

# The total $e^+e^- \rightarrow ZH$ cross section $\sigma_{ZH}$ and mass measurement from the recoil

Ang Li

(APC-Paris, Université de Paris, CNRS/IN2P3)

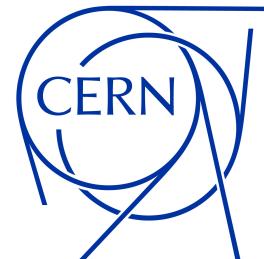
On behalf of the FCC-ee ZH analysis team

3rd FCC-France / Higgs & ElectroWeak Factory Workshop

Annecy, December 2<sup>nd</sup> 2021



Université  
de Paris



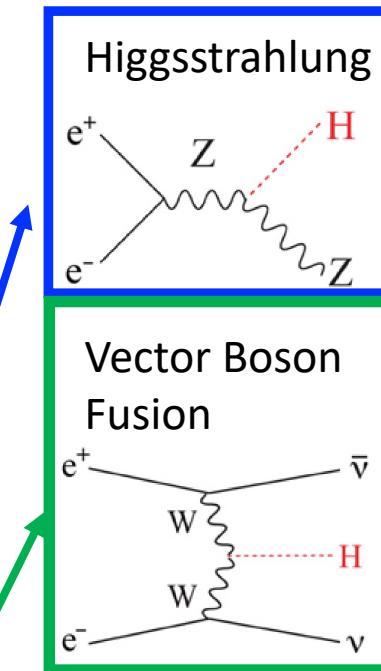
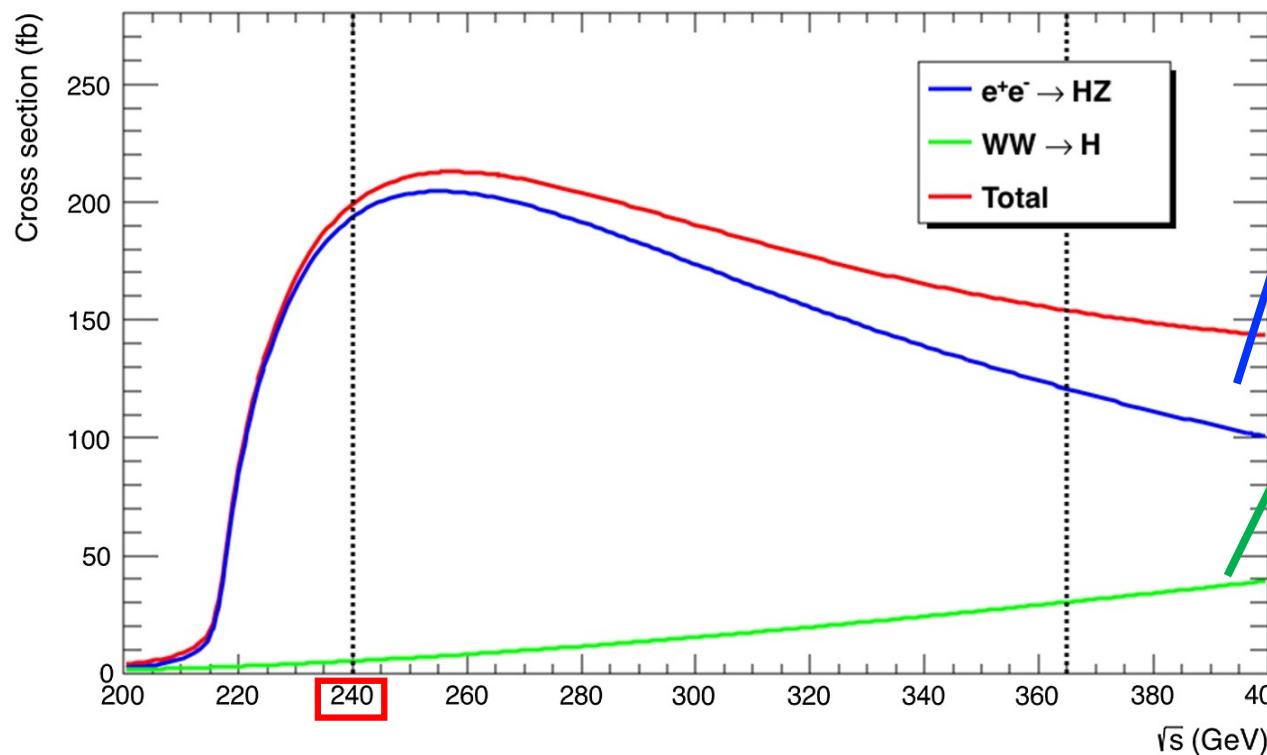
FUTURE  
CIRCULAR  
COLLIDER

- Motivation
- Recoil mass technique
- Event selection
- Signal and background modelling
- Statistical analysis and Systematics

# Motivation

➤ Goal: precise measurements of ZH cross section and Higgs mass

- Current best result:  $m_H = 125.38 \pm 0.14 (\pm 0.12)$  GeV @CMS
- At FCC-ee,  $m_H$  and  $\sigma_{ZH}$  accuracy will reach a few MeV and 0.5%, respectively
  - Measure  $g_{HZZ}$ , Higgs width ( $\Gamma_H$ ) and other Higgs couplings
- Electron Yukawa coupling measurement via s-channel
  - $e^+e^- \rightarrow H$  @ $\sqrt{s} = m_H$  ( $\Gamma_H = 4.2$  MeV) (details on [arXiv:2107.02686](#))
- Trilinear Higgs-self coupling (details on [arXiv:1809.10041](#))



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

- Signal:  $e^+e^- \rightarrow ZH \rightarrow l\bar{l} + X$

ZH is the dominant Higgs production process @ 240 GeV  $e^+e^-$  machine

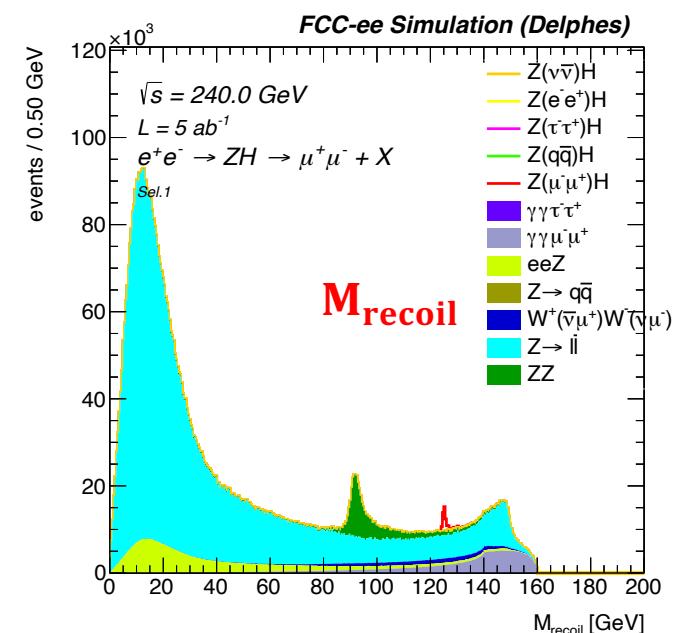
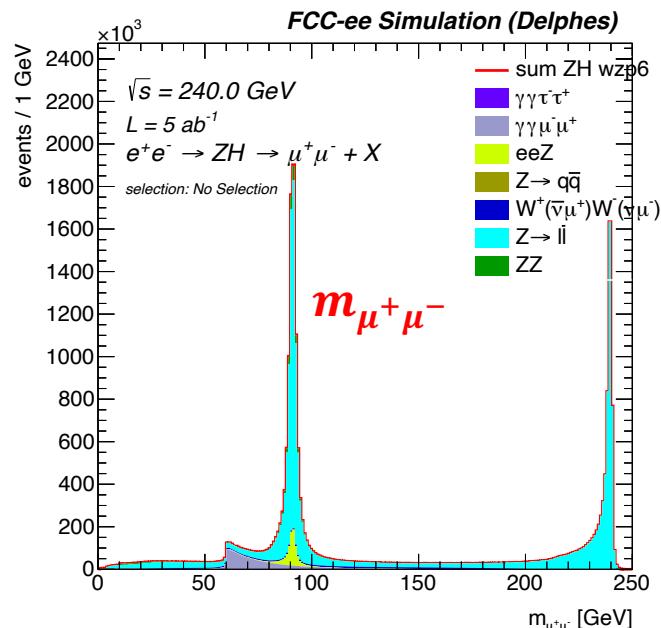
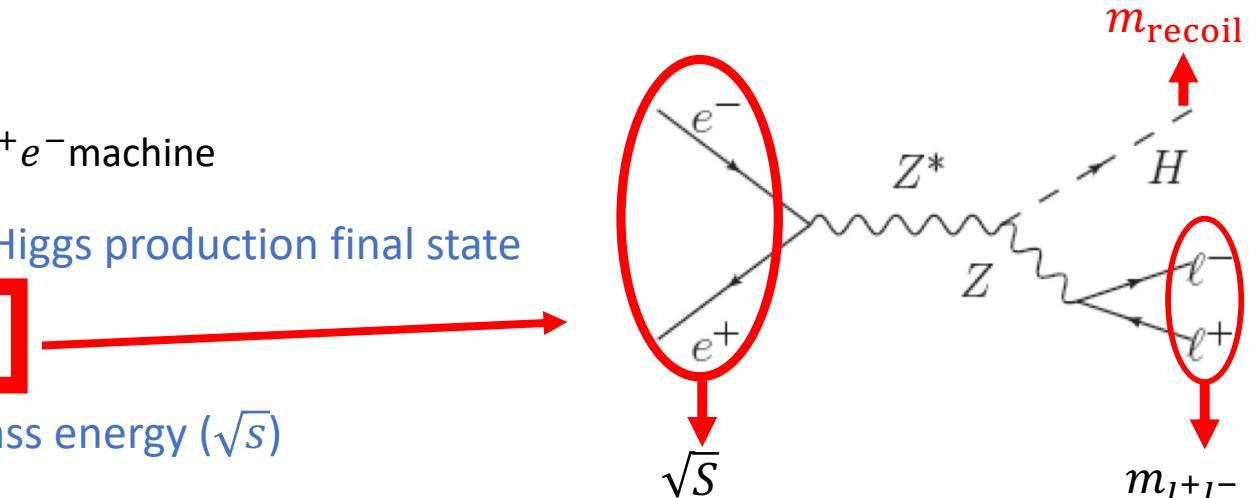
- $M_{\text{recoil}}$  from the Z production without measuring the Higgs production final state

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

- Sensitive to the precise knowledge of the centre-of-mass energy ( $\sqrt{s}$ ) and Initial State Radiation (ISR)

- Model-independent study

- WW, ZZ and  $Z/\gamma \rightarrow l\bar{l}$  Backgrounds @ 240 GeV



# Signal, Background Monte-Carlo simulation

## Monte-Carlo simulation:

- $\sqrt{s} = 240 \text{ GeV}$
- Luminosity:  $L = 5 \text{ ab}^{-1}$
- Initial State Radiation (ISR) and Final State Radiation (FSR) on
- Beam Energy Spread (BES) set to  $0.165\% = \pm 198 \text{ MeV}$  (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.  $Z(\nu\bar{\nu})H$  (Whizard)
5.  $Z(e^+e^-)H$  (Whizard)

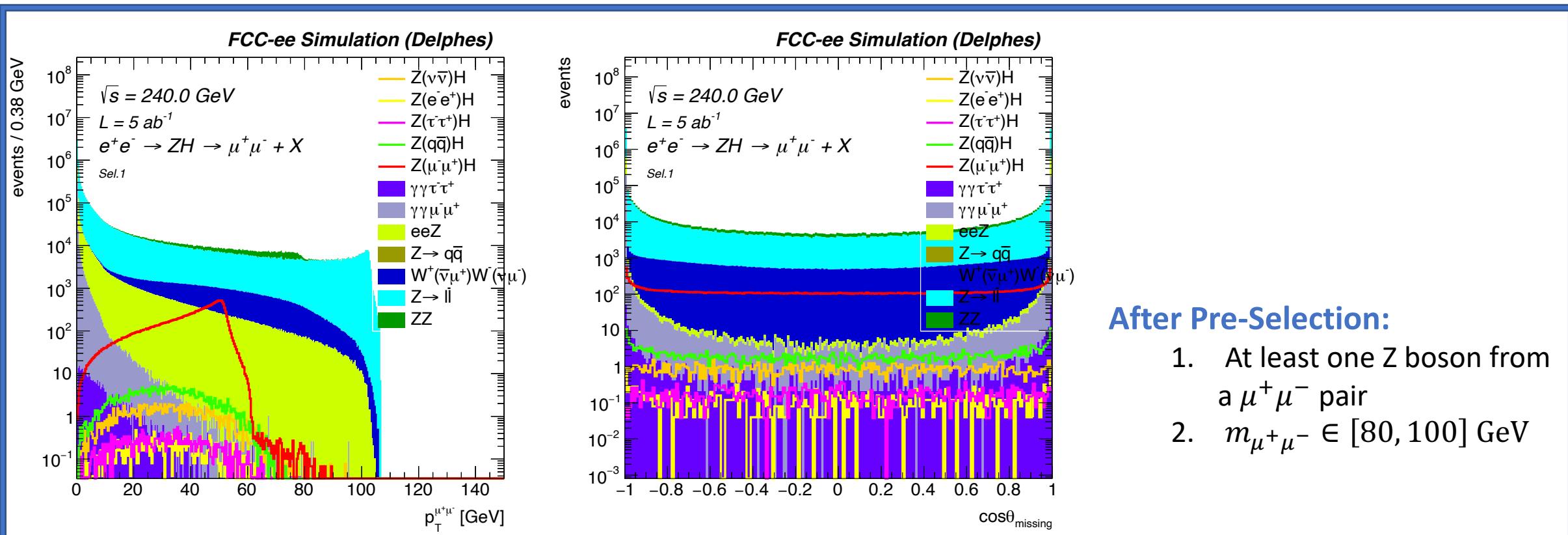
### • Backgrounds:

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

# Event Selection

## 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  $\sim 125$  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 ( $Z/\gamma^* \rightarrow ll$ )
5.  $|\cos \theta_{\text{missing}}| < 0.98$  → Polar angle of missing momentum, reduce  $\gamma\gamma$  processes. ISR emitted approximately collinear with the incoming beams escapes detection in the beam pipe

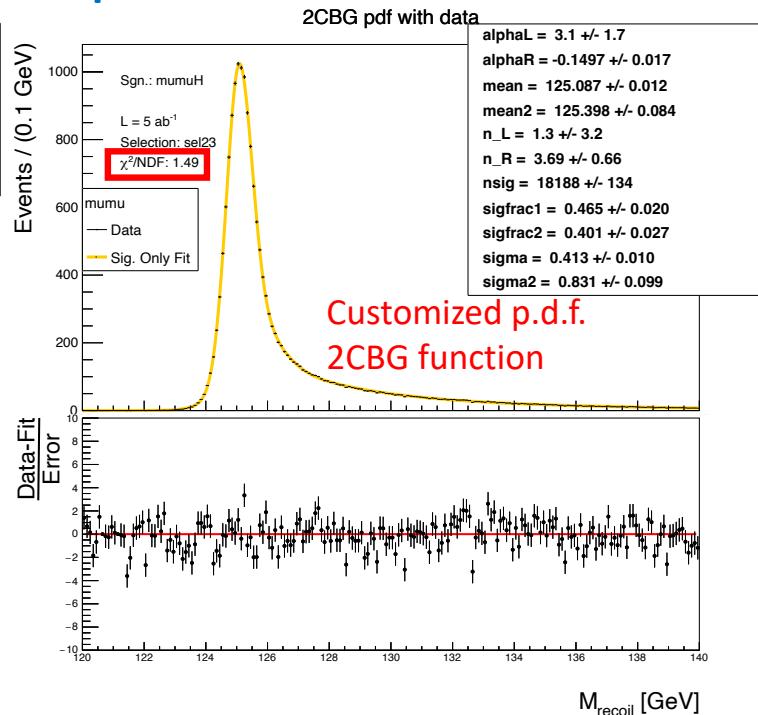
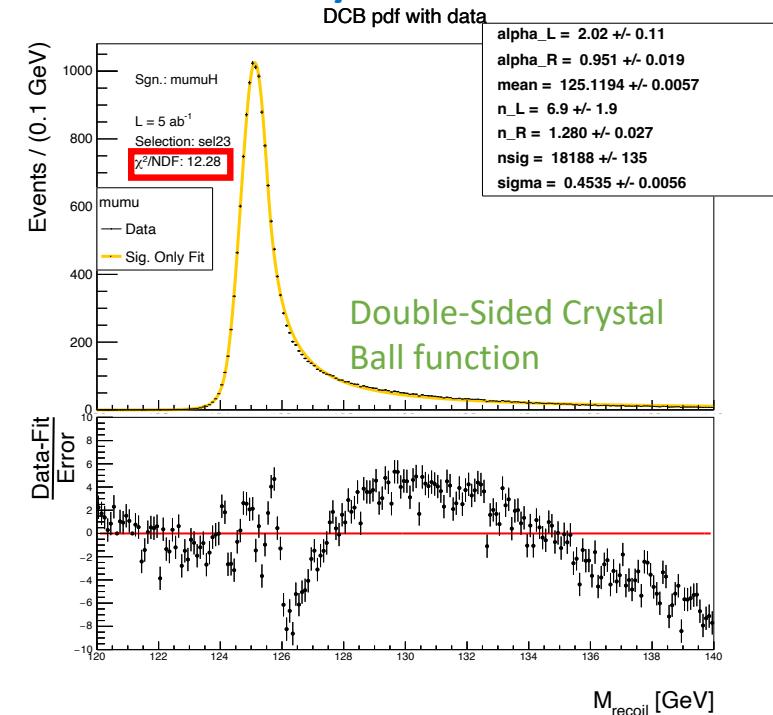


## After Pre-Selection:

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

# 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:

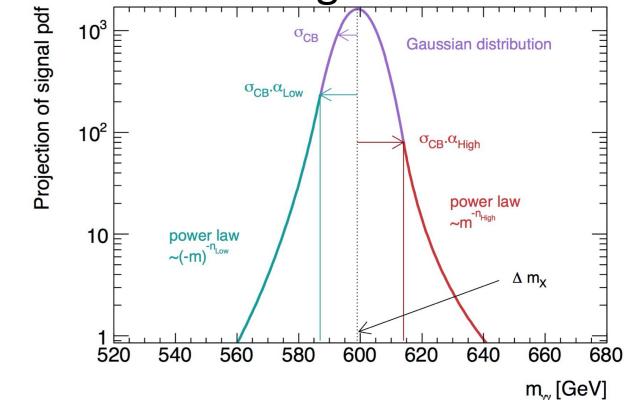
- Two **crystal-ball functions** (left and right), sharing mean and width
- Added Gaussian to cope with the high tails
- Gaussian suppressed in norm ( $sigfrac1 + sigfrac2 > 0.8$ )
- In total 10 “free” parameters (+1 normalization)
- $pdf(M_{recoil}) = sigfrac1 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_L, n_L) + sigfrac2 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_R, n_R) + (1 - sigfrac1 - sigfrac2) \cdot Gauss(M_{recoil}; \mu_2, \sigma_2)$

## 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

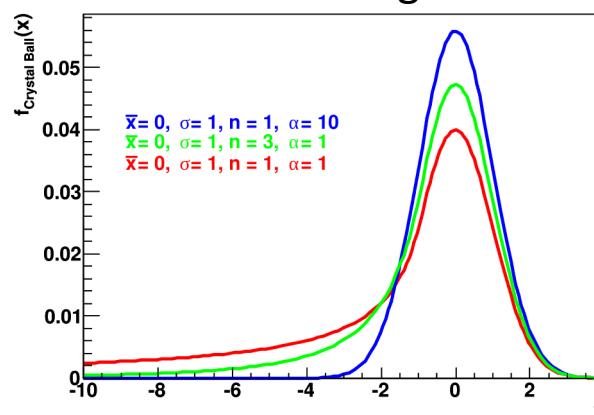


## Crystal-Ball function:

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

## Gaussian Core

## Power law tail on right or left



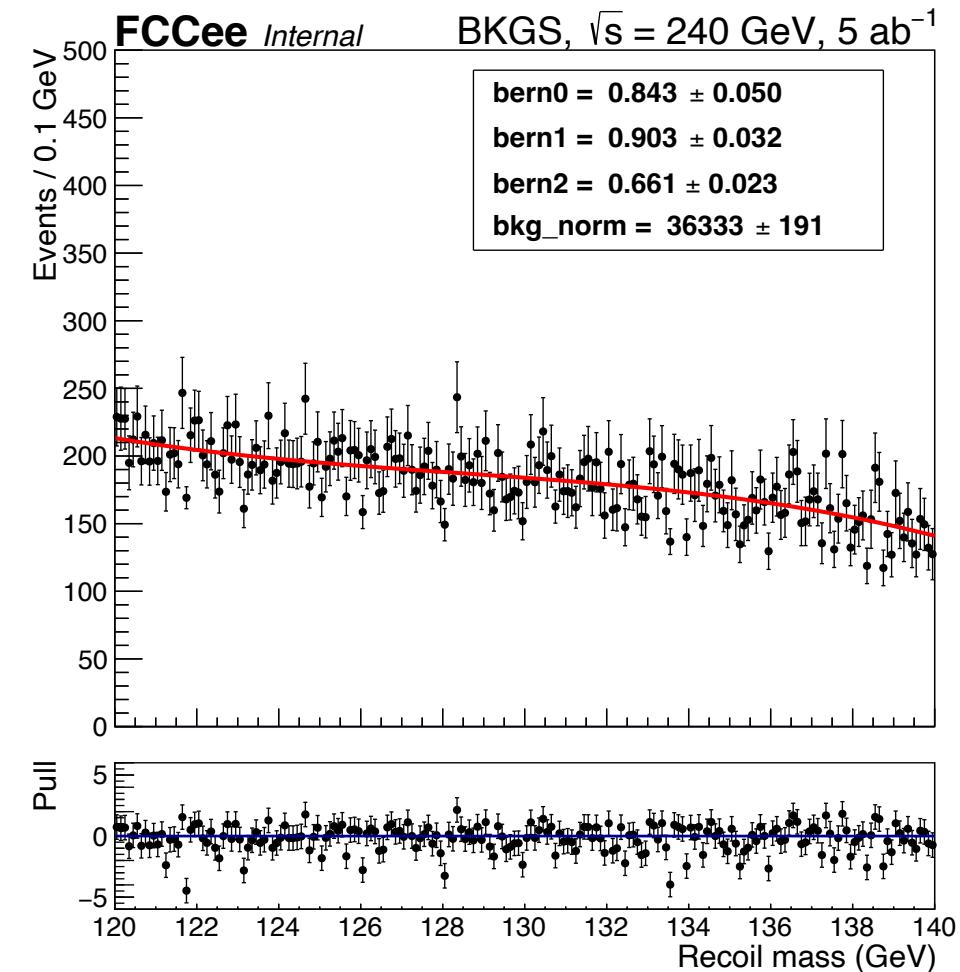
# Background modelling

## Statistical treatment of backgrounds:

- All backgrounds are merged
- Smoothly falling background modelled as third-order polynomial fit
- Keep polynomial coefficients constant, but keep total normalization floating
- Sufficient statistics for all backgrounds ( $\sim 4x$  expected at  $5 \text{ ab}^{-1}$ ), except for  $Z/\gamma^* \rightarrow l\bar{l}$  where 10 times more MC will be desirable

## Backgrounds:

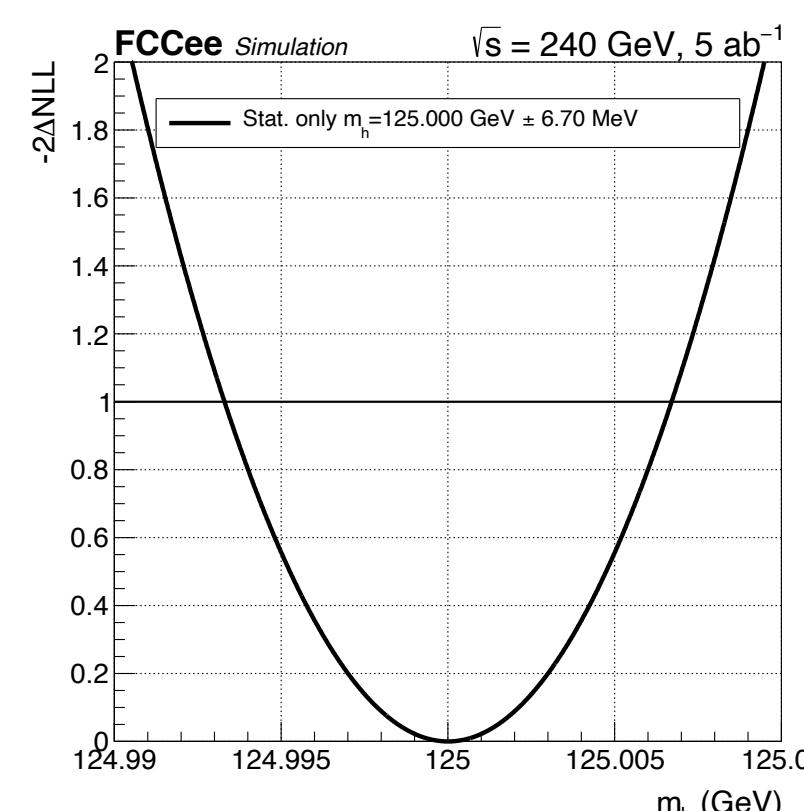
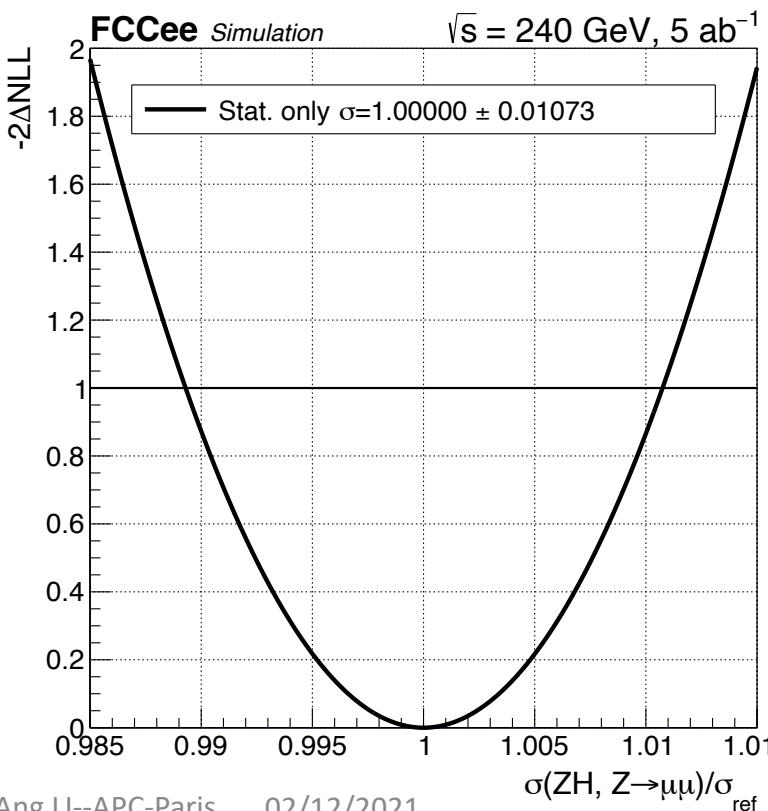
1.  $ZZ(\text{inclusive})$ , (Pythia)
2.  $W^+(\nu\mu^+)W^-(\bar{\nu}\mu^-)$ , (Pythia)
3.  $Z \rightarrow l^+l^-$ , (Pythia)
4.  $Z \rightarrow q\bar{q}$ , (Pythia)
5.  $eeZ$ , (Whizard)
6.  $\gamma\gamma \rightarrow \mu^+\mu^-$ , (Whizard)
7.  $\gamma\gamma \rightarrow \tau^+\tau^-$  (Whizard)



# Statistical Analysis

## Statistical analysis performed using Combine (CMS statistical framework)

- Signal and background analytical shaped are fitted to pseudo-data Asimov dataset
  - Injected 125.0 GeV signal with cross-section of 0.0067656 pb (ref.)
  - Free parameters: signal norm, background norm and  $m_H$  float
- Likelihood scans to extract cross-section and Higgs mass with robust uncertainties
- First, without accounting for experimental uncertainties → **stat-only result**



**Stat-only uncertainties:**

- Cross-section:  $\sim 1.1\%$
- Higgs mass: 6.7 MeV

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

# Systematic uncertainties

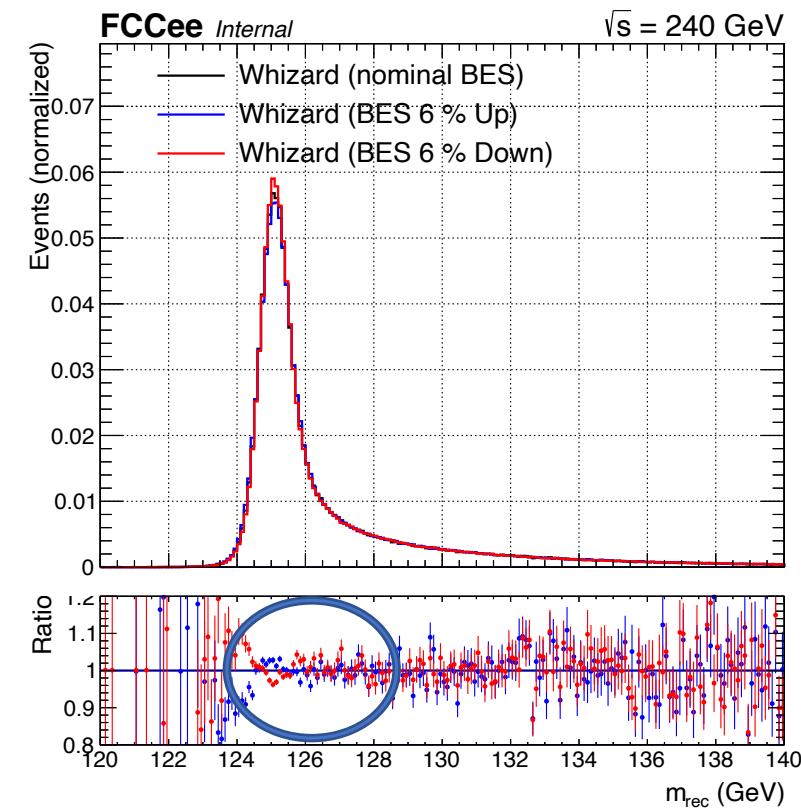
## Study of systematic uncertainties to assess the impact on the Higgs mass and cross-section measurement

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

1) Beam energy spread uncertainty (nominal BES @ 120 GeV per beam:  $\pm 0.165\% = \pm 0.198$  MeV)

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

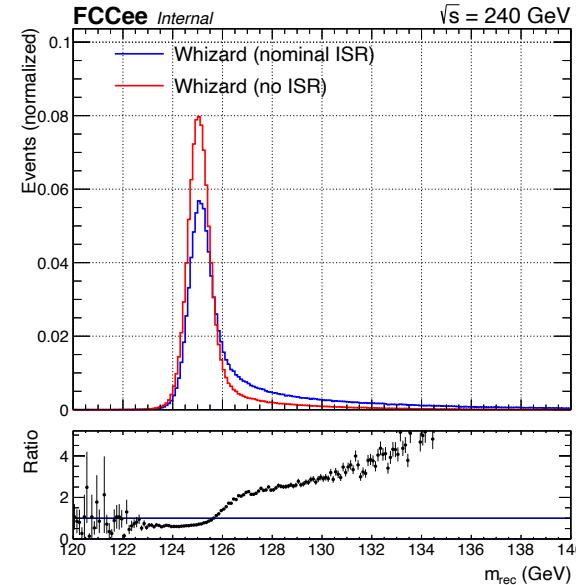
- Generated perturbed signal samples @ 125.0 GeV with:
- i. 6% BES variation: 2-3% shape effect observed at mass peak
  - ii. 1% BES variation: negligible variation  $\sim$  within statistical uncertainty



# Systematic uncertainties

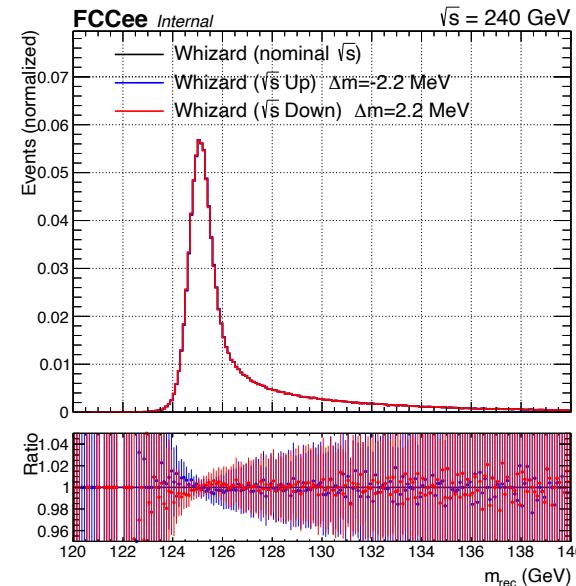
## 2) Initial State Radiation: ISR has impact on shape and normalization

- ISR treatment in Whizard using structure function approach: photon  $p_T$  spectrum
  1. Either strict collinear approximation ( $p_T = 0$ )
  2. Or ad-hoc implementation of a physical spectrum (default sample)
- Generated perturbed sample in the strict collinear approximation  
Rather drastic → 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) Centre-of-mass: $\pm 2$ MeV

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



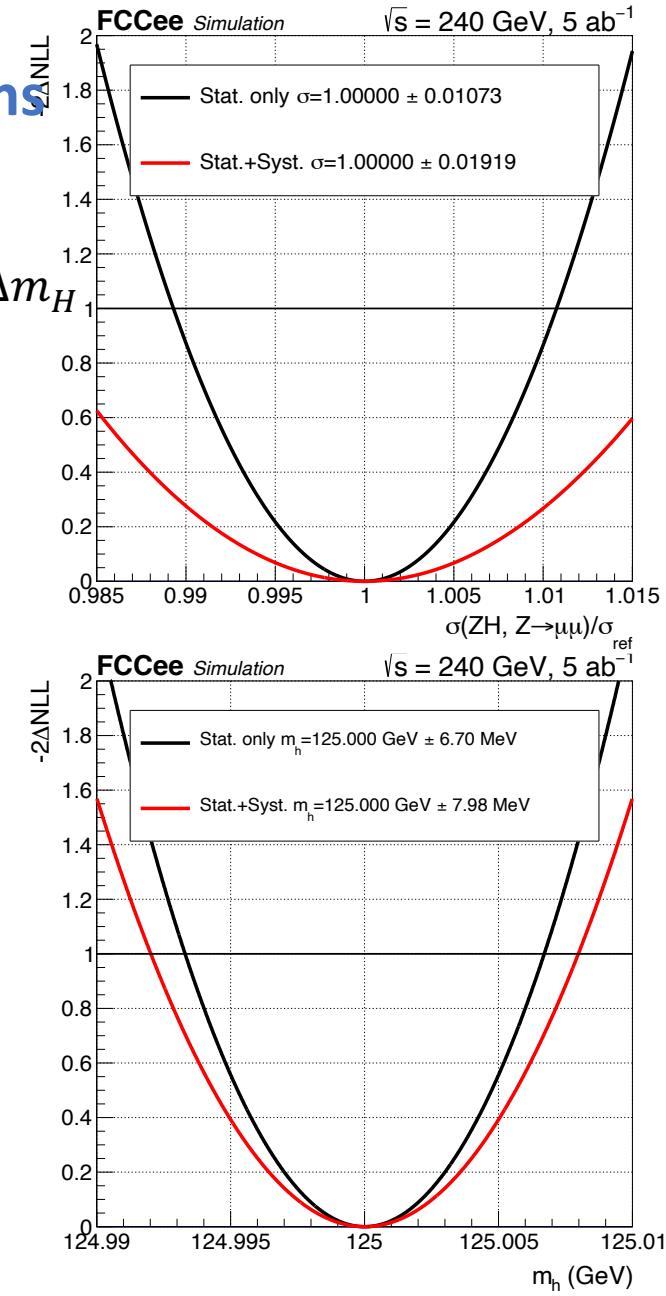
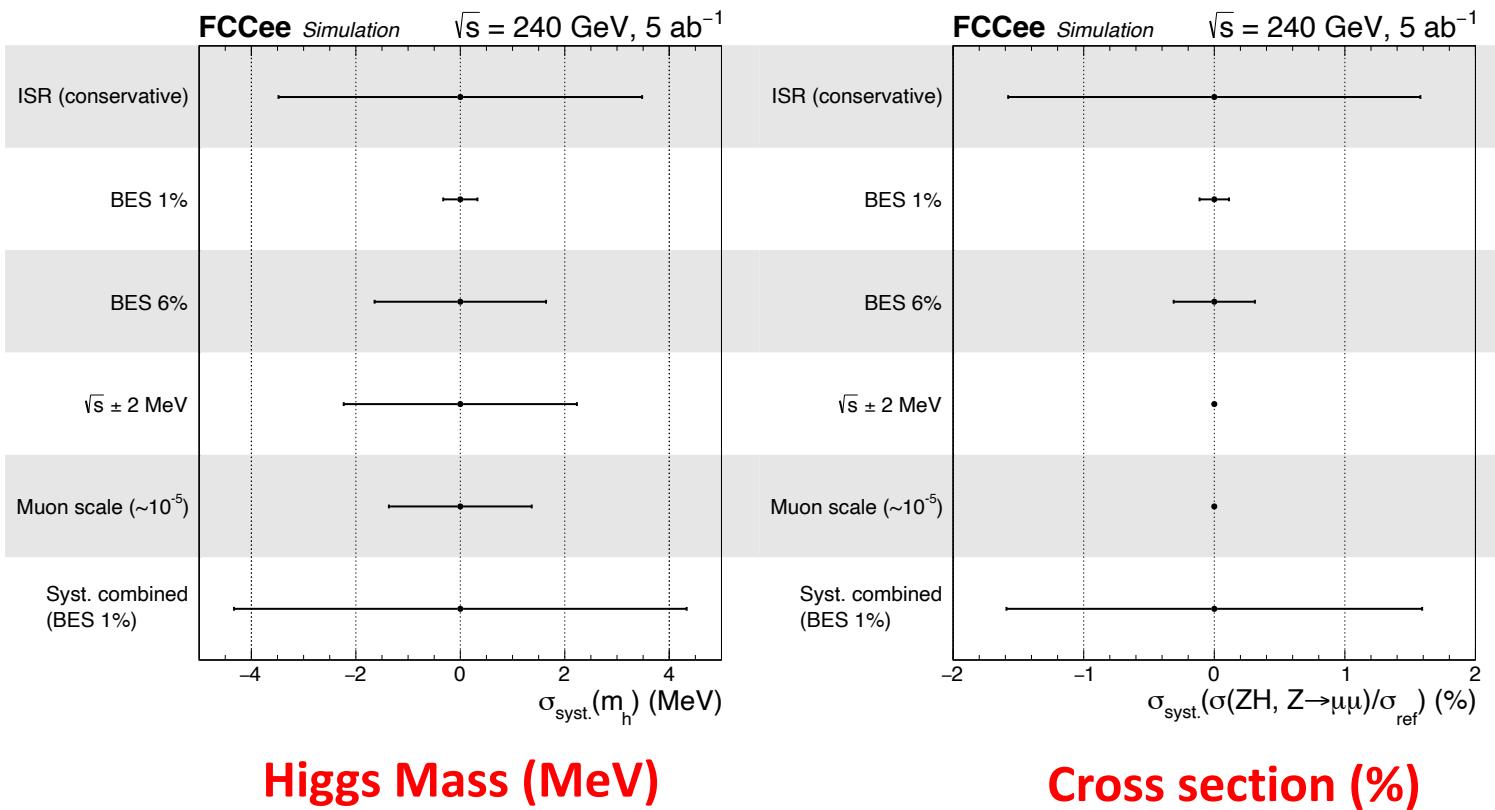
## 4) Muon momentum scale: relative scale uncertainty variation of $10^{-5}$

- Directly affects  $m_{\mu^+\mu^-}$ , hence shift in recoil mass
- Statistical potential to measure muon scale  $\sim 10^{-6}$ , but so far limited to yield  $10^{-5}$  uncertainty

# Systematic uncertainties

## Systematic variations included in likelihood as Gaussian constraint terms

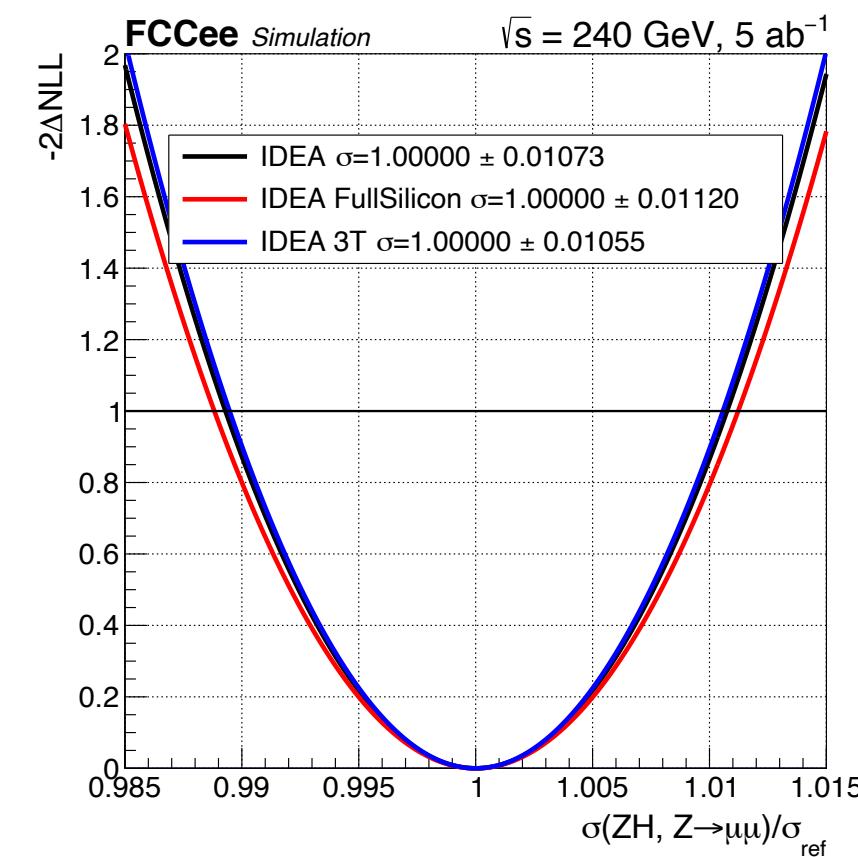
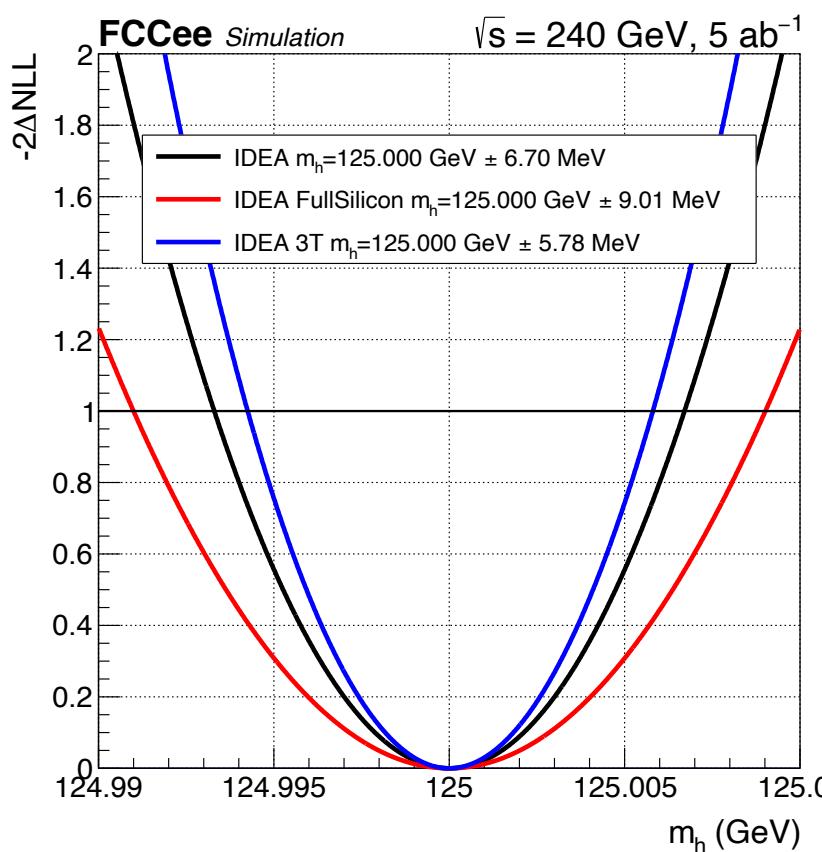
- Inclusion of all systematics:  $\Delta m_H \sim 8.0$  MeV and  $\Delta\sigma \sim 1.9$  %
- Breakdown of uncertainties: vary systematics one by one, extract  $\sigma_{syst.}^2 = \sigma_{tot.}^2 - \sigma_{stat.}^2$ .
- ISR dominant (but conservatively estimated), muon scale /  $\sqrt{s}$  accounts for  $\sim 2$  MeV on  $\Delta m_H$
- Impact on cross-section limited, except ISR



# IDEA detector configurations

## Different IDEA detector configuration studied:

1. Magnetic field increased from 2T to 3T → expected better momentum resolution
2. 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
3. Effect on mass scales with resolution, impact on cross-section uncertainty is limited



**Stat-only results**

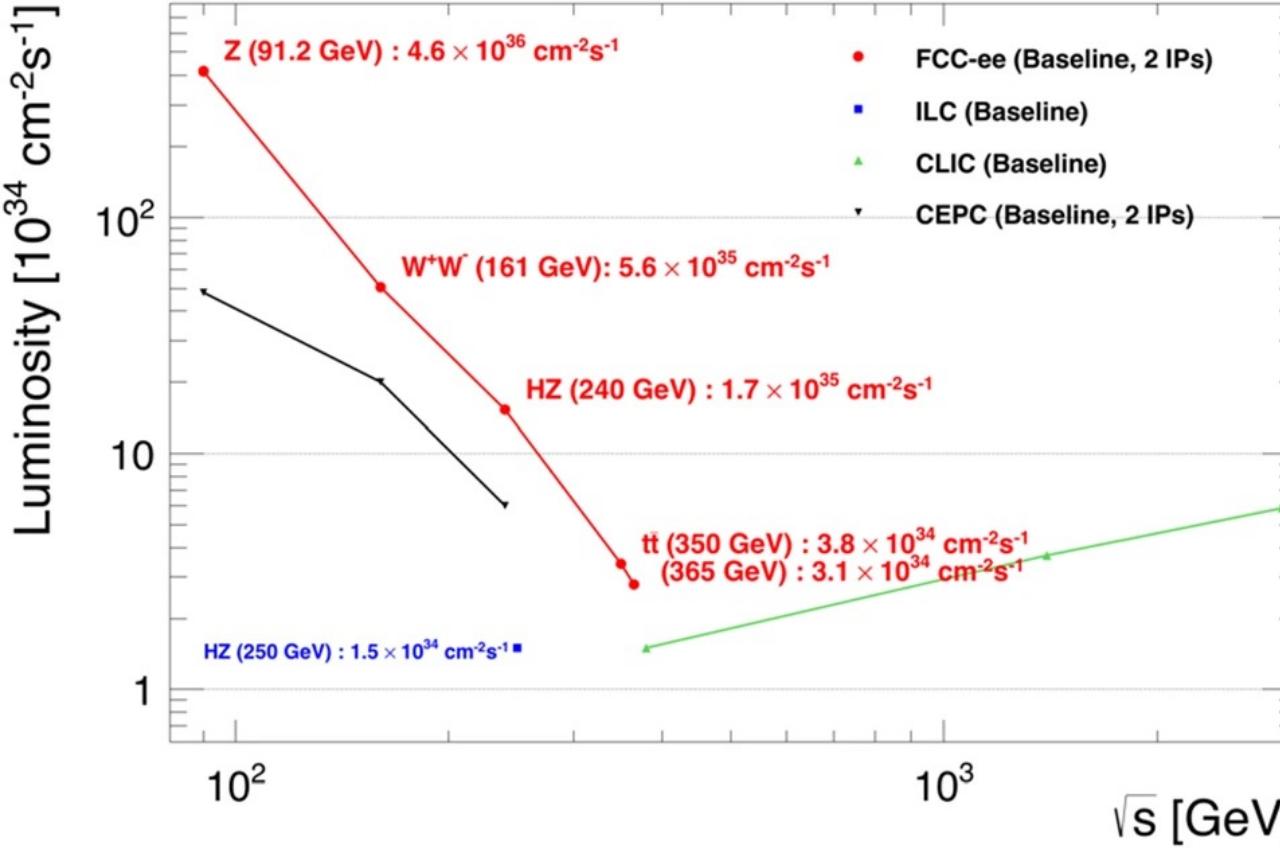
IDEA	$\Delta m_H (\text{MeV})$	$\Delta \sigma (\%)$
Nominal	6.7	1.07
FullSilicon	9.0	1.12
3T	5.8	1.06

## ❖ Conclusion:

- In the Higgs measurements at the  $e^+e^-$  colliders, the “ZH recoil mass” allows for the measurement of  $m_H$  with an uncertainty down to a few MeV
- The Higgs boson width ( $\Gamma = 4.1$  MeV in the SM), will also be measured directly for the first time
- Measurement of the HZZ coupling will be a “standard candle” for other Higgs coupling measurements
- Statistical analysis yields Higgs mass uncertainty 6.7 MeV, cross-section 1.1% (stat-only)
- Inclusion of systematic uncertainties results into 8.0 MeV / 1.9% respectively, where ISR dominant but conservatively estimated
- These first results will be improved with more advanced techniques

# Backup

# FCC-ee Luminosities



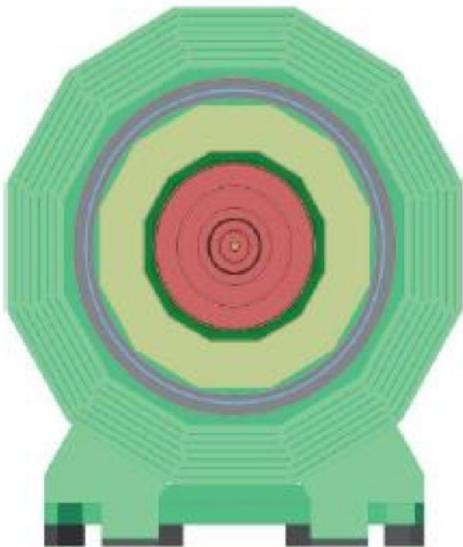
## FCC Physics Opportunities

- 4 baseline working points
  - Z pole @91.2 MeV
  - $W^+W^-$  threshold @ 161GeV
  - ZH threshold @ 240 GeV
  - $t\bar{t}$  threshold @ 365 GeV

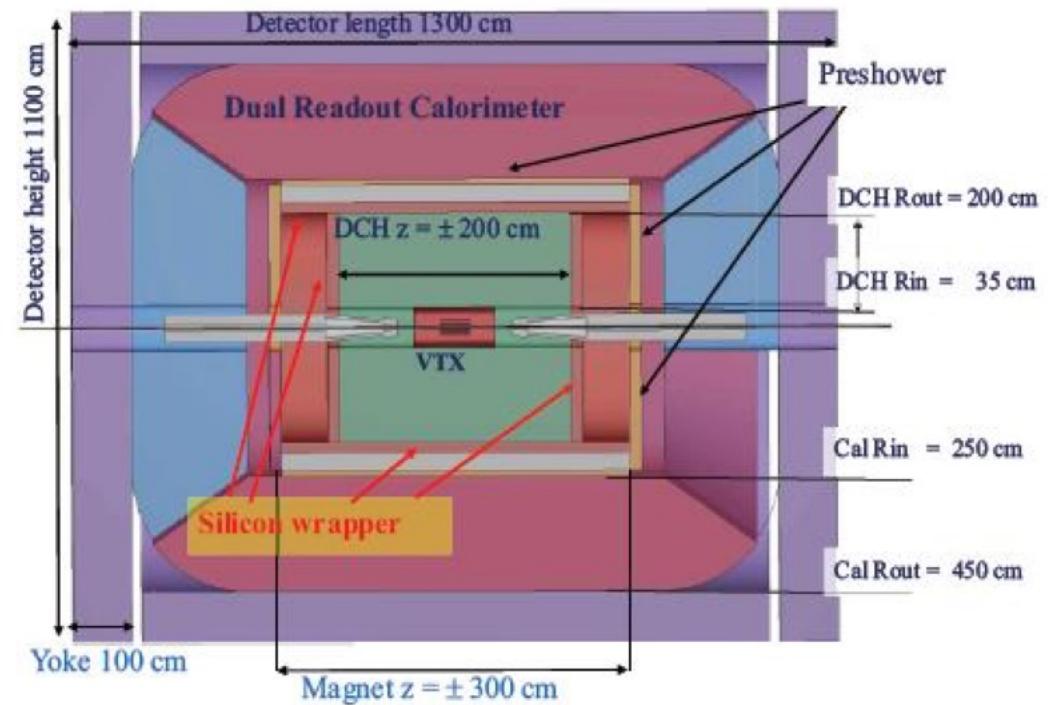
Phase	Run duration (years)	Centre-of-mass energies (GeV)	Integrated luminosity ( $\text{ab}^{-1}$ )	Event statistics
FCC-ee-Z	4	88–95	150	$3 \times 10^{12}$ visible Z decays
FCC-ee-W	2	158–162	12	$10^8$ WW events
FCC-ee-H	3	240	5	$10^6$ ZH events
FCC-ee-tt(1)	1	340–350	0.2	$t\bar{t}$ threshold scan
FCC-ee-tt(2)	4	365	1.5	$10^6$ $t\bar{t}$ events

# Detectors under study

## CLD



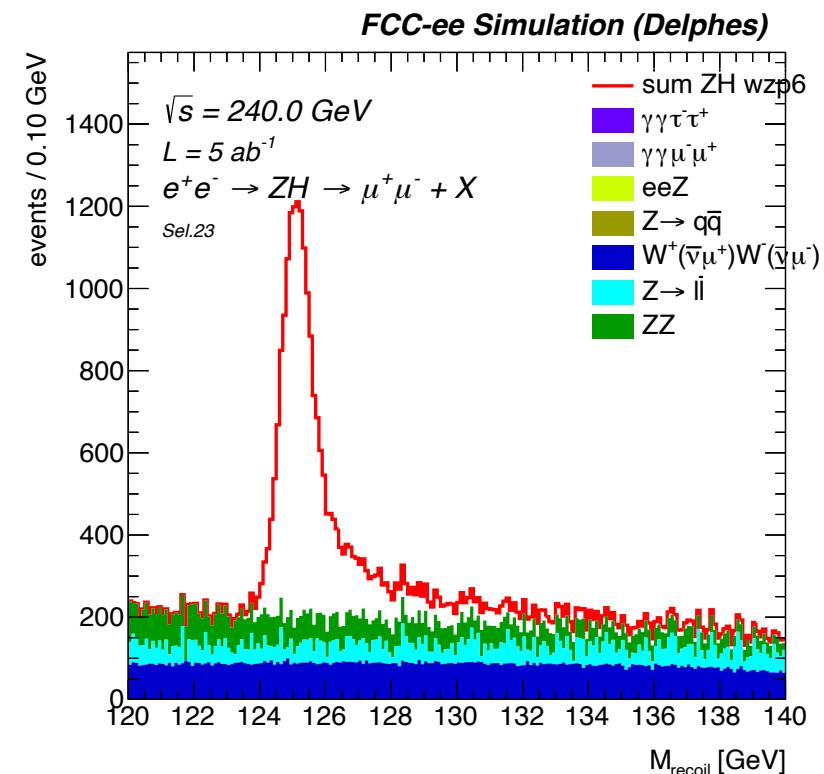
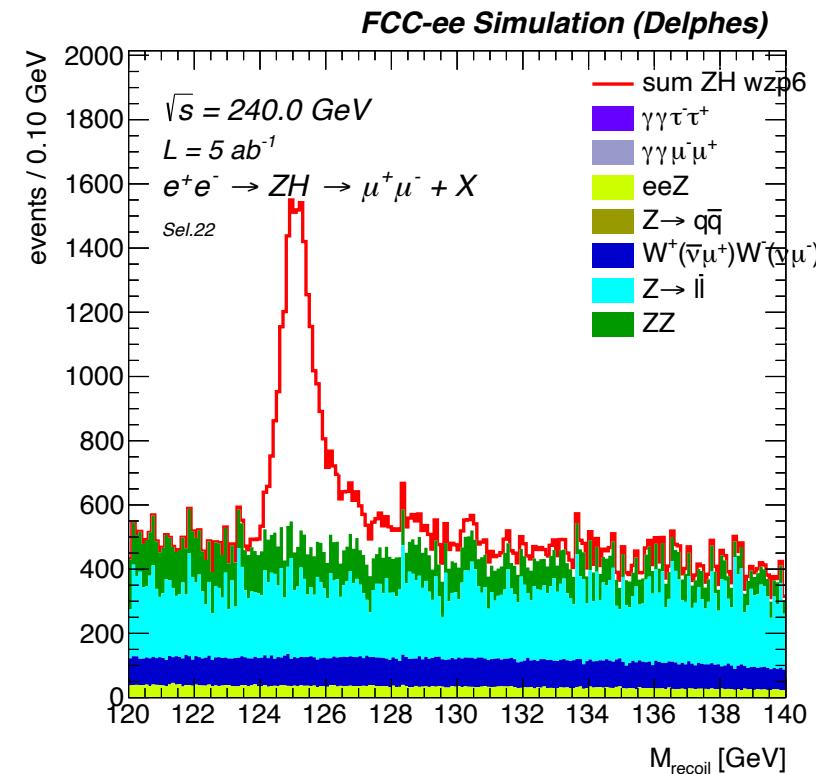
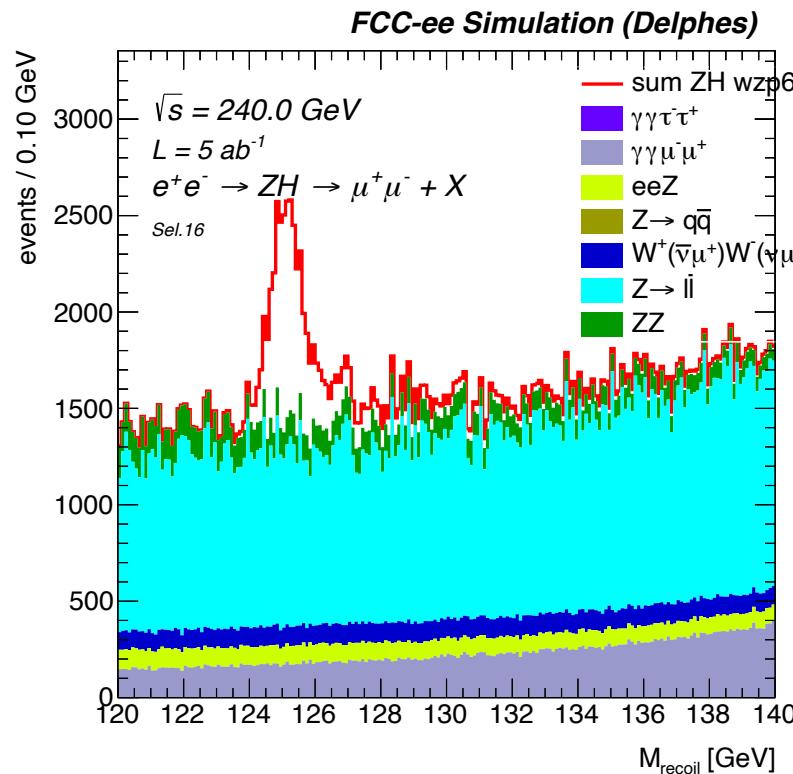
## IDEA



- 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

- 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/cerenkov fibers
  - $\mu$ Rwell for muon detection

# Evaluation of $M_{recoil}$ distribution



## APC-0-Selection:

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

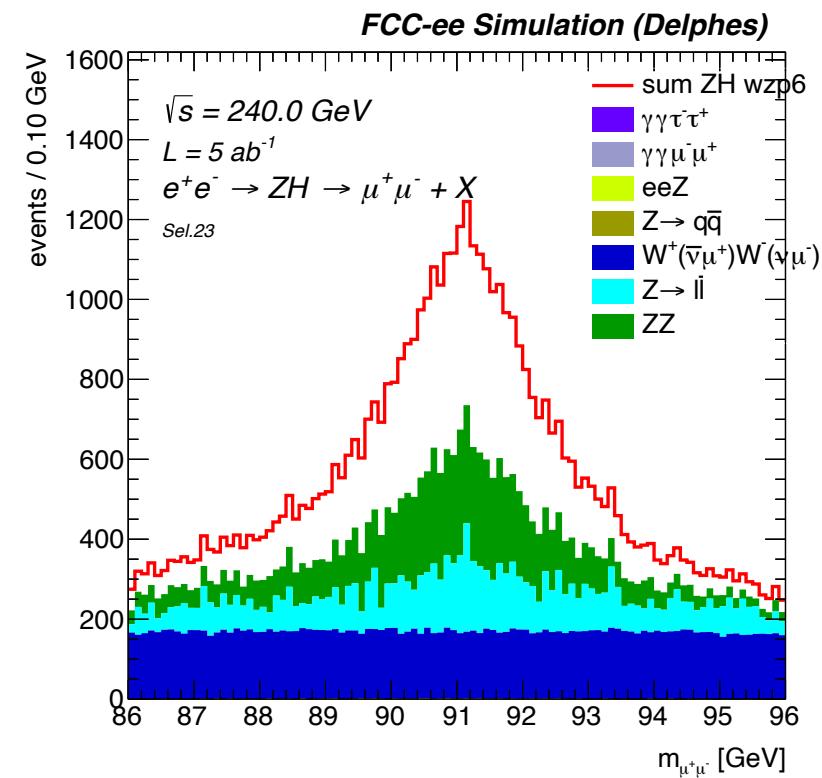
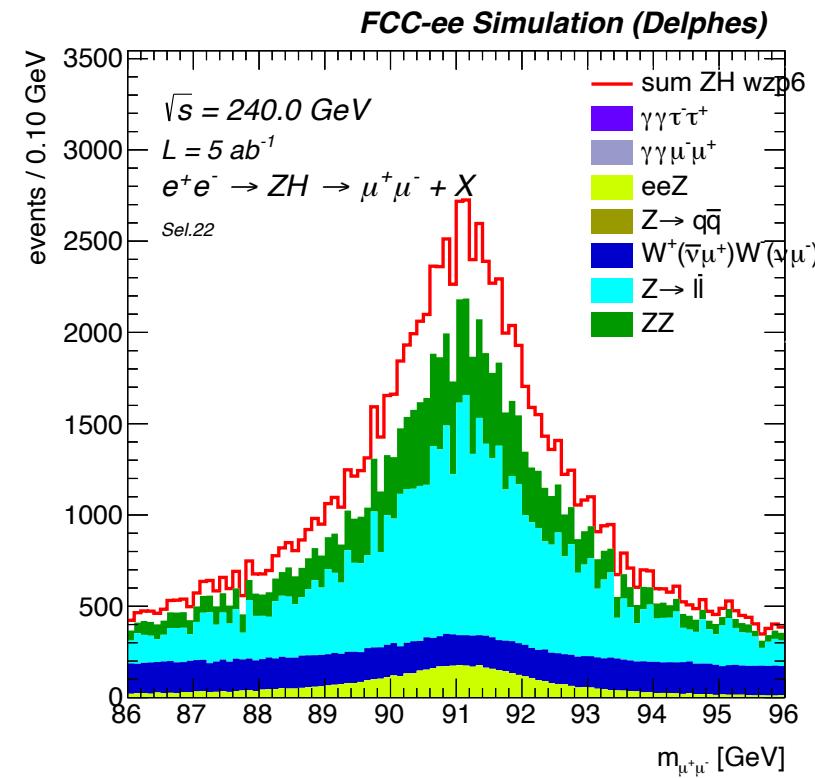
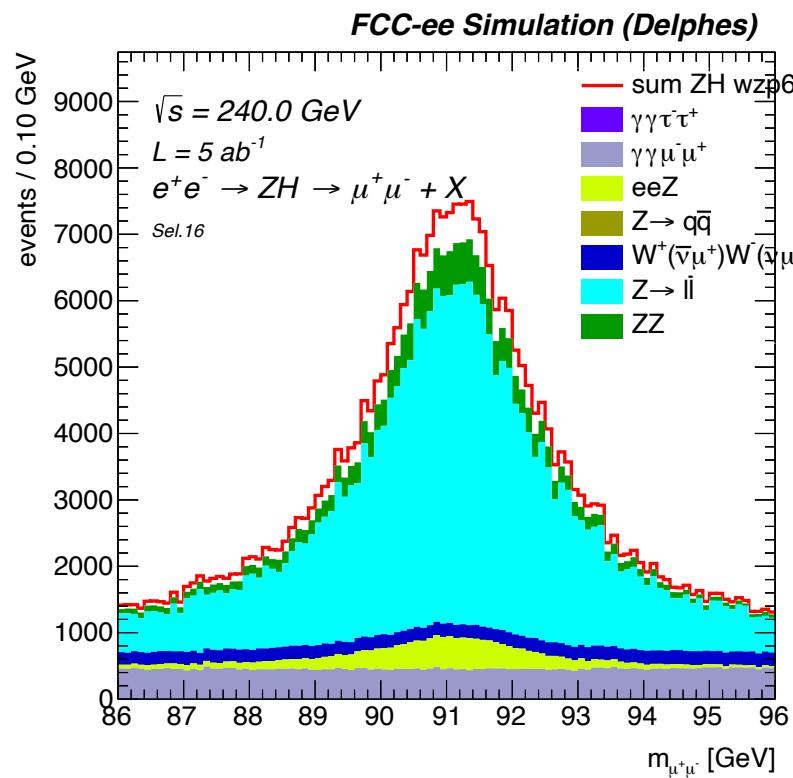
## APC-1-Selection:

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

## APC-2-Selection:

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

# Evaluation of $m_{\mu^+\mu^-}$ distribution



## APC-0-Selection:

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

## APC-1-Selection:

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

## APC-2-Selection:

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

# Expected value of the coupling constant

$$\sigma_{ZH} \times \mathcal{B}(H \rightarrow X\bar{X}) \propto \frac{g_{HZZ}^2 \times g_{HXX}^2}{\Gamma_H} \quad \text{and} \quad \sigma_{H\nu_e\bar{\nu}_e} \times \mathcal{B}(H \rightarrow X\bar{X}) \propto \frac{g_{HWW}^2 \times g_{HXX}^2}{\Gamma_H},$$

- The  $\sigma_{ZH}$  accuracy could reach 0.5%

[arXiv:2106.15438](https://arxiv.org/abs/2106.15438)

- Obtaining the ZH cross section, one can determine  $g_{HZZ}$  and Higgs width ( $\Gamma_H$ )
- $g_{HZZ}$ ,  $g_{HWW}$ ,  $g_{Hgg}$  and  $g_{H\tau\tau}$  are expected to reach per mille precision

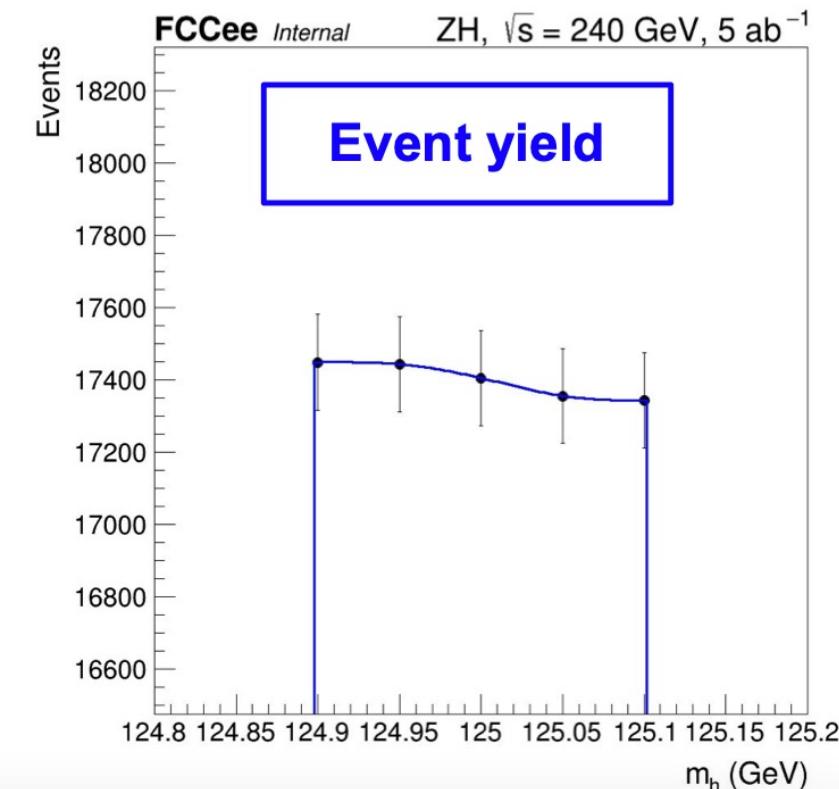
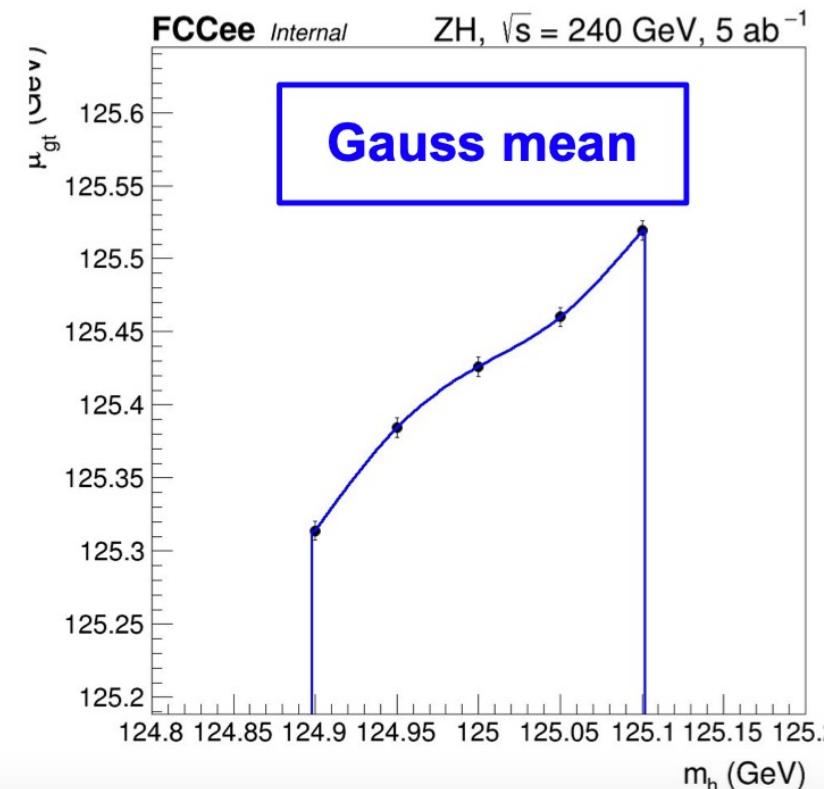
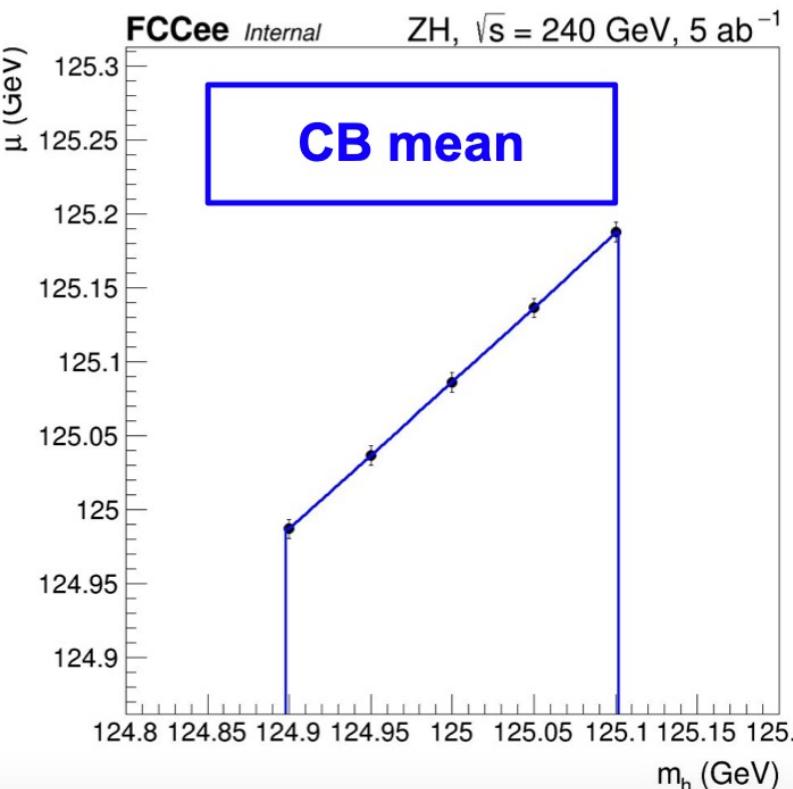
$\sqrt{s}$	240 GeV		365 GeV	
Integrated luminosity	5 ab $^{-1}$		1.5 ab $^{-1}$	
$\delta(\sigma\mathcal{B})/\sigma\mathcal{B}$ (%)	ZH	$\nu_e\bar{\nu}_e$	H	$\nu_e\bar{\nu}_e$
H $\rightarrow$ any	$\pm 0.5$		$\pm 0.9$	
H $\rightarrow$ b $\bar{b}$	$\pm 0.3$	$\pm 3.1$	$\pm 0.5$	$\pm 0.9$
H $\rightarrow$ c $\bar{c}$	$\pm 2.2$		$\pm 6.5$	$\pm 10$
H $\rightarrow$ gg	$\pm 1.9$		$\pm 3.5$	$\pm 4.5$
H $\rightarrow$ W $^+W^-$	$\pm 1.2$		$\pm 2.6$	$\pm 3.0$
H $\rightarrow$ ZZ	$\pm 4.4$		$\pm 12$	$\pm 10$
H $\rightarrow$ $\tau^+\tau^-$	$\pm 0.9$		$\pm 1.8$	$\pm 8$
H $\rightarrow$ $\gamma\gamma$	$\pm 9.0$		$\pm 18$	$\pm 22$
H $\rightarrow$ $\mu^+\mu^-$	$\pm 19$		$\pm 40$	
H $\rightarrow$ invisible	$< 0.3$		$< 0.6$	

Coupling	Precision (%) ( $\kappa$ framework / EFT)
$g_{HZZ}$	0.17 / 0.26
$g_{HWW}$	0.41 / 0.27
$g_{Hbb}$	0.64 / 0.56
$g_{Hcc}$	1.3 / 1.2
$g_{Hgg}$	0.89 / 0.82
$g_{H\tau\tau}$	0.66 / 0.57
$g_{H\mu\mu}$	3.9 / 3.8
$g_{H\gamma\gamma}$	1.3 / 1.2
$g_{HZ\gamma}$	10. / 9.3
$g_{Htt}$	3.1 / 3.1
$\Gamma_H$	1.1

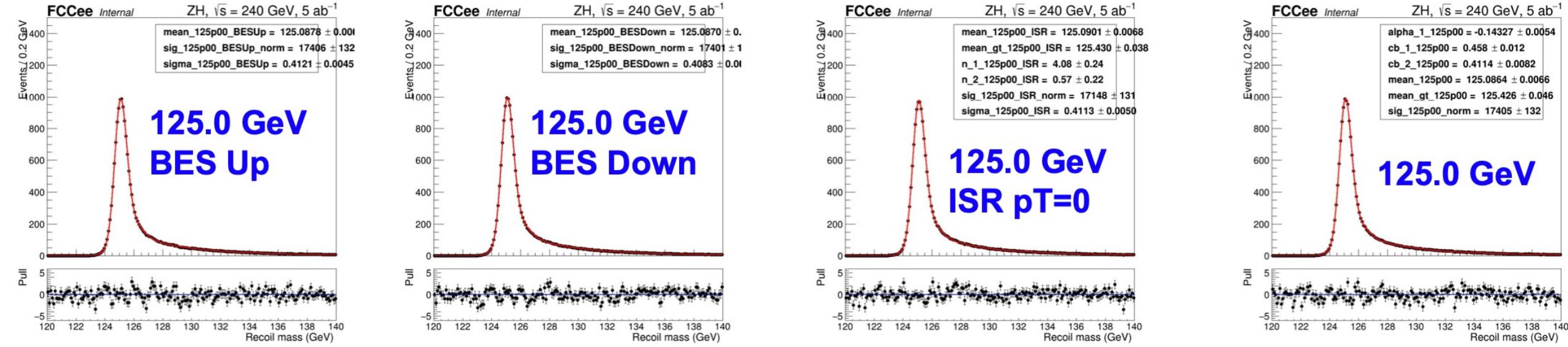
# Fitting model and parameter settings

## How does the signal shape change as function of (true) Higgs mass $m_h$ ?

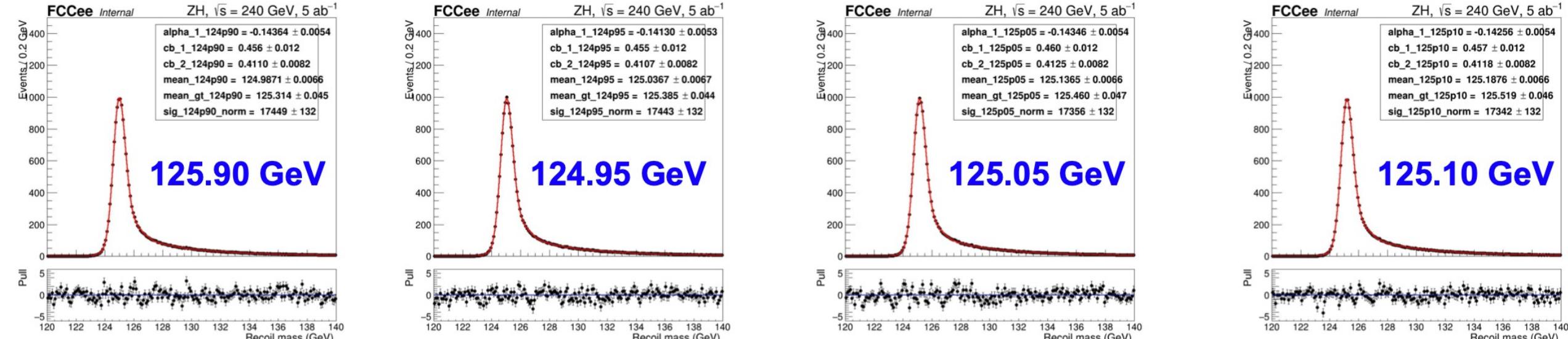
- Generated extra samples around 125 GeV: 124.9, 124.95, 125.05, 125.1 GeV
- Found only significant dependency on the mean (both CB and Gauss) and yields
  - Dependency as function of  $m_h$  described using Spline
- Other parameters set as constant (best-fit parameters @ 125.0 GeV, see backup for all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



# Signal fits with 2CBG



No bias in fits observed



## Decomposition of 2CBG

<b>Signal PDF</b>	<b>1.000</b>
<b>CB1</b>	<b>0.4580</b>
<b>CB2</b>	<b>0.4114</b>
<b>Gauss</b>	<b>0.1306</b>

