Higgs Physics at FCC-ee: mass and cross-section studies using ZH recoil

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FUTURE CIRCULAR COLLIDER

Outline

FCCee and Higgs physics overview

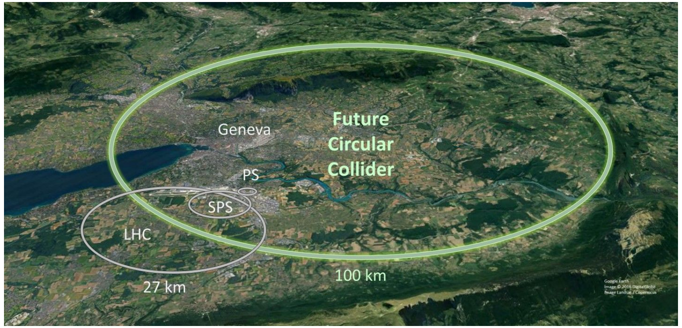
Case study on Higgs mass and cross section measurement

- **Overview and event selection**
- **Signal and background modelling**
- **Statistical analysis and systematics**

FCCee overview

Current design

- e+/e- rings with ~ 100 km in circumference
- Colliding at 2 interaction points



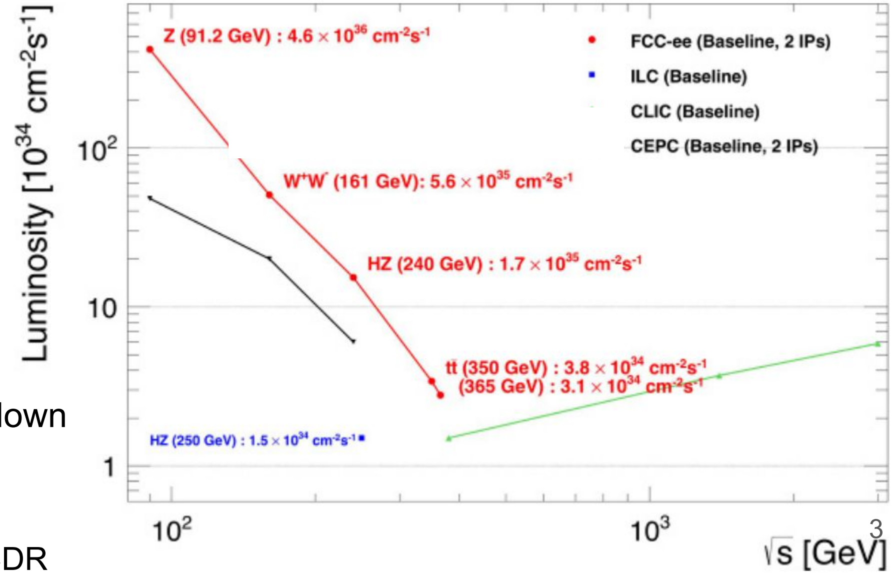
Multiple energy points exploiting large range of physics (*)

- **Z-pole** 91.2 GeV, 4y ~ 150 /ab

  → estimates Δm_Z ~ 100 keV, Γ_Z ~ 100 keV
- **WW-pole** 161 GeV, 2y ~ 12 /ab

  → estimates Δm_W ~ 0.3 MeV, Γ_Z ~ 0.3 MeV
- **H-pole** 240 GeV, 3y ~ 5 /ab → **This talk!**
- **tt-pole** 365 GeV, 5y ~ 1.5 /ab

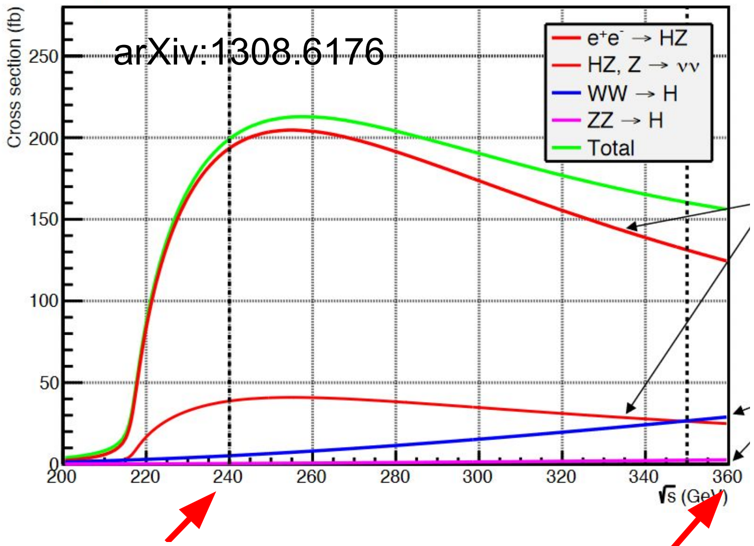
  → estimates Δm_{top} ~ 20 MeV



→ Large constraints on SM EWK parameter space, narrowing down closure tests hence sensitive to new physics up to 70 TeV scale

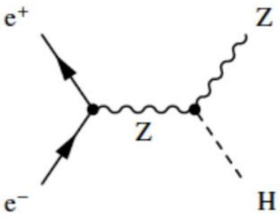
(*) Data from FCCee CDR

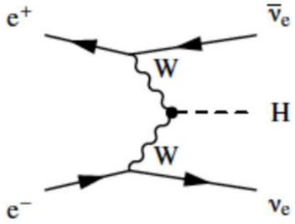
Higgs physics at FCCee



240 GeV, 5 /ab
10^6 ZH events
25k WWH events

365 GeV, 1.5 /ab
200k ZH events
50k WWH events





Higgs-pole at 240 GeV

- Higgs–strahlung dominant: e^+e^- → ZH
- Precise Higgs **mass measurement** up to ~O(MeV)
- Measurement of **decay-mode-independent xsec** up to % level, sensitive to new physics H → invisible
- Higgs width extracted from H → ZZ up to % level

Top threshold at 365 GeV

- Opens significance for WW fusion: e^+e^- → WWvv → Hvv

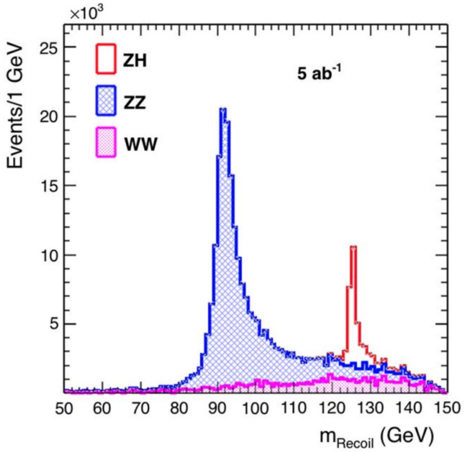
Combined performance at both energy points

- Higgs coupling precision < % level
- In particular, exotic Higgs decays constraint to < 1 %
- Probing CP violation using H → ττ phase

Higgs mass and cross section estimates

Case study: estimate the Higgs mass and decay-mode independent cross-section

- Probe $e^+e^- \rightarrow ZH \rightarrow ll + X$ at 240 GeV
- $Z \rightarrow \mu\mu$ considered for now (electron channel will be added)
- Backgrounds: dominated by vector boson (pair) production: WW, ZZ, Z/γ*
- Assess impact on dominant systematic uncertainties (both machine and detector)

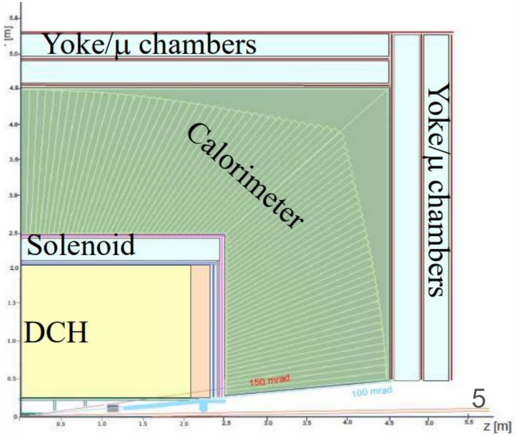


Recoil mass: sharp peak at Higgs mass, width dominated by detector resolution

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

Sample production and analysis within official FCC framework

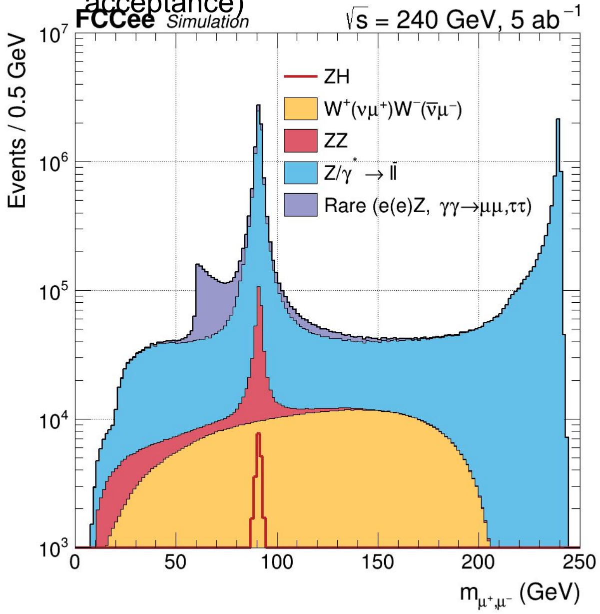
- Generators: Whizard+Pythia (signal) and Pythia (backgrounds); see backup
- Reconstruction with Delphes
- “IDEA” detector: silicon vertex detector + drift chambers embedded in 2T solenoid, double-readout copper calorimeter, μRwell muon chambers

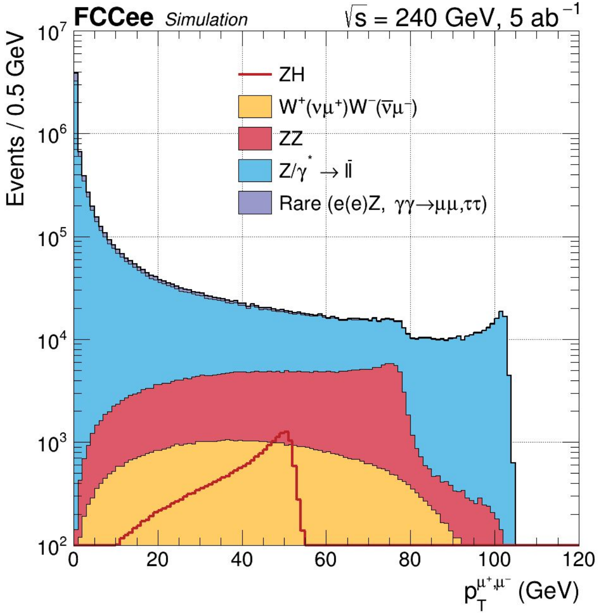


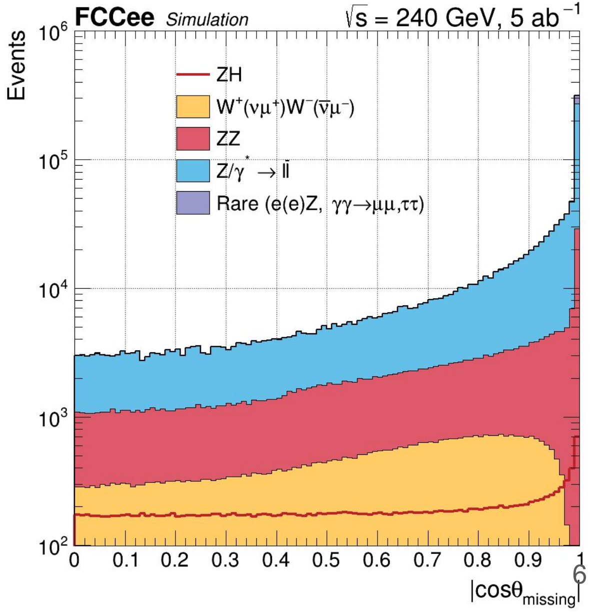
Event selection

Muon object selection: p_T > 10 GeV, standard isolation and acceptance criteria

1. Single μμ pair with charge 0
2. 86 < m(μμ) < 96 GeV: focus on Z-resonance kinematics phase space
3. 20 < p_T(μμ) < 70 GeV: signal mainly within this region, large suppression of Z/γ* → ll
4. |cos($\theta_{missing}$)| < 0.98: polar angle of missing momentum, effectively reduces γγ→μμ,ττ (ISR collinear with beam pipe escaping acceptance)





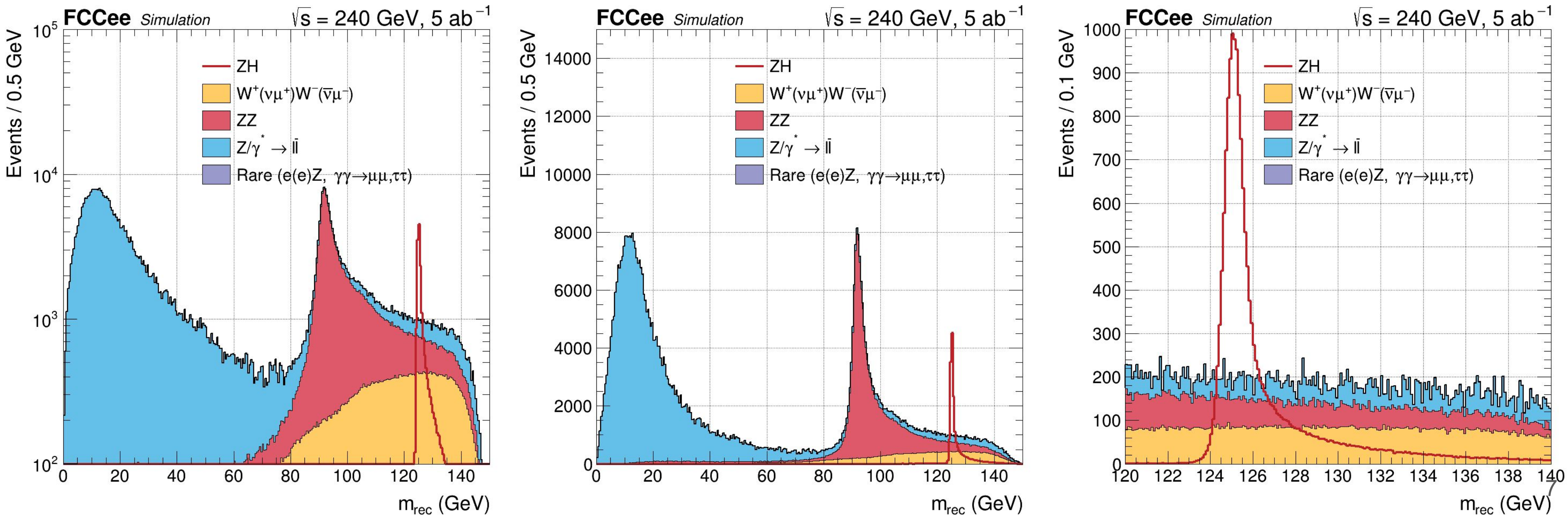


Recoil mass distribution

Additional cut on recoil mass distribution, focusing on 125 GeV recoil region: $120 < m_{rec}$ 140 GeV

- Signal exhibits sharp peak around ~ 125 GeV, width dominated by detector resolution effects, high-mass tail sensitive to ISR
- Smoothly falling background

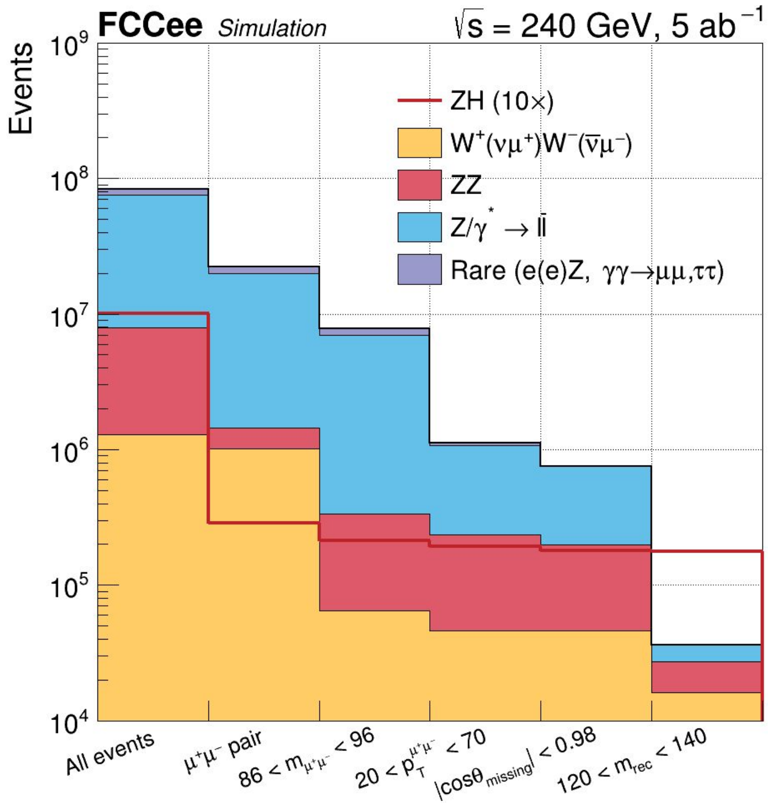
→ Recoil at Z-peak allows to constrain and tune data/MC (can be used as control region with data)



Event yields

Z(μμ)H	**17405.28 ± 24.26**
Z(ττ)H	11.6 ± 0.6
Z(ee)H	9.0 ± 0.6
Z(qq)H	165.9 ± 3.4
Z(νν)H	66.8 ± 2.3

WW → μμ	16194.4 ± 45.7
ZZ	10835.9 ± 85.8
Z/γ* → ll	9269.3 ± 254.0
Rare (e(e)Z,γγ→μμ,ττ)	33.2 ± 2.2
Z/γ*→qq	0.0 ± 0.0
Total backgrounds	**36333 ± 191**

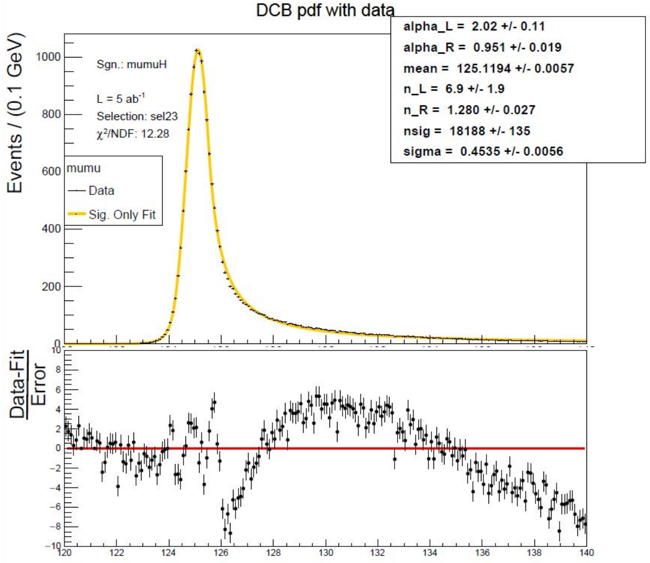


Signal modelling (1)

Correct signal modelling crucial to assess impact of shape on mass dependency and shape systematic uncs.

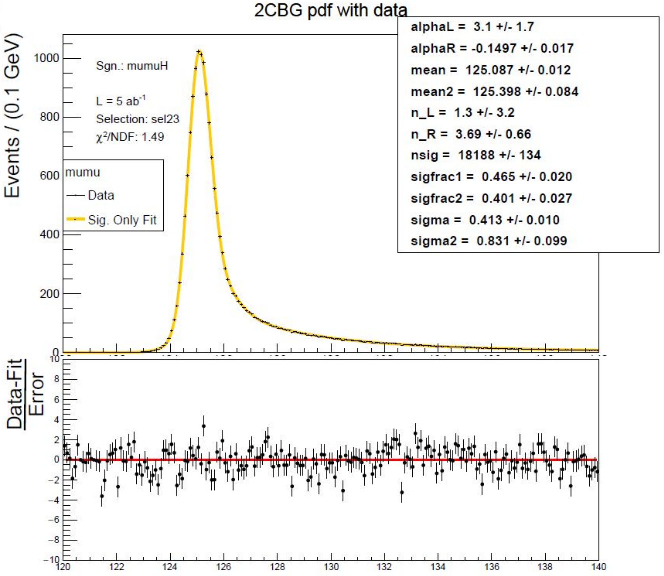
- Typically recoil models as (two-sided) Crystal-Ball, but does not describe well the Whizard recoil distributions (nor Pythia)
- Efforts to optimize and tune signal parameterization: new proposed PDF with 2 CBs + Gaussian to fit the tails

$$\mathrm{pdf}_{rec} = cb_1 \mathrm{CB}(\mu, \sigma, \alpha_1, n_1) + cb_2 \mathrm{CB}(\mu, \sigma, \alpha_2, n_2) + \mathrm{Gauss}(\mu_{gt}, \sigma_{gt})$$



M_{recoil} [GeV]

Two-sided Crystal-Ball



M_{recoil} [GeV]

New/Improved PDF

New proposed PDF:

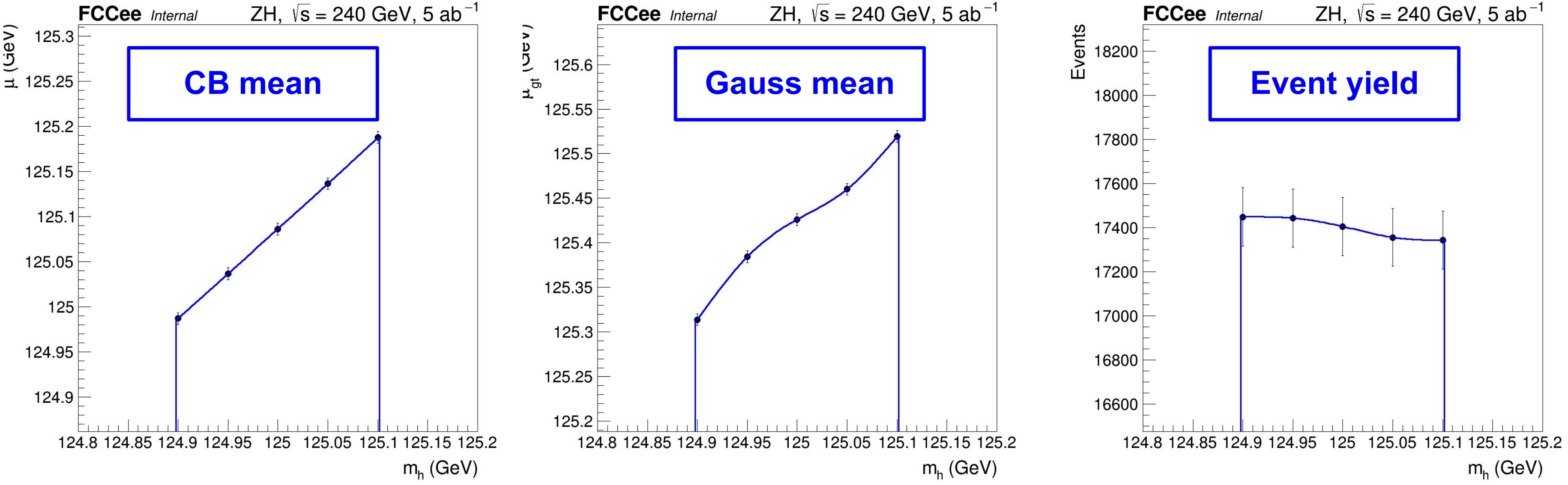
- 10 free params + norm
- High DOF
- Interpretation of params not straightforward (especially 2 mass terms)

Additional studies involving signal shape modelling with other MC generators (Sherpa)

Signal modelling (2)

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

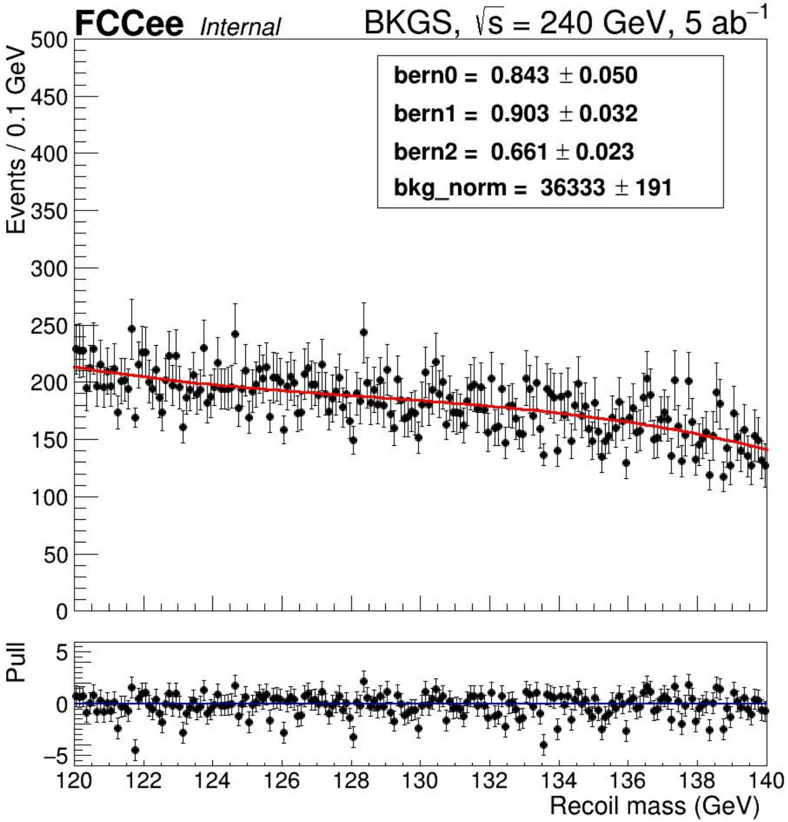
- Generated extra samples around 125 GeV: 124.9, 124.95, 125.05, 125.1 GeV
- Found only significant dependency on the mean (both CB and Gauss) and yields
  - Dependency as function of mH described using Spline
- Other parameters set as constant (best-fit parameters @ 125.0 GeV, see backup for all fits)



Background modelling

Statistical treatment of backgrounds

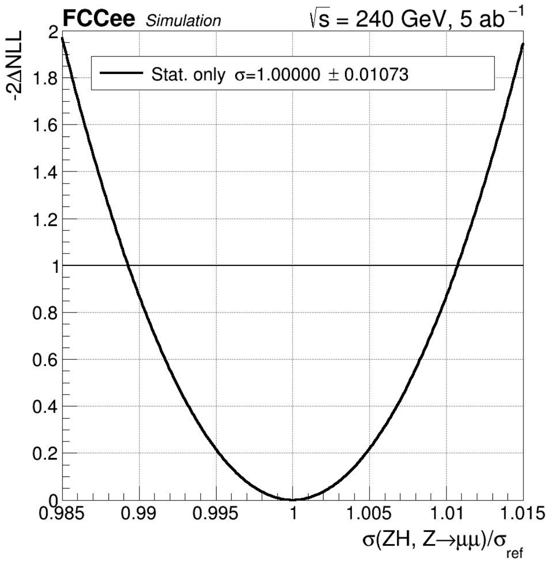
- All backgrounds are merged
- Smoothly falling background modelled as **third-order polynomial fit**
- Keep polynomial coefficients constant, but keep total normalization floating
- Sufficient sample statistics for all backgrounds (~ 4x expected at 5 /ab), except for Z/γ*→ll where slightly more MC is necessary

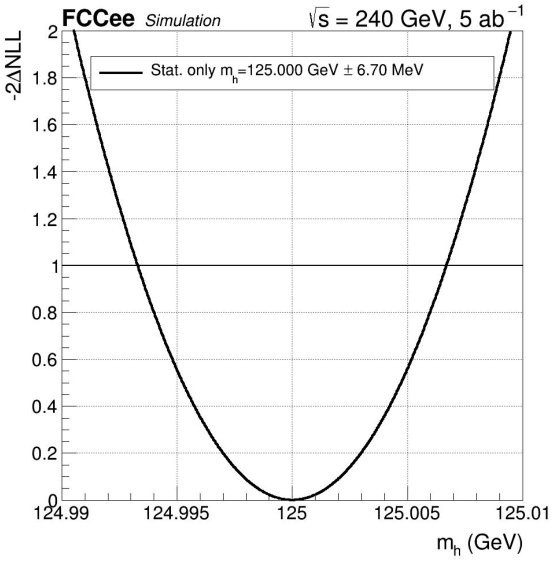


Likelihood scans

Statistical analysis performed using Combine, the CMS statistical framework developed in context of Higgs analyses (*)

- Signal and background analytical shapes are fitted to pseudo-data Asimov dataset (= randomized with mean=signal+background)
    - Injected 125.0 GeV signal with cross-section of 0.0067656 pb (ref)
    - Free parameters: signal norm, background norm and mH floating
- Likelihood scans to extract cross-sections and Higgs mass with robust uncertainties
- First, w/o accounting for experimental uncertainties → **stat-only result**





Stat-only uncertainties:
→ Cross-section: ~ 1.1 %
→ Higgs mass: 6.70 MeV

(*) The ATLAS, CMS Collaborations, and LHC Higgs Combination Group. Procedure for the LHC Higgs boson search combination in Summer 2011. Technical Report CMS-NOTE-2011-005. ATL-PHYS-PUB-2011-11, CERN, Geneva, Aug 2011

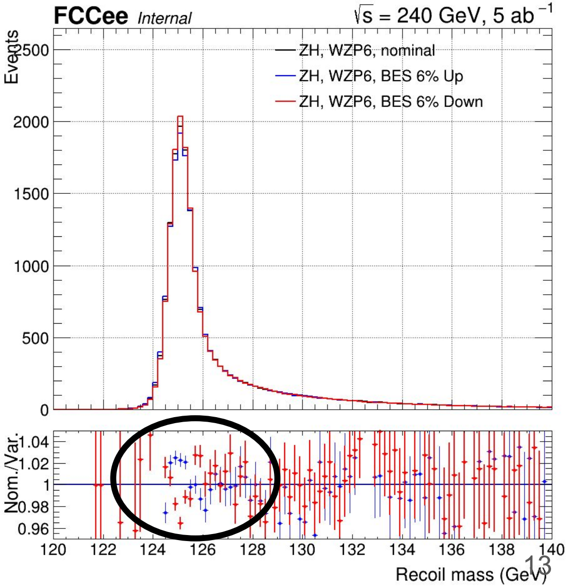
Systematic uncertainties (1)

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

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

1) Beam energy spread uncertainty (nominal BES: ± 0.165% = ± 198 MeV)

- Uncertainty driven by 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**



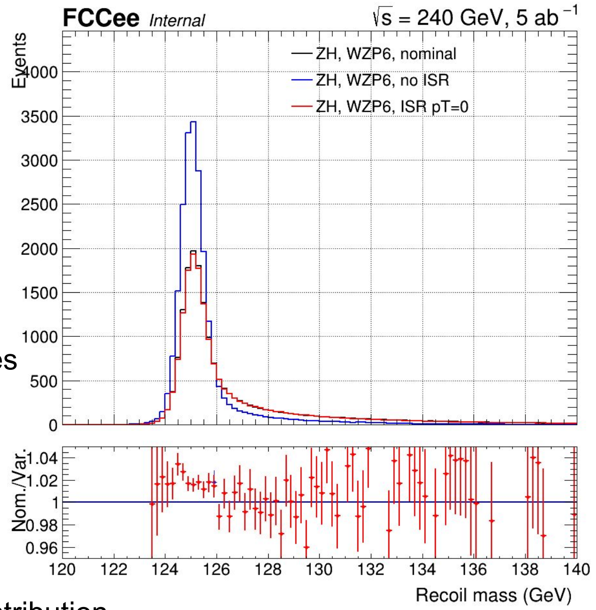
Generated perturbed signal samples @ 125.0 GeV with:

- 6% BES variation: 2-3 % shape effect observed at mass peak
- 1% BES variation: negligible variation ~ within statistical uncertainty

Systematic uncertainties (2)

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

- ISR treatment in Whizard using structure function approach: photon p_T spectrum
  - either strict collinear approximation (p_T = 0)
  - or ad-hoc implementation of a physical spectrum (default sample)
- Generated perturbed sample in the strict collinear approximation
  - rather drastic → **very conservative estimation of ISR uncertainty !**
- Benchmarking against KKMC at Z-peak and/or Sherpa to obtain more realistic uncertainties for ISR treatment
- Can be constrained directly using data-driven techniques (including BES)



3) Center-of-mass: +/- 2 MeV

- √s parameter in the recoil mass definition → uncertainty induces ~ linear shift the recoil distribution
- Precision estimated to be 2 MeV at 240 GeV using radiative return events Z → ll or Z → qq

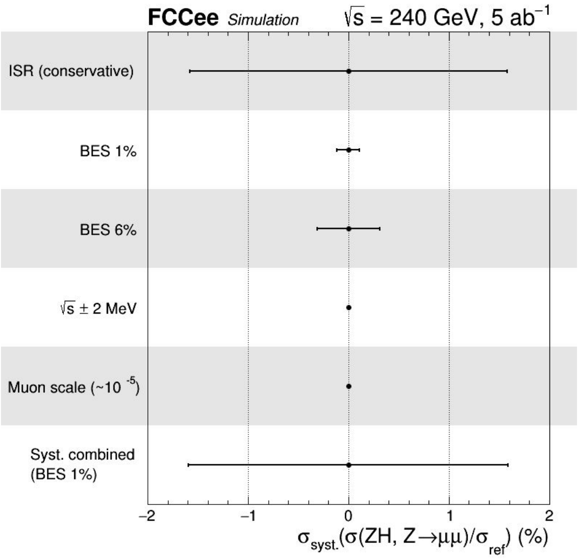
4) Muon momentum scale: relative scale uncertainty variation of 1e-5

- Directly affects m(μμ), hence shift in recoil mass
- Statistical potential to measure muon scale ~ 1e-6, but NMR probes so far limited to yield 1e-5 uncertainty

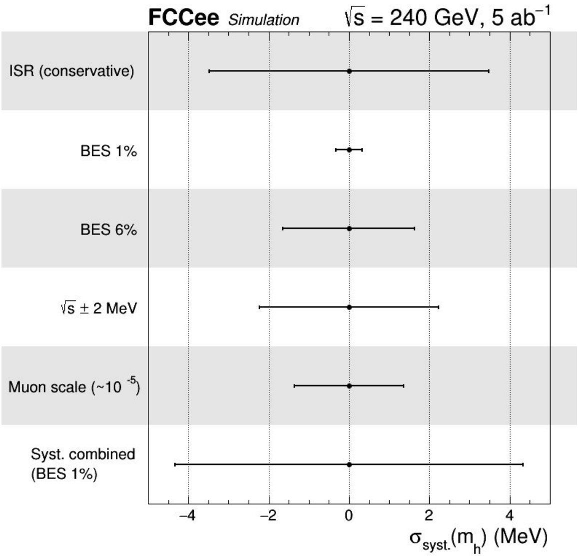
Systematic uncertainties (3)

Systematic variations included in likelihood as Gaussian constraint terms

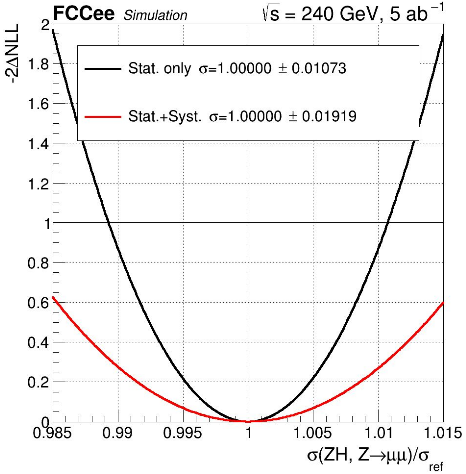
- Inclusion of all systematics: Δm_H = 7.98 MeV and $\Delta\sigma$ = 1.92 %
- Breakdown of uncertainties: vary systematics one by one, extract $\sigma^2_{syst} = \sigma^2_{tot} - \sigma^2_{stat}$
- ISR dominant (but conservatively estimated), muon scale/√s accounts for ~ 2 MeV on Δm_H
- Impact on cross-section limited, except ISR

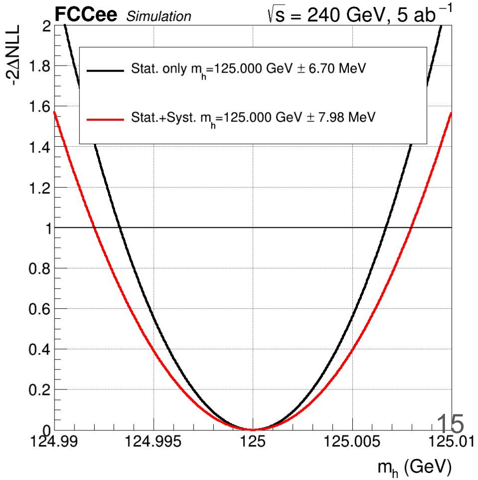


Cross section (%)



Mass (MeV)





Summary and outlook

FCCee programme delivers high-precision EWK measurements, constraining parameter space of the SM with high sensitivity for new physics and discovery potential

Presented case study ZH recoil analysis

- Extract Higgs mass and decay-mode independent cross-section with proper uncertainties
- Statistical analysis yields Higgs mass uncertainty 6.7 MeV, cross-section 1.1 % (stat-only)
- Inclusion of systematic uncertainties results into 8 MeV / 1.9% respectively, where ISR dominant but conservatively estimated

Outlook

- Benchmark ISR against KKMC/Sherpa and validate ISR treatment in Whizard
- Signal shape studies between Whizard and Sherpa
- Inclusion of electron channel

Backup

Signal and background samples

Monte-Carlo campaign ("Spring2021"):

- Center-of-mass 240 GeV, luminosity of 5 /ab
- ISR, FSR enabled, Beam Energy Spread (BES) set to 0.165% = ± 198 MeV (cfr. CDR)
- IDEA detector; detector response modelled with Delphes

Signal samples (Whizard+Pythia6)

-	Z(μμ)H	0.0067656 pb
-	Z(ττ)H	0.0067518 pb
-	Z(ee)H	0.0071611 pb
-	Z(qq)H	0.13635 pb
-	Z(νν)H	0.046191 pb

→ nominal Higgs mass 125.00 GeV

→ off-mass samples generated at +/- 50 and +/- 100 MeV

Background samples (Pythia8)

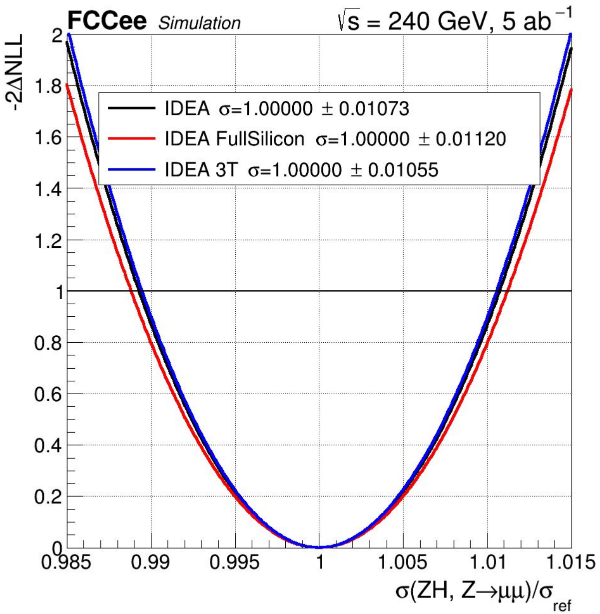
-	ZZ	1.35899 pb	
-	WW→μμ	0.25792 pb	
-	Z/γ*→ll	13.7787 pb	
-	Z/γ*→qq	52.6539 pb	
-	e(e)Z (*)	0.20736 pb	
-	γγ→μμ (*)	1.5523 pb	[m_{gen}(μμ) > 60 GeV]
-	γγ→ττ (*)	0.836 pb	[m_{gen}(ττ) > 60 GeV]

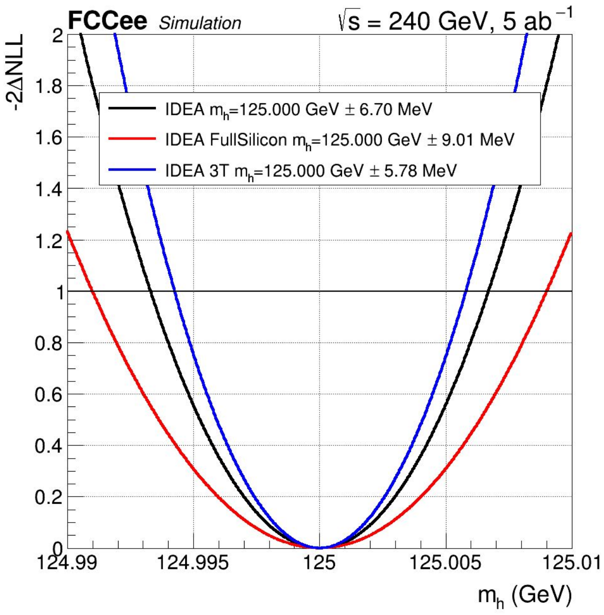
(*) Generated with Whizard+Pythia6

IDEA detector configurations

Different IDEA detector configurations studied:

- Magnetic field increased from 2T to 3T → expected better momentum resolution
- FullSilicon tracker instead of drift chamber → degraded resolution due to enhanced multiple scattering, especially at low p_T and in the range relevant for this analysis
- Effect on mass scales with resolution, impact on cross-section uncertainty limited

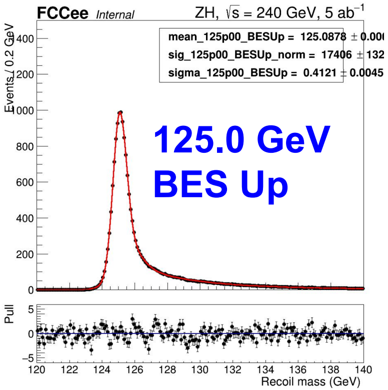


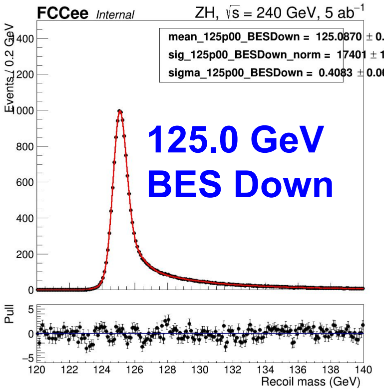


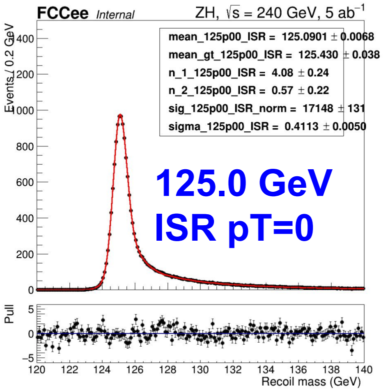
Stat-only results

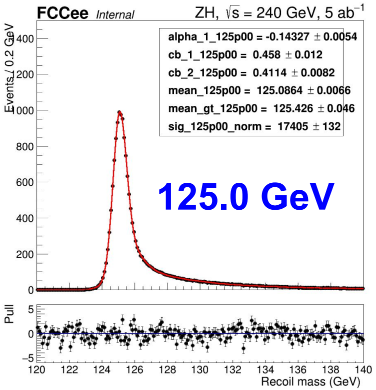
IDEA	Δm_H (MeV)	Δσ (%)
Nominal	**6.70**	**1.07**
FullSilicon	**9.01**	**1.12**
3T	**5.78**	**1.06**

Signal Fits with 2CBG

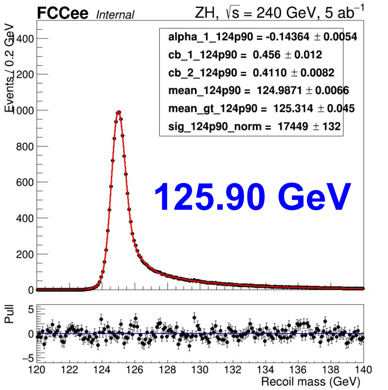


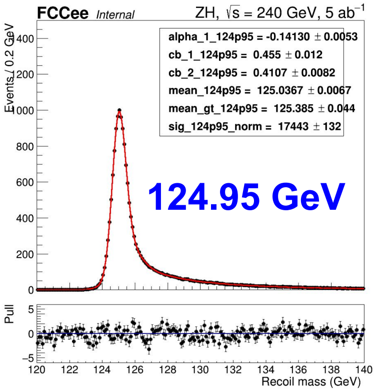


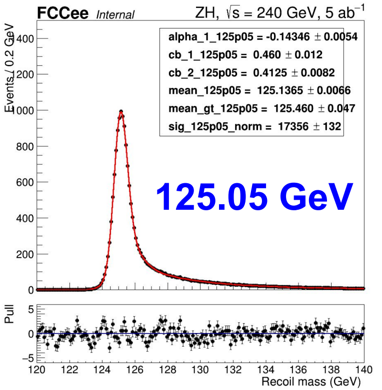


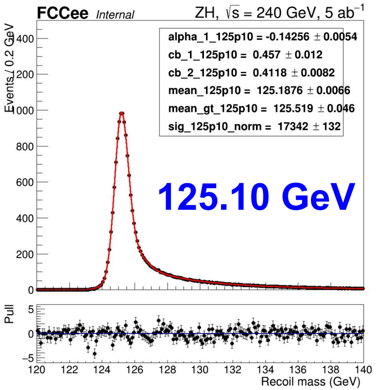


No bias in fits observed

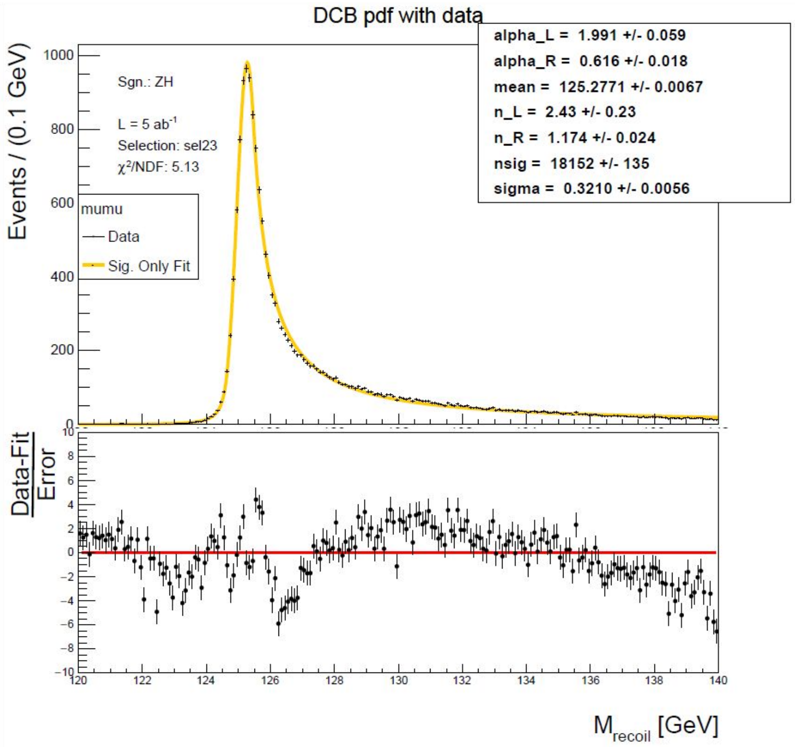


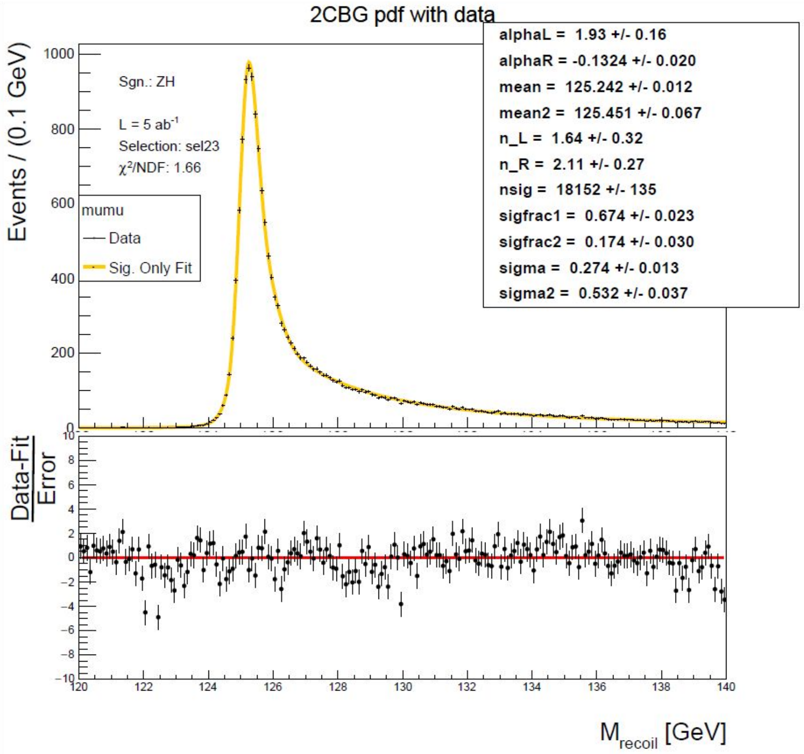






Signal modelling with Pythia



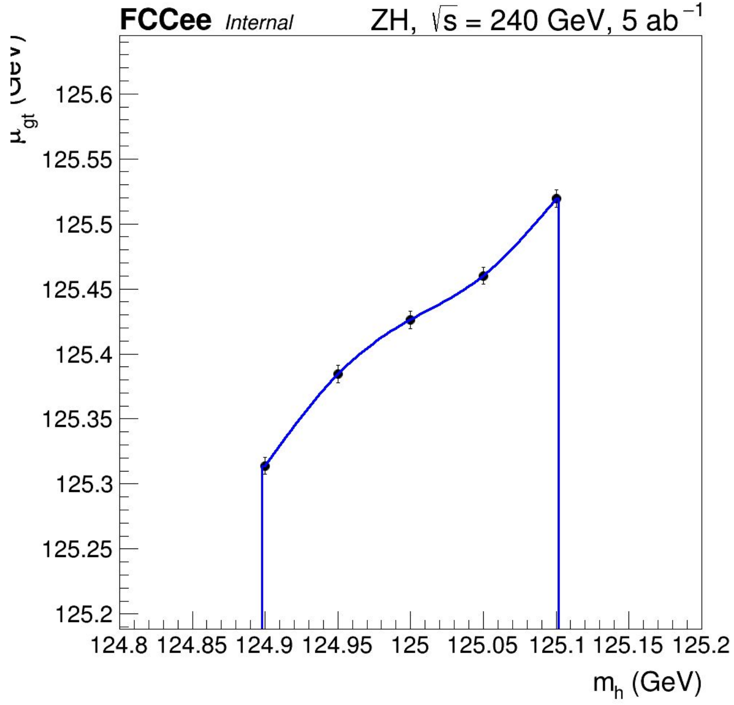


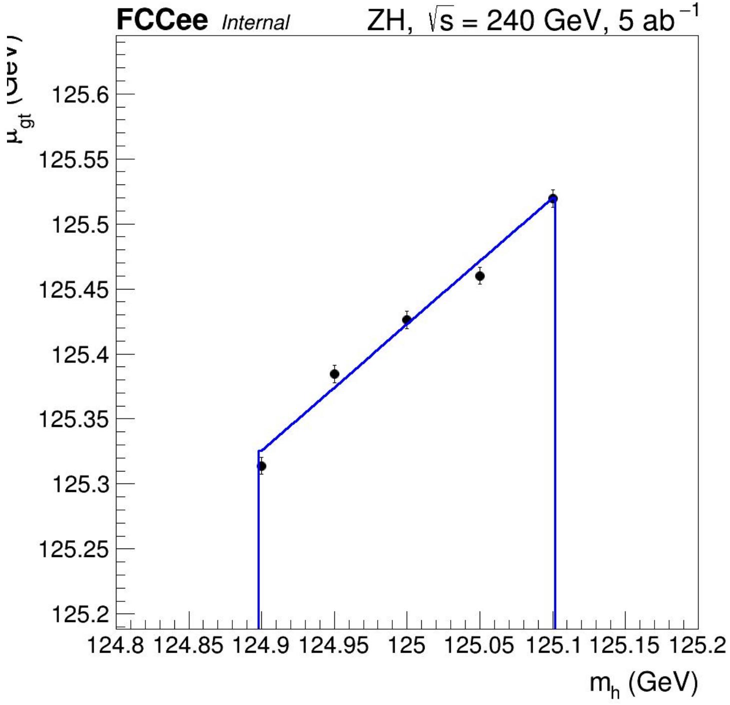
Gauss tail mean: Spline vs. Linear

Cross-section unc.: -1.880/+1.937 %
Mass unc.: -7.946/+7.947 MeV

Cross-section unc.: -1.877/+1.934 %
Mass unc.: -7.881/7.864 MeV

Difference in mass uncertainty ~ 74 keV, cross-section negligible





Decomposition of PDF 2CBG

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