Measurements of the ZH cross section at the Future e^+e^- Circular Collider at 240 & 365 GeV

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Jamboree FCC 2024
July 2nd, 2024

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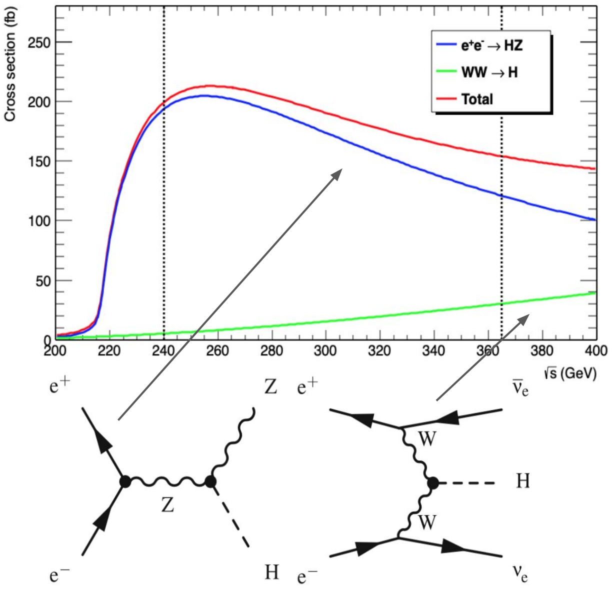
Contents

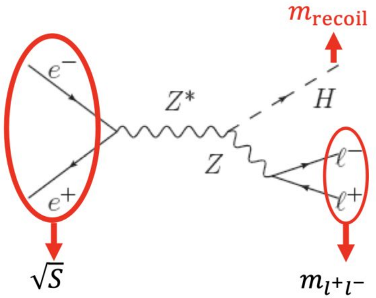
- Comparative analysis between 240 and 365 GeV
- Boosted decision Tree Algorithm
- Fitting strategy

Introduction



- ➢ Future circular collider project: **feasibility study** for **estimations** on the **uncertainties** on **cross-section** of the **ZH** process and **Higgs mass (125 GeV)**
- ➢ Signal: $e^+e^- \to ZH \to \mu^+\mu^- + X$
  $e^+e^- \to ZH \to e^+e^- + X$
- ➢ 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 √s = 240 GeV:
  - Cross-section: **0.60 %**
  - Higgs mass: **4.0 MeV**
- ➢ **Goal:** Measurement of the ZH cross-section at 365 GeV following 240 GeV methodology

	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	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	3.6	0.36	0.75
Run time (year)	2	2	2	0	3	1	4
Number of events	6×10^{12}Z		2.4×10^8WW		2.175×10^6HZ $+6.75 \times 10^4 WW \to H$	$1.9 \times 10^6 t\bar{t}$ $+4.26 \times 10^5$HZ $+1 \times 10^5 WW \to H$	

2.175×10^6HZ at 240 GeV
$+4.26 \times 10^5$HZ at 365 GeV

The run at 365 GeV provides 20% more ZH events at 0.75 ab⁻¹ during 4 years (total 3.0 ab⁻¹)

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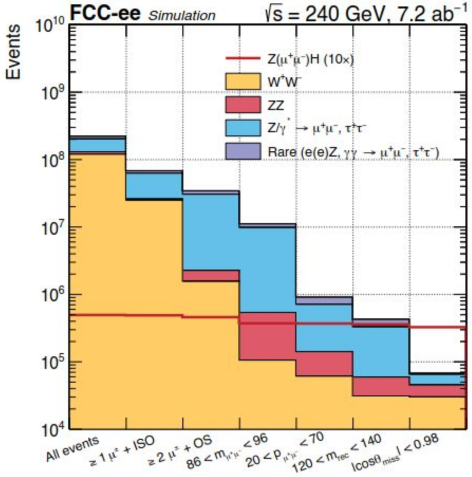
Monte Carlo samples and events selection

Using Fast simulation **DELPHES**:

- **Signal:**
  - $Z(\ell^+\ell^-)H$ (Whizard/Pythia)
- **Backgrounds:**
  - W^+W^- (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. Preselection:
   - Select at least 2 leptons with opposite sign
   - One lepton required to be isolated
2. $m_{l^+l^-} \in [86, 96]$ GeV
3. $p_{l^+l^-} \in [20, 70]$ GeV (> 20 GeV at 365 GeV)
4. $m_{recoil} \in [120, 140]$ GeV



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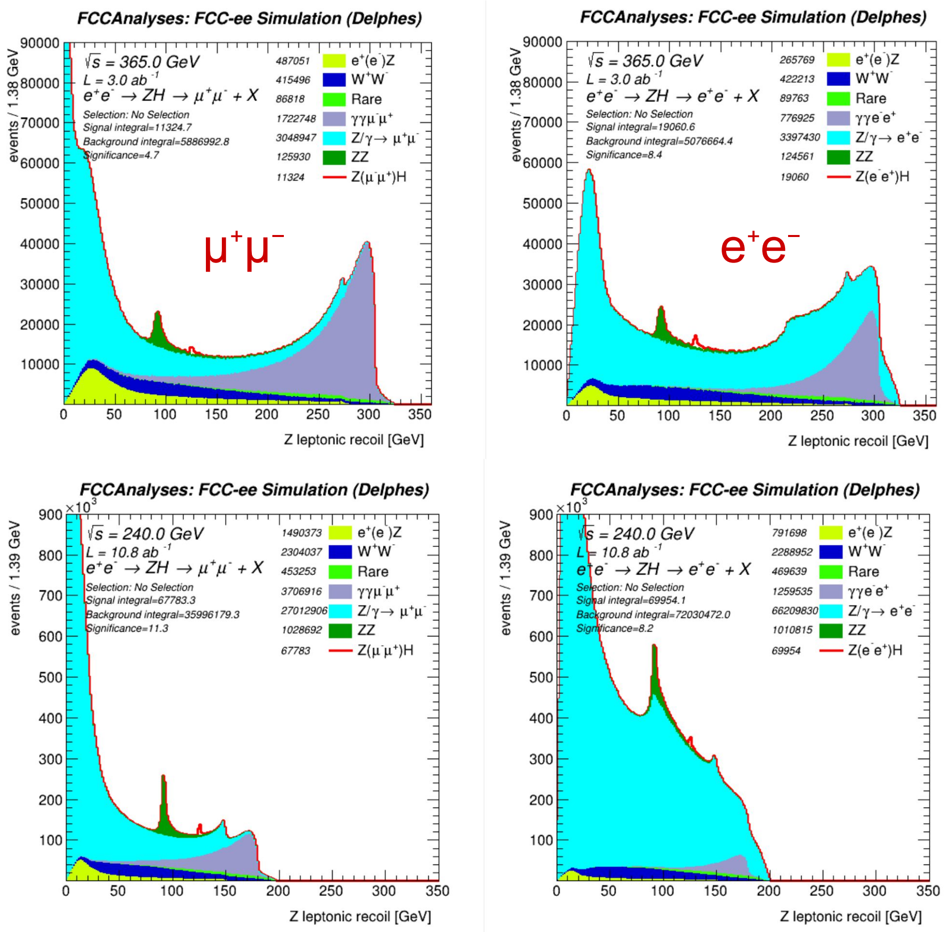
Comparison 240/365 GeV with Preselection Cuts

365 GeV ⇒

240 GeV ⇒



➢ **Differences**

- Luminosity is **3.0** ab^{-1} at √s=**365 GeV** and **10.8** ab^{-1} at √s=**240 GeV**
- Signal yields ~**5** times lower for $\mu^+\mu^-$ corresponding to lower luminosity and cross-section
- **Shape** of the background
- Signal peak with **lower resolution** but significantly less background at 365 GeV

Comparison mrecoil distribution at 365 GeV (top) and 240 GeV (bottom) for the $\mu^+\mu^-$ and e^+e^- channel with preselection cuts

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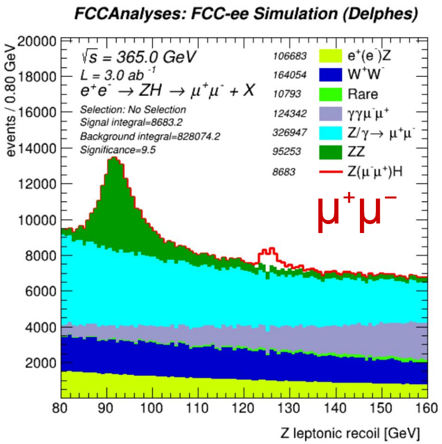
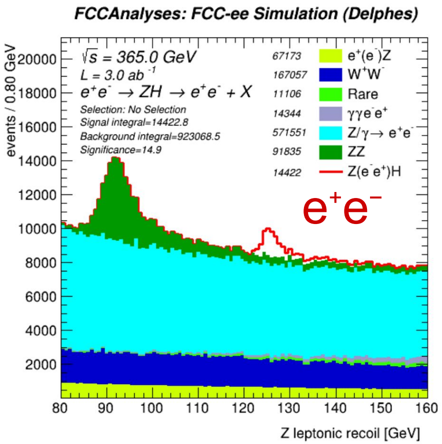
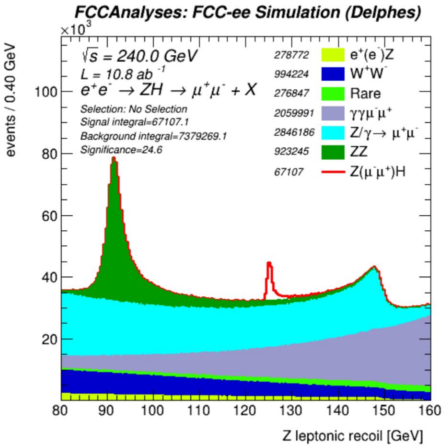
Comparison 240/365 GeV with Preselection Cuts

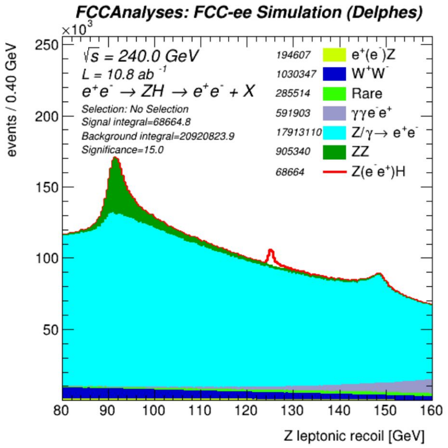
365 GeV ⇒





240 GeV ⇒





➢ **Zoom between 80 and 160 GeV**

- Luminosity is **3.0** ab^{-1} at $\sqrt{s}$=**365 GeV** and **10.8** ab^{-1} at $\sqrt{s}$=**240 GeV**
- Signal yields **5** times lower for $\mu^+\mu^-$ corresponding to lower luminosity and cross-section
- **Shape** of the background
- Signal peak with **lower resolution** but significantly less background at 365 GeV

Comparison m_{recoil} distribution at 365 GeV (top) and 240 GeV (bottom) for the $\mu^+\mu^-$ and e^+e^- channel with preselection cuts

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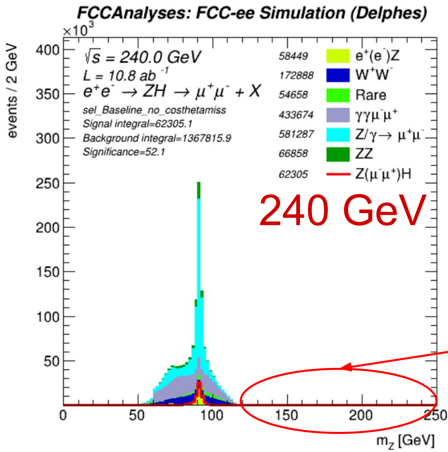
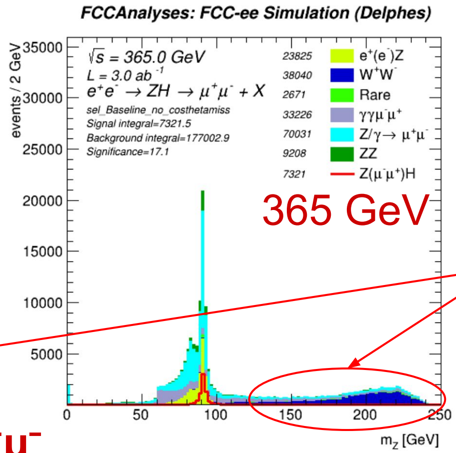
Invariant Mass and Recoil Mass distributions

Invariant Mass Distribution ⇒

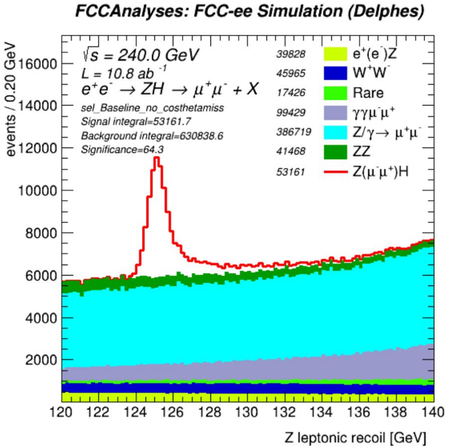
$\mu^+\mu^-$

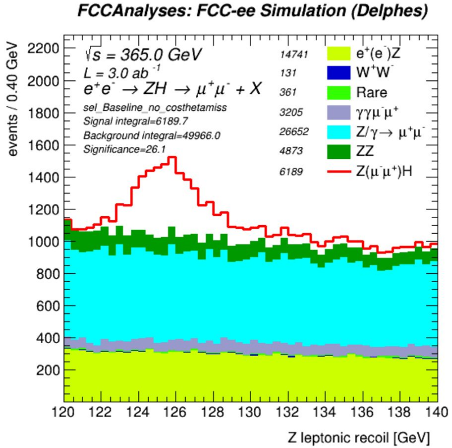
Recoil Mass Distribution ⇒





$\mu^+\mu^-$





➢ **Events basic selection:**

1. Pre-selection (2 leptons opposite sign)
2. $m_{l^+l^-} \in [86, 96]$ GeV
3. $p_{l^+l^-} \in [20, 70]$ GeV (>20 for √s=365 GeV)
4. $m_{recoil} \in [120, 140]$ GeV

➢ **WW negligible** at √s=365 GeV
- The cut on the **mass** is **removing them**

➢ Resolution **2.3** times wider at √s=365 GeV

➢ **Significance** (S/sqrt(S + B)) is **~26** at √s=**365 GeV**, vs. **~64** at √s=**240 GeV** for $\mu^+\mu^-$ and **~27 vs ~47** for e^+e^- channel with the basic selection cuts.

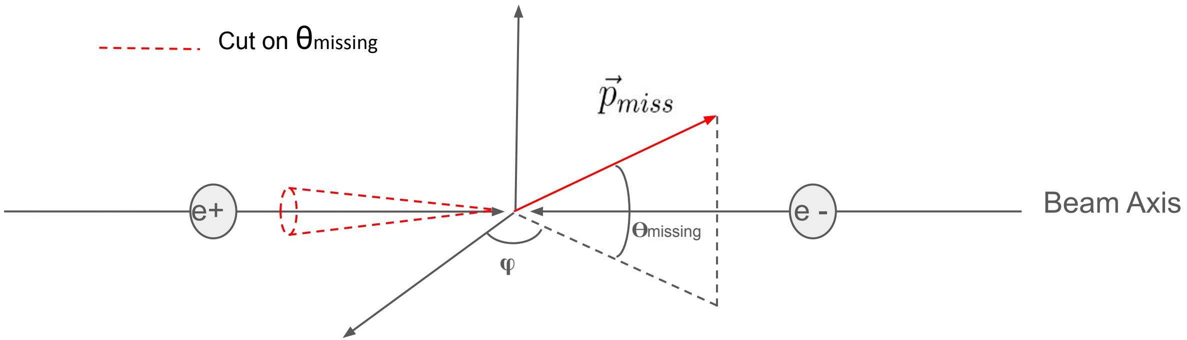
Missing momentum

- The **missing momentum** is defined by the **negative vectorial sum** of the momenta of all reconstructed particles:

$$\vec{p}_{miss} = -\sum_{n_{part}} \vec{p}_{rec}$$

- **θmissing** is the **polar angle** of the **missing momentum vector** with respect to the **beam axis**

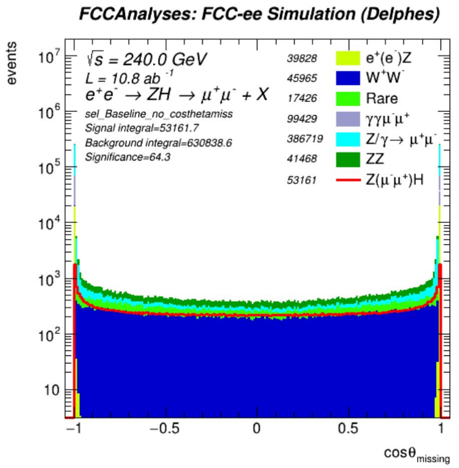
- The requirement $|\cos \theta_{missing}| < $ **0.98** is used for the **mass analysis only,** which means that we are removing events mostly collinear to the beam axis

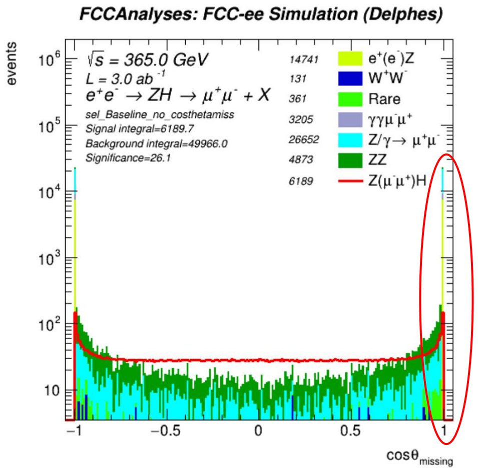


Cos $\theta_{missing}$ selection cut & Recoil mass distribution

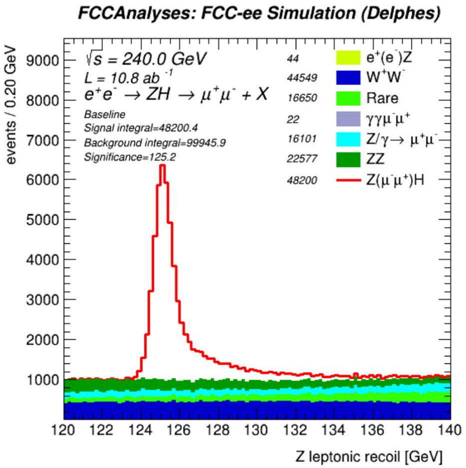
Cos $\theta_{missing}$ Distribution ⇒

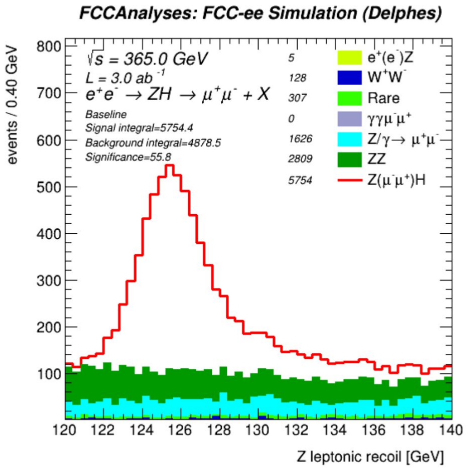
$\mu^+\mu^-$





Recoil Mass Distribution ⇒





- The requirement $|\cos\theta_{missing}| < 0.98$ used for **mass analysis only**
- This requirement is removing a lot of background concentrated in the **last bins**
- **Significance** (S/sqrt(B)) is **~56** at **365 GeV**, vs. **~125** at **240 GeV** for $\mu^+\mu^-$
- Introduces **biases** on the Higgs decay modes that break the **model independence,** which is not important for mass analysis

Cos $\theta_{missing}$ distribution at 240/365 GeV for $\mu^+\mu^-$ channel with baseline selection cuts

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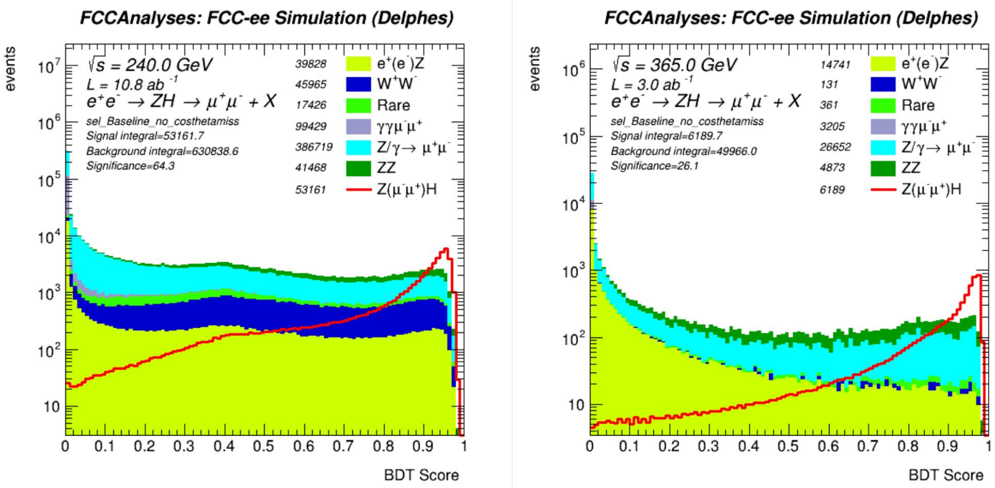
Boosted Decision Tree

- ➢ Using a Machine learning algorithm to **separate signal** and **background**, a Boosted Decision Tree (BDT)
- ➢ The BDT allows for a **model independent** analysis
- ➢ Training_variables for BDT:

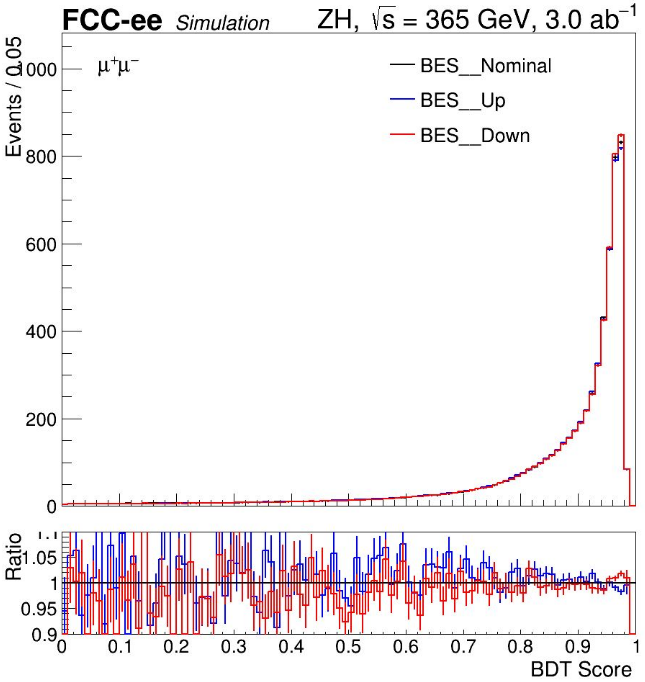
Variable	Description
$p_{\ell^+\ell^-}$	Lepton pair momentum
$\theta_{\ell^+\ell^-}$	Lepton pair polar angle
$m_{\ell^+\ell^-}$	Lepton pair invariant mass
$p_{l_{\text{leading}}}$	Momentum of the leading lepton
$\theta_{l_{\text{leading}}}$	Polar angle of the leading lepton
$p_{l_{\text{subleading}}}$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

- ➢ **BDT Score comparison** between 365 and 240 GeV
- ➢ This **BDT score** is **fitted** to measure the **ZH cross-section value**



BDT score comparison at 240 GeV (left) and 365 GeV (right) for $\mu^+\mu^-$ channel with basic selection cuts

Systematic uncertainties



Effect of the beam energy spread uncertainty (±10 %) on the Z(e, e)H recoil mass distribution

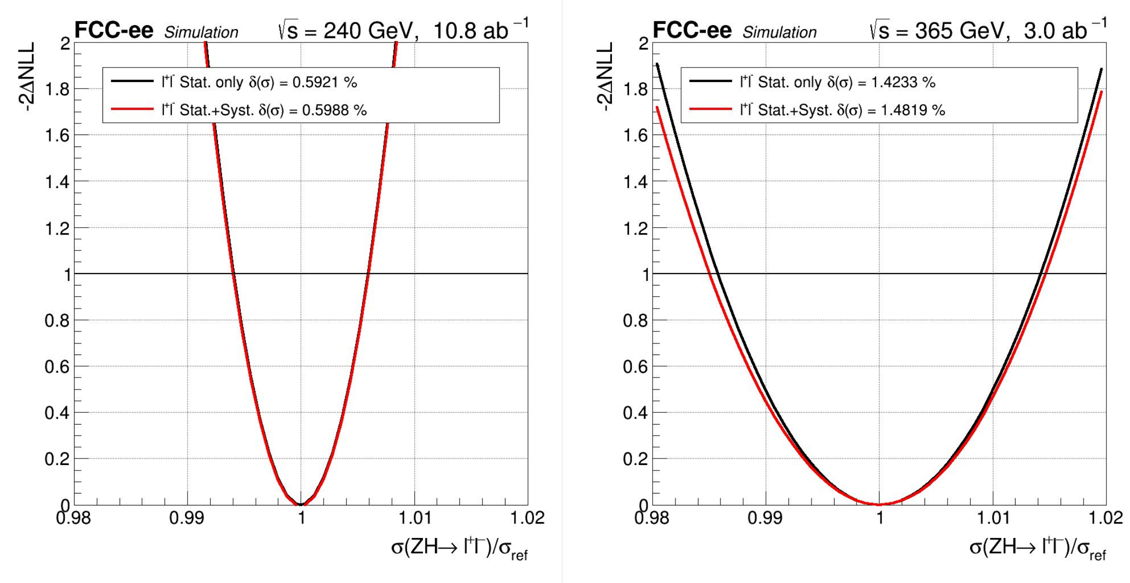
- **Beam energy spread**: Uncertainty coming from the accelerator equipment, spread of the nominal gaussian distribution of the beam. **1%** at 240 GeV and **10%** at 365 GeV.
- **Centre-of-mass (√s)**: Uncertainty on the centre-of-mass energy which is expected to be known at the **2 MeV** level for 240 and 365 GeV
- **Lepton momentum scale**: Uncertainty on the momentum of leptons measured assumed to be **10^{-5}** for 240 and 365 GeV

	ZH	
$\sqrt{s}$ energy	240	365
BES	0.089%	0.41%
$\sqrt{s}$ unc.	0.0042%	0.002%
μ momentum	0.0002%	0.0002%
e momentum	0.0002%	0.0002%
Stat only	0.59%	1.42%
Syst only	0.089%	0.41%

- **Greater impact of systematics** at 365 GeV compared with analysis at 240 GeV c.o.m

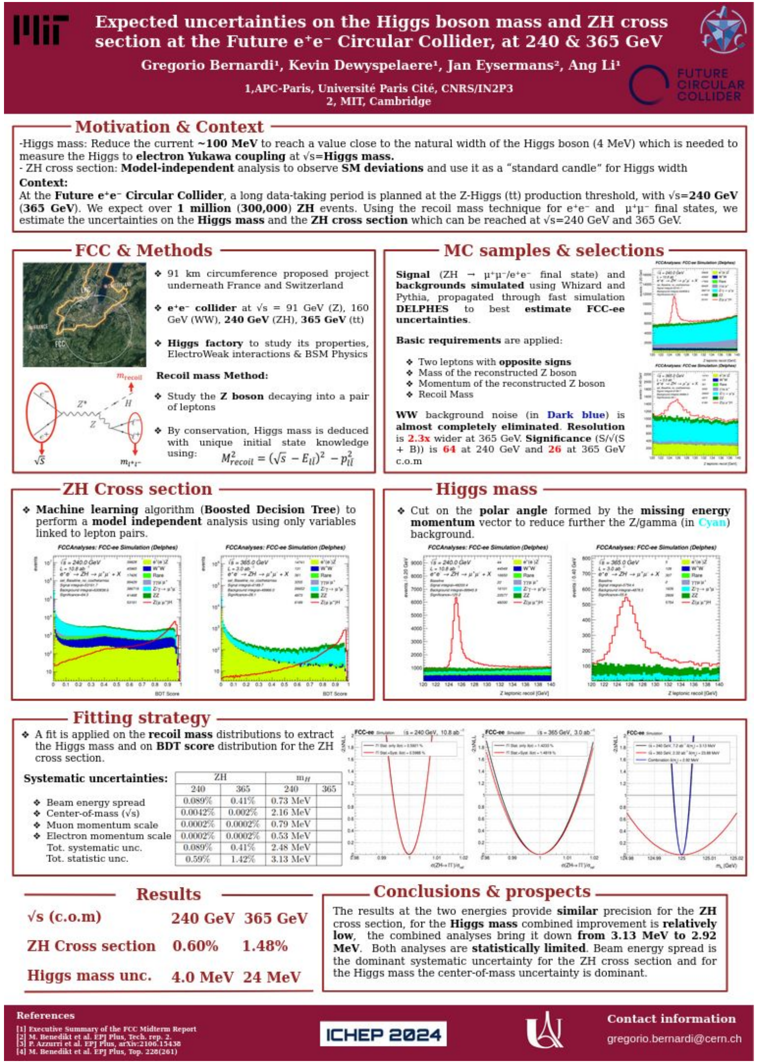
Table of systematic uncertainties of the analysis at 240 and 365 GeV centre of mass

$\mu^+\mu^-$ and e^+e^- statistical and systematic uncertainties on cross-section measurement at √s=240 & 365 GeV



Likelihood scan of the ZH cross section at √s=240 GeV & 365 GeV

- By fitting and combining the **two channels**, we obtain the cross-section (here it is normalized to the SM) with its **statistical** and **systematic** uncertainties
- The **ratio** between the measured cross-section and expected SM value
- **1.42%** Statistical uncertainties at √s=**365 GeV** compared to **0.59%** at √s=**240 GeV**
- **1.48%** Stat+Syst uncertainties at √s=**365 GeV** compared to **0.60%** at √s=**240 GeV**



Poster presentation

- ➢ Poster presentation during the High energy Physics conference (**ICHEP**) at Prague in july 2024
- ➢ Presentation of the main results for the **Higgs mass** and the **ZH cross section** measurement at √s=240 & 365 GeV

Link: https://ichep2024.org/

Conclusion

	significance		
$\sqrt{s}$	240 (10.8 ab^{-1})	365 (3.0 ab^{-1})	365 (10.8 ab^{-1})
$\mu^+\mu^-$	64.3	26.1	49.52
e^+e^-	47.4	27.0	51.23
	Statistical uncertainties		
Combined	0.592%	1.423%	0.750%
	Stat+Syst uncertainties		
Combined	0.599%	1.482%	0.781%

- **With the same luminosity,** we have 1.3 times less significance for $\mu^+\mu^-$ & 1.1 times more for e^+e^- at **365 GeV** compared to **240 GeV**, because the background is smaller for e^+e^-
- 2.3 times less resolution for each channel at **365 GeV**
- Stat+Syst uncertainties with 10.8 ab^{-1} would be 0.781% by combining channels at 365 GeV
- Analysis is **statistically limited**. Beam energy spread (BES) is the dominant systematic uncertainty for ZH cross section analysis

Thank you for your attention

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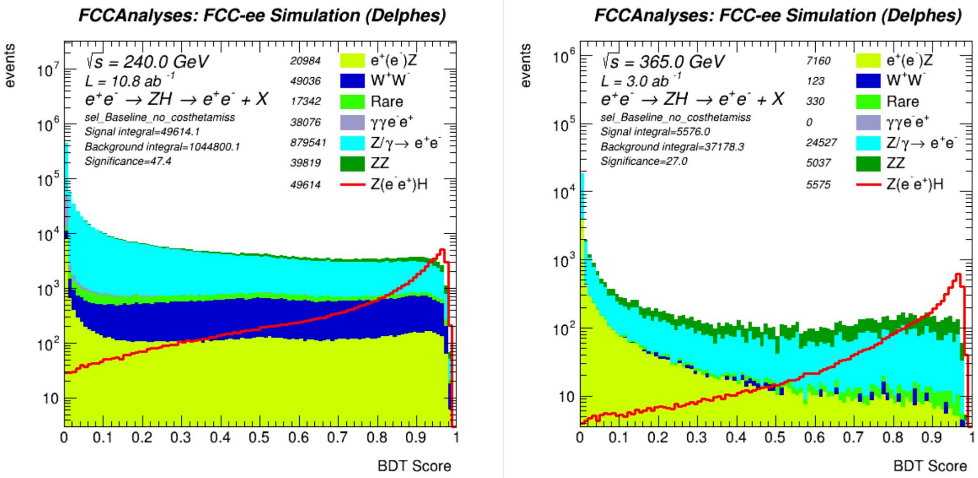
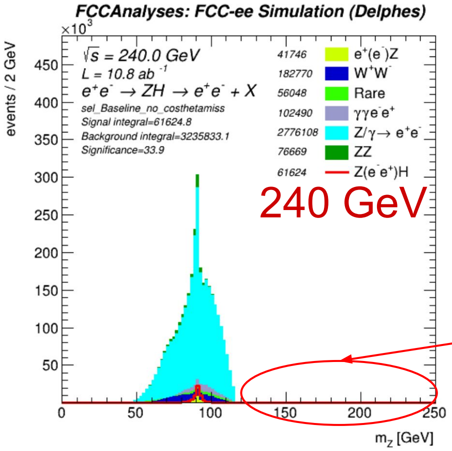


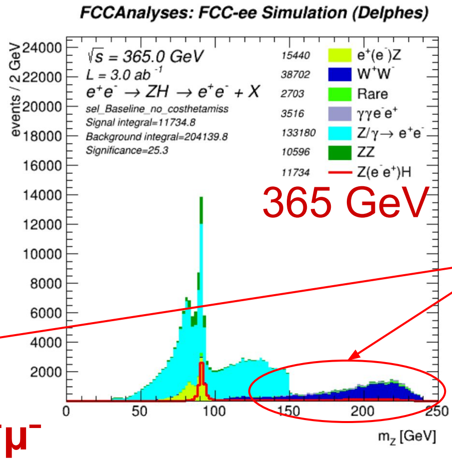
BDT score comparison at 240 GeV (left) and 365 GeV (right) for $\mu^+\mu^-$ channel with basic selection cuts

Invariant Mass and Recoil Mass distributions

Invariant Mass Distribution ⇒

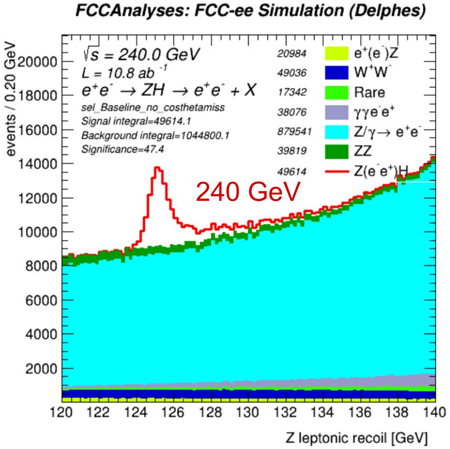
$\mu^+\mu^-$

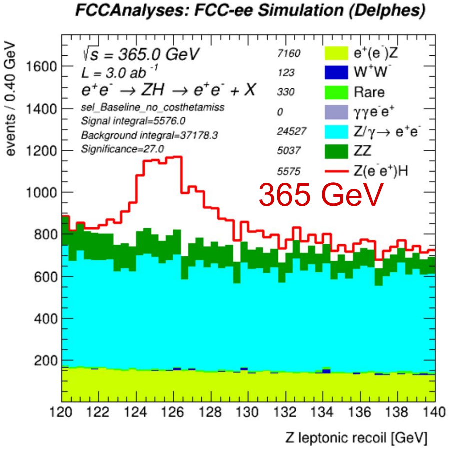




$\mu^+\mu^-$

Recoil Mass Distribution ⇒





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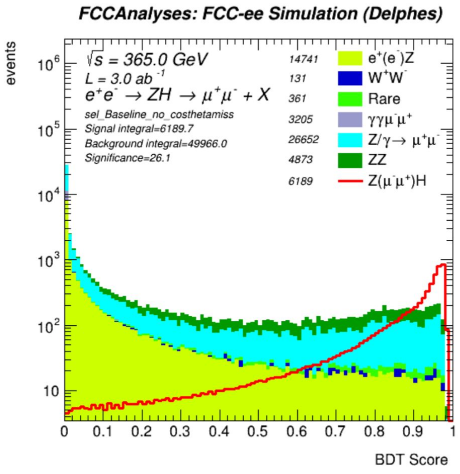
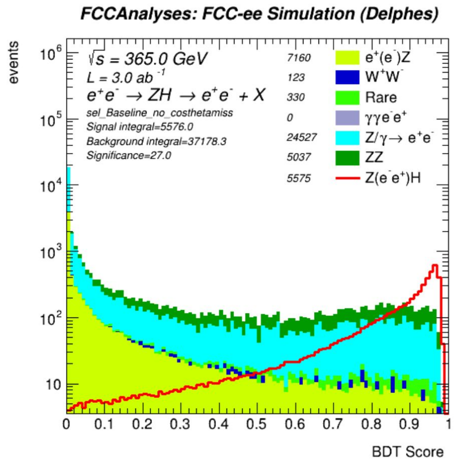
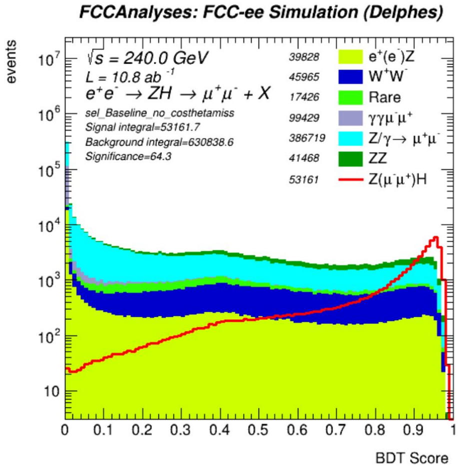
BDT score for $\mu^+\mu^-$ and e^+e^- at 365/240 GeV

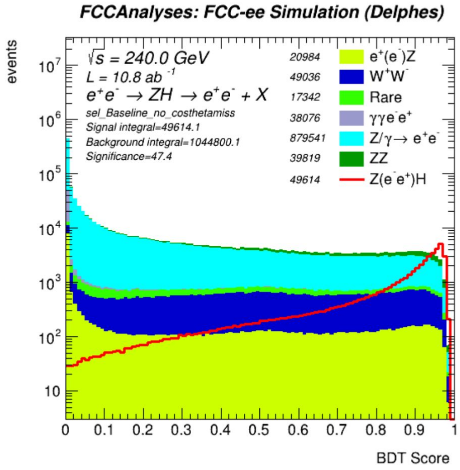
365 ⇒





240 ⇒

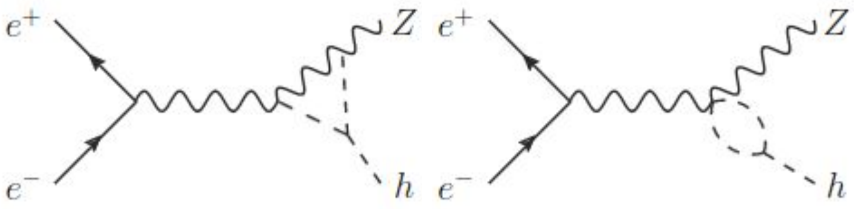




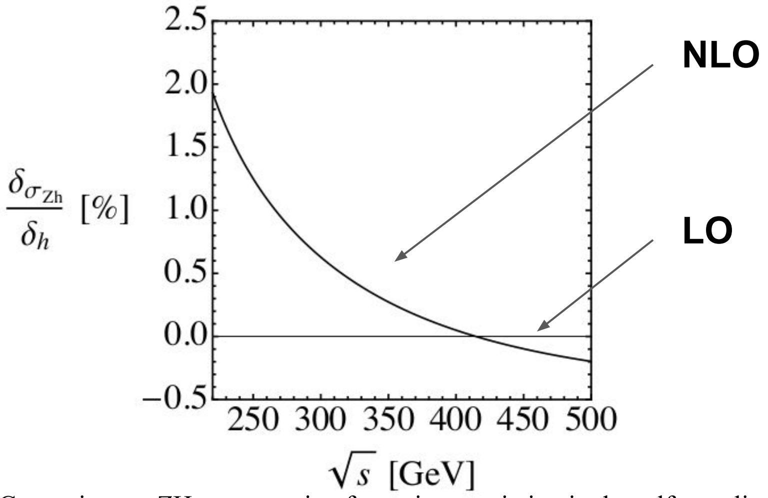
➢ **Cut used:**

- two leptons
- opposite sign
- one lepton required to be isolated
- cut on Z mass [86,96]
- cut Z momentum > 20 GeV

Thesis project
⇒ FCC indirect probe higgs self-coupling measurement



Next Leading Order vertex corrections of the ZH process

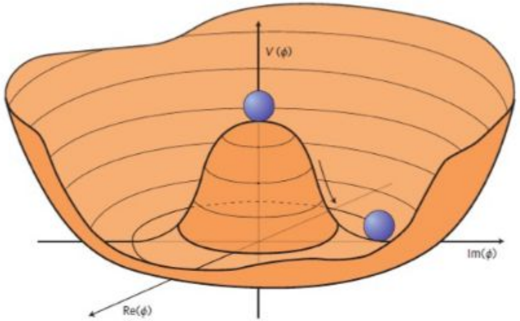


Corrections to ZH cross-section for a given variation in the self-coupling, δh , as a function of the centre-of-mass energy

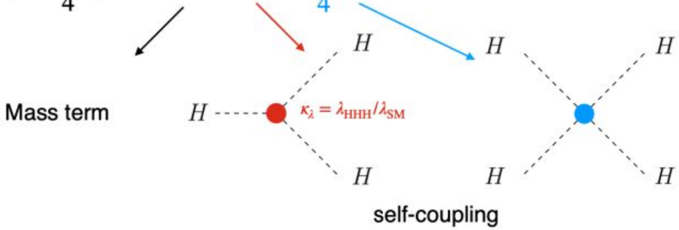
- As an extension of my **internship**, I will work on an **indirect** method to measure the **Higgs self-coupling** in the **FCC feasibility study**
- Using the same **Recoil mass** method and by considering **Next-to-leading order diagrams**, the curve gives the **impact** of the self-coupling diagrams on the cross-section as a function of the centre-of-mass energy relative to SM rate
- By comparing **240 & 365 GeV** centre-of-mass analyses we will be able to extract the **self-coupling parameter**
- Because the Z leptonic decay is **statistically limited**, we will consider **other Z decay channels** such as bb, cc quarks… and combine them

Back up slides: Higgs potential

- A scalar field, the Higgs field present throughout the universe, with a non-zero vacuum expectation value
- Fundamental matter particles acquire mass through their interaction with the Higgs field
- Measurement of λ is crucial to reconstruct the Higgs potential and therefore test the Higgs mechanism
- “Mexican” potential, vacuum expectation values leads to spontaneous symmetry breaking



$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \supset \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4$$



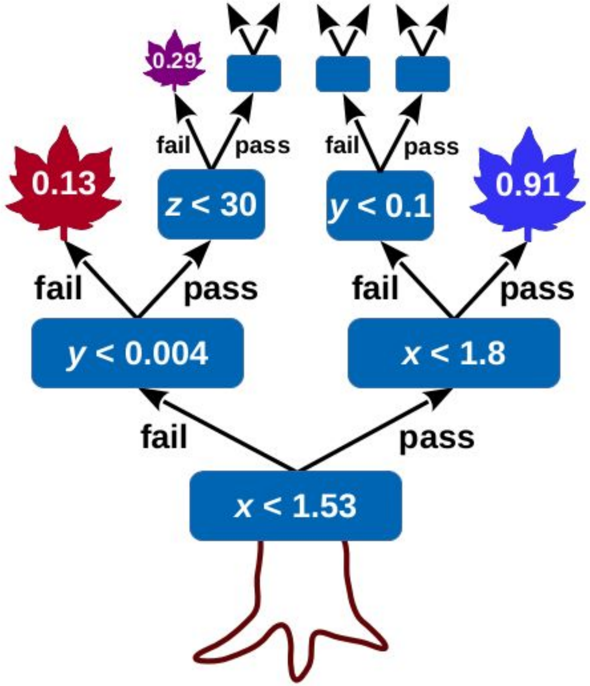
Back up slides: Future circular collider

- An Higgs factory, 1 Million events production at 240 GeV and 200,000 events at 365 GeV centre-of-mass. Expected precision on Higgs couplings to SM particles at the sub-percent level.
- FCC-ee will provide a first measurement of the Higgs self-coupling to ~30%
- Different center-of-mass energies: 91 GeV for Z, 160 GeV for WW, 240 GeV for Higgs and 365 GeV for top pairs
- The FCC-ee tunnel will be re-used for FCC-hh, proton-proton collisions at 100 TeV in the c-o-m.
- Study on Higgs properties, search for Dark matter, Electroweak, Top and Heavy Flavour physics.

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	FCC-$ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	**< 1.0**	**< 1.0**

Comparison of Higgs boson couplings expected from FCC-ee data and compared to those from HL-LHC

Back up slides: Boosted decision tree



Graphical representation of a decision tree. Blue rectangles are internal nodes with their associated splitting criterion; leaves are terminal nodes with their purity.

- Decision trees: it consists in extending a **simple cut-based analysis** by continuing to analyse events that **fail** a **particular criterion**. Many, if not most, events do not have all characteristics of either **signal or background**
- Tree boosting: Boosting is a method of **combining many weak learners** (trees) into a **strong classifier**. We are giving **weight** to trees relative to their **accuracy**.
- After each iteration each data sample is given a weight based on its **misclassification**. The more often a data sample is misclassified, the more **important** it becomes.

Back up slides: b-jet identification

➢ A jet is defined as a collimated spray of stable particles arising from the fragmentation and hadronisation of a parton(quark or gluon) after a collision.

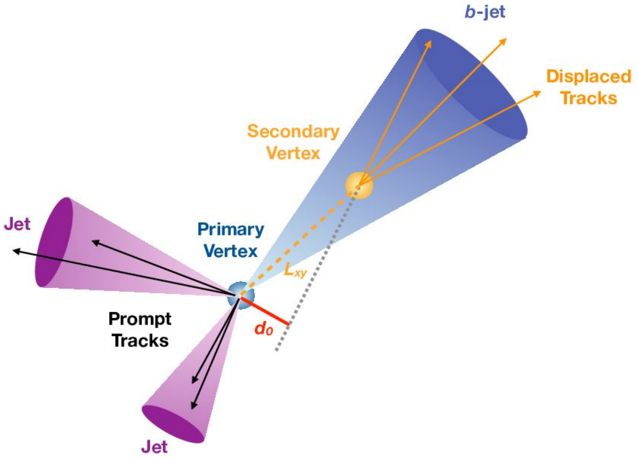
➢ **Goal**: **discriminate b-jets vs c-, light quark or gluon jets**

➢ Tracking information such as impact parameter or secondary/tertiary vertices

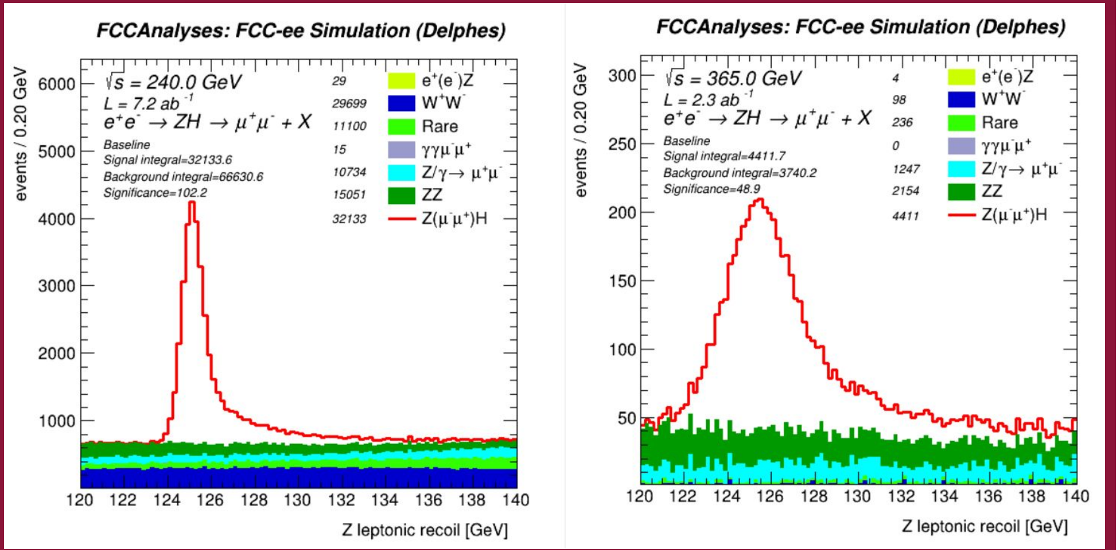
➢ Use of algorithm such as MV2 for boosted decision tree based and DL1 for deep neural network

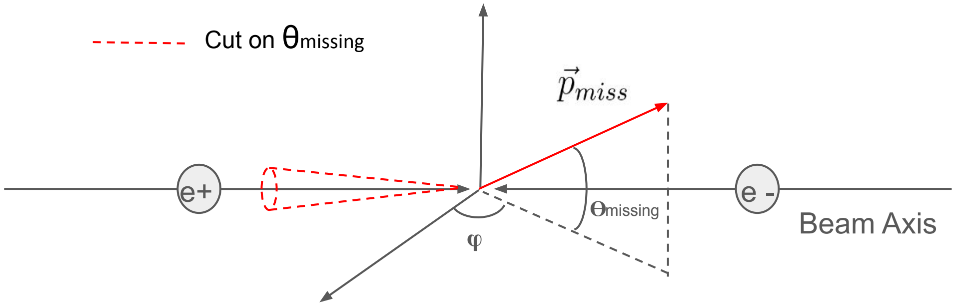
➢ Measurement of b-tagging efficiencies using transverse momentum

➢ Charged particles are governed by helicoidal trajectories due to the influence of the solenoidal magnetic field



Back up slides: Higgs mass analysis

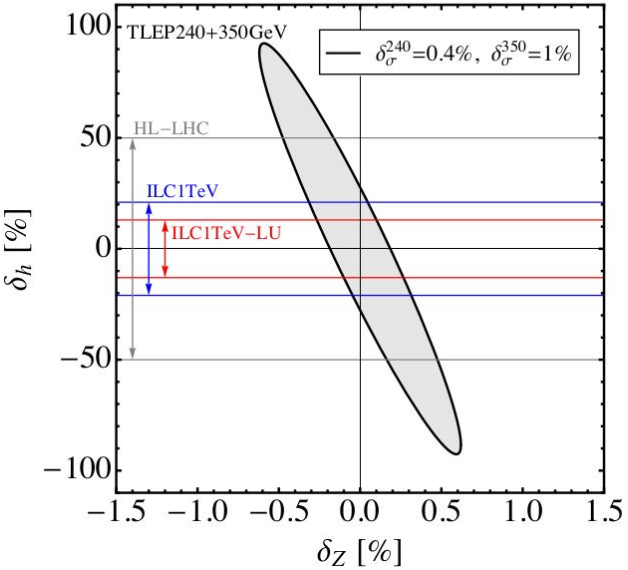




- The **missing momentum** is defined by the **negative vectorial sum** of the momenta of all reconstructed particles: $\vec{p}_{miss} = -\sum_{n_{part}} \vec{p}_{rec}$
- **θmissing** is the **polar angle** of the **missing momentum vector** with respect to the **beam axis**
- The requirement |cos θmissing| < **0.98** is used for the **mass analysis only,** which means that we are removing events mostly collinear to the beam axis
- This cut is used only for the **mass analysis**
- **Significance** (S/sqrt(B)) is **~49** at **365 GeV**, vs. **~102** at **240 GeV** for $\mu^+\mu^-$ and **~44 vs ~84** for e^+e^- channel

DEWYSPELAERE Kevin

Back up slides: Considering HZZ coupling



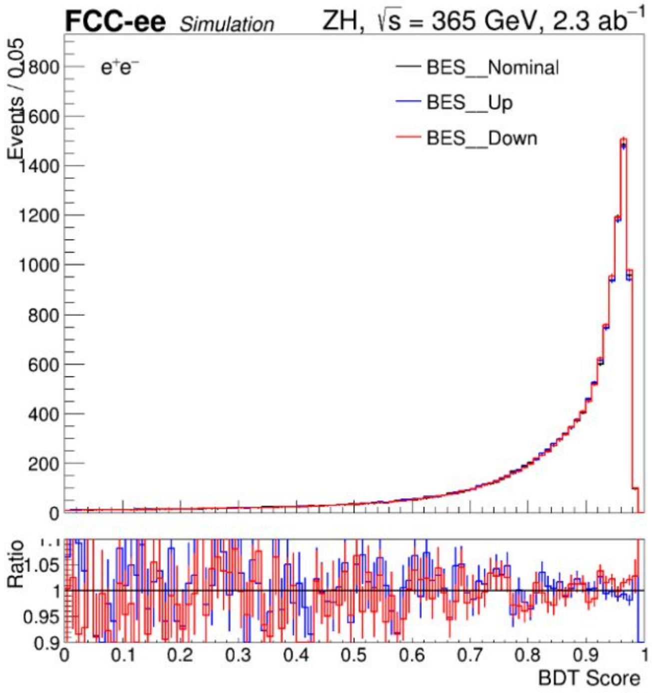
Indirect elliptic constraints possible plot for the two coupling parameters δh and δz

- We need to take in consideration the **HZZ coupling** parameter that is **linked** to the **Higgs self-coupling** parameter in this context
- In the case of a **ZH cross-section measurement** and by considering NLO diagrams, we can **constrain** a **linear combination** of the deviations of the two **couplings**:

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- Combinations of precision associated production measurements at different center of mass energies may be used to determine **ellipse-plot constraints** on the combined parameter space of **δZ** and **δh**

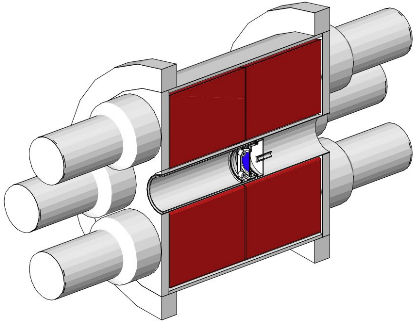
Back up slides: Systematic uncertainties

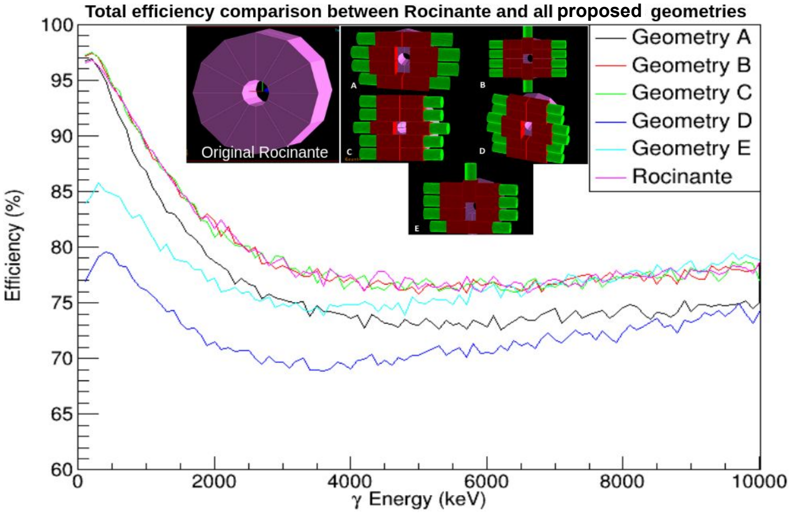


Effect of the beam energy spread uncertainty (±10 %) on the Z(e, e)H recoil mass distribution

- **Beam energy spread**: Uncertainty coming from the accelerator equipment, spread of the nominal gaussian distribution of the beam. 1% at 240 GeV and 10% at 365 GeV.
- **Centre-of-mass ($\sqrt{s}$)**: Uncertainty on the the centre-of-mass energy which is expected to be known at the 2 MeV level for 240 and 365 GeV
- **Lepton momentum scale**: Uncertainty on the momentum of leptons measured assumed to be 10^{-5} for 240 and 365 GeV

Back up slides: The Rocinante detector





Total efficiency comparison between Rocinante and all proposed geometries

- **Rocinante** detector made of **12** crystals of **barium fluoride** (BaF_2)
- **Improve** the **geometry** by adding light protection **teflon** and **aluminium cover**
- Include **Lanthanum Bromide** ($LaBr_3$) more efficient modules
- I used **Geant4** simulations to study 5 geometries to keep the gamma detection efficiency as close as possible to the original
- We found that the **C geometry** was the best because it retained a **similar efficiency** to the **original** and did not have the **geometric drawbacks** of the others.
- Finally I also aimed at finding a **new geometry** in order to **widen the hole** without cutting crystals

Uncertainty breakdown on cross-section measurement at √s=240 & 365 GeV