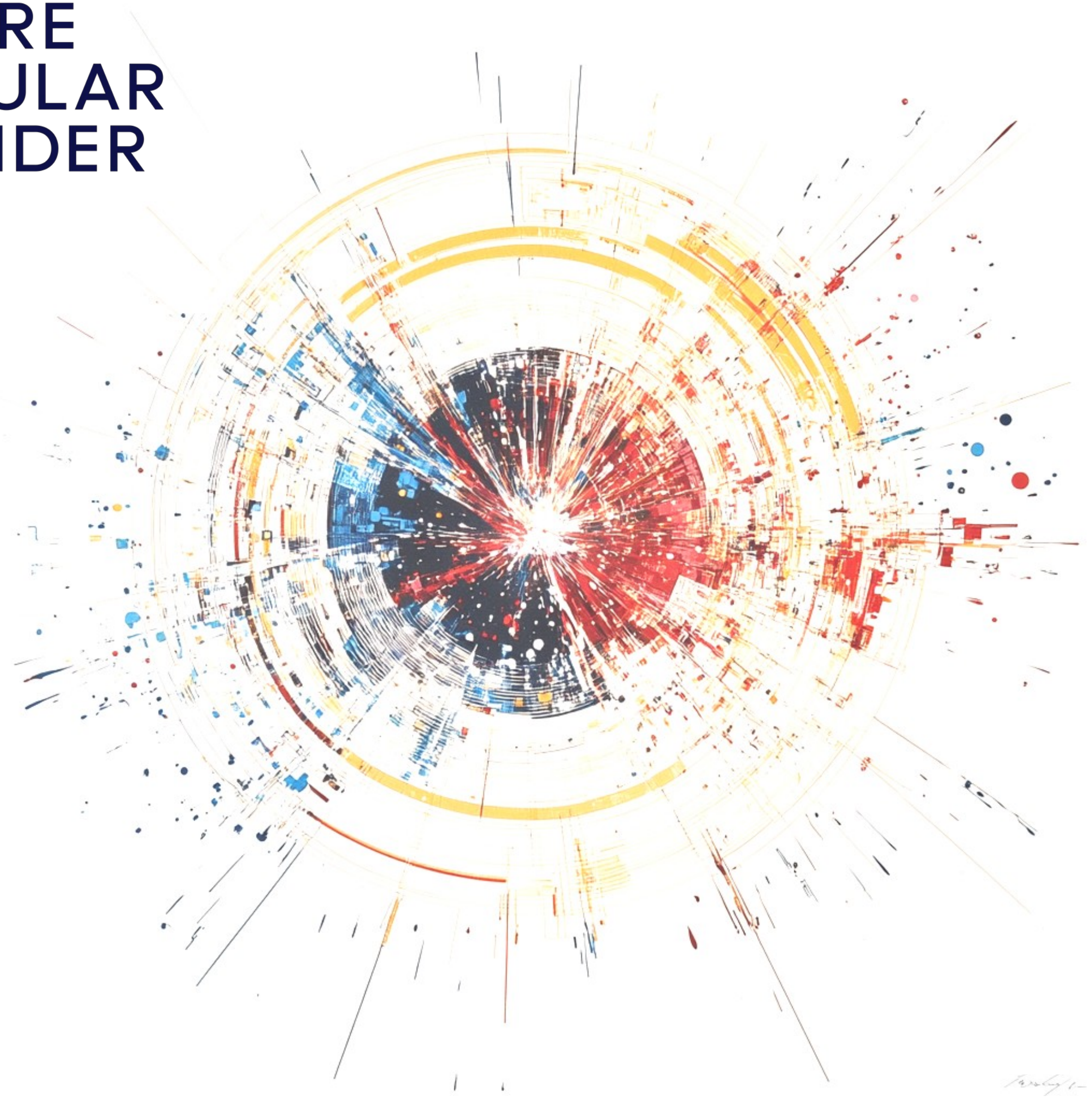
Higgs physics at FCC-ee



Louis Portalès

Higgs Hunting – 25/09/2024

The LHC legacy

Extensive Higgs physics program currently ongoing at (HL-)LHC

→ **Higgs mass measured at per-mil level**
- Can expect ~10-20 MeV precision with HL-LHC

→ **Higgs width measurements (model dependant): ~50% unc. with Run 2**
- Although direct measurement hard to achieve even at HL-LHC

→ **Higgs couplings**
- 0(1-5%) precision achievable for bosonic & 3rd gen fermionic couplings (+ $g_{H\mu\mu}$)
- 95% CL exclusion of κ_λ=0 within reach

→ **Overall Impressive precision despite the harsh conditions of p-p collisions**

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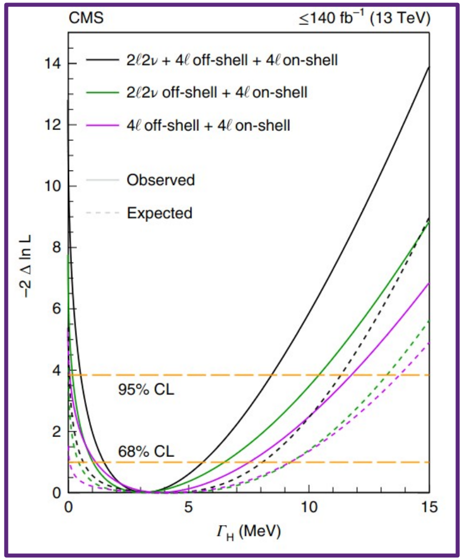

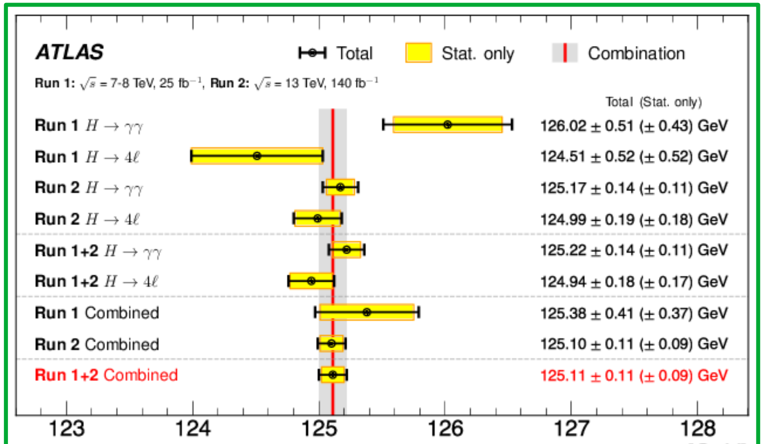

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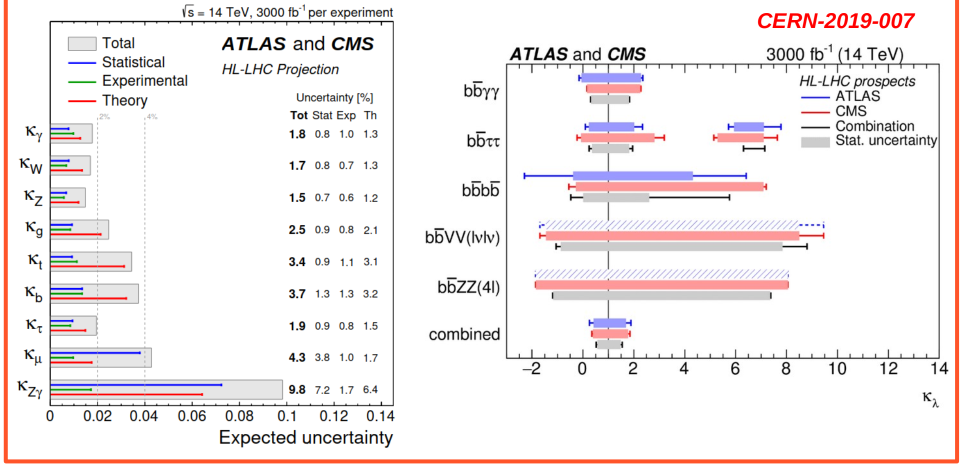
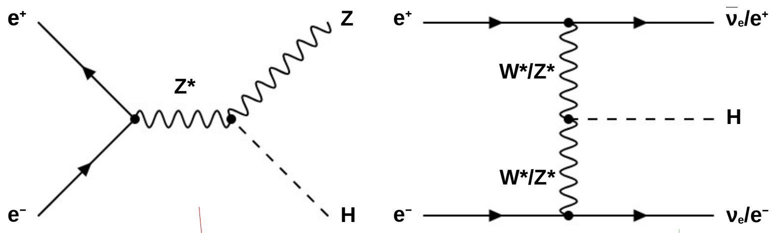


CERN-2019-007

A new look with FCC-ee

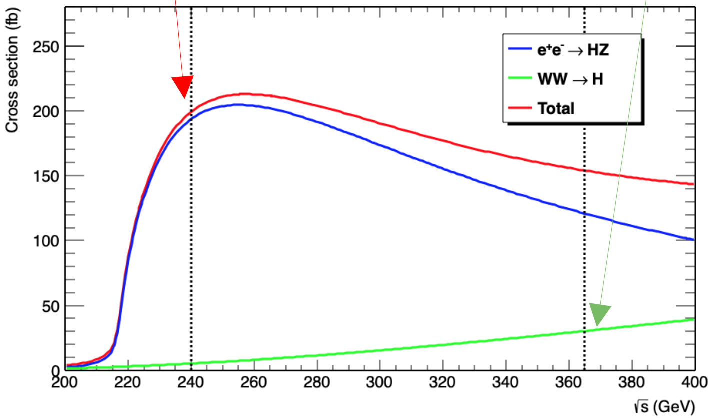


At FCC-ee, things will look much different

→ **Datasets enriched in ZH (@ 240 GeV) and VBF-H (@365 GeV) will be gathered**

- "ZH" run @ 240 GeV (10.8 ab^{-1} w/ 4 IP): ~ 2 million ZH, ~ 50.000 VBF events
- "ttbar" run @ 365 GeV (3 ab^{-1} w/ 4 IP): ~ 400.000 ZH, ~ 100.000 VBF events

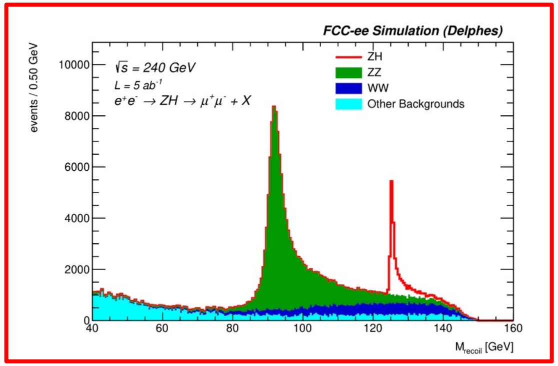
  → + possibly ee→H run @ 125 GeV, although challenging



→ **e^+e^- collisions → clean environment**

- Small background & high signal efficiencies
- No PDFs! Initial state energy precisely known
  - Allowing inclusive study of H production (in ZH), only looking at the Z boson:
    - Recoil mass: $M^2_{\mathrm{rec.}} = s - 2E_Z\sqrt{s} + M_Z^2$

      → Model independent characterisation of the Higgs boson



→ **Extensive Higgs physics program can be foreseen**

- Already being prepared as part of the FCC feasibility study
  - And used to give direction to the parallel detector R&D efforts
- A few are highlighted in the next slides

Measuring the Higgs mass

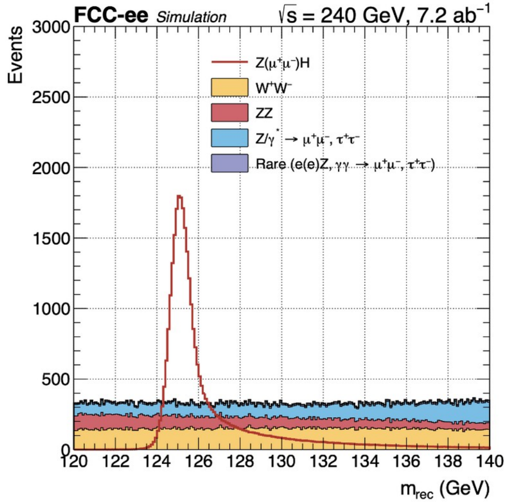
Higgs mass from inclusive analysis

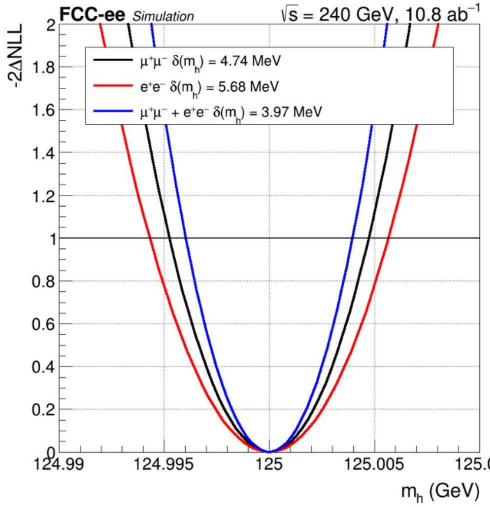
→ Using recoil mass in Z(ll)H events (l=e,μ)

- Simple event selection
  - 2 SF-OS leptons
  - $86 < m_{ll} < 96$ GeV
  - $20 < p_{ll} < 70$ GeV ($p_{ll} > 20$ GeV @ $\sqrt{s}$=365 GeV)
  - $120 < m_{rec} < 140$ GeV
- Simple combined fit of recoil mass
  - Combining ee & μμ categories
  - With realistic array of systematic uncertainties:
    → Beam energy spread, $\sqrt{s}$ & energy scales (e/μ)
- Expecting δm ~ 4 MeV (3.1 stat. + 2.5 syst)
  - Assuming 10.8 ab^{-1} of data (4 IP scenario)
  - Sensitivity ~ fully driven by $\sqrt{s}$ = 240 GeV

→ Thorough study of detector design impact

- Larger variations from track resolution
  - High field & lighter tracker beneficial
- But no dramatic impact from detector configuration
  - All tested scenarios reaching ~ 4 MeV
    → Resolution on mH at the level of Γ_H





Annotation	Final state	Muon 240 GeV	Electron 240 GeV	Combination 240 GeV
Nominal configuration	Nominal	3.92(4.74)	4.95(5.68)	3.07(3.97)
	Inclusive	3.92(4.74)	4.95(5.68)	3.10(3.97)
Crystal ECAL to Dual Readout	Degradation electron resolution	3.92(4.74)	5.79(6.33)	3.24(4.12)
Nominal 2 T → field 3 T	Magnetic field 3T	3.22(4.14)	4.11(4.83)	2.54(3.52)
IDEA drift chamber → CLD Si tracker	Silicon tracker	5.11(5.73)	5.89(6.42)	3.86(4.55)
Impact of Beam Energy Spread	BES 6% uncertainty	3.92(4.79)	4.95(5.92)	3.07(3.98)
Impact of Beam Energy Spread	Disable BES	2.11(3.31)	2.93(3.88)	1.71(2.92)
Perfect (=gen-level) momentum resolution	Ideal resolution	3.12(3.95)	3.58(4.52)	2.42(3.40)
	Freeze backgrounds	3.91(4.74)	4.95(5.67)	3.07(3.96)
	Remove backgrounds	3.08(4.13)	3.51(4.58)	2.31(3.45)

Inclusive ZH cross-section

Similar analysis/selection as mass measurement

→ **But training/fitting dedicated BDTs**

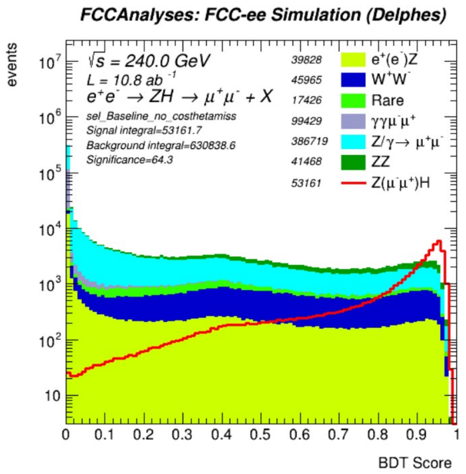
- 4 in total: (Z→ee/μμ) x (√s = 240,365 GeV)
  - Combining Z decay channels separately for the two √s

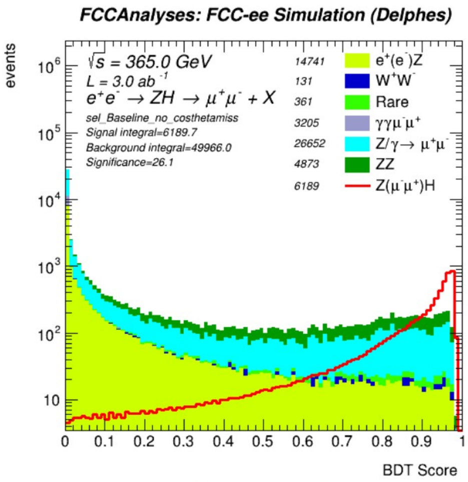
→ **Cross-section measurement statistically-dominated**

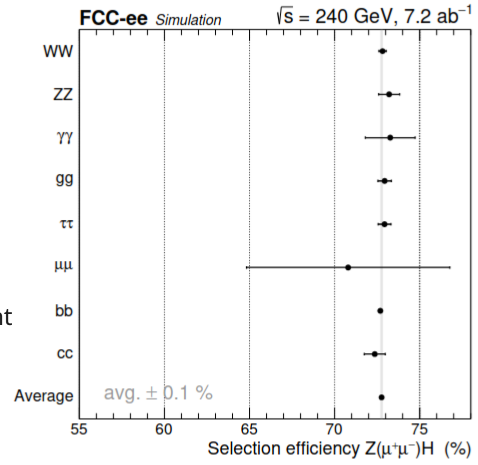
- √s = 240 GeV: δσ ~ 0.6 % (0.59 % stat-only)
- √s = 365 GeV: δσ ~ 1.5 % (1.42 % stat-only)

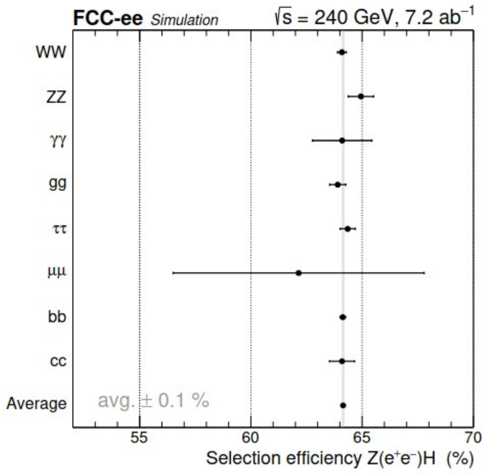
→ **Directly translates to constraints on g_{HZZ}**

- As $\sigma(ZH) \sim g_{HZZ}^2$
  - Opens up possibility of precise Higgs couplings measurements through exclusive ZH(H→xx) analyses
  - Accessible through recoil-like analysis, as decay-mode independent





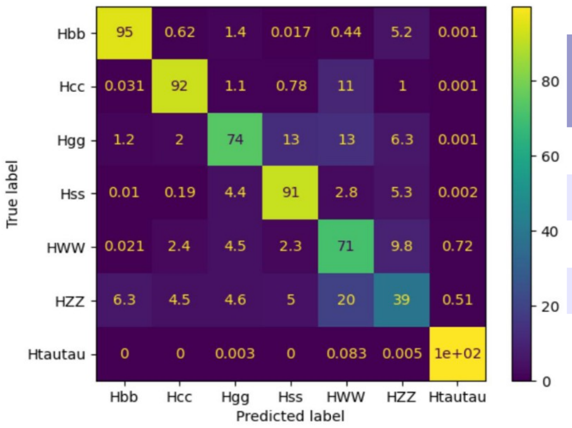




Hadronic Higgs decays

We have never been as good at "jet tagging"

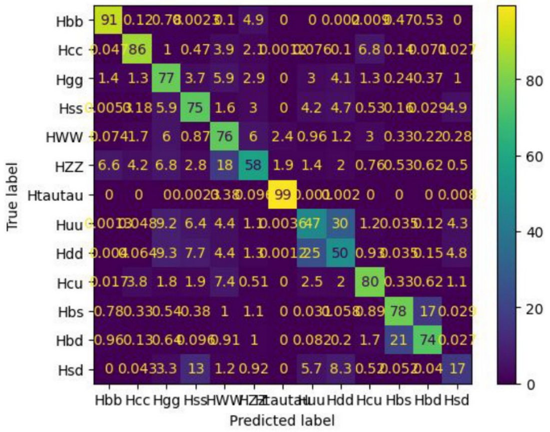
→ **"ParticleNet" jet tagger**
- GNN-based flavour tagging algorithm
  - Already widely used in CMS
  - Now also used for FCC prospect studies



	δ(σ×BR) [%]			
	Z(ll)H	Z(νν)H	Z(qq)H	Comb.
H→bb	0.7	0.4	0.3	0.22
H→cc	4.1	2.2	3.3	1.7
H→ss	230	150	440	120
H→gg	2.2	1.1	3.1	0.9
H→ WW	1.8	1.1	8.7	1.1

→ **Going for the second generation**
- "FCC version" of Pnet classes jets into b/c/s/g/τ
- Tested so far in 3 complementary analyses
  - Orthogonal through Z decay choice (Z→ll,νν,qq)
  - All performing combined fits of Higgs/Z-boson mass
  - Using "Higgs decay" categories, defined from PNet + kinematic features
- Here considering 10.8 ab^{-1} @ 240 GeV
  - Expected ~ 10 % sensitivity improvement from combination with 365 GeV

→ **Extension to light quarks & exotic (FCNC) decays**
- Similar approach, with additional classes in discriminant
  - So far only considering Z→νν
  - Still far from SM, but significant room for improvement



	σ×BR 95% CL	BR(SM)
H→dd	1.4e-03	6e-07
H→uu	1.5e-03	1.4e-07
H→bs	3.7e-04	e-07
H→bd	2.7e-04	e-09
H→sd	7.7e-04	e-11
H→cu	2.5e-04	e-20

Leptonic Higgs decay

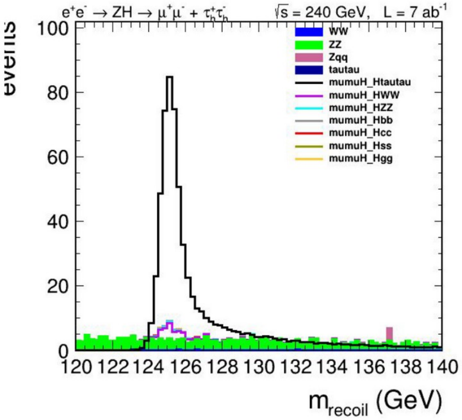
H→μμ & H→ττ similarly probed through ZH production

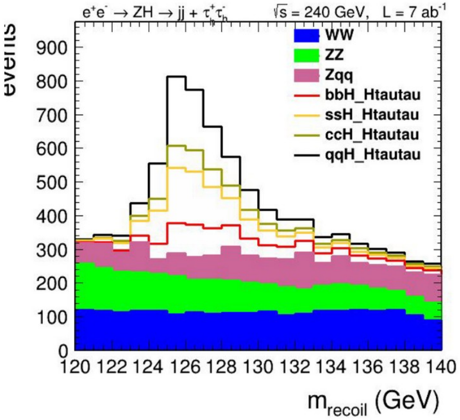
→ H→ττ

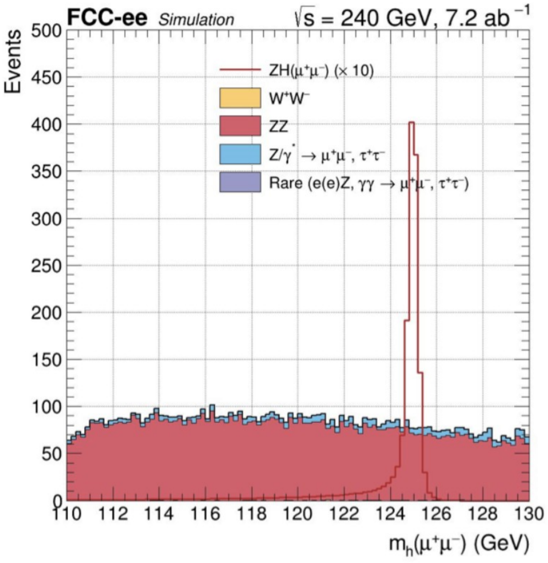
- Similar “recoil mass selection” as for ZH analysis
  - In Z decay categories (ee/μμ/bb/qq, νν not yet considered)
  - Focusing on √s=240 GeV, assuming 7.2 ab^{-1}
- For now targeting hadronic tau decays only
  - Tau reconstruction procedure studied in several separated efforts
  - Optimal solution to be determined
- (Very) preliminary sensitivity estimates
  - Sub-percent uncertainties on σxBR(ZH,H→tautau)
  - Driven by Z→qq channels ONLY statistical for now

→ H→μμ

- “Recoil mass selection”
- 2 additional high-momentum muons
  - Using well-resolved mμμ distribution in fit
- Reaching δ(σ×BR) < 20%
  - Again driven by Z→qq channel







About the electron Yukawa

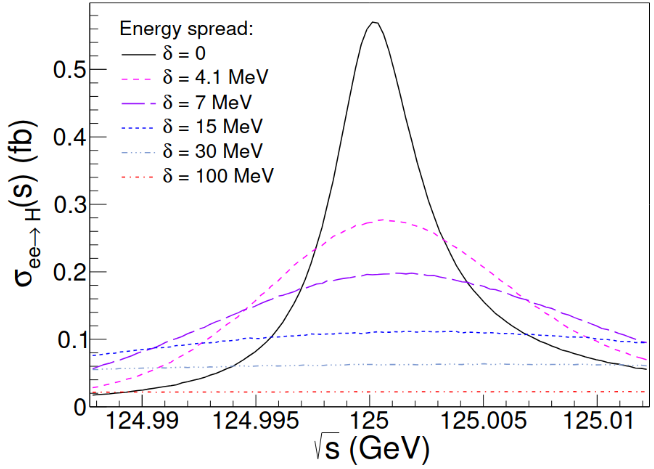
An absolute challenge: BR(H→ee) ~ 10^{-9} !

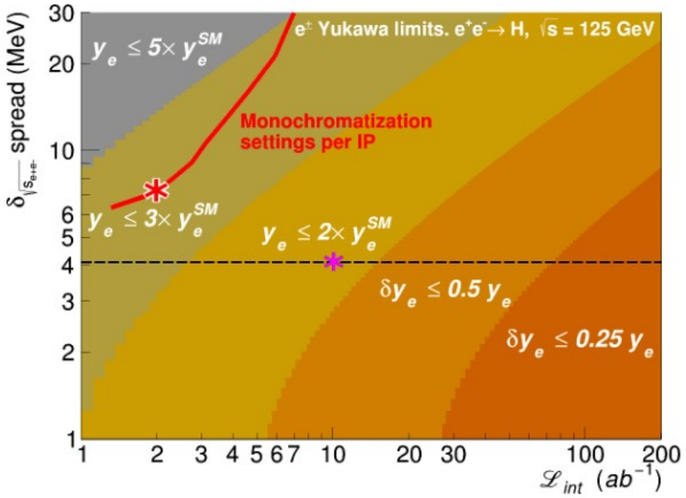
→ But not entirely out of the picture

- Would require a dedicated run at 125 GeV
  - Targetting s-channel ee→H production
- BUT also extremely challenging requirements
  - Higgs mass measured with < 5 MeV uncertainty → ok (240/365 GeV program)
  - (Very!) high luminosity → ok (several ab^{-1}/year/IP of data achievable at 125 GeV)
  - Extremely precise control of beams, with ideally BES ~ Γ_H → hard to achieve

→ With current best knowledge of achievable sensitivy

- Assuming monochromatization of beams (→ BES~7 MeV)
  - Reaching $y_e < 3 \times y_e^{SM}$ (95% CL) assuming 2 ab^{-1} (1 IP, 1 year of data)
  - Naive scaling with 2 years & 4 IP (→ 16 ab^{-1}): could ~ reach $y_e < y_e^{SM}$





Invisible Higgs decay

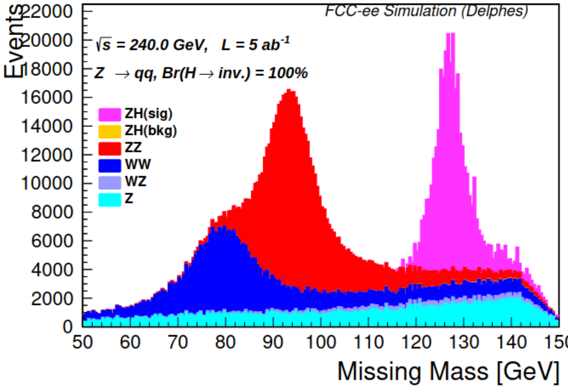
→ **Yet another ZH analysis**

- Investigating Z→ll/qq
  - 5 categories: ee/μμ/bb/cc/qq
  - Further splitting into Njet categories → better background control
  - Requiring large missing momentum (p_{miss} > 10-20 GeV)
- Extracting limits on BR(H→inv.) from m_{miss} fit

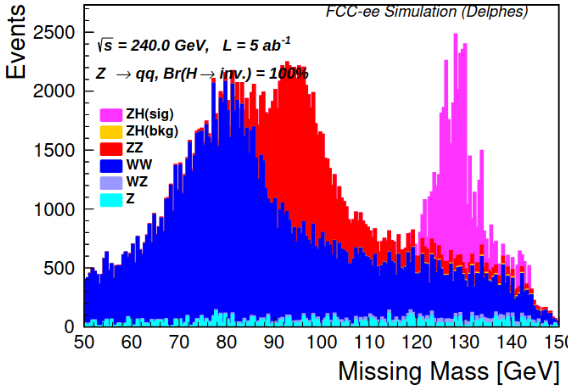
→ **Able to reach SM-level sensitivity**

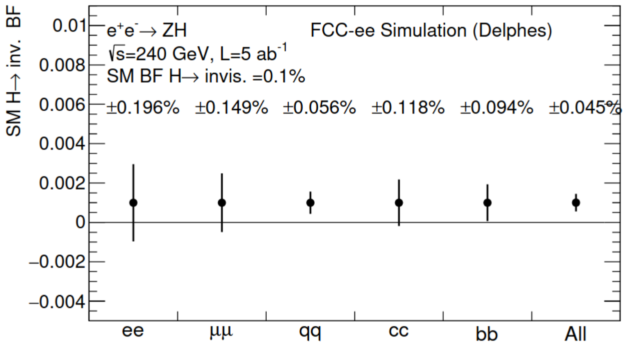
- ~ 2σ significance (w/ 5 ab^{-1})
- Capable of observing eventual H→DM decays
  - With down to BR~0.2%

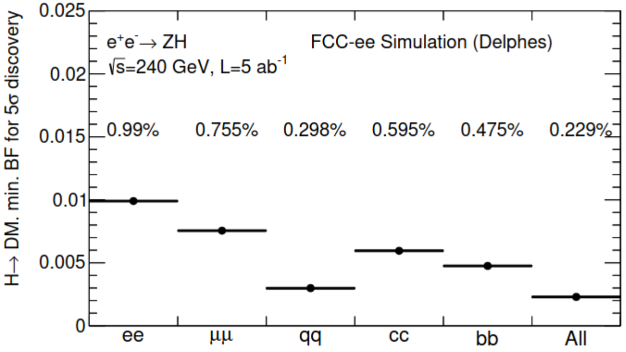
$\leq$ 2 jets



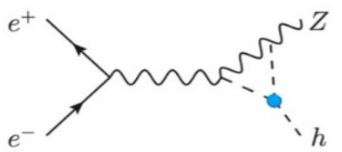
$\geq$ 4 jets

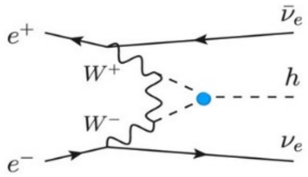






Higgs boson self coupling





HH production not accessible at FCC-ee energies

→ But Higgs self coupling accessible through NLO corrections

- Can be probed exclusively
  - Through combined fit of various Higgs decay modes:

Decay Modes

$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

$C_1^{\Gamma_{\rm tot}} \equiv \sum_j {\rm BR}^{\rm SM}(j) C_1^\Gamma(j)$ ~2.3x10-3

- And/or inclusively
  - Taking advantage of the energy-dependance of the correction

→ Sensitivity mostly driven by statistics

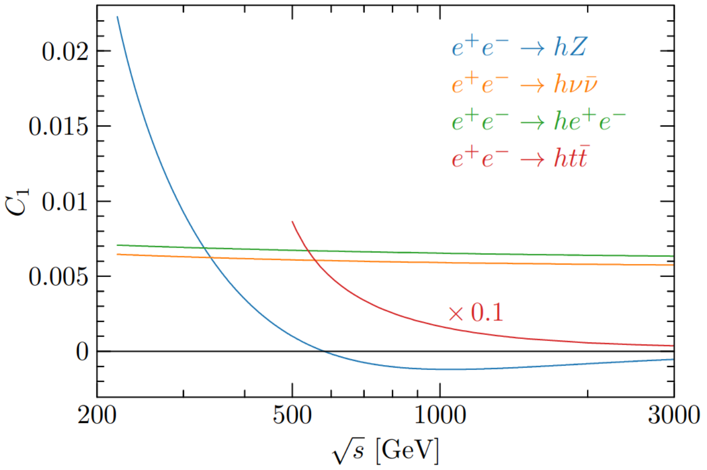
- Can realistically achieve $\delta\lambda < 30\%$
  - $\delta\lambda$ = 28% from latest prospects
  - Still requires an update with the latest scenario:
    → 4 IP, 10.8 ab^{-1} @ 240 GeV + 3 ab^{-1} @ 365 GeV
    → Updated machine parameters (+ detector models)

$$\sigma_{i,\rm NLO} = Z_{\rm H}\sigma_{i,\rm LO}\left(1 + \kappa_\lambda C_{1,i}\right)$$

Universal wave function renormalization

LO cross-section

Process & energy dependent coeff. From loop-tree interference

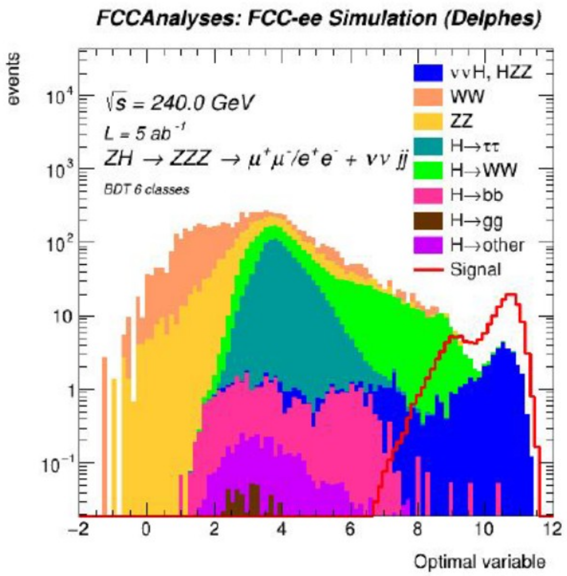


Higgs boson width

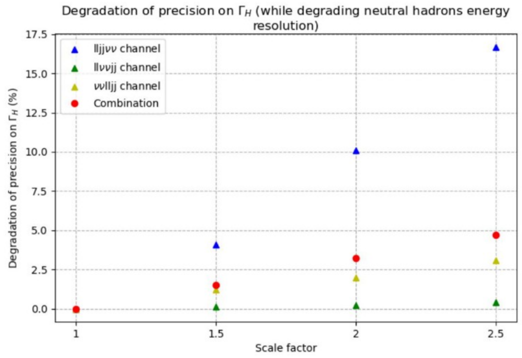
Clean access to Γ_H at FCC-ee

→ Through ZH(H→ZZ*) analysis $\Gamma_H \propto \frac{\sigma^2_{ZH}}{\sigma_{ZH,H(ZZ^*)}}$

- σ(ZH, H→ZZ*) estimated from dedicated analysis
  - Large number of different final states, 5 considered so far
    → Z(→ll)H(vvqq) + Z(→ll)H(qqvv) + Z(vv)H(llqq)
    → Z(→ll)H(4q)
    → Z(→qq)H(→qq)
  - Using multiclass BDTs to enhance sensitivity
- Latest estimates from Feasibility study:
  - δ(σ×BR) ~ 14 % from ZZZ*→6q analysis
  - δ(σ×BR) ~ 8.4 % from ZZZ*→2l+4q analysis
  - δ(σ×BR) ~ 3.1 % from ZZZ*→2l+2v+2q analysis
- Yielding $\delta\Gamma_H$ ~ 4 %
  - Preliminary estimate!
    → Found not to be too sensitive to neutral hadron energy res.
    → Further tuning of the sub-leading channels in progress



Uncertainty in Γ_H(%)	
Total	4.6%
Statistics	4.5%
H(WW*) normalisation (5%)	0.8%
ZZ normalisation (10%)	0.2%
WW normalisation (10%)	0.1%



→ Through H→WW* & VBF H→bb

- Slightly more complex approach
  - Not yet tackled in the Feasibility study
- Could allow to reach $\delta\Gamma_H$ ~ 1 %

$$\Gamma_H \propto \frac{\sigma(\nu\nu H \to bb)\sigma(ZH)^2}{\sigma(ZH \to bb)\sigma(ZH \to WW^*)}$$

Conclusion & take-away

Extensive Higgs physics program at the FCC-ee

→ Unprecedented precision can be achieved for most accessible quantities (mass, width, couplings, ...)

- Based on most up to date accelerator design & expected Luminosities

Excellent playground to understand detector requirement

→ Tackled as part of the ongoing FCC feasibility studies

- Overall limited impact from detector designs seen so far on measurements
- BUT still a lot uncovered / to understand

The effort is still young

→ Most results are (very) preliminary

- Most analyses can likely be significantly improved
- And many just started, or are just at the “concept” stage at this point

→ But we’re getting a clearer picture of what can be achieved by the day

Parameter	FCC-ee CDR	FCCee today
$H\to WW$	1 %	2.0 %
$H\to ZZ$	3.6 %	4.6 %
$H\to gg$	1.6 %	0.94 %
$H\to\gamma\gamma$	7.5 %	3.5 %
$H\to cc$	1.8 %	1.92 %
$H\to bb$	0.25 %	0.22 %
$H\to\mu\mu$	15.8 %	19.5 %
$H\to\tau\tau$	0.75 %	0.9%
$H\to Z\gamma$		
$H\to ss$	–	124 %
Invisible	< 0.25 %	< 0.18 %
m_H	5 MeV	4 MeV
Γ_H	1 %	4%
κ_λ	42 %	30%