Higgs Prospects at FCC-ee

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Introduction: the FCC-ee project

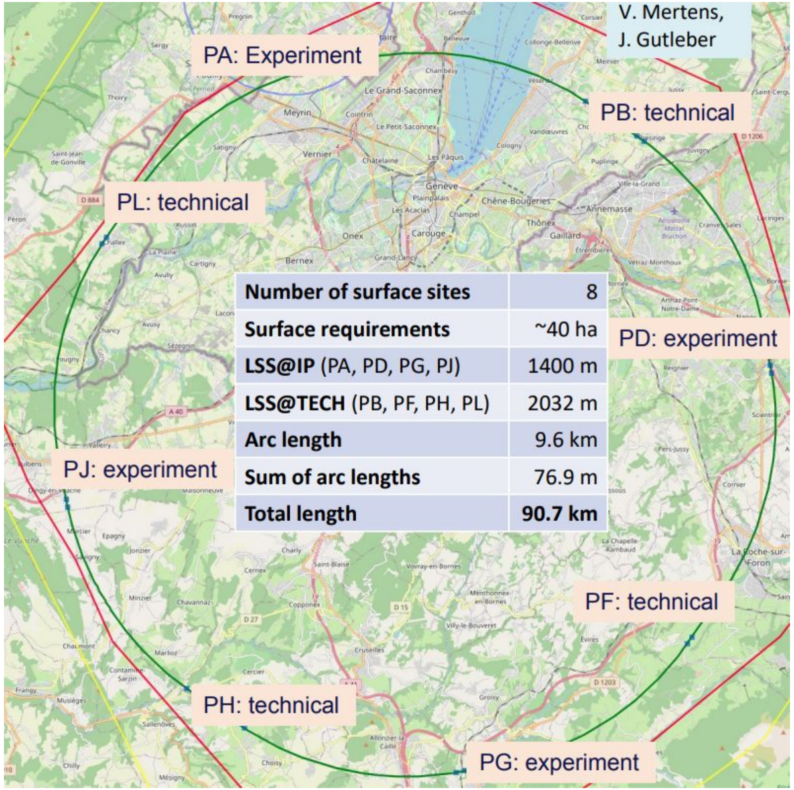
Comprehensive long-term program maximizing physics opportunities

- Last European Strategy: next collider project should be a **Higgs Factory**

- 90.7 km circular collider at CERN: e^+e^-, then pp in long-term future
  - Z pole, WW threshold, ZH threshold, tt threshold

- Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment** (protected zones), **infrastructure** (water, electricity, transport), machine **performance**

- Mid-term report of Feasibility Study end of 2023 ; very well received
  - End of feasibility study **advanced to March 2025**



Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

FCC-ee physics programme

"Higgs Factory" Programme

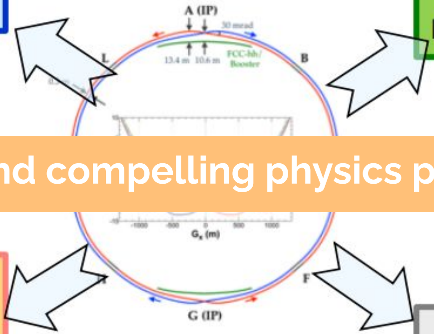
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W...
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Very broad and compelling physics programme

Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

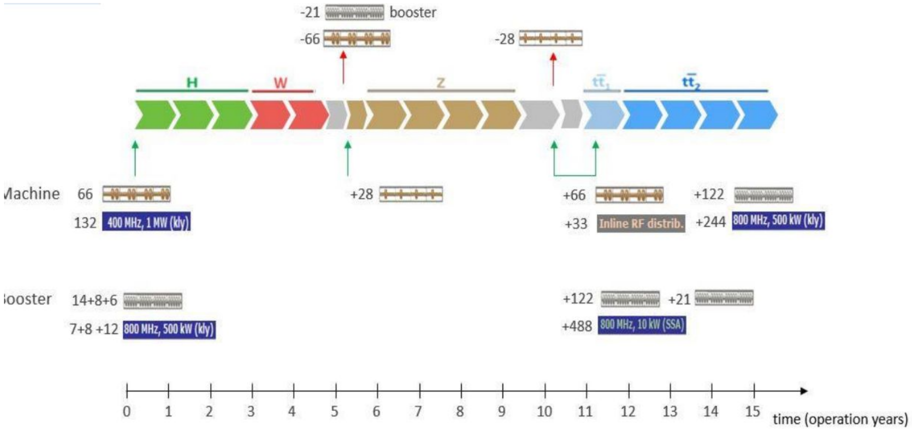
Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

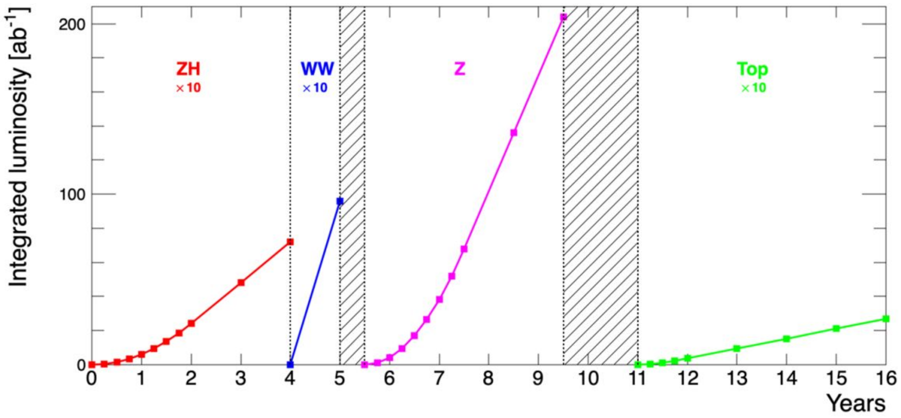
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes - LLPs

Higgs in the FCC-ee physics case

FCC-ee is designed to be a Higgs factory

- Higgs physics: cornerstone of the FCC-ee physics programme
  - Running plan could start with ZH instead of increasing center-of-mass energy
- Several important results in the Interim Report
  - Mass measurement
  - Hadronic couplings
  - Self-coupling
  - Invisible BR
- Further developments in the works
  - Width
  - CP Properties





SM Lagrangian and Higgs interactions

$$\mathscr{L}_{\rm SM} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

Gauge interactions, structurally like those in QED, QCD, EW, **studied for many decades** (but now with a scalar)

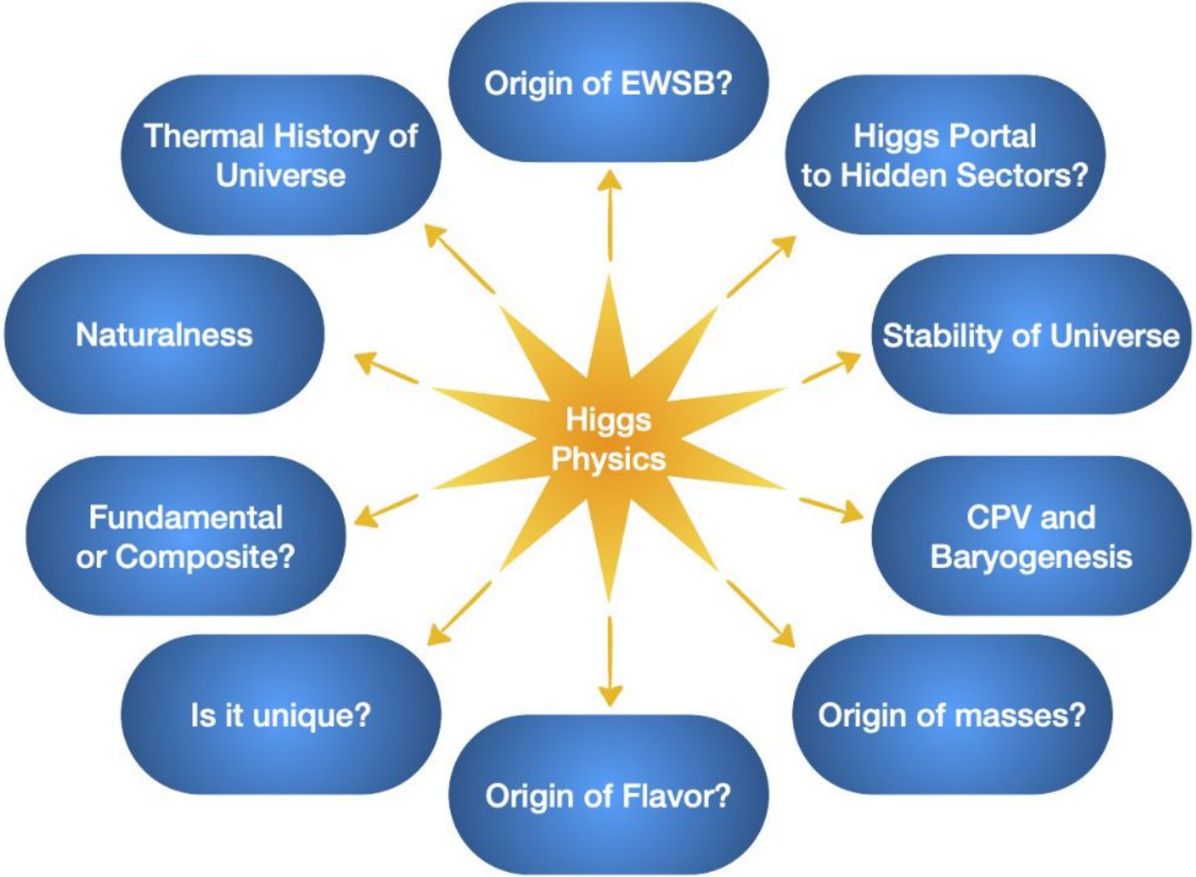
Yukawa interactions. Responsible for fermion masses, and induces "fifth force" between fermions. **Direct study started only in 2018!**

Higgs potential → self-interaction ("sixth?" force between scalars).

Holds the SM together.

Unobserved

Higgs and unknowns



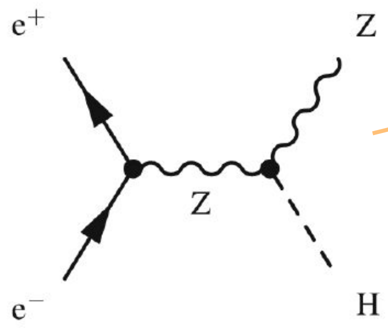
The FCC-ee Higgs dataset

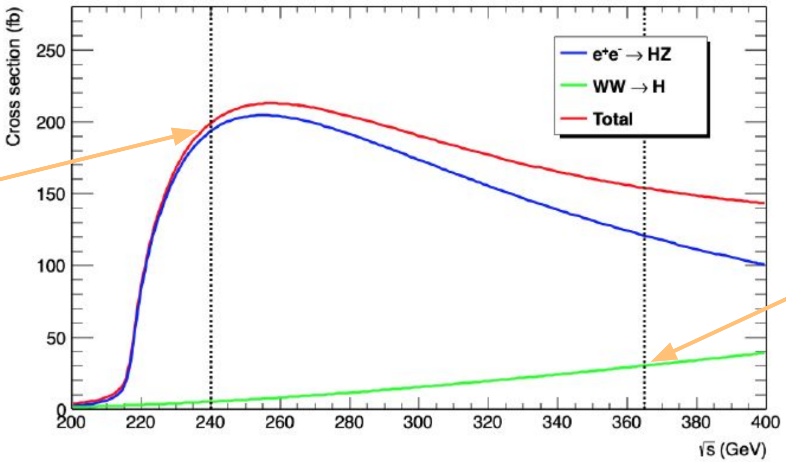
Higgsstrahlung

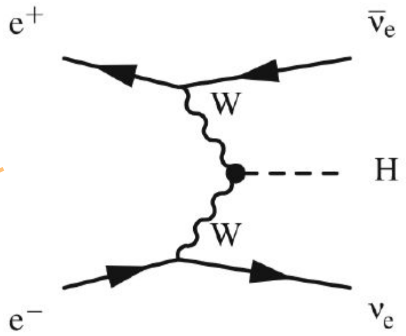
- 1 million clean ZH events at 240 GeV
  - (for 2 experiments)

Vector boson scattering

- Decent statistics (50k events) at 365 GeV
- Very complementary for many of the measurements







Higgs Physics Overview

Couplings

- Huge improvements wrt LHC in many places
  - Necessary to reach exclusion of some classic BSM models
  - In particular limits on total width and BR_{inv} very powerful

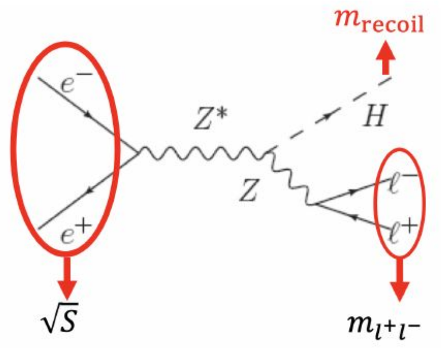
	HL-LHC (*)	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM (**)	1.3
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	0.17
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	0.43
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	0.61
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	1.21
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	1.01
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	0.74
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–
$\delta g_{HHH} / g_{HHH}$ (%)	50	~40 (indirect)
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%

But also:

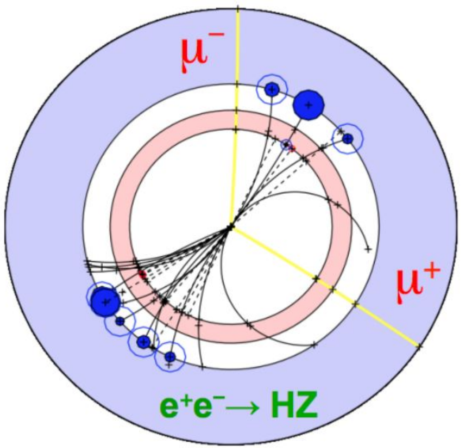
- Mass measurement
- CP properties (using e.g τ decays)

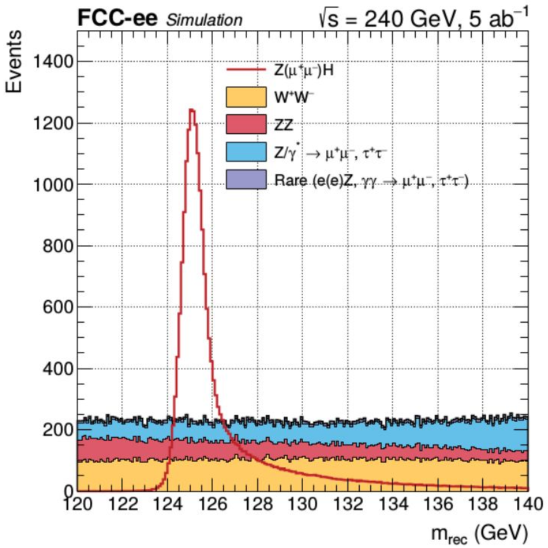
Higgs recoil analysis

The basis for many measurements at 240 Gev



$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$





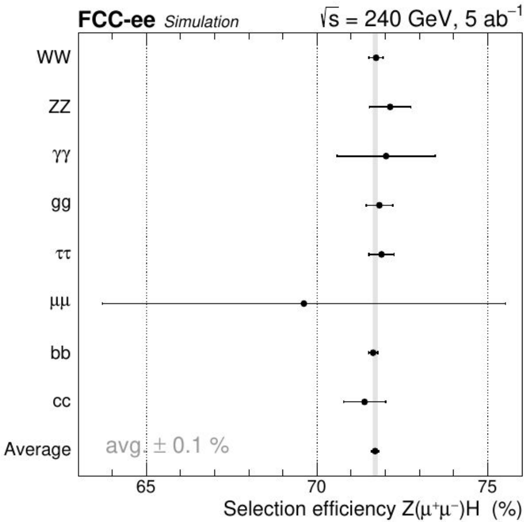
Very clean peak to fit !

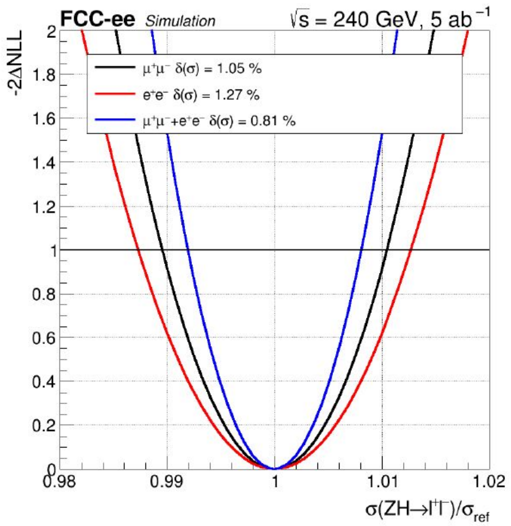
- Either use it to tag the Higgs without looking at its decays
- Or "only" as an excellent S/B discriminant for numerous analyses (couplings, mass)

ZH total cross-section

Maybe the most important measurement of all ?

- Unique to e^+e^- colliders
  - Gives **absolute** ZH coupling g_Z
  - Then can obtain Γ_H (ZH → ZZZ*)
  - Then gives all other **absolute** couplings !
    ZH → ZXX ⇒ g_X



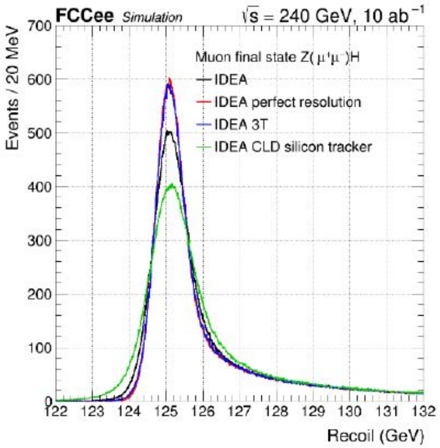


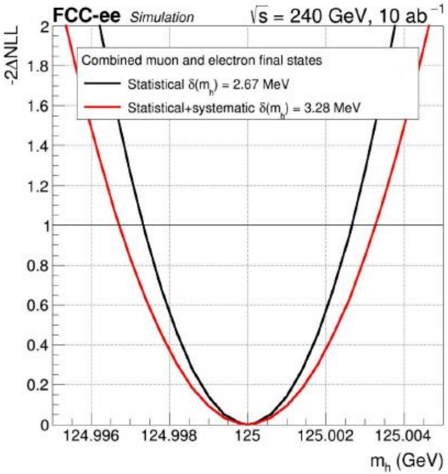
- In practice
  - Challenge: analysis selection **must not bias** on the Higgs decays
  - Easy to do for Z → ll
  - Can use BDT on Z kinematics to improve the sensitivity
  - Reach **0.8% uncertainty** on σ_{ZH} combining e and μ

Higgs mass measurement

Ultimate precision on Higgs mass is kinda important…

- Motivations
  - O(10 MeV) needed for per-mille precision on g_Z and g_W
  - O(4 MeV) needed for electron Yukawa search
- A source of important detector constraints





Need an ultimate tracker

- High field if possible
- Transparent
  - CLD worse performance from multiple scattering wrt drift chamber

using μμ channel

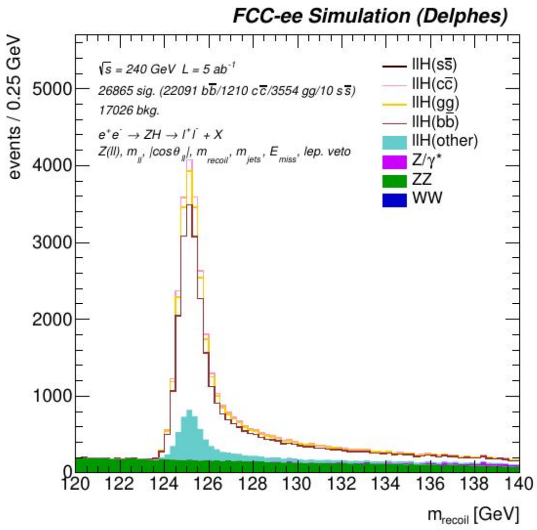
tracking system	Δm_H (MeV) stat.only	Δm_H (MeV) stat + syst
IDEA 2T	**3.49**	**4.27**
Perfect	**2.67**	**3.44**
IDEA 3T	**2.89**	**3.97**
CLD 2T	**4.56**	**5.32**

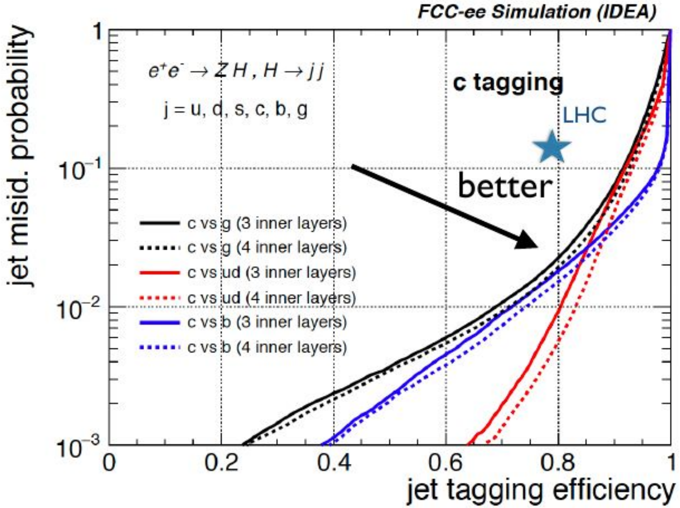
LHC: ~100 MeV

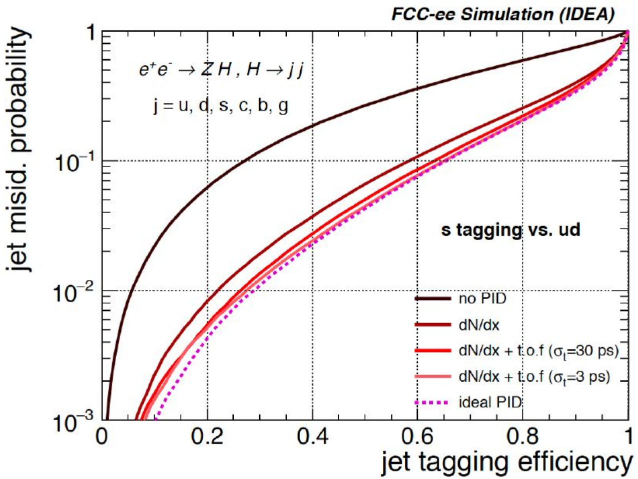
Study of H→hadrons

Much cleaner environment at FCC-ee vs LHC makes it a game changer !

- Two main ingredients
  - Low backgrounds (esp. Z → ll, but Z → νν also good)
  - Exquisite flavour tagging capabilities
    - Leveraging state-of-the-art ML 'ParticleNet' techniques
    - Including PID for **s-tagging** !

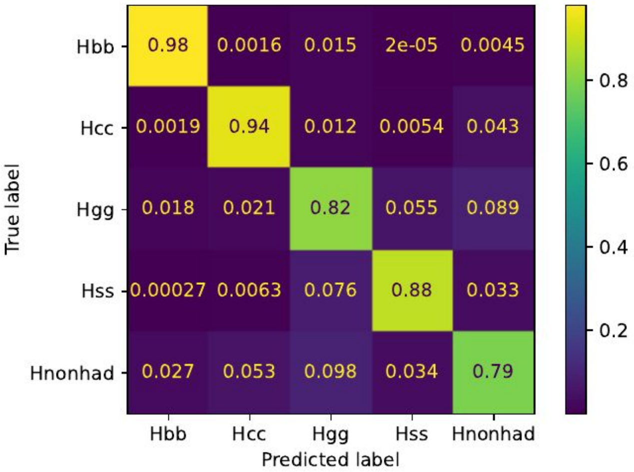






H→hadrons

δμ/μ (%)	bb	cc	ss	gg
Z → ee, μμ	0.8	4.9	410	2.7
Z → νν	0.35	2.6	137	1.1
Z → had	0.3	3.5	436	2.4
Combination	**0.22**	**1.9**	**125**	**0.95**

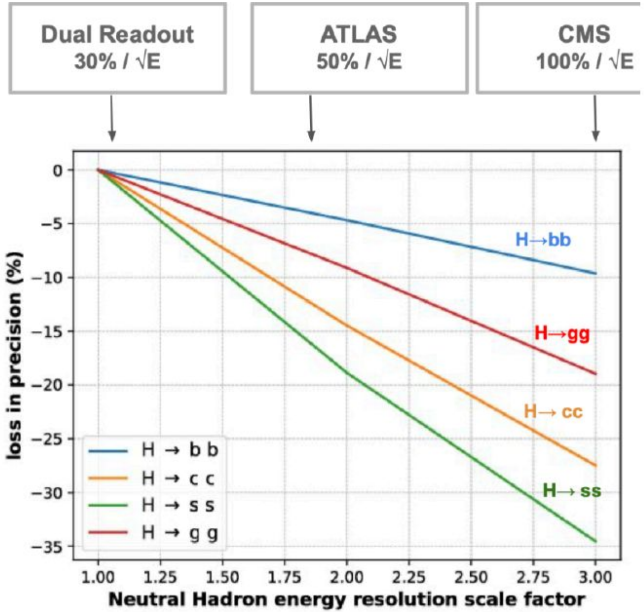


- Excellent precision on couplings to b-, c-quarks, and gluons
  - Benefits a lot from combination of all Z decay channels
  - MVA techniques and multidimensional categorization are mandatory
- Precision on H → ss very encouraging (numbers here assume 2 experiments)
  - Still very new: not foreseen in FCC CDR
  - Can we squeeze sore more perf and get **3σ evidence for H → ss with 4 experiments ?**
  - Would complete the landscape of **second generation Yukawas** !

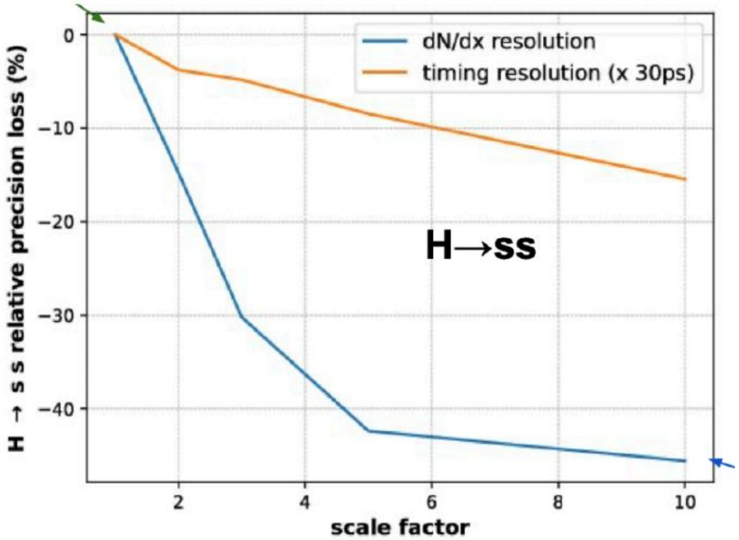
Higgs physics for detector requirements

H → hadrons: quite sensitive to detector performance !

Neutral hadron energy resolution



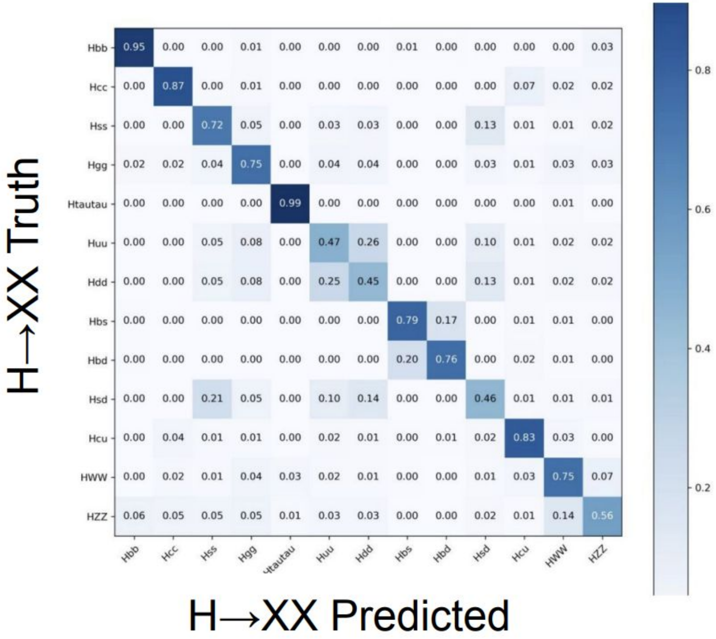
PID Performance



In particular **ultimate performance crucial for H → ss**

H → hadrons anomalous couplings

- Flavour tagging algorithm trained to separate all jet flavours
  - Limits on light Yukawa couplings
  - FCNC limits



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 total width measurement

Not been studied in details in the past few years

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BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%

How do we get this ?

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

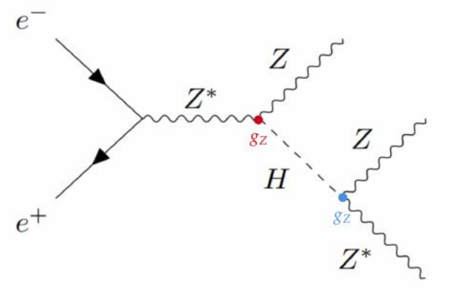
- Through ZH → ZZZ*
  - Most straightforward
  - Recoil analysis gives σ_{ZH} hence g_Z
  - Then ZZZ* gives BR(ZZ*) hence Γ_H
  - ~2-3% precision expected
- Through VBF
  - A bit more convoluted
  - Combine ZH cross-section, BR(bb), BR(WW*) at 240 GeV, and WW→H→bb at 365 GeV
  - 1-2% precision expected

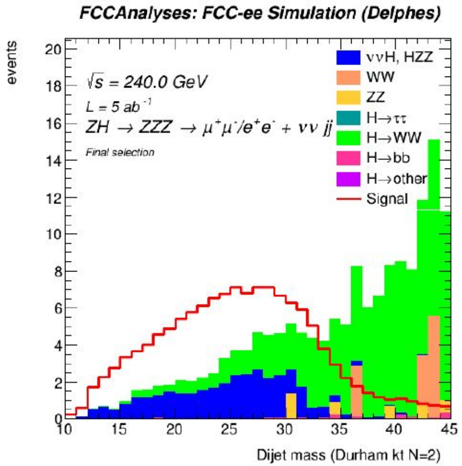
$$\frac{\sigma(ZH \to bb)\sigma(ZH \to WW^*)}{\sigma(\nu\nu H \to bb)\sigma(ZH)^2} \propto \Gamma_H$$

Higgs width through H→ZZ*: first studies

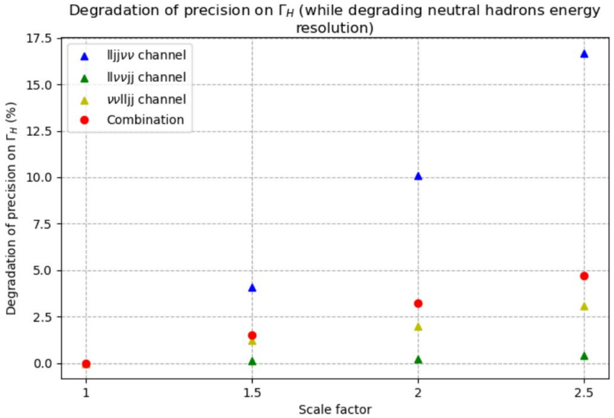
3 Z in the final state: lots of fun !

- Many decay channels to study !
  - ll, νν, qq decays for each Z
  - Not always high statistics
- The 3 Z are not interchangeable:
  - "Recoil" Z vs "Higgs" Zs
  - H → ZZ*: on-shell vs off-shell Z
- First studies with llννqq channels
  - Good compromise of statistics and cleanliness
  - **4.6%** including 3 sub-channels



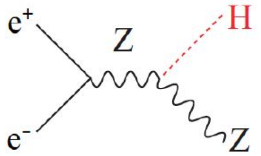


δΓ/Γ (%)	llννqq	llqqνν	ννllqq	combination
Cut-based	9.0	17	8.7	6.6
BDT	7.4	10.7	6.9	4.6



Higgs self-coupling

At FCC-ee: appears at higher-order corrections to ZH production !



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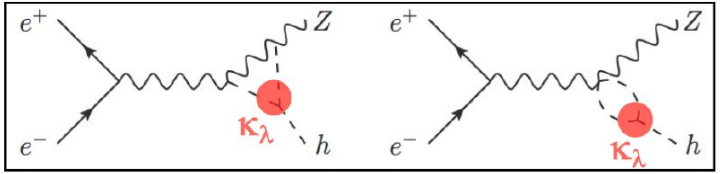
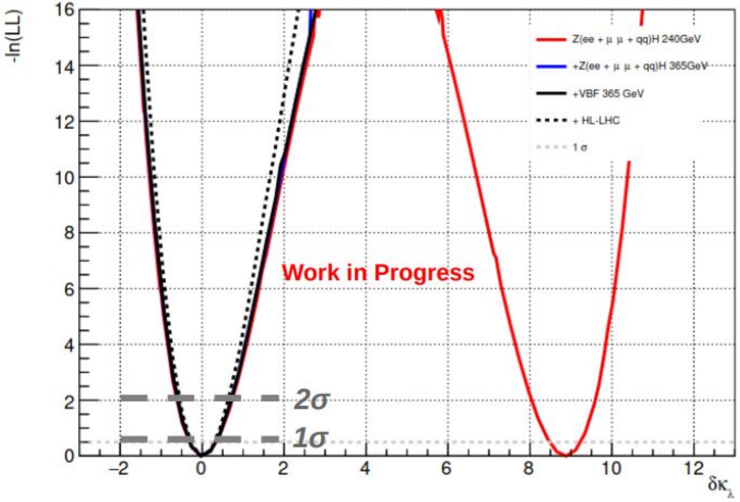
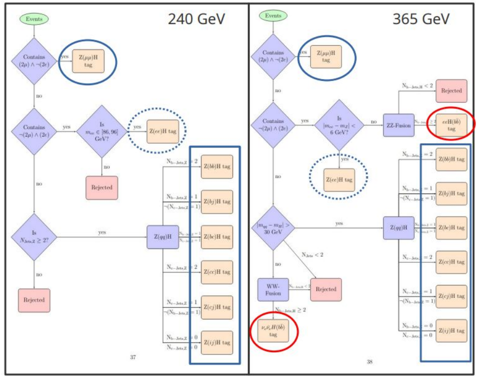


- Need to use √s = 240 **and** 365 GeV to resolve degeneracy with g_V
- Expect **~20%** precision with 4IPs from global fit
  - Maybe not "as nice as" direct HH evidence, but very compelling performance !



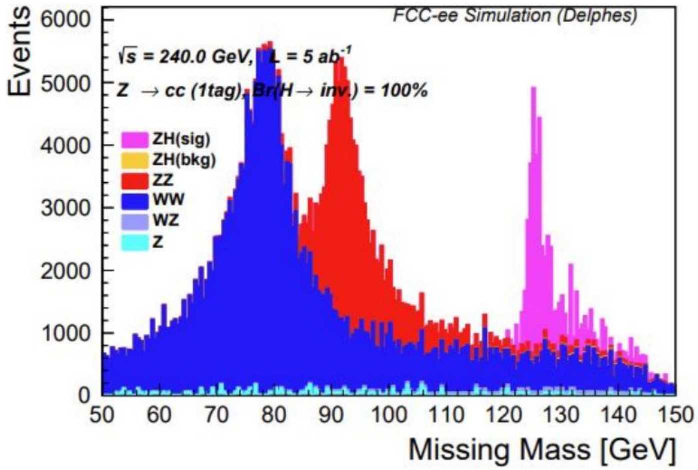


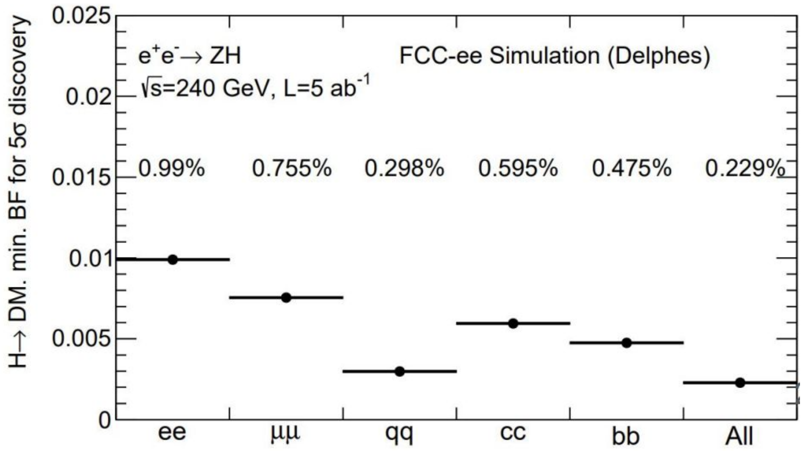
Complex analysis !

H → invisible

Typical H → DM signature

- H → invisible in SM: H → ZZ → 4ν, BR ~ 0.1%
- FCC-ee search: ZH, with on-shell Z and invisible mass ~ 125 GeV
  - Use all Z decay modes to improve sensitivity
  - Discovery of H → inv for BR of 0.2%

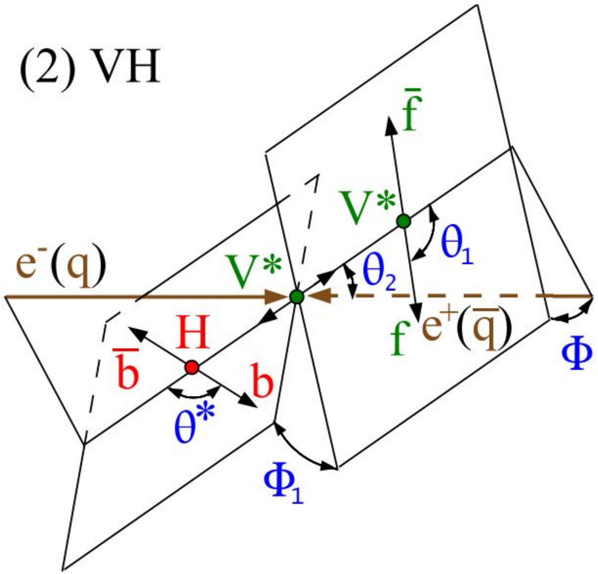




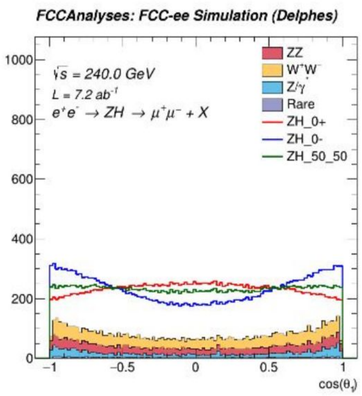
CP violation in Higgs sector

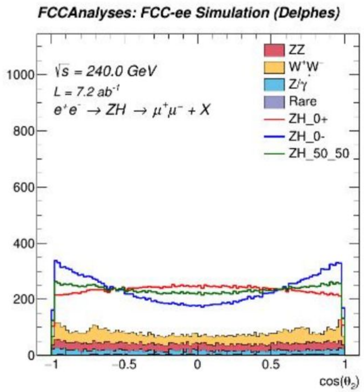
Anomalous CP couplings ?

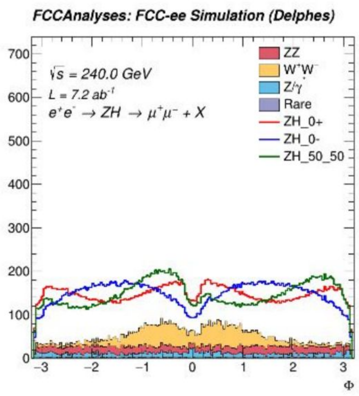
- Implementation of Matrix Element Likelihood Approach (MELA)
  - Extension of what has been used at the LHC
- Application to Z(ee, μμ)H(XX)
  - Construct CP even/odd templates and fit for CP-odd hypothesis
  - Resulting $\delta f_{CP}^{HZZ} \sim 5.4 \times 10^{-5}$ (68 % CL)



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







The unique case for ee $\rightarrow$ H

Bohr radius

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$

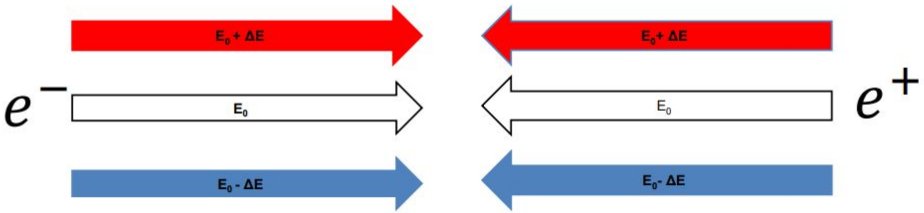
- Electron mass determines size of all atoms
- It sets energy levels of all chemical reactions

Reaching ee→H

Very unique, but hard !

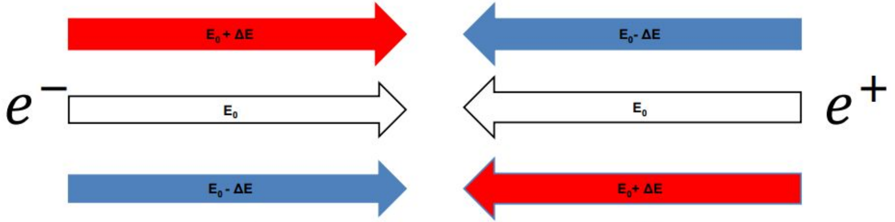
Monochromatization factor $\lambda = \left(1 + \sigma_\delta^2\left(\frac{D_x^{*2}}{\sigma_{x\beta}^{*2}} + \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}}\right)\right)^{1/2}$

Standard mode

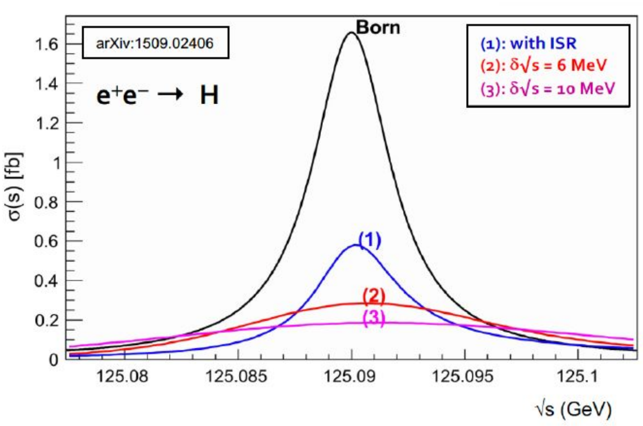


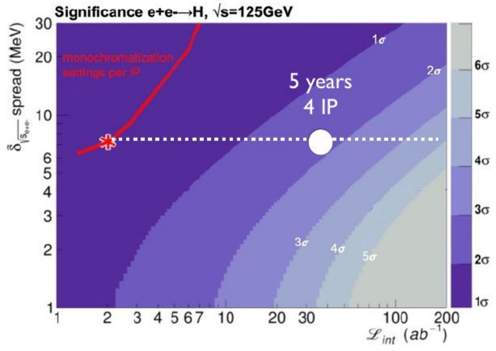
CM energy $w = 2(E_0 + \Delta E)$

Monochromatization mode



CM energy $w = 2E_0 + O(\Delta E)^2$





Can hope for ~2σ with 5 years and 4 IPs

Conclusions

- FCC-ee promises to be a fantastic tool to understand the Higgs boson in depth
  - Extraordinary complementarity with HL-LHC
- Studies of expected sensitivity well advanced
  - But... a lot to cover !
  - Some important holes to fill for the conclusion of the FCC feasibility study
  - In a number of cases, performance even better than what was planned for latest European Strategy
- Driving challenging constraints for the accelerator and detectors
  - PID for $H \rightarrow ss$
  - Hadronic energy resolution
  - Center-of-mass resolution for $ee \rightarrow H$