# ZH Cross-section measurement at 365 GeV

*Gregorio Bernardi[1], Kevin Dewyspelaere[1], Jan Eysermans[2], Ang Li[1]*

Higgs Performance meeting
Apr 22th, 2024

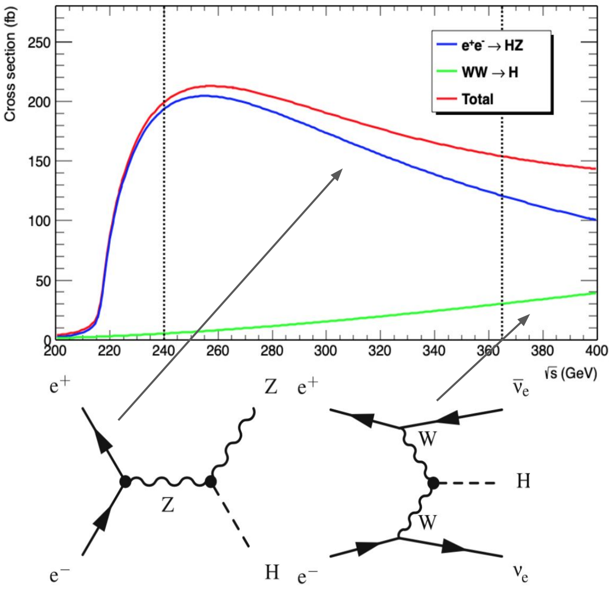
1,APC-Paris, Université Paris Cité, CNRS/IN2P3
2, MIT

FUTURE CIRCULAR COLLIDER

# Summary

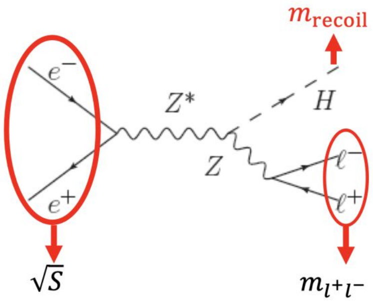
- Introduction
- Comparative analysis between 240 and 365 GeV
- Boosted decision Tree
- Conclusion/Future steps

# Introduction




- ➢ Goal: measurement of the ZH cross-section at 365 GeV following 240 GeV methodology
- ➢ Signal: $e^+e^- \to ZH \to \mu^+\mu^- + X$ (focus on muons)
  $e^+e^- \to ZH \to e^+e^- + X$
- ➢ Z decaying leptonically and use of the recoil mass method:

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




- ➢ **Uncertainties at 240 GeV:**
  - Cross-section: 0.69 %
  - Higgs mass: 4.0 MeV

| | Z, years 1-2 | Z, later | WW, years 1-2 | WW, later | ZH | $t\bar{t}$ | |
|---|---|---|---|---|---|---|---|
| $\sqrt{s}$ (GeV) | 88, 91, 94 | | 157, 163 | | 240 | 340-350 | 365 |
| Lumi/IP ($10^{34} cm^{-2}s^{-1}$) | 70 | 140 | 10 | 20 | 5.0 | 0.75 | 1.20 |
| Lumi/year ($ab^{-1}$) | 34 | 68 | 4.8 | 9.6 | 2.4 | 0.36 | 0.58 |
| Run time (year) | 2 | 2 | 2 | 0 | 3 | 1 | 4 |
| Number of events | $6 \times 10^{12}$ Z | | $2.4 \times 10^8$ WW | | $1.45 \times 10^6$ HZ $+4.5 \times 10^4$ $WW \to H$ | $1.9 \times 10^6$ $t\bar{t}$ $+3.3 \times 10^5$ HZ $+8 \times 10^4$ $WW \to H$ | |

$1.45 \times 10^6$ ZH at 240 GeV
$0.33 \times 10^6$ ZH at 365 GeV

**Include 365 GeV**
**Gain ~23% ZH events**

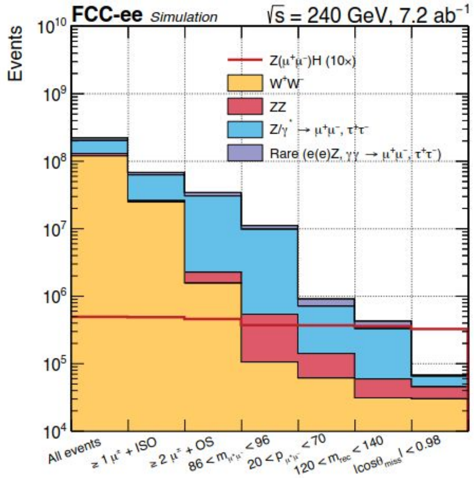

DEWYSPELAERE Kevin

# Monte Carlo samples and events selection

- **Signal:**
  - $Z(\mu^+\mu^-)H$ (Whizard/Pythia)
- **Background:**
  - $W^+W^-$ (Pythia)
  - $\gamma\gamma \to \mu\mu$ (Whizard/Pythia)
  - $e^+e^-Z$ (Whizard/Pythia)
  - $ZZ$ (Pythia)
  - $Z/\gamma \to \mu^+\mu^-$ (Whizard/Pythia)
- **Rare backgrounds:**
  - $Z(qq)$ (Pythia)
  - $Z(\tau^+\tau^-)H$ (Whizard/Pythia)
  - $Z(\nu\nu)H$ (Whizard/Pythia)
  - $\gamma\gamma \to \mu^+\mu^-$ (Whizard/Pythia)
  - $\gamma\gamma \to \tau^+\tau^-$ (Whizard/Pythia)

- **Events basic selection:**

1. Select at least 2 leptons:
   - Momentum $p_\ell > 20$ GeV
   - Opposite sign
   - One lepton required to be isolated
2. $m_{l^+l^-} \in [86, 96]$ GeV
3. $p_{l^+l^-} \in [20, 70]$ GeV
4. $m_{recoil} \in [120, 140]$ GeV





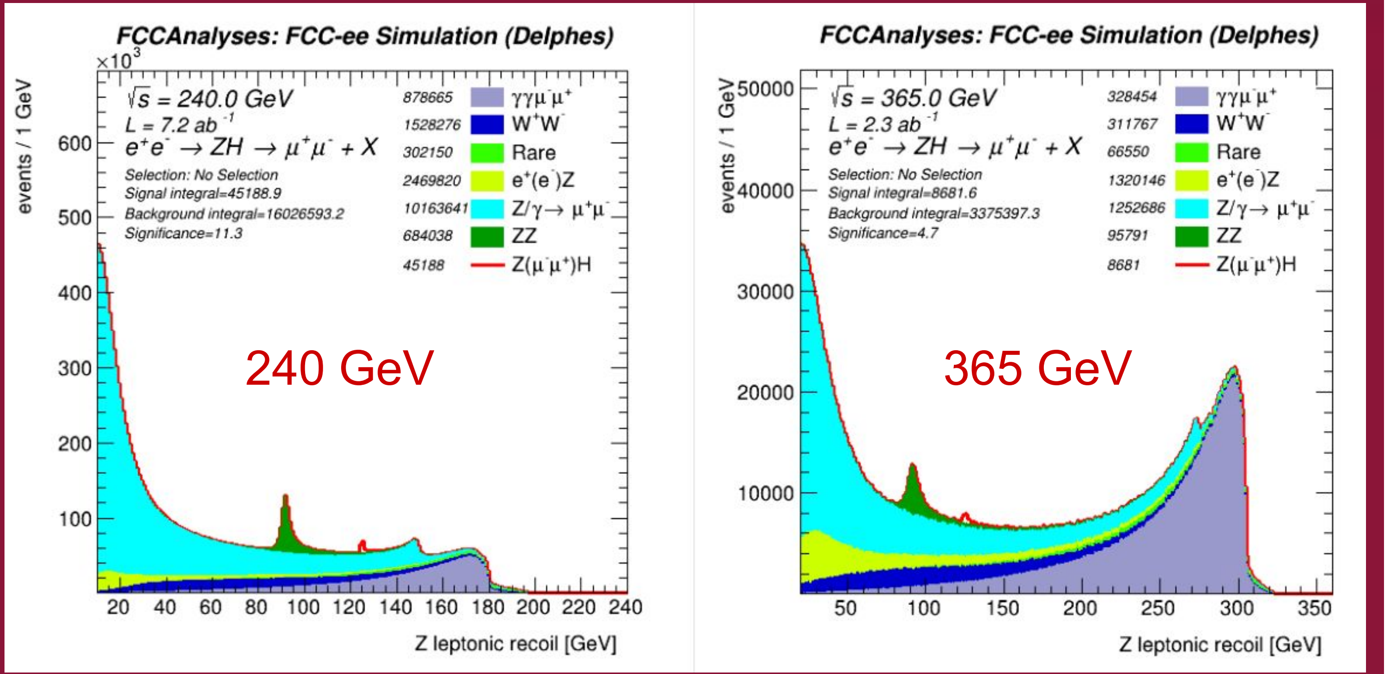

DEWYSPELAERE Kevin

# Comparative analysis at 240 and 365 GeV center of mass



DEWYSPELAERE Kevin

# Comparison 240/365 GeV without selection

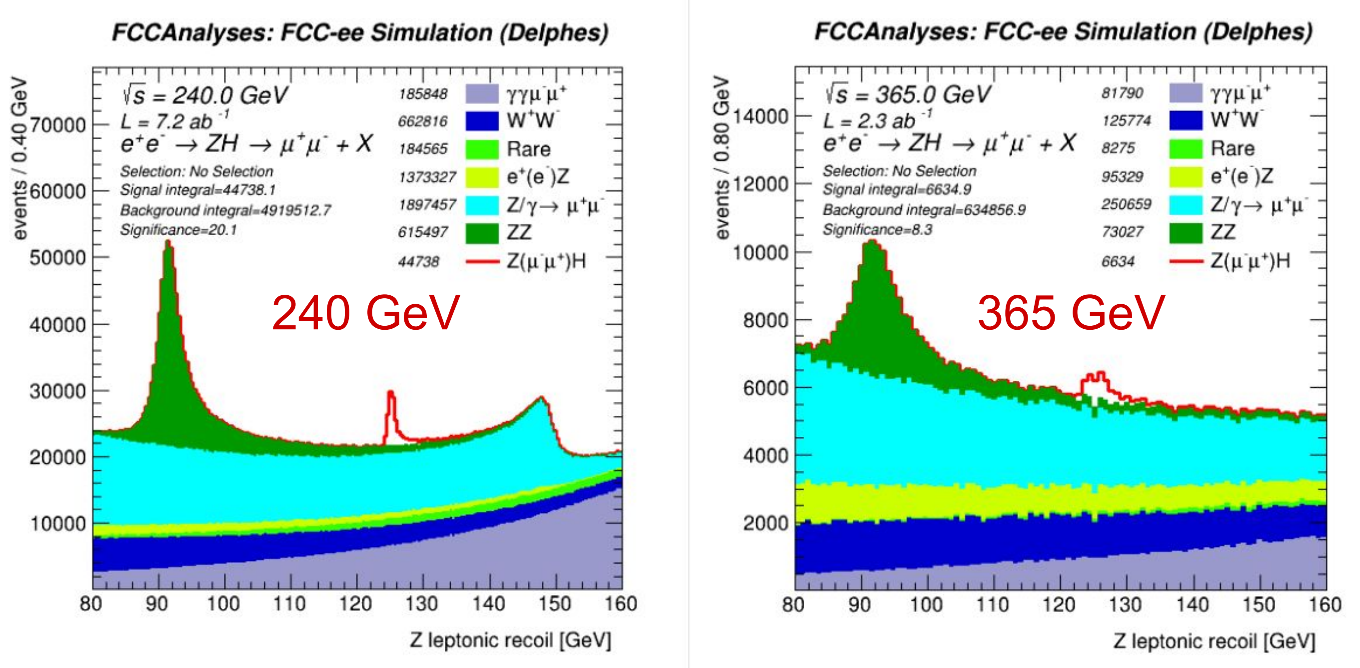



Comparison mrecoil distribution at 240 GeV (left) and 365 GeV (right) for the $\mu^+\mu^-$ channel in linear scale without selection

➢ **Differences**

- Luminosity from **7.2** to **2.3** ab$^{-1}$
- Signal yields **5** times lower
- Find the recoil mass peak from calculation at higher energy

# Comparison 240/365 GeV without selection




Comparison mrecoil distribution at 240 GeV (left) and 365 GeV (right) for the μ+μ− channel in linear scale without selection

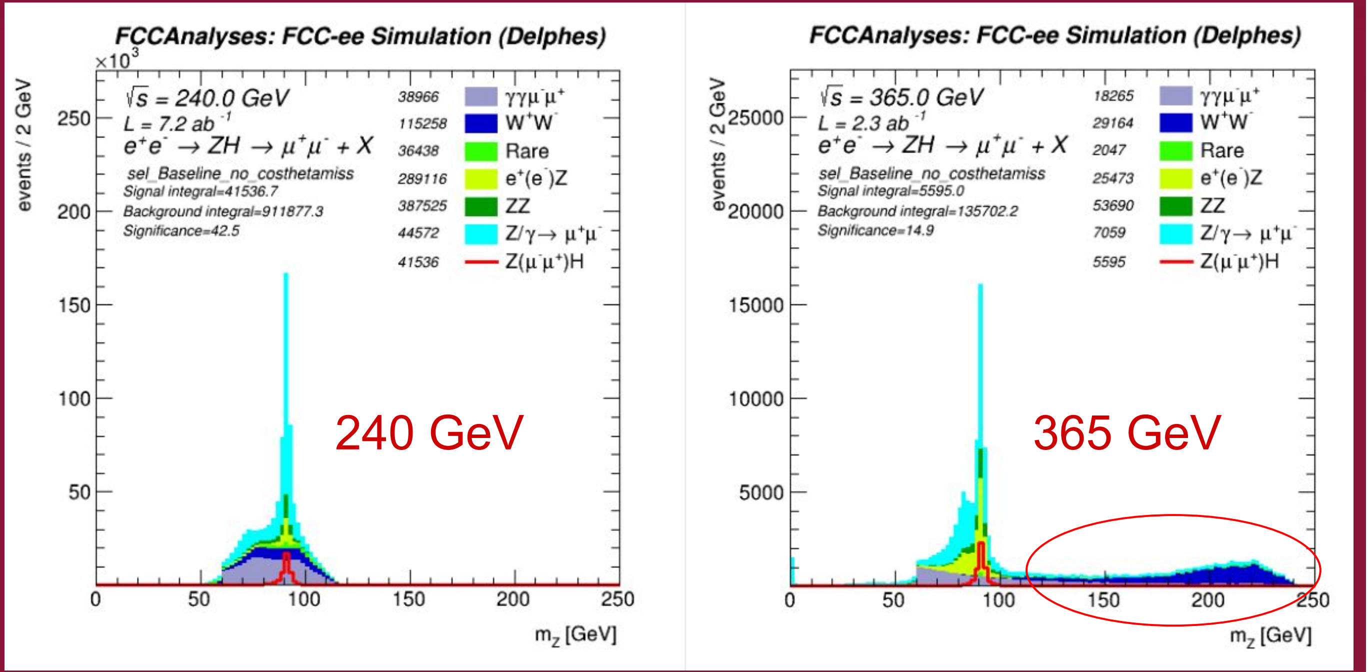
➢ **Zoom between 80 and 160 GeV**

- Luminosity from **7.2** to **2.3** ab$^{-1}$
- Signal yields **5** times lower
- **Shape** of the background
- Signal with **lower resolution**



*DEWYSPELAERE Kevin*

# Reconstructed Z Mass (without Z mass selection cut)



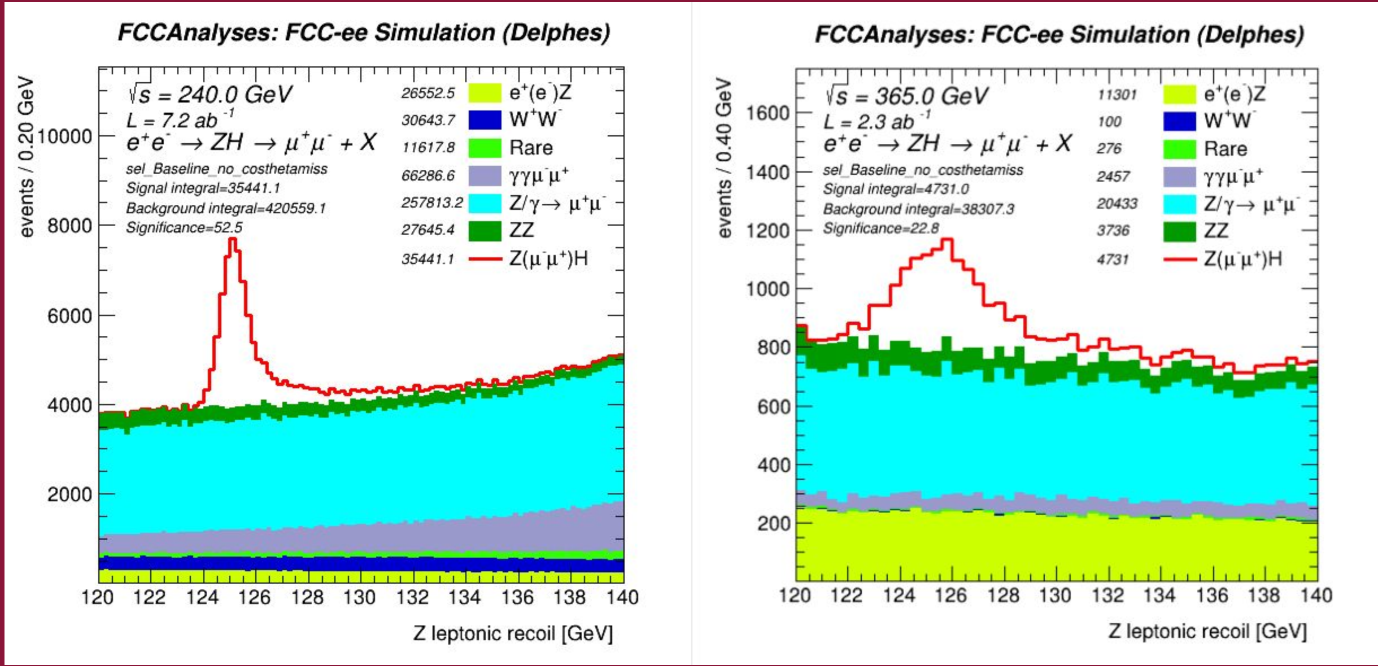

Reconstructed Z mass comparison at 240 GeV (left) and 365 GeV (right) for mumu channel without zll mass selection cut

- **WW background** is moved to **higher energy** for 365 GeV
- The **cut** $m_{l^+l^-} \in [86, 96]$ GeV is **removing it**
- **Better signal** over background at 365 GeV



DEWYSPELAERE Kevin

# Mass recoil of the Z leptons with basic selection cuts



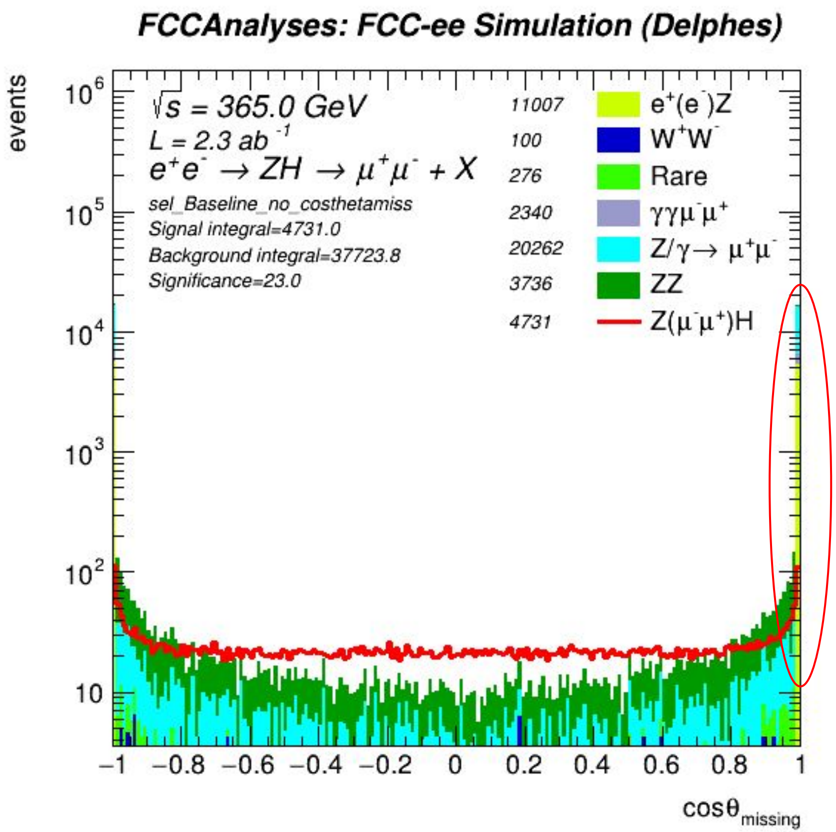

$m_{recoil}$ distribution comparison at 240 GeV (left) and 365 GeV (right) for mumu channel without cos $\theta_{miss}$ selection cut

- ➢ **Momentum Cut < 70 GeV** removed at 365 GeV
- ➢ **WW negligible** at 365 GeV
  - The cut on the mass is removing them
- ➢ Resolution **3.5** times wider at 365 GeV
- ➢ **7.5** times less **signal** and **11** times less **background**
- ➢ **Significance** (S/sqrt(S+B) is **~23** at **365 GeV**, vs. **~53** at **240 GeV** with the preselection cuts.
- ➢ **Selection** used for **ZH cross-section measurement with BDT**



*DEWYSPELAERE Kevin*

# Cos θmiss selection cut



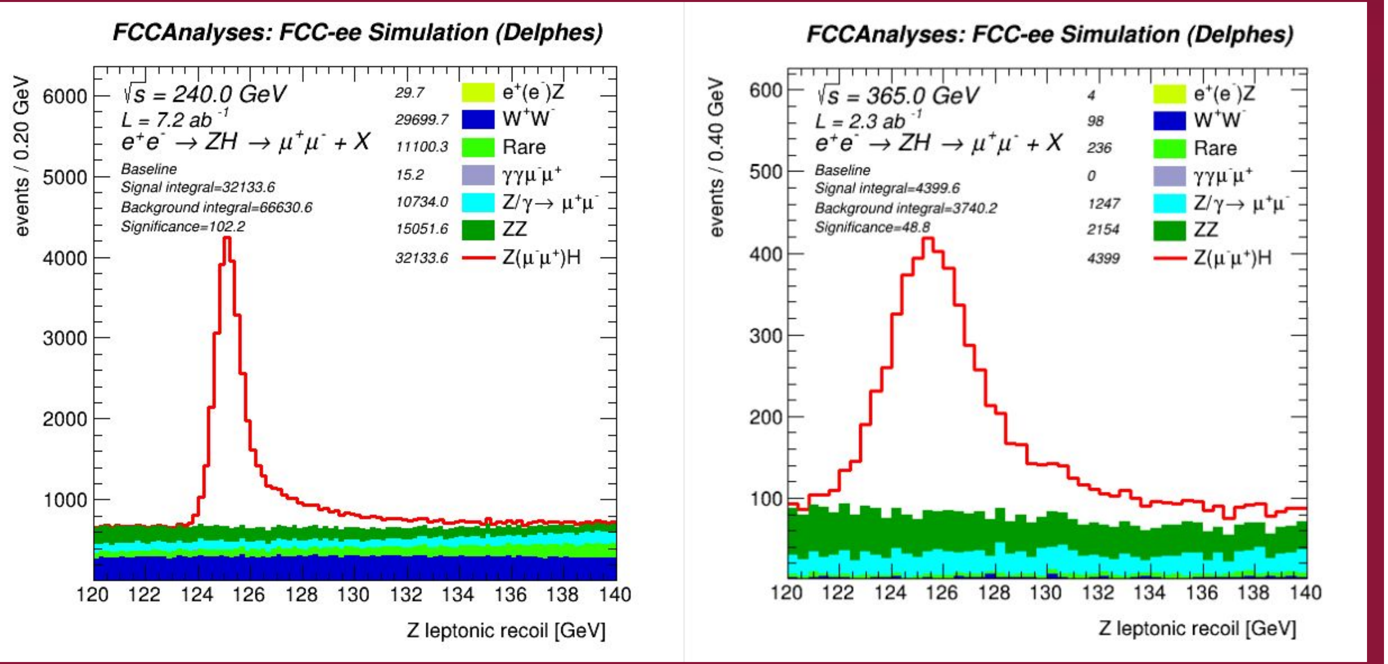

Cos θmissing distribution at 365 GeV (right) for mumu channel with selection cuts

- **Missing Energy** refers to the amount of energy that is **not measured**
- **Missing transverse E** is the **negative** vectorial sum of the transverse momenta
- **θmiss** is the **angle** of the **missing transverse energy vector**
- Cut $|\cos \theta_{miss}| < 0.98$ used for **mass analysis only**



*DEWYSPELAERE Kevin*

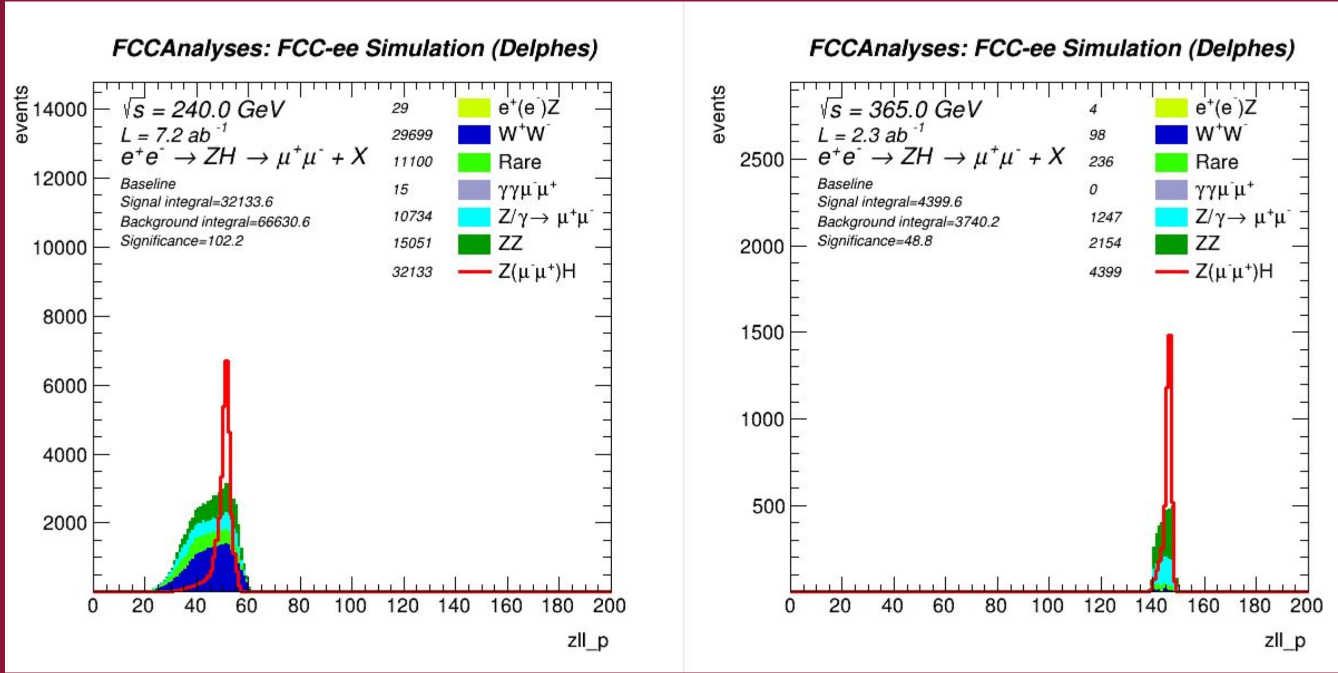
# Mass recoil of the Z leptons with cos θmiss selection cut




- Cut |cos θmiss| < **0.98** used for **mass analysis only**
- To reduce the **Z/γ event** which typically contain hard ISR photons **collinear to the beam**
- **Significance** at **49** at 365 GeV
- **7** times less **signal** and **18** times less **background**

mrecoil distribution comparison 240 GeV (left) and 365 GeV (right) for mumu channel with selection cuts

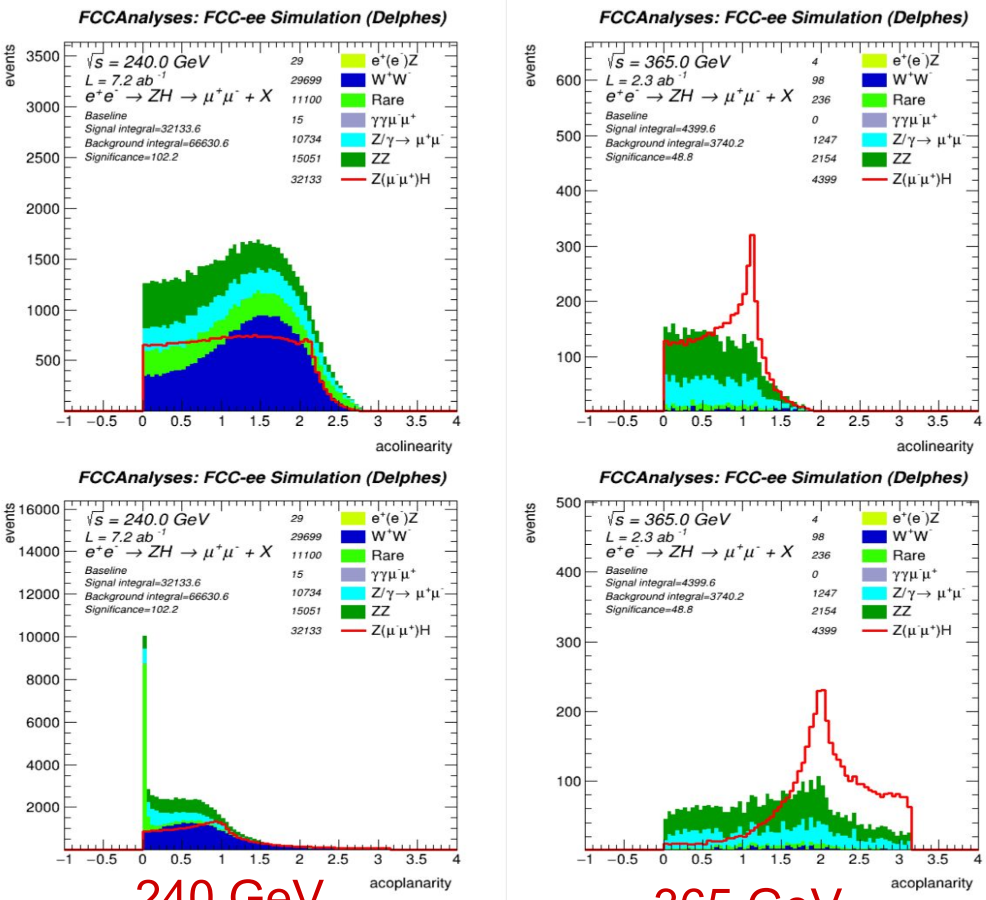
# Momentum of the reconstructed Z boson




Momentum of the reconstructed Z boson comparison 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut

- Z momentum higher by about 100 GeV at 365 GeV
- less background but more concentrated at 365 GeV
- System boosted at 365 GeV

# Acollinearity and acoplanarity of the reconstructed Z boson




240 GeV

365 GeV

- **Acollinearity:**

$$\Delta\theta_{\ell^+\ell^-}$$

- **Acoplanarity:**

$$\pi - \Delta\phi_{\ell^+\ell^-}$$

- **Boosted system**
- **At 365 GeV, we have sharp peaks appearing at ~1 (acolinearity) and at ~2 (acoplanarity) for the signal**

Acollinearity (up) and acoplanarity (down) of the reconstructed Z boson comparison 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut


DEWYSPELAERE Kevin

# Boosted Decision Tree

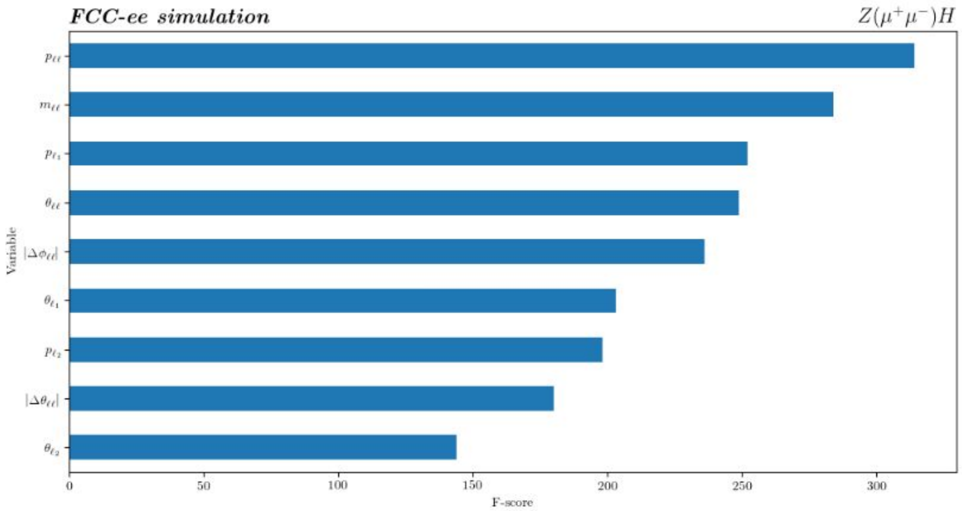

DEWYSPELAERE Kevin

# Boosted Decision Tree

- **Machine learning algorithm that separates signal and background by giving a BDT score**
- **BDT offers model independent analysis**
- **Nominal samples (winter 2023) are used to train the BDT**
- **Training_variables for BDT:**

| Variable | Description |
|---|---|
| $p_{\ell^+\ell^-}$ | Lepton pair momentum |
| $\theta_{\ell^+\ell^-}$ | Lepton pair polar angle |
| $m_{\ell^+\ell^-}$ | Lepton pair invariant mass |
| $p_{l_{\text{leading}}}$ | Momentum of the leading lepton |
| $\theta_{l_{\text{leading}}}$ | Polar angle of the leading lepton |
| $p_{l_{\text{subleading}}}$ | Momentum of the subleading lepton |
| $\theta_{l_{\text{subleading}}}$ | Polar angle of the subleading lepton |
| $\pi - \Delta\phi_{\ell^+\ell^-}$ | Acoplanarity of the lepton pair |
| $\Delta\theta_{\ell^+\ell^-}$ | Acolinearity of the lepton pair |

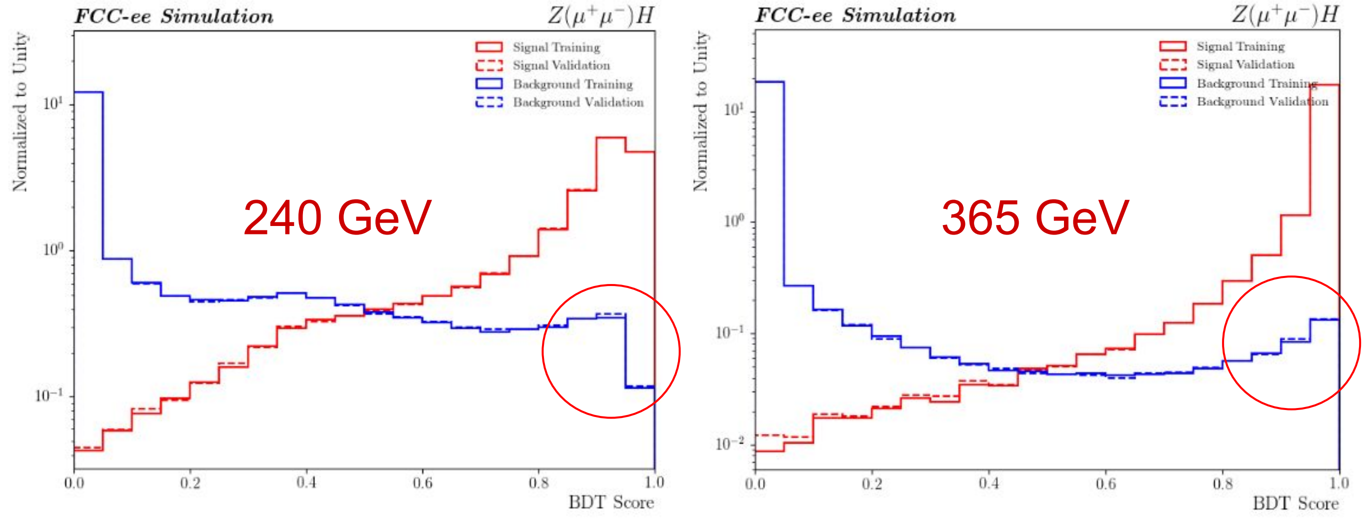
- **Number of events for BDT training:**
  - All signals passed the basic selection
  - Total Number of backgrounds = Total Number of Signals
  - Number of events of each process is proportional to their cross-section×cut efficiency
  - 1/2 of events for training
  - 1/2 of events for testing






DEWYSPELAERE Kevin

# BDT score comparison

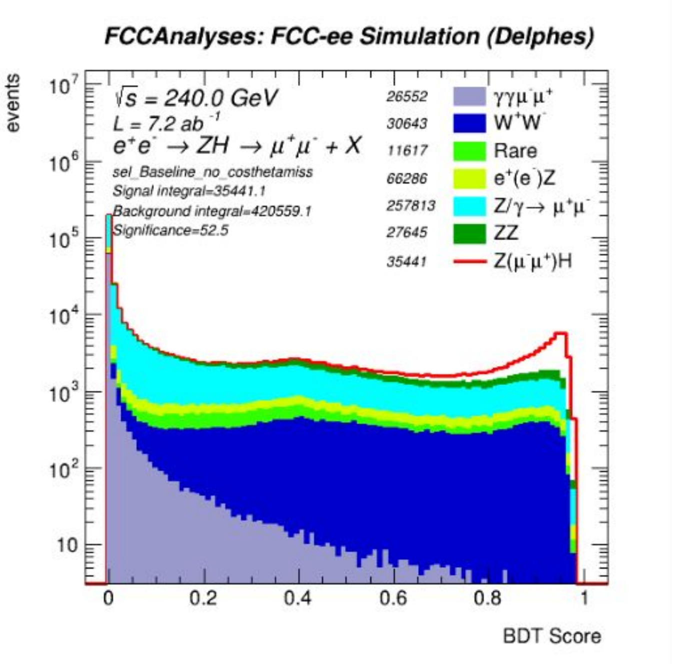


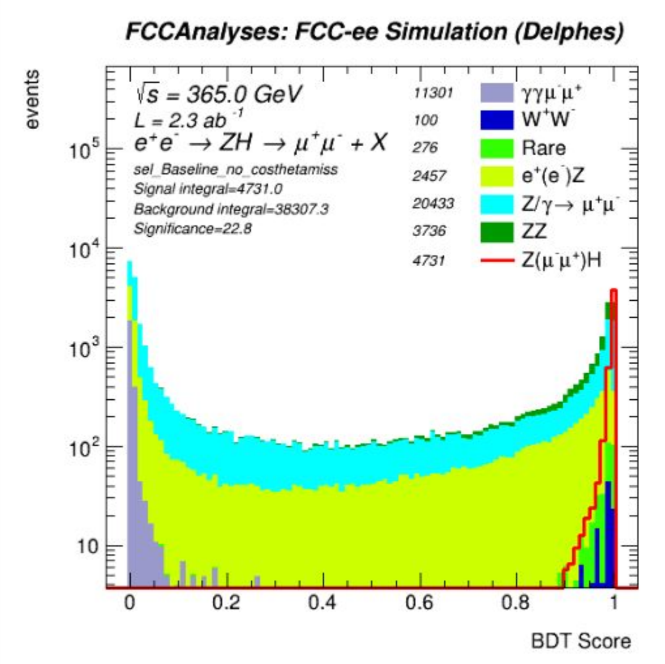

BDT score comparison 240 GeV (left) and 365 GeV (right) for mumu channel

- **Prove** the **universality** of the **BDT model** used
- At 365 GeV, we are **investigating** why **background** is **rising** at **high score**


*DEWYSPELAERE Kevin*

# BDT Score comparison



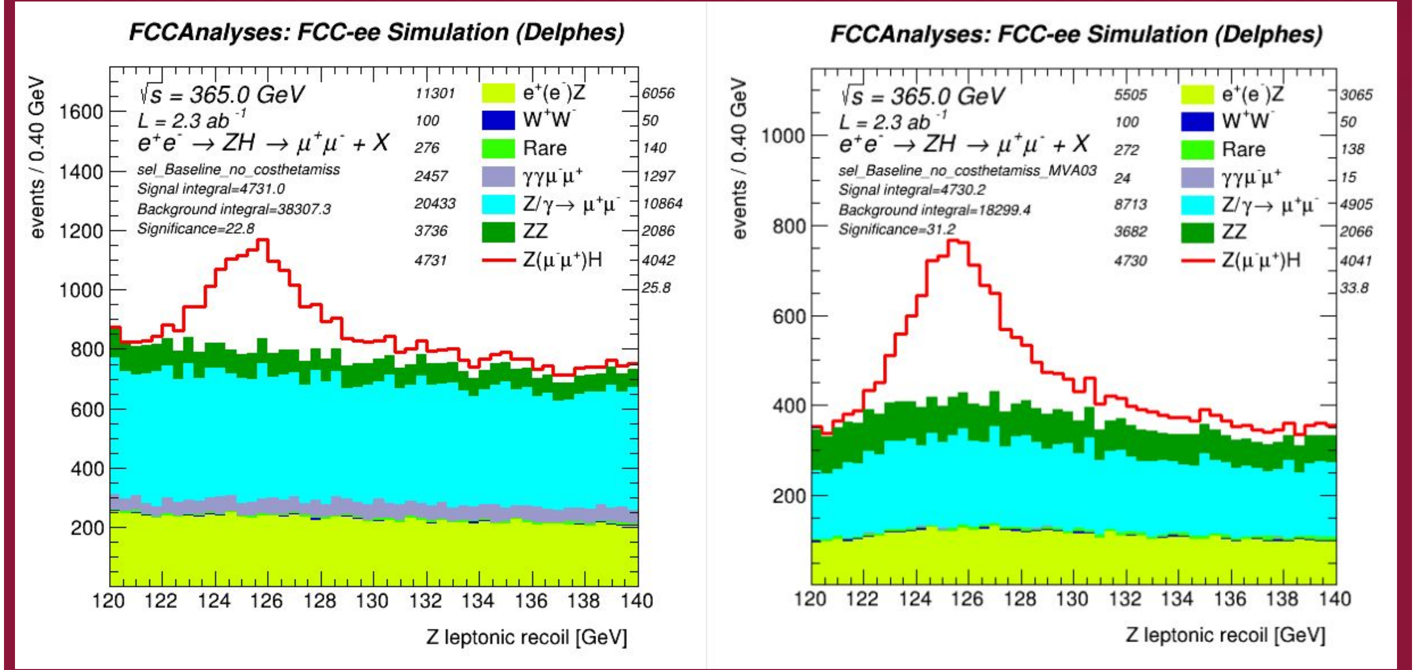

BDT score comparison 240 GeV (left) and 365 GeV (right) for mumu channel

- **BDT score** comparison for **signal** and **background**
- At 365 GeV, we're **investigating** to know why **background** is **rising** at **high score**
- This **BDT score** will be fitted to measure the **ZH cross-section**



DEWYSPELAERE Kevin

# Mass recoil of the Z leptons with and without BDT requirement




$m_{recoil}$ distribution comparison 365 GeV for mumu channel without BDT selection (left) and with BDT score selection cut > 0.3 (right)

- We apply a **cut** on the **BDT score** to see its **performance**.
- **Significance** from **22** to **31**
- With **BDT score > 0.3**, background is divided by **2**


DEWYSPELAERE Kevin

# Conclusion

- **Kinematic variables** analysis clearly shows the effect of the **strongly boosted system** at 365 GeV

- **Yields**, **luminosity** and **shape** of the **backgrounds** are changed

- **The WW background** is essentially removed by the cut of the **Z mass**

- Lower **resolution** but better **signal-to-background ratio**

- BDT model used for ZH cross-section measurement



*DEWYSPELAERE Kevin*

# Future steps

- ➢ Improve **the BDT training model**
  - Investigating in the rising background at high score
  - Training BDT with each samples separately

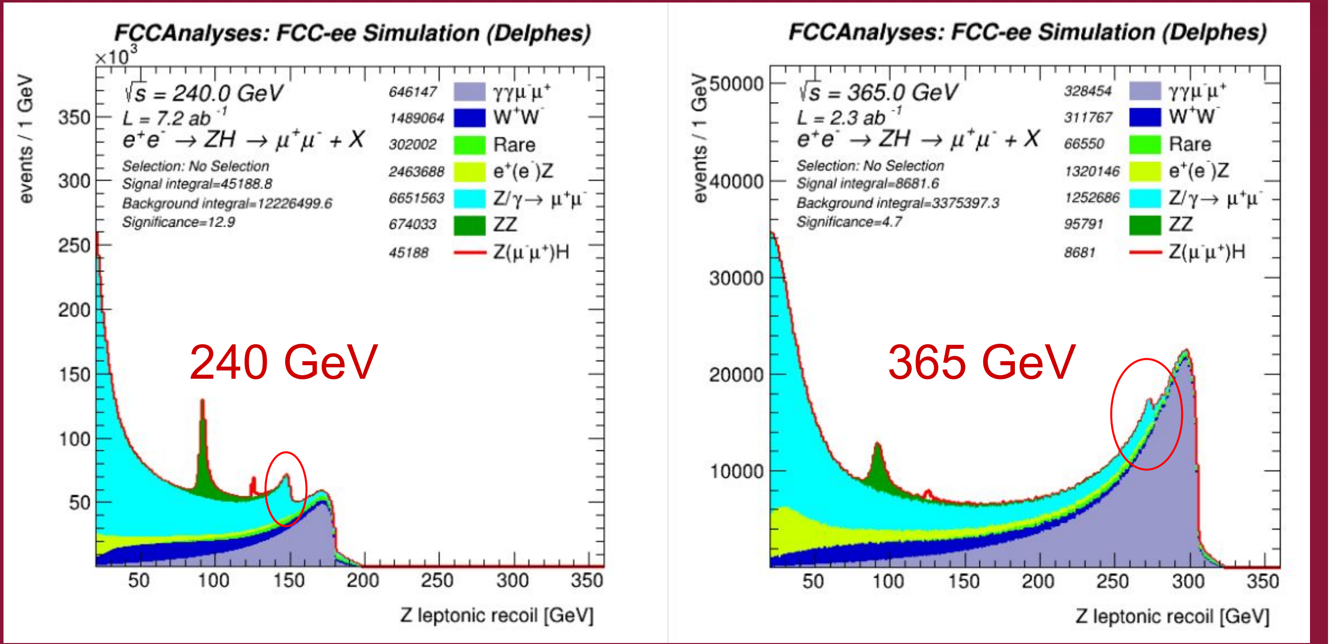
- ➢ Do the analysis for **ee** channel (expect better momentum resolution)

- ➢ Use **Combine** to obtain results on the uncertainty of the ZH cross-section at 365 GeV

- ➢ Perform **mass** analysis

# Back up

# Comparison 240/365 GeV without selection

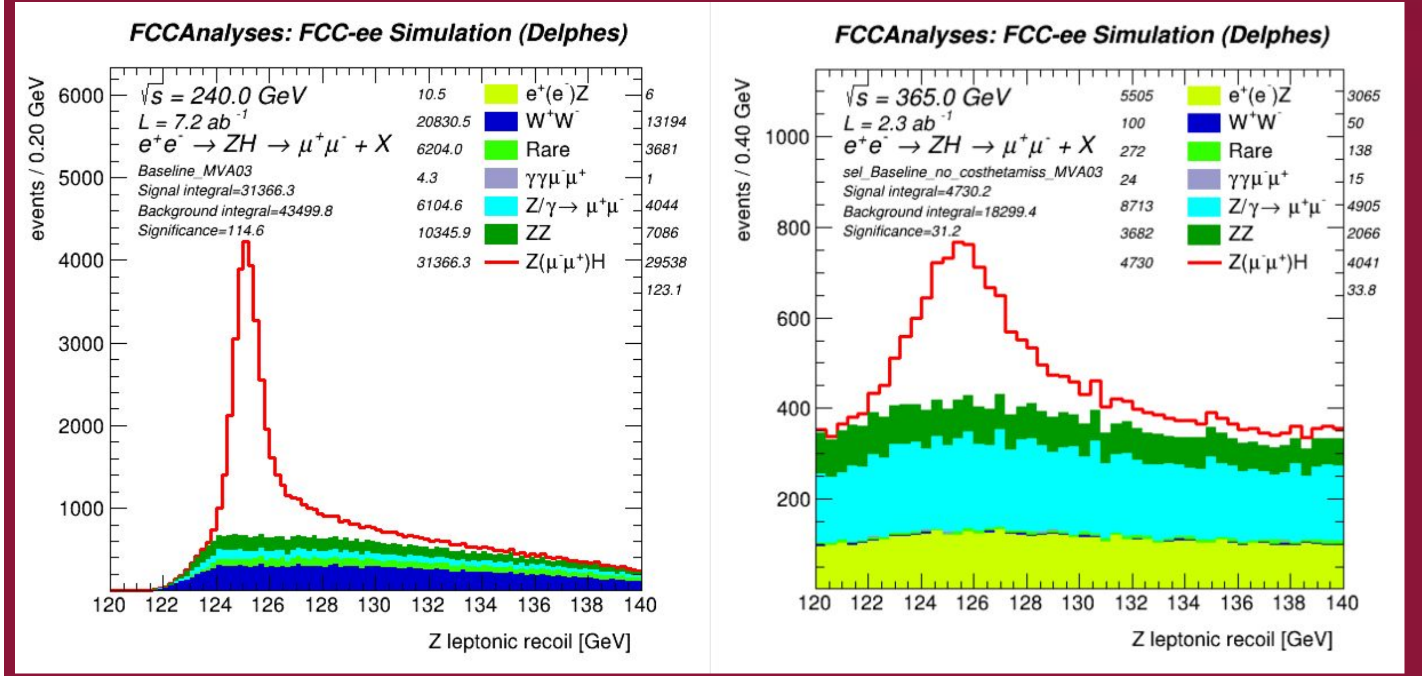



Comparison mrecoil distribution at 240 GeV (left) and 365 GeV (right) for the μ+μ− channel in linear scale without selection

➢ **Differences**

- From 7.2 to 2.3 $ab^{-1}$ luminosity
- Event Number divided by 10
- Find the recoil mass peak from calculation at higher energy

# Mass recoil of the Z leptons with trained BDT machine learning



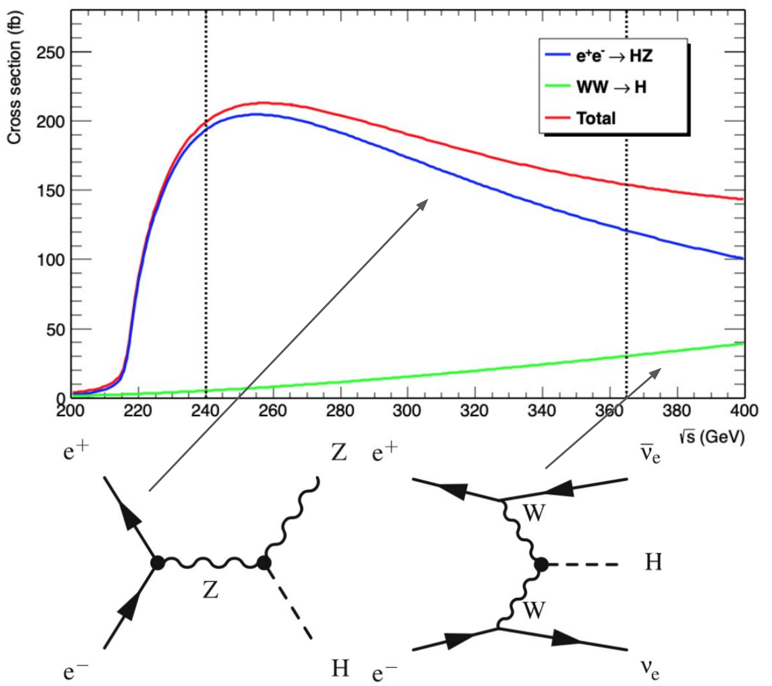

mrecoil distribution comparison 240 GeV (left) and 365 GeV (right) for mumu channel with BDT score > 0.3 selection cut

- Boosted decision Tree (BDT) machine learning used to extract signal and background by giving them a score.
- Backgrounds have low scores
- For the moment nominal samples are used to trained the BDT
- We ordered the training samples



DEWYSPELAERE Kevin

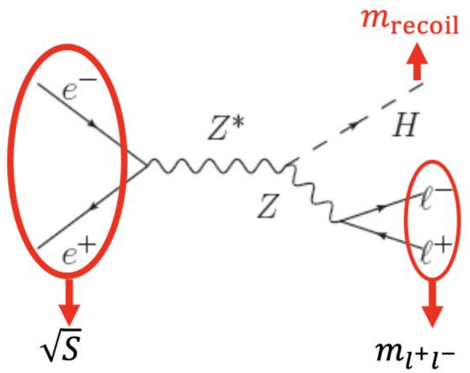
# Introduction




Improved-Born Higgs production cross-sections for the Higgsstrahlung process and the WW fusion process, incorporating initial state radiation, are predicted by HZHA

- **Goal: measurement of the ZH cross-section at 365 GeV**
- **Signal:** $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- + X$
- **Use of events with a Z decaying leptonically and reconstruction of the mass recoil without considering Higgs products:**

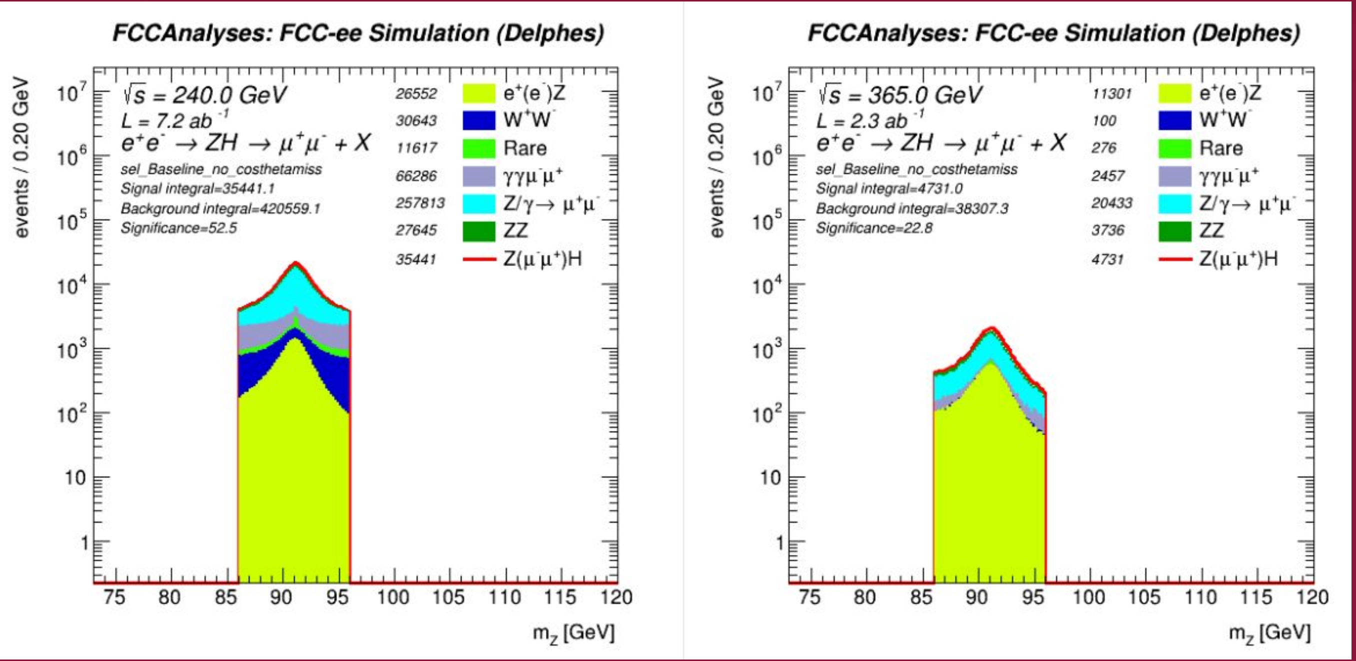
$$M^2_{recoil} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$






DEWYSPELAERE Kevin

# Reconstructed Z Mass without selection



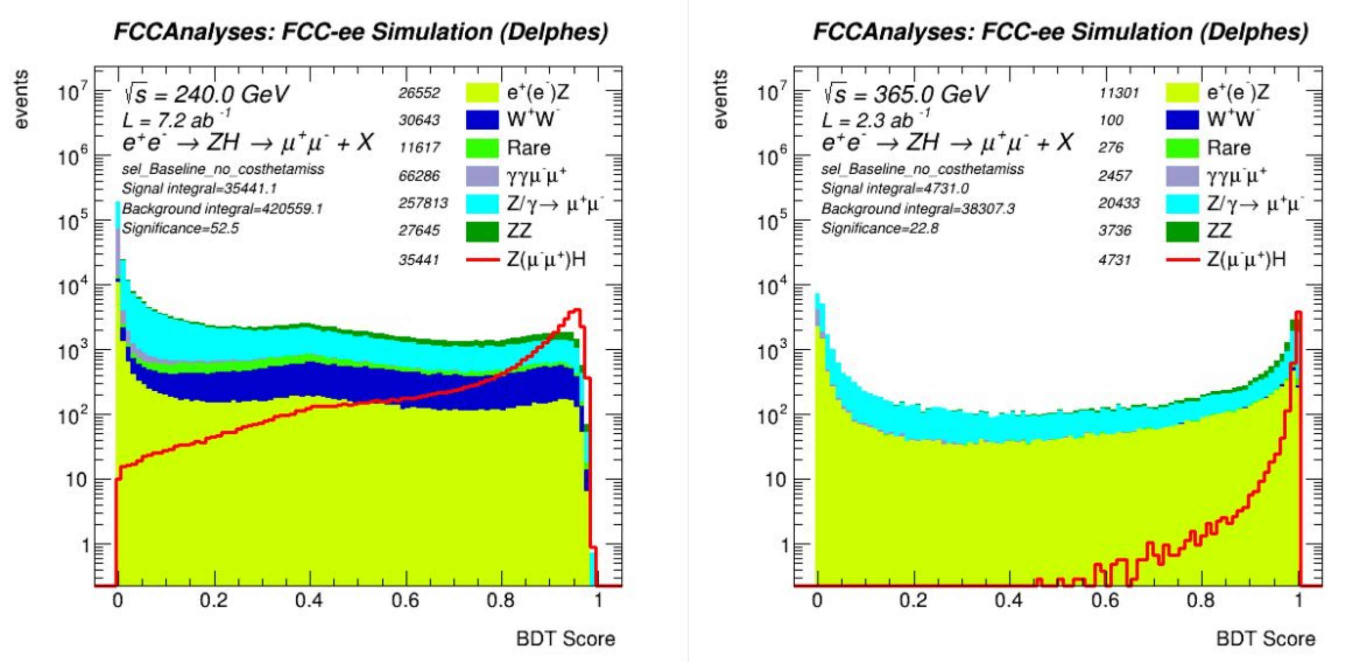

➢ C

Reconstructed Z mass comparison at 240 GeV (left) and 365 GeV (right) for mumu channel without zll mass selection cut



DEWYSPELAERE Kevin

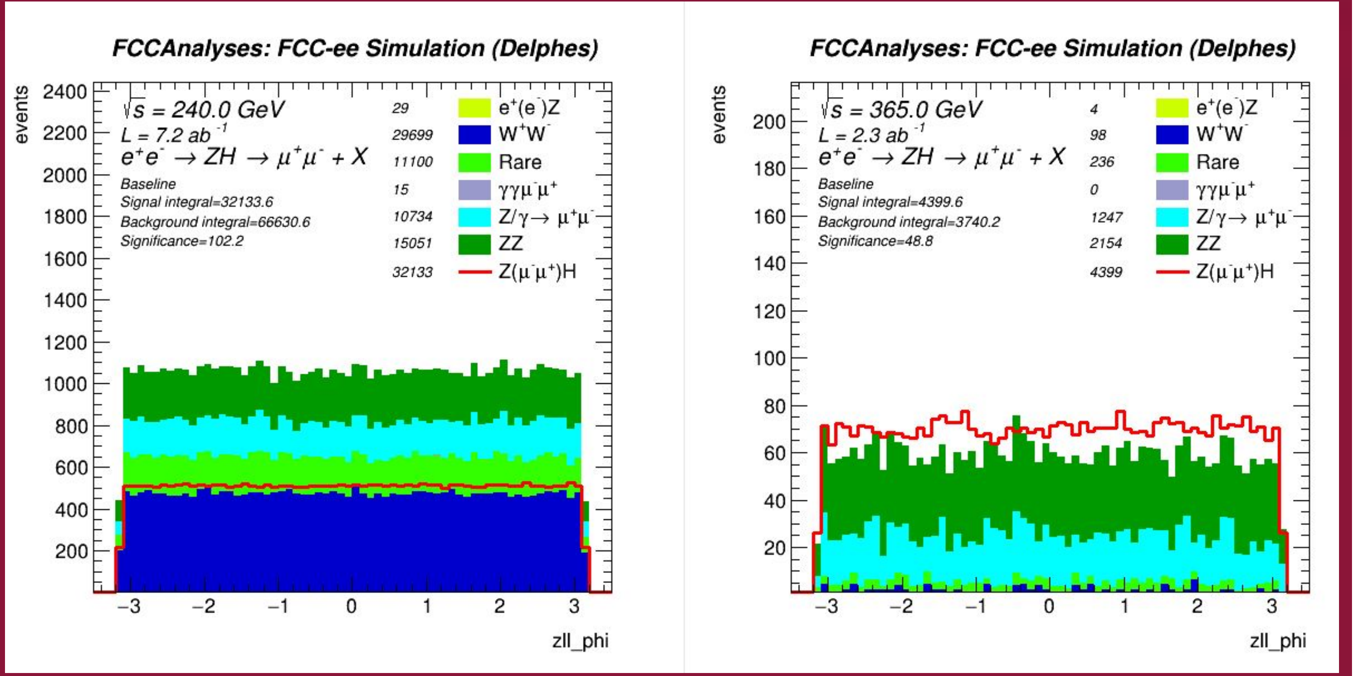
# BDT Score comparison




- **BDT score** comparison for **signal** and **background**
- At 365 GeV, we're **investigating** to know why **background** is **rising** at **high score**
- This BDT score will be used in the **final ZH cross-section fitting**

BDT score comparison 240 GeV (left) and 365 GeV (right) for mumu channel

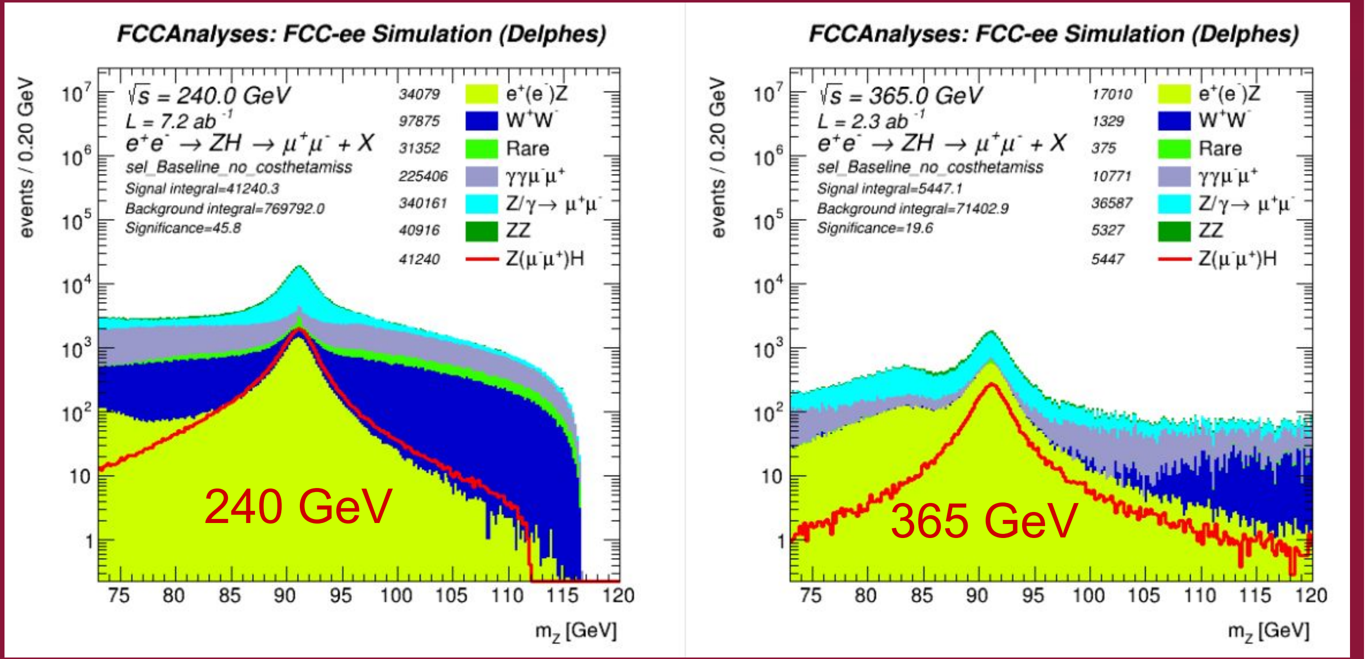
# Phi angle of the reconstructed Z boson




Phi angle of the reconstructed Z boson comparison at 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut

- At 365 GeV $Z/\gamma$ and ZZ backgrounds are dominant

# Reconstructed Z Mass without zll mass selection cut

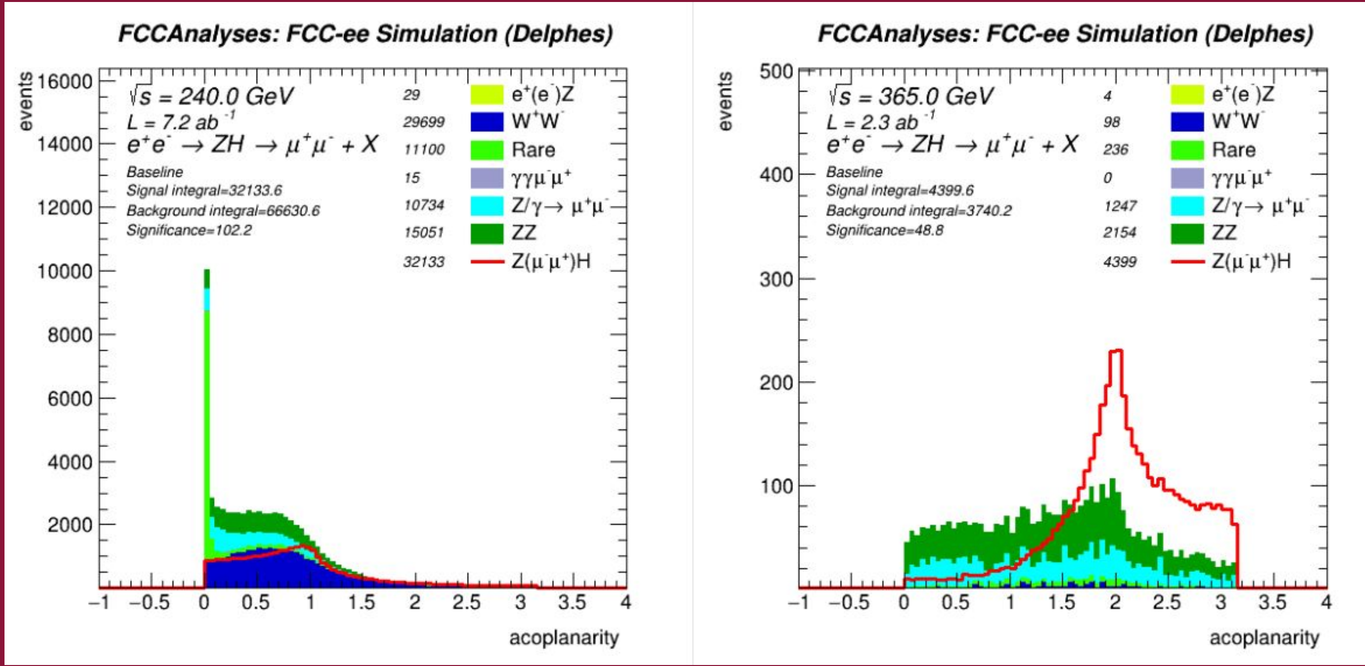



- WW background is moved to higher energy for 365 GeV
- The cut at 86 < zll mass < 96 GeV is removing them

Reconstructed Z mass comparison at 240 GeV (left) and 365 GeV (right) for mumu channel without zll mass selection cut


DEWYSPELAERE Kevin

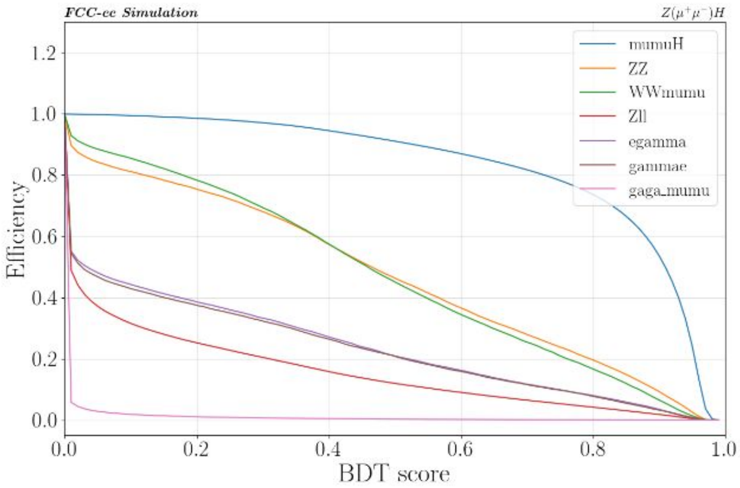
# Acoplanarity of the reconstructed Z boson

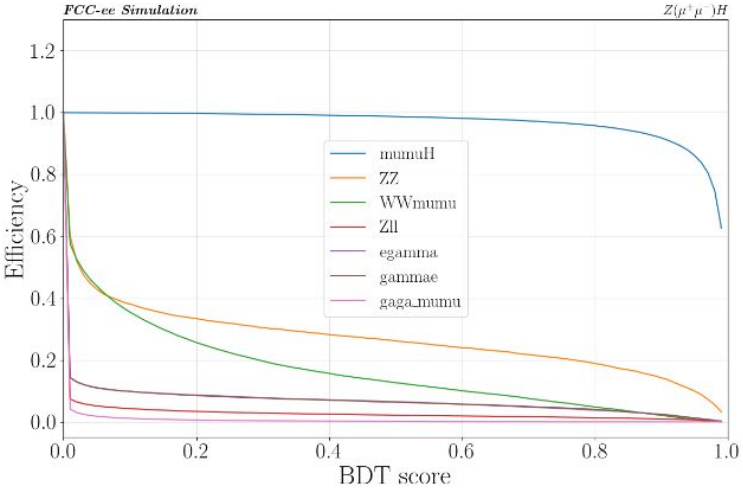



- ➢ Higher acoplanarity for signal at 365 GeV
- ➢ Peak at 2

Acoplanarity of the reconstructed Z boson comparison 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut

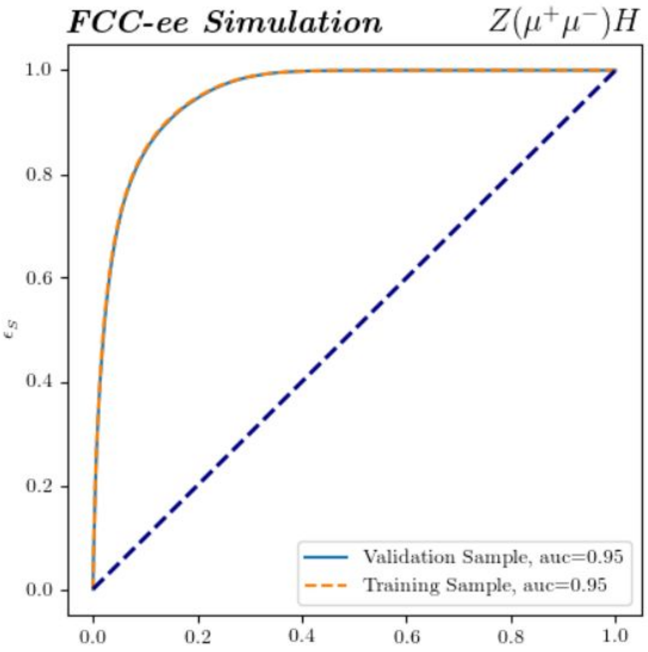
# Efficiency of the BDT

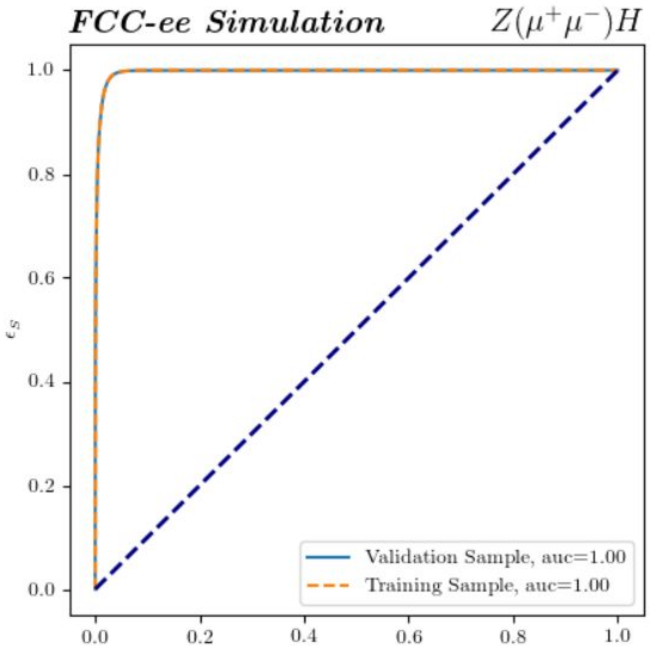



Efficiency comparison 240 GeV (left) and 365 GeV (right) for mumu channel

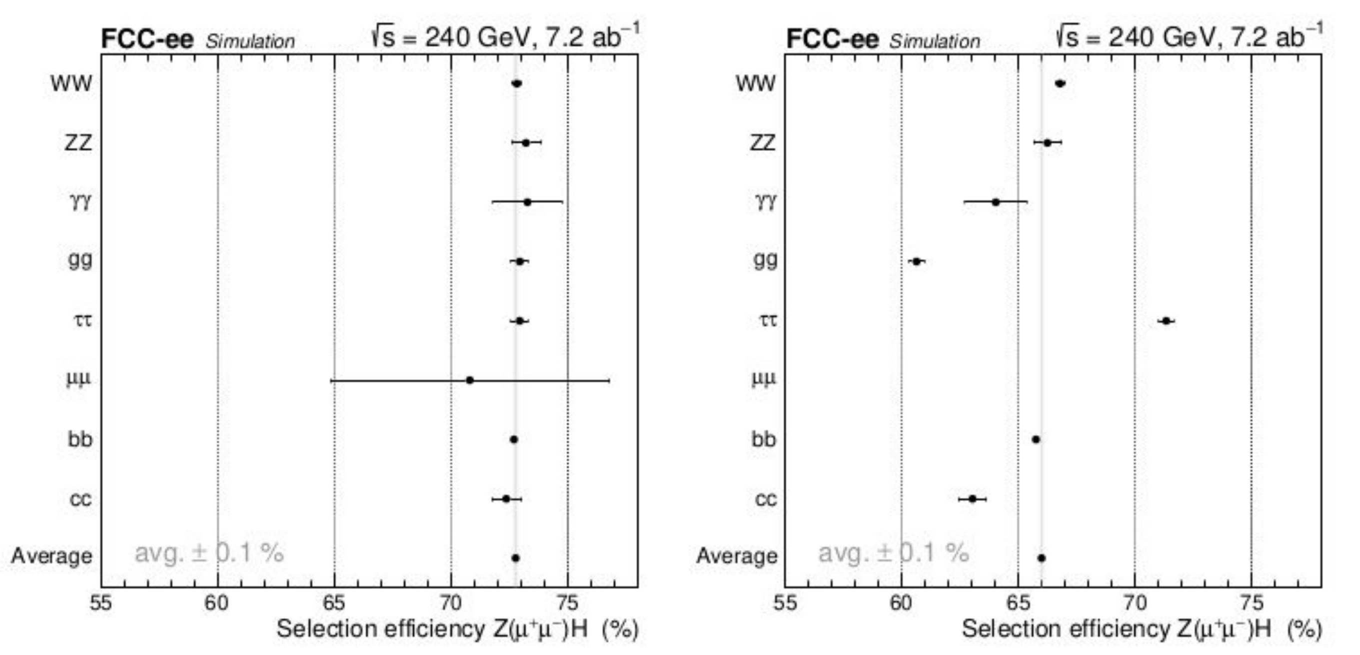
# Efficiency of the BDT




Efficiency comparison 240 GeV (left) and 365 GeV (right) for mumu channel

# Training_variables for BDT

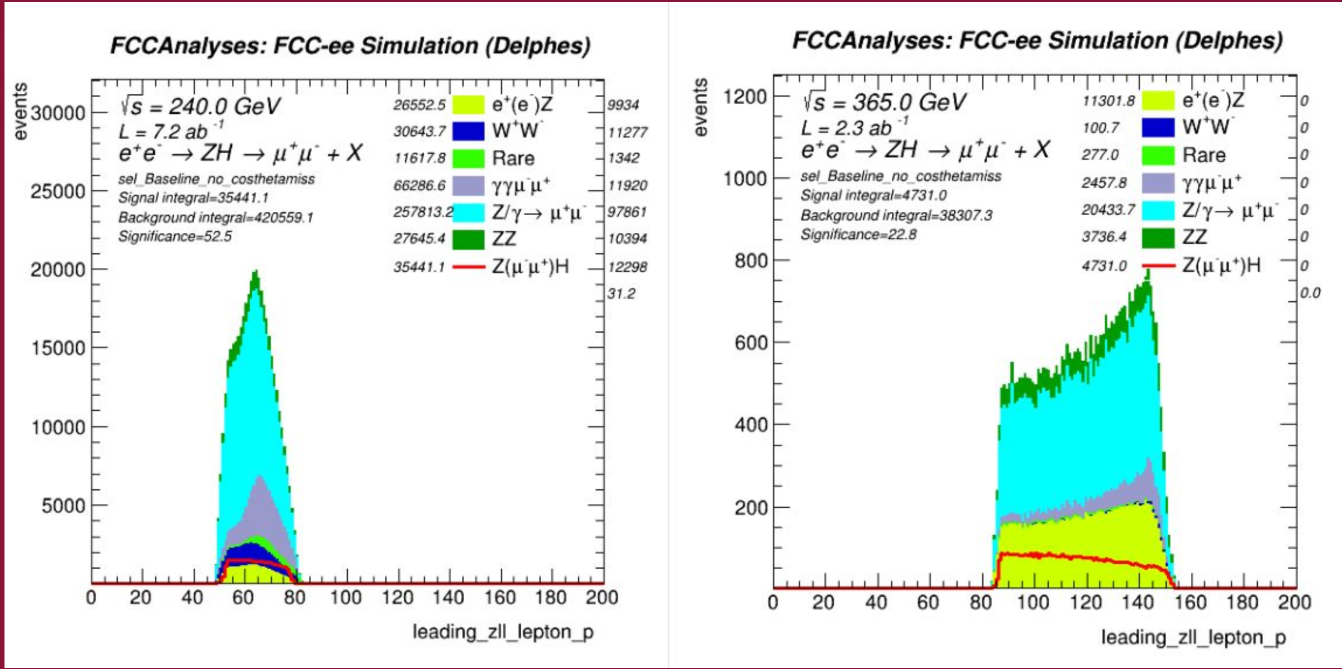



Selection efficiency of the different Higgs decay modes with Z ⇒ mumu, The left column shows the selection efficiency with the basic selection (without cos(θmiss ) cut), and the right column shows selection efficiency with baseline selection (with cos(θmiss ) cut).



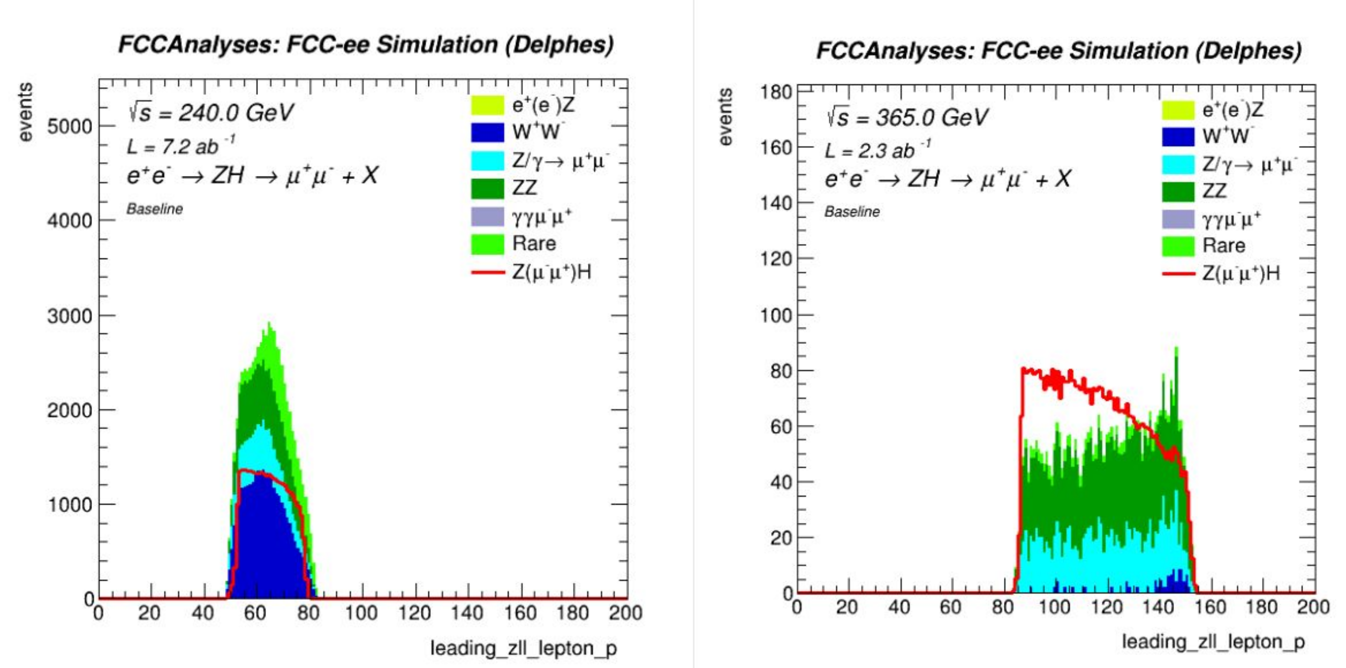
*DEWYSPELAERE Kevin*

# Momentum of the leading lepton coming from the Z decay




Momentum of the leading lepton coming from the Z decay comparison 240 GeV (left) and 365 GeV (right) for mumu channel

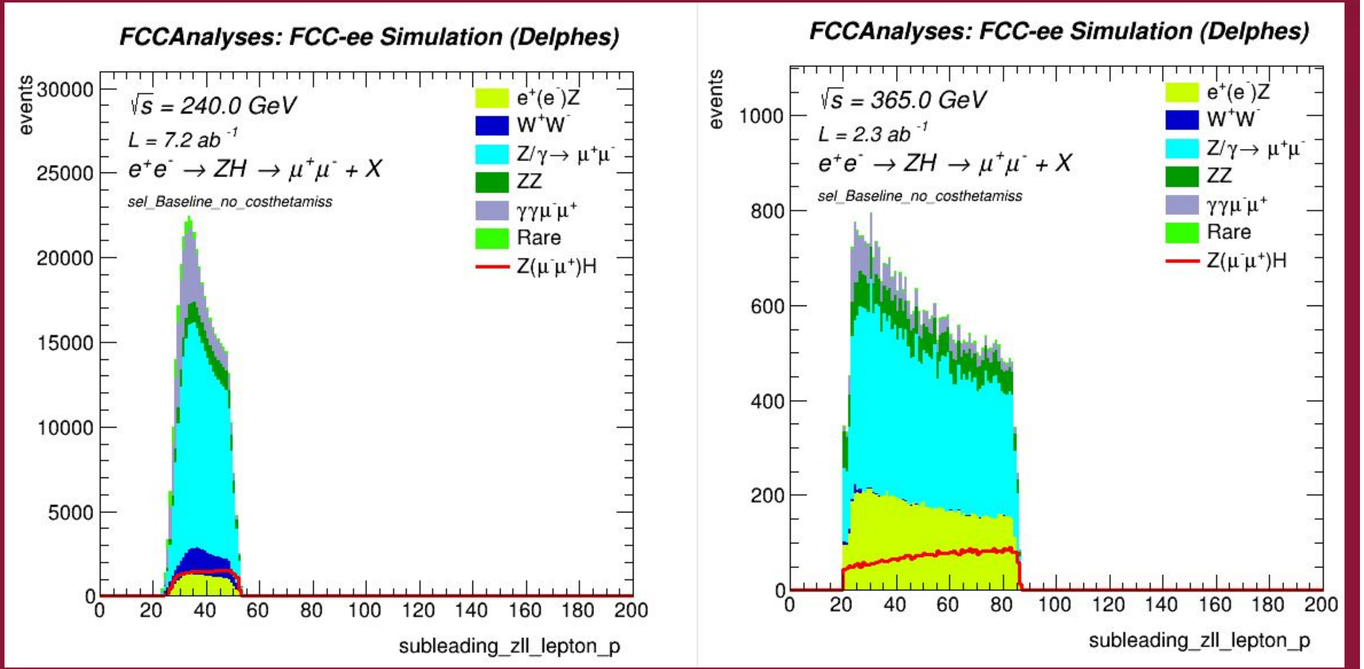
# Momentum of the leading lepton coming from the Z decay




Momentum of leading lepton coming from the Z decay comparison at 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut


DEWYSPELAERE Kevin

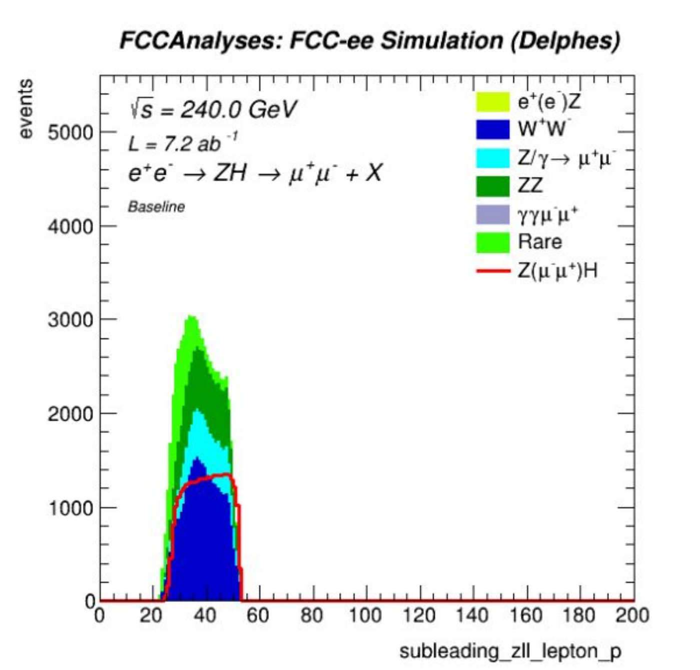
# Momentum of the subleading lepton coming from the Z decay

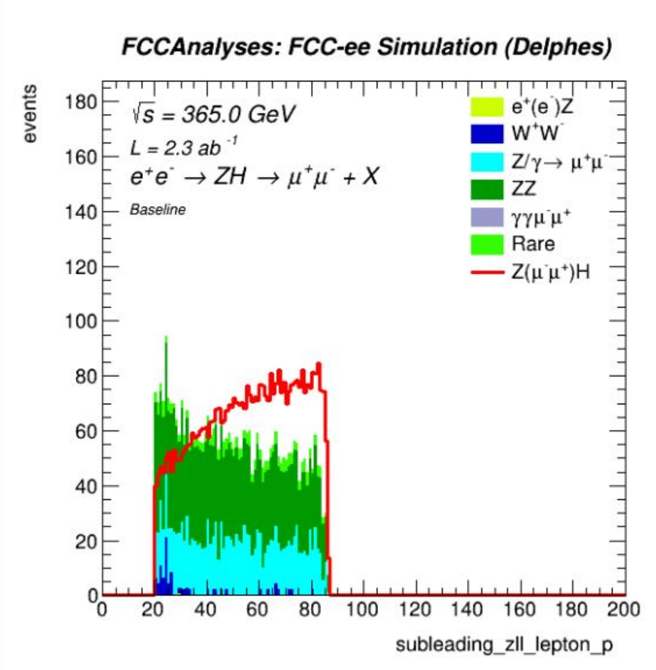



Momentum of the subleading lepton coming from the Z decay comparison 240 GeV (left) and 365 GeV (right) for mumu channel


DEWYSPELAERE Kevin

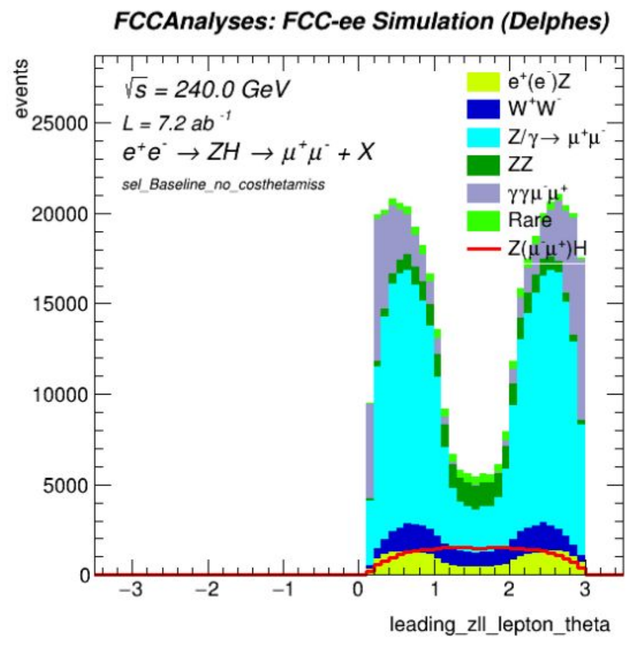
# Momentum of the subleading lepton coming from the Z decay

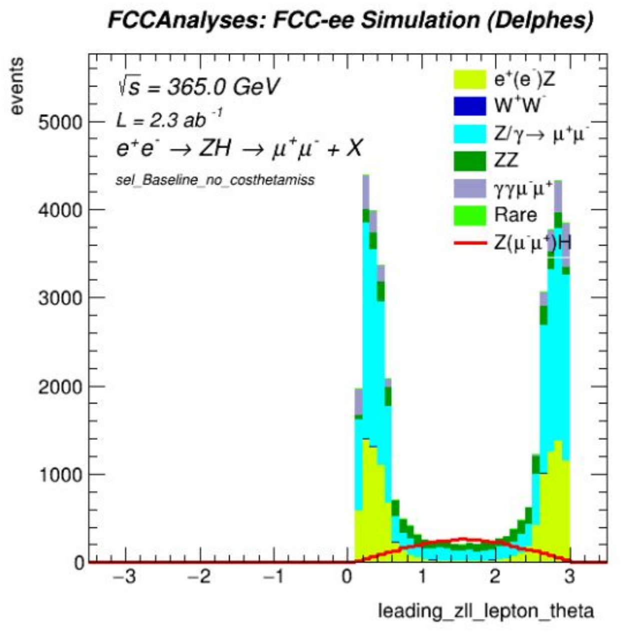



Momentum of the leading lepton coming from the Z decay comparison 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut

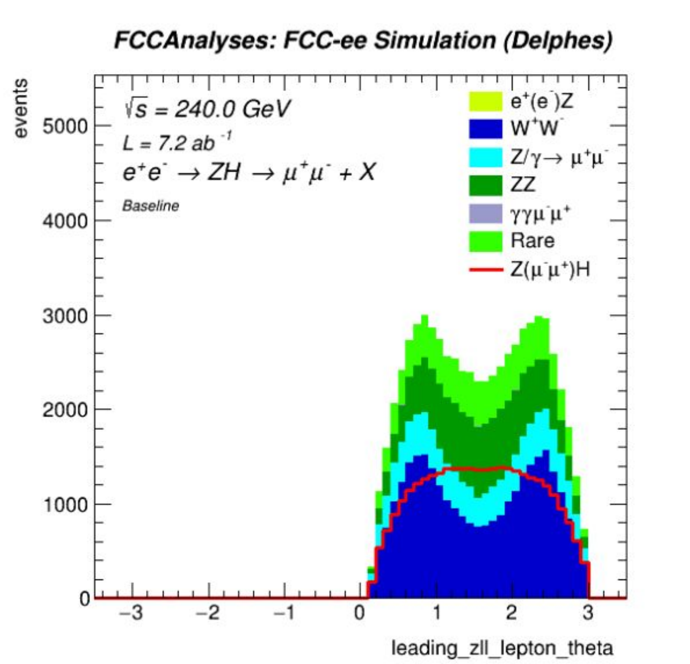
# Theta angle of the leading lepton coming from the Z decay

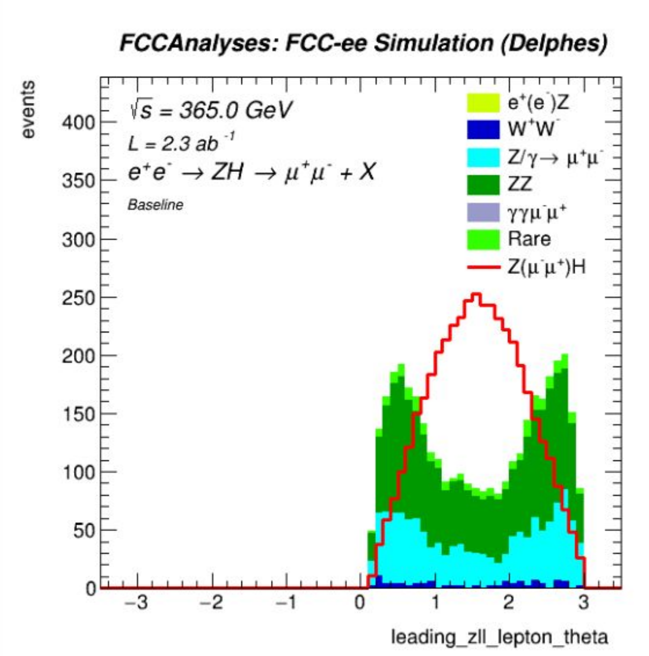



Theta angle of the leading lepton coming from the Z decay comparison at 240 GeV (left) and 365 GeV (right) for mumu channel

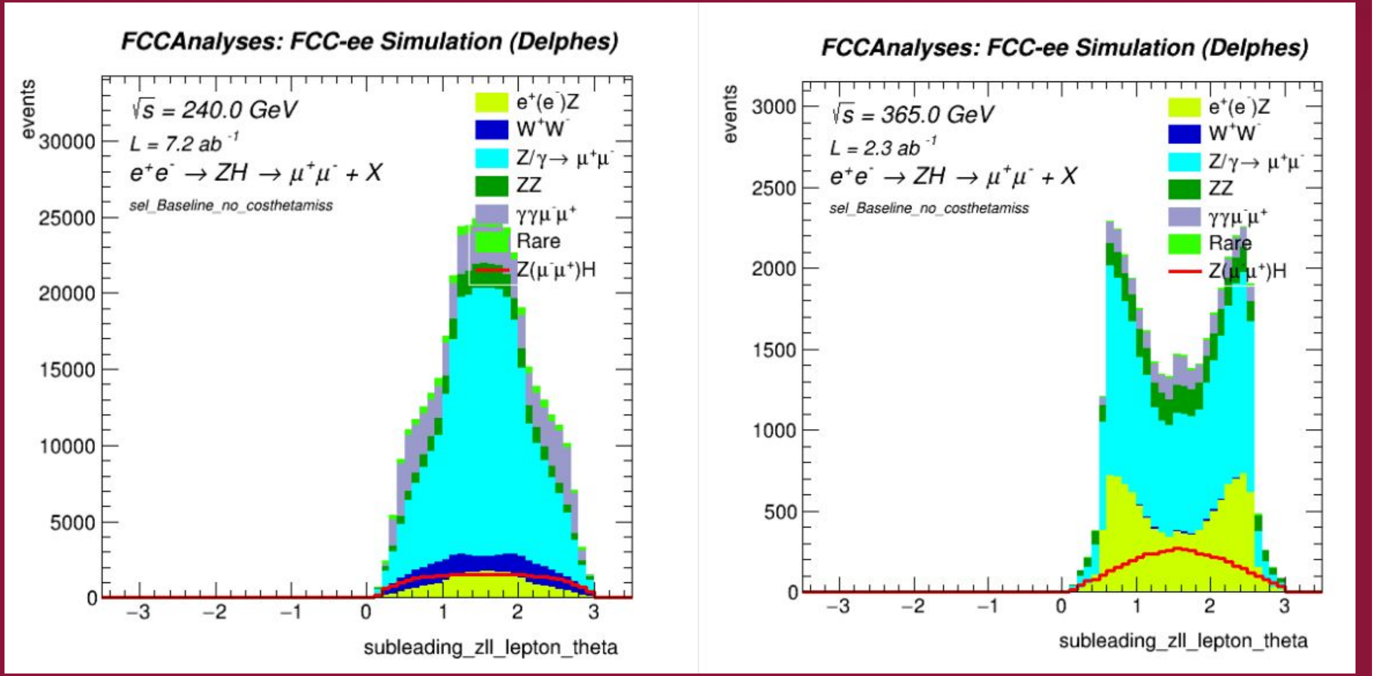
# Theta angle of the leading lepton coming from the Z decay




Theta angle of the leading lepton coming from the Z decay comparison at 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut

# Theta angle of the subleading lepton coming from the Z decay

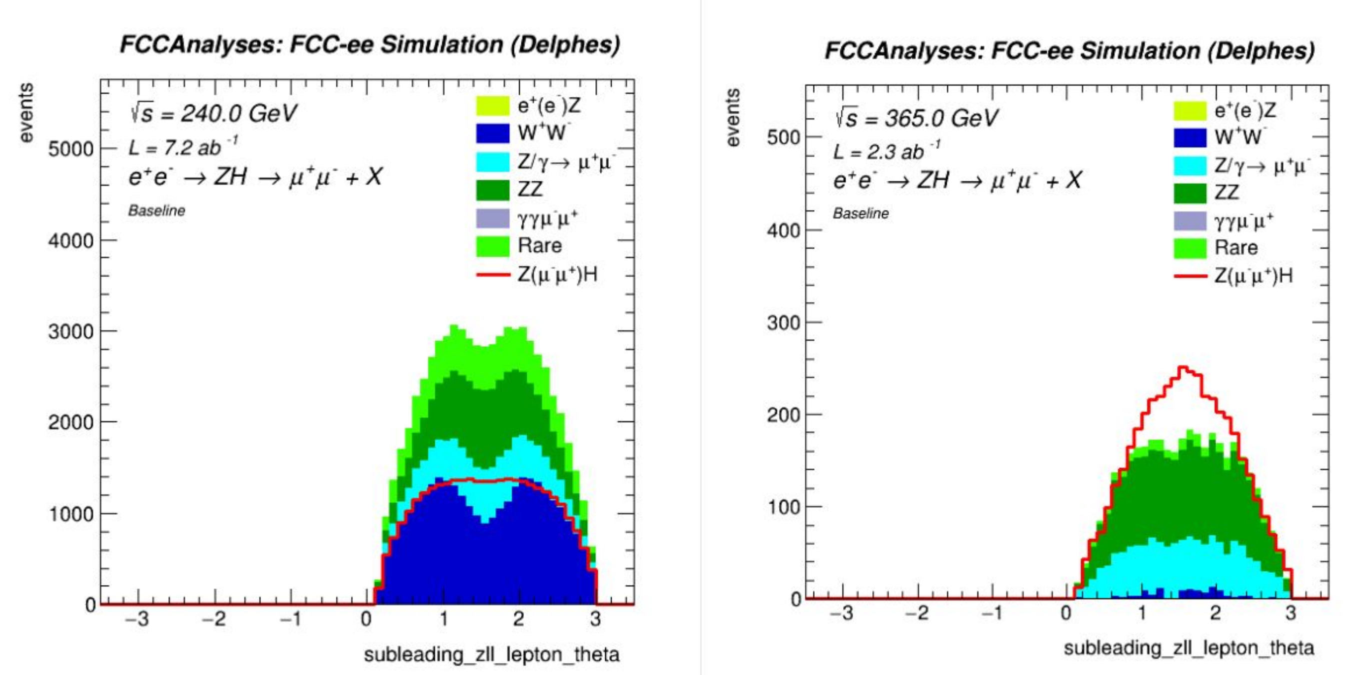



Theta angle of the subleading lepton coming from the Z decay comparison at 240 GeV (left) and 365 GeV (right) for mumu channel



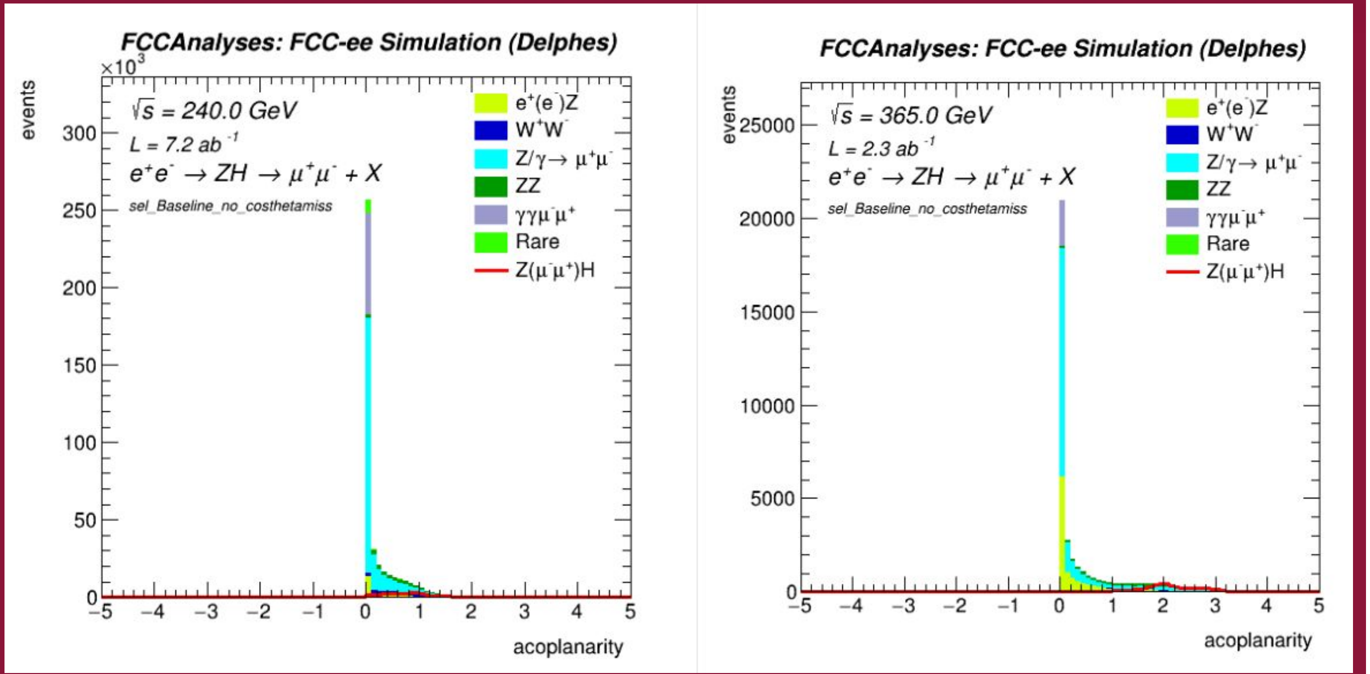
DEWYSPELAERE Kevin

# Theta angle of the subleading lepton coming from the Z decay



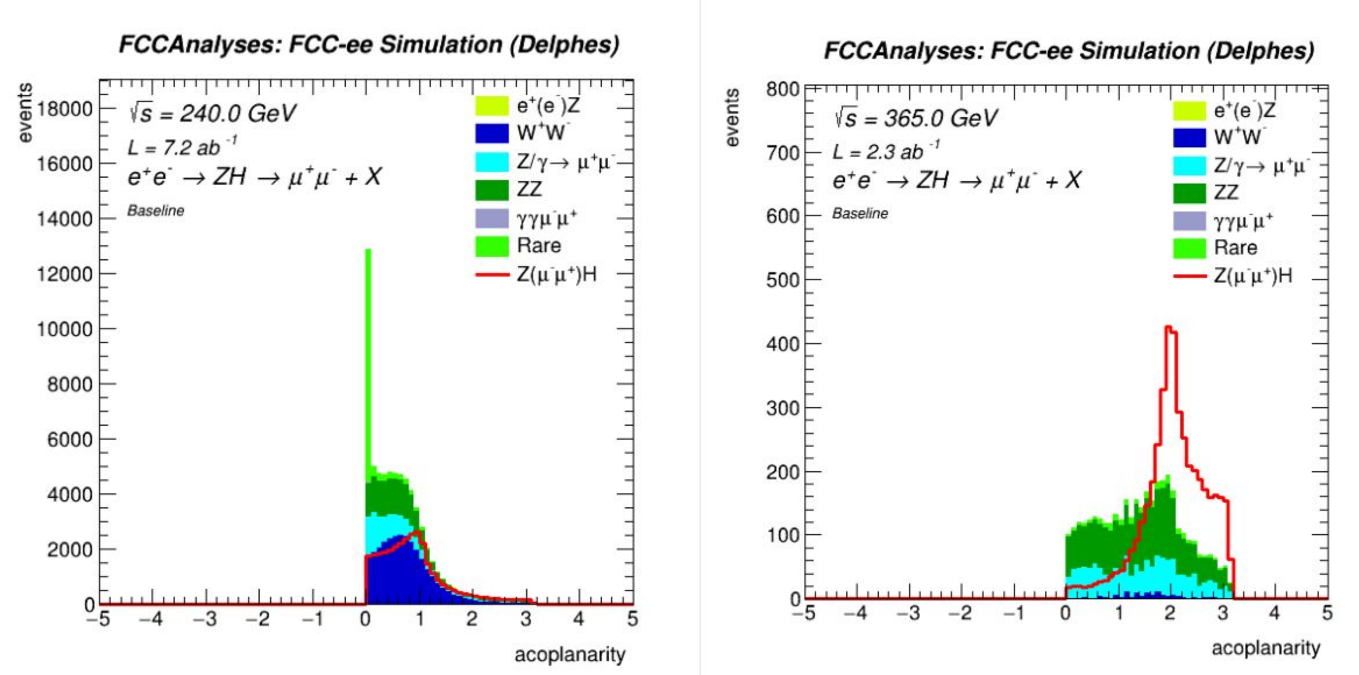

Theta angle of the subleading lepton coming from the Z decay comparison at 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut

# Acoplanarity of the reconstructed Z boson




Acoplanarity of the reconstructed Z boson comparison 240 GeV (left) and 365 GeV (right) for mumu channel

# Acoplanarity of the reconstructed Z boson

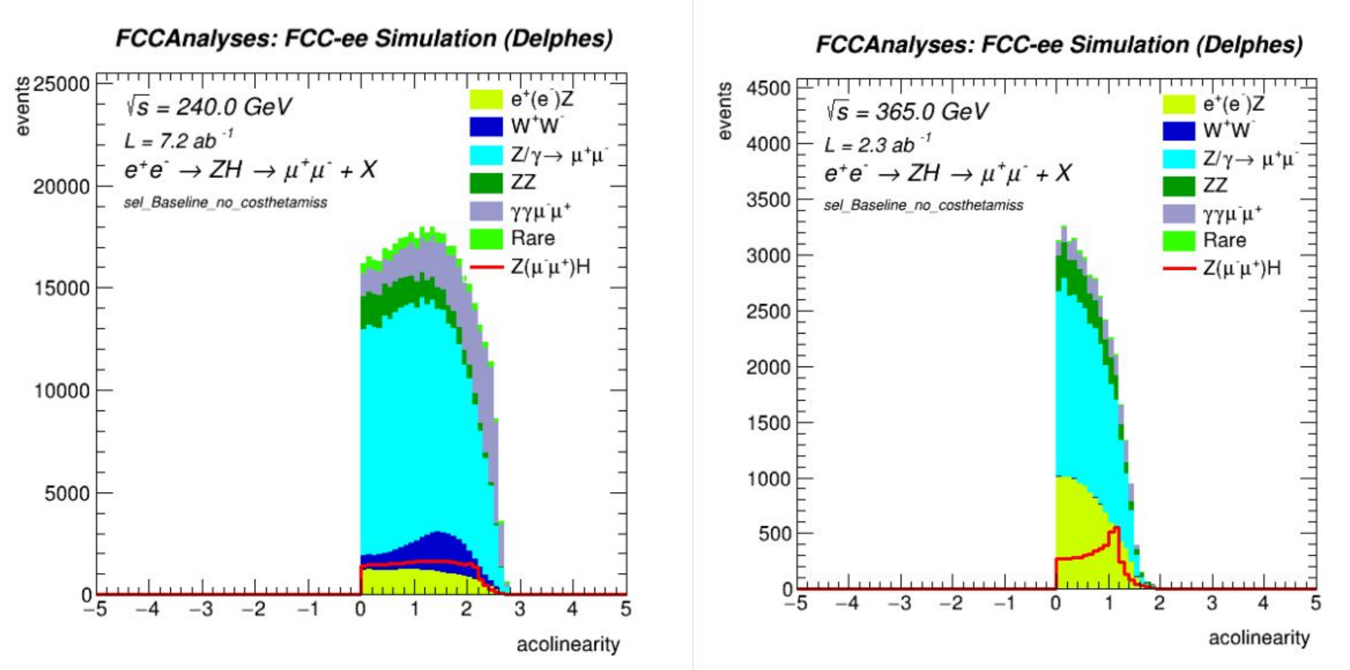



Acoplanarity of the reconstructed Z boson comparison 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut



DEWYSPELAERE Kevin

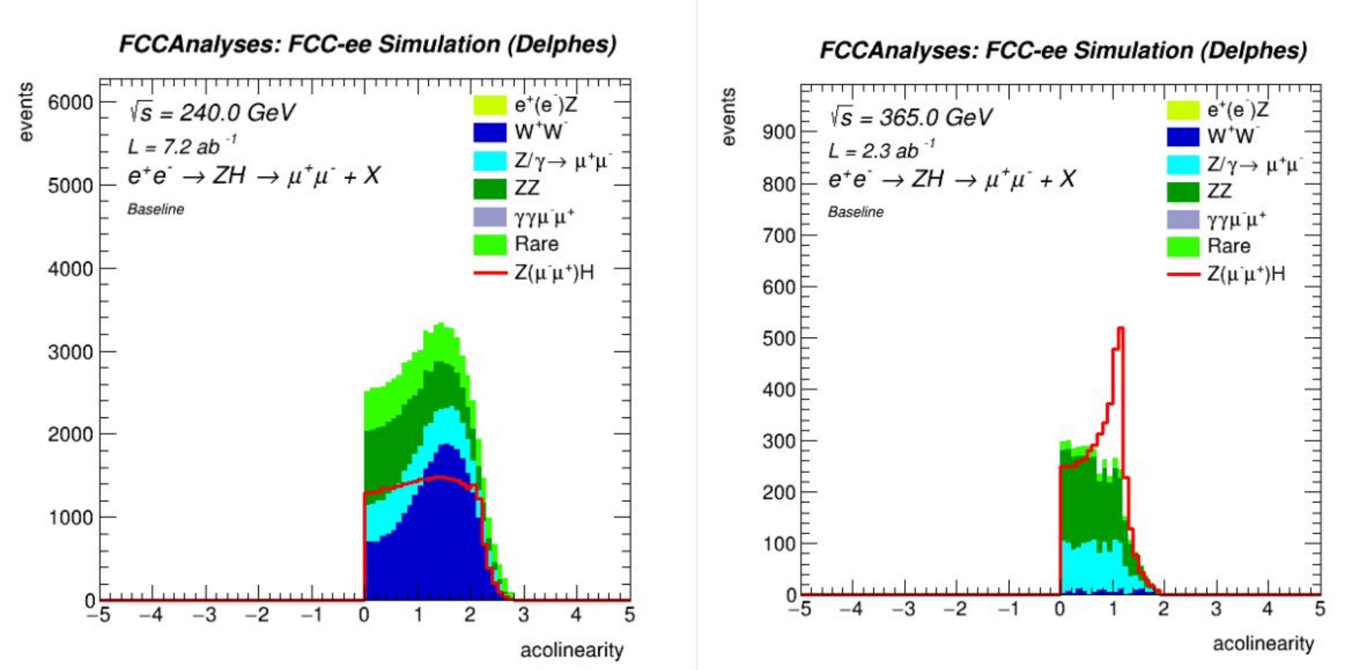
# Acollinearity of the reconstructed Z boson




Acollinearity of the reconstructed Z boson comparison 240 GeV (left) and 365 GeV (right) for mumu channel

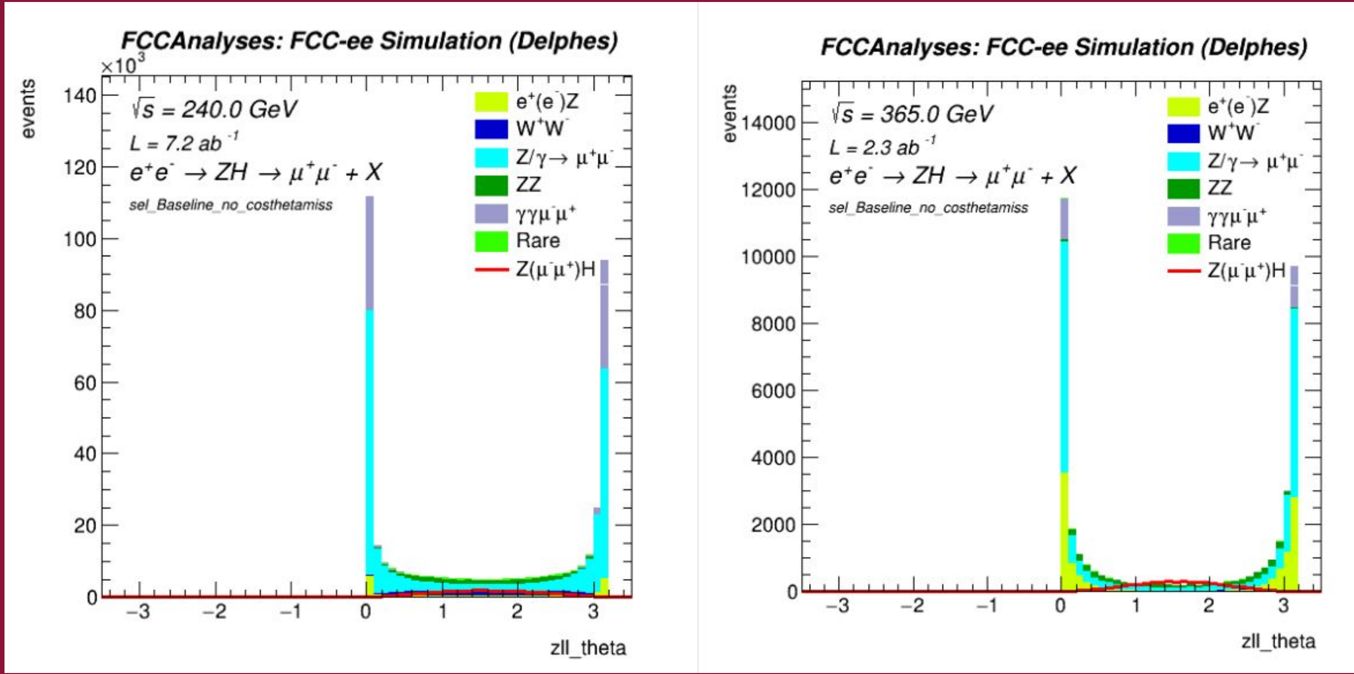

DEWYSPELAERE Kevin

# Acollinearity of the reconstructed Z boson



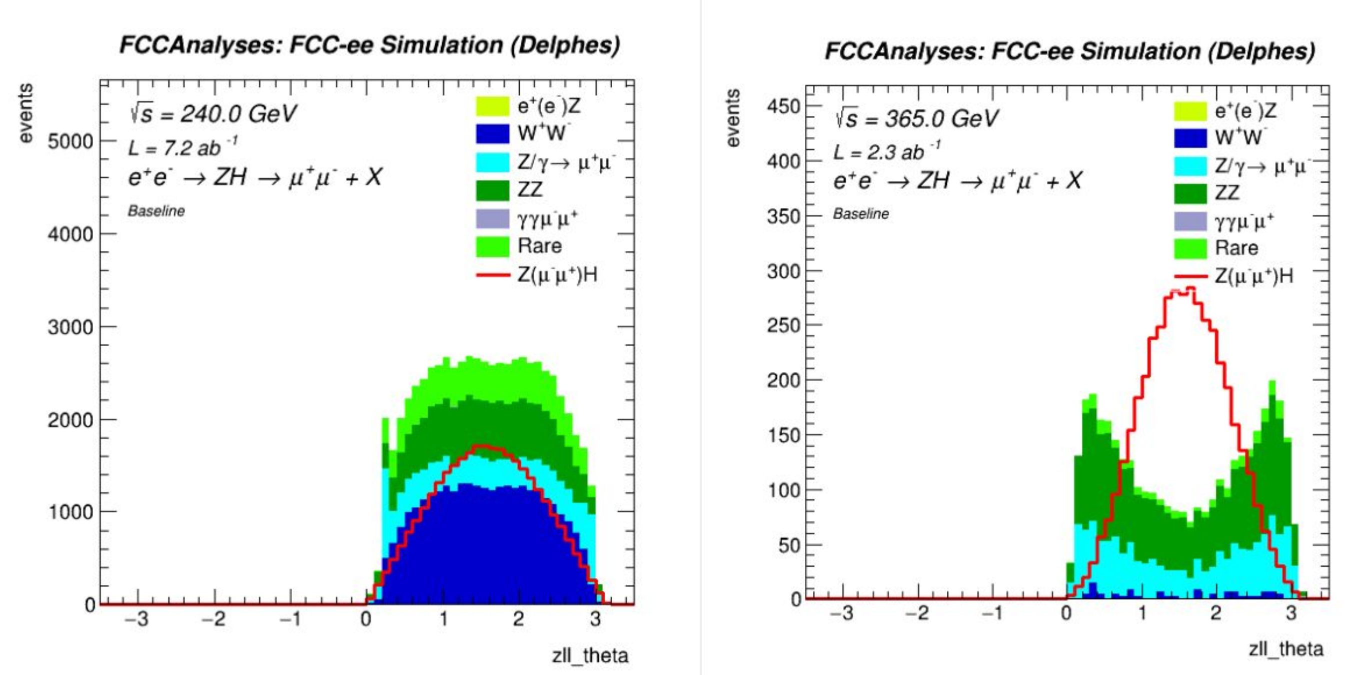

Acollinearity of the reconstructed Z boson comparison 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut

# Theta angle of the reconstructed Z boson




Theta angle of the reconstructed Z boson comparison at 240 GeV (left) and 365 GeV (right) for mumu channel

# Theta angle of the reconstructed Z boson

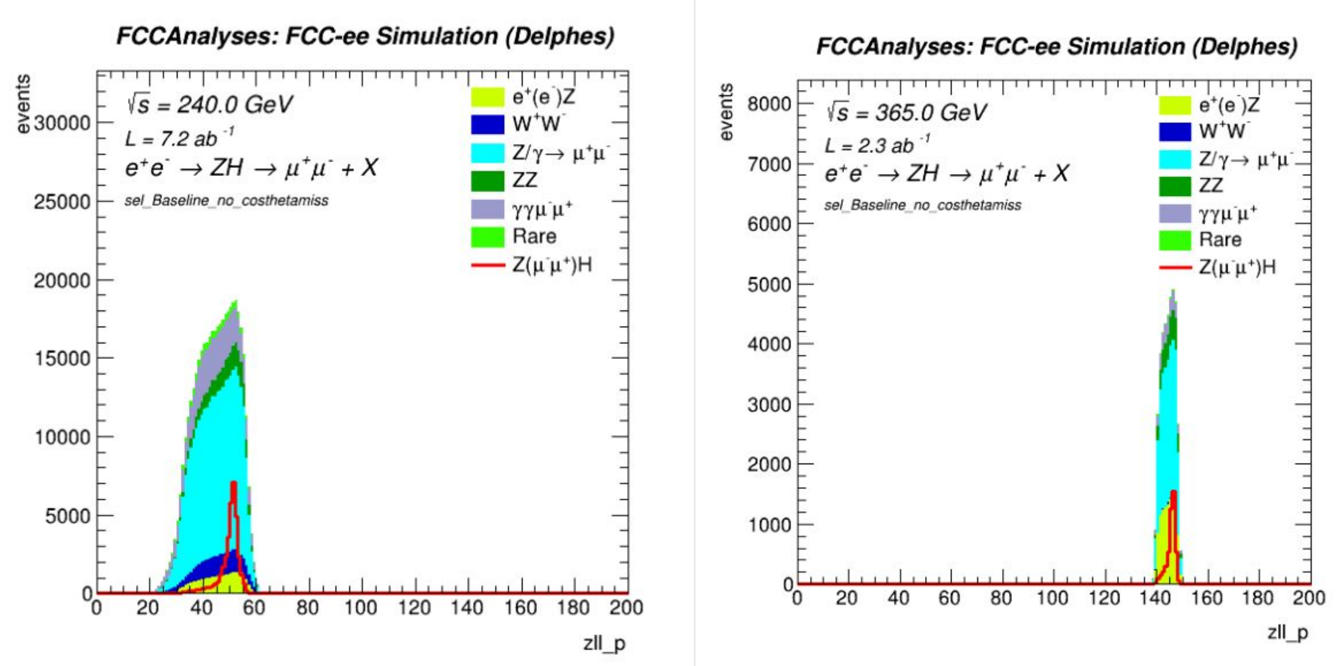



Theta angle of the reconstructed Z boson comparison at 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut



DEWYSPELAERE Kevin

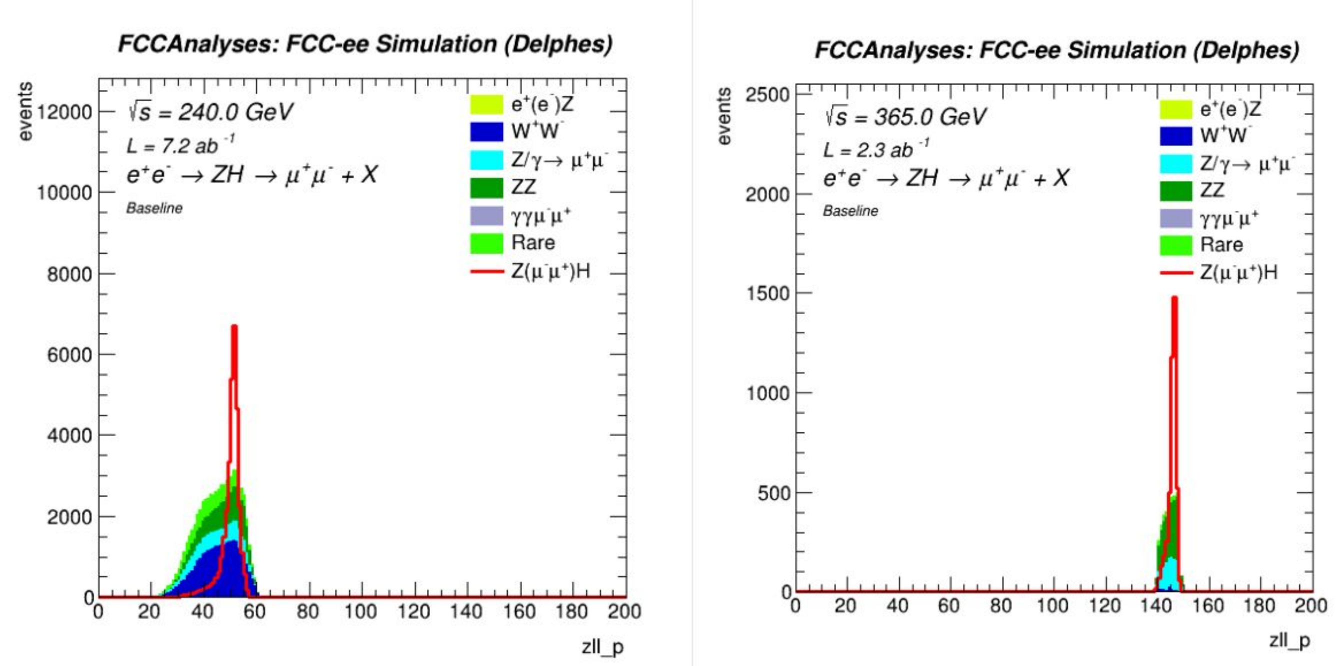
# Momentum of the reconstructed Z boson




Momentum of the reconstructed Z boson comparison at 240 GeV (left) and 365 GeV (right) for mumu channel

- Z momentum gain 100 GeV at 365 GeV

# Momentum of the reconstructed Z boson

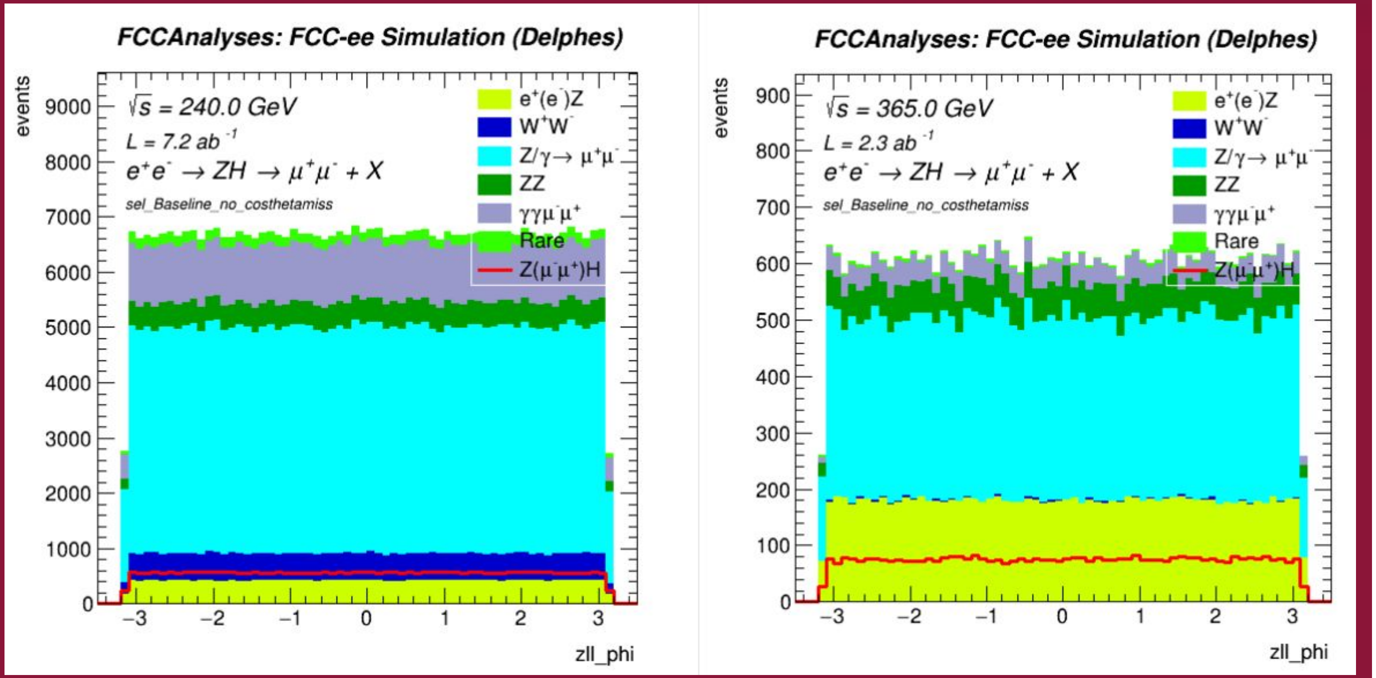



Momentum of the reconstructed Z boson comparison 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut

- **Z momentum gain 100 GeV at 365 GeV**


DEWYSPELAERE Kevin

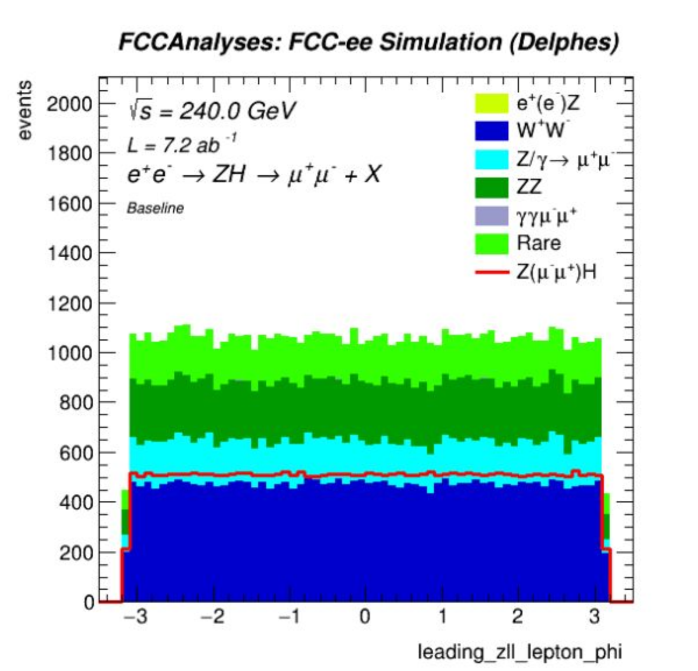
# Phi angle of the reconstructed Z boson

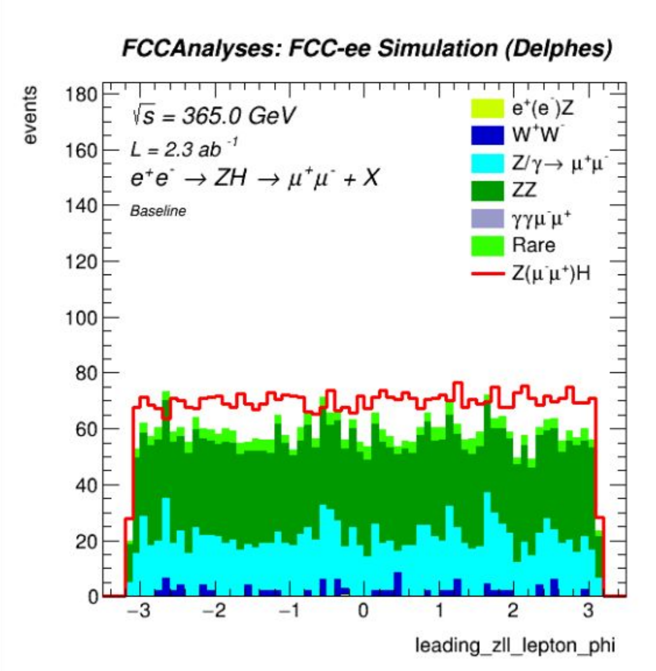



- Number of events divided by 3
- We gain a bit of signal noise ratio
- Need to add integrals and SNR number on the plot

Phi angle of the reconstructed Z boson comparison at 240 GeV (left) and 365 GeV (right) for mumu channel

# Phi angle of the reconstructed Z boson




- Number of events divided by 3
- We gain a bit of signal noise ratio
- Need to add integrals and SNR number on the plot

Phi angle of the reconstructed Z boson comparison at 240 GeV (left) and 365 GeV (right) for mumu channel with cos θmiss selection cut

# Sample used for BDT training

-

| Sample Name | Process | Generator | Training + Validation | cross-section (pb) |
|---|---|---|---|---|
| **Higgs Processes** | | | | |
| wzp6_ee_mumuH | $e^+e^- \to \mu^+\mu^- H$ | WHIZARD + PYTHIA6 | 873007 | 0.0067643 |
| **Diboson Processes** | | | | |
| p8_ee_ZZ | $e^+e^- \to ZZ$ | PYTHIA8 | 59261 | 1.35899 |
| p8_ee_WW_mumu | $e^+e^- \to WW \to \mu^+\nu_\mu\mu^-\bar{\nu_\mu}$ | PYTHIA8 | 62966 | 0.25792 |
| **Dilepton Processes** | | | | |
| wzp6_ee_mumu | $e^+e^- \to \mu^+\mu^-$ | WHIZARD + PYTHIA6 | 551655 | 5.288 |
| **Electron Photon Processes** | | | | |
| wzp6_egamma_eZ_Zmumu | $e^-\gamma \to e^- Z(\mu^+\mu^-)$ | WHIZARD + PYTHIA6 | 28662 | 0.10368 |
| wzp6_gammae_eZ_Zmumu | $e^+\gamma \to e^+ Z(\mu^+\mu^-)$ | WHIZARD + PYTHIA6 | 28512 | 0.10368 |
| **Photon Photon Processes** | | | | |
| wzp6_gaga_mumu_60 | $\gamma\gamma \to \mu^+\mu^-$ | WHIZARD + PYTHIA6 | 141949 | 1.5523 |

| Sample Name | Process | Generator | Training + Validation | cross-section (pb) |
|---|---|---|---|---|
| **Higgs Processes** | | | | |
| wzp6_ee_eeH | $e^+e^- \to e^+e^- H$ | WHIZARD + PYTHIA6 | 769907 | 0.0067643 |
| **Diboson Processes** | | | | |
| p8_ee_ZZ | $e^+e^- \to ZZ$ | PYTHIA8 | 29894 | 1.35899 |
| p8_ee_WW_ee | $e^+e^- \to WW \to e^+\nu_e e^-\bar{\nu_e}$ | PYTHIA8 | 34874 | 0.25792 |
| **Dilepton Processes** | | | | |
| wzp6_ee_ee_Mee_30_150 | $e^+e^- \to e^+e^-$ (30-150 GeV) | WHIZARD + PYTHIA6 | 660832 | 8.305 |
| **Electron Photon Processes** | | | | |
| wzp6_egamma_eZ_Zee | $e^-\gamma \to e^- Z(e^+e^-)$ | WHIZARD + PYTHIA6 | 7883 | 0.05198 |
| wzp6_gammae_eZ_Zee | $e^+\gamma \to e^+ Z(e^+e^-)$ | WHIZARD + PYTHIA6 | 7887 | 0.05198 |
| **Photon Photon Processes** | | | | |
| wzp6_gaga_ee_60 | $\gamma\gamma \to e^+e^-$ | WHIZARD + PYTHIA6 | 28534 | 0.873 |

Samples used for the BDT analysis, $\mu^+\mu^-$ (up) and $e^+e^-$ (down)



*DEWYSPELAERE Kevin*