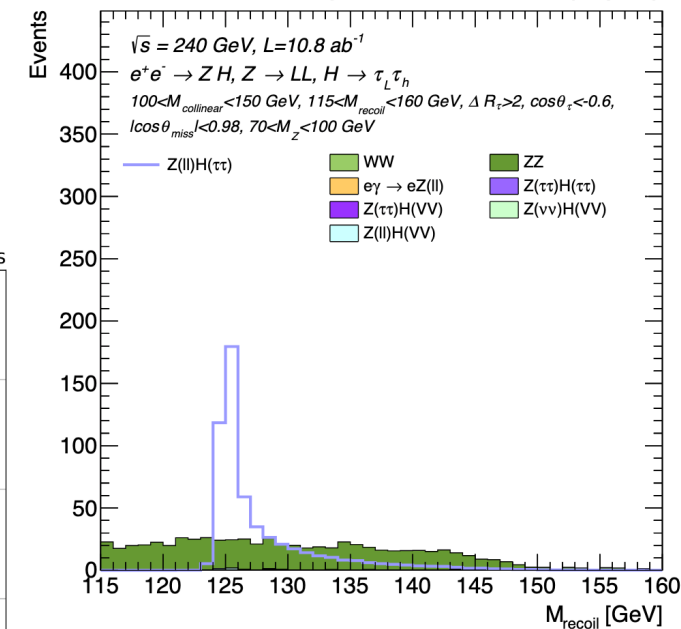
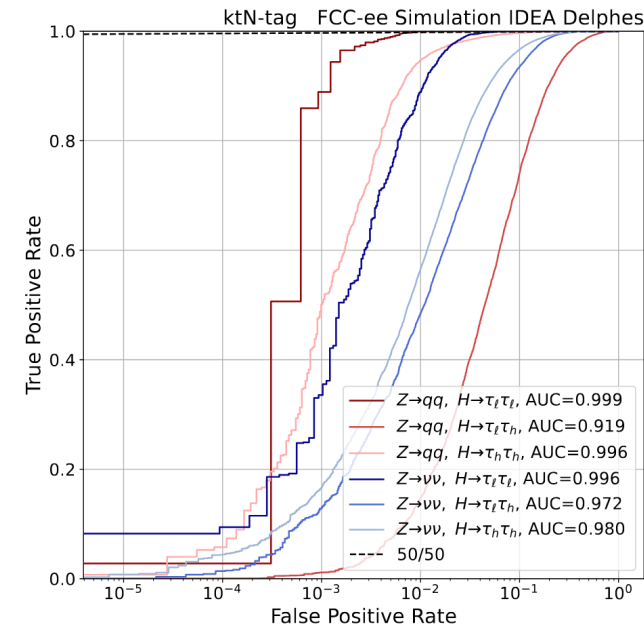
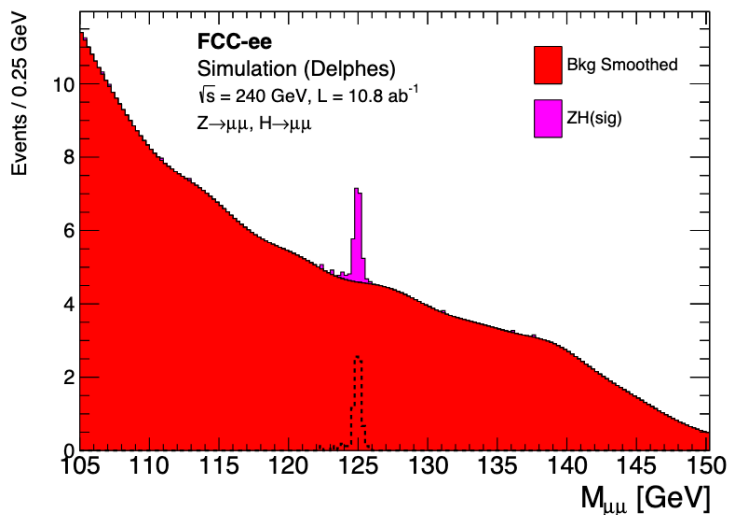
$$H \rightarrow \mu^+ \mu^-, \tau^+ \tau^-$$

Selection steps ($H \rightarrow \mu^+ \mu^-$):

- Reconstruct the Z and H for the different channels
- Apply some kinematic cuts
- Smooth the background
- Fit the $m_{\mu\mu}$ distribution for each channel

Selection steps ($H \rightarrow \tau^+ \tau^-$):

- Reconstruct τ s with a ParticleNet algorithm
- Consider the $\tau_l \tau_l, \tau_l \tau_h, \tau_h \tau_h$ pairs
- Separate ZH from VBF at 365 GeV in $\nu\bar{\nu}\tau^+\tau^-$ category
- Apply some kinematic cuts
- Use a BDT to separate signal from background



Channel	240 GeV	365 GeV	
	ZH	ZH	VBF
$H \rightarrow \mu^+ \mu^-$	11%	26%	-
$H \rightarrow \tau^+ \tau^-$	0.58%	1.27%	13.54%

$H \rightarrow \mu^+ \mu^-$: <https://repository.cern/records/63abq-gc172>

$H \rightarrow \tau^+ \tau^-$: <https://repository.cern/records/d3y9x-8a819>

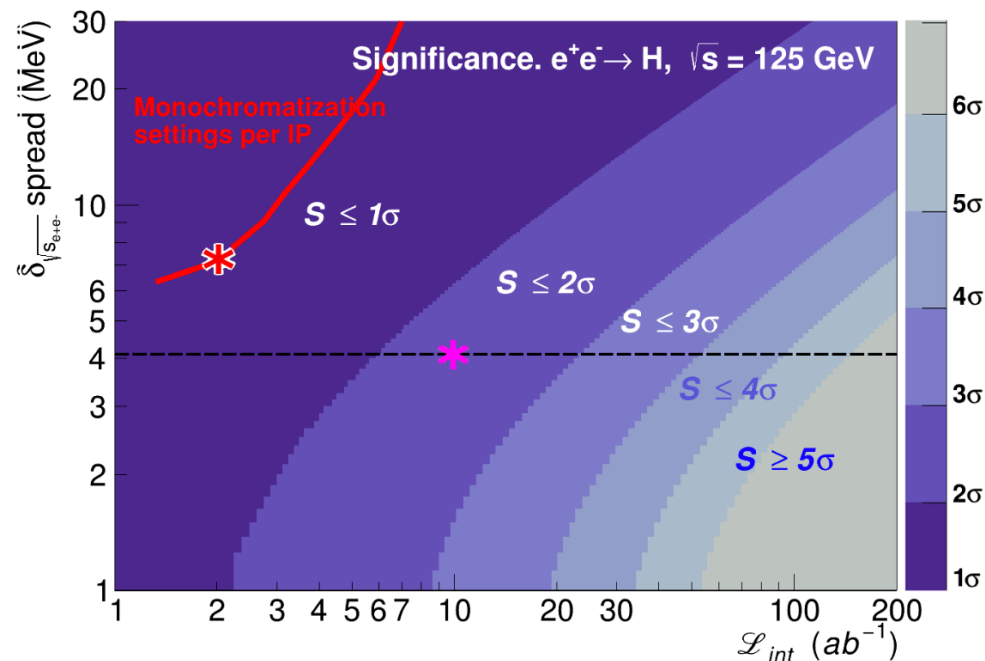
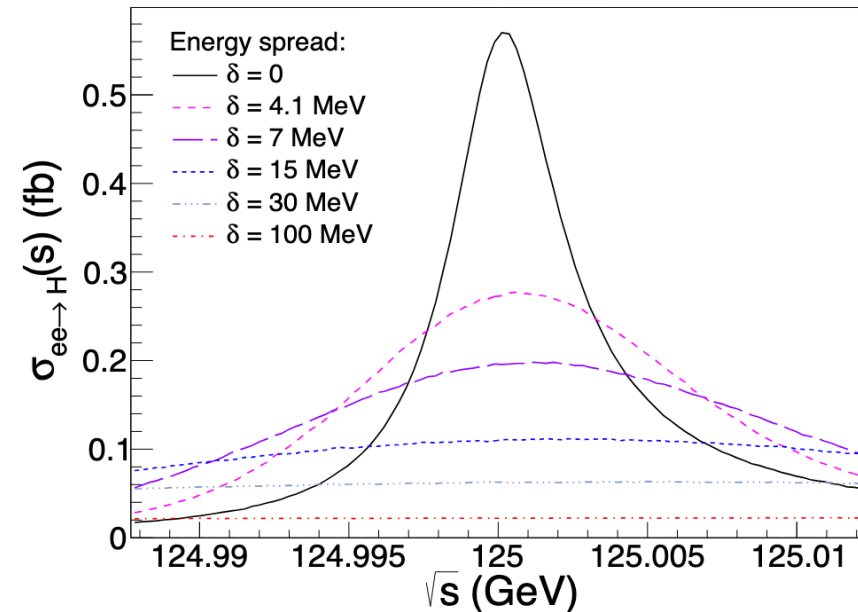
ELECTRON YUKAWA

$\mathcal{B}(H \rightarrow e^+e^-) \sim \mathcal{O}(10^{-9}) \rightarrow$ **impossible to measure this decay at FCC-ee**

- But can measure $e^+e^- \rightarrow H$ production in a dedicated run at $\sqrt{s} = 125 \text{ GeV}$

Requirements:

- Precision on Higgs mass $\Delta m_H < 5 \text{ MeV}$
 - Achievable (see slide 9)
- Large luminosity (very rare event)
 - 2.8k expected events/IP/year at 10 ab^{-1}
- **Need excellent beam monochromatisation ($\sim \Gamma_H$)**



$H \rightarrow gg$ and $H \rightarrow WW^* \rightarrow \ell \nu jj$ decays are the best channel

- $Z \rightarrow gg$ is forbidden but need good gluon vs light-jet separation
- $H \rightarrow WW^* \rightarrow \ell \nu jj$ also gives a great significance
 - Other channels are overwhelmed by background processes

Could reach 5σ discovery in a few years

$H \rightarrow Z\gamma, \gamma\gamma$

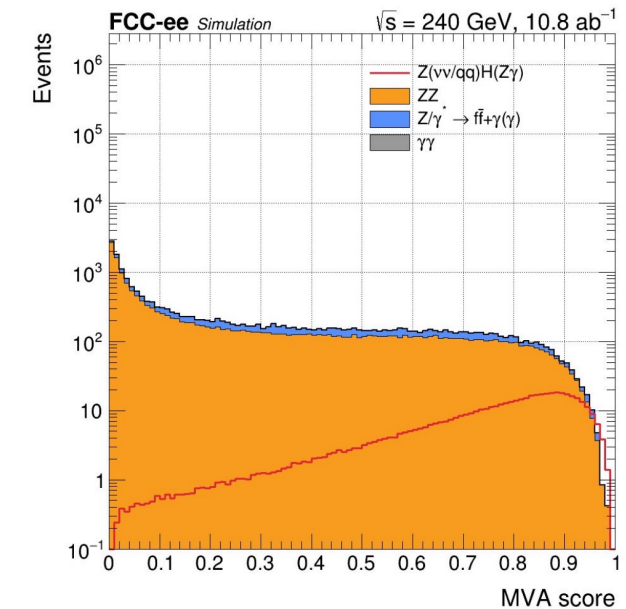
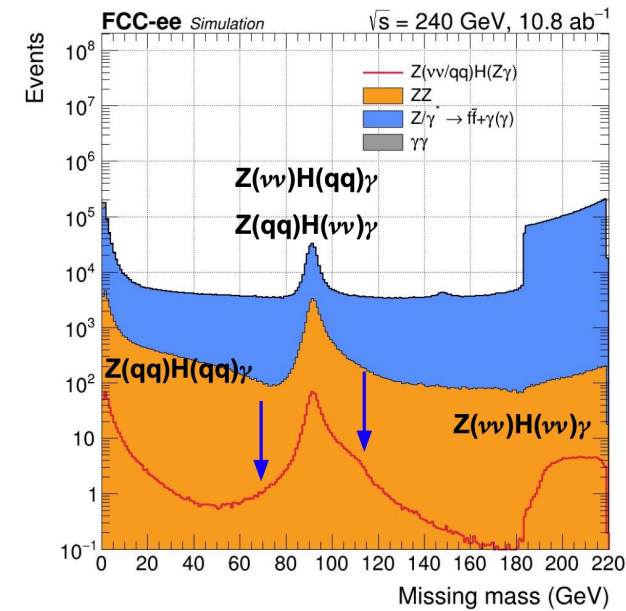
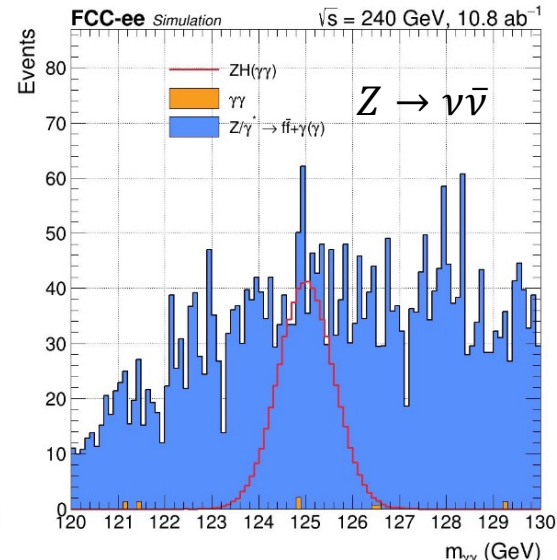
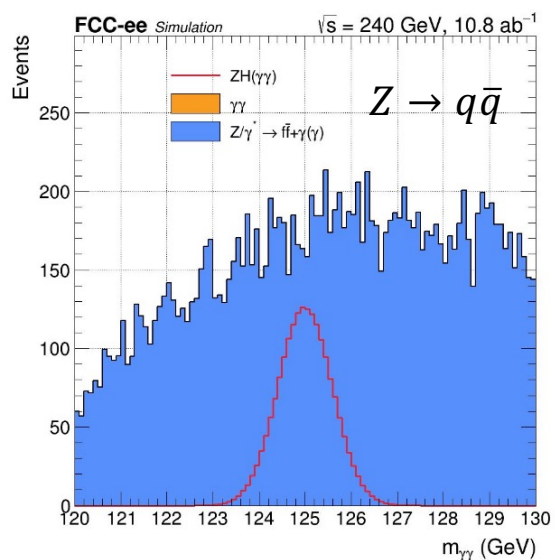
Only done for $Z(q\bar{q})H$ and $Z(\nu\bar{\nu})H$ channels

Selection steps ($H \rightarrow Z\gamma$):

- Use m_{miss} to categorize the channels
- Use the recoil mass method to reconstruct the Z and H
- Separate ZH and VBF with m_{miss} at 365 GeV
- Train a BDT to separate signal from background
- Fit on the BDT score distribution

Selection steps ($H \rightarrow \gamma\gamma$):

- Use recoil mass method to reconstruct the Z and H
- Separate ZH and VBF with m_{miss} at 365 GeV
- Fit on the $m_{\gamma\gamma}$ distribution to extract the precision



Channel	240 GeV	365 GeV	
	ZH	ZH	VBF
$H \rightarrow Z\gamma$	11.81%	21.94%	23.14%
$H \rightarrow \gamma\gamma$	3.63%	12.90%	14.71%

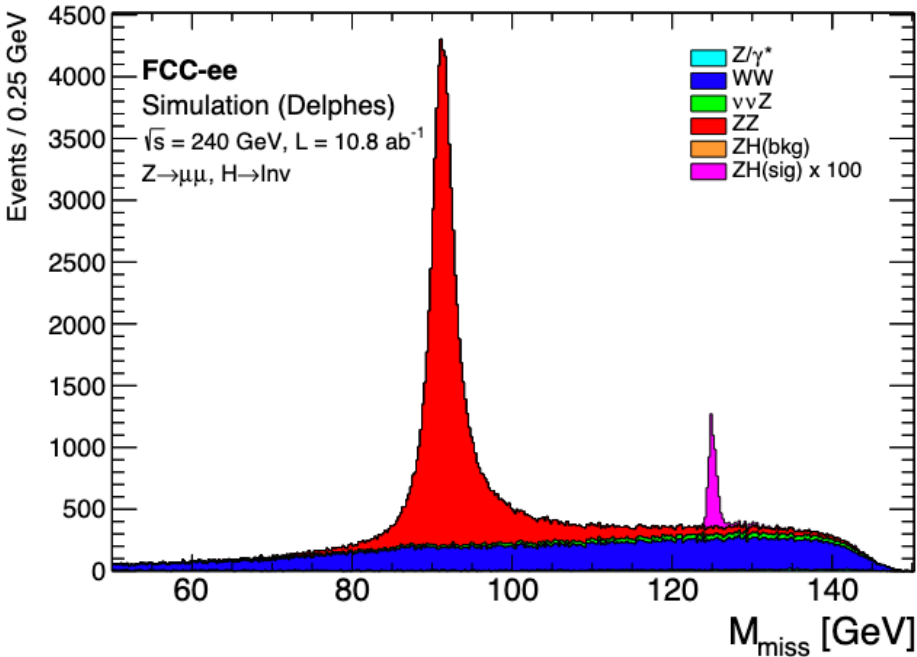
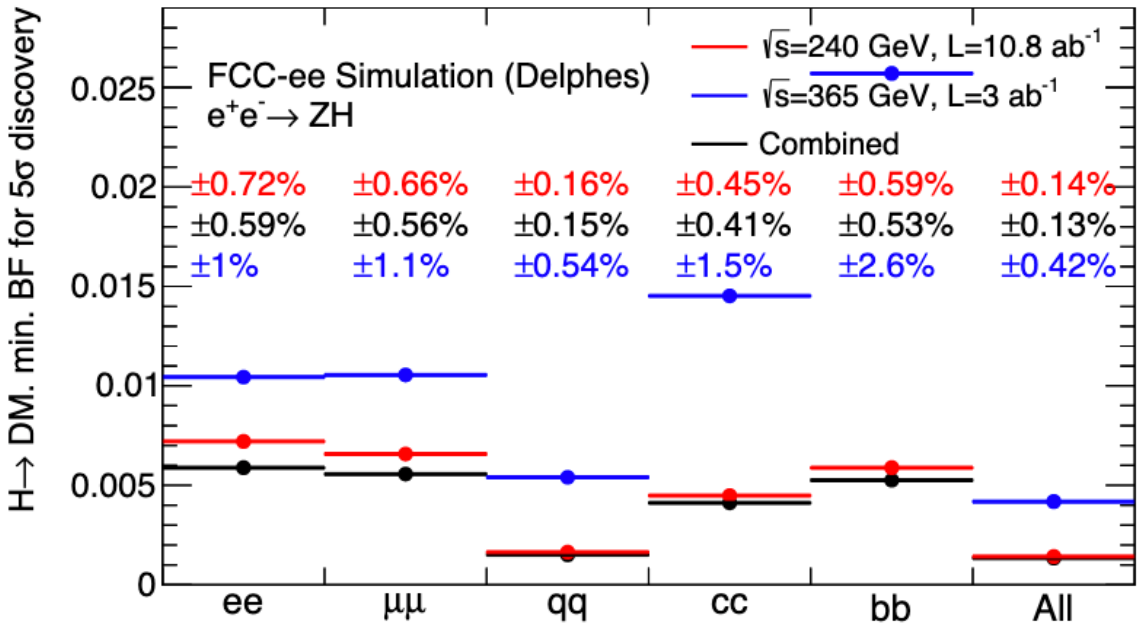
HIGGS TO INVISIBLE

Important channel as BSM can hide there

Selection steps:

- Categorize events depending on the number of lepton/tagged b/c -jets
- Use m_{miss} to extract the precision and BSM discovery sensitivity

Can detect $H \rightarrow DM$ down to $\mathcal{B}(H \rightarrow DM) \geq 0.14\%$



Channel	240 GeV	365 GeV
$H \rightarrow Inv$	0.027%	0.082%

CONCLUSION

FCC-ee allows for precise measurements:

%-level precision or better can be reached for most couplings

- Provide absolute normalization thanks to g_{HZZ} measurement
- Can also push the limits on rare and invisible decays

$\sim 4 \text{ MeV}$ precision can be achieved for m_H measurement

- Would allow g_{Hee} measurement in a dedicated run

σ_{ZH} can be measured at sub-percent level

- Important for g_{HZZ} to use as a standard candle
- Also important to get a precise measurement of κ_λ

Analysis mostly done in fast simulation

- Will need a lot of work to move to full simulation for the TDR
- Important to use FullSim to drive future detector performance
 - Studies are ongoing to make the analysis in FullSim

$\sqrt{s}$	240 GeV		365 GeV	
$\mathcal{L}$	10.8 ab^{-1}		3.12 ab^{-1}	
Channel	ZH	$\nu_e \bar{\nu}_e H$	ZH	$\nu_e \bar{\nu}_e H$
$H \rightarrow all$	0.31%	-	0.52%	-
$H \rightarrow b\bar{b}$	0.21%	1.89%	0.41%	0.67%
$H \rightarrow c\bar{c}$	1.61%	19.4%	3.13%	3.49%
$H \rightarrow s\bar{s}$	120%	990%	360%	290%
$H \rightarrow gg$	0.80%	5.5%	2.21%	2.66%
$H \rightarrow \mu^+ \mu^-$	11%	-	26%	5.6%*
$H \rightarrow \tau^+ \tau^-$	0.58%	-	1.27%	13.54%
$H \rightarrow WW^*$	0.8%	-	1.8%*	2.1%*
$H \rightarrow ZZ^*$	2.5%	-	8.3%*	4.6%*
$H \rightarrow Z\gamma$	11.81%	-	21.94%	23.14%
$H \rightarrow \gamma\gamma$	3.63%	-	12.90%	14.71%
$H \rightarrow Inv$	0.027%	-	0.082%	-

(*): Values rescaled from FCC CDR

THANKS FOR LISTENING

Contact us at: fcc-ped-physicsgroup-higgs-admin@cern.ch

General Mailing list: FCC-PED-PhysicsGroup-Higgs@cern.ch

BACK-UP SLIDES

$H \rightarrow ZZ^*, WW^*$ DETAILED CONTRIBUTIONS

$$H \rightarrow ZZ^*$$

Final state	Precision
$Z(\nu\bar{\nu})H(ZZ^* \rightarrow jjjj)$	11.0%
$Z(\ell^+\ell^-)H(ZZ^* \rightarrow jjjj)$	7.6%
$Z(jj)H(ZZ^* \rightarrow jjjj)$	8.2%
$Z(\nu\bar{\nu})H(ZZ^* \rightarrow \ell^+\ell^-jj)$	4.7%
$Z(\ell^+\ell^-)H(ZZ^* \rightarrow \nu\bar{\nu}jj)$	5.0%
$Z(\ell^+\ell^-)H(ZZ^* \rightarrow jj\nu\bar{\nu})$	7.3%
$Z(jj)H(ZZ^* \rightarrow \ell^+\ell^-\nu\bar{\nu})$	13.5%
$Z(jj)H(ZZ^* \rightarrow \nu\bar{\nu}\ell^+\ell^-)$	19.3%
$Z(jj/\nu\bar{\nu})H(ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-)$	10%
$Z(\ell^+\ell^-)H(ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-)$	29.7%
Combination	2.5%

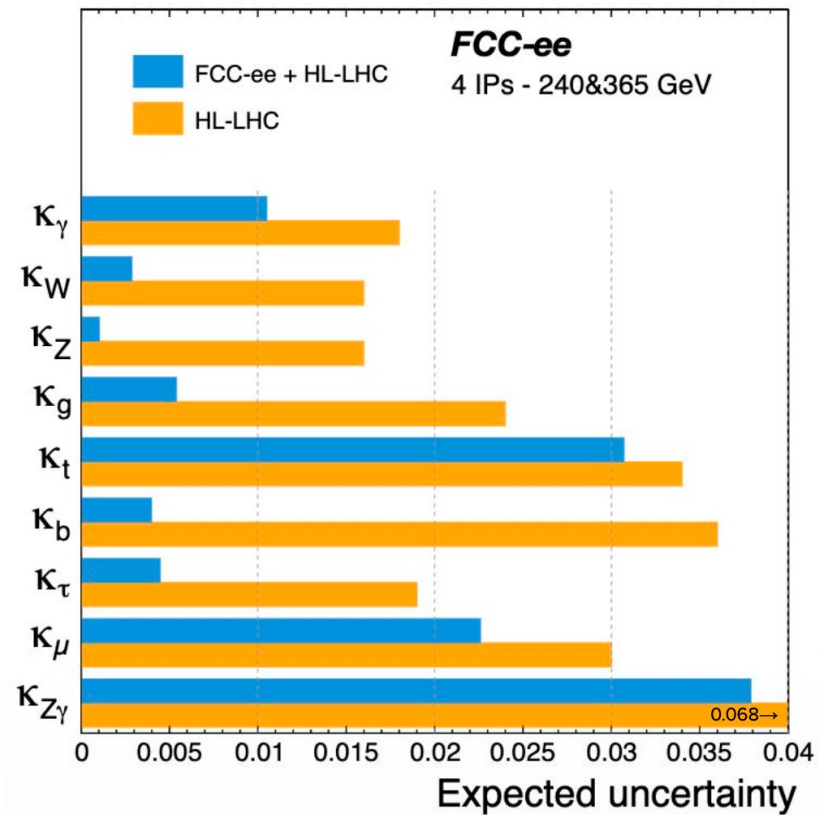
$$H \rightarrow WW^*$$

Channel	Precision
$Z(\nu\bar{\nu})H(WW^* \rightarrow jjjj)$	1.3%
$Z(\ell^+\ell^-)H(WW^* \rightarrow jjjj)$	1.60%
$Z(jj)H(WW^* \rightarrow jjjj)$	1.48%
Combination	0.8%

COMPARISON TO HL-LHC

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	—	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$ \kappa_s $ (%)	—	+29 −67	+29 −67
Γ_H (%)	—	0.78	0.69
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}

From FCC Feasibility Report
<https://cds.cern.ch/record/2928193>



<https://indico.in2p3.fr/event/33627/contributions/154115/>

IDEA DETECTOR CONCEPT

Muon chambers

- 3 layers, gas detector
- Spatial resolution $< 400\ \mu\text{m}$

Dual-readout calorimeter

- 2 m capillaries
- Alternate Cherenkov and scintillation fibers
- $\sigma_{EM} \approx 10\%/\sqrt{E}$, $\sigma_{had} \approx 30\%/\sqrt{E}$

Preshower

- 2 layers, gas detector
- Spatial resolution $< 100\ \mu\text{m}$

Superconducting solenoid

- 2T, $R = 2.0 - 2.4\ \text{m}$
- $0.74 X_0$, $0.16\ \lambda$ at 90°

Drift chamber:

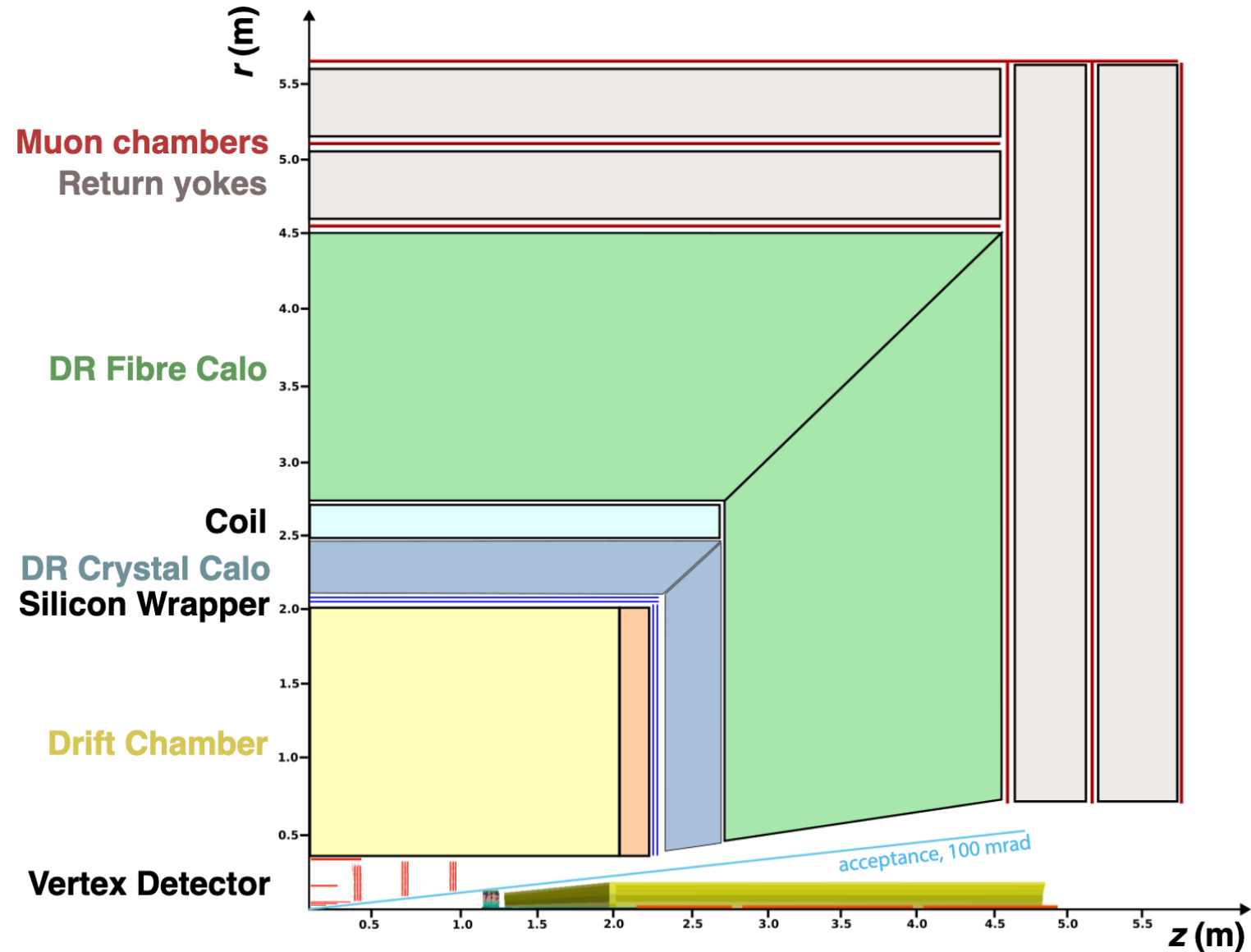
- 112 layers, $R = 35 - 200\ \text{cm}$
- $0.016 X_0$ at 90°

Silicon vertex detector

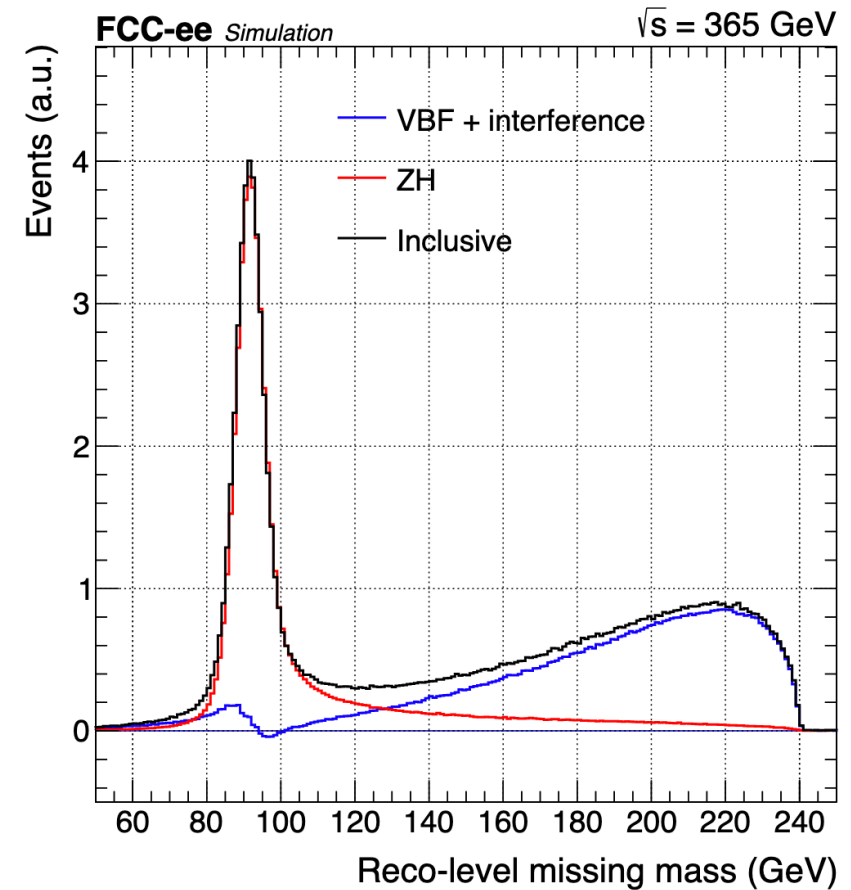
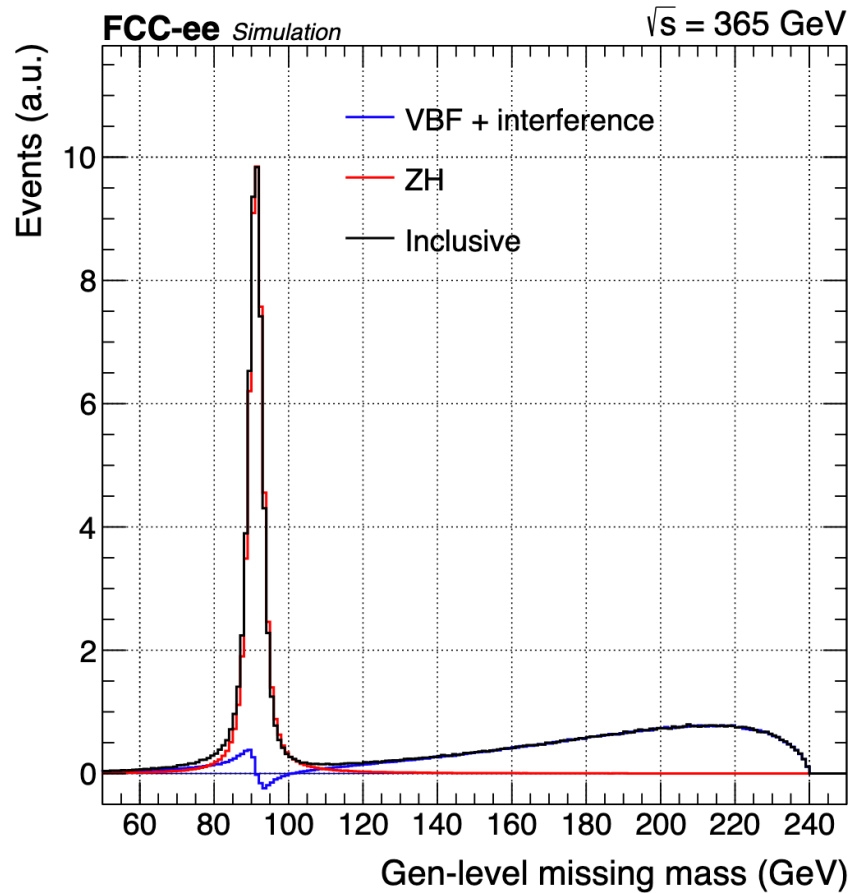
- 5 layers, $R = 1.7 - 34\ \text{cm}$
- Pixel $20 \times 20\ \mu\text{m}^2$

Beam pipe

- $R \sim 1.5\ \text{cm}$



ZH/VBF SEPARATION



For ZH sample:

- Generate $e^+e^- \rightarrow \nu_\mu \bar{\nu}_\mu H$ with weight 3

For VBF:

- Generate $e^+e^- \rightarrow \nu_e \bar{\nu}_e H$
- Remove the $e^+e^- \rightarrow \nu_\mu \bar{\nu}_\mu H$ from $e^+e^- \rightarrow \nu_e \bar{\nu}_e H$ to get VBF with interference