Higgs physics at FCCee

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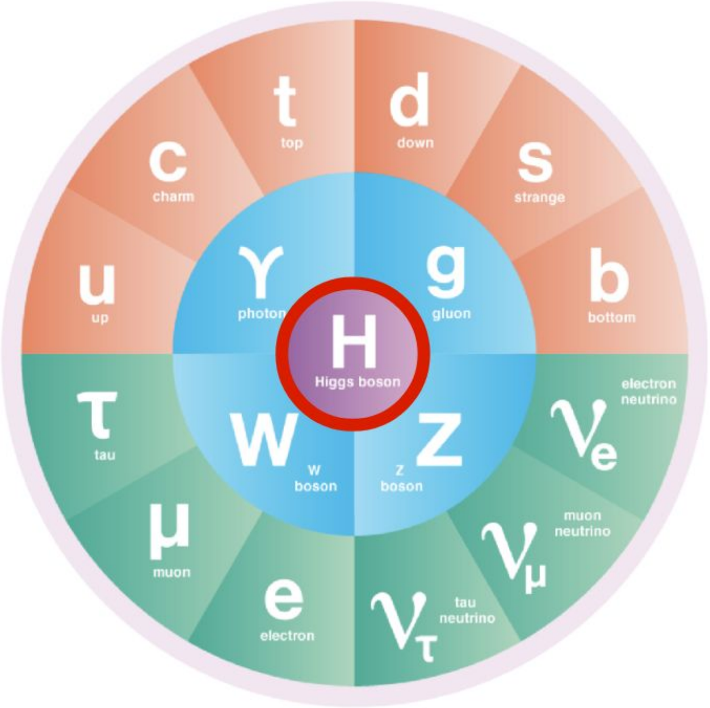
FCC France workshop, 22/11/2023

Introduction

2023: Year of the FCC Feasibility Study Interim Report

Higgs physics: cornerstone of the FCC-ee physics programme

- Several important results in the Interim Report



Goals of this presentation:

- Showcase some of the main results
- Ideas to go further than the report

SM Lagrangian and Higgs interactions

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

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

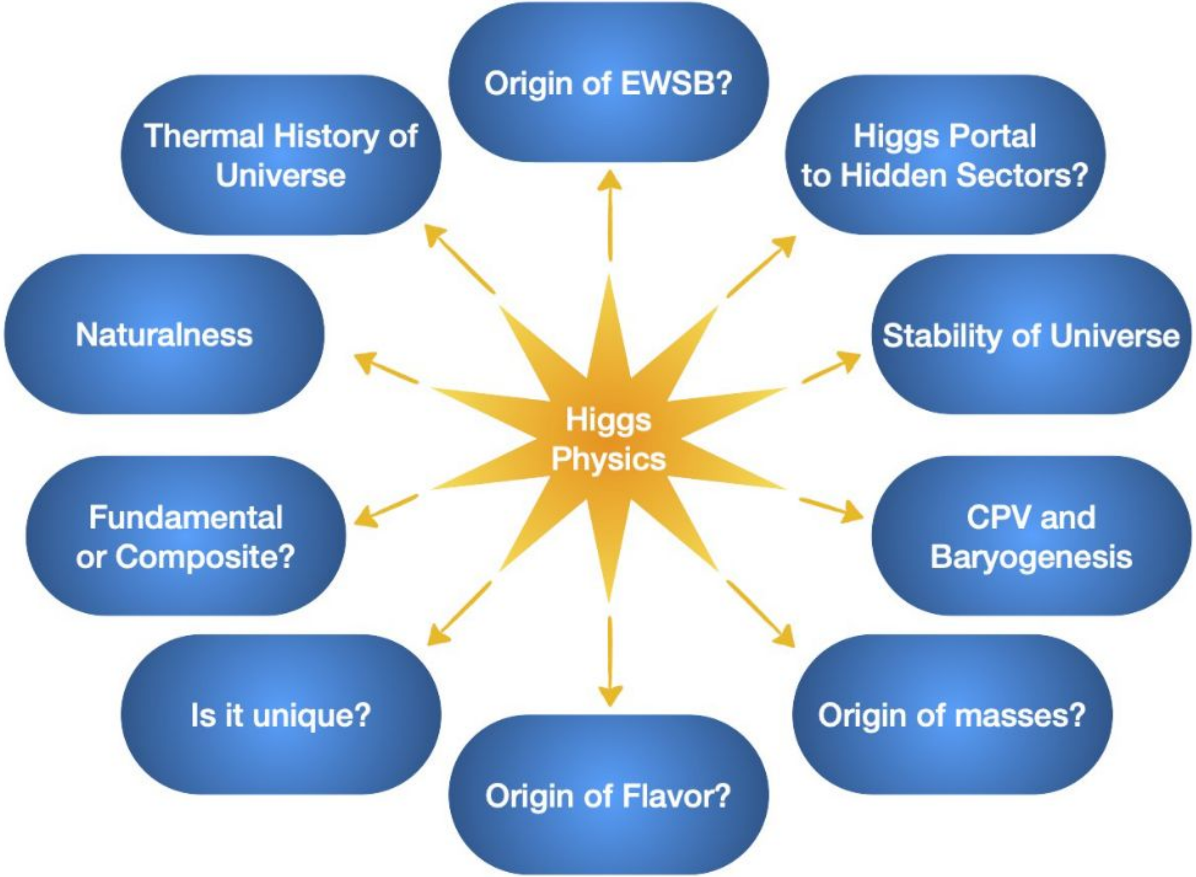
Yukawa interactions. Responsible for fermion masses, and induces “fifth force” between fermions. **Direct study started only in 2018!**

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

Holds the SM together.

Unobserved

Higgs and unknowns



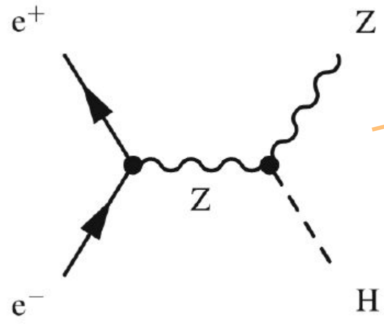
The FCC-ee Higgs dataset

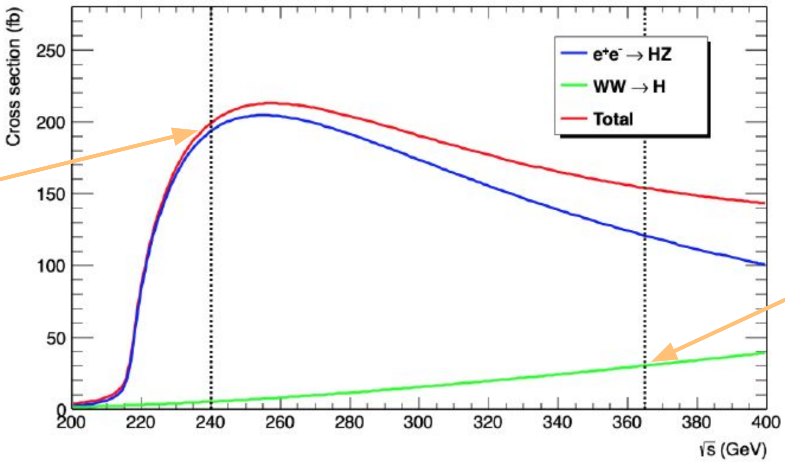
Higgsstrahlung

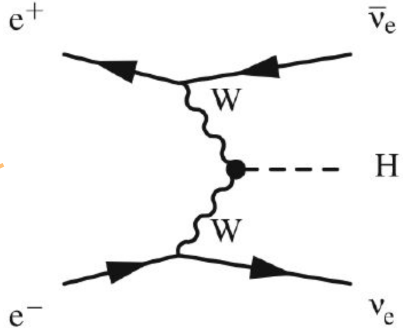
- 1 million clean ZH events at 240 GeV
- (2 experiments)

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 BRinv very powerful

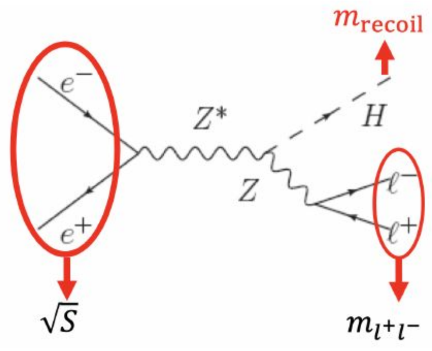
	HL-LHC (*)	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM (**)	1.3
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	0.17
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	0.43
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	0.61
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	1.21
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	1.01
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	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:

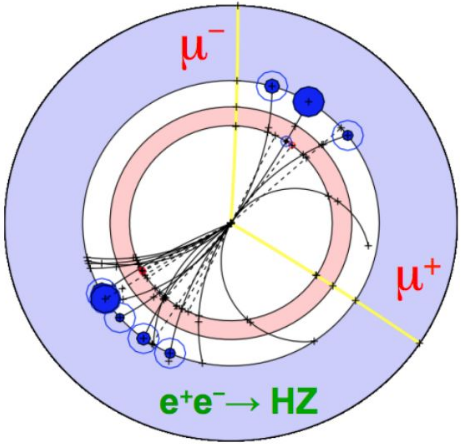
- Mass measurement
- CP properties (using τ)

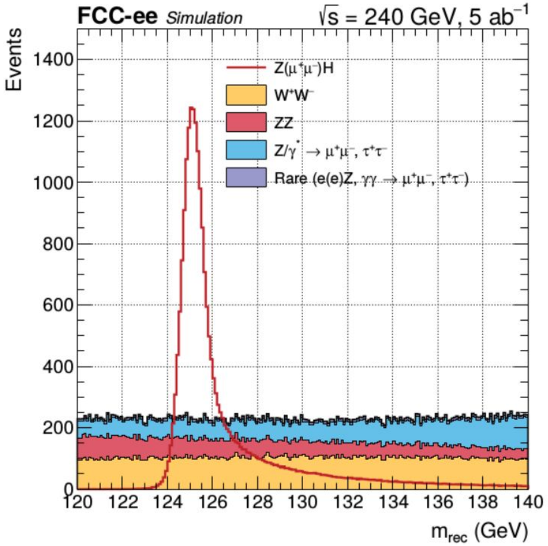
Higgs recoil analysis

The basis for many measurements at 240 Gev



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





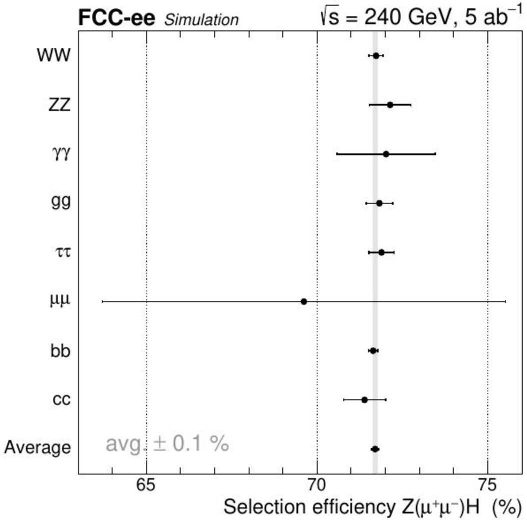
Very clean peak to fit !

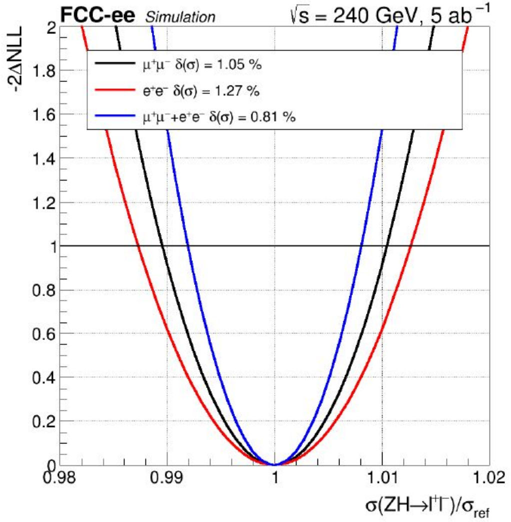
- Either use it to tag the Higgs without looking at its decays
- Or “only” as an excellent S/B discriminant for numerous analyses (couplings, mass)

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



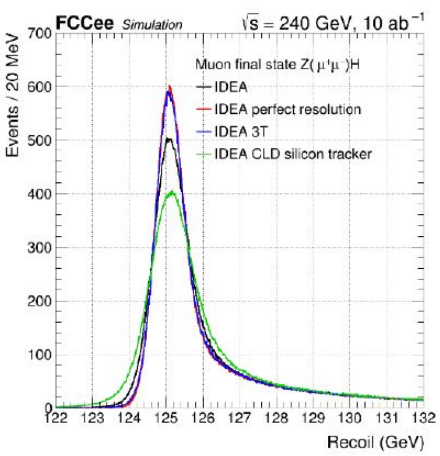


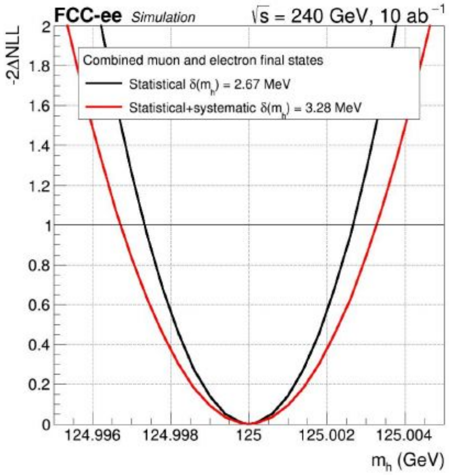
- In practice
  - Challenge: analysis selection **must not bias** on the Higgs decays
  - Easy to do for Z → ll
  - Can use BDT on Z kinematics to improve the sensitivity
  - Reach **0.8% uncertainty** on σ_{ZH} combining e and μ

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

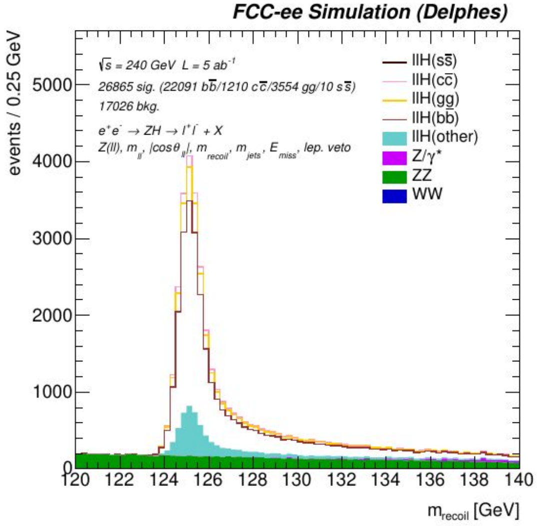
tracking system	Δm_H (MeV) stat.only	Δm_H (MeV) stat + syst
IDEA 2T	3.49	4.27
Perfect	2.67	3.44
IDEA 3T	2.89	3.97
CLD 2T	4.56	5.32

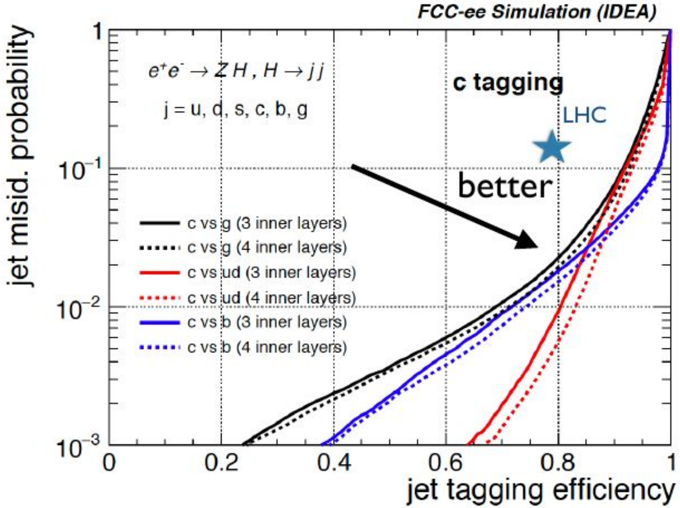
LHC: ~100 MeV

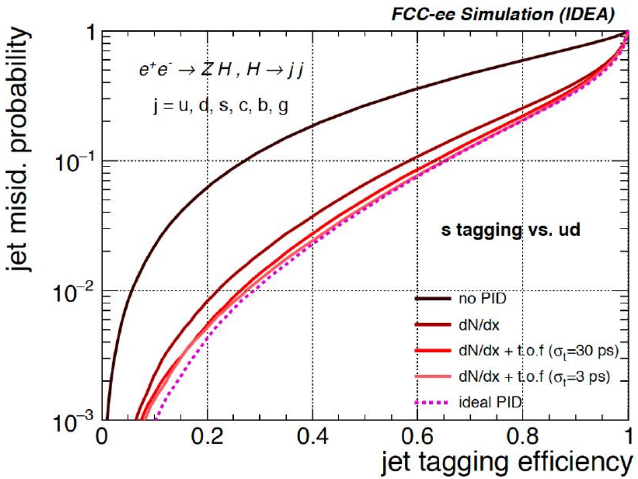
Study of H→hadrons

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** !



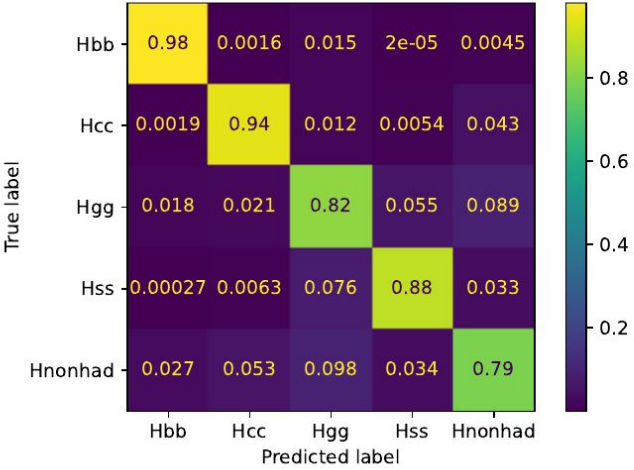




H→hadrons: prospects

- Excellent precision on couplings to b-, c-quarks, and gluons
- With 10 ab^{-1}, decent sensitivity to H → ss

δμ/μ (%)	bb	cc	ss	gg
Z → ee, μμ	0.6	3.5	290	1.5
Z → νν	0.3	2.1	100	0.8

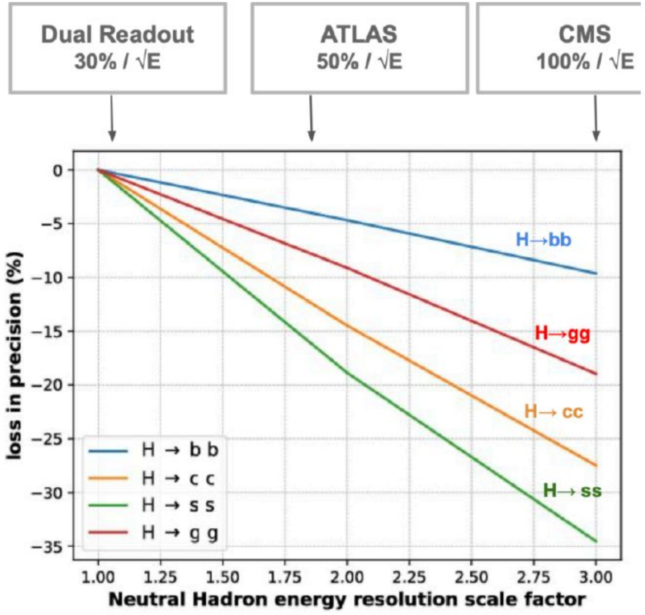


- Study of Z → hadrons channel still ongoing
  - **3σ on H → ss seams in reach !**
  - Would complete the landscape of **second generation Yukawas** !

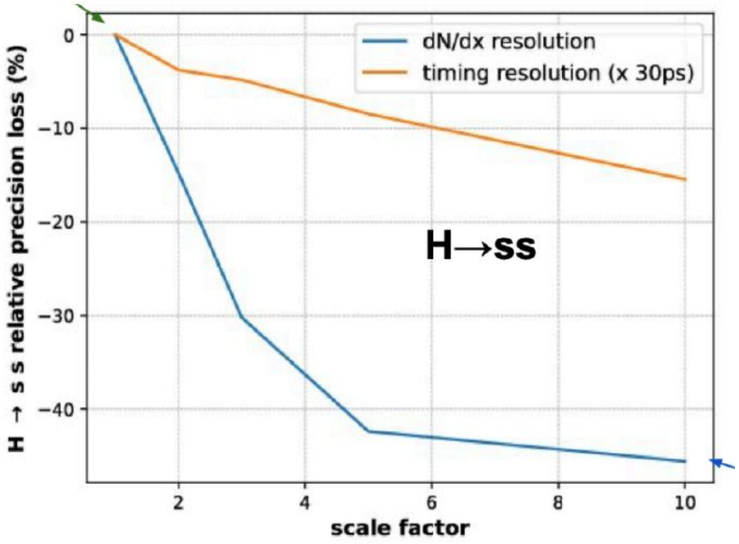
Higgs physics for detector requirements

H → hadrons: quite sensitive to detector performance !

Neutral hadron energy resolution



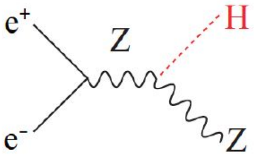
PID Performance



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

Higgs self-coupling

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



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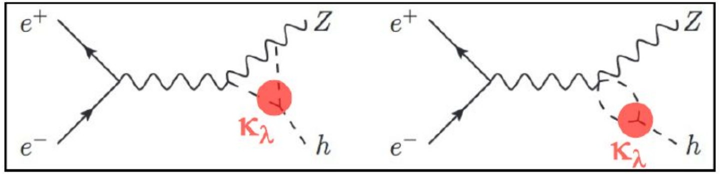
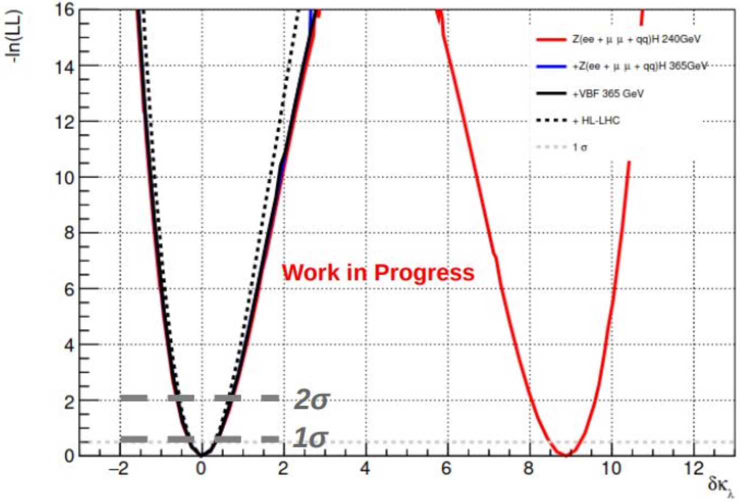
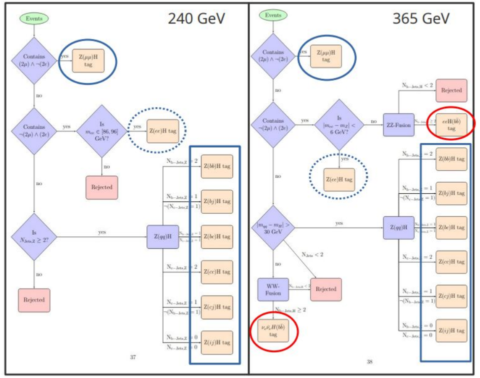


Laboratoire Leprince-Ringuet

- Need to use √s = 240 **and** 365 GeV to resolve degeneracy with g_V

- Expect **~20%** precision with 4IPs from global fit





Complex analysis !

The unique case for ee→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

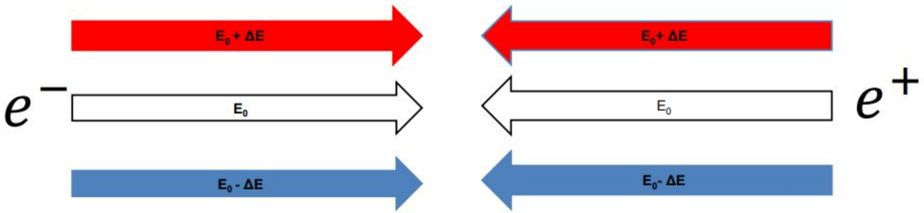
Reaching ee→H

Very unique, but hard !

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

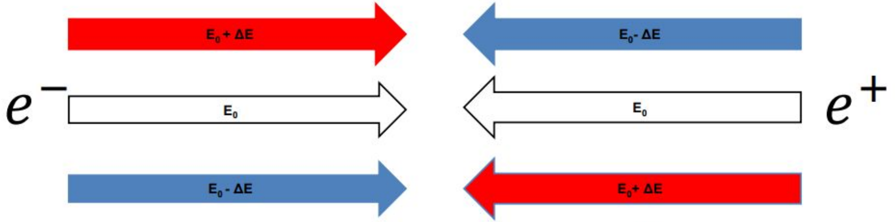
Monochromatization factor $\lambda = \left(1 + \sigma_\delta^2 \left(\frac{D_x^{*2}}{\sigma_{x\beta}^{*2}} + \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}}\right)\right)^{1/2}$

Standard mode

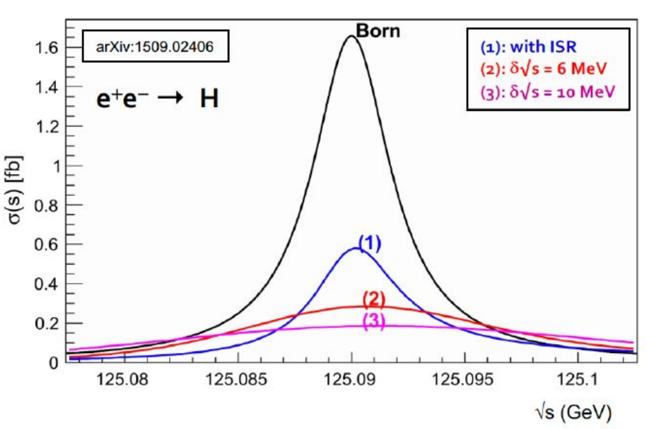


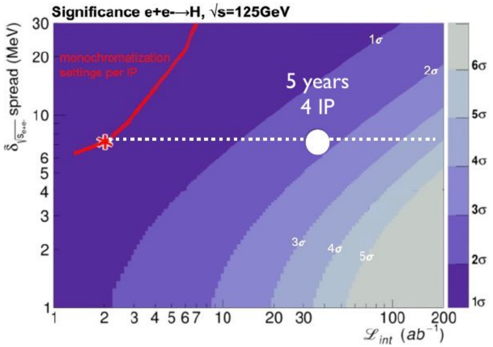
CM energy $w = 2(E_0 + \Delta E)$

Monochromatization mode



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





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

What next ?
A *very biased* take

Higgs total width measurement

Not been studied in details in the past few years

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$\delta g_{HHH} / g_{HHH}$ (%)	50	~40 (indirect)
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%

How do we get this ?

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

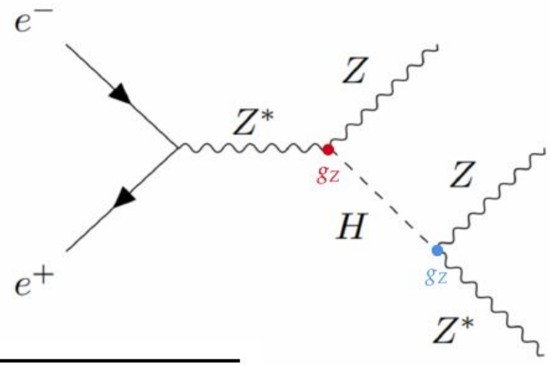
- Through ZH → ZZZ*
  - Most straightforward
  - Recoil analysis gives σ_{ZH} hence g_Z
  - Then ZZZ* gives BR(ZZ*) hence Γ_H
  - ~2-3% precision expected
- Through VBF
  - A bit more convoluted
  - Combine ZH cross-section, BR(bb), BR(WW*) at 240 GeV, and WW→H→bb at 365 GeV
  - 1-2% precision expected

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

Higgs width through H→ZZ*: channels

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

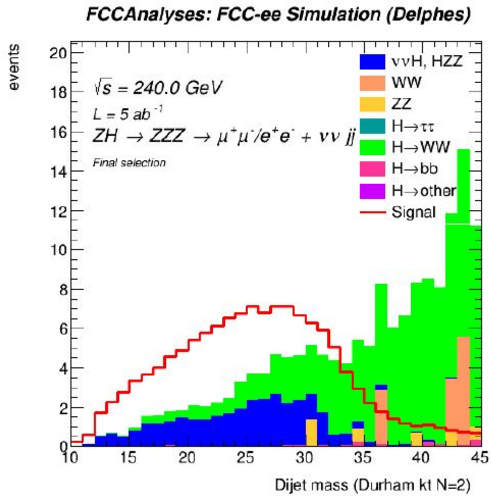


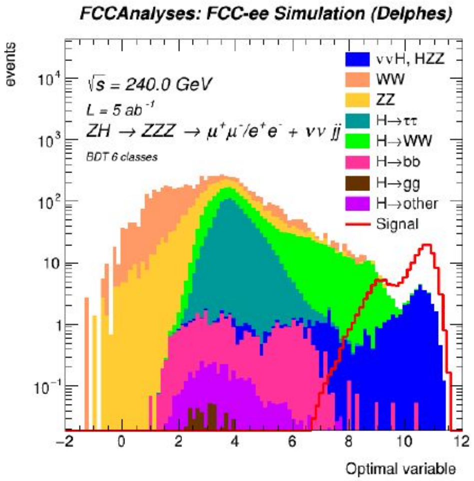
ZZZ^* decay type	Number of events for $L = 5\,ab^{-1}$	Z combinatorics (objects pairing)	Particle combinatorics (jets)
Fully hadronic	~ 9000	*hard+*	*hard+*
Fully leptonic	~ 8	*hard+*	*easy+*
Mixed channels	~ 1500	*easy+*	*easy*
2 leptons, 4 jets	~ 2600	*hard*	*hard*
2 jets, 4 leptons	~ 250	*hard*	*easy*

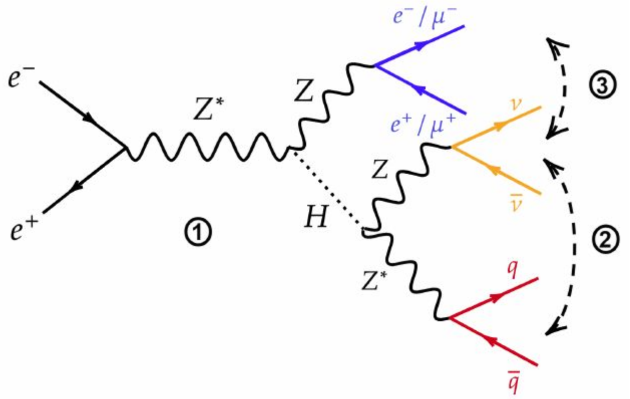
ZH→ZZZ*→llvvqq

Study of 3 of the "mixed" channels (Inès Combes internship, 2023)

- Fun final state: leptons, neutrinos, jets
  - 6 possible sub-channels
- Start by hand-crafting cuts to get used of the topology
- Then move to simple BDT to gain in precision







ZH→ZZZ*→llννqq: results

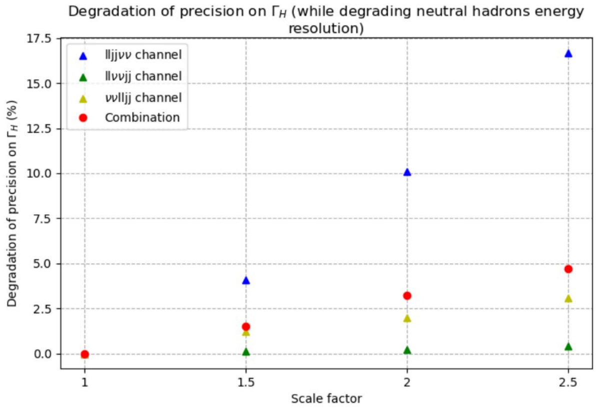
- 4.6% precision achievable with only these 3 sub-channels !

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

- Fully dominated by stat. uncertainties

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%

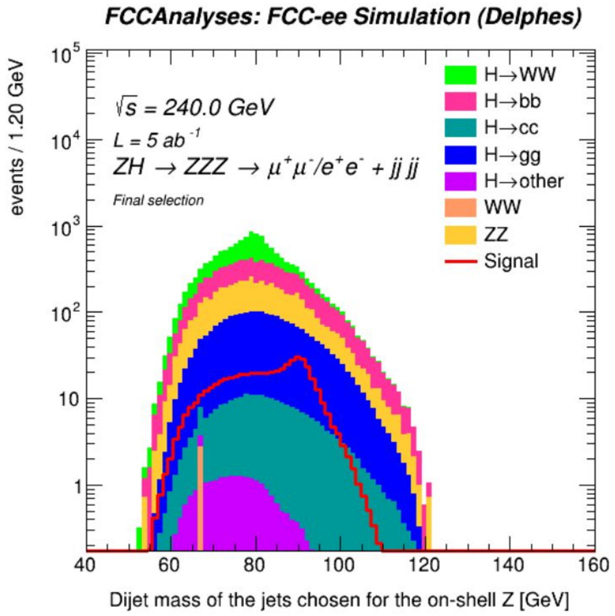
- Fairly robust wrt neutral hadron energy resolution



ZH→ZZZ*→llqqq

Surprises on the path

- Started by looking at ZZ* → jets as larger BR
- Was meant to be a test bed for hadronic energy resolution:
  - separation Z → jets from W → jets



Very poor separation !

Even assuming 30%/√E

ZH→ZZZ*→llqqq

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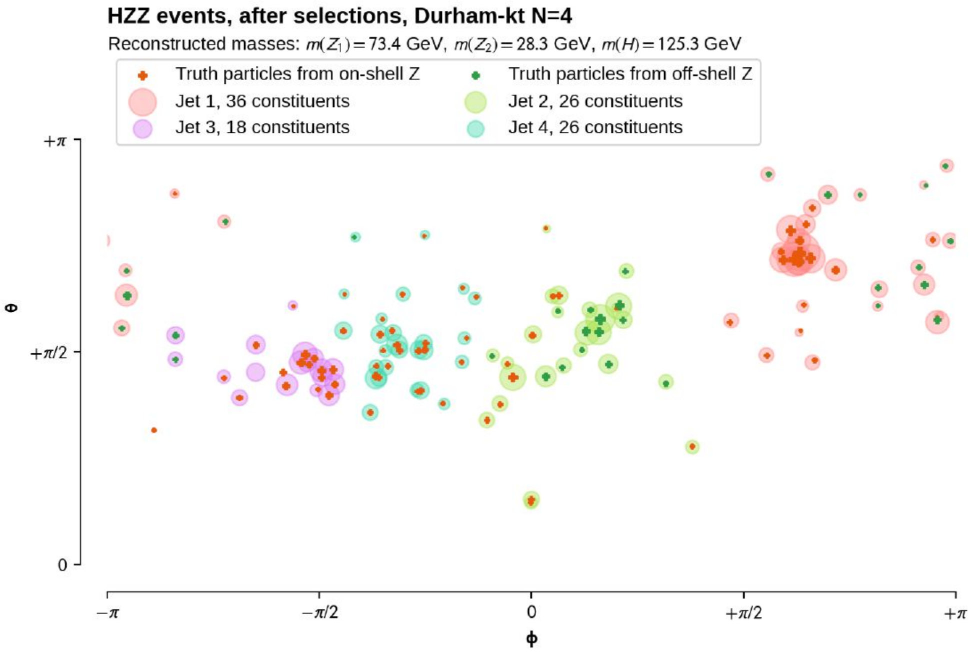

- Issue is **intrinsic**: particles from the decay of (low energy) Z and Z* are mixed in the theta/phi plane
  - seems very tough to find any jet finding algorithm that would work

- The claim that **4% on jet energy resolution** at 45 GeV is necessary to separate HZZ from HWW seems **irrelevant**, at least at √s = 240 GeV

Higgs width: a great project

Higgs width measurement as a research project:

- Many final states to explore
  - Already with ZH → ZZZ*
  - And even more with the measurement using VBF events
  - The ultimate precision will come from the **combination of all of them !**
    - There is not 1 channel that dominates the overall sensitivity

- Work for everyone
  - Many channels are easily accessible for newcomers: other “mixed” channels, 4 lepton channels…
  - More difficult problems for more experienced researchers: VBF analysis ; more granularity in channels with flavour tagging ; add channels with tau leptons to increase stat…
  - Hard problems for experts to solve: ZZ → 4 jets reconstruction

A good candidate to collaborate in the French community in this post-interim report ?

Conclusions

- Higgs physics is one of the main drivers of the FCC-ee physics programme
- Many important studies were performed for the interim report
  - Strengthen the FCC-ee case
  - FCC-ee should **settle the case of the second generation fermions** !
- Many studies are still poorly covered or uncovered
  - The case for **Higgs width measurement** seems very strong