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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for the

FCC collaboration

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

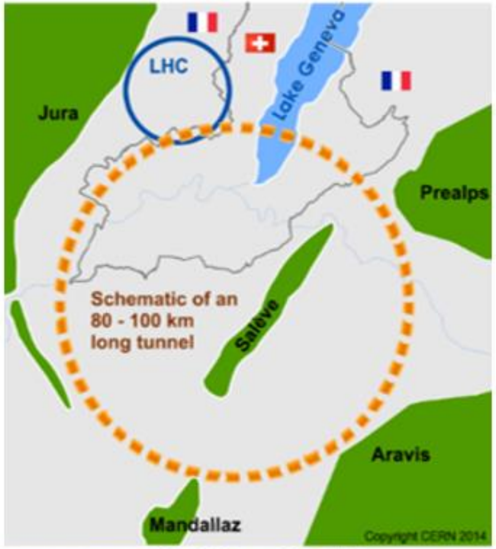
Comprehensive cost-effective program maximizing physics opportunities

- 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

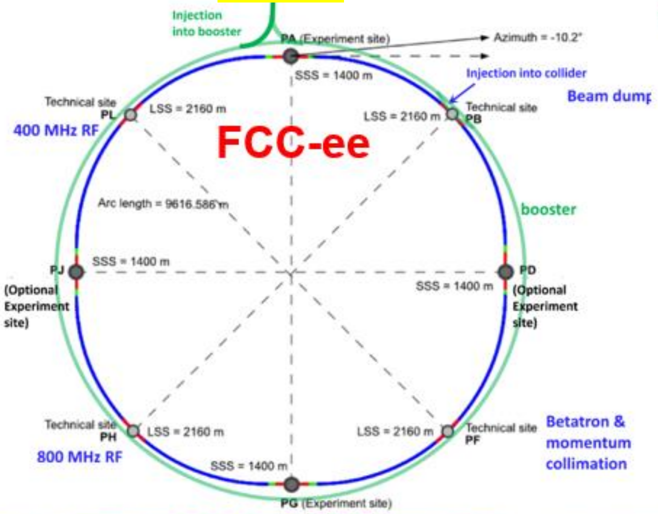
Complementary physics

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

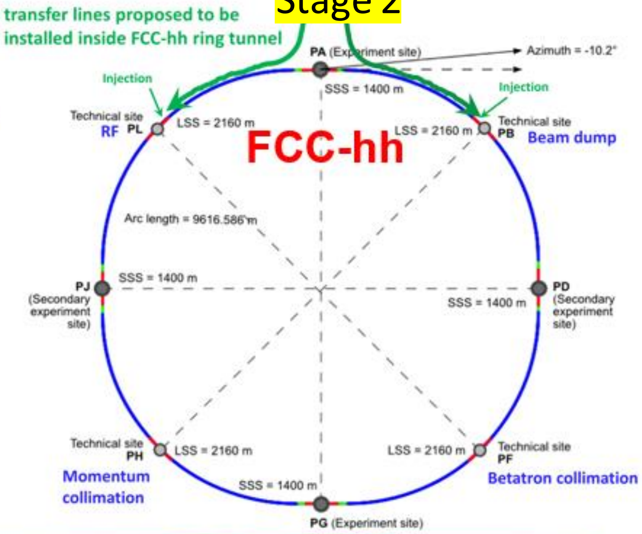
The FCC project is fully integrated with HL-LHC exploitation and provides a natural transition for higher precision and energy



Stage 1



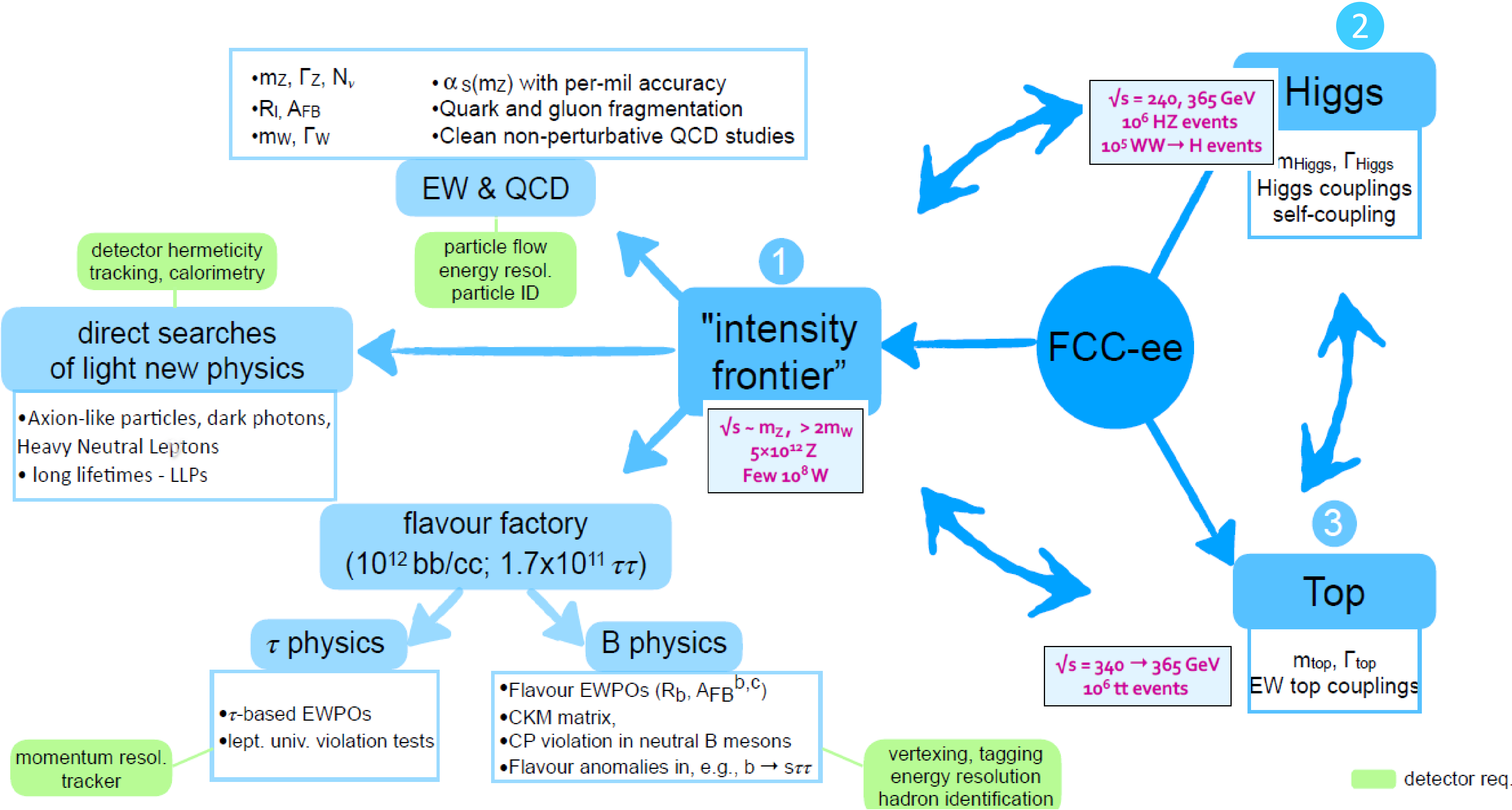
Stage 2



2020 - 2040 | 2045 - 2060 | 2065 - 2090

FCC

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



- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W

- $\alpha_s(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

EW & QCD

particle flow
energy resol.
particle ID

detector hermeticity
tracking, calorimetry

direct searches of light new physics

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

①

"intensity frontier"

$\sqrt{s} \sim m_Z$, $> 2m_W$
5×10^{12} Z
Few 10^8 W

FCC-ee

②

Higgs

$\sqrt{s}$ = 240, 365 GeV
10^6 HZ events
10^5 WW → H events

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

③

Top

$\sqrt{s}$ = 340 → 365 GeV
10^6 $t\bar{t}$ events

m_{top}, Γ_{top}
EW top couplings

flavour factory
(10^{12} bb/cc; 1.7×10^{11} $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

momentum resol.
tracker

B physics

- Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \to s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

🟩 detector req.

Higgs Physics at FCC-ee

FCC-ee offers broad potential for precision Higgs measurements

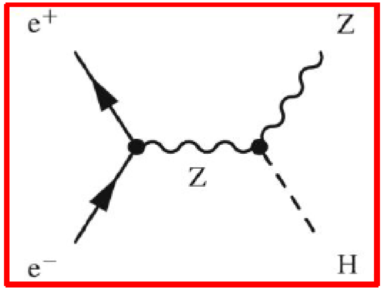
- Higgs factory: production of **2M Higgs** bosons
- Clean environment
- Relative small backgrounds, **large S/B**

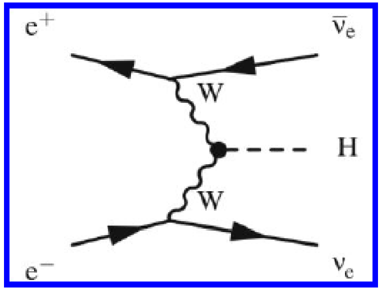
Total Higgs production @ FCC-ee (baseline – 4 IP)

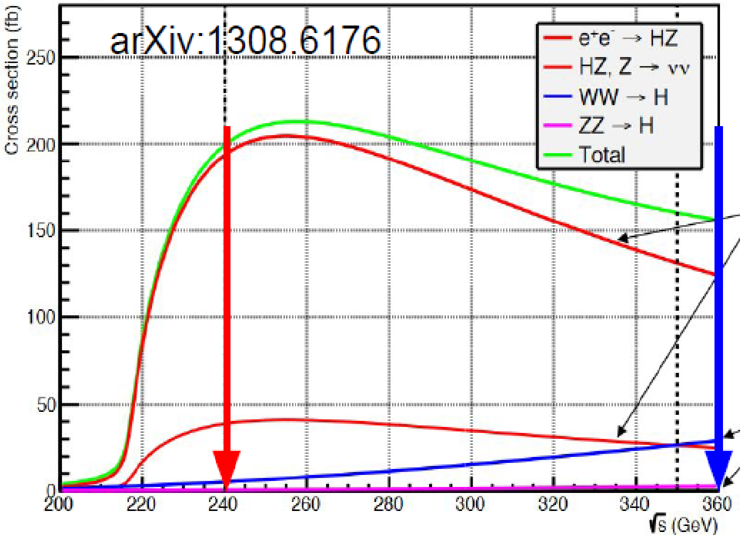
Threshold	ZH production	VBF production
240 GeV / 10.8 ab^{-1}	2.2 M	67 k
365 GeV / 3 ab^{-1}	330 k	80 k

Main production mechanisms

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







Higgs Physics at the ZH threshold

FUTURE CIRCULAR COLLIDER

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**

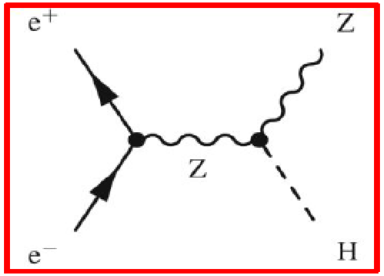
$$m^2_{recoil} = (\sqrt{s} - E_{ff})^2 - p^2_{ff}$$
$$= s + m^2_Z - 2E_{ff}\sqrt{s} \quad \approx m^2_H$$

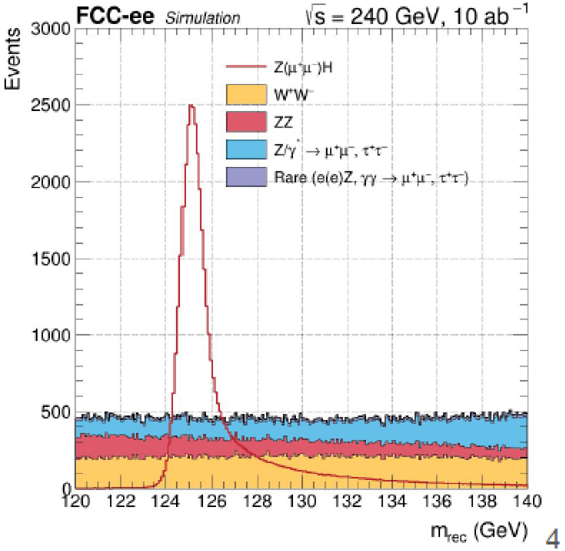
- tag additional decays of the Higgs – challenging in multijet environment

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)



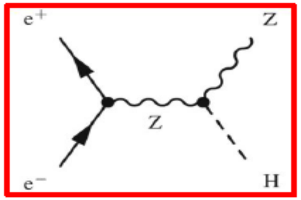


$m_{recoil} \in [120, 140]$ GeV

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



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

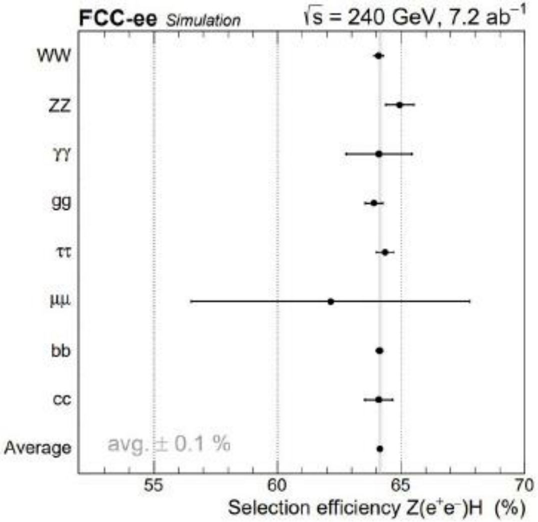
absolute HZZ coupling meas.

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:**

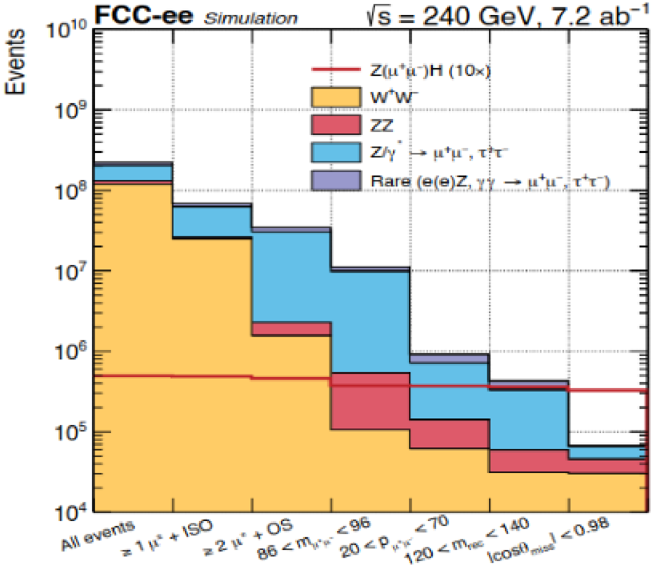
Preselection: Select at least 2 leptons:

- Opposite sign
- One lepton required to be isolated

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

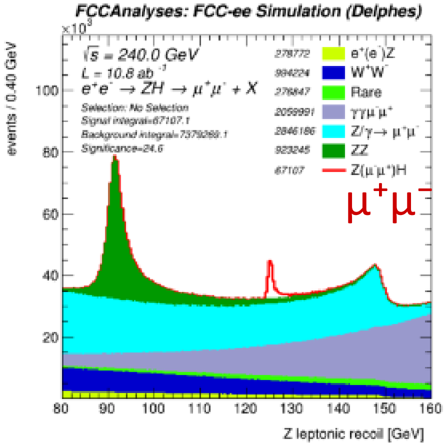
$p_{l^+l^-} \in [20, 70]$ GeV (> 20 GeV at 365 GeV)

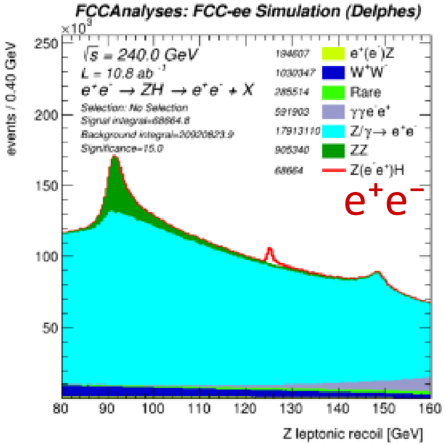
$m_{recoil} \in [120, 140]$ GeV



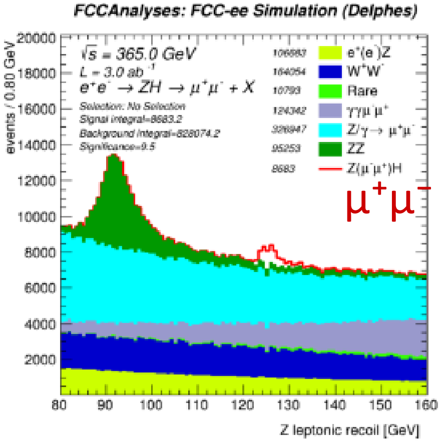
Comparison 240/365 GeV with Preselection Cuts (zoom)

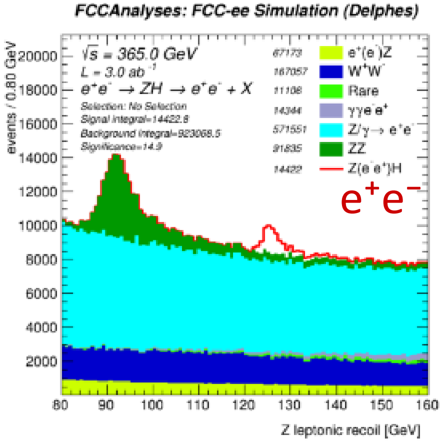
240 GeV ⇒





365 GeV ⇒





➢ **Zoom between 80 and 160 GeV**

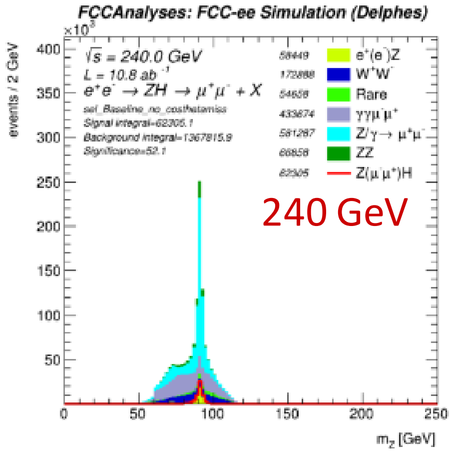
- Luminosity is **10.8** ab^{-1} at √s=**240 GeV**
  3.0 ab^{-1} at √s=**365 GeV**

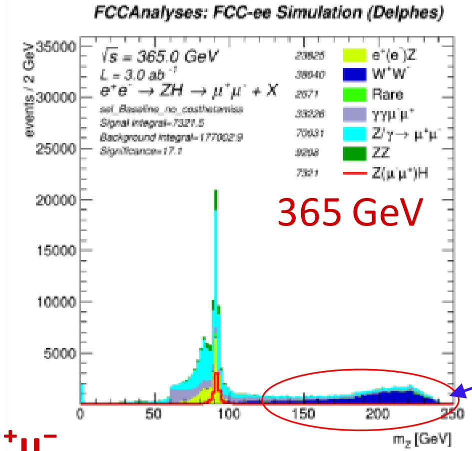
- **Different shapes** of the background before selection cuts

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

Invariant Mass and Recoil Mass distributions

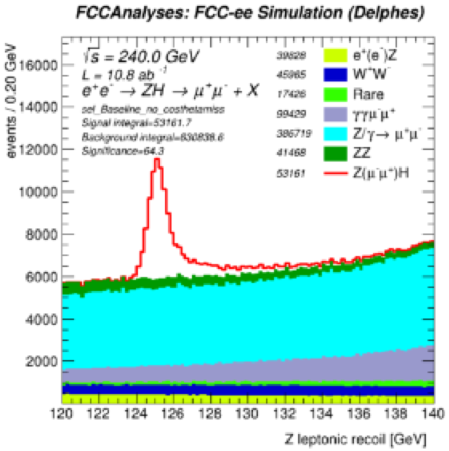
Invariant Mass Distribution ⇒

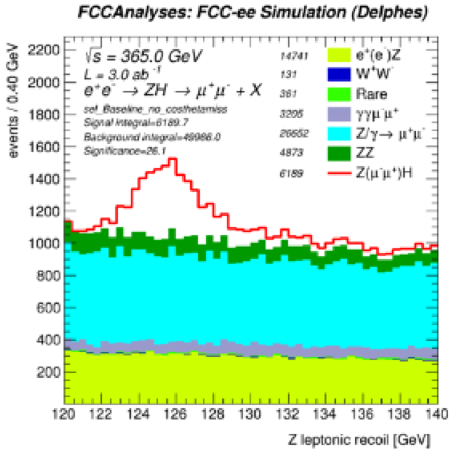




$\mu^+\mu^-$

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**

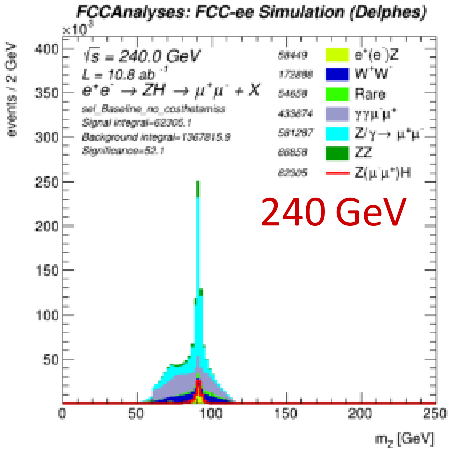
➢ Resolution **~2.3** times wider at √s=365 GeV

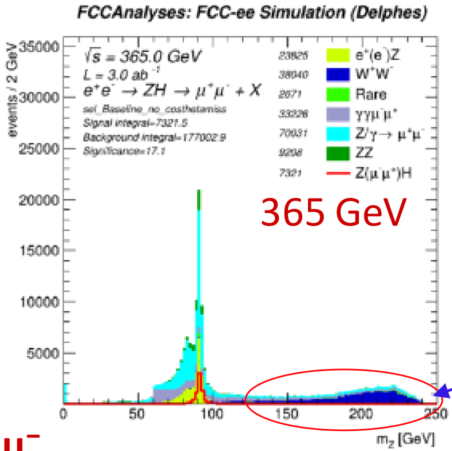
S/B still needs to be improved to gain precision

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

Invariant Mass and Recoil Mass distributions

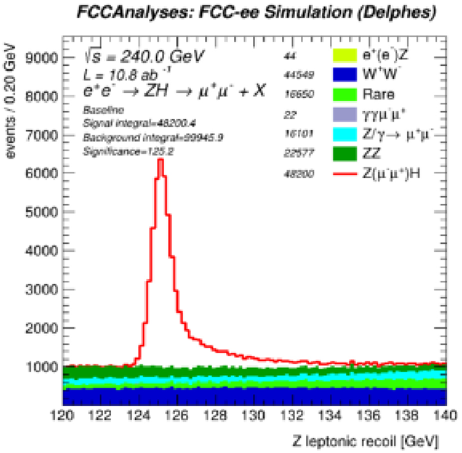
Invariant Mass Distribution ⇒

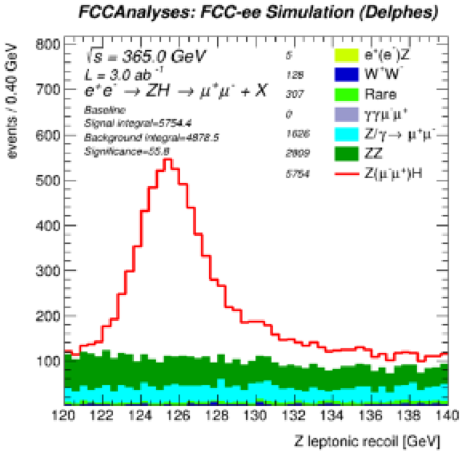




$\mu^+\mu^-$

Recoil Mass Distribution ⇒





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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**

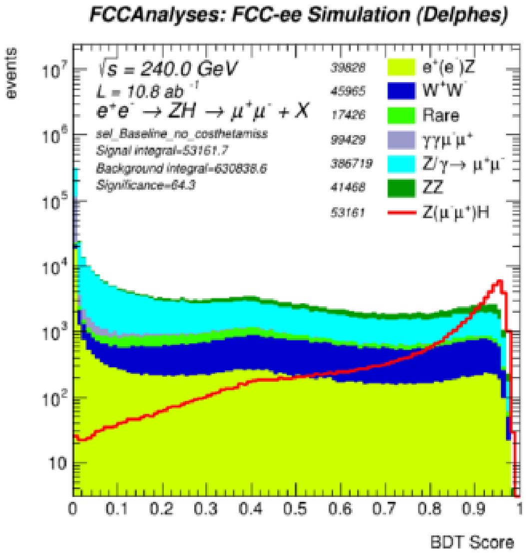
- Resolution **~2.3** times wider at √s=365 GeV

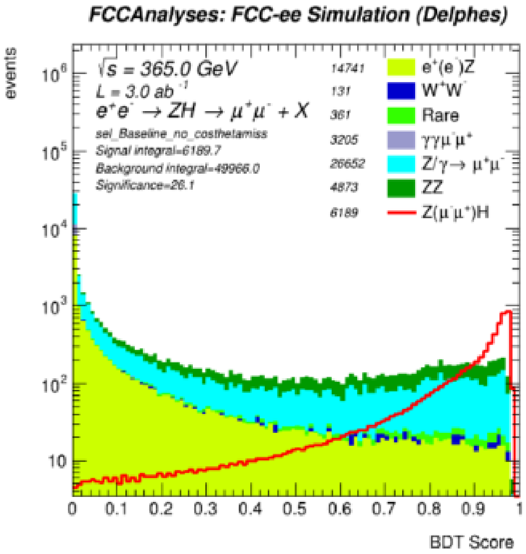
With Cos theta$_{\text{miss}}$ cut for Higgs mass analysis, Background strongly reduced

Boosted Decision Tree used for σ_{ZH} analysis

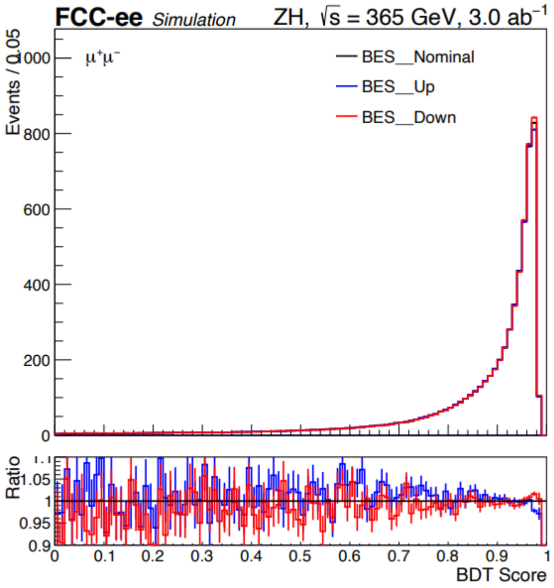
- Use of a Machine learning algorithm to **separate signal** from **background**, a Boosted Decision Tree (BDT)
- The BDT, using only variables from the leptons of the Z, allows for a **model independent** analysis
- **BDT Score comparison** between 365 and 240 GeV
- This **BDT score** is **fitted** to measure the **ZH cross-section value**
- 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





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

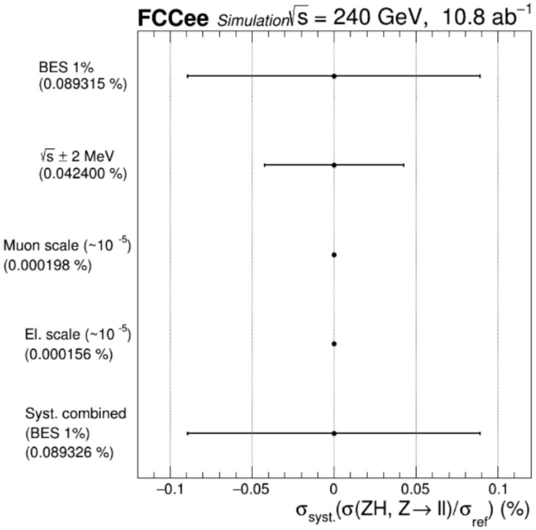
- **Lepton momentum scale**: Uncertainty from the momentum of leptons assumed to be known at **10^{-5}** precision level both for 240 and 365 GeV

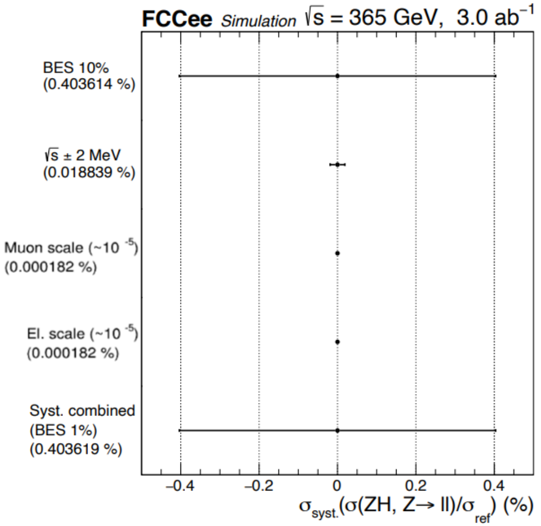
- **Beam energy spread, depends on the beam energy.**

  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.

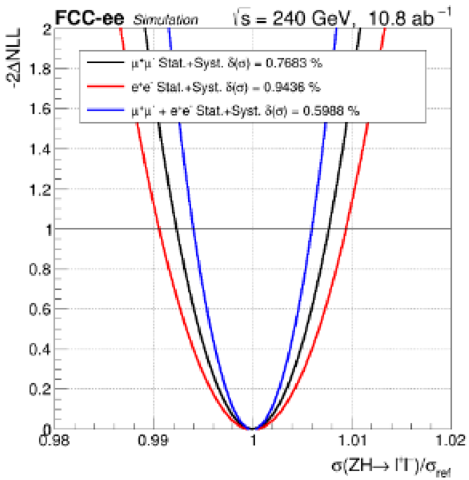
  Uncertainty assumed on the BES value is **~1%** at 240 GeV and **~10%** at 365 GeV ➔Dominant systematic for ZH cross section measurement

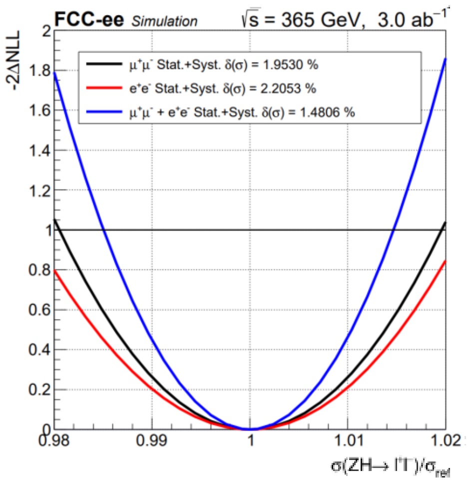
- **ISR uncertainty** is not estimated precisely yet, but expected to be smaller

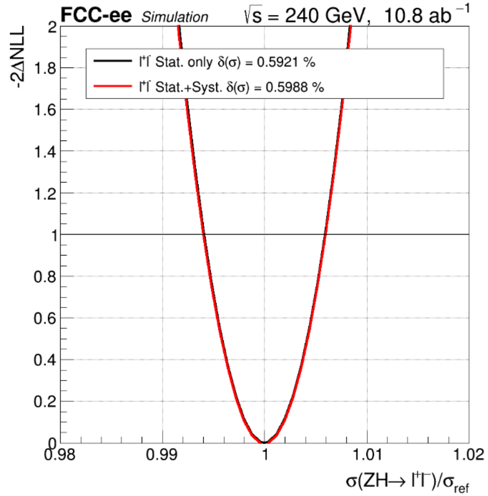


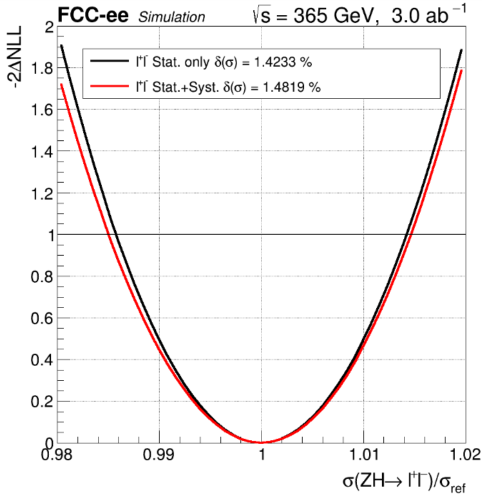


ZH cross-section measurements (μ⁺μ⁻, e⁺e⁻ and combined) at √s=240 & 365 GeV





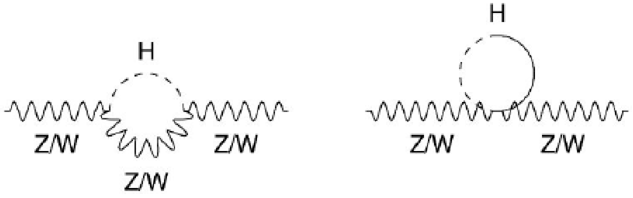




- By fitting the BDT output we obtain the cross-section, with its **statistical** and **stat+systematics** uncertainties.
- **1.42%** Statistical uncertainty at √s=**365 GeV** compared to **0.59%** at √s=**240 GeV**
- **1.48%** Stat+Syst uncertainties at √s=**365 GeV** compared to **0.60%** at √s=**240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

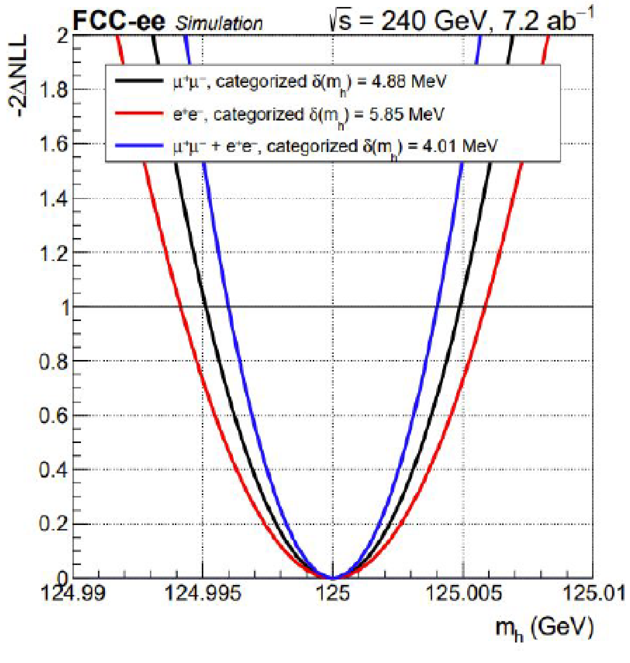


$$\sin^2\theta_W = \left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

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

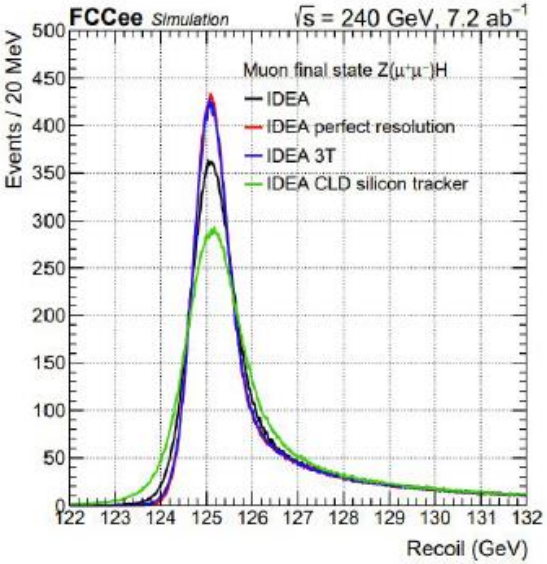
Higgs mass extracted from fitting recoil distribution

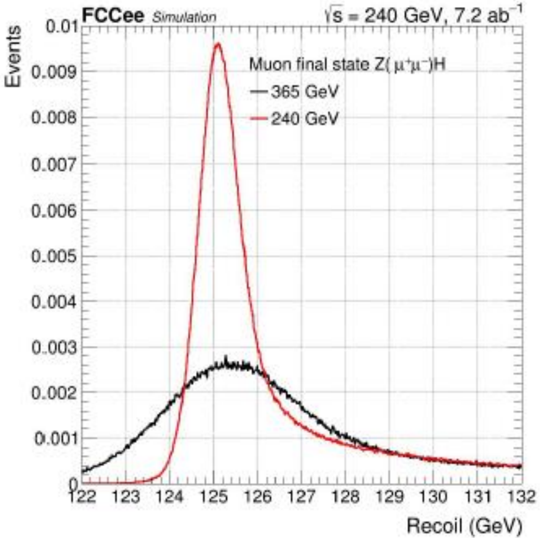
$$M^2_{recoil} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

- 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)





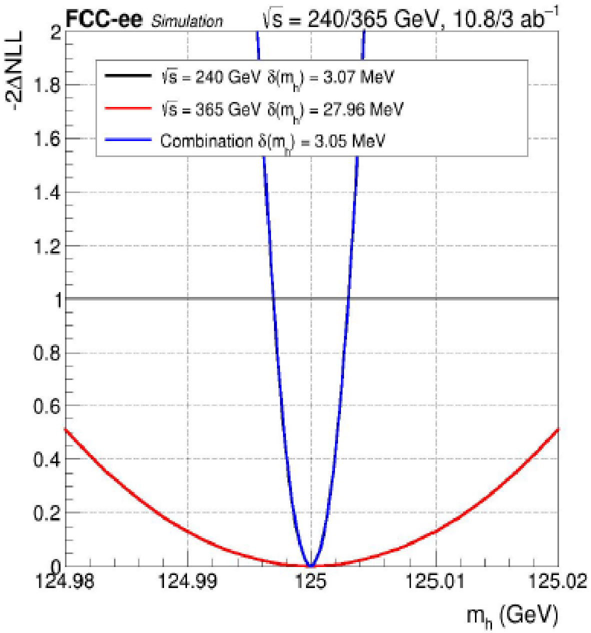
Higgs Mass Results and Systematics at 240 and 365 GeV

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

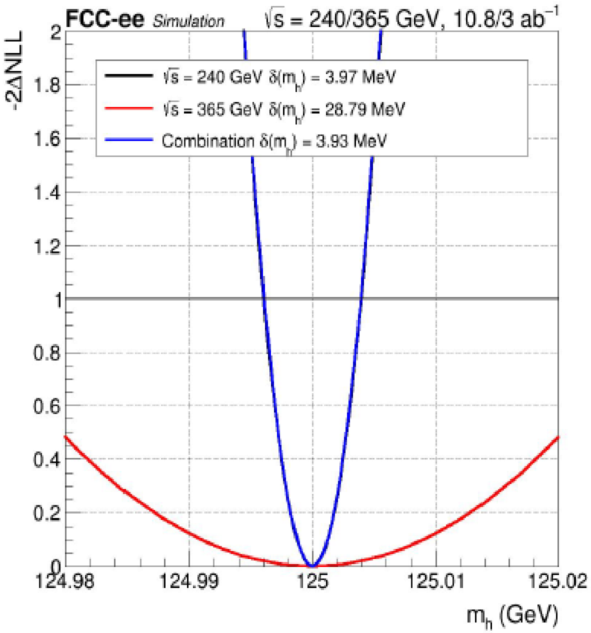
- **Current combined uncertainty: 3.05(3.93) MeV**
- Systematics contribute ~2.5 MeV, ecm uncertainty dominant
- Improvement by adding 365 GeV ~ 1%

Systematics:

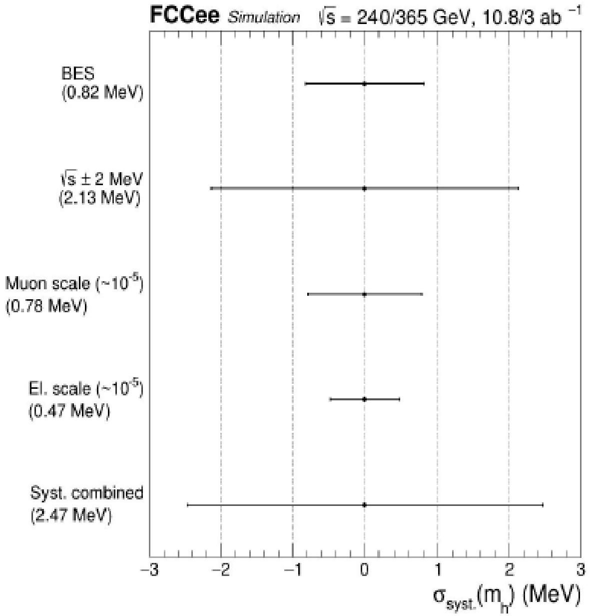
For the Higgs mass, the systematic uncertainty is dominated by the uncertainty on the c.o.m energy



Stat. Only



Stat.+Syst.



Higgs Mass Sensitivities ➔ experimental constraints

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, new for ICHEP, also 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

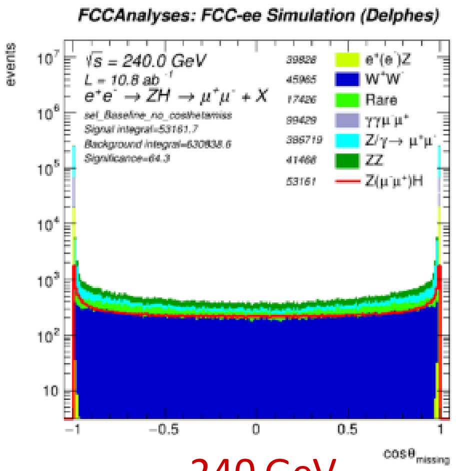
- Systematics and detector constraints have been studied and presented, and will help to determine the best detector configurations for FCC-ee in the FCC feasibility study

FCC-ee Parameters

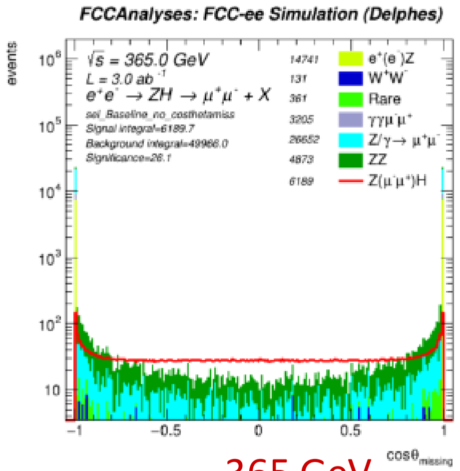
FCC-ee parameters	**unit**	**Z**	**WW**	**ZH**	**ttbar**
√s	GeV	88 - 94	157.2 - 162.5	240	350-365
Inst. Lumi / IP	10^{34} cm^{2} s^{-1}	182	19.4	7.3	1.33
Integrated lumi / 4IP	ab^{-1} / yr	87	9.3	3.5	0.65
N bunches/beam	-	10 000	880	248	36
bunch spacing	ns	30	340	1 200	8 400
L*	m	2.2	2.2	2.2	2.2
crossing angle	mrad	30	30	30	30
vertex size (x)	µm	5.96	14.7	9.87	27.3
vertex size (y)	nm	23.8	46.5	25.4	48.8
vertex size (z)	mm	0.4	0.97	0.65	1.33
vertex size (t)	ps	36.3	18.9	14.1	6.5
Beam energy spread	%	0.132	0.154	0.185	0.221

Comparison 240/365 GeV after Selection Cuts

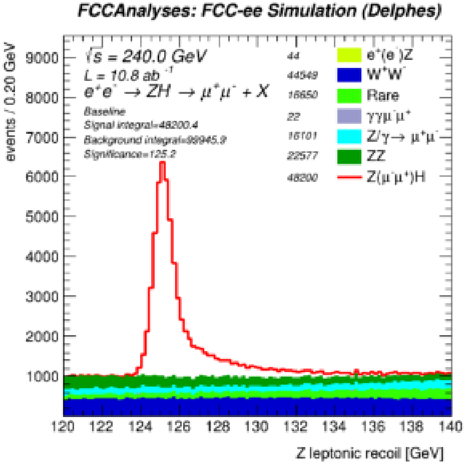
Cos θ_{missing} Distribution
⇒

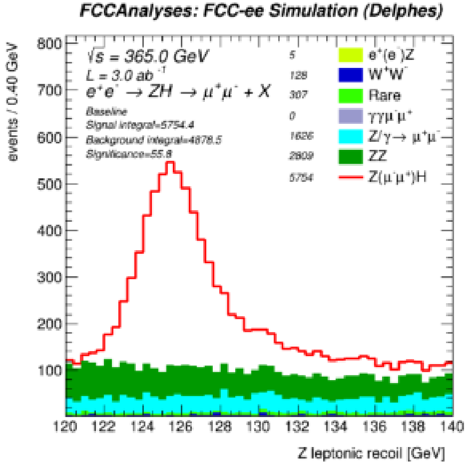


240 GeV



365 GeV





Recoil Mass Distribution
⇒

- The requirement $|\cos\theta_{\text{missing}}| < 0.98$ is used for the **mass analysis only**
- **Θ_{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