

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

Proyecto Física Computacional

Sebastián Fuenzalida Garrido

Universidad Técnica Federico Santa María

January 14, 2021

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# Introduction and motivations

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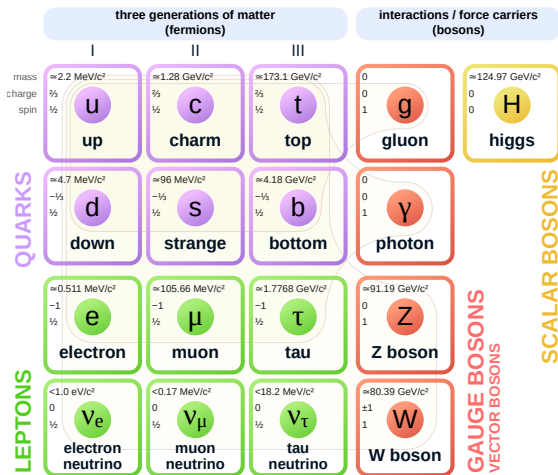
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- All the elementary particles acquire mass through their interaction with the **Higgs field**.

# 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 below 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).

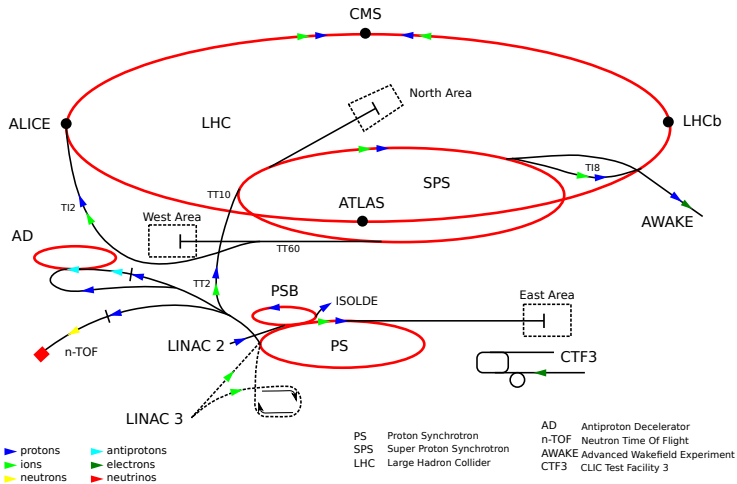
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- In 2012, the ATLAS and CMS collaborations reported an excess of events between  $2\sigma$  and  $3\sigma$  near 125 GeV.





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- These decay channels correspond to:  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow ZZ \rightarrow 4l$ ,  $H \rightarrow WW \rightarrow l\nu l\nu$ ,  $H \rightarrow \tau\tau$ , and  $H \rightarrow b\bar{b}$ , where  $l$  stand for  $e^-$  and  $\mu^-$ .

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

## Theoretical framework

- ROOT is an object-oriented C++ framework aimed at solving the data analysis challenges of high-energy physics.

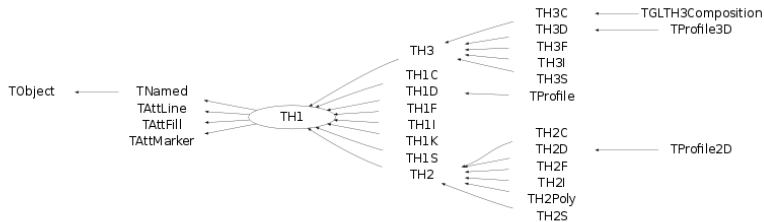
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- Among the libraries we have libraries for histograms, graphs, fitting, mathematical functions, etc.
- An example of how the classes are organized is shown below for the histogram library:



The class hierarchy of histogram classes

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- It focuses on centre-of-mass energies greater than about 10 GeV.
- It comprises a coherent set of physics models for the evolution from a few-body high-energy ('hard') scattering 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

```
1 > cd pythia8303/examples
```

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

```
1 # ROOT (turn off all warnings for readability).
2 mymain01: $(PYTHIA) $$@.cc
3 ifeq ($(ROOT_USE),true)
4     $(CXX) $$@.cc -o $$@ -w $(CXX_COMMON) $(ROOT_LIB
5         )\
6         '$(ROOT_CONFIG) --cflags --glibs '
7 else
8     $(error Error: $$@ requires ROOT)
9 endif
```

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

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

```

1  for (int iEvent = 0; iEvent < number_of_events; ++
    iEvent)
2  {
3      pythia.next();
4      Int_t ie = 0;
5      for (Int_t i = 0; i < pythia.event.size(); ++i)
6      {
7          if (pythia.event[i].id() == 11)
8          {
9              ie = i;
10             m_e_histogram -> Fill(pythia.event[ie].m()
11         );
12     }
13 }

```

```
1  for (int iEvent = 0; iEvent < number_of_events; ++  
    iEvent)  
2  {  
3      pythia.next();  
4      Int_t imu = 0;  
5      for (Int_t i = 0; i < pythia.event.size(); ++i)  
6      {  
7          else if (pythia.event[i].id() == 13)  
8          {  
9              imu = i;  
10             m_mu_histogram -> Fill(pythia.event[imu].m());  
11         }  
12     }  
13 }
```



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

```
1 > make mymain01
2 ./mymain01 > myout01
```

This will generate the following output:

```

76 *----- PYTHIA Process Initialization -----*
77 |
78 | We collide p+ with p+ at a CM energy of 1.300e+04 GeV
79 |
80 |-----|
81 |
82 | Subprocess                                Code | Estimated
83 |                                           | max (mb)
84 |-----|
85 |
86 | f fbar -> H (SM)                        901 | 9.030e-09
87 | g g -> H (SM)                          902 | 2.524e-07
88 | gamma gamma -> H (SM)                  903 | 8.477e-12
89 | f fbar -> H0 Z0 (SM)                  904 | 5.187e-09
90 | f fbar -> H0 W+- (SM)                 905 | 9.431e-09
91 | f f' -> H0 f f'(Z0 Z0 fusion) (SM)    906 | 1.835e-08
92 | f_1 f_2 -> H0 f_3 f_4 (W+ W- fusion) (SM) 907 | 4.832e-08
93 | g g -> H t tbar (SM)                 908 | 5.102e-08
94 | q qbar -> H t tbar (SM)              909 | 2.603e-08
95 |
96 |
97 *----- End PYTHIA Process Initialization -----*

```

```

127 ----- PYTHIA Info Listing -----
128
129 Beam A: id = 2212, pz = 6.500e+03, e = 6.500e+03, m = 9.383e-01.
130 Beam B: id = 2212, pz = -6.500e+03, e = 6.500e+03, m = 9.383e-01.
131
132 In 1: id = 21, x = 1.508e-03, pdf = 2.813e+01 at Q2 = 1.562e+04.
133 In 2: id = 21, x = 6.131e-02, pdf = 1.561e+00 at same Q2.
134
135 Subprocess g g -> H (SM) with code 902 is 2 -> 1.
136 It has sHat = 1.562e+04.
137     alphaEM = 7.846e-03, alphaS = 1.238e-01 at Q2 = 1.562e+04.
138
139 Impact parameter b = 6.777e-01 gives enhancement factor = 1.643e+00.
140 Max pT scale for MPI = 1.300e+04, ISR = 1.300e+04, FSR = 1.300e+04.
141 Number of MPI = 5, ISR = 12, FSRproc = 54, FSRreson = 12.
142
143 ----- End PYTHIA Info Listing -----

```

```

145 ----- PYTHIA Event Listing (hard process) -----
146
147 no      id name      status  mothers  daughters  colours  p_x    p_y    p_z      e      m
148 0        90 (system)   -11    0    0    0    0    0    0.000  0.000  0.000 13000.000 13000.000
149 1        2212 (p+)    -12    0    0    3    0    0    0.000  0.000  6500.000 6500.000 0.938
150 2        2212 (p+)    -12    0    0    4    0    0    0.000  0.000 -6500.000 6500.000 0.938
151 3         21 (g)      -21    1    0    5    0  101 102  0.000  0.000  9.802  9.802  0.000
152 4         21 (g)      -21    2    0    5    0  102 101  0.000  0.000 -398.531 398.531 0.000
153 5         25 (h0)     -22    3    4    6    7    0  0.000  0.000 -388.730 408.333 124.999
154 6         4 c         23    5    0    0    0  103 0  49.441  8.740 -315.857 319.826 1.500
155 7        -4 cbar      23    5    0    0    0    0 103 -49.441 -8.740 -72.873 88.507 1.500
156                               Charge sum: 0.000      Momentum sum: 0.000  0.000 -388.730 408.333 124.999
157
158 ----- End PYTHIA Event Listing -----

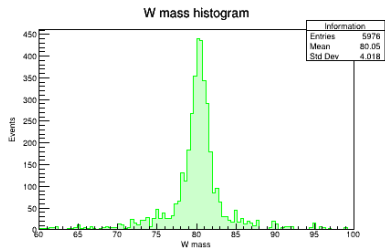
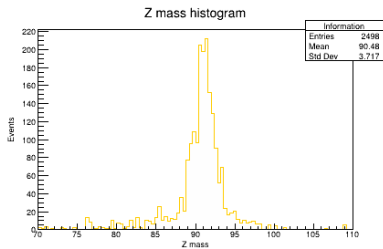
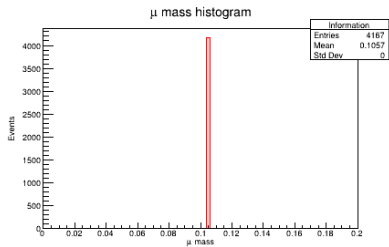
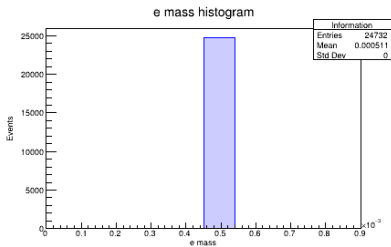
```

160	PYTHIA Event Listing (complete event)														
161	no	id	name	status	mothers	daughters	colours	p_x	p_y	p_z	e	n			
162	0	90	(system)	-11	0	0	0	0	0.000	0.000	0.000	13000.000	13000.000		
163	0			-12	0	0	270	0	0	0	0.000	0.938			
164	1	2212	(p+)	-12	0	0	271	0	0	0	0.000	0.938			
165	2	2212	(p+)	-12	0	0	271	0	0	0	0.000	0.938			
166	3	21	(g)	-21	6	0	5	0	101	102	0.000	9.802	0.000		
167	4	21	(g)	-21	7	7	5	0	102	101	0.000	398.531	0.000		
168	5	25	(hb)	-22	3	4	8	8	0	0	0.000	388.730	408.333	124.999	
169	6	21	(g)	-41	10	10	9	3	101	104	0.000	38.246	0.000		
170	7	21	(g)	-42	11	0	4	4	102	101	-0.000	-398.531	398.531	0.000	
171	8	25	(hb)	-44	5	5	12	12	0	0	44.676	28.554	-358.914	383.739	124.999
172	9	21	(g)	-43	6	0	13	13	102	104	-44.676	-28.554	-1.371	53.039	0.000
173	10	21	(g)	-42	15	15	6	6	101	104	0.000	-0.000	38.246	38.246	0.000
174	11	21	(g)	-41	16	0	14	7	102	105	-0.000	0.000	-446.740	446.740	0.000
175	12	25	(hb)	-44	8	8	17	17	0	0	44.664	40.774	-390.060	414.040	124.999
176	13	21	(g)	-44	9	9	18	18	102	104	-44.677	-27.658	-6.023	52.889	0.000
177	14	21	(g)	-43	11	0	19	19	101	105	0.013	-13.116	-12.411	18.057	0.000
178	15	21	(g)	-42	21	0	10	10	101	104	-0.000	-0.000	38.246	38.246	0.000
179	16	21	(g)	-41	22	22	20	11	106	105	0.000	0.000	-722.639	722.639	0.000
180	17	25	(hb)	-44	12	12	23	23	0	0	37.479	31.810	-393.439	415.735	124.999
181	18	21	(g)	-44	13	13	24	24	102	104	-45.203	-28.315	-5.647	53.637	0.000
182	19	21	(g)	-44	14	14	25	25	101	105	-0.259	-13.455	-12.376	18.283	0.000
183	20	21	(g)	-43	16	0	26	26	106	102	7.983	9.960	-272.931	273.229	0.000
184	21	21	(g)	-41	34	34	27	15	107	104	-0.000	0.000	59.555	59.555	0.000
185	22	21	(g)	-42	35	0	16	16	106	105	-0.000	-0.000	-722.639	722.639	0.000
186	23	25	(hb)	-44	17	17	36	36	0	0	35.355	30.136	-386.750	409.095	124.999
187	24	21	(g)	-44	18	18	37	37	102	104	-49.775	-31.919	-12.300	60.396	0.000
188	25	21	(g)	-44	19	19	28	29	101	105	-0.822	-13.899	-13.412	19.333	0.000
189	26	21	(g)	-44	20	20	39	39	106	102	7.955	9.938	-270.832	271.131	0.000
190	27	21	(g)	-43	21	0	30	30	107	101	7.287	5.744	20.211	22.239	0.000
191	28	21	(g)	-51	25	0	38	38	108	105	-0.160	-16.166	-4.996	16.921	0.000

```

1893 *----- PYTHIA Error and Warning Messages Statistics -----*
1894 |
1895 | times    message
1896 |
1897 |      19  Error in Pythia::next: hadronLevel failed; try again
1898 |      15  Error in StringFragmentation::fragment: stuck in joining
1899 |       4  Error in StringFragmentation::fragmentToJunction: caught in junction flavour loop
1900 |       2  Warning in HadronWidths::pickMasses: angular momentum and running widths not used
1901 |       4  Warning in PhaseSpace2to2tauyz::trialKin: maximum for cross section violated
1902 |       1  Warning in Pythia::check: energy-momentum not quite conserved
1903 |       5  Warning in Pythia::check: not quite matched particle energy/momentum/mass
1904 |       2  Warning in SimpleSpaceShower::pT2nextQCD: small daughter PDF
1905 |       4  Warning in SimpleSpaceShower::pT2nextQCD: weight above unity
1906 |       7  Warning in SimpleTimeShower::findMEcorr: ME weight above PS one
1907 |       1  Warning in SimpleTimeShower::pTnext: negative dipole mass.
1908 |      71  Warning in StringFragmentation::fragmentToJunction: bad convergence junction rest frame
1909 |
1910 *----- End PYTHIA Error and Warning Messages Statistics -----*

```



## Results

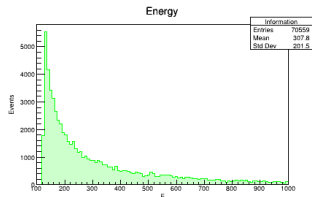
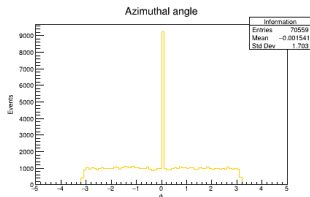
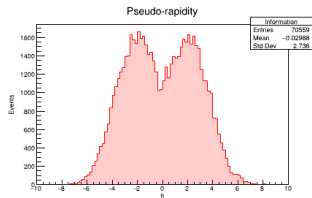
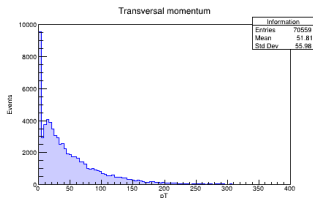


# A simple analysis of the Higgs

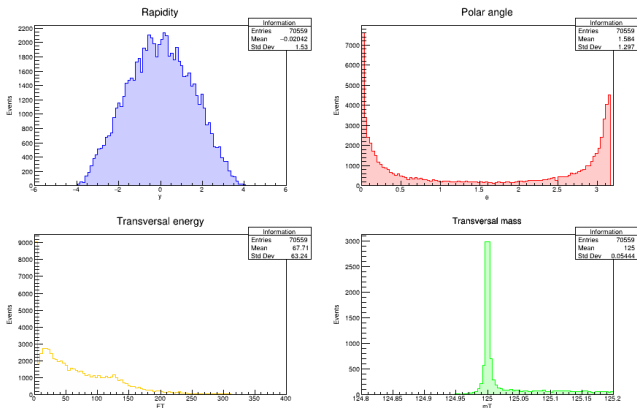
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# A simple analysis of the Higgs

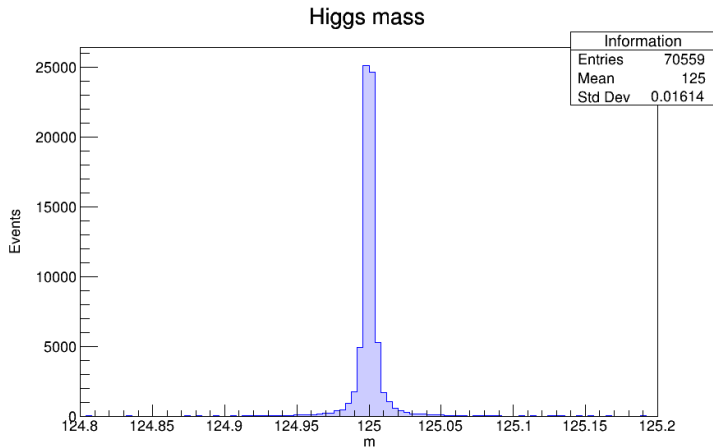
- Before to show the main analysis of this project let's study in first place the kinematical variables associated with the Higgs boson.
- Indeed, the histogram for the variables  $p_T$ ,  $\eta$ ,  $\phi$  and  $E$  have the form



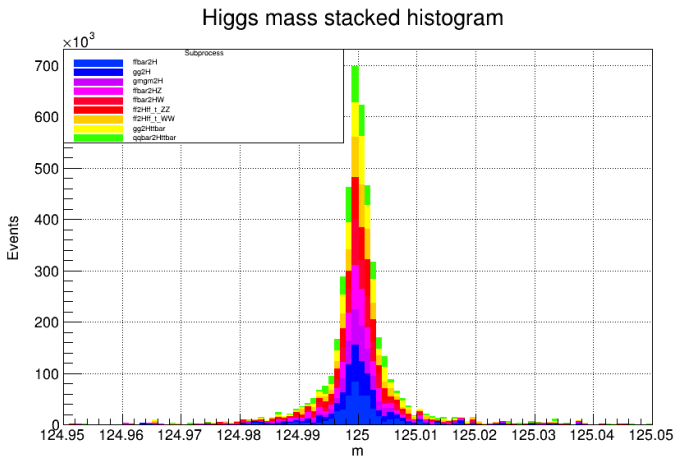
- Furthermore, the histogram for the variables  $y$ ,  $\theta$ ,  $E_T$  and  $m_T$  have the form



- 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  $f\bar{f} \rightarrow H^0$ ,  $gg \rightarrow H^0$ ,  $\gamma\gamma \rightarrow H^0$ ,  $f\bar{f} \rightarrow H^0 Z^0$ ,  $f\bar{f} \rightarrow H^0 W^\pm$ ,  $f f' \rightarrow H^0 f f'$ ,  $f_1 f_2 \rightarrow H^0 f_3 f_4$ ,  $gg \rightarrow H^0 t\bar{t}$  and  $q\bar{q} \rightarrow H^0 t\bar{t}$  is shown in the stacked mass histogram



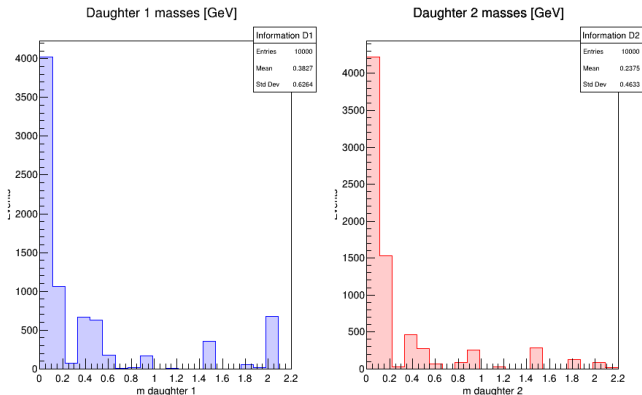
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- The diphoton mass receive contributions from a large irreducible background from quantum chromodynamics.

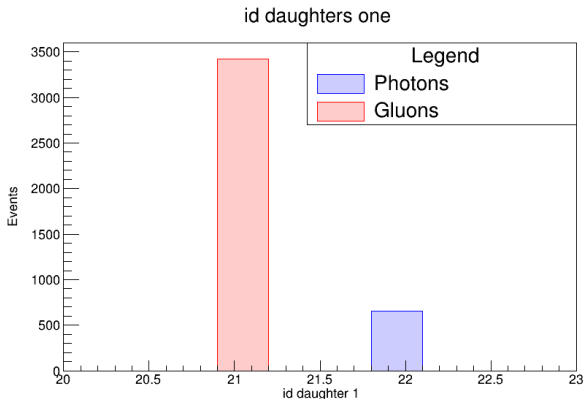
- In the  $H \rightarrow \gamma\gamma$  channel we made a search of the diphoton mass  $m_{\gamma\gamma}$  in the range 110 – 150 GeV.
- The diphoton mass receive contributions from a large irreducible background from quantum chromodynamics.
- The channel  $H \rightarrow \gamma\gamma$  is one of the most promising channels in the search of the SM Higgs boson in low mass range.

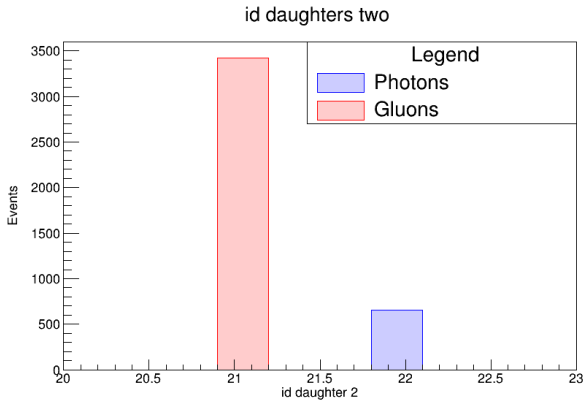


- Now, let's try to reconstruct the SM Higgs boson in the  $H \rightarrow \gamma\gamma$  channel. Indeed, the distribution of the masses of the all possible daughter (according to PYTHIA) of the SM Higgs boson is



- 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



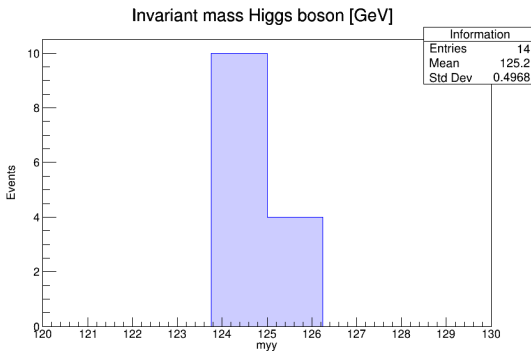


- From above we see that we have daughters that correspond to photons and gluons. However, we are interested only on the photon daughters.

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- In this way, by using the formula

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

we get the following histogram for the diphoton mass:



$$H \rightarrow c\bar{c}$$

- When the Higgs boson was discovered, this particle was measured in the decay channel  $\gamma\gamma$ ,  $ZZ$ ,  $WW$  and  $\tau\tau$ .

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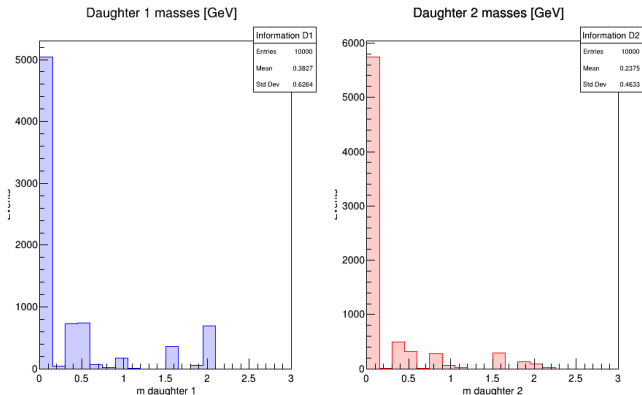
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- Recently, ATLAS and CMS reported the coupling of the  $H$  boson with the quarks  $t$  and  $b$ .
- Thus, the next objective is the measurement of the coupling of  $H$  with second generation quarks ( $c$  and  $s$ ).

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

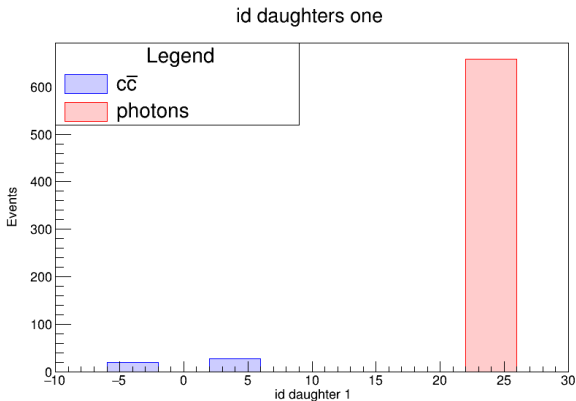


- From the previous histogram we have that there is a very low production of daughters between the mass range  $1 - 1.5 \text{ GeV}$ , where the charm quark is located.

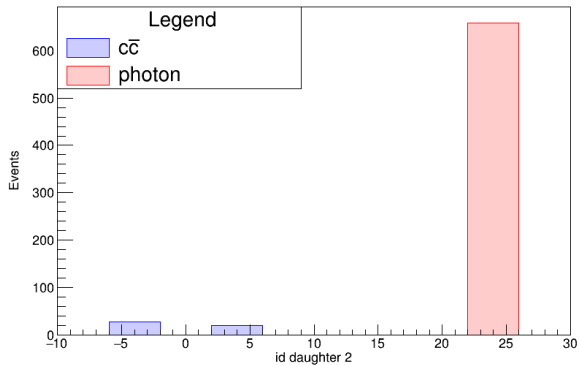
- From the previous histogram we have that there is a very low production of daughters between the mass range  $1 - 1.5$  GeV, where the charm quark is located.
- This is expected, because the branching fraction for the decay  $H \rightarrow c\bar{c}$  is  $0.0288^{+0.0016}_{-0.0006}$ . This says that the coupling of the Higgs to the quarks  $c\bar{c}$  is very weak.

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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



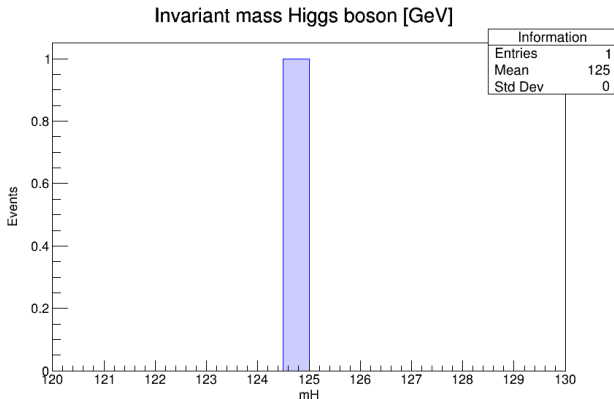
id daughters two



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

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

we get the following histogram





## Conclusions and remarks

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

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- The simulations were made with 10000  $pp$  collisions. However, we can go further with more collisions by using computational clusters (e.g. LXPLUS).

# Acknowledgments

I would like to thanks the professors Edson Carquin and Juan Manuel Flores for the very enlightening lectures on Computational Physics imparted during this semester. This work is supported by Beca Interna del programa de doctorado de la Universidad Técnica Federico Santa María.

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

**Muchas gracias por la atención!**