Search for the Higgs Boson at the LHC

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Outline of the talk:

1. Introduction, the Higgs boson in the Standard Model

2. The Standard Model Higgs boson search
   - ATLAS and CMS results in various channels
     (with some focus on $H \rightarrow WW \rightarrow l^+ l^- l^+ l^-$)
   - The combination of searches

3. Prospects and outlook

Disclaimer: I will try to highlight the most important results on searches for the Higgs boson. The coverage is not complete, i.e. not all results available will be presented.
The Standard Model of Particle Physics

(i) Constituents of matter: quarks and leptons
(ii) Four fundamental forces
    (described by quantum field theories, except gravitation)
(iii) The Higgs field  (problem of mass)
Why do we need the Higgs Boson?

The Higgs boson enters the Standard Model to solve two fundamental problems:

• **Masses of the vector bosons W and Z:**

  Experimental results:
  \[ M_W = 80.399 \pm 0.023 \text{ GeV} / c^2 \]
  \[ M_Z = 91.1875 \pm 0.0021 \text{ GeV} / c^2 \]

  A local gauge invariant theory requires massless gauge fields

• **Divergences in the theory** (scattering of W bosons)

\[ -iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty \]
The Higgs mechanism

Spontaneous breaking of the SU(2) x U(1) gauge symmetry

- Scalar fields are introduced
  \[ \phi = \frac{1}{\sqrt{2}} \left( \phi_1 + i \phi_2 \right) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \]

  Potential:
  \[ V(\phi) = \mu^2 (\phi^* \phi) + \lambda (\phi^* \phi)^2 \]

- For \( \mu^2 < 0, \lambda > 0 \), minimum of potential:
  \[ \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2 \]
  \[ v^2 = -\mu^2 / \lambda \]

- Perturbation theory around ground state:
  \[ \phi_0(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \]
  
  3 massive vector fields:
  \[ m_{W^\pm} = \frac{1}{2} v g \]
  \[ m_Z = \frac{m_W}{\cos \theta_W} \]

  1 massless vector field:
  \[ m_\gamma = 0 \]

  1 massive scalar field: The Higgs boson \( H \)
  \[ m_H = \sqrt{\lambda v^2} \]

\( v = \) vacuum expectation value
\[ v = \frac{1}{\sqrt{\sqrt{2} G_F}} = 246 \text{ GeV} \]
The Higgs mechanism (cont.)

- Coupling terms of W- and Z-bosons and fermions to the Higgs field:

- The introduced scalar fields can also be used to generate fermion masses

\[ m_f = \frac{g_f v}{\sqrt{2}} \Rightarrow g_f = \frac{m_f \sqrt{2}}{v} \]

- Higgs boson self-coupling

\[ L = \ldots - \lambda v h^3 - \frac{1}{4} \lambda h^4 \]

and finally

- Higgs boson regulates divergences in the WW scattering cross section
The Higgs boson as a UV regulator

Scattering of longitudinally polarized $W$ bosons

\[ -iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{m_W^2} \quad \text{for} \quad s \rightarrow \infty \]

Higgs boson guarantees unitarity (if its mass is $< \sim 1$ TeV)

\[ -iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty \]
Higgs Boson Decays

The decay properties of the Higgs boson are fixed, if the mass is known:

- $W^+$, $Z$, $t$, $b$, $c$, $\tau$, $\ldots$, $g$, $\gamma$
- $W^-$, $Z$, $t$, $b$, $c$, $\tau$, $\ldots$, $g$, $\gamma$

![Graph showing BR (H) vs. M_H (GeV) with various lines for different decay modes]
Constraints on the Higgs boson mass

1. Constraints from theory

2. Indirect limits from electroweak precision data (theory and experiment)

3. Limits from Direct Searches (LEP, Tevatron)
(i) Tighter Higgs mass constraints from theory:

Stronger bounds on the Higgs-boson mass result from the energy dependence of the Higgs coupling $\lambda(Q^2)$
(if the Standard Model is assumed to be valid up to some scale $\Lambda$)

$$
\lambda(Q^2) = \lambda_0 \left\{ 1 + \frac{3\lambda_0}{2\pi^2} \log \left( \frac{Q^2}{v^2} \right) + \cdots - \frac{3g_t^4}{32\pi^2} \log \left( \frac{Q^2}{v^2} \right) + \cdots \right\}
$$

where $\lambda_0 = \frac{m_h^2}{v^2}$

Upper bound: diverging coupling (Landau Pole)

Lower bound: stability of the vacuum (negative contribution from top quark dominates)

Mass bounds depend on scale $\Lambda$
up to which the Standard Model should be valid

Hambye, Risselmann et al.
(ii) Indirect limits from electroweak precision data \((m_W \text{ and } m_t)\)

Sensitivity to the Higgs boson and other new particles via quantum corrections:

\[ m_H = 92^{+34}_{-26} \text{ GeV/c}^2 \]

\[ m_H < 161 \text{ GeV/c}^2 \] (95 % CL)
(iii) Constraints from direct searches

- $m_H > 114.4$ GeV  
  from direct searches at LEP

- $m_H < 156$ GeV or $m_H > 177$ GeV  
  from direct searches at the Tevatron
Begin of a new era in particle physics
Data taking in 2011

Original goal to collect 1 fb\(^{-1}\) already surpassed in June 2011

- World record on instantaneous luminosity on 22. April 2011:
  \[4.67 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\]
  (Tevatron record: \[4.02 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\])
  meanwhile: \[> 10^{33} \text{ cm}^{-2} \text{ s}^{-1}\]

- Collect per day as much luminosity as in 2010

- Data taking efficiency is high

- Pile-up is high
  (high intensity bunches)
Production Cross Sections at the LHC

- Inelastic proton-proton reactions: $10^9 / \text{s}$
- $\text{bb pairs}$: $5 \times 10^6 / \text{s}$
- $\text{tt pairs}$: $8 / \text{s}$
- $W \rightarrow e \nu$: $150 / \text{s}$
- $Z \rightarrow e e$: $15 / \text{s}$
- Higgs (150 GeV): $0.2 / \text{s}$
- Gluino, Squarks (1 TeV): $0.03 / \text{s}$
An impressive number of processes has already been measured. Excellent agreement with the Standard Model predictions.
Higgs boson production at the LHC

\[ \sigma(pp \rightarrow H + X) \text{ [pb]} \]

\[ \sqrt{s} = 14 \text{ TeV} \]

NLO / NNLO

Gluon Fusion

Vector boson fusion

tt associated production

WH/ZH associated production

MRST
Higher order corrections:

Independent variation of renormalization and factorization scales
(with $0.5 \, m_H < \mu_F, \mu_R < 2 \, m_H$)
Useful Higgs Boson Decays at Hadron Colliders

**at high mass:**
*Lepton* final states
(via $H \rightarrow WW, ZZ$)

**at low mass:**
*Lepton and Photon* final states
(via $H \rightarrow WW^*, ZZ^*$)

*Tau* final states

The dominant *bb decay mode* is only useable in the associated production mode ($ttH, W/Z H$)

(due to the huge QCD jet background, leptons from W/Z or tt decays)
$H \rightarrow WW \rightarrow \ell \nu \ell \nu$

- Large $H \rightarrow WW$ BR for $m_H \sim 160$ GeV/c$^2$
- Neutrinos $\rightarrow$ no mass peak, $\rightarrow$ use transverse mass

- Large backgrounds: WW, Wt, tt

- Two main discriminants:
  (i) Lepton angular correlation
  (ii) Jet veto: no jet activity in central detector region

Channel with highest sensitivity!
Sensitive to a Standard Model Higgs boson already now, with 1 fb$^{-1}$!
Search for $H \rightarrow WW \rightarrow l_1 \nu_l l_2 \nu_l$

- Select events with two opposite sign leptons ($e$, $\mu$) $p_T(l_1) > 25$ GeV
  $p_T(l_2) > 20$ GeV ($e$), 15 GeV ($\mu$)

- First look at invariant mass distributions $\rightarrow$ good agreement for all channels

\[ L_{\text{int}} = 1.70 \text{ fb}^{-1} \]

\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 1.70 \text{ fb}^{-1} \]

$ee, \mu\mu$: large $Z/\gamma^*$ production background (Drell-Yan), can be rejected by Z mass veto
$e\mu$: residual contribution from $Z \rightarrow \tau\tau$, $e\nu\mu\nu$ and top production
Search for $H \rightarrow WW \rightarrow l\nu l\nu$ (cont.)

- Additional discrimination: missing transverse energy

$$E_{T,\text{rel}}^{\text{miss}} = \begin{cases} E_T^{\text{miss}} & \text{if } \Delta\phi \geq \pi/2 \\ E_T^{\text{miss}} \cdot \sin \Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases}$$

Apply additional cuts on: $Z$-mass veto (previous slide) $|m_l - m_Z| < 15$ GeV $(ee, \mu\mu)$

$E_{T,\text{rel}}^{\text{miss}} > 40$ GeV $(ee,\mu\mu)$,

$> 25$ GeV $(e\mu)$
Search for \( H \rightarrow WW \rightarrow l\nu l\nu \) (cont.)

- Split sample according to jet multiplicity (\( E_T > 25 \text{ GeV} \))
  (different production modes, different background compositions)

- Jet distribution well described
  
  \# observed events: 4051
  \# expected background: 4000 ± 500

\[\rightarrow\text{Select 0- and 1-jet events}\]
Search for H → WW → lν lν (cont.)

• Further discrimination using m_ℓℓ and Δφ between the two leptons:

![Graphs showing data and MC distributions for m_ℓℓ and Δφ for 0 jet and 1 jet scenarios.]
Search for $H \to WW \to l\nu l\nu$ (cont.)

Transverse mass distributions:

$\sqrt{s} = 7$ TeV, $\int L dt = 1.70$ fb$^{-1}$

- No evidence for an excess above Standard Model backgrounds
- Use statistical methods to quantify this and extract a limit on the production cross section

\[ m_T = \sqrt{(E_{T}^\ell + E_{T}^{\text{miss}})^2 - (p_{T}^\ell + p_{T}^{\text{miss}})^2} \]
Search for $H \rightarrow WW \rightarrow l\nu l\nu$ (cont.)

- number of events at various cut stages-

### 0 jet

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>WW</th>
<th>$W + \text{jets}$</th>
<th>$Z/\gamma^* + \text{jets}$</th>
<th>$t\bar{t}$</th>
<th>$tW/\tau b/\tau q b$</th>
<th>$WZ/ZZ/W\gamma$</th>
<th>Total Bkg.</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Veto</td>
<td>82 ± 17</td>
<td>430 ± 40</td>
<td>70 ± 40</td>
<td>160 ± 150</td>
<td>37 ± 13</td>
<td>28 ± 7</td>
<td>11 ± 3</td>
<td>740 ± 160</td>
<td>738</td>
</tr>
<tr>
<td>$p_T^{\ell\ell} &gt; 30$ GeV</td>
<td>79 ± 17</td>
<td>390 ± 40</td>
<td>60 ± 30</td>
<td>28 ± 11</td>
<td>35 ± 12</td>
<td>25 ± 7</td>
<td>10 ± 3</td>
<td>540 ± 80</td>
<td>574</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 50$ GeV</td>
<td>56 ± 12</td>
<td>98 ± 13</td>
<td>17 ± 7</td>
<td>12 ± 7</td>
<td>6 ± 3</td>
<td>4.8 ± 1.5</td>
<td>1.2 ± 0.4</td>
<td>139 ± 20</td>
<td>175</td>
</tr>
<tr>
<td>$\Delta\phi_{\ell\ell} &lt; 1.3$</td>
<td>48 ± 11</td>
<td>76 ± 10</td>
<td>9 ± 4</td>
<td>8 ± 6</td>
<td>5 ± 2</td>
<td>4.8 ± 1.5</td>
<td>1.1 ± 0.3</td>
<td>105 ± 16</td>
<td>131</td>
</tr>
<tr>
<td>$0.75 m_H &lt; m_T &lt; m_H$</td>
<td>34 ± 7</td>
<td>43 ± 6</td>
<td>5 ± 2</td>
<td>2 ± 4</td>
<td>2.2 ± 1.4</td>
<td>1.2 ± 0.8</td>
<td>0.7 ± 0.3</td>
<td>53 ± 9</td>
<td>70</td>
</tr>
<tr>
<td>$ee$</td>
<td>5.2 ± 1.2</td>
<td>6.2 ± 0.9</td>
<td>0.9 ± 0.4</td>
<td>0.8 ± 1.4</td>
<td>0.3 ± 0.3</td>
<td>0 ± 0.3</td>
<td>0.07 ± 0.05</td>
<td>8.2 ± 1.7</td>
<td>9</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>17 ± 4</td>
<td>22 ± 3</td>
<td>2.8 ± 1.3</td>
<td>0 ± 1.3</td>
<td>1.1 ± 0.5</td>
<td>0.8 ± 0.6</td>
<td>0.31 ± 0.19</td>
<td>27 ± 4</td>
<td>32</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>11 ± 2</td>
<td>14 ± 2</td>
<td>1.0 ± 0.6</td>
<td>1 ± 3</td>
<td>0.8 ± 1.1</td>
<td>0.4 ± 0.4</td>
<td>0.31 ± 0.09</td>
<td>18 ± 5</td>
<td>29</td>
</tr>
</tbody>
</table>

### 1 jet

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>WW</th>
<th>$W + \text{jets}$</th>
<th>$Z/\gamma^* + \text{jets}$</th>
<th>$t\bar{t}$</th>
<th>$tW/\tau b/\tau q b$</th>
<th>$WZ/ZZ/W\gamma$</th>
<th>Total Bkg.</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \text{ jet}$</td>
<td>41 ± 7</td>
<td>158 ± 16</td>
<td>31 ± 19</td>
<td>60 ± 60</td>
<td>390 ± 100</td>
<td>140 ± 20</td>
<td>10.7 ± 1.4</td>
<td>800 ± 120</td>
<td>756</td>
</tr>
<tr>
<td>$b$-jet veto</td>
<td>40 ± 7</td>
<td>154 ± 16</td>
<td>29 ± 18</td>
<td>60 ± 50</td>
<td>140 ± 40</td>
<td>54 ± 9</td>
<td>10.6 ± 1.4</td>
<td>450 ± 70</td>
<td>440</td>
</tr>
<tr>
<td>$p_T^{\ell\ell} &lt; 30$ GeV</td>
<td>32 ± 6</td>
<td>127 ± 13</td>
<td>16 ± 9</td>
<td>30 ± 30</td>
<td>90 ± 20</td>
<td>41 ± 7</td>
<td>7.0 ± 0.9</td>
<td>310 ± 50</td>
<td>312</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$ veto</td>
<td>32 ± 6</td>
<td>124 ± 14</td>
<td>14 ± 7</td>
<td>30 ± 20</td>
<td>84 ± 19</td>
<td>39 ± 7</td>
<td>6.8 ± 1.4</td>
<td>300 ± 30</td>
<td>301</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 50$ GeV</td>
<td>22 ± 5</td>
<td>27 ± 5</td>
<td>2.1 ± 1.0</td>
<td>8 ± 6</td>
<td>17 ± 6</td>
<td>9 ± 2</td>
<td>1.5 ± 0.4</td>
<td>64 ± 10</td>
<td>69</td>
</tr>
<tr>
<td>$\Delta\phi_{\ell\ell} &lt; 1.3$</td>
<td>19 ± 4</td>
<td>21 ± 4</td>
<td>1.8 ± 0.9</td>
<td>4 ± 5</td>
<td>14 ± 5</td>
<td>8 ± 2</td>
<td>1.2 ± 0.3</td>
<td>50 ± 9</td>
<td>54</td>
</tr>
<tr>
<td>$0.75 m_H &lt; m_T &lt; m_H$</td>
<td>12 ± 3</td>
<td>10 ± 2</td>
<td>0.8 ± 0.4</td>
<td>1.1 ± 1.8</td>
<td>6.9 ± 1.9</td>
<td>3.4 ± 1.4</td>
<td>0.6 ± 0.3</td>
<td>23 ± 4</td>
<td>23</td>
</tr>
<tr>
<td>$ee$</td>
<td>1.7 ± 0.4</td>
<td>1.4 ± 0.4</td>
<td>0.12 ± 0.06</td>
<td>0.07 ± 0.12</td>
<td>0.6 ± 0.3</td>
<td>0.5 ± 0.3</td>
<td>0.10 ± 0.09</td>
<td>2.8 ± 0.7</td>
<td>5</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>6.3 ± 1.5</td>
<td>5.7 ± 1.3</td>
<td>0.5 ± 0.3</td>
<td>0.6 ± 1.0</td>
<td>3.7 ± 1.3</td>
<td>2.0 ± 1.0</td>
<td>0.39 ± 0.20</td>
<td>13 ± 3</td>
<td>11</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>3.9 ± 0.9</td>
<td>3.3 ± 0.7</td>
<td>0.1 ± 0.2</td>
<td>0.5 ± 0.5</td>
<td>2.6 ± 1.5</td>
<td>1.0 ± 0.9</td>
<td>0.08 ± 0.06</td>
<td>8 ± 2</td>
<td>7</td>
</tr>
</tbody>
</table>
How are the backgrounds normalized?

- Most important backgrounds are WW continuum production and tt production.

  Both are well described by the Standard Model calculations / Monte Carlos.

- Cross-check / normalization is performed in defined control regions:
  
  * **WW control region:**
    
    remove cuts on $\Delta \phi$ cut and require:
    
    - $m_{ll} > 80$ GeV/c$^2$ (e$\mu$)
    - $m_{ll} > m_Z + 15$ GeV/c$^2$ (ee, $\mu\mu$)
  
  * **tt control region via b-tag selections**
  
  * **Z+jets / Drell-Yan** (suffers from $E_T^{miss}$ / lepton mismodelling)

### Number of events in WW control region

<table>
<thead>
<tr>
<th>$e e + e \mu + \mu \mu$</th>
<th>Signal</th>
<th>WW</th>
<th>$W + \text{jets}$</th>
<th>$Z/\gamma^* + \text{jets}$</th>
<th>$t\bar{t}$</th>
<th>$tW/tb/tq\bar{b}$</th>
<th>WZ/ZZ/Wγ</th>
<th>Total Bkg.</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>$1.4 \pm 0.3$</td>
<td>$190 \pm 20$</td>
<td>$18 \pm 15$</td>
<td>$5 \pm 7$</td>
<td>$22 \pm 9$</td>
<td>$13 \pm 4$</td>
<td>$7 \pm 3$</td>
<td>$250 \pm 50$</td>
<td>$238$</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>$0.020 \pm 0.011$</td>
<td>$22 \pm 3$</td>
<td>$3 \pm 3$</td>
<td>$1 \pm 5$</td>
<td>$3.8 \pm 1.9$</td>
<td>$1.1 \pm 1.0$</td>
<td>$0.29 \pm 0.09$</td>
<td>$30 \pm 6$</td>
<td>$45$</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$1.4 \pm 0.3$</td>
<td>$126 \pm 17$</td>
<td>$14 \pm 10$</td>
<td>$0.9 \pm 0.7$</td>
<td>$13 \pm 6$</td>
<td>$8 \pm 2$</td>
<td>$5 \pm 3$</td>
<td>$170 \pm 40$</td>
<td>$150$</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>$0.030 \pm 0.012$</td>
<td>$38 \pm 5$</td>
<td>$1.6 \pm 1.5$</td>
<td>$4 \pm 3$</td>
<td>$5 \pm 2$</td>
<td>$4.0 \pm 1.4$</td>
<td>$1.1 \pm 0.3$</td>
<td>$53 \pm 8$</td>
<td>$43$</td>
</tr>
</tbody>
</table>
Table 2: Experimental sources of systematic uncertainty per object or event.

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Treatment in the analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Resolution (JER)</td>
<td>~ 14%, see Ref. [69]</td>
</tr>
<tr>
<td>Jet Energy Scale (JES)</td>
<td>Takes into account close-by jets effect, jet flavor composition uncertainty and event pile-up uncertainty in addition to global JES uncertainty. Global JES &lt; 10% for $p_T &gt; 15$ GeV and $</td>
</tr>
<tr>
<td></td>
<td>Pile-up uncertainty 2-5% for $</td>
</tr>
<tr>
<td></td>
<td>These are summed in quadrature before application.</td>
</tr>
<tr>
<td>Electron Selection Efficiency</td>
<td>Separate systematics for electron identification, reconstruction and isolation, added in quadrature. Total uncertainty of 2-5% depending on $\eta$ and $E_T$</td>
</tr>
<tr>
<td>Electron Energy Scale</td>
<td>Uncertainty smaller than 1%, depending on $\eta$ and $E_T$</td>
</tr>
<tr>
<td>Electron Energy Resolution</td>
<td>Energy varied within its uncertainty, 0.6% of the energy at most $\eta$ and $p_T$</td>
</tr>
<tr>
<td>Muon Selection Efficiency</td>
<td>0.3-1% as a function of $\eta$ and $p_T$</td>
</tr>
<tr>
<td>Muon Momentum Scale</td>
<td>$\eta$ dependent scale offset in $p_T$, up to ~ 0.13%</td>
</tr>
<tr>
<td>Muon Momentum Resolution</td>
<td>$p_T$ and $\eta$ dependent resolution smearing functions, $\leq 5%$</td>
</tr>
<tr>
<td>b-tagging Efficiency</td>
<td>$p_T$ dependent scale factor uncertainties, 5.6-15%, see Ref. [68]</td>
</tr>
<tr>
<td>b-tagging Mis-tag Rate</td>
<td>up to 21% as a function of $p_T$, see Ref. [68]</td>
</tr>
<tr>
<td>Missing Transverse Energy</td>
<td>13.2% uncertainty on topological cluster energy</td>
</tr>
<tr>
<td></td>
<td>Electron and muon $p_T$ changes from smearing propagated to MET</td>
</tr>
<tr>
<td></td>
<td>Effect of out-of-time pileup: MET smeared by 5 GeV in 1/3 of MC events</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.7% [25]</td>
</tr>
</tbody>
</table>
Sensitivity and exclusion

- Calculate cross sections that can be excluded with a 95% C.L. \( = \sigma_{95} \)
- Normalize them to the Standard Model cross sections for a given Higgs mass

Excluded mass regions (95% C.L.):
- \( 154 < m_H < 186 \) GeV
- Expected exclusion:
  - \( 135 < m_H < 196 \) GeV

The observed limits at neighboring mass points are highly correlated due to the limited mass resolution in this final state;
- Jump in the expected and observed limits at 220 GeV is caused by a change in the selection at that point
Significance for $H \rightarrow WW$

The expected (dashed) and observed (solid) signal significances

The expected (dashed) and observed (solid) probabilities for the background-only scenario, $P_0$
The expected (dashed) and observed (solid) signal significances

The expected (dashed) and observed (solid) probabilities for the background-only scenario, $P_0$
What does the CMS experiment see?

- A very similar analysis
- Good agreement between data and expectations from Standard Model processes without a Higgs boson
Results from CMS on the $H \rightarrow WW \rightarrow \ell\nu \ell\nu$ search:
$L = 1.55$ fb$^{-1}$ (large fraction of 2011 data)

- Data are in “reasonable” agreement with expectations from Standard Model processes;
- Important background normalized using control regions in data (like ATLAS)
CMS sensitivity and exclusion

- Very similar results as the ATLAS collaboration:
  Similar sensitivity, similar excluded mass range, 2σ like excess at low mass

Excluded mass regions (95% C.L.):
147 < m_H < 194 GeV
Expected exclusion:
135 < m_H < 200 GeV
What can be the cause of this excess?

• $H \rightarrow WW$ is a “difficult” channel!
  - no resonant structure / mass reconstruction not possible

• Excess can be due to:
  - First indications of a signal?
  - A statistical fluctuation?
  - systematic uncertainties in modelling of the Standard Model backgrounds (low mass)
    correlated systematic uncertainties between the two experiments, since they use the same Monte Carlo generators

• More data needed to perform many more systematic checks

• Support from other channels needed, e.g. $H \rightarrow ZZ^*$ or $H \rightarrow \gamma\gamma$
**Signal:** \( \sigma \text{BR} = 5.7 \text{ fb} \) \((m_H = 100 \text{ GeV})\)

**Background:**
- Top production:
  \( tt \rightarrow Wb \ Wb \rightarrow \ell \nu \ c \nu \ \ell \nu \ c \nu \)
  \( \sigma \text{BR} \approx 1300 \text{ fb} \)
- Associated production \( Z \ bb \)
  \( Z \ bb \rightarrow \ell \ell \ c \nu \ c \nu \)

**Background rejection:**
Leptons from b-quark decays
- non isolated
- do not originate from primary vertex
  \((\text{B-meson lifetime: } \sim 1.5 \text{ ps})\)

Dominant background after isolation cuts: \( ZZ \) continuum

Discovery potential in mass range from \( \sim 130 \) to \( \sim 600 \text{ GeV/c}^2 \)
$H \rightarrow ZZ^{(*)} \rightarrow \mu\mu \mu\mu$ candidate event

$m_{12} = 90.6$ GeV

$m_{34} = 47.4$ GeV
ATLAS results on $H \rightarrow ZZ^* \rightarrow 4l$ searches

- Data corresponding to 2.28 fb$^{-1}$ (taken up to August 2011) included
- No excess above Standard Model expectations visible

$\text{L}_{\text{int}} = 1.96 - 2.28$ fb$^{-1}$

- Rare decay $\rightarrow$ still limited by the available integrated luminosity
- Challenging for $m_H < 130$ GeV, requires low $p_T$ leptons
- However, Standard Model sensitivity already reached at high mass
ATLAS and CMS results for $H \rightarrow ZZ^* \rightarrow 4\ell$
over the full mass range

**ATLAS**

$H \rightarrow ZZ^* \rightarrow 4\ell$

$\int L dt = 1.96 - 2.28$ fb$^{-1}$

$\sqrt{s} = 7$ TeV

$95\%$ CL limit on $\sigma/\sigma_{SM}$

- **Observed CL**
- **Expected CL**

$\pm 1\sigma$

$\pm 2\sigma$

$M_H$ [GeV]

**CMS preliminary 2011**

$L_{int} = 1.66$ fb$^{-1}$

$95\%$ CL limit on $\sigma/\sigma_{SM}$

- **Observed Limit**
- **Expected Limit**

$\pm 1\sigma$

$\pm 2\sigma$

$M_H$ [GeV/c$^2$]
Decay modes at low mass: \( H \rightarrow \gamma\gamma \)

Main backgrounds:
- \( \gamma\gamma \) irreducible background
- \( \gamma \)-jet and jet-jet (reducible)

\[
\sigma_{\gamma j+jj} \sim 10^6 \sigma_{\gamma\gamma} \quad \text{with large uncertainties}
\]
\[
\text{need } R_j > 10^3 \quad \text{for } \varepsilon_\gamma \approx 80\% \text{ to get } \sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}
\]

- Main exp. tools for background suppression:
  - photon identification
  - \( \gamma \) / jet separation (calorimeter + tracker)

Sensitivity in the low mass region, however, higher integrated luminosities required
ATLAS results on $H \rightarrow \gamma\gamma$ searches

- Data corresponding to $1.08 \text{ fb}^{-1}$ analyzed, more to come soon…
- Sensitivity to Standard Model Higgs boson cross section not yet reached, as expected

\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 1.08 \text{ fb}^{-1} \]

\begin{itemize}
  \item Sensitivity is stable / flat in the low mass region, access to the 115 GeV region;
  \item Channel is less sensitive to pile-up
\end{itemize}
More channels at low mass?

With higher integrated luminosities more channels are expected to contribute:

(i) Tau decay mode via Vector Boson Fusion: \(qq H \rightarrow qq \tau \tau\)

(ii) \(bb\) decay mode via the associated production with vector bosons or top quarks:

\(WH, ZH\) or \(ttH\) with \(H \rightarrow bb\)

(very challenging)
Higgs boson search at high mass?

- Search at high mass is easier at the LHC;

- Higgs boson decays nearly 100% into WW or ZZ pairs, which give charged leptons, neutrinos, b-jets,…

- Important search channels:
  - $H \rightarrow WW \rightarrow \ell\nu\ell\nu$
  - $H \rightarrow WW \rightarrow \ell\nuqq$
  - $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$
  - $H \rightarrow ZZ \rightarrow \ell\ellqq$
  - $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$
Results from ATLAS on various high mass search channels:
\[ L = 1.04 - 2.28 \text{ fb}^{-1} \] (up to data taken shortly before Lepton-photon conference)

Also in these channels: data are consistent with expectations from Standard Model background processes

→ work out significances / statistics
Current status of the Higgs boson search at the LHC
-ATLAS and CMS-

- The two collaborations show similar performance
  - in terms of analysis power in the collaboration (many channels)
  - in terms of sensitivity
  - in terms of conclusions on the existence of the Higgs boson
Putting everything together
The grand combination of channels

- So far: ATLAS and CMS combinations available (summer conferences)
- Combination ATLAS + CMS is also ready; will be released this Friday, at HCP conference
Current status of the Higgs boson search at the LHC
-ATLAS and CMS combinations-

Excluded mass regions (95% C.L.):

\[ 146 < m_H < 232 \text{ GeV} \]
\[ 256 < m_H < 282 \text{ GeV} \]
\[ 296 < m_H < 466 \text{ GeV} \]

Excluded mass regions (95% C.L.):

\[ 145 < m_H < 216 \text{ GeV} \]
\[ 226 < m_H < 288 \text{ GeV} \]
\[ 310 < m_H < 400 \text{ GeV} \]
Prospects (new future)

- What can be done with 5 fb$^{-1}$ of data?
  Will most likely be shown in December this year, council meeting at CERN

- How much luminosity is needed for a 3$\sigma$ evidence or a 5$\sigma$ discovery?
  (in particular at low mass)

- Can the Higgs be ruled out?
  or can it be discovered with the 2011/2012 data?
Expectations for higher integrated luminosities
-95% C.L. exclusion limits-

- 95% C.L. exclusion can be reached with 5 fb⁻¹ in one experiment
- However, needs the combination of all low-mass channels
Expectations for higher integrated luminosities -discovery significances-

- For a $3\sigma$ effect in one experiment for a Higgs boson with a mass of 115 GeV, more than 10 fb$^{-1}$ will be needed.

- Significant gain by increasing the energy from 7 to 8 TeV; $3\sigma$ with $\sim$10 fb$^{-1}$

- Combined result of the two experiments will be interesting!
What, if no Higgs boson is found

• Well, this would be a big discovery!
  The Standard Model would be proven to be wrong

• Maybe Nature is not as simple as thought?
  In this case: the LHC is a unique facility to investigate further
  - It might “only” take more running time
    (e.g. modified couplings in more complicated Higgs scenarios, like composite Higgs bosons)
  - We all might get many years older before WW scattering is precisely measured
  - Invisibly decaying Higgs scenarios are very very difficult to be measured at the LHC
What, if the Higgs boson will be found soon

- Well, this would be a big discovery!

→ Measure its parameters and prove that it is a Higgs boson

Example:

 Precision on ratio of couplings to W coupling at the 20% level, needs high luminosity

Higgs boson self coupling very difficult to measure; maybe not even possible at the sLHC (needs further studies)

- A discovery of a light Higgs boson would also indicate “new physics”
Summary and Conclusions

• LHC machine and detectors are running extremely well!

• An impressive list of high quality physics measurements has already been performed

• The search for the Higgs boson has started very well
  - So far: data consistent with the Standard Model background hypothesis without a Higgs boson signal
  - Important new mass ranges have been excluded; however, the most interesting one not yet covered, but sensitivity will be reached soon

• Exiting times ahead of us!