FCCee Case Study: $e^{+}e^{-}$→ZH Recoil mass and Z boson mass

2nd FCC-France Workshop
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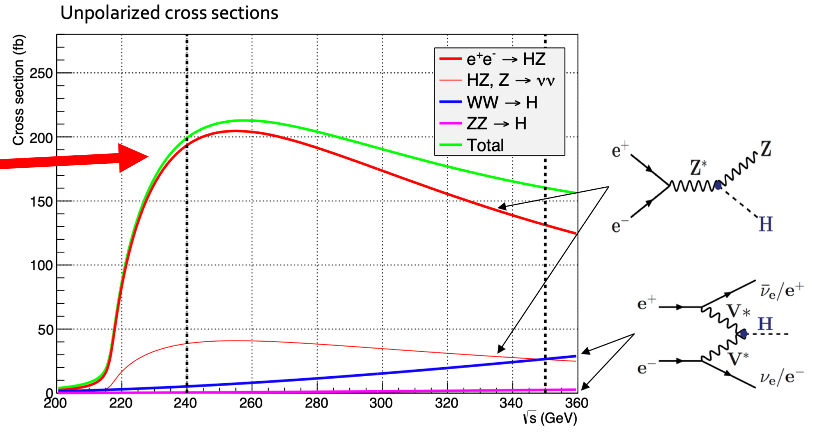
Motivation

- Goal: Measurement of the ZH total cross section



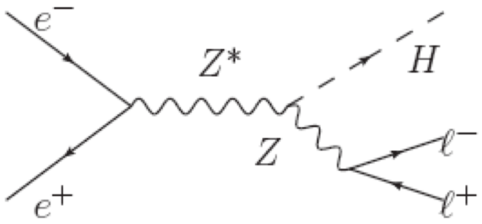
arXiv:1308.6176

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

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

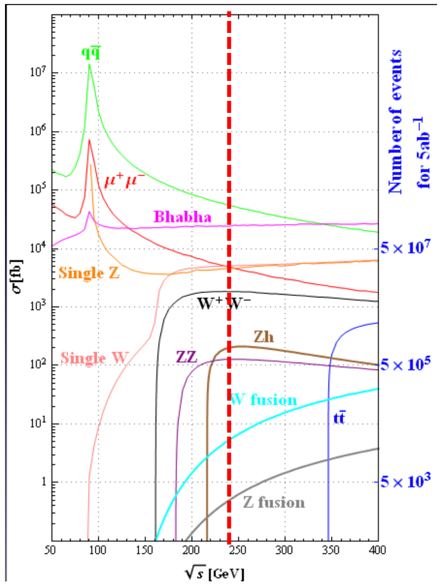
- Use events with a Z decaying leptonically, and reconstruct M_{recoil} from the Z production without measuring the Higgs production final state

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



- The reconstruct is M_{recoil} sensitive to the precise knowledge of the centre-of-mass energy

- WW & ZZ Background @ 240 GeV



Simulations

- **Simulation configurations:**
  - **Generator:** Pythia 8 (DelphesPythia8_EDM4HEP)

  - **Detector card:**
    - **IDEA:** $DELPHES_DIR/cards/IDEAtrkCov.tcl
    - **CLD:** /afs/cern.ch/user/s/selvaggi/public/4Emilia/delphes_card_CLDtrkCov_Tagging.tcl
      CLD tracker, the other parts are still IDEA

  - **Channels: ZH, ZZ and WW**
    - 10^7 events for each channel produced inclusively
    - Focus on $\mu^+\mu^-$ pair final state (e^+e^- final state reconstruction has some issues)

  - $\sqrt{s} = 240$ GeV

  - **ISR and FSR on**

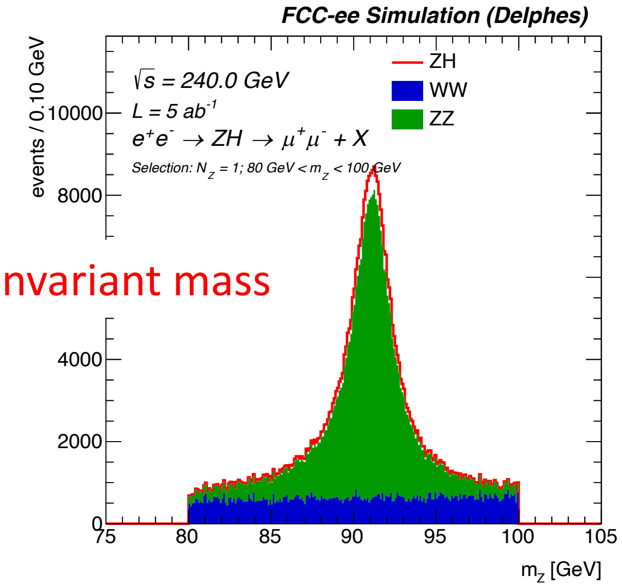
Event Selection and Settings

- **Generator Level:**
  - $|\eta_\mu| < 3.0$

- **Analysis Level Selection:**
  - $N_Z = 1$ (Only one Z candidate (pair of leptons) is allowed)
  - $80\ \text{GeV} < m_Z < 100\ \text{GeV}$ (m_Z is the di-muon invariant mass)
  - $p_{T_\mu} > 10\ \text{GeV}$

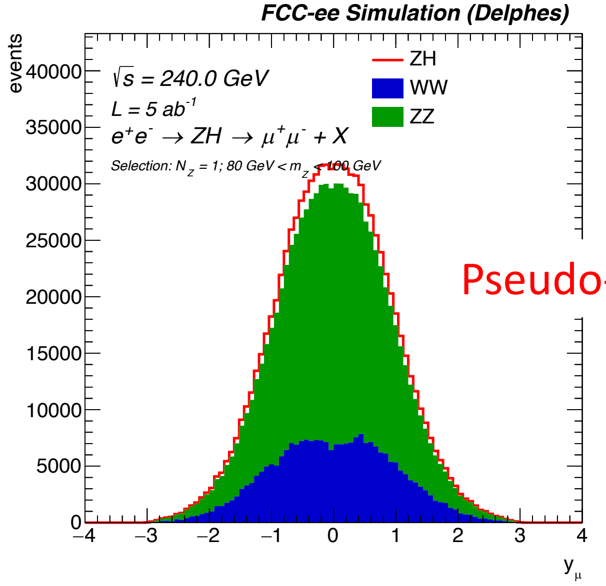
- **Luminosity:**
  $L = 5\ ab^{-1}$

- **Variables:**
  M_{recoil}
  $m_Z = m_{l\bar{l}}$

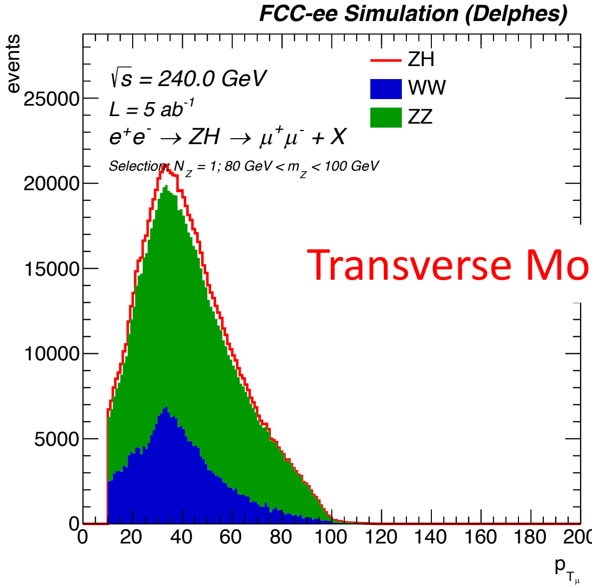


di-Muon invariant mass

Stacked Plots

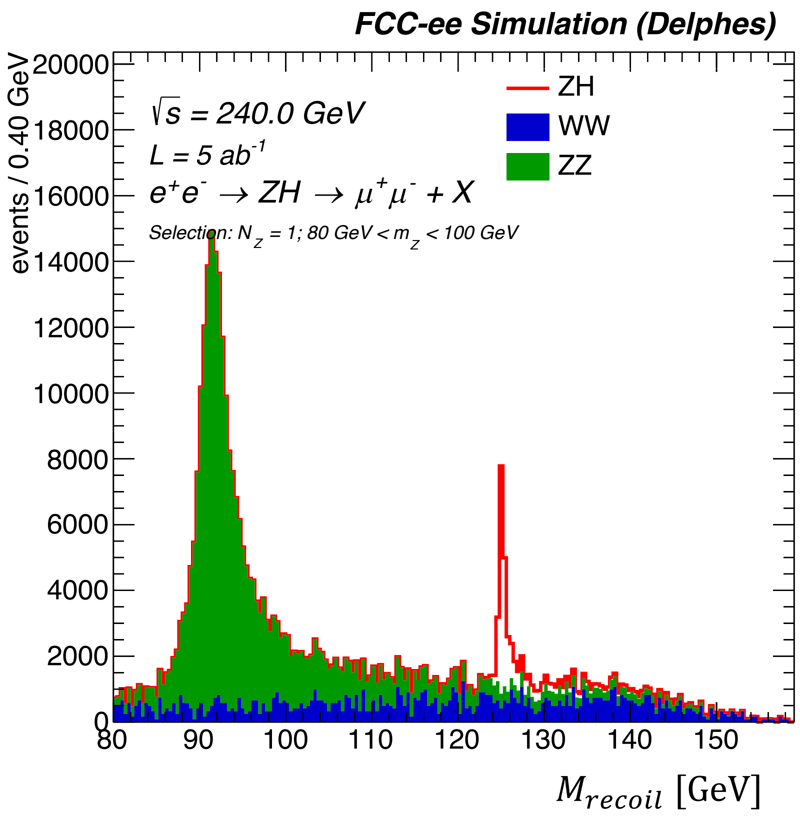


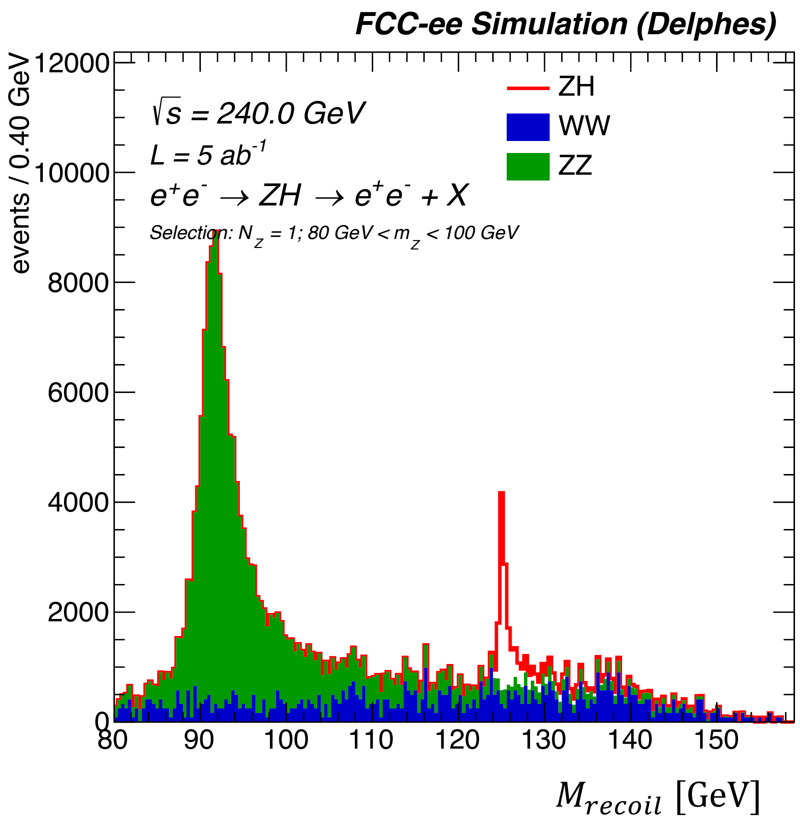
Pseudo-Rapidity



Transverse Momentum

Comparison of IDEA with e^+e^- and $\mu^+\mu^-$ final state





IDEA simulation $\mu^+\mu^-$ final state

10^6 events for each channel

After selection — Full range: M_{recoil} ∈[0, 200] GeV

Entries: ZH: 24475, ZZ: 45489, WW: 1470

Events: ZH: 24601.9, ZZ: 307933.5, WW: 120823.0

IDEA simulation e^+e^- final state

10^6 events for each channel

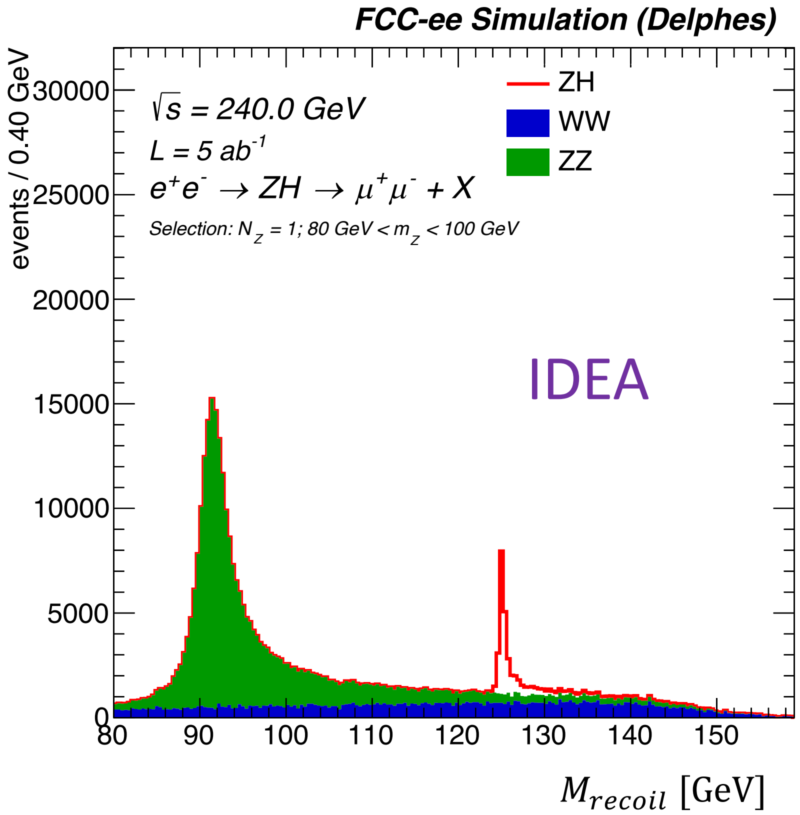
After selection — Full range: M_{recoil} ∈[0, 200] GeV

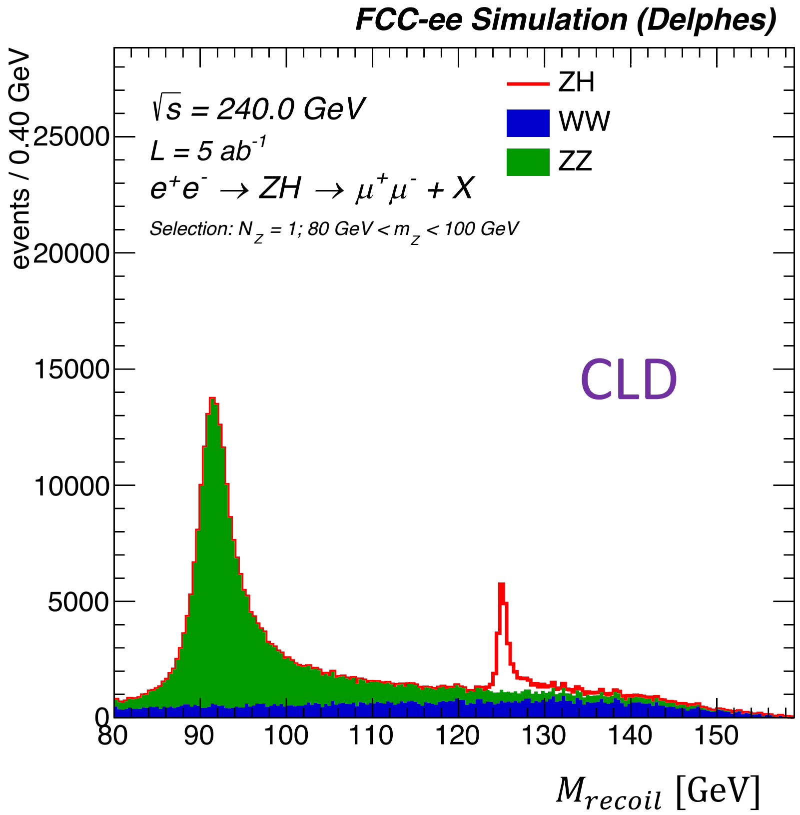
Entries: ZH: 14235, ZZ: 27111, WW: 985

Events: ZH: 14308.8, ZZ:183613.1, WW: 80959.6

The IDEA simulation with 10^7 events is identical with Clement's result

Comparison of IDEA and CLD Simulation of the $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- + X$





IDEA simulation

10^7 events for each channel

After selection

Entries: ZH: 244859
ZZ: 456495
WW: 15119

Full range: $M_{recoil} \in [0, 200]$ GeV

Events: ZH: 24612.9
ZZ: 308891.6
WW: 124184.7

CLD simulation

10^7 events for each channel

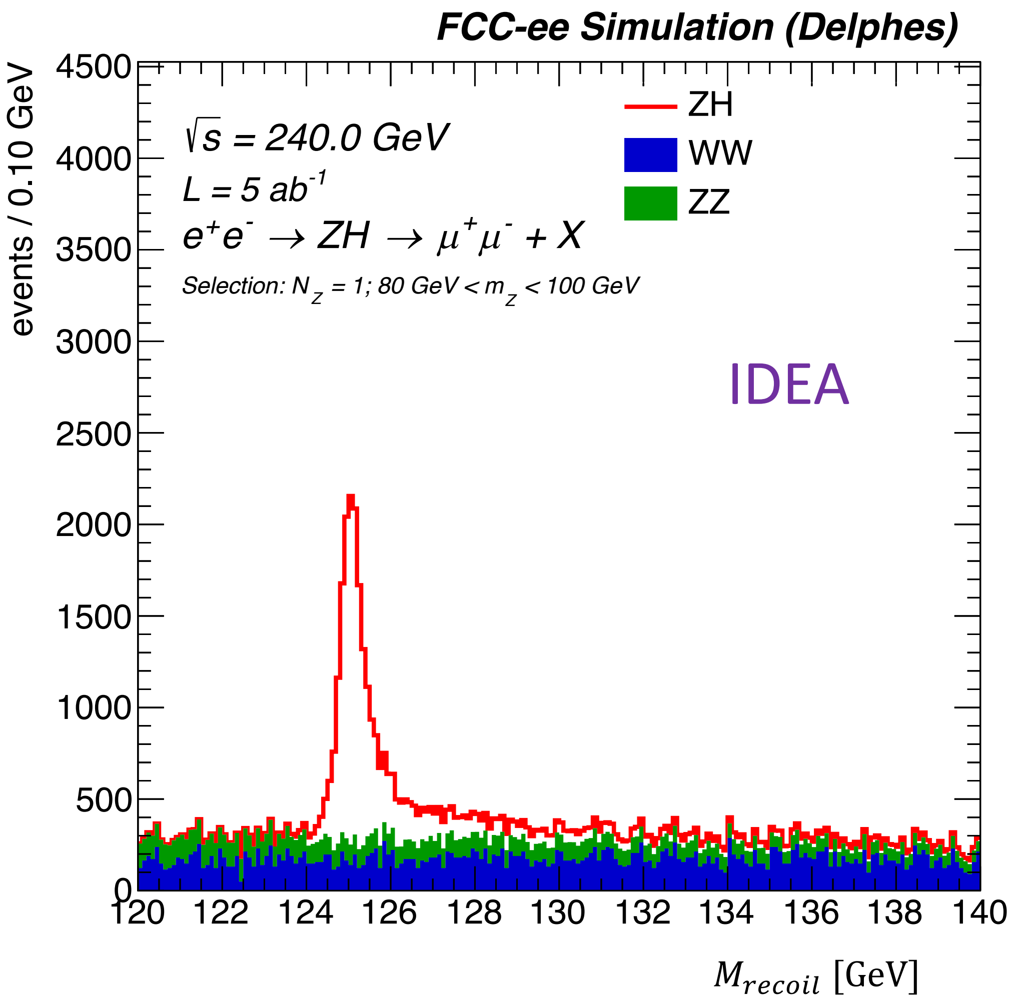
After selection

Entries: ZH: 244997
ZZ: 456234
WW: 15137

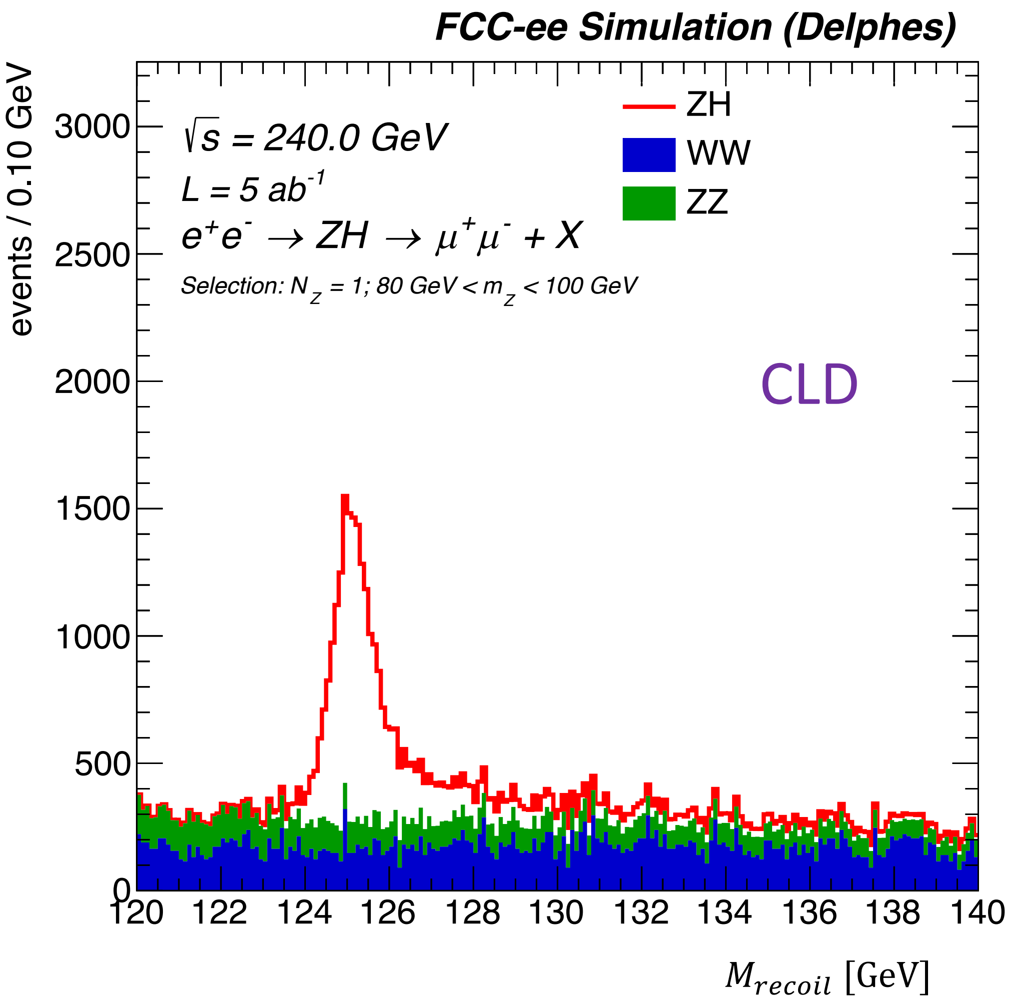
Full range: $M_{recoil} \in [0, 200]$ GeV

Events: ZH: 24626.7
ZZ: 307889.4
WW: 124217.5

Comparison of IDEA and CLD Simulation of the $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- + X$



IDEAtrkCov



CLDtrkCov

Drop in the ZH peak region

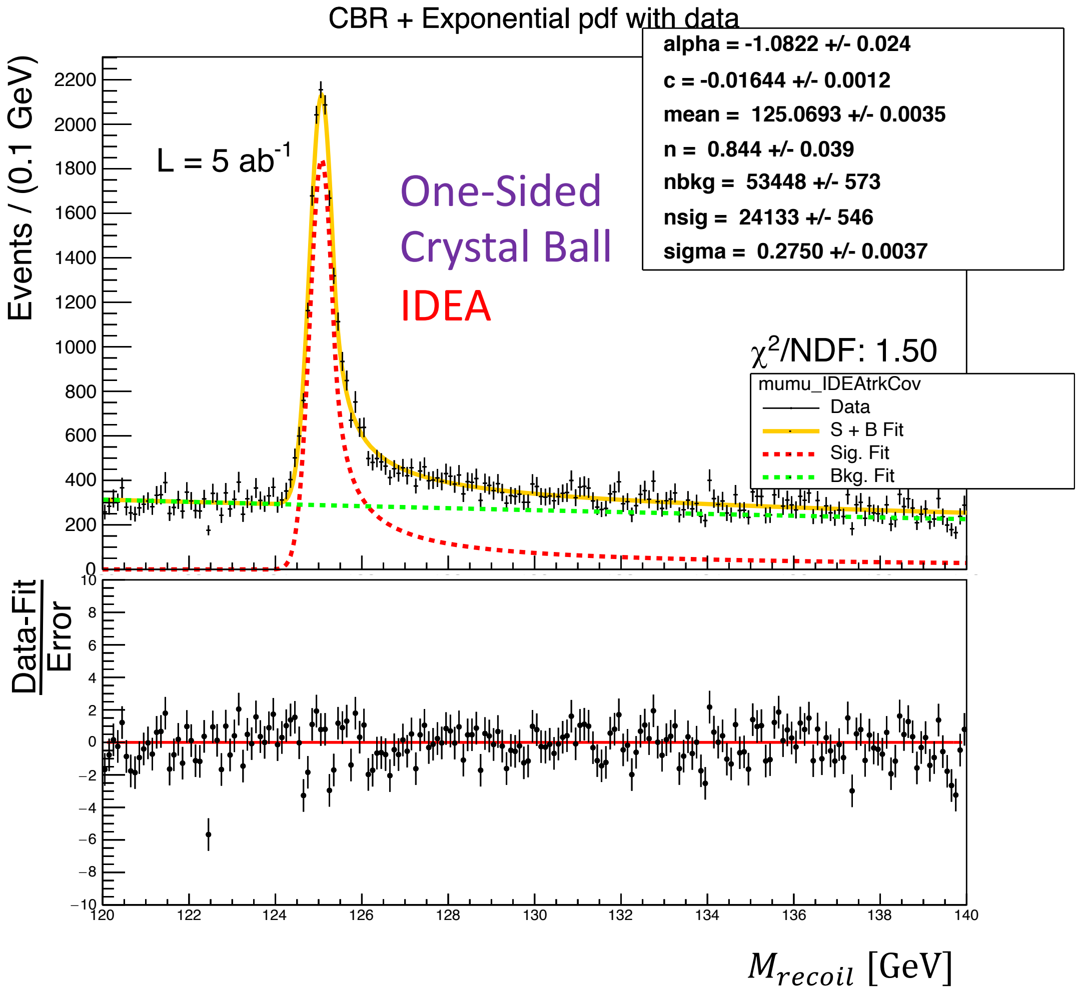
Fitting the M_{recoil} and M_z, parameter settings

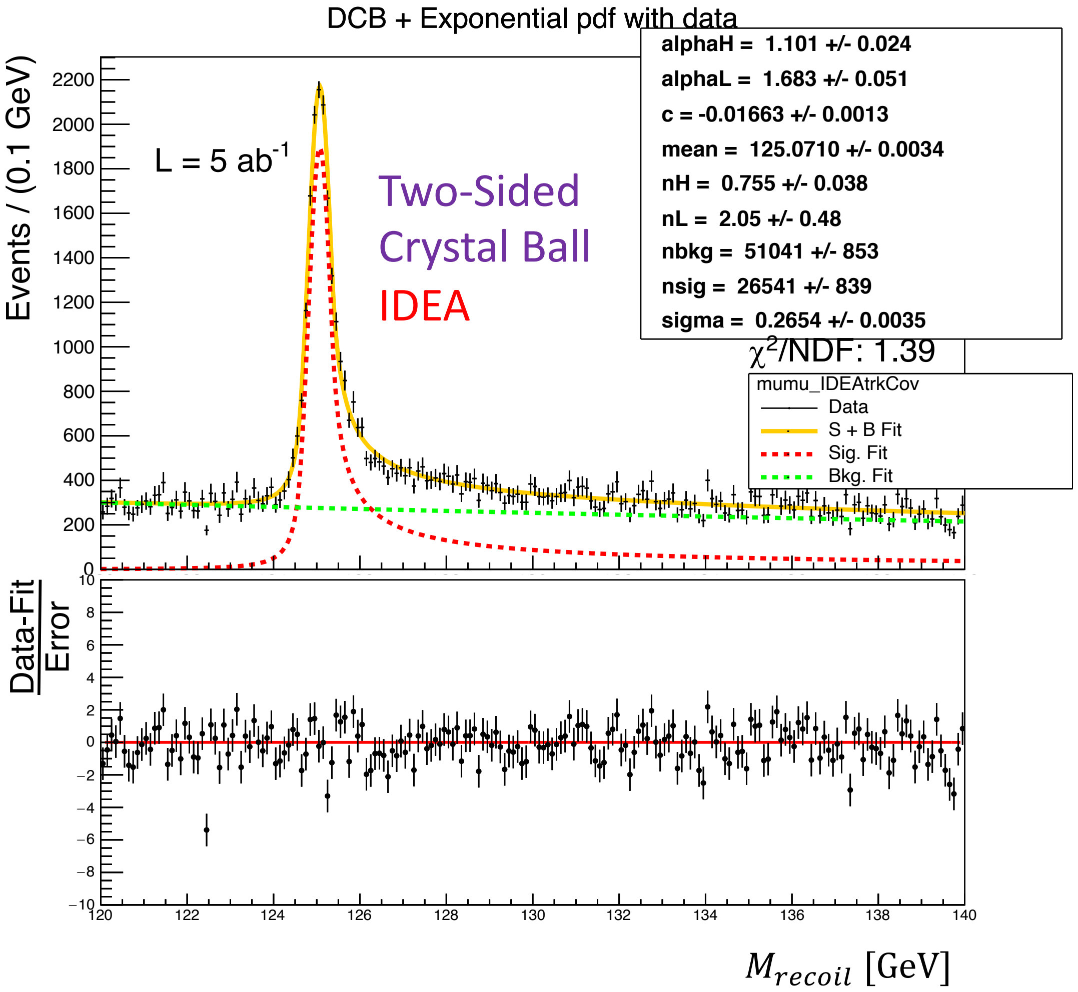
- **Signal:**
  - ZH
- **Background:**
  - ZZ, WW
- **Fitting functions**
  - Signal: Landau, Breit-Wigner and Crystal Ball
  - Signal = RooLandau(m, mean, sigma)
    RooBreitWigner(m, mean, sigma)
    RooCBShape(m, mean, sigma, a, n)
    RooTwoSidedCBShape(m ,mean, sigma, aL, nL, aH, nH)
  - Background: Exponential
  - Background = RooExponential(m, c)
  - S + B = nsig*signal + nbkg*background

An example of a fit with a One-Sided Crystal Ball + Exponential functions

- $S(m; \alpha, n, m_0, \sigma) \sim \begin{cases} \exp\left(-\frac{(m - m_0)^2}{2\sigma^2}\right), & for\ \frac{m-m_0}{\sigma} > -\alpha \\ A \cdot \left(B - \frac{m-m_0}{\sigma}\right), & for\ \frac{m-m_0}{\sigma} \leq -\alpha \end{cases}$
- $\mathrm{B}(m; c) \sim \exp(c \cdot m)$
- $f(m; c, \alpha, n, m_0, \sigma, nsig, nbkg) = nsig \cdot S + nbkg \cdot B$

One- and Two-Sided Crystal Ball + Exponential fit of M_{recoil} in the Higgs region (120-140 GeV)



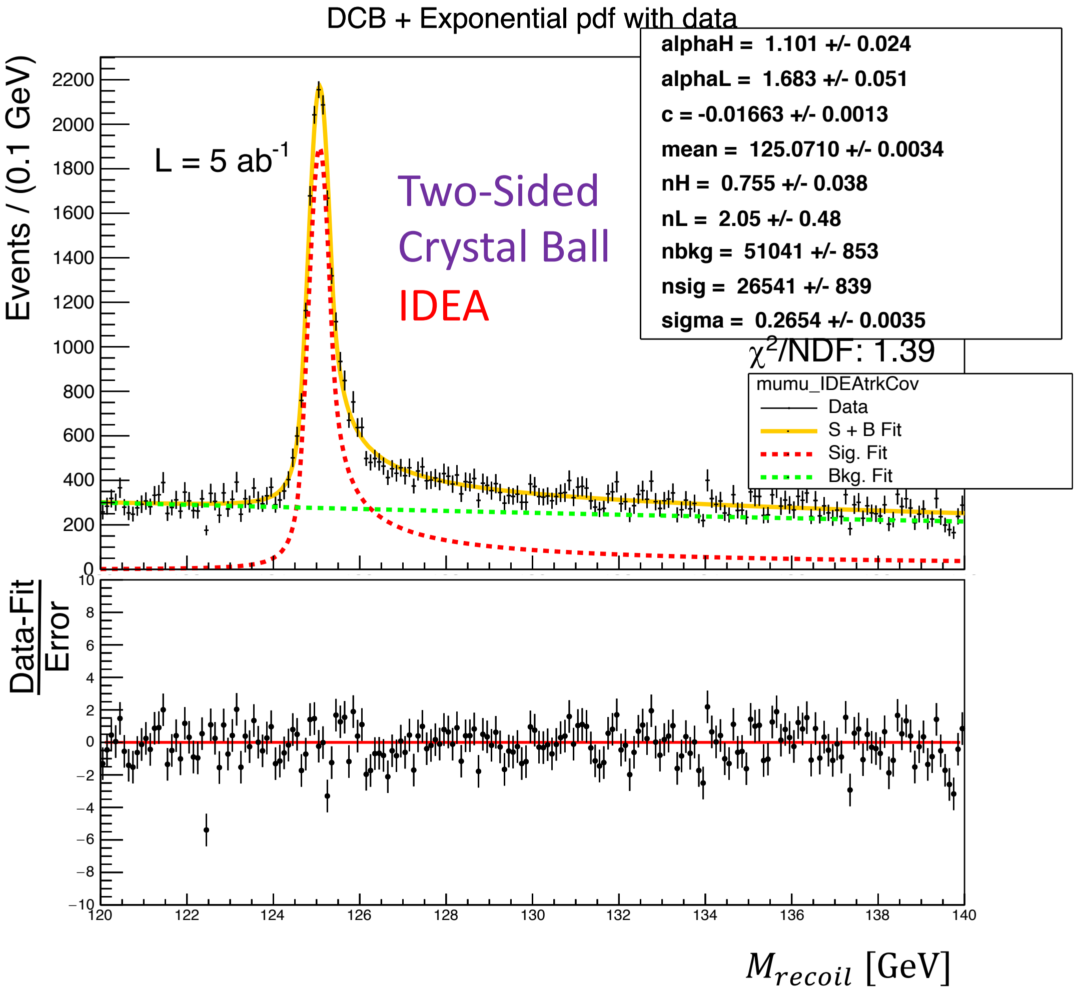


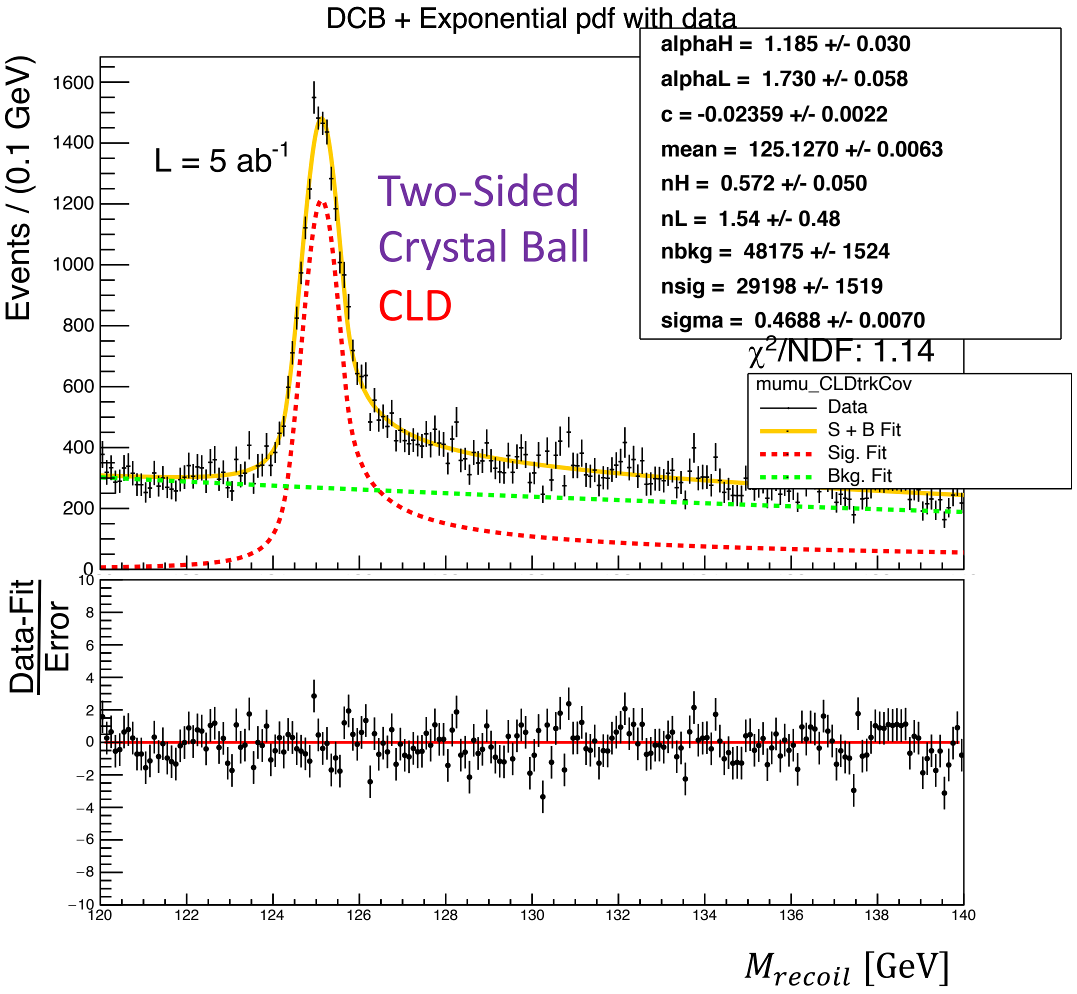
IDEAtrkCov: $\sigma_{RMS} = 0.275 \pm 0.0037$ GeV
$M_{recoil} = 125.069 \pm 0.0035$ GeV

IDEAtrkCov: $\sigma_{RMS} = 0.265 \pm 0.0035$ GeV
$M_{recoil} = 125.071 \pm 0.0034$ GeV

Two-Sided Crystal Ball function gives better fit result than One-Sided Crystal Ball but larger signal uncertainty

Two-Sided Crystal Ball + Exponential fit of M_{recoil} in the Higgs region (120-140 GeV)





IDEAtrkCov: $\sigma_{RMS} = 0.265 \pm 0.0035$ GeV

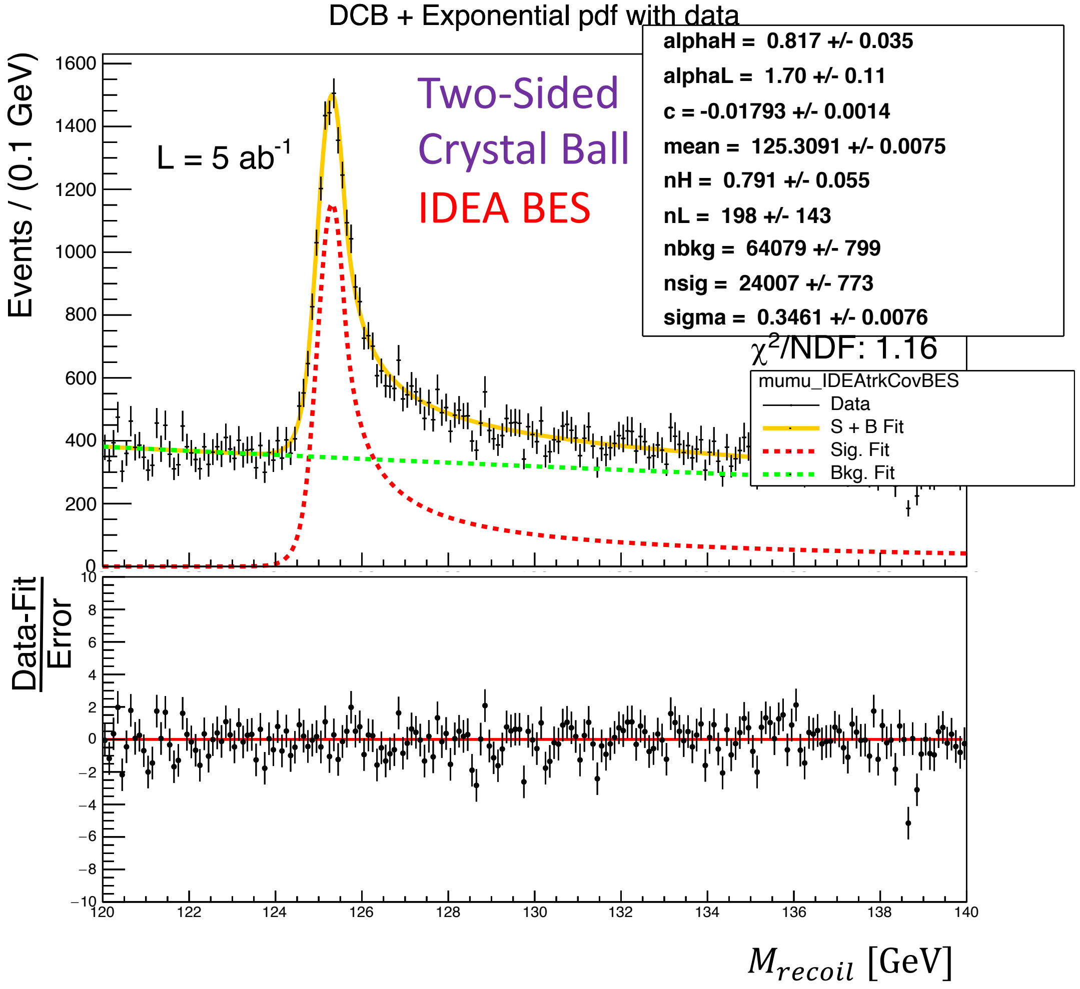
$M_{recoil} = 125.071 \pm 0.0034$ GeV

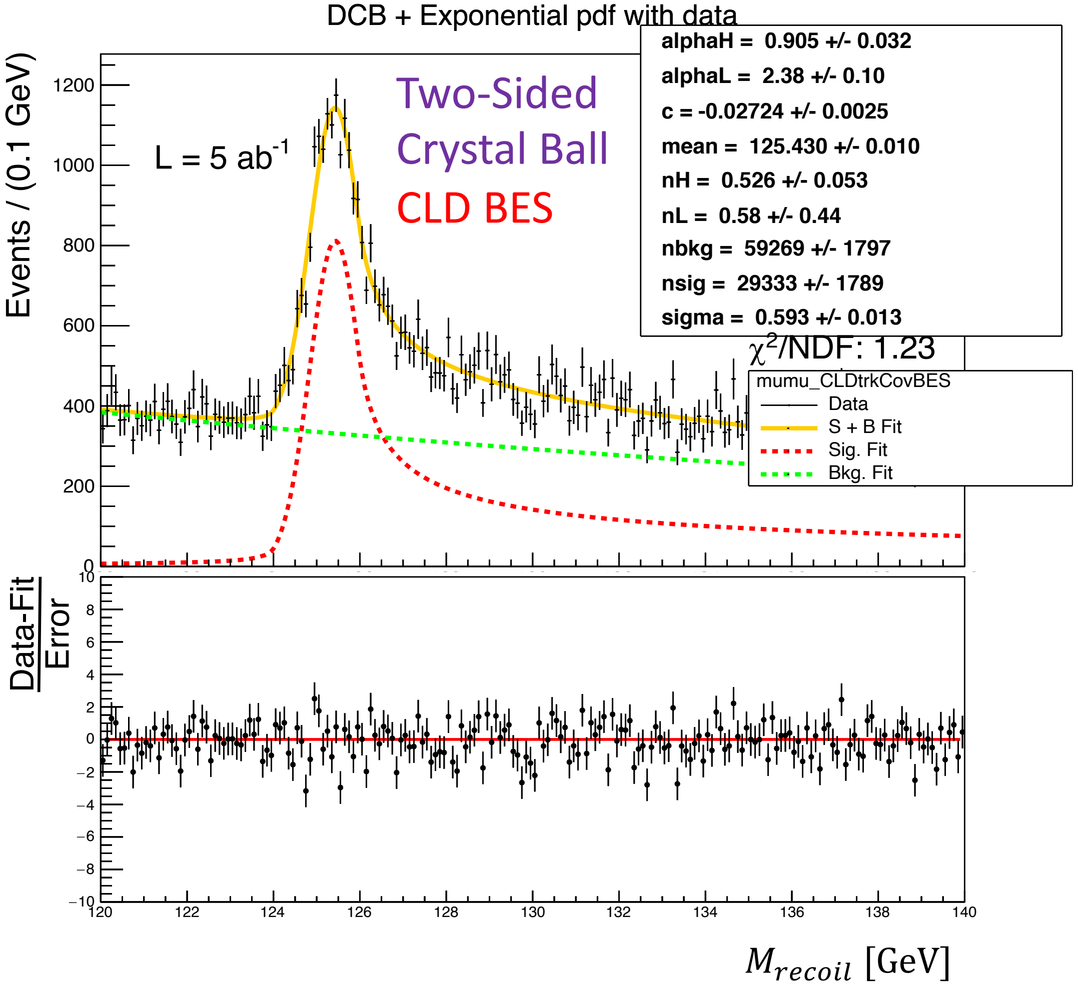
CLDtrkCov: $\sigma_{RMS} = 0.469 \pm 0.0070$ GeV

$M_{recoil} = 125.127 \pm 0.0063$ GeV

The sigma obtained in fit of the CLD simulation is about 75% larger than the IDEA one

Two-sided Crystal Ball + Exponential fit of M_{recoil} in the Higgs region (120-140 GeV) with BES





IDEAtrkCovBES: $\sigma_{RMS} = 0.346 \pm 0.0076$ GeV
$M_{recoil} = 125.309 \pm 0.0075$ GeV

CLDtrkCovBES: $\sigma_{RMS} = 0.593 \pm 0.013$ GeV
$M_{recoil} = 125.43 \pm 0.010$ GeV

Beam Energy Spread: Beams:sigmaPzA = 0.198 (GeV)
Beams:sigmaPzB = 0.198 (GeV)

M_{recoil} fitted Width, $\chi^2/_{NDF}$ and fitted mass in the Higgs region

Two-Sided Crystal Ball Fit	σ_{IDEA}	IDEA $\chi^2/_{NDF}$	σ_{CLD}	CLD $\chi^2/_{NDF}$
Without BES	0.265	1.39	0.469	1.14
With BES	0.346	1.16	0.593	1.23

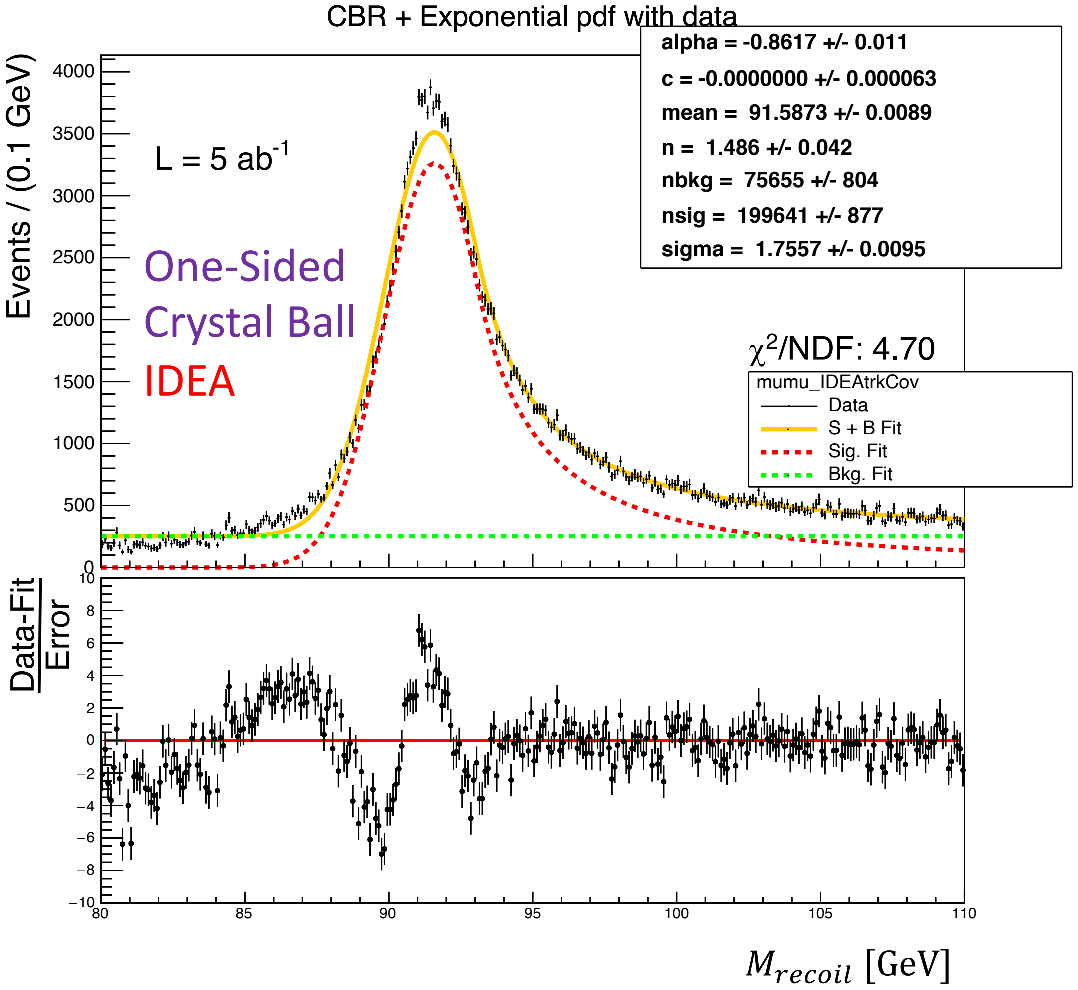
The width of CLD σ_{CLD} is ~ 75 % larger than σ_{IDEA}
After including the Beam Energy Spread, the width of IDEA and CLD are enlarged by ~ 30 %

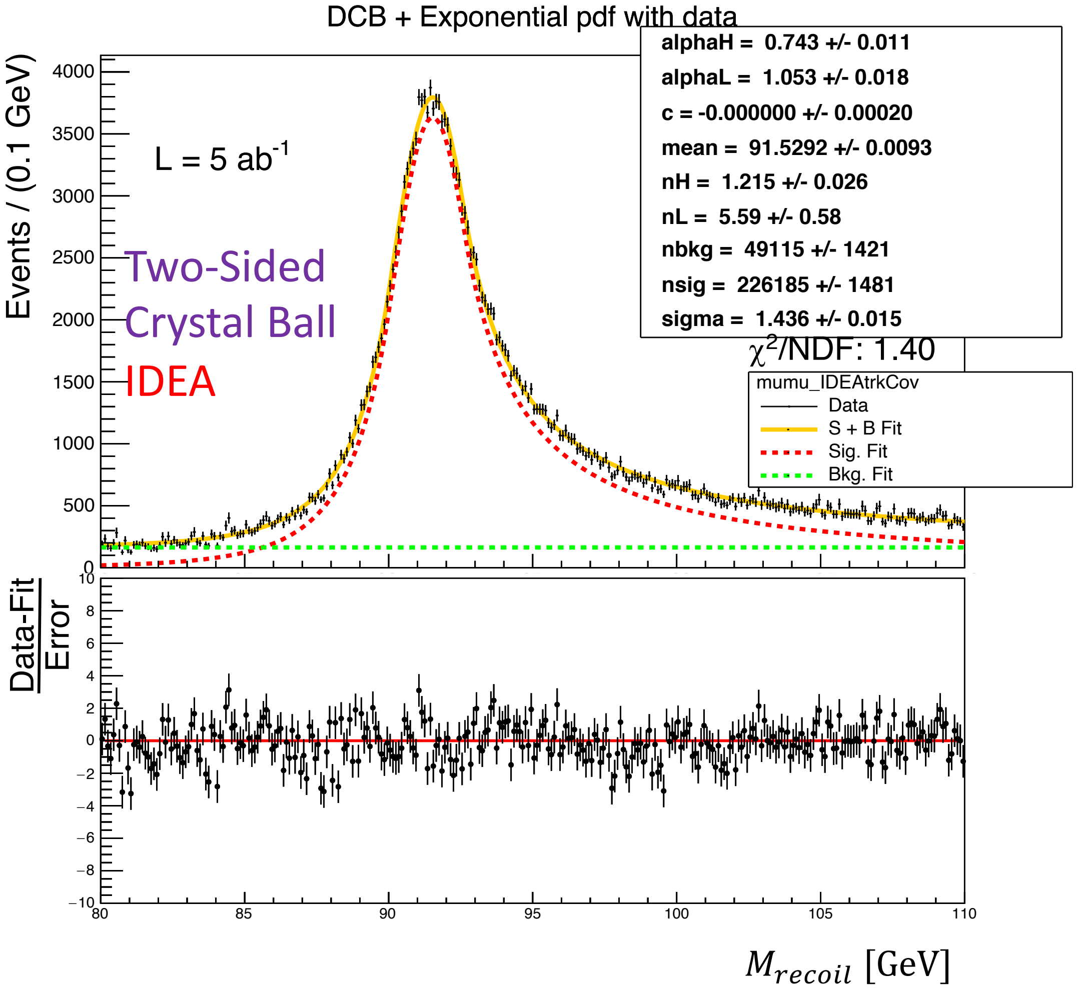
For Crystal Ball, σ represents the Standard Deviation (RMS) of the central Gaussian

Two-Sided Crystal Ball Fit	IDEA		CLD	
	M_H (GeV)	Δ_{M_H} (MeV)	M_H (GeV)	Δ_{M_H} (MeV)
Without BES	125.071	3.4	125.127	6.3
With BES	125.309	7.5	125.430	10

The uncertainty of the fitted mass of CLD is 85% larger than IDEA,
After including the Beam Energy Spread, the uncertainty of the fitted mass of IDEA is increased by about 120%

One- and Two-sided Crystal Ball + Exponential fit of M_{recoil} in the Z region (80-110 GeV)



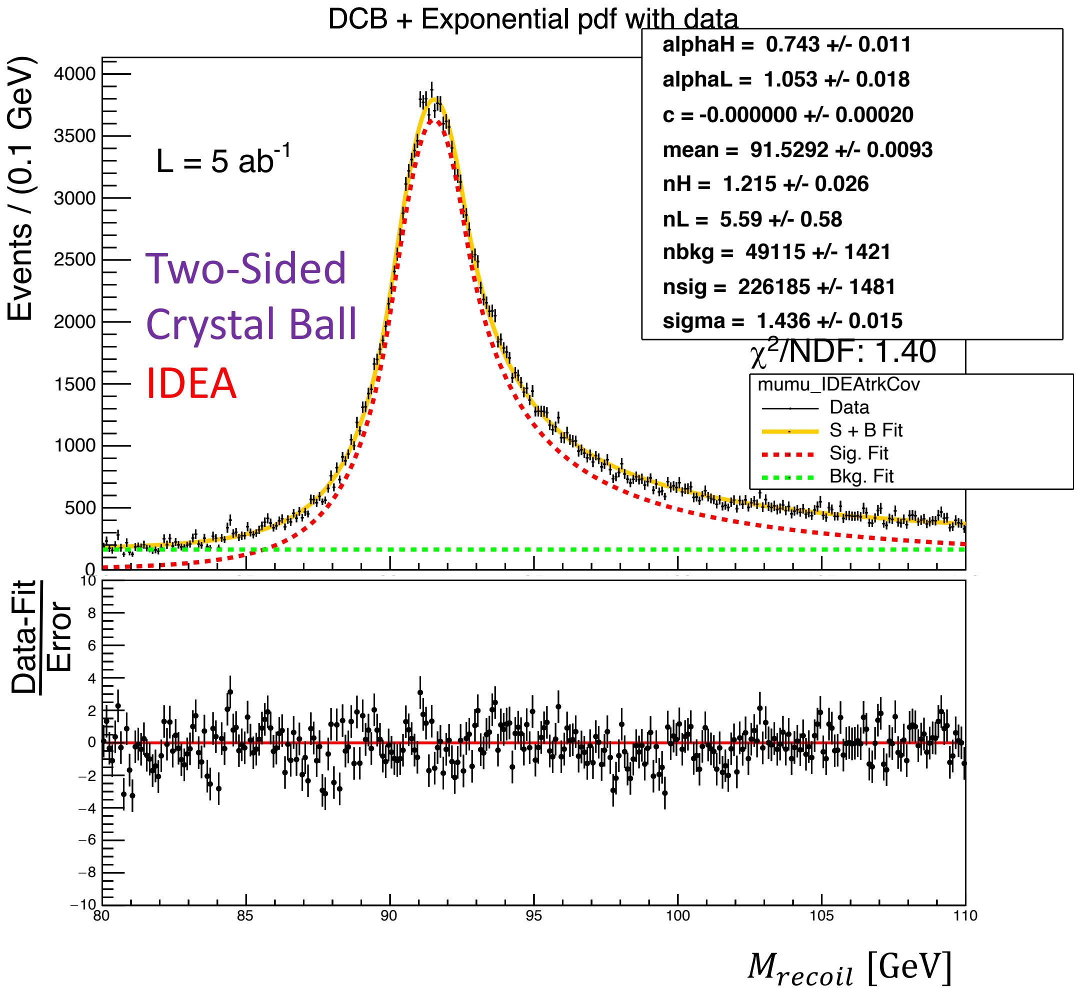


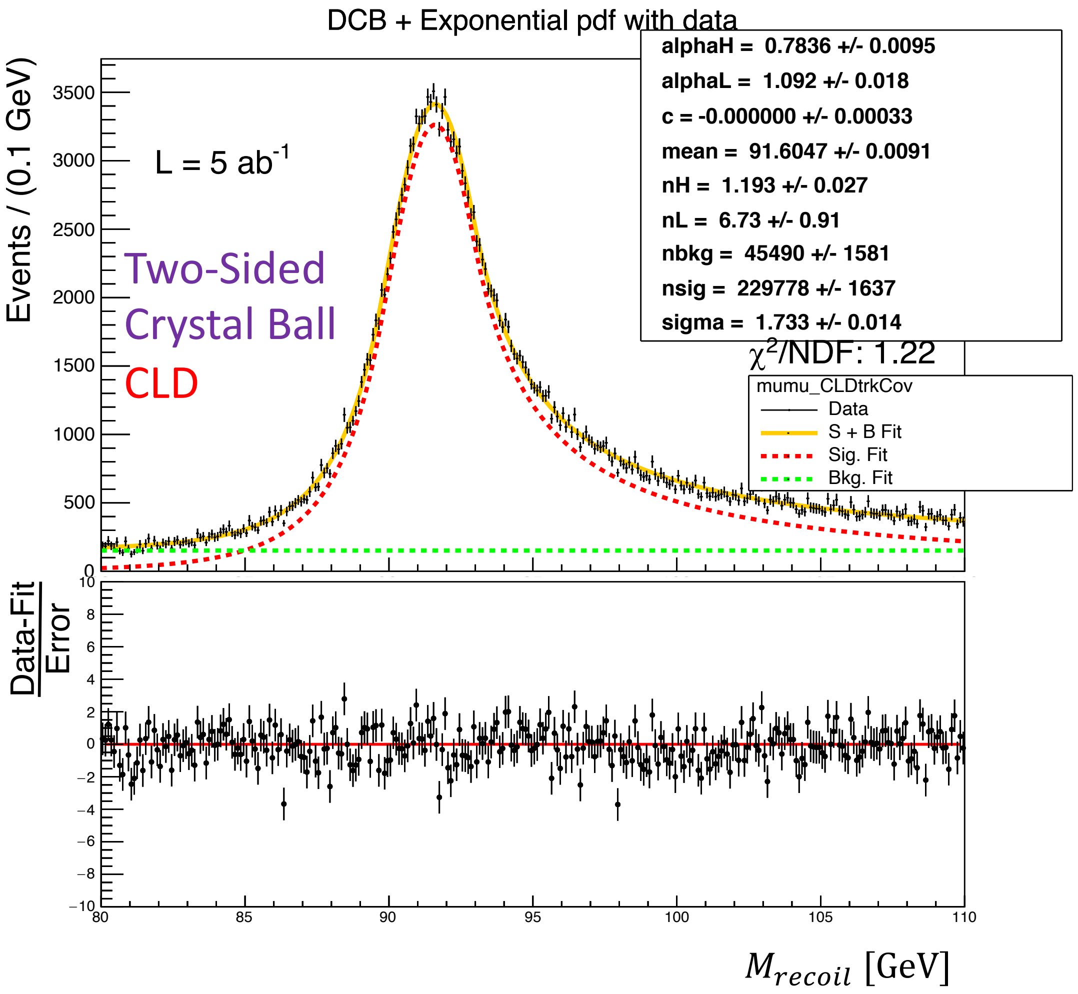
IDEAtrkCov: $\sigma_{RMS} = 1.756 \pm 0.0095$ GeV
$M_{recoil} = 91.587 \pm 0.0089$ GeV

IDEAtrkCov: $\sigma_{RMS} = 1.44 \pm 0.015$ GeV
$M_{recoil} = 91.529 \pm 0.0093$ GeV

One-Sided Crystal Ball distribution has discrepancy on the left tail and in the peak with the data, also poor χ^2/NDF
Two-Sided Crystal Ball gives good fit result but larger signal uncertainty

Two-Sided Crystal Ball + Exponential fit of M_{recoil} in the Z region (80-110 GeV)





IDEAtrkCov: $\sigma_{RMS} = 1.44 \pm 0.015$ GeV

$M_{recoil} = 91.529 \pm 0.0093$ GeV

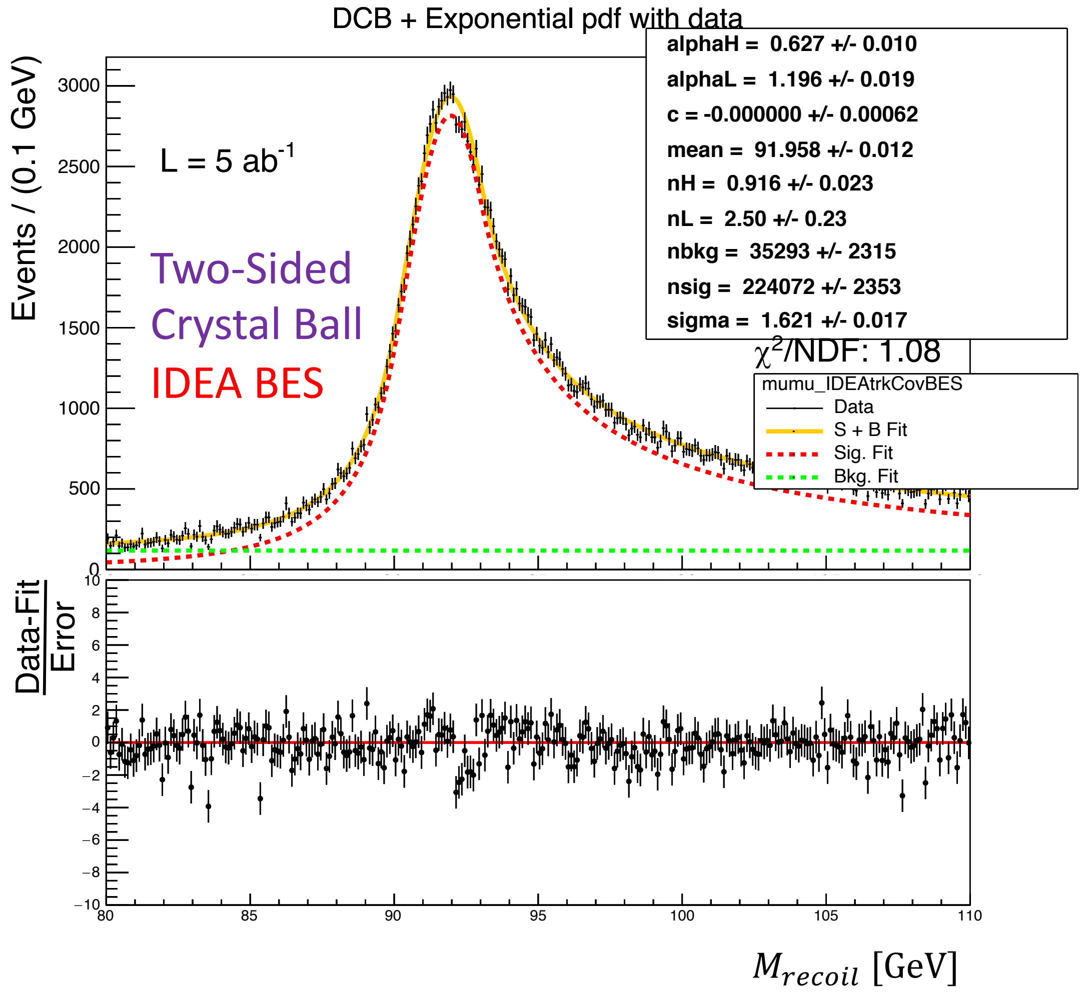
CLDtrkCov: $\sigma_{RMS} = 1.73 \pm 0.014$ GeV

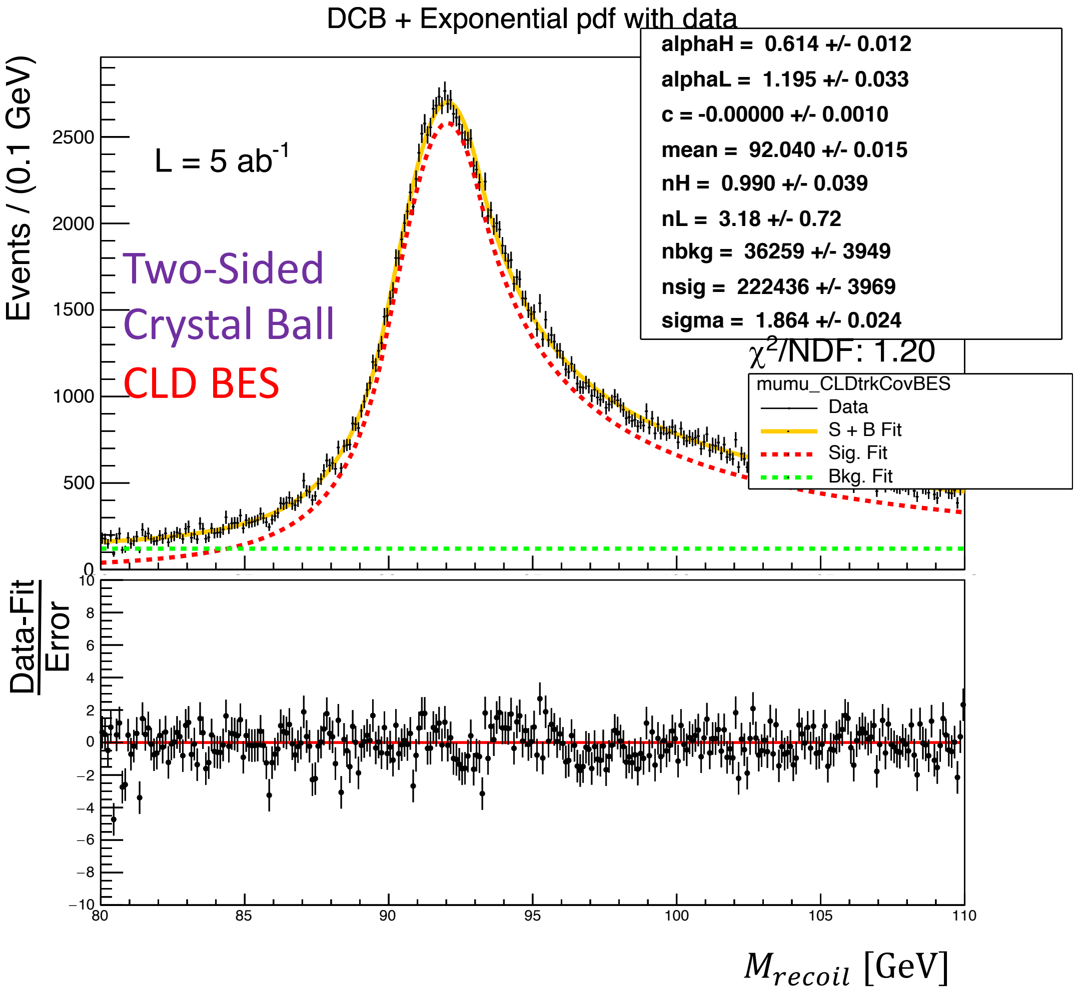
$M_{recoil} = 91.605 \pm 0.0091$ GeV

Two-Sided Crystal Ball distribution describes the data well, $\chi^2/_{NDF} \sim 1.2 - 1.4$

CLD has larger width than IDEA, by about 20%

Two-Crystal Ball + Exponential fit of M_{recoil} with BES in the Z region (80-110 GeV)





IDEAtrkCov: $\sigma_{RMS} = 1.62 \pm 0.017$ GeV
$M_{recoil} = 91.96 \pm 0.012$ GeV

CLDtrkCov: $\sigma_{RMS} = 1.86 \pm 0.024$ GeV
$M_{recoil} = 92.04 \pm 0.015$ GeV

After adding BES, the Two-Sided Crystal Ball distribution still describes the data well, $\chi^2/_{NDF} \sim 1.1 - 1.2$

CLD has larger width than IDEA, by about 15%

M_{recoil} fitted Width, $\chi^2/_{NDF}$ and fitted mass in the Z region (80-110 GeV)

Two-Sided Crystal Ball Fit	σ_{IDEA}	IDEA $\chi^2/_{NDF}$	σ_{CLD}	CLD $\chi^2/_{NDF}$
Without BES	1.436	1.40	1.733	1.22
With BES	1.621	1.08	1.864	1.20

- The width of CLD σ_{CLD} is $\sim 15-20\%$ larger than σ_{IDEA}
- After including the Beam Energy Spread, the width of IDEA and CLD are enlarged by ~ 10 %

For Crystal Ball, σ represents the Standard Deviation (RMS) of the central Gaussian

Two-Sided Crystal Ball Fit	IDEA		CLD	
	M_Z (GeV)	Δ_{M_Z} (MeV)	M_Z (GeV)	Δ_{M_Z} (MeV)
Without BES	91.529	9.3	91.605	9.1
With BES	91.958	12	92.040	15

- Without BES, the uncertainty of the fitted mass of CLD is similar with IDEA
- The uncertainty on the mass without BES does not change much because the intrinsic Z width is large
- After including BES, the uncertainty of the fitted mass of IDEA is increased by 25%
- The detector effect is smaller than the intrinsic Z width

Reconstructed Z Boson Mass Fit Settings

- **M_Z is reconstructed from the leptons pair ($\mu^+\mu^-$)**

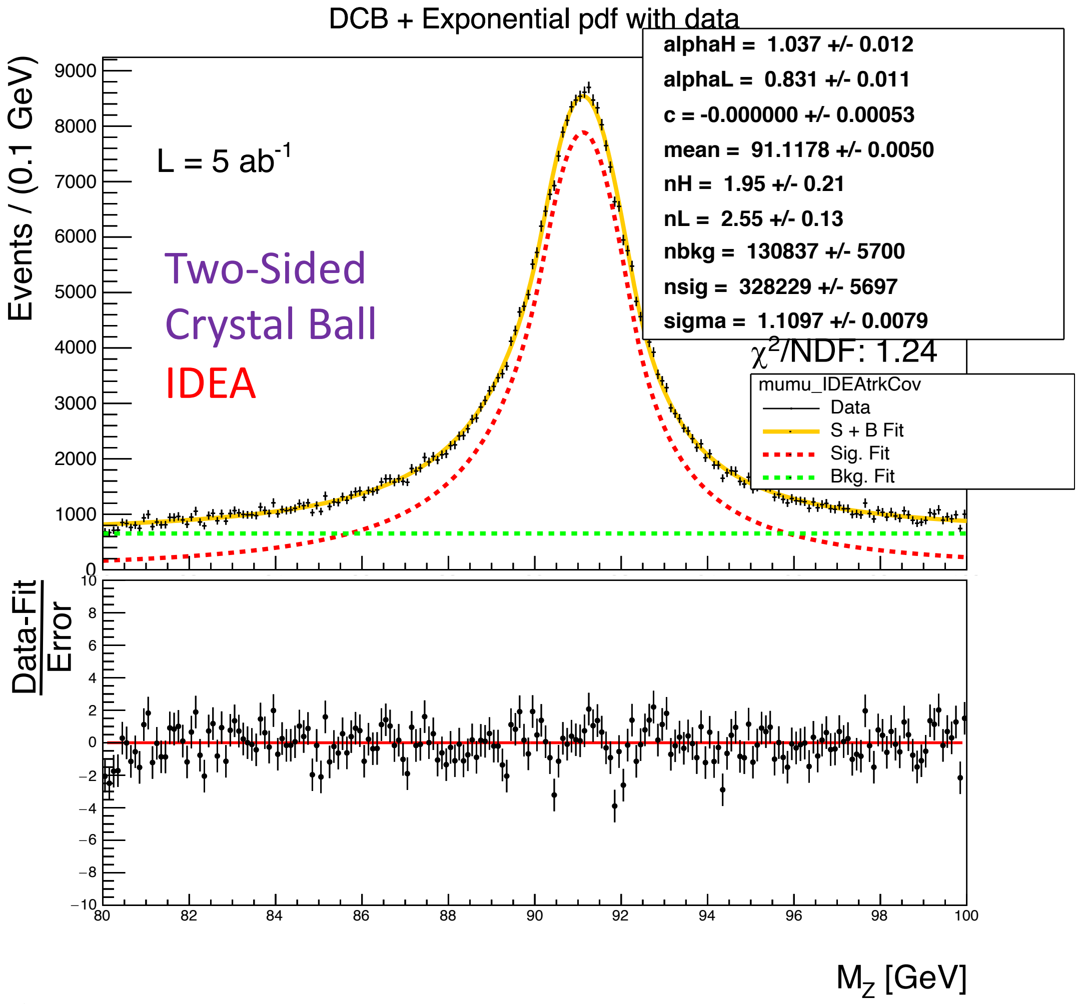
- **Both ZH and ZZ channels have a leptonic Z mass peak**
  - The simulated samples are studied inclusively

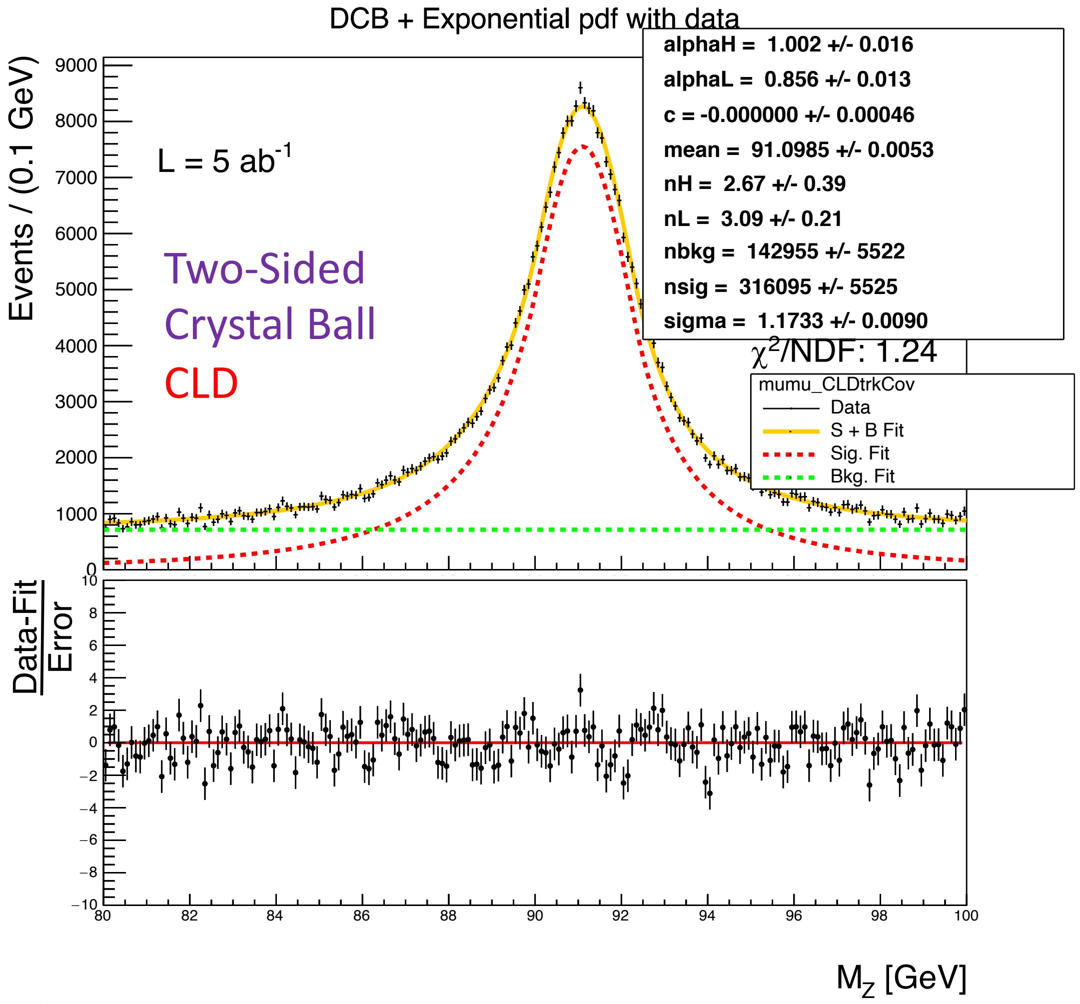
- **0.1 GeV binning**

- **$M_Z \in [80, 100]$ GeV**

- **Two-Sided Crystal Ball function as signal**

Two-Sided Crystal Ball + Exponential fit of M_Z in the Z region (80-100 GeV)





IDEAtrkCov: $\sigma_{RMS} = 1.110 \pm 0.0079$ GeV

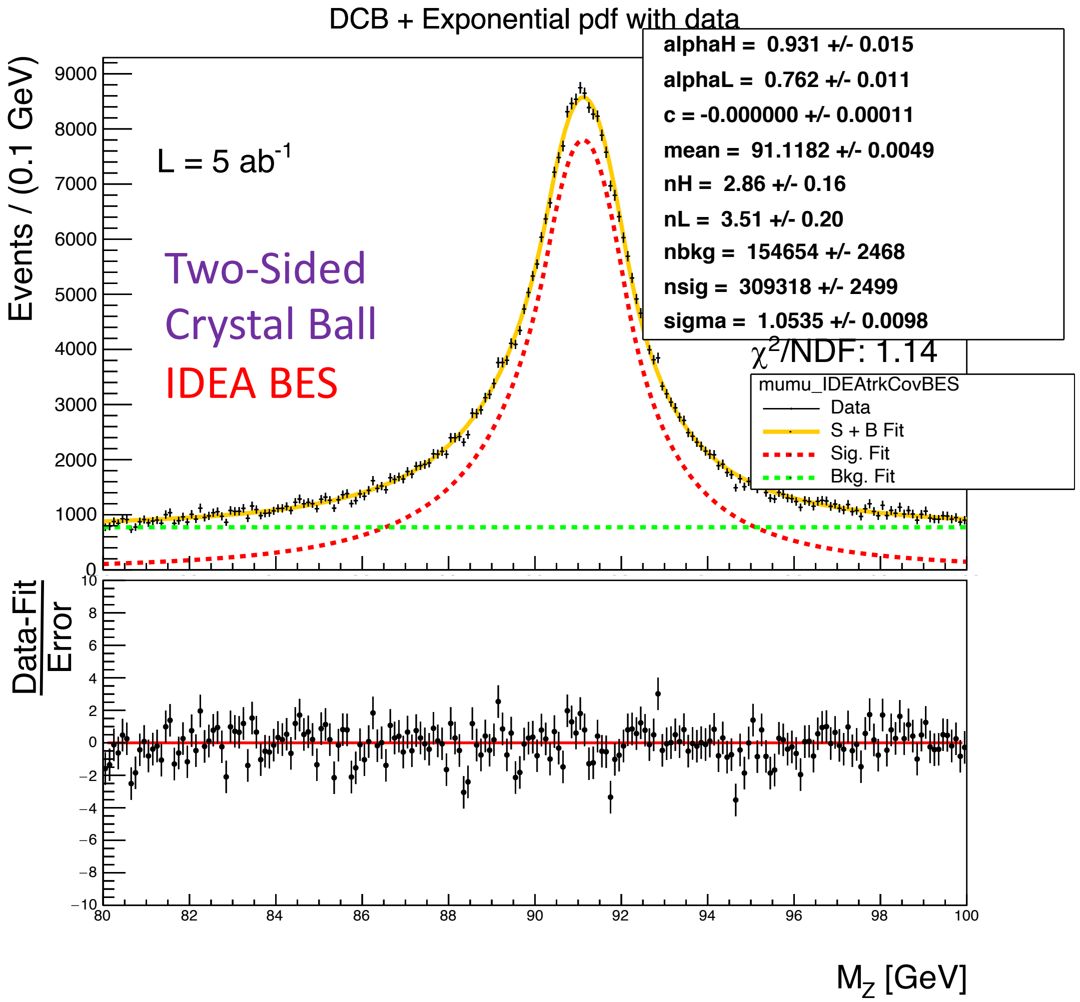
$M_Z = 91.118 \pm 0.0050$ GeV

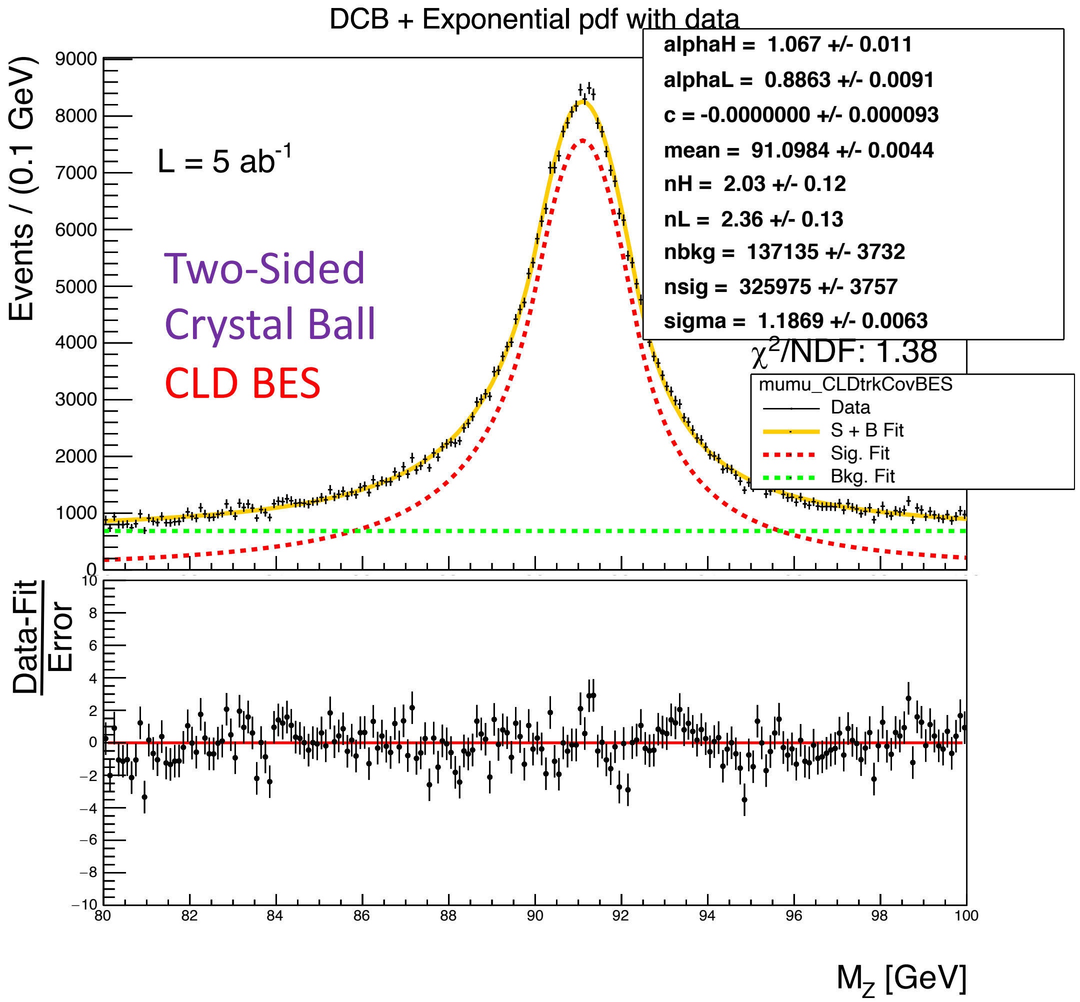
CLDtrkCov: $\sigma_{RMS} = 1.173 \pm 0.0090$ GeV

$M_Z = 91.099 \pm 0.0053$ GeV

CLD has larger width IDEA, by ~ 6%

Two-Sided Crystal Ball + Exponential fit of M_Z with BES in the Z region (80-100 GeV)





IDEAtrkCovBES: $\sigma_{RMS} = 1.053 \pm 0.0098$ GeV

$M_Z = 91.118 \pm 0.0049$ GeV

CLDtrkCovBES: $\sigma_{RMS} = 1.187 \pm 0.0063$ GeV

$M_Z = 91.098 \pm 0.0044$ GeV

After adding BES, Two-Sided Crystal Ball distribution still has $\chi^2/_{NDF} \sim 1.1 - 1.4$

CLD has larger width than IDEA, by ~ 13%

M_Z fitted Width, $\chi^2/_{NDF}$ and fitted mass in the Z mass region (80-100 GeV)

Two-Sided Crystal Ball fit	σ_{IDEA}	IDEA $\chi^2/_{NDF}$	σ_{CLD}	CLD $\chi^2/_{NDF}$
Without BES	1.110	1.24	1.173	1.24
With BES	1.05	1.14	1.19	1.38

The width of CLD σ_{CLD} is $\sim 5-10$ % larger than σ_{IDEA}
BES has no visible effect on the fitted width as expected

Two-Sided Crystal Ball Fit	IDEA		CLD	
	M_Z (GeV)	Δ_{M_Z} (MeV)	M_Z (GeV)	Δ_{M_Z} (MeV)
Without BES	91.118	5.0	91.099	5.3
With BES	91.118	4.9	91.102	4.4

The uncertainty of the fitted mass of CLD is close to IDEA,
After including the Beam Energy Spread, the uncertainty of the fitted mass of IDEA stays almost the same

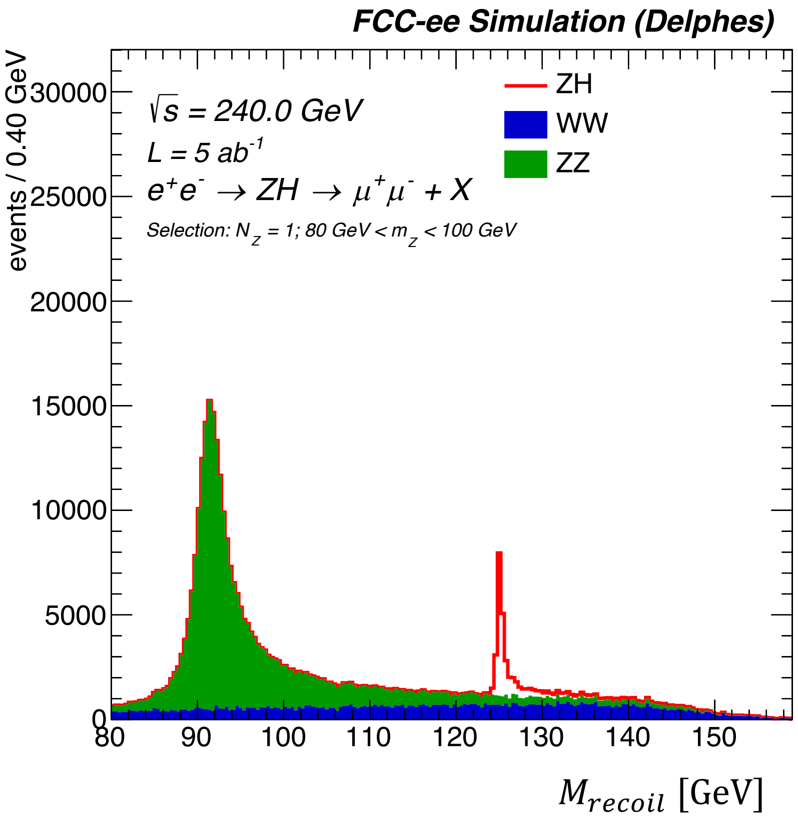
Conclusions

- This first study of ZH production allows for a comparison of IDEA and CLD tracking performance
- For $M_{recoil} \in [120, 140]$ GeV
  - Two-Sided Crystal Ball distribution gives the best fit results
  - The width of CLD σ_{CLD} is $\sim 75\ \%$ larger than σ_{IDEA}
  - After including the Beam Energy Spread, the width of IDEA and CLD are enlarged by ~ 30 %
  - For IDEA w/o BES, the fitted mass is 125.069 GeV $\pm$ 4 MeV.
- For $M_{recoil} \in [80, 110]$ GeV
  - Two-Sided Crystal Ball distribution gives the best fit results
  - The width of CLD σ_{CLD} is $\sim 15 - 20\ \%$ larger than σ_{IDEA}
  - After including the Beam Energy Spread, the width of IDEA and CLD are enlarged by ~ 10 %
  - For IDEA w/o BES, the fitted mass is 91.529 GeV $\pm$ 9 MeV.
- For direct M_Z Reconstruction ($M_Z \in [80, 100]$ GeV)
  - Two-Sided Crystal Ball distribution gives the best fit results
  - The width of CLD σ_{CLD} is $\sim 5 - 10\ \%$ larger than σ_{IDEA}
  - The Beam Energy Spread has negligible effect on the width
  - For IDEA with or w/o BES, the fitted mass is 91.118 GeV $\pm$ 5 MeV.

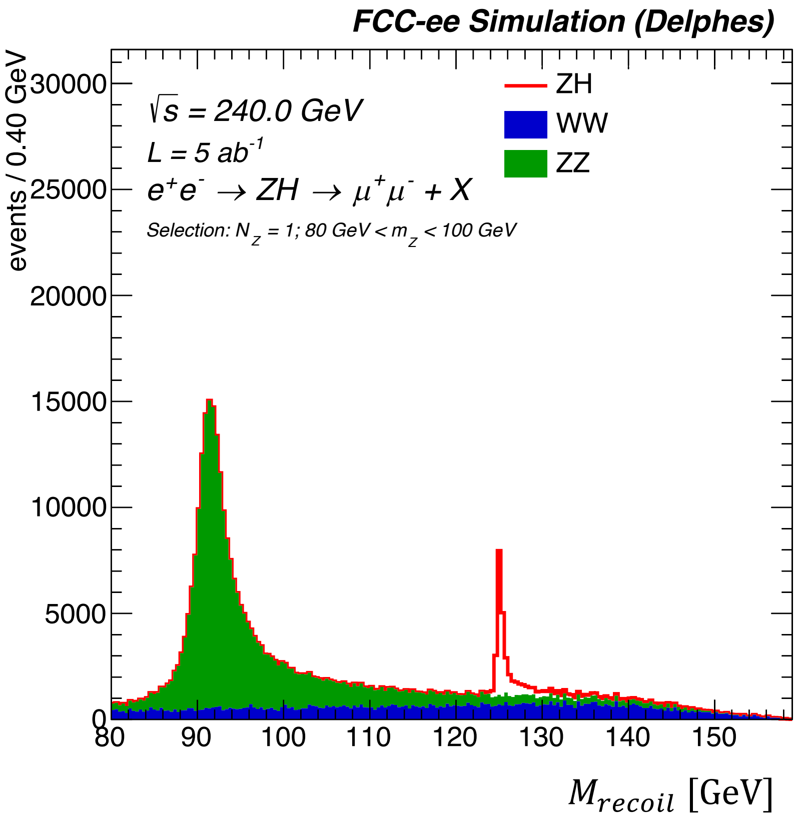
Thanks for the help from Clement and Emmanuel

BackUp

Simulation of the $e^+e^- \to ZH \to \mu^+\mu^- + X$



IDEA simulation (done by A. L.)
10^7 events for each channel
After selection
Entries: ZH: 244859
ZZ: 456495
WW: 15119



IDEA simulation (done by C. H.)
~ 10^7 events for each channel
After selection
Entries: ZH: 242018
ZZ: 454355
WW: 15298

2-3 hours for 10^7 events
(Fri. – Sun.)
+ 10 hrs (Mon. – Thu.)

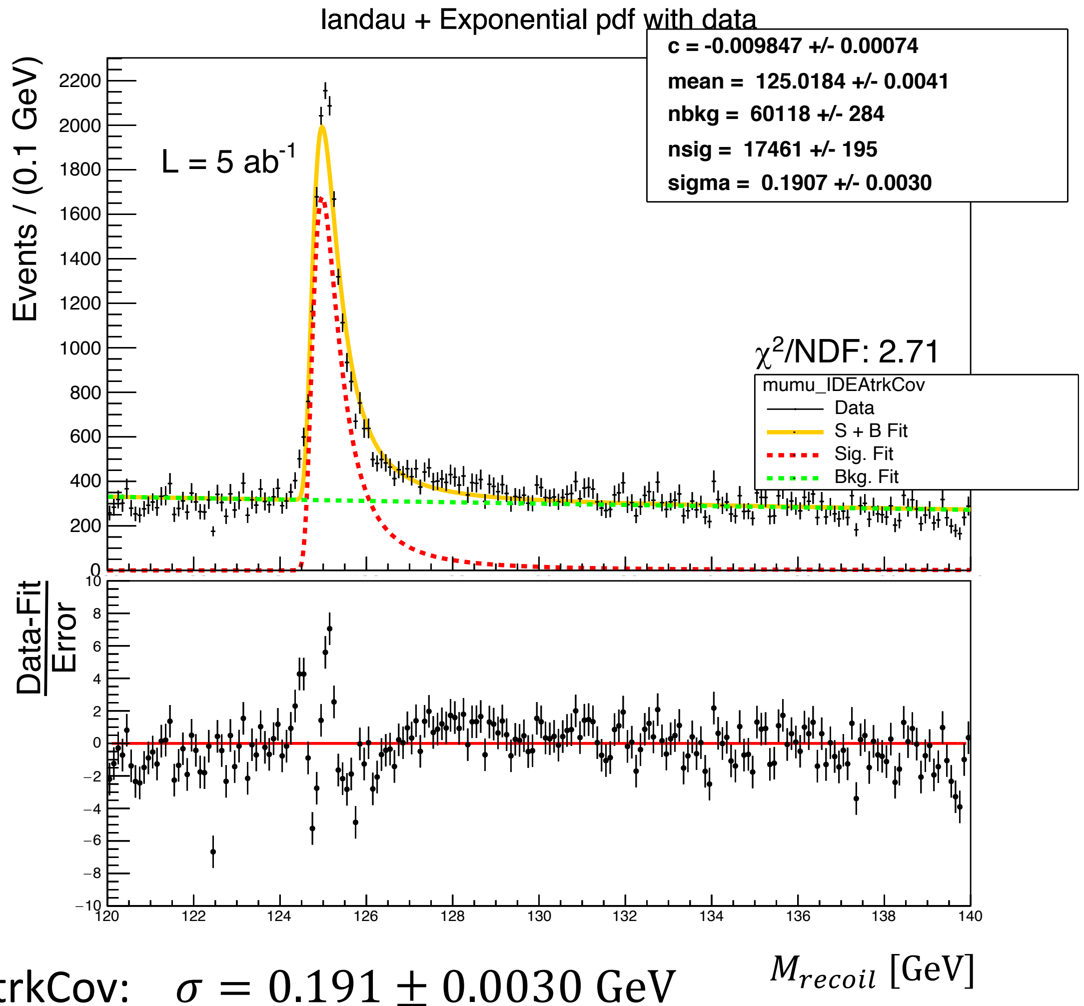
~60-80GB (/afs/```/work maximum 100GB)

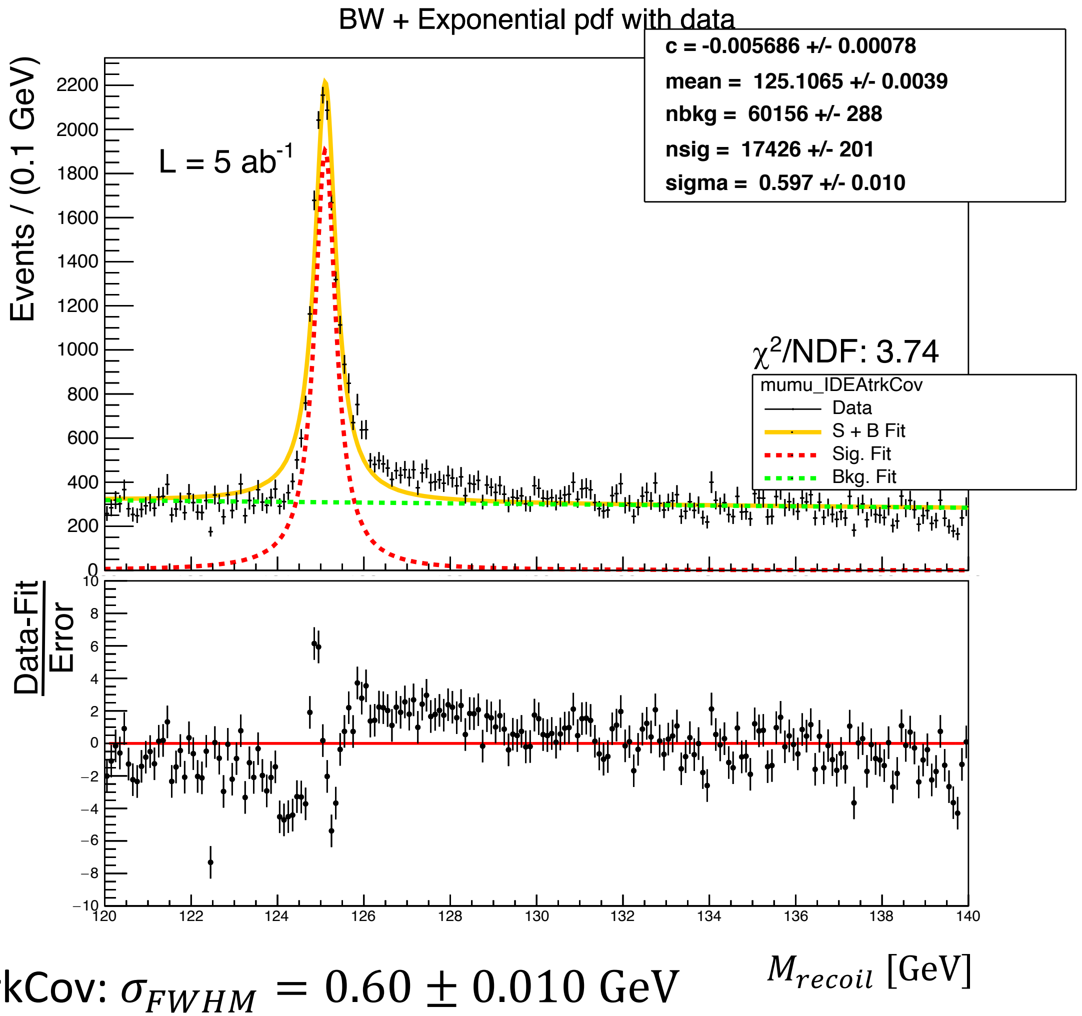
Copying from /work to /eos takes ~2 hours (slow)

Data saved in my cernBOX (maximum 1TB)

Need more space for data

Landau or Breit-Wigner + Exponential fit of M_{recoil} in the Higgs region (120-140 GeV)



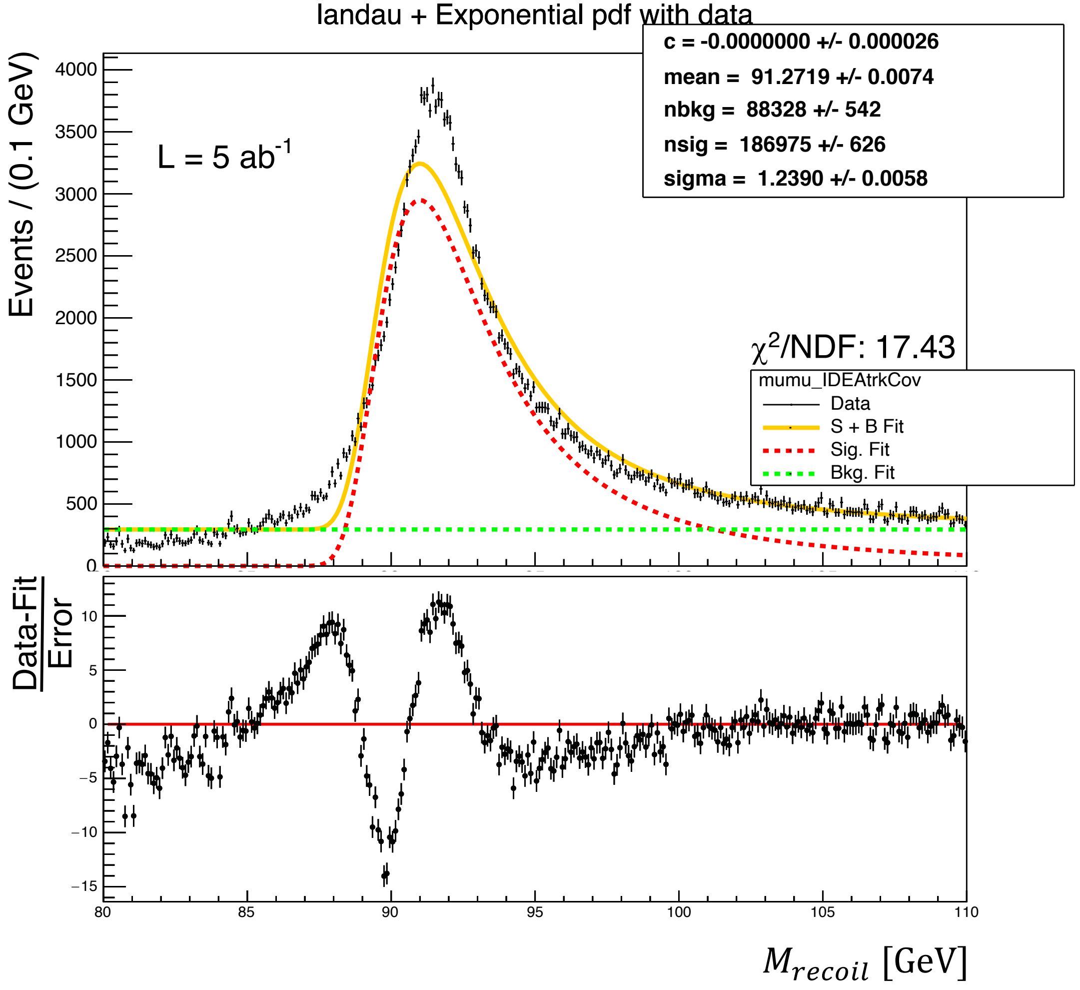


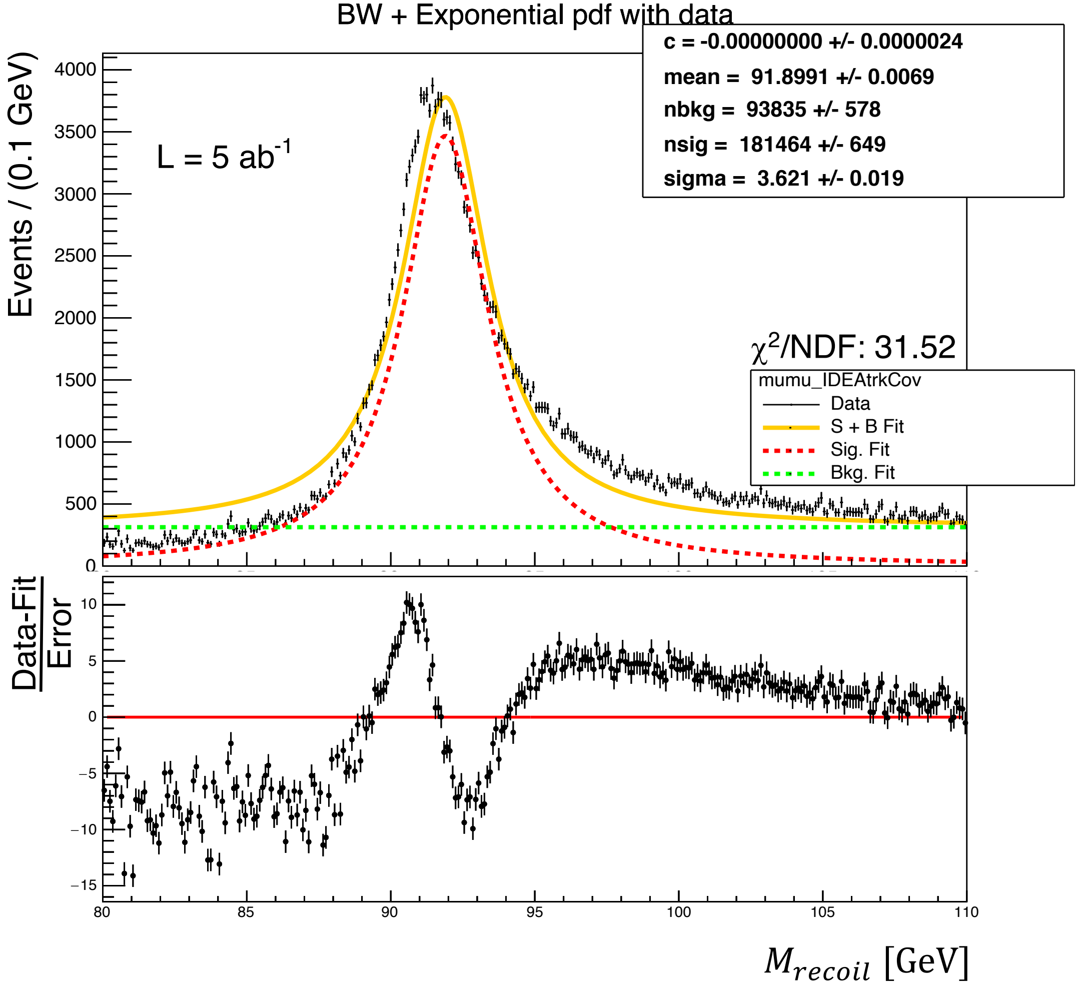
IDEAtrkCov: $\sigma = 0.191 \pm 0.0030$ GeV
$M_{recoil} = 125.018 \pm 0.0041$ GeV

IDEAtrkCov: $\sigma_{FWHM} = 0.60 \pm 0.010$ GeV
$M_{recoil} = 125.107 \pm 0.0039$ GeV

The simulated data (will be called data in the following) and the Landau fit result have large differences in the peak region
The Data and the Breit-Wigner fit result have large differences in the side bands

Landau or Breit-Wigner + Exponential fit of M_{recoil} in the Z region (80-110 GeV)





IDEAtrkCov: $\sigma = 1.239 \pm 0.0058$ GeV

$M_{recoil} = 91.272 \pm 0.0074$ GeV

IDEAtrkCov: $\sigma_{FWHM} = 3.62 \pm 0.019$ GeV

$M_{recoil} = 91.899 \pm 0.0069$GeV

Landau distribution is not a good candidate to describe the M_{recoil} distribution in the Z region

Breit-Wigner distribution has significant deviation on both tails than the data

M_{recoil} Fitted Signal Yield in the Higgs region with and w/o BES

Two-Sided Crystal Ball Fit	**IDEA**			**CLD**		
	N_{signal}	$\Delta_{N_{signal}}$	$N_{sig}/\Delta N_{sig}$	N_{signal}	$\Delta_{N_{signal}}$	$N_{sig}/\Delta N_{sig}$
Without BES	26514	839	3.2%	29198	1519	5.2%
With BES	24007	773	3.2%	29333	1789	6.1%

The signal yield of CLD is ~ 10 – 20 % more than IDEA

Software

- **Simulation:**
  - Condor_submit.py
    - Submit jobs to HTCondor
    - Can automatically produce pythia card, random number
    - One can customize: number of events per root file
number of root files
  - Checking_missing_events.py
    - Can check which job is failed
  - Results_check.py
    - Can verify the output root files
- **fit.py:**
  - Can automatically fit histograms, (one need to adjust the parameters if the fit is failed)
  - All the fits in this presentation were created by this program
- **Two Sided Crystal Ball**
  - Copied from ATLAS-HGamTool

Possibility to include them into the FCCAnalyses and FCCeePhysicsPerformance ?