Discovery of a new boson

Part I: Experimental analysis: mass measurement
Part II: Measurement of properties
A massless theory

The standard model describes the interactions between matter and forces

- Gauge invariance plays a crucial role
  \( \psi(x) \rightarrow e^{i\alpha(x)} \psi(x) \)

- Gauge bosons, conserved “charges”

<table>
<thead>
<tr>
<th>Forces:</th>
<th>E&amp;M</th>
<th>Weak</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td>U(1)</td>
<td>SU(2)</td>
<td>SU(3)</td>
</tr>
<tr>
<td>Conserved</td>
<td>Q</td>
<td>isospin</td>
<td>color</td>
</tr>
<tr>
<td>Mediators</td>
<td>( \gamma )</td>
<td>( W^\pm, Z )</td>
<td>gluons</td>
</tr>
</tbody>
</table>

\[ \mathcal{L}_{SM} = \frac{1}{4} W_{\mu \nu} W^{\mu \nu} - \frac{1}{4} B_{\mu \nu} B^{\mu \nu} - \frac{1}{4} G_{\mu \nu}^a G^{a \mu \nu} \]

- Kinetic en. and self-inter. of gauge bosons

\[ + \bar{L} \gamma^\mu (i \partial_\mu - \frac{1}{2} g \tau \cdot W_\mu - \frac{1}{g} \gamma \cdot YB_\mu) L + \bar{R} \gamma^\mu (i \partial_\mu - \frac{1}{2} g \gamma \cdot YB_\mu) R \]

- Kin. en. and EW interactions of fermions

\[ + g''' (\bar{q} \gamma^\mu T_a q) G_\mu^a \]

- Interactions between quarks and gluons

Adding a mass term \( m^2 W_\mu W^\mu \) makes \( \mathcal{L} \) not gauge-invariant, but the \( W \) and \( Z \) have mass!

- Need to break SU(2)xU(1) to keep gauge invariance

- Spontaneous symmetry breaking: symmetric \( \mathcal{L} \), ground state is not
Electroweak symmetry breaking

- Add $\phi$, a new (complex doublet) scalar field with potential:
  $$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad V(\phi) = \lambda \left( \phi^\dagger \phi - \frac{v^2}{2} \right)^2$$
  - Breaks $SU(2) \times U(1) \rightarrow U(1)$
  - 4 d.o.f $\rightarrow$ 3 longitudinal polarizations of $W^+, W^-, Z^0$
    + 1 new scalar boson: $H$
  - Lowest energy of vacuum $v/\sqrt{2}$

- The scalar's kinetic energy includes a term that becomes:
  $$\frac{1}{4} g^2 W^\mu \phi^\dagger W_\mu \phi \rightarrow \frac{1}{8} g^2 v^2 W^\mu W_\mu = \frac{1}{2} M_W^2 W^\mu W_\mu$$
  A mass term for the $W$ and $Z$ bosons!

- Interactions with fermions:
  - Fermion masses are generated in a gauge invariant way by arbitrary coupling, proportional to mass:
  $$y f \phi f \rightarrow \frac{y v}{\sqrt{2}} f f + \frac{y}{\sqrt{2}} f h f$$

P. Higgs, Phys. Rev. Lett. 13 (1964) 508,
Predictions

2010 J.J. Sakurai Prize
“For elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses”

- A new scalar boson $s=0$, $P=+1$, $m_h = \sqrt{2\lambda \cdot v}$
  - Discover resonance, measure its mass ✔
  - Measure its properties (spin, parity)
- Couplings to bosons
  - Test relative strength between $\gamma$, $W$, $Z$
- Couplings to fermions
  - Perhaps something else gives rise to the fermion masses?
- Self coupling
  - Test strength (will need lots of data!)
The Large Hadron Collider

- p-p collider at $\sqrt{s}=7, 8$ TeV
- 26 km long, 100m underground
- Delivered luminosity: $18$ fb$^{-1}$
- Peak luminosity: $7 \times 10^{33}$ cm$^2$s$^{-1}$
- Crossing rate: 40 MHz
- Rare processes: 1 in $10^{13}$
The CMS detector

The CMS solenoid magnet:
- Magnetic length: 12.5 m
- Free bore diameter: 6 m
- Central B Field: 4 T
- Weight: 12,000 ton
- Temperature: 4.2°K
- Nominal current: 20 kA
- Radial Pressure: 64 atm
- Stored energy: 2.7 GJ

USS Ronald Reagan (88,000 tons) at 20 mph
Total weight: 14000 t
Overall diameter: 15 m
Overall length: 28.7 m

ECAL
76k scintillating PbWO₄ crystals
Scintillator/brass interleaved ~7k ch

3.8T Solenoid

IRON YOKE

Pixel Tracker ECAL HCAL Muons Solenoid coil

Pixels & Tracker
- Pixels (100x150 μm²) ~ 1 m² ~66M ch
- Si Strips (80-180 μm) ~200 m² ~9.6M ch

MUON BARREL
250 Drift Tubes (DT) and 480 Resistive Plate Chambers (RPC)

MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Particle detection in CMS

https://cms-docdb.cern.ch/cgi-bin/PublicEPPOGDocDB/RetrieveFile?docid=97&version=1&filename=CMS_Slice_elab.swf
UR contributions to CMS

- **Hadronic calorimeter**: design, construction, commissioning
  - 70,000 plastic scintillator tiles

- **Silicon detector**: prototyped, tested, and commissioned Si modules
  - 200 square meters of Si (100 kg)

- **Objects**: tracks, $\mu$, jets, b-jets

- **Physics**: $W$, $Z$, top, searches, H
Physics at a hadron collider is like... drinking from a fire hose

\[ N = \sigma [\text{cm}^2] L [\text{cm}^{-2}\text{s}^{-1}] \sim \text{MHz} \]

LHC at 8 TeV and \( L = 7 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1} \) produces \( \sim 750 \text{ H/hour} \)

\( \sqrt{s} = 7 \text{ TeV} \)

\(~70\) papers published on standard model physics at 7 and 8 TeV:
no deviations from predictions have been observed
H production and decay

The scalar can be produced via different interactions (protons at 4 TeV mostly contain gluons)
Production cross section $\sigma$ depends on the unknown H mass
The scalar then decays in one of several final states: the fraction of each decay also depends on the unknown H mass. All channels are needed to establish the nature of the new particle. $M_H = 125$ GeV: all decays possible!
Search for $H \rightarrow \gamma\gamma$

- We need to separate this:
  - Only a small fraction of jets can mimic a photon – but there are a lot of jets!
  - Channel with tiny decay width, but small backgrounds
  - Scintillator Electromagnetic calorimeter designed to achieve:
    \[
    \frac{\delta E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{0.16\text{GeV}}{E}
    \]

- From this:
  - Use shape info to separate from $\pi \rightarrow \gamma\gamma$
Diphoton analysis

\[ E^2 = (mc^2)^2 + (|\tilde{p}|c)^2 \]

\[ m_H = \sqrt{\left( \sum \frac{E_i}{c^2} \right)^2 - \left( \sum \frac{\vec{p}_i}{c} \right)^2} \]

\[ m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)} \]
Diphoton analysis

- Select events with 2 photons:
  - Use MVA trained to reject fakes using observed shower-shape differences, isolation
  - Select pair with highest $\Sigma p_T$
  - $p_T^{y1} > m_{yy}/3$ ; $p_T^{y2} > m_{yy}/4$
  - $|\eta| < 2.5$

- Use MVA to separate H signal from backgrounds
  - Inputs: photon $p_T$, $\eta$, and MVA output, $\cos \Delta \phi_{yy}$, and per-event mass resolution

- Include VBF channel
  - 2 isolated $\gamma$ + 2 forward jets
  - Large s/b, but small s

- Cross checks:
  - Mass fits with sidebands
  - Simple cut-based analysis
Diphoton results

Combination of 11 different categories

Events are weighted by S/B

Fit backgrounds to polynomials

Clear “bump” seen over falling background

Here the $m_{\gamma\gamma}$ resolution of $\sim 2$ GeV is crucial!
$H \rightarrow \gamma\gamma$ candidate event
**Golden channel:**
- Very good mass resolution
- Low (real) backgrounds
- Need high efficiency: decay width $\sim 0.06^2$
- Very small statistics

Expect $164\pm11$, observe 172 events in [70-800] GeV
We can use kinematics

- **MELA discriminant**
  - Exploit decay of scalar X into two heavy Z bosons that then decay to two charged leptons
- **Significant gain in S/B: most sensitive channel**
- **MELA is mostly insensitive to the spin of the H: relies on character of backgrounds**
- **MELA > 0.5 consistent with S+B**
Candidate event $H \rightarrow ZZ^* \rightarrow \mu\mu\mu\mu$
Candidate event $H \to ZZ^* \to e\mu e\mu$
Combined significance


- **CMS expected:** 4.7\(\sigma\)  
  - 1 in 3.5\(\cdot\)10\(^6\) chance of a background fluctuation  
  - \(m_H = 125.3 \pm 0.4\) (stat.) \(\pm 0.5\) (sys.) GeV

- **ATLAS expected:** 4.6\(\sigma\)  
  - \(m_H = 126.0 \pm 0.4\) (stat.) \(\pm 0.4\) (sys.) GeV
The Standard Model of particle physics
Years from concept to discovery

Source: The Economist
Conclusions

Observation in CMS, and independently in ATLAS, of a new boson with a mass of roughly 125 GeV decaying to vector bosons

It is certainly looking and walking like the SM scalar boson. Does it also quack like the SM Higgs boson?

Some questions:
- Are the relative signal strengths and couplings consistent? Maybe!
- We know it's a boson, we also know it is not spin 1. Is it spin 0? Maybe!
- If it is spin 0, is it a scalar or a pseudoscalar? Maybe!
- Does it couple to fermions? Maybe!
- Is the width accounted for in the accessible channels? Maybe!

Lots of work still to do!
Extra slides

For more information:
## Higgs Decays

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Fraction</th>
<th>Useful Branching fraction</th>
<th>Background Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom quarks</td>
<td>60%</td>
<td>30%</td>
<td>Tens of thousands:1</td>
</tr>
<tr>
<td>WW*</td>
<td>15%</td>
<td>~2%</td>
<td>Few:1</td>
</tr>
<tr>
<td>ZZ*</td>
<td>4%</td>
<td>0.014%</td>
<td>Comparable</td>
</tr>
<tr>
<td>gluons</td>
<td>10%</td>
<td>10%</td>
<td>Millions:1</td>
</tr>
<tr>
<td>taus</td>
<td>8%</td>
<td>6%</td>
<td>A long story</td>
</tr>
<tr>
<td>Charm quarks</td>
<td>6%</td>
<td>3%</td>
<td>Tens of thousands:1</td>
</tr>
<tr>
<td>Two photons</td>
<td>0.2%</td>
<td>0.2%</td>
<td>Few:1</td>
</tr>
</tbody>
</table>

For a ~125 GeV Higgs

The quantity of signal is but one element in designing an analysis. The level of background is at least as important. While I will only barely touch on it, so is triggerability: you cannot analyze an event that you didn’t record.
\[ \pi \rightarrow \gamma \gamma \]

Parton level

Particle Jet

Energy depositions in calorimeters
Ratio of WW and ZZ couplings:
Both dominated by gluon fusion production
Ratio of signal strengths is therefore dominantly the ratio of couplings to W/Z
Separate fit to WW and ZZ with $M_H = 125.3 \pm 0.6$ GeV