

Overview of Higgs and Top Activities

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7th FCC Physics Workshop – February 1, 2024



FUTURE
CIRCULAR
COLLIDER



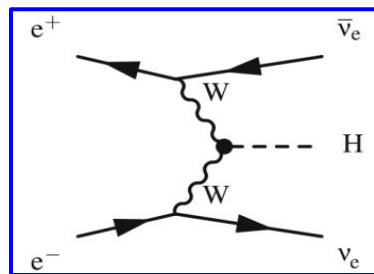
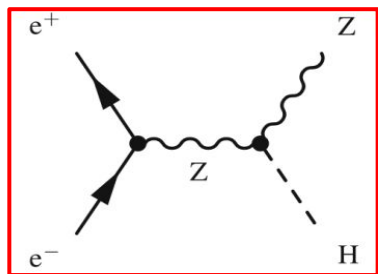
Higgs Physics at FCC-ee

FCC-ee offers broad potential for precision Higgs measurements

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

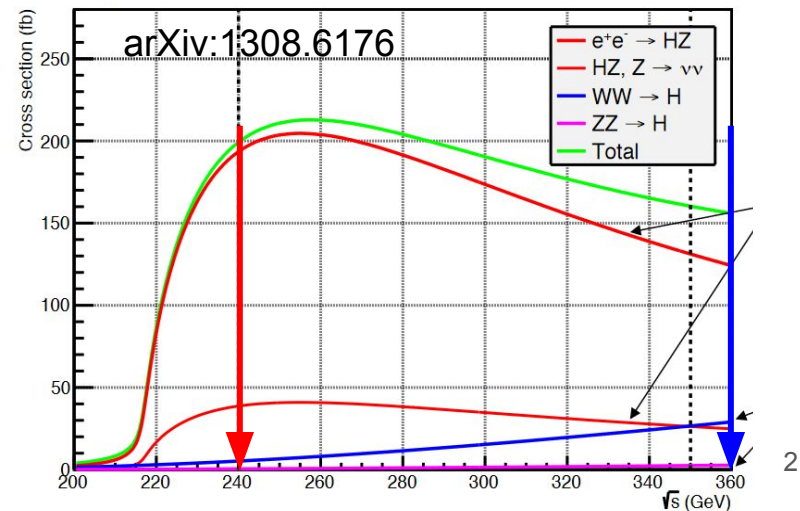
Main production mechanisms

- **ZH production** “Higgs–strahlung”
- **Vector boson fusion** (VBF), WW dominant



Total Higgs production @ FCC-ee (baseline – 4 IP)

Threshold	ZH production	VBF production
240 GeV / 7.2 ab⁻¹	1.45 M	45 k
365 GeV / 3 ab⁻¹	330 k	80 k



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

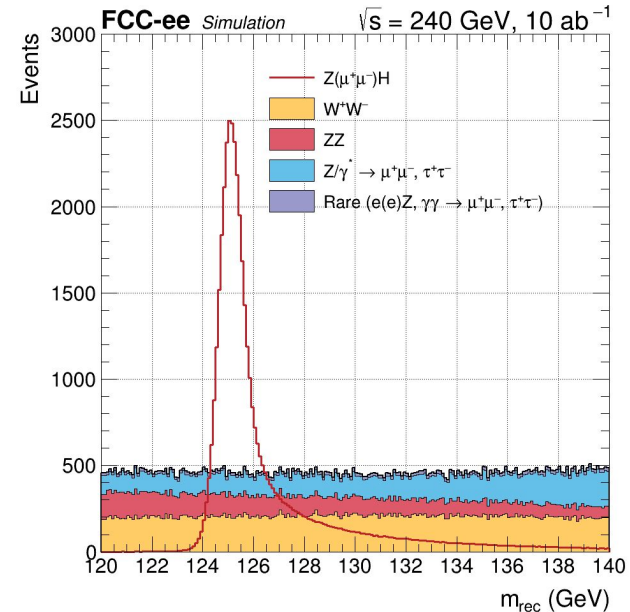
$$\begin{aligned} m_{recoil}^2 &= (\sqrt{s} - E_{ff})^2 - p_{ff}^2 \\ &= s + m_Z^2 - 2E_{ff}\sqrt{s} \approx m_H^2 \end{aligned}$$

- 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
- Flavour tagging for Higgs couplings
- Jet reconstruction algorithms



Experimental Programme

Fundamental properties

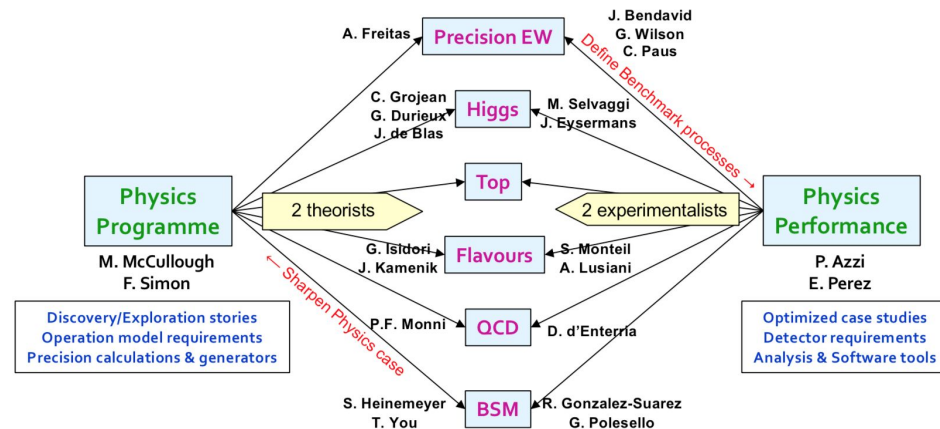
- Mass
- Width
- Model independent ZH cross-section
- Self-coupling
- Invisible branching fraction

Yukawa couplings

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

Contributions to the Mid-term Report

Three notes were ready for mid-term report

- **Measurement of Higgs boson hadronic decays with $Z(\rightarrow\nu\nu/\ell\ell)H$ events at FCC-ee at $\sqrt{s} = 240$ GeV**
Andrea Del Vecchio, Loukas Gouskos, Giovanni Marchiori, Michele Selvaggi
- **Higgs to invisible at the FCC-ee**
Andrew Mehta, Nikolaos Rompotis
- **Higgs boson mass and model-independent ZH cross-section at FCC-ee in the di-electron and di-muon final states**
Jan Eysermans, Gregorio Bernardi, Li Ang

Other contributions from various analyses completed the contribution to the mid-term report

Many thanks for all the work and participation!

Total ZH Production Cross-section

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
- Once known, determine couplings to $H \rightarrow XX$ in a model independent way
- Similarly measuring the HWW coupling strength at 365 GeV

$$\sigma_{ZH} \times \mathcal{B}(H \rightarrow X\bar{X}) \propto \frac{g_{HZZ}^2 \times g_{HXX}^2}{\Gamma_H}$$

$$\sigma_{H\nu_e\bar{\nu}_e} \times \mathcal{B}(H \rightarrow X\bar{X}) \propto \frac{g_{HWW}^2 \times g_{HXX}^2}{\Gamma_H}$$

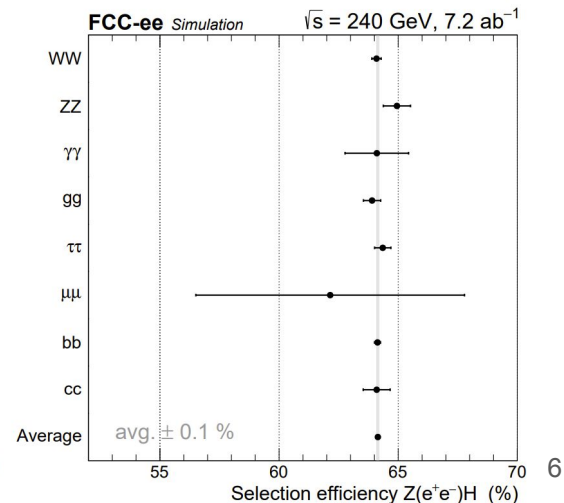
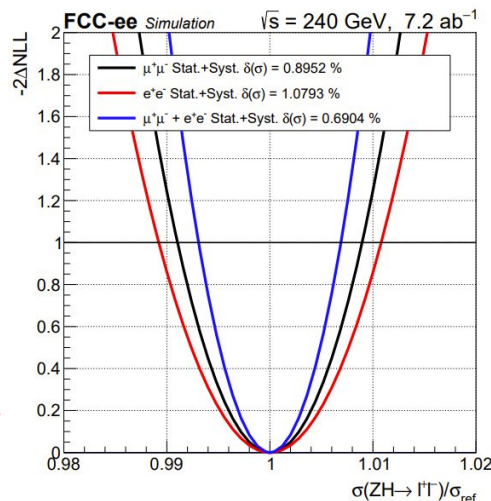
FCC-ee sensitivity prediction to $g_Z \sim 0.2\%$

Example analysis in $Z(\ell\ell)H(XX)$ final state

Probe electron and muon final states

- Clean and sharp recoil distribution
- Cutflow + MVA to reduce backgrounds
- Can minimize the model-dependency
- Combined precision of $\delta\sigma \approx 0.7\%$

Z(qq)H(XX) to be explored to bring uncertainty down, but challenging to retain model-independence



Measuring the individual Higgs \rightarrow XX decay modes give access to Γ_H

At 240 GeV, measuring $H \rightarrow ZZ^*$

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

At 365 GeV, measuring $H \rightarrow bb$

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

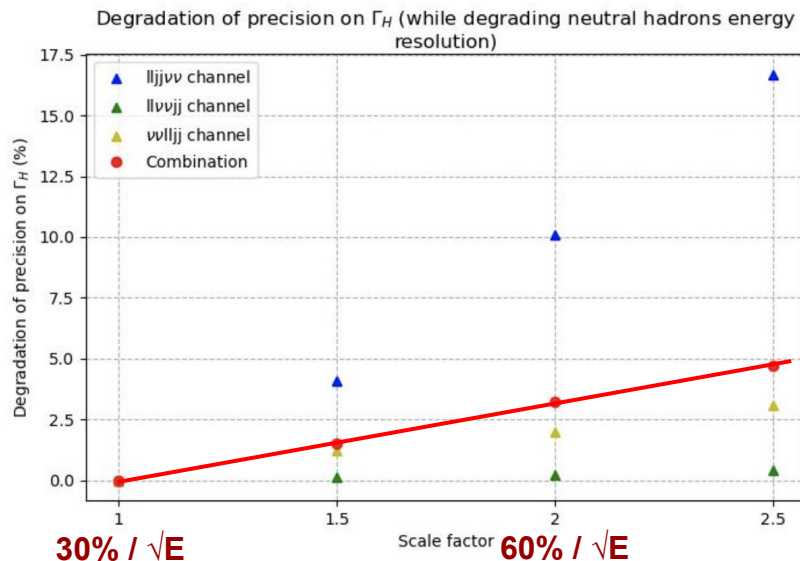
Expected precision $\Gamma_H \sim 1\%$ (MeV level)

Several efforts ongoing in the above channels @ 240 GeV

- Challenging: MVA techniques for optimization/categorization
- 6 jets final state $ZH(ZZ^*)$, $ZH(WW^*)$ – $\delta\Gamma_H \sim 30\%$
- $2l2\nu2j$ – $\delta\Gamma_H \sim 4\%$

Many channels to investigate (27 final states)

\rightarrow More person power welcome, especially at 365 GeV



Higgs Couplings

Couplings determined from the HZZ cross section in model independent way

But also measure them directly

→ Deviations sensitive to new physics

Higgs couplings measured directly in several final states Z(XX)H(YY)

- Highest statistics in 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 – classification – multi-dimensional likelihood fits

Global fits in κ -3 framework ([arXiv:1905.03764](https://arxiv.org/abs/1905.03764))

Expected relative uncertainties on Higgs couplings (5 ab^{-1})

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_Y	1.60	1.3	1.3	0.31
κ_{ZY}	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 yet covered

Several efforts to measure the Higgs couplings to hadrons (bb, cc, ss) and gluons

Z(l \bar{l})H(XX): neural to categorize in H flavour decay modes; fit on recoil distribution

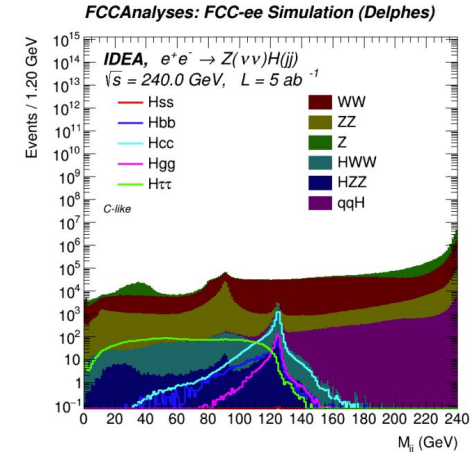
Z(vv)H(XX): neural to categorize in H flavour decay modes; 2D fit on visible and missing mass

Z(qq)H(qq): multi-jet environment – categorization in flavours, 2D fit on recoil and dijet system

In general, usage of MVA techniques and multidimensional categorization to optimize the signal+bkg separation

- Results shown for different final states
- First combination efforts done (stat-only combination for now)
- Sensitivity for ss?

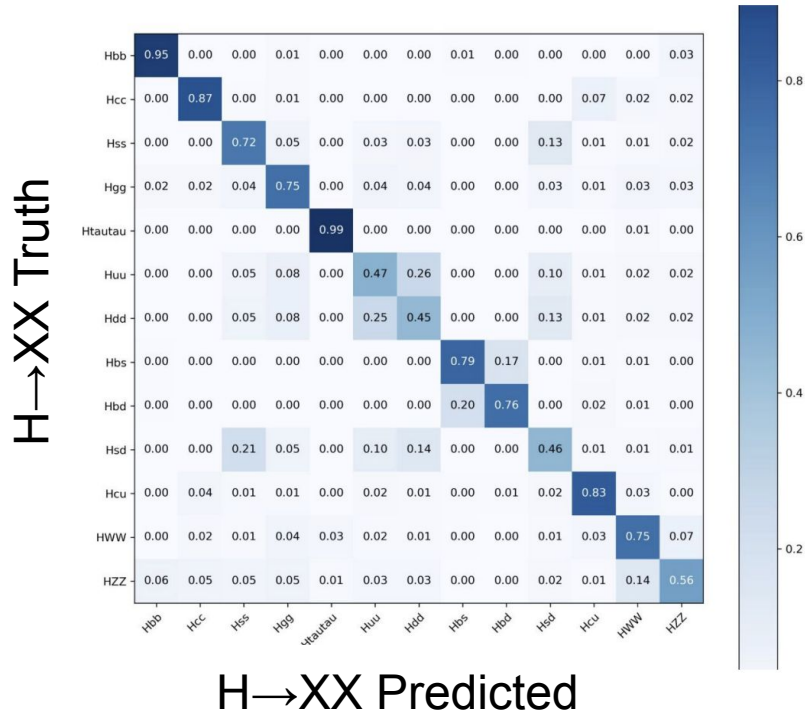
Final state	Z(l \bar{l})H(jj) [%]	Z(vv)H(jj) [%]	Z(jj)H(jj) [%]	Comb. [%]
H \rightarrow bb	0.81	0.36	0.3	0.22
H \rightarrow cc	4.93	2.6	3.5	1.92
H \rightarrow gg	2.73	1.1	2.4	0.94
H \rightarrow ss	410	137	436	124



Higgs Hadronic Couplings (light +FCNCs)

Can use up, down, strange, charm and bottom flavour categories to extract upper limits on:

- Light Yukawa: up and down
- FCNCs: bs, bd, cu, sd



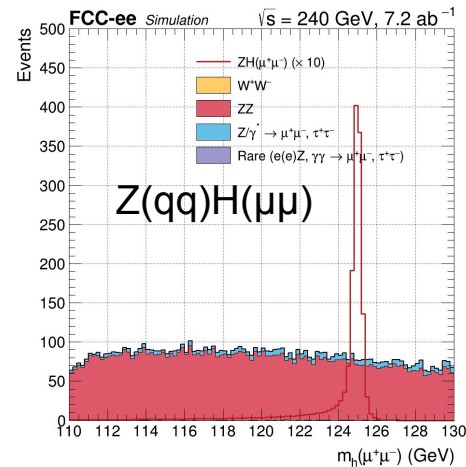
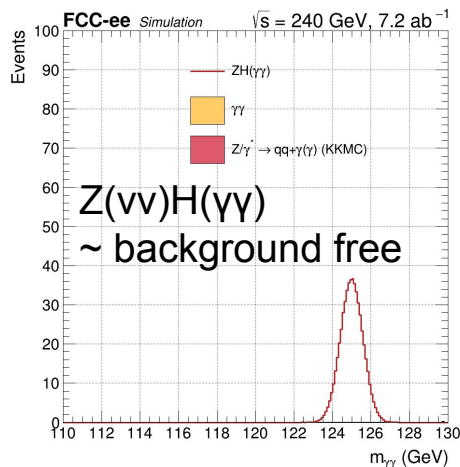
Final state	upper limit BR(H→xx) 95% CL
H → dd	1.7e-03
H → uu	1.8e-03
H → bd	3.3e-04
H → bs	4.5e-04
H → cu	3.0e-04
H → sd	9.5e-04

Higgs Rare Decays

Probe the $\mu\mu$ and $\gamma\gamma$ cross-sections

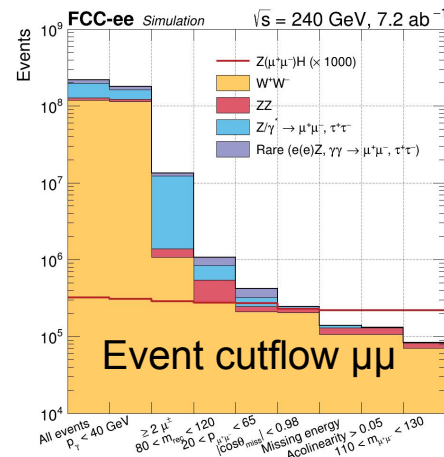
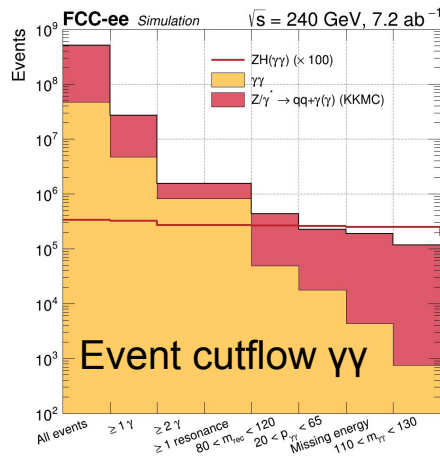
Analysis strategy:

- Tag 2 muons/photons that form the Higgs candidate
- Baseline selection reducing the backgrounds
- Categorize w.r.t. associated Z decays: qq , $\nu\nu$, $\mu\mu$, ee
- Fit the combined Higgs invariant mass distributions simultaneously for all 4 categories



Implementation of $H \rightarrow \gamma\gamma$ and $H \rightarrow \mu\mu$ analyses

- Simple cut and count with categorization



Encouraging results:

- $H \rightarrow \mu\mu$ 19.5 % (ultimate 5.65 %)
- $H \rightarrow \gamma\gamma$ 3.8 % (ultimate 1.75 %)

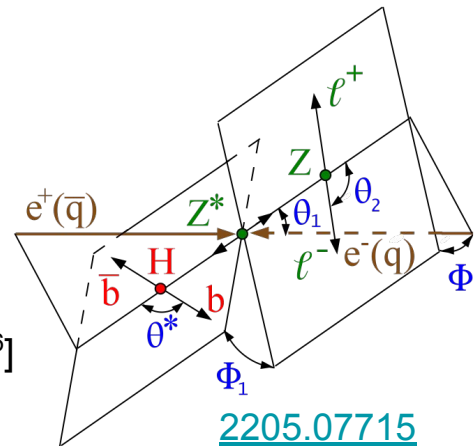
Higgs CP Studies

Recent work on Higgs CP studies to constrain anomalous couplings

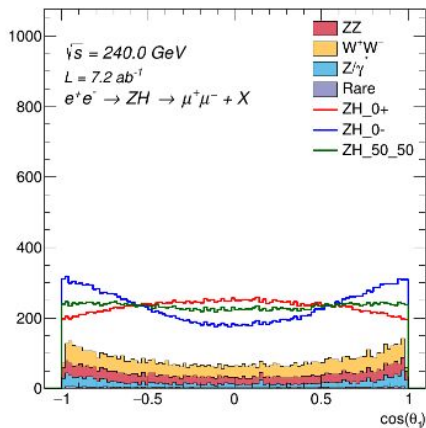
- Implemented Matrix Element Likelihood Approach (MELA) in FCCAnalyses
- Per-event reweighting according to Higgs CP hypothesis

Current application to $Z(ee, \mu\mu)H(XX)$ cross-section analysis

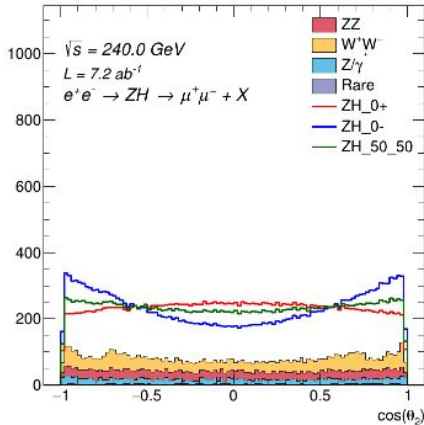
- Construct CP even/odd templates and fit for CP-odd hypothesis
- Resulting $\delta f_{CP}^{HZZ} \sim 5.4 \times 10^{-5}$ (68 % CL) [projections HL-LHC: $\delta f_{CP}^{HVV} \sim 3 \times 10^{-6}$]
- Can be used/applied to any other analysis



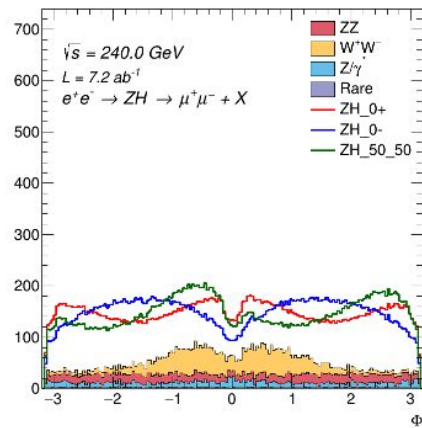
FCCAnalyses: FCC-ee Simulation (Delphes)



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FCCAnalyses: FCC-ee Simulation (Delphes)



$$f_{CP}^{HX} \equiv \frac{\Gamma_{H \rightarrow X}^{CP \text{ odd}}}{\Gamma_{H \rightarrow X}^{CP \text{ odd}} + \Gamma_{H \rightarrow X}^{CP \text{ even}}}$$

Higgs Mass: Context and Requirements

Higgs mass enters SM EWK parameters via radiative corrections, depending logarithmically on m_H , e.g.

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

$$\begin{aligned} \Delta r &\sim \ln(m_H) \\ \Delta r &\sim m_t^2 \\ \Delta r &\sim \text{new physics?} \end{aligned}$$

Needs for FCC-ee

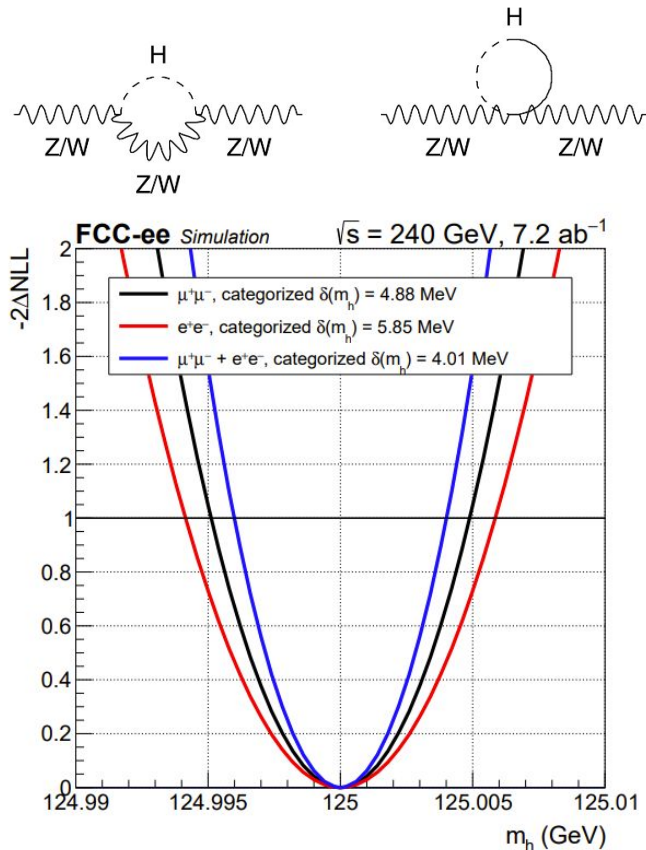
- Very high precision on cross-sections, sub-percent level
- This translates to a Higgs mass requirement $< O(10)$ MeV to **control the radiative corrections** for the cross-sections and branching fractions

Roadmap for ultimate precision on Higgs mass

TODAY
~ 150 MeV

HL-LHC
~ 20 MeV

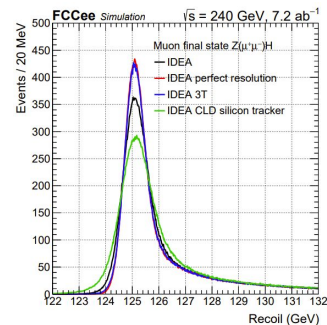
FCC-ee
4 MeV



Higgs Mass – Detector Requirements

Extended studies performed regarding detector/accelerator effects on the Higgs mass

→ Looking at impact on m_H uncertainty stat. (stat.+syst.) in MeV



Nominal configuration

Crystal ECAL to Dual Readout

Nominal 2 T → field 3 T

IDEA drift chamber → CLD Si tracker

Impact of Beam Energy Spread uncertainties

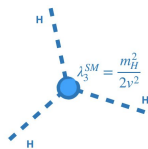
Perfect (=gen-level) momentum resolution

Fit configuration	$\mu^+\mu^-$ channel	e^+e^- channel	combination
Nominal	4.10 (4.88)	5.17 (5.85)	3.14 (4.01)
Inclusive	4.84 (5.53)	6.16 (6.73)	3.75 (4.50)
Degradation electron resolution (*)	4.10 (4.88)	5.98 (6.49)	3.32 (4.11)
Magnetic field 3T	3.38 (4.28)	4.30 (5.00)	2.60 (3.54)
CLD 2T (silicon tracker)	5.51 (6.07)	6.20 (6.70)	4.01 (4.66)
BES 6% uncertainty	4.10 (5.01)	5.17 (6.10)	3.14 (4.09)
Disable BES	2.27 (3.42)	3.11 (4.04)	1.80 (2.99)
Ideal resolution	2.89 (3.95)	3.89 (4.56)	2.39 (3.33)
Freeze backgrounds	4.10 (4.88)	5.17 (5.85)	3.14 (4.00)
Remove backgrounds	3.37 (4.34)	3.85 (4.80)	2.49 (3.56)

Higgs Self-coupling at FCC-ee

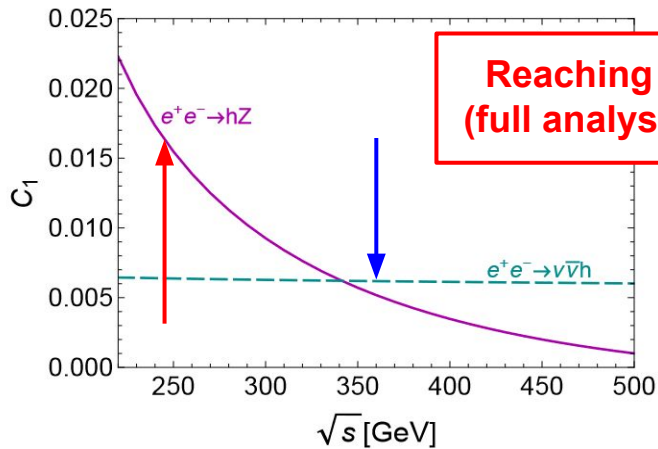
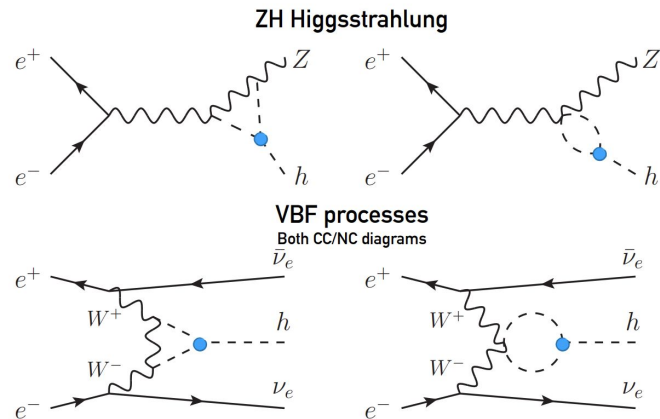
Probe *indirectly* trilinear Higgs self coupling λ_3 through single Higgs boson cross section

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

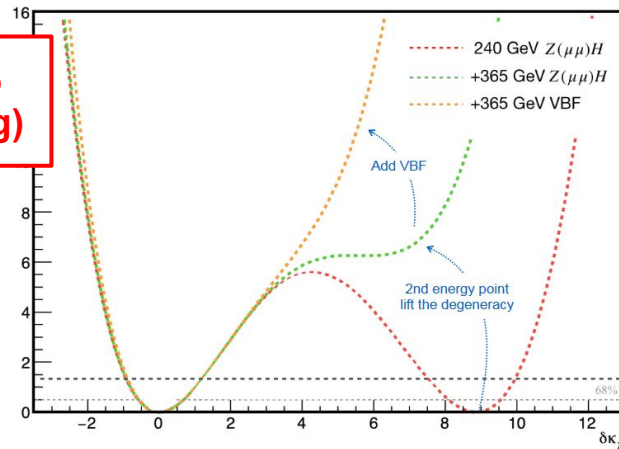


Total cross section can be measured O(1%) at FCC-ee

- 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



Reaching $\delta\kappa_\lambda \sim 30\%$
(full analysis ongoing)



Top Threshold

Current run plan at the top threshold

- 1 year threshold scan 340–350 GeV: total $\sim 1.4 \text{ ab}^{-1}$
- 4 years at 365 GeV: total $\sim 2.3 \text{ ab}^{-1}$

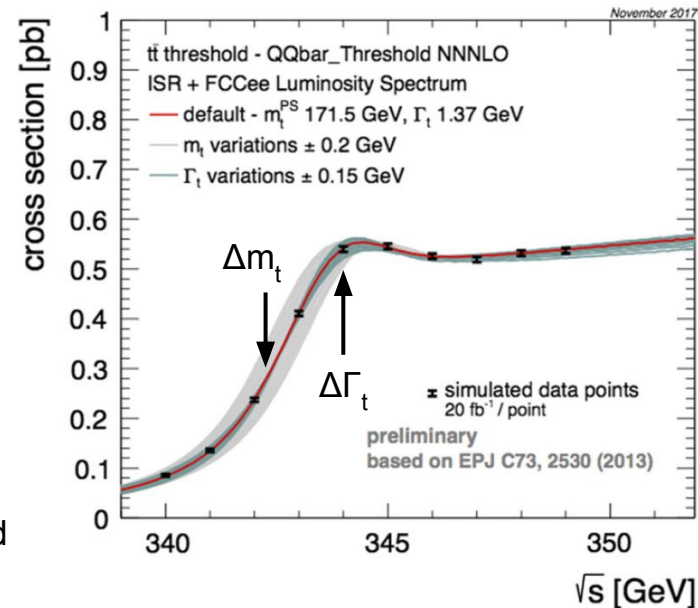
Threshold scan to extract the Top mass and width (similar as WW)

- Relative large uncertainty on top mass ($\pm 0.5 \text{ GeV}$ from HL-LHC)
- Need to constrain shape in optimal way
- Possible to constrain backgrounds (below) and ttH (above)
- Multipoint scan in 5 GeV window [340, 345], each $\sim 25 \text{ /fb}$ to be studied

At 365 GeV, with 2.3 ab^{-1}

- Top properties
- Higgs properties ($ee \rightarrow \nu\nu H$): total cross-section, couplings, width

CONTRIBUTIONS NEEDED

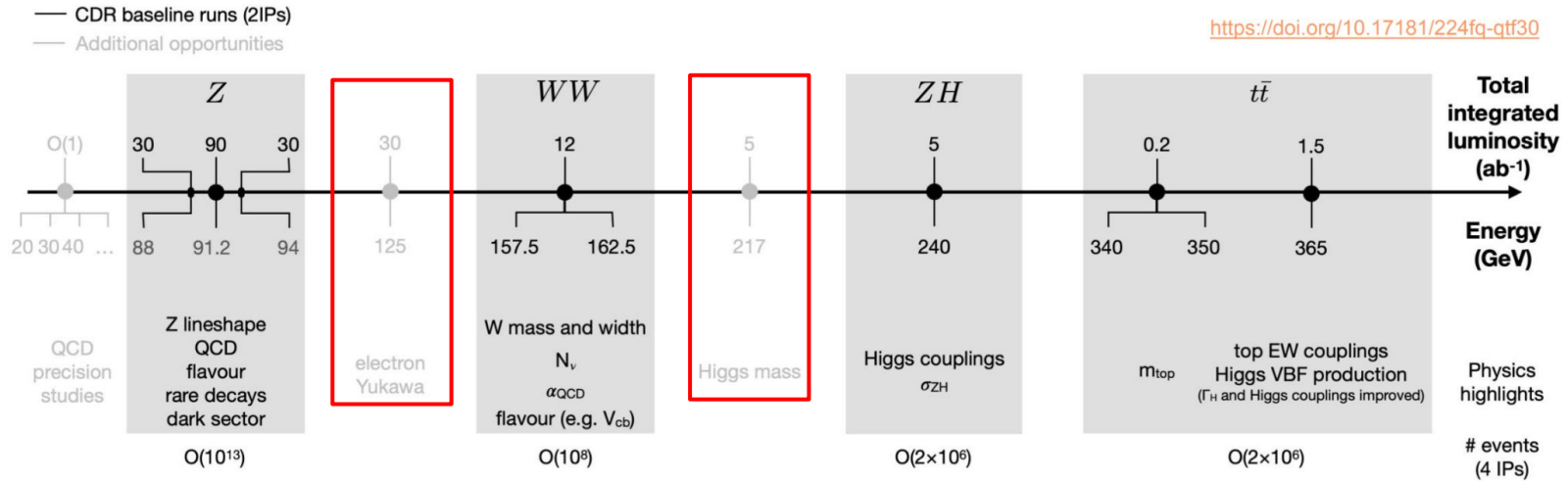


→ Δm_t (stat) $\sim 17 \text{ MeV}$

→ $\Delta \Gamma_t$ (stat) $\sim 45 \text{ MeV}$

Opportunities for Extended FCC-ee Run?

<https://doi.org/10.17181/224fq-qtf30>

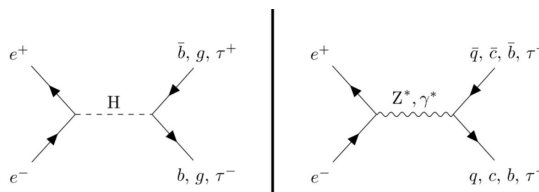


As presented by C. Grojean on Monday, we can always dream of an extended FCC-Run

Opportunities of intermediate energy points:

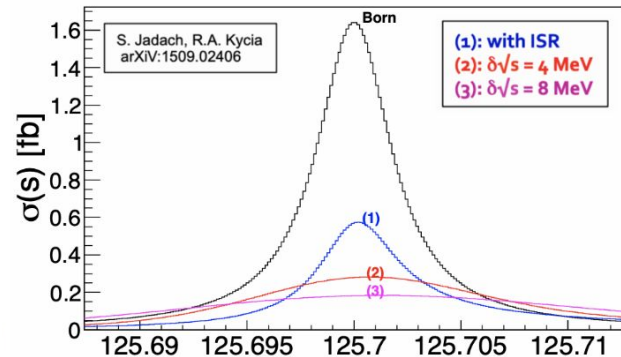
- $e^+e^- \rightarrow H$ at $\sqrt{s} = 125$ GeV – probe electron-Yukawa coupling
 - This requires the Higgs mass to be known < 5 MeV
- $e^+e^- \rightarrow ZH$ at $\sqrt{s} = 217$ GeV – probe Higgs mass from threshold

Electron-Yukawa



Probe electron-Yukawa coupling

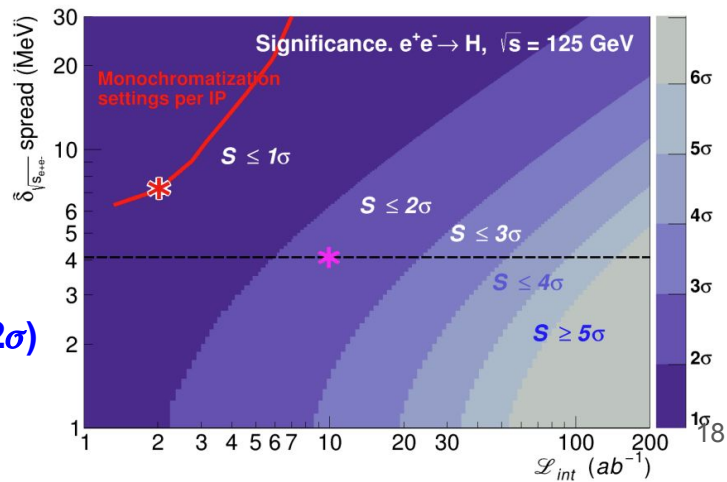
- Direct measurement with coupling too small to be measured
- Using s-channel and beam monochromotization at $\sqrt{s} = 125$ GeV
 - ISR+FSR \rightarrow 40 % reduction
 - Beam energy spread $\sim \Gamma_H$: $\delta E = 4.2$ MeV \rightarrow 45 % reduction
 - Potential uncertainty on the Higgs mass
 - Total convoluted cross section ~ 280 ab $^{-1}$: **large lumi needed**
- Cope with large backgrounds ($Z \rightarrow XX$)
 - $H \rightarrow gg$ most significant (absence of $Z \rightarrow gg$)
 - Efficient reduction using BDT/MVA (bkg reduction 17x, sig 2x)
 - Many channels to explore



Expectations

- About ~ 20 ab $^{-1}$ /y @ $\sqrt{s} = 125$ GeV \rightarrow **$\sim 6k$ eeH bosons /y**
- Significance 2 years running with 4 IP \rightarrow **limit $y_e < 1.6 \times y_e (1.2\sigma)$**

[arXiv:2107.02686](https://arxiv.org/abs/2107.02686)



Alternative Measurement of Higgs mass?

Higgs mass dependency on the total cross-section as function of \sqrt{s}

- Loop diagrams contribute logarithmically in m_H to the cross-section
- Maximal sensitivity obtained at $\sqrt{s} \sim 217$ GeV

Run FCC-ee at $\sqrt{s} = 217$ GeV to infer the Higgs mass with O(5) MeV precision

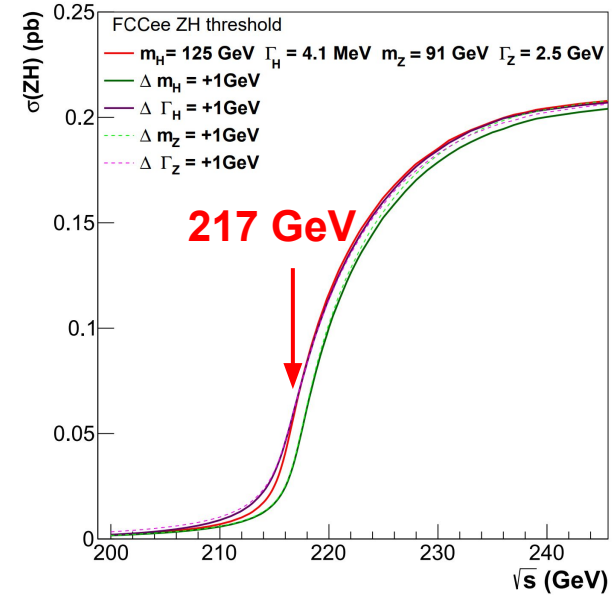
- Rely on accurate measurements of Z mass and width at the Z-pole
- SM-only assumptions – new physics can break the dependency
- Syst. effects of various sorts to be evaluated: luminosity, ecm, background, theory

Back-of-the-envelope statistical-only estimations

$$\left(\sqrt{\sigma_{ZH}} \frac{dm}{d\sigma_{ZH}} \right)_{\min} \simeq 350 \text{ MeV} \sqrt{\text{fb}^{-1}} \simeq 10 \text{ MeV} \sqrt{\text{ab}^{-1}} \quad (\text{ultimate estimations, } Q=\sqrt{\text{lep}}=1)$$

→ **Collecting 5 ab^{-1} at $\sqrt{s} \sim 217$ GeV, 5 MeV uncertainty**

→ More realistically, including systematics degrades this to 10 MeV



Reducing the Systematic Uncertainties

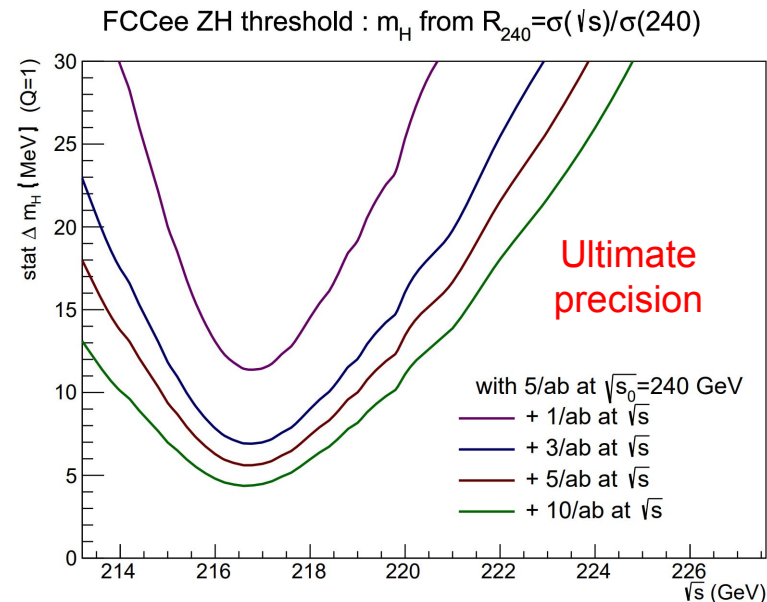
Construct the cross-section ratio using $\sqrt{s} = 217$ and 240 GeV

$$R = \frac{\sigma_{\text{ZH}} \times \mathcal{B}(Z \rightarrow f\bar{f}) \times \mathcal{B}(H \rightarrow X\bar{X})|_{\sqrt{s}=217 \text{ GeV}}}{\sigma_{\text{ZH}} \times \mathcal{B}(Z \rightarrow f\bar{f}) \times \mathcal{B}(H \rightarrow X\bar{X})|_{\sqrt{s}=240 \text{ GeV}}} = \frac{\sigma_{\text{ZH}}(\sqrt{s} = 217 \text{ GeV})}{\sigma_{\text{ZH}}(\sqrt{s} = 240 \text{ GeV})}$$

→ Experimental and theory uncertainties cancel mostly

→ Sensitivity reached ~ 5 MeV

Run config	Uncertainty (MeV)
5 ab^{-1} @ 217, 5 ab^{-1} @ 240	5 MeV
10 ab^{-1} @ 240 GeV	3 MeV



Can provide independent measurement of Higgs mass w.r.t. recoil mass method

But need to perform the “real” analysis for realistic numbers

Where are we today?

Made a lot of progress over the past years, mainly focused at the 240 GeV threshold

Missing elements for the Feasibility Study for next 1.5 years

- Higgs @ 240 GeV: WW, ZZ (expansion of H width efforts)
- Higgs @ 365 GeV: the total cross-section, couplings, width
- Tau physics
 - Higgs \rightarrow tau tau can put unique detector requirements for tau ID and reconstruction
 - Synergies with Tau polarization at Z pole
- Others: angular analysis, differential measurements

Top activities

- Threshold mass, width
- EW couplings ttZ , V_{ts} , FCNCs

Parameter	FCC-ee CDR	FCCee today
$H \rightarrow WW$	1 %	–
$H \rightarrow ZZ$	3.6 %	4.6 %
$H \rightarrow gg$	1.6 %	0.94 %
$H \rightarrow \gamma\gamma$	7.5 %	3.5 %
$H \rightarrow cc$	1.8 %	1.92 %
$H \rightarrow bb$	0.25 %	0.22 %
$H \rightarrow \mu\mu$	15.8 %	19.5 %
$H \rightarrow \tau\tau$	0.75 %	–
Invisible	< 0.25 %	< 0.18 %
$H \rightarrow ss$	–	124 %
m_H	5 MeV	4 MeV
Γ_H	1 %	4%
κ_λ	42 %	30%

Summary and Conclusions

Presented overview of ongoing Higgs analyses at FCC-ee

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

- Detector performance and optimization
- Studied many analyses at 240 GeV and contributions to the mid-term report

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

Michele Selvaggi, Jan Eysermans

Programme

Gauthier Durieux, Christophe Grojean, Jorge De Blas Mateo

FCC-PED-PhysicsGroup-Higgs@cern.ch

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, Giovanni Marchiori, George Iakovidis)
 - $Z(jj)H$, $Z(vv)H(jj)$ and $Z(jj)H(jj)$ final states
- **ee \rightarrow 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 $\mu\mu$, $\gamma\gamma$, $Z\gamma$** (Jan Eysermans)
- **Higgs width $ZH(ZZ) 6j$** (Nicolas Morange, Aman Desai)
- **Anomalous, HZ differential** (Juan Alcaraz, Maria Cepeda)
- **H $\rightarrow \tau\tau$** (Markus Klute, Xunwu Zuo)

more mature



less mature



Invisible Higgs Decays

In SM, the Higgs decays indirectly to invisible particles via $H \rightarrow ZZ \rightarrow \nu\nu\nu\nu$, accounts for BR 0.1%

- Deviations sensitive to new physics

Analysis covered at FCC and

- Typical fit on missing mass and/or enhanced sensitivity using BDT
- Improvements and detector configs
- Systematic uncertainties to be evaluated and implemented in the fit

Channel	ILC-SID (%)	FCC-IDEA (%)
Electron	0.33	0.20
Muon	0.27	0.15
Hadrons	0.25	0.045
Combined	0.16	0.045

Main challenge is the mass resolution and background suppression

Discovery sensitivity if $BR(H \rightarrow DM) \sim 0.2\%$

