Measurement of the Higgs properties at FCC-ee

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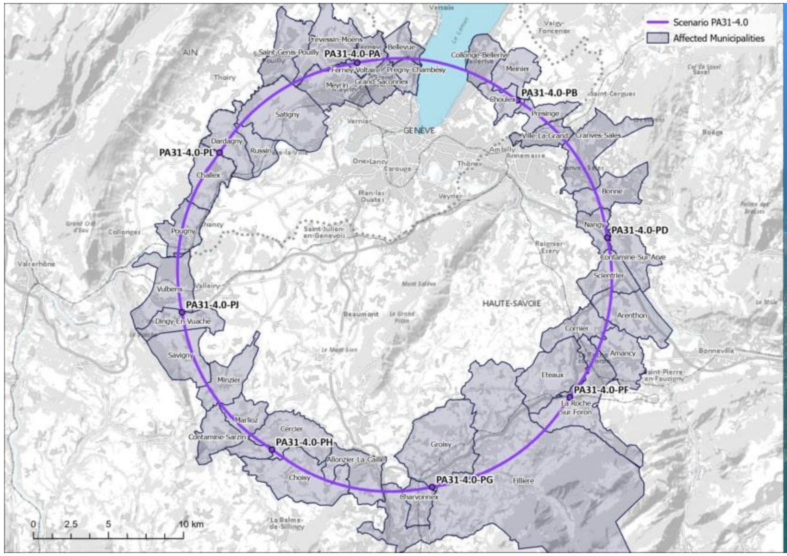
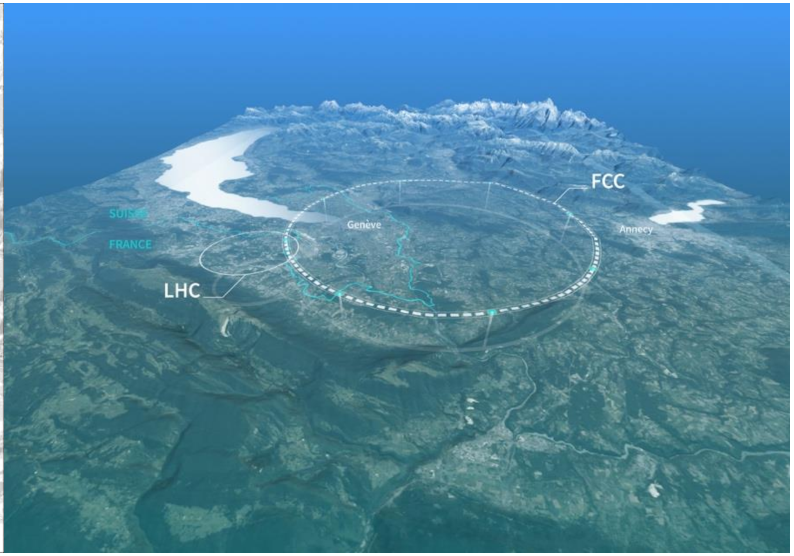
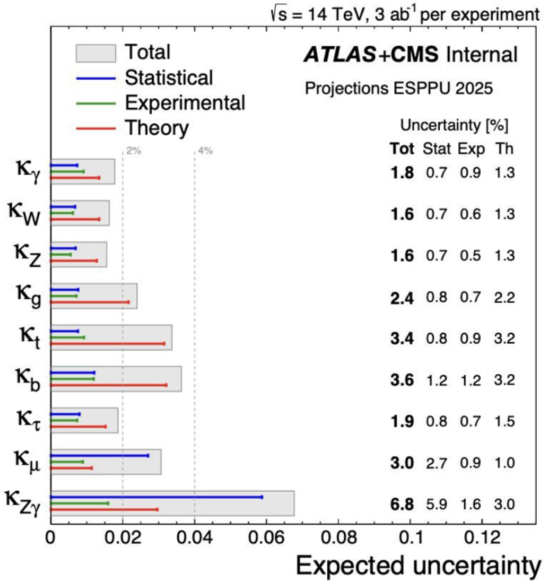




Landscape of the Higgs physics for HL-LHC

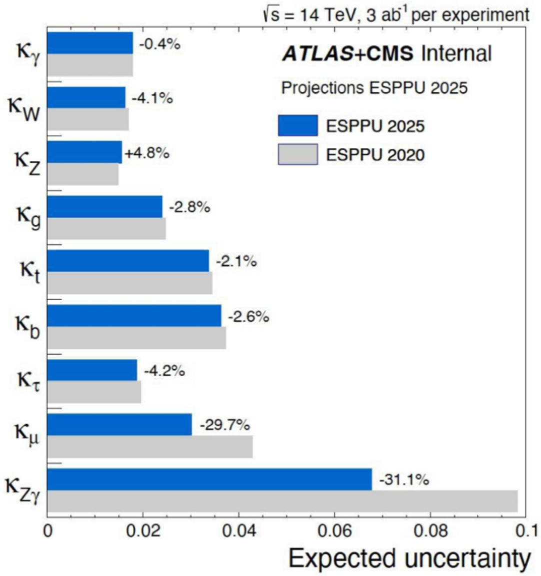
- **HL-LHC and future colliders would explore in detail the Higgs properties:** understand the deep origin of EWSB

- **Beyond HL-LHC measurements:**
  - ✓ couplings to fermions to %-level, to bosons to per-mil
  - ✓ self-coupling
  - ✓ invisible decays
  - ✓ BSM Higgses



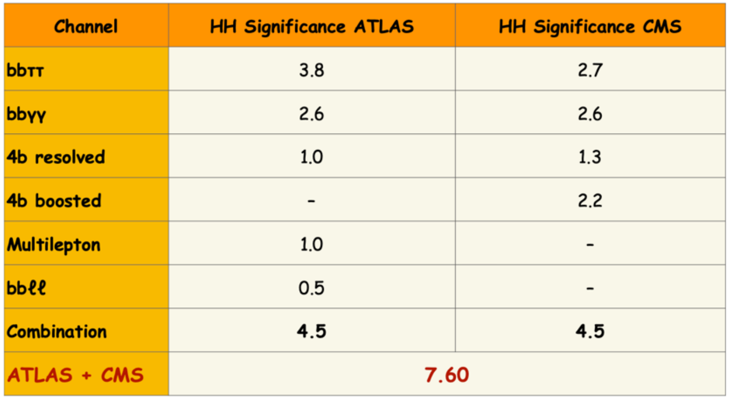
Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.7	0.9	1.3
κ_W	**1.6**	0.7	0.6	1.3
κ_Z	**1.6**	0.7	0.5	1.3
κ_g	**2.4**	0.8	0.7	2.2
κ_t	**3.4**	0.8	0.9	3.2
κ_b	**3.6**	1.2	1.2	3.2
κ_τ	**1.9**	0.8	0.7	1.5
κ_μ	**3.0**	2.7	0.9	1.0
$\kappa_{Z\gamma}$	**6.8**	5.9	1.6	3.0

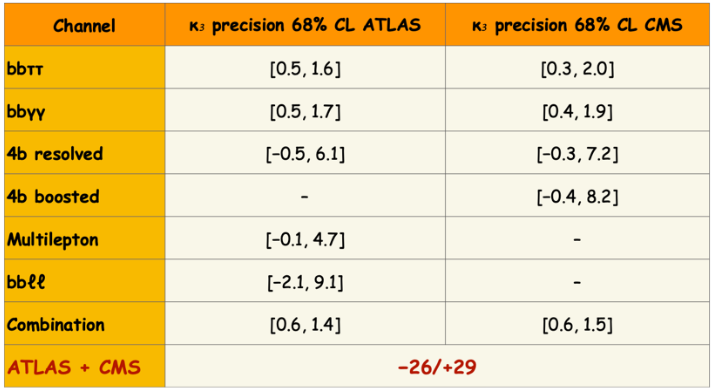


Theory uncertainties are dominating

- **Non-resonant HH projections: 3000 fb^{-1}**



Channel	HH Significance ATLAS	HH Significance CMS
bbττ	3.8	2.7
bbγγ	2.6	2.6
4b resolved	1.0	1.3
4b boosted	-	2.2
Multilepton	1.0	-
bbℓℓ	0.5	-
Combination	**4.5**	**4.5**
ATLAS + CMS	7.60	



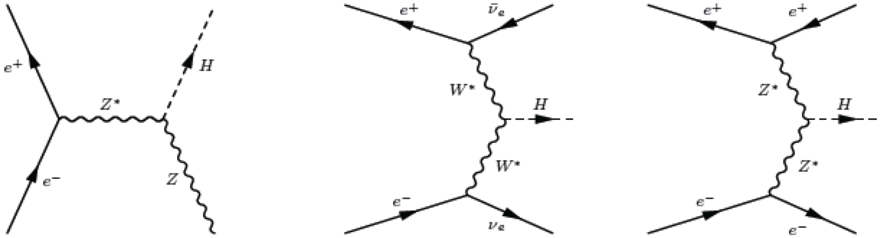
Channel	κ₃ precision 68% CL ATLAS	κ₃ precision 68% CL CMS
bbττ	[0.5, 1.6]	[0.3, 2.0]
bbγγ	[0.5, 1.7]	[0.4, 1.9]
4b resolved	[-0.5, 6.1]	[-0.3, 7.2]
4b boosted	-	[-0.4, 8.2]
Multilepton	[-0.1, 4.7]	-
bbℓℓ	[-2.1, 9.1]	-
Combination	[0.6, 1.4]	[0.6, 1.5]
ATLAS + CMS	**-26/+29**	

Combined evidence >7σ.

Precision on k_λ=1 ~26%

Higgs production at FCC-ee

Higgs-strahlung or $e^+e^- \rightarrow ZH$

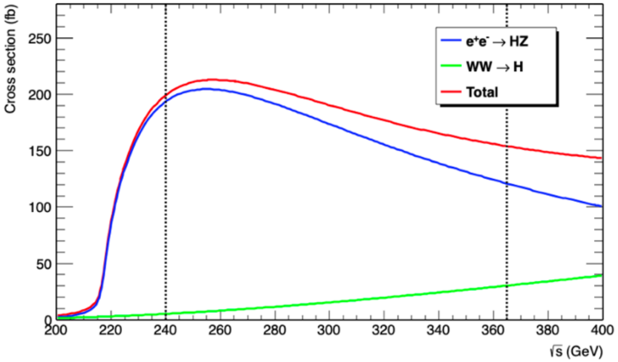


VBF production: $e^+e^- \rightarrow \nu\nu H$ (W fusion)
$e^+e^- \rightarrow He^+e^-$ (Z fusion)

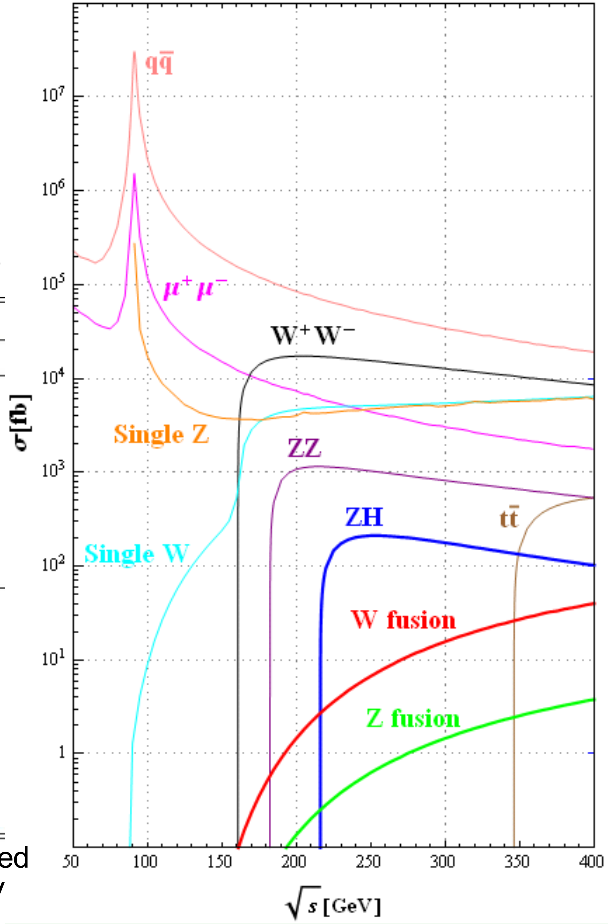
$\sqrt{s} = 240.0$ GeV

Process	Cross section
Higgs boson production, cross section in fb	
$e^+e^- \rightarrow ZH$	212
$e^+e^- \rightarrow \nu\bar{\nu}H$	6.72
$e^+e^- \rightarrow e^+e^-H$	0.63
Total	219
Background processes, cross section in pb	
$e^+e^- \rightarrow e^+e^-$ (Bhabha)	25.1
$e^+e^- \rightarrow q\bar{q}$	50.2
$e^+e^- \rightarrow \mu\mu$ (or $\tau\tau$)	4.40
$e^+e^- \rightarrow WW$	15.4
$e^+e^- \rightarrow ZZ$	1.03
$e^+e^- \rightarrow eeZ$	4.73
$e^+e^- \rightarrow e\nu W$	5.14

$\mathcal{L}$= 10.8 ab^{-1} in 3 years with 4 detectors located at 4 interaction points (IPs), at $\sqrt{s}$=240 GeV

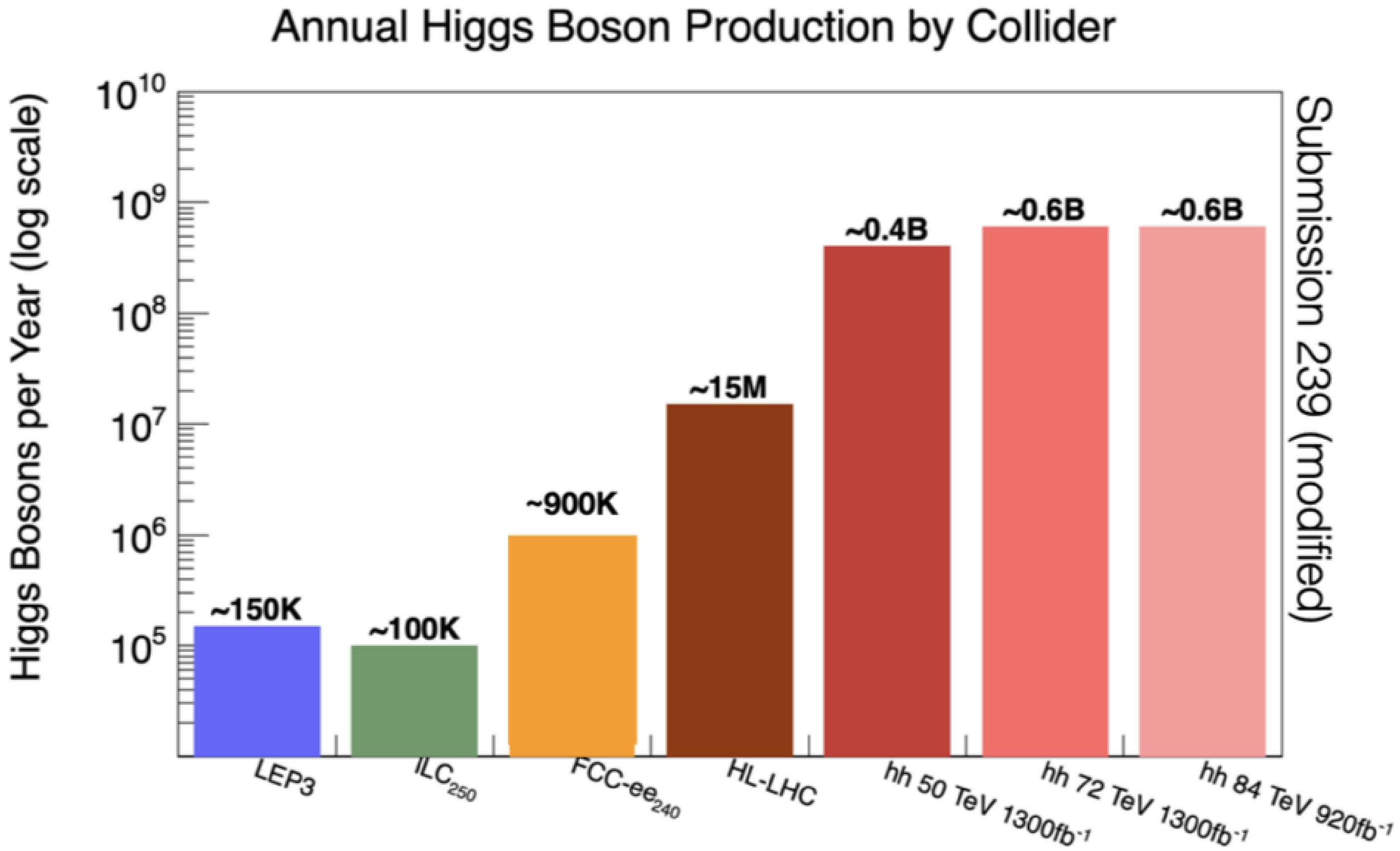


Background sources



VBF xsection increases significantly with the centre-of-mass energy → dominant process above 450 GeV

Higgs yield at colliders

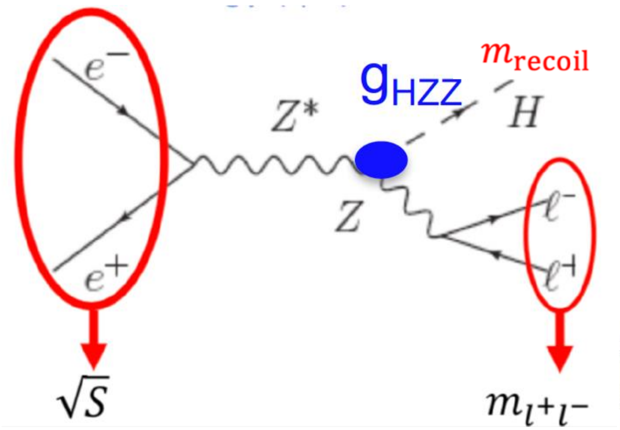


- e^+e^- colliders produce less Higgs bosons than the LHC, but they benefit from precise knowledge of initial stage and a “clean” experimental environment.
- *pp* colliders allow measurements of rare decays

- e^+e^- and *pp* colliders are complementary to fully explore the Higgs sector

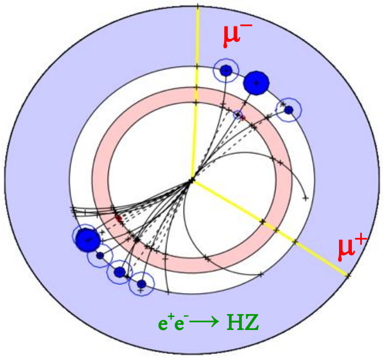
Global strategy for Higgs studies

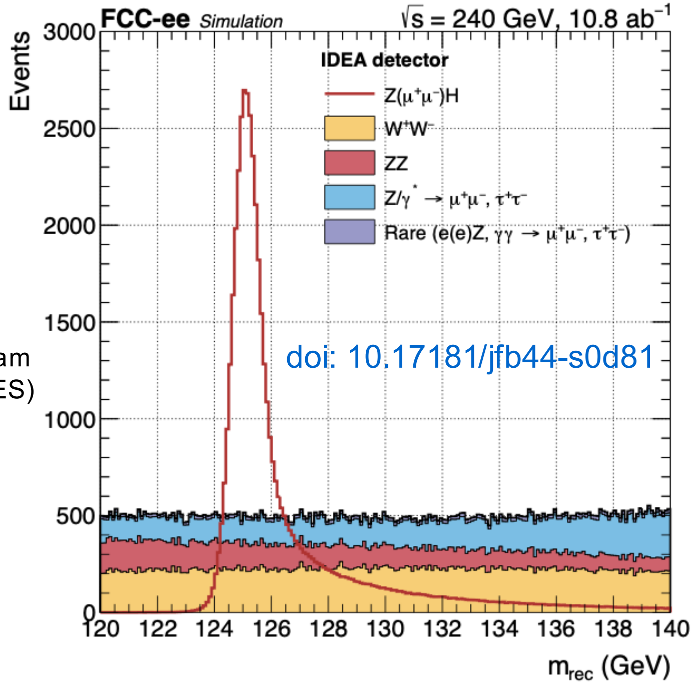
Eur. Phys. J. Plus 137(1), 23 (2022)



$\sigma(e^+e^- \to HZ)\ \alpha\ g^2_{HZZ}$

ZH events tagged by the Z, without reconstructing the Higgs decay. Unique to lepton colliders.





doi: 10.17181/jfb44-s0d81

affected by the Beam Energy Spread (BES) and Initial State Radiation (ISR)

e.g. when Z → leptons :

$$m^2_{\text{recoil}} = s + m^2_{\ell\ell} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

A fit to the recoil mass distribution allows:

- measurement of σ(ZH) independent of the Higgs decay mode with **0.31 %** uncertainty. Hence an absolute determination on g_{HZZ}

→ **$\delta g_{HZZ}/g_{HZZ}$ ~ 0.1-0.2 %** (also including Z→had)

- a precise meas. of the **Higgs mass → $\delta m_H/m_H$ ~ O(MeV)** (w.r.t **20 MeV for HL-LHC**)

Easiest case: Z → lep.

- Z → had: more careful design of the analysis

Model-independent Higgs couplings measurements

Known g_{HZZ} it is possible to measure σ x BR for specific Higgs decays

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X}\overline{\mathrm{X}}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

- H → ZZ* provides Γ_H
- H → XX provides g_{HXX}

H → ZZ* provides Γ_H :

$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

→ **$\delta\Gamma_H / \Gamma_H$ ~ several %**

Select events with H → bb, cc, gg, WW, tt, γγ, μμ, Zγ, …

→ deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , g_{Htt} , $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …

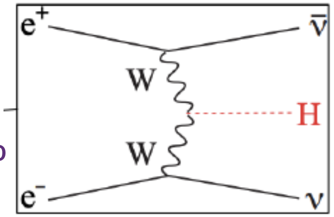
Select events with H → "nothing" → deduce Γ(H→invisible)

→ **$\delta g_{XX}/g_{XX}$ ~ 1 %**

a model-indep determination of Higgs couplings.

Data at higher energy bring important additional observables:

$$\sigma_{\mathrm{H}\nu_e\bar{\nu}_e} \times \mathcal{B}(\mathrm{H} \to \mathrm{X}\overline{\mathrm{X}}) \propto \frac{g^2_{\mathrm{HWW}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$



First ννH → ννbb ~ $g_{HWW}^2\, g_{Hbb}^2 / \Gamma_H$

- ννbb / (ZH(bb) ZH(WW) ~ g_{HZZ}^4 / Γ_H = R → Γ_H precision at 1%

Then do ννH →ννWW ~ g_{HWW}^4 / Γ_H

- R / ννWW ~ g_{HWW}^4 / g_{HZZ}^4
- g_{HWW} precision to few permil

At the end: Higgs couplings and Γ_H extracted from a global fit to all σ x BR (Kappa framework, SMEFT framework)

HZ selection strategy

doi:10.17181/jfb44-s0d81, Eur. Phys. J. Plus 137(1), 23 (2022)

MC simulation based on Whizard:

- $\sqrt{s}$ = 240 GeV, $\mathcal{L}$ = 10.8 ab^{-1}
- IDEA detector; detector response modelled with Delphes

Baseline selection:

- at least 2 OS leptons with p>20 GeV, one isolated
- in case of more than 2 leptons in event, select pair minimizing

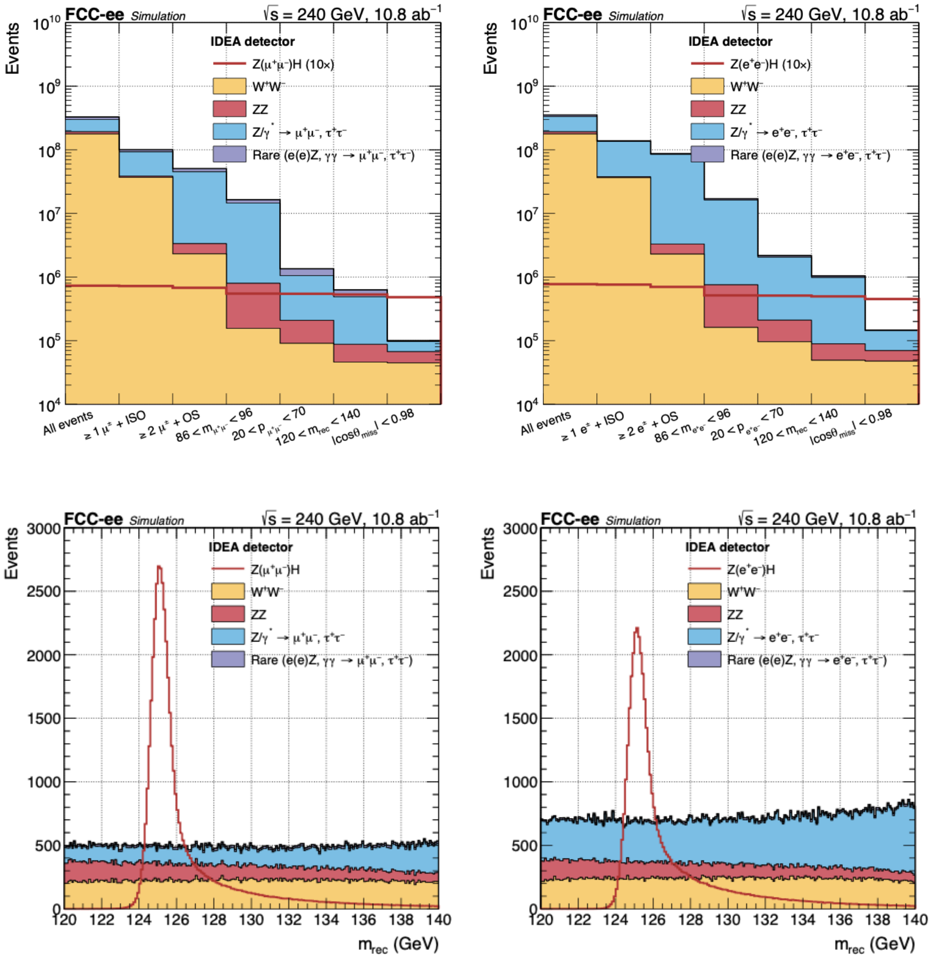
$$\chi^2 = 0.6 \times (\mathrm{m}_{\ell\ell} - \mathrm{m_Z})^2 + 0.4 \times (\mathrm{m_{recoil}} - \mathrm{m_h})^2$$

- tight selection of Z mass between [86, 96] GeV
- Background reduction by cut on
  - Z p_T [20, 70] GeV to suppress Z/γ*
  - $|\cos(\theta_{miss})| < 0.98$ for Z→ll, $\gamma\gamma \to ee/\mu\mu/\tau\tau$ events

Parametric fit based on recoil mass distribution:

- Fit function: double-sided Crystal-ball + Gaussian core
- Free parameter: H mass, signal and bkg normalization

Analysis workflow based on recoil method using Z(μμ/ee) final state

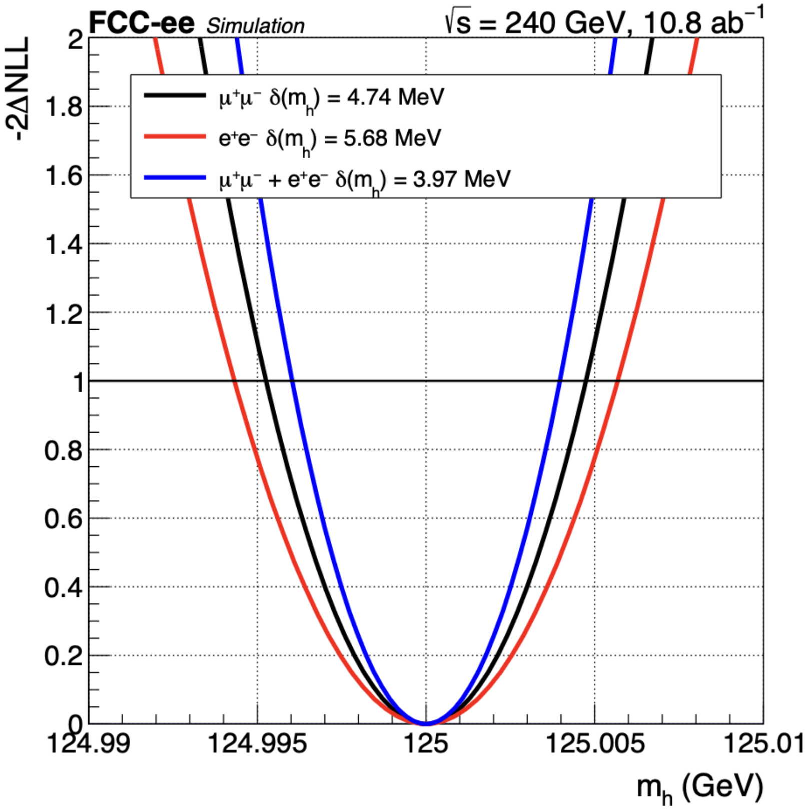


Higgs mass measurement

Likelihood scans to extract uncertainties on mass

Stat. + syst. uncertainties:

- **Higgs mass: 3.97 MeV at 68% C.L.**



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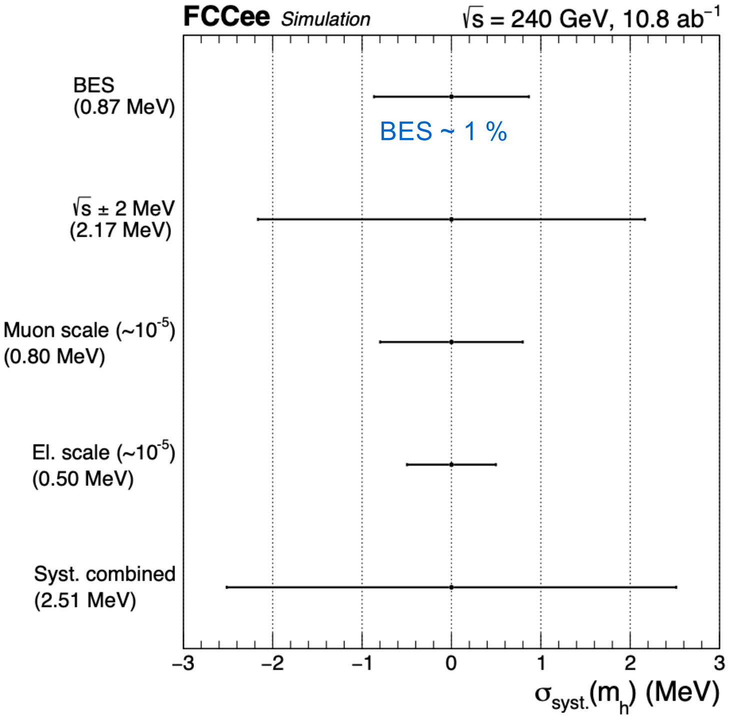
Source of uncertainty:

- Beam Energy Spread (BES)
- Initial State Radiation (ISR)
- Muon momentum scale
- Center-of-mass energy - dominant
- FSR uncertainty

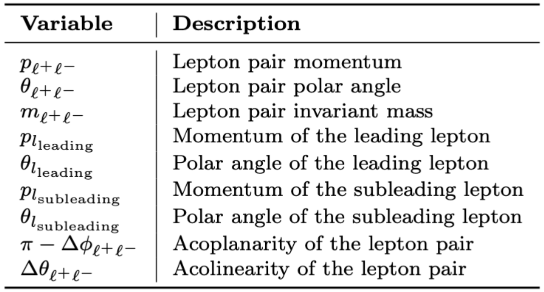


HZ cross section measurement

doi:10.17181/jfb44-s0d81, Eur. Phys. J. Plus 137(1), 23 (2022)

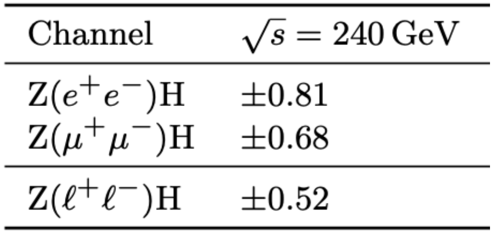
For the ZH cross-section measurement, after applying the basic selection criteria, the $|\cos\theta_{miss}|$ cut is omitted and replaced by a BDT approach to further suppress background.

input variables for BDT

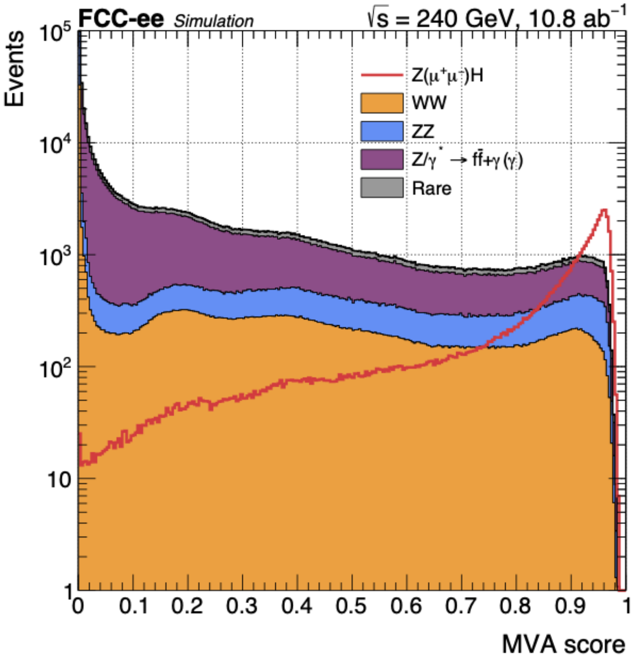


Variable	Description
$p_{\ell^+\ell^-}$	Lepton pair momentum
$\theta_{\ell^+\ell^-}$	Lepton pair polar angle
$m_{\ell^+\ell^-}$	Lepton pair invariant mass
$p_{l_{\text{leading}}}$	Momentum of the leading lepton
$\theta_{l_{\text{leading}}}$	Polar angle of the leading lepton
$p_{l_{\text{subleading}}}$	Momentum of the subleading lepton
$\theta_{l_{\text{subleading}}}$	Polar angle of the subleading lepton
$\pi - \Delta\phi_{\ell^+\ell^-}$	Acoplanarity of the lepton pair
$\Delta\theta_{\ell^+\ell^-}$	Acolinearity of the lepton pair

Stat. uncertainty in %:

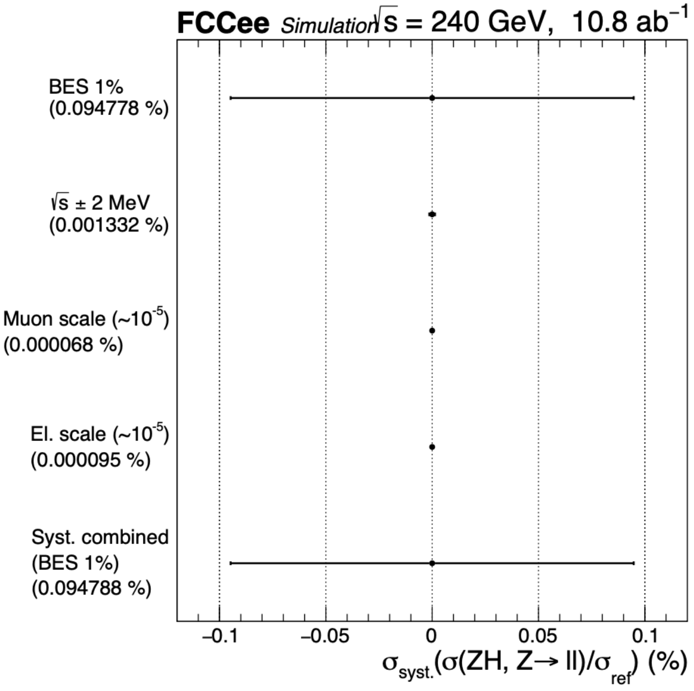


Channel	$\sqrt{s} = 240$ GeV
$Z(e^+e^-)H$	± 0.81
$Z(\mu^+\mu^-)H$	± 0.68
$Z(\ell^+\ell^-)H$	± 0.52



The impact of systematic uncertainties is found to be below 1%, mostly from BES

The overall impact of systematics is minimal, and the measurement remains fully statistically dominated

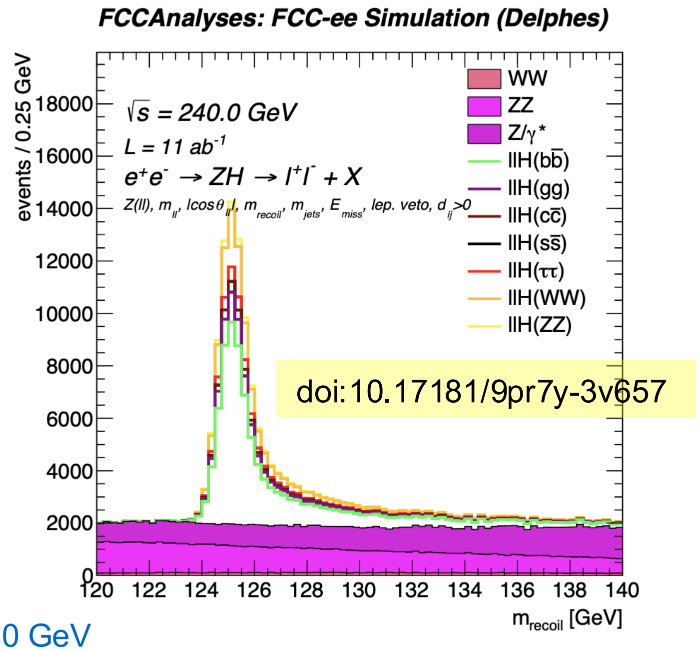


H→qq (hadrons) and progress on jet flavour tagging

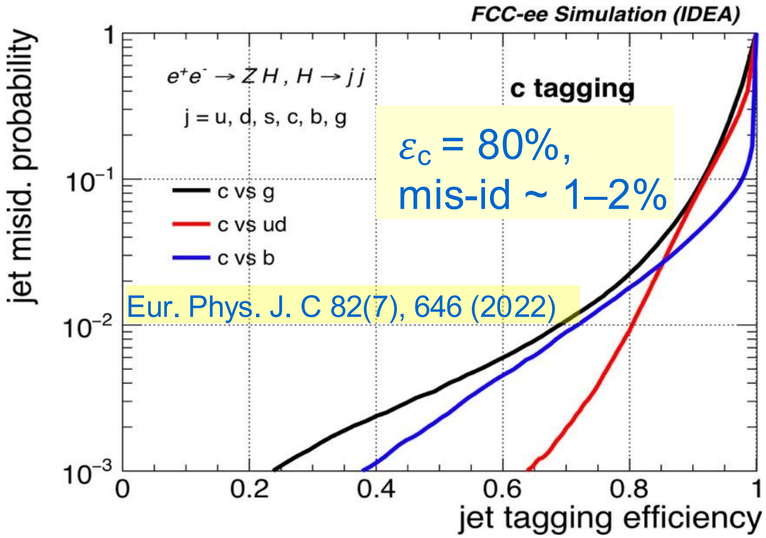
High precision Higgs BRs to hadron measurements:

- coupling of the H to bottom and charm, **gluons**, and **strange**
- bb, cc, ss, gg final states in addition to WW, ZZ, ττ
- classification is performed by a neural network (NN)
- Key ingredients:
  - tagging of b, c and g jets
  - detector requirements (tracking, vertexing, timing) and particle flow algorithm used
- State-of-the-art flavour-tagging algorithm developed recently in the context of FCC-ee based on GNN

- Z(ll)H(qq)
- Z(νν)H(qq)
- Z(qq)H(qq)



doi:10.17181/9pr7y-3v657



ε_c = 80%, mis-id ~ 1–2%

Eur. Phys. J. C 82(7), 646 (2022)

Z(ll)H(qq) @ √s = 240 GeV

Signal strength	Categories						
	$b\bar{b}$	$c\bar{c}$	gg	$s\bar{s}$	ZZ	WW	$\tau\tau$
Uncertainty (%)	0.60	3.47	1.93	223	7.65	1.49	2.54

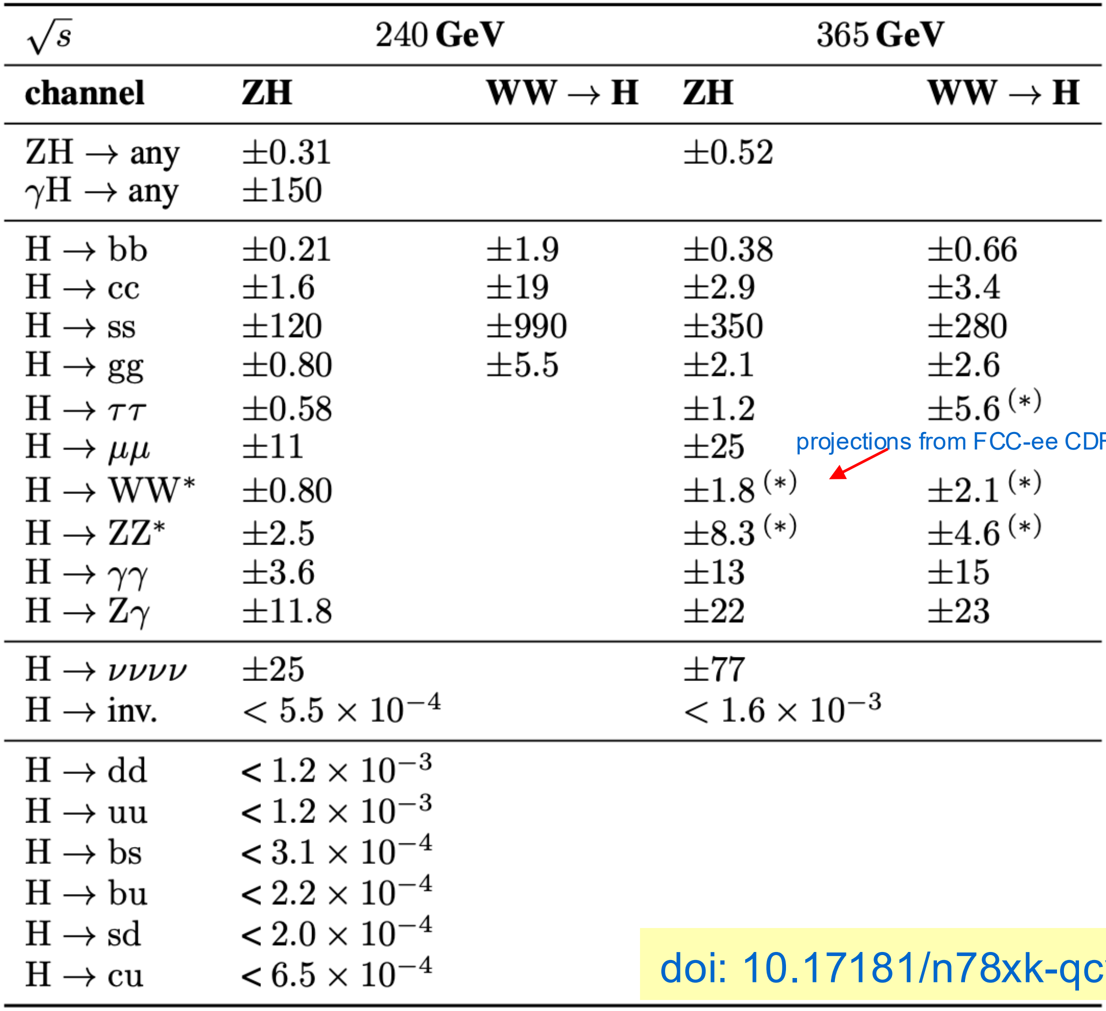
The combination of the three Z boson final states leads to expected uncertainties on σ_{ZH} × B(H →XX) @68%CL :

- 0.21%, on H → bb
- 1.6% on H → cc
- 0.8% on H → gg
- 90% on H → ss
- 1.0% of H →WW

σ(HZ) x BR and σ(WW→H) x BR measurements

The combine fit was performed by the HEPfit community

Uncertainty on σ * BR in %

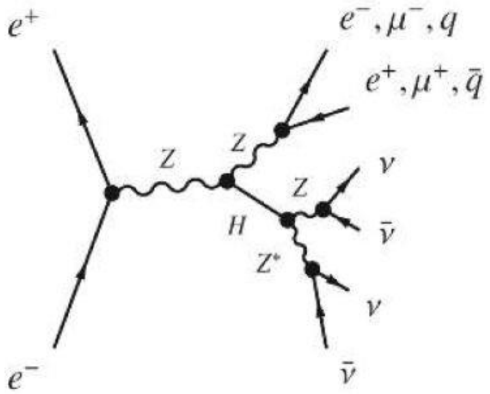


$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
H → $\tau\tau$	±0.58		±1.2	±5.6 $^{(*)}$
H → $\mu\mu$	±11		±25	
H → WW*	±0.80		±1.8 $^{(*)}$	±2.1 $^{(*)}$
H → ZZ*	±2.5		±8.3 $^{(*)}$	±4.6 $^{(*)}$
H → $\gamma\gamma$	±3.6		±13	±15
H → Zγ	±11.8		±22	±23
H → $\nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

projections from FCC-ee CDR

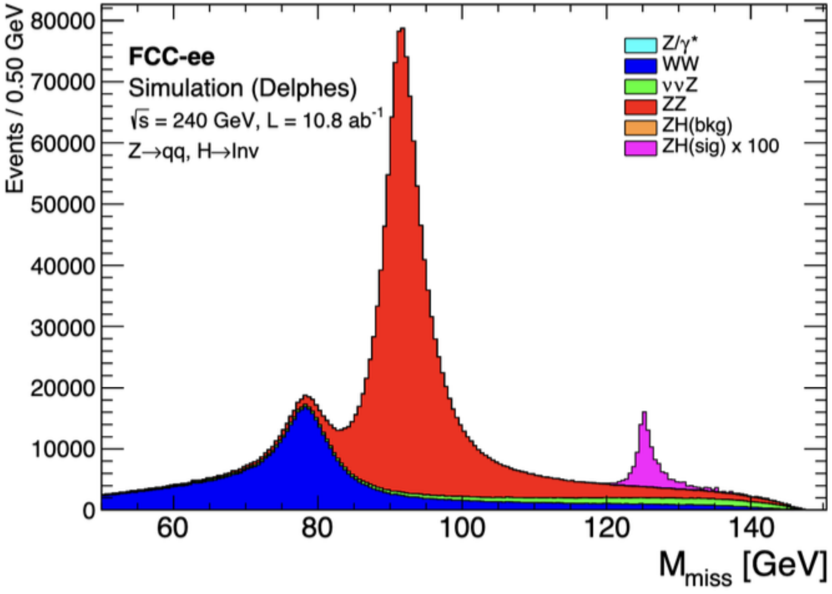
doi: 10.17181/n78xk-qcv56

Higgs to invisible particles analysis

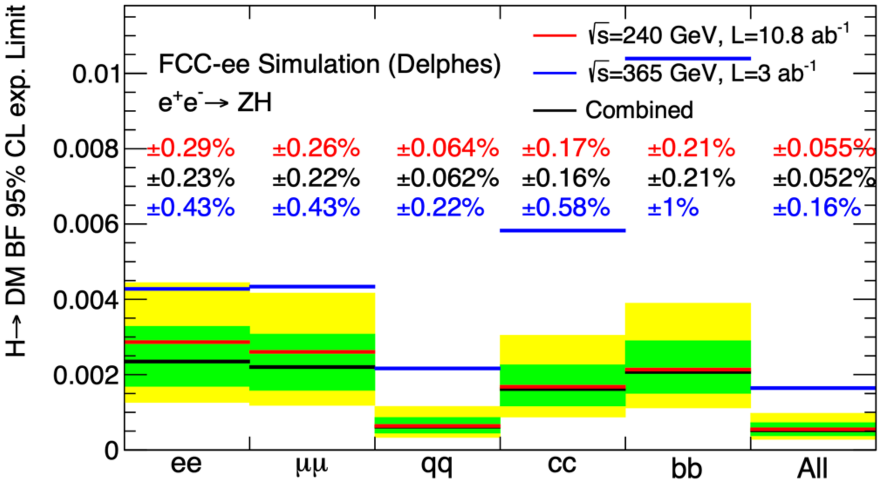


- only invisible decay in the SM: H → ZZ → νννν (BR = 0.106%)
- best individual measurements from ZH→qq + missing energy using recoil mass or missing mass at the Z peak
  - → requires excellent hadronic energy resolution
- tag the Z using muon, electron and hadron final states (qq and bb), Z peak [87, 96] GeV
- calculate missing mass m_{miss} as 240 GeV minus visible mass m_{vis}

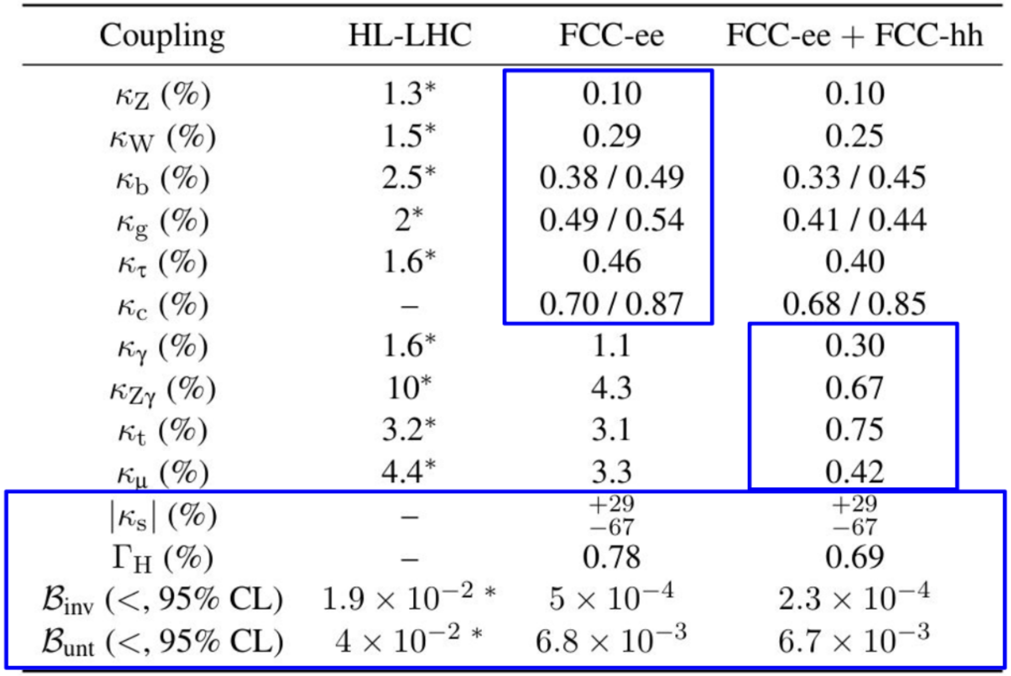
doi: 10.17181/7hbn8-3d233



BR(H → inv) > 0.052 excluded @ 95%CL



Uncertainty on Higgs couplings and width: latest



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
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{\mathrm{inv}}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\mathrm{unt}}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

- Couplings to H →bb can be improved compared to the HL-LHC to reach sub-prcent-level precision
- Couplings to H →cc can be measured at the % level
- Sensitivity to the strange-quark Yukawa coupling with potential evidence

- FCC-ee and FCC-hh Integrated Programme is complementary and provide ~ **order of magnitude improvement** of all Higgs coupling w.r.t HL-LHC
- Neverthless, until FCC-hh, HL-LHC is still going to be the best machine for $Z\gamma$, $\mu\mu$ (rare decays) and ttH coupling determination for the next decades years
- HL-LHC has no access to charm Yukawa coupling
- FCC-ee has limited access to top Yukawa coupling (only via loop corrections to $e^+e^- \rightarrow$ tt cross section indirectly)

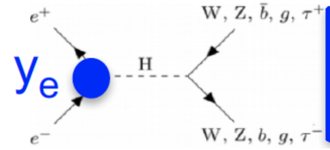
Higgs Yukawa coupling to electron

Eur. Phys. J. Plus 137 (2022) 201

FCC-ee: unique opportunity to study the Higgs Yukawa coupling to electron, y_e, via resonant s-channel production $e^+e^- \rightarrow H$ in a dedicated run at the Higgs pole, $\sqrt{s} = m_H$.

In the SM:

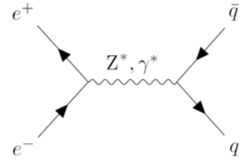
- the Yukawa coupling of the electron is $y_e = \sqrt{2}\, m_e/v = 2.8\cdot 10^{-6}$
- $BR(H \rightarrow e^+e^-) \approx 5 \times 10^{-9}$



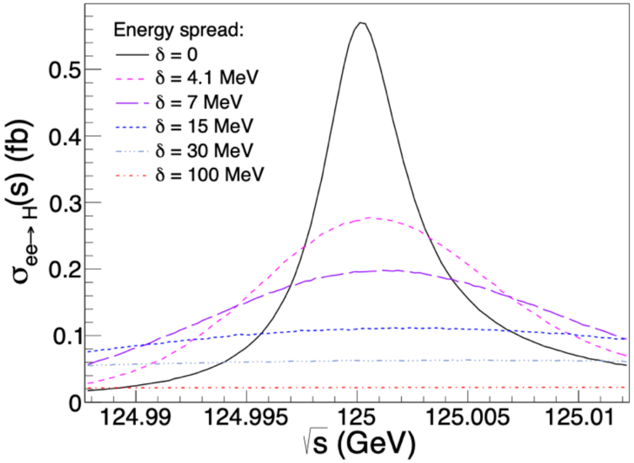
$\sigma(e^+e^- \rightarrow H)_{B\text{-}W} = 1.64$ fb as peak cross section

$\sigma(e^+e^- \rightarrow H)_{spread} = 280$ ab (ISR + $\sqrt{s}_{spread} = \Gamma_H = 4.2$ MeV)

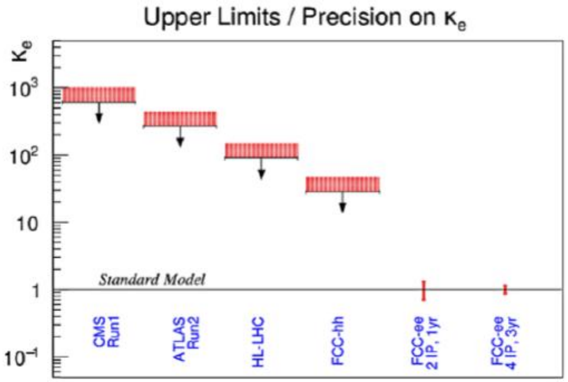
Main background



- Beams must be monochromatized such that the spread of their center-of-mass energy is commensurate with the narrow width of the SM Higgs boson
- Generator-level study for signal+background for 10 decay channels:
  - most significant channel: **H→gg** (quark-gluon tagging via ML, for light mistag ~ 1%), H→WW* →lν+jets



For 10 ab^{-1} & $\sqrt{s}_{spread} = \Gamma_H$: Signif ≈ 1.3σ



upper limit @ 95CL on the electron Yukawa coupling at 1.6 times the SM value for each detector for one year→ **x 100 better than for HL-LHC**

What is not covered for HZ analyses yet

HWW final states	240	365
Z(vv)WW(qqqq)	not optimized (byproduct from Higgs hadronic couplings) - reference	not optimized (byproduct from Higgs hadronic couplings) - reference
Z(vv)WW(lvqq)	missing	missing
Z(vv)WW(lvlv)	missing	missing
Z(ll)WW(qqqq)	Puebla/Jan – 2 lepton final state - reference	missing
Z(ll)WW(lvqq)	Michaela/George/Jan - ongoing	missing
Z(ll)WW(lnulnu)	Gadi/Jan - ongoing	missing
Z(qq)WW(qqqq)	Aman/Mila/Jan (with Kinematic fit) - reference	missing
Z(qq)WW(lvqq)	missing	missing
Z(qq)WW(lvlv)	missing	missing
HZZ final states		
Z(vv)ZZ(qqqq)	not optimized (byproduct from Higgs hadronic couplings) - reference	not optimized (byproduct from Higgs hadronic couplings) - reference
Z(vv)ZZ(vvvv)	missing	missing
Z(vv)ZZ(llll)	Yehia/Nicola/Michele/Jan - reference	missing
Z(vv)ZZ(vvqq)	missing	missing
Z(vv)ZZ(llqq)	Nicolas/Ines - reference	missing
Z(vv)ZZ(vvll)	missing	missing
Z(ll)ZZ(qqqq)	not optimized (byproduct from Higgs hadronic couplings) - reference	not optimized (byproduct from Higgs hadronic couplings) - reference
Z(ll)ZZ(vvvv)	missing	missing
Z(ll)ZZ(llll)	Sara/Michele - reference	missing
Z(ll)ZZ(vvqq)	Nicolas/Ines - reference	missing
Z(ll)ZZ(llqq)	missing	missing
Z(ll)ZZ(vvll)	missing	missing
Z(qq)ZZ(qqqq)	Aman/Mila/Jan (with Kinematic fit) - reference	missing
Z(qq)ZZ(vvvv)	missing	missing
Z(qq)ZZ(llll)	Yehia/Nicola/Michele/Jan - reference	missing
Z(qq)ZZ(vvqq)	missing	missing
Z(qq)ZZ(llqq)	missing	missing
Z(qq)ZZ(vvll)	Sara/Michele - reference	missing

H→ττ, bb, cc, ss, gg are studied in detail. H→ZZ and H→ττ CP studied through ZH production

Priorities of the Higgs team

- Complete H→ZZ and WW analyses, especially at √s=365 GeV
- Move to FULL simulation for IDEA and first Higgs studies in full simulation
- Finalize current papers for publication (apart from FCC notes)
- Low priority: perform the combine fit by using CMS combine tools and compare with HEPFit

Conclusions

- FCC is a unique project, offering an extremely complete and compelling programme, with synergies and complementarities between the various machines and running scenarios (FCC-ee, FCC-hh) → prospects for 100 years of great physics at energy and intensity frontiers!

- FCC-ee provides ultimate precision in Higgs sector, aimed at starting at CERN in e^+e^- mode, shortly after the end of the HL-LHC.

- FCC-ee will produce almost 3 million Higgs in a clean environment:
  - allows for model independent measurement of Higgs properties
  - **an order-of-magnitude** improvement in precision in Higgs decay channels

- FCC-hh will provide precise meaurement of the Higgs tri-linear self coupling, of the top Yukava coupling and inspection of the Higgs rare decays

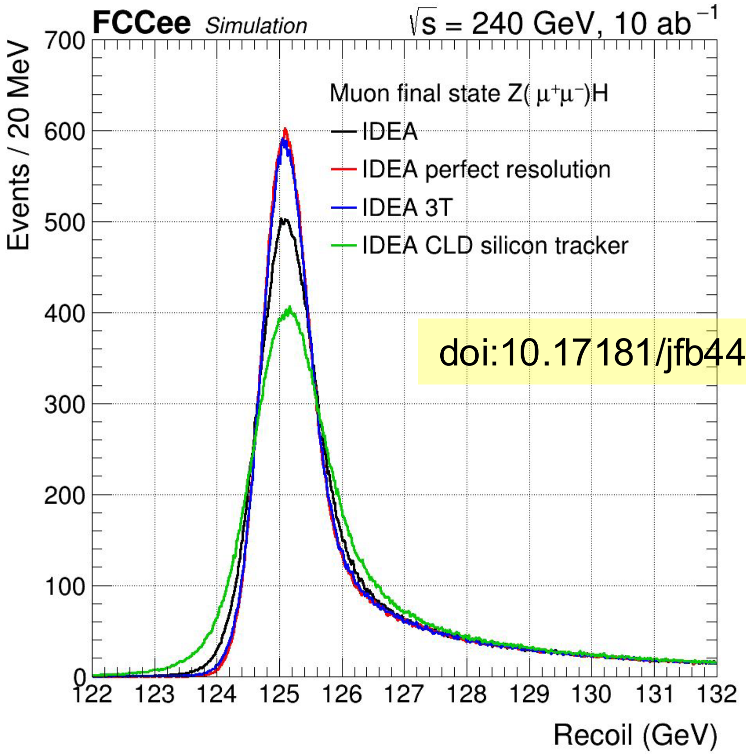
- New experimental developments coming in: progress on detector R&D, reconstruction algorithms, ML revolution, allow to contemplate more ambitious goals
  - There is room for new and more organized contributions …join the team!

In contact with X. Zuo, J. Eisemann, M. Selvaggi

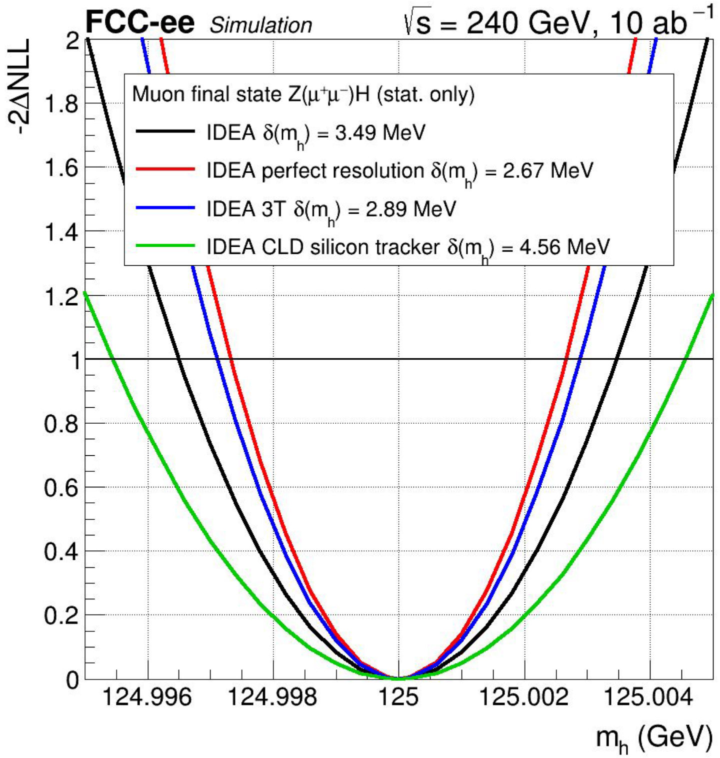
Backup

Constraint on detector requirement from H mass measurement

Higgs boson mass to be measured with a precision better than its natural width (4MeV), in view of a potential run at the Higgs resonance



doi:10.17181/jfb44-s0d81



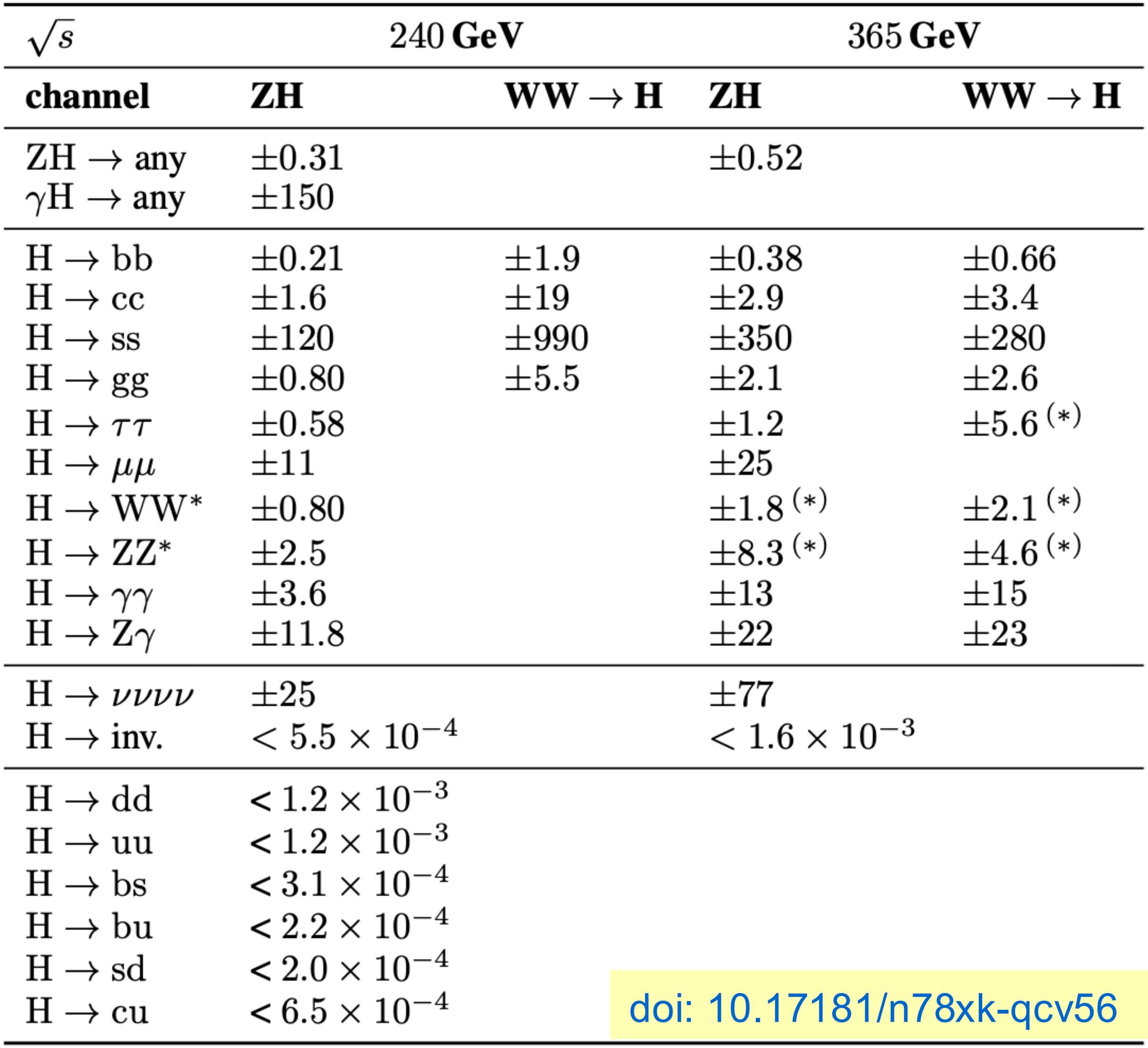
μ from Z, with momentum of O(50) GeV, to be measured with a p_T resolution smaller than the BES for the momentum measurement not to limit the mass resolution

- achieved with the baseline IDEA detector → uncertainty of 3.49 MeV with 10 ab^{-1}
- CLD performs less well because of the larger amount of material → larger effects of MS

If the B increased from 2T to 3T → 50% improvement of the momentum resolution
14% improvement on the total mass uncertainty

σ(HZ) x BR and σ(WW→H) x BR measurements

Uncertainty on σ * BR in %



$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
H → $\tau\tau$	±0.58		±1.2	$\pm 5.6^{(*)}$
H → $\mu\mu$	±11		±25	
H → WW^*	±0.80		$\pm 1.8^{(*)}$	$\pm 2.1^{(*)}$
H → ZZ^*	±2.5		$\pm 8.3^{(*)}$	$\pm 4.6^{(*)}$
H → $\gamma\gamma$	±3.6		±13	±15
H → Zγ	±11.8		±22	±23
H → $\nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

doi: 10.17181/n78xk-qcv56

Higgs self coupling at √s < 500 GeV – i.e. ZH & tt thresholds

arXiv:2503.13719v2

Probe *indirectly* trilinear Higgs self coupling **λ_3** through higher-order corrections to single-Higgs processes

O(few%) NLO correction to SM observable (i.e the cross section) parameterized according to:

$$\Sigma_{\rm NLO} = \underset{\substack{\downarrow \\ \text{Universal coefficient} \\ \text{from wave function}}}{\boxed{Z_H}}\Sigma_{\rm LO}(1+\kappa_\lambda \underset{\substack{\downarrow \\ \text{Process and kinematic} \\ \text{dependent coefficient}}}{\boxed{C_1}}) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$

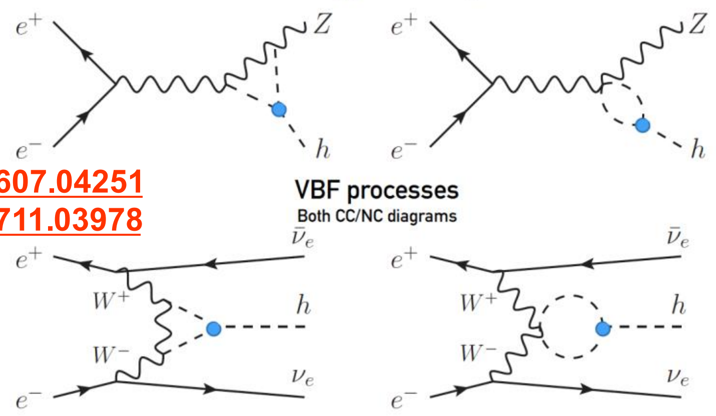
C_1 process-dependent coefficient that encodes the interference between the NLO amplitudes and the LO ones

The total (NLO) cross section can be measured O(1%):

- possible probing NLO deviations from SM: $\delta\kappa_\lambda = \kappa_\lambda - 1$
- parameter C_1 sensitive to √s: exploit different sensitivities at 240 GeV and 365 GeV:
  - ZH @ 240 GeV
  - VBF @ 365 GeV

Vertex corrections (linear in k_λ)

arXiv:1607.04251
arXiv:1711.03978

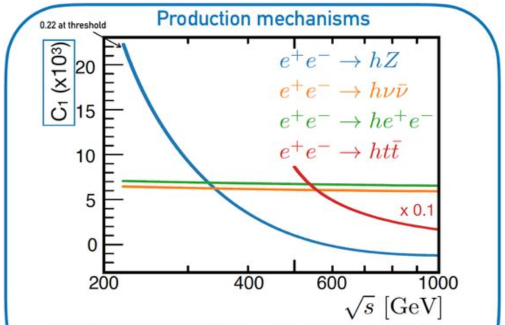


ZH Higgsstrahlung

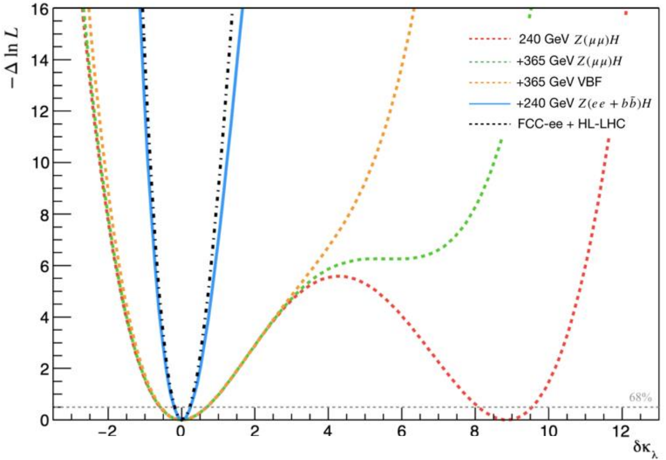
VBF processes

Both CC/NC diagrams

Production mechanisms



Negligible impact of a modified λ_{HHH} on the angular asymmetries. At 1-loop C_1 for HZ, WW-boson fusion and ZZ-boson fusion are independent of the beam polarization.

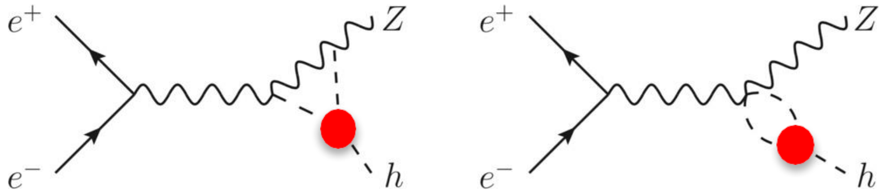


The secondary minimum easily excluded adding a 2nd energy point

Higgs self coupling at FCC-ee (√s < 500 GeV)

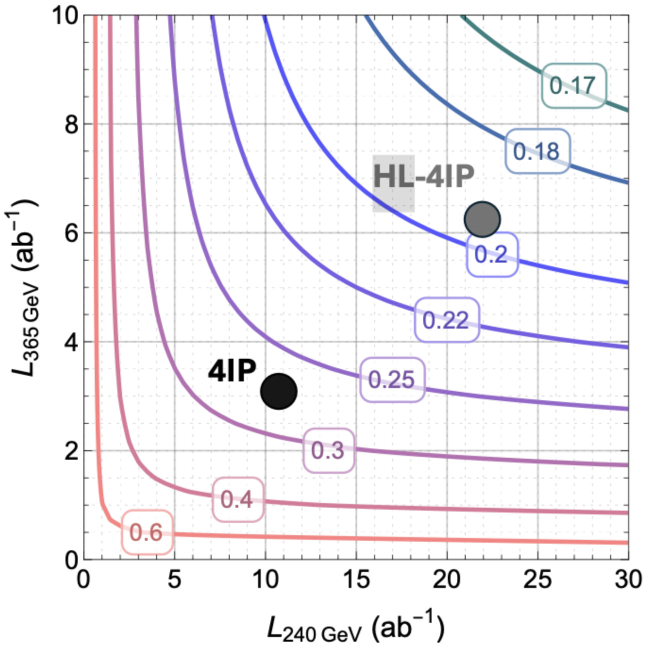
NB: 365 GeV → ZHH threshold, but too low ZHH x-section

λ_3 affects single-Higgs prod at NLO



e.g. 100% variation on λ_3 modifies σ(ZH) by ~ 2% at 240 GeV and ~ 0.5% at 365 GeV. Larger than / comparable with the exp. precision on σ(ZH)

Precise measurement of σ(ZH) constrains a combination of λ_3 and g_{HZZ}.
Measurements at two values of √s needed to determine separately λ_3 and g_{HZZ}.



- Recent: 4 IPs. Running at √s = 240 and 365 GeV

→ **δκ$_\lambda$ ~ 28% for FCC-ee**

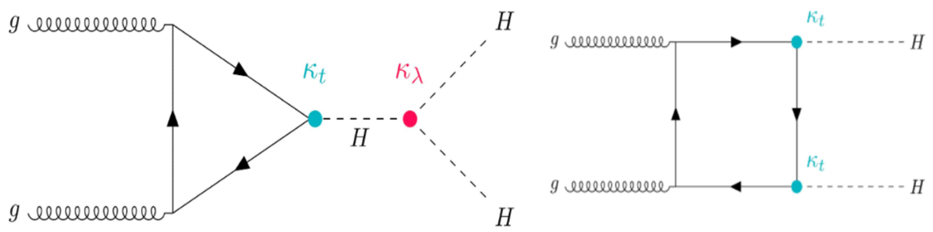
~ 18% (combining with HL-LHC)

arXiv:2505.00272v1

With 4 IPs: 5σ observation of λ_3 within reach with 15 years of operation at FCC-ee

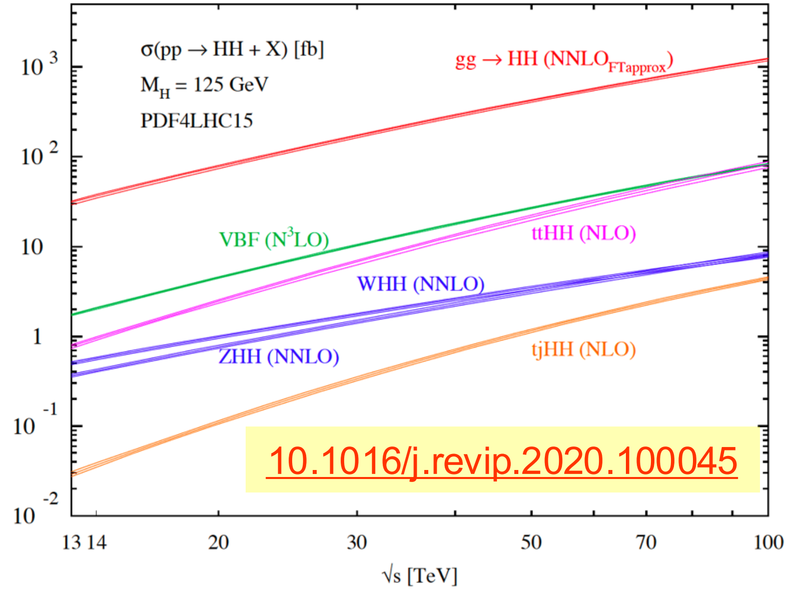
Higgs self coupling at FCC-hh via HH

Gluon gluon Fusion (ggF)

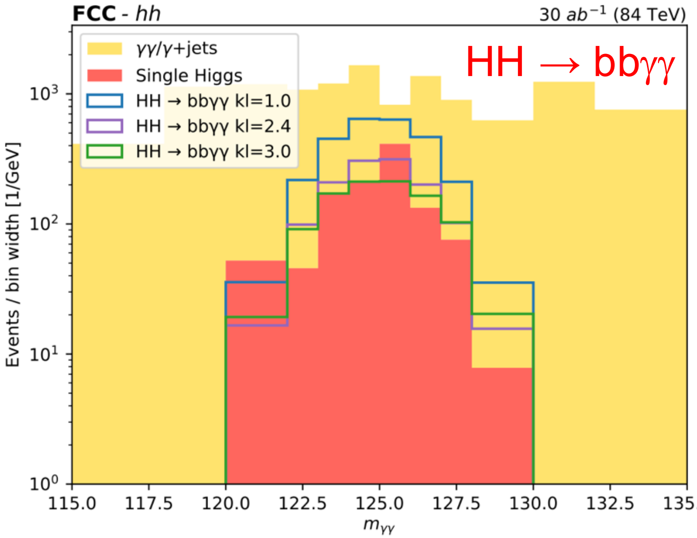


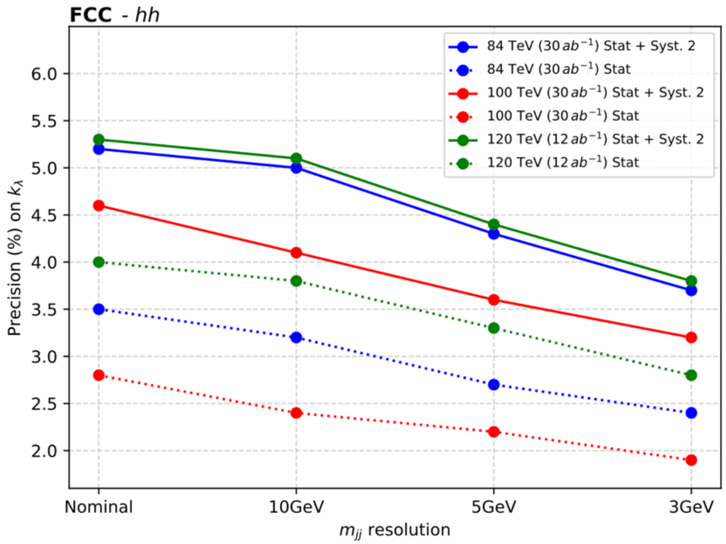
destructive interference

Most sensitivity in channels that can be cleanly tagged: HH → bbγγ HH → bbbb, HH → bbττ



10.1016/j.revip.2020.100045





Depending on the di-jet mass resolution and systematic assumptions →

Exp. prec. on κ_λ @ 68% C.L.:

- 3.2% to 5.4% at 84 TeV
- 2.8% to 4.8% at 100 TeV

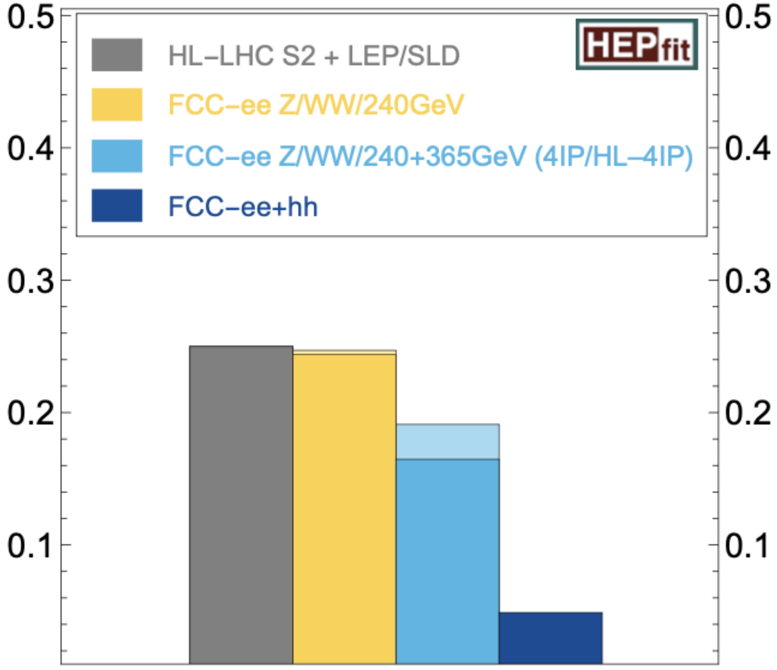
doi:10.17181/w6928-gr929

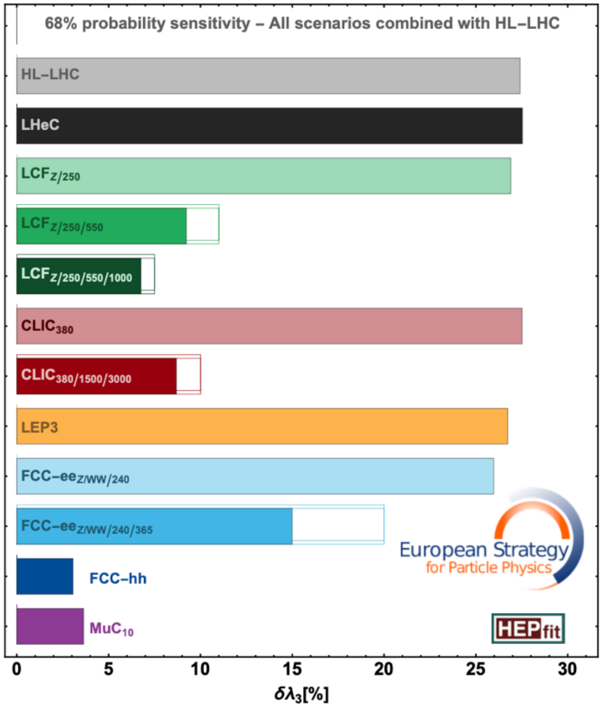
Precision on Higgs self couplings

HL-LHC
26–29%

+FCC-ee
~18%

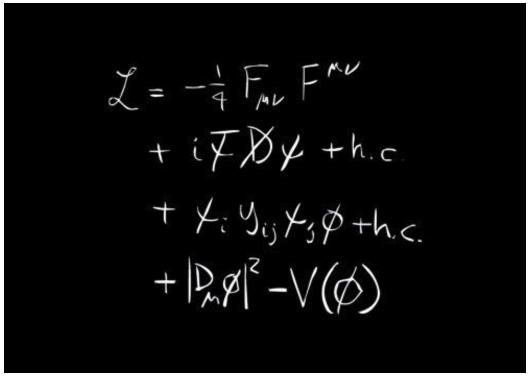
+FCC-hh
2–3%





The Higgs self coupling

- The Higgs self-couplings λ_i are still largely unconstrained experimentally
- These couplings provide key information on the shape of the Higgs potential V (H) which has important physics implications (e.g. stability of the universe, JHEP08(2012) 098
- known m_H (~125 GeV), SM predicts $\lambda_3 = m_H^2 / 2v^2$ (~0.13)
- $\lambda_3 = \lambda_4$ in SM



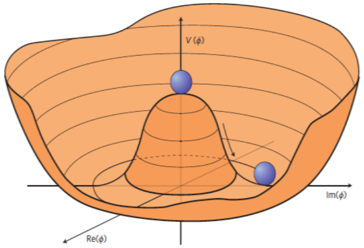
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$m_H = \sqrt{2\lambda v^2}$$

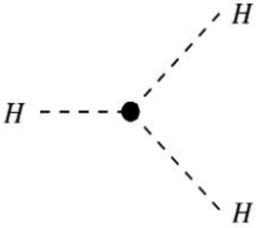
$$v \simeq 246 \text{ GeV.}$$

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

$$\kappa_\lambda = \lambda_3 / \lambda_3^{\text{SM}}$$



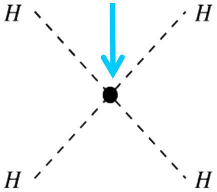
Mass term



Higgs trilinear self-coupling (κλ)
Higgs pair production

Higgs quadratic self-coupling

SM quartic Higgs coupling out of reach even for HL-LHC



PRD 72, 053008

- λ_3 can be directly accessed through the production of Higgs boson pairs (HH)
- contributions also come from single Higgs production (H) via NLO EW corrections

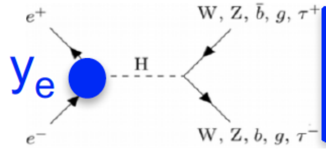
Higgs Yukawa coupling to electron

arXiv:2107.02686

FCC-ee: unique opportunity to study the Higgs Yukawa coupling to electron, **y_e**, via resonant s-channel production **$e^+e^- \rightarrow$ H** in a dedicated run at the Higgs pole, $\sqrt{s} = m_H$.

In the SM:

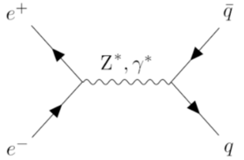
- the Yukawa coupling of the electron is $y_e = \sqrt{2}\, m_e/v = 2.8 \cdot 10^{-6}$
- $BR(H \rightarrow e^+e^-) \approx 5 \times 10^{-9}$

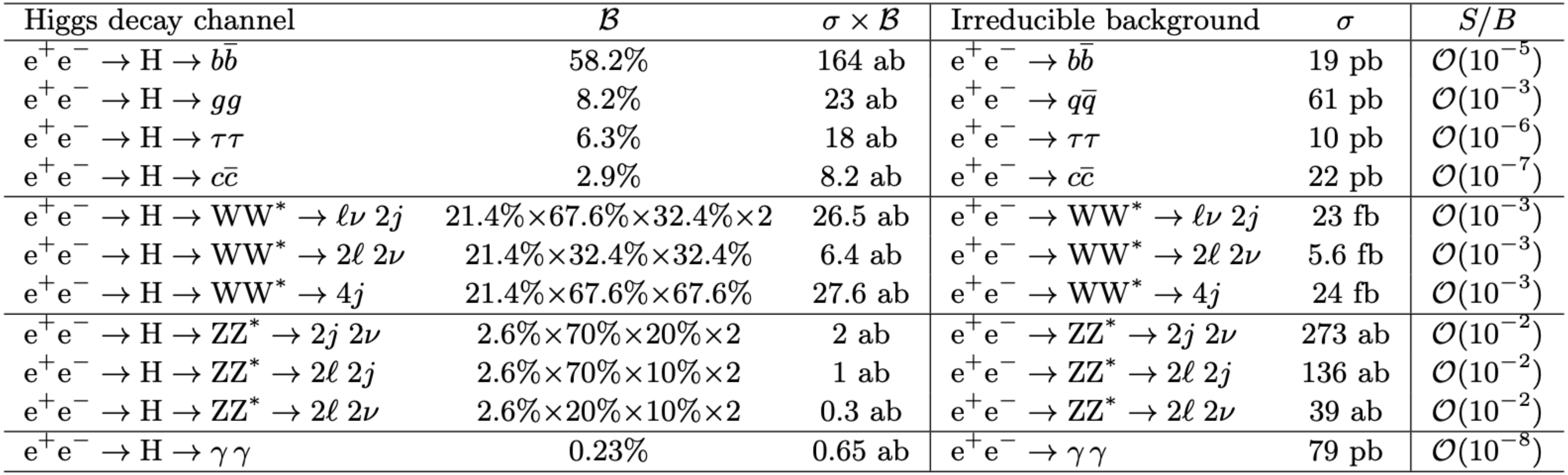


$\sigma(e^+e^- \rightarrow H)_{B\text{-}W} = 1.64$ fb

$\sigma(e^+e^- \rightarrow H)_{spread} = 280$ ab (ISR + $\sqrt{s}_{spread} = \Gamma_H = 4.2$ MeV)

background





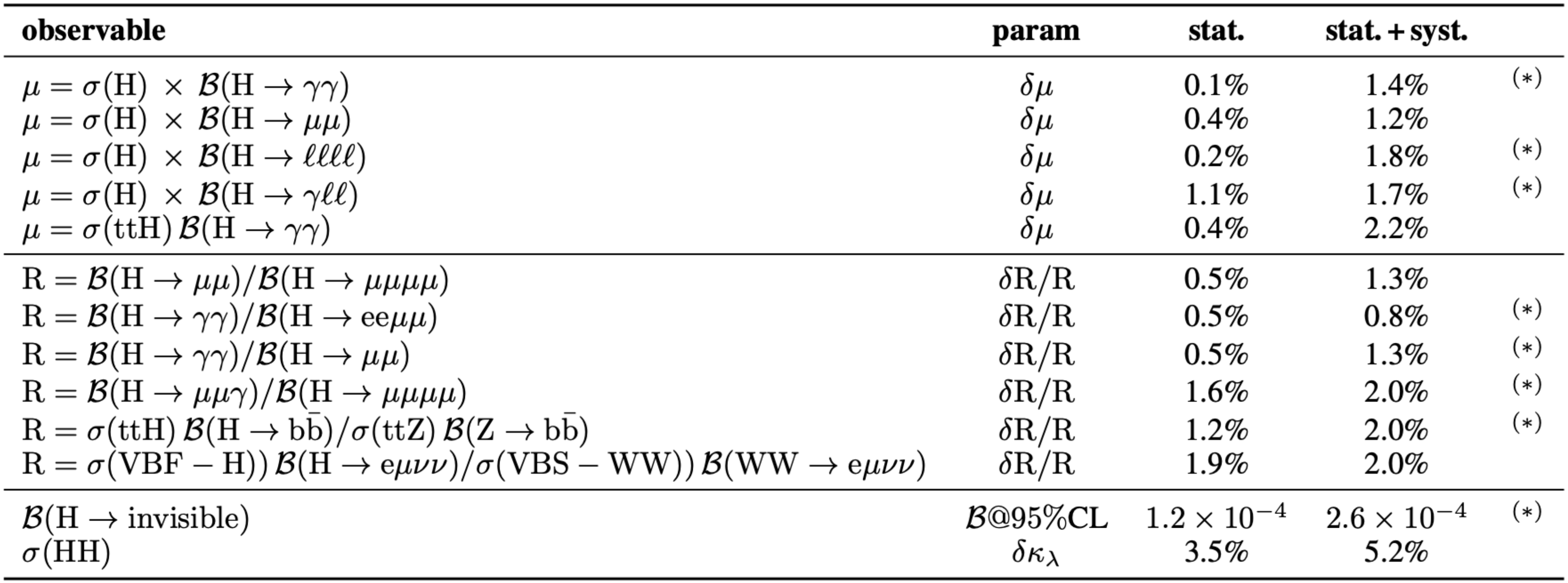
Higgs decay channel	$\mathcal{B}$	$\sigma \times \mathcal{B}$	Irreducible background	σ	S/B
$e^+e^- \rightarrow H \rightarrow b\bar{b}$	58.2%	164 ab	$e^+e^- \rightarrow b\bar{b}$	19 pb	$\mathcal{O}(10^{-5})$
$e^+e^- \rightarrow H \rightarrow gg$	8.2%	23 ab	$e^+e^- \rightarrow q\bar{q}$	61 pb	$\mathcal{O}(10^{-3})$
$e^+e^- \rightarrow H \rightarrow \tau\tau$	6.3%	18 ab	$e^+e^- \rightarrow \tau\tau$	10 pb	$\mathcal{O}(10^{-6})$
$e^+e^- \rightarrow H \rightarrow c\bar{c}$	2.9%	8.2 ab	$e^+e^- \rightarrow c\bar{c}$	22 pb	$\mathcal{O}(10^{-7})$
$e^+e^- \rightarrow H \rightarrow WW^* \rightarrow \ell\nu\, 2j$	21.4%×67.6%×32.4%×2	26.5 ab	$e^+e^- \rightarrow WW^* \rightarrow \ell\nu\, 2j$	23 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \rightarrow H \rightarrow WW^* \rightarrow 2\ell\, 2\nu$	21.4%×32.4%×32.4%	6.4 ab	$e^+e^- \rightarrow WW^* \rightarrow 2\ell\, 2\nu$	5.6 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \rightarrow H \rightarrow WW^* \rightarrow 4j$	21.4%×67.6%×67.6%	27.6 ab	$e^+e^- \rightarrow WW^* \rightarrow 4j$	24 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \rightarrow H \rightarrow ZZ^* \rightarrow 2j\, 2\nu$	2.6%×70%×20%×2	2 ab	$e^+e^- \rightarrow ZZ^* \rightarrow 2j\, 2\nu$	273 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \rightarrow H \rightarrow ZZ^* \rightarrow 2\ell\, 2j$	2.6%×70%×10%×2	1 ab	$e^+e^- \rightarrow ZZ^* \rightarrow 2\ell\, 2j$	136 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \rightarrow H \rightarrow ZZ^* \rightarrow 2\ell\, 2\nu$	2.6%×20%×10%×2	0.3 ab	$e^+e^- \rightarrow ZZ^* \rightarrow 2\ell\, 2\nu$	39 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \rightarrow H \rightarrow \gamma\gamma$	0.23%	0.65 ab	$e^+e^- \rightarrow \gamma\gamma$	79 pb	$\mathcal{O}(10^{-8})$

Complementarity/synergy between HL-LHC, FCC-ee and FCC-hh

FCC-hh measurements of Rare Higgs decays

FCC-hh will produce about 30 billion Higgs bosons in 30 ab^{-1} allowing measurements of H → γγ , H → μμ , H → Zγ, , with 1-2% uncertainty (systematically limited)

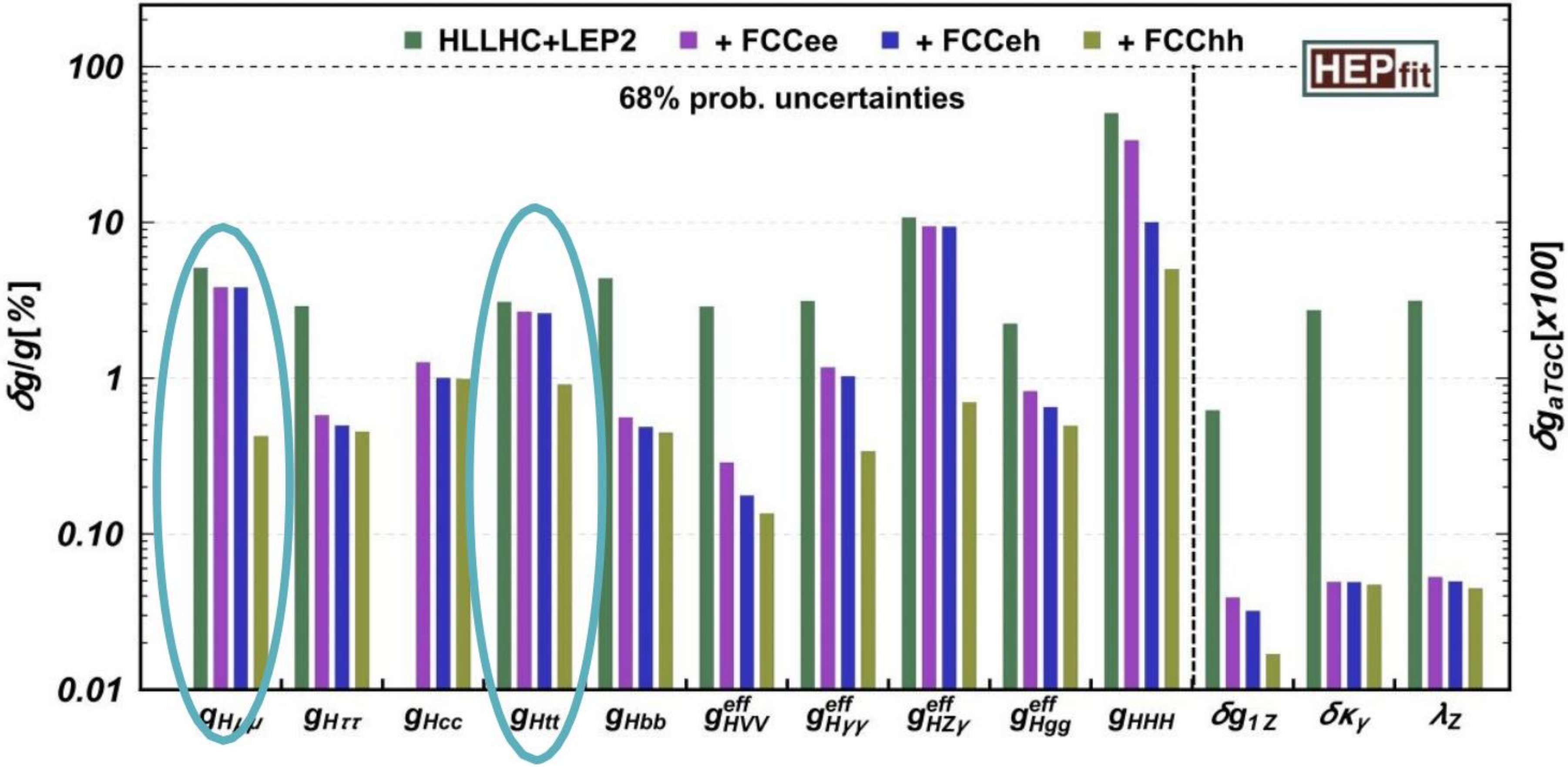
doi: 10.17181/n78xk-qcv56



observable	**param**	**stat.**	**stat. + syst.**	
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu$	0.1%	1.4%	(∗)
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \mu\mu)$	$\delta\mu$	0.4%	1.2%	
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \ell\ell\ell\ell)$	$\delta\mu$	0.2%	1.8%	(∗)
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \gamma\ell\ell)$	$\delta\mu$	1.1%	1.7%	(∗)
$\mu = \sigma(\mathrm{ttH})\, \mathcal{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu$	0.4%	2.2%	
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \mu\mu)/\mathcal{B}(\mathrm{H} \to \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	1.3%	
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \gamma\gamma)/\mathcal{B}(\mathrm{H} \to \mathrm{ee}\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	0.8%	(∗)
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \gamma\gamma)/\mathcal{B}(\mathrm{H} \to \mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	1.3%	(∗)
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \mu\mu\gamma)/\mathcal{B}(\mathrm{H} \to \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	1.6%	2.0%	(∗)
$\mathrm{R} = \sigma(\mathrm{ttH})\, \mathcal{B}(\mathrm{H} \to \mathrm{b\bar{b}})/\sigma(\mathrm{ttZ})\, \mathcal{B}(\mathrm{Z} \to \mathrm{b\bar{b}})$	$\delta\mathrm{R}/\mathrm{R}$	1.2%	2.0%	(∗)
$\mathrm{R} = \sigma(\mathrm{VBF-H}))\, \mathcal{B}(\mathrm{H} \to \mathrm{e}\mu\nu\nu)/\sigma(\mathrm{VBS-WW}))\, \mathcal{B}(\mathrm{WW} \to \mathrm{e}\mu\nu\nu)$	$\delta\mathrm{R}/\mathrm{R}$	1.9%	2.0%	
$\mathcal{B}(\mathrm{H} \to \mathrm{invisible})$	$\mathcal{B}$@95%CL	1.2×10^{-4}	2.6×10^{-4}	(∗)
$\sigma(\mathrm{HH})$	$\delta\kappa_\lambda$	3.5%	5.2%	

Higgs couplings: HL-LHC, FCCee, FCChh

Phys. Rev. Lett. 132 (2024) 221802



- HL-LHC is still going to be the best machine for Zγ, μμ (rare decays) and ttH coupling determination for the next decades years (until FCC-hh)
- HL-LHC has no access to charm Yukawa coupling
- FCC-ee has limited access to top Yukawa coupling (only via loop corrections to $e^+e^- \rightarrow tt$ cross section indirectly)