FUTURE CIRCULAR COLLIDER

Expected precisions on the Higgs boson mass and ZH production cross section at √s=240 & 365 GeV at the Future e+e- Circular Collider (FCC-ee)

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FCC collaboration

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The FCC integrated program (ee + hh) at CERN goes beyond the successful LEP + LHC (1976-2041) program

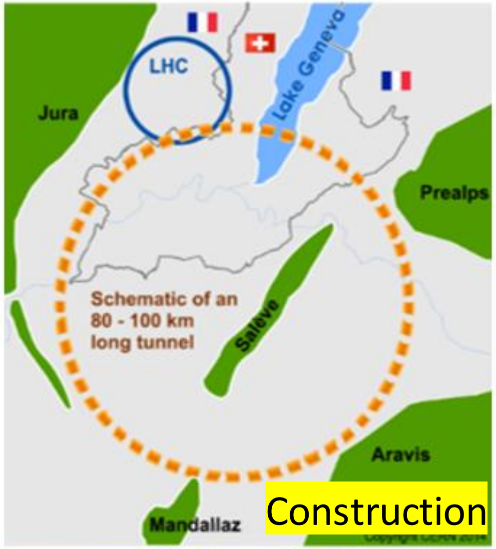
Comprehensive cost-effective program maximizing physics opportunities

- Construction: during HL-LHC data-taking
- Stage 1: FCC-ee (Z, W, ZH, tt) as first generation Higgs, EW and top e^+e^- factory at highest luminosities.
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier

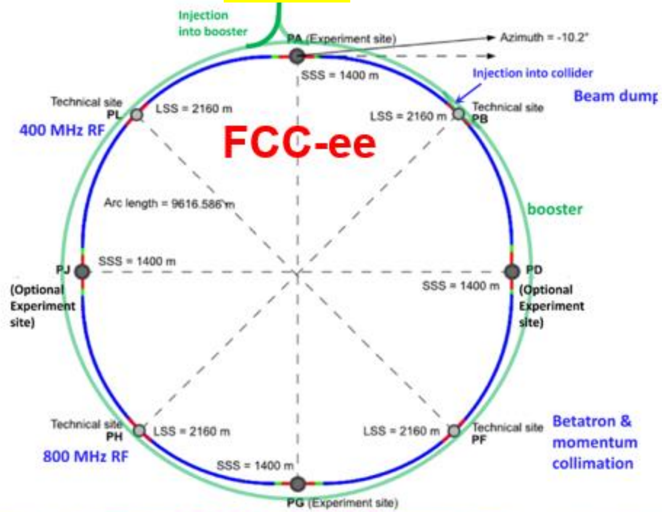
Complementary physics

- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.

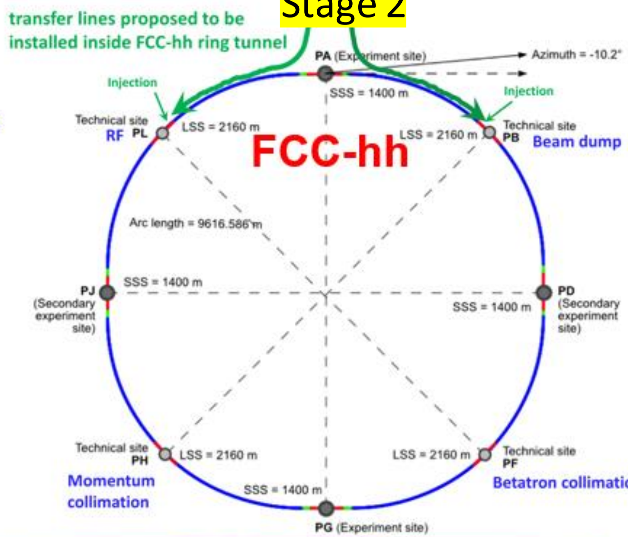
The FCC project is fully integrated with HL-LHC exploitation and provides a natural transition for higher precision and energy



Stage 1

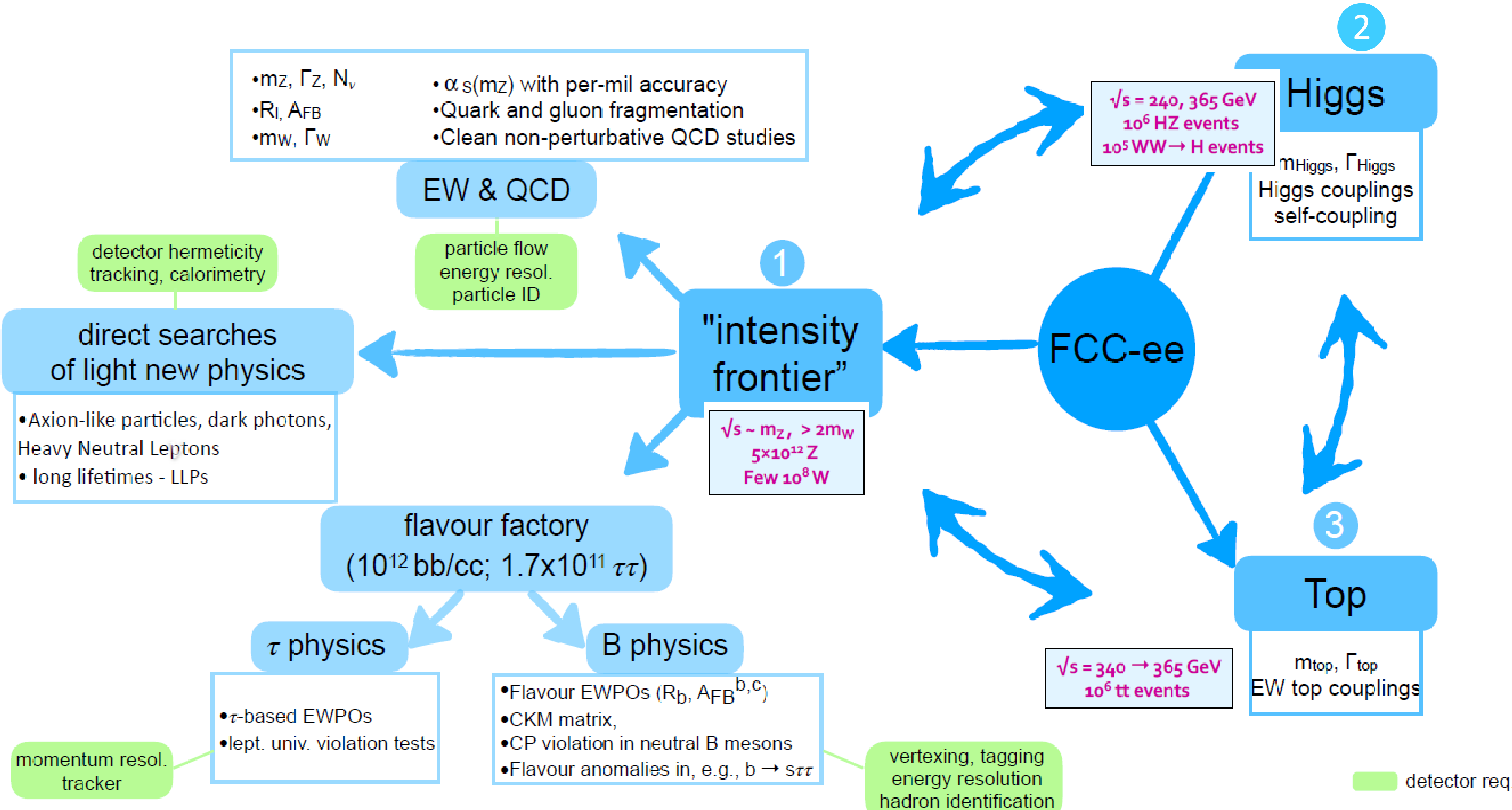


Stage 2



2020 - 2040 | 2045 - 2060 | 2065 - 2090

at Circular Colliders → Rich e^+e^- Physics Program …



Higgs Physics at FCC-ee

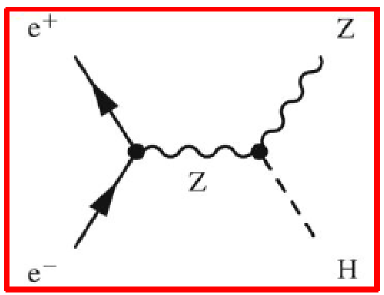
FCC-ee offers broad potential for precision Higgs measurements

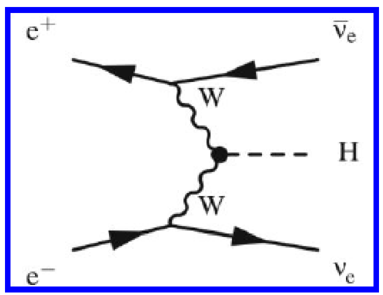
- Higgs factory: production of **2M Higgs** bosons
- Clean environment
- Relative small backgrounds, **large S/B**

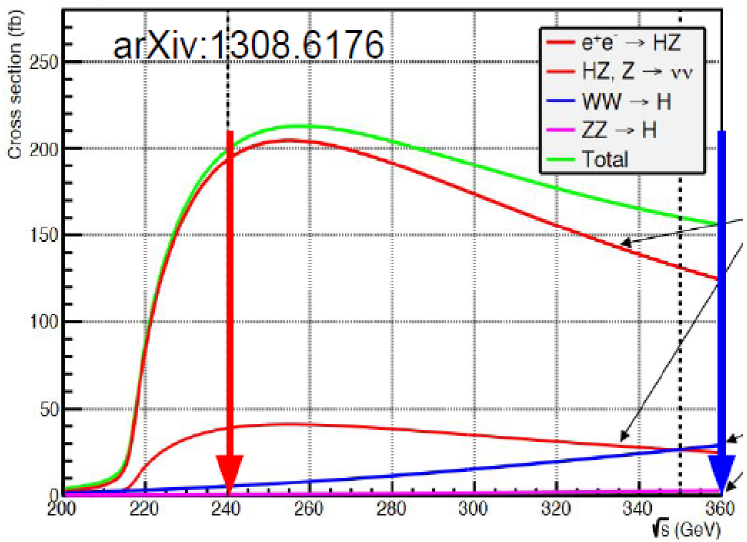
Total Higgs production @ FCC-ee (baseline – 4 IP)		
Threshold	ZH production	VBF production
240 GeV / 10.8 ab^{-1}	2.2 M	67 k
365 GeV / 3 ab^{-1}	330 k	80 k

Main production mechanisms

- **ZH production** "Higgs–strahlung"
- **Vector boson fusion** (VBF), WW dominant







Higgs Physics at the ZH threshold

Highest precision obtained from ZH analyses @ 240 GeV

Main strategy of such analyses based on recoil method

- Tag the Z boson (tight invariant mass constraints) using leptons or jets
- Compute **recoil**, distribution sharp peaked at Higgs mass, **width dominated by detector resolution**

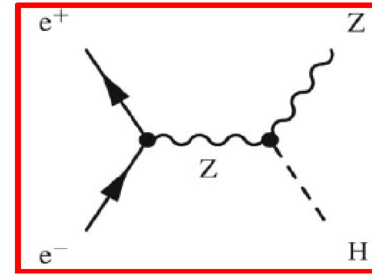
$$m^2_{recoil} = (\sqrt{s} - E_{ff})^2 - p^2_{ff}$$
$$= s + m^2_Z - 2E_{ff}\sqrt{s} \quad \approx m^2_H$$

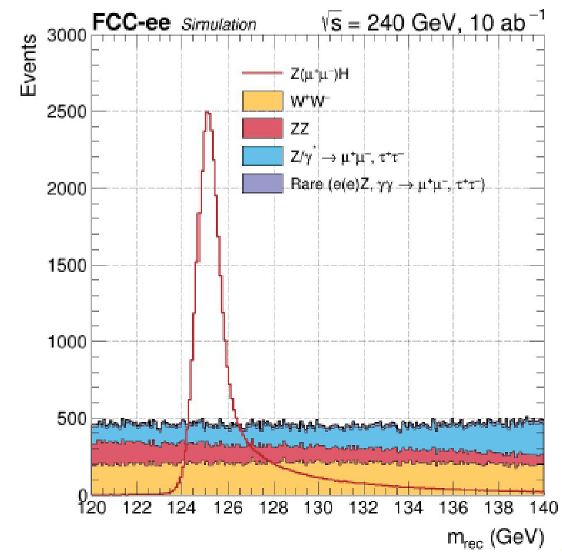
- tag additional decays of the Higgs – challenging in multijet environment

Backgrounds: dominated by vector boson (pair) production (WW, ZZ) and Z/γ*

Challenges for the Higgs programme

- Detector performance: tracking, vertexing, timing, angular
- Flavour tagging for Higgs couplings
- Jet clustering algorithms (in particular in fully hadronic final states)



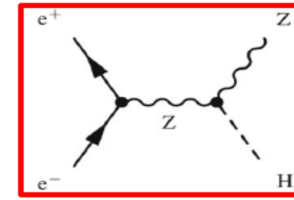


$m_{recoil} \in [120, 140]$ GeV

The total ZH cross section measurement

Crucial is to measure HZZ coupling strength in a model-independent way

- unique to e^+e^- colliders because of known initial state, not possible at hadron colliders
- challenge to ensure **model-independence**
- once known, **determines couplings to H→XX** in a model independent way



$$\sigma\left(e^+e^- \to ZH\right) \propto g^2_{HZZ}$$

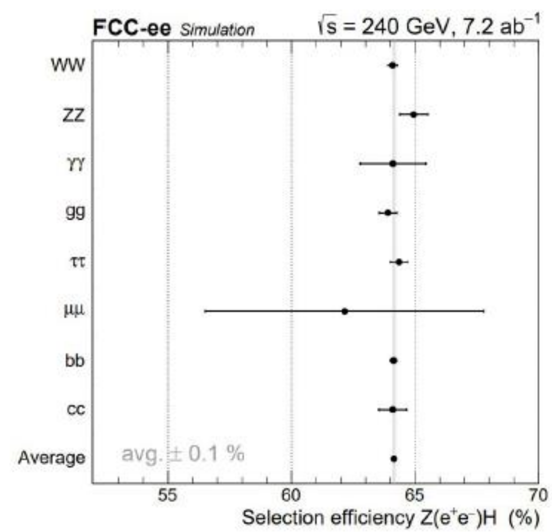
absolute HZZ coupling meas.

Example analysis in Z(ll)H(XX) final state

Probe electron and muon final states

- Clean and sharp recoil distribution
- Cutflow + MVA to reduce backgrounds
- Can minimize the model-dependency

Z(qq)H(XX) to be explored to bring uncertainty down, but challenging to retain model-independence



Monte Carlo Samples

Using Fast simulation **DELPHES**:

- **Signal:**
  - $Z(\mu^+\mu^-)H$ (Whizard/Pythia)
- **Backgrounds:**
  - W^+W^- (Pythia)
  - e^+e^-Z (Whizard/Pythia)
  - ZZ (Pythia)
  - $Z/\gamma \to \mu^+\mu^-$ (Whizard/Pythia)
- **Rare backgrounds:**
  - $Z(qq)$ (Pythia)
  - $Z(\tau^+\tau^-)H$ (Whizard/Pythia)
  - $Z(\nu\nu)H$ (Whizard/Pythia)
  - $\gamma\gamma \to \mu^+\mu^-$ (Whizard/Pythia)
  - $\gamma\gamma \to \tau^+\tau^-$ (Whizard/Pythia)

Event Selection

- **Events basic selection:**

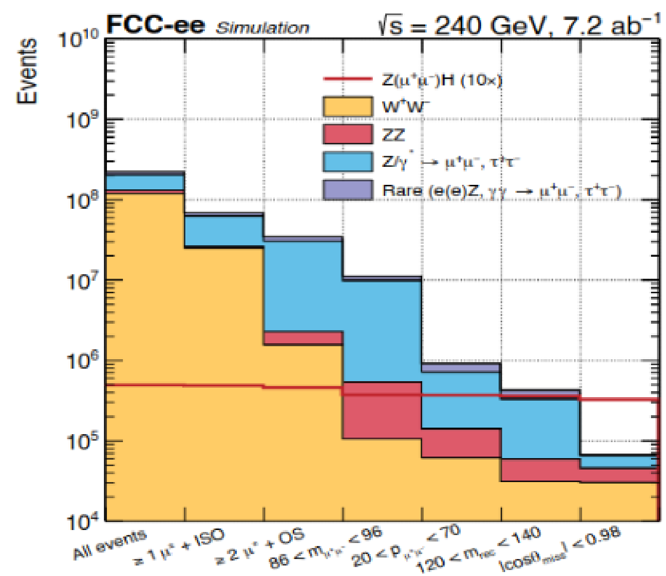
Preselection: Select at least 2 leptons:

- Opposite sign
- One lepton required to be isolated

$m_{l^+l^-} \in [86, 96]$ GeV

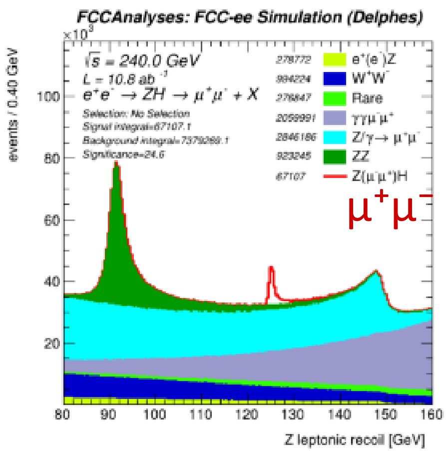
$p_{l^+l^-} \in [20, 70]$ GeV (> 20 GeV at 365 GeV)

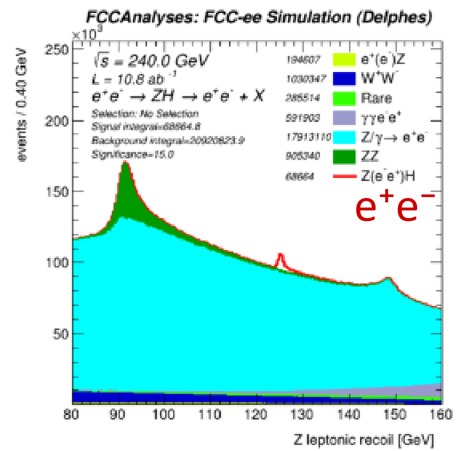
$m_{recoil} \in [120, 140]$ GeV



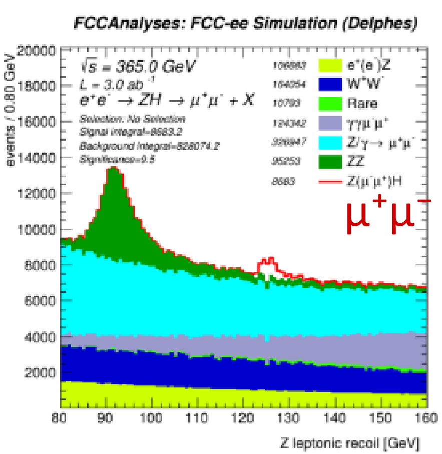
Comparison 240/365 GeV with Preselection Cuts (zoom)

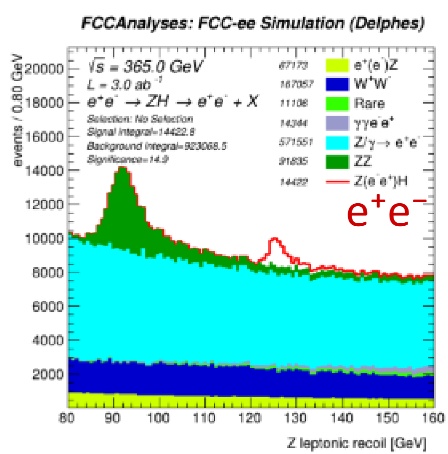
240 GeV ⇒





365 GeV ⇒





➢ **Zoom between 80 and 160 GeV**

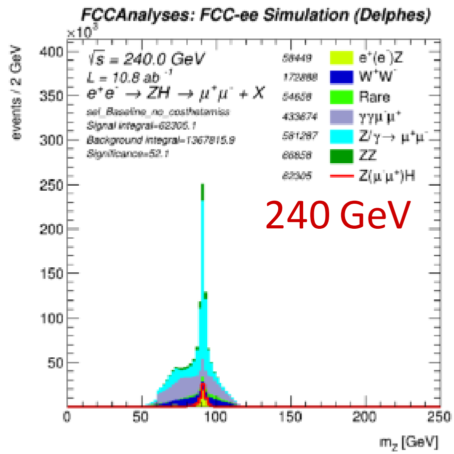
- Luminosity is **10.8** ab^{-1} at √s=**240 GeV**
  3.0 ab^{-1} at √s=**365 GeV**

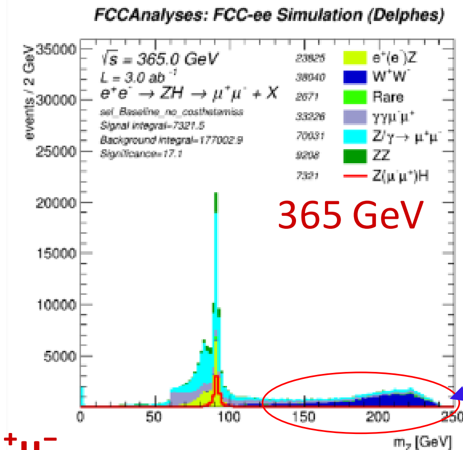
- **Different shapes** of the background before selection cuts

- Signal peak has **lower resolution** but also less background at 365 GeV

Invariant Mass and Recoil Mass distributions

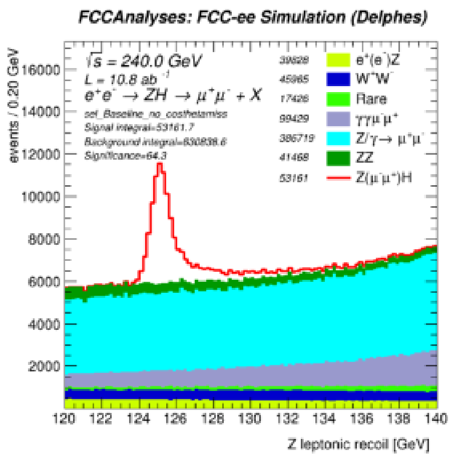
Invariant Mass Distribution ⇒

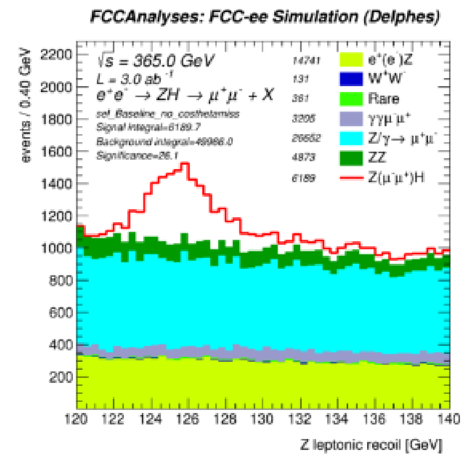




$\mu^+\mu^-$

Recoil Mass Distribution ⇒





➢ **Basic event selection:**

Pre-selection (2 leptons opposite sign)

+

$m_{l^+l^-} \in [86, 96]$ GeV

$p_{l^+l^-} \in [20, 70]$ GeV (>20 for √s=365 GeV)

$m_{recoil} \in [120, 140]$ GeV

➢ **WW becomes negligible** at √s=365 GeV
Since it « moves » to higher invariant masses and the cut on the Z-**mass removes it**

➢ Resolution **~2.3** times wider at √s=365 GeV

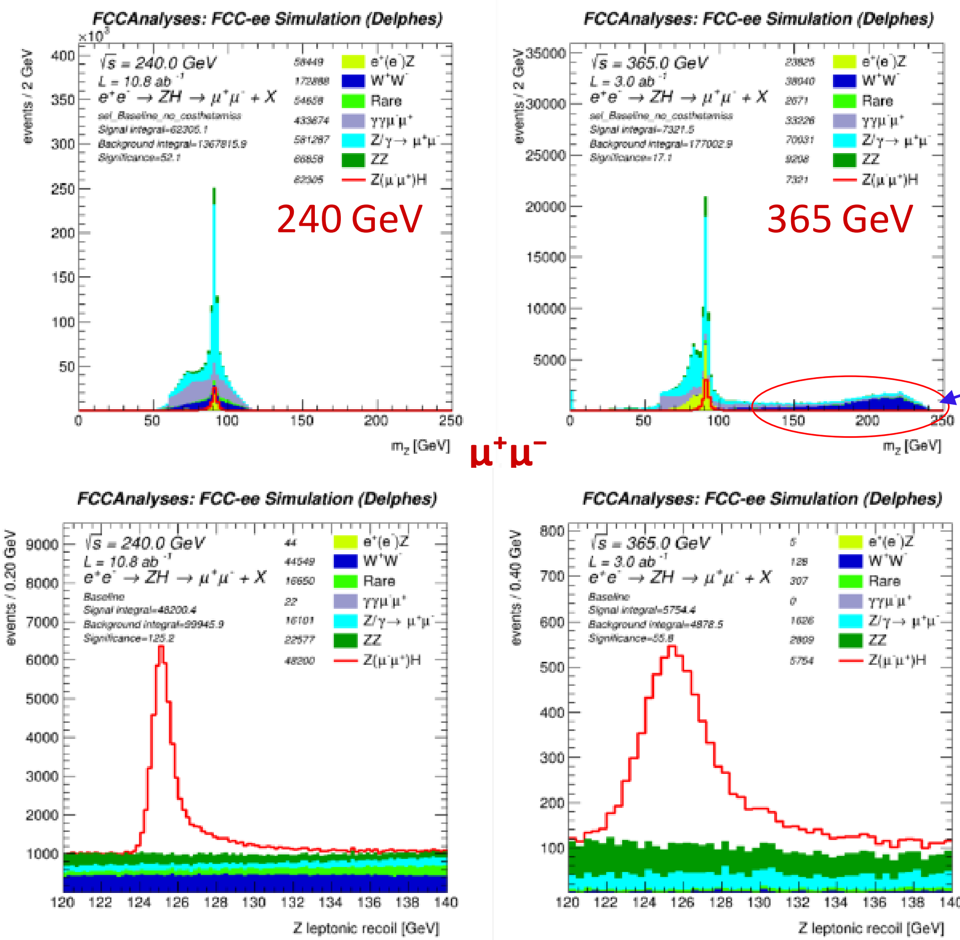
S/B still needs to be improved to gain precision

- BDT for model independent analysis, ZH cross section
- Cos theta$_{miss}$ cut for Higgs mass analysis

Invariant Mass and Recoil Mass distributions

Invariant Mass Distribution ⇒

Recoil Mass Distribution ⇒



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With Cos theta$_{miss}$ cut for Higgs mass analysis, Background strongly reduced

Boosted Decision Tree used for σ_{ZH} analysis

- Use of a Machine learning algorithm to **separate signal** from **background**, a Boosted Decision Tree (BDT)

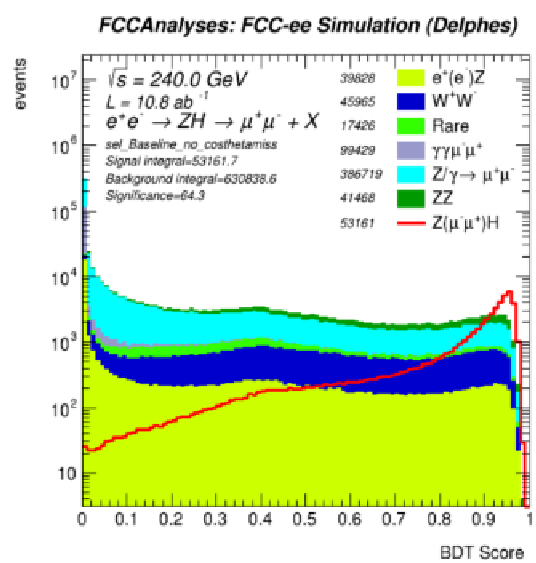
- The BDT, using only variables from the leptons of the Z, allows for a **model independent** analysis

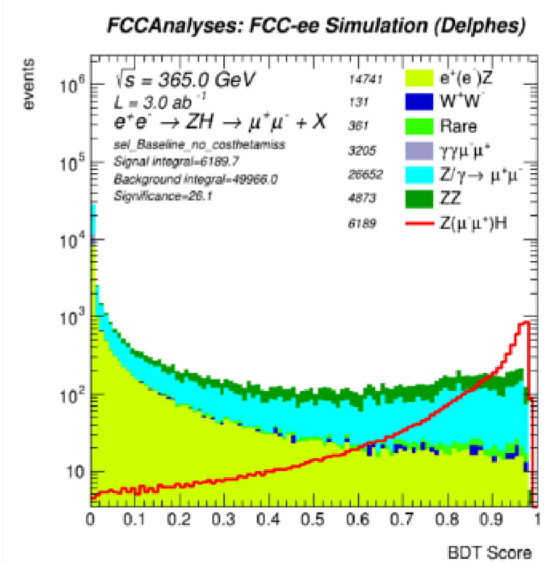
- Training_variables for BDT:

Variable	Description
$p_{\ell^+\ell^-}$	Lepton pair momentum
$\theta_{\ell^+\ell^-}$	Lepton pair polar angle
$m_{\ell^+\ell^-}$	Lepton pair invariant mass
$p_{l_{\text{leading}}}$	Momentum of the leading lepton
$\theta_{l_{\text{leading}}}$	Polar angle of the leading lepton
$p_{l_{\text{subleading}}}$	Momentum of the subleading lepton
$\theta_{l_{\text{subleading}}}$	Polar angle of the subleading lepton
$\pi - \Delta\phi_{\ell^+\ell^-}$	Acoplanarity of the lepton pair
$\Delta\theta_{\ell^+\ell^-}$	Acolinearity of the lepton pair

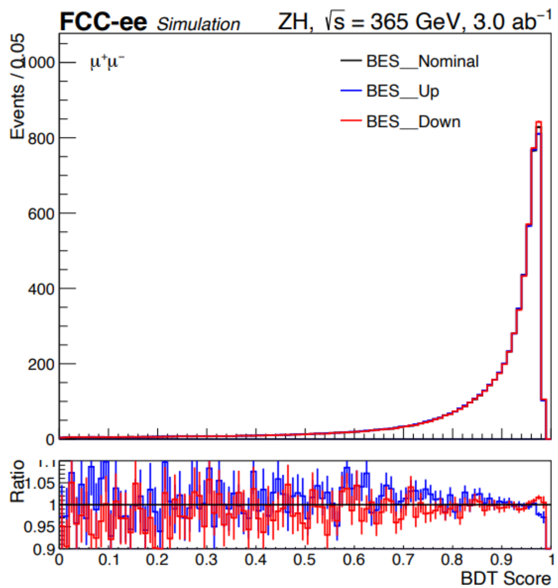
- **BDT Score comparison** between 365 and 240 GeV

- This **BDT score** is **fitted** to measure the **ZH cross-section value**





Systematic uncertainties for ZH cross section measurement



- **Centre-of-mass (√s)**: Uncertainty on the centre-of-mass energy which is expected to be known at the **~2 MeV** level for 240 and 365 GeV

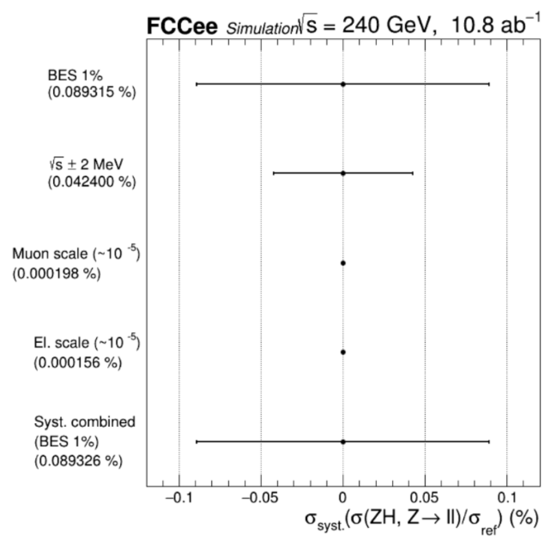
- **Lepton momentum scale**: Uncertainty from the momentum of leptons assumed to be known at $\mathbf{10^{-5}}$ precision level both for 240 and 365 GeV

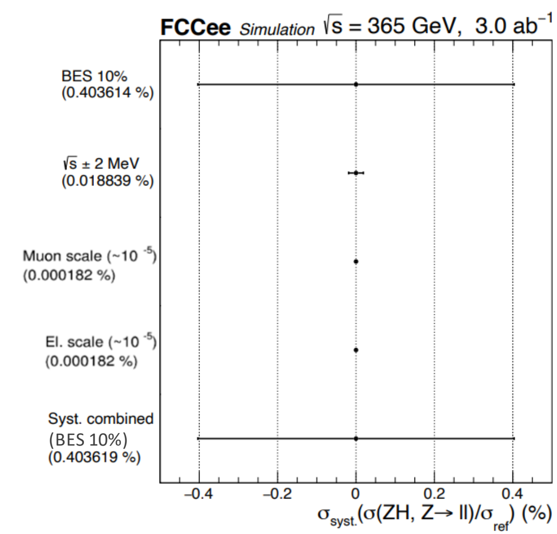
- **Beam energy spread, depends on the beam energy.**

  At a center-of-mass energy of 240 (365) GeV, the beam energy spread (BES) is ±0.185% (±0.221%) per beam, i.e. ±222 (±403) MeV.

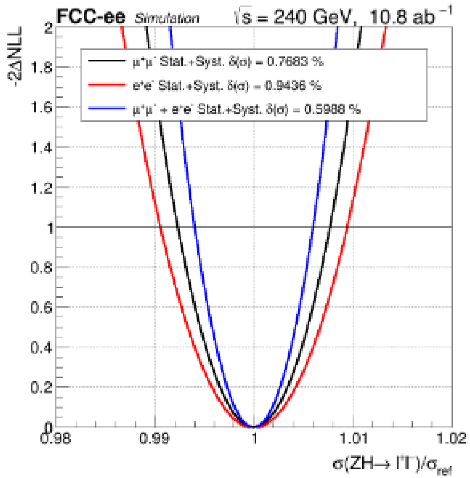
  Uncertainty assumed on the BES value is **~1%** at 240 GeV and **~10%** at 365 GeV ➔ Dominant systematic for ZH cross section measurement

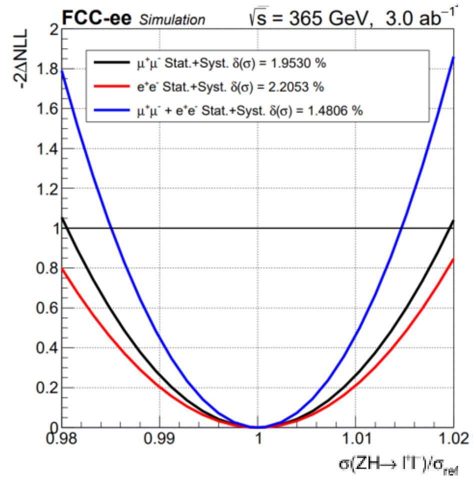
- **ISR uncertainty** is not estimated precisely yet, but expected to be smaller

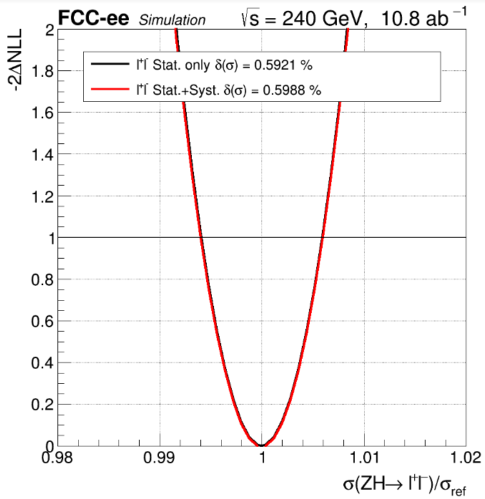


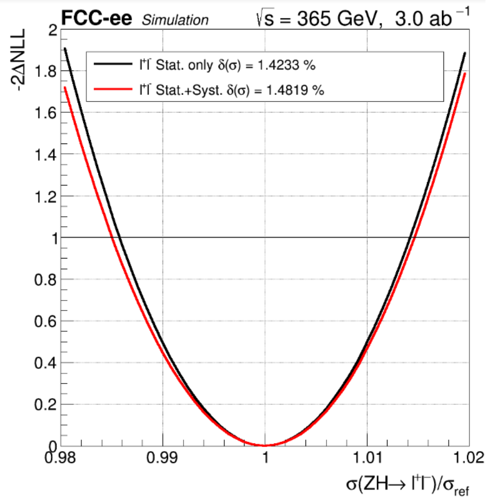


ZH cross-section measurements ($\mu^+\mu^-$, e^+e^- and combined) at $\sqrt{s}$=240 & 365 GeV



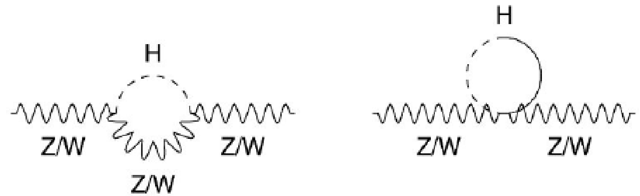






- By fitting the BDT output we obtain the cross-section, with its **statistical** and **stat+systematics** uncertainties.
- **1.42%** Statistical uncertainty at $\sqrt{s}$=**365 GeV** compared to **0.59%** at $\sqrt{s}$=**240 GeV**
- **1.48%** Stat+Syst uncertainties at $\sqrt{s}$=**365 GeV** compared to **0.60%** at $\sqrt{s}$=**240 GeV**
- **Systematics are larger at 365 GeV, but ZH cross section precision still dominated by statistics**
- **Intrinsic sensitivity is similar (~25% larger) at 365 GeV vs. 240 GeV for ZH cross section,** contrarily to the mass measurement where the difference is much larger (see below)

Higgs Mass Measurements



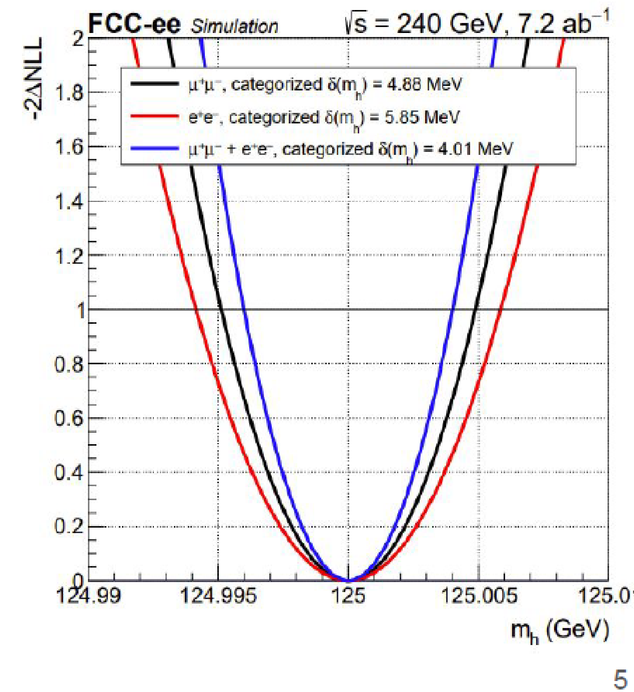
Higgs mass enters SM EWK parameters via radiative corrections, depending logarithmically on m_H, e.g.

$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

$\Delta r \sim \ln(m_H)$
$\Delta r \sim m_t^2$
$\Delta r \sim$ new physics?

Needs for FCC-ee

- Very high precision on cross-sections, sub-percent level
- This translates to a Higgs mass requirement < O(10) MeV to control the radiative corrections for the cross-sections and branching fractions



Roadmap for ultimate precision on Higgs mass

TODAY	HL-LHC	FCC-ee
~ 150 MeV	~ 20 MeV	~ 4 MeV

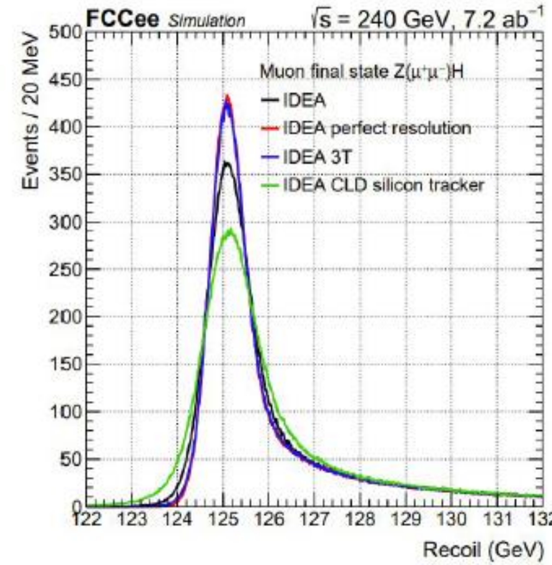
Together with precise Top and W/Z masses, Higgs mass will provide stringent test of the Standard Model

Higgs Mass Analysis and Studies

Higgs mass extracted from fitting recoil distribution

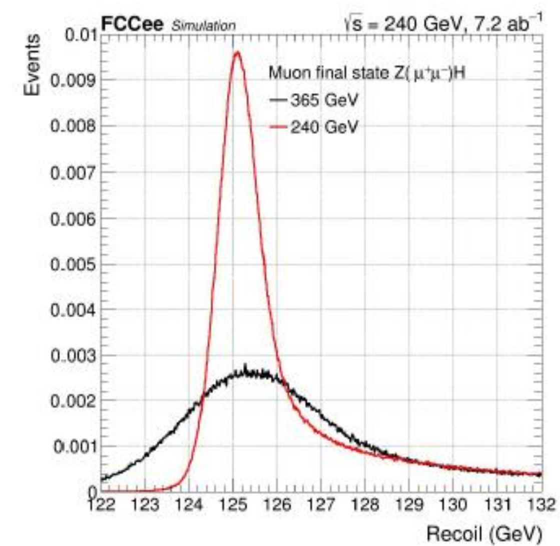
$$M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

- Muon and electron final states
- Tight event selection (follow closely the ZH cross-section selection)
- Categorize in central and forward regions to probe different material budget
    - In total 3 categories: central, forward, central+forward
- Done at center-of-mass 240 and 365 GeV
    - Limited sensitivity at 365 due to small statistics, higher BES and ISR



Simultaneous fit over all the 12 categories (2 flavor, 3 angular categories, 2 ECM)

Final state	Muon	Electron	Combination
Categorized (7.2 ab^{-1} + 3.0 ab^{-1})	4.79(5.50)	6.06(6.68)	3.76(4.53)
Inclusive (7.2 ab^{-1} + 3.0 ab^{-1})	4.83(5.51)	6.15(6.70)	3.80(4.54)



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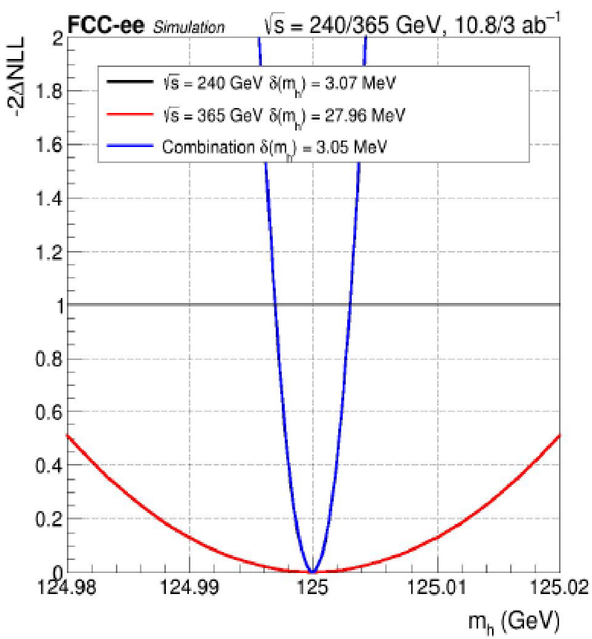
Higgs Mass Results and Systematics at 240 and 365 GeV

Using 10.8 ab-1 (240 GeV) and 3 ab-1 (365 GeV)

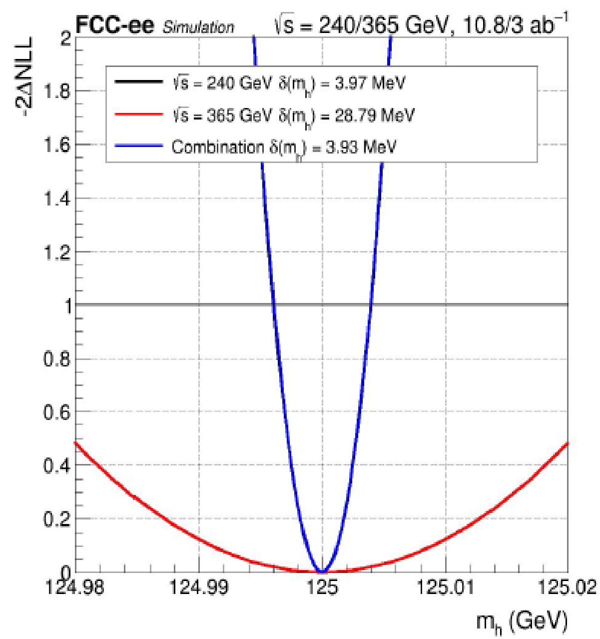
- **Current combined uncertainty: 3.05(3.93) MeV**
- Systematics contribute ~2.5 MeV, ecm uncertainty dominant
- Improvement by adding 365 GeV ~ 1%

Systematics:

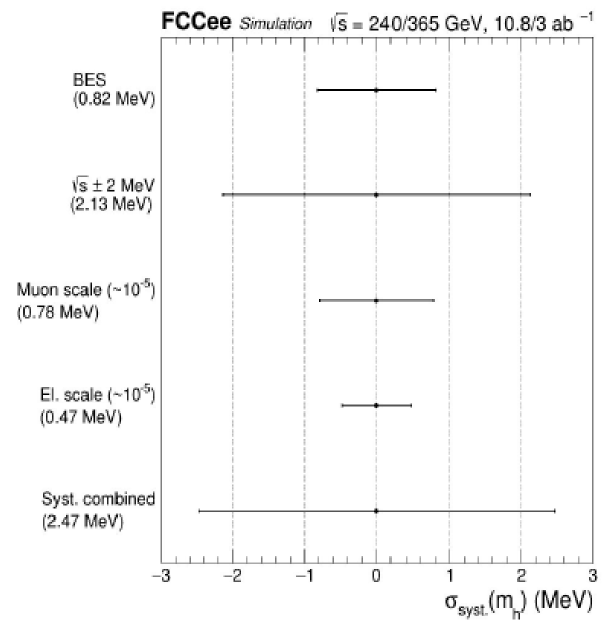
For the Higgs mass, the systematic uncertainty is dominated by the uncertainty on the c.o.m energy



Stat. Only



Stat.+Syst.



Higgs Mass Sensitivities → experimental constraints

FCC

at 240 GeV, 10.8 ab-1

Nominal configuration →

Crystal ECAL to Dual Readout →

Nominal 2 T → field 3 T →

IDEA drift chamber → CLD Si tracker →

Impact of Beam Energy Spread →

Perfect (=gen-level) momentum resolution →

Final state	Muon	Electron	Combination
Nominal	3.92(4.74)	4.95(5.68)	3.07(3.97)
Categorized	3.92(4.74)	4.95(5.68)	3.10(3.97)
Degradation electron resolution			3.24(4.12)
Magnetic field 3T	3.22(4.14)	4.11(4.83)	2.54(3.52)
Silicon tracker	5.11(5.73)	5.89(6.42)	3.86(4.55)
BES 6% uncertainty	3.92(4.79)	4.95(5.92)	3.07(3.98)
Disable BES	2.11(3.31)	2.93(3.88)	1.71(2.92)
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)

- we want to get down to **$\Delta m_H \sim \Gamma_H \sim$ 4 MeV** to allow for electron Yukawa at $\sqrt{s}$ = 125 GeV
- as expected, tracking resolution highly impacts m_H precision
- light tracker/ **high B field** highly preferable

Summary

- The ZH cross section and the Higgs boson masses expected measurements have been presented at 240 GeV and at 365 GeV c.o.m.

- σ_{ZH} is measured in a model independent way with 0.6% accuracy at 240 GeV,
  1.5% at 365 GeV

  opening the way to precise Higgs couplings measurements

- The Higgs boson mass is measured with 4.0 MeV accuracy at 240 GeV,
  3.9 MeV when adding 365 GeV

  allowing for precise tests of the SM

- Systematics and detector constraints have been studied and presented, and will help to determine the best detector configurations for FCC-ee in the FCC feasibility study

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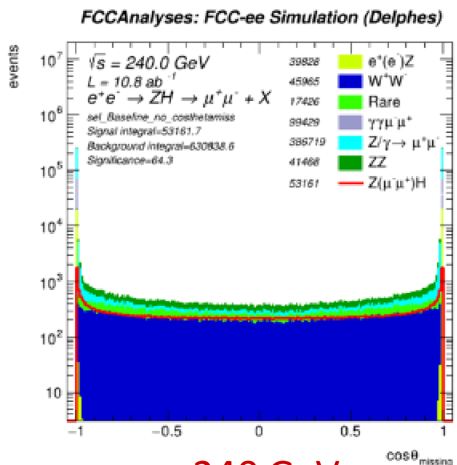
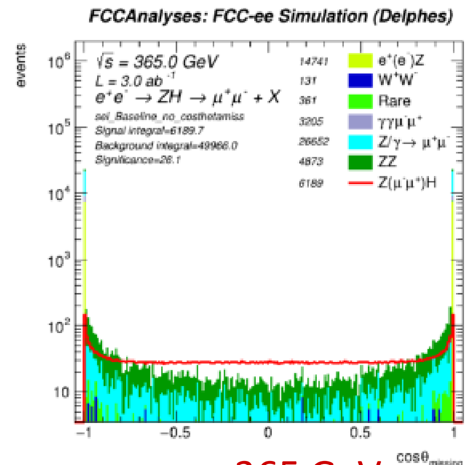
Comparison 240/365 GeV after Selection Cuts

Cos θmissing Distribution ⇒

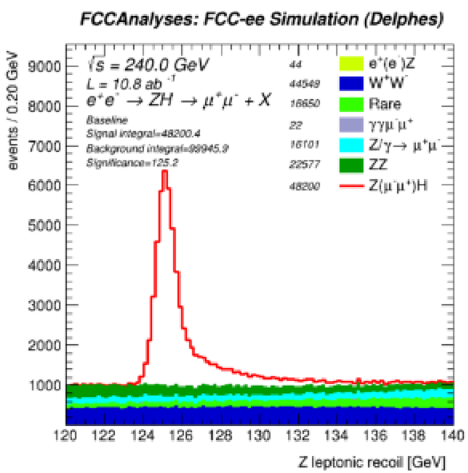


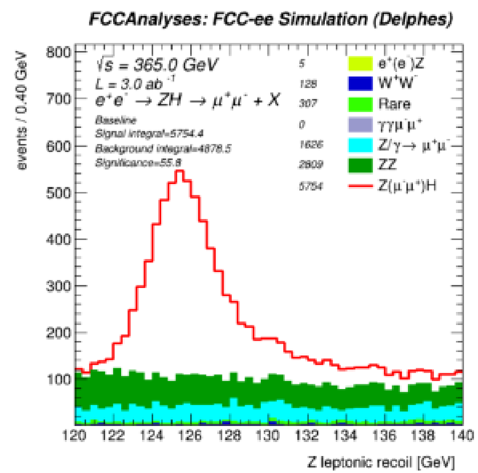
240 GeV



365 GeV

Recoil Mass Distribution ⇒





- The requirement $|\cos \theta_{missing}| <$ **0.98** is used for the **mass analysis only**
- $\Theta_{missing}$ is the **polar angle** of the **missing momentum vector** with respect to the beam axis
- This requirement is removing the large background concentrated in the **last bins.** The remaining background becomes small
- This Introduces **biases** on the Higgs decay modes that break the **model independence,** which is not crucial for the mass analysis
- Width of the recoil mass becomes more than 2 times larger at 365 GeV (due to BES and lepton momentum resolution)
  ➔Significant loss in mass precision

Missing momentum polar angle

- The **missing momentum** is defined by the **negative vectorial sum** of the momenta of all reconstructed particles:

$$\vec{p}_{miss} = -\sum_{n_{part}} \vec{p}_{rec}$$

- **$\Theta_{missing}$** is the **polar angle** of the **missing momentum vector** with respect to the **beam axis**

- The requirement $|\cos\theta_{missing}| < 0.98$ is used for the **mass analysis only,** which means that we are removing events mostly collinear to the beam axis