Toward a Measurement of the Higgs Boson Mass with Natural-Width Precision at future e^+e^- colliders

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The 2026 International Workshop on the High Energy Circular Electron Positron Collider Oct 21–26, 2026

FUTURE CIRCULAR COLLIDER

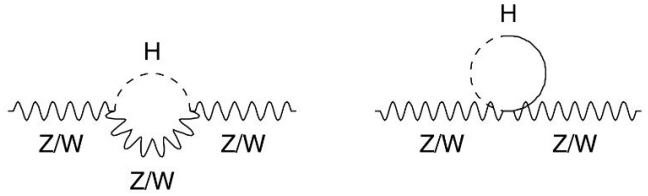
CERN

Higgs mass: context and requirements

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?

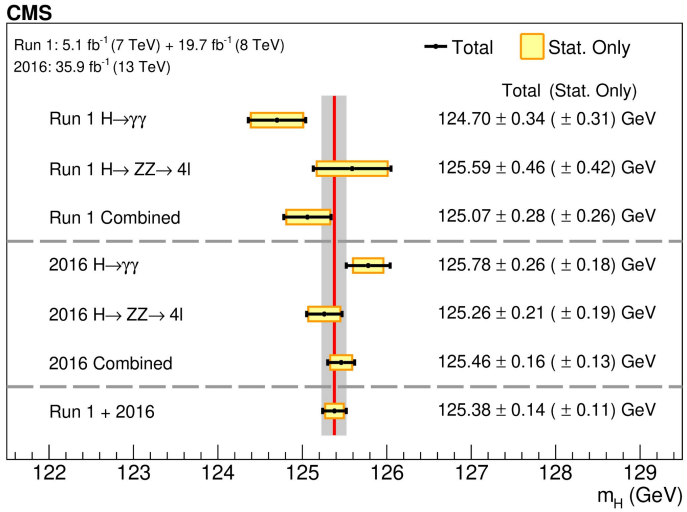


Higgs mass at LHC and HL-LHC

- Current Higgs mass precision ~ 150 MeV
- HL-LHC precision brings this down to 20 MeV (ultimate achievable with Phase-II detectors)
- Sufficient precision to control the radiative corrections

Needs for the future

- Very high precision on cross-section, 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
- For ee→H at √s 125 GeV, need to know the Higgs mass < Higgs width ~ 4.1 MeV



→ Explore the ultimate Higgs mass measurement; challenging measurement at FCC-ee with stringent requirements on the detector and machine parameters

Today's focus on FCC-ee, but methods and detector requirements similar for other electron-positron colliders

Higgs Physics at FCC-ee

FCC-ee offers broad potential for precision Higgs measurements

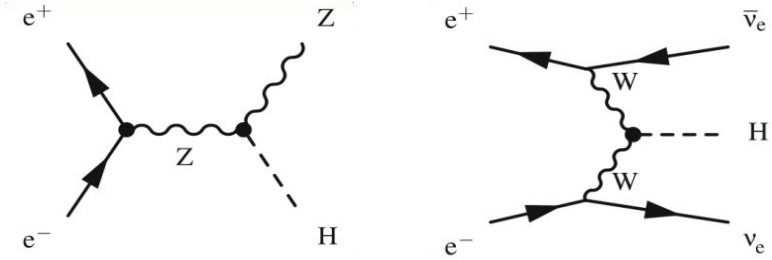
- Higgs factory: production of million Higgs bosons
- Clean environment
- Relative small backgrounds, high S/B

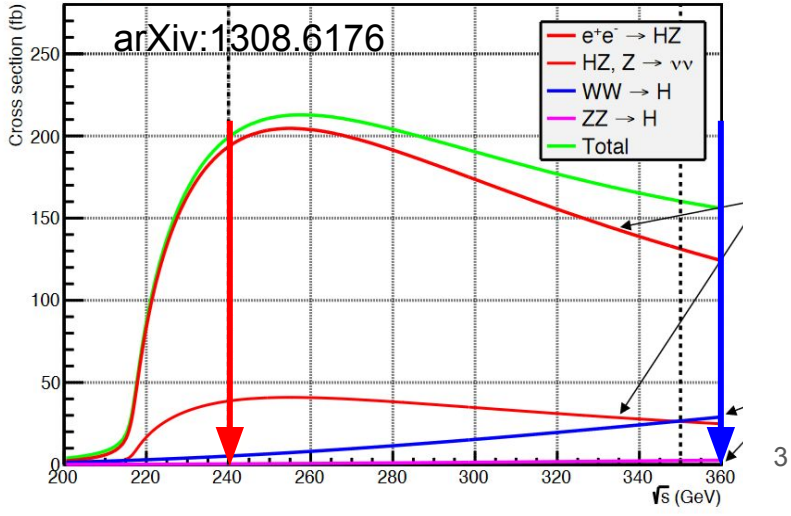
Main production mechanisms

- **ZH production** "Higgs–strahlung" – also used for light scalar Higgs at the Z-pole
- **Vector boson fusion** (VBF), WW dominant

Higgs production @ FCC-ee (baseline)		
Threshold	ZH production	VBF production
240 GeV / 5 ab^{-1}	1e6	2.5e4
365 GeV / 1.5 ab^{-1}	2e5	5e4

FCC-ee Higgs performance: *exploit various production and decay channels and combination to establish the detector requirements that will match the systematic uncertainties with the statistical ones*





Strategy and challenges

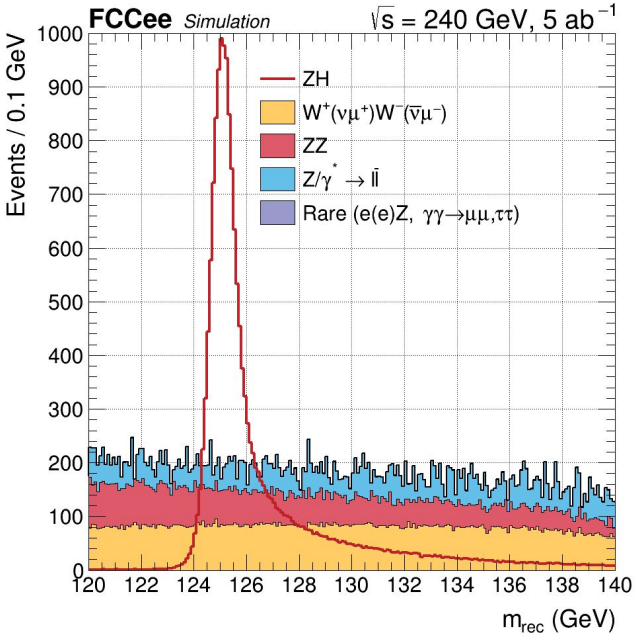
Highest precision obtained from ZH analyses @ 240 GeV

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

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

- Either fit and/or apply cuts on recoil distribution



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

Challenges for the Higgs programme

- Detector performance: resolution, tracking, vertexing, timing, angular
- Flavor tagging for Higgs couplings
- Jet reconstruction algorithms (inclusive vs. exclusive)

Case study: measuring m_H using the recoil mass method

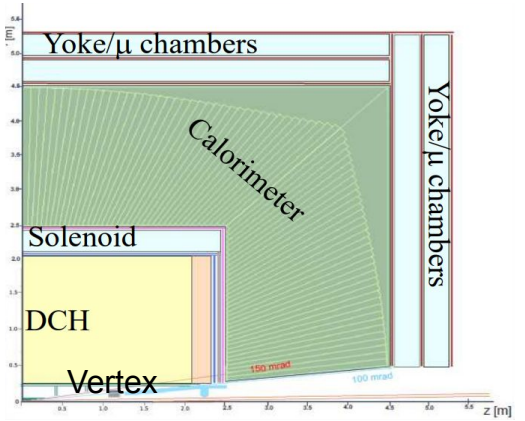
Detector and Monte-Carlo

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IDEA detector (optimized)

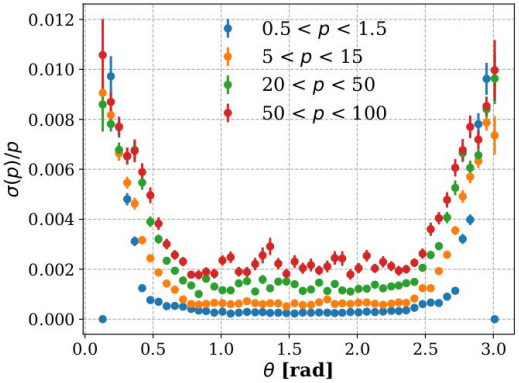
- Silicon pixel vertex detector + drift chamber → excellent muon resolution ~ 0.15%
- Solenoid 2T → thin coil
- Crystal ECAL (à la CMS) + dual readout calorimetry, outside solenoid
  - Brem photon recovery in ECAL; worsen resolution w.r.t. muons with ~ 20%
- Muon chambers μRwell (RPC+GEM like)

→ Large tracking volume with small yoke for optimal track resolution



Monte-Carlo campaign:

- ZH produced with Whizard (125 GeV, off-mass samples generated at +/- 50 and +/- 100 MeV)
- Diboson backgrounds with Pythia
- Center-of-mass 240 GeV, scaled to a luminosity of 5 /ab
- ISR, FSR enabled, Beam Energy Spread (BES) set to 0.185% = ± 222 MeV
- IDEA detector; detector response modelled with Delphes
  - Tracks smeared using track covariance matrix, calculated with the drift chamber configuration



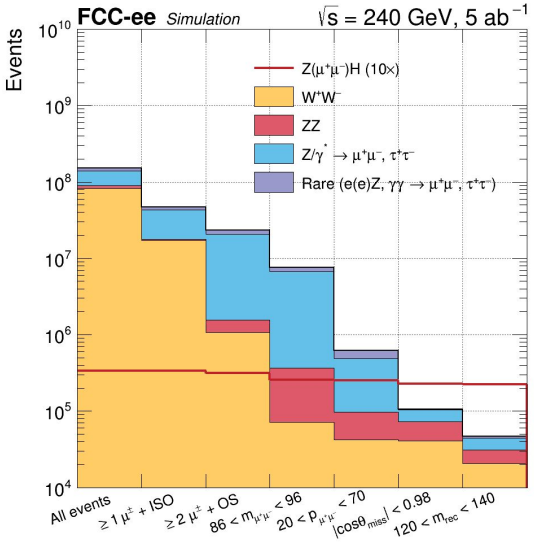
Z($\mu\mu$)H mass analysis

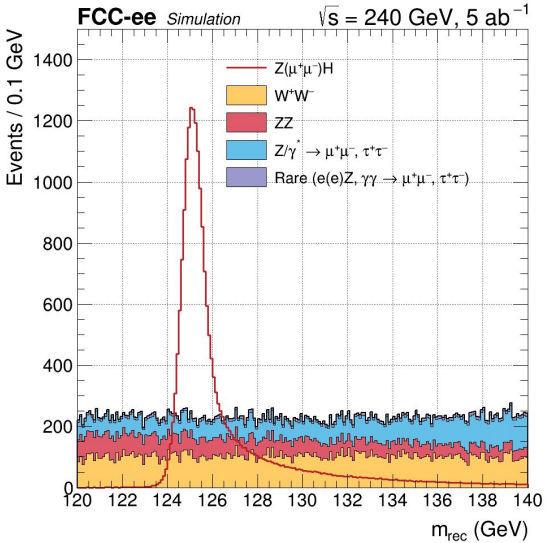
The analysis cutflow is as follows:

- Select at least 2 leptons:
  - Momentum p > 20 GeV
  - Opposite sign
  - One lepton required to be isolated
- Pair the leptons in case more than 2 leptons found:
  - Take pair that minimizes

    $\chi^2 = ((m(\mu\mu) - 91.2)^2 + 0.4*(recoil - 125)^2)$
  - Pairing efficiency ~ 100 %
- Z mass window cut [86, 96] GeV
- p_T (Z) [20, 70] GeV
- $|\cos(\theta_{miss})| < 0.98$: mainly suppresses Z/$\gamma$ backgrounds with ISR imbalance
- Recoil window [120, 240] GeV → used in fit

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





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

Z(ee)H mass analysis

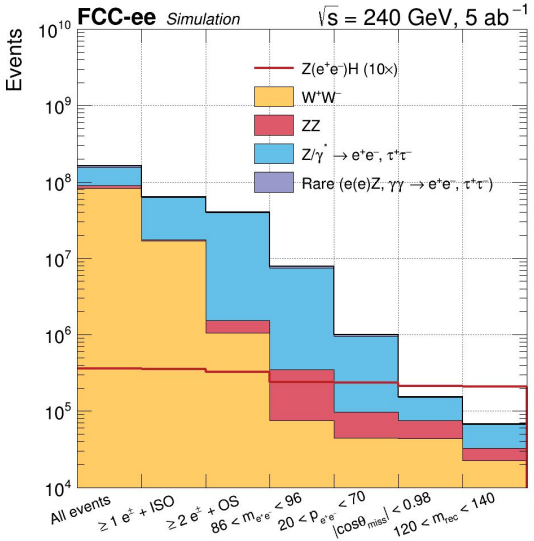
Inclusion of electron channels

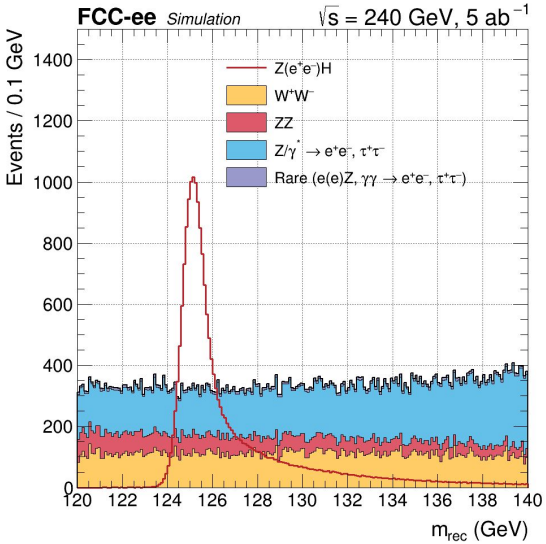
- Electrons smeared additionally with a **factor of 1.2** w.r.t. muons (from track covariance matrix) to take into account degradation due to brem
- Whizard samples include small fraction of VBF which slightly degrades resolution

Same event selection for electron channel

- Higher Z/γ background due to t-channel

Due to higher backgrounds and worse resolution, electron channel will be subdominant w.r.t. the muon channel





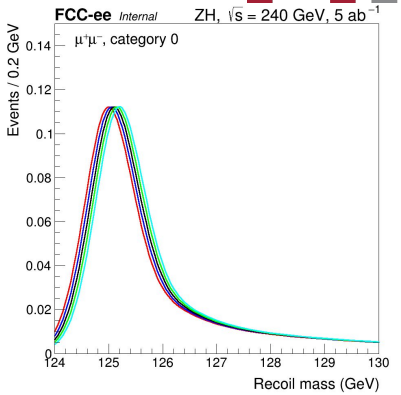
Backgrounds dominated by vector boson (pair) production (WW, ZZ) and single Z/γ*

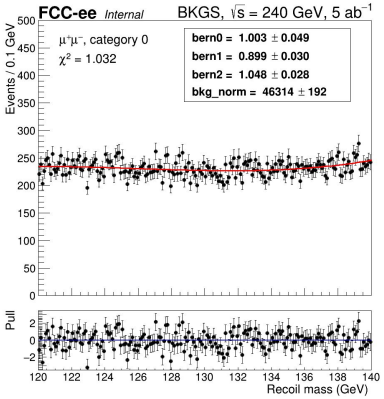
Signal parameterization Z($\mu\mu$)H

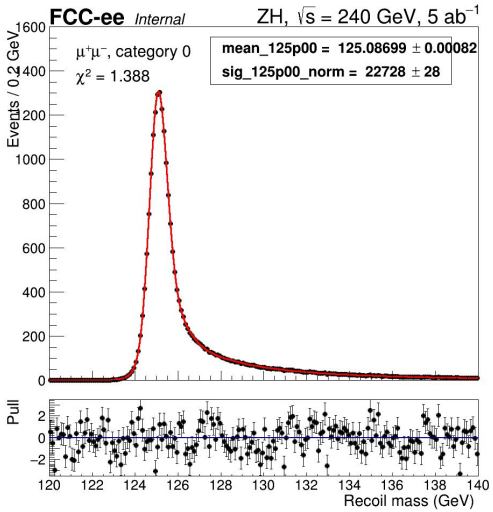
Choice of suitable PDF: 2 Crystal-Ball with Gaussian core

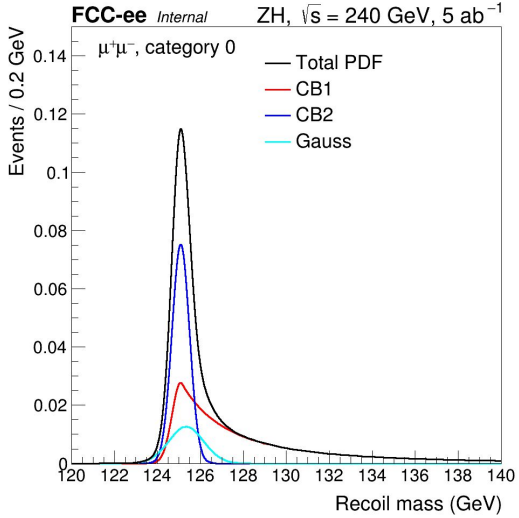
- Fit done for several mass samples (125.00 ± 50 MeV, ± 100 MeV)
- Parameterize mean and other components as function of m_h

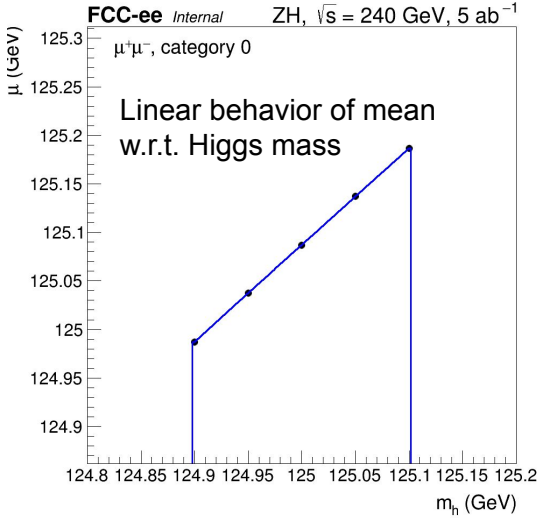
Backgrounds modeled as 3th order polynomial











Mass fits for Z($\mu\mu$)H, Z(ee)H, combination

Signal and background model injected in RooFit/Combine,

- m_h signal, background normalizations floating
- Likelihood scan to extract mass uncertainty

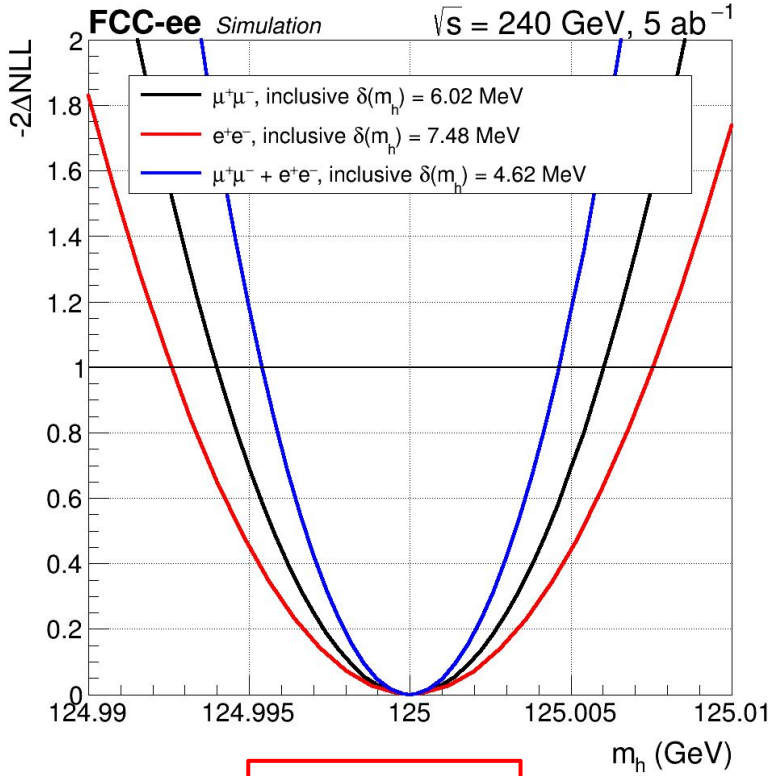
Muon channel **6.0 MeV**

Electron channel **7.5 MeV**

Electron channel worse with factor ~ 1.25 w.r.t. muons, driven by resolution scaling with factor 1.2 (residuals due to background, VBF)

Combined uncertainty 4.6 MeV (stat. only)

Sensitivity driven by muon channel, electrons gain ~ 25%

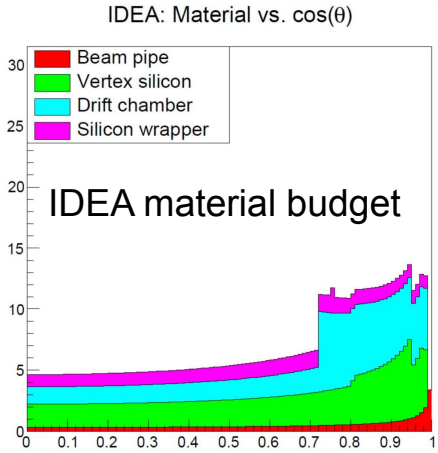


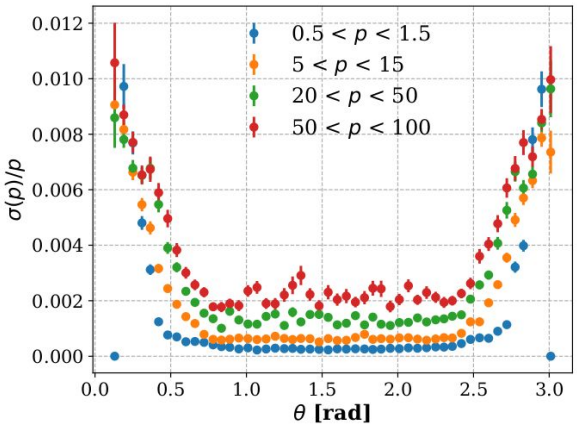
STAT. ONLY

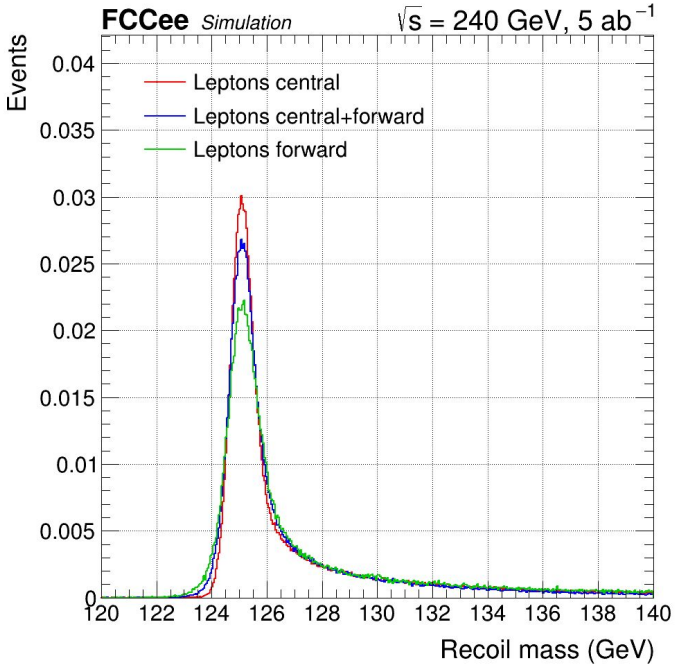
Improvement of Higgs mass measurement

Lepton momentum resolution degraded in forward region due to higher material budget

- Split leptons in central and forward regions
  - Central defined as $0.8 < \theta < 2.34$, forward: the rest
  - In total 3 categories: central, forward, central+forward
- Perform combined statistical fit in all categories







Combination Z($\mu\mu$)H and Z(ee)H

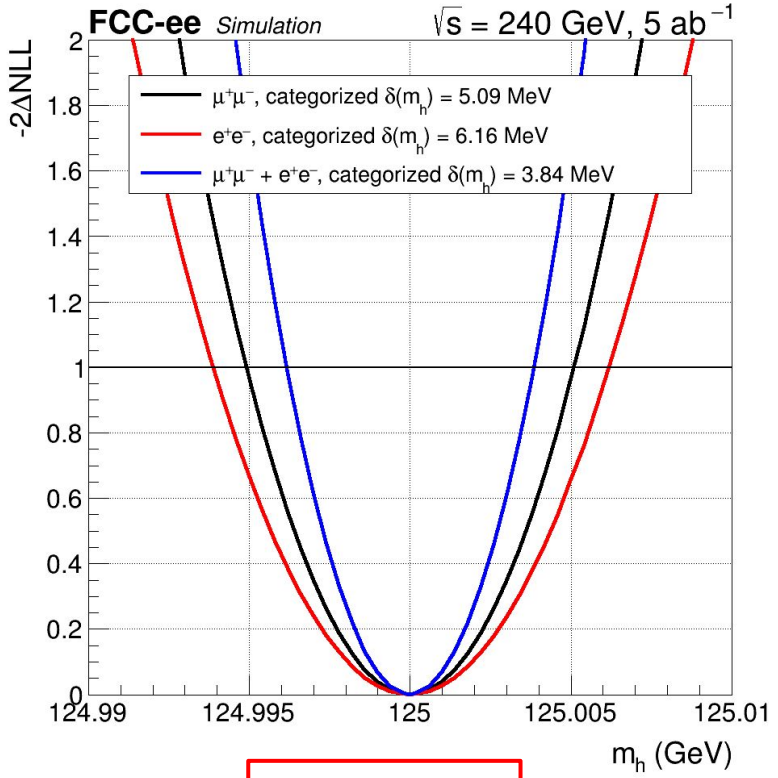
Likelihood scan to extract mass uncertainty

- In total 6 combined mass fits

Muon channel	**5.1 MeV**
Electron channel	**6.2 MeV**
Combined uncertainty	**3.8 MeV (stat. only)**

Systematic effects can become non-negligible at 3.8 MeV statistical uncertainty

- What are the main limitations of the m_H analysis and their uncertainties, in terms of detector and machine requirements?



STAT. ONLY

Detector requirements for ultimate m_H

Extracting the mass using Z($\mu\mu$) and Z(ee)H events, the track resolution is the dominant detector requirement

Excellent muon track resolution

- Light drift chamber ~ 5% X0

Electron resolution

- Low energy tail due to Bremsstrahlung photons degrades the track resolution
- Good performance of Brem photon recovery due to crystal calorimeter: electrons comparable to muons (~ 20% res. degradation)
- Optimal Brem recovery puts some constraints on the ECAL granularity (optimal 5x5 or 10x10 mm^2, cfr. CMS 22x22 mm^2)

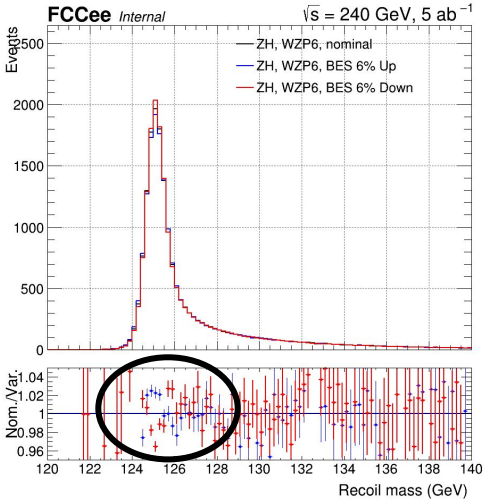
Lepton momentum scale

- Directly affects m(ll), hence shift in recoil mass
- Nuclear magnetic resonance (NMR) probes for measuring the B-field leads to a scale uncertainty of ~ 1e–5
- Statistical potential to measure lepton scale ~ 1e–6

Machine requirements for ultimate m_H

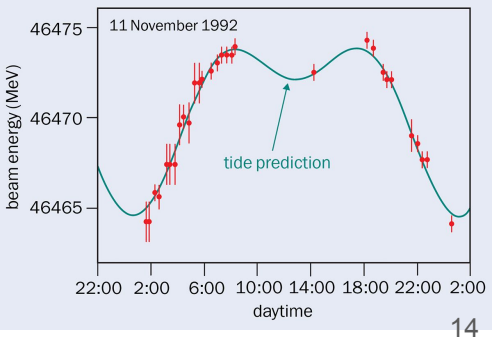
Beam energy spread

- Directly broadens the recoil resolution, hence mass measurement
- Currently set in simulations to ± 0.185% → ± 222 MeV
- Uncertainties:
  - Accelerator instrumentation: bunch length measurement up to 0.3 mm accuracy or better → **6% BES uncertainty**
  - Data-driven BES constraining possible ee→ ff(γ); e.g. longitudinal momentum imbalance of dimuon spectrum and/or Bhabha during fill → **estimated to be 1% BES uncertainty**



Center-of-mass energy

- ECM enters the recoil definition and impacts position of the mass peak
- At √s=240 GeV and above, *no resonant depolarization possible* → need data-driven methods
- Using radiative return events Z → ff, precision estimated to be 2 MeV (for constant √s)
- √s subjected to time-dependent effects (tides, train) that can could contribute O(100) MeV to the energy spread
  - Need to follow the evolution of √s using ee→ Z+γ events or ee→ WW or ZZ events
  - More detailed analysis do be done; technique to be validated proven at lower ECM where resonant depolarization is available



Inclusion of systematics

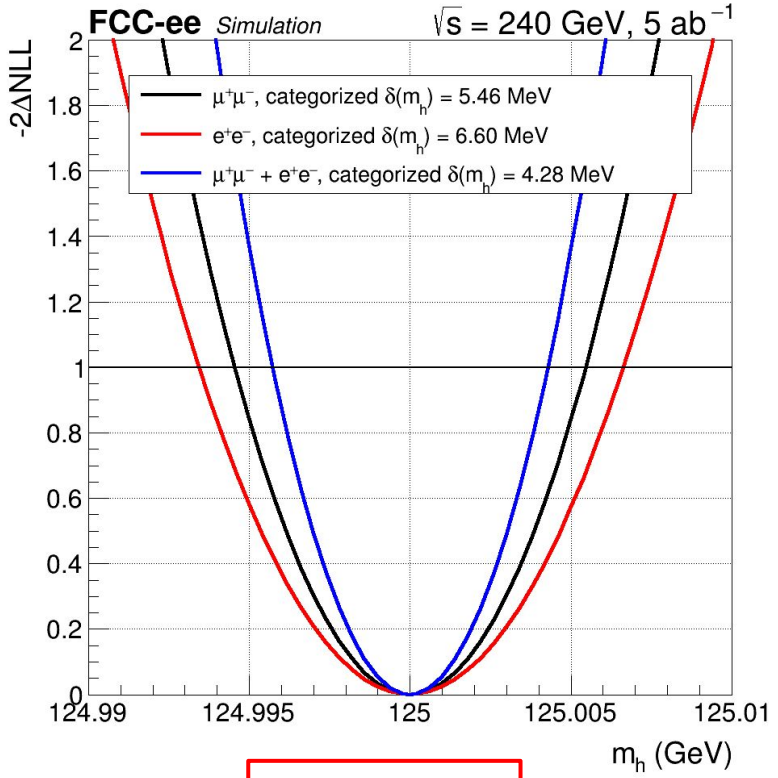
Several systematics implemented in the fit

- Beam energy spread uncertainty estimated to be 1% BES unc.
  (additional MC samples perturbed around the nominal value)
- Center-of-mass: +/- 2 MeV
- Lepton momentum scale: relative scale uncertainty variation of 1e–5

Combine likelihood scans to extract the mass uncertainty

- **Total uncertainty of 4.3 MeV** (~ 10% worsening w.r.t. stat. only)
- Todo: include ISR systematics via KKMC reweighting technique

Uncertainty breakdown	Impact on mH (MeV)
Statistical	**3.80**
Stat. + Syst.	**4.28**
Beam Energy Spread	0.62
Center-of-mass	1.77
Muon scale	0.56
Electron scale	0.48



Areas for improvement

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Detector magnetic field

- Baseline 2T, can go to 3T
- Preliminary studies show improvement of ~ 15% → 3.30 MeV (stat. only estimations)
    - Limited increase of performance resolution due to dominating BES
- Increased complications of MDI to maintain high luminosity despite increased beam emittance due to the higher field

Number of interaction points

- Baseline 2 IPs, discussion for 4 IPs ongoing, resulting in a statistical increase of factor 1.7
- Expected improvement of $\sqrt{1.7}$ → 3.0 MeV (stat. only estimations)

Hadronic final state Z(qq)H – large statistics

- Driven by jet resolution and reconstruction; systematic effects more dominant
- Tag the qq pairs from Z, use recoil method to extract the mass
    - Optimization using flavor categorization to cover phase space
    - Kinematic fit could improve
- Not yet started, but scoping studies will be performed

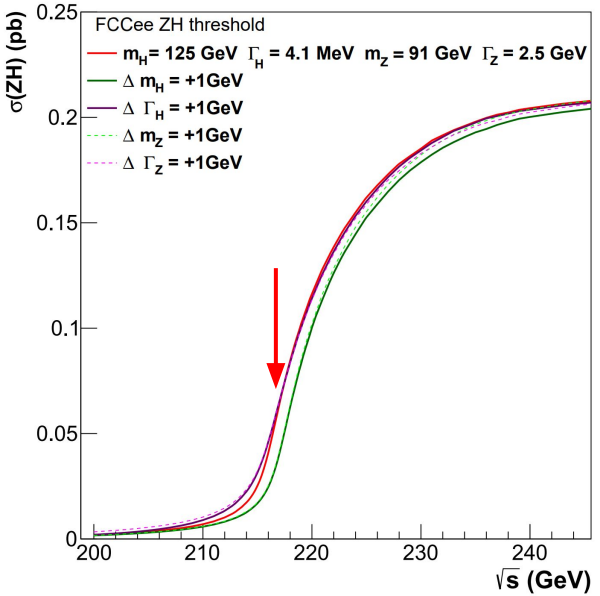
Alternative method for measuring m_H: the ZH threshold

[Based on arXiv:2106.15438]

ZH threshold – alternative measurement?

Exploit the dependency of the Higgs mass on the total cross-section as function of center-of-mass

- Loop diagrams contribute logarithmically in m_H to the cross-section
- Maximal sensitivity obtained at $\sqrt{s}$ ~ 217 GeV



Run FCC-ee at $\sqrt{s}$ = 217 GeV to infer the Higgs mass with O(5) MeV precision

- Rely on accurate measurements of Z mass and width at the Z-pole
- SM-only assumptions – new physics can break the dependency
- Systematic effects of various sorts to be evaluated: luminosity, ecm, background, theory)

Back-of-the-envelope statistical-only estimations

$$\left(\sqrt{\sigma_{\mathrm{ZH}}}\frac{dm}{d\sigma_{\mathrm{ZH}}}\right)_{\mathrm{min}} \simeq 350\,\mathrm{MeV}\sqrt{\mathrm{fb}^{-1}} \simeq 10\,\mathrm{MeV}\sqrt{\mathrm{ab}^{-1}}$$ (ultimate estimations, Q=√ep =1)

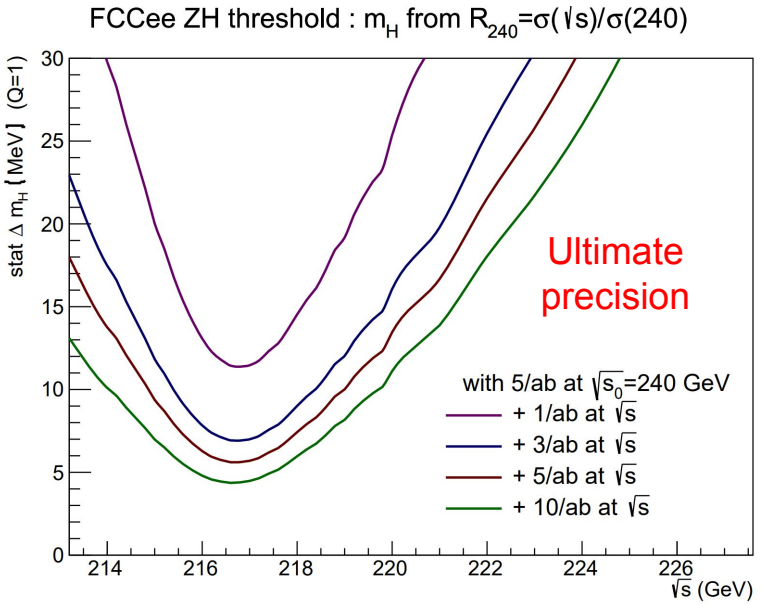
→ Collecting 5 ab^{-1} at $\sqrt{s}$ ~ 217 GeV, <u>5 MeV uncertainty</u>
→ More realistically, including systematics degrades this to 10 MeV

Reducing the systematic uncertainties

Construct the cross-section ratio using √s = 217 and 240 GeV:

$$R = \frac{\sigma_{ZH} \times \mathcal{B}(Z \to f\bar{f}) \times \mathcal{B}(H \to X\overline{X})|_{\sqrt{s}=217\,GeV}}{\sigma_{ZH} \times \mathcal{B}(Z \to f\bar{f}) \times \mathcal{B}(H \to X\overline{X})|_{\sqrt{s}=240\,GeV}} = \frac{\sigma_{ZH}(\sqrt{s} = 217\,GeV)}{\sigma_{ZH}(\sqrt{s} = 240\,GeV)}$$

- Need to collect 5 ab^{-1} at √s = 240 GeV, and 5 –10 ab^{-1} at 217 GeV
- Exclusive decays can be made more pure, optimizing the sensitivity to the cross-section
- Experimental and theory uncertainties cancel mostly
- Provides independent measurement of Higgs mass w.r.t. recoil mass method



Ultimate precision estimated to be 5 MeV (for 5 ab^{-1} at √s = 217 GeV)

- Competitive with the 4.3 MeV at 240 GeV only using the recoil method
- Requires to collect in total 10 ab^{-1}, might be worth to take all 10 ab^{-1} at 240 GeV
- Need to perform analysis for realistic numbers

Run config	Uncertainty (MeV)
5 ab^{-1} @ 217, 5 ab^{-1} @ 240	3.25 MeV
10 ab^{-1} @ 240 GeV	3 MeV

Summary and outlook

Presented overview of ongoing Higgs mass analysis at FCC-ee

Performed analysis with statistical fit in the Z($\mu\mu$) and Z(ee)H final states using the recoil method

- Statistical-only 3.8 MeV for 5 ab^{-1}, including experimental systematics it degrades to 4.3 MeV
- Discussed main detector and machine requirements to achieve such precision

Orthogonal measurement using dependency of m_H on the cross-section vs. $\sqrt{s}$

- Maximal sensitivity obtained on m_H at $\sqrt{s}$ = 217 GeV
- Standalone uncertainty of ~ 10 MeV when collecting 5 ab^{-1} at $\sqrt{s}$ = 217 GeV
- Combined with 5 ab^{-1} at $\sqrt{s}$ = 240 GeV, the ratio-method results in an ultimate uncertainty of 3.25 MeV

→ Realistic Higgs mass measurement with precision of 3–4 MeV within reach

→ Other Z decay modes (qq, $\tau\tau$) with larger statistics will bring down the ultimate precision, though imposes different detector requirements and systematic effects