Optimal Collision Energy for Higgs Precision Measurements at the ILC250

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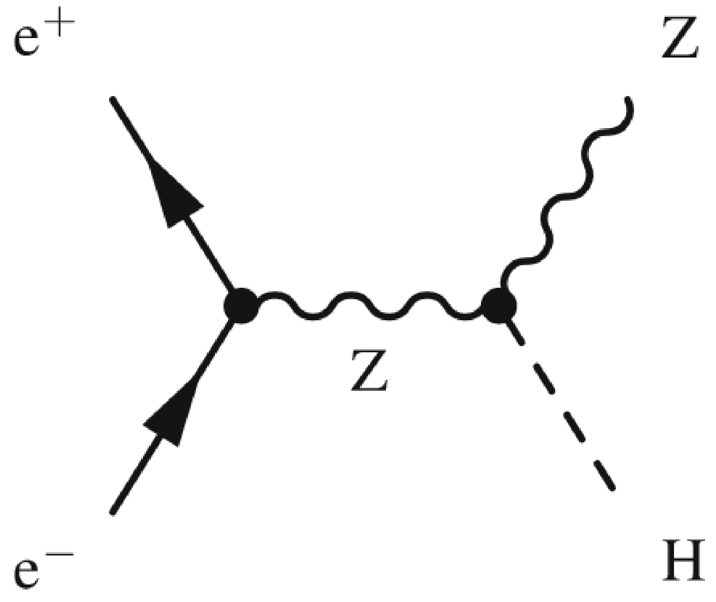
Motivation

The aim of this research is to define the optimal energies for the **I**nternational **L**inear **C**ollider to work at, so as to have the best accuracy on:

- Cross-Section (to be studied in a **model independent** approach) of the process $e^+e^- \to ZH$ (mostly Higgsstrahlung) σ_{ZH}
- Anomalous Couplings



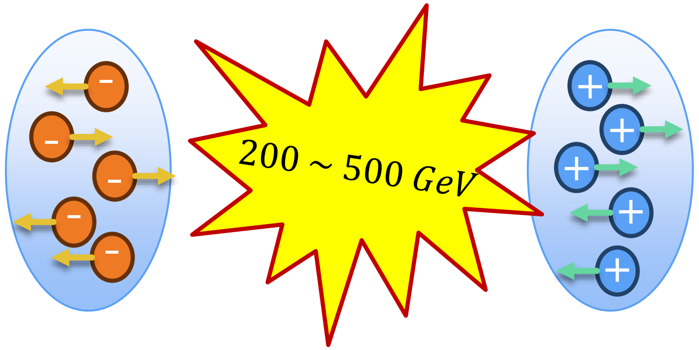
What is ILC?

- **I**nternational **L**inear **C**ollider
- Works at a **luminosity** of 2000 fb^{-1}
- **Lepton** collider exploiting e^+e^- collisions in 2 different beam configurations

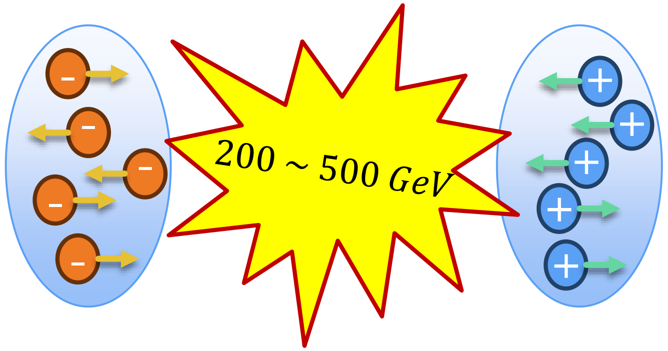
$$Polarization: \quad P = \frac{N_R - N_L}{N_R + N_L} \Rightarrow N_L = \frac{1-P}{2}, N_R = \frac{1+P}{2}$$

$$Luminosity: L = \frac{1}{\sigma}\frac{dN}{dt} \quad ; \quad N = \int \sigma \cdot L \, dt$$

$(P_{e^-}, P_{e^+}) = (-0.8, 0.3)$



$(P_{e^-}, P_{e^+}) = (0.8, -0.3)$

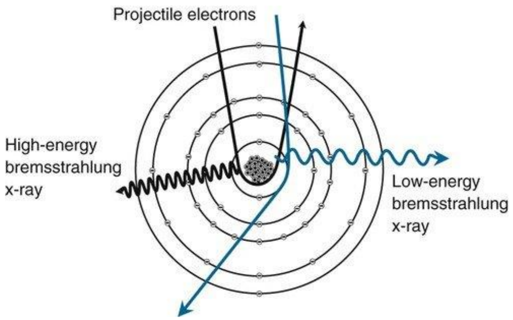


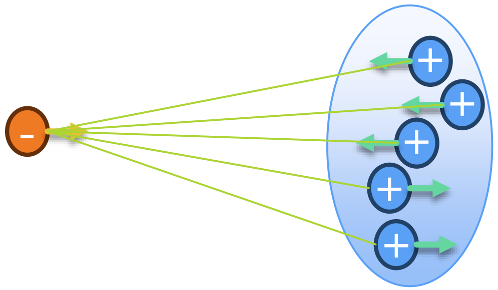
Radiative Energy Loss in linear colliders

- As the beams approach the collision point, they undergo some physical phenomena that decrease their energy at the moment of the collision. They're typically emitted preferentially in the longitudinal direction.

Soft Interactions

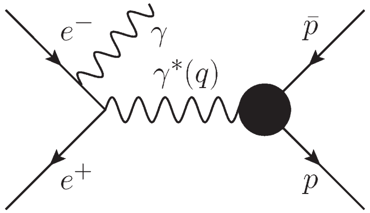
- ❑ Bremsstrahlung: arising from the interaction of the beams with the detector nuclei
- ❑ Beamstrahlung: arising from the interaction of one of the beams with the other beam



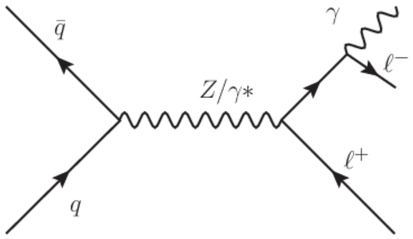


Hard Interactions

- ❑ **I**nitial **S**tate **R**adiation ISR



- ❑ **F**inal **S**tate **R**adiation FSR



Anomalous Couplings: Introduction

- We want to study the Beyond the Standard Model (BSM) behaviour of the ZZH vertex
- To do so, we'll use the framework of **Standard Model Effective Field Theory** (SMEFT)
- Anomalous couplings strongly depend on momenta and angular distribution

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i,d>4} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}^{(d_i)}$$

Λ – new physics scale

$\mathcal{O}^{(d_i)}$ – EFT operator of dimension d_i

c_i – Wilson coefficient

$$\mathcal{L}_{ZZH} = M_Z^2 \left(\underbrace{\frac{1}{v} + \frac{a_Z}{\Lambda}}_{} \right) Z_\mu Z^\mu h + \frac{b_Z}{2\Lambda} Z_{\mu\nu} Z^{\mu\nu} h + \frac{\tilde{b}_Z}{2\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu} h$$

Only affects scale

Affect shape as well

$$Z_{\mu\nu} = \underbrace{\partial_\mu}_{p_\mu} Z_\nu - \underbrace{\partial_\nu}_{p_\nu} Z_\mu \qquad \tilde{Z}_{\mu\nu} = \epsilon_{\mu\nu\sigma\rho} Z^{\sigma\rho}$$

Anomalous Couplings: Methodology

- We'll study anomalous coupling by building a chi-squared function and looking at its contour at 1 for three different energy points
- **Key idea**: constructing a linear combination of the three chi-squared and studying it to determine how to get the best measurement

$$\chi^2 = \underbrace{\sum_{i=1}^{n}\left[\frac{N_{SM}\varepsilon_i \frac{1}{\sigma_{SM}}\frac{d\sigma_{SM}}{dx}(x_i) - N_{BSM}\varepsilon_i \frac{1}{\sigma_{BSM}}\frac{d\sigma_{BSM}}{dx}(x_i;a,b)}{\Delta\sigma(x_i)}\right]^2}_{\chi^2_{shape}} + \underbrace{\left[\frac{\sigma_{SM} - \sigma_{BSM}(a,b)}{\delta\sigma\cdot\sigma_{SM}}\right]^2}_{\chi^2_{cross-section}}$$

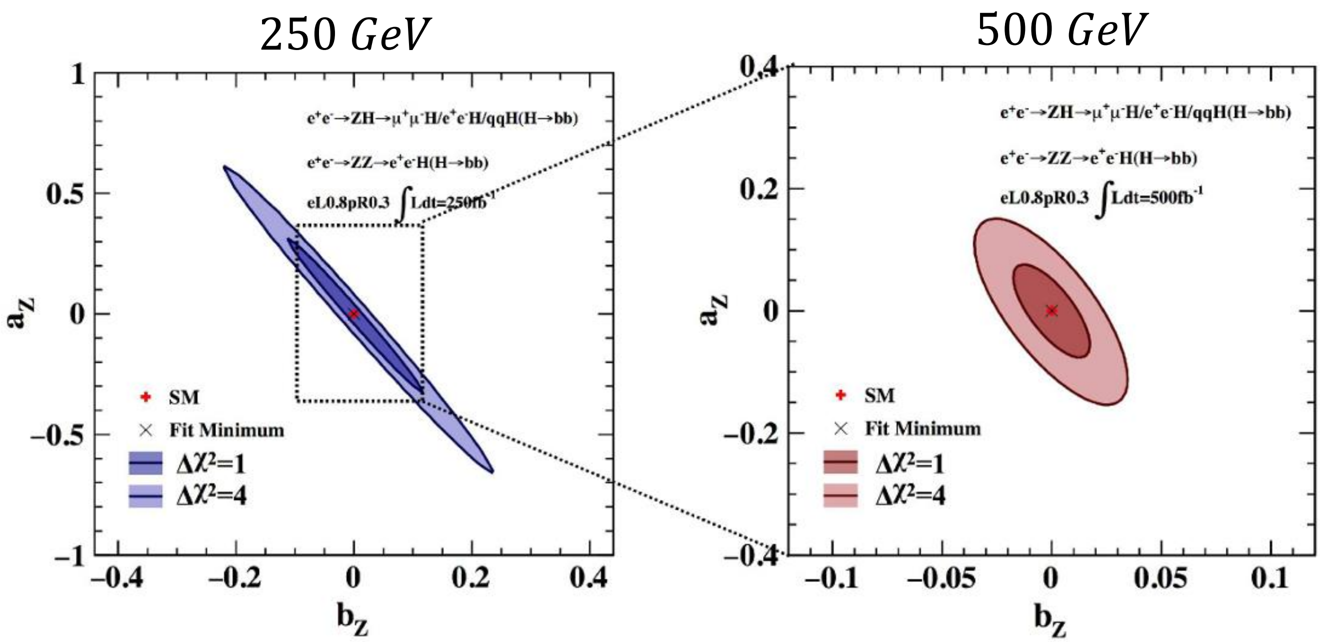
$\chi^2 = 1$ gives the 1σ bound!!!

$$\chi^2_{2000\,fb^{-1}} = c_{240}\chi^2_{240} + c_{250}\chi^2_{250} + c_{260}\chi^2_{260}$$

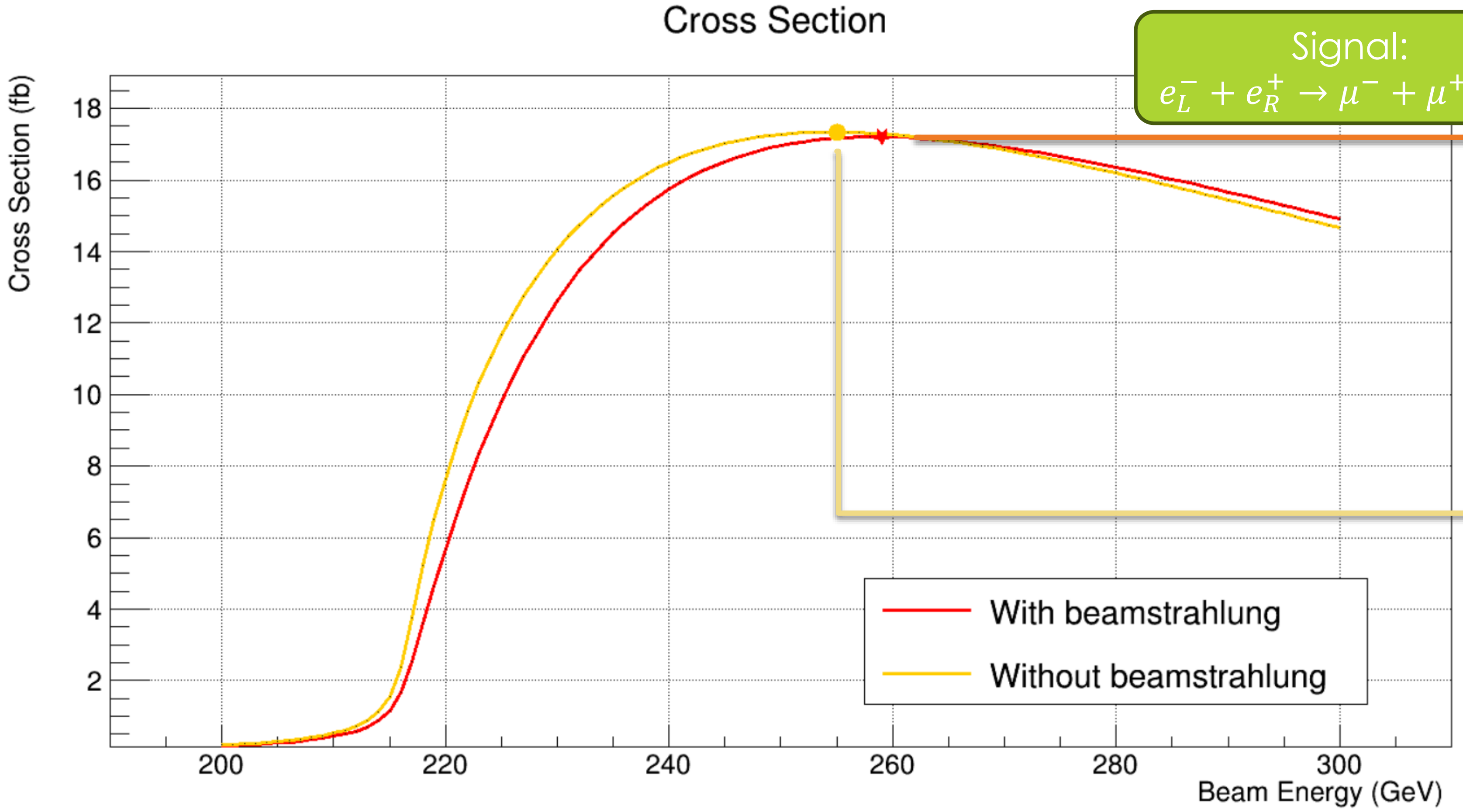
Physical meaning of c_E
fraction of total luminosity to be accumulated at energy E

Anomalous Couplings: Methodology

- Major issue: **Correlation**
- Given the linear combination $\chi_{2000\ fb}$, we will look a the $\chi_{2000\ fb} = 1$ contour and try to minimize: *correlation*, *a uncertainty*, *b uncertainty* and *area*



Energy dependency of Cross-Section



Signal:
$e_L^- + e_R^+ \rightarrow \mu^- + \mu^+ + H$

259 GeV
1.721E+01

255 GeV 1.734E+01 fb

Analysis Framework

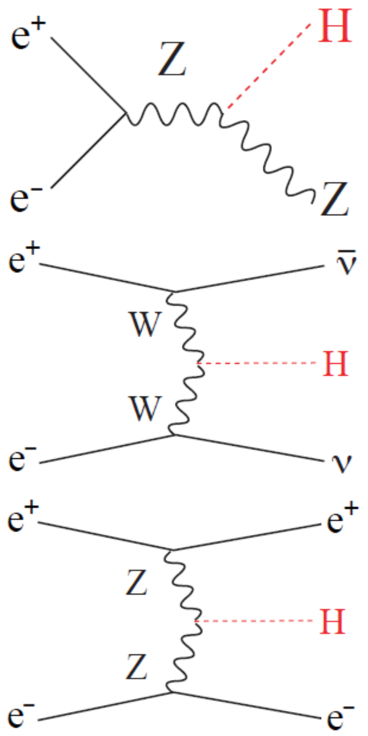
Signal:
$e_L^- + e_R^+ \rightarrow \mu^- + \mu^+ + H$

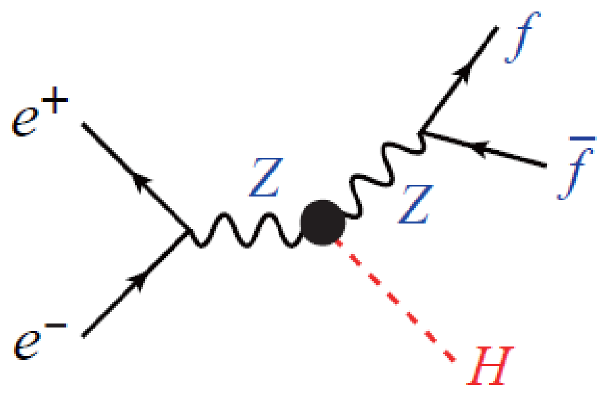
- The simulation and reconstruction tools are the ones provided from **ILCSoft**
- The Monte Carlo samples of the different process have been generated through **WHIZARD**
- The model for the parton shower and hadronization is taken from **PYTHIA**
- Following the generation, the events are passed through an **ILD** (**I**nternational **L**arge **D**etector) simulation based on **GEANT4**
- The event reconstruction is performed using the **Marlin** framework
- The **PandoraPFA** algorithm is implemented for calorimeter clustering and the analysis of tracks through a particle flow approach
- The energy we've studied is 250GeV (we plan to analyse 240, 250 GeV as well)
- We have assumed a luminosity of $2000 fb^{-1}$
- The beam configuration taken into account is $(P_{e^-}, P_{e^+}) = (-0.8, 0.3)$

The recoil mass technique

Signal:
$e_L^- + e_R^+ \rightarrow \mu^- + \mu^+ + H$

- Without assuming any specific decays for the Higgs, the recoil mass technique allows us to find with great accuracy the Higgs mass





$$M_{rec}^2 = (\sqrt{s} - E_{l^+l^-})^2 - |\vec{p}_{l^-} + \vec{p}_{l^+}|^2$$

Lepton selection

μ ID	e ID
$p_{\mathrm{track}} > 5 \quad \mathrm{GeV}$	$p_{\mathrm{track}} > 5 \quad \mathrm{GeV}$
$E_{\mathrm{CAL,tot}}/p_{\mathrm{track}} < 0.3$	$0.5 < E_{\mathrm{CAL,tot}}/p_{\mathrm{track}} < 1.3$
$E_{\mathrm{yoke}} < 1.2 \quad \mathrm{GeV}$	$E_{\mathrm{ECAL}}/E_{\mathrm{CAL,tot}} > 0.9$
$\lvert d_0/\delta d_0 \rvert < 5$	$\lvert d_0/\delta d_0 \rvert < 50$
$\lvert z_0/\delta z_0 \rvert < 5$	$\lvert z_0/\delta z_0 \rvert < 5$

- After several pairs are selected, an MVA-driven algorithm is used to make sure these leptons do not come from the Higgs decay. The principle of this algorithm is making sure that the invariant mass of the di-lepton system is as close as possible to the Z boson's mass.

Cross-Section Measurement

Signal:
$e_L^- + e_R^+ \rightarrow \mu^- + \mu^+ + H$

- After finding the best lepton pair, the background needs to be suppressed by imposing some cuts to the measured quantities. Our general rule of thumb for finding a good cut is to boost the induced **significance**

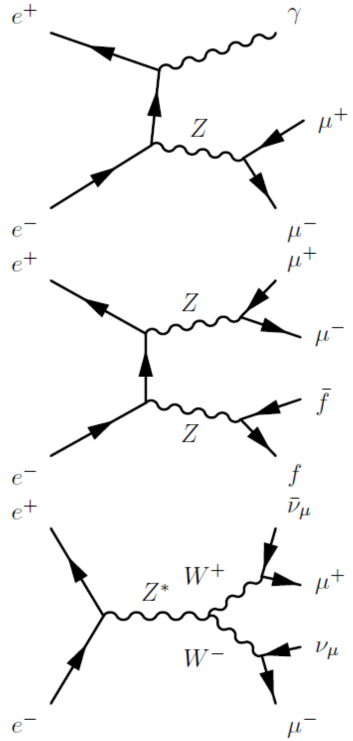
Due to the assumption of Poissonian distribution:

$$\frac{\Delta\sigma}{\bar{\sigma}} = \frac{1}{\sum_{i=0}^{nbin} \mathcal{S}_i^2}$$

$$\sigma_{ZH} = \frac{N_S}{BR(Z \longrightarrow l^+ l^-)\varepsilon_S L}$$

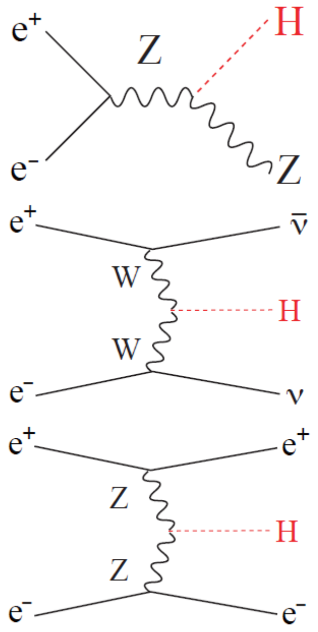
$$signficance:\ \mathcal{S} = \frac{S}{\sqrt{S+B}} \sim \frac{\bar{\sigma}}{\Delta\sigma}$$

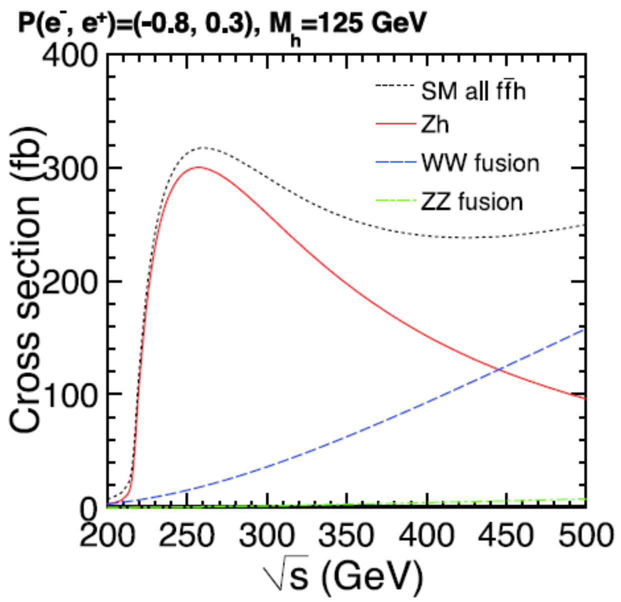
$$efficiency:\ \varepsilon = \frac{N_{after\ cut}}{N_{before\ cut}}$$

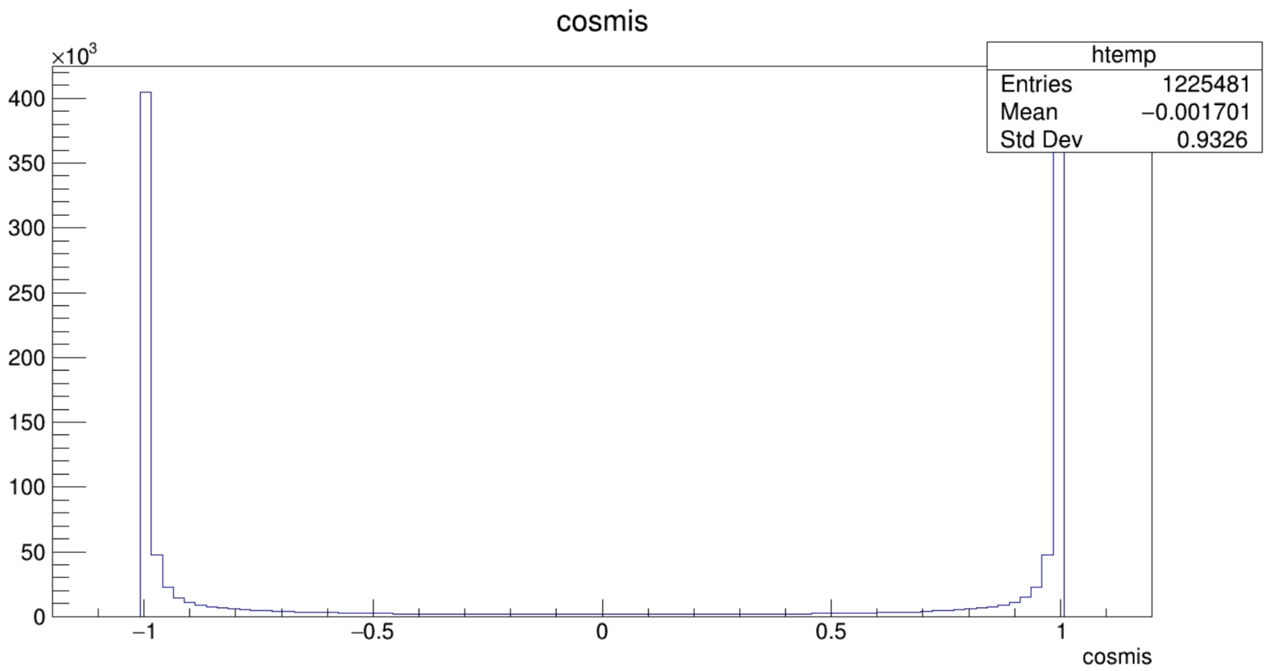


Aftermaths of energy loss: Radiative Return

- Depending on how much energy each particle loses, the probability of a process taking place gets higher or lower. Such a phenomenon is called **radiative return**. Let's look at an example

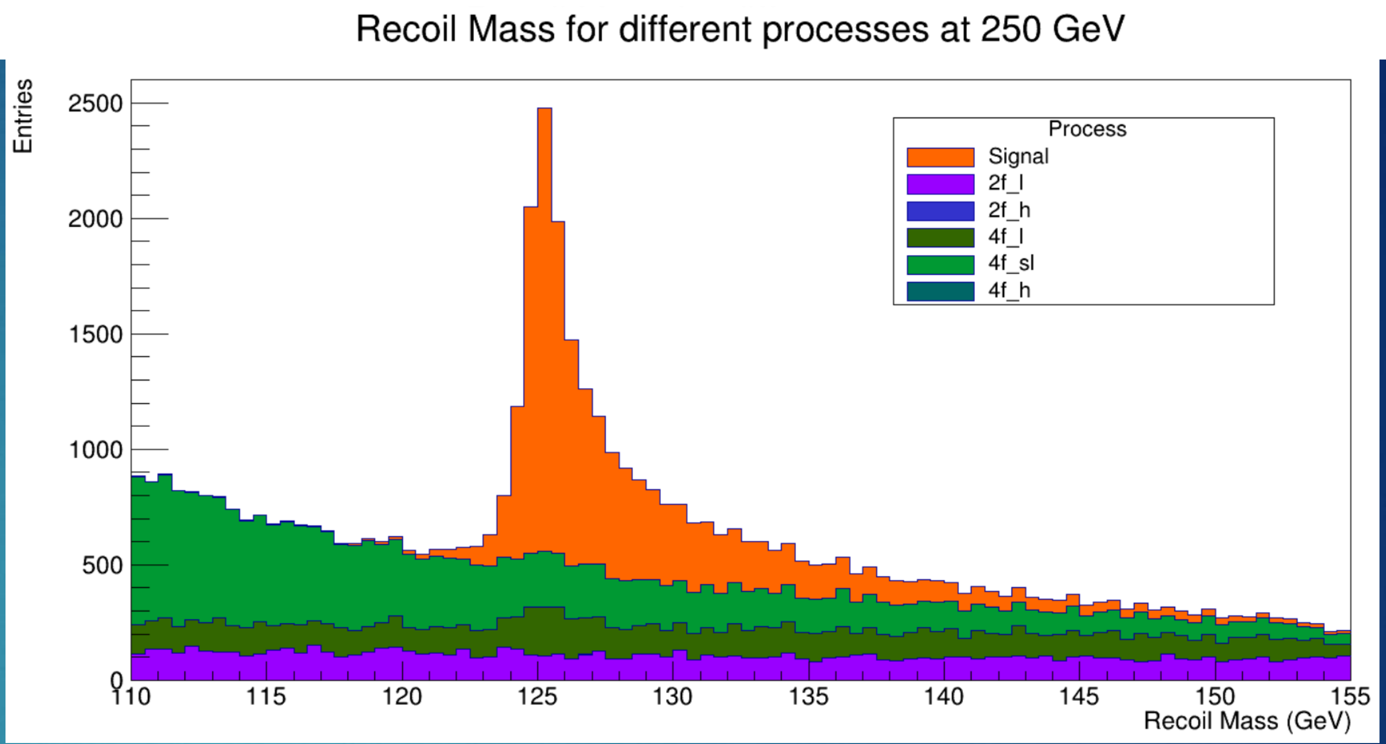






SM Analysis

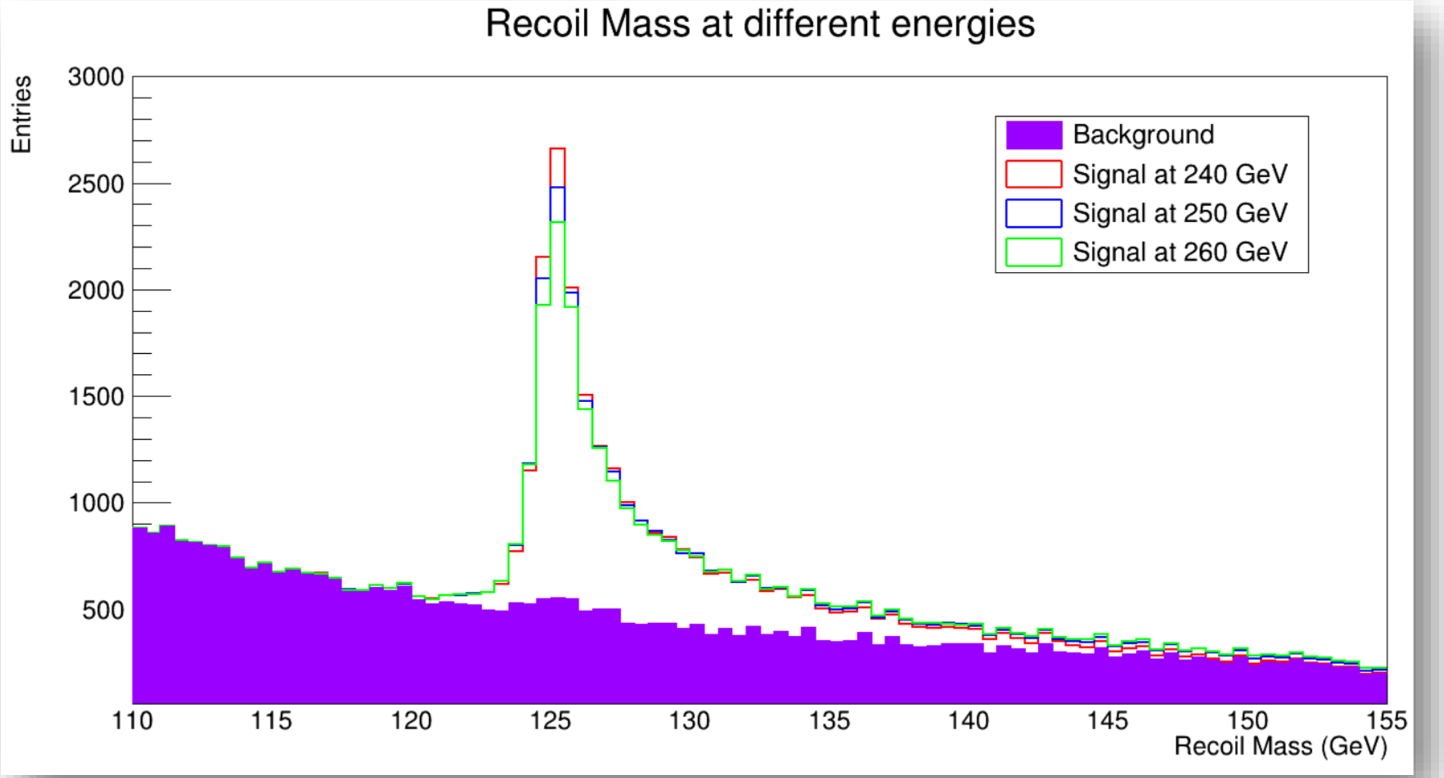
$$\frac{\Delta\sigma}{\bar{\sigma}} \cong 1.12\%$$

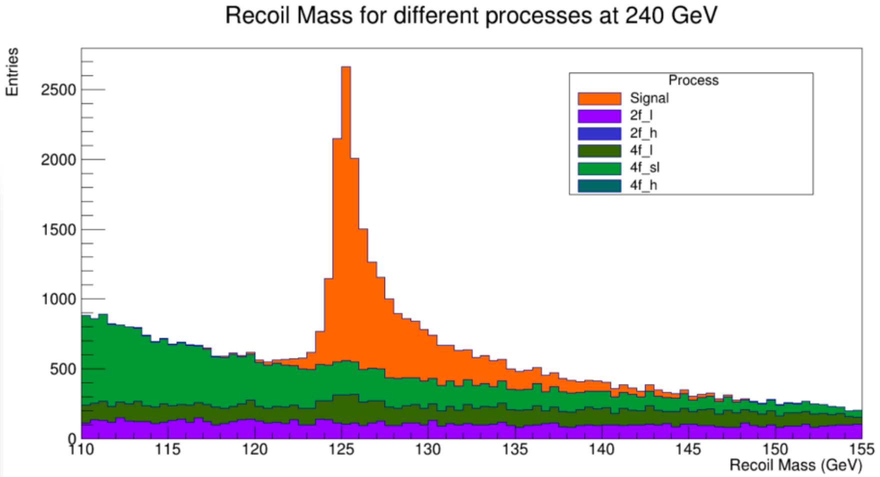


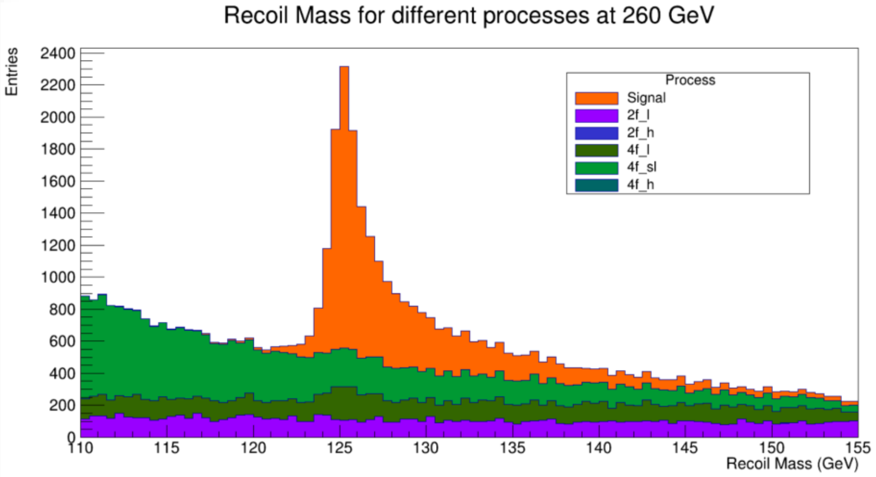
Cut	Signal	Signal Efficiency	Signal Significance	2f_l	2f_h	4f_l	4f_sl	4f_h	Total Bkg
No cut	20616	1	9.4	$2.6 \cdot 10^7$	$1.55 \cdot 10^8$	$2.08 \cdot 10^7$	$3.83 \cdot 10^7$	$3.36 \cdot 10^7$	$2.73 \cdot 10^8$
Precuts	19429	94.2%	9.2	$1.46 \cdot 10^6$	5338	$2.18 \cdot 10^6$	824257	271	$4.47 \cdot 10^6$
$l^+l^- = \mu^+\mu^-$	19419	94.2%	13.9	$1.41 \cdot 10^6$	43.21	325287	209695	2.15	$1.95 \cdot 10^6$
$m_Z \in (84,100)$	17425	84.5%	15.5	$1.02 \cdot 10^6$	8.25	76712	157181	0.72	$1.25 \cdot 10^6$
$E_{vis} > 10$	17418	84.5%	16.7	841930	8.25	68265	157181	0.72	$1.07 \cdot 10^6$
$\lvert\cos(\vartheta_{mis})\rvert < 0.975$	15672	76%	23	290219	5.75	35940	123119	0.48	449284
$m_{recoil} \in (110,155)$	15579	75.5%	66	96.2	1.45	10493	19954	0.48	40066

Recoil Mass at different energies

- Background changes are assumed negligible
- Same cuts are applied

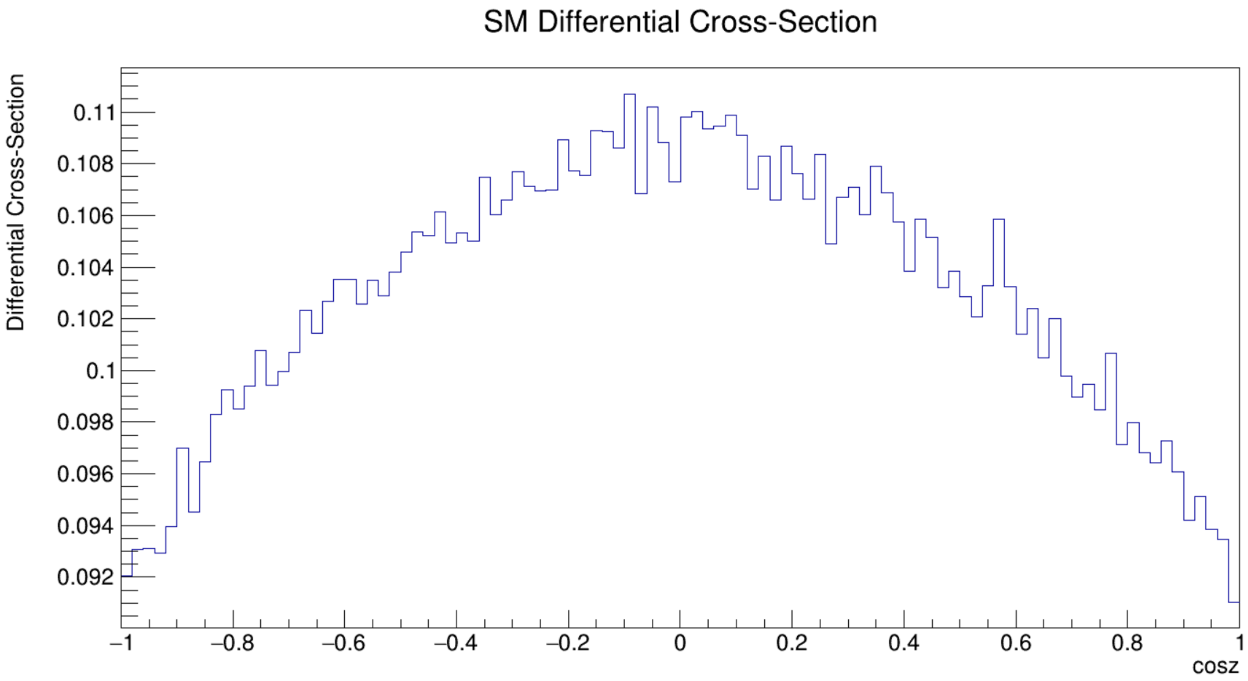


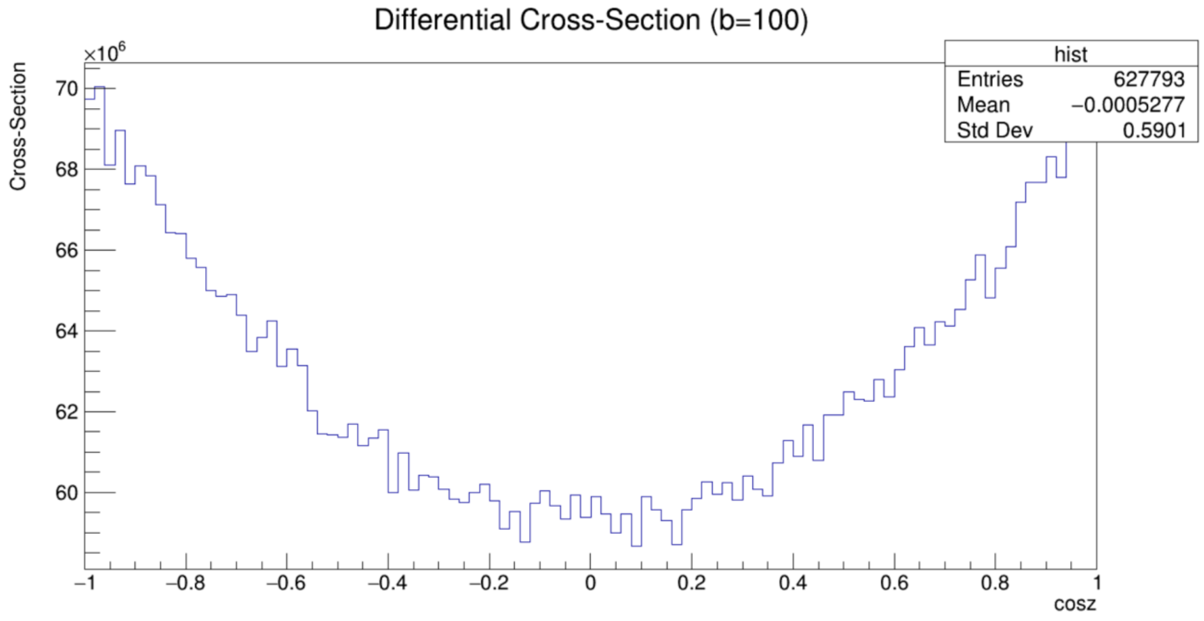




SM and BSM angular distributions

- As seen earlier, shape is one of the best parameters to determine the structure of BSM physics

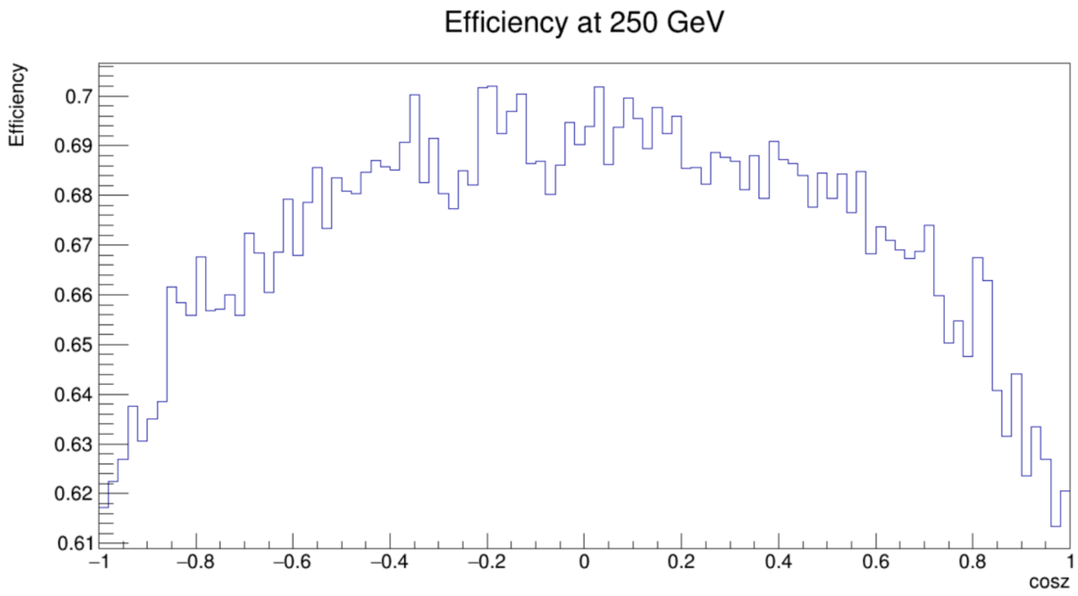


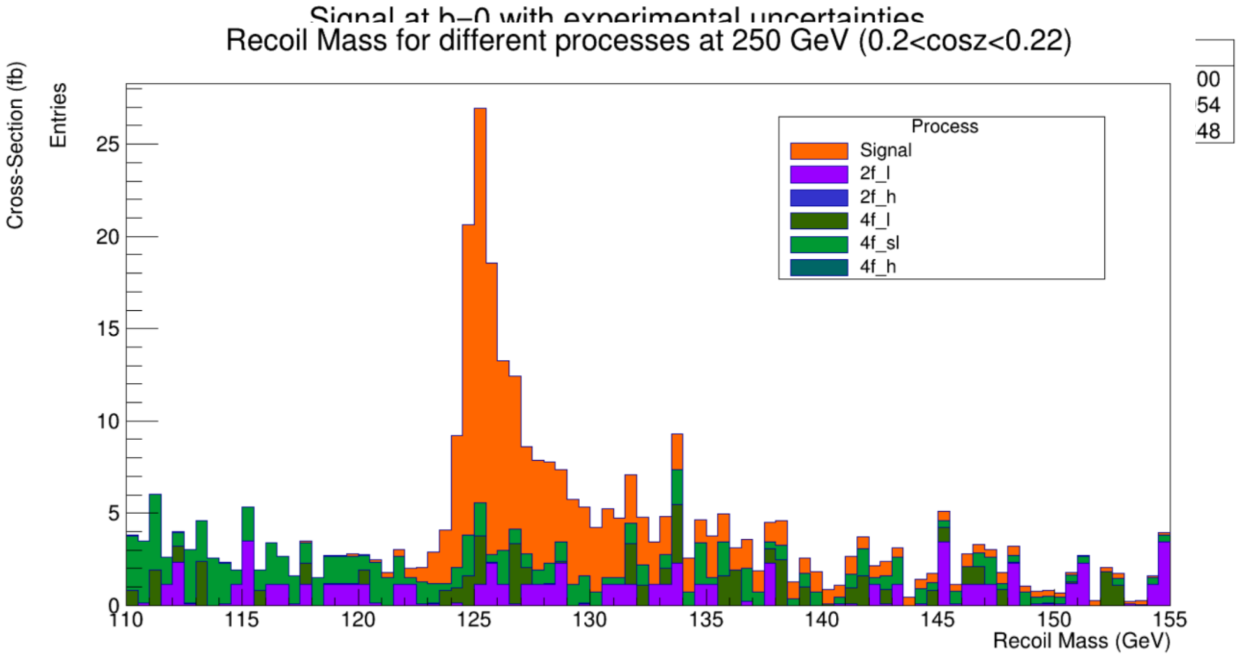


Uncertainties and efficiencies

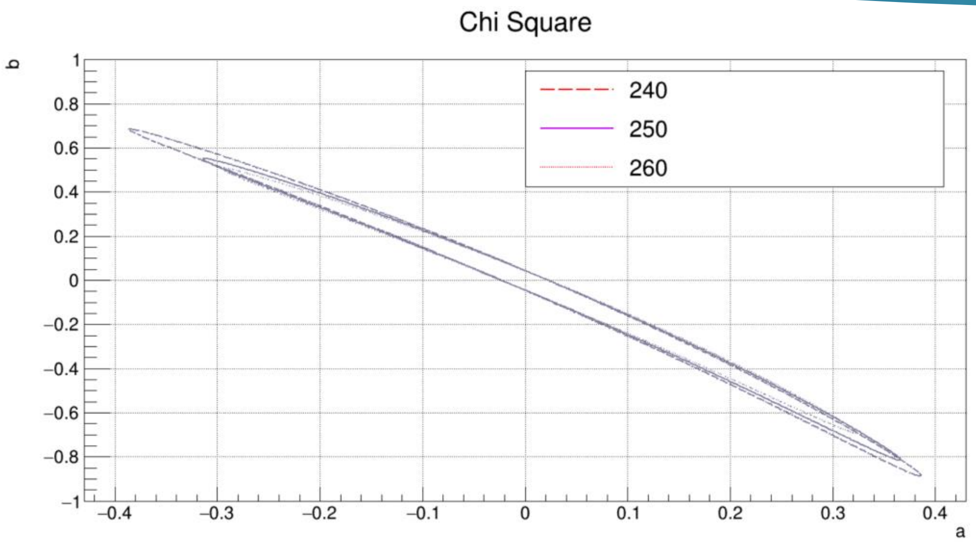
$$\frac{\Delta\sigma_i}{\sigma_i} = \frac{1}{\sqrt{\sum_j {s_{ij}}^2}}$$

- To calculate bin by bin uncertainties we have looked at the recoil mass distribution for each single bin evaluated the uncertainty of the resulting histogram





Anomalous coupling study



$$\chi^2_{2000\ fb^{-1}} = c_{240}\chi^2_{240} + c_{250}\chi^2_{250} + c_{260}\chi^2_{260}$$

$$\chi^2 = \sum_{i=1}^{n} [\frac{N_{SM}\varepsilon_i \frac{1}{\sigma_{SM}} \frac{d\sigma_{SM}}{dx}(x_i) - N_{BSM}\varepsilon_i \frac{1}{\sigma_{BSM}} \frac{d\sigma_{BSM}}{dx}(x_i; a, b)}{\Delta\sigma(x_i)}]^2 + [\frac{\sigma_{SM} - \sigma_{BSM}(a,b)}{\delta\sigma \cdot \sigma_{SM}}]^2$$

	χ^2_{240}	χ^2_{250}	χ^2_{260}	**Best achieved**	$(c_{240}, c_{250}, c_{260})$
Correlation	-0.9942	-0.9937	-0.9929	-0.9929	(0,0,1)
$2\Delta a$	0.775	0.681	0.623	0.622	(0.1,0,0.9)
$2\Delta b$	1.57	1.37	1.21	1.21	(0,0,1)
Area	0.057832	0.04923	0.04413	0.04379	(0.1,0.1,0.8)

Conclusions

Summary

In the course of this presentation we have:

- Carried on a recoil mass analysis at 250 GeV
- Extended the analysis to 240, 260 GeV
- Searched for the optimal energy combination to study anomalous couplings in the ZZH vertex

To-do list

- Double-check using other tools, such as Tminuit
- Implement another energy point at 300 GeV

Thank you for the attention!