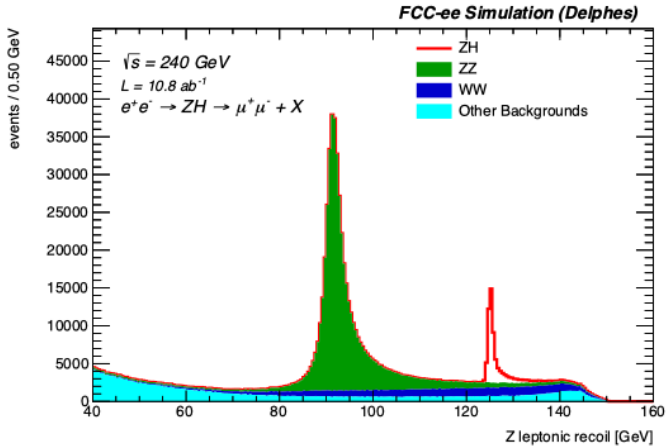
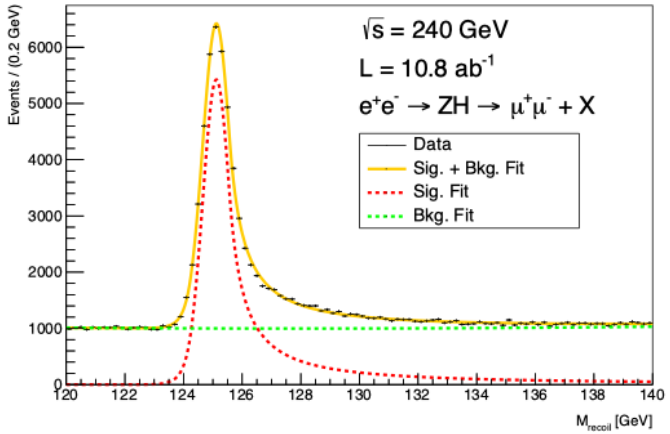
Absolute Higgs boson cross section, mass, and width at FCC-ee





Ang Li (ang.l@cern.ch)

Brookhaven National Laboratory

On behalf of the FCC collaboration

Lepton-Photon 2025, Madison, Aug. 28, 2025

@BrookhavenLab

Outline

- ❖ Introduction
- ❖ Higgs mass
- ❖ ZH cross-section
- ❖ Higgs Width
- ❖ Conclusion

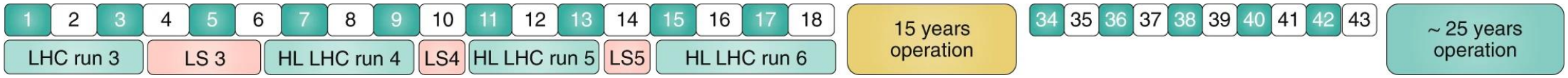
- ❑ **Results been included in**
  - ➢ ESPPU, Prospects in Electroweak, Higgs and Top physics at FCC [Link]
  - ➢ FCC Feasibility Study Report [Link]

- ❑ **FCC-ee has a very rich Higgs program:**
  - ➢ Higgs Couplings
  - ➢ Higgs self-coupling
  - ➢ Higgs to Invisible decays
  - ➢ Electron-Yukawa
  - ➢ CP Properties
  - ➢ etc.

Higgs: Introduction

Nature Physics **volume 16**, pages 402–407 (2020)
10.17181/yr3v6-dgh16

Sarah Eno's talk for more details about the FCC program



FCC-ee

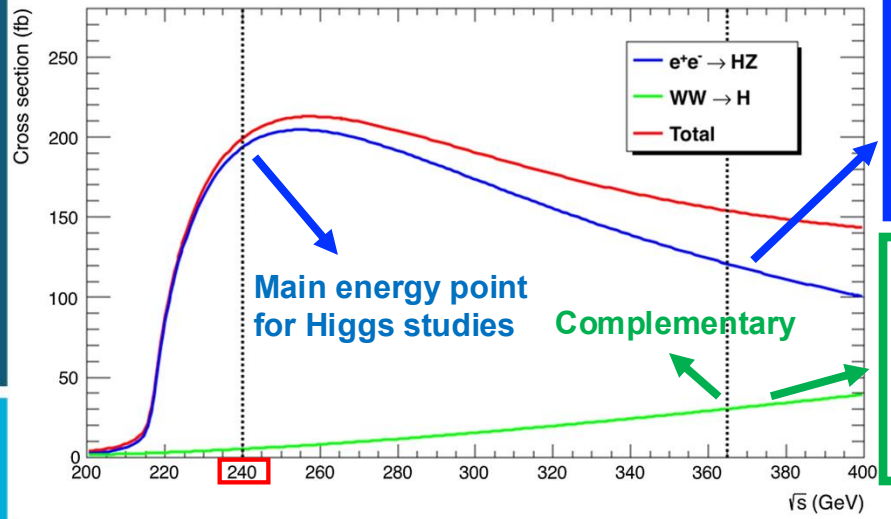
FCC-hh

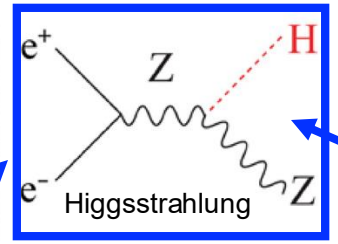
Gregorio Bernardi's talk on FCC-hh

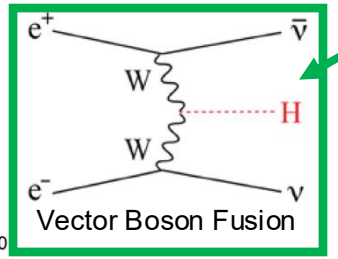
Baseline:

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated Lumi (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	$6\,10^{12}$ Z	$2.4\,10^{8}$ WW	$2.2\,10^{6}$ HZ + 65k WW → H	$2\,10^{6}$ $t\bar{t}$ +370k HZ +92k WW → H	

- **To study the precision that we can achieve at FCC-ee**
- **Study how detector variation impact the analysis**







Higgs Physics at FCC-ee

Main Production Mechanisms at 240 and 365 GeV

- ZH production "Higgs-strahlung"
- Vector Boson Fusion (VBF): WW dominant

Optional run at 125 GeV s-channel $e^+e^- \to H$

- Direct Probe of electron-Yukawa coupling
- Requires beam monochromatization

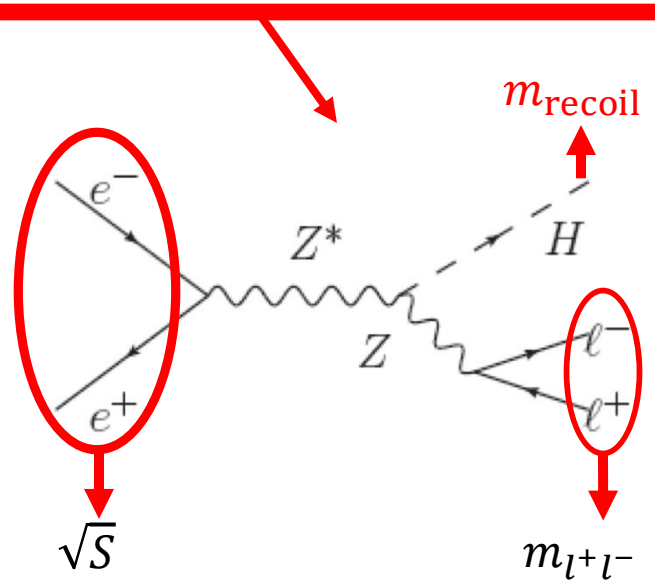
Michael Peskin's talk for the prospects for Higgs physics

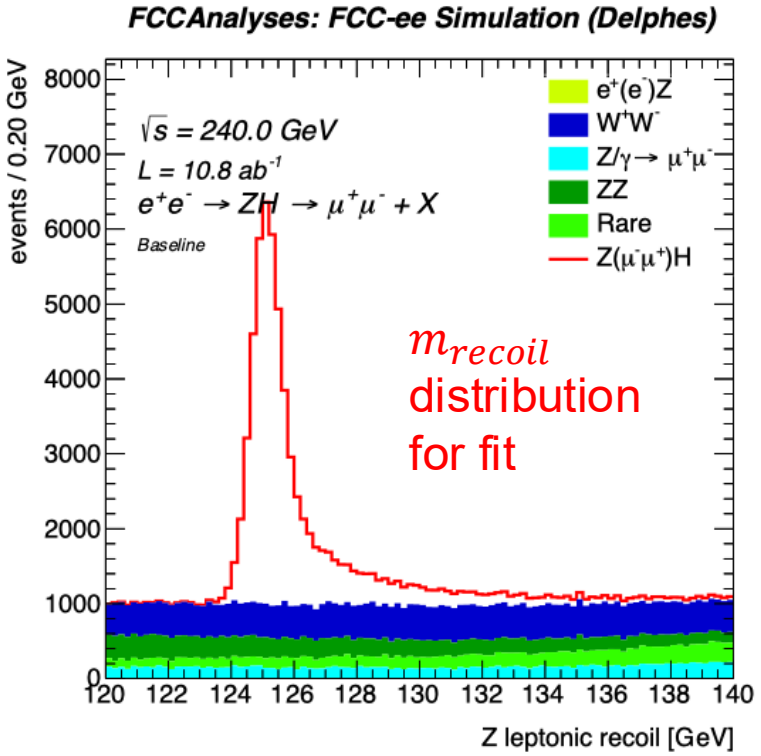
Higgs mass

Gregorio Bernardi
Jan Eysermans
Ang Li
DOI 10.17181

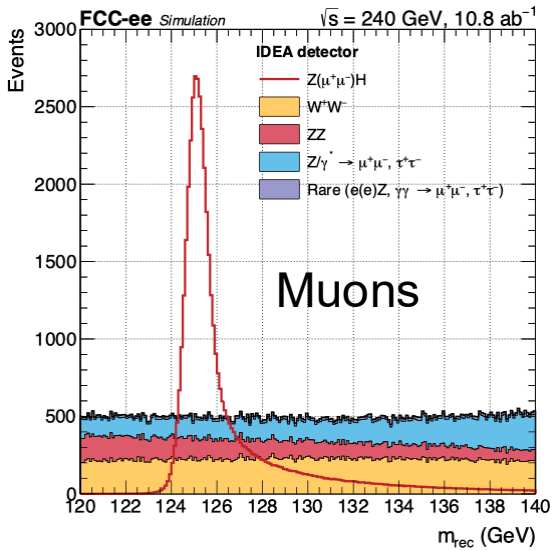
- Current best from LHC $\delta m_H \sim 100$ MeV, (20 MeV @ HL-LHC)
- At FCC-ee, Higgs mass will reach MeV level accuracy, ($\Gamma_H \sim 4.1$ MeV)
- Electron and Muons final states: $e^+e^- \to ZH \to l^+l^- + XX$, ($Z \to \mu^+\mu^-, e^+e^-$)
- M_{recoil} from the Z production without measuring the Higgs production final state

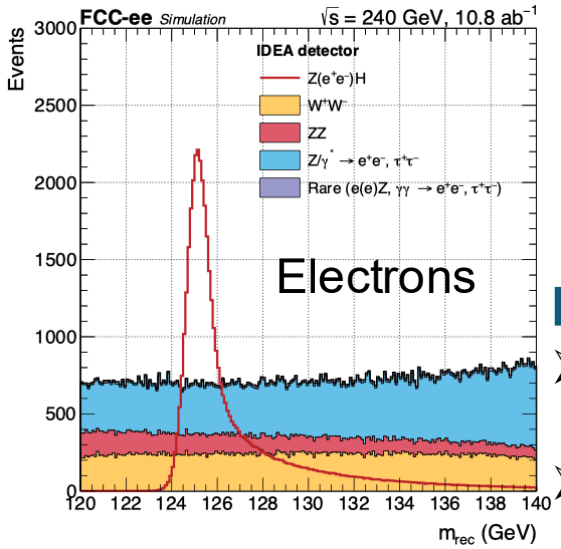
$$m^2_{\text{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

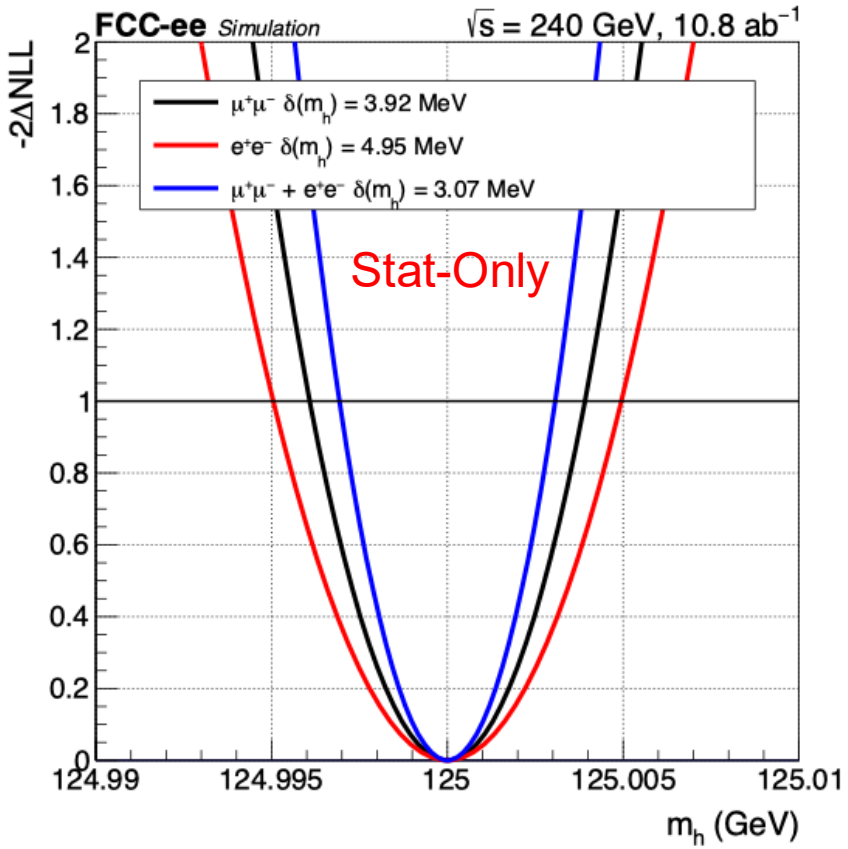


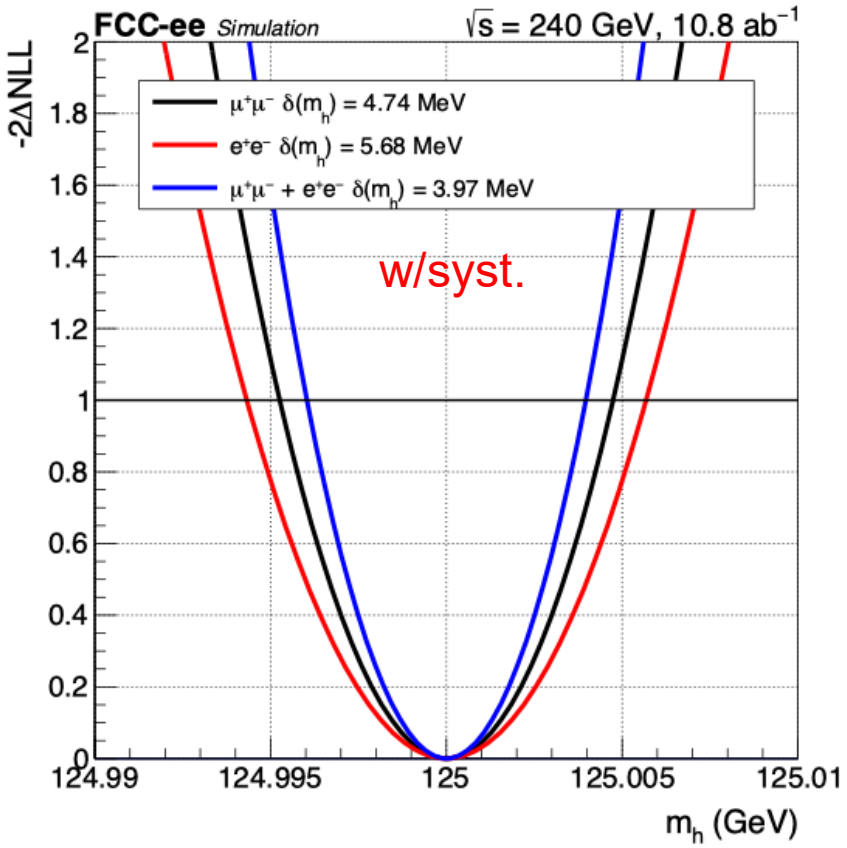


Higgs mass









Higgs mass, Fit with analytic shape

- Signal Shape: 2 Crystal-Ball and a Gaussian
- Backgrounds modelled as polynomial (3rd order)
- m_H as Parameter of Interest (POI)

- **Muon channel plays the leading role**
- **Uncertainty Stat-Only, and w/ systematics:**
  - **Higgs mass: 3.07 MeV → 3.97 MeV**
- **Dominant Syst. Unc. :**
  Centre-of-mass with ~ 2 MeV

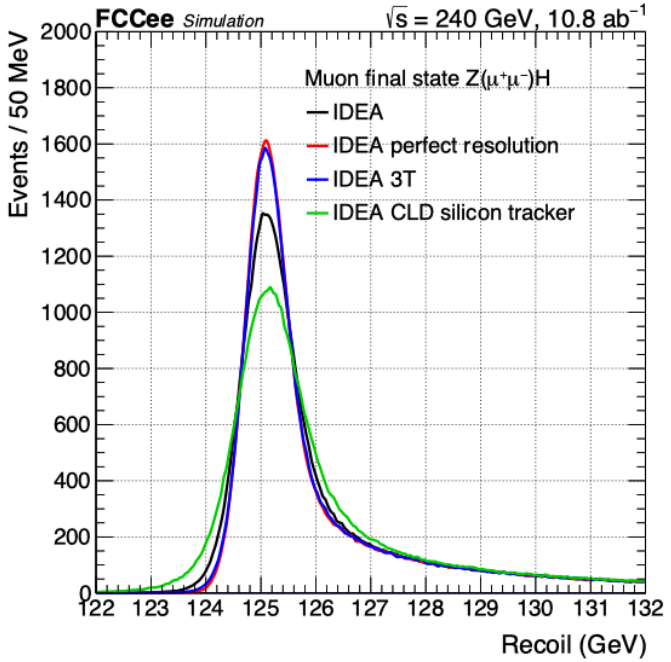
Higgs mass: Detector Requirement

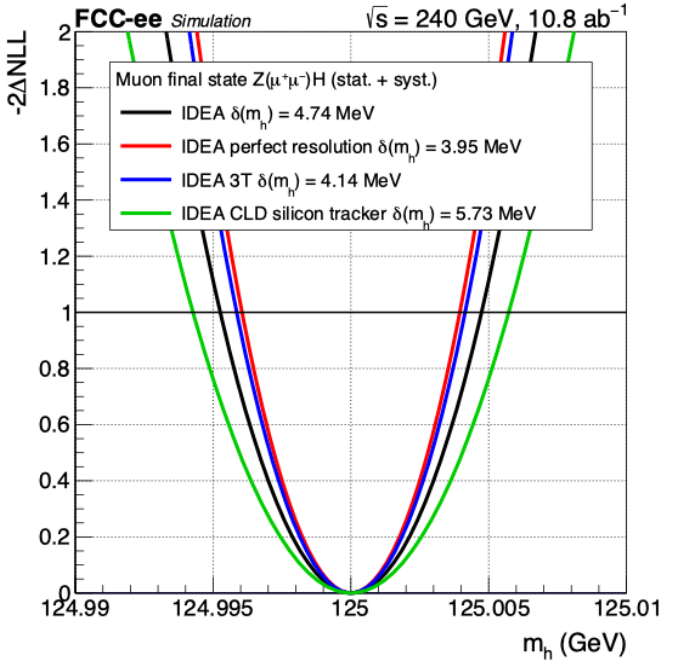
Some extended studies performed regarding detector effects

- Assuming “perfect” (generator-level) momentum resolution
- Nominal 2 T magnetic field → 3 T (stronger field → better tracking)
- IDEA drift chamber → CLD silicon tracker

	Combined
Nominal	3.07 (3.97)
Ideal resolution	2.42 (3.40)
Magnetic Field 3T	2.54 (3.52)
CLD 2T (silicon tracker)	3.86 (4.55)

Feedbacks to the Detector Design from Analysis

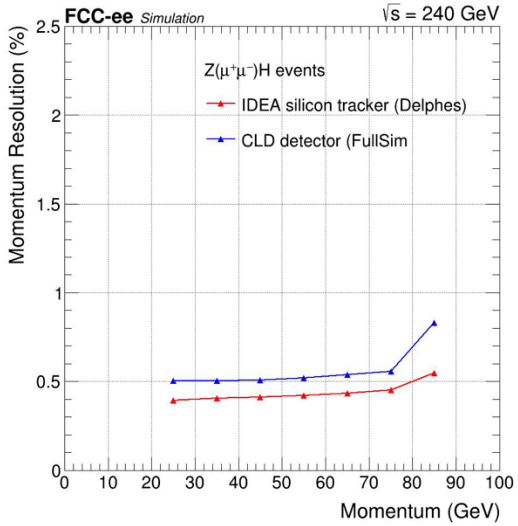


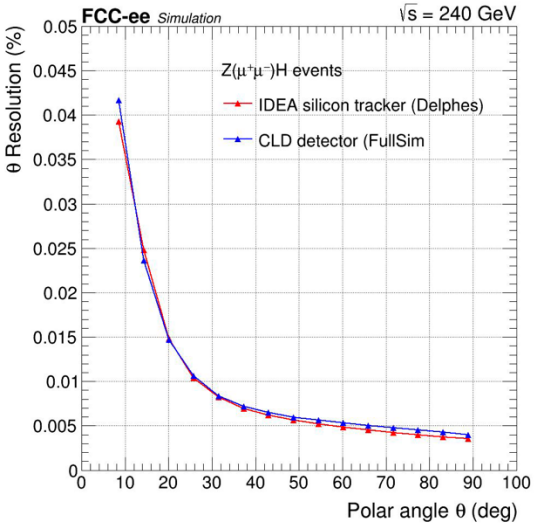


Wonyong Chung’s talk about IDEA detector

Higgs mass with Full Sim (Muon)

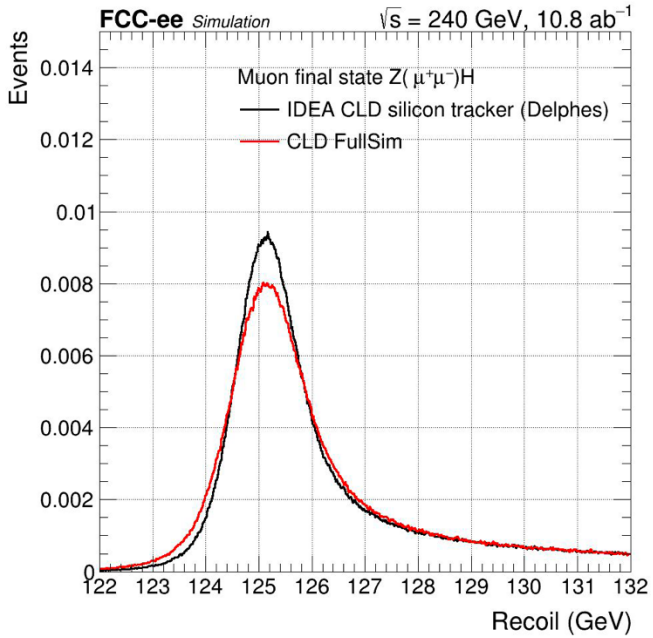
- **Study Muon resolutions based on Z($\mu\mu$)H events**
  - Slightly worse momentum in FullSim (residual difference in material budget, smearing)
  - Angular resolutions OK
- **FullSim recoil distribution slightly worse than Delphes**
- **Repeat the fit procedure as for the Delphes analysis**
  - Statistical-only fit, no systematics

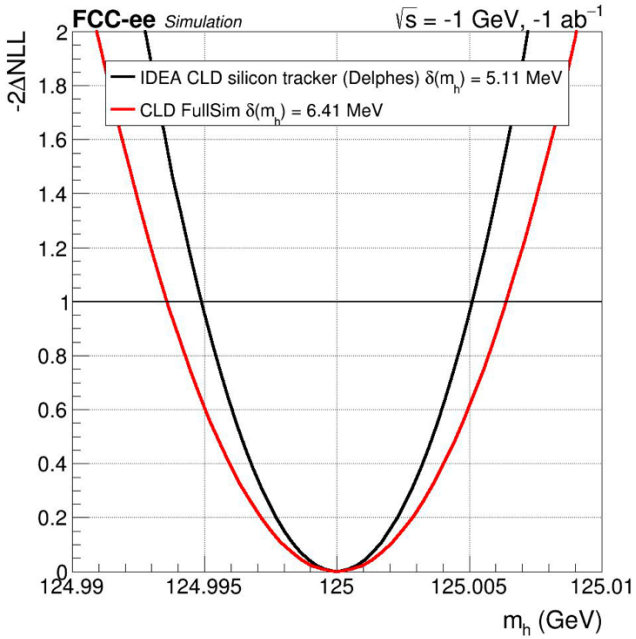




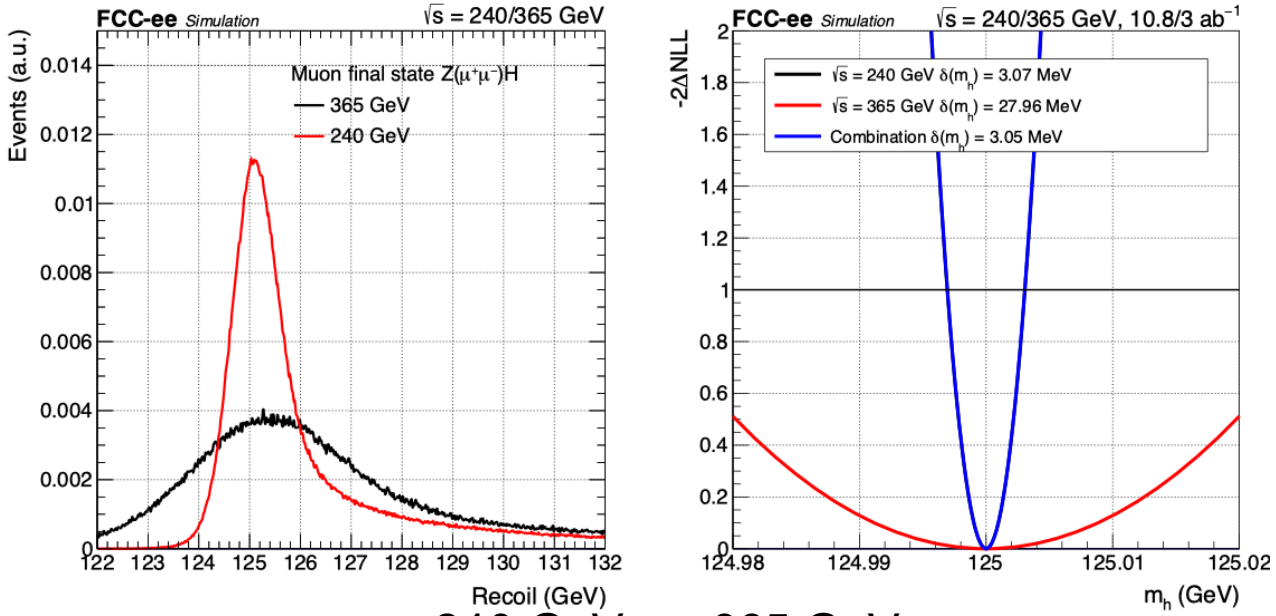
	Uncertainty
Delphes	5.11 MeV
FullSim	6.41 MeV

- **FullSim is 25% worse than Delphes**





Higgs mass: 240 GeV v.s. 365 GeV



240 GeV vs. 365 GeV

ΔM_H	stat-only	w/ syst.
$\sqrt{s} = 240$ GeV	3.07 MeV	3.97 MeV
$\sqrt{s} = 365$ GeV	27.96 MeV	28.79 MeV

- **At $\sqrt{s} = 365$ GeV**
  - Reduced statistics
  - Broadened recoil distribution
  - 365 GeV only: 27.96 (28.79) MeV uncertainty stat-only (w/ syst.) on Higgs mass
  - Combined with 365 GeV brings it down from **3.07** MeV to **3.05** MeV (Stat-Only) **~1%** improvement

Total ZH production cross-section

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DOI 10.17181

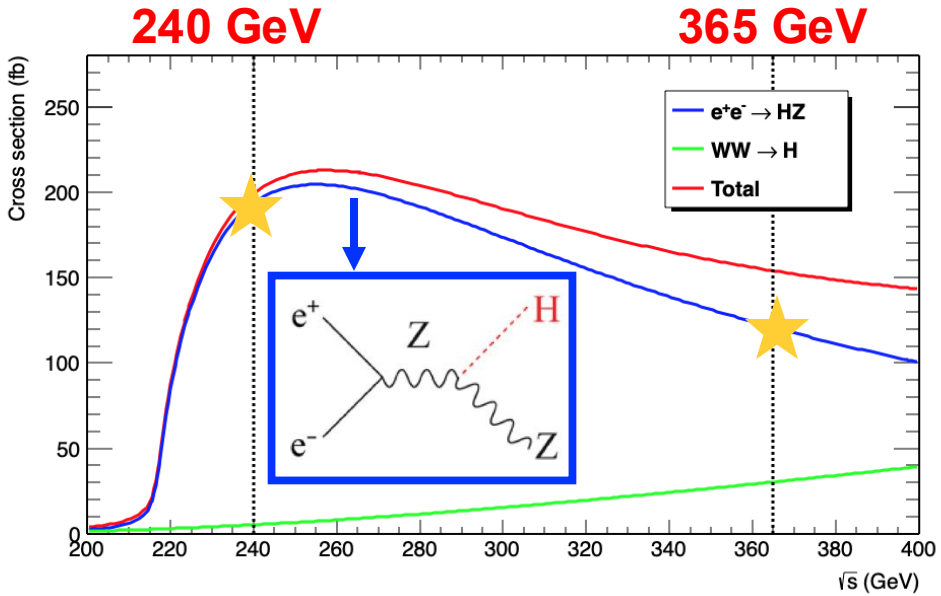
Measure the ZH cross-section in a Model-Independent way

- Unique to electron-positron colliders because of known initial state
- Challenge to ensure model-independent
- Once know, determine Higgs couplings ($H \to XX$) in a model independent way

At FCC-ee ZH cross-section is expected to be per mile level accuracy

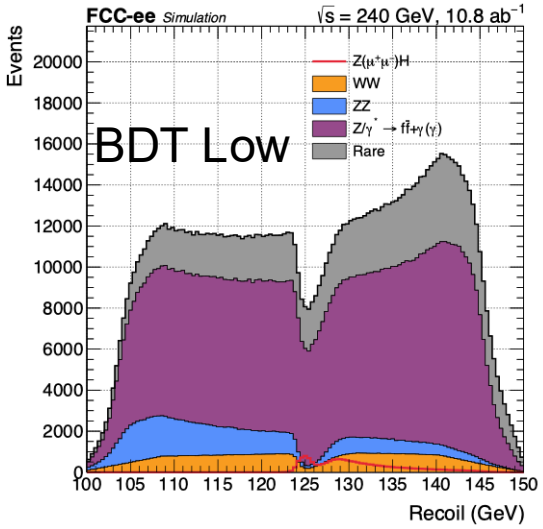
- Done in leptonic and hadronic channel based on Z decay
- $e^+e^- \to ZH \to l^+l^-/q\bar{q} + XX, (Z \to \mu^+\mu^-, e^+e^-, q\bar{q})$

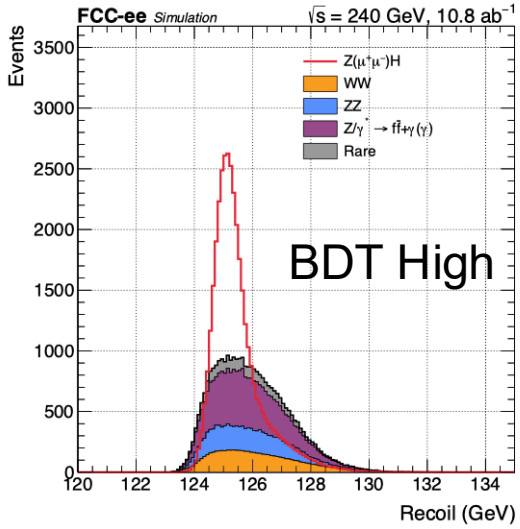
Two independent measurements at 240 and 365 GeV



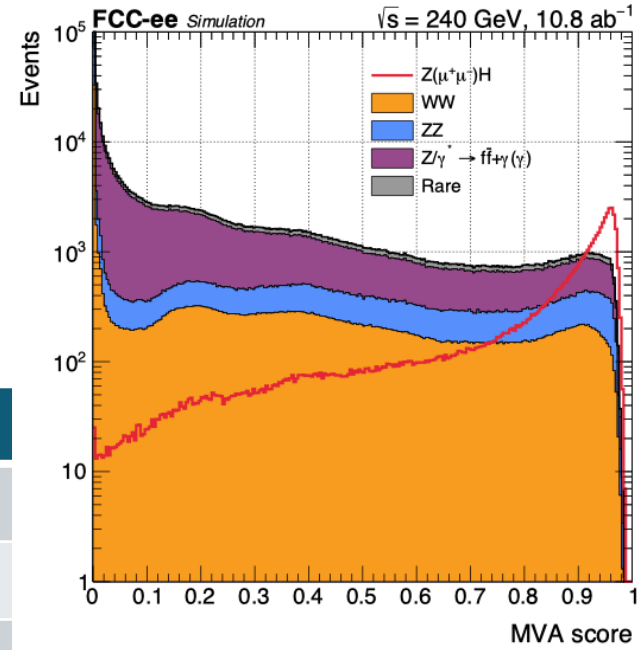
Total ZH cross-section -- Leptonic

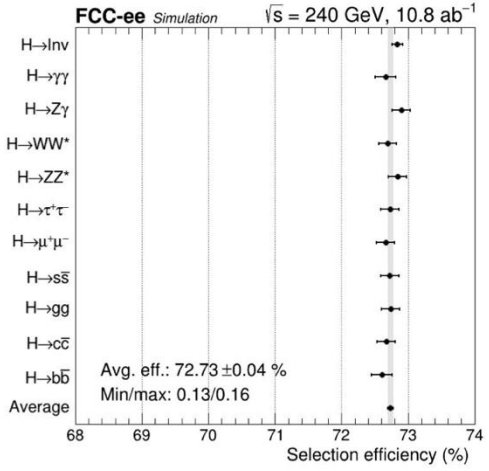
- **Identify the associated Z boson in model-independent way**
  - Identification of 2 tight, opposite sign leptons (electrons or muons)
  - Selection using kinematics of the leptons only
  - BDT based on these variables to further suppress backgrounds
  - Fit on recoil mass in low and high of the BDT
- **Combined uncertainty of 0.52(1.35)% at $\sqrt{s}$=240(365) GeV**

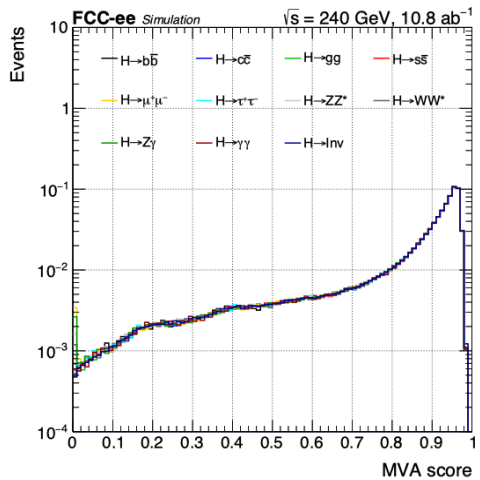




Uncertainty on ZH (%)		
$\sqrt{s}$(GeV)	240	365
Muon	0.68	1.83
Electron	0.81	1.95
Combination	0.52	1.35



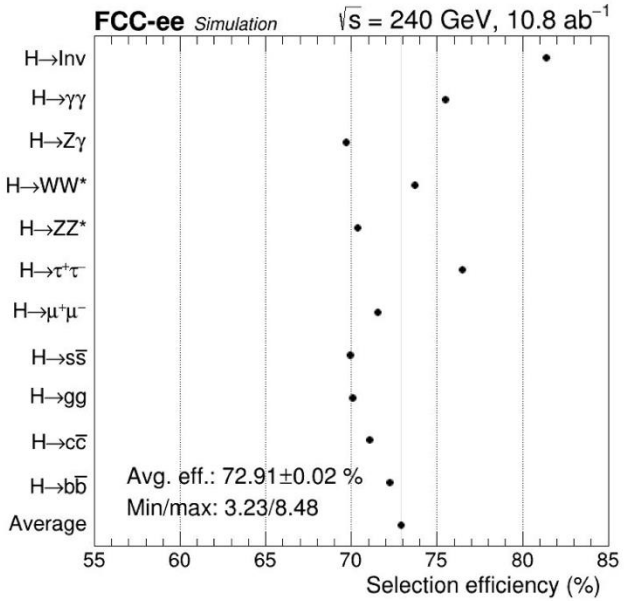




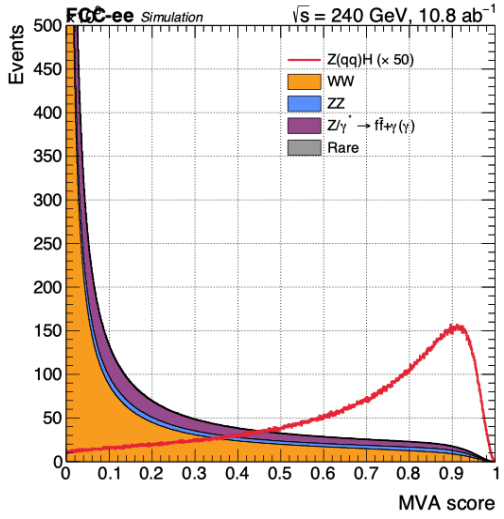
- **Result absolute model independent for all SM Higgs decays within ~ 0.2%, including H→ inv.**

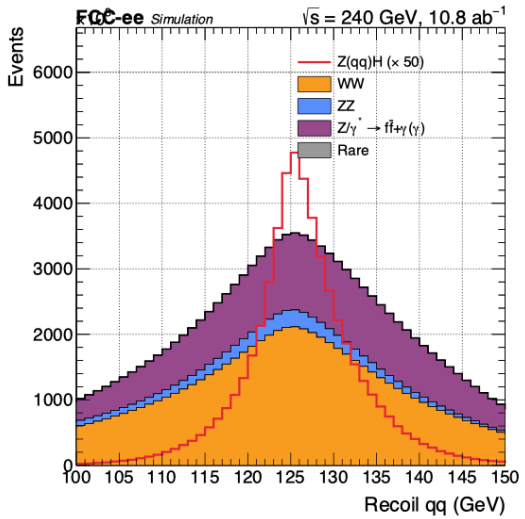
Total ZH cross-section -- Hadronic

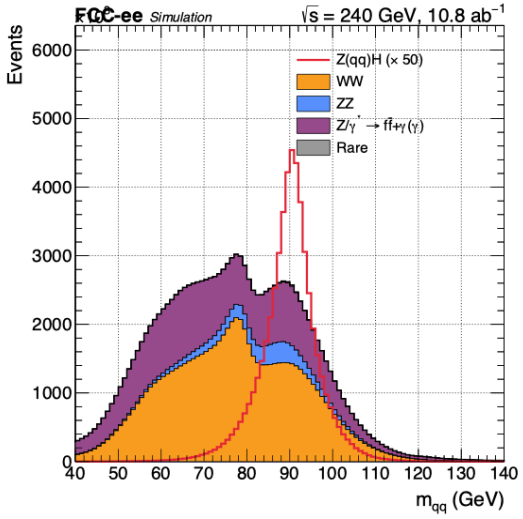
- **Hadronic vs Leptonic**
  - Hadronic channel benefits from large BR (≈70% vs ≈7% for leptonic)
- **Decay-mode dependence**
  - Hard to achieve full independence in event selection efficiency (10% spread)
  - But it does not translate to a dependence in signal extraction (verified with bias test)

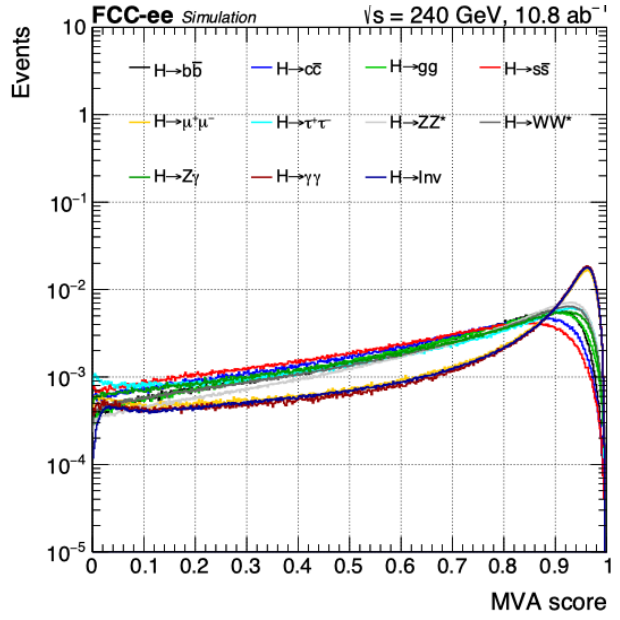


- **2D fit on m_{recoil}-$m_{q\bar{q}}$ plane in 2 regions of BDT discriminator**
- **Total uncertainty of 0.38(0.57)% at $\sqrt{s}$=240(365) GeV**









Total ZH cross-section – Combined

Channel	$\sqrt{s}$ = 240 GeV	$\sqrt{s}$ = 365 GeV
$Z(e^+e^-)H$	±0.81%	±1.95%
$Z(\mu^+\mu^-)H$	±0.68%	±1.83%
$Z(\ell^+\ell^-)H$	±0.52%	±1.35%
Z(qq)H	±0.38%	±0.57%
ZH	±0.31%	±0.52%

- **Hadronic** channel plays the leading role
- **Leptonic** channel helps to improve the uncertainty by ~18%

Total ZH cross-section – Bias test

- **Model independence assessed via bias tests**
  - Perturb each Br to induce $\delta\sigma_{ZH} = X\%$
  - Compare bias with expected uncertainty
- **Leptonic analysis (prior 5%)**
  - A 5% shift in σ_{ZH} would be visible in data
- **Hadronic analysis (prior 1%)**
  - Assume σ_{ZH} known to 1% from leptonic analysis
- **Conservativeness of priors**
  - Priors can be relaxed, as σ_{ZH} precision will reach ~0.3% from combined measurements
- **Model-independent σ_{ZH} → Model-independent branching ratio measurement**

Bias on σ(ZH) (%)			
	Leptonic	Hadronic	Combination
Injected Bias	5%	1%	1%
$H \to b\bar{b}$	-0.01	0.00	-0.01
$H \to c\bar{c}$	-0.01	-0.02	-0.01
$H \to gg$	-0.01	-0.03	-0.01
$H \to s\bar{s}$	-0.01	-0.01	-0.01
$H \to \mu^+\mu^-$	+0.04	-0.01	+0.04
$H \to \tau^+\tau^-$	-0.01	-0.01	-0.01
$H \to ZZ$	+0.33	+0.33	+0.33
$H \to WW$	-0.02	-0.03	-0.02
$H \to Z\gamma$	+0.32	+0.32	-0.32
$H \to \gamma\gamma$	+0.00	-0.01	+0.00
$H \to inv.$	+0.01	+0.01	+0.01

Higgs width

L = 5 ab^{-1}

DOI 10.17181

Nicolas Morange
Combes, Inès
Jan Eysermans
Michele Selvaggi
Aman Desai

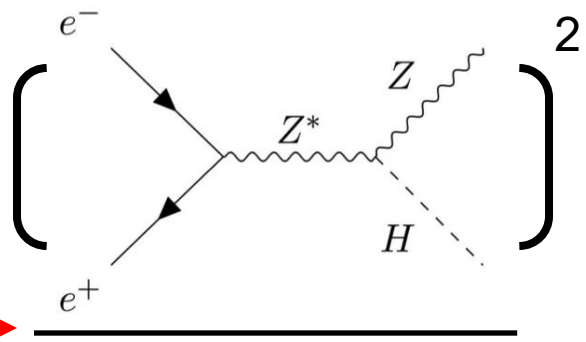
Measuring the individual $H \to XX$ decay modes gives access to Higgs width (Γ_H)

- At 240 GeV, measuring $H \to ZZ$ (ZH)
- At 240+365 GeV, measuring $H \to b\bar{b}$ (VBF)
- Expected precision $\Gamma_H \sim 1\%$
- Model independent Γ_H → Model independent couplings

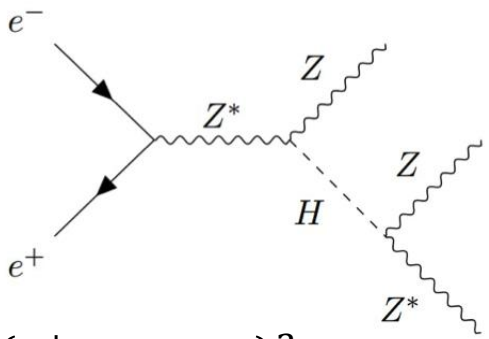
$$\sigma_{ZH} \times Br(H \to X\bar{X}) \propto \frac{g^2_{HZZ} \times g^2_{HXX}}{\Gamma_H}$$

240 GeV:

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



→ Inclusive ZH cross-section



→ $H \to ZZ$ decay

365 GeV:

$$\Gamma_H \propto \frac{\sigma(e^+e^- \to \nu\bar{\nu}H, H \to b\bar{b})\sigma(e^+e^- \to ZH)^2}{\sigma(e^+e^- \to ZH, H \to b\bar{b})\sigma(e^+e^- \to ZH, H \to W^+W^-)}$$

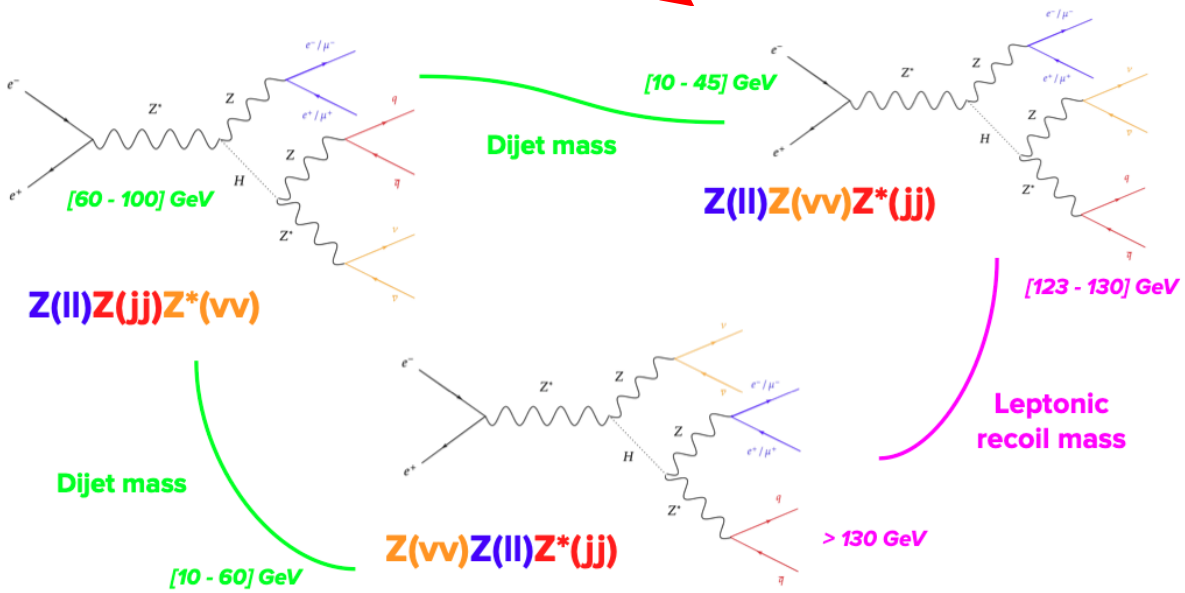
Higgs width

Inclusive ZH cross-section

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

$ZH \to ZZZ^\star$ at 240 GeV:

- $l\bar{l}\nu\bar{\nu}qq$,
  - 3 categories,
  - BDT for classification,
  - **4.6%** precision on Γ_H



- $l\bar{l}qqqq$,
  - particles from the decay of (low energy) Z and Z* are mixed in the theta/phi plane
  - **12.4%** precision on Γ_H

- $qqqqqq$,
  - BDT to classify the events
  - Signal significance is 5.01

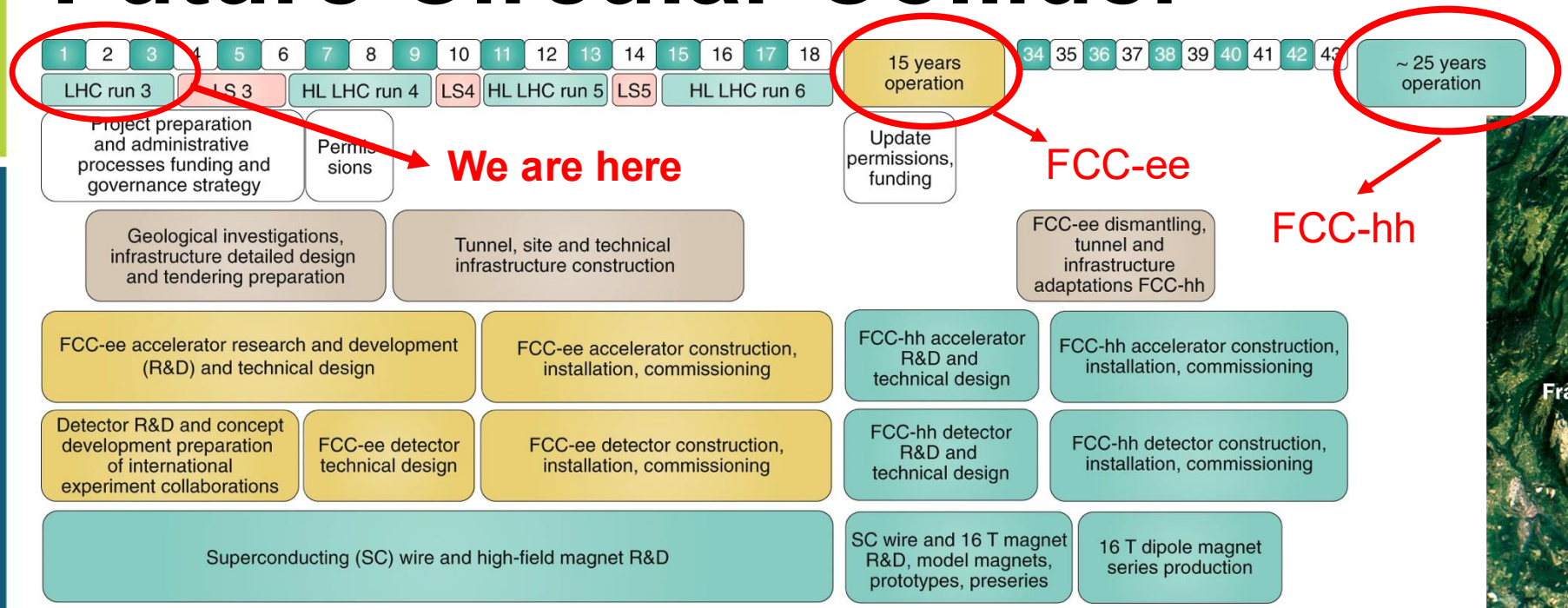
Summary

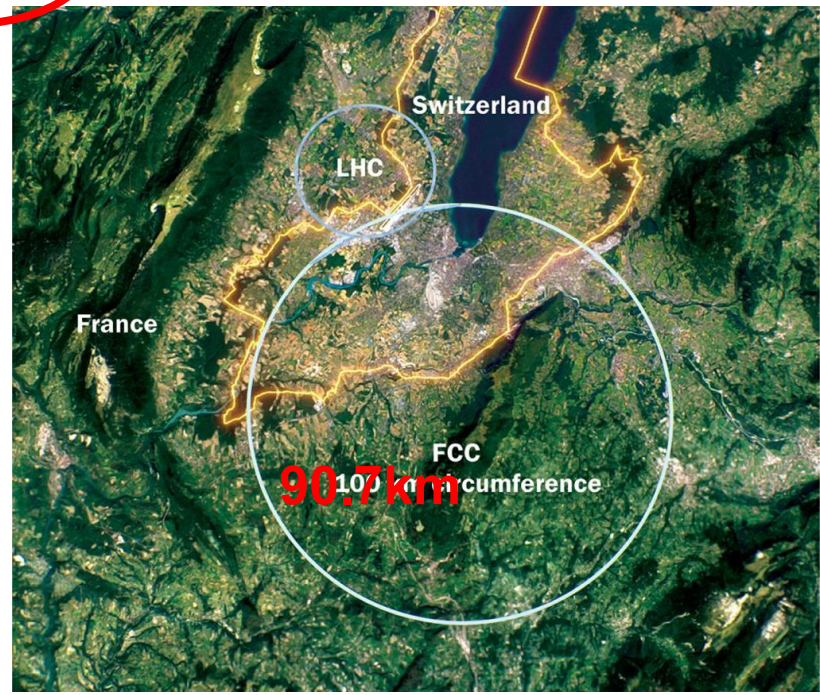
- **FCC will run as Electron-Positron Collider (FCC-ee) then Hadron Collider (FCC-hh)**
  - FCC-ee will run at different energy point from ~90 GeV to 365 GeV
  - Higgs studies mainly at $\sqrt{S}$=240 GeV, 365 GeV as a complementary point
- **Higgs mass**
  - At 240 GeV, Higgs mass uncertainty reach 3.07 (3.97) MeV
  - Stronger Magnetic field can improve the Higgs mass uncertainty
  - Full Silicon instead of Drift chamber will worse the Higgs mass uncertainty
  - Including 365 GeV, Higgs mass uncertainty improved ~ 1%
- **Total ZH cross-section**
  - Leptonic and Hadronic channel
  - ZH cross-section reach ~0.31% (0.52%) at 240 (365) GeV
  - Model independent insured, bias test
- **Higgs width**
  - Need to combine with more decay modes
  - Combining all channels, Higgs width uncertainty will reach ~1%

FCC-ee will give us a great chance to measure the Higgs mass in precision and total ZH cross-section and Higgs width in a model-independent way

Backup

Future Circular Collider



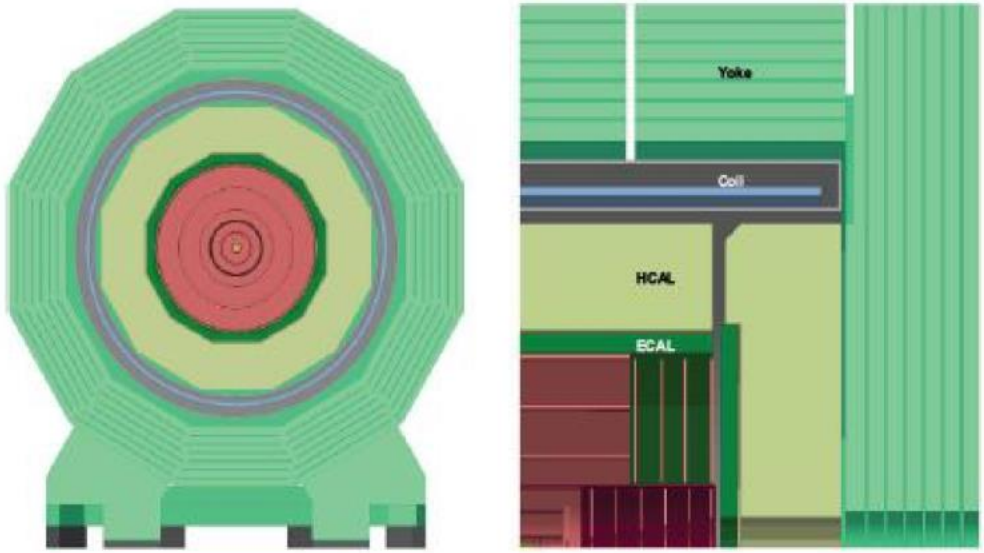


1. On the 18 years of preparation
   1) Feasibility study (5 years) → We are at the end of the Feasibility study
   2) Approval of FCC by CERN Council
   3) then civil constructions
   4) then machine and detectors construction
2. 15 years of FCC-ee on different energy points
3. ~10 years to change the magnets between, and change the detectors
4. 25 years of FCC-hh

1) **FCC-ee**: e^+e^- at ~90-365 GeV, as first-generation Z, Higgs and top factory at high luminosities
2) **FCC-hh**: $p-p$ at 100 TeV as natural continuation of LHC at energy frontier
3) Circumference ~90 km (LHC: ~27 KM)

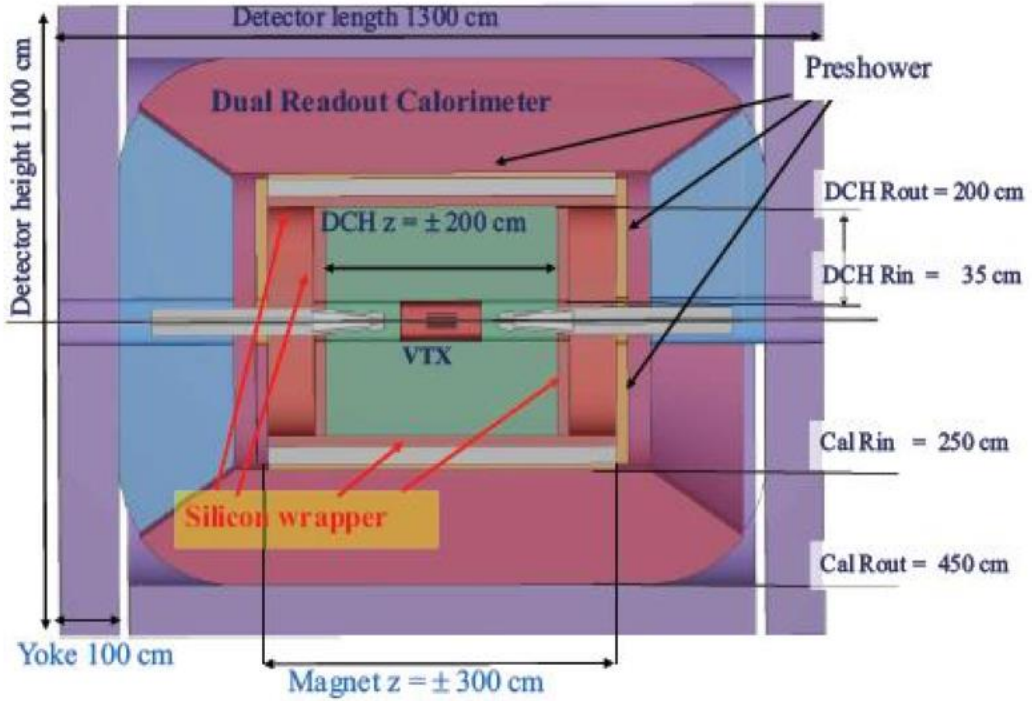
Detectors

CLD



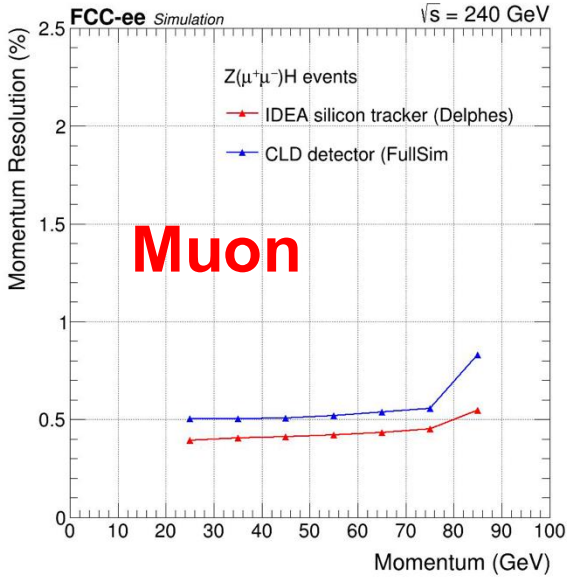
- conceptually extended from the CLIC detector design
  - full silicon tracker
  - 2T magnetic field
  - high granular silicon-tungsten ECAL
  - high granular scintillator-steel HCAL
  - instrumented steel-yoke with RPC for muon detection

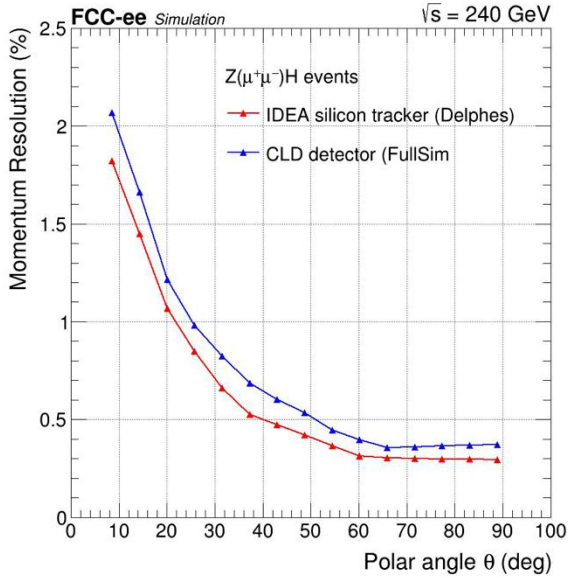
IDEA

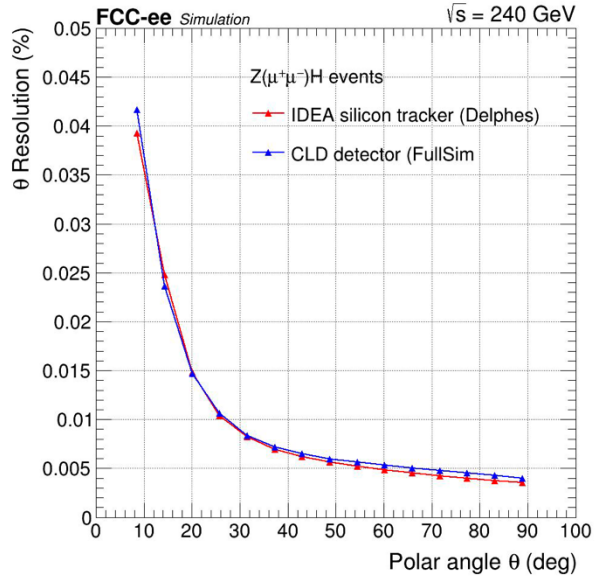


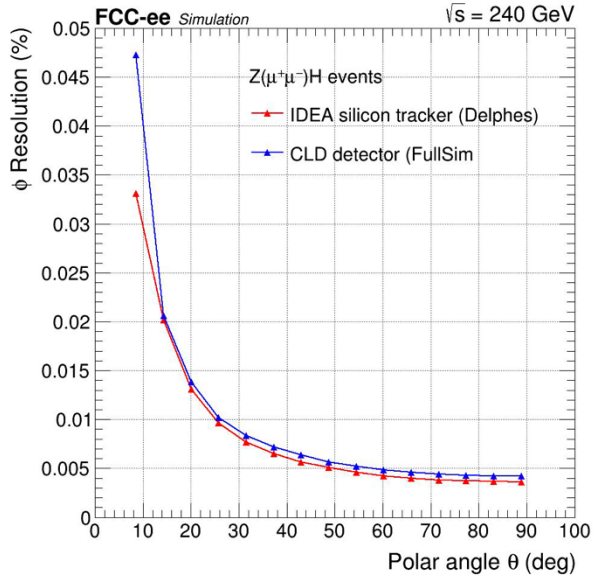
- explicitly designed for FCC-ee/CepC
  - silicon vertex
  - low X_0 drift chamber
  - drift-chamber silicon wrapper
  - MPGD/magnet coil/lead preshower
  - dual-readout calorimeter: lead-scintillating/ cerenkhov fibers
- μRwell for muon detection

FullSim: Momentum and Angular resolution



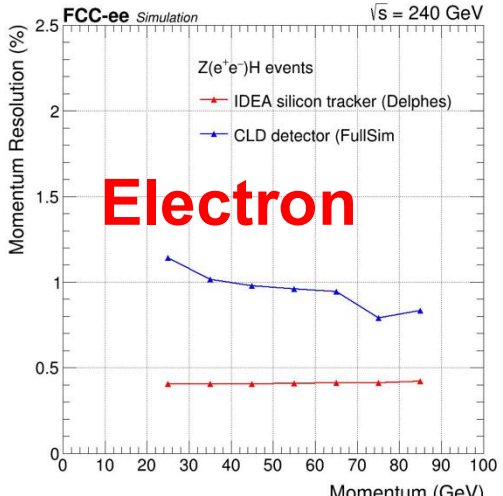






➢ Muon resolutions based on Z($\mu\mu$)H events

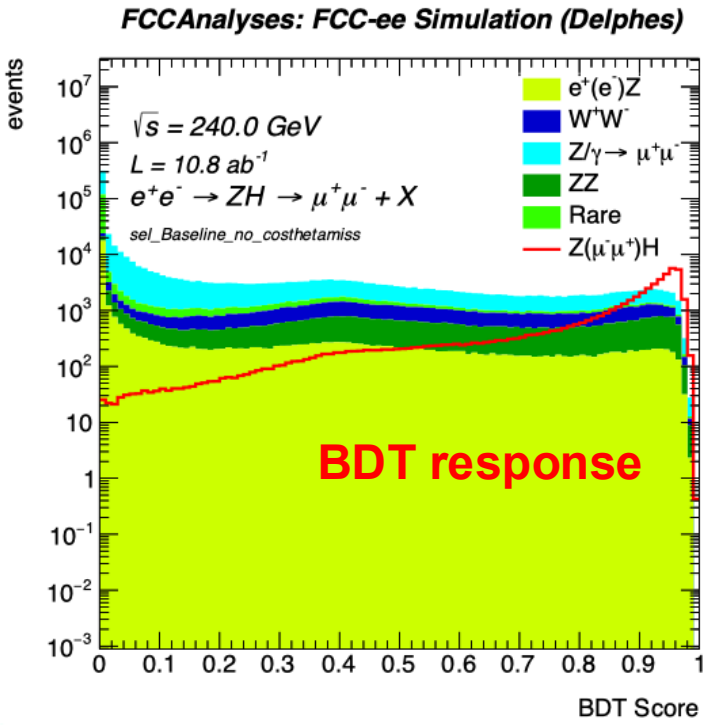
- Slightly worse momentum in FullSim (residual difference in material budget, smearing)
- Angular resolutions OK

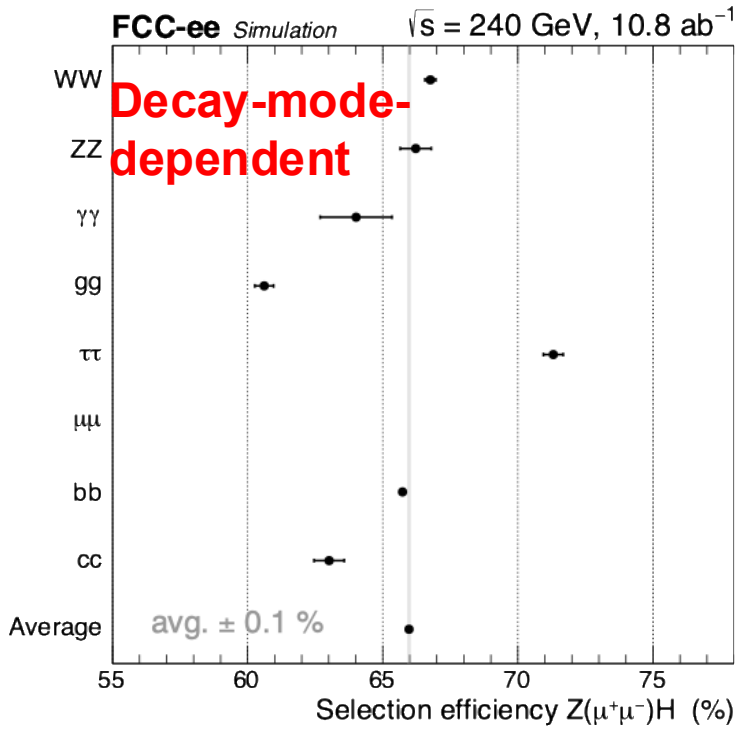


Electron resolutions based on Z(ee)H events

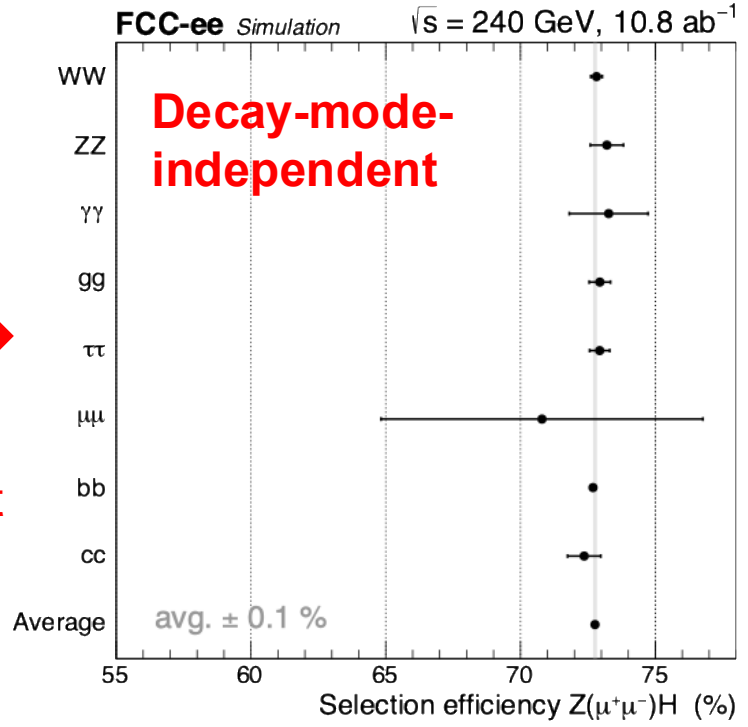
- Visibly worse momentum in FullSim
- No Bremsstrahlung recovery in CLD reconstruction
  - Some work already done
  - Detector requirements for ECAL (Link)
  - Attempt for MVA-based brem recovery (Link)

Total ZH production cross-section



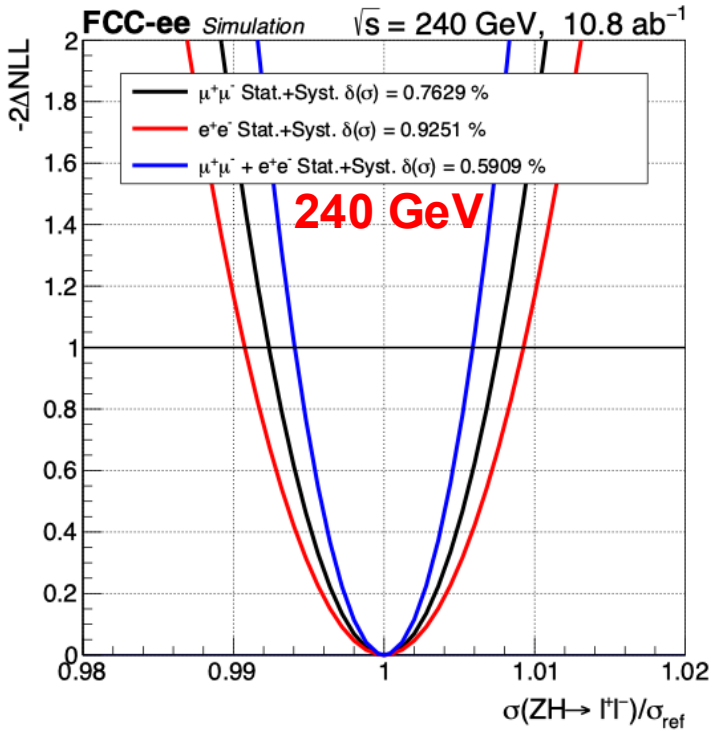


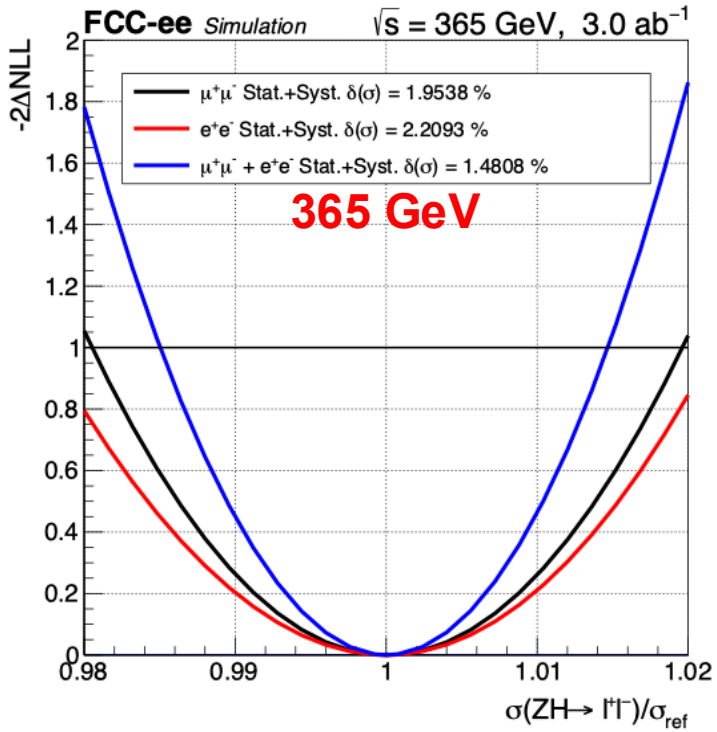
Remove $\cos\theta_{miss}$ cut

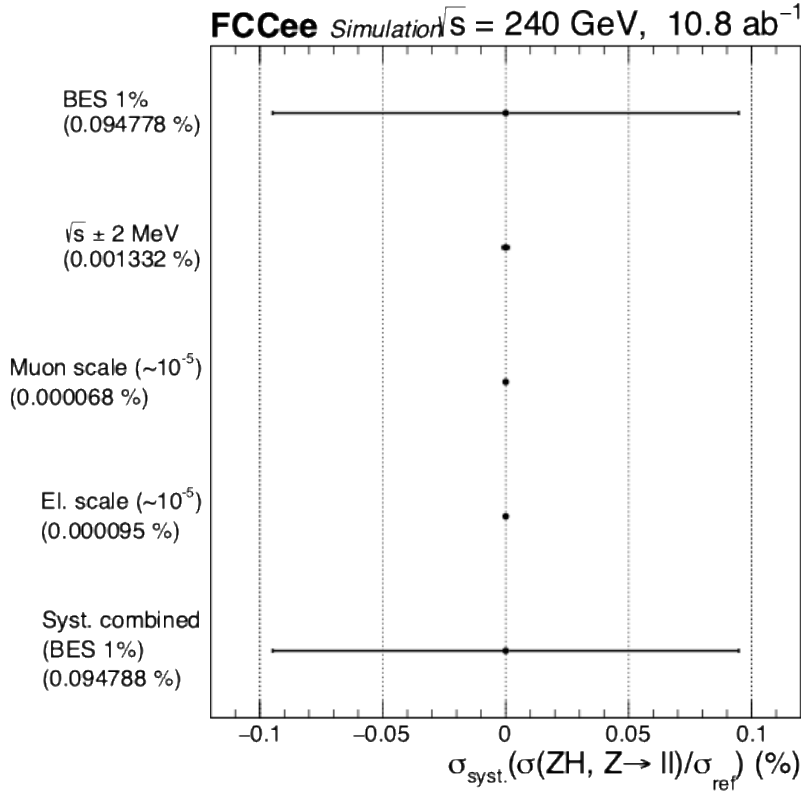


- Remove Decay-Mode dependent event selection → $\cos\theta_{miss}$
- Introduce BDT approach to keep decay-mode independency
- Fit on BDT distribution

ZH cross-section







- **Likelihood scan to extract ZH cross−section uncertainty**
  - Sensitivity driven by muon channel; electrons gain ~ 24%
- **Systematics are negligible (0.58%→0.59%)**
  - Leading Systematic is Beam Energy Spread (BES)

$\delta\sigma_{ZH}/\sigma_{ZH}$	stat-only	w/ syst.
$\sqrt{s} = 240$ GeV,	0.58%	0.59%
$\sqrt{s} = 365$ GeV,	1.42%	1.48%