Simulation and analysis of the production of the Higgs boson in pp collisions using `PYTHIA` and `ROOT`

Proyecto Física Computacional

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Introduction and motivations

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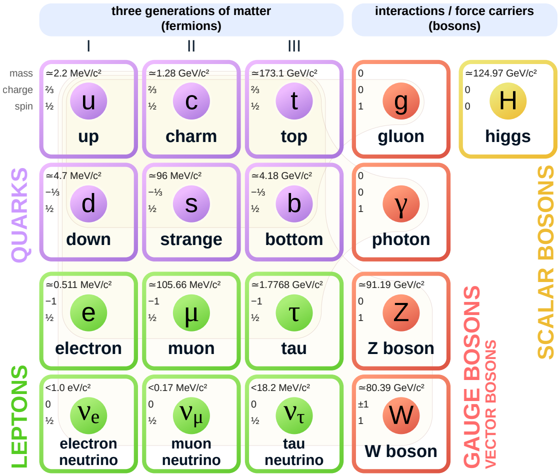
- All the elementary particles acquire mass through their interaction with the **Higgs field**.

Standard Model of Elementary Particles



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- The particles masses are considered parameters to be determined experimentally.
- The range of possible values for the Higgs boson are all bellow the 1 TeV.
- The data taken from the LEP and SLC colliders, the Tevatron, and other experiments predicted the Higgs boson mass in the range 90 GeV $-$ 152 GeV at the 95% confidence level (CL).

- Furthermore, other searches at LEP excluded values lower than 114.4 GeV at 95% CL, and measurements at Tevatron excluded mass range 162 GeV – 166 GeV at 95% CL.

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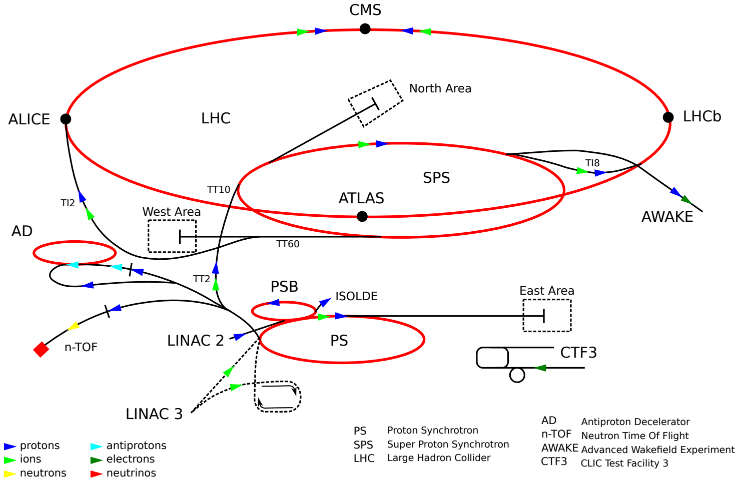
- The CMS experiment excluded at 95% CL masses from 127 to 600 GeV. The ATLAS experiment excluded also at 95% CL masses in the ranges 111.4 – 116.4, 119.4 – 122.1, and 129.2 – 541 GeV.
- In 2012, tha ATLAS and CMS colaborations reported an excess of events between 2σ and 3σ near 125 GeV.


CMS
North Area
ALICE
LHC
LHCb
TI8
SPS
TT10
ATLAS
TI2
West Area
AWAKE
AD
TT60
TT2
PSB
ISOLDE
East Area
n-TOF
LINAC 2
PS
CTF3
LINAC 3
protons
ions
neutrons
antiprotons
electrons
neutrinos
PS Proton Synchrotron
SPS Super Proton Synchrotron
LHC Large Hadron Collider
AD Antiproton Decelerator
n-TOF Neutron Time Of Flight
AWAKE Advanced Wakefield Experiment
CTF3 CLIC Test Facility 3

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- The channels with the highest sensitivity for discovering the SM Higgs boson with a mass near 125 GeV are $H \to \gamma\gamma$ and $H \to ZZ \to 4l$.

Theoretical framework

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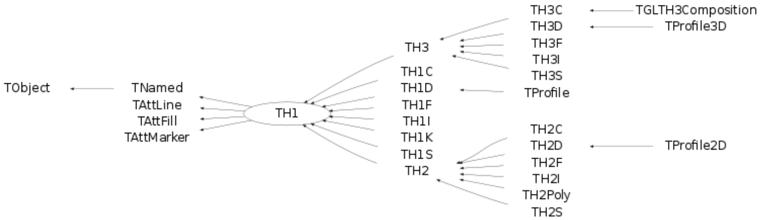
- Among the libraries we have libraries for histograms, graphs, fitting, mathematical functions, etc.
- An example of how the classes are organized is shown bellow fow the histogram library:



The class hierarchy of histogram classes

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- It comprises a coherent set of physics models for the evolution from a few-body high-energy ('hard') scaterring process to a complex multihadronic final state.
- The particles are produced in vacuum, but also can be added external detector effects to the simulation.

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- `PYTHIA` can be run standalone, but it can also interfaced with a set of other libraries.
- Among the libraries we have `AlpGen`, `MadGraph`, `PowHeg`, `FastJet` and `ROOT`.
- For this project we are interested only in `ROOT`.

A simple PYTHIA algorithm

Let's make a simple PYTHIA algorithm. Indeed, go to the directory

```
> cd pythia8303/examples
```

In such directory, create the file `mymain01.cc`. Once the file is created, modify the `Makefile` located in the same directory:

```
# ROOT (turn off all warnings for readability).
mymain01: $(PYTHIA) $$@.cc
ifeq ($(ROOT_USE),true)
	$(CXX) $@.cc -o $@ -w $(CXX_COMMON) $(ROOT_LIB)\
	 `$(ROOT_CONFIG) --cflags --glibs`
else
	$(error Error: $@ requires ROOT)
endif
```

Now, in the file `mymain01.cc` add the following lines of code:

```
Pythia pythia;
pythia.readString("HiggsSM:all = on");
pythia.readString("Beams:eCM = 13000.");
pythia.readString("Next:numberShowEvent = 2");
pythia.init();
```

```
for (int iEvent = 0; iEvent < number_of_events; ++iEvent)
{
    pythia.next();
    Int_t ie = 0;
    for (Int_t i = 0; i < pythia.event.size(); ++i)
    {
        if (pythia.event[i].id() == 11)
        {
            ie = i;
            m_e_histogram -> Fill(pythia.event[ie].m());
        }
    }
}
```

```
for (int iEvent = 0; iEvent < number_of_events; ++iEvent)
{
    pythia.next();
    Int_t imu = 0;
    for (Int_t i = 0; i < pythia.event.size(); ++i)
    {
         else if (pythia.event[i].id() == 13)
    {
        imu = i;
        m_mu_histogram -> Fill(pythia.event[imu].m());
    }
    }
}
```

Finally, to compile the algorithm write the following commands in the terminal shell

```
> make mymain01
./mymain01 > myout01
```

This will generate the following output:

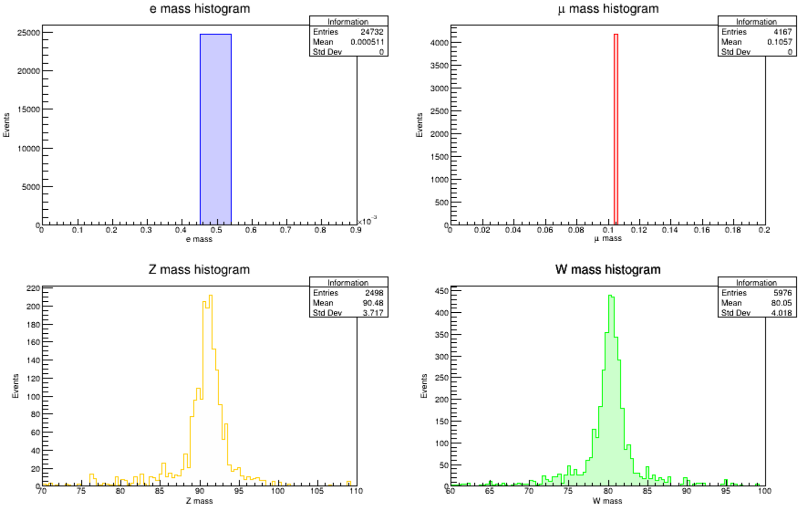
```
*-------  PYTHIA Process Initialization  --------------------------*
|                                                                   |
| We collide p+ with p+ at a CM energy of 1.300e+04 GeV             |
|                                                                   |
|-------------------------------------------------------------------|
|                                                     |             |
| Subprocess                                    Code |   Estimated |
|                                                     |    max (mb) |
|                                                     |             |
|-------------------------------------------------------------------|
|                                                     |             |
| f fbar -> H (SM)                               901 |   9.030e-09 |
| g g -> H (SM)                                  902 |   2.524e-07 |
| gamma gamma -> H (SM)                          903 |   8.477e-12 |
| f fbar -> H0 Z0 (SM)                           904 |   5.187e-09 |
| f fbar -> H0 W+- (SM)                          905 |   9.431e-09 |
| f f' -> H0 f f'(Z0 Z0 fusion) (SM)             906 |   1.835e-08 |
| f_1 f_2 -> H0 f_3 f_4 (W+ W- fusion) (SM)      907 |   4.832e-08 |
| g g -> H t tbar (SM)                           908 |   5.102e-08 |
| q qbar -> H t tbar (SM)                        909 |   2.603e-08 |
|                                                                   |
*-------  End PYTHIA Process Initialization ------------------------*
```

```
 --------  PYTHIA Info Listing  ---------------------------------------

 Beam A: id =   2212, pz =  6.500e+03, e =  6.500e+03, m =  9.383e-01.
 Beam B: id =   2212, pz = -6.500e+03, e =  6.500e+03, m =  9.383e-01.

 In 1: id =   21, x =  1.508e-03, pdf =  2.813e+01 at Q2 =  1.562e+04.
 In 2: id =   21, x =  6.131e-02, pdf =  1.561e+00 at same Q2.

 Subprocess g g -> H (SM) with code 902 is 2 -> 1.
 It has sHat =  1.562e+04.
     alphaEM =  7.846e-03,  alphaS =  1.238e-01    at Q2 =  1.562e+04.

 Impact parameter b =  6.777e-01 gives enhancement factor =  1.643e+00.
 Max pT scale for MPI =  1.300e+04, ISR =  1.300e+04, FSR =  1.300e+04.
 Number of MPI =     5, ISR =    12, FSRproc =    54, FSRreson =    12.

 --------  End PYTHIA Info Listing  ------------------------------------
```

```
 --------  PYTHIA Event Listing  (hard process)  -----------------------------------------------------------------------------

    no        id  name            status     mothers   daughters     colours      p_x        p_y        p_z         e          m
     0        90  (system)           -11     0     0     0     0     0     0      0.000      0.000      0.000  13000.000  13000.000
     1      2212  (p+)               -12     0     0     3     0     0     0      0.000      0.000   6500.000   6500.000      0.938
     2      2212  (p+)               -12     0     0     4     0     0     0      0.000      0.000  -6500.000   6500.000      0.938
     3        21  (g)                -21     1     0     5     0   101   102      0.000      0.000      9.802      9.802      0.000
     4        21  (g)                -21     2     0     5     0   102   101      0.000      0.000   -398.531    398.531      0.000
     5        25  (h0)               -22     3     4     6     7     0     0      0.000      0.000   -388.730    408.333    124.999
     6         4  c                   23     5     0     0     0   103     0     49.441      8.740   -315.857    319.826      1.500
     7        -4  cbar                23     5     0     0     0     0   103    -49.441     -8.740    -72.873     88.507      1.500
                                   Charge sum:  0.000           Momentum sum:      0.000      0.000   -388.730    408.333    124.999

 --------  End PYTHIA Event Listing  -----------------------------------------------------------------------------------------
```

```
 --------  PYTHIA Event Listing  (complete event)  ---------------------------------------------------------------------------------

    no        id  name            status     mothers   daughters     colours      p_x        p_y        p_z         e          m
     0        90  (system)           -11     0     0     0     0     0     0      0.000      0.000      0.000  13000.000  13000.000
     1      2212  (p+)               -12     0     0   270     0     0     0      0.000      0.000   6500.000   6500.000      0.938
     2      2212  (p+)               -12     0     0   271     0     0     0      0.000      0.000  -6500.000   6500.000      0.938
     3        21  (g)                -21     6     0     5     0   101   102      0.000      0.000      9.802      9.802      0.000
     4        21  (g)                -21     7     7     5     0   102   101      0.000      0.000   -398.531    398.531      0.000
     5        25  (h0)               -22     3     4     8     8     0     0      0.000      0.000   -388.730    408.333    124.999
     6        21  (g)                -41    10    10     9     3   101   104      0.000      0.000     38.246     38.246      0.000
     7        21  (g)                -42    11     0     4     4   102   101     -0.000     -0.000   -398.531    398.531      0.000
     8        25  (h0)               -44     5     5    12    12     0     0     44.676     28.554   -358.914    383.739    124.999
     9        21  (g)                -43     6     0    13    13   102   104    -44.676    -28.554     -1.371     53.039      0.000
    10        21  (g)                -42    15    15     6     6   101   104      0.000     -0.000     38.246     38.246      0.000
    11        21  (g)                -41    16     0    14     7   102   105     -0.000      0.000   -446.740    446.740      0.000
    12        25  (h0)               -44     8     8    17    17     0     0     44.664     40.774   -390.060    414.040    124.999
    13        21  (g)                -44     9     9    18    18   102   104    -44.677    -27.658     -6.023     52.889      0.000
    14        21  (g)                -43    11     0    19    19   101   105      0.013    -13.116    -12.411     18.057      0.000
    15        21  (g)                -42    21     0    10    10   101   104     -0.000     -0.000     38.246     38.246      0.000
    16        21  (g)                -41    22    22    20    11   106   105      0.000      0.000   -722.639    722.639      0.000
    17        25  (h0)               -44    12    12    23    23     0     0     37.479     31.810   -393.439    415.735    124.999
    18        21  (g)                -44    13    13    24    24   102   104    -45.203    -28.315     -5.647     53.637      0.000
    19        21  (g)                -44    14    14    25    25   101   105     -0.259    -13.455    -12.376     18.283      0.000
    20        21  (g)                -43    16     0    26    26   106   102      7.983      9.960   -272.931    273.229      0.000
    21        21  (g)                -41    34    34    27    15   107   104     -0.000      0.000     59.555     59.555      0.000
    22        21  (g)                -42    35     0    16    16   106   105     -0.000     -0.000   -722.639    722.639      0.000
    23        25  (h0)               -44    17    17    36    36     0     0     35.355     30.136   -386.750    409.095    124.999
    24        21  (g)                -44    18    18    37    37   102   104    -49.775    -31.919    -12.300     60.396      0.000
    25        21  (g)                -44    19    19    28    29   101   105     -0.822    -13.899    -13.412     19.333      0.000
    26        21  (g)                -44    20    20    39    39   106   102      7.955      9.938   -270.832    271.131      0.000
    27        21  (g)                -43    21     0    30    30   107   101      7.287      5.744     20.211     22.239      0.000
    28        21  (g)                -51    25     0    38    38   108   105     -0.160    -16.166     -4.996     16.921      0.000
```

```
 *-------  PYTHIA Error and Warning Messages Statistics  ----------------------------------------------------------* 
 |                                                                                                                 | 
 |  times   message                                                                                                | 
 |                                                                                                                 | 
 |     19   Error in Pythia::next: hadronLevel failed; try again                                                   | 
 |     15   Error in StringFragmentation::fragment: stuck in joining                                               | 
 |      4   Error in StringFragmentation::fragmentToJunction: caught in junction flavour loop                      | 
 |      2   Warning in HadronWidths::pickMasses: angular momentum and running widths not used                      | 
 |      4   Warning in PhaseSpace2to2tauyz::trialKin: maximum for cross section violated                           | 
 |      1   Warning in Pythia::check: energy-momentum not quite conserved                                          | 
 |      5   Warning in Pythia::check: not quite matched particle energy/momentum/mass                              | 
 |      2   Warning in SimpleSpaceShower::pT2nextQCD: small daughter PDF                                           | 
 |      4   Warning in SimpleSpaceShower::pT2nextQCD: weight above unity                                           | 
 |      7   Warning in SimpleTimeShower::findMEcorr: ME weight above PS one                                        | 
 |      1   Warning in SimpleTimeShower::pTnext: negative dipole mass.                                             | 
 |     71   Warning in StringFragmentation::fragmentToJunction: bad convergence junction rest frame                | 
 |                                                                                                                 | 
 *-------  End PYTHIA Error and Warning Messages Statistics  ------------------------------------------------------* 
```


e mass histogram
Information
Entries 24732
Mean 0.000511
Std Dev 0
Events
e mass
×10⁻³
μ mass histogram
Information
Entries 4167
Mean 0.1057
Std Dev 0
Events
μ mass
Z mass histogram
Information
Entries 2498
Mean 90.48
Std Dev 3.717
Events
Z mass
W mass histogram
Information
Entries 5976
Mean 80.05
Std Dev 4.018
Events
W mass

Results

A simple analysis of the Higgs

- Before to show the main analysis of this project let's study in first place the kinematical variables associated with the Higgs boson.

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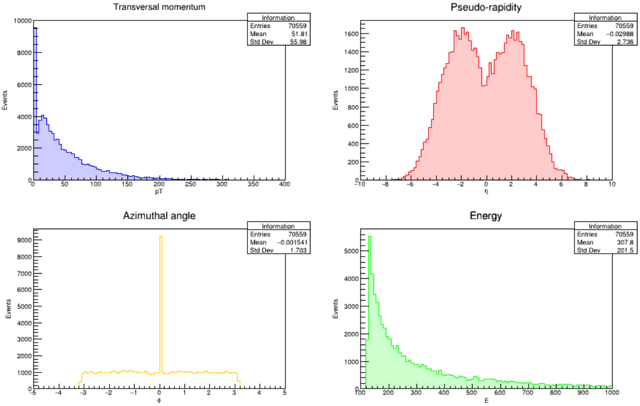
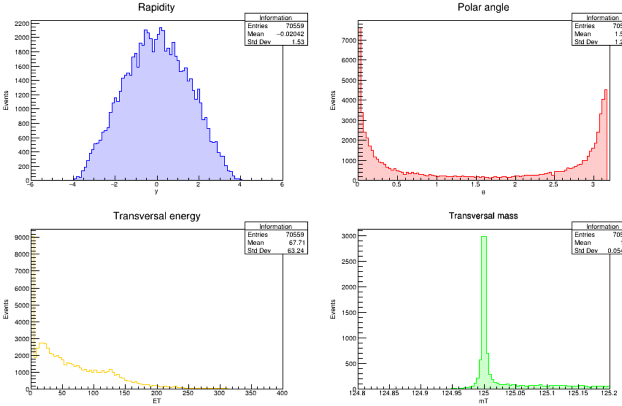
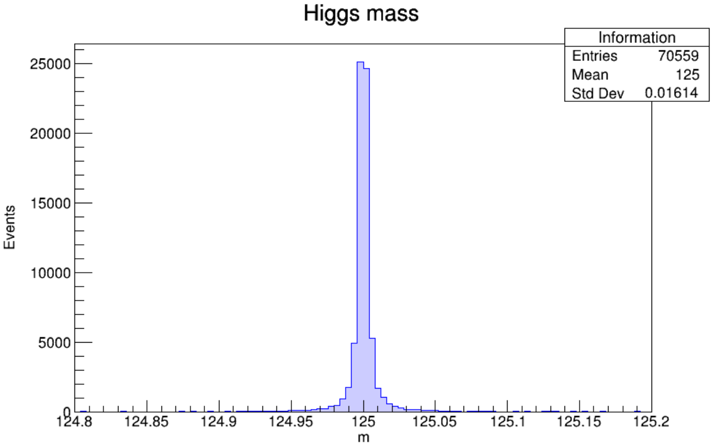
- Indeed, the histogram for the variables p_T, η, ϕ and E have the form



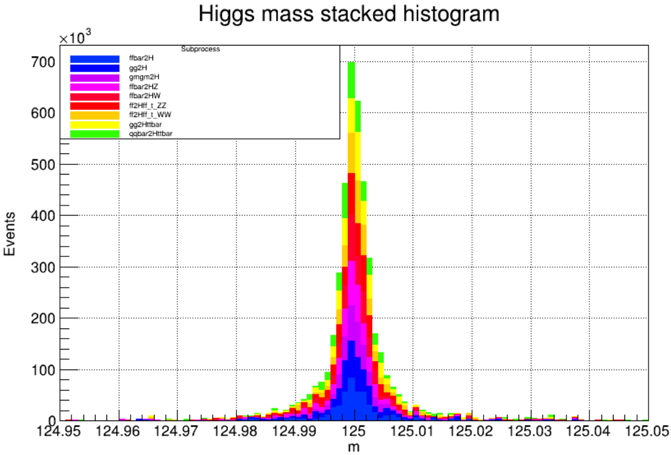
- Furthermore, the histogram for the variables y, θ, E_T and m_T have the form



- On the other hand, the mass of the Higgs boson have the following distribution:



- Finally, the production of the Higgs boson due to the processes $f\bar{f} \to H^0$, $gg \to H^0$, $\gamma\gamma \to H^0$, $f\bar{f} \to H^0 Z^0$, $f\bar{f} \to H^0 W^{\pm}$, $ff' \to H^0 ff'$, $f_1 f_2 \to H^0 f_3 f_4$, $gg \to H^0 t\bar{t}$ and $q\bar{q} \to H^0 t\bar{t}$ is shown in the stacked mass histogram



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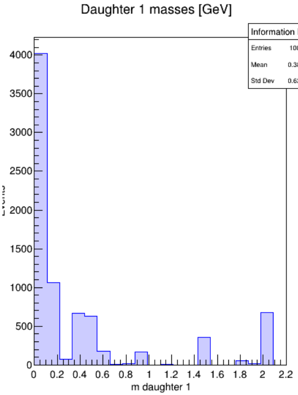
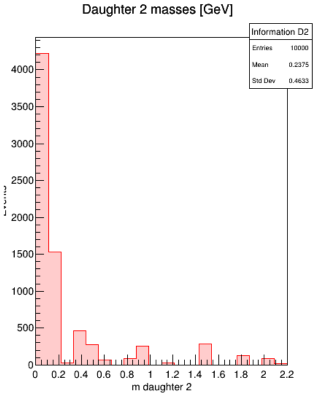
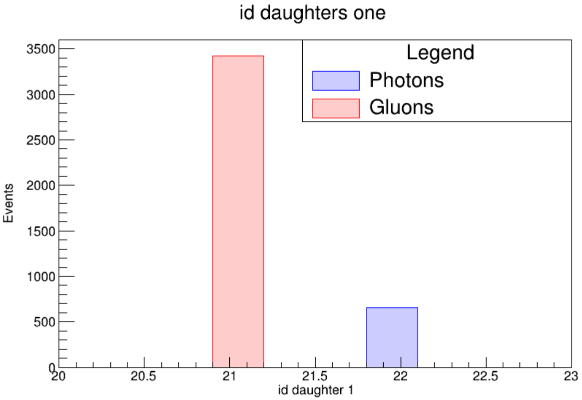
- The diphoton mass receive contributions from a large irreducible background from quantum chromodynamics.
- The channel $H \to \gamma\gamma$ is one of the most promising channels in the search of the SM Higgs boson in low mass range.

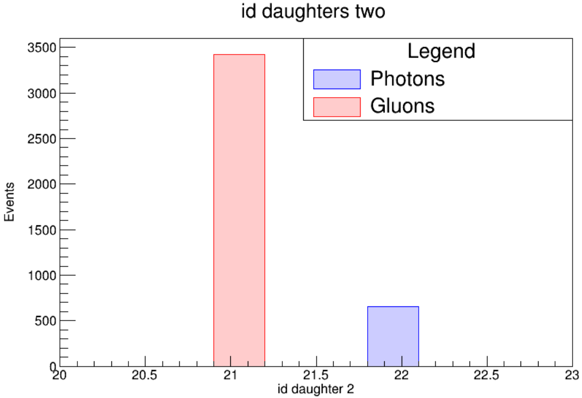
- Now, let's try to reconstruct the SM Higgs boson in the $H \to \gamma\gamma$ channel. Indeed, the distribution of the masses of the all possibles daughter (according to `PYTHIA`) of the SM Higgs boson is





- From the above histogram, we see that the majority of the events corresponds to daughter that are massless. Indeed, by doing a histogram of the ID of the daughters that are massless we get




id daughters two
Legend
Photons
Gluons
Events
3500
3000
2500
2000
1500
1000
500
0
20
20.5
21
21.5
22
22.5
23
id daughter 2

- From above we see that we have daughters that correspond to photons and gluons. However, we are interested only on the photon daughters.

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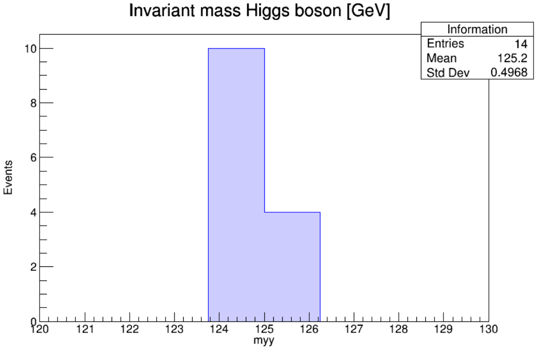
- In this way, by using the formula

$$m_{\gamma\gamma} = \sqrt{2p_{T,1}p_{T,2}\left(\cosh\left(\eta_1 - \eta_2\right) - \cos\left(\phi_1 - \phi_2\right)\right)}, \qquad (1)$$

we get the following histogram for the diphoton mass:



$H \to c\bar{c}$

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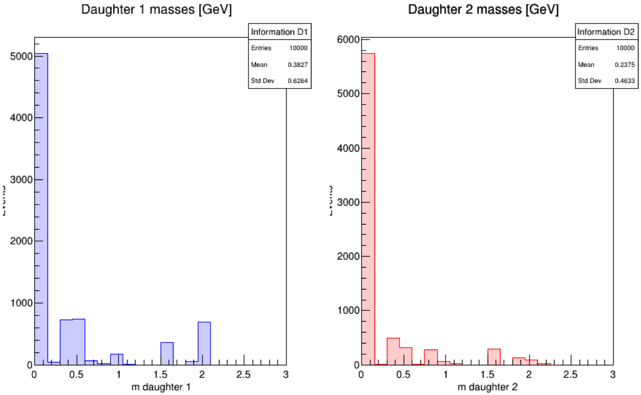
- However, one of the highest priorities of the LHC is the measurement of the coupling of the H boson with other SM particles.
- Recently, ATLAS and CMS reported the coupling of the H boson with the quarks t and b.
- Thus, the next objetive is the measurement of the coupling of H with second generation quarks (c and s).

- Now, let's analyse the decay $H \to c\bar{c}$ by using the `PYTHIA` simulator. Indeed, again we have that the mass of the possible daughters are distributed according to the following histogram:



- From the previous histogram we have that there is a very low production of daughters between the mass range $1 - 1.5$ GeV, where the charm quark is located.

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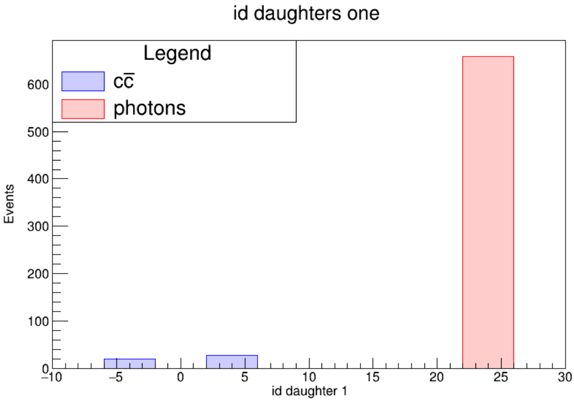
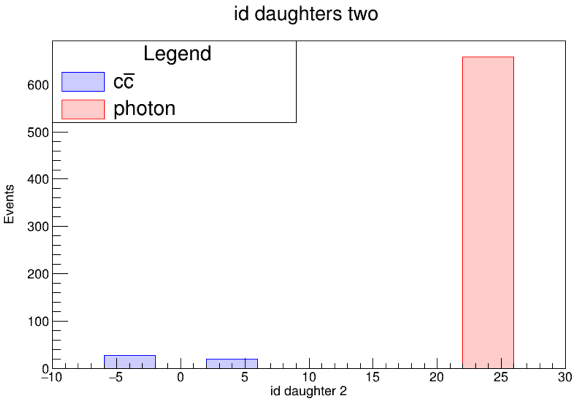
- Indeed, the coupling of the Higgs with the third generation quarks $b\bar{b}$ is much strong.

- In this way, by making a histogram with the ID of the produced charm quarks we get

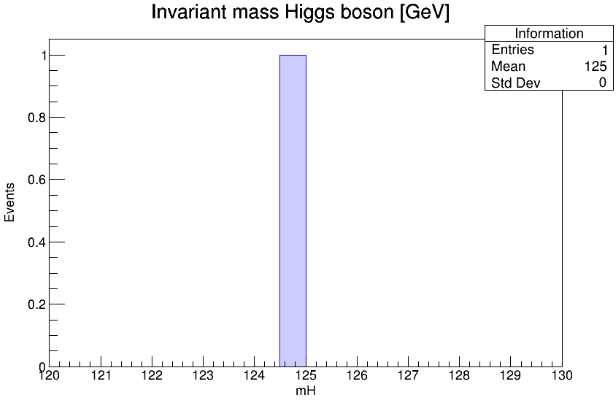



id daughters two
Legend
$c\bar{c}$
photon
Events
600
500
400
300
200
100
0
−10
−5
0
5
10
15
20
25
30
id daughter 2

- Finally, by using the center-of-mass formula for a 2−body decay process

$$M = \sqrt{m_1^2 + m_2^2 + 2\left(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2\right)}, \tag{2}$$

we get the following histogram



Conclusions and remarks

- In this project we have tackled the problem of analyse the decay channels $H \to \gamma\gamma$ and $H \to c\bar{c}$.

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- The simulations were made with 1000 pp collisions. However, we can go further with more collisions by using computational clusters (e.g. `LXPLUS`).

Acknowledgments

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The references for this work can be finded in the project document.

Muchas gracias por la atención!