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

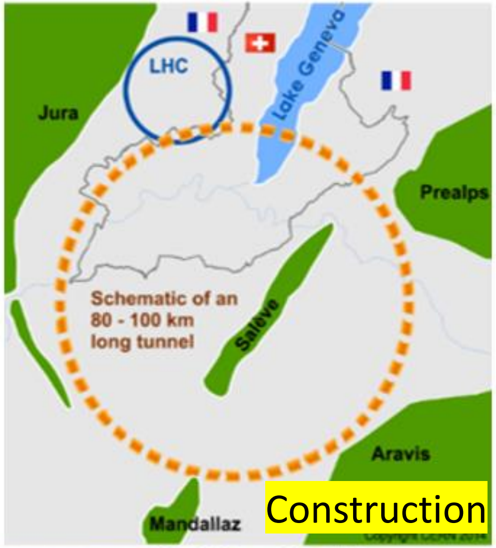
Comprehensive cost-effective program maximizing physics opportunities

- **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.

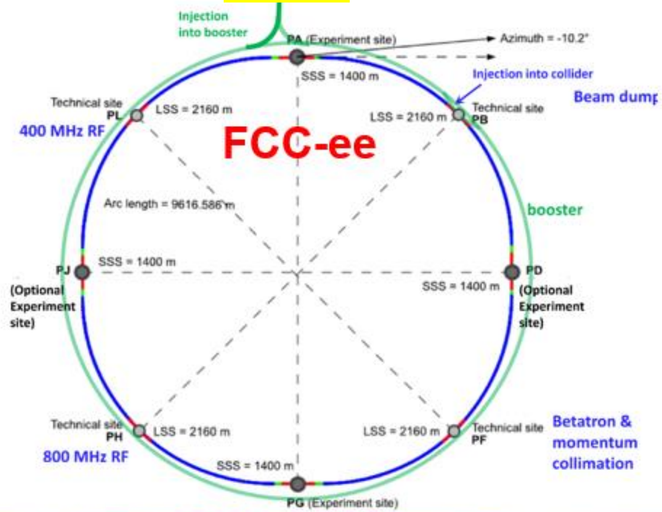
The FCC project is fully integrated with HL-LHC exploitation and provides a natural transition for higher precision and energy




Construction

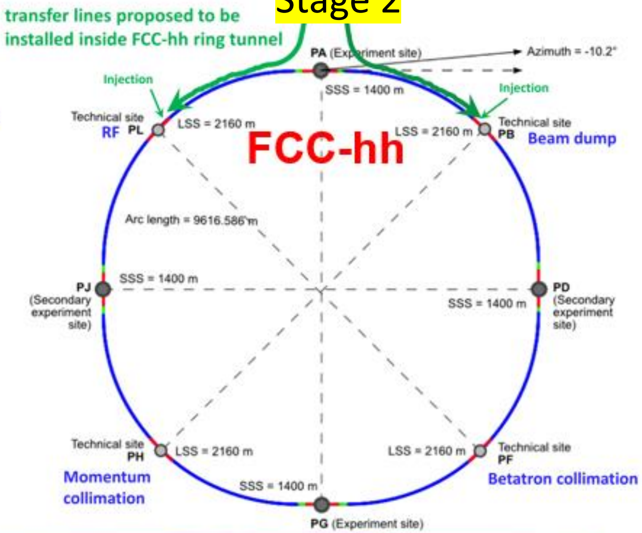
2020 - 2040

Stage 1



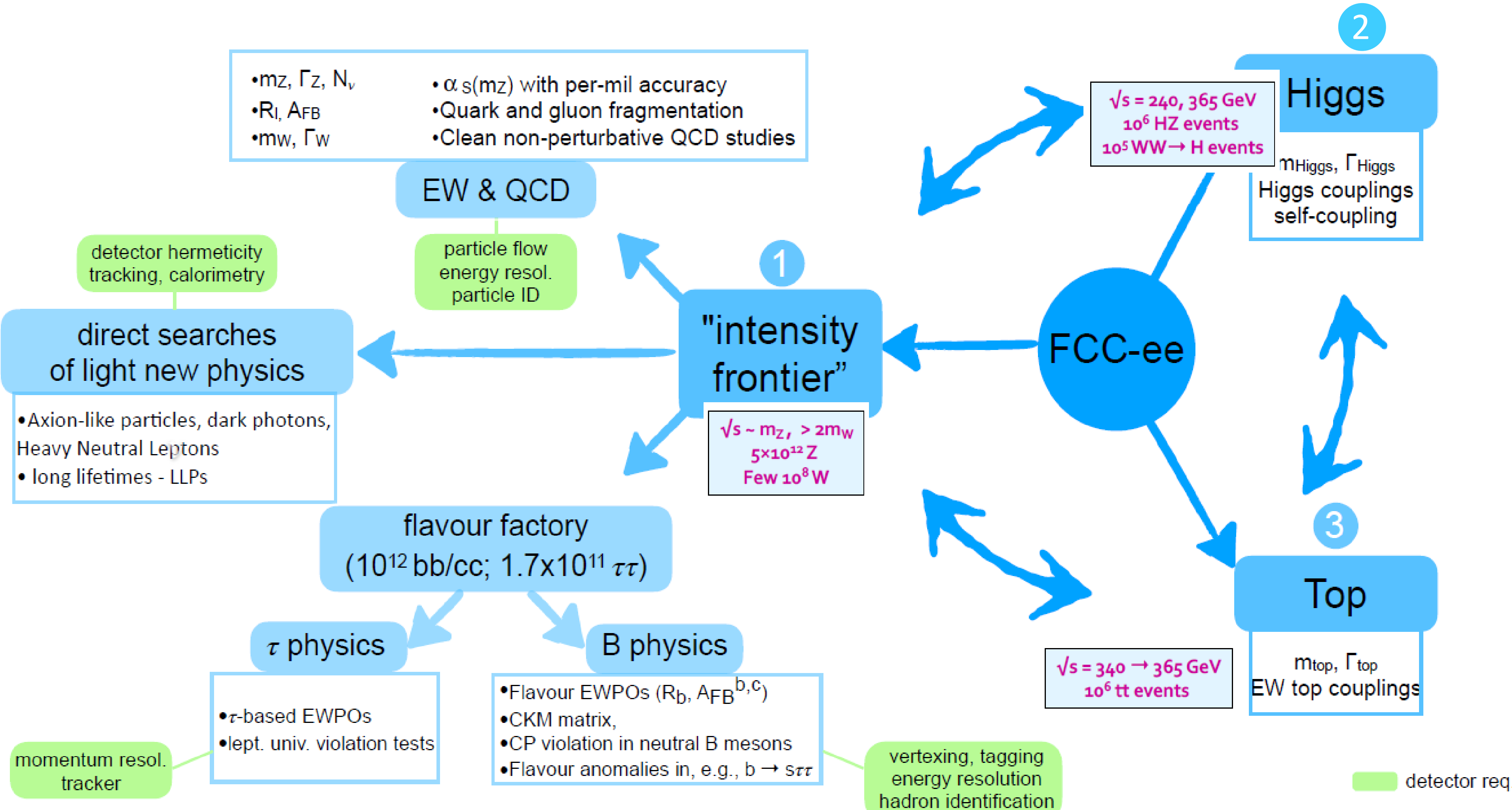

2045 - 2060

Stage 2




2065 - 2090

# at Circular Colliders ➔ Rich $e^+e^-$ Physics Program …



# Higgs Physics at FCC-ee

FUTURE CIRCULAR COLLIDER

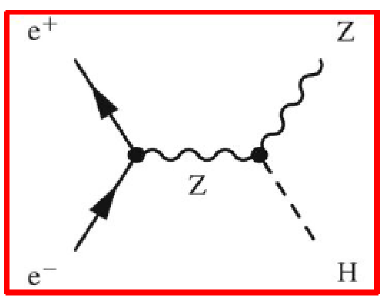
## FCC-ee offers broad potential for precision Higgs measurements

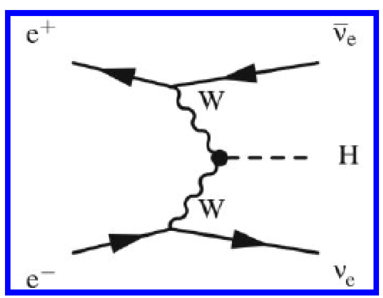
- Higgs factory: production of **2M Higgs** bosons
- Clean environment
- Relative small backgrounds, **large S/B**

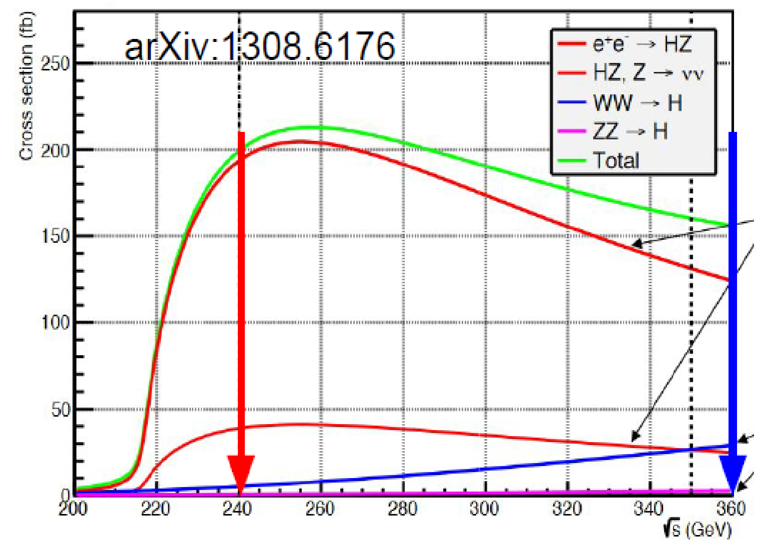
| Total Higgs production @ FCC-ee (baseline – 4 IP) | | |
|---|---|---|
| Threshold | ZH production | VBF production |
| **240 GeV / 10.8 ab$^{-1}$** | 2.2 M | 67 k |
| **365 GeV / 3 ab$^{-1}$** | 330 k | 80 k |

**Main production mechanisms**

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



# Higgs Physics at the ZH threshold

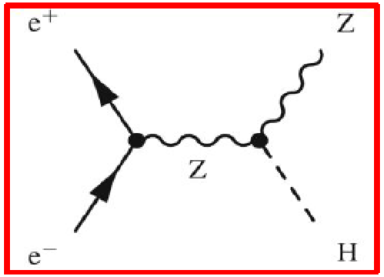
**Highest precision obtained from ZH analyses @ 240 GeV**

**Main strategy of such analyses based on recoil method**

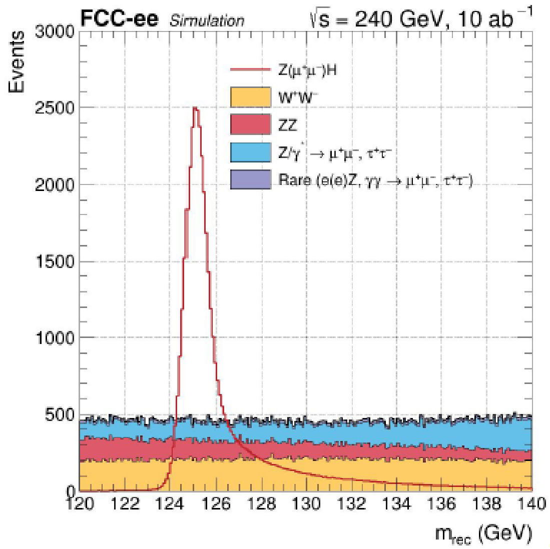
- Tag the Z boson (tight invariant mass constraints) using leptons or jets
- Compute **recoil**, distribution sharp peaked at Higgs mass, **width dominated by detector resolution**

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

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




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




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

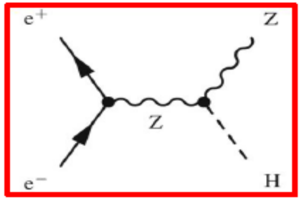
**Challenges for the Higgs programme**

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

# 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




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

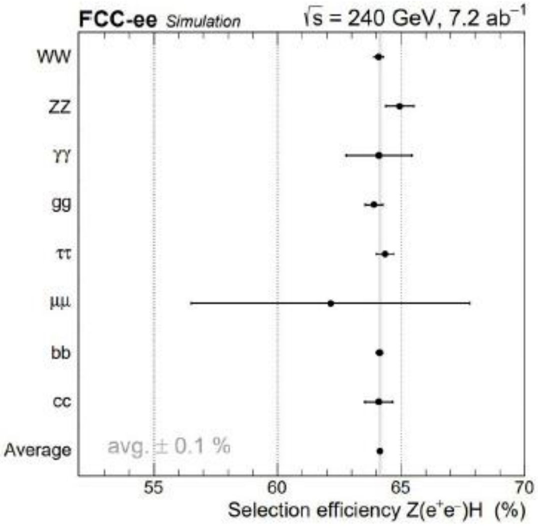
absolute HZZ coupling meas.

**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

# Event Selection

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)

- **Events basic selection:**

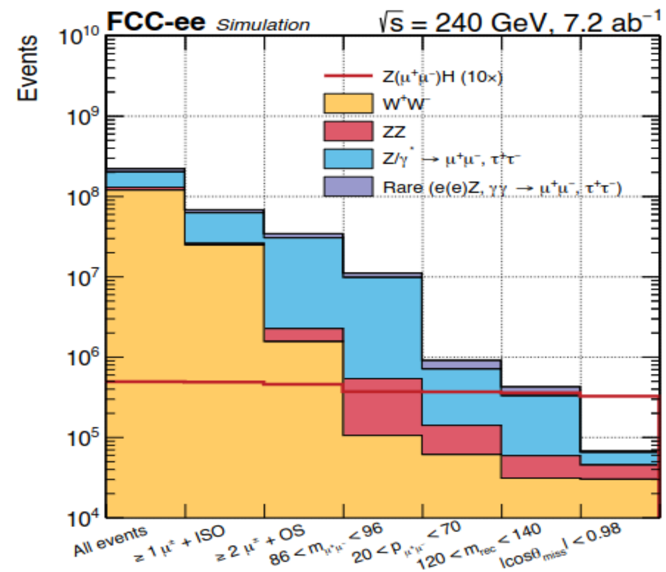
Preselection: Select at least 2 leptons:

- Opposite sign
- One lepton required to be isolated

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

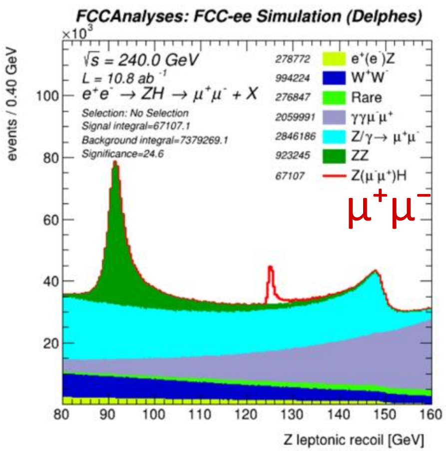
$p_{l^+l^-} \in [20, 70]$ GeV ( > 20 GeV at 365 GeV)

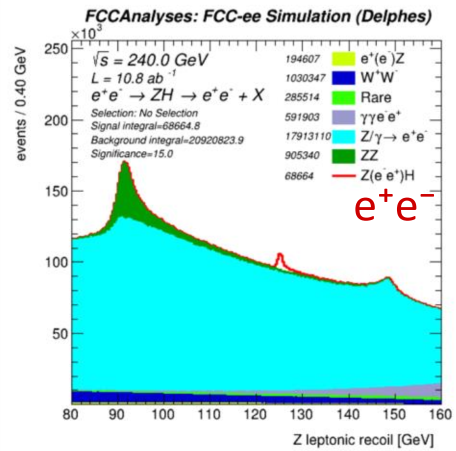
$m_{recoil} \in [120, 140]$ GeV



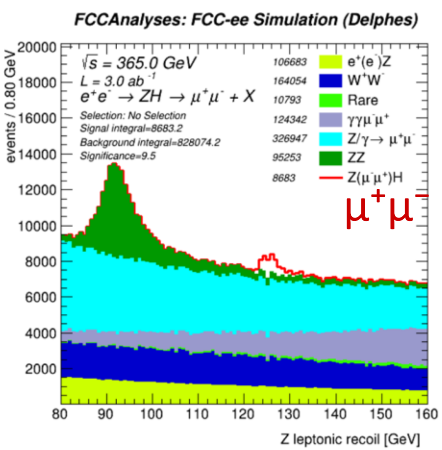
# Comparison 240/365 GeV with Preselection Cuts (zoom)

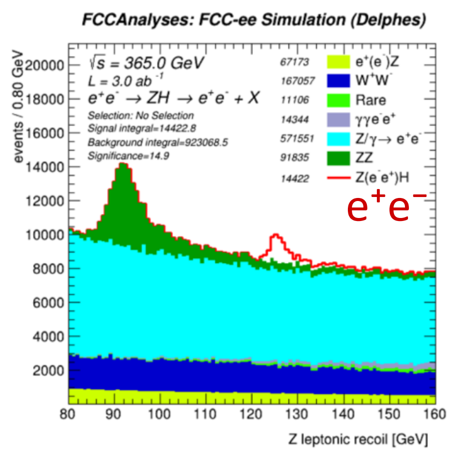
**240 GeV** ⇒




**365 GeV** ⇒




➢ **Zoom between 80 and 160 GeV**

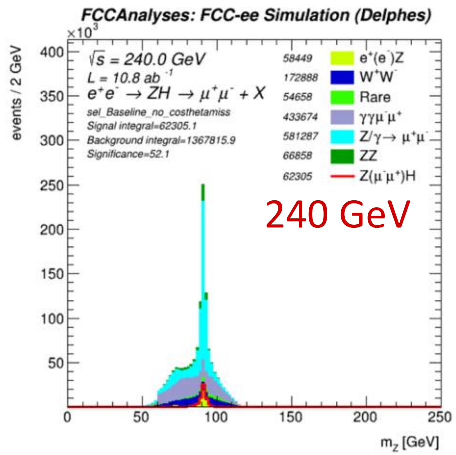
- Luminosity is **10.8** $ab^{-1}$ at √s=**240 GeV**
  **3.0** $ab^{-1}$ at √s=**365 GeV**

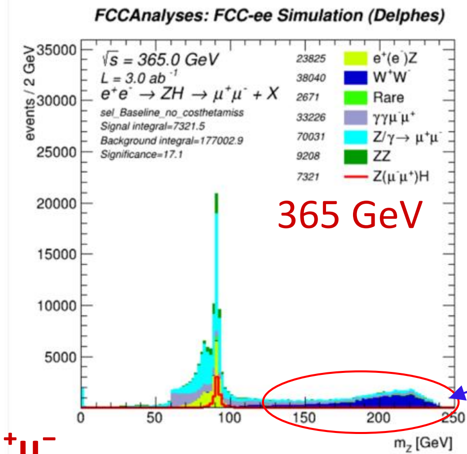
- **Different shapes** of the background before selection cuts

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

# Invariant Mass and Recoil Mass distributions

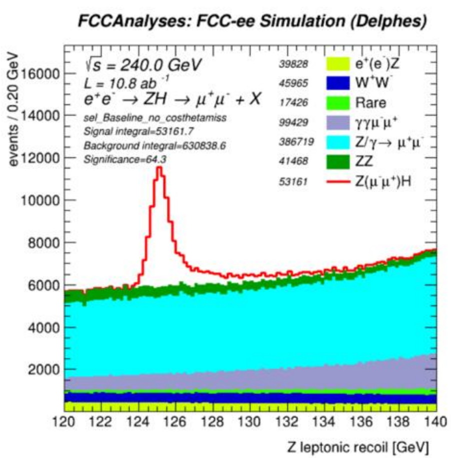
**Invariant Mass Distribution ⇒**

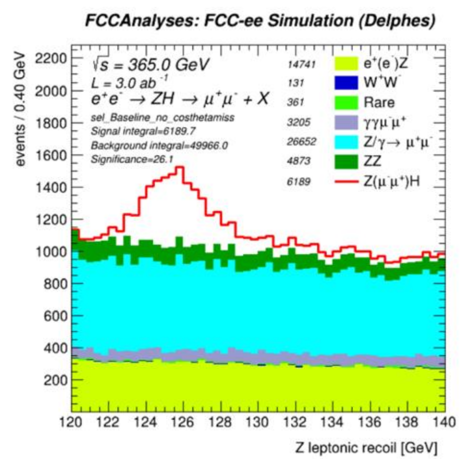



$\mu^+\mu^-$

**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

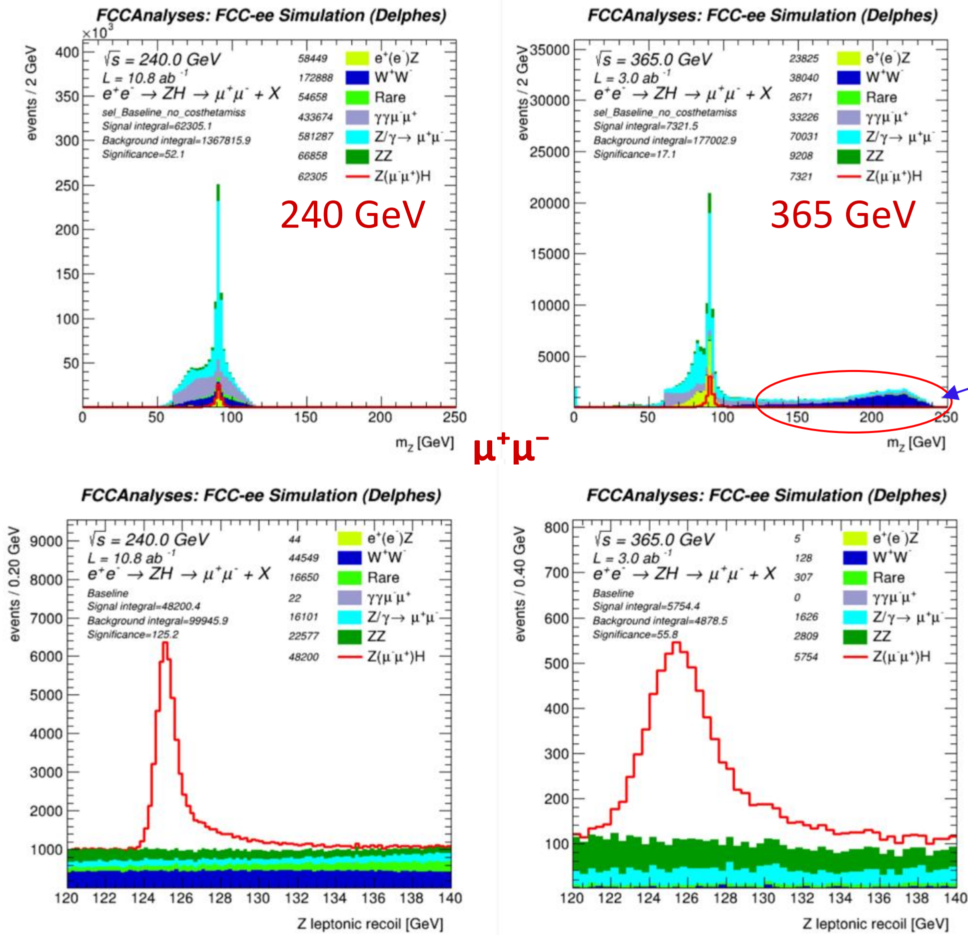
**S/B still needs to be improved to gain precision**

- 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 ⇒**




- **Basic event selection:**

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

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- **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

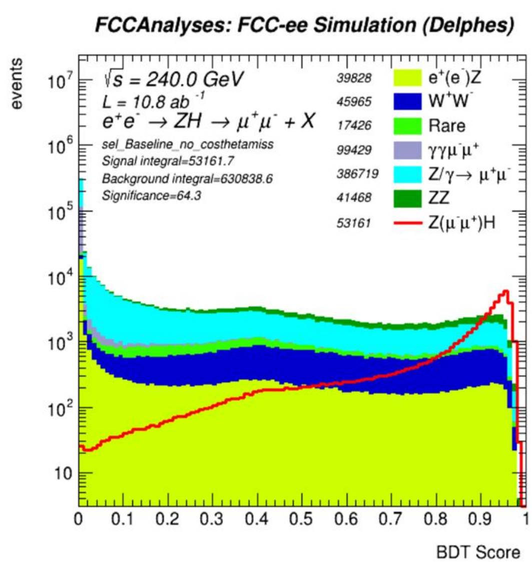
**With Cos theta$_{miss}$ cut for Higgs mass analysis, Background strongly reduced**

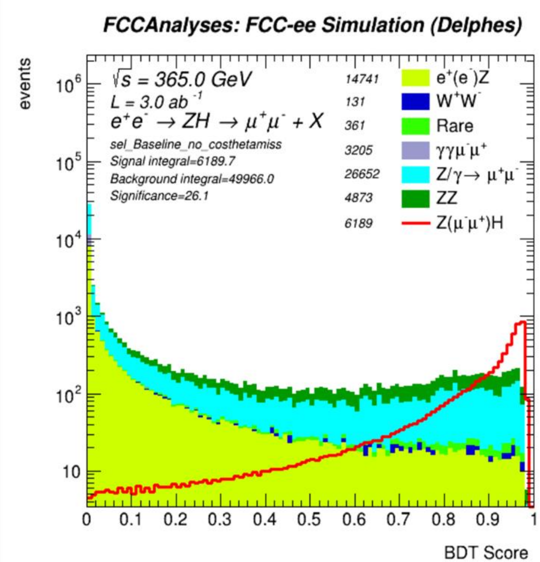
# Boosted Decision Tree used for $\sigma_{ZH}$ analysis

- 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**



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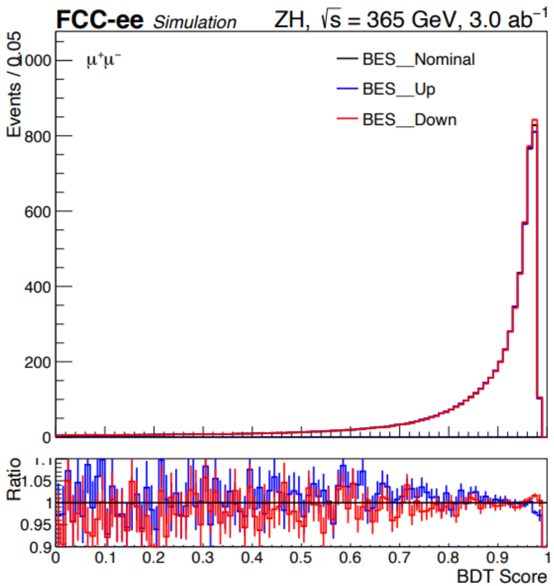
# Systematic uncertainties for ZH cross section measurement




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

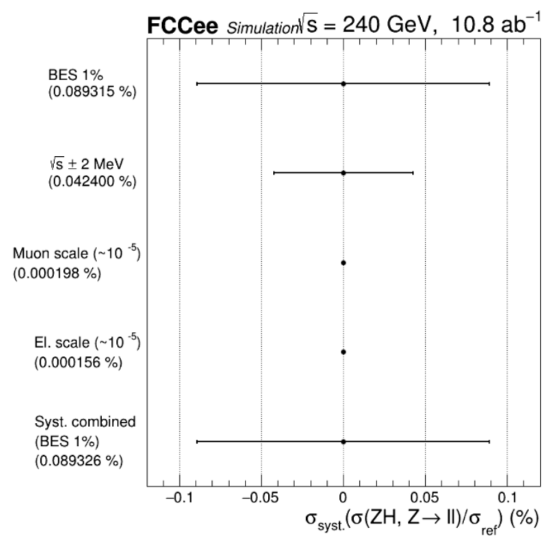
  At a center-of-mass energy of 240 (365) GeV, the beam energy spread (BES) is ±0.185% (±0.221%) per beam, i.e. ±222 (±403) MeV.

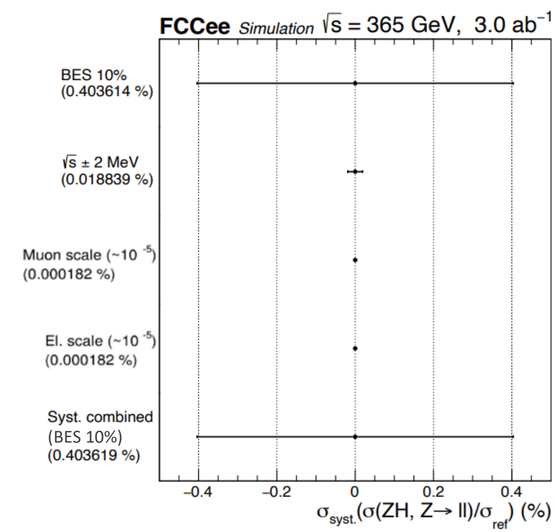
  Uncertainty assumed on the BES value is **~1%** at 240 GeV and **~10%** at 365 GeV ➔Dominant systematic for ZH cross section measurement

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

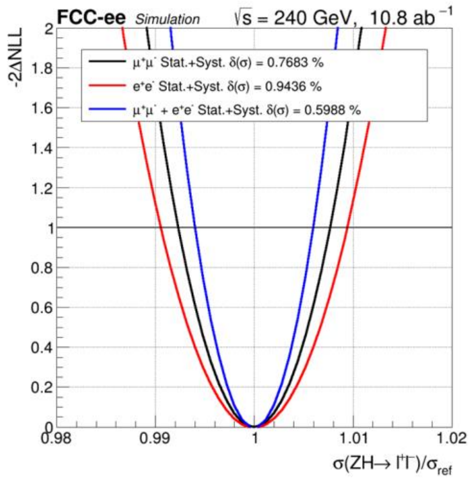
- ➢ **Centre-of-mass (√s)**: Uncertainty on the centre-of-mass energy which is expected to be known at the **~2 MeV** level for 240 and 365 GeV

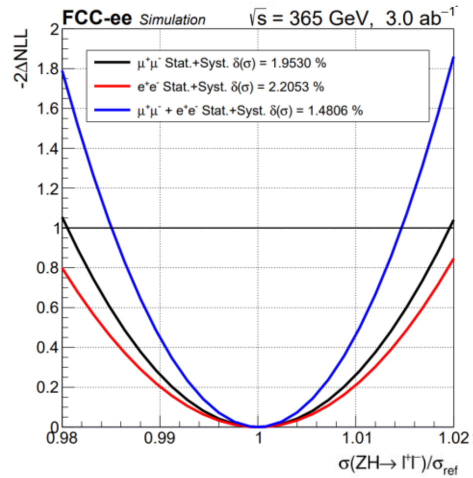
- ➢ **Lepton momentum scale**: Uncertainty from the momentum of leptons assumed to be known at **$10^{-5}$** precision level both for 240 and 365 GeV

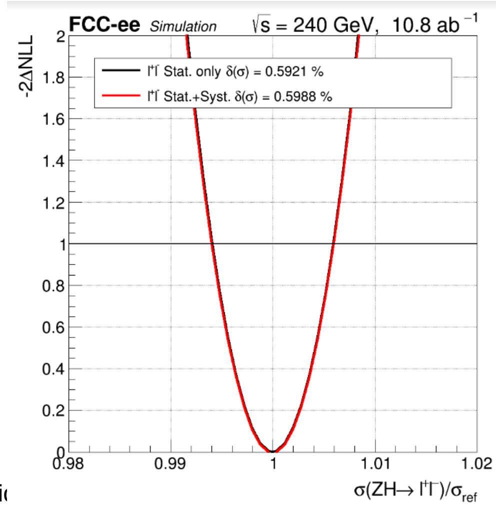


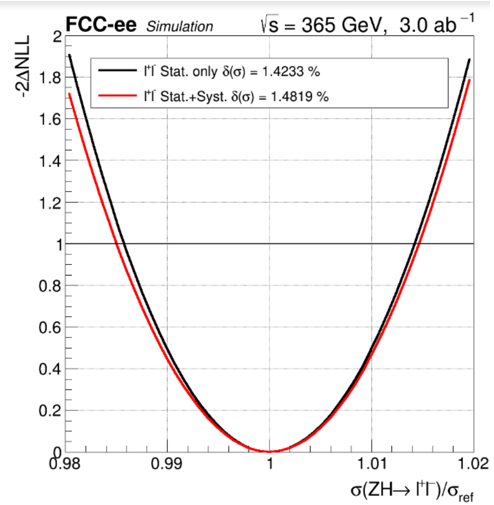



# ZH cross-section measurements ($\mu^+\mu^-$, $e^+e^-$ and combined) at $\sqrt{s}$=240 & 365 GeV



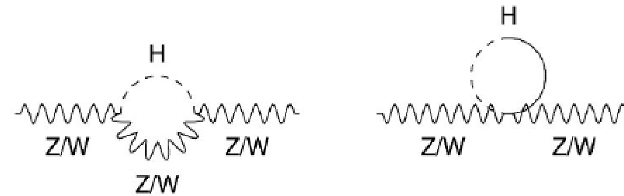

- By fitting the BDT output we obtain the cross-section, with its **statistical** and **stat+systematics** uncertainties.
- 1.42% Statistical uncertainty at $\sqrt{s}$=**365 GeV** compared to 0.59% at $\sqrt{s}$=**240 GeV**
- 1.48% Stat+Syst uncertainties at $\sqrt{s}$=**365 GeV** compared to 0.60% at $\sqrt{s}$=**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.**

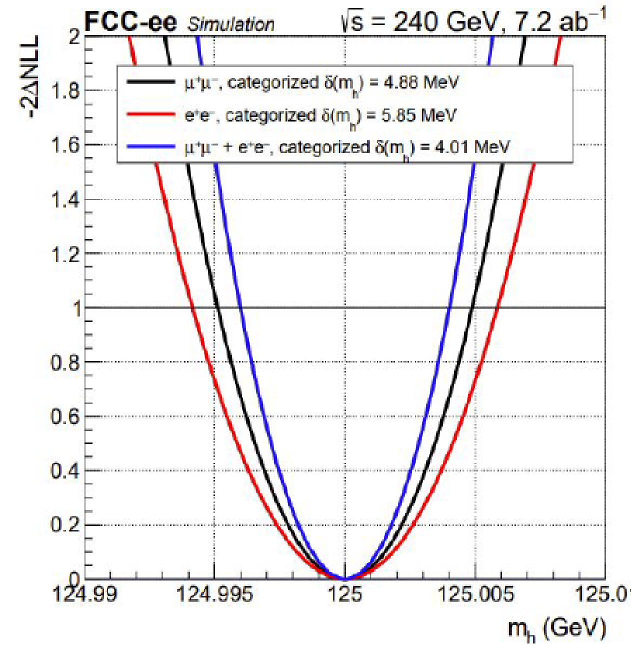
$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

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

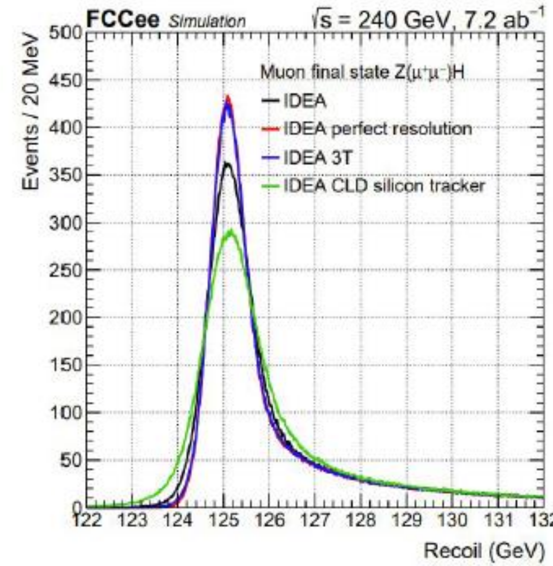
## Higgs mass extracted from fitting recoil distribution

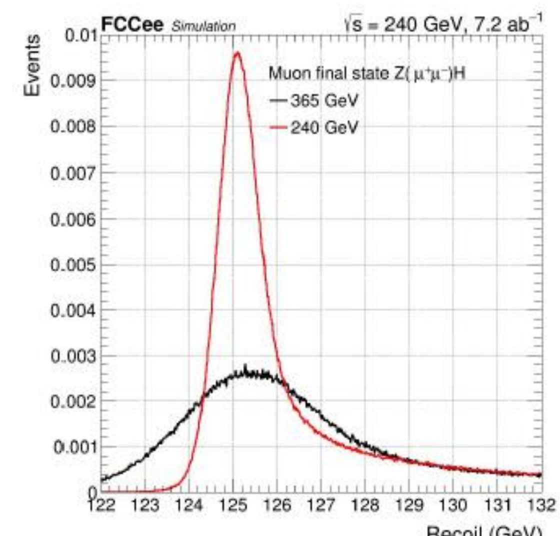
$$M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

- 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) |



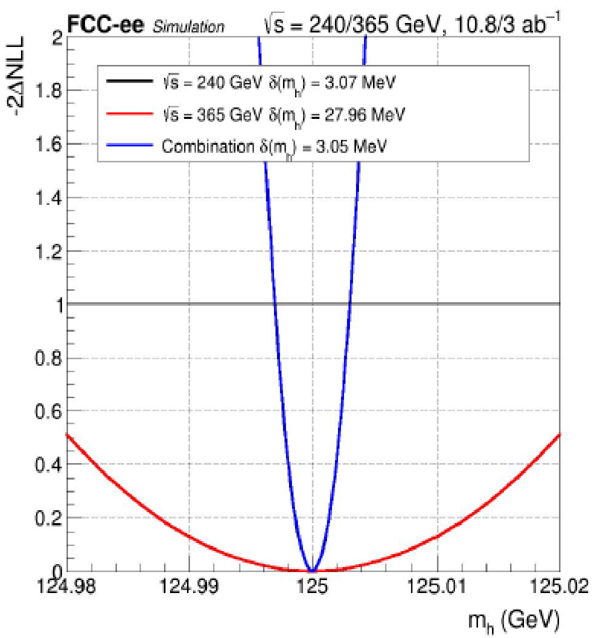
# Higgs Mass Results and Systematics at 240 and 365 GeV

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

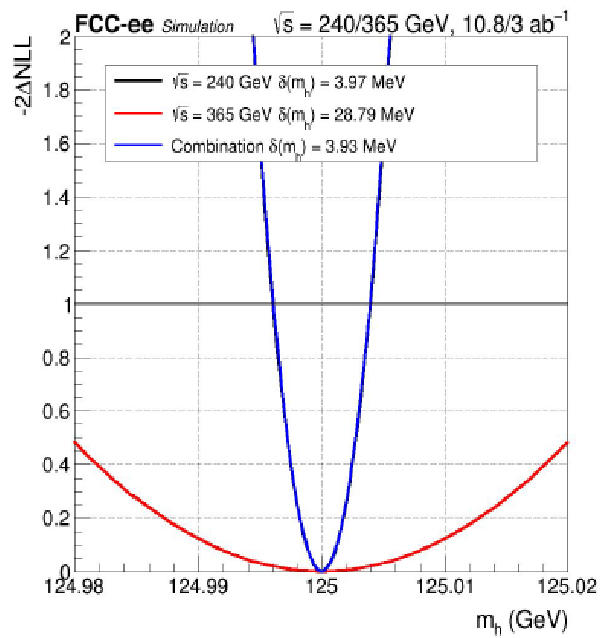
- **Current combined uncertainty: 3.05(3.93) MeV**
- Systematics contribute ~2.5 MeV, ecm uncertainty dominant
- Improvement by adding 365 GeV ~ 1%

**Systematics:**

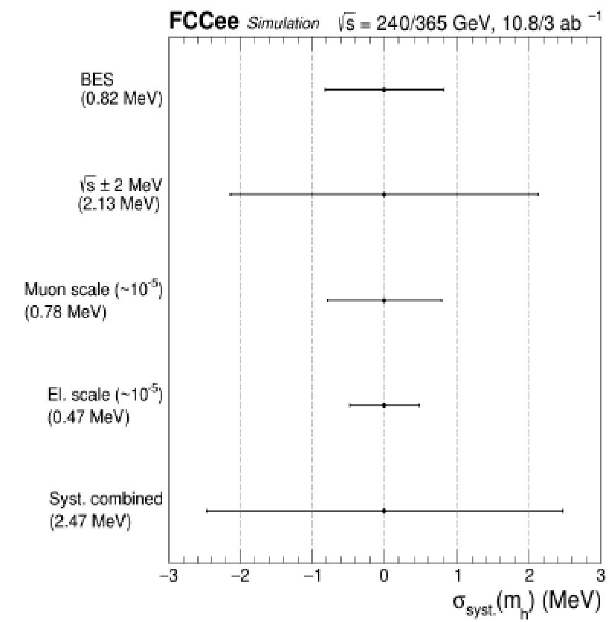
For the Higgs mass, the systematic uncertainty is dominated by the uncertainty on the c.o.m energy




**Stat. Only**




**Stat.+Syst.**



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# Higgs Mass Sensitivities → experimental constraints

**at 240 GeV, 10.8 ab-1**

| 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) |

**Nominal configuration** → Nominal

**Crystal ECAL to Dual Readout** → Degradation electron resolution

**Nominal 2 T → field 3 T** → Magnetic field 3T

**IDEA drift chamber → CLD Si tracker** → Silicon tracker

**Impact of Beam Energy Spread** → BES 6% uncertainty / Disable BES

**Perfect (=gen-level) momentum resolution** → Ideal resolution

- 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

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# 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.

- $\sigma_{ZH}$ 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