Higgs mass and ZH cross-section from $Z(\mu^+\mu^-)H$ events

Ang LI
(APC-Paris, Université de Paris, CNRS/IN2P3)
On behalf of the FCC-ee ZH analysis team

FCC Week
February 7th, 2022

Outline

- **Motivation and introduction**
- **Event selection**
- **Signal and background modelling**
- **Statistical analysis and Systematics**
- **Delphes and Full Simulation comparison**

Motivation

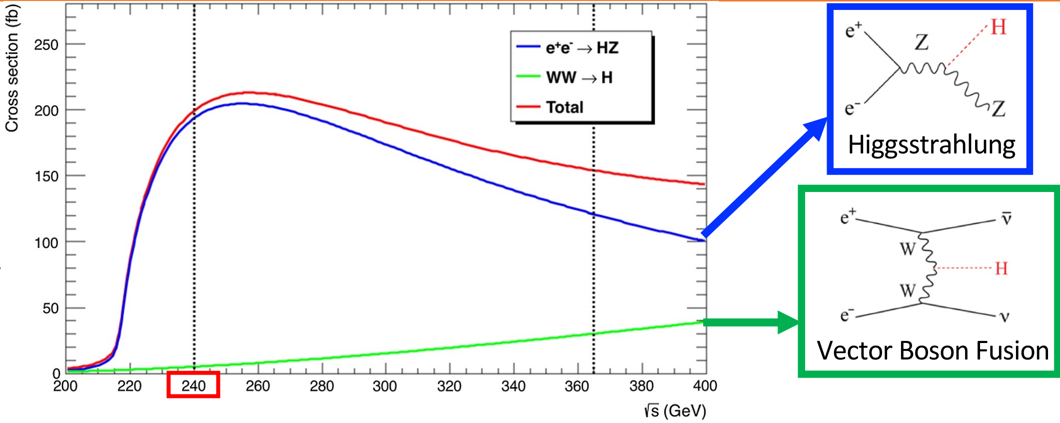
FUTURE CIRCULAR COLLIDER

- Goal: precise measurements of ZH cross section and Higgs mass
  - Current best result LHC: $m_H = 125.38 \pm 0.14(\pm 0.12)$ GeV
  - At FCC-ee, m_H and σ_{ZH} accuracy will reach a few MeV and 0.5%, respectively
    - → Measure g_{HZZ}, Higgs width (Γ_H) and other Higgs couplings
- Signal: $e^+e^- \rightarrow ZH \rightarrow l\bar{l} + X$

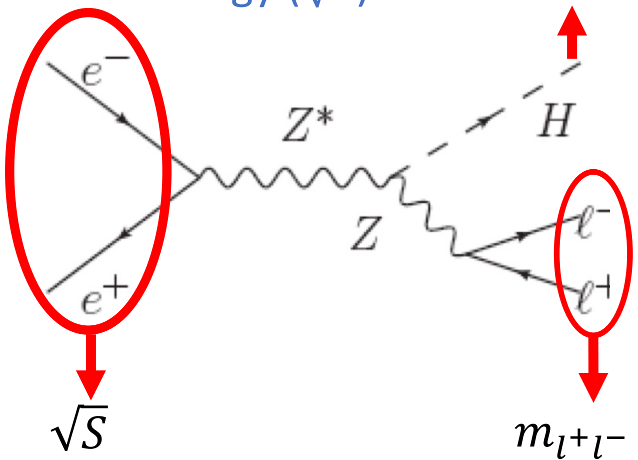
  ZH is the dominant Higgs production process @ 240 GeV e^+e^-machine
- Model-independent study
- M_{recoil} from the Z production without measuring the Higgs production final state

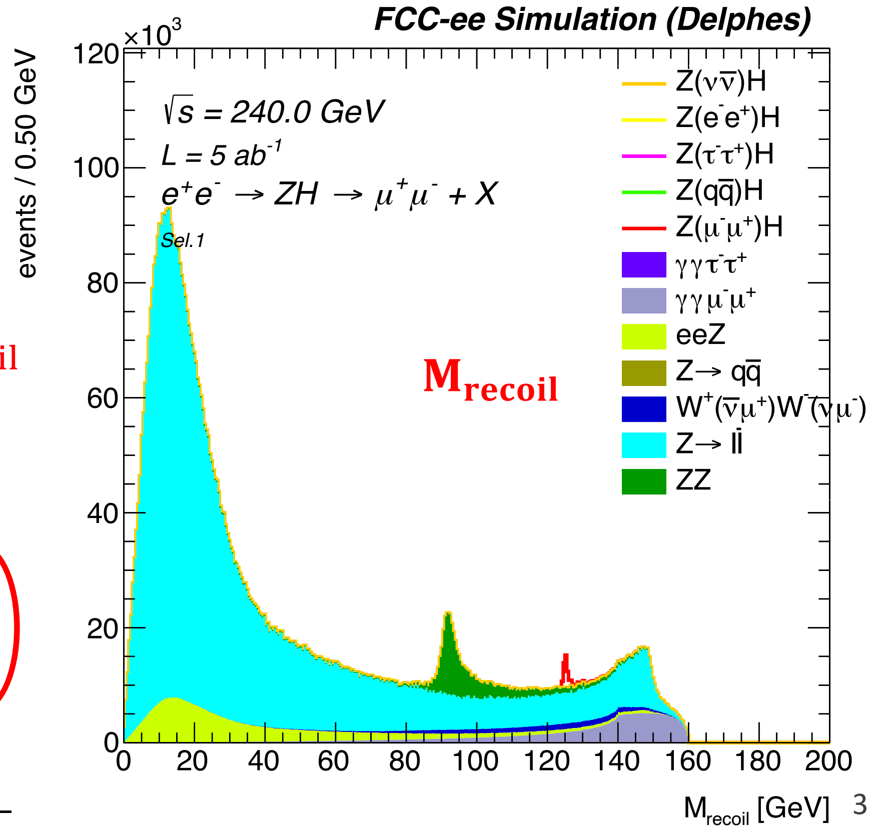
$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

- Sensitive to the precise knowledge of the centre-of-mass energy ($\sqrt{s}$) and Initial State Radiation (ISR)
- WW, ZZ and dilepton backgrounds @ 240 GeV
- So far, focus on the $Z \rightarrow \mu^+\mu^-$ channel



1. ZH optimal event rate is at $\sqrt{s} \sim 240$ GeV : $\sigma \sim 200$ fb ~ 10^6 events (@ $L = 5\ ab^{-1}$)
2. Data at $\sqrt{s} \sim 365$ GeV, 1.8×10^5 ZH and 0.45×10^5 WW-fusions (~30%) (@ $L = 1.5\ ab^{-1}$)





Signal, Background Monte-Carlo simulation, Event Selection

➢ Monte-Carlo simulation:

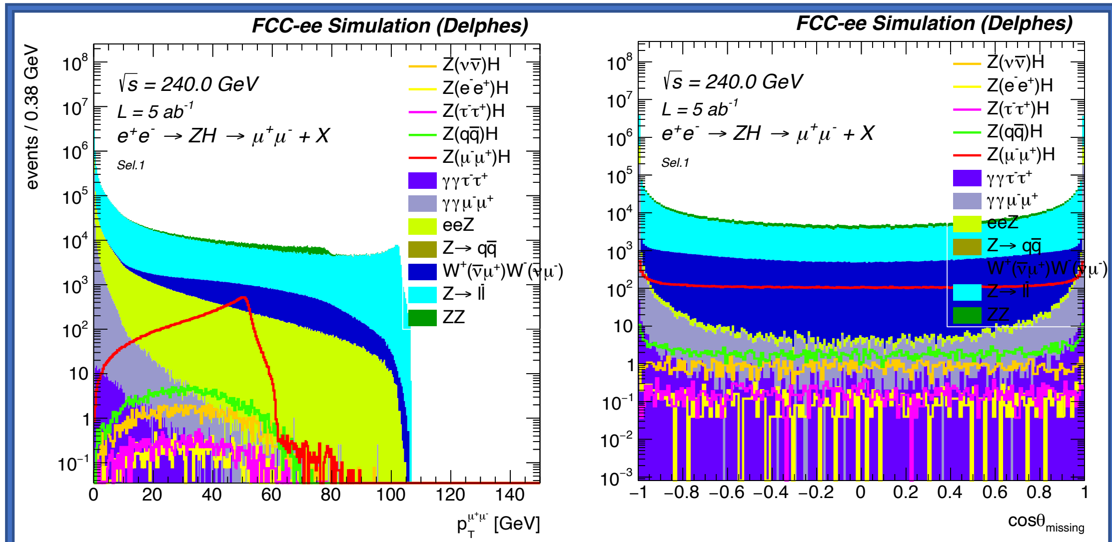
- $\sqrt{s} = 240$ GeV
- Luminosity: $L = 5\ ab^{-1}$
- Initial State Radiation (ISR) and Final State Radiation (FSR) on
- Beam Energy Spread (BES) set to 0.165%= $\pm$ 198MeV (from CDR)
- IDEA detector; detector response modelled with Delphes

➢ Signals:

1. $Z(\mu^+\mu^-)H$, (Whizard)
2. $Z(\tau^+\tau^-)H$, (Whizard)
3. $Z(q\bar{q})H$, (Whizard)
4. $\nu_e\bar{\nu}_eH$, (Whizard)
5. e^+e^-H (Whizard)

➢ Backgrounds:

1. ZZ(inclusive), (Pythia)
2. $W^+(\nu\mu^+)W^-(\bar{\nu}\mu^-)$, (Pythia)
3. $Z \to l^+l^-$, (Pythia)
4. $Z \to q\bar{q}$, (Pythia)
5. eeZ, (Whizard)
6. $\gamma\gamma \to \mu^+\mu^-/\tau^+\tau^-$ (Whizard)



After Pre-Selection:

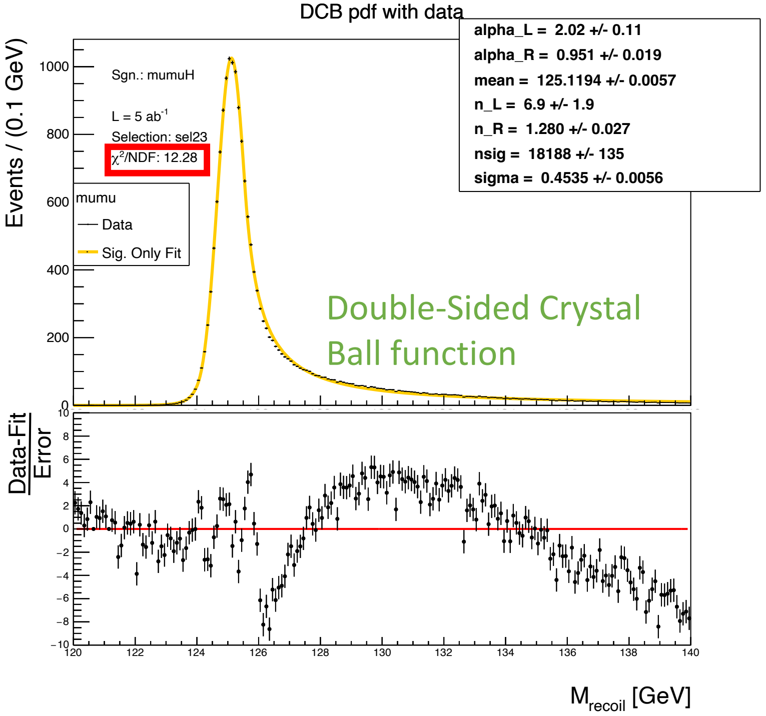
1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [80, 100]$ GeV

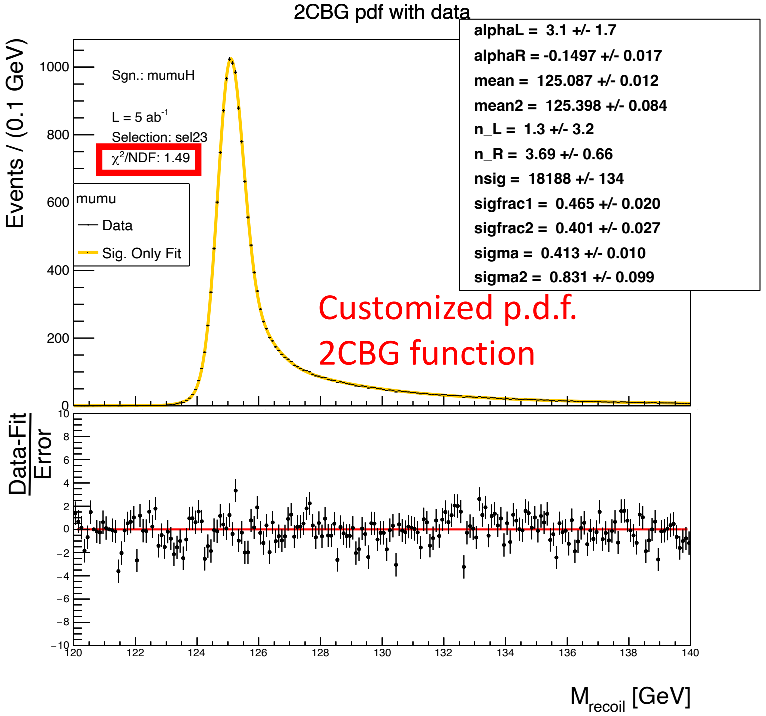
➢ Event-Selection:

1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV → focus on Z resonance space
3. $M_{\text{recoil}} \in [120, 140]$ GeV → Signal exhibits sharp peak around ~ 125 GeV,
4. $p_T^{\mu^+\mu^-} \in [20, 70]$ GeV → Signal mainly within this region, Low $p_T^{\mu^+\mu^-}$ cuts back-to-back events ($Z/\gamma^* \to ll$)
5. $|\cos\theta_{missing}| < 0.98$ → Polar angle of missing momentum, reduce $\gamma\gamma$ processes. ISR emitted approximately collinear with the incoming beams escapes detection in the beam pipe

Double-sided crystal-ball fit v.s. customized p.d.f.

Double-sided crystal-ball fit vs. customized p.d.f.





Customized p.d.f. 2CBG:

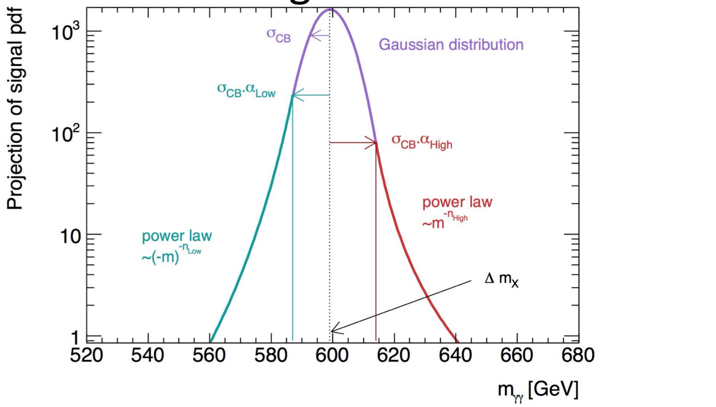
- Two crystal-ball functions (left and right), sharing mean and width
- Added Gaussian to cope with the high tails
- Gaussian suppressed in norm ($sigfrac1 + sigfrac2 > 0.8$)
- In total 9 "free" parameters which are fitted to the data
- $pdf(M_{recoil}) = sigfrac1 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_L, n_L)$
  $+ sigfrac2 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_R, n_R)$
  $+ (1 - sigfrac1 - sigfrac2) \cdot Gauss(M_{recoil}; \mu_2, \sigma_2)$

Double sided Crystal-Ball function:

$$f_S(x;\vec{\theta}) = \begin{cases} \left(\frac{n_L}{|\alpha_L|}\right)^{n_L} \exp\left(\frac{-|\alpha_L|^2}{2}\right)\left(\frac{n_L}{|\alpha_L|} - |\alpha_L| - \frac{x-\mu}{\sigma}\right)^{-n_L}, & \text{for } \frac{x-\mu}{\sigma} \leq -\alpha_L \\ \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right), & \text{for } -\alpha_L < \frac{x-\mu}{\sigma} < \alpha_R \\ \left(\frac{n_R}{|\alpha_R|}\right)^{n_R} \exp\left(\frac{-|\alpha_R|^2}{2}\right)\left(\frac{n_R}{|\alpha_R|} - |\alpha_R| + \frac{x-\mu}{\sigma}\right)^{-n_R}, & \text{for } \frac{x-\mu}{\sigma} \geq \alpha_R, \end{cases}$$

Gaussian Core

Power law tail on right and left

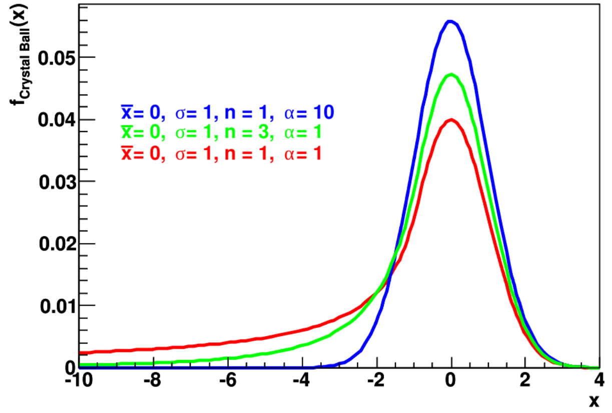


Crystal-Ball function:

$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot \left(B - \frac{x-\bar{x}}{\sigma}\right)^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

Gaussian Core

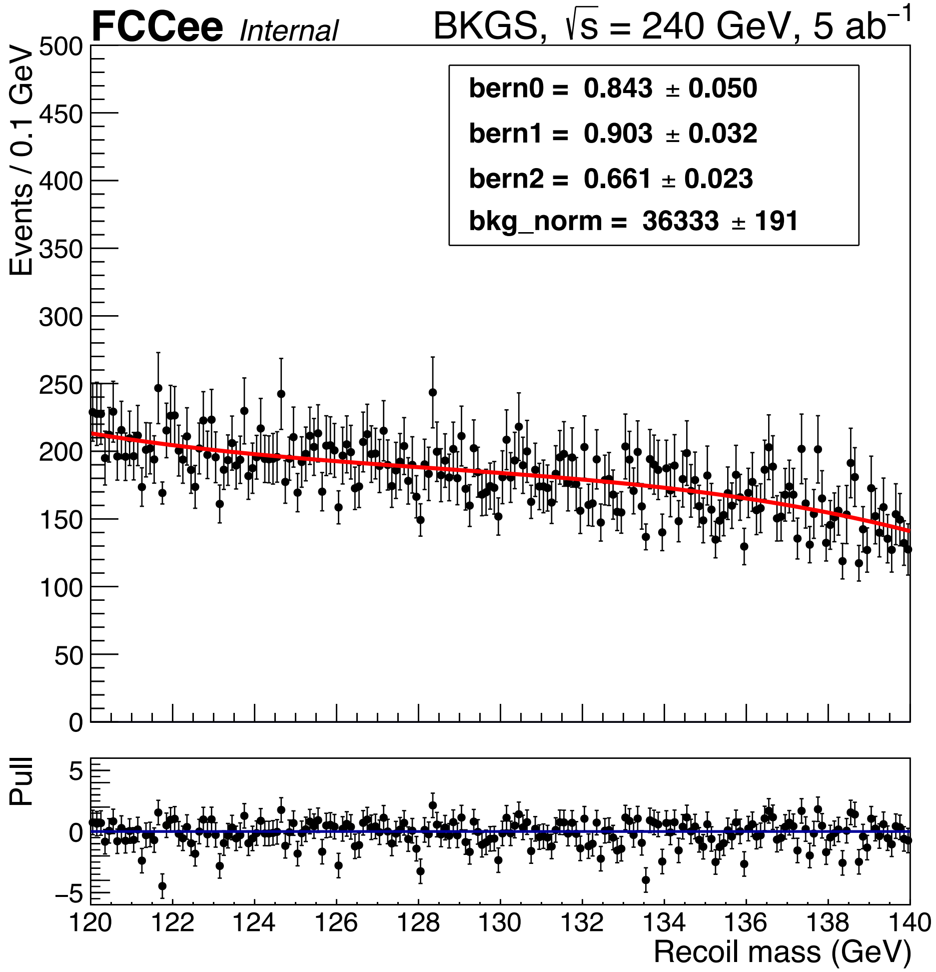
Power law tail on right or left



Background modelling

Statistical treatment of backgrounds:

- All backgrounds are merged
- Smoothly falling background modelled as third-order polynomial fit
- Polynomial coefficients constant are fitted to the data (keep total normalization floating)
- Sufficient statistics for all backgrounds



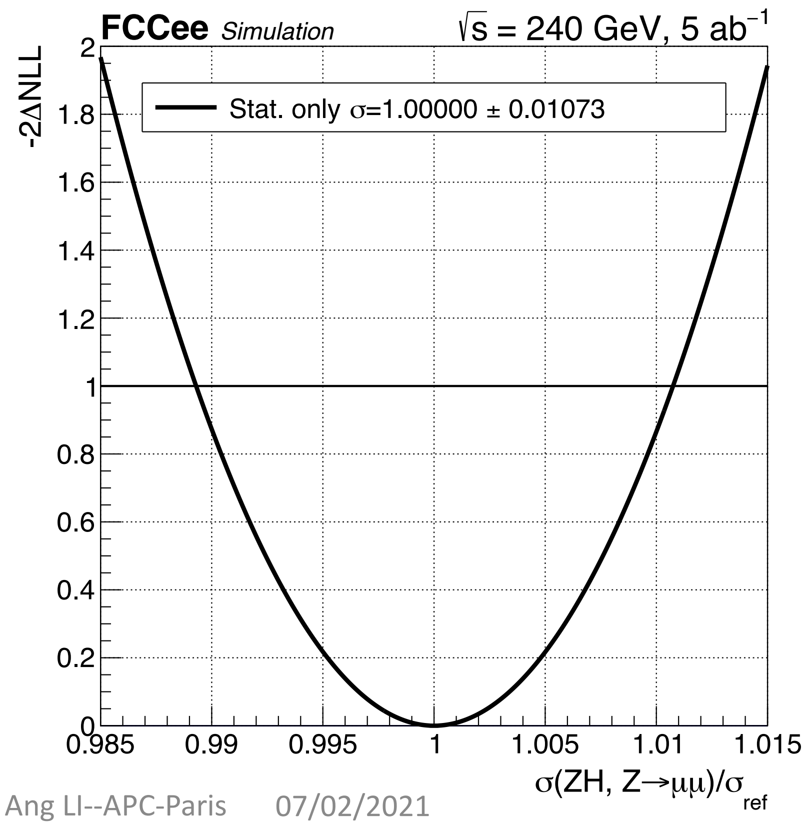
Backgrounds:

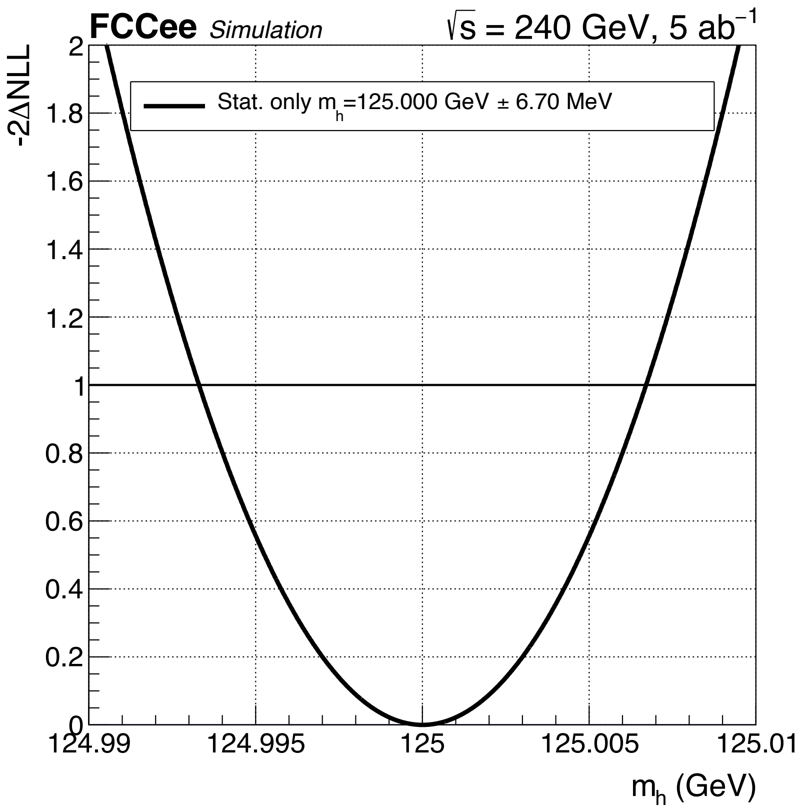
1. ZZ(inclusive), (Pythia)
2. $W^+(\nu\mu^+)W^-(\bar{\nu}\mu^-)$, (Pythia)
3. $Z \rightarrow l^+l^-$, (Pythia)
4. $Z \rightarrow q\bar{q}$, (Pythia)
5. eeZ, (Whizard)
6. $\gamma\gamma \rightarrow \mu^+\mu^-/\tau^+\tau^-$ (Whizard)

Statistical Analysis

Statistical analysis performed using Combine (CMS statistical framework)

- Signal and background analytical shapes are fitted to pseudo-data Asimov dataset
  - Injected 125.0 GeV signal with cross-section of ~ 0.00677 pb
  - Free parameters: signal, background normalizations and m_H
- Likelihood scans to extract cross-section and Higgs mass with robust uncertainties
- First, without accounting for experimental uncertainties → statistical-only result





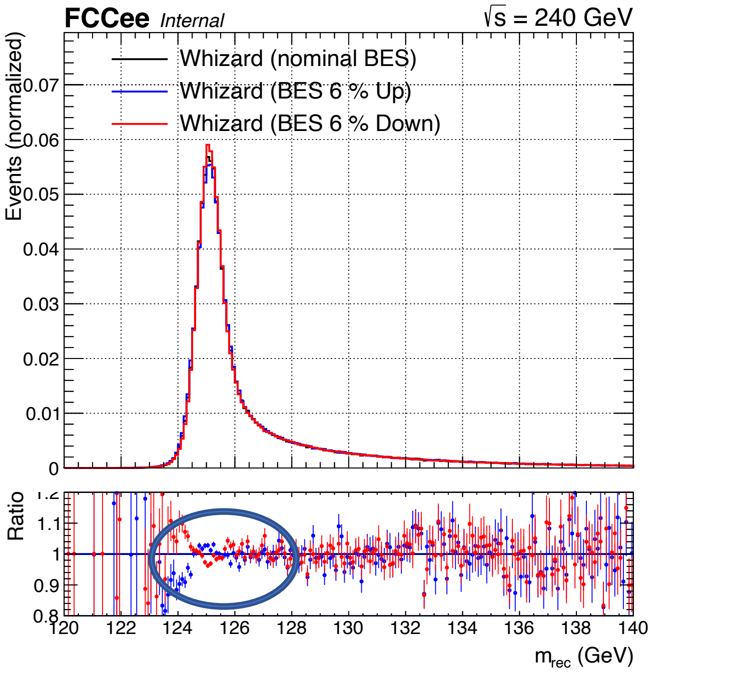
Stat-only uncertainties:
- Cross-section: ~ 1.07%
- Higgs mass: 6.7 MeV

$Z(\mu^+\mu^-)H$ only,
will combine with other final states

Systematic uncertainties

Study of systematic uncertainties to assess the impact on the Higgs mass and cross-section measurement

- Uncertainties directly affect the recoil distribution shape and normalization
- Can be constrained with data, depending on source of uncertainty
- Considered uncertainties: BES, ISR, FSR, centre-of-mass, muon momentum scale

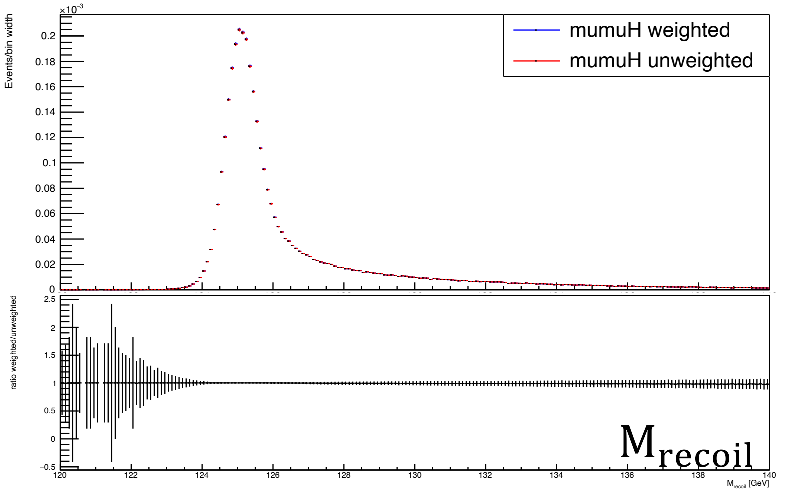


1) Beam energy spread uncertainty:

(nominal BES @ 120 GeV per beam: $\pm$ 0.165% = $\pm$ 0.198 MeV [Table S.1 of the CDR])

1. Determination of BES by bunch length measurement up to 0.3 mm accuracy → 6% BES uncertainty
2. Data-driven BES constraining possible $ee \rightarrow ff(\gamma)$ → 1% BES uncertainty

- Generated additional signal samples @ 125.0 GeV with:
  - i. 6% BES variation: 2-3% shape effect observed at mass peak
  - ii. 1% BES variation: negligible variation ~ within statistical uncertainty



2) Initial State Radiation: ISR has impact on shape and normalization

- Recently revisited
- ISR treatment in Whizard using structure function approach + ad-hoc photon p_T spectrum
- Benchmark Whizard and KKMC using $e^+e^- \rightarrow \mu^+\mu^-$ ISR samples
- KKMC being the state-of-the-art for ISR treatment, reweight the Whizard samples to KKMC with the p_T spectrum and take the difference as the systematic uncertainty

Systematic uncertainties

3) Centre-of-mass uncertainty: $\pm$ 2 MeV

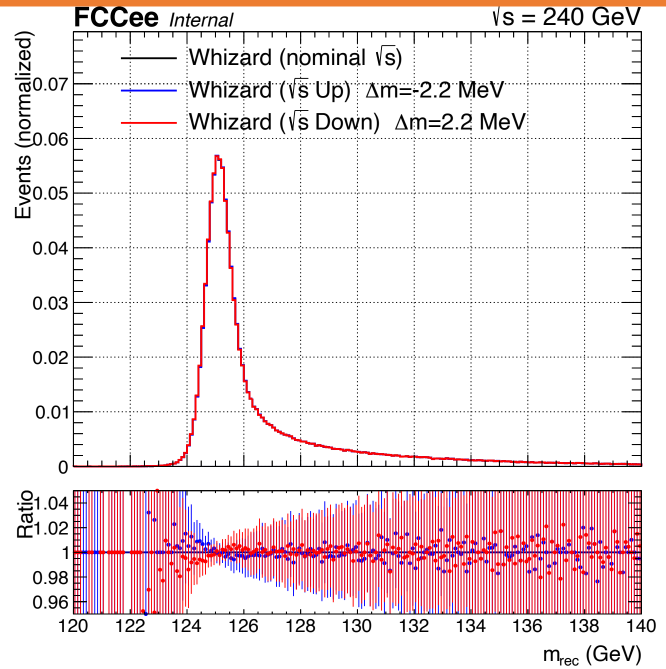
- $\sqrt{S}$ parameter in the recoil mass definition → uncertainty induces ~ linear shift in the recoil mass distribution
- Precision estimated to be 2 MeV at 240 GeV using radiative return events $Z \rightarrow l\bar{l}$ or $Z \rightarrow q\bar{q}$

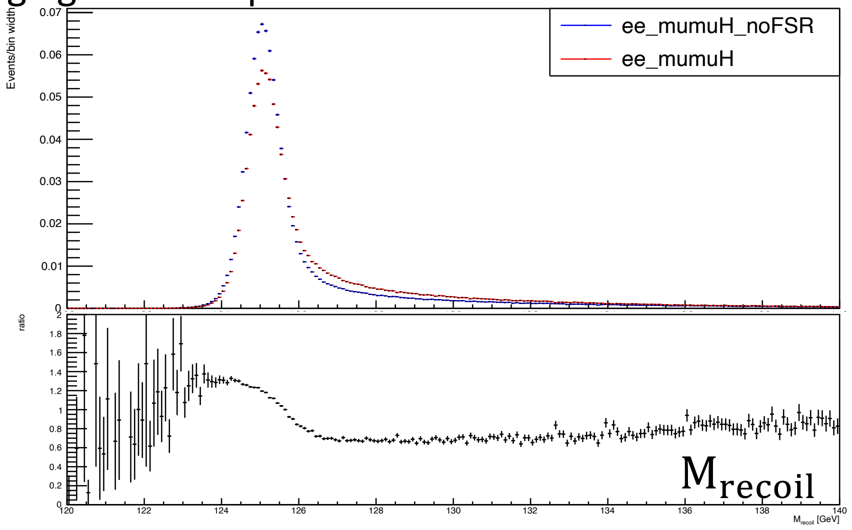
4) Muon momentum scale: relative scale uncertainty variation of 10^{-5}

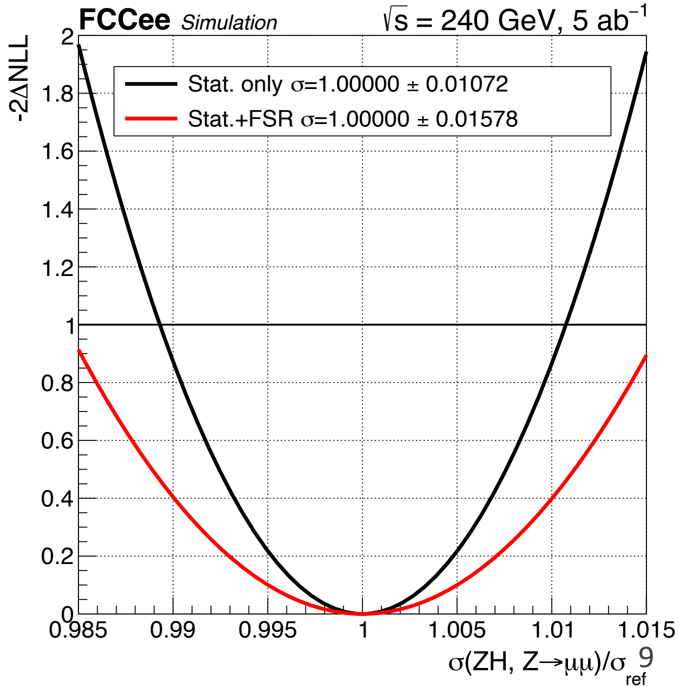
- Directly affects $m_{\mu^+\mu^-}$, hence shift in recoil mass
- Statistical potential to measure muon scale ~ 10^{-6}, but conservatively use 10^{-5} (the expected level of the magnetic field monitoring)

5) Final State Radiation: FSR has impact on shape and normalization

- Generated additional sample without FSR
  Too drastic → unrealistic estimation of FSR uncertainty!
- To do: Benchmarking against Sherpa to obtain more realistic uncertainties for FSR treatment



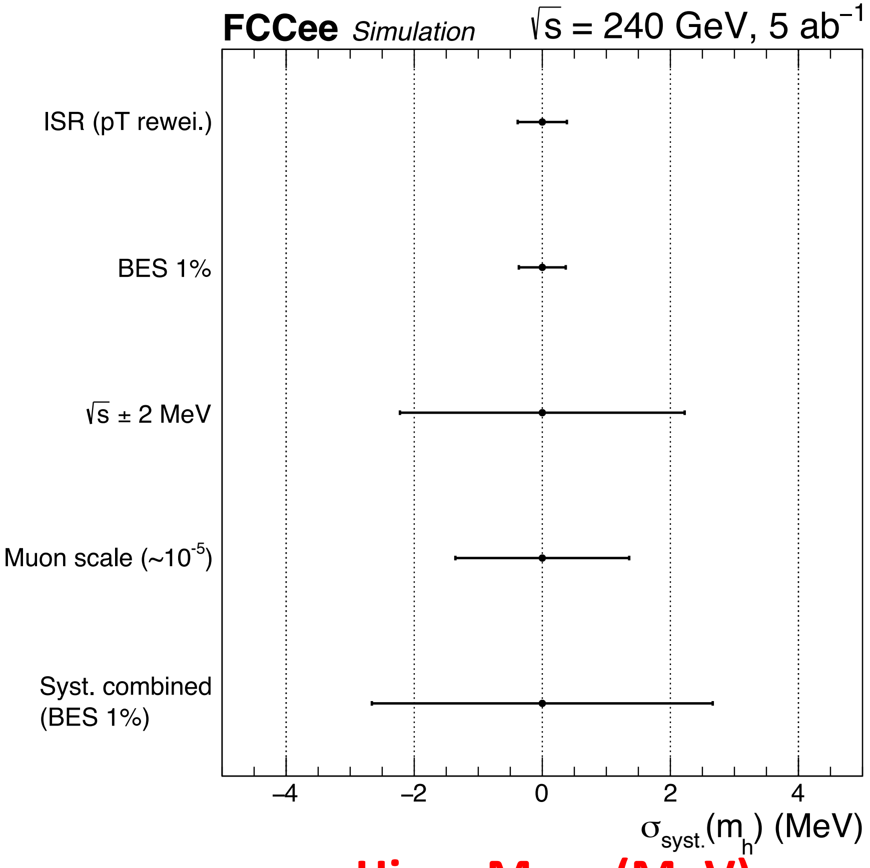




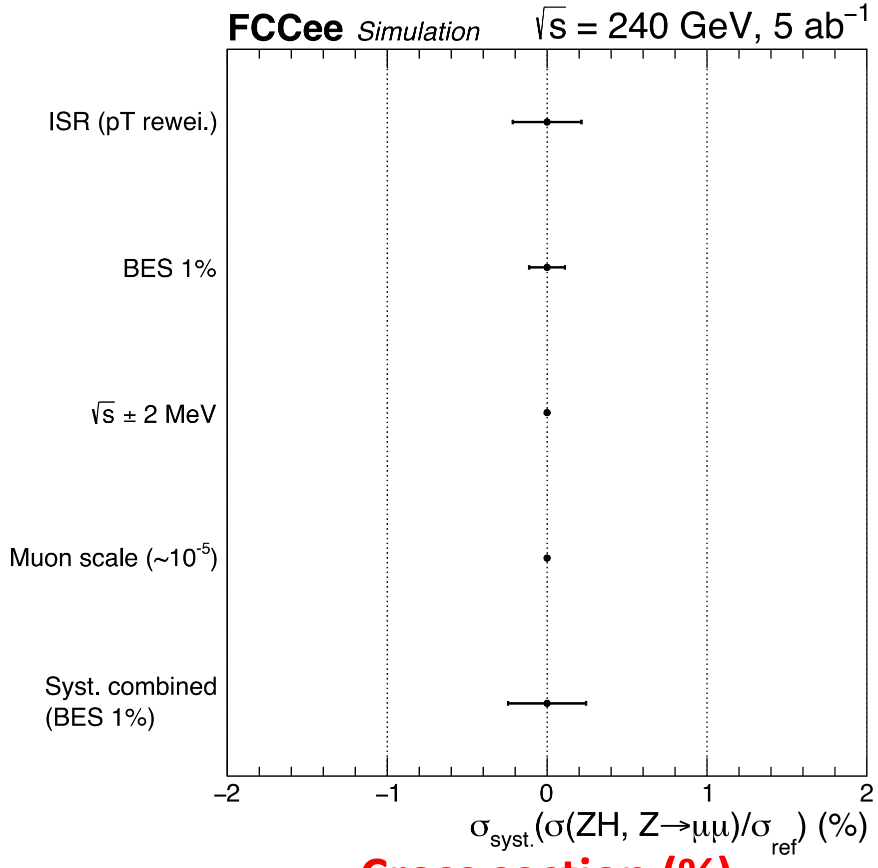
Systematic uncertainties

Systematic variations included in likelihood as Gaussian constraint terms

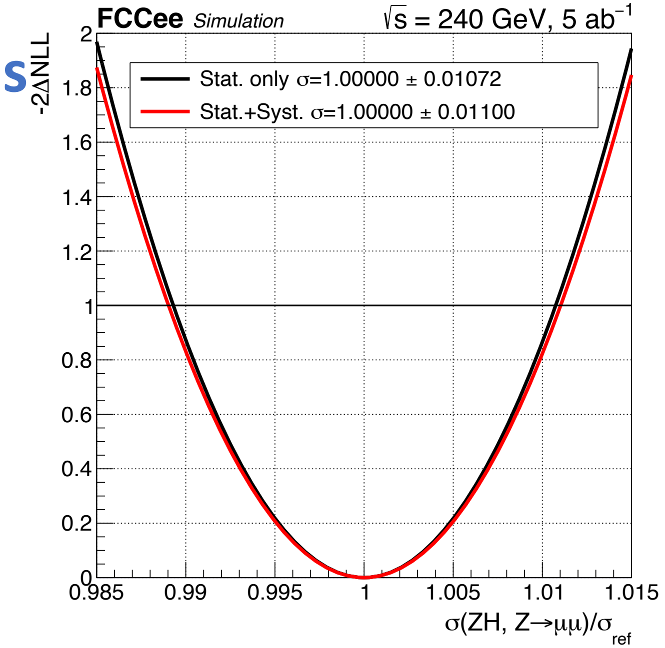
- Inclusion of all systematics (besides FSR): $\Delta m_H \sim 7.2$ MeV and $\Delta\sigma \sim 1.10$ %
- Breakdown of uncertainties: vary systematics one by one, extract $\sigma^2_{syst.} = \sigma^2_{tot.} - \sigma^2_{stat.}$
- muon scale / $\sqrt{s}$ accounts for ~ 2 MeV on Δm_H
- Impact on cross-section limited

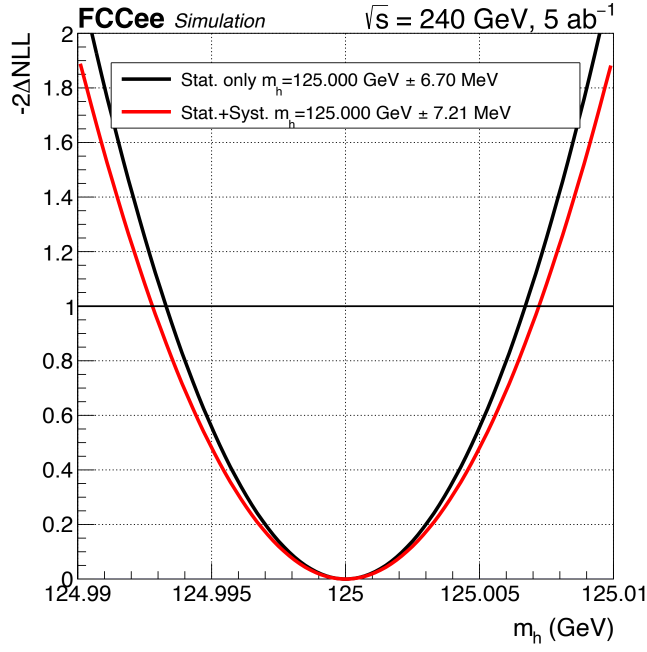


Higgs Mass (MeV)



Cross section (%)

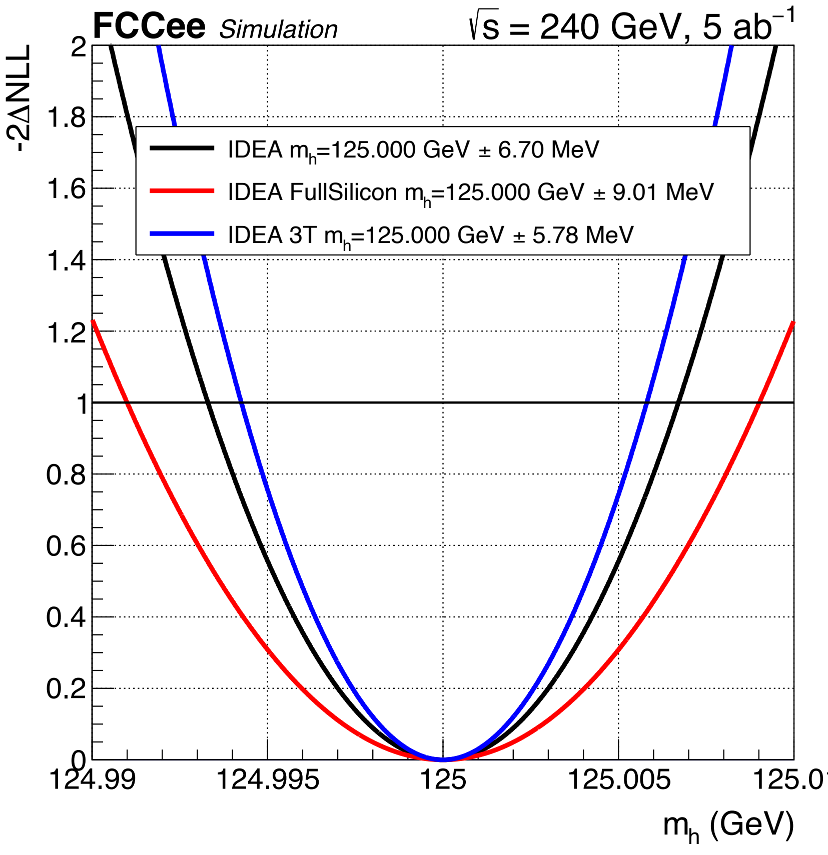


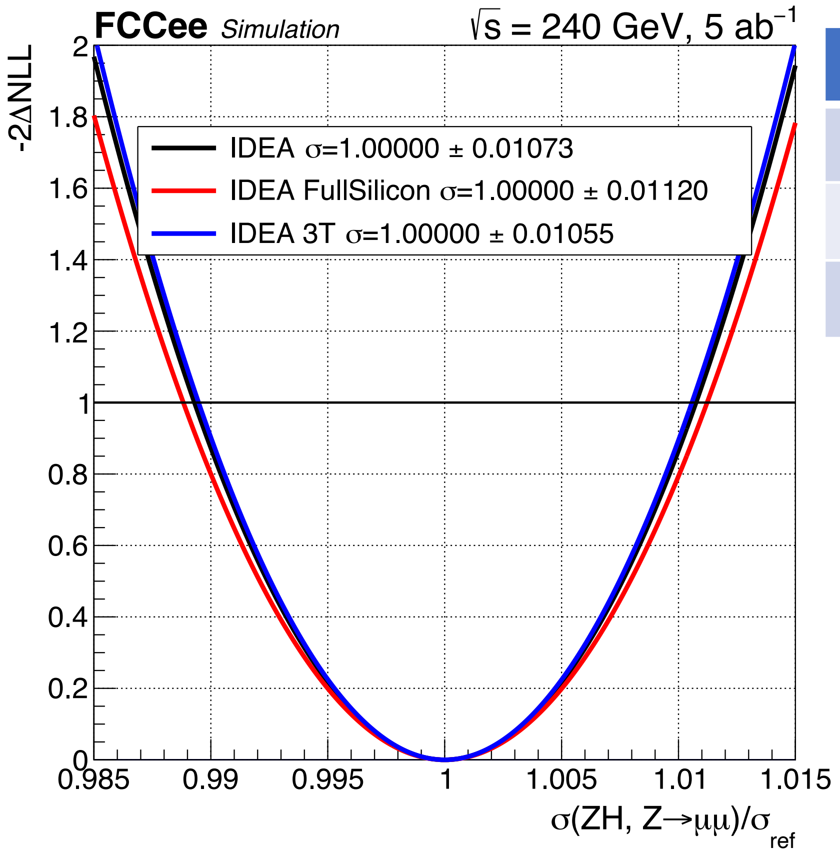


Detector configurations

Different detector configuration studied:

1. Magnetic field increased from 2T to 3T → expected better momentum resolution
2. FullSilicon tracker instead of drift chamber (a la CLD) → degraded resolution due to enhanced multiple scattering, especially at low p_T and in the range relevant for this analysis





Stat-only results

IDEA	Δm_H (MeV)	$\Delta\sigma$ (%)
Nominal	6.7	1.07
FullSilicon	9.0	1.12
3T	5.8	1.06

2T→3T

- significant effect on m_H
- small effect on x-section

M_{recoil} in Delphes and in Full Simulation

M_{recoil} in Delphes and in Full Simulation

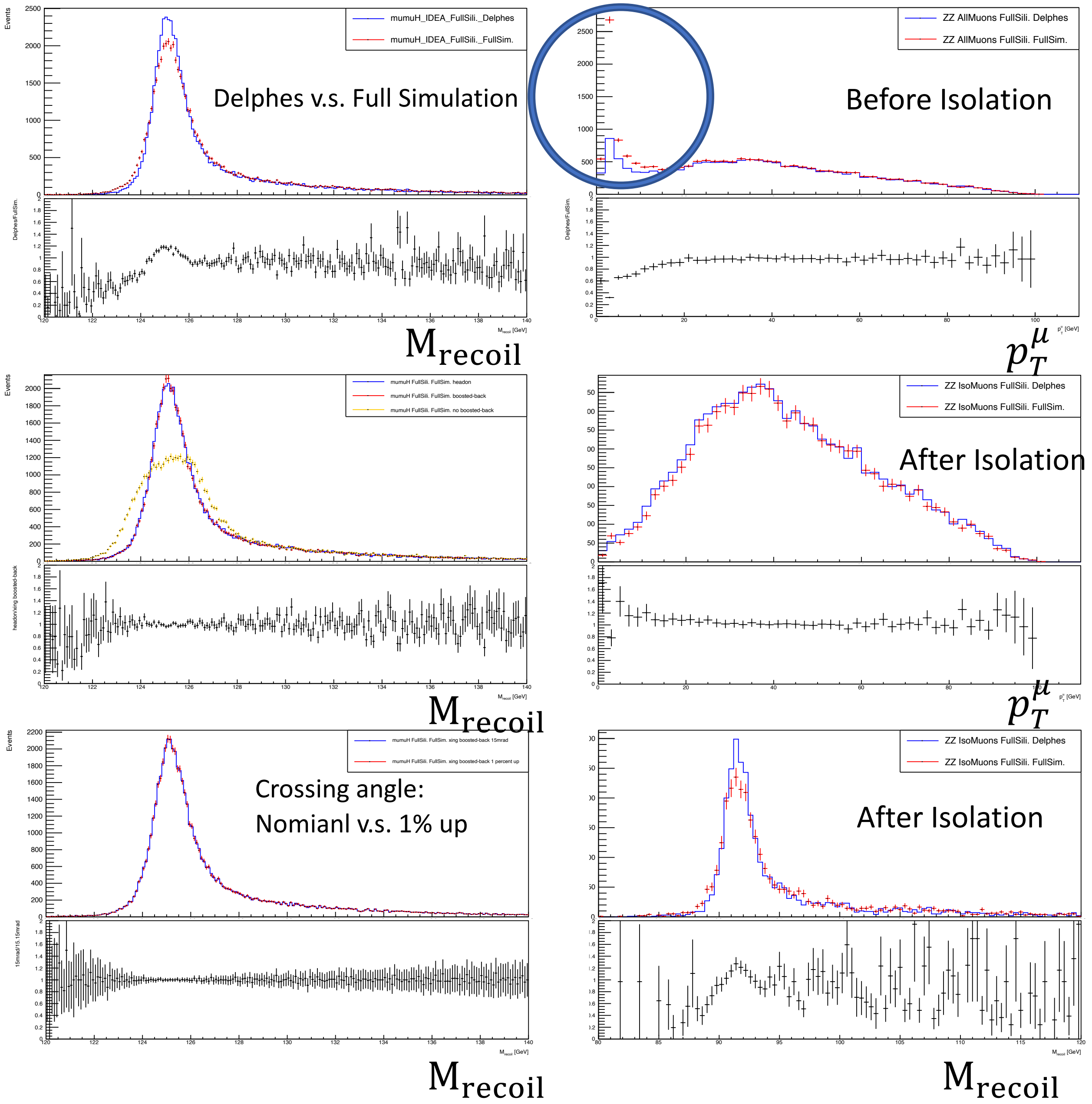
- Delphes: simplified detector card
- Full Simulation: performed by GEANT, more precise, Pandora reconstruction
- Analysis code developed over Delphes could be reused over the FullSim samples
- M_{recoil} in full simulation has slightly lower resolution
- The Difference between Delphes and Full Simulation is acceptable considering the simplified description

Fake Muon and muon isolation

- Fake muons are at low p_T, and are suppressed with an isolation criteria
- Delphes does not produce fake muons but it is not a problem for this analysis

Crossing Angle

- Head-on: not accounting for beams crossing angle
- Generated 15 mrad (ref.) crossing angle and 1% up and down sample, and boosted them back to head-on reference
- This analysis does not require the crossing angle to be known very precisely



Summary and outlook

❖Summary:

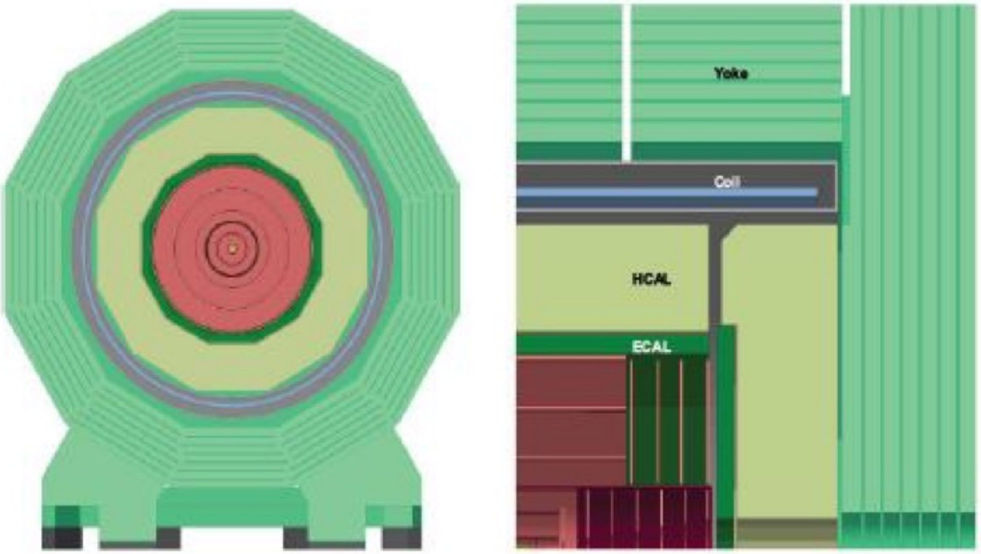
- ❑Optimized event selection to reject main backgrounds
- ❑Signal modelling with customized PDF
- ❑Statistical analysis yields Higgs mass uncertainty 6.7 MeV, cross-section 1.07 % (stat-only)
- ❑Inclusion of systematic uncertainties results into 7.2 MeV / 1.10% respectively
- ❑Difference between Delphes and Full Simulation is acceptable considering the simplified description
- ❑This analysis does not require the crossing angle to be known very precisely
- ❑Increasing detector magnetic field from 2T to 3T has significant effect on m_H but small effect on cross-section

❖Outlook:

- ❑Documentation of all studies + paper
- ❑FSR uncertainty
- ❑Inclusion of electron channel
- ❑Systematics due to the background shape
- ❑Categorisation of the events

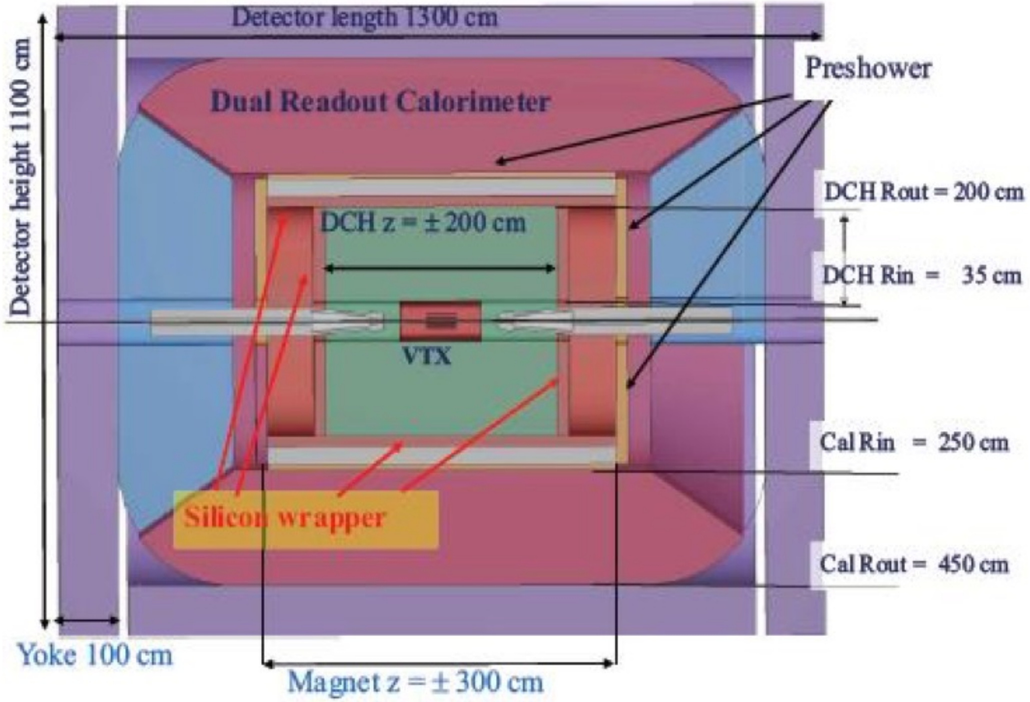
Backup

CLD



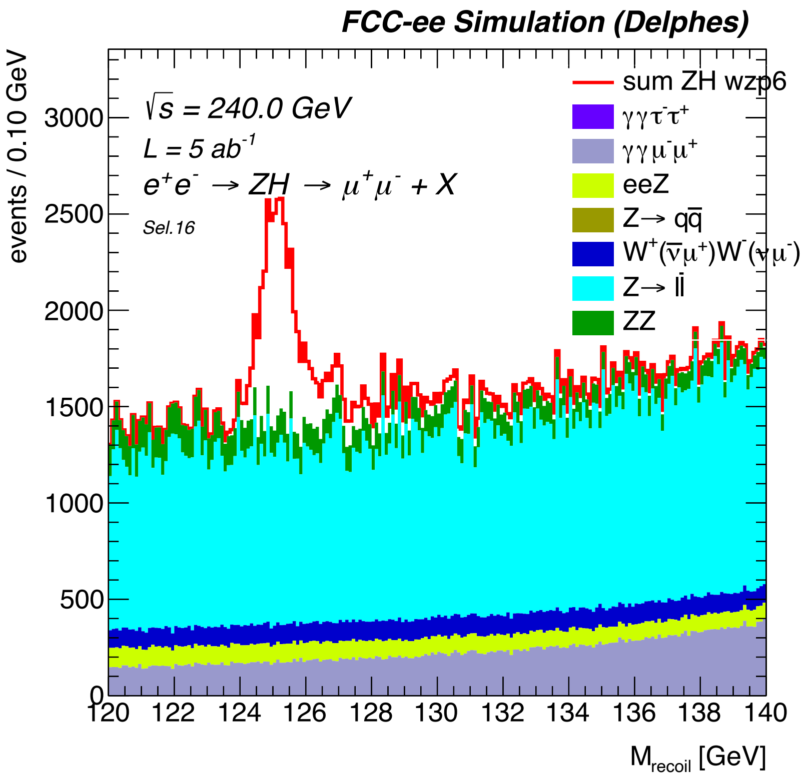
- conceptually extended from the CLIC detector design
  - full silicon tracker
  - 2T magnetic field
  - high granular silicon-tungsten ECAL
  - high granular scintillator-steel HCAL
  - instrumented steel-yoke with RPC for muon detection

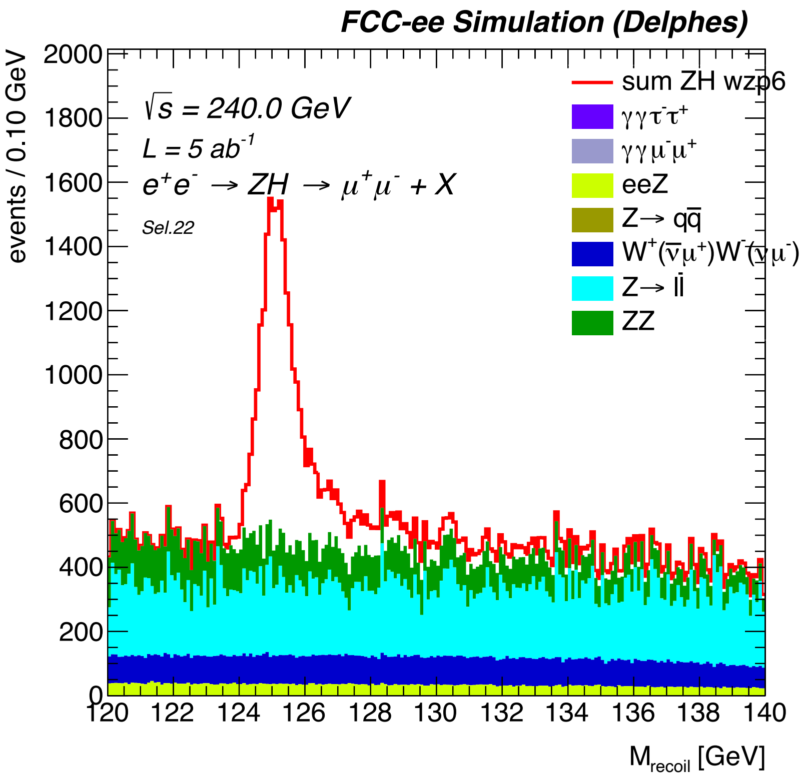
IDEA

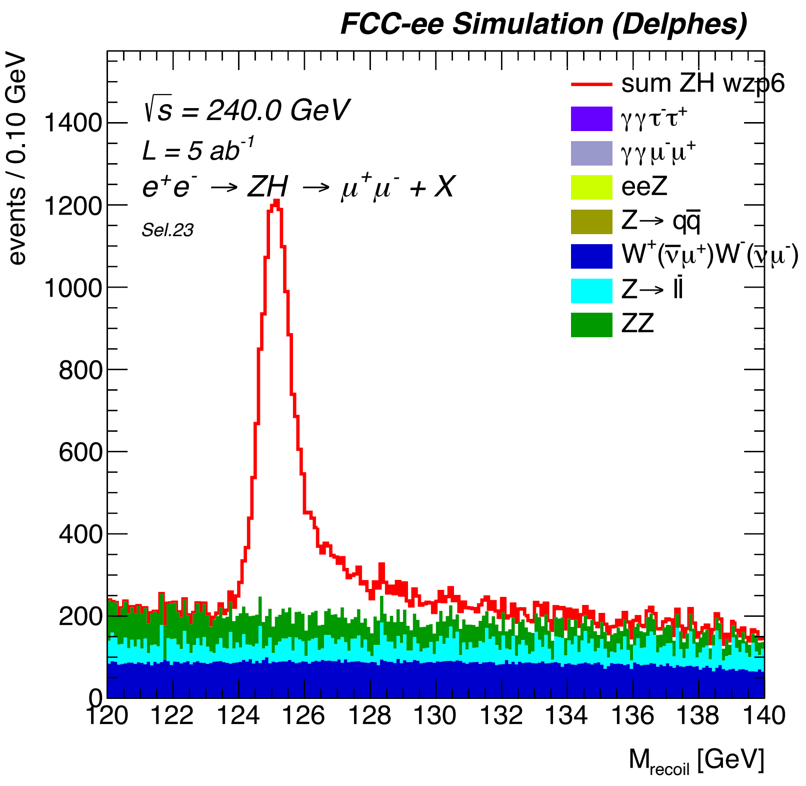


- explicitly designed for FCC-ee/CepC
  - silicon vertex
  - low X_0 drift chamber
  - drift-chamber silicon wrapper
  - MPGD/magnet coil/lead preshower
  - dual-readout calorimeter: lead-scintillating/ cerenkhov fibers
- μRwell for muon detection

Evaluation of M_{recoil} distribution







APC-0-Selection:

1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV
3. $M_{\text{recoil}} \in [120, 140]$ GeV

APC-1-Selection:

1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV
3. $M_{\text{recoil}} \in [120, 140]$ GeV
4. $p_T^{\mu^+\mu^-} \in [20, 70]$ GeV

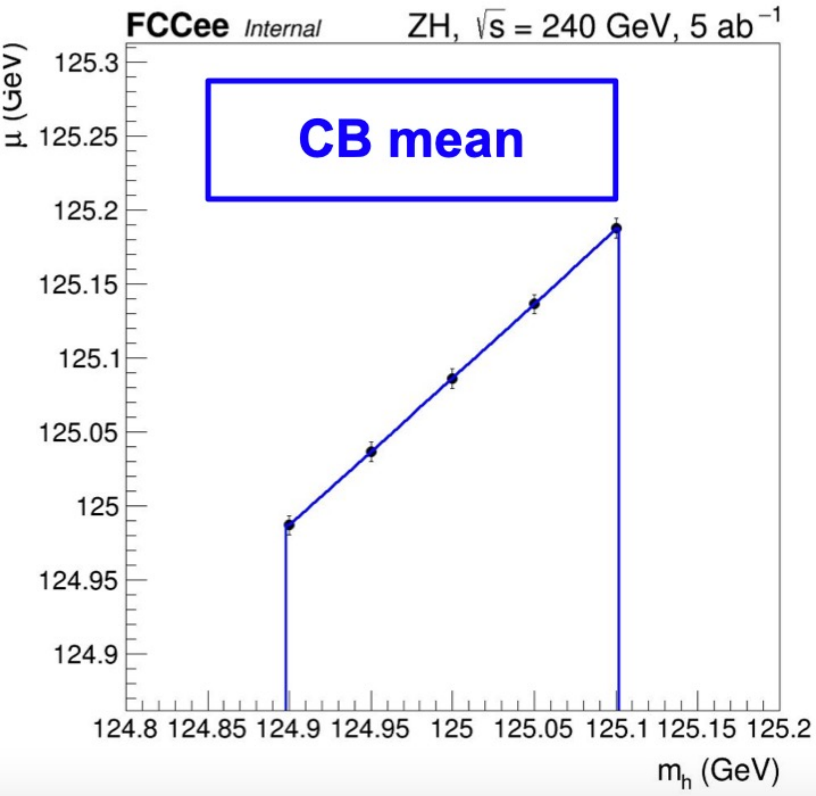
APC-2-Selection:

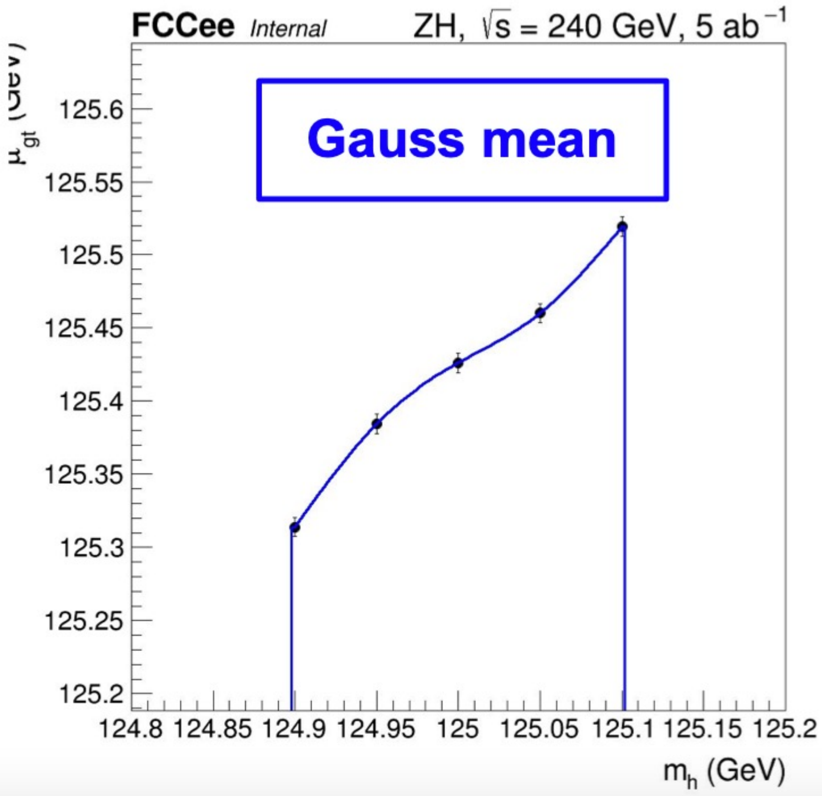
1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV
3. $M_{\text{recoil}} \in [120, 140]$ GeV
4. $p_T^{\mu^+\mu^-} \in [20, 70]$ GeV
5. $|\cos\theta_{missing}| < 0.98$

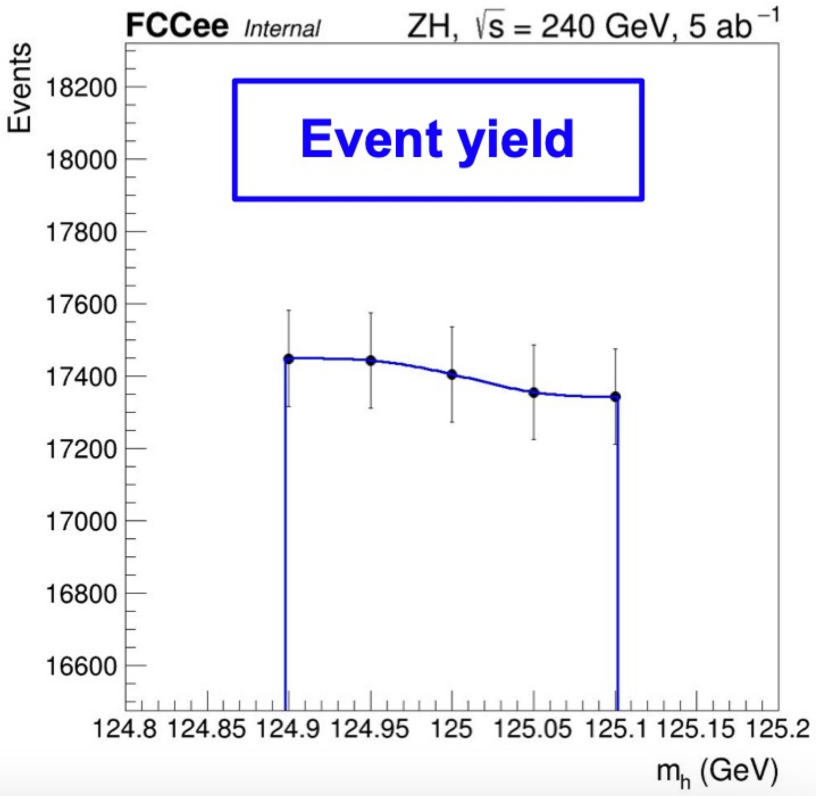
Fitting model and parameter settings

How does the signal shape change as function of (true) Higgs mass mH?

- Generated extra samples around 125 GeV: 124.9, 124.95, 125.05, 125.1 GeV
- Found only significant dependency on the mean (both CB and Gauss) and yields
    - Dependency as function of mH described using Spline
- Other parameters set as constant (best-fit parameters @ 125.0 GeV, see backup for all fits)

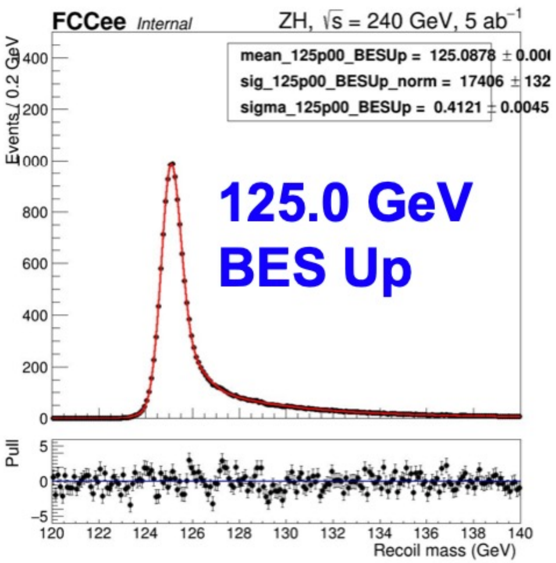


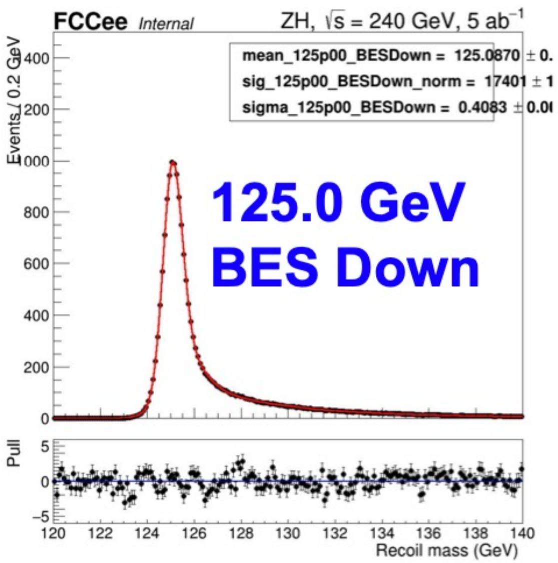


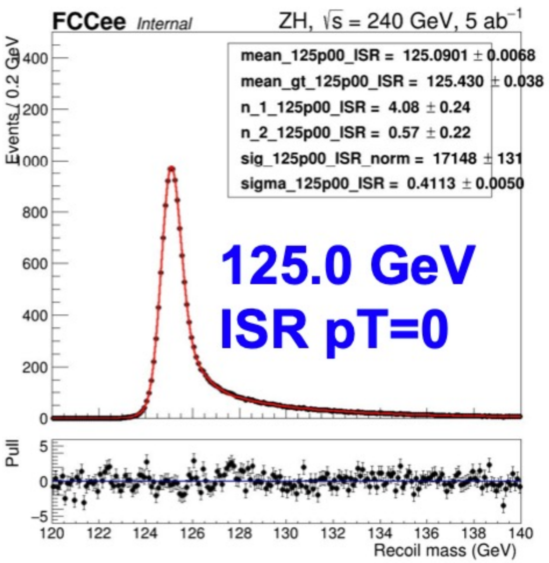


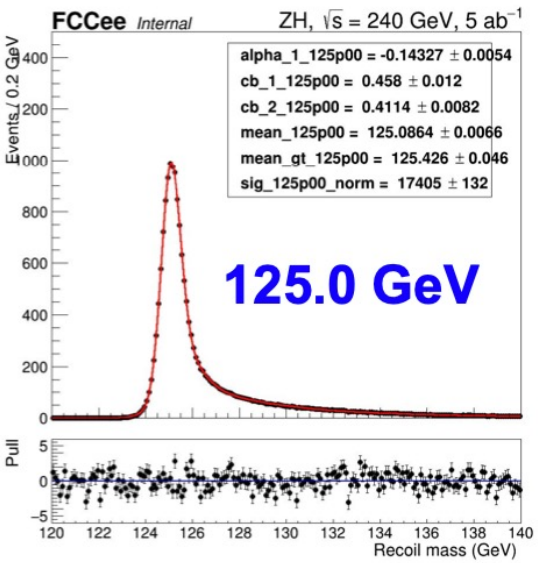
FUTURE CIRCULAR COLLIDER

Signal fits with 2CBG

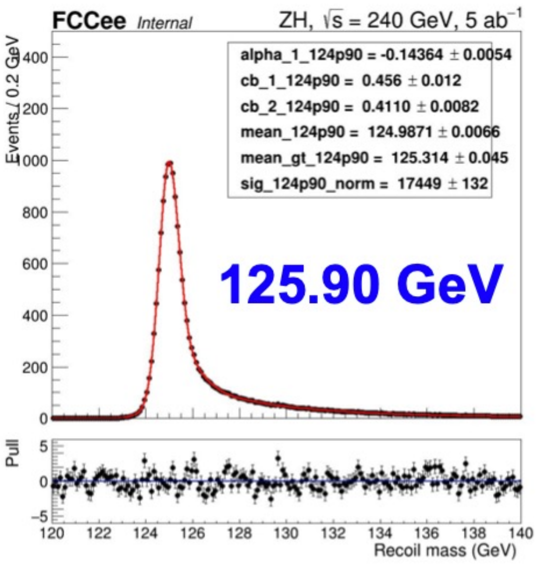


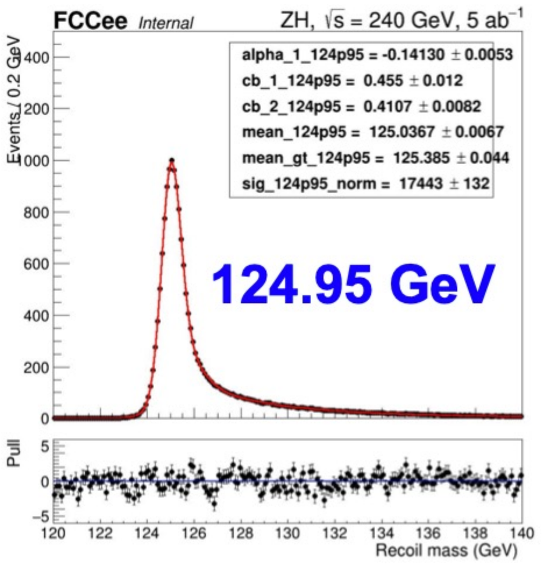


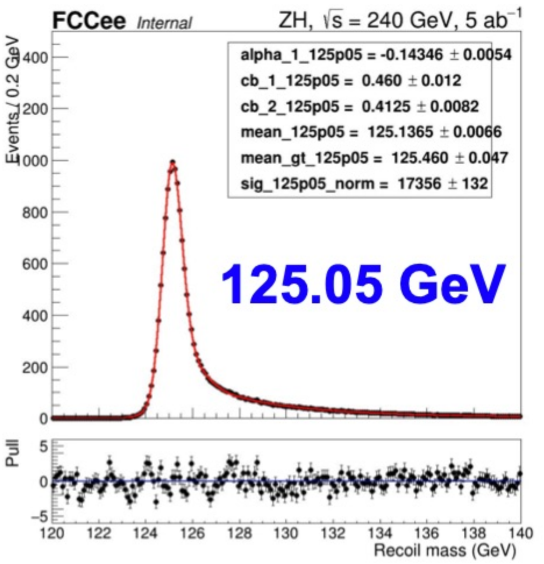


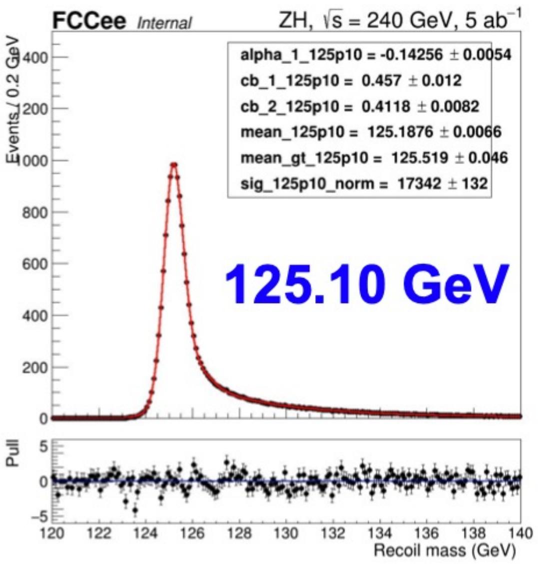


No bias in fits observed



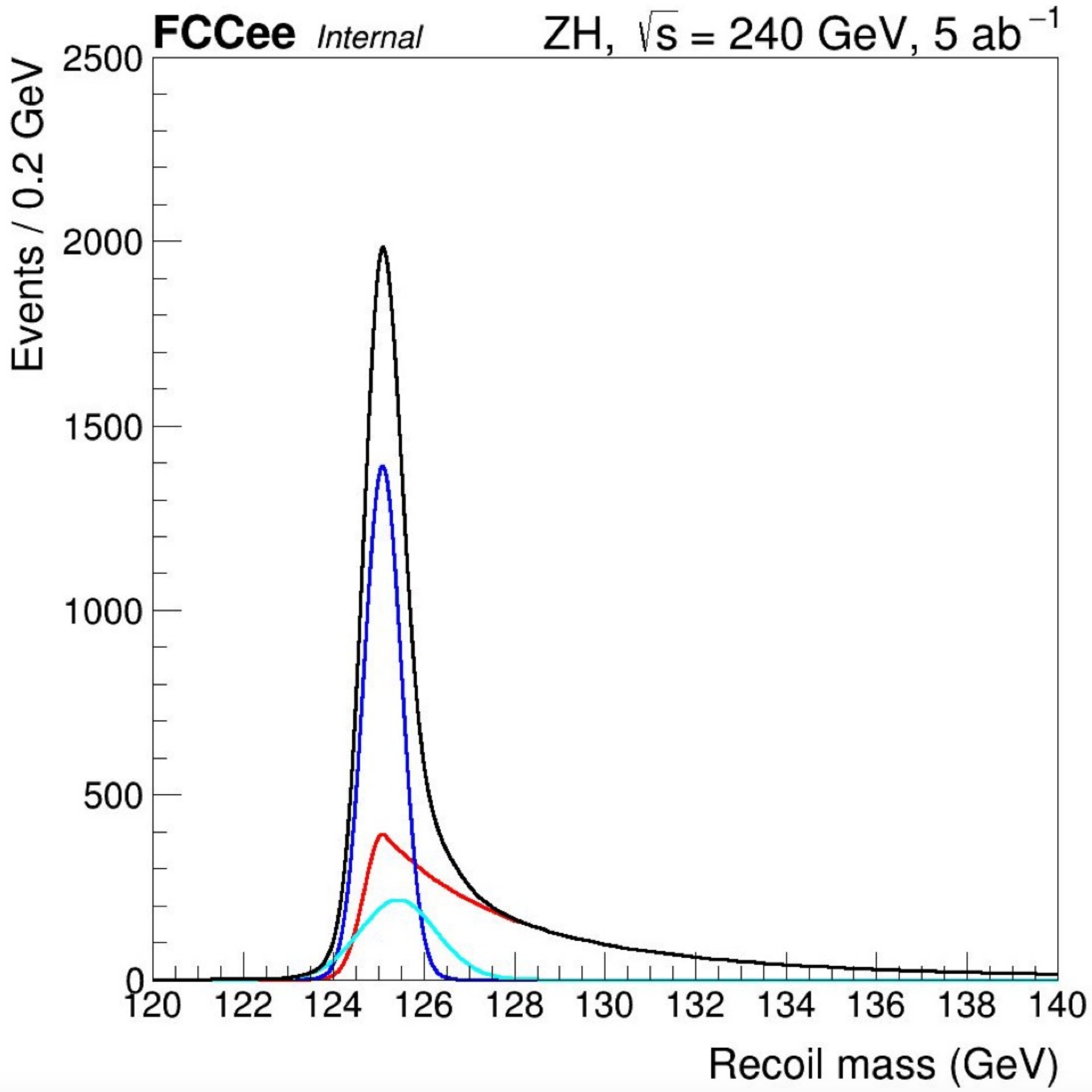




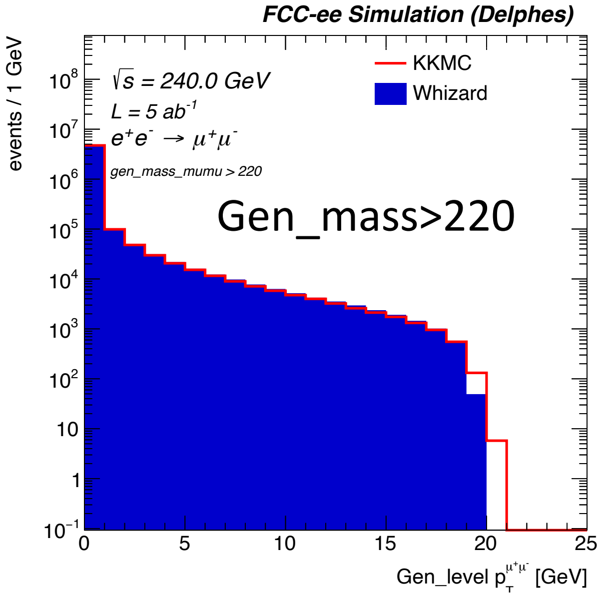


Decomposition of 2CBG

Signal PDF	**1.000**
CB1	**0.4580**
CB2	**0.4114**
Gauss	**0.1306**

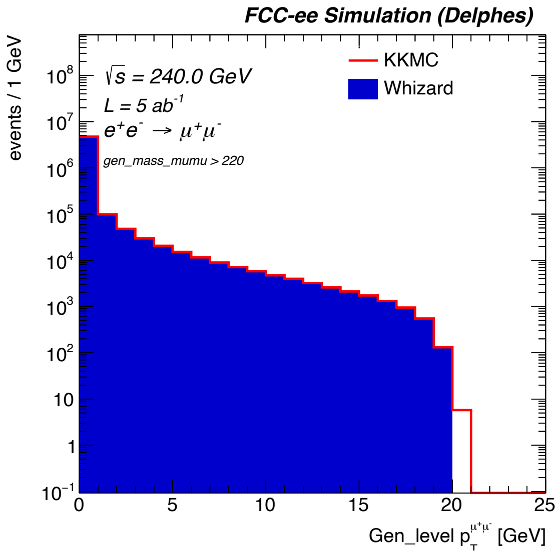


$p_T^{\mu^-\mu^+}$ with and without gen mass> 220 selection

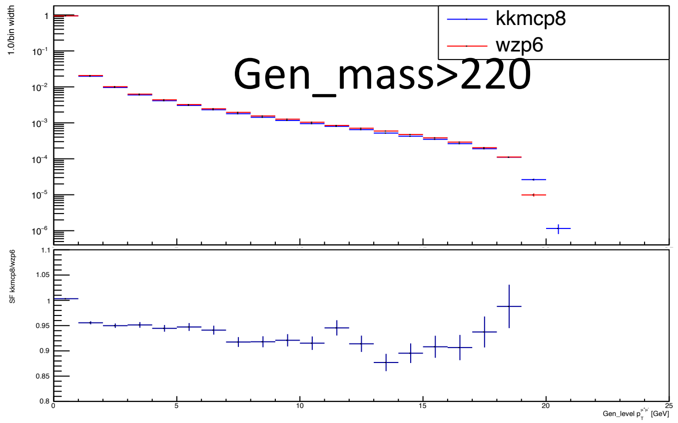


No FSR

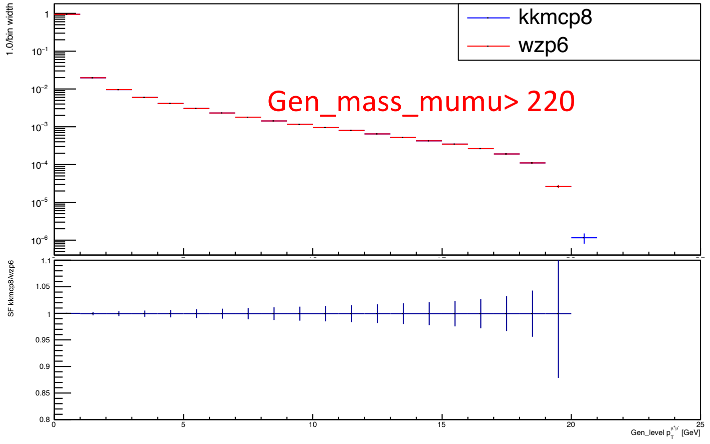
With ISR



After Reweigthing

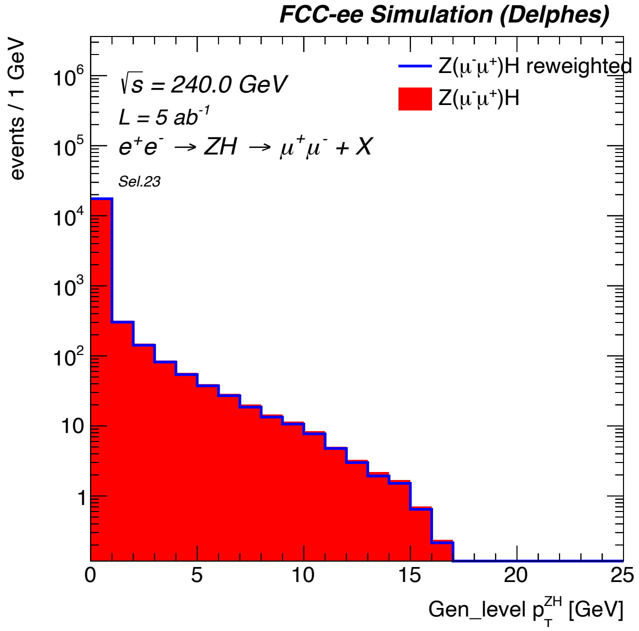


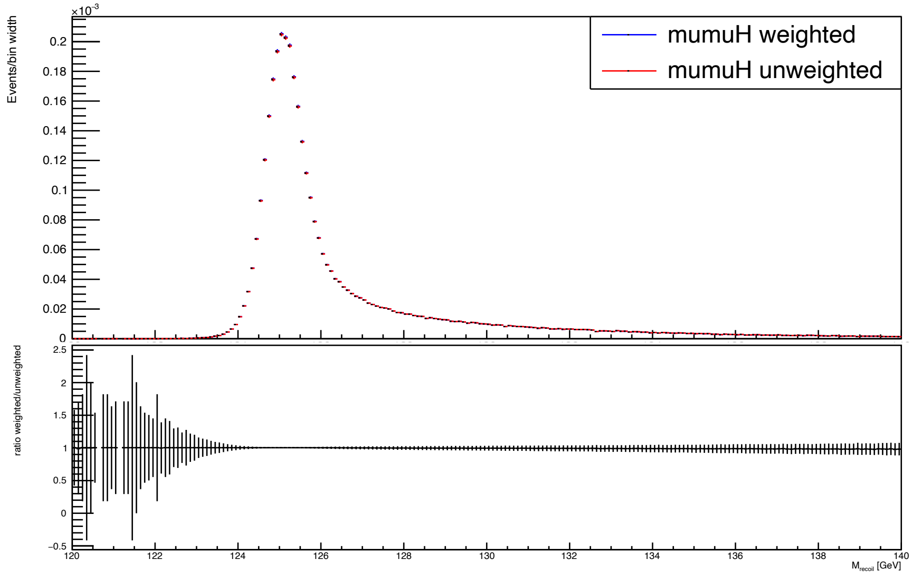
kkmcp8/wzhp6



p_T^{ZH} mumuH reweighting

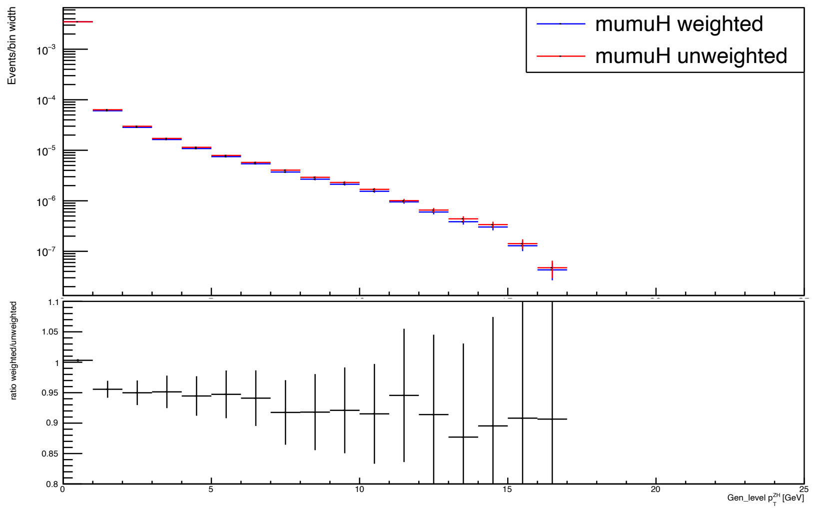
After Reweigthing





M_recoil

Reweighting applied to data Gen_mass_ZH>220 and corresponding Gen_pt_ZH values



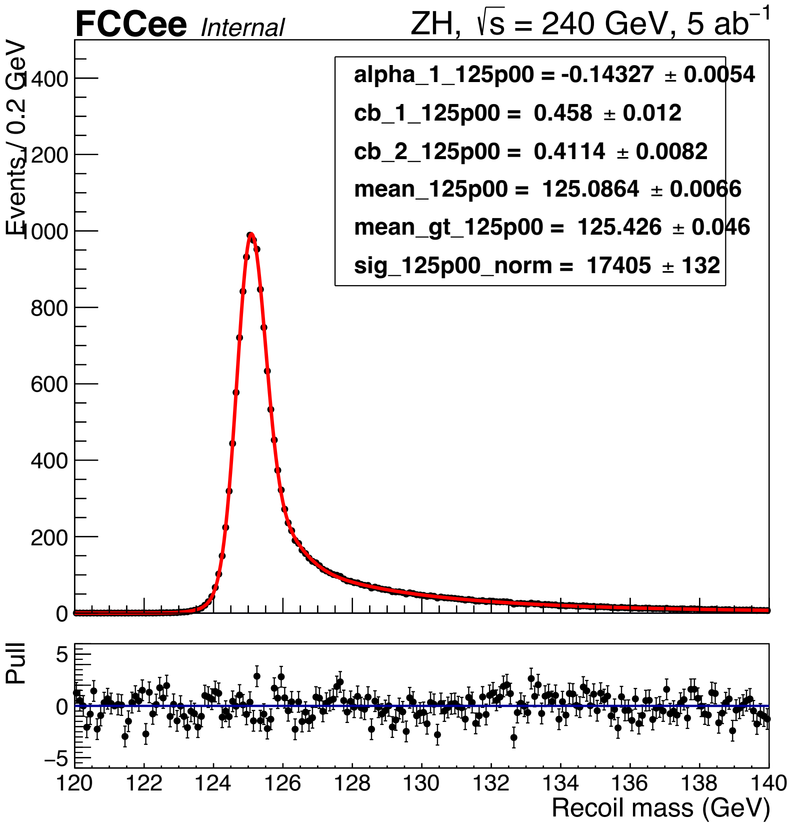
Gen_pt_ZH

- Reweighting is well applied (Gen_pt_ZH plot)
- M_recoil Reweighted/unweigthed ratio ~1

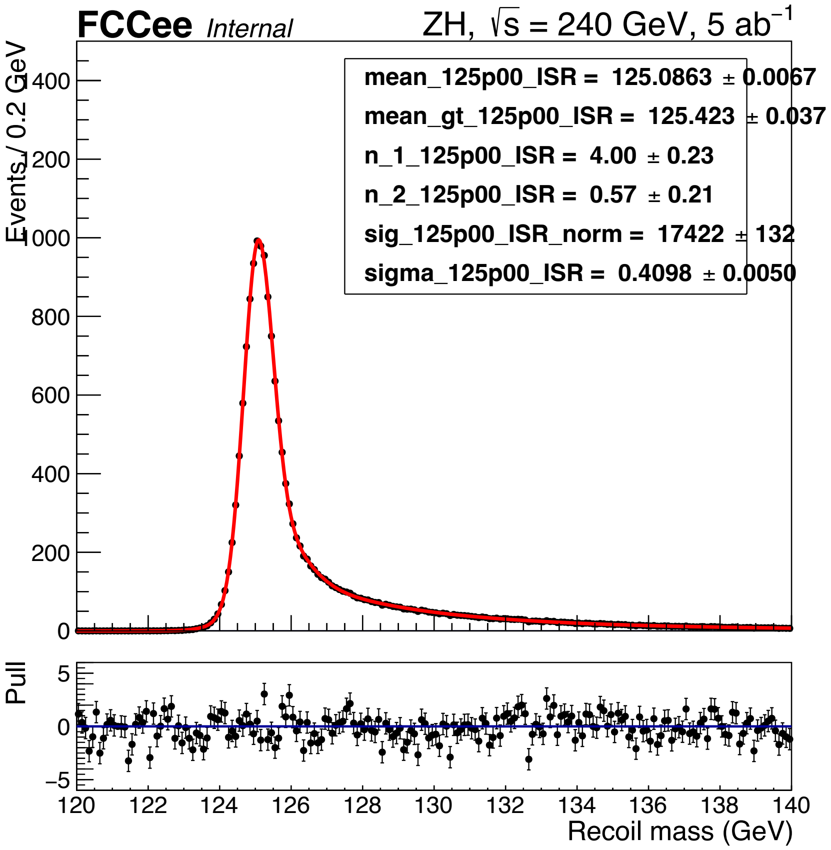
Event-Selection:

1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV
3. $M_{\mathrm{recoil}} \in [120, 140]$ GeV
4. $p_T^{\mu^+\mu^-} \in [20, 70]$ GeV
5. $|\cos\theta_{missing}| < 0.98$

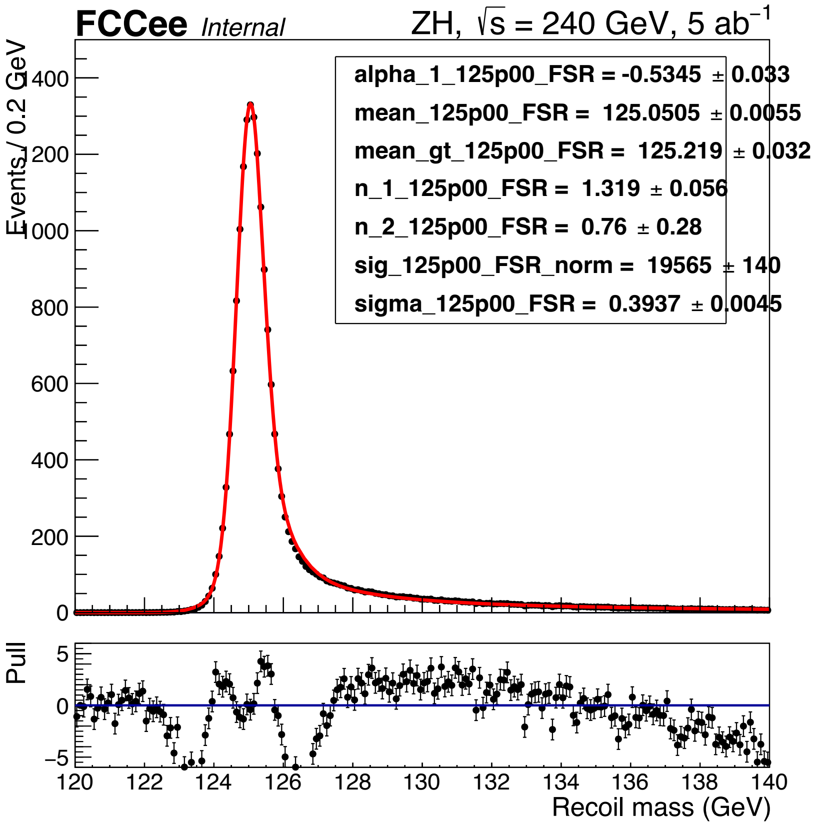
p_T^{ZH} mumuH reweighting, mH Combine fit



Stat. Only



Stat.+ISR (rewei.)



Stat.+FSR (noFSR)