Measurement of the Higgs properties at FCC-ee

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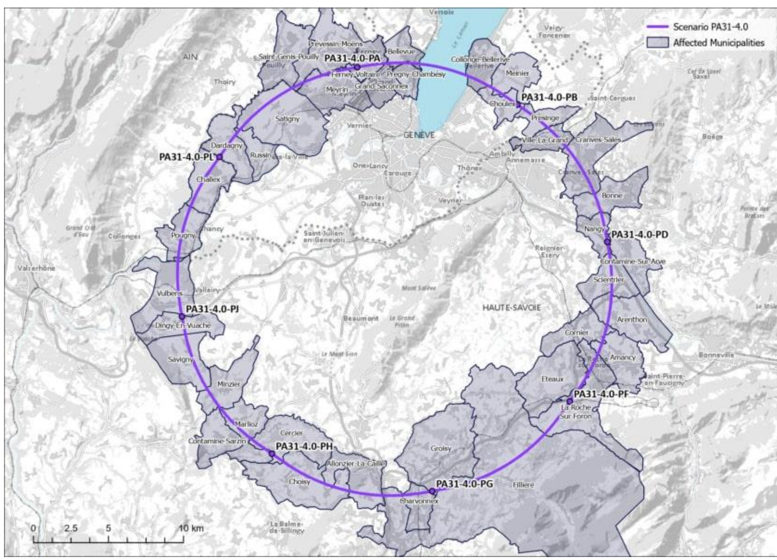
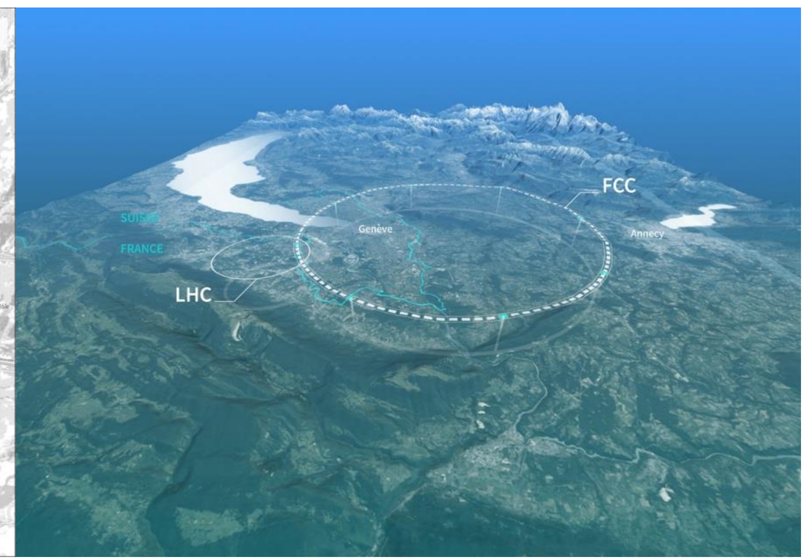
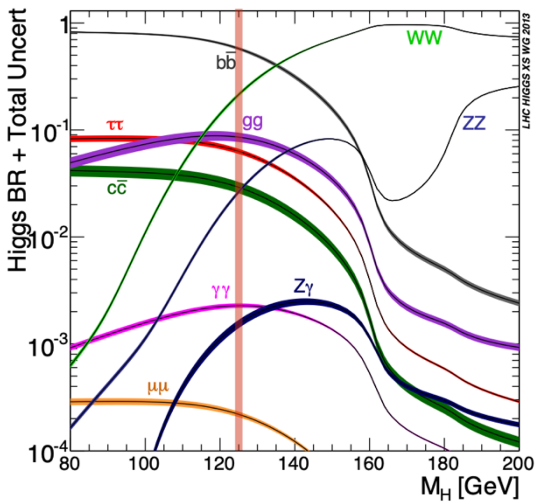




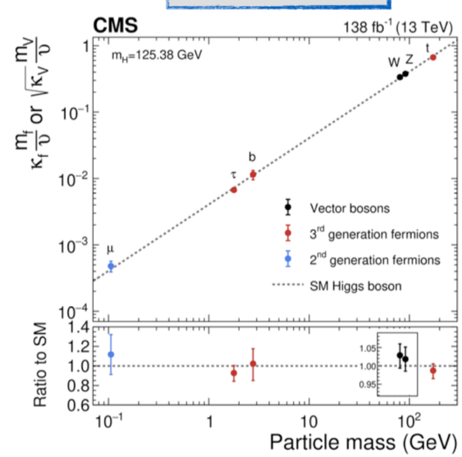
Landscape of the Higgs physics today

So far many questions still open for Higgs physics:

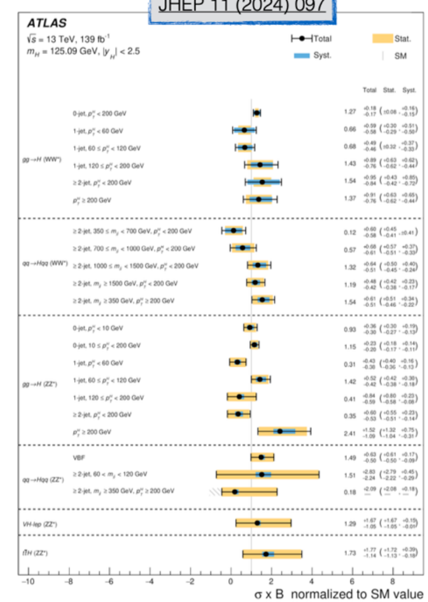
- ✓ How well the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?
- ✓ How do precision electroweak observables provide us information about the Higgs boson properties and/or BSM physics?
- ✓ why the Higgs boson remains light?— the heart of the naturalness problem
- ✓ What is the best path towards measuring the Higgs potential ?
- ✓ To what extent can we tell whether the Higgs is fundamental or composite?



Nature 607 (2022) 60-68



JHEP 11 (2024) 097

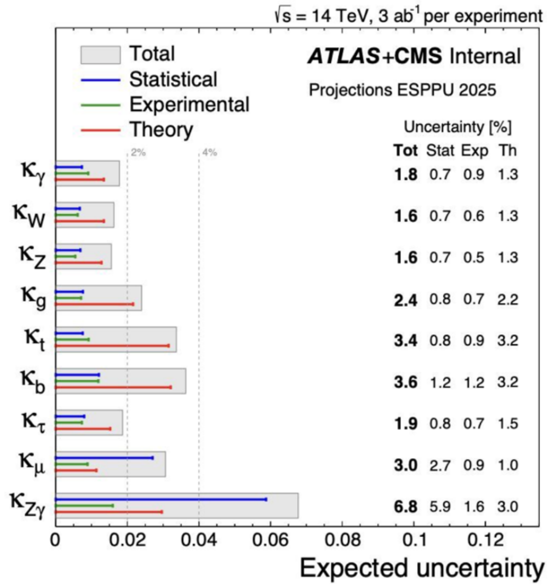


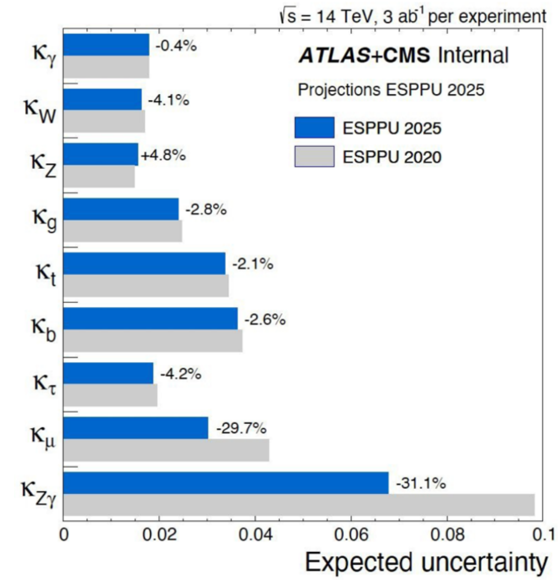
- ✓ Couplings to gauge bosons and 3rd generation fermions close to SM expectations (~ 10% precision), evidence for 2nd generation fermion coupling ($H \rightarrow \mu\mu$), all mesurements consistent with CP-even scalar
- ✓ LHC experiments entered era of differential corss section measurements (EFT fits, etc.)

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





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	κ_λ precision 68% CL ATLAS	κ_λ 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%

European Strategy 2020

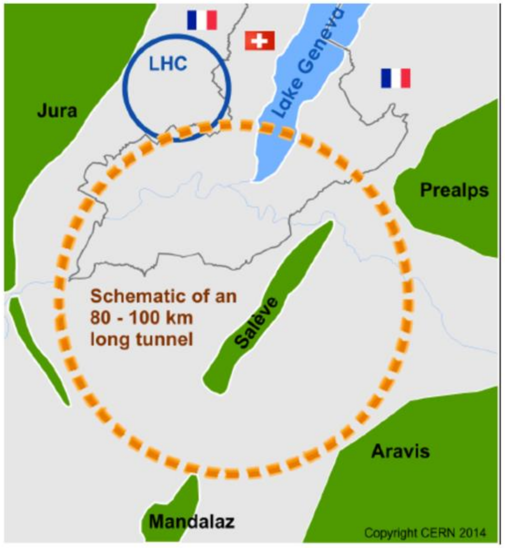
*"**An electron-positron Higgs factory is the highest priority next collider**. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."*

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

FCC project @ CERN: a new 100 km tunnel in the Geneva region, for two complementary machines covering the largest phase space in the high energy frontier:

- **extreme precision circular e+e-collider (FCC-ee) with** variable collision energy from 90-360 GeV
- **highest energy reach in pp collisions** (**FCC-hh**): 100 TeV

FCC Feasibility Study (FS) launched in 2021:
- To be carried out in 2021-2025
- Mid-term review in Autumn 2023
- March 2025: documentation submitted to ES committe



European Strategy 2025

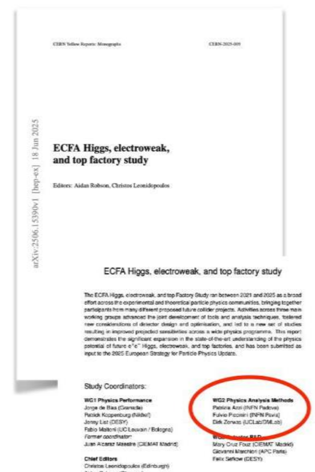
Published! Feasibility Study Reports

And a YellowReport on Future HTE factories

https://cds.cern.ch/record/2928193

https://cds.cern.ch/record/2928194

https://cds.cern.ch/record/2928793



https://arxiv.org/pdf/2506.15390

02/10/2025

Physics Briefing Book

CERN-ESU-2025-001
30 September 2025

Physics Briefing Book

Input for the 2026 update of the European Strategy for Particle Physics

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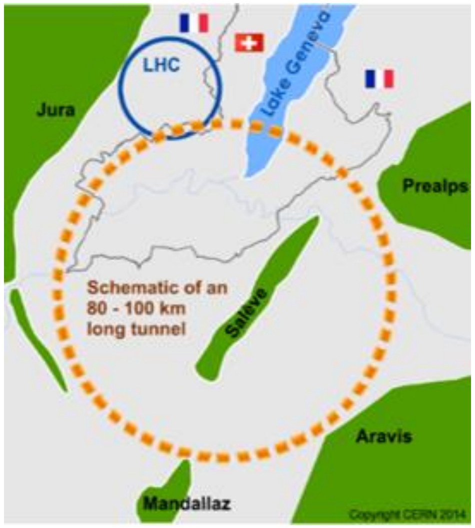
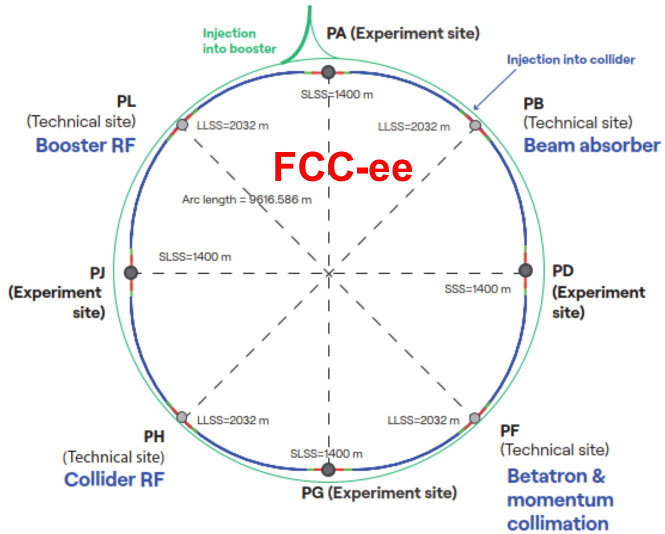
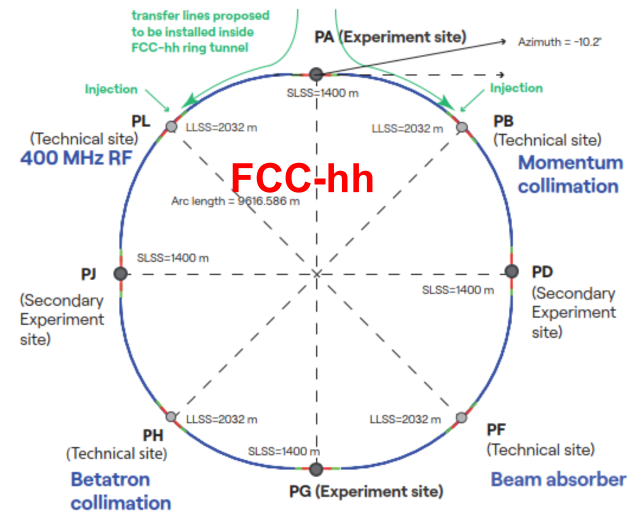
European Strategy 2025

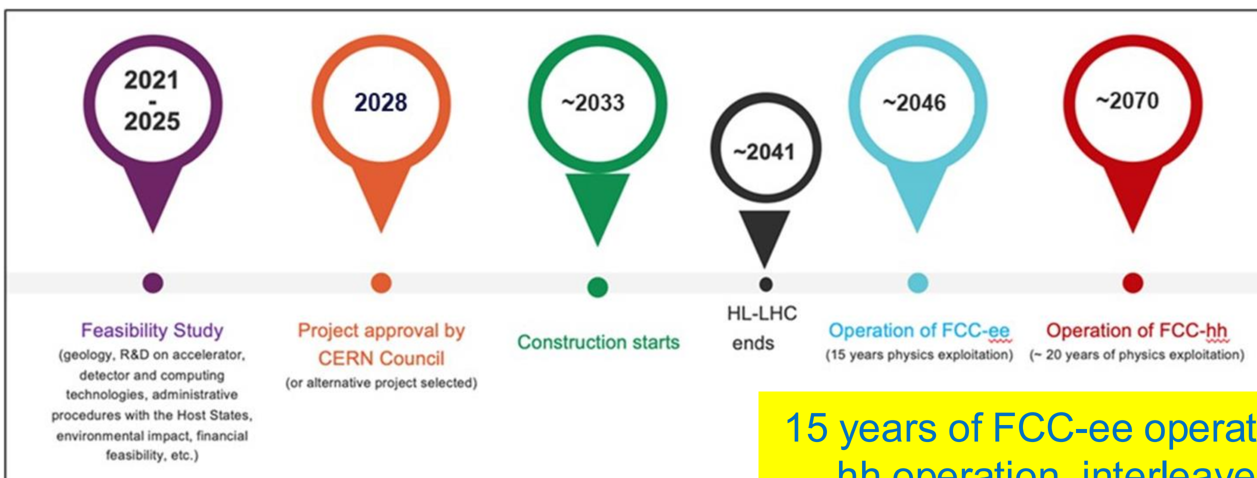
FCC integrated program - timeline







2020 - 2045 | **2046 - 2065** | **2070 - 2100**

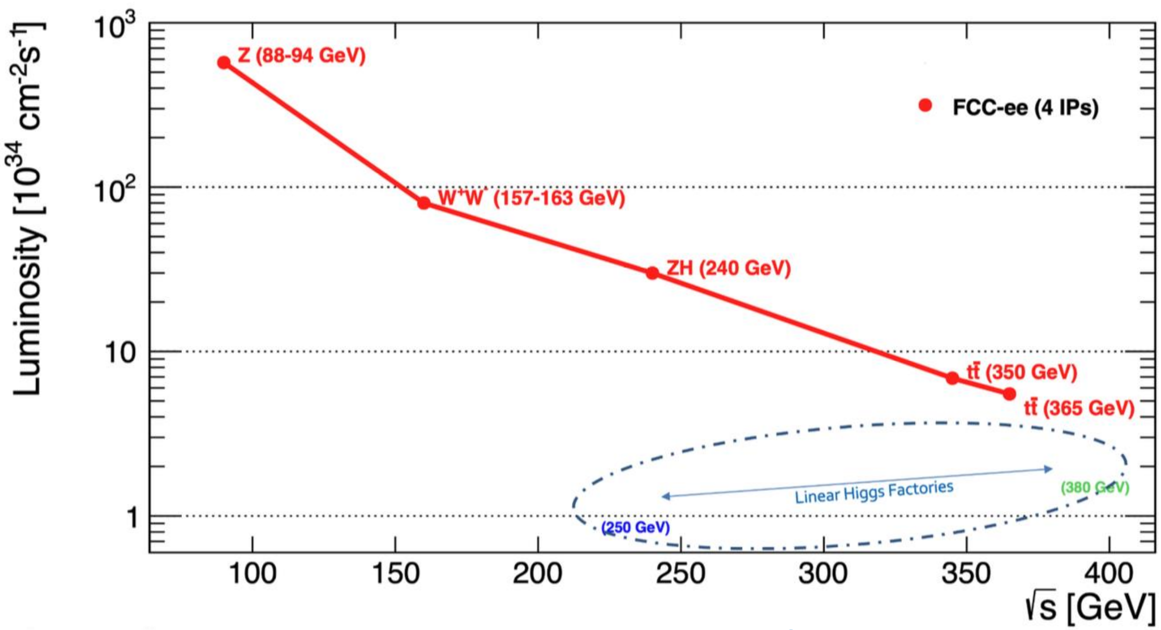


Ambitious schedule taking into account:

- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until 2041
- ❑ project preparatory phase with adequate resources immediately after Feasibility Study

15 years of FCC-ee operation followed by 25 years of FCC-hh operation, interleaved with a shutdown of 10 years

Machine luminosity for physics at FCC-ee



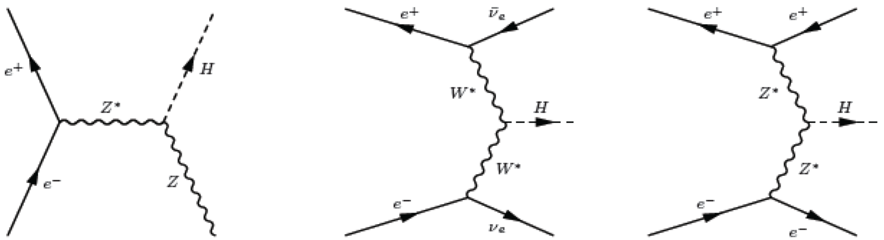
- Higgs factory:
  - 2.2×10^6 $e^+e^- \rightarrow HZ$
- EW & Top factory:
  - 6×10^{12} $e^+e^- \rightarrow Z$ (LEPx10^5)
  - 2.4×10^8 $e+e^- \rightarrow W^+W^-$
  - 2×10^6 $e^+e^- \rightarrow tt$
- Flavor factory:
  - 5×10^{12} $e^+e^- \rightarrow bb, cc$
  - 10^{11} $e^+e^- \rightarrow \tau^+\tau^-$

~100 kHz of physics data at the Z pole

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 → H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW → H	

Higgs production at FCC-ee

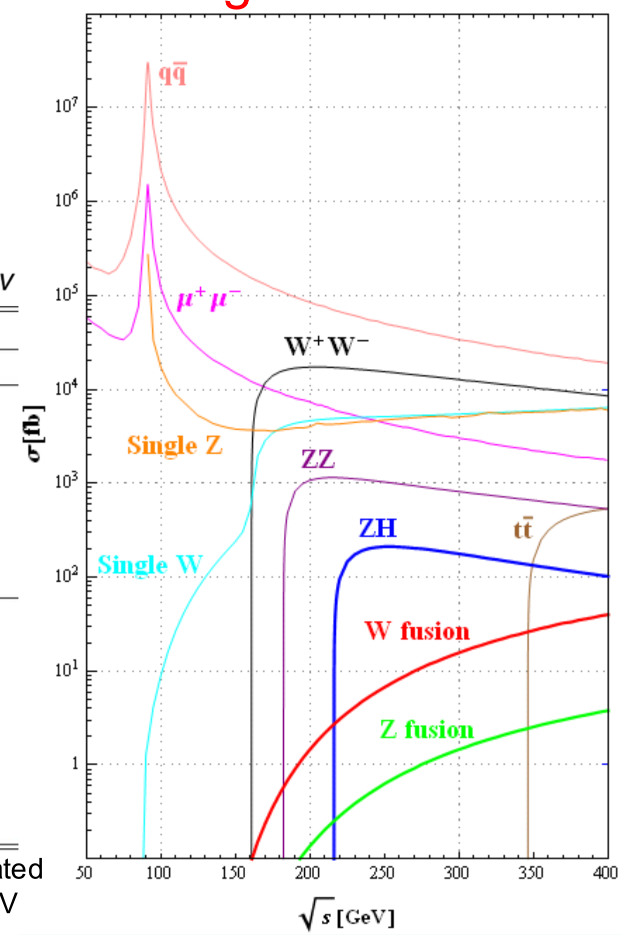
Higgs-strahlung or $e^+e^- \rightarrow ZH$

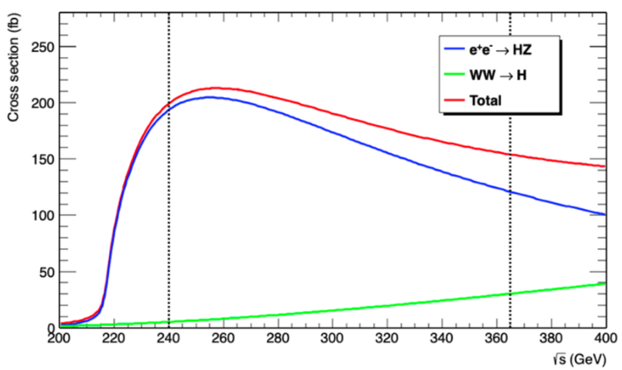


VBF production: $e^+e^- \rightarrow \nu\nu H$ (W fusion)

$e^+e^- \rightarrow He^+e^-$ (Z fusion)

Background sources





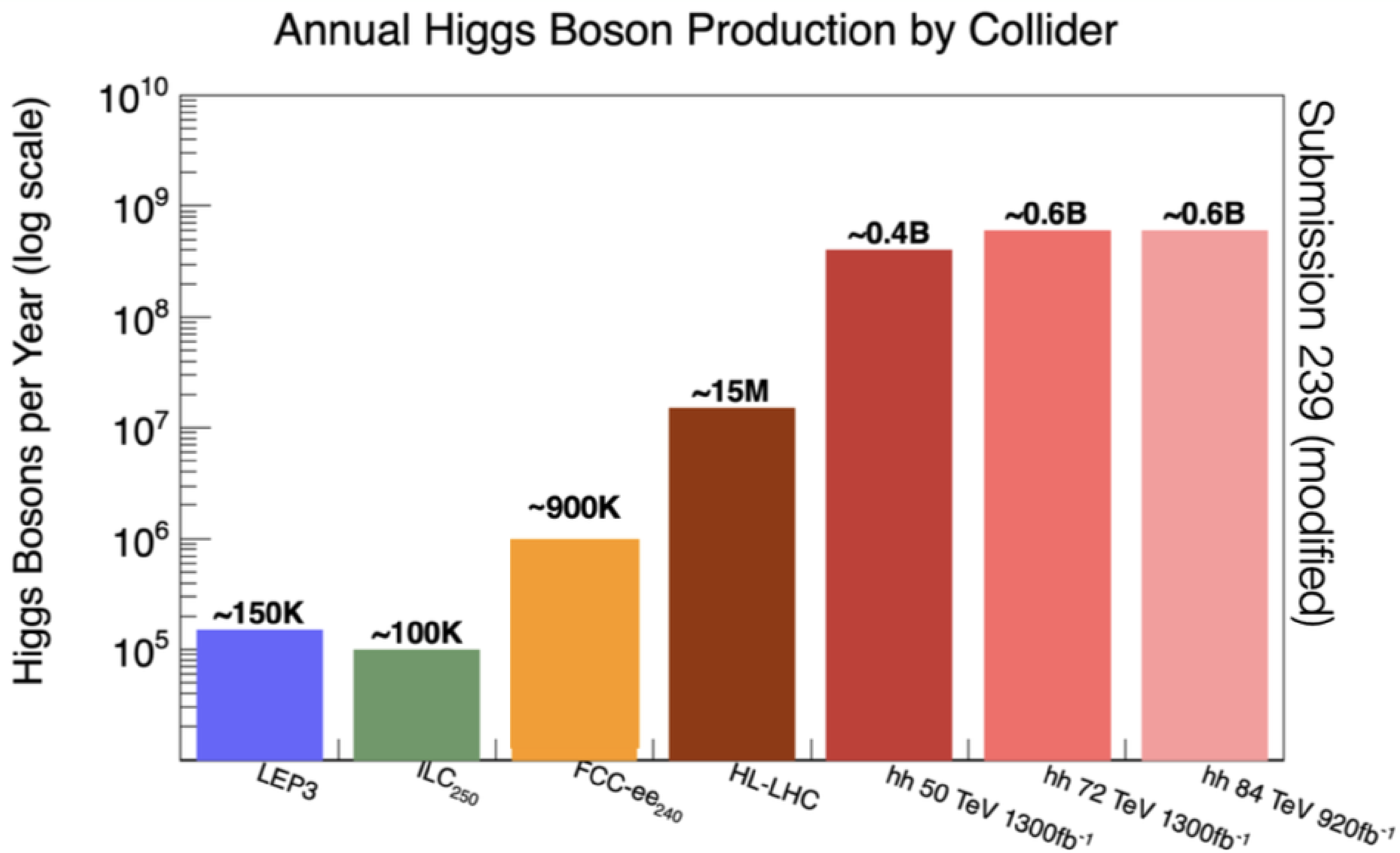
$\sqrt{s}$ = 240.0 GeV

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

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

Higgs yield at colliders

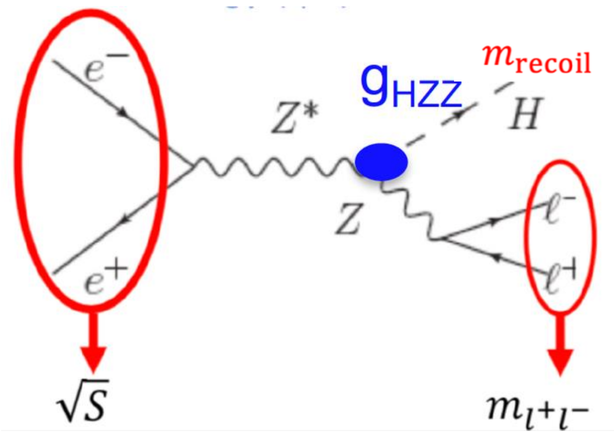


- e^+e^- colliders produce less Higgs bosons than the LHC, but they benefit from precise knowledge of initial stage and a "clean" experimental environment.
- *pp* colliders allow measurements of rare decays

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

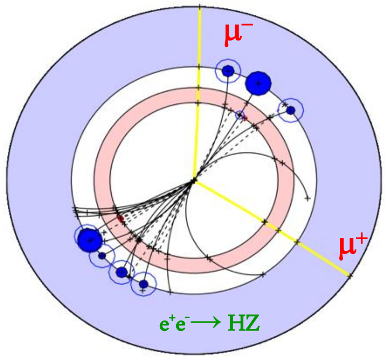
Global strategy for Higgs studies

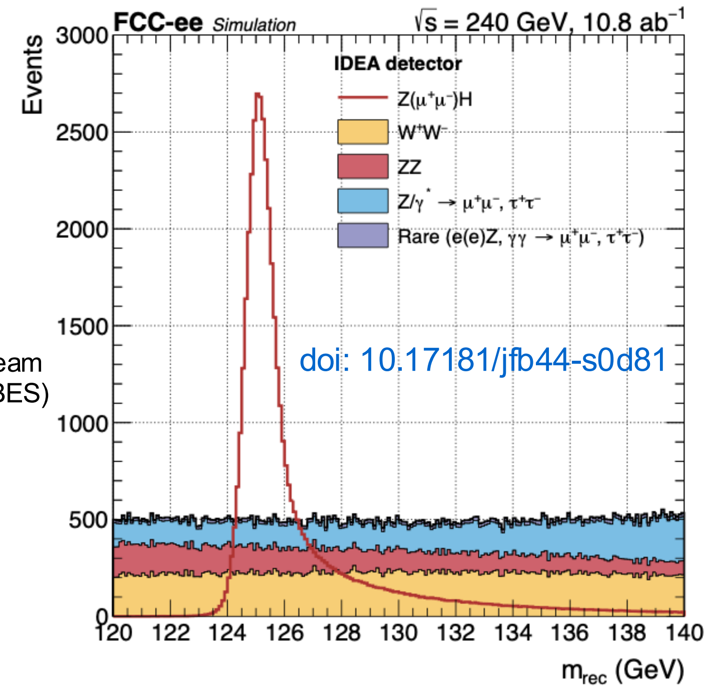
Eur. Phys. J. Plus 137(1), 23 (2022)



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

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





e.g. when $Z \rightarrow$ leptons :

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

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

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: $Z \rightarrow$ lep.

- $Z \rightarrow$ 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

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

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

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

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

Select events with H → bb, cc, gg, WW, tt, γγ, μμ, Zγ, … → **$\delta g_{XX}/g_{XX}$ ~ 1 %**

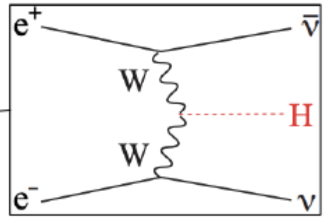
→ deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , g_{Htt} , $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …

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

a model-indep determination of Higgs couplings.

Data at higher energy bring important additional observables:

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



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

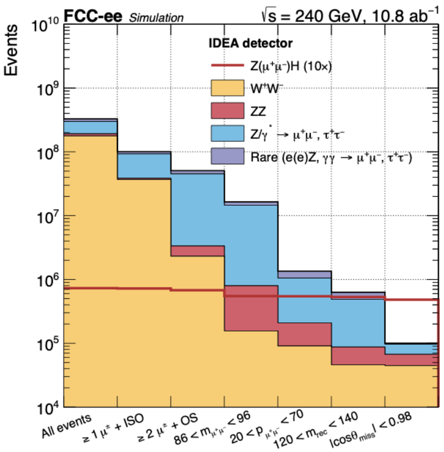
$$\chi^2 = 0.6 \times (m_{\ell\ell} - m_Z)^2 + 0.4 \times (m_{recoil} - m_h)^2$$

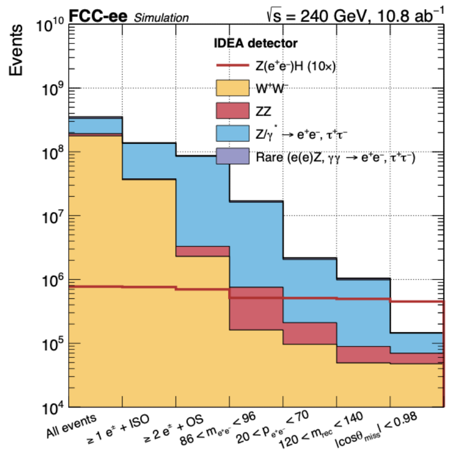
- tight selection of Z mass between [86, 96] GeV
- Background reduction by cut on
  - Z p_T [20, 70] GeV to suppress Z/γ*
  - $|\cos(\theta_{miss})|$ < 0.98 for Z→ll, γγ→ee/μμ/ττ events

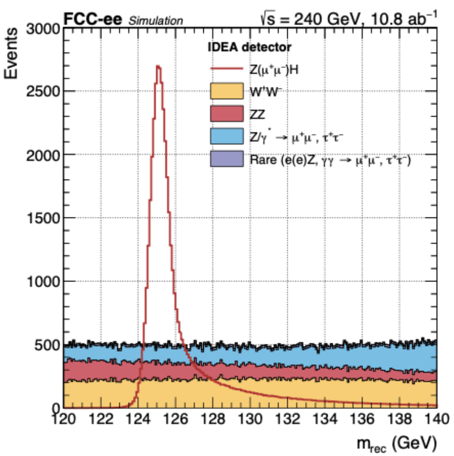
Parametric fit based on recoil mass distribution:

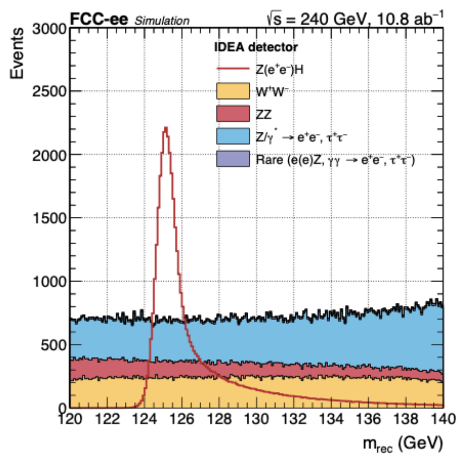
- Fit function: double-sided Crystal-ball + Gaussian core
- Free parameter: H mass, signal and bkg normalization

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







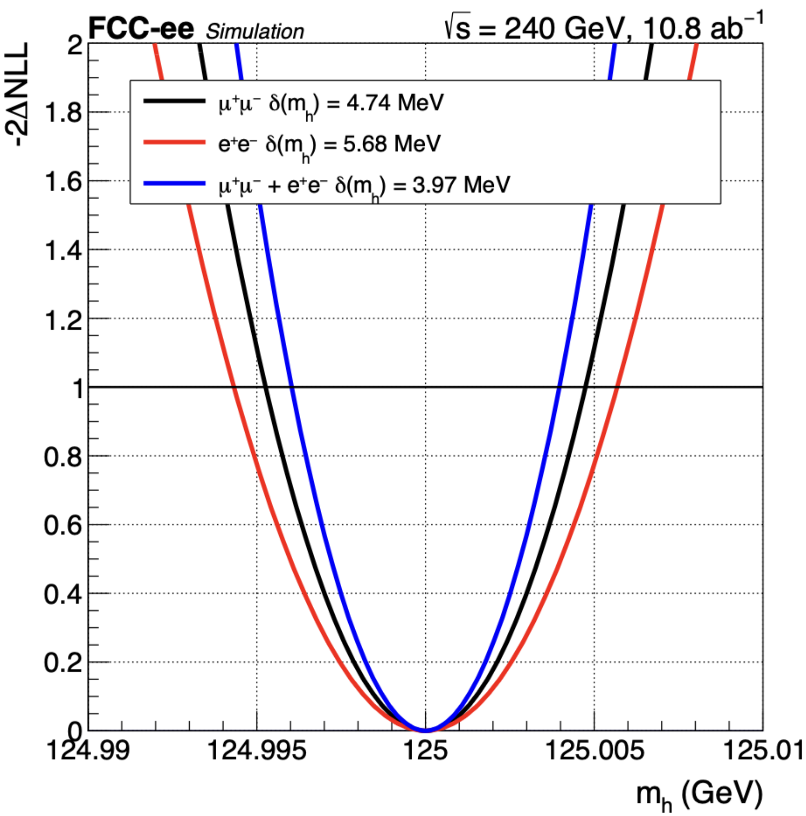


Higgs mass measurement

Likelihood scans to extract uncertainties on mass

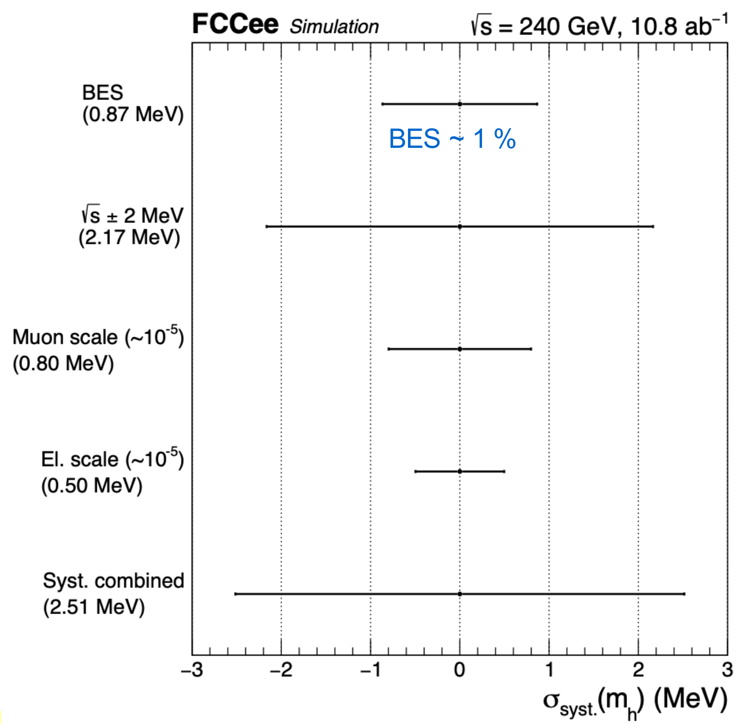
Stat. + syst. uncertainties:

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



Source of uncertainty:

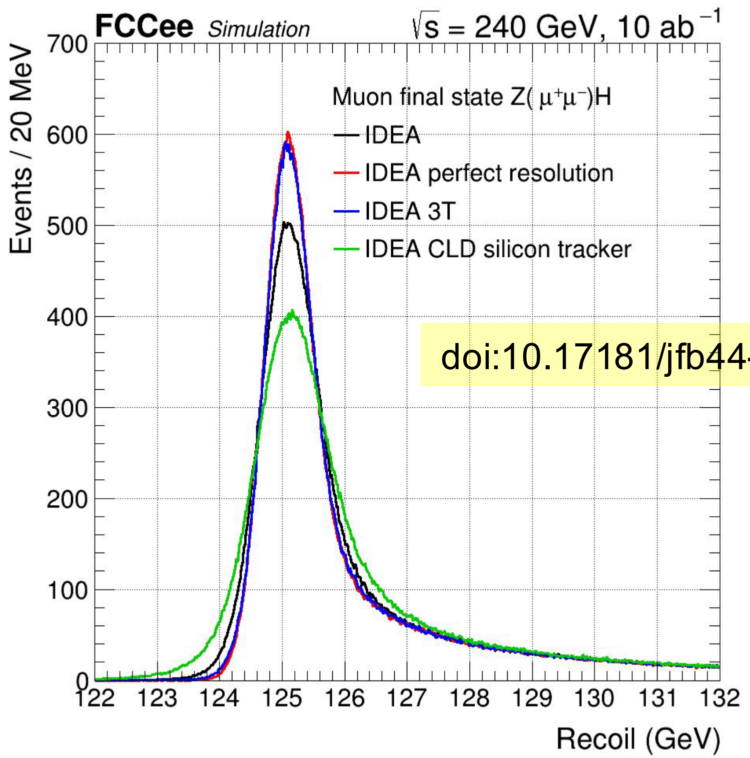
- Beam Energy Spread (BES)
- Initial State Radiation (ISR)
- Muon momentum scale
- Center-of-mass energy - dominant
- FSR uncertainty



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

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



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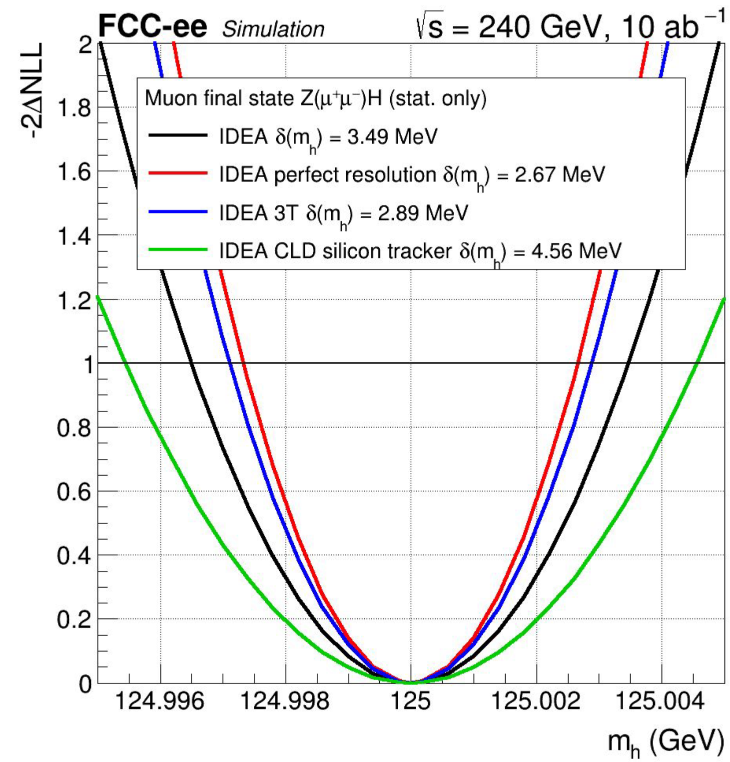


μ from Z, with momentum of O(50) GeV, to be measured with a p_T resolution smaller than the BES for the momentum measurement not to limit the mass resolution

- 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

HZ cross section measurement

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

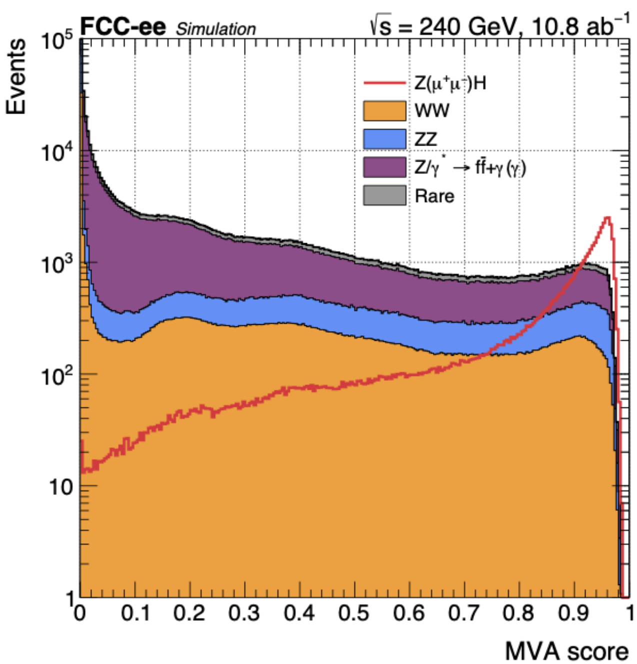
For the ZH cross-section measurement, after applying the basic selection criteria, the $|\cos\theta_{miss}|$ cut is omitted and replaced by a BDT approach to further suppress background.

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

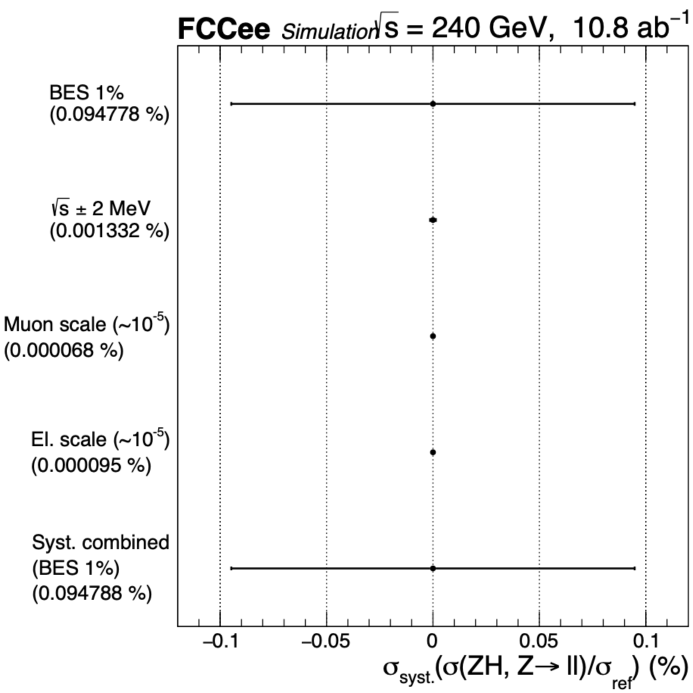
Stat. uncertainty in %:

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

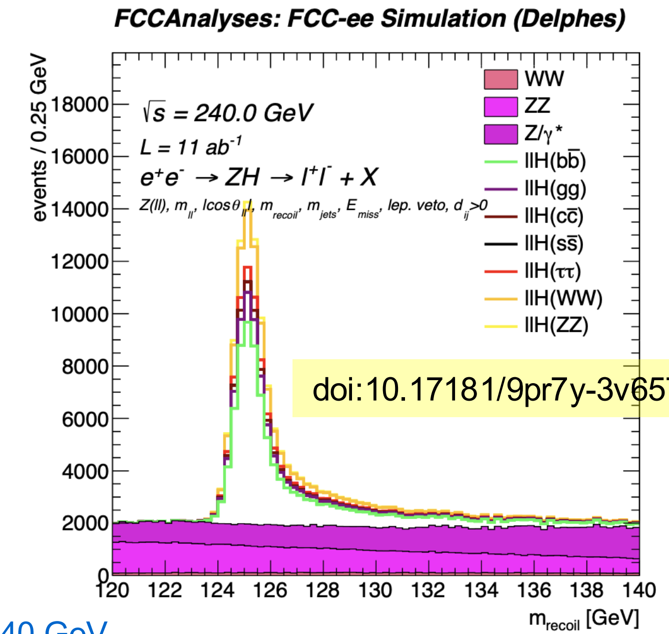


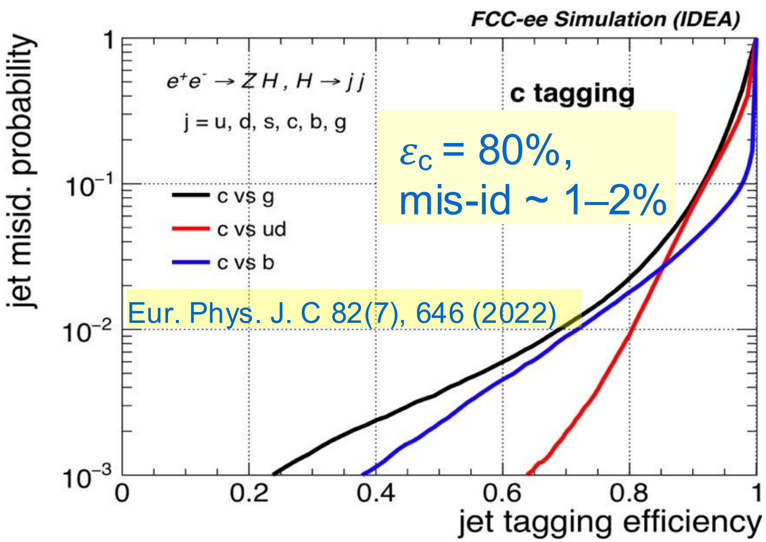
H→qq (hadrons) and progress on jet flavour tagging

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)





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

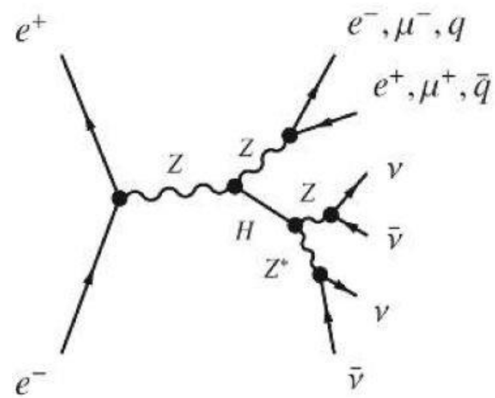
Uncertainty on σ * BR in %

$\sqrt{s}$	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

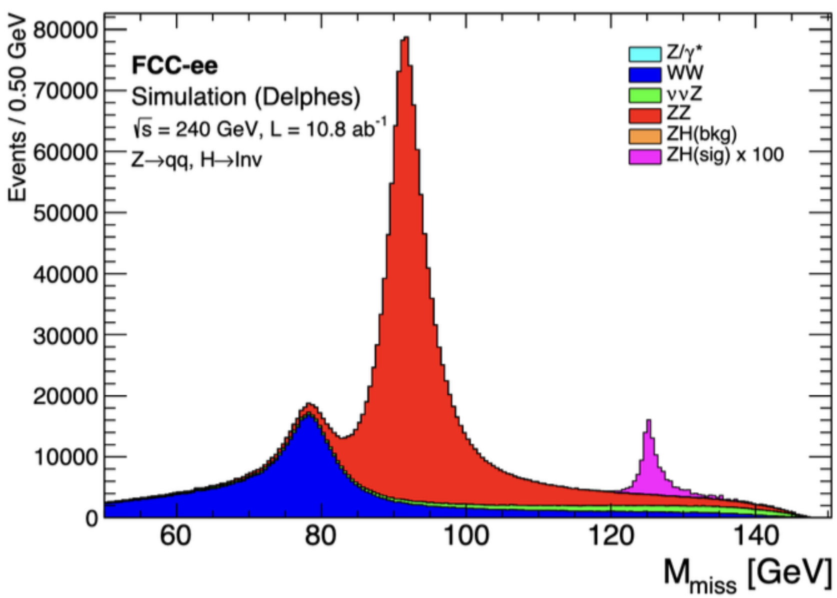
doi: 10.17181/n78xk-qcv56

Higgs to invisible particles analysis

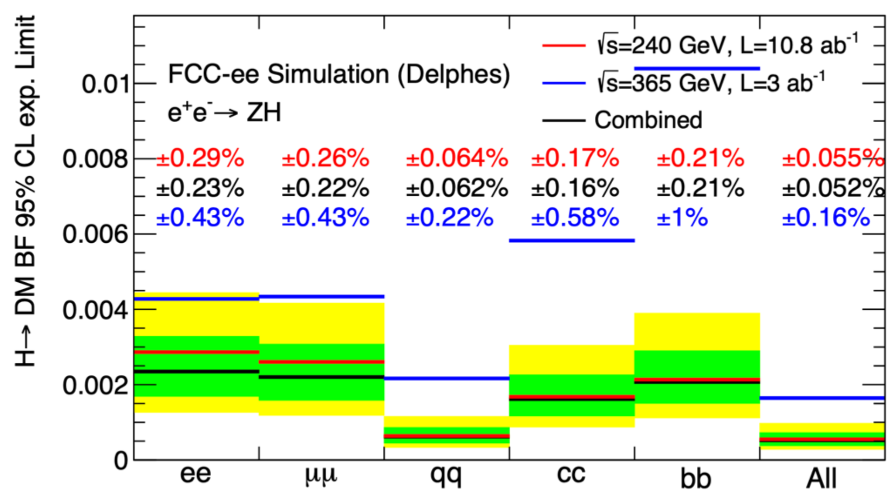


- only invisible decay in the SM: H → ZZ → νννν (BR = 0.106%)
- best individual measurements from ZH→qq + missing energy using recoil mass or missing mass at the Z peak
  - → requires excellent hadronic energy resolution
- tag the Z using muon, electron and hadron final states (qq and bb), Z peak [87, 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
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 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-percent-level precision.
- Couplings to H →cc can be measured at the percent 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 Zγ, μμ (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)

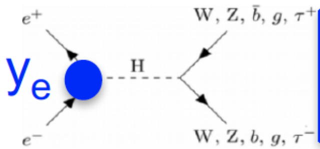
Higgs Yukawa coupling to electron

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:

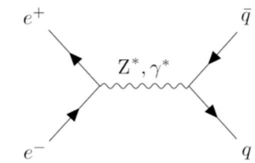
- the Yukawa coupling of the electron is $y_e = \sqrt{2}\, m_e/v = 2.8 \cdot 10^{-6}$
- $BR(H \rightarrow e^+e^-) \approx 5 \times 10^{-9}$



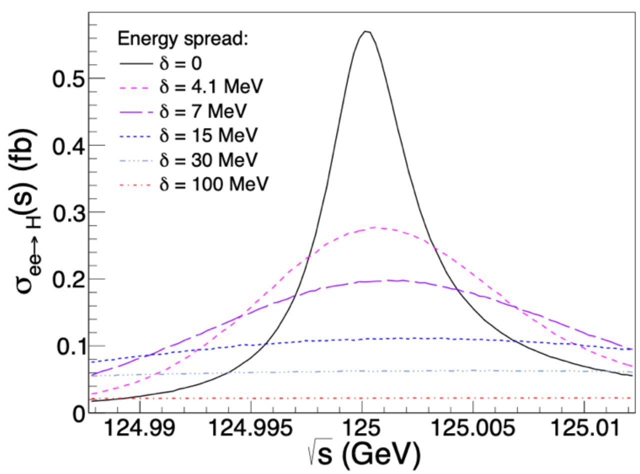
$\sigma(e^+e^- \rightarrow H)_{B\text{-}W} = 1.64$ fb as peak cross section

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

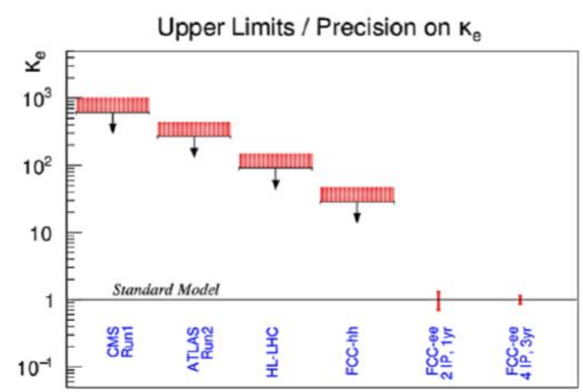
Main background



- 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**

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:

$$\Sigma_{\rm NLO} = \boxed{Z_H}\,\Sigma_{\rm LO}(1+\kappa_\lambda \boxed{C_1}) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$

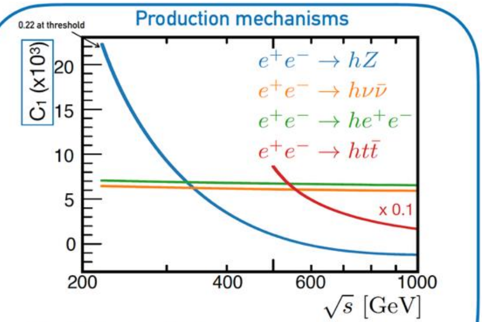
Z_H: Universal coefficient from wave function

C_1: Process and kinematic dependent coefficient

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

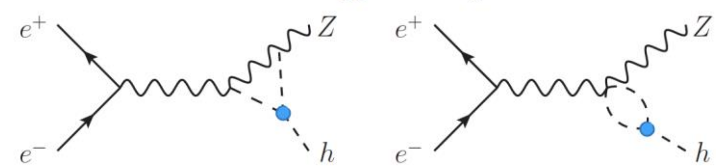


Negligible impact of a modified λ_{HHHH} on the angular asymmetries. At 1-loop C_1 for HZ, WW-boson fusion and ZZ-boson fusion are independent of the beam polarization.

Vertex corrections (linear in k_λ)

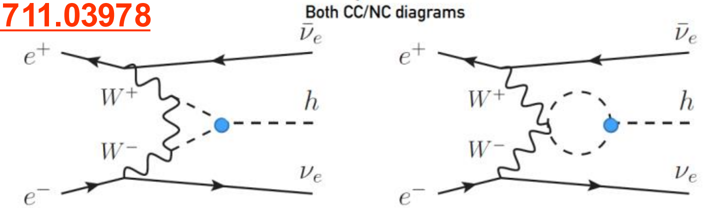
arXiv:1607.04251
arXiv:1711.03978

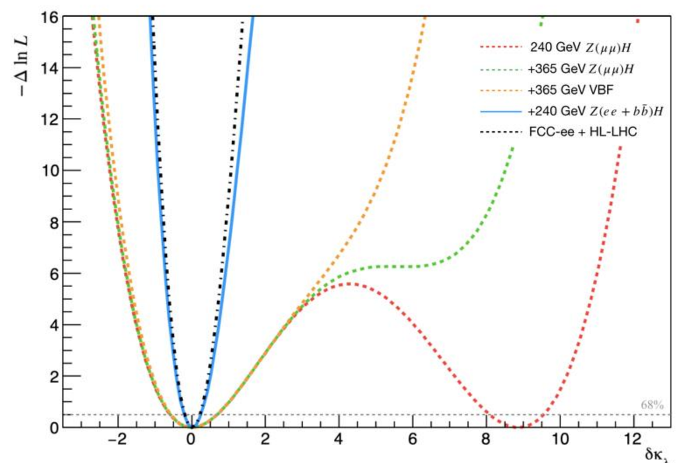
ZH Higgsstrahlung



VBF processes

Both CC/NC diagrams



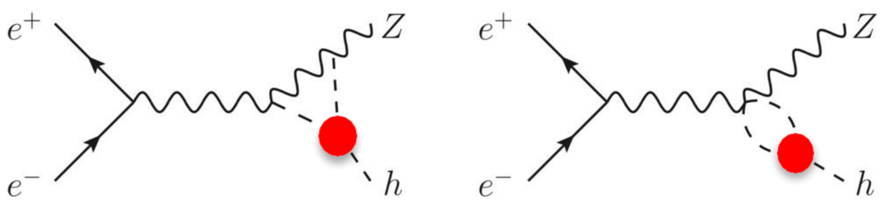


The secondary minimum easily excluded adding a 2nd energy point

Higgs self coupling at FCC-ee ($\sqrt{s}$ < 500 GeV)

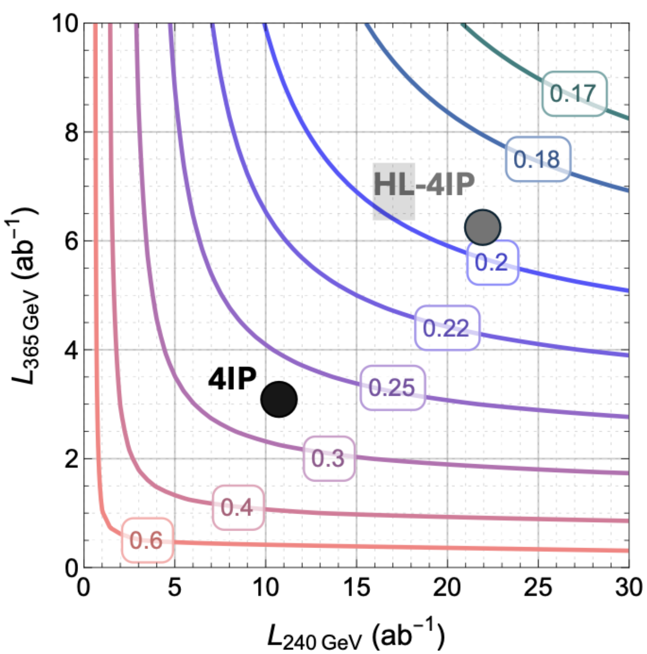
NB: 365 GeV → ZHH threshold, but too low ZHH x-section

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 $\sqrt{s}$ needed to determine separately λ_3 and g_{HZZ}.



- Recent: 4 IPs. Running at $\sqrt{s}$ = 240 and 365 GeV

→ **$\delta\kappa_\lambda$ ~ 28% for FCC-ee**

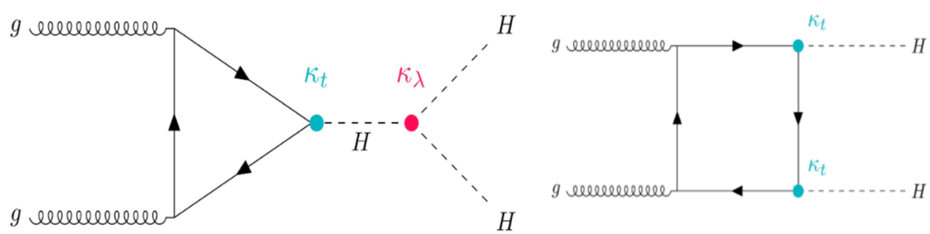
~ 18% (combining with HL-LHC)

arXiv:2505.00272v1

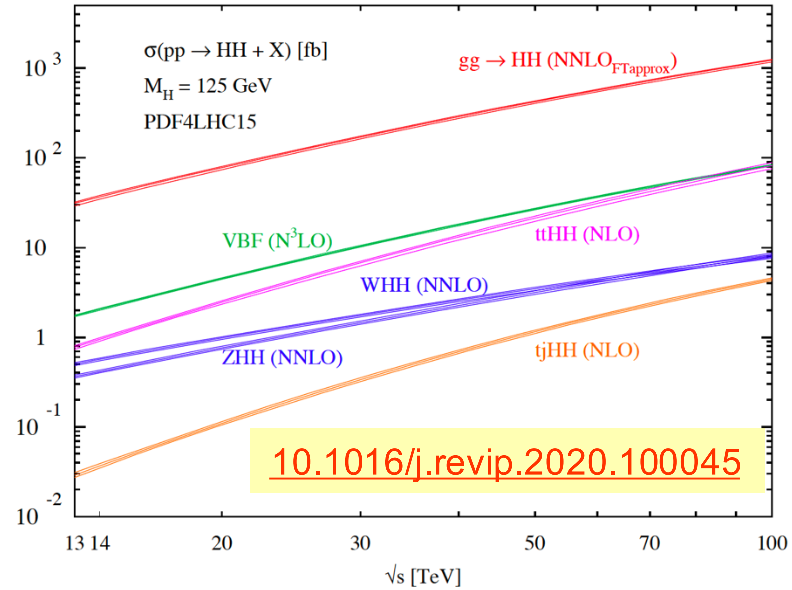
With 4 IPs: 5σ observation of λ_3 within reach with 15 years of operation at FCC-ee

Higgs self coupling at FCC-hh via HH

Gluon gluon Fusion (ggF)

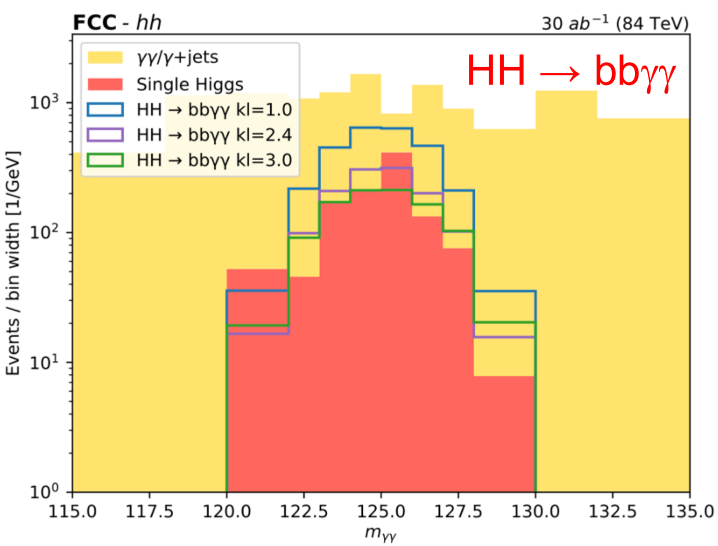


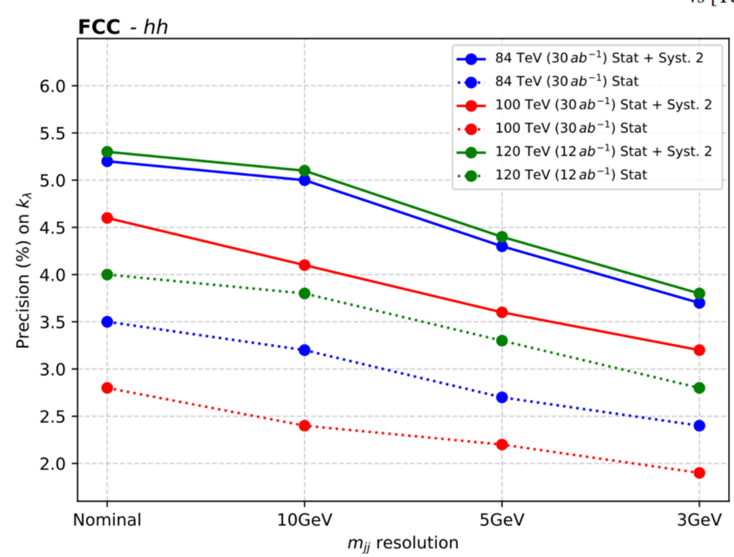
destructive interference



10.1016/j.revip.2020.100045

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





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

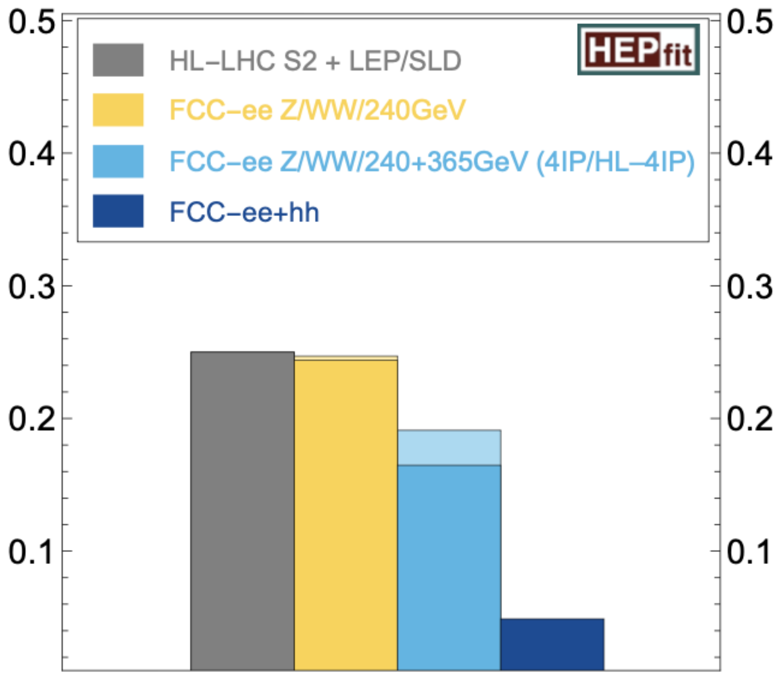
Exp. prec. on κ_λ @ 68% C.L.:

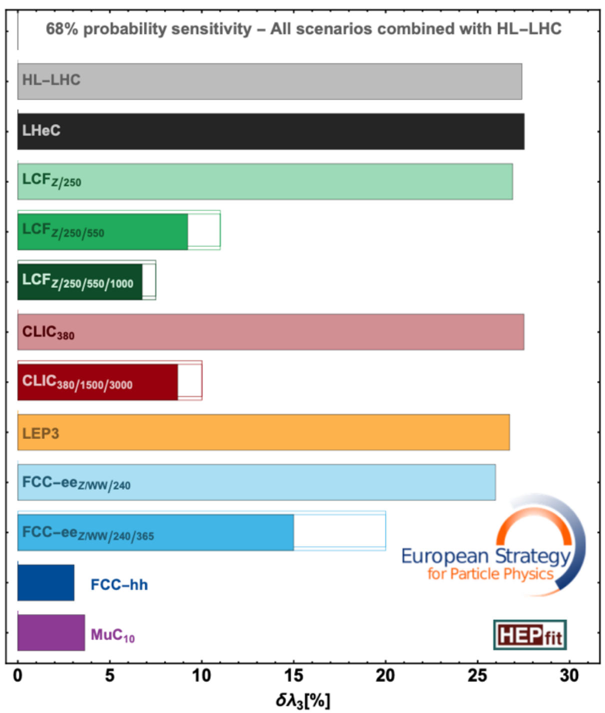
- 3.2% to 5.4% at 84 TeV
- 2.8% to 4.8% at 100 TeV

doi:10.17181/w6928-gr929

Precision on Higgs self couplings

HL-LHC	+FCC-ee	+FCC-hh
26–29%	~18%	2–3%





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!

Backup

Open Symposium on the European Strategy for Particle Physics

23–27 giu 2025
Venice Lido
Europe/Rome fuso orario

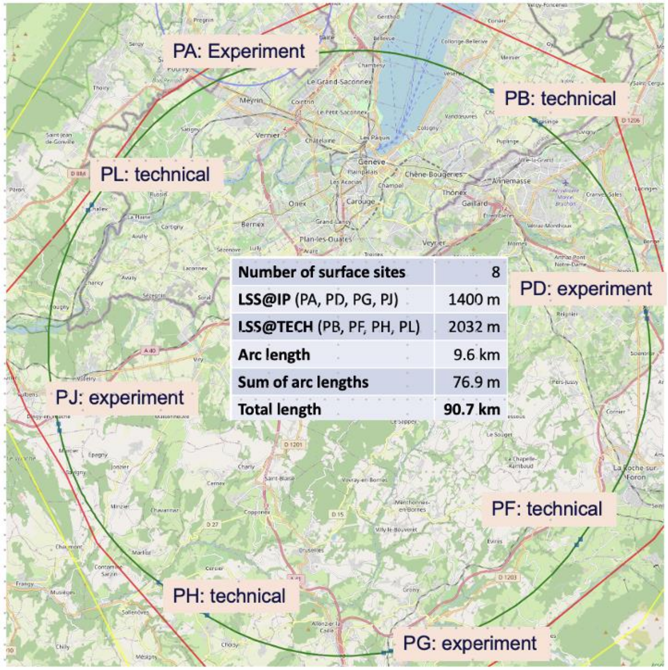
Inserisci il termine di ricerca

European Strategy 2025

FCC Feasibility Study

- Started in 2021 → Report completed in March 2025, earlier than initially planned, to align with ESPP input submission deadline
- It covers the geological, technical, environmental and territorial feasibility of a 91-km ring and its infrastructure in the Geneva basin, and scientific potential and required technologies for FCC-ee and FCC-hh. Good progress also on financial aspects (→ see later)
- Total cost-to-completion: **15.3 CHF billion for FCC-ee**
  ∽ 30 US billion for FCC-hh

Vol. 1: Physics, Experiments and Detectors (~ 260 pages)
Vol. 2: Accelerators, Technical Infrastructure and Safety (~ 600 pages)
Vol. 3: Civil Engneering, Implementation and Sustainability (~ 330 pages)



Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	90.7 km

An extraordinary collective effort by the FCC community, involving some 1500 contributors from 162 institutions in 38 countries

The **breadth and depth of the results are unprecedented for a project at this stage of development.**

Report being reviewed by expert committee, and then by Council and its subordinate bodies before end of year.

Ring placement selected out of ~ 100 variants taking into account geological, environmental, surface (land availability, access to roads, etc.), infrastructure (water, electricity, transport) constraints, machine performance, etc.

European Strategy

PR07.25
27.06.2025

Venice event brings future of particle physics into focus

Venice, Italy, 27 June 2025. This week, more than 600 scientists met in Venice, Italy, to debate the future direction of European particle physics in the global context. The Open Symposium is an important step in the ongoing update of the European Strategy for Particle Physics (ESPP), providing particle physicists in Europe and beyond with an opportunity to assess scientific priorities and technological approaches for the medium- and long-term future.

The Strategy recommendations, which will reflect the ambitions and priorities of the community, are expected to be submitted to the CERN Council in early 2026. Projects are approved by the Council through a separate decision-making process, taking the Strategy recommendations and other considerations into account.

The previous ESPP update in 2020 emphasised the importance of ensuring Europe's continued scientific and technological leadership. Building on the discovery of the Higgs boson at CERN's Large Hadron Collider (LHC), it recommended an electron-positron "Higgs factory" as the highest-priority next facility after the LHC reaches the end of its operational lifetime in 2041 and that Europe should have the long-term ambition to operate a proton-proton collider at the highest achievable energies.

"The time is ripe to forge a brilliant future for our field in Europe, together with our global partners," said Fabiola Gianotti, CERN Director-General. "The worldwide CERN community's achievements in implementing the 2020 ESPP update prove that we are a strong community, capable of designing, building and operating facilities of astounding complexity that consistently exceed expectations. This is our greatest asset as we prepare for even more ambitious projects."

A total of 266 submissions from the community, spanning all aspects of particle physics, formed the basis for vibrant discussions during the week-long Open Symposium. Participants from almost 40 countries, including many early-career researchers, expressed the need for an ambitious and innovative research programme that will maintain CERN as a world-leading centre for collider physics while also ensuring a diverse programme that maximises physics reach and includes approaches complementary to colliders. Contributions from researchers in neighbouring fields also demonstrated the rich connections between particle physics and nuclear and astroparticle physics.

Identifying the most promising flagship collider to succeed the LHC at CERN is a central aim of the 2026 ESPP update. In direct response to the 2020 Strategy update, a feasibility study for a Future Circular Collider (FCC) facility that could host a 91 km-circumference electron-positron collider followed by an energy-frontier proton-proton collider in the same tunnel was conducted, and the report was released in March 2025. In addition to the FCC, other projects under consideration in the relevant time frame are an electron-positron linear collider at CERN and smaller colliders that would re-use the LHC tunnel. Great progress has also been made towards a muon collider, but several years of R&D work are still needed to demonstrate its feasibility.

National input from members of the high-energy physics communities in CERN's 25 Member States so far indicate broad support for the FCC programme on account of its outstanding scientific potential and long-term strategic value. Underscoring the importance of continued dialogue and assessment, discussions on alternative options will continue. Several important steps remain before the ESPP recommendations are finalised. Expert ESPP panels are working on a comparative evaluation of proposed future colliders in terms of their physics potential, environmental impact and sustainability, technical maturity, cost, required human resources and implementation timelines.

"I am happy to see that the recommendations of the 2020 ESPP update and their implementation via the FCC Feasibility Study enjoy overwhelming support from the vast majority of the high-energy physics community as well as leading experts," said Costas Fountas, President of the CERN Council. "The discovery of the Higgs boson at the LHC in 2012 marked the start of a new journey of discovery that can only be realised by a future collider with the broadest and most powerful research programme, and the CERN Council eagerly awaits the community's final recommendations."

The ESPP conclusions are eagerly awaited, as delays in reaching agreement on which collider should follow the LHC are viewed by the community as a risk to CERN's leadership and its potential to attract interest from scientists across the world.

Following rich dialogue at the Open Symposium, discussions will continue in the coming months. Together with a second round of input from the national communities, which is to be submitted by 14 November, they will provide the basis for the final Strategy recommendations to be drafted in December.

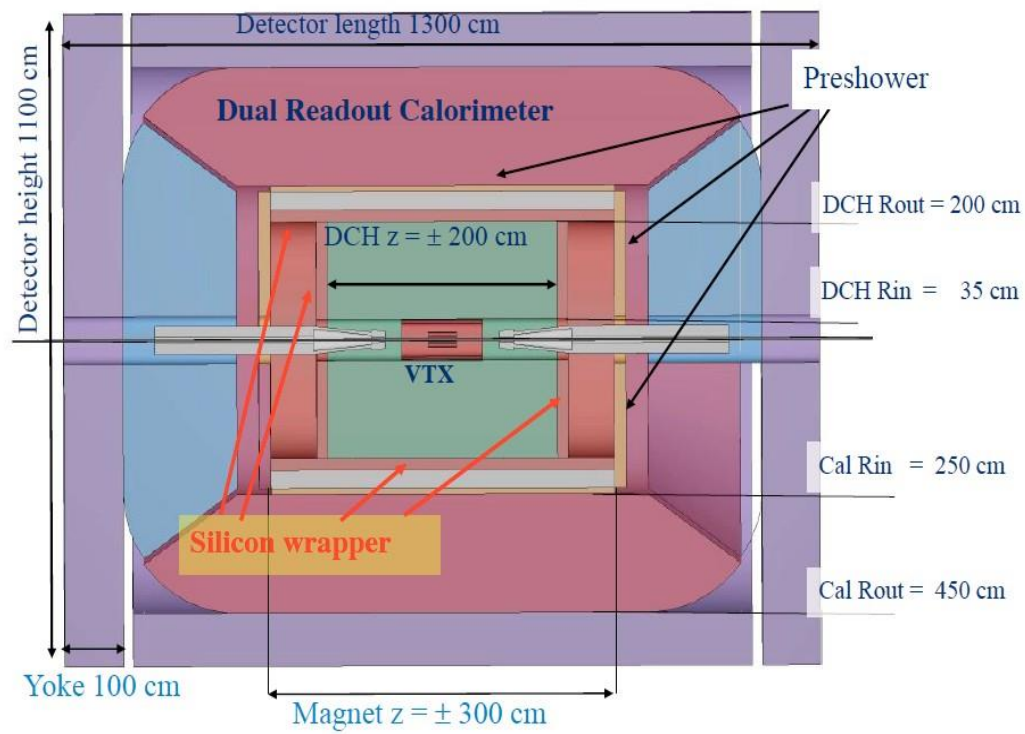
"I am pleased to see so many colleagues from Europe and beyond participating actively in debating the scientific input received from the particle physics community in order to define the next large accelerator project that will allow CERN and Europe to maintain their leading role in our field," said Karl Jakobs, Strategy Secretary. "In addition, the scientific goals and priorities in other areas of physics were discussed. We anticipate further rich input and discussion as the 2026 ESPP update enters its final strait."

Detector requirements for an experiment at FCC-ee

Critical Detector	Required Performance
Tracker	$\Delta(1/p_{\mathrm{T}}) \sim 2 \times 10^{-5} \oplus 1 \times 10^{-3}/(p_{\mathrm{T}} \sin\theta)$
Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

As an example: **IDEA** proposal

- a silicon pixel vertex detector
- a large-volume extremely-light drift wire chamber
- surrounded by a layer of silicon micro-strip detectors
- a thin low-mass superconducting solenoid coil
- a preshower detector
- a dual read-out calorimeter
- muon chambers inside the magnet return yoke



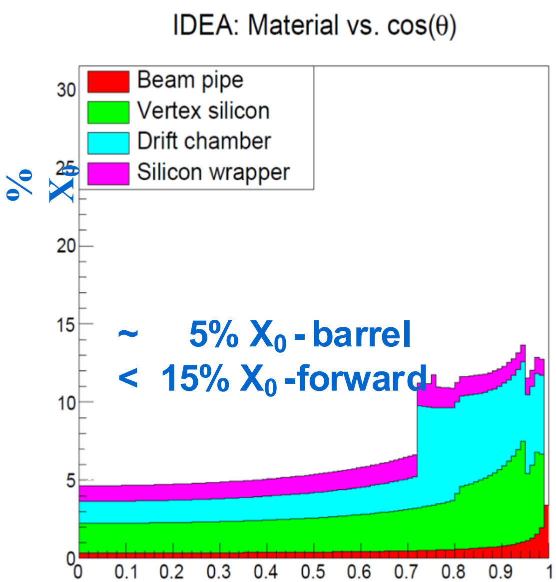
Requirements on track momentum resolution

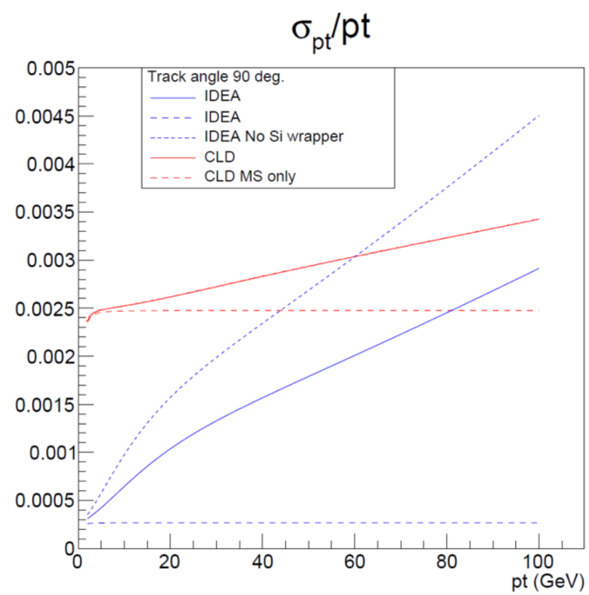
The IDEA Drift Chamber is designed to cope with transparency

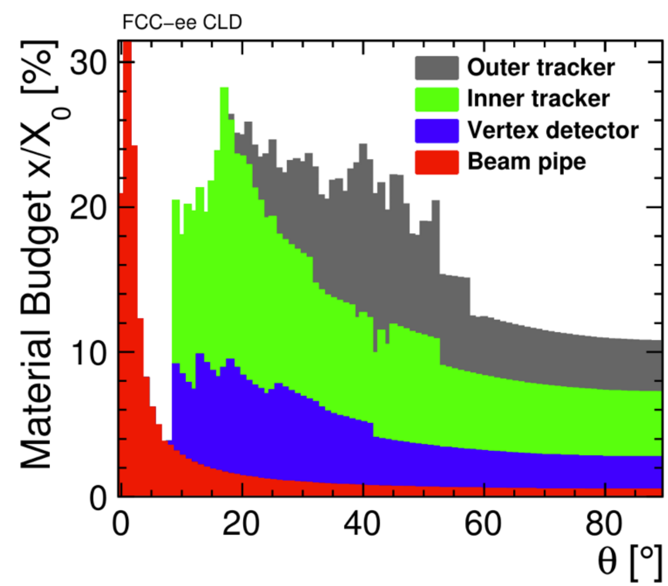
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius 0.35m, outer radius 2m
- length L = 4m

The CLD silicon tracker is made of:

- six barrel layers, at radii ranging between 12.7 cm and 2.1 m, and of eleven disks.
- the material budget for the tracker modules is estimated to be 1.1 – 2.1% of a radiation length per layer







For 10 GeV (50 GeV) μ emitted at an angle of 90° w.r.t the detector axis, the p_T resolution is

- about 0.05 % (0.15%) with the very light IDEA DCH
- about 0.25% (0.3%) with the CLD full silicon tracker, being dominated by the effect of MS

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

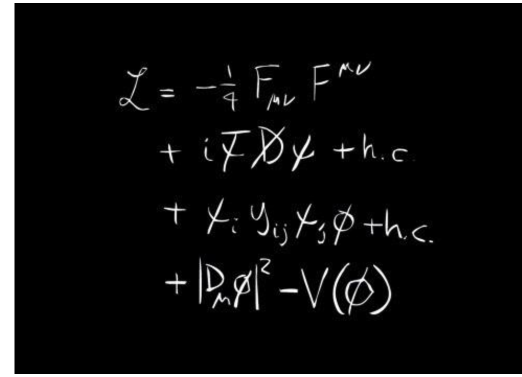
Uncertainty on σ * BR in %

$\sqrt{s}$	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	±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	$< 6.5 \times 10^{-4}$			

doi: 10.17181/n78xk-qcv56

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

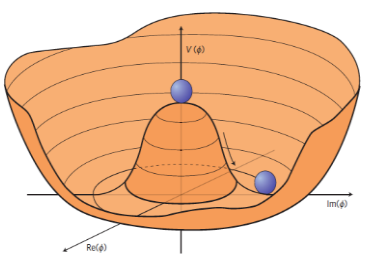


$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

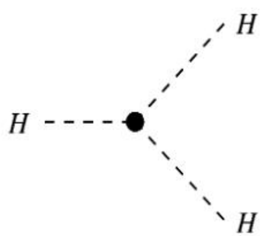
$$m_H = \sqrt{2\lambda v^2}$$

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

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



Mass term

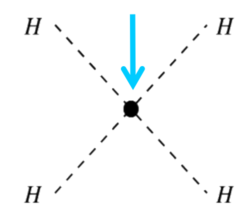


Higgs trilinear self-coupling (κλ)

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

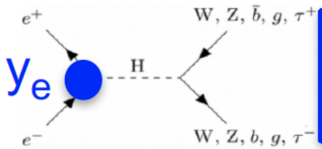
Higgs Yukawa coupling to electron

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:

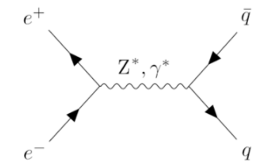
- the Yukawa coupling of the electron is $y_e = \sqrt{2}\, m_e/v = 2.8 \cdot 10^{-6}$
- $BR(H \rightarrow e^+e^-) \approx 5 \times 10^{-9}$



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

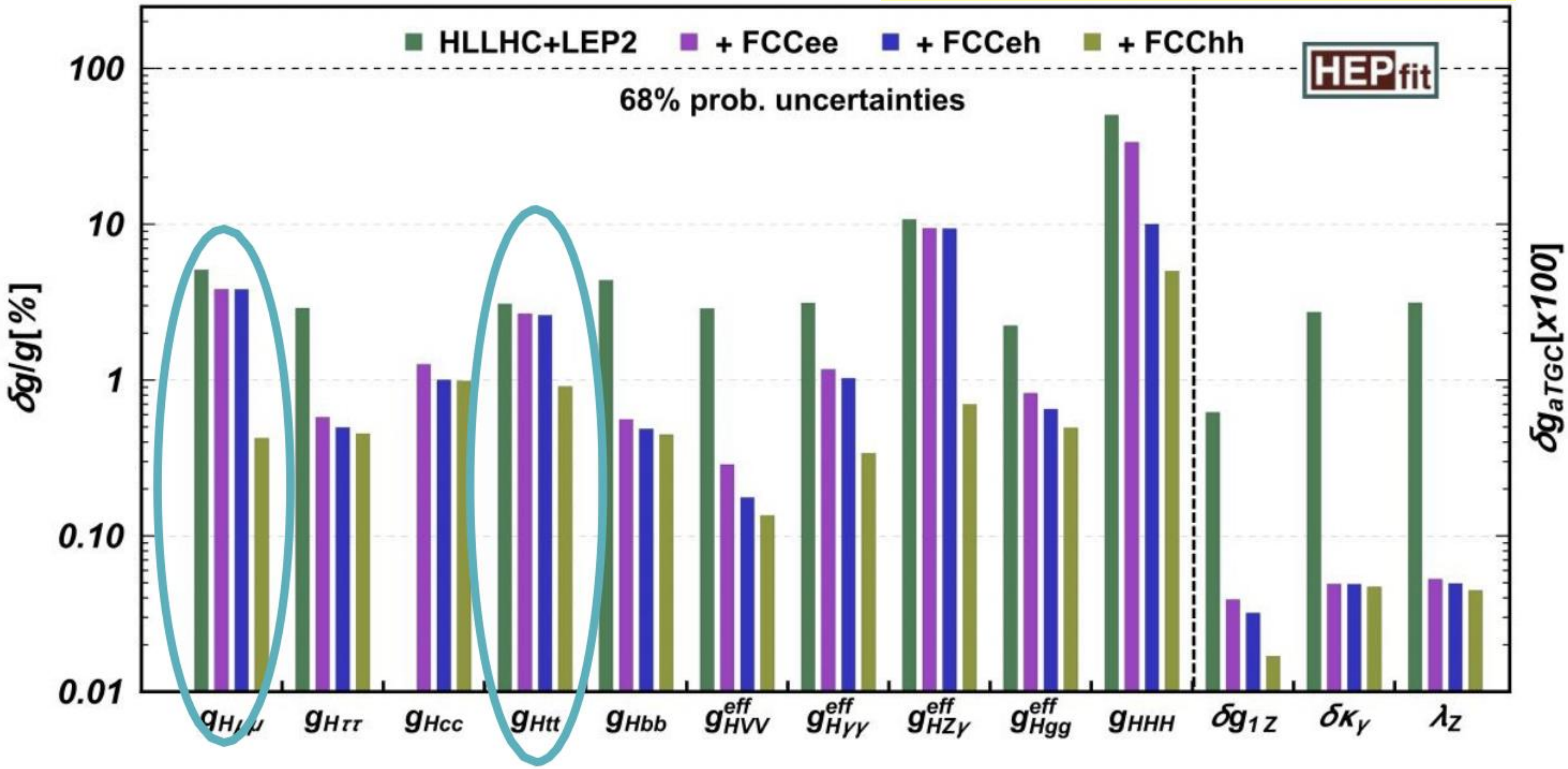
FCC-hh will produce about 30 billion Higgs bosons in 30 ab^{-1} allowing measurements of $H \rightarrow \gamma\gamma$, $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$, , with 1-2% uncertainty (systematically limited)

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)

Comparison of accelerators