Search for the SM Higgs boson in the $H \rightarrow WW(*) \rightarrow l\nu l\nu$ decay channel at LHC

MINI-WORKSHOP ON HIGGS SEARCH AT LHC
March 28, 2012 - LNF

Roberto Di Nardo – LNF INFN
Outline

- LHC operations in 2011
- Higgs production and decay
- The $H \rightarrow WW(*) \rightarrow l\ell\nu\nu$ searches in ATLAS and CMS
  - Experimental signature
  - Backgrounds
  - Systematic uncertainties
  - Results
LHC operation: the 2011 data taking

Excellent LHC performances in 2011:
• Delivered 5.7 fb\(^{-1}\) @ATLAS and CMS
• Peak luminosity \(3.6 \times 10^{33}\) cm\(^{-2}\) s\(^{-1}\)
• several machine parameters pushed beyond design

Experiments perform very well:
• High data taking efficiency
  • ATLAS(93.5%) CMS(91%)
• High fraction (90-96%) used for the analyses
...and a new challenge: the pileup

A possible problem for:
- Trigger
- Lepton isolation
- $E_T$ miss
- JES-JER
The SM @ $\sqrt{s}=7$ TeV

- An impressive number of processes have already been measured.
- Cross-sections measured up to few pb.
  - Excellent agreement with the Standard Model predictions.
  - Important for background estimates in Higgs boson searches.

- Useful as benchmark processes for object performance studies.
Understanding of detector performances: $E_T^{\text{miss}}$

- $Z \rightarrow ll$: no true MET
  - Resolution can be estimated as the width distribution of $E_x^{\text{miss}}$ and $E_y^{\text{miss}}$
  - Fundamental to understand (and reduce) especially with the increasing pileup

- $W \rightarrow lv$: real MET
  - $m_T$ fit of the lepton- $E_T^{\text{miss}}$ system
  - Determination of the $E_T^{\text{miss}}$ scale
- NNLO prediction for SM Higgs production cross section in most cases
  - theory uncertainties reduced to < 20% (e.g. ggf: pdf ~8%, scale ~ 10%)
- Huge progress also in the theoretical predictions of numerous and complex backgrounds
- H → WW →lvνν most sensitive channel
H → WW final state

Three possible final state for H → WW:

1. H → WW → lvlv
   - Relatively clean, background dominated by irreducible WW background.

2. H → WW → lvqq
   - High W+jets background
   - used at high m_H
   - excluded x2 SM x-sec

3. H → WW → 4q
   - Hopeless due to QCD bkg

Not covered in this talk.
The H→WW(*)→lνlν channel

Experimental signature:
• Two leptons (e or μ):
  • Opposite sign
  • Isolated
  • High p_T
• Two neutrinos:
  • Large E_T^{miss}
  • No mass peak (mass resolution~20%) → counting experiment

\[ m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - |\vec{p}_T^{\ell\ell} + \vec{p}_T^{miss}|^2} \]

Main Backgrounds:
• WW irreducible (topological cut helps)
• W+jet, Z+jet, tt, WZ, ZZ

The Challenge: understand backgrounds and normalize to control regions
Similar approach for ATLAS and CMS

Single lepton trigger (ATLAS)

Single or di-lepton trigger (CMS)

object selection

Leading lepton: $p_T > 25 \text{ GeV}$ (20 GeV)
sub-leading leptons: $p_T > 15 \text{ GeV}$ (10 GeV)
Jets anti-btagged: $p_T > 25 \text{ GeV}$ (30 GeV)

**MET**

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

ee, $\mu\mu$: $E_{T,\text{rel}}^{\text{miss}} > 45 \text{ GeV}$ (40 GeV, nvtx dependent)
e$\mu$: $E_{T,\text{rel}}^{\text{miss}} > 25 \text{ GeV}$ (20 GeV)
Event selection II

Z veto for $ee, \mu\mu : |m_{ll} - m_Z| > 15 \text{ GeV} \quad \text{(common)}$

- $m_{ll} > 12 \text{ GeV} \quad (ee, \mu\mu)$
- $m_{ll} > 10 \text{ GeV} \quad (e\mu)$
- $m_{ll} > 20 \text{ GeV} \quad (ee, \mu\mu)$
- $m_{ll} > 12 \text{ GeV} \quad (e\mu)$

Additional DY rejection

- $p_T^{ll} > 45 \text{ GeV} \quad (ee, \mu\mu)$
- $p_T^{ll} > 30 \text{ GeV} \quad (e\mu)$
- $p_T^{ll} > 45 \text{ GeV}$
Jet multiplicity & VBF

- Different $tt$ contamination depending on the number of jets per event
  - $tt$ final state: $llvv+bjets+Njets$
  - Anti $b$-jet veto used for $tt$ bkg reduction
- Analysis performed in jet categories:
  - 0 jet: very clean
  - 1 jet: $tt$ contamination
  - 2 jet: $tt$ contamination, VBF topology handle

**VBF signature:**
- very forward high $p_T$ jets, very high $M_{jj}$
  - 2 jet selection tuned on VBF-like signal
- central jet veto (ATLAS):
  - no selected jets in $|\eta| < 3.2$
  - 2 highest $p_T$ jets back to back in $\eta$
    - $\Delta\eta_{jj} > 3.8$, $m_{jj} > 500$ GeV (ATLAS)
    - $\Delta\eta_{jj} > 3.5$, $m_{jj} > 450$ GeV (CMS)
Topological cuts

- Extra requirements to optimize the sensitivity for a SM Higgs boson search

### ATLAS

- 3 $m_H$ regions
- $\Delta \phi_{ll}$
- $m_{ll}$
- $m_T$ shape for fit

<table>
<thead>
<tr>
<th>Low mass selection</th>
<th>Intermediate mass selection</th>
<th>High mass selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H &lt; 200 \text{ GeV}$</td>
<td>$m_H = 200 \text{ GeV} - 300 \text{ GeV}$</td>
<td>$m_H &gt; 300 \text{ GeV}$</td>
</tr>
<tr>
<td>$M_{ll} &lt; 50 \text{ GeV}$</td>
<td>$M_{ll} &lt; 150 \text{ GeV}$</td>
<td>No $M_{ll}$ cut to increase signal acceptance</td>
</tr>
<tr>
<td>$\Delta \phi &lt; 1.8$</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$m_{T}$ shape used in fit (0jet,1jet)</td>
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<td>$m_{T}$ shape used in fit (0jet,1jet)</td>
</tr>
</tbody>
</table>

### CMS

- Optimized for various $m_H$ values
- Leading and subleading $p_T$
- $\Delta \phi_{ll}$
- $m_{ll}$
- $m_T$ range

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$p_T^{\ell,\text{max}}$ [GeV]</th>
<th>$p_T^{\ell,\text{min}}$ [GeV]</th>
<th>$m_{ll}$ [GeV]</th>
<th>$\Delta \phi_{\ell\ell}$ [$^\circ$]</th>
<th>$m_T$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>$&gt;$</td>
<td>20</td>
<td>10 (15)</td>
<td>40</td>
<td>115</td>
</tr>
<tr>
<td>130</td>
<td>$&gt;$</td>
<td>25</td>
<td>10 (15)</td>
<td>45</td>
<td>90</td>
</tr>
<tr>
<td>160</td>
<td>$&gt;$</td>
<td>30</td>
<td>25</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>200</td>
<td>$&gt;$</td>
<td>40</td>
<td>25</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>250</td>
<td>$&gt;$</td>
<td>55</td>
<td>25</td>
<td>150</td>
<td>140</td>
</tr>
<tr>
<td>300</td>
<td>$&gt;$</td>
<td>70</td>
<td>25</td>
<td>200</td>
<td>175</td>
</tr>
<tr>
<td>400</td>
<td>$&gt;$</td>
<td>90</td>
<td>25</td>
<td>300</td>
<td>175</td>
</tr>
</tbody>
</table>
The Backgrounds
SM WW Backgrounds

- Crucial background for $H \to WW$ search
  - Same signature
  - Interesting because sensitive to anomalous TGCs
- Main backgrounds:
  - $Z + \text{jets}$ and top
- Production cross section measured from both ATLAS and CMS

**ATLAS**

$53.4 \pm 2.1 \text{(stat.)} \pm 4.5 \text{(syst.)} \pm 2.1 \text{(lumi.) pb}$

**CMS**

$55.3 \pm 3.3 \text{(stat.)} \pm 6.9 \text{(syst.)} \pm 3.3 \text{(lumi.) pb}$

- NLO prediction: $45.1 \pm 2.8 \text{ pb}$
Irreducible background: same final state of $H \to WW$

Only way to distinguish it $\rightarrow$ exploit spin correlation

Leptons tends to go in the same direction

Low $m_{ll}$

$$m_{ll} = \sqrt{2E_1E_2(1-\cos \Delta \phi_{12})}$$
WW background control region

- WW non-resonant contribution estimated from data in the low-mass $m_H < 200$ GeV.
- done using events with a high dilepton mass + MC extrapolation into signal region

$$N_{S.R.}^{WW} = N_{C.R.}^{WW} \cdot \alpha$$

**ATLAS**
- $M_{ll} > 80$ GeV for $e\mu$
- $M_{ll} > (m_Z + 15$ GeV) for $ee/\mu\mu$

**CMS**
- $M_{ll} > 100$ GeV

- For $m_H > 200$ GeV large overlap between $H \rightarrow WW$ and non resonant $WW$
- simulation is used for the estimation

The total uncertainty: 10% for 0-jet and 24% for 1-jet selections
Drell Yan background

\( Z/\gamma^* + \text{jets} \) mainly rejected with \( E_{T,\text{rel}}^{\text{miss}} \) cut

Normalize MC using \( Z \) control region – ABCD method using METRel-Mll

\[
A_{\text{data}} = B_{\text{data}} \times \frac{C_{\text{data}}}{D_{\text{data}}}
\]

Uncertainty: 56% for \( H+0\text{jet} \) and 25% for \( H+1\text{jet} \) analysis respectively
Top background

- Definition of data control sample to normalize MC prediction
- E.g. H+ 1-jet and H+ 2-jet analyses,
  - reversing the b-jet veto
  - Remove the requirements on $\Delta \phi_{ll}$, $m_{ll}$.

ATLAS: 23% uncertainty for the 0-jet channel, 30% otherwise
CMS: 25% uncertainty for the 0-jet channel, 10% otherwise
Other backgrounds

- **W+jets background**
  - control sample with inverted lepton ID passing loose criteria

- **WZ/ZZ**
  - Leptons coming from two different bosons
  - estimated from MC simulation

- **Wγ**
  - Normalization from high purity three-lepton control sample

- **Wγ** estimated from simulation
  - Cross-checked with same sign sample
CMS and ATLAS Results

arXiv:1202.1489, CMS-HIG-11-024
ATLAS-CONF-2012-012
**ATLAS Results**

**ATLAS Preliminary**

\( \sqrt{s} = 7 \text{ TeV}, \int L \, dt = 4.7 \text{ fb}^{-1} \)

- **H→WW^{(*)}→ℓνν** + 0 jets

- **H→WW^{(*)}→ℓνν** + 1 jet

### Events / 10 GeV

<table>
<thead>
<tr>
<th><strong>m_T [GeV]</strong></th>
<th><strong>Signal</strong></th>
<th><strong>Total Bkg.</strong></th>
<th><strong>Obs.</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>25 ± 7</td>
<td>173 ± 22</td>
<td>174</td>
</tr>
<tr>
<td>80</td>
<td>60 ± 17</td>
<td>607 ± 63</td>
<td>629</td>
</tr>
<tr>
<td>100</td>
<td>6 ± 2</td>
<td>45 ± 7</td>
<td>56</td>
</tr>
<tr>
<td>120</td>
<td>23 ± 9</td>
<td>229 ± 55</td>
<td>232</td>
</tr>
<tr>
<td>140</td>
<td>0.4 ± 0.2</td>
<td>0.5 ± 0.2</td>
<td>0</td>
</tr>
<tr>
<td>160</td>
<td>2.5 ± 0.6</td>
<td>4.2 ± 1.7</td>
<td>2</td>
</tr>
</tbody>
</table>
- in 9 channels (ee, μμ, eμ) x (0 jet, 1 jet, 2 jet) for each $M_H$
- No significant excess in the mass range $110 < m_H < 600$ GeV
  - 95% C.L. expected exclusion for $127 < m_H < 234$ GeV
  - 95% C.L. observed exclusion for $130 < m_H < 260$ GeV
<table>
<thead>
<tr>
<th>$m_H$</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0 jet</td>
</tr>
<tr>
<td>120</td>
<td>136</td>
<td>136.7 ± 12.7</td>
<td>15.7 ± 0.8</td>
</tr>
<tr>
<td>130</td>
<td>193</td>
<td>191.5 ± 14.0</td>
<td>45.2 ± 2.1</td>
</tr>
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<td>160</td>
<td>111</td>
<td>101.7 ± 6.8</td>
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<td></td>
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<td>1 jet</td>
</tr>
<tr>
<td>120</td>
<td>72</td>
<td>59.5 ± 5.9</td>
<td>6.5 ± 0.3</td>
</tr>
<tr>
<td>130</td>
<td>105</td>
<td>79.9 ± 7.7</td>
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<td></td>
<td></td>
<td></td>
<td>2 jet</td>
</tr>
<tr>
<td>120</td>
<td>8</td>
<td>11.3 ± 3.6</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>130</td>
<td>10</td>
<td>13.3 ± 4.0</td>
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<td>23.8 ± 6.4</td>
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**CMS Results**

![Graph showing CMS results with data and various backgrounds.](image-url)

- **0 jet**
- **1 jet**
- **2 jet**
Multivariate approach

- BDT trained at different masses
- $H \rightarrow WW$ signal and non-resonant WW background

- Inputs: $p_T^{\text{lept}}, M_{ll}, \Delta \phi_{ll}, \Delta R_{ll}, M_T$

- Uncertainties:
  - signal efficiency $\sim 20\%$
  - background $\sim 15\%$

- BDT classifier output used for CL estimation
CMS Results

- No significant excess in the mass range $110 < m_H < 600$ GeV
- 95% C.L. expected exclusion for $127 < m_H < 270$ GeV
- 95% C.L. observed exclusion for $129 < m_H < 270$ GeV
- Small excess at low mass (BDT analysis)
Conclusions

- **H → WW → lνlν** is one of the most sensitive Higgs search channels
  - Fundamental ingredient in the final combination with the other channels

- **H → WW → lνlν** exclusion limits:
  - ATLAS: range 130-260 GeV
  - CMS: range 129-270 GeV

- No hint for a Standard Model Higgs in this channel.

- With the **2012 data** we will be able to “close the gap”
  - Expect discovery or exclusion this year!

- …in the meantime LHC…
Collisions at $\sqrt{s}=8$ TeV will arrive very soon!!
backup
**ATLAS**

- 2T superconducting solenoid. Inner Detector: silicon pixel/strip tracker with a straw tube tracker. $|\eta| < 2.5$
- LAr electromagnetic and iron-scintillator tile hadronic calorimeters cover $|\eta| < 4.9$.
- Muon spectrometer in toroidal magnetic field covers $|\eta| < 2.7$.

**CMS:**

3.8T superconducting solenoid. Silicon pixel and strip tracker cover $|\eta| < 2.5$
- Crystal electromagnetic and brass-scintillator hadronic calorimeters cover $|\eta| < 3.0$ and a Quartz-fiber Cherenkov calorimeter covers to $|\eta| < 5.0$.
- Muons gas-ionization detectors in the solenoid yoke.
### CMS

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<td>1-jet $m_H = 125$ GeV</td>
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ATLAS Preliminary 2011 Data

\[
\int L dt = 4.6-4.9 \text{ fb}^{-1}
\]

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

95% CL Limit on \( \sigma/\sigma_{\text{SM}} \)

\( m_H \text{ [GeV]} \)

CLs Limits
Signal strength ATLAS

ATLAS Preliminary

- Best fit
- $-2 \ln \lambda(\mu) < 1$ \( \int L dt = 4.7 \text{ fb}^{-1} \)

$\sqrt{s} = 7 \text{ TeV}$

$m_H \text{ [GeV]}$

ATLAS Preliminary

- Best fit
- $-2 \ln \lambda(\mu) < 1$ \( \int L dt = 4.7 \text{ fb}^{-1} \)

$\sqrt{s} = 7 \text{ TeV}$

$m_H \text{ [GeV]}$
mT 2 jet

ATLAS Preliminary

$\sqrt{s} = 7$ TeV, $\int L \, dt = 4.7$ fb$^{-1}$

$H \rightarrow WW^{(*)} \rightarrow llvl + \geq 2$ jets

Events / 10 GeV

$\ m_T$ [GeV]
**Light jet rejection**

**ATLAS Preliminary**

- JetProb
- SV0
- IP3D
- SV1
- IP3D+SV1
- JetFitter
- IP3D+JetFitter

**tt simulation, √s = 7 TeV**

- \( p_{T}^{jet} > 20 \text{ GeV}, |\eta^{jet}| < 2.5 \)