Higgs Physics In Future Colliders

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Content

The Standard Model Content

- Fermions
- Bosons

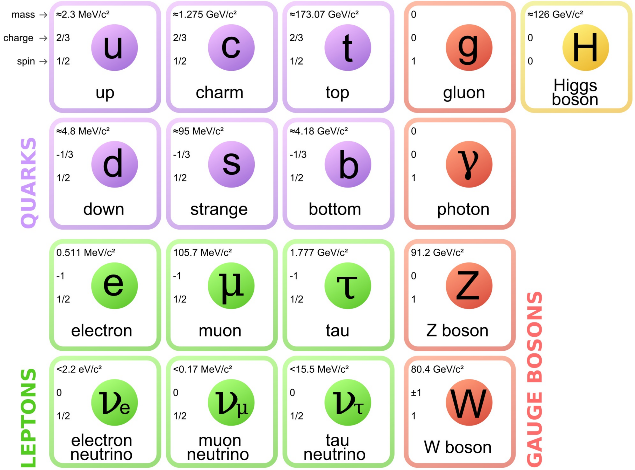


Figure: The standard model

The Higgs Boson

- It is a massive boson that was theorized by Peter Higgs in 1964 to give masses to the W and Z bosons. It was first discovered by CERN at the LHC in 2012 with a mass of 125 GeV.
- From the content of the standard modern, we know that they have masses of 80.4GeV/c^2 and 91.2GeV/c^2 respectively. We need our Lagrangian density to stay gauge invariant, thus we can't have the following term : $\frac{1}{8\pi}\left(\frac{mc}{\hbar}\right)^2 A^\mu A_\mu$.
- As a result, we can't add the mass term by hand. Therefore, we had to have a mechanismin which gives the W and Z masses and also not spoil the gauge invariant.

The Higgs Boson

- The theoretical physicists Robert Brout, François Englert and Peter Higgs made a proposal to give the particles mass while staying gauge invariant. The proposal was the Brout-Englert-Higgs mechanism which gives a mass to the W and Z when they interact with an invisible field called the Higgs field

Production mechanisms of the Higgs boson

- The Higgs production has many channels, but we are interested in the channels related to pp hadron colliders as we will work with the large hadron collider (LHC) and the future circular collider (FCC-hh). There are four main channels ordered from the most dominant to the least dominant:

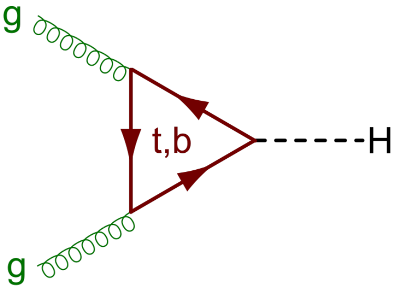


Figure: The production channel of the gluon fusion

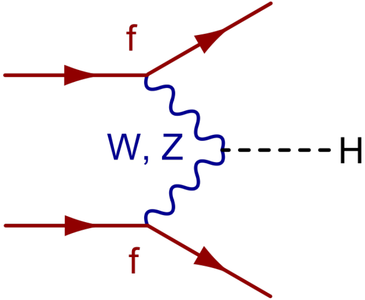


Figure: The production channel of the vector boson fusion

Production mechanisms of the Higgs boson

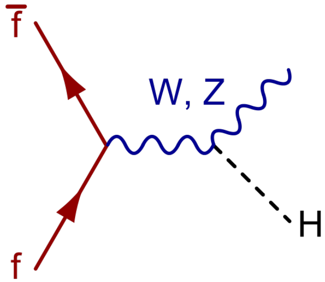


Figure: The production channel of Higgs Strahlungn

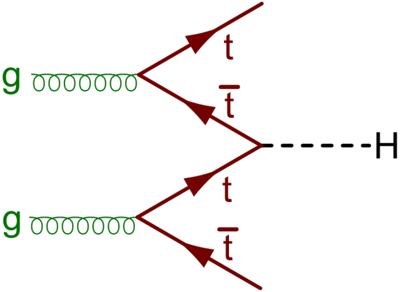


Figure: The production channel of Top Fusion

The decay channel used for the Higgs

- The Higgs bosons decay into a pair of fermions or bosons. The Higgs boson is estimated to have a mass of 125 GeV which is the second most highest particle mass ever after the top quark. Thus, it decays fast, with a decay time of 1.6×10^{-22}s.
- Therefore, there is no experimental technology to detect the Higgs before its decay. Thus, we have to study the decay channels in order to have an insight into whether a Higgs boson is produced or not. In this thesis, we will focus on the Higgs decay into two photon .

Pseudorapidity

- It describes the angle of the produced particles relative to the beam.

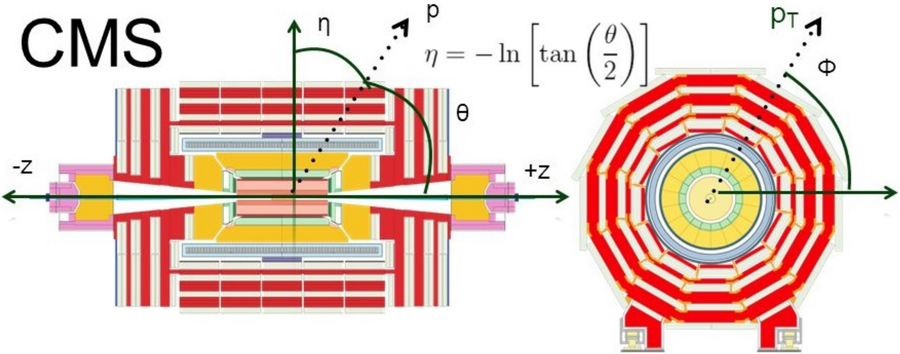


Figure: Pseudorapidity in CMS detector

Pseudorapidity

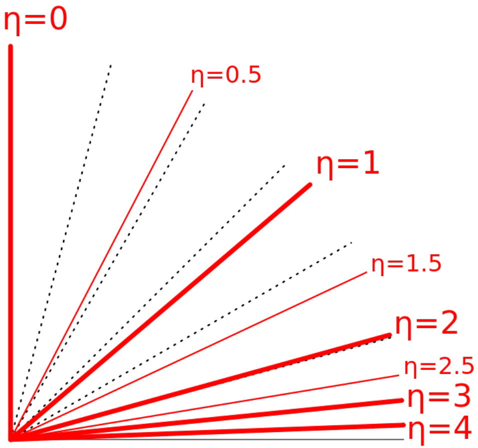


Figure: Pseudorapidity

Coordinate System

- The ϕ angle is the normal azimuthal angle. Here, it is the angle that is made with the x-axis.

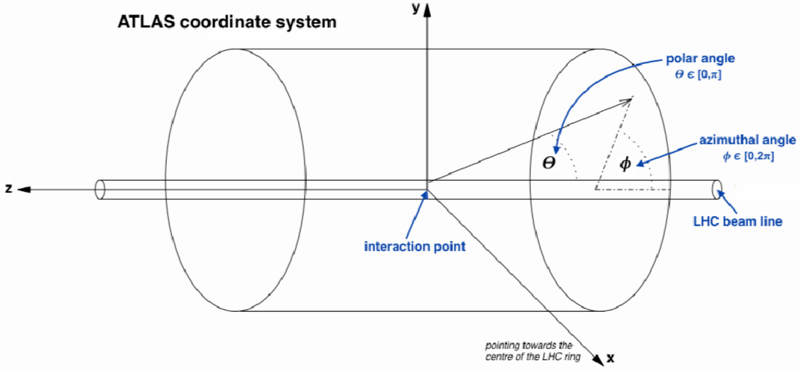


Figure: Coordinates used in ATLAS

Coordinate System

- In our system we used a four-vector called Tlorentz vector:

$$p^{\mu} = \begin{pmatrix} p_T \\ \eta \\ \phi \\ M \end{pmatrix}$$

- p_T is the transverse momentum, which is the momentum perpendicular to the direction of the beam.
- M is the invariant mass estimated by:

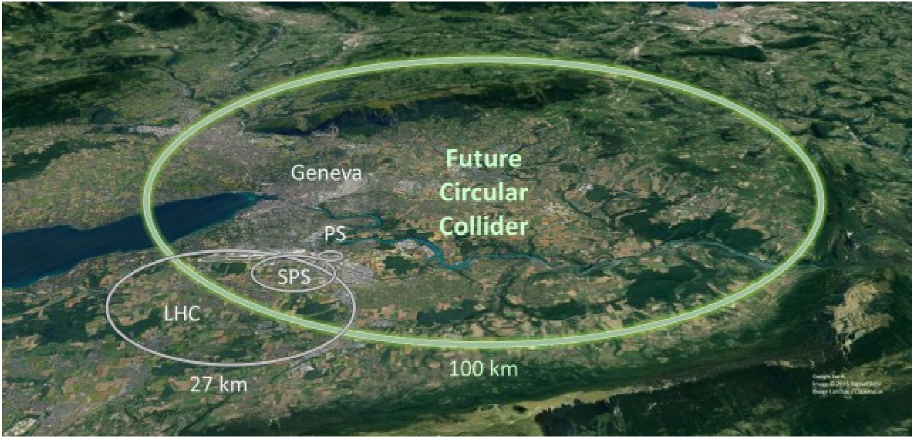
$$M = \sqrt{E^2 - p^2} \quad (c = 1)$$

The Large Hadron Collider (LHC)

- The LHC is the largest particle collider that has ever been built in the world. The European Organization for Nuclear Research (CERN) has built it between 1998 and 2008.
- 27 km circumference.
- $\sqrt{s} = 14$ TeV

The Future Circular Collider (FCC)

- The FCC is a proposed collider for the future by CERN
- 100 km circumference
- $\sqrt{s} = 100$ TeV
- Luminosity with more than 10 times the LHC



The Future Circular Collider (FCC)

The FCC has 3 types of colliders:

- electron/positron collider (FCC-ee): it is a lepton collider with energies ranging from (90 to 350) GeV.
- High-Energy LHC: it will be in the same tunnel of the LHC, but it will have stronger dipole magnets to increase the center of mass energy by a factor of two (27 TeV). Also, it will provide 3 times the luminosity provided by the high luminosity LHC.
- FCC-hh: it is a hadron collider (proton proton collider) with center of mass energy of 100 TeV. In our thesis, we will work with the FCC-hh to get results for the Higgs mass. Note: in the rest of the thesis, I will use FCC to indicate the FCC-hh.

Methodology for Data Generation, Simulation, and Analysis

- The goal is to simulate the pp collisions at the LHC at $\sqrt{s} = 14$ TeV, and the FCC at center of mass-energy $\sqrt{s} = 100$ TeV. The goal of the collision is to produce the Higgs Boson which will be detected from its decay in the two photons channel.

$$pp \rightarrow h \rightarrow \gamma\gamma$$

- The simulation will be done using luminosity of 300 fb^{-1} for the LHC, while it will be 3000 fb^{-1} for the FCC.

The Technical Tools

MadGraph

- MadGraph simulates the pp collision and generates the events.
- The frame-work provides a strong tool for the generation of hard events, and computations of the cross-section.
- The MadGraph has integrated tools which can be installed and run through MadGraph

Pythia8

- Used for Hadronization and Showering
- Pythia does the job of hadronization, Confining the resulting quarks and gluons to their hadrons. Pythia is the event generator for the showering by simulating the final and initial states of the radiation.

Delphes

Delphes is a program used to simulate the detector.

The Technical Tools

ROOT CERN

Delphes will create an output of ROOT file. We will then edit it and write the C++ code for analyzing the data and creating the histograms.

```
student@eslam:~$ root
   ------------------------------------------------------------------
  | Welcome to ROOT 6.18/04                        https://root.cern |
  |                               (c) 1995-2019, The ROOT Team |
  | Built for linuxx8664gcc on Jan 04 2020, 00:37:25               |
  | From tags/v6-18-04@v6-18-04                                     |
  | Try '.help', '.demo', '.license', '.credits', '.quit'/'.q'    |
   ------------------------------------------------------------------

root [0]
```

Figure: ROOT Open Window

Steps for Events Generation and Simulation

- Running MadGraph
- Generation of the event
- Setting the parameters for 14 TeV and 100 TeV
- The ROOT Analysis

Running MadGraph

```
student@eslam:~/mad/MG5_aMC_v2_7_3$ ./bin/mg5_aMC
```

```
************************************************************
*                                                          *
*                    W E L C O M E  to                     *
*             M A D G R A P H 5 _ a M C @ N L O            *
*                                                          *
*                                                          *
*                 *                       *                *
*                   *        * *        *                  *
*                     * * * * 5 * * * *                    *
*                   *        * *        *                  *
*                 *                       *                *
*                                                          *
*         VERSION 2.7.3                 2020-06-21         *
*                                                          *
*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
*                            and                           *
*            http://amcatnlo.web.cern.ch/amcatnlo/         *
*                                                          *
*               Type 'help' for in-line help.              *
*           Type 'tutorial' to learn how MG5 works         *
*    Type 'tutorial aMCatNLO' to learn how aMC@NLO works   *
*    Type 'tutorial MadLoop' to learn how MadLoop works    *
*                                                          *
************************************************************
load MG5 configuration from input/mg5_configuration.txt
```

Generation of the event

- We will generate the interaction with the MadGraph using the following:

```
MG5_aMC>generate p p > h > a a
```

- Then we will save the output and launch it

Setting the Parameters for the 14 TeV

```
The following switches determine which programs are run:
/==========================================================================\
| 1. Choose the shower/hadronization program      shower = Pythia8         |
| 2. Choose the detector simulation program     detector = Delphes         |
| 3. Choose an analysis package (plot/convert)  analysis = ExRoot          |
| 4. Decay onshell particles                     madspin = OFF             |
| 5. Add weights to events for new hypp.        reweight = OFF             |
\==========================================================================/
Either type the switch number (1 to 5) to change its setting,
Set any switch explicitly (e.g. type 'shower=OFF' at the prompt)
```

Figure: Opening Pythia and Delphes for 14TeV

```
Do you want to edit a card (press enter to bypass editing)?
/------------------------------------------------------------\
|  1. param    : param_card.dat                              |
|  2. run      : run_card.dat                                |
|  3. pythia8  : pythia8_card.dat                            |
|  4. delphes  : delphes_card.dat                            |
\------------------------------------------------------------/
```

Figure: Cards used for 14TeV Run

Setting the Parameters for the 14 TeV

```
#*********************************************************************
  tag_1     = run_tag ! name of the run
#*********************************************************************
# Number of events and rnd seed                                       *
# Warning: Do not generate more than 1M events in a single run        *
#*********************************************************************
  100000 = nevents ! Number of unweighted events requested
  0    = iseed   ! rnd seed (0=assigned automatically=default))
#*********************************************************************
# Collider type and energy                                            *
# lpp: 0=No PDF, 1=proton, -1=antiproton, 2=photon from proton,      *
#                                         3=photon from electron      *
#*********************************************************************
     1         = lpp1    ! beam 1 type
     1         = lpp2    ! beam 2 type
     7000.0      = ebeam1  ! beam 1 total energy in GeV
     7000.0      = ebeam2  ! beam 2 total energy in GeV
# To see polarised beam options: type "update beam_pol"

#*********************************************************************
```

Figure: Setting parameters for 14TeV Run

Setting the Parameters for the 100 TeV

- We will do the same as before. However, for the Delphes program, we will make it off. We did this as if we leave it open it will run using the card for the LHC detector which will provide non-accurate results. We will use Delphes after the run is finished using another command to run using the FCC card which simulates the detector of the FCC.

```
The following switches determine which programs are run:
/==============================================================================\
| 1. Choose the shower/hadronization program     shower = Pythia8               |
| 2. Choose the detector simulation program    detector = OFF                   |
| 3. Choose an analysis package (plot/convert) analysis = ExRoot                |
| 4. Decay onshell particles                    madspin = OFF                   |
| 5. Add weights to events for new hypp.       reweight = OFF                   |
\==============================================================================/
```

Figure: Pythia is open while Delphes is Off for 100 TeV Run

Setting the Parameters for the 100 TeV

```
#*********************************************************************
#                       MadGraph5_aMC@NLO                            *
#                                                                    *
#                     run_card.dat MadEvent                          *
#                                                                    *
#  This file is used to set the parameters of the run.               *
#                                                                    *
#  Some notation/conventions:                                        *
#                                                                    *
#   Lines starting with a '# ' are info or comments                  *
#                                                                    *
#   mind the format:   value    = variable     ! comment             *
#                                                                    *
#   To display more options, you can type the command:               *
#      update full_run_card                                          *
#*********************************************************************
#
#*********************************************************************
# Tag name for the run (one word)                                    *
#*********************************************************************
  tag_1     = run_tag ! name of the run
#*********************************************************************
# Number of events and rnd seed                                      *
# Warning: Do not generate more than 1M events in a single run       *
#*********************************************************************
  100000 = nevents ! Number of unweighted events requested
  0     = iseed    ! rnd seed (0=assigned automatically=default))
#*********************************************************************
# Collider type and energy                                           *
# lpp: 0=No PDF, 1=proton, -1=antiproton, 2=photon from proton,      *
#                                          3=photon from electron    *
#*********************************************************************
     1        = lpp1    ! beam 1 type
     1        = lpp2    ! beam 2 type
     50000.0     = ebeam1  ! beam 1 total energy in GeV
     50000.0     = ebeam2  ! beam 2 total energy in GeV
```

Getting the Cross Section

Results in the heft-full for p p > h > a a

Currently Running

Run Name	Tag Name	Cards	Results	Status/Jobs		
				Queued	Running	Done
run_01	tag_1	param_card run_card delphes_card	0.02088 ± 1.252e-05 (pb)	Done		

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 7000.0 x 7000.0 GeV	tag_1	0.02088 ± 1.3e-05	100000	parton madevent	LHE rootfile	remove run launch detector simulation
					pythia8	LOG HEPMC	remove run launch detector simulation
					delphes	LOG rootfile	remove run

Results in the heft-full for p p > h > a a

Currently Running

Run Name	Tag Name	Cards	Results	Status/Jobs		
				Queued	Running	Done
run_01	tag_1	param_card run_card	0.2928 ± 0.0001809 (pb)	Done		

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 50000.0 x 50000.0 GeV	tag_1	0.2928 ± 0.00018	100000	parton madevent	LHE rootfile	remove run launch detector simulation
					pythia8	LOG HEPMC	remove run launch detector simulation

Main Page

The weight for the 14 TeV Run

- MCLum $100000/20.88 = 4789.27\ fb^{-1}$. The weight value will be $300/4789 = 0.062$

```
float cross_section = 20.88;  // The Cross-Section in fb
float N = 100000;     // Number of events
float DataLum = 300;         //  Luminosity of data in fb^-1
float MCLum = N / cross_section;  // Luminosity of Monte-Carlo  in fb^-1
float weight = DataLum / MCLum;        // Weight of the simulation process with respect to data
```

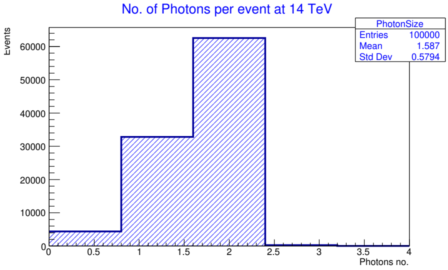
The weight for the 100 TeV Run

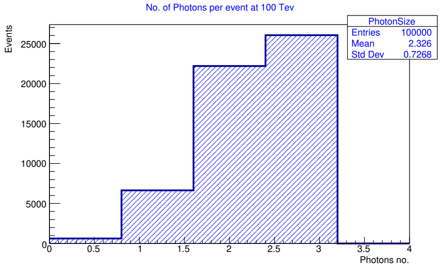
- MCLum $100000/292.78 = 341.55\ fb^{-1}$. The weight value will be $3000/341.55 = 8.78$
- The weight for the FCC divided by the weight of LHC gives $8.78/0.062 = 141$

```
float cross_section = 292.78;  // The Cross-Section in fb
float N = 100000;     // Number of events
float DataLum = 3000;       //  Luminosity of data in fb^-1
float MCLum = N / cross_section;  // Luminosity of Monte-Carlo  in fb^-1
float weight = DataLum / MCLum;        // Weight of the simulation process with respect to data
```

Number of photons per event

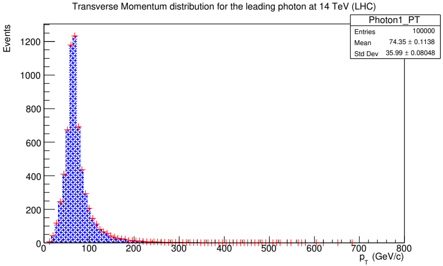
- The mean is higher for FCC
- The histograms isn't weighted. For the LHC case: $60000 \times 0.06 = 3600$. For the FCC case: $23000 \times 8.78 = 210000$

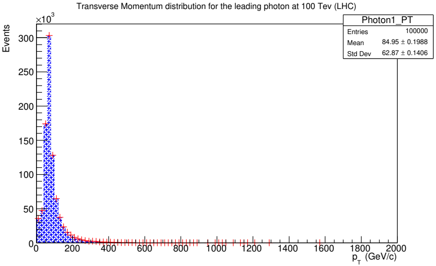




Transverse momentum for the leading photon

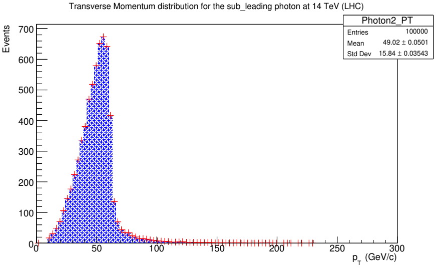
- Transverse momentum for FCC is higher reaching 1600 GeV/c.
- This is helpful for making high momentum cuts in order to decrease the background and noise effects. This will help to distinguish the photons coming from noise and those coming from the Higgs Decay.
- Mean is higher for FCC: the higher the center of mass-energy, the higher the transverse momentum of the resulting leading photons.

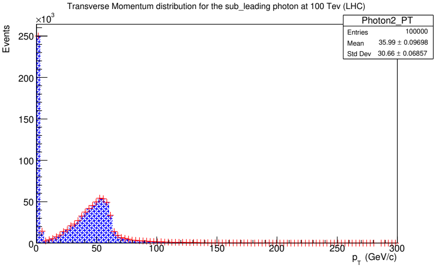




Transverse momentum for the sub-leading photon

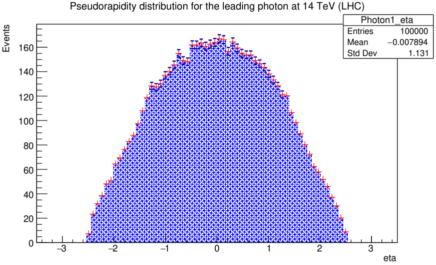
- In the transverse momentum histograms for the sub-leading photons, we note that their momentum is much less than the previous ones for the leading photons. This makes sense as the leading photons are the ones detected with high energies. Thus, they will also have higher transverse momentum.

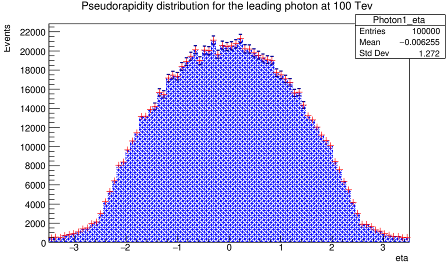




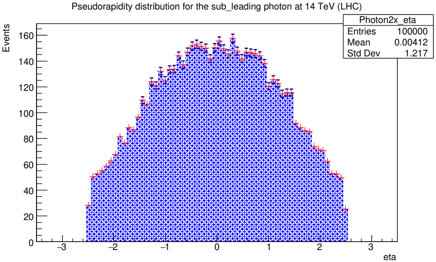
Pseudorapidity for the leading photon

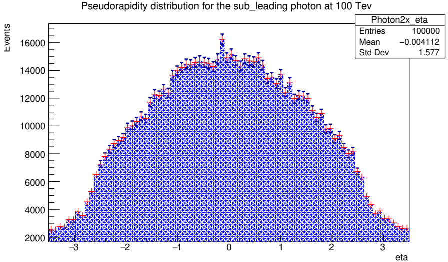
- The Pseudorapidity for the leading photon at LHC $-2.5 < \eta < 2.5$ while at FCC $-3.5 < \eta < 3.5$
- FCC requires a better detector in order to be able to have more coverage to detect the new spread of leading photons.
- Centered around zero





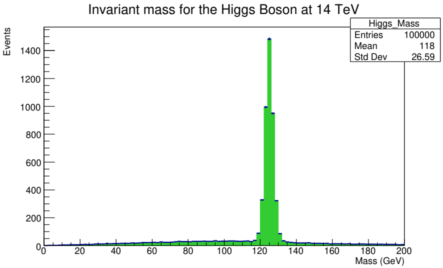
Pseudorapidity for the sub-leading photon

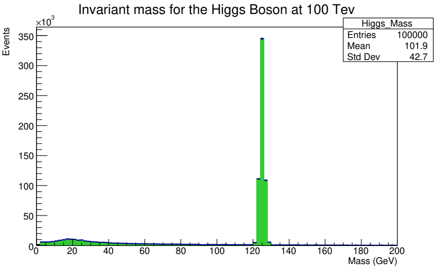




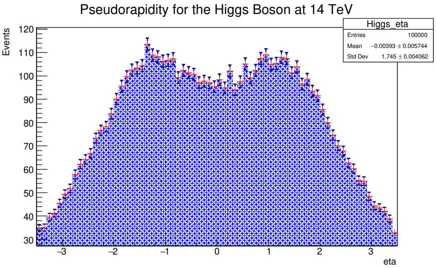
Invariant mass distribution for the Higgs Boson

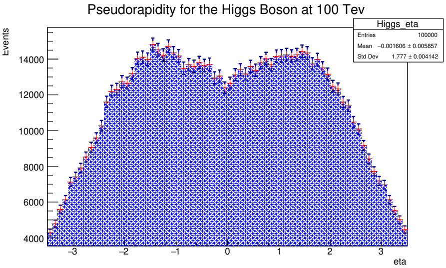
- In the case of FCC, we have an enormous number of produced Higgs (350×10^3) in the range of 125 GeV. The ration between the number for FCC and LHC is $(350 \times 10^3)/1400 = 250$. Which is close to the ratio of weights (141)
- In the case of FCC, we have less spread in the small range around the 125 GeV peak.





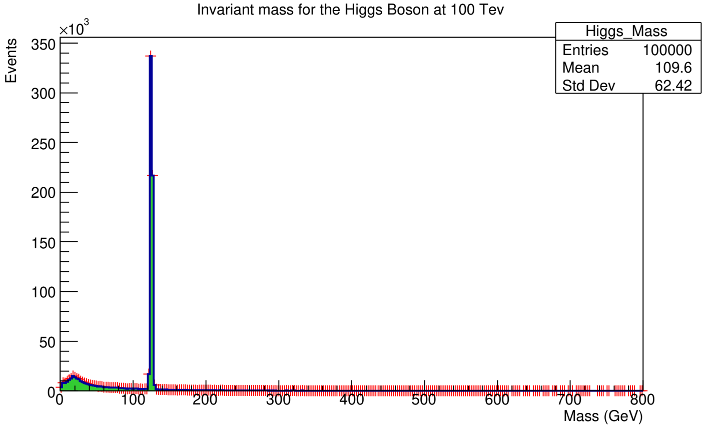
Pseudorapidity for the Higgs Boson





The mass of the Higgs in the FCC with an extended x-axis

- The standard deviation and mean increased from the previous case (200 GeV maximum of x-axis)
- New particles with masses over the 200 GeV or errors in reconstruction of Higgs from the two photons



The End