Higgs decays and couplings at FCC-ee

Alexis Maloizel (APC-Paris, CNRS/IN2P3)

On behalf of FCC Collaboration

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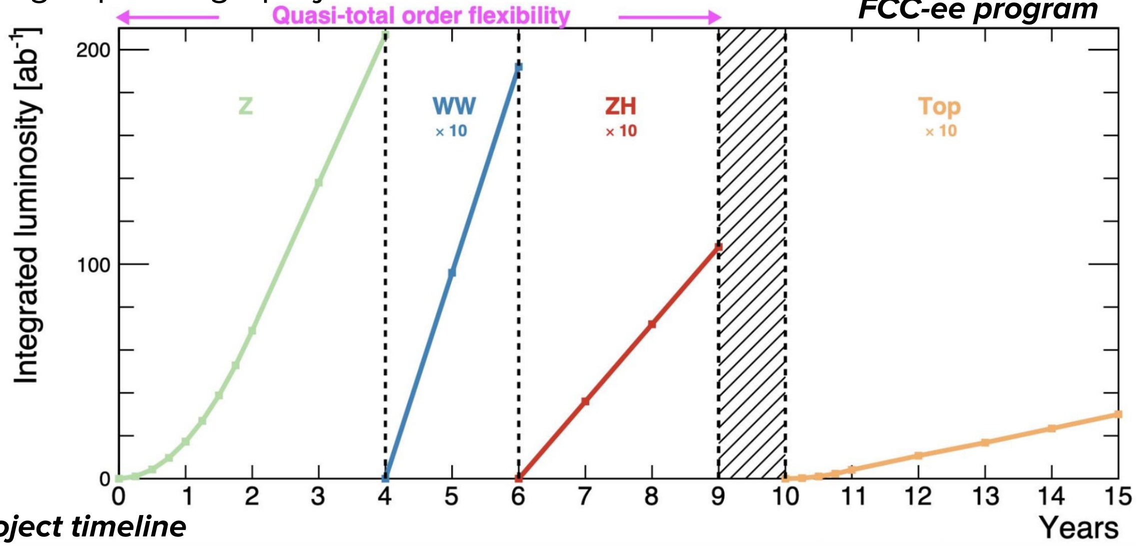
FCC Project

- FCC is the proposed post-LHC CERN's flagship 2-stage project (e+e- , pp)
- **4 Interaction Points**
- **90 km** circular collider
- **FCC-ee**
  - extremely large Z-pole dataset
  - millions of clean Higgs boson
  - high stats Top studies
- **FCC-hh**
  - Energy-frontier physics exploration
  - **85 TeV** at **~1 ab^{-1}**

FCC-ee program



Possible FCC project timeline

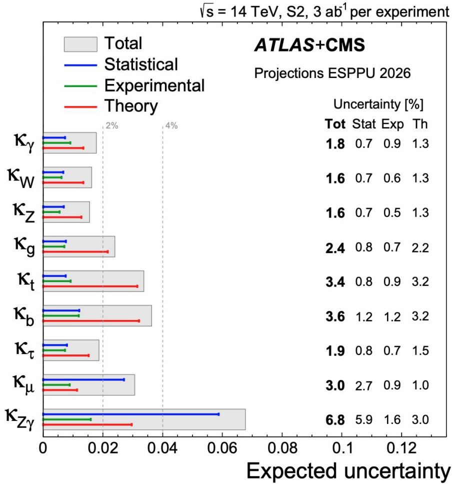
Motivations

- Precise measurements of Higgs couplings might yield to deviation from SM → Possible BSM physics

- FCC-ee allows precise, model-independent measurement of numerous couplings including some unobservable at the LHC
  - H→Hadrons = 80% of H decays and LHC only measures bottom Yukawa
  - H→gg is very sensitive to BSM

HL-LHC projections (2040)

reference link

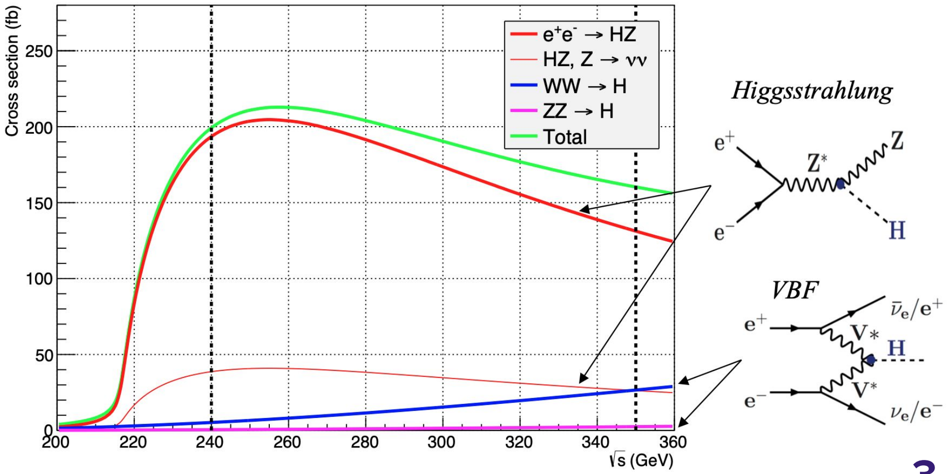


Mostly limited by stats. and th. unc.
Not model independent

4 interactions points

	$\sqrt{s}$ (GeV)	Luminosity (ab^{-1})	ZH Events	WW Fusion Events
3 years	240	10.8	2.2M	65k
5 years	365	3.12	0.37M	92k

- Extremely clean environment (e^+e^-)
  - small backgrounds
  - high signal efficiency for most Higgs decays
  - Precise kinematics constraints



Couplings to b, c, g, s

Measurement of Higgs boson hadronic decays at FCC-ee
https://doi.org/10.17181/3jjdh-6fz97

Z decay channels

$Z \to ll$, $l = e, \mu$

BR($Z \to ll$) ~ 6.7 %

$Z \to qq$

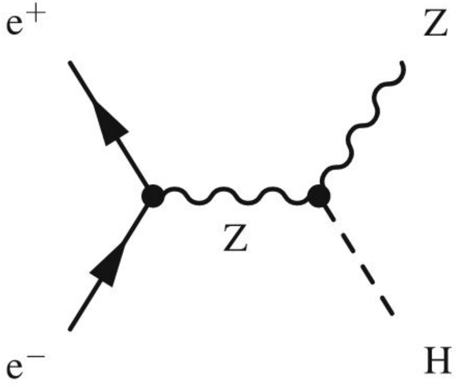
BR($Z \to qq$) ~ 67%

Limited by jet clustering

$Z \to \nu\nu$

BR($Z \to \nu\nu$) ~ 20%

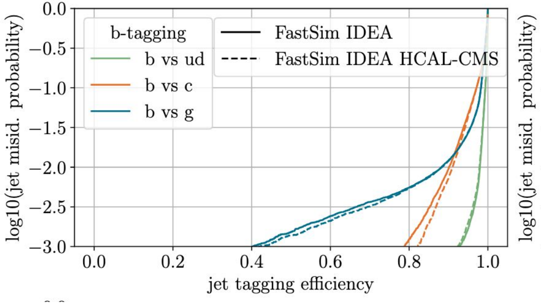
Requires a separation of ZH and VBF productions processes
(separe templates/signal strengths)



recoil strategy ($Z \to xx$)

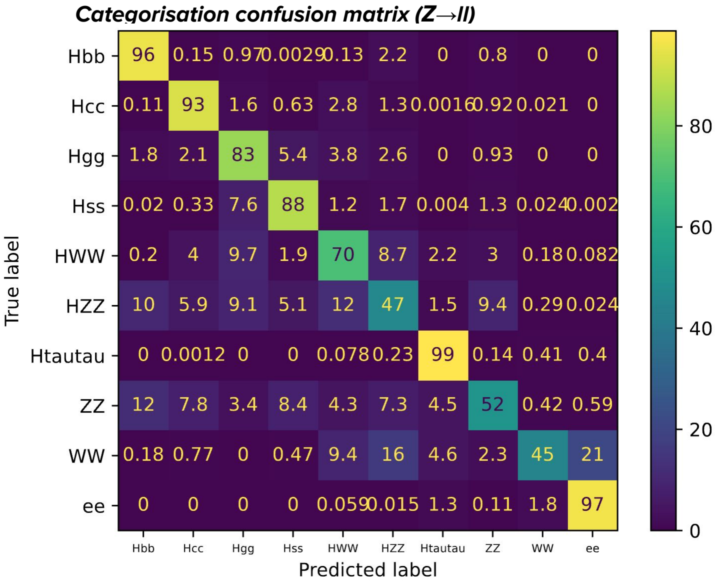
$$m^2_{recoil} = (\sqrt{s} - E_{x\bar{x}})^2 - p^2_{x\bar{x}}$$

link



Analysis strategy

- **S/B optimization** with kinematic selection
- **Categorization** using ParticleNet tagger output
  *(7 outputs **(b,c,s,g,d,u,tau)** for each jets)*
- **Simultaneous fit** on all categories
- **Combination** of all Z decay channe



Couplings to b, c, g, s

Measurement of Higgs boson hadronic decays at FCC-ee
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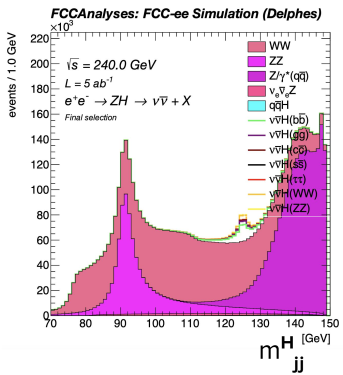
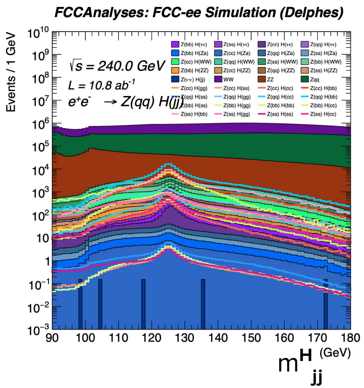
- Monte Carlo stats uncertainties included
- WW, ZZ, ττ are byproducts of this hadronic decays study and dedicated analysis yield better sensitivities



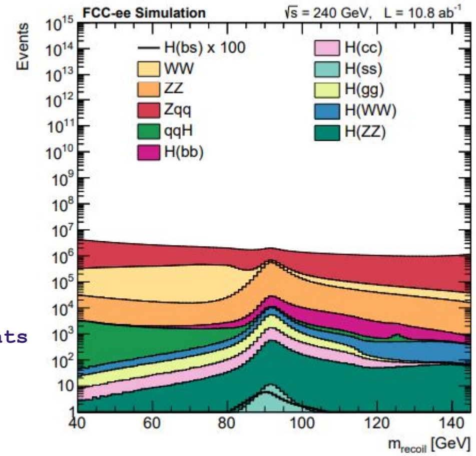


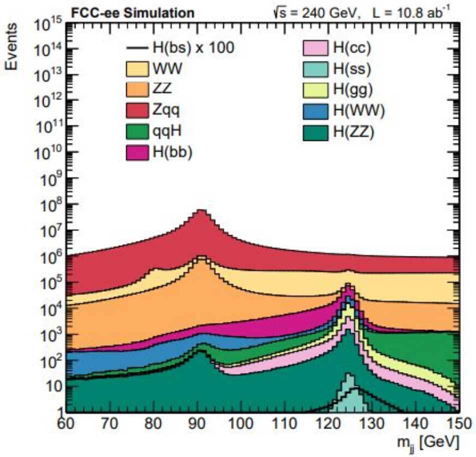
Expected sensitivity (%) of σ.BR(H⟶jj) at 68% CL

240 GeV L = 10.8ab^{-1}		H⟶bb	H⟶cc	H⟶gg	H⟶ss	H⟶ZZ	H⟶WW	H⟶ττ
Combined	**ZH**	0.21	1.6	0.80	120	9.94	1.17	3.67
	VBF	1.9	19	5.50	990	130	15.6	∞
365 GeV L = 3.12ab^{-1}		**H⟶bb**	**H⟶cc**	**H⟶gg**	**H⟶ss**	**H⟶ZZ**	**H⟶WW**	**H⟶ττ**
Combined	**ZH**	0.38	2.9	2.1	350	26.0	3.18	11.0
	VBF	0.66	3.4	2.6	280	37.1	5.36	24.2

Light Yukawa couplings and FCNC

- Using a similar analysis strategy, one can also extract upper limits at **95% CL** of :
  - Light quark Yukawa couplings (*u* and *d*)
  - Flavour changing neutral currents Higgs decays (H ⟶ *bs, bd, sd, cu*)





Measuring Light Yukawa couplings and Flavour Changing Neutral Currents in Higgs hadronic decays at the FCC-ee

https://doi.org/10.17181/7xjde-ebj45

L=10.8ab^{-1} at 240 GeV

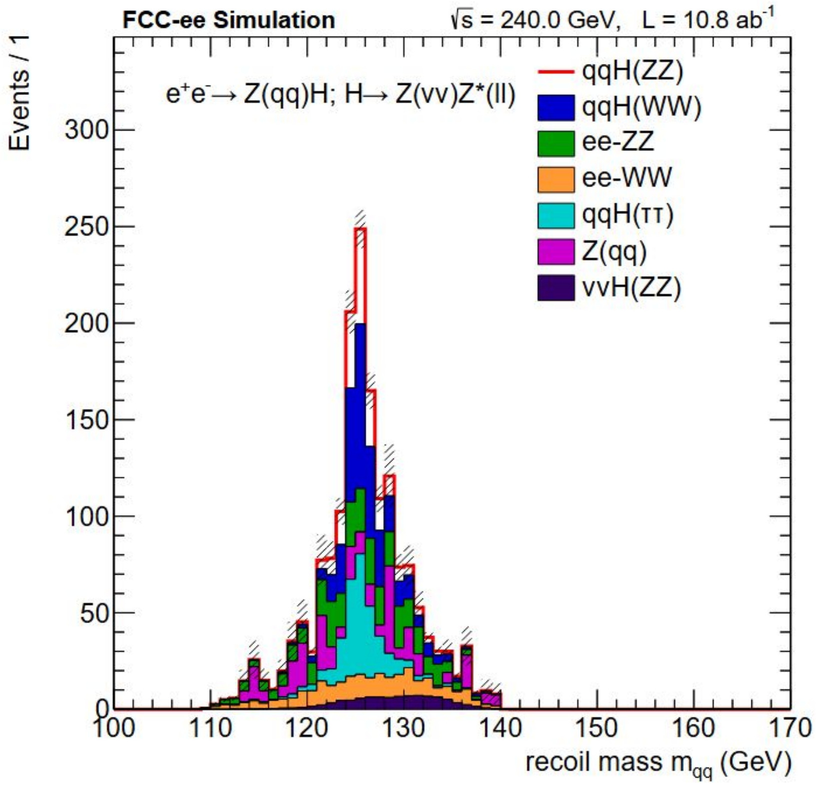
Decay	SM Prediction	this work (95% CL)	current constraints
$H \to uu$	1.2×10^{-7}	$< 1.2 \times 10^{-3}$	3×10^{-2}
$H \to dd$	5.5×10^{-7}	$< 1.2 \times 10^{-3}$	7×10^{-3}
$H \to bs$	9×10^{-8}	$< 3.1 \times 10^{-4}$	$< 1.6 \times 10^{-3}$
$H \to bd$	4×10^{-9}	$< 2.2 \times 10^{-4}$	$< 10^{-3}$
$H \to cu$	3×10^{-20}	$< 2.0 \times 10^{-4}$	$< 2 \times 10^{-3}$
$H \to sd$	2×10^{-15}	$< 6.5 \times 10^{-4}$	—

H → ZZ

HWW and HZZ in the fully hadronic final states at the FCC-ee
https://doi.org/10.17181/jxx9k-b9z97

Measurements of the ZH→ZZZ*→qqllvv and qqvvll final states at FCC-ee
https://doi.org/10.17181/fnwcp-qfs39

- Analysis only performed at **240 GeV**
- Need to consider all the possible final states
  - **Z→ll,$\nu\nu$ & H→ZZ→jjjj** (slides 4-5)
  - **Z→jj & H→ZZ→jjjj**
    - Exclusive jet reconstruction with N=6
    - Use of combinatorics for jets pairing
    - 2 BDTs to separate sig/bkg and ZZ/WW signal components
  - **ZH→jjll$\nu\nu$ (best sensitivity)**
    - Separation with WW signal components done with the same BDT
  - **Z→ll,jj,$\nu\nu$ & H→ZZ→4l**
    - Similar strategy as above



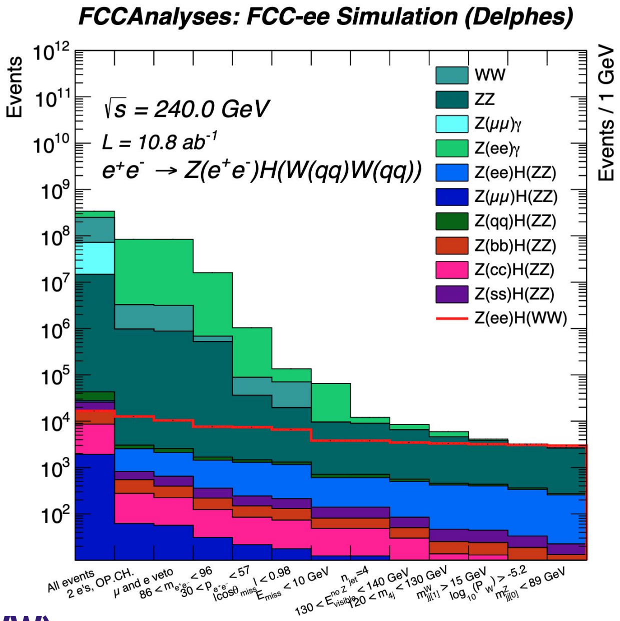
Expected sensitivity (%) of σ.BR(H⟶ZZ)

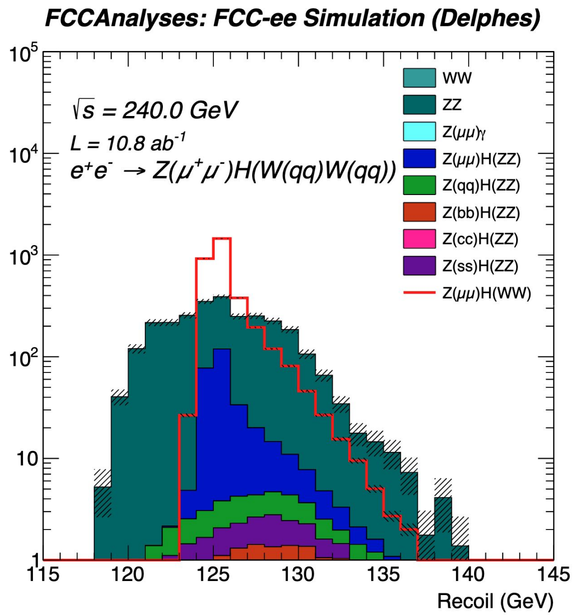
240 GeV L = 10.8ab^{-1}	H→ZZ
Combined	2.5

Precision measurement of Higgs production cross section in the four-lepton final state at the FCC-ee
https://doi.org/10.17181/ey2ff-hgv83

H → WW

- Analysis only performed at **240 GeV**
- Leptonic decays of the WW pair have not yet been studied
- **Z→νν & H→WW→jjjj** (slides 4-5)
- **Z→ll & H→WW→jjjj**
  - N = 4 exclusive Durham jet reconstruction
  - Classification using a BDT
- **Z→jj & H→WW→jjjj**
  - Same analysis than the one for **Z**





Expected sensitivity (%) of σ.BR(H⟶WW)

240 GeV L = 10.8ab^{-1}	H⟶WW
Z→νν & H→WW→jjjj	1.3
Z→ll & H→WW→jjjj	1.6
Z→jj & H→WW→jjjj	1.5

HWW and HZZ in the fully hadronic final states at the FCC-ee
https://doi.org/10.17181/jxx9k-b9z97

Measurement of the Higgs boson decay in Z(ll)H, H→WW at FCC-ee
https://doi.org/10.17181/1d9a2-qgm10

240 GeV L = 10.8ab^{-1}	H⟶WW
combined	0.8

Coupling to τ

Measurements of Hττ cross-section at FCC-ee
https://doi.org/10.17181/d3y9x-8a819

- Analysis of **H→ττ** for ZH with **Z→ll, $\nu\nu$, jj**
- $\tau_l\tau_l$, $\tau_l\tau_h$, $\tau_h\tau_h$ pairs considered

Selection:

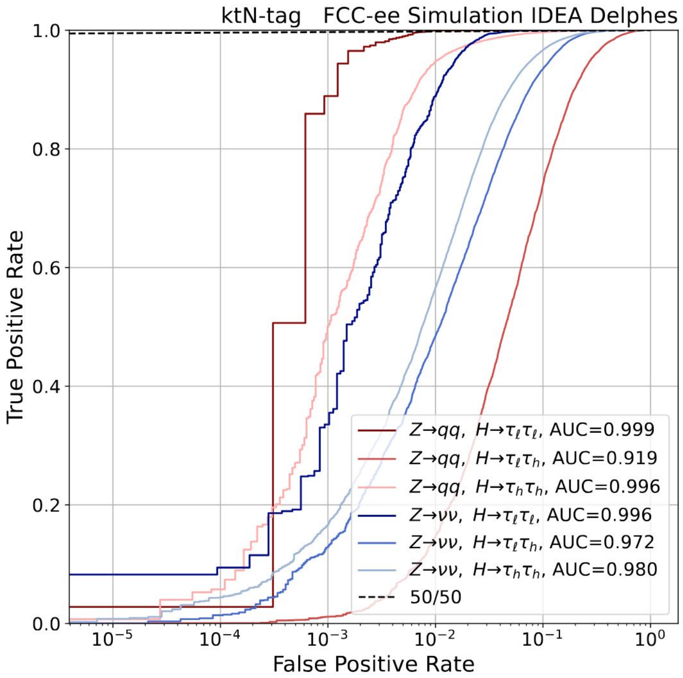
- Exactly two leptons (jets) for Z→ll (Z→jj)
- two taus with opposite charge
- cuts on kinematics

Categorization:

- BDT classification trained using the kinematics of the reconstructed pairs
- Separation of **ZH** and **VBF** contributions at **365GeV** in **$\nu\nu$H** final state

Results are obtained by fitting the BDT outputs.

sig-bkg BDT separation ROCs



Expected sensitivity (%) of σ.BR(H⟶ττ) at 68% CL

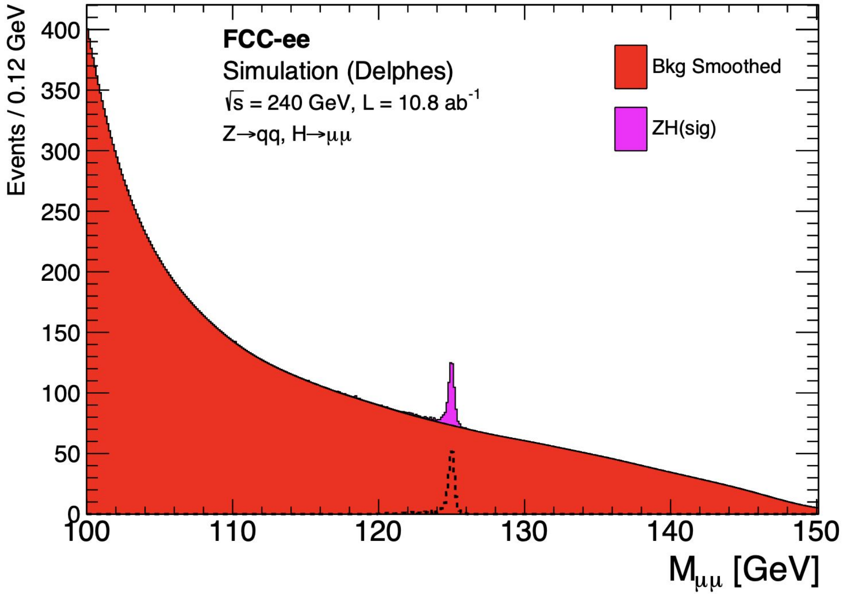
240 GeV L = 10.8ab^{-1}		H⟶ττ
	ZH	0.58

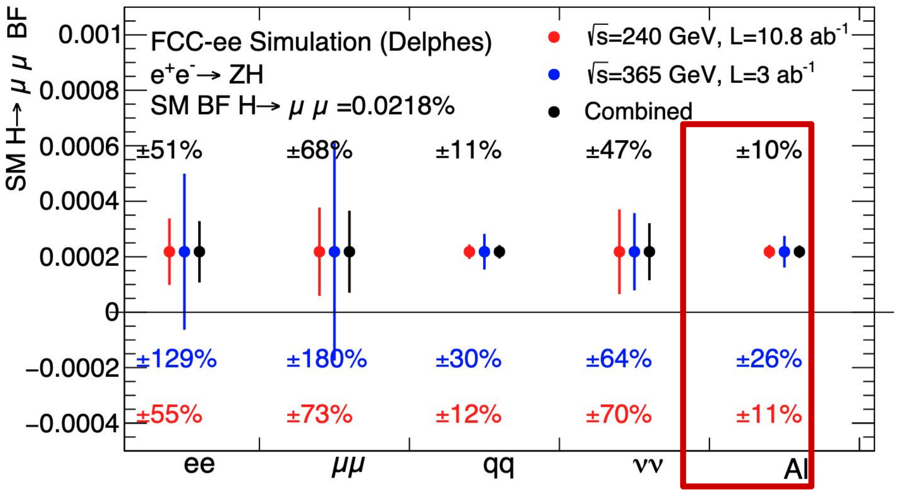
Expected sensitivity (%) of σ.BR(H⟶ττ) at 68% CL

365 GeV L = 3.12ab^{-1}		H⟶ττ
	ZH	1.27
	VBF	13.54

Coupling to μ

- Analysis on **Z(ll,$\nu\nu$,jj)H(μμ)** both at **240** & **365 GeV**
- Selection on the Z kinematics, angular variables of the muon pair, … *(see bottom right table)*
- **Fit** on the invariant mass of the **muon pair**





Precision on $\sigma(e^+e^- \to ZH) \times \mathcal{B}(H \to \mu^+\mu^-)$

Z Decay Channel	Description / Notes	Precision (%)
At $\sqrt{s} = 240$ *GeV*		
$Z \to \nu\nu$	Background dominated by WW, reduced via p_T^{miss} and angle cuts	11 (combined)
$Z \to \ell\ell$	No extra selection in e^+e^- or $\mu^+\mu^-$ channels	
$Z \to jj$	Photon veto reduces $Z\gamma$ background (dominant channel)	
$Z \to$ all	Fit to $m_{\mu\mu}$ distribution	
At $\sqrt{s} = 365$ *GeV*		
$Z \to$ all	Same strategy, higher background; reduced acceptance	26

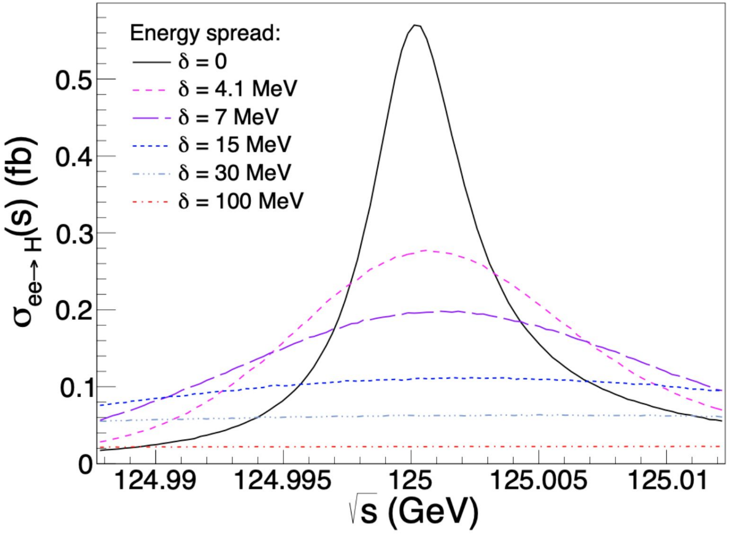
Result tables taken from this [G. Iakovidis' talk]

Measurement of the Higgs to muons branching fraction at the FCC-ee
https://doi.org/10.17181/63abg-gc172

Electron Yukawa

arXiv:2107.02686

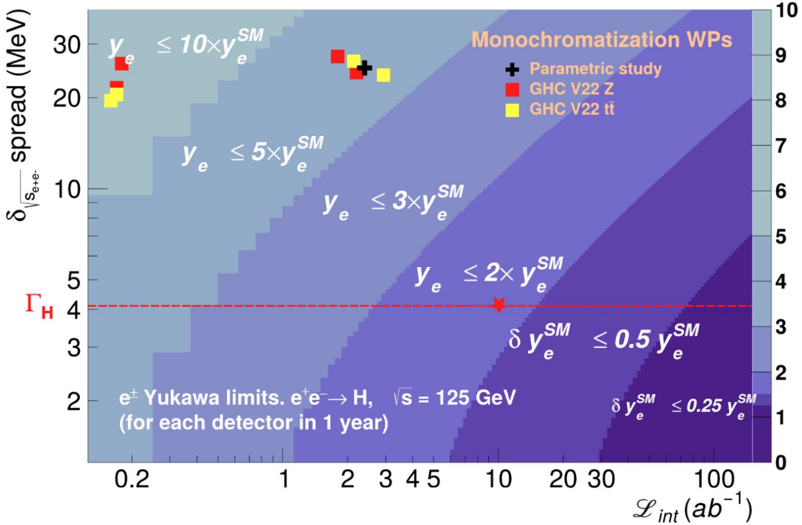
- **Dedicated run at $\sqrt{s}$ = 125GeV** with **resonant** H production *(only possibility to probe e^- Yukawa, $B(H \to ee) \sim O(10^{-9})$)*
- Coupling constrained from the **production mode**



Requirements:

- Excellent beam **monochromatisation** ($\sim \Gamma_H$ *(4Mev)*)
- Large **luminosity** (very rare counting experiment)
  - 2.8k expected events/year at 10 ab^{-1}
- Precision on **H mass** < 5 MeV

- Multiple H decays analysis, count on BDT classification
- $e^+e^- \to gg$ is best channel *(Z→gg is forbidden, but very good light-q vs. gluon jet tagging needed)*
- Potential probing of y_e at **SM level**
- Estimate of **4σ expected** with **4 IP** in **4 years**

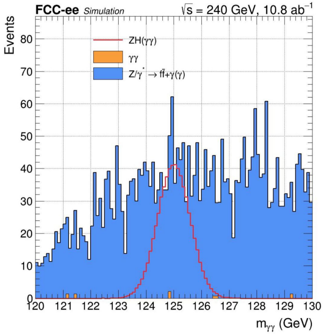


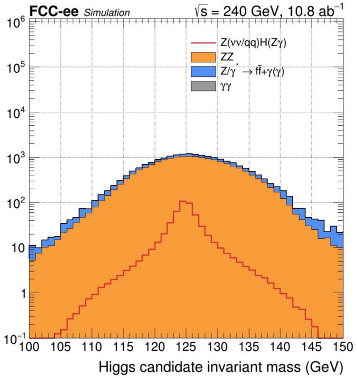
H ⟶ γγ, Zγ

- Very low statistics channel but with clean signatures
- Performed both at **240** & **365 GeV** with ZH and VBF separation

H→γγ:

- Cut-based analysis on the invariant mass of the Higgs decay
- Selection on event kinematics
- **Categorization** depending on the **Z decay** (ll, jj, $\nu\nu$)
- Simultaneous **fit** on the **γγ** pair **invariant mass**





Z→vv

Expected precision of Higgs boson decays to two photons and Z boson with a photon at the FCC-ee

https://doi.org/10.17181/nh2gr-z8j07

H→Zγ:

- **Z** decays to **jj** or $\boldsymbol{\nu\nu}$
- Veto on leptons and high missing energy
- **Classification** with a **BDT**
- **Fit** on the **BDT output**

Precision on $\sigma(e^+e^- \to ZH) \times \mathcal{B}(H \to Z\gamma)$

Final State	Description	Precision (%)
At $\sqrt{s} = 240$ GeV (combined)		
$\nu\nu jj\gamma$	$Z(\nu\nu)H[Z(jj)\gamma]$	$\boxed{11.8}$
$jj\nu\nu\gamma$	$Z(jj)H[Z(\nu\nu)\gamma]$	
At $\sqrt{s} = 365$ GeV		
ZH production	$H \to Z\gamma$	22.0
WW→H production	$H \to Z\gamma$	23.0

great improvement from previous expectations

Precision on $\sigma(e^+e^- \to ZH) \times \mathcal{B}(H \to \gamma\gamma)$

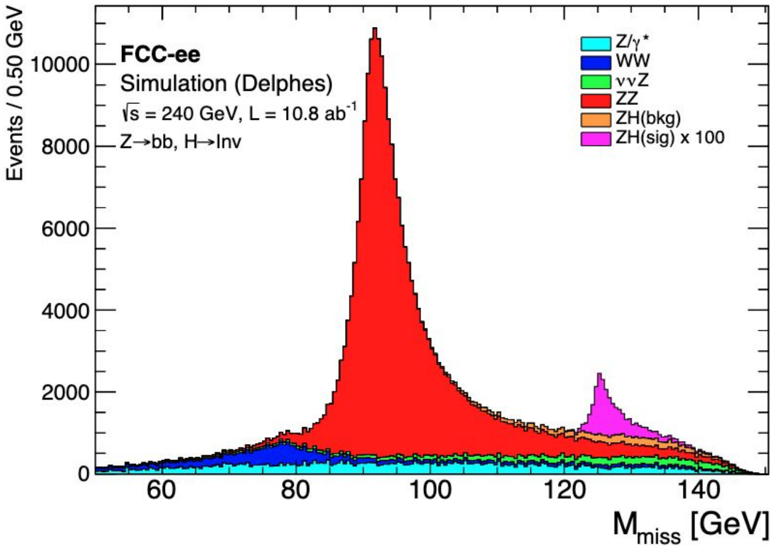
Final State	Description	Precision (%)
At $\sqrt{s} = 240$ GeV (combined)		
$\nu\nu\gamma\gamma$	Invisible Z recoil	$\boxed{3.6}$
$\ell\ell\gamma\gamma$	Leptonic Z decay	
$jj\gamma\gamma$	Hadronic Z decay	
At $\sqrt{s} = 365$ GeV (by production mode, $\nu\nu\gamma\gamma$ only)		
ZH production	$Z(\nu\nu)H(\gamma\gamma)$	13.0
WW→H production	$WW \to H(\gamma\gamma)$	15.0

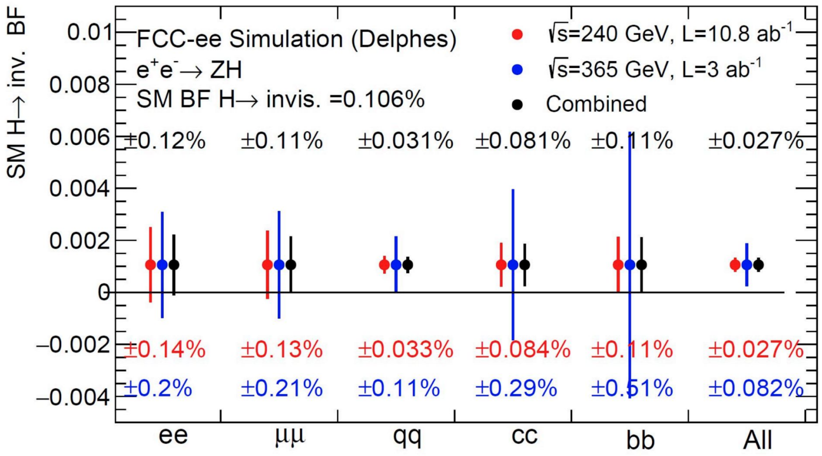
H ⟶ invisible

Higgs to invisible at the FCC-ee
https://doi.org/10.17181/9b128-qgc43

- Potential BSM couplings would induce deviations from SM *(BR=0.1%)*

- ZH production with all **visible Z decays** *(Z⟶ll,qq)*
- Analysis of **H⟶ZZ⟶νννν** performed at **240 & 365 GeV**
- Categorization based on number of leptons *(Z⟶ll)* and number of tagged b/c-jets *(Z⟶qq)*
- Fit on missing mass distribution





Expected sensitivity (%) of σ.BR(H⟶inv)

240 GeV	$L = 10.8ab^{-1}$	**H⟶inv**
	combined	0.027
365 GeV	$L = 3.12ab^{-1}$	**H⟶inv**
	combined	0.082

Conclusions

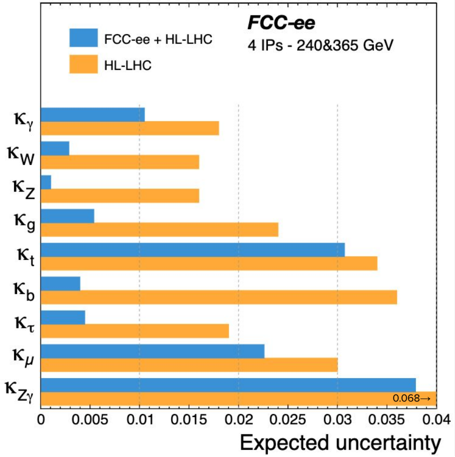
- We can reach **%-level** or better sensitivity for many couplings
- **Great prospects** in comparison to other future proposed experiments
- Some improvement still obtainable in some analysis
- Great complementarity with FCC-hh
  - **FCC-ee** measures greatly **abundant decays**
  - **Rare H decays** (μμ, Zγ, γγ, Za...) can be accessed at **%-level** at **FCC-hh**
  - FCC-ee provides **absolute normalisation** for FCC-hh thanks to **g_Z absolute measurement**

Also

$\delta\kappa_s$**~60%**

FCC-ee fit allows

BR(inv) & BR(exotic) ≠ 0



* Results extrapolated from *Conceptual Design Report*

Expected sensitivity (%) of σ.BR(H⟶XX)

	240 GeV L = 10.8ab^{-1}		365 GeV L = 3.12ab^{-1}	
	ZH	**VBF**	**ZH**	**VBF**
H→bb	0.21	1.9	0.38	0.66
H→cc	1.6	19	2.9	3.4
H→gg	0.80	5.5	2.1	2.6
H→ss	120	990	350	280
H→WW	0.80		1.8*	2.1*
H→ZZ	2.5		8.3*	4.6*
H→ττ	0.58		1.2*	5.6*
H→μμ	11		25	
H→γγ	3.6		13	15
H→Zγ	11.8		22	23
H→inv	0.027		0.082	

Backup

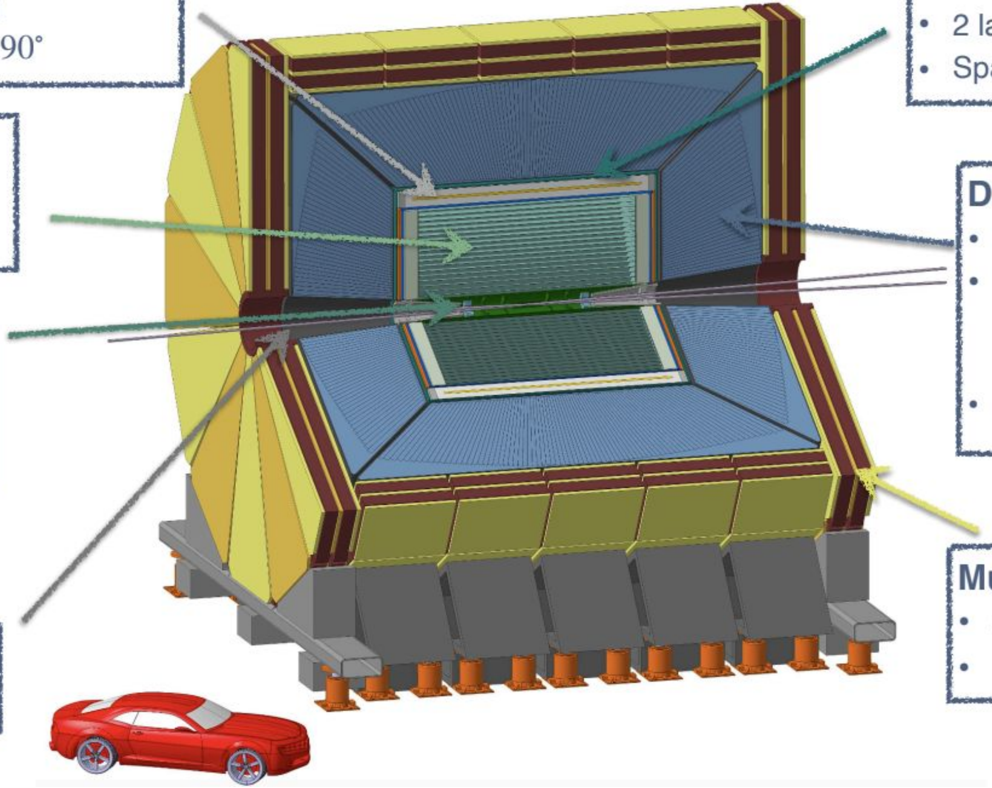
IDEA Detector concept

Superconducting solenoid
- 2 T, R = 2.0 - 2.4 m
- $0.74\ X_0,\ 0.16\ \lambda\ @90^\circ$

Wire drift chamber
- 112 layers, R = 35 - 200 cm
- $0.016\ X_0 @ 90^\circ$

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

Beam pipe
- R ~ 1.5 cm



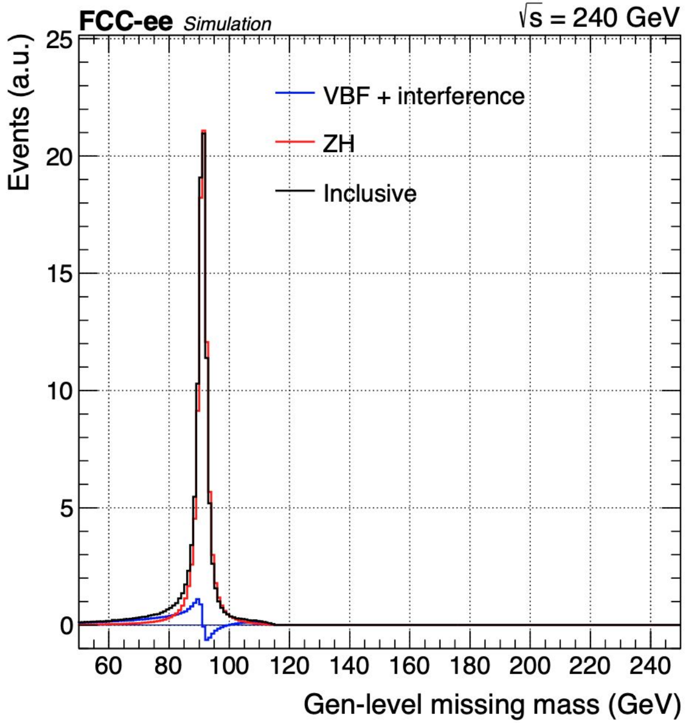
Preshower
- 2 layers, gas detector
- Spatial reso < 100 μm

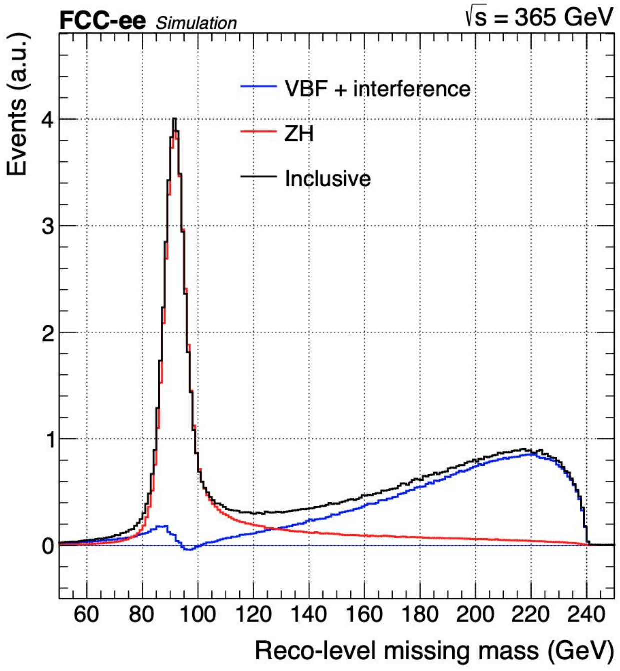
Dual-readout calorimeter
- 2 m capillaries
- Alternate Cherenkov and scintillation fibers
- $\sigma_{EM} \approx \frac{10\,\%}{\sqrt{E}}\ ,\ \sigma_{had} \approx \frac{30\,\%}{\sqrt{E}}$

Muon chambers
- 3 layers, gas detector
- Spatial reso < 400 μm

ZH & VBF separation

- ZH : $e^+e^- \to \nu_\mu \nu_\mu * 3$
- VBF : $e^+e^- \to \nu_e \nu_e$ - $e^+e^- \to \nu_\mu \nu_\mu$ (w/ interference)





Coupling to τ : detailed contributions @240GeV

ZH

	Cut-based analysis		BDT analysis	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
$Z \to qq,\ H \to \tau_\ell \tau_\ell$	-26.36% , +26.12%	-23.40% , +23.09%	-4.18% , +4.31%	-2.86% , +2.91%
$Z \to qq,\ H \to \tau_\ell \tau_h$	-2.52% , +2.50%	-2.47% , +2.42%	-1.51% , +1.50%	-1.22% , +1.23%
$Z \to qq,\ H \to \tau_h \tau_h$	-1.44% , +1.43%	-2.22% , +2.18%	-1.51% , +1.50%	±0.97%
$Z \to qq$	±1.17%	-1.42% , +1.46%	±0.79%	±0.67
$Z \to \ell\ell,\ H \to \tau_\ell \tau_\ell$	-16.95% , +17.41%		-	
$Z \to \ell\ell,\ H \to \tau_\ell \tau_h$	-4.10% , +4.18%	-5.22% , +5.39%	-	
$Z \to \ell\ell,\ H \to \tau_h \tau_h$	-1.81% , +1.83%	-2.24% , +2.26%	-	
$Z \to \ell\ell$	-1.66% , +1.67%	-2.03% , +2.08%	-	
$Z \to \nu\nu,\ H \to \tau_\ell \tau_\ell$	-420.15%, +418.79%		-104.80%, +105.46%	
$Z \to \nu\nu,\ H \to \tau_\ell \tau_h$	-64.14% , +64.10%	-53.90% , +53.87%	-13.67% , +13.72%	-16.64% , +16.67%
$Z \to \nu\nu,\ H \to \tau_h \tau_h$	-30.33% , +30.19%	-39.76% , +39.59%	-6.15% , +6.13%	-6.27% , +6.31%
$Z \to \nu\nu$	-10.06% , +10.10%	-13.19% , +13.22%	-4.39% , +4.45%	-4.73% , +4.71%
Combined	-0.90%, +0.91%	±1.01%	-0.77%, +0.78%	±0.66%

Coupling to τ : detailed contributions @365GeV

ZH

	ParticleNet tau reconstruction			
	Cut-based analysis		BDT analysis	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
$Z \to qq,\ H \to \tau_\ell \tau_\ell$	-63.23%, +63.32%	-45.10%, +44.97%	-18.75%, +18.93%	-10.96%, +11.08%
$Z \to qq,\ H \to \tau_\ell \tau_h$	-22.63%, +22.48%	-16.82%, +16.64%	-3.24%, +3.29%	-2.36%, +2.38%
$Z \to qq,\ H \to \tau_h \tau_h$	-8.58%, +8.54%	-8.61%, +8.42%	-2.31%, +2.36%	-1.86%, +1.87%
$Z \to qq$	-8.04%, +8.01%	-7.77%, +7.64%	-1.79%, +1.85%	-1.38%, +1.39%
$Z \to \ell\ell,\ H \to \tau_\ell \tau_\ell$	-43.18%, +45.44%		-	
$Z \to \ell\ell,\ H \to \tau_\ell \tau_h$	-9.97%, +10.47%	-13.75%, +14.56%	-	
$Z \to \ell\ell,\ H \to \tau_h \tau_h$	-4.77%, +4.89%	-5.41%, +5.56%	-	
$Z \to \ell\ell$	-4.32%, +4.41%	-5.04%, +5.16%	-	
$Z \to \nu\nu,\ H \to \tau_\ell \tau_\ell$	±235.98%		±208.72%	
$Z \to \nu\nu,\ H \to \tau_\ell \tau_h$	±71.81%	±69.37%	±65.43%	±79.14%
$Z \to \nu\nu,\ H \to \tau_h \tau_h$	±26.42%	±26.55%	±25.71%	±30.04%
$Z \to \nu\nu$	±25.78%	±26.60%	±23.98%	±27.90%
Combined	±3.63%	±3.19%	±1.69%	±1.32%

VBF

	Cut-based analysis		BDT analysis	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
$\nu_e \nu_e\ H(\to \tau_\ell \tau_\ell)$	±336.67%		±215.14%	
$\nu_e \nu_e\ H(\to \tau_\ell \tau_h)$	±81.15%	±77.27%	±55.37%	±64.16%
$\nu_e \nu_e\ H(\to \tau_h \tau_h)$	±24.00%	±23.18%	±24.88%	±26.89%
$\nu_e \nu_e H$	±23.41%	±24.02%	±22.07%	±25.06%

Coupling to Z and W : detailed contributions

H(ZZ)

Final State	Description	Precision (%)
$\nu\nu jjjj$	$Z(\nu\nu)H(jjjj)$, hadronic Higgs decay	11.0
$\ell\ell jjjj$	$Z(\ell\ell)H(jjjj)$, hadronic Higgs decay	7.6
$jjjjjj$	Fully hadronic (6 jets), χ^2 fit	8.2
$\nu\nu\ell\ell jj$	$Z(\nu\nu)Z(\ell\ell)Z^*(jj)$	4.7
$\ell\ell\nu\nu jj$	$Z(\ell\ell)Z(\nu\nu)Z^*(jj)$	5.0
$\ell\ell jj\nu\nu$	$Z(\ell\ell)Z(jj)Z^*(\nu\nu)$	7.3
$jj\ell\ell\nu\nu$	Orthogonal sub-channel	13.0
$jj\nu\nu\ell\ell$	Orthogonal sub-channel	19.0
$(Z \to jj/\nu\nu) + 4\ell$	$H \to 4\ell$, extra Z hadronic/invisible	10.0
6ℓ	Fully leptonic (rare) final state	30.0
Combined		**2.5**

H(WW)

Final State	Description	Precision (%)
$\nu\nu jjjj$	$Z(\nu\nu)H[W(jj)W(jj)]$, hadronic H	1.3
$\ell\ell jjjj$	$Z(\ell\ell)H[W(jj)W(jj)]$, likelihood fit on recoil mass	1.6
$jjjjjj$	simultaneous $H \to WW^*$ and ZZ^* extraction	1.48
Combined		**0.8**

Comparison with ILC

- Results rescaled to reach similar luminosity
- Additional scalings to remove impact of beam polarization
- **Results for ILC would correspond to a ~4x longer data taking period compared to FCC**

Collider	FCC CDR	FCC ESPPU	LCF ESPPU	LCF	LCF $\times\sqrt{1.2}$
Integrated luminosity	$10.8\ \text{ab}^{-1}$	$10.8\ \text{ab}^{-1}$	$2.7\ \text{ab}^{-1}$	$10.8\ \text{ab}^{-1}$	$10.8\ \text{ab}^{-1}$
$\text{H} \to \text{any}$	±0.36	±0.31	±0.62	±0.31	±0.34
$\text{H} \to \text{bb}$	±0.20	±0.21	±0.41	±0.21	±0.22
$\text{H} \to \text{cc}$	±1.5	±1.6	±2.5	±1.25	±1.37
$\text{H} \to \text{gg}$	±1.3	±0.8	±2.1	±1.05	±1.15
$\text{H} \to \text{W}^+\text{W}^-$	±0.8	±0.8	±1.4	±0.70	±0.77
$\text{H} \to \text{ZZ}$	±3.0	±2.5	±5.5	±2.75	±3.01
$\text{H} \to \tau^+\tau^-$	±0.6	±0.58	±0.95	±0.48	±0.52
$\text{H} \to \gamma\gamma$	±6.1	±3.6	±10	±5.00	±5.48