Overview of Higgs and Top Activities

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Higgs Physics at FCC-ee

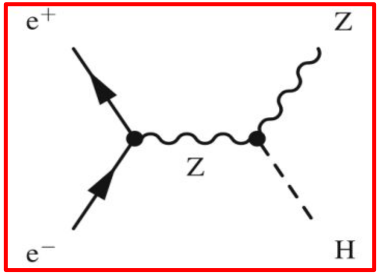
FCC-ee offers broad potential for precision Higgs measurements

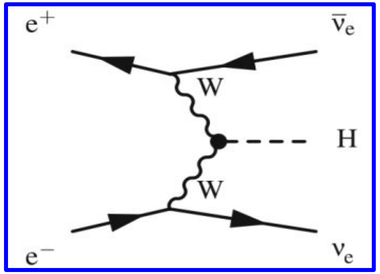
- Higgs factory: production of **2M Higgs** bosons
- Clean environment
- Relative small backgrounds, **large S/B**

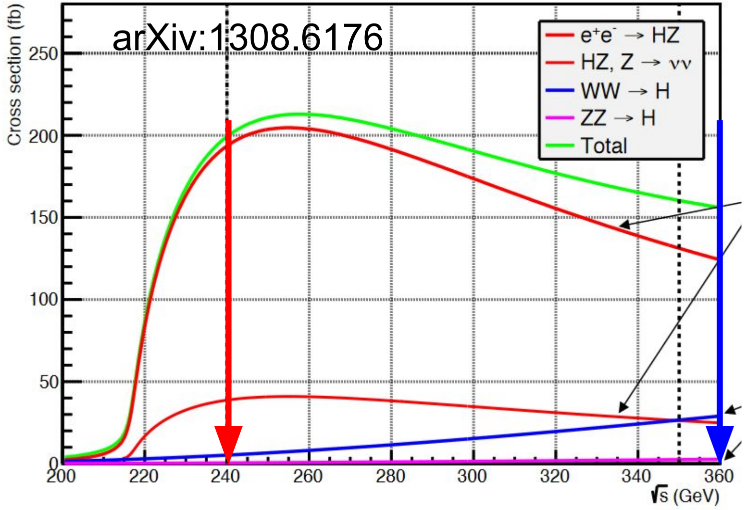
Main production mechanisms

- **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 / 10.8 ab^{-1}	2.2 M	67 k
365 GeV / 3 ab^{-1}	330 k	80 k







Experimental Programme

Fundamental properties

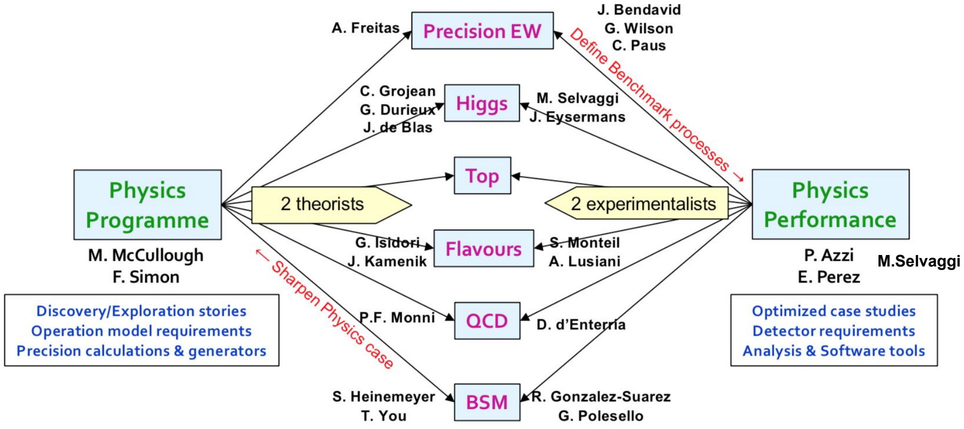
- Mass
- Width
- Model independent ZH cross-section
- Self-coupling
- Invisible branching fraction

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→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**

The ZH Threshold

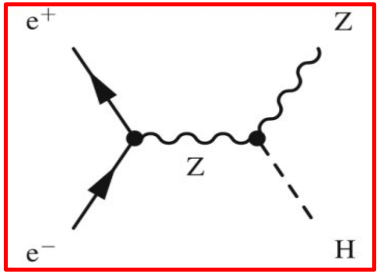
Highest precision obtained from ZH analyses @ 240 GeV

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**

$$m^2_{recoil} = \left(\sqrt{s} - E_{ff}\right)^2 - p^2_{ff}$$
$$= s + m^2_Z - 2E_{ff}\sqrt{s} \approx m^2_H$$

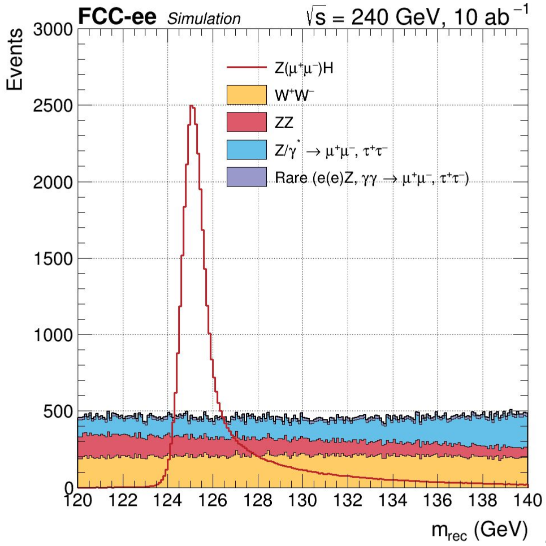
- tag additional decays of the Higgs – challenging in multijet environment



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

Challenges for the Higgs programme

- Detector performance: tracking, vertexing, timing, angular
- Flavour tagging for Higgs couplings
- Jet clustering algorithms (in particular in fully hadronic final states)

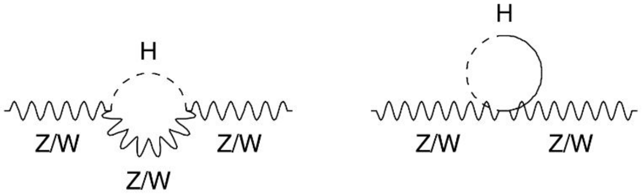


Higgs Mass: Context and Requirements

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

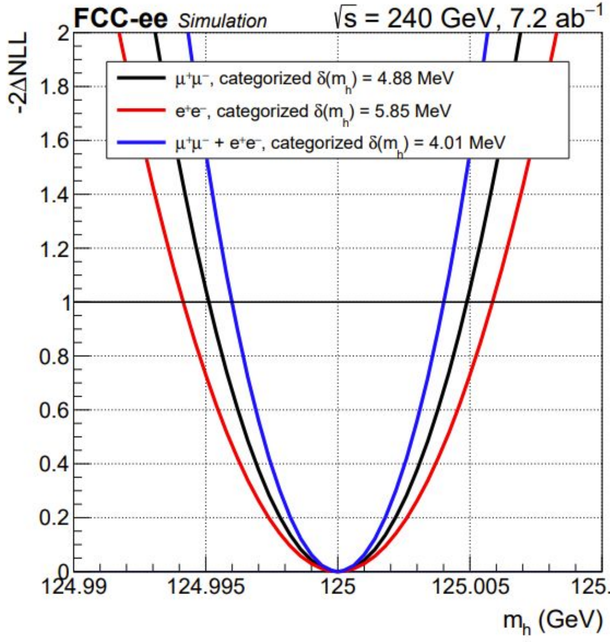
$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

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



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



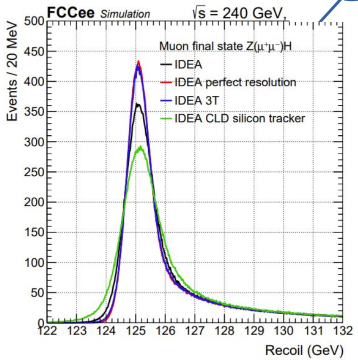
Roadmap for ultimate precision on Higgs mass

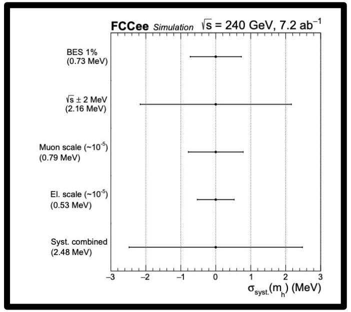
TODAY	HL-LHC	FCC-ee
~ 150 MeV	~ 20 MeV	4 MeV

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 → Nominal

Crystal ECAL to Dual Readout → Degradation electron resolution (*)

Nominal 2 T → field 3 T → Magnetic field 3T

IDEA drift chamber → CLD Si tracker → CLD 2T (silicon tracker)

Impact of Beam Energy Spread uncertainties → BES 6% uncertainty, Disable BES

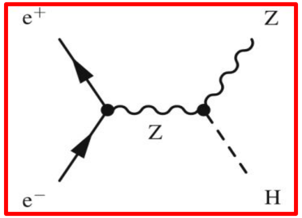
Perfect (=gen-level) momentum resolution → Ideal resolution

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)

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, **determines couplings to H→XX** in a model independent way
- similarly measuring the HWW coupling strength at 365 GeV



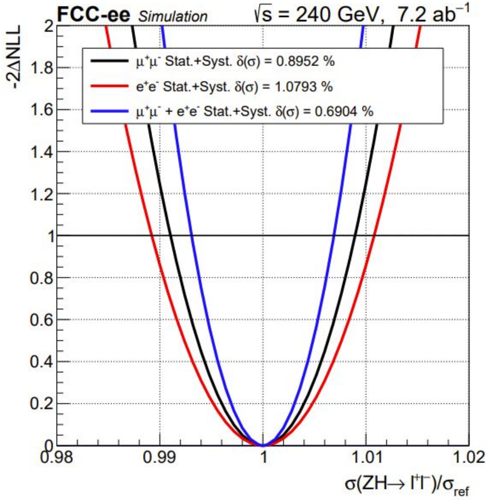
FCC-ee sensitivity prediction to g_Z ~ 0.13% (with 10.8 ab^{-1})

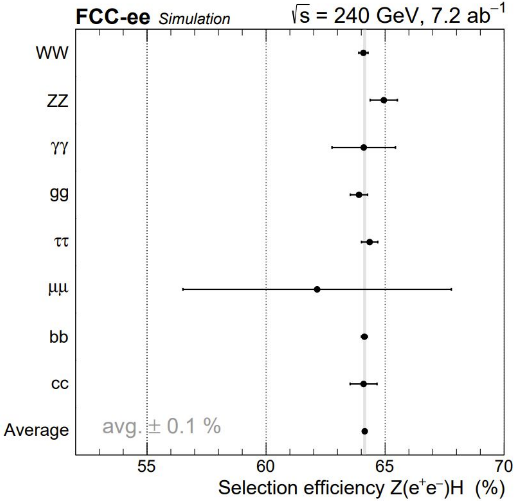
$$\sigma_{ZH} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HZZ} \times g^2_{HXX}}{\Gamma_H}$$

Example analysis in Z(ll)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 (stat dominated) precision of
  - **$\delta\sigma \approx 0.57\%$**





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

Higgs Width

Measuring the individual Higgs → XX decay modes give access to Γ_H

At 240 GeV, **measuring H→ZZ***

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

At 365 GeV, **measuring H→bb**

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

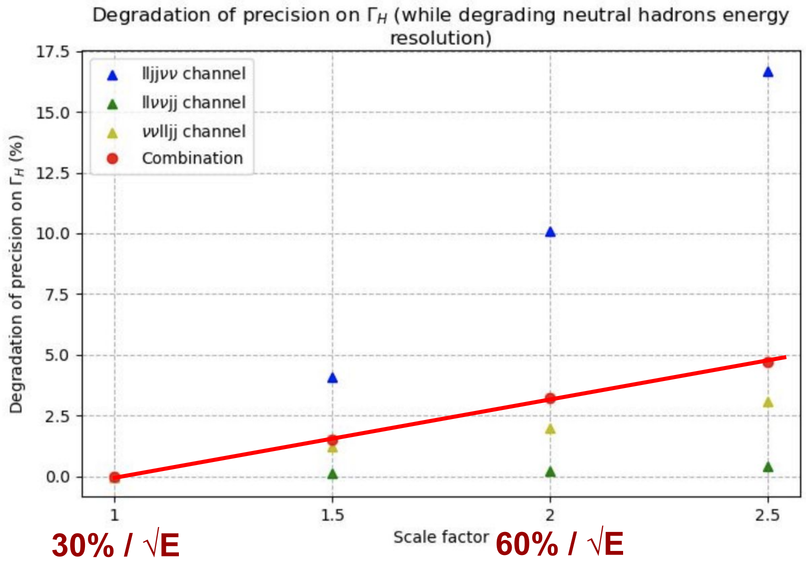
Expected precision Γ_H ~ 1% (MeV level)

Several efforts ongoing in the above channels @ 240 GeV

- Challenging: MVA techniques for optimization/categorization
- 6 jets final state ZH(ZZ*), ZH(WW*) – $\delta\Gamma_H$ ~ 14%
- 2l2v2j – $\delta\Gamma_H$ ~ 3.2%

Many channels to investigate (27 final states)

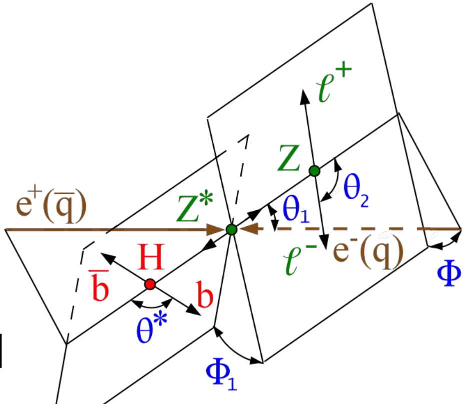
→ More person power welcome, especially at 365 GeV



Higgs CP Studies

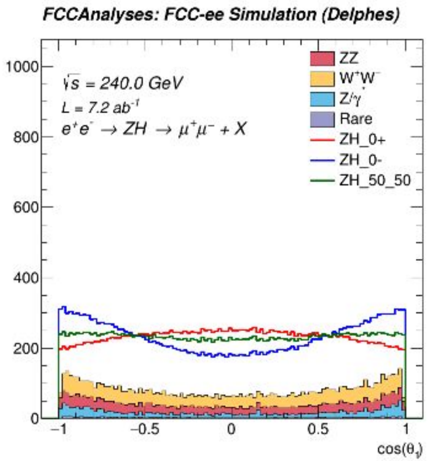
Recent work on Higgs CP studies to constrain anomalous couplings

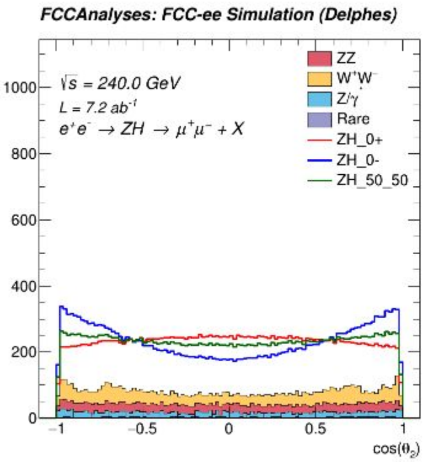
- Implemented Matrix Element Likelihood Approach (MELA) in FCCAnalyses
- Per-event reweighting according to Higgs CP hypothesis

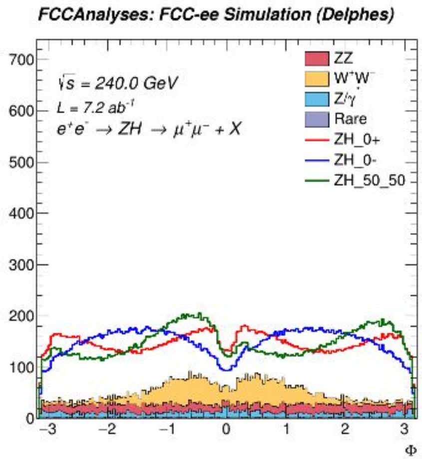


Current application to Z(ee,$\mu\mu$)H(XX) cross-section analysis

- Construct CP even/odd templates and fit for CP-odd hypothesis
- Resulting **δf_{CP}^{HZZ} ~ 4.4 x 10^{-5}** (68 % CL) [projections HL-LHC: δf_{CP}^{HVV} ~ 3 x 10^{-6}]
- Can be used/applied to any other analysis







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

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)

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_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 yet covered

Higgs Hadronic Couplings

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

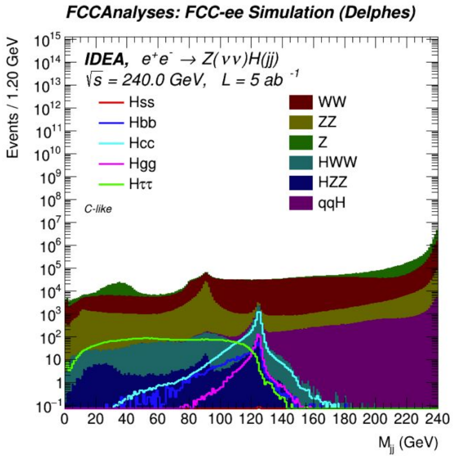
Z(ll)H(XX): neural to categorize in H flavour decay modes; fit on recoil distribution
Z(vv)H(XX): neural to categorize in H flavour decay modes; 2D fit on visible and missing mass
Z(qq)H(qq): multi-jet environment – categorization in flavours, 2D fit on recoil and dijet system

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?

10.8 ab-1

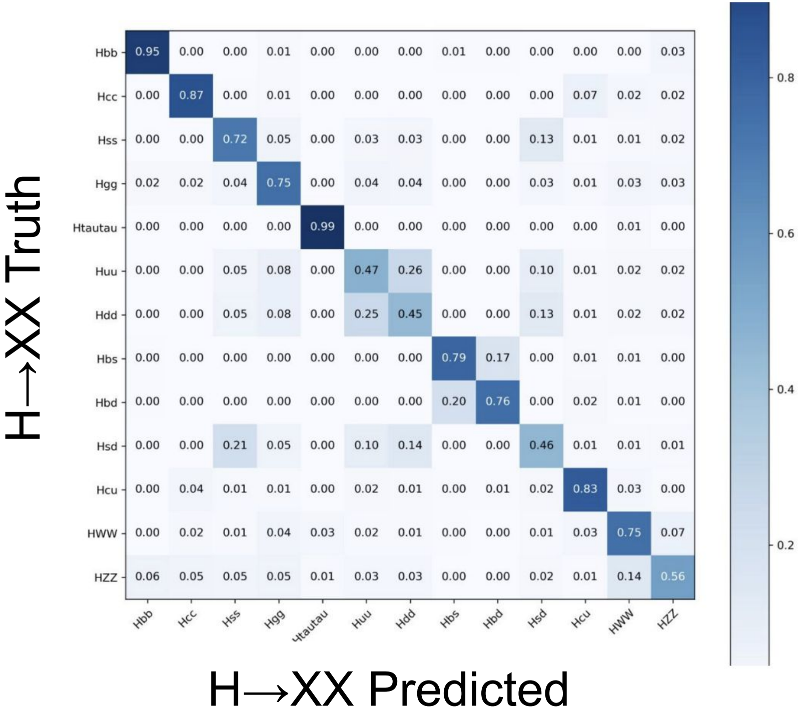
Final state	Z(ll)H(jj) [%]	Z(vv)H(jj) [%]	Z(jj)H(jj) [%]	Comb. [%]
$H \rightarrow bb$	0.55	0.24	0.204	0.15
$H \rightarrow cc$	3.35	1.77	2.38	1.30
$H \rightarrow gg$	1.86	0.75	1.63	0.65
$H \rightarrow ss$	280	93	296	80



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



10.8 ab-1

Final state	upper limit BR(H→xx) 95% CL
H → dd	1.4e-03
H → uu	1.5e-03
H → bd	2.7e-04
H → bs	3.7e-04
H → cu	2.5e-04
H → sd	7.7e-04

using vvjj final state only!

Higgs Rare Decays

Probe the μμ and γγ cross-sections

Analysis strategy:

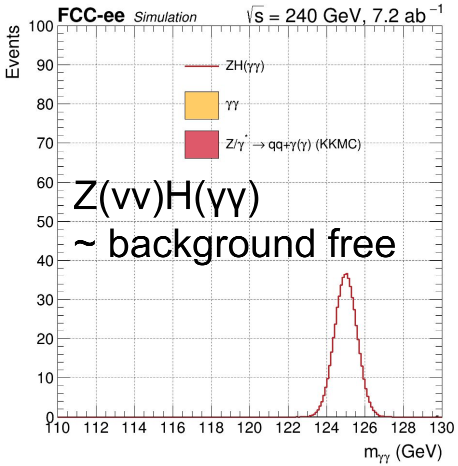
- Tag 2 muons/photons that form the Higgs candidate
- Baseline selection reducing the backgrounds
- Categorize w.r.t. associated Z decays: qq, νν, $\mu\mu$, ee
- Fit the combined Higgs invariant mass distributions simultaneously for all 4 categories

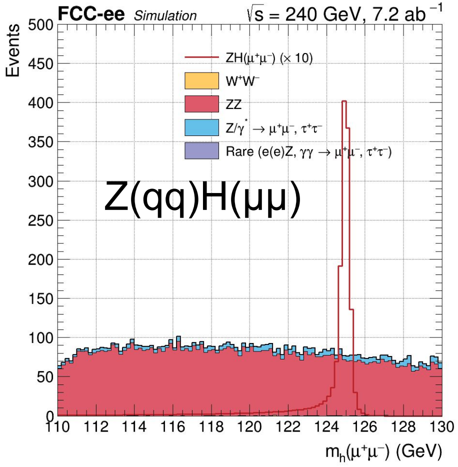
Implementation of H → γγ and H → $\mu\mu$ analyses

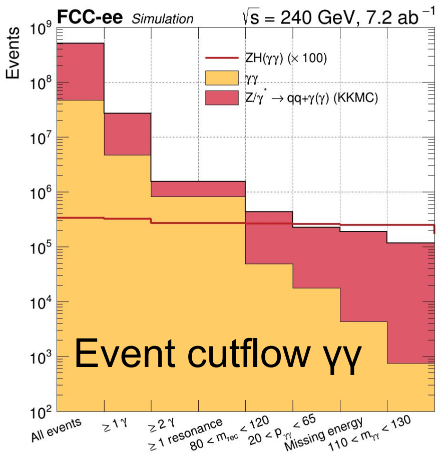
- Simple cut and count with categorization

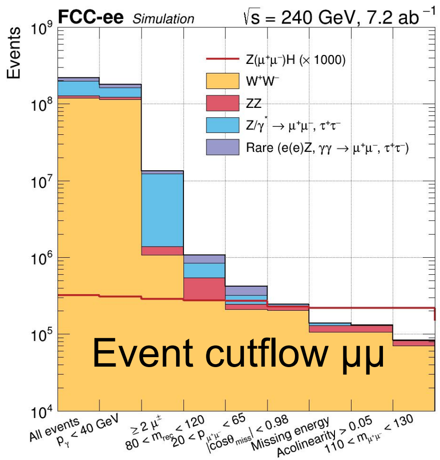
Encouraging results:

- **H → $\mu\mu$ 15.9 % (ultimate 5.65 %)**
- **H → γγ 3.1 % (ultimate 1.75 %)**





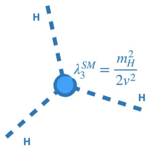


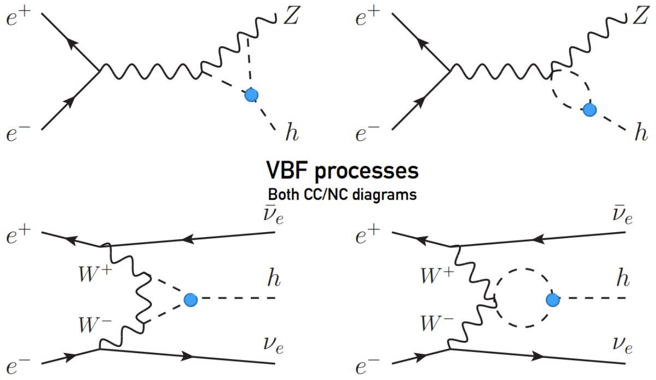


Higgs Self-coupling at FCC-ee

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

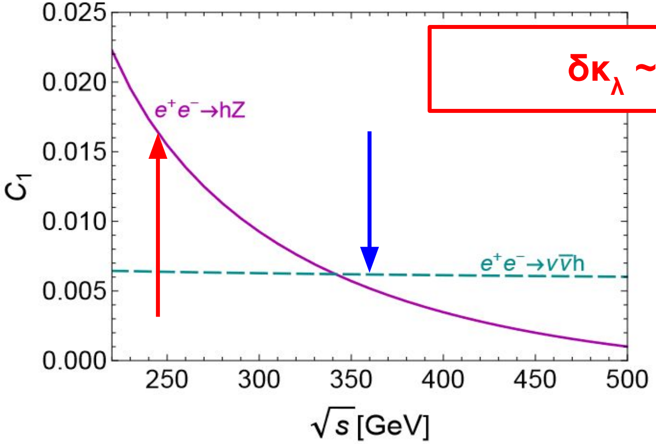
$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1 + \kappa_\lambda C_1) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$



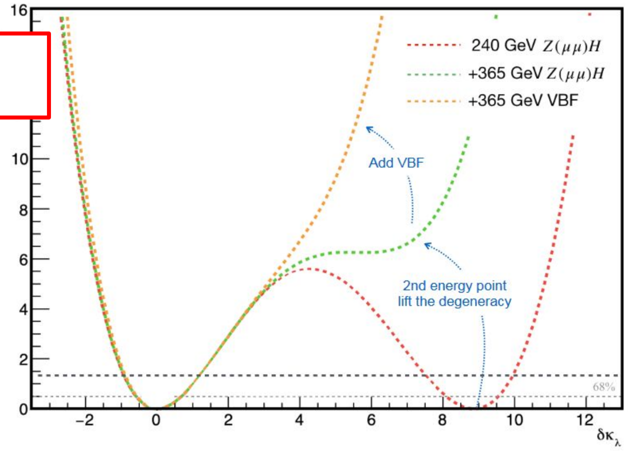


Total cross section can be measured O(1%) at FCC-ee

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



$\delta\kappa_\lambda \sim 24\%$



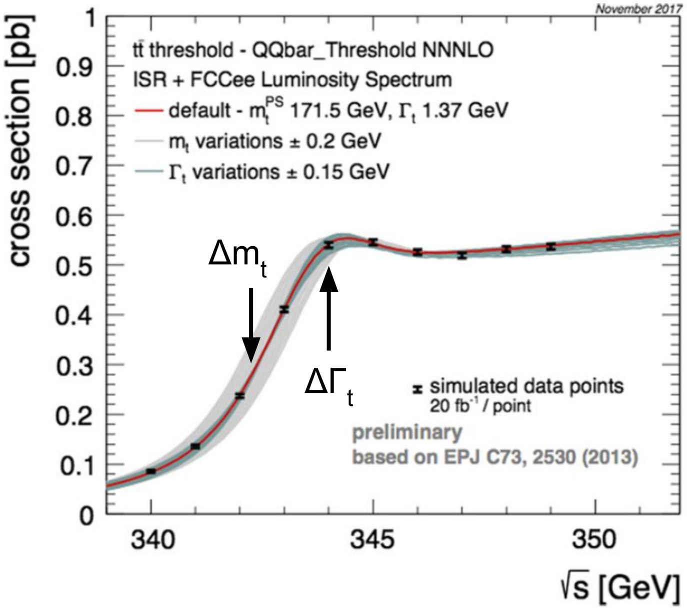
Top Threshold

Current run plan at the top threshold

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

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

- Relative large uncertainty on top mass (+/- 0.5 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 ~ 25 /fb to be studied



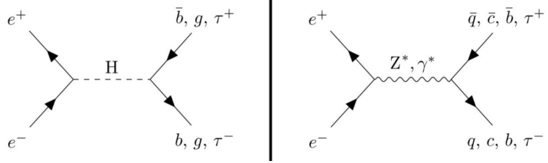
At 365 GeV, with 2.3 ab^{-1}

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

→ Δm_t (stat) ~ 17 MeV

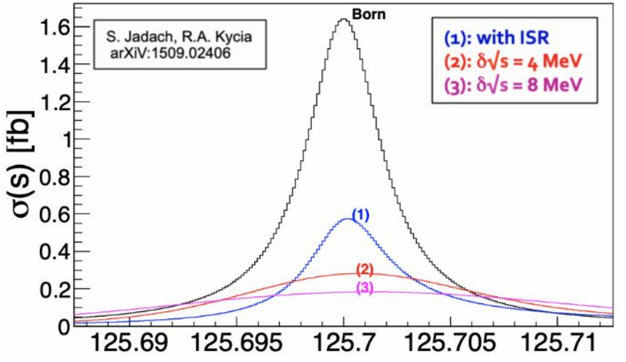
→ $\Delta\Gamma_t$ (stat) ~ 45 MeV

Electron-Yukawa



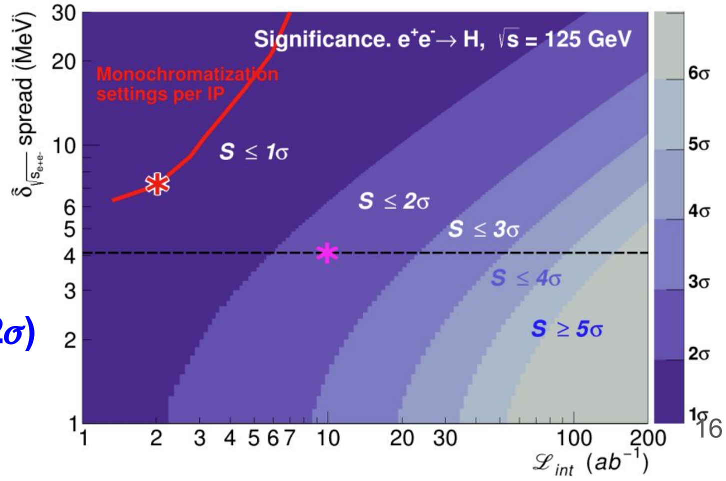
Probe electron-Yukawa coupling

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



Expectations

- About ~ 20 ab^{-1}/y @ √s = 125 GeV → **~ 6k eeH bosons /y**
- Significance 2 years running with 4 IP → **limit y_e < 1.6 x y_e (1.2σ)**



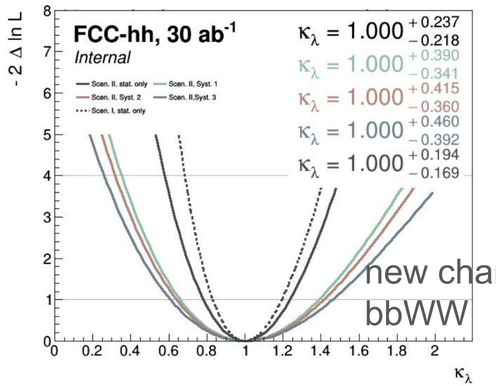
arXiv:2107.02686

Higgs at FCC-hh

Taliercio, Mastrapasqua, Stapf

- **FCC-hh complements** where FCC-ee is statistics limited or not enough sqrt(s)
  - **rare** decay modes (**H → μμ, γγ, Zγ, ll**)
  - Higgs-self coupling
- FCC-ee allows for an absolute coupling determination thanks to knowledge of HZZ coupling
- FCC-hh can then measure ratios **BR(XX)/BR(ZZ)** for ultimate precision

Higgs self-coupling



new channel bbWW

precision

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	0.4	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	0.65	0.7	0.6
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	0.9	1.0	0.8

	Stat only	Syst 1
No assumption on $m_{\bar{b}b}$ resolution	3.2%	3.6%
10 GeV $m_{\bar{b}b}$ res	2.5%	2.7%
5 GeV $m_{\bar{b}b}$ res	2.0%	2.3%
3 GeV $m_{\bar{b}b}$ res	**1.8%**	**2.0%**

improved bbγγ

Where are we today?

Made a lot of progress over the past years, mainly focused at the 240 GeV threshold, but effort at 365 has started

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 → 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, Vts, FCNCs

Parameter	FCC-ee CDR	FCCee today
H→WW	1 %	1.6 %
H→ZZ	3.6 %	2.9 %
H→gg	1.6 %	1.3 %
H→γγ	7.5 %	2.8 %
H→cc	1.8 %	1.3 %
H→bb	0.25 %	0.15 %
H→μμ	15.8 %	15.9 %
H→$\tau\tau$	0.75 %	0.7%
H→Zγ	-	-
H→ss	–	80 %
Invisible	< 0.25 %	< 0.18 %
m_H	5 MeV	4 MeV
Γ_H	1 %	3%
κ_λ	42 %	24%

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
- Many analyses and final state at 240 GeV are covered
- 365 for Higgs and Top effort has started and will be completed for the midterm 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

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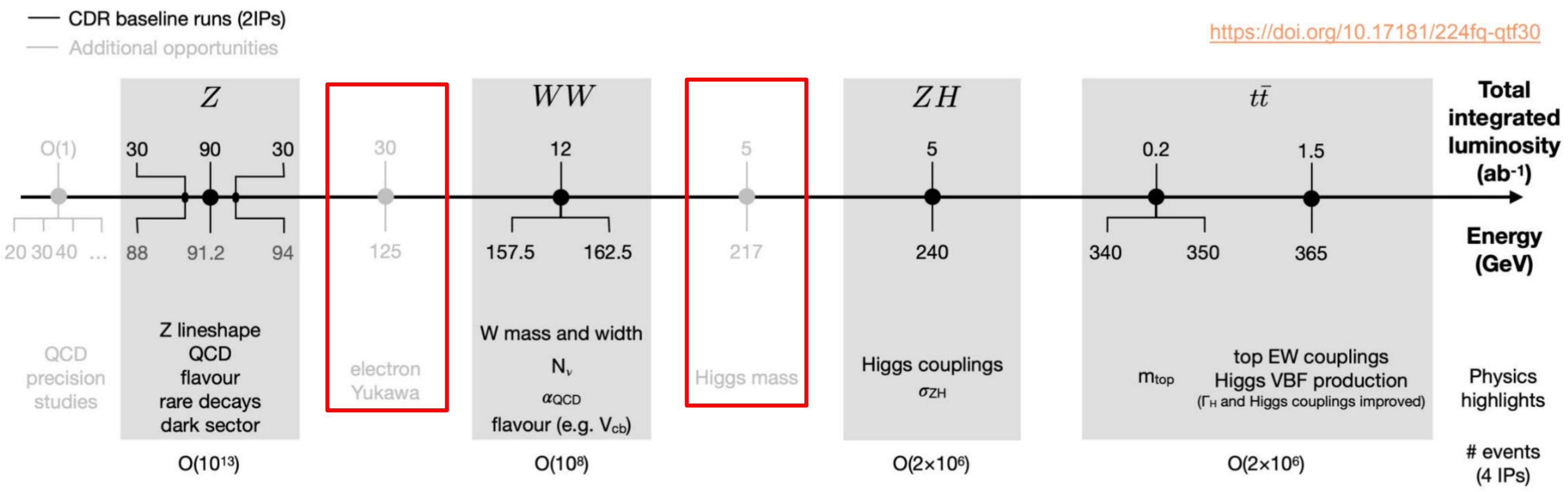
Opportunities for Extended FCC-ee Run?

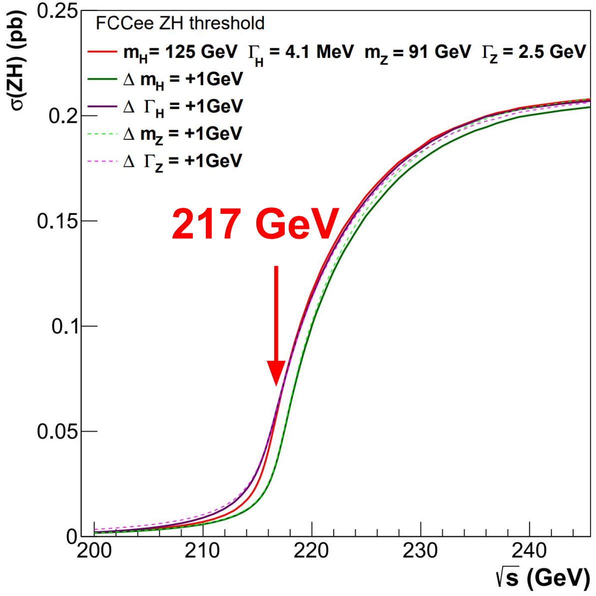


As presented by C. Grojean on Monday, we can always dream of an extended FCC-Run

Opportunities of intermediate energy points:

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

Alternative Measurement of Higgs mass?



Higgs mass dependency on the total cross-section as function of √s

- Loop diagrams contribute logarithmically in m_H to the cross-section
- Maximal sensitivity obtained at √s ~ 217 GeV

Run FCC-ee at √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

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

→ **Collecting 5 ab^{-1} at √s ~ 217 GeV, 5 MeV uncertainty**

→ More realistically, including systematics degrades this to 10 MeV

Reducing the Systematic Uncertainties

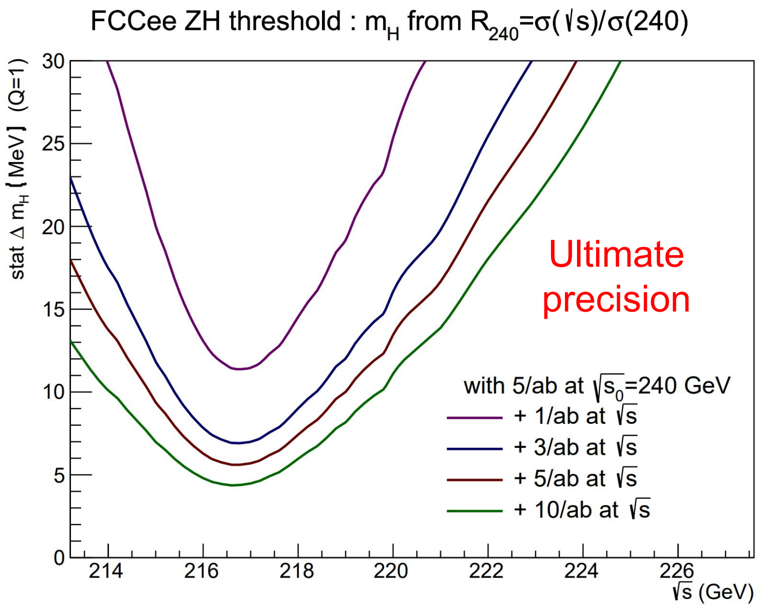
Construct the cross-section ratio using √s = 217 and 240 GeV

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

→ **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

Contributions to the Mid-term Report

Three notes were ready for mid-term report

- **Measurement of Higgs boson hadronic decays with Z(→νν/ll)H events at FCC-ee at √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!

Invisible Higgs Decays

In SM, the Higgs decays indirectly to invisible particles via H → ZZ → $\nu\nu\nu\nu$, 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→DM) ~ 0.2%