**30th International Symposium on Lepton Photon Interactions at High Energies**

# Higgs Measurements at FCC


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With special thanks to Andy Mehta, Emmanuel Perez, Patrizia Azzi and Uta Klein

# Higgs and its status

- The Higgs boson is the latest fundamental particle discovered
  - Crucial component of the SM
  - Crucial component of beyond SM physics
  - Large part of the LHC physics programme
- As such it plays a very important role in the design of any high-energy frontier future collider
  - HL-LHC: benchmarked against HH production
  - $e^-e^+$ *Higgs* factories: CepC, FCC-ee, ILC, CLIC
  - Future Hadron colliders (FCC-hh) and hadron-electron machines (FCC-eh)

**In this talk I will cover Higgs studies in the context of FCC-ee-hh-eh**

# The FCC concept

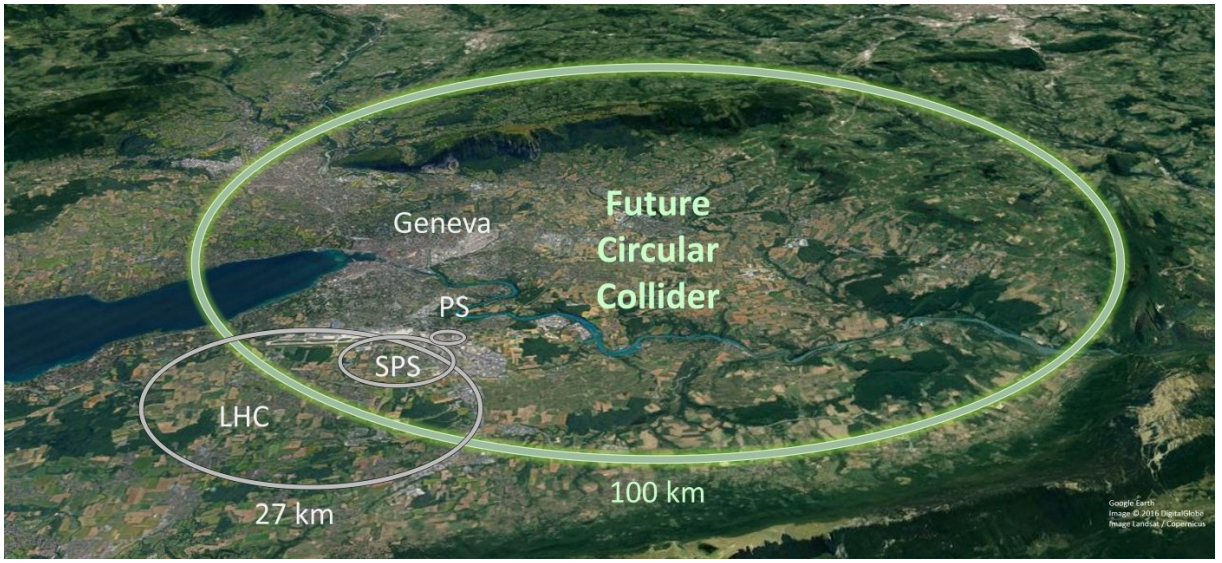
- The FCC is a proposed future circular collider at CERN

→ New tunnel 100km in the Geneva area

→ The tunnel will host several accelerators:

- ***FCC-ee***: electron-positron collider, several √s, ~15 years
- ***FCC-hh***: proton (/heavy ion) collider, √s = 100 TeV, ~25 years
- Possibility to run ***FCC-eh*** (electron-proton collider) concurrently with FCC-hh, electron energy 60 GeV

For all these machines Higgs physics is either a strategic priority or an important part of their physics programme




**Main resource for physics, accelerator and performance:**
**FCC Conceptual design report (2019):** https://fcc-cdr.web.cern.ch/

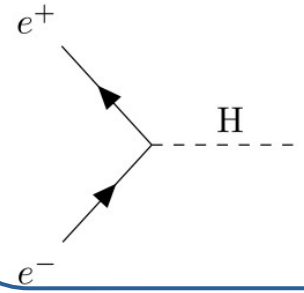
# FCC-ee

- Electron-positron collider at several √s
  2 IP assumed for the studies shown here

FCC CDR (2019) Volume 1

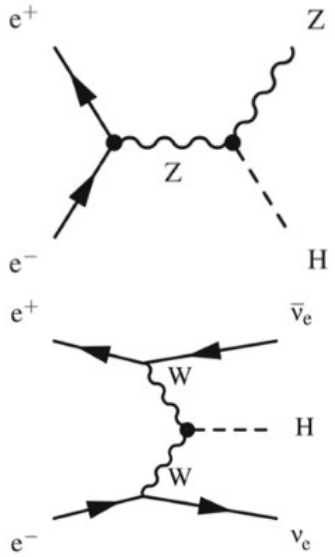
| Phase | Run duration | Centre-of-mass energies (GeV) | Integrated luminosity ($ab^{-1}$) | Event statistics |
|---|---|---|---|---|
| FCC-ee-Z | 4 | 88–95 | 150 | $3 \times 10^{12}$ visible Z decays |
| FCC-ee-W | 2 | 158–162 | 12 | $10^8$ WW events |
| FCC-ee-H | 3 | 240 | 5 | $10^6$ ZH events |
| FCC-ee-tt(1) | 1 | 340–350 | 0.2 | $t\bar{t}$ threshold scan |
| FCC-ee-tt(2) | 4 | 365 | 1.5 | $10^6$ $t\bar{t}$ events |

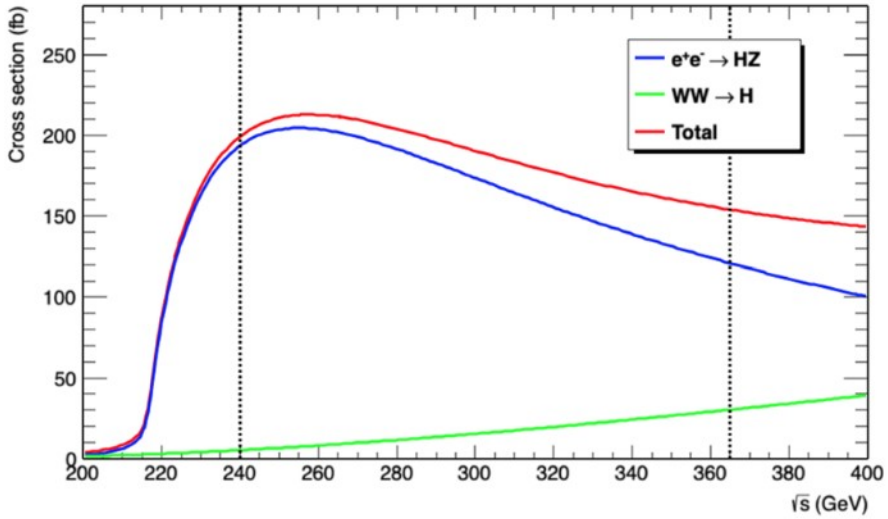
Studies for the potential of √s = 125 GeV (see next talk!)




*1 million* Higgs bosons produced in association with Z

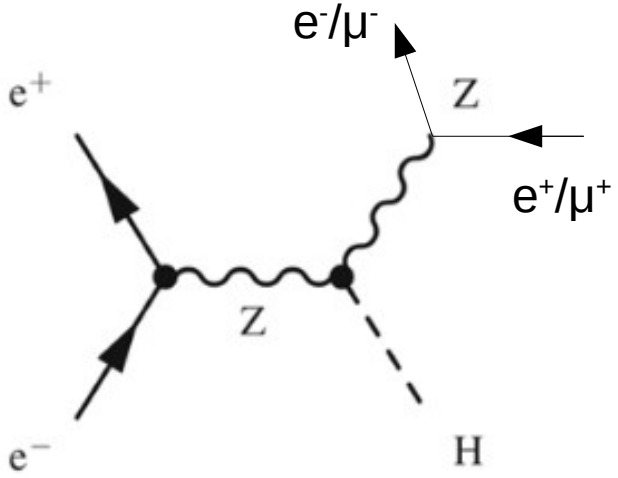
*0.1 million* Higgs bosons produced via WW fusion



# FCC-ee: recoil method

- Absolute determination of $g_{HZZ}$: unique feature of lepton colliders



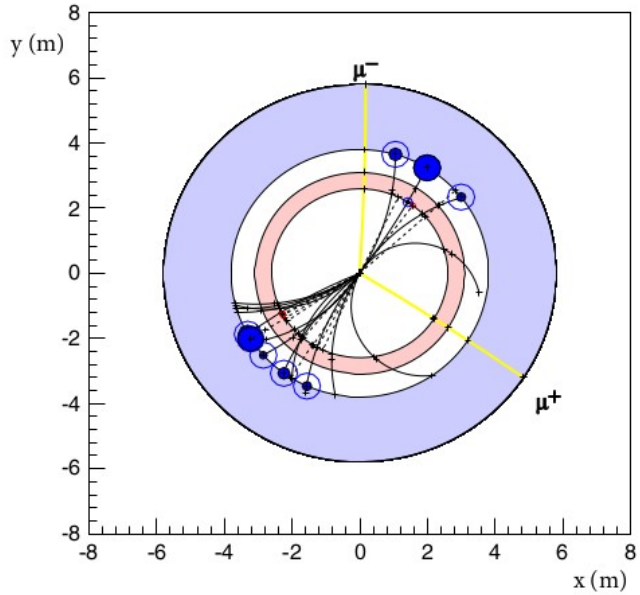

- Tag the Z decay

- Calculate the recoil mass $M^2_{recoil} = s + m^2_{ll} - 2\sqrt{s}(E_{l1} + E_{l2})$

- Measure the cross section σ(ee→ ZH) independently of the Higgs decay, i.e. ***absolute measurement of $g_{HZZ}$***

- Subsequently Higgs total width with σ(ee→ ZH) x B(H→ ZZ) and in a similar way all other couplings that the FCC-ee is sensitive to

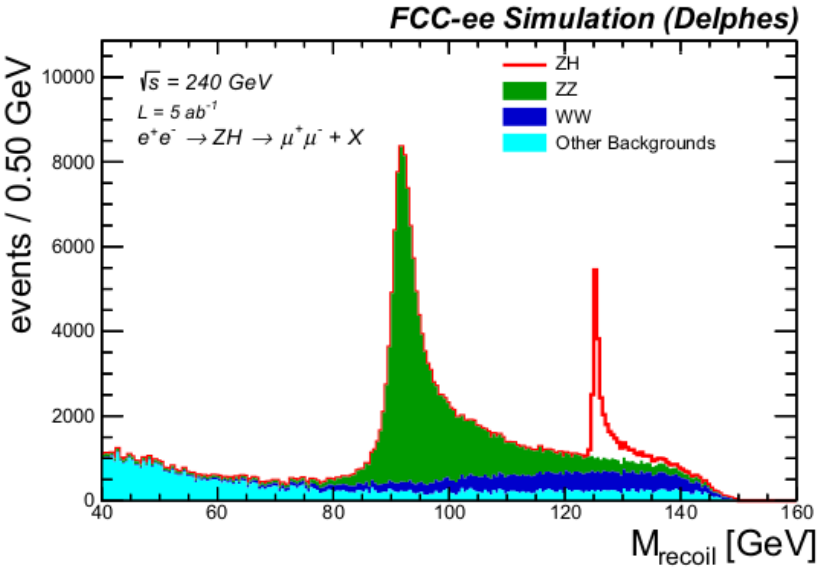
- Synergy with other colliders: the result will inform future Higgs measurements

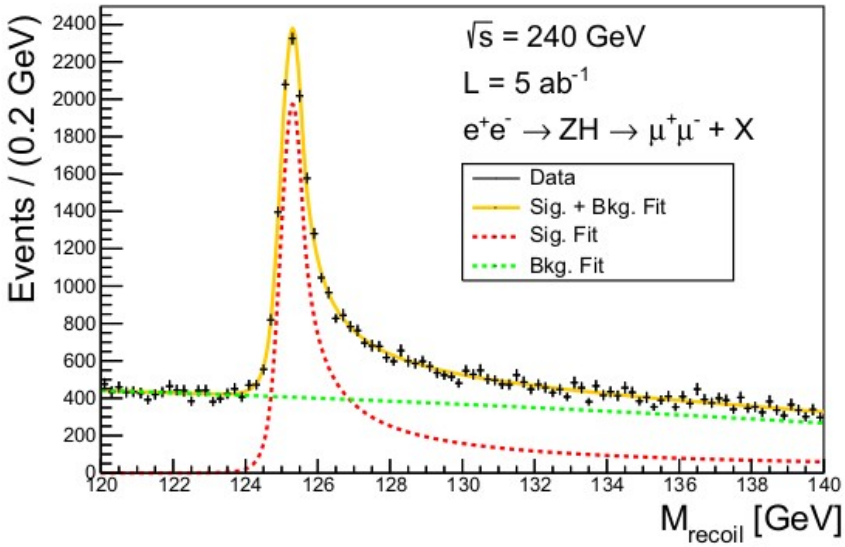


# FCC-ee: recoil method example

- Recent study used Z→μμ only with some estimation of systematics

Eur. Phys. J. Plus (2022) 137:23




Estimate σ(ee→ZH) to 1% (on the cross section) (expect 2x smaller by combining all channels – still larger than ultimate statistical precision)

# FCC-ee: Higgs couplings

- Estimated Higgs branching ratio & coupling measurement precision

FCC CDR (2019) Volume 1

| $\sqrt{s}$ (GeV) | 240 | | 365 | |
|---|---|---|---|---|
| Luminosity ($ab^{-1}$) | 5 | | 1.5 | |
| $\delta(\sigma BR)/\sigma BR$ (%) | HZ | $\nu\bar{\nu}$ H | HZ | $\nu\bar{\nu}$ H |
| $H \to$ any | $\pm 0.5$ | | $\pm 0.9$ | |
| $H \to b\bar{b}$ | $\pm 0.3$ | $\pm 3.1$ | $\pm 0.5$ | $\pm 0.9$ |
| $H \to c\bar{c}$ | $\pm 2.2$ | | $\pm 6.5$ | $\pm 10$ |
| $H \to gg$ | $\pm 1.9$ | | $\pm 3.5$ | $\pm 4.5$ |
| $H \to W^+W^-$ | $\pm 1.2$ | | $\pm 2.6$ | $\pm 3.0$ |
| $H \to ZZ$ | $\pm 4.4$ | | $\pm 12$ | $\pm 10$ |
| $H \to \tau\tau$ | $\pm 0.9$ | | $\pm 1.8$ | $\pm 8$ |
| $H \to \gamma\gamma$ | $\pm 9.0$ | | $\pm 18$ | $\pm 22$ |
| $H \to \mu^+\mu^-$ | $\pm 19$ | | $\pm 40$ | |
| $H \to$ invis. | $< 0.3$ | | $< 0.6$ | |

Branching ratios from the recoil method

Statistical uncertainties only

κ-framework fit

| Lumi ($ab^{-1}$) | $5_{240}$ | $+1.5_{365}$ | + HL-LHC |
|---|---|---|---|
| Years | 3 | +4 | |
| $\delta\Gamma_H/\Gamma_H$ (%) | 2.7 | **1.3** | 1.1 |
| $\delta g_{HZZ}/g_{HZZ}$ (%) | 0.2 | **0.17** | 0.16 |
| $\delta g_{HWW}/g_{HWW}$ (%) | 1.3 | **0.43** | 0.40 |
| $\delta g_{Hbb}/g_{Hbb}$ (%) | 1.3 | **0.61** | 0.56 |
| $\delta g_{Hcc}/g_{Hcc}$ (%) | 1.7 | **1.21** | 1.18 |
| $\delta g_{Hgg}/g_{Hgg}$ (%) | 1.6 | **1.01** | 0.90 |
| $\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%) | 1.4 | **0.74** | 0.67 |
| $\delta g_{Hmm}/g_{H\mu\mu}$ (%) | 10.1 | **9.0** | 3.8 |
| $\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%) | 4.8 | **3.9** | 1.3 |
| $\delta g_{Htt}/g_{Htt}$ (%) | – | – | 3.1 |
| $BR_{EXO}$ (%) | $< 1.2$ | $< \mathbf{1.0}$ | $< \mathbf{1.0}$ |

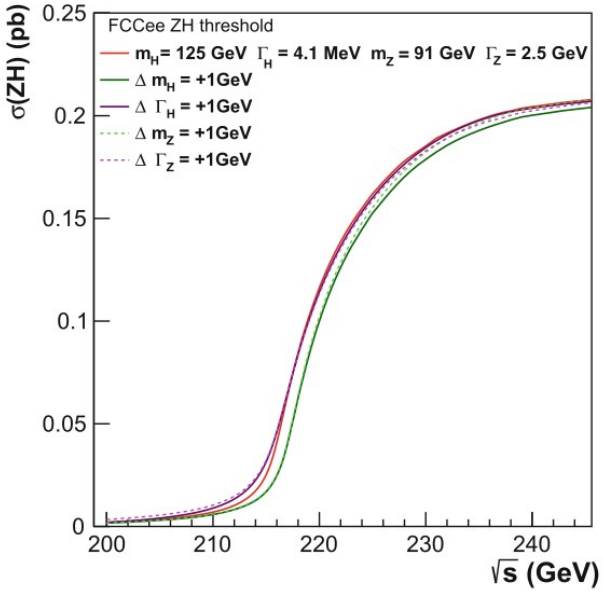
Combination using model-independent FCC-ee data improves the measurement wrt to HL-LHC standalone 3.4% expectation

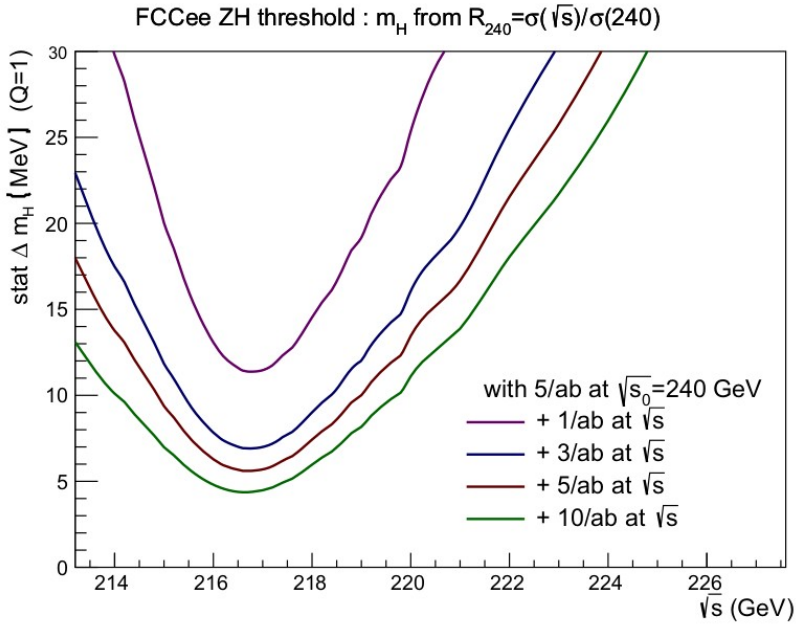
# FCC-ee: Higgs mass measurement

- Higgs mass is less of a priority since it will be measured at ~20 MeV at HL-LHC which is good enough (barring ee->H)
- There are two ways of measuring it:
  - From the recoil method: ~8 MeV (μμ only + conserv. syst.)

Talk by J Eysermans (FCC week June 2021)

  - From a scan of the ZH threshold ~10 MeV

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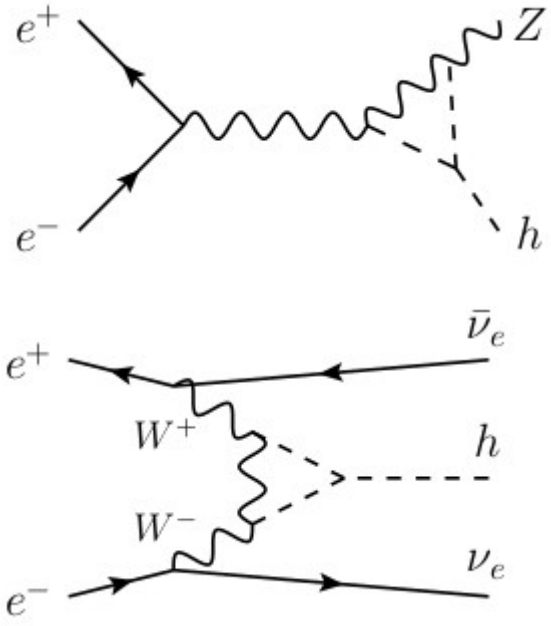
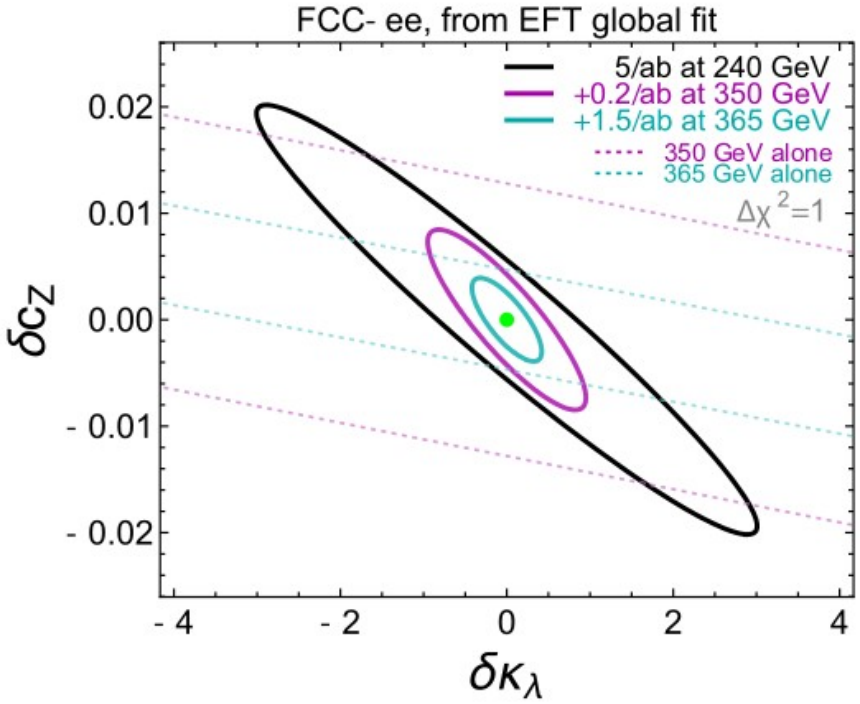
# FCC-ee: self-coupling

- Sensitivity to Higgs self-coupling from higher-order corrections




Contributions to the cross section depend significantly on √s




Expected: 33% on self-coupling (24% with 4 IPs)

JHEP 02, 178 (2018)

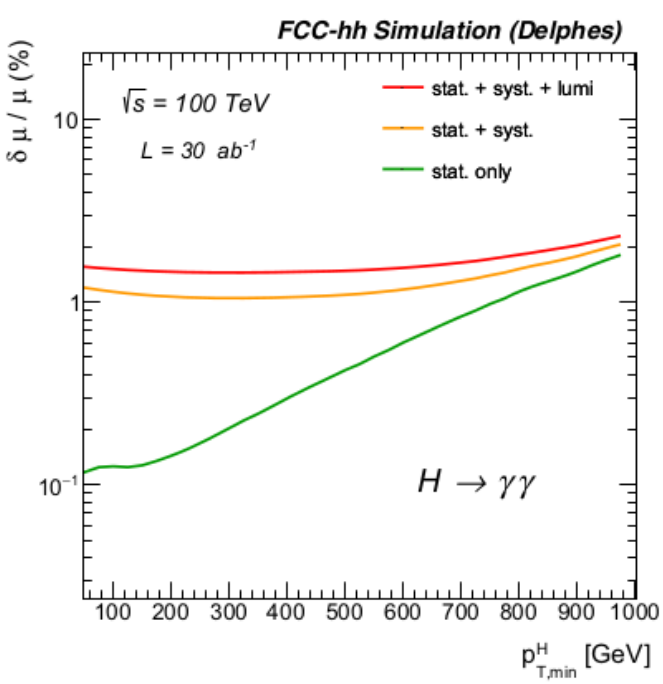
# FCC-hh

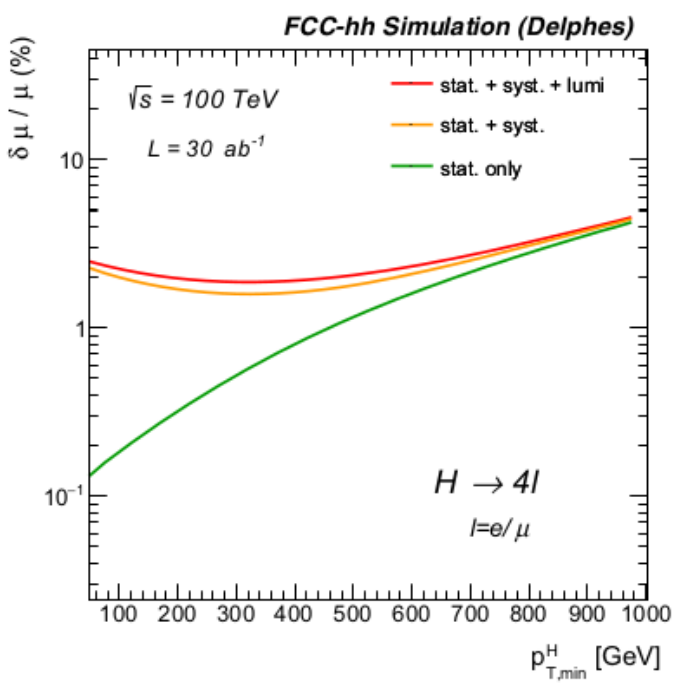
- FCC-hh plan is to deliver ~30 $ab^{-1}$ of pp collisions at 100 TeV during ~25 years of operation
  - ×10 the lumi of HL-LHC, but also ~ ×7 the energy and ~×8 the collision rate
  - Higgs production rate is ~ ×100-500 the HL-LHC rates
    - Precision in rare Higgs decays e.g. H→γγ, μμ, Zγ
  - Precision measurements high Higgs pT beyond 1 TeV
  - Synergy with FCC-ee
  - Best measurement of Higgs self-coupling wrt any other future machine

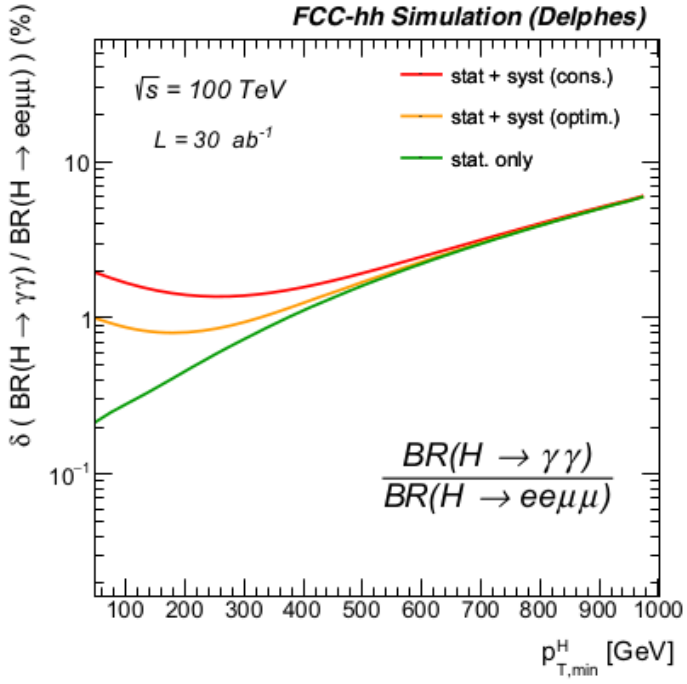
# Higgs pT in FCC-hh

- Access to precision differential cross section measurements to well below 10% in the multi-TeV region

FCC CDR (2019) Volume 1



# Higgs decays in FCC-hh

FCC CDR (2019) Volume 1

- Cross section and BRs measurements

| Observable | Precision (stat) | Precision (stat+syst+lumi) |
|---|---|---|
| $\mu = \sigma(H) \times B(H \to \gamma\gamma)$ | 0.1% | 1.5% |
| $\mu = \sigma(H) \times B(H \to \mu\mu)$ | 0.28% | 1.2% |
| $\mu = \sigma(H) \times B(H \to 4\mu)$ | 0.18% | 1.9% |
| $\mu = \sigma(H) \times B(H \to \gamma\mu\mu)$ | 0.55% | 1.6% |
| $\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$ | 5% | 7.0% |
| $R = B(H \to \mu\mu)/B(H \to 4\mu)$ | 0.33% | 1.3% |
| $R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$ | 0.17% | 0.8% |
| $R = B(H \to \gamma\gamma)/B(H \to 2\mu)$ | 0.29% | 1.4% |
| $R = B(H \to \mu\mu\gamma)/B(H \to \mu\mu)$ | 0.58% | 1.8% |
| $R = \sigma(t\bar{t}H) \times B(H \to b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \to b\bar{b})$ | 1.05% | 1.9% |
| $B(H \to \text{invisible})$ | $1 \times 10^{-4}$ | $2.5 \times 10^{-4}$ |

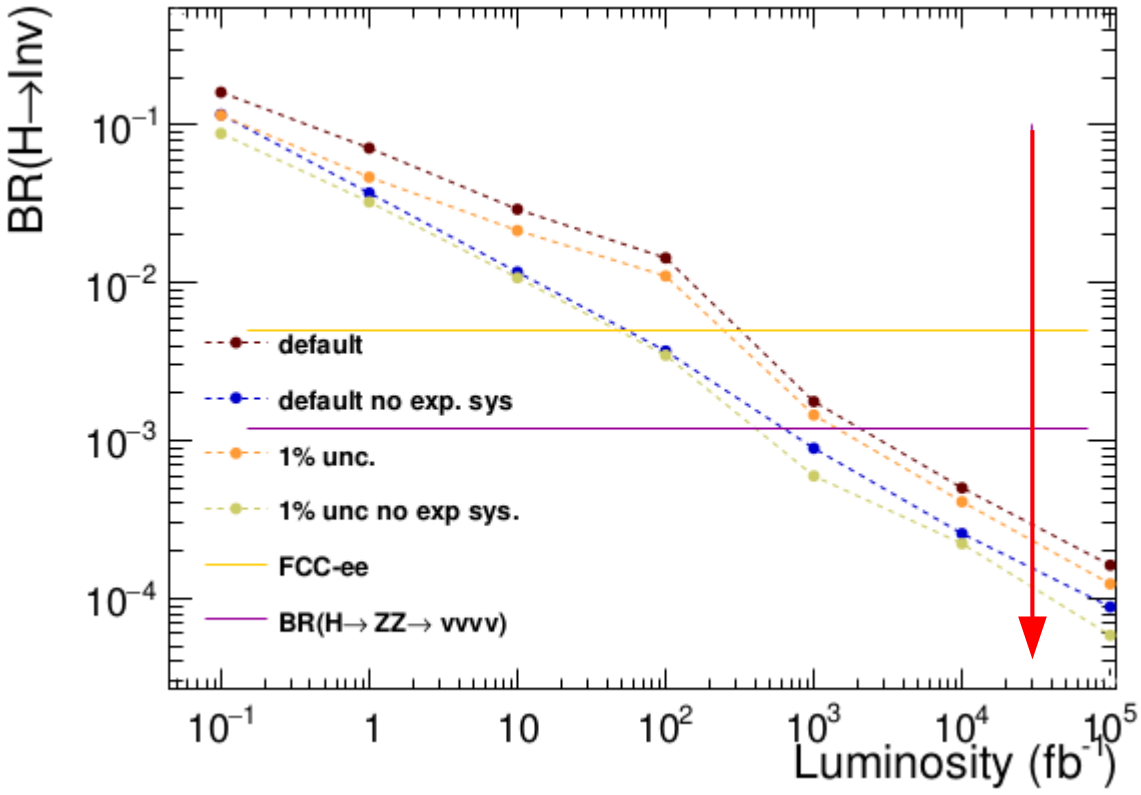
- Synergy with FCC-ee
  - Using HZZ from FCC-ee and the FCC-hh ratio measurements you can get γγ @0.4% , μμ @0.7%, Zγ @0.9%
  - Top Yukawa from ttH/ttZ (with FCC-ee H→bb) @ 1%

FCC CDR (2019) Volume 1
CERN-ACC-2018-0045
J. Phys. G 43(3), 035001 (2016)

# Higgs to invisible in FCC-hh

CERN-ACC-2018-0045

- Higgs to invisible by looking at events with large missing ET, following current LHC searches
  - Sensitivity BR ~ a few $10^{-4}$ (c.f. H→4ν ~0.1%)



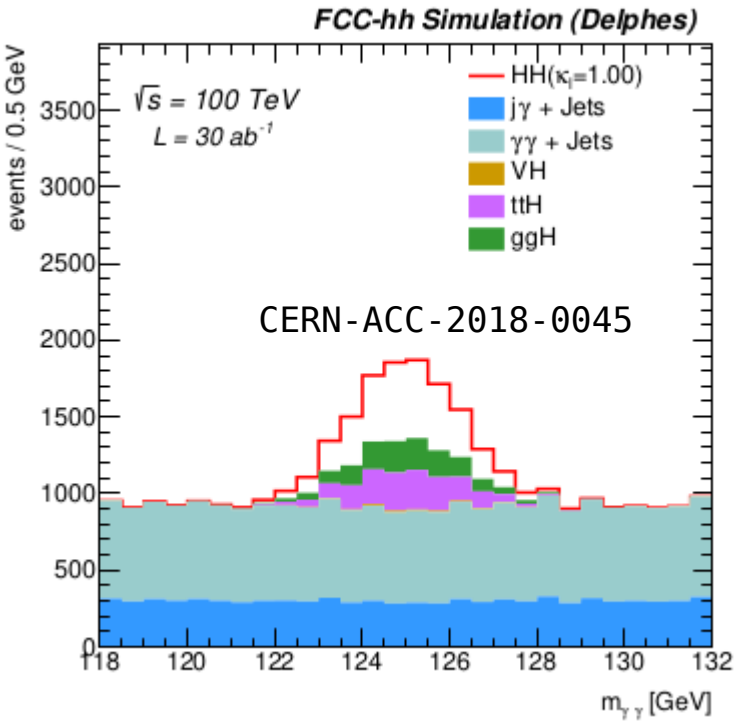

FCC-hh expected lumi at 30 $ab^{-1}$

# Multi-Higgs production in FCC-hh

- Most promising signature is gg→HH→bbγγ and has been studied in several documents

| Sensitivity to Higgs self-coupling | |
|---|---|
| FCC CDR (2019) Volume 1 | 6.5% |
| CERN-ACC-2018-0045 | 6% |
| J. Phys. G 43(3), 035001 (2016) | 10% |

- Other channels have been studied as well



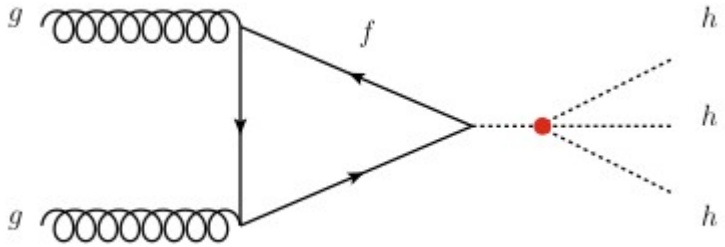

FCC CDR (2019) Volume 1

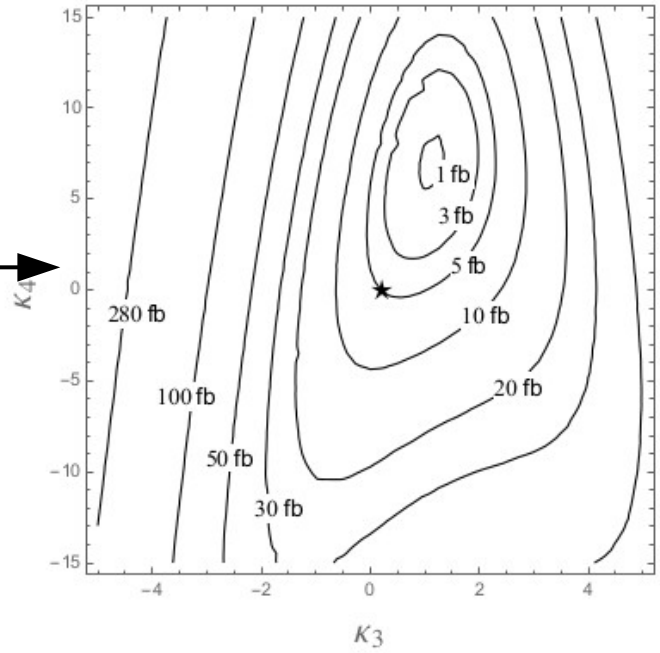
**Table 10.2** Precision of the direct Higgs self-coupling measurement in gg → HH production, for various decay modes, from the FCC-hh detector performance studies

| | $b\bar{b}\gamma\gamma$ | $b\bar{b}ZZ^*[\rightarrow 4\ell]$ | $b\bar{b}WW^*[\rightarrow 2j\ell\nu]$ | 4b + jet |
|---|---|---|---|---|
| $\delta\kappa_\lambda$ | 6.5% | 14% | 40% | 30% |

# Multi-Higgs production in FCC-hh

- Triple Higgs production has been explored as well: σ ~ 5 fb @ FCC-hh



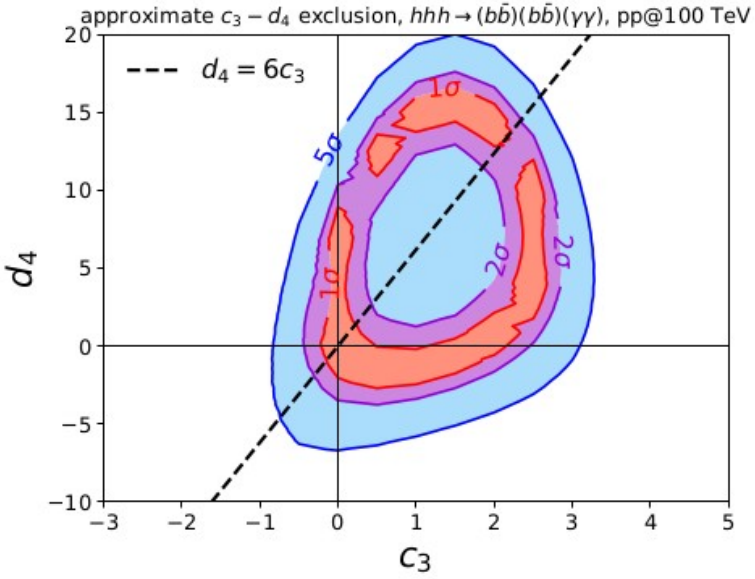

Signatures studied:

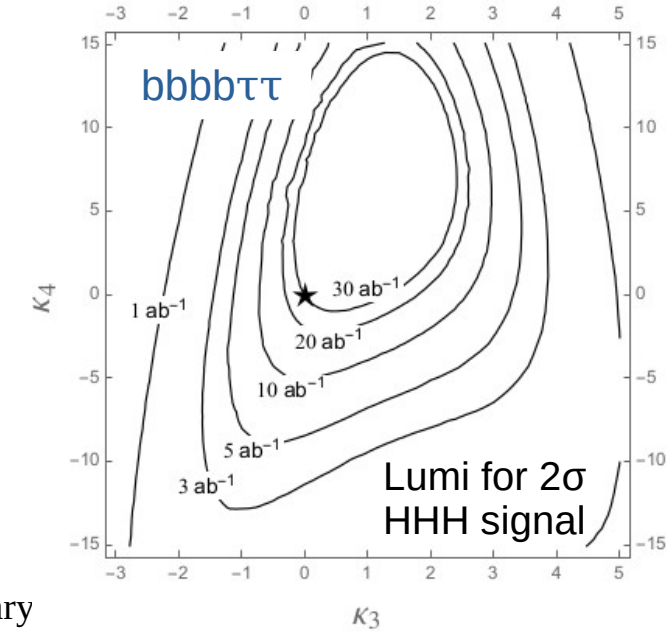
pp→HHH→bbbbγγ
(BR~ 0.23%)

JHEP 02, 006 (2016)

pp→HHH→bbbbττ
(BR~ 6.3%)

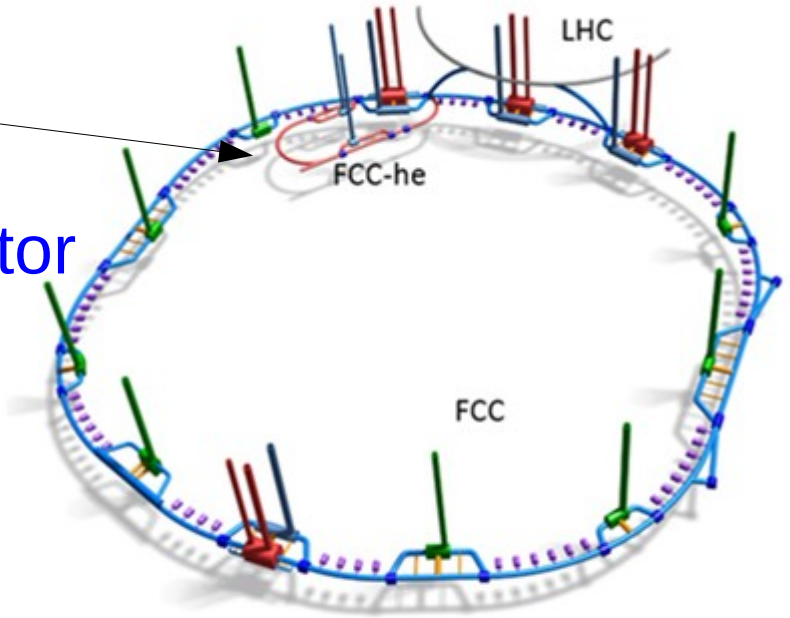
PLB 771, 354–358 (2017)



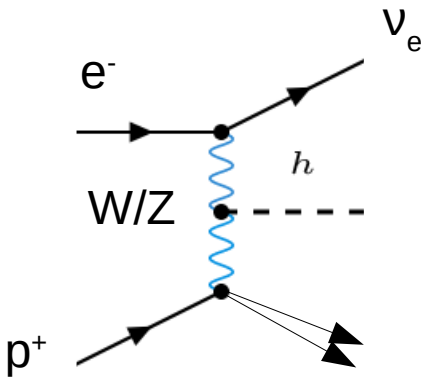
# FCC-eh

- FCC-eh will collide a proton beam from FCC-hh (50 TeV) with a 60 GeV electron beam provided by an electron recovery linac
  - Runs concurrently with FCC-hh
  - 20–25 years of operation, 1 detector
  - 2 $ab^{-1}$, low pile-up
  - Physics:
    - very precise PDF measurements, strong coupling constant measurement & other QCD physics
    - Nuclear physics
    - Higgs physics, Leptoquarks, heavy neutrinos etc



# Higgs production in FCC-eh

- Higgs production mainly via WW or ZZ fusion




WW fusion: 1 pb
ZZ fusion: 0.15 pb → About $2\times10^6$ Higgs events

Higgs couplings can be measured with precision similar to FCC-ee

| Collider | HL-LHC | FCC-ee | FCC-eh |
|---|---|---|---|
| Luminosity ($ab^{-1}$) | 3 | + 1.5 @ 365 GeV | 2 |
| Years | 25 | + 4 | 20 |
| $\delta\Gamma_H/\Gamma_H$ (%) | SM | **1.3** | SM |
| $\delta g_{HZZ}/g_{HZZ}$ (%) | 1.5 | **0.17** | 0.43 |
| $\delta g_{HWW}/g_{HWW}$ (%) | 1.7 | **0.43** | 0.26 |
| $\delta g_{Hbb}/g_{Hbb}$ (%) | 3.7 | **0.61** | 0.74 |
| $\delta g_{Hcc}/g_{Hcc}$ (%) | SM | **1.21** | 1.35 |
| $\delta g_{Hgg}/g_{Hgg}$ (%) | 2.5 | **1.01** | 1.17 |
| $\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%) | 1.9 | **0.74** | 1.10 |
| $\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%) | 4.3 | **9.0** | n.a. |
| $\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%) | 1.8 | **3.9** | 2.3 |
| $\delta g_{Htt}/g_{Htt}$ (%) | 3.4 | – | 1.7 |
| $BR_{EXO}$ (%) | SM | < **1.0** | n.a. |

FCC CDR (2019) Volume 1

# Multi-Higgs production in FCC-eh

- Di-Higgs production can be also probed in FCC-eh

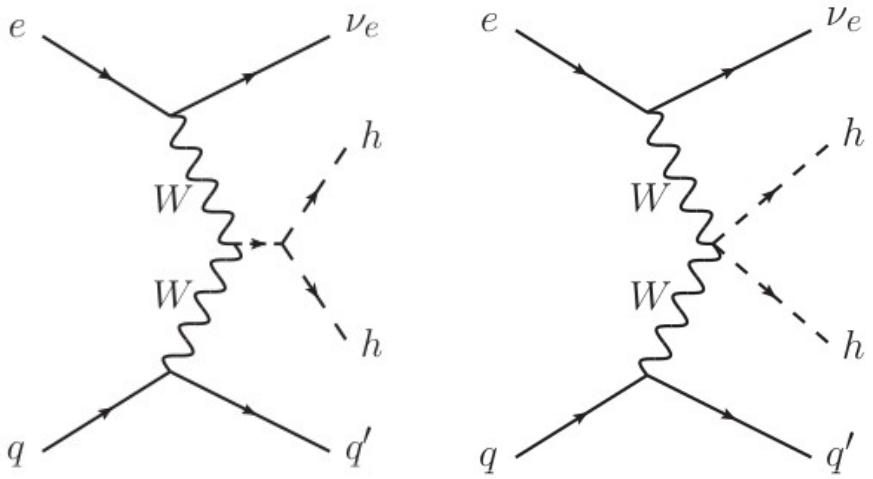
Uses hh->4b in a cut-based analysis

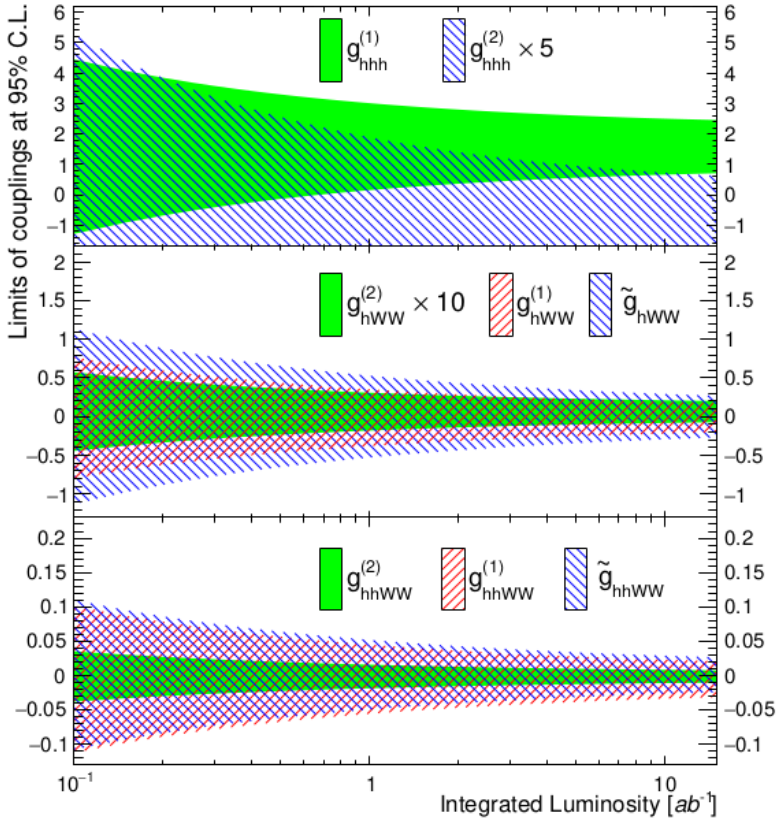
$\sigma \approx 0.28$ fb i.e. ~560 events (incl b-tagging) @ 2 ab$^{-1}$

Probes both hhh and hhWW couplings

PLB 764 (2017) 247-253

Estimate of ~20% precision in self-coupling (@10 ab$^{-1}$)
Prospects to be improved to ~10% (@3 ab$^{-1}$)



# Summary

- FCC offers a complete package for Higgs physics
  - Ultimate precision to Higgs couplings to sub-% level
  - Measurement of Higgs self-coupling
  - Access to rare Higgs processes, incl. quartic couplings
  - Synergy among the different accelerators of the project: FCC-ee, FCC-hh and FCC-eh with each of them bringing unique features