Hunting down the Higgs boson at the LHC

Kajari Mazumdar
DHEP, TIFR

• Introduction
• Higgs boson production and decay
• Statistical method
• Experimental aspects of some of the searches
• Results
Recapitulation

- Interactions of elementary particles are determined by symmetries.
- The symmetry group of electroweak interactions is SU(2)XU(1).
- The fundamental interactions among elementary particles, fermions, are mediated by exchange particles, called gauge bosons.
- Symmetries require the gauge bosons to be massless.
- Mediator of electromagnetic interaction, photon, is massless \(\Rightarrow\) infinite range of interaction.
- However, we see that the weak interaction has finite range \(\Rightarrow\) the mediators for charged and neutral currents, \(W^\pm\) and \(Z^0\) particles, are massive.

\(\Rightarrow\) spontaneous symmetry breaking (SSB).
Question: How to provide masses to $W$ and $Z$, while preserving the symmetry?

Answer: We only need to preserve the symmetry of the interactions, not of the whole theory.

In other words, the Lagrangian of the theory is invariant under the symmetry, but the ground state is not.

Most famous example is ferromagnet whose Lagrangian is invariant under rotation, but the magnetization is not.

Anderson-Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

At low energy or ground state the potential is still symmetric, but not the position of the ball. At higher energy the shape of the potential is different --> phase transition
In EW theory, the SSB is implemented via Higgs mechanism through the introduction of a set of scalar fields.

The signature of this mechanism is the Higgs boson: a massive, scalar particle whose coupling to each of the other particles is proportional to the mass of that particle.

Higgs boson is not yet observed in experiments. Mass of the Higgs boson is not known, it is an input to the theory. It has to be hunted out!

One of the main goals of high energy physics experiments is to discover the Higgs boson. Advancement of technology is essential to achieve the feat.

What makes the search of Higgs boson so crucial?

The Higgs mechanism is the signature of SSB in the standard model (SM) of electroweak interaction.
The Large Hadron Collider (LHC)

- All the experimental data till date confirms the predictions of SM very well in terms of properties of the mediators and their interactions with the fermions.

- However the confirmation of EWSB is still awaited: Higgs boson has been elusive.

- One of the main motivations of LHC is to find the Higgs boson.

- LHC is also a fail-safe machine.

- It is possible that SSB occurs not by the Higgs mechanism, but by some other means.

- In such a case, LHC experiments are also capable of observing signals of such a mechanism.

- Today we discuss about the results of Higgs boson searches, mainly in CMS experiment.
Theoretically, in SM Higgs boson can be of any mass upto about 600 GeV/c². Indirect measurements of Higgs boson mass from various experimental observations ⇒ Higgs boson is likely to be light.

LHC is broad band machine⇒ can produce particles of mass upto few TeV/c²
Proton-Proton bunch/beam: 1400
Protons/bunch: $2 \times 10^{11}$
Beam energy: 3.5 TeV ($1 \text{ TeV} = 10^{12} \text{ eV}$)
Luminosity: $2 \times 10^{33}$/cm$^2$/s
Crossing rate: 20 MHz
Collisions: $10^8$ Hz

Summer, 2011

Selection of 1 in $10,000,000,000,000,000$
SM Higgs production at LHC: theoretical predictions

- **Gluon-gluon fusion**
  - $H^0$ production
  - 20 pb for $m_H = 120$ GeV

- **Vector boson fusion**

- **Associated production with vector boson**

- **Associated production with heavy quarks**

**Event rate = cross-section* BR**
- * instantaneous luminosity
- * experimental efficiency
- * detector acceptance

→ high integrated luminosity
  * needed for rare processes
Higgs decay in SM

Higgs coupling is proportional to the mass of the particle it couples to.

Searches in 3 general regions

- Low mass (110-140): $H \rightarrow \gamma\gamma, \tau\tau, bb, WW^*, ZZ^*$
- Medium mass (140-200): $H \rightarrow WW(2l2\nu)$
- High mass (200-600): $H \rightarrow ZZ(4l), ZZ(2l2\nu), ZZ(2l2j), WW(2l2\nu)$

LHC experiments (ATLAS, CMS) have invested heavily in detecting photons and leptons, jets, missing energy accurately:

- tracking device.
- electromagnetic calorimeter (mass resolution ~0.5%)
- muon spectrometer. (mass resolution ~1%)
- Jet and missing energy measurements much better than anticipated.
High inst. lumi → lots of pile up events in detector
Higgs Width

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\Gamma_H$ [GeV]</th>
<th>$m_H$ [GeV]</th>
<th>$\Gamma_H$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>$0.2573 \times 10^{-2}$</td>
<td>220</td>
<td>2.301</td>
</tr>
<tr>
<td>110</td>
<td>$0.2938 \times 10^{-2}$</td>
<td>240</td>
<td>3.397</td>
</tr>
<tr>
<td>120</td>
<td>$0.3600 \times 10^{-2}$</td>
<td>260</td>
<td>4.767</td>
</tr>
<tr>
<td>130</td>
<td>$0.5006 \times 10^{-2}$</td>
<td>280</td>
<td>6.443</td>
</tr>
<tr>
<td>140</td>
<td>$0.8281 \times 10^{-2}$</td>
<td>300</td>
<td>8.452</td>
</tr>
<tr>
<td>150</td>
<td>$0.1744 \times 10^{-1}$</td>
<td>320</td>
<td>10.81</td>
</tr>
<tr>
<td>155</td>
<td>$0.3042 \times 10^{-1}$</td>
<td>340</td>
<td>13.50</td>
</tr>
<tr>
<td>160</td>
<td>$0.8255 \times 10^{-1}$</td>
<td>360</td>
<td>17.57</td>
</tr>
<tr>
<td>165</td>
<td>0.2434</td>
<td>380</td>
<td>23.04</td>
</tr>
<tr>
<td>170</td>
<td>0.3760</td>
<td>400</td>
<td>29.16</td>
</tr>
<tr>
<td>180</td>
<td>0.6291</td>
<td>450</td>
<td>46.82</td>
</tr>
<tr>
<td>190</td>
<td>1.036</td>
<td>500</td>
<td>67.94</td>
</tr>
<tr>
<td>200</td>
<td>1.426</td>
<td>600</td>
<td>122.5</td>
</tr>
</tbody>
</table>

For low mass of Higgs boson experimental resolution is critical! A total of 144 mass points searched in the 110 - 600 GeV range, placed according to achievable resolution.
The CMS experiment

3381 scientists and engineers (including ~840 students) from 173 institutes in 40 countries
CMS measurements of EW bosons and di-bosons

Yesterday’s discovery and today’s signal are indeed tomorrow’s background for Higgs search.

All measured values are consistent with SM predictions

Thesis of A. Saha on W-charge asymmetry

Thesis of D. Majumder on $W\gamma$ measurement
Statistical issues

- The treatment is decided upon *before* looking at data to avoid any bias.
- Higgs boson signal is too small compared to the background.

- Sensitivity of experiments are at their limits. eg., compare mass resolution of different channels with Higgs natural width at different mass values.

- There are many systematics involved in measurements: * nuisances* ➔ consider signal and background events as func.s of nuisance parameters.

- Used “**CLs**” construction to be conservative in the presence of background fluctuations.

- Calculate p-value at mass point s to indicates the compatibility of observation with background only hypothesis. lower p-value ➔ significant excess compared to background expectation.
**Statistical method: limit setting**

CLs method to set limits on $\mu = \sigma / \sigma_{SM}$

→ Frequentist approach including systematic error evaluation

$\mu$: strength of signal → for standard model Higgs boson hypothesis

$\mu = 1$, only background hypothesis $\Rightarrow \mu = 0$

Likelihood function: $L(\text{data}|\mu, \theta) = L_{\text{obs}}(\text{data}|\mu, \theta) \cdot L(\theta_0|\theta)$

Prob. of observing the data given $\mu$, $\theta$, nuisance parameter. For counting experiment with $b(\theta)$ background and $s(\theta)$ signal it is a Poisson($N | \mu \cdot s(\theta) + b(\theta)$)

Deals with systematics

$\Theta_0$: default value of nuisance parameter, evaluated from data.

$\Theta$: distributed around $\Theta_0$

   different types of pdfs for various systematics (eg. Gaussian for the ones which can take on both positive and negative values, etc. etc.)
Examples of *nuisances* in different channels

1. Uncertainty in cross-section $\sim 20\% \rightarrow$ affects all the signal and background processes mainly due to: parton density functions.

2. Higher order corrections $\rightarrow$ scale uncertainties for different processes

3. Modelling of underlying event and parton showering

4. Luminosity of the machine ($\sim 6\%$)

5. Efficiencies of muon, electron, .. ($90$-$99\%$)

6. Energy resolution of photon, electron, momentum resolution of $\mu$

7. Energy scale of electron ($\sim 3\%$)

.....

Some are applicable across all channels, some pertains to specific channels.
Statistical Procedure

For each value of the signal strength $\mu = \sigma / \sigma_{SM}$

1. Evaluate on the data the test statistics to discriminate between hypotheses: Higgs (signal exists) and only background

Test-statistic: profile likelihood ratio:

$$q_\mu = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}$$

2. generate an ensemble of pseudo experiments for background-only and signal+background with $\theta^{\text{obs}}_0$, $\theta^{\text{obs}}_\mu$

   for the cases of no signal and for the particular value of $\mu$ using $\theta$ which fits the observations the best.

3. Evaluate test statistics for pseudo-exp, compare with observed value.

If $CL_s < 0.05$, then the value of $\mu$ is excluded at 95% CL.
Quantifying excess of events

- For a given mass construct test statistics
- For a given observation of background only hypothesis, $q^{\text{obs}}$
- Evaluate the approximate p-value:
  $$\bar{p} = \frac{1}{2} \left[ 1 - \text{erf} \left( \frac{\sqrt{q_0^{\text{obs}}}}{2} \right) \right]$$

Convert p-value to significance $Z$, for one-sided Gaussian tail

$$p = \int_{-\infty}^{0} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2) \, dx.$$  

for $Z=5$, $p$-value$=2.8 \times 10^{-7}$

Look Elsewhere Effect

- When establishing the significance for possible signal due to Higgs boson, we are inadvertently biased towards the region of maximum likelihood.

- However the background fluctuations may occur anywhere and might conjure to show excess of events; or sometimes, deficit.
- Hence the dilution effect has to be considered $\Rightarrow$ reduced significance.
Main backgrounds: continuum production of ZZ: irreducible + reducible processes.

$H \rightarrow ZZ \rightarrow 4l$: all final state particles are visible

- Invariant masses can be constructed well mass resolution 1%
- high sensitivity at low mass regions

Candidate event in r-z view. Candidate mass $\sim 360$ GeV
• Cross-section consistent with SM background of continuum ZZ production.
• No significant excess of events at any fixed mass
• Excluded Higgs mass 180-420 GeV/c^2 at 95% CL
Feature:
W-spins are anti-aligned in H-decay
⇒ Charged leptons tend to be in the same direction.
Signature: 2 highly isolated leptons
+ missing transverse energy
+ no central jet/hadronic activity
⇒ Higgs mass cannot be reconstructed completely
⇒ Essentially counting experiment
⇒ Both selection cut based and multi-variant analyses.

High sensitivity over whole range, but low mass resolution (~30 GeV/c²)
Exclusion limit from $H \rightarrow WW$: 150 -193 GeV/$c^2$

Cut based analysis

- Higgs boson mass (GeV/$c^2$)

Boosted Decision Tree

Interesting excess of events in low mass range for categories:
- $H \rightarrow WW+0$ jet
- $H \rightarrow WW +1$ jet

More data needed for confirmation
Analysis:

• Various categories according to the position of photon in different parts of the detector, photon conversion, etc.
• Stringent isolation condition for $\gamma$ to reduce pile up effect.

• Task at hand: better calibration of EM calorimeter required.

• Low sensitivity, high mass resolution of 1-2 GeV/c$^2$

• Look for $\gamma\gamma$ mass peak above background estimated from side band $\rightarrow$ tiny signal over smoothly falling very large background, estimated with Bernstein function.

• Good mass resolution of di-photon essential.
  $\rightarrow$ energy resolution of Electro-magnetic Calorimeter crucial.
  $\rightarrow$ vertex resolution: tough job in presence of many pileups.

H$\rightarrow$\gamma\gamma
No significant excess of events:
• two bumps with local p-values 3-4% (<2σ)
• LEE: probability to observe a 2σ-excess for background-only hypothesis is ~60%.
Standard model Higgs combination results from CMS for 1.1 fb$^{-1}$

<table>
<thead>
<tr>
<th>channel</th>
<th>mass range (GeV/c$^2$)</th>
<th>luminosity (fb$^{-1}$)</th>
<th>number of sub-channels</th>
<th>type of analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110-140</td>
<td>1.1</td>
<td>8</td>
<td>mass shape (unbinned)</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>110-140</td>
<td>1.1</td>
<td>6</td>
<td>mass shape (binned)</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow 2\ell 2\nu$</td>
<td>110-600</td>
<td>1.1</td>
<td>5</td>
<td>MVA (binned); cut&amp;count</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4\ell$</td>
<td>110-600</td>
<td>1.1</td>
<td>3</td>
<td>cut&amp;count</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 2\ell 2\nu$</td>
<td>250-600</td>
<td>1.1</td>
<td>2</td>
<td>cut&amp;count</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 2\ell 2q$</td>
<td>226-600</td>
<td>1.0</td>
<td>6</td>
<td>mass shape (unbinned)</td>
</tr>
</tbody>
</table>

- Low mass: 22 channels, high mass: 18 , 142 nuisance parameters
- (PAS HIG-11-011)
• At high masses, the combination gives a large gain over all individual analyses

• At very low mass, excess in the $H \rightarrow WW$ analysis makes combination equal or even more conservative than the $H \rightarrow yy$ search would imply on its own.
In the low mass part (114-149 GeV/c^2) a couple of interesting regions show excesses larger than 3σ (local significance without correction for LEE effects). Further study with the new data will confirm if it is a background fluctuation or a first sign of the Higgs boson.
ATLAS results

\[ \int \text{Ldt} = 1.0-1.2 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

The figure shows the 95% CL limit on \( \sigma/\sigma_{\text{SM}} \) vs. \( m_H [\text{GeV}] \). The observed CLs and expected limits are indicated by the green and yellow bands, respectively. The regions 155 < \( M_H < 190 \) and 295 < \( M_H < 450 \) GeV/c\(^2\) are excluded at 95% CL.
If there are 4 fermion generations, the SM4 Higgs boson is excluded in the 120-600 GeV/c^2 mass range at 95% CL.

Fermiophobic Higgs boson, of mass > 111 GeV/c^2 ruled out at 95% CL
Conclusion

LHC is at the threshold of discovery.

CMS and ATLAS collaborations have declared similar regions of exclusion for mass.

The standard model of Higgs boson may be just lurking around the corner. It is a bit too early to judge conclusively.

It is a matter of more data (and hence time) which will indicate if the excess of events already seen by ATLAS and CMS experiments, based on about 1 fb\(^{-1}\) of data, is indeed genuine, or just background fluctuations.

The combined results of the two experiments will be announced during Lepton Photon conference in 3 weeks’ time.

LHC machine is performing much better than expected and scheduled to deliver about 7-8 fb\(^{-1}\) by end of 2012 ➔ the issue of the existence of Higgs boson will be settled very soon.  

Stay Tuned!
Backup
no significant excess of events:
three bumps with local p-values ~1-5%
the two smallest p-value bumps would require ~ $4\cdot\sigma_{SM}$ cross section
no significant excess of events:
three bumps with local p-values ~1-5%
the two smallest p-value bumps would require ~ 4 \sigma_{SM} cross section
Combine results of 6 search channels.
Low mass range: $H \rightarrow \tau\tau$

- binned $m_{vis}$ distributions in 6 exclusive final states

- observed exclusion: $\sim 10 \cdot \sigma_{SM}$
  - observed $\approx$ expected
  - shape is rather featureless, due to the broad $m_{\tau\tau}$ resolution

- no significant excess:
  - LEE trial factor $\sim 1$
High mass range: $H \rightarrow ZZ$

- cut-and-count with sliding cuts ($m_H$) in two event categories

- observed exclusion: $1-4 \cdot \sigma_{SM}$
  - variations are within $\pm 2\sigma$ statistical bands
  - correlation “length” agrees with the “effective” $m_H$ mass window size of 50 (200) GeV at low (high) Higgs mass

- no significant excess of events:
  - one bump at $m_H \sim 290$ with local p-values $\sim 1\%$
  - the bump would require $\sim 2 \cdot \sigma_{SM}$ cross section
High mass range: $H \rightarrow ZZ$

- unbinned $m_{\ell\ell j}$ analysis $\rightarrow 2\ell 2q$ in six event categories

- observed exclusion: $2-10 \cdot \sigma_{SM}$
  - variations are within $\pm 2\sigma$ statistical bands
  - correlation “length” agrees with the “effective” $m_{ZZ}$ peak width of 3% (6%) at 250 (500) GeV Higgs mass

- no significant excess of events:
  - three bumps with local p-values ~1-5%
  - the two smallest p-value bumps would require $\sim 4 \cdot \sigma_{SM}$ cross section
The challenge of 2011 data taking
First step with data: di-photon resonance within minutes of collision