Discovering new particles in a collider: statistical data analysis

Higgs discovery

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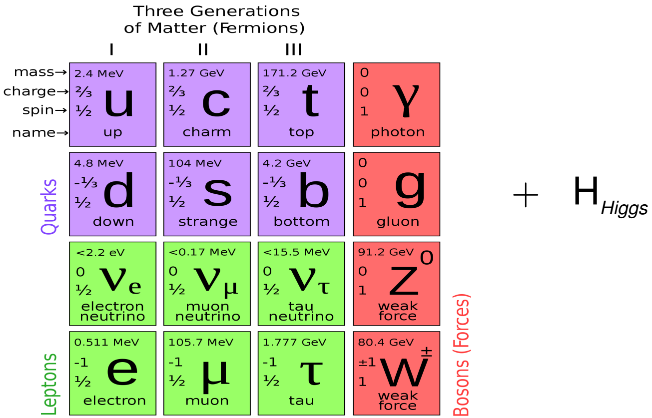
Module 4

Part I

Preliminaries

The Standard Model of Elementary Particles

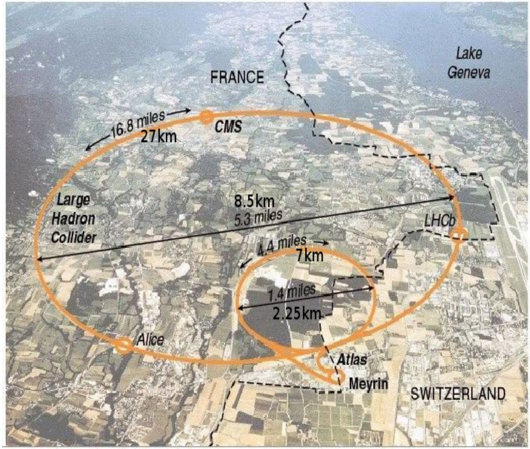


The Higgs Mechanism

- Higgs field in vacuum has a constant vacuum value (the *vev*)
  All masses of particles are proportional to this *vev*.
- Perturbations around the vacuum Higgs state will be physical particles (like photons are perturbations of an electromagnetic field)
  $\Rightarrow$ the new particles are Higgs bosons

How to see a Higgs? Smash protons at the LHC!

- LHC: Large Hadron Collider
- Near Geneva, under the Swiss/French border
- 27km circunference, underground.



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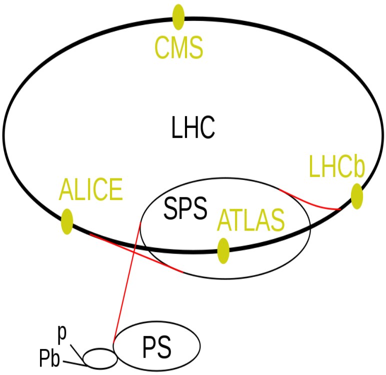
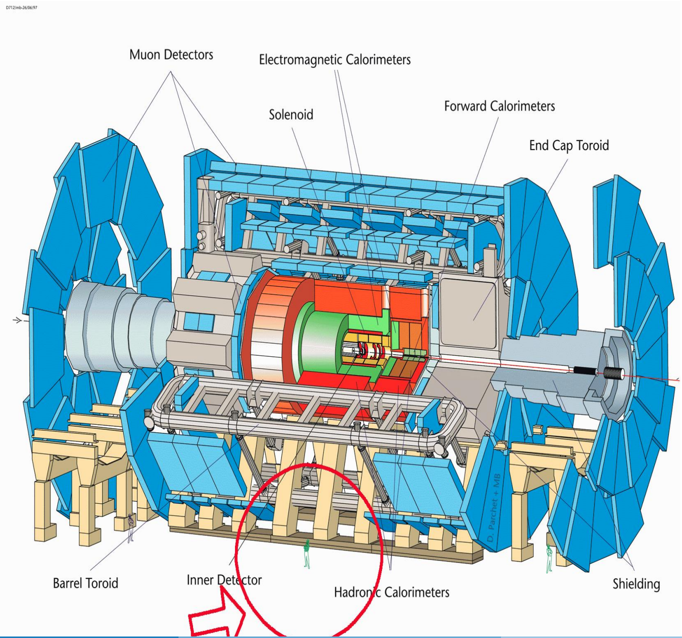
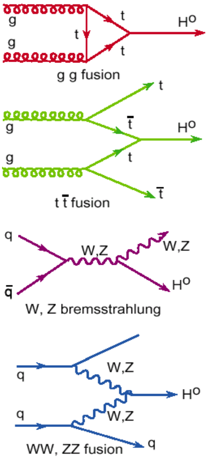


- *proton* – *proton* collisions at 13 TeV
- protons going at about 99.9999991% of the speed of light are smashed against each other
- 10^9 inelastic events per second! (a billion per second)

Atlas Detector at the LHC

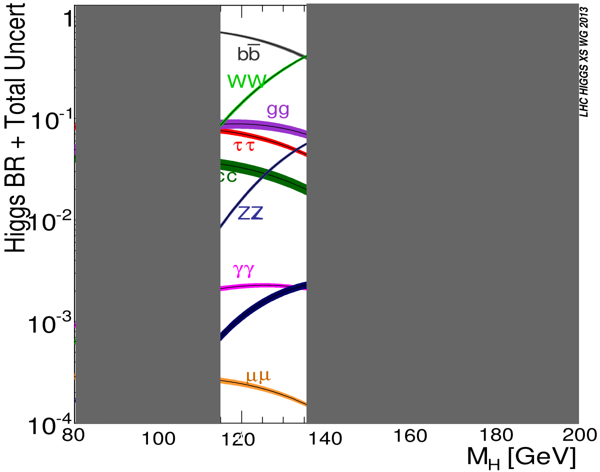


LHC Higgs production



⇒ 0.4 Higgs events per second, or 24 Higgses per minute, or 1500 Higgses produced during this class...

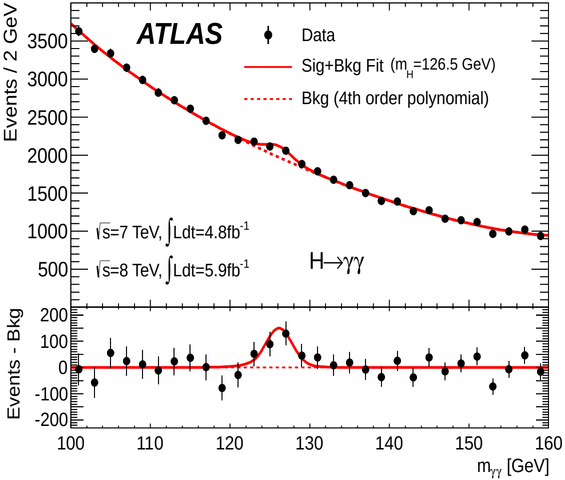
Higgs decays:Branchings



How does the Higgs decay? : Branchings of Higgs vs. its mass

Search strategy

Look for the decay $H \to \gamma\gamma$



2012 Higgs discovery in diphoton channel ATLAS

Part II

Where is the Higgs? Statistical data analysis

Special Relativity-kinematics - 101

- Higgs will decay into two photons.
- Energy is conserved ($E_h = E_{\gamma_1} + E_{\gamma_2}$)
- Momentum is conserved ($\vec{P}_h = \vec{P}_{\gamma_1} + \vec{P}_{\gamma_2}$)
- Energy is special relativistic ($E_h^2 = m_h^2 + |P_h|^2$ and $E_{\gamma_i}^2 = |P_i|^2$)

From the third eq. we write

$$m_h^2 = E_h^2 - |P_h|^2$$

We square the first eq. and the second eq. , and we substract them:

$$E_h^2 - |P_h|^2 = 2E_{\gamma_1}E_{\gamma_2} - 2\vec{P}_{\gamma_1}.\vec{P}_{\gamma_2}$$

So that finally

$$m_h^2 = 2E_{\gamma_1}E_{\gamma_2} - 2\vec{P}_{\gamma_1}.\vec{P}_{\gamma_2}$$

Measuring energies and momenta of photons, we get the Higgs mass!

Special Relativity-kinematics

In practice, measured quantitites (for massles particles) will be

- The transverse momentum of particles: $|p_T|^2 = p_x^2 + p_y^2$, with p_z being along the beam direction.
- The azimuthal angle ϕ of particle's momentum
- The pseudo-rapidity η, related to the polar angle of particle's momentum ($\eta = -\ln(\tan\theta/2)$)

Then, the previous formula becomes

$$m_h^2 \simeq 2\,|\mathbf{p}_T(1)||\mathbf{p}_T(2)|\left(\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)\right)$$

Data

“Experimental” data file will look like:

```
#</LesHouchesEvents>
#
## Integrated weight (pb)  : 6.512
## Number of Event         : 500000
 #  typ    eta    phi    pt   jmas  ntrk  btag  had/em  dum1  dum2
 0          1   897
 1   0  -1.210  4.477  54.04  0.00  0.0  0.0   0.01  0.0  0.0
 2   0  -0.581  1.304  47.48  0.00  0.0  0.0   0.00  0.0  0.0
 3   6   0.000  6.050   1.76  0.00  0.0  0.0   0.00  0.0  0.0
 0          2   897
 1   0  -0.079  2.152  33.90  0.00  0.0  0.0   0.01  0.0  0.0
 2   0   1.932  5.294  42.61  0.00  0.0  0.0   0.01  0.0  0.0
 3   6   0.000  2.477   2.92  0.00  0.0  0.0   0.00  0.0  0.0
```

This is 2 events. We will have 500 000 events to treat..

Data

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```

Type of particle.
- 0 = photon
- 1 = electron
- 2 = muon
- 3 = tau
- 4 = jet
- 6 = missing transv. energy

Pseudo-rapidity

Azimuthal angle (rads)

Transverse momentum (GeV)

Counting Statistics

- **Binomial distribution**: Success or failure trials
  We define $P_{binomial}(k)$ as the probability of observing k positives in n trials with p the probability of a single succes.

  $$P_{binomial}(k) = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k}$$

  Example: define success as obtaining a 4 by throwing a dice.
  Probability of obtaining 50 successes in 100 throws:

  $$\begin{aligned} p &= 1/6 \\ k &= 50 \\ n &= 100 \end{aligned}$$

Counting Statistics

- **Poisson distribution**: Can be thought of the limit of binomial when $p \to 0$ and $n \to \infty$
  - Define P_k as the probability to count in a concrete experiment k events when the expected (average) count is μ.

$$P_{Poisson}(k) = \frac{\mu^k}{k!} e^{-\mu}$$

  - The variance σ^2 is equal to the average

$$\sigma^2 = \mu$$

  - The standard deviation σ is

$$\sigma = \sqrt{\mu}$$

Example: The expected number of observed diphoton events with a total energy between 100 GeV and 102 GeV is $\mu = 8000$. The probability to observe $k = 8050$ diphoton events is

$$P_{Poisson}(8050) = \frac{8000^{8050}}{8050!} e^{-8000}$$

Counting Statistics

- **Gauss Distribution**: can be obtained from Poisson distribution when μ is large.
  In general,

$$P_{Gauss}(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(x-x_0)^2}{\sigma^2}}$$

Meaning of σ, 2σ, 3σ ...5σ (probability).

- Percent Prob. of obs. events beyond 1σ is 32%
- Percent Prob. of obs. events beyond 2σ is 4.5%
- Percent Prob. of obs. events beyond 3σ is 0.27%
- Percent Prob. of obs. events beyond 5σ is 5×10^{-5} %

In general the Percent Probability of obs. events within $(N\sigma)$ is $(1 - erf(N/\sqrt{2})) \times 100\%$

Counting Statistics

- **Significance of a deviation:**

If we count an excess of events, we would like to know if it is a statistical fluctuation or if it is really something NEW.

We need the probability of observing an excess (SIGNAL) over the expected number of events (BACKGROUND).
We have

$$Obs. \quad = \quad B + S$$

The standard deviation in Poisson is the square root of the expected number, i.e $\sigma = \sqrt{B}$. So we would like to know, how many σ does the excess (Signal) represent. This is the “poor man’s/woman’s” definition of Signal Signicance:

$$Significance = \frac{S}{\sqrt{B}} \quad (\equiv \ how\ many\ \sigma\ away\ from\ expected)$$

Part III

Procedure

Lab procedure

- Construct a histogram: count number of diphotons with an invariant energy between M and M+2GeV
- Fit the obtained curve to obtain an “average/background” curve
- obtain $S = Obs - B$ and compute signal significance for any excess
- Claim the discovery (or not) of a Higgs of a given mass!