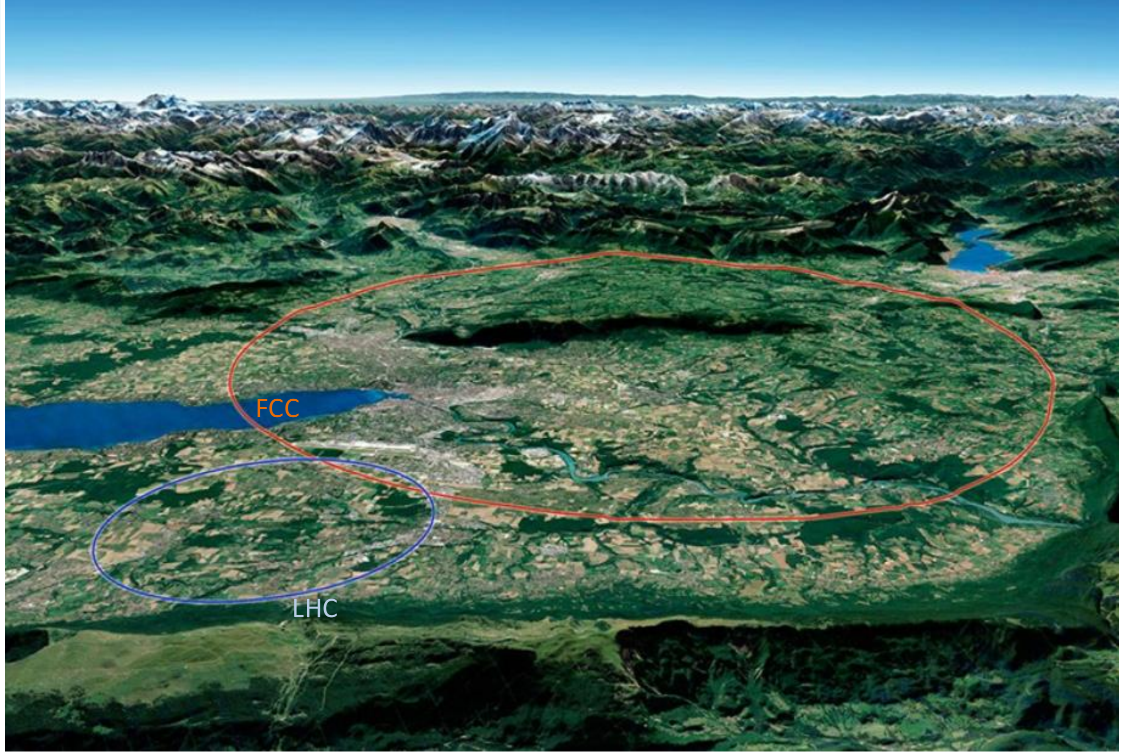

Precise Higgs mass measurements and Cross Section measurements at the FCC-ee

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On behalf of the FCC collaboration

ICHEP 2022, Bologna, 08/07/2022

Layout

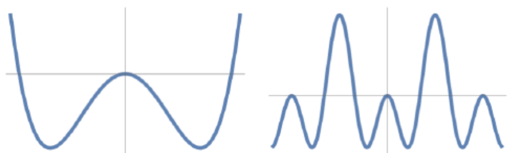
- What is FCC, and the FCC-ee Higgs/Physics potential
- Higgs mass and cross section measurements at FCC-ee
- Other Higgs measurements
- Next steps

Even after HL-LHC, the Higgs boson/field will still need to be better understood

→ The Higgs boson is a unique object, a scalar particle/field (spin 0), not a matter field, not a boson mediating a gauge interaction, but a field carrying a new type of interaction of the Yukawa type.

→ Many proposals for new accelerators to study it beyond LHC, and to study Beyond SM physics.

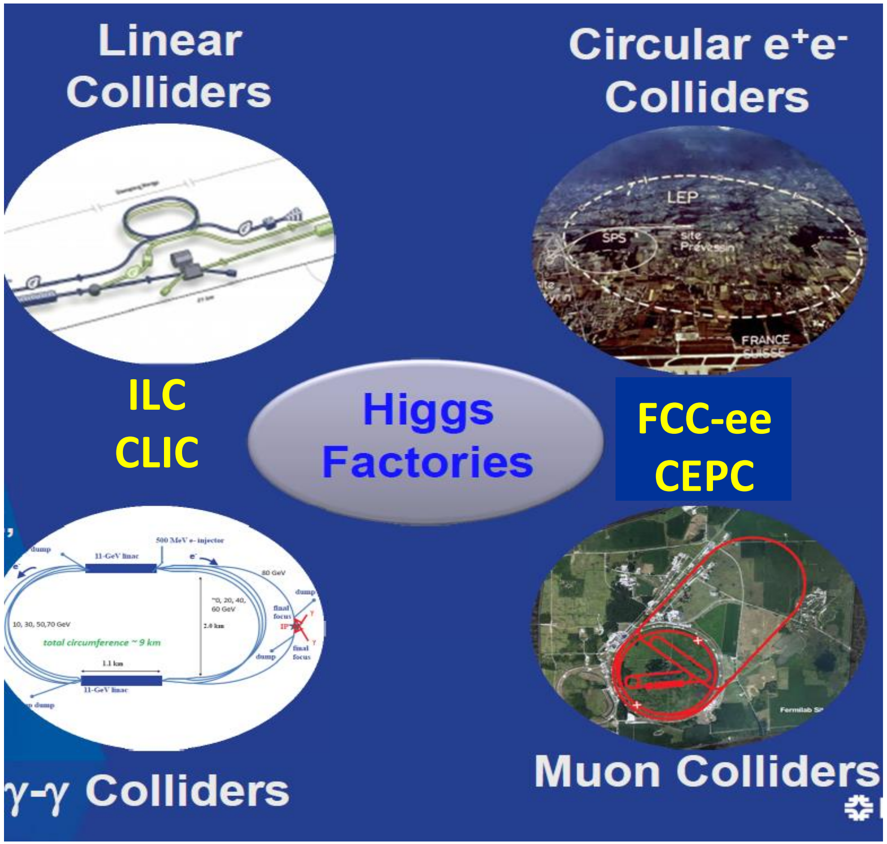
- Precise nature of the Higgs boson ?
- Origin of electroweak symmetry breaking (EWSB) ?
- Shape of the Higgs potential ?



Landau-Ginzburg Higgs   Nambu-Goldstone Higgs

- Strength of the electroweak phase transition ? What is its role just after the big bang ? Inflation ? Does it couple to Dark Matter ?

➔ We need to determine precisely and in a model independent way the Higgs couplings and the Higgs self-couplings to answer these questions.



The FCC integrated program (ee+hh) at CERN is inspired by the successful LEP – LHC (1976-2041) program

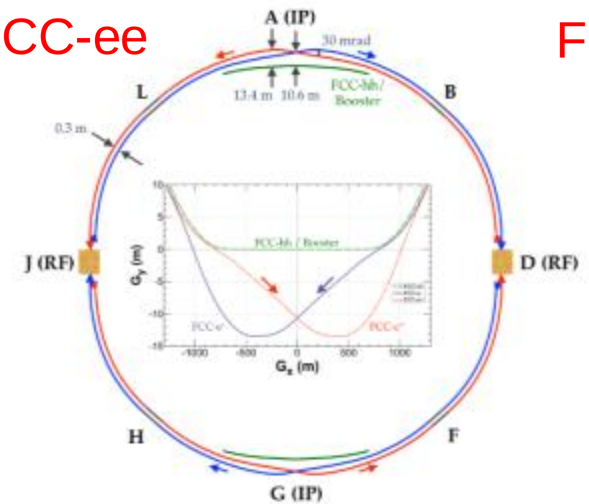
Comprehensive cost-effective program maximizing physics opportunities

- Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs, EW and top factory at highest luminosities.
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with heavy ions and eh options.

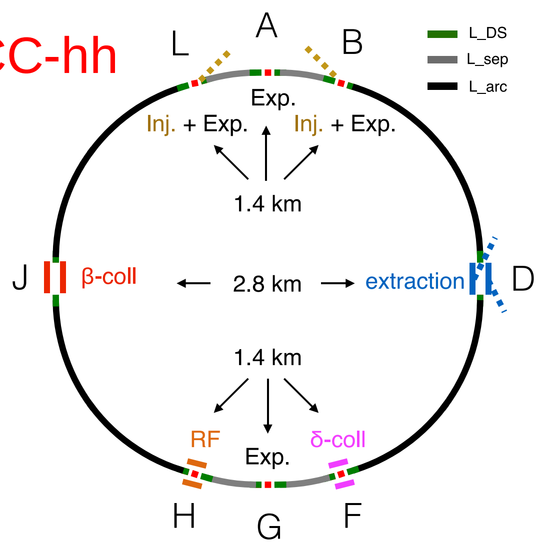
Complementary physics

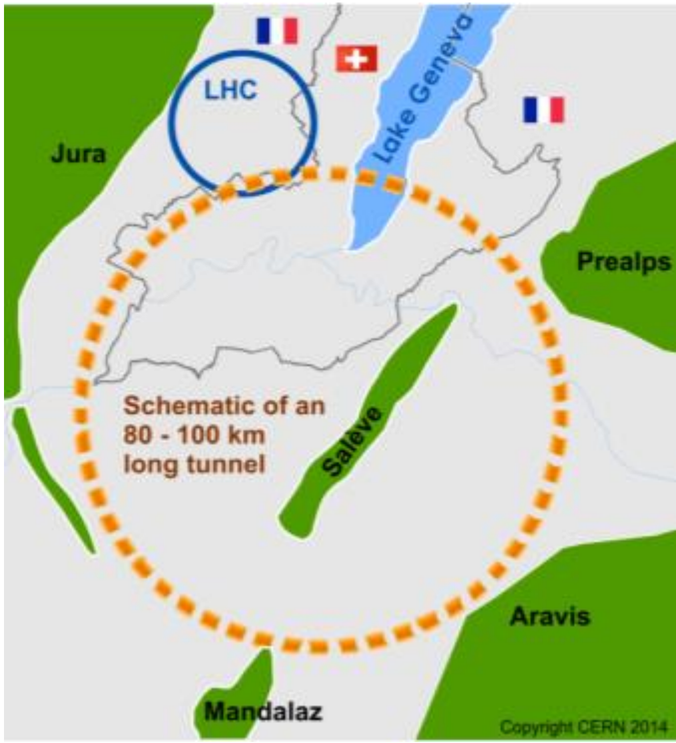
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.
- FCC-INT project plan is fully integrated with HL-LHC exploitation

FCC-ee



FCC-hh





The Rich FCC-ee physics program

M. Dam ECFA R&D road map input
https://indico.cern.ch/event/994685/

"Higgs Factory" Programme

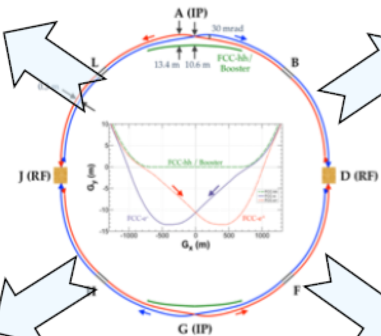
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W...
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

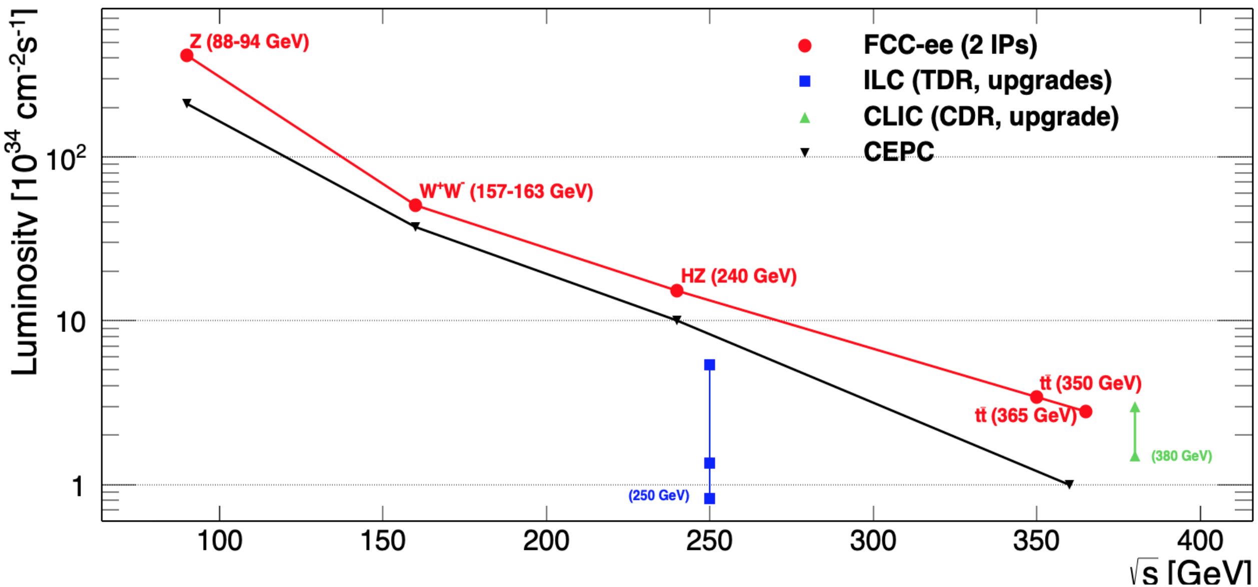
- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z:

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes - LLPs

FCC-ee run plan

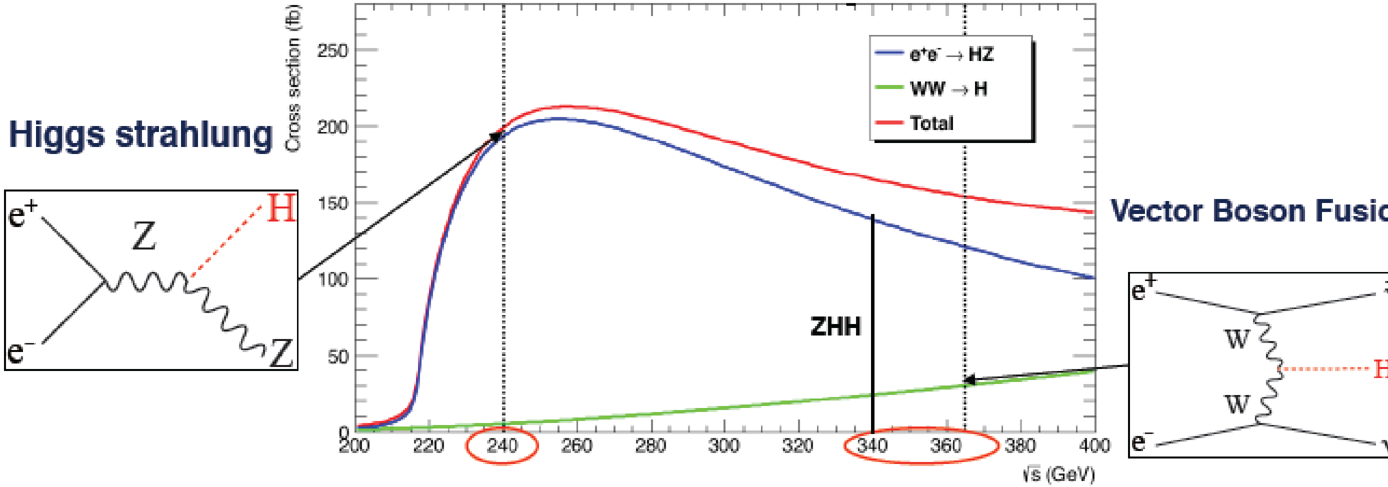


Phase	Run duration (years)	Center-of-mass Energies (GeV)		Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	± <100 KeV	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	<200 KeV	12	10^8 WW events
FCC-ee-H	3	240	± 2 MeV	5	10^6 ZH events
FCC-ee-tt	5	345-365	± 5 MeV	1.5	10^6 $t\bar{t}$ events
s channel H	?	125	± 2 MeV	10?	5000 events

Extracted from FCC CDR

LEP * 10^5
LEP * 2.10^3
Never done
Never done
Never done

Higgs boson production at FCC-ee



FCC-ee as a Higgs factory:

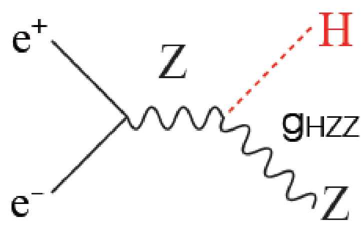
Higgs-strahlung (e+e → ZH): event rate & Signal/Bkgd are optimal at √s ~ 240 GeV : σ ~200 fb

- 10^6 e+e- → ZH events with 5 ab^{-1}
- Target : (few) per-mil precision, statistics-limited.
- Complemented with ~200k events at √s = 350 – 365 GeV (of which 30% are via the WW fusion channel)
  → useful for measuring self-coupling and Γ_H precisely.

- The Higgs-strahlung process is an *s*-channel process → maximal just above the threshold of the process
- Vector Boson Fusion is a *t*-channel process which yields a cross section that grows logarithmically with the c-o-mass energy

Higgs studies through recoil mass in ZH production, vs. Higgs @LHC

@FCC-ee : The Higgs mass can be reconstructed from **M_{recoil}** in ZH events using the Z decaying leptonically and beam energy constraints, w/o looking at the H decay.

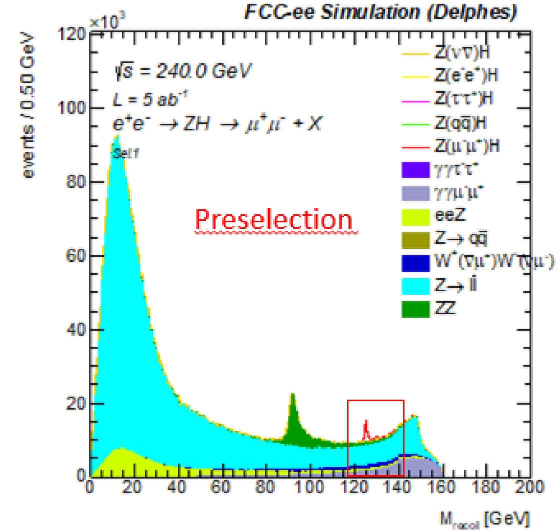


$$\boxed{m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)}$$

E_+, E_- lepton energies from Z decay

$$\sigma\left(e^+e^- \rightarrow ZH\right) \propto g_{HZZ}^2$$

absolute HZZ coupling meas.

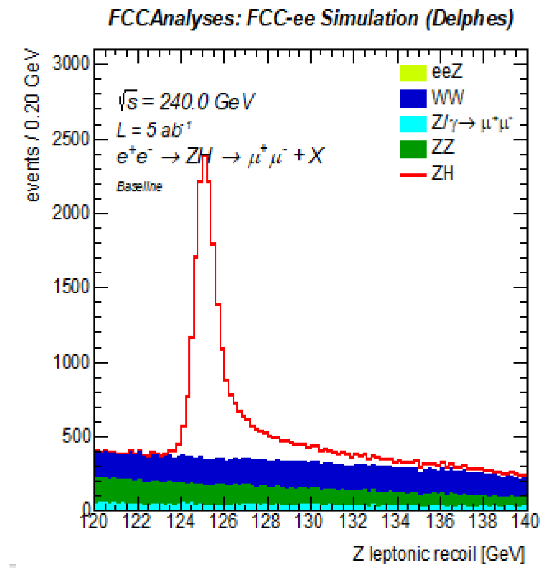


➢ Signal Simulation:

1. $Z(\mu^+\mu^-)H$ (Whizard)
2. $Z(\tau^+\tau^-)H$ (Whizard)
3. $Z(q\bar{q})H$ (Whizard)
4. $\nu_e\bar{\nu}_e H$ (Whizard)
5. e^+e^-H (Whizard)

➢ Backgrounds Simulation:

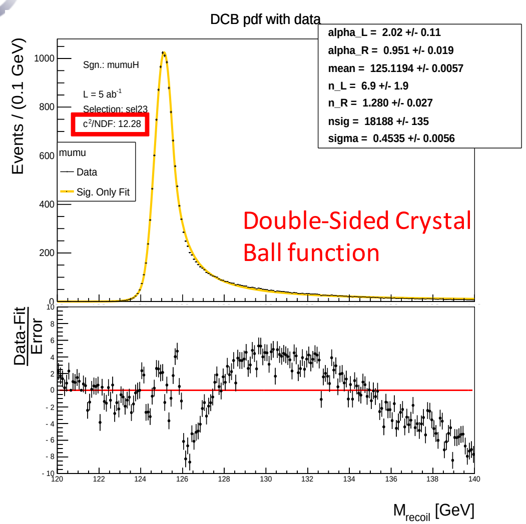
1. ZZ(inclusive) (Pythia)
2. $W^+(\nu\mu^+)W^-(\bar{\nu}\mu^-)$ (Pythia)
3. $Z \rightarrow l^+l^-$ (Pythia)
4. $Z \rightarrow q\bar{q}$ (Pythia)
5. eeZ (Whizard)
6. $\gamma\gamma \rightarrow \mu^+\mu^-/\tau^+\tau^-$ (Whizard)

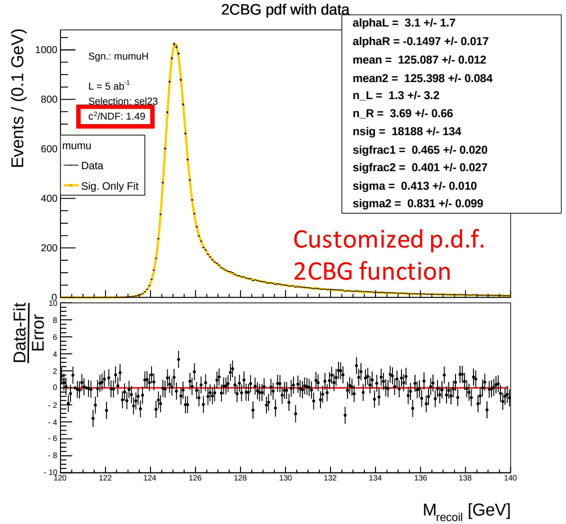


Event Selection:

1. Preselection: at least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV → focus on Z resonance space
3. $M_{recoil} \in [120, 140]$ GeV → Signal exhibits sharp peak around ~ 125 GeV,
4. $p_T^{\mu^+\mu^-} \in [20, 70]$ GeV → Low $p_T^{\mu^+\mu^-}$ cuts back-to-back events ($Z/\gamma^* \rightarrow ll$)
5. $|\cos\theta_{missing}| < 0.98$ → Reduce $\gamma\gamma$ processes. ISR emitted collinearly with the incoming beams, escaping detection in the beam pipe

Signal and background fits



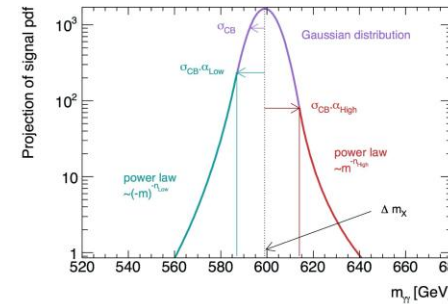


Double sided Crystal-Ball function:

$$f_S(x;\vec{\theta}) = \begin{cases} \left(\frac{n_L}{|\alpha_L|}\right)^{n_L} \exp\left(\frac{-|\alpha_L|^2}{2}\right)\left(\frac{n_L}{|\alpha_L|} - |\alpha_L| - \frac{x-\mu}{\sigma}\right)^{-n_L}, & \text{for } \frac{x-\mu}{\sigma} \leq -\alpha_L \\ \exp(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2), & \text{for } -\alpha_L < \frac{x-\mu}{\sigma} < \alpha_R \\ \left(\frac{n_R}{|\alpha_R|}\right)^{n_R} \exp\left(\frac{-|\alpha_R|^2}{2}\right)\left(\frac{n_R}{|\alpha_R|} - |\alpha_R| + \frac{x-\mu}{\sigma}\right)^{-n_R}, & \text{for } \frac{x-\mu}{\sigma} \geq \alpha_R, \end{cases}$$

Gaussian Core

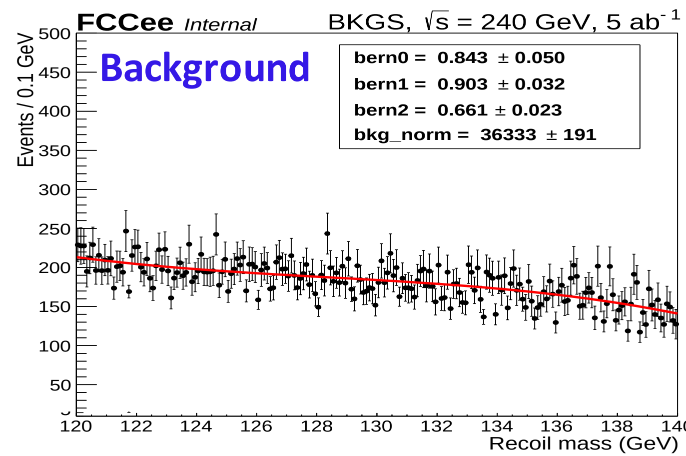
Power law tail on right and left



- Customized pdf: two crystal-ball functions (left/right), sharing mean & width, with an additional Gaussian to cope with the asymmetric tails
- $pdf(M_{recoil}) = sigfrac1 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_L, n_L) + sigfrac2 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_R, n_R) + (1 - sigfrac1 - sigfrac2) \cdot Gauss(M_{recoil}; \mu_2, \sigma_2)$

Statistical treatment of backgrounds:

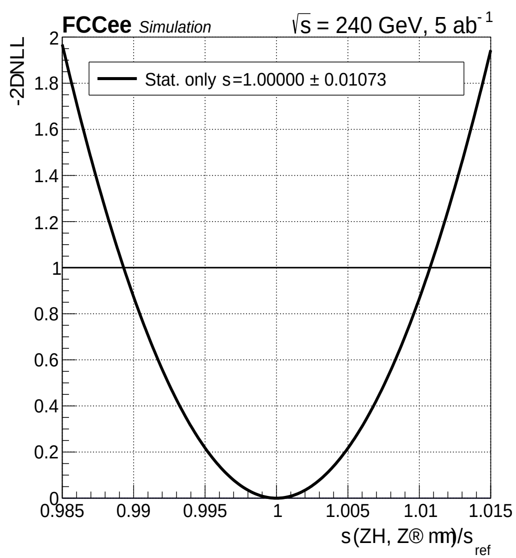
- All backgrounds are merged
- Smoothly falling background modelled as third-order polynomial fit
- Polynomial coefficients constant are fitted to the data (keep total normalization floating)
- Sufficient statistics for all backgrounds

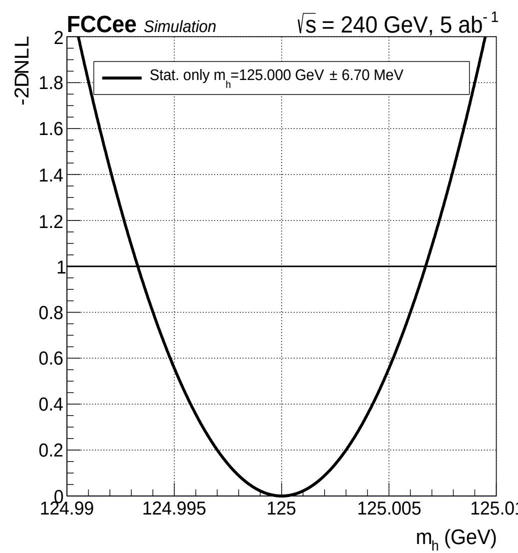


Statistical Analysis of the Results

Statistical analysis performed using Combine (CMS statistical framework)

- ❑ Signal and background analytical shapes are fitted to pseudo-data Asimov dataset
  - ➢ Injected 125.0 GeV signal with cross-section of ~ 0.00677 pb, and simulated backgrounds
  - ➢ Free parameters: signal and background normalizations, and m_H
- ❑ Likelihood scans to extract cross-section and Higgs mass with robust uncertainties
- ❑ First, without accounting for experimental uncertainties → statistical-only result





Statistical-only uncertainties:

- Higgs mass: 6.7 MeV
- Cross-section: 1.07 %

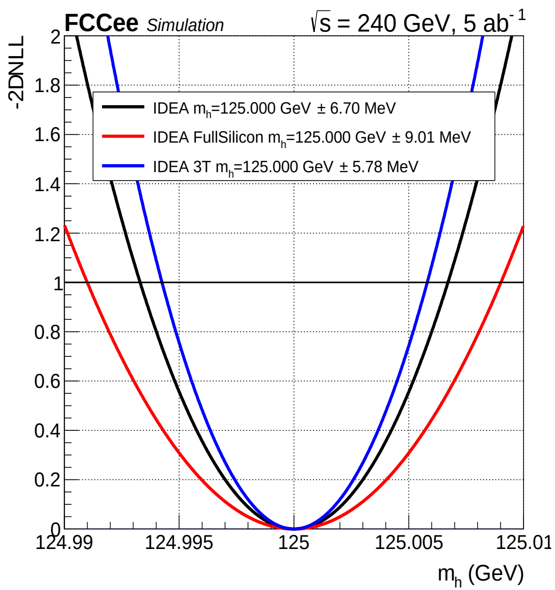
$Z(\mu^+\mu^-)H$ only,

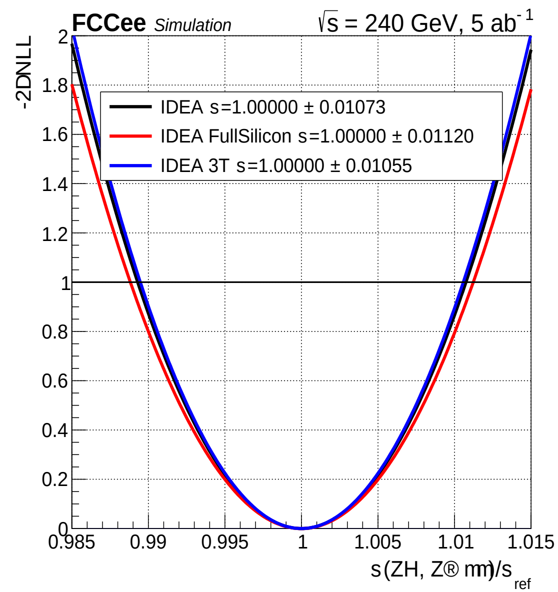
To be combined with other final states

Effect of Different Detector configurations

Different detector configuration studied:

1. Magnetic field increased from 2T to 3T → expect better momentum resolution
2. Full-Silicon tracker (à la CLD) instead of drift chamber → degraded resolution due to enhanced multiple scattering, especially at low p_T and in the range relevant for this analysis





results

IDEA	Δm_H (MeV)	$\Delta\sigma$ (%)
Nominal	6.7	1.07
FullSilicon	9.0	1.12
3T	5.8	1.06

2T → 3T

- significant effect on m_H
- small effect on x-section

Systematic uncertainties

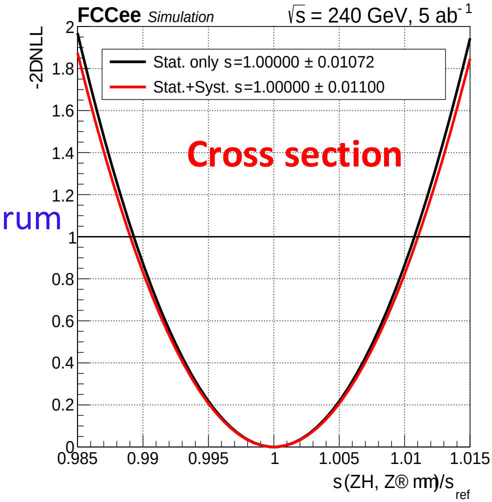
Systematic variations included in likelihood as Gaussian constraint terms

- muon scale accounts for ~ 2 MeV on Δm_H
- Beam Energy Spread (BES) ~ 1% at 240 GeV, constrained using $ee \rightarrow ff(\gamma)$
- Initial State Radiation (ISR) estimated using KKMC by reweighting Whizard p_T spectrum
- Muon momentum scale ~ 10^{-5}

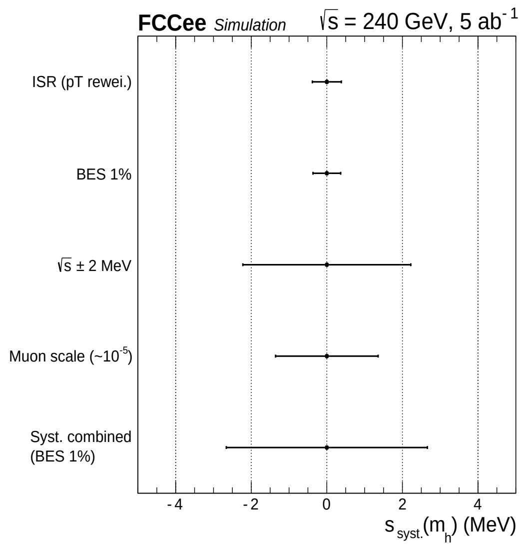
Inclusion of all systematics: $\boldsymbol{\Delta m_H \sim 7.2}$ **MeV and** $\boldsymbol{\Delta\sigma \sim 1.10\ \%}$

➔ Impact on cross-section precision is limited

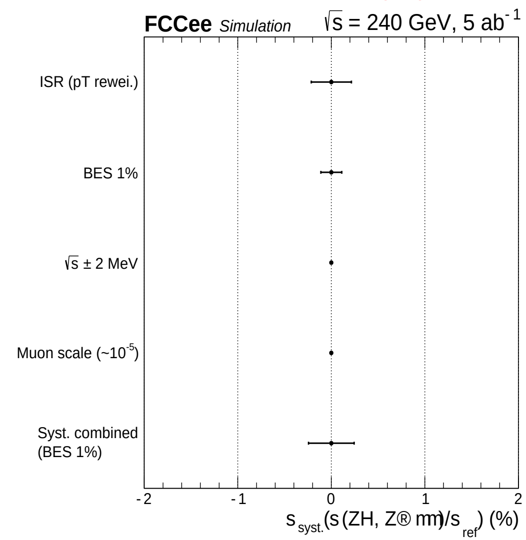
➔ further improvements combinining with Z→ee & jetjet

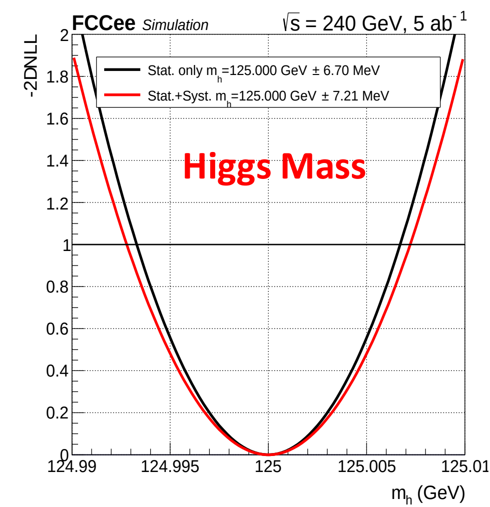


Higgs Mass (MeV)



Cross section (%)





Physics analysis program in the FCC-ee Higgs group

Global fits in κ-3 framework (arXiv:1905.03764)
Expected relative uncertainties on Higgs couplings

Ch.	HL-LHC	+ 240 GeV	+ 240+365 GeV	+ FCC-hh
κ_W	0.99	**0.88**	**0.41**	0.19
κ_Z	0.99	**0.20**	**0.17**	0.16
κ_g	2.00	**1.20**	**0.90**	0.5
κ_γ	1.60	1.3	1.3	0.31
$\kappa_{Z\gamma}$	10.0	10.0	10.0	0.7
κ_c	–	**1.50**	**1.30**	0.96
κ_t	3.20	3.10	3.10	0.96
κ_b	2.50	**1.00**	**0.64**	0.48
κ_μ	4.40	4.00	3.90	0.43
κ_τ	1.60	**0.94**	**0.66**	0.46
Inv.	1.9	**0.22**	**0.19**	0.024

Analysis not covered
Analysis ongoing

Intrinsic properties

- Mass
- Decay-mode independent cross section
- Width
- Invisible decays
- Self coupling

Higgs couplings

- Vector boson couplings, WW, ZZ
- Fermions
- Electron Yukawa coupling

LHC caveats, comparison with FCC

- LHC measures only couplings ratios
- Many SM couplings cannot be seen at LHC (light quarks, electror
- Couplings to gluons are measured through gg→H production cross section
- HL-LHC will produce much more Higgs than FCC-ee, hence dominate the precisions for ttH, Hμμ, HZγ until FCC-hh

All other couplings would be measured with better than 1% precision at FCC-ee with 4IP (except κ_s and 1st generation)

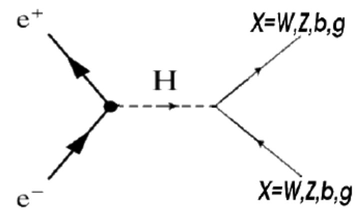
FCC-ee numbers are given for 2 IP. Precision on couplings improves by ~30% with 4IP

Yukawa coupling to electrons via s-channel e+e- → H production

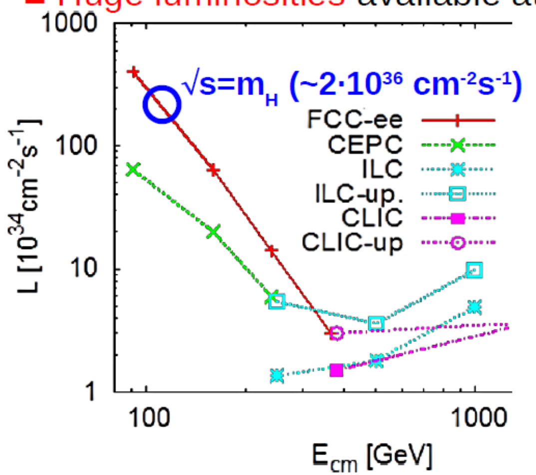
First generation Yukawa coupling will not be accessible at HL-LHC, FCC-hh or any other ee machine

- Higgs decay to e^+e^- is unobservable: $BR(H\to e^+e^-) \propto m_e^2 \approx 5\cdot10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu\to H) \approx 70$ pb. Tiny κ_e Yukawa coupling ⇒ Tiny $\sigma(ee\to H)$:

$$\sigma(e^+e^-\to H) = \frac{4\pi\Gamma_H^2 Br(H\to e^+e^-)}{(\hat{s}-M_H^2)^2+\Gamma_H^2 M_H^2} = 1.64\ \text{fb}\ (m_H=125\ \text{GeV},\ \Gamma_H=4.2\ \text{MeV})$$



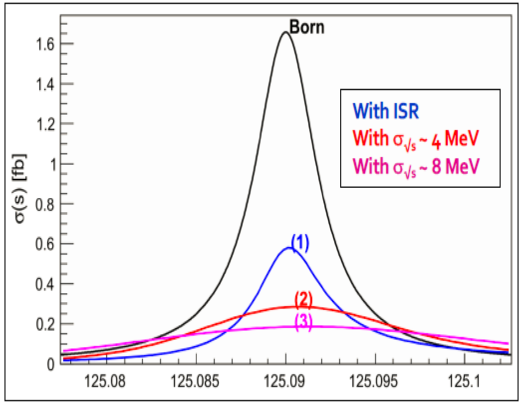
- Huge luminosities available at FCC-ee:

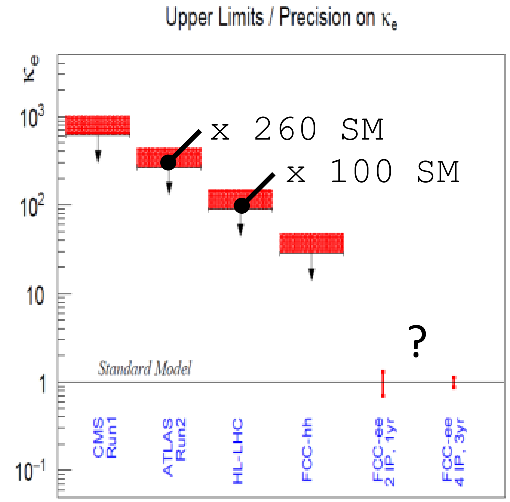


In theory, FCC-ee running at H pole-mass $L_{int} \approx 20\ ab^{-1}$/yr would produce O(30.000) H's

IFF we can control: (i) beam-energy spread, (ii) ISR, and (iii) huge backgrounds, then:

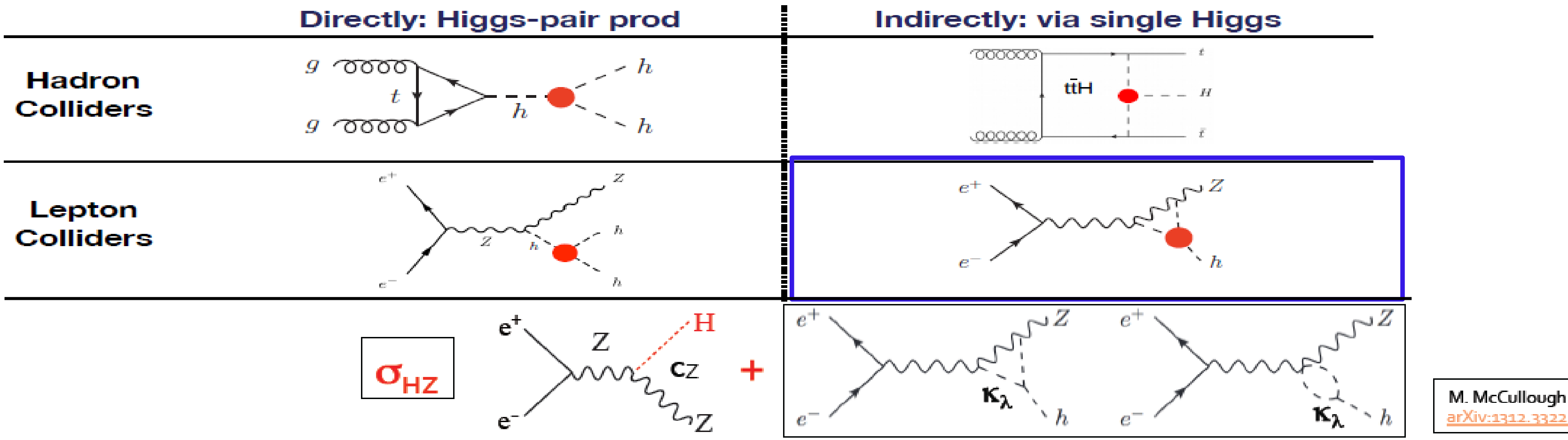
→ Electron Yukawa coupling measurable.
→ Higgs width measurable (threshold scan)?
→ Separation of possible nearly-degen. H's?



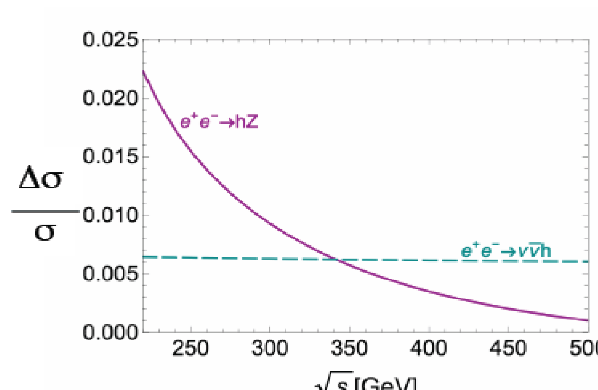


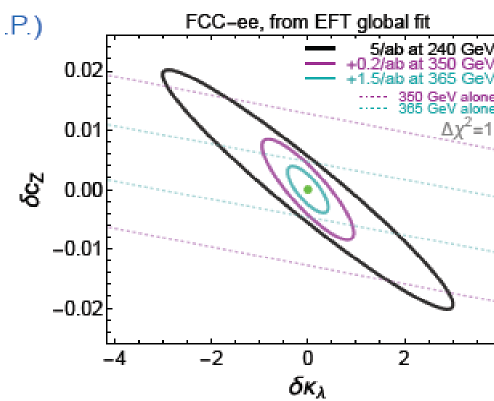
Most significant channel: e^+e^- → H → gg → jj final state

Measurement of the Higgs self-coupling



- assuming all other couplings at MS, $\Delta\kappa_\lambda/\kappa_\lambda \sim 19\%$ (12% 4 I.P.)
- maximum sensitivity at the threshold production





- from a global EFT fit $\Delta\kappa_\lambda/\kappa_\lambda \sim 21\%$ (4 IPs)
- changing CMS energy helps in reducing correlations

50% sensitivity: establish that $h^3 \neq 0$ at 95%CL
20% sensitivity: 5σ discovery of the SM h^3 coupling
5% sensitivity: getting sensitive to quantum corrections to Higgs potential

Summary and Outlook

- The Future Circular Collider is an ambitious project with optimized Physics potential in all SM areas, including in Higgs Physics, aimed at starting at CERN in e+e- mode, shortly after the end of the HL-LHC

- The analysis of Z($\rightarrow\mu\mu$) H events yields Higgs mass uncertainty of 7.2 MeV, and 1.10% for the cross-section. Improvements are under way (combining more channels, MVA selection to increase signal statistics…)
- Increasing detector magnetic field from 2T to 3T or using a transparent drift chamber vs. a full silicon detector brings significant improvement on m_H but has a small effect on the cross-section measurement.

- Couplings measurements are foreseen to achieve better than 1% precision (except for the few statistically limited, who will be precisely measured at FCC-hh and improved significantly over those from HL-LHC)

- At FCC-ee observation of H to ee Yukawa and of Higgs self-coupling may be achieved

More on the Higgs program and on the complementarity of the ee and hh program will be developed in the following talk

backup

Physics of the Higgs boson at FCC-ee

Baseline: at 240 and 365 GeV, collect in total 1.2M ZH events and 0.1M WW→H events per experiment

- **Statistics-limited measurements:**
  - Higgs couplings to fermions & bosons;
    → Model-independent, normalized to e+e- → ZH cross-section
    → fixed candle for past (HL-LHC) and future (FCC-hh) studies at hadron colliders (H→ ZZ)
  - Higgs properties: Higgs mass and width, CP violation, H→ gg ,
- **Close to discovery level:**
  - Higgs self-coupling via loop diagrams :
    → complementarity to HH production at higher energy machines, like HL-LHC, or later FCC-hh
- **Unique possibility:**
  - Measure Higgs to electron coupling in s-channel production e+e-→H @ $\sqrt{s}$ = 125 GeV
    highly demanding on luminosity, monochromatization with 2 or 4 IPs?
    → test of first generation Yukawa coupling