Higgs Performance at FCC-ee

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Higgs Physics at FCC-ee



FCC-ee offers broad potential for precision Higgs measurements

- Higgs factory: production of million Higgs bosons
- Clean environment
- Relative small backgrounds, high S/B

Main production mechanisms

- ZH production "Higgs-strahlung"
- Vector boson fusion (VBF), WW dominant





Not in baseline run, but optional $e^+e^- \rightarrow H$ at 125 GeV

- Probe directly electron-Yukawa coupling
- Requires beam monochromotisation

Total Higgs production @ FCC-ee	(baseline – 4 IP)
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Threshold	ZH production	VBF production	
240 GeV / 10 ab ⁻¹	2 M	50 k	
365 GeV / 3 ab ⁻¹	0.4 M	0.1 M	



The ZH threshold

Highest precision obtained from ZH analyses @ 240 GeV

Main strategy of such analyses based on recoil method

- Tag the Z boson (tight invariant mass constraints) using leptons or jets
- Compute recoil, distribution sharp peaked at Higgs mass, width dominated by detector resolution $m_{recoil}^2 = (\sqrt{s} E_{ff})^2 p_{ff}^2$

$$= s + m_Z^2 - 2E_{ff}\sqrt{s} \approx m_H^2$$

- Tag additional decays of the Higgs – challenging in multijet environment

Backgrounds: dominated by vector boson (pair) production (WW, ZZ) and Z/γ^*

Challenges for the Higgs programme

- Detector performance: resolution, tracking, vertexing, timing, angular
- Flavor tagging for Higgs couplings
- Jet reconstruction algorithms





Experimental Programme

Fundamental properties

- Mass
- Width
- Model independent ZH cross-section
- Self-coupling
- Invisible branching fraction

Yukawa couplings

- Vector bosons (ZZ, WW)
- Hadrons (uu,dd,ss,cc,bb)
- Taus
- Exotic/Rare ($\gamma\gamma$, $\mu\mu$, $Z\gamma$)
- Electron at $\sqrt{s} = 125 \text{ GeV}$

Others

- FCNCs together with $H \rightarrow qq$
- Angular studies (prod. and decay), CP observables, ...
- Differential measurements
- Anomalous couplings
- Searches for additional Higgs (e.g. light Higgs in 2HDM models)



Analyses mostly statistically driven, but precision strongly depends on detector performance

Establish the detector requirements that maximise

the Higgs physics potential

- As part of the FCC Feasibility Study, to be completed by the end of 2025
- Mid-term review of feasibility study in 2023

FUTURE

CIRCULAR

Overview of ongoing analyses



- **Recoil Higgs mass and cross-section** (Ang Li, Jan Eysermans, Gregorio bernardi)
- **Higgs to invisible** (Andrew Mehta, Nikolaos Rompotis, BNL)
- Higgs to bb, cc, gg, ss (Loukas Gouskos, Andrea Del Vecchio, Laurent Forthomme, Michele Selvaggi, Reham Aly,
 Giovanni Marchiori)
 - Z(jj)H, Z(vv)H(jj) and Z(jj)H(jj) final states
- ee → H (David d'Enterria, Victoria Martin Julia Allen, Mojtaba Mohammadi Najafabadi, Kunal Gautam, Freya Blekman)
- Higgs self-coupling (Roberto Salerno, Roy Lemmon, Nico Harringer, Louis Portales, Abraham Tishelman-Charny, Elizabeth Brost)
 - In VBS (vvH(bb), eeH(bb))
- **Rares:** Higgs $\mu\mu$, $\gamma\gamma$, $Z\gamma$ (MIT)
- Anomalous, HZ differential (Juan Alcaraz, Maria Cepeda)
- $\mathbf{H} \rightarrow \boldsymbol{\tau} \boldsymbol{\tau}$ (Markus Klute, Xunwu Zuo)
- Higgs width ZH(ZZ) 6j (Aman Desai)



more mature

Monte Carlo and Tools

Monte Carlo campaign

- Latest winter 2023 campaign
- IDEA detector simulated with Delphes
 - Full track covariance reconstruction (large/light drift chamber, 2T)
 - Crystal electromagnetic calorimeter
- Exhaustive list of processes using Whizard event generator
 - List can be found here
 - Contact us if need for more samples/processes

Available tools

- Analysis using FCCAnalysis framework, based on RDataframe
 - See presentation on Tuesday by J. Smiesko for more details
- Jet clustering: several algorithms available, inclusive and exclusive
- Jet tagging Weaver/ParticleNET
 - Trained for b/c/s/g/u/d/r
 - Detail and performance in talk L. Gouskos
 - Also works for Z→qq events (see E. Perez)







Total ZH production cross-section *L. Portales*

Crucial is to measure HZZ coupling strength in a model-independent way

- Unique to e⁺e⁻ colliders because of known initial state, not possible at hadron colliders
- Challenge to ensure model-independence ("easy for Z(II)")
- Once known, determine couplings to $H \rightarrow XX$ in a model independent way
- Similarly measuring the HWW coupling strength at 365 GeV

$$\sigma_{\rm ZH} \times \mathcal{B}({\rm H} \to {\rm X}\overline{{\rm X}}) \propto \frac{g_{\rm HZZ}^2 \times g_{\rm HXX}^2}{\Gamma_{\rm H}} \ \, {\rm and} \ \, \sigma_{{\rm H}\nu_{\rm e}\bar{\nu}_{\rm e}} \times \mathcal{B}({\rm H} \to {\rm X}\overline{{\rm X}}) \propto \frac{g_{\rm HWW}^2 \times g_{\rm HXX}^2}{\Gamma_{\rm H}}$$
FCC-ee sensitivity prediction to ~ 0.15%

- Example analysis in Z(II)H(XX) final state
- Reach 0.6% (stat. only), combined muon and electron channels

Measuring the individual Higgs \rightarrow XX decay modes give access to $\Gamma_{_{\rm H}}$

- At 240 GeV, measuring $H \rightarrow ZZ$
- At 240+365 GeV, measuring H→bb
- Expected precision $\Gamma_{\mu} \sim 1\%$ (MeV level)

$$\Gamma_H \propto \frac{\sigma \left(e^+e^- \to \nu \bar{\nu} H, H \to bb\right) \sigma \left(e^+e^- \to ZH\right)^2}{\sigma \left(e^+e^- \to ZH, H \to bb\right) \sigma \left(e^+e^- \to ZH, H \to WW\right)}$$

 $\Gamma_H \propto \frac{\sigma \left(e^+e^- \to ZH, H \to ZZ\right)^2}{\sigma \left(e^+e^- \to ZH\right)}$



Higgs self coupling

Probe *indirectly* trilinear Higgs self coupling λ_3 through single Higgs boson cross section

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

Total cross section can be measured O(1%) at FCC-ee

- Higgs decay-mode independent \rightarrow challenge for Z(qq)
- Probing NLO deviations from SM: $\delta \kappa_{\lambda} = \kappa_{\lambda} 1$
- C_1 sensitive to \sqrt{s} : exploit different sensitivities at both energies





2nd energy point lift the degeneracy

L. Portales

 $\Delta \ln L$

-2

0

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FUTURE

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Higgs couplings

Measure precisely Higgs couplings

- Higgs coupling strengths determined from the HZZ cross section in model independent way
- Deviations sensitive to new physics

Higgs couplings measured directly in several final states ZH, $Z \rightarrow XX$ and $H \rightarrow YY$

- Highest statistics with hadronic final states
- Challenges in detector requirements for hadronic resolution, separation and PID
- Background suppression (WW, ZZ)
- Jet reconstruction and kinematic fits
- Jet flavour tagging (neural network based)
- Analysis optimization using neural networks multi-dimensional likelihood fits

Typical analysis uses different categories through neural networks with a direct multi-dimensional fit



Global fits in κ -3 framework (<u>arXiv:1905.03764</u>)

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
κ _{zγ}	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
κμ	4.40	4.00	3.90	0.43
K	1.60	0.94	0.66	0.46
Inv.	1.9	0.22	0.19	0.024

Analysis not yet covered

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Higgs mass: context and requirements

Higgs mass enters SM EWK parameters via radiative corrections, depending logarithmically on $m_{\rm H}$, e.g.

$$\sin^2 \theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1 - \Delta r}$$

Needs for FCC-ee

- Very high precision on cross-sections, sub-percent level
- This translates to a Higgs mass requirement < O(10) MeV to control the radiative corrections for the cross-sections and branching fractions

 $\Delta r \sim \ln(m_H)$ $\Delta r \sim m_t^2$

 $\Delta r \sim new physics?$

- For ee \rightarrow H at \sqrt{s} 125 GeV, need to know the Higgs mass < Higgs width ~ 4.1 MeV

Roadmap for ultimate precision on Higgs mass

- Current Higgs mass precision ~ 150 MeV
- HL-LHC precision brings this down to 20 MeV (ultimate achievable)
- Measure Higgs mass directly at FCC-ee using the recoil mass distribution
 - Use both muon and electron channels
 - Ultimate 3.3 MeV achievable, including experimental uncertainties



Electron-Yukawa

Probe electron-Yukawa coupling

- Direct measurement with coupling too small to be measured
- Using s-channel and beam monochromotization at \sqrt{s} = 125 GeV

 \bar{b}, g, τ^+

Η

 Z^*, γ^*

- ISR+FSR \rightarrow 40 % reduction
- Beam energy spread ~ $\Gamma_{\rm H}$: δE = 4.2 MeV \rightarrow 45 % reduction
- Potential uncertainty on the Higgs mass
- Total convoluted cross section ~ 280 ab⁻¹: large lumi needed
- Cope with large backgrounds ($Z \rightarrow XX$)
 - $H \rightarrow gg \text{ most significant (absence of } Z \rightarrow gg)$
 - Efficient reduction using BDT (bkg reduction 17x, sig 2x)
 - Potentially improve with exclusive ee→gg(cc)
- Expectations
 - About ~ 20 ab⁻¹/y @ \sqrt{s} = 125 GeV \rightarrow ~ 6k eeH bosons /y
 - Significance 2 years running with 4 IP \rightarrow limit y_e < 1.6 x y_e (1.2 σ)





arXiv:2107.02686

Open analyses



Higgs experimental programme widely covered, but still some key analyses missing/not started

Higgs width

- Preliminary studies done, more person power needed
- Multi jet environment 6 jets final state ZH(ZZ*), ZH(WW*) challenging
- Possibility to also exploit 365 GeV (ee $\rightarrow vvH$)

Taus

- Reconstruction/identification/tagging
- Coupling strength, angular, CP

Rare and exotic $(\gamma\gamma, \mu\mu, Z\gamma)$

- Will be tackled during the summer at MIT

Angular analysis, CP observables, differential measurements

Summary and conclusions

Presented brief overview of ongoing Higgs analyses at FCC-ee

Assess Higgs precision measurements with actual analysis techniques (generation \rightarrow analysis \rightarrow fit)

- Detector performance and optimization
- Studying jet tagging, flavor, jet reconstruction algorithms
- Study of systematic uncertainties
- More details in next 2 talks

Open analyses still to be covered for experimental assessment

- Contact us in case of interest
- We hold regular analysis meetings subscribe to e-group



FCC-ee Higgs conveners Performance

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