High Mass Higgs to WW or ZZ

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On behalf of ATLAS and CMS collaborations

Higgs Hunting 2013
Introduction

• A light Higgs boson of mass around 126 GeV discovered in 2012
• Compulsory to complete search for SM-like heavy Higgs boson
  • Legacy results for SM Higgs exclusion up to 1TeV; to conclude the SM chapter
• BSM scenarios predict existence of additional resonance at high mass, with couplings similar to SM Higgs
  • Re-interpretation of high mass search in light of h(126) discovery
• Most recent results from ATLAS and CMS reported here
  • Up to 5 fb\(^{-1}\) @ 7 TeV and 20 fb\(^{-1}\) @ 8 TeV
Differences from low mass search

- SM Higgs predominantly decays into WW or ZZ in high mass region
  - Cross section decreases with $m_H$; high BR channels favored in high mass search
  - VBF cross section becomes comparable with ggF

- Large SM Higgs width
  - Narrow width approximation breaks down; Higgs lineshape is corrected to match results from complex-pole scheme approach
  - Interference between signal and continuum background is large
Interference

Signal

Background

interferes with

Estimated using MC which include interference (MCFM, gg2VV, aMC@NLO);
Effects to both total cross sections and distributions
H→ZZ→2l2l′

Fully reconstructed mass with excellent resolution;
Clean signature, good sensitivity over wide mass range;
Limited by statistics at high mass

ATLAS-CONF-2013-013
4.6+20.7fb⁻¹

ATLAS Preliminary
- Data
- Background ZZ⁺
- Background Z+jets, t̅t
- Syst.Unc.

H→ZZ⁺→4l
\(\sqrt{s} = 7\) TeV: \(Ldt = 4.6\) fb⁻¹
\(\sqrt{s} = 8\) TeV: \(Ldt = 20.7\) fb⁻¹

95% CL limit on \(\sigma \times BR\) [fb]

Limits on cross section times branching ratio for ggF and VBF+VH production separately
H \rightarrow ZZ \rightarrow 2l2l'$

CMS-PAS-HIG-13-002
(5.1+19.6 fb$^{-1}$)

130-827 GeV excluded
(including 2l2τ)

Friday, July 26, 2013
H→ZZ→2l2ν

- Competitive branching fraction
- Required a pair of isolated e or μ \( (p_T>20 \text{ GeV}) \) from Z boson decay + large \( E_T^{\text{miss}} \); no mass peak
- Challenge: Z+jets background - fake \( E_T^{\text{miss}} \) from jet mis-measurement
- Event categories: VBF, ggF(0jet, ≥1jet)
  - Optimized separately for VBF and ggF
  - \( m_H \) dependent \( E_T^{\text{miss}} \) cut in ggF category

Z+jets modeled using γ+jets

CMS-PAS-HIG-13-014 (5.0+19.6 fb⁻¹)
Shape based: $M_T(ggF), E_T^{miss}(VBF)$

$$M_T^2 = \left[ \sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{miss}^2 + M(\ell\ell)^2} \right]^2 - \left[ \vec{p}_T(\ell\ell) + \vec{E}_T^{miss} \right]^2$$

248-930 GeV excluded
Combination of $H\to ZZ\to 2l2l'(4l+2l2\tau)$, $H\to ZZ\to 2l2v$ and $H\to ZZ\to 2l2q$ (Observed limits for individual channels superimposed)

$2l2l'$ is the most sensitive at below 500 GeV;
$2l2nu$ dominates at above 500 GeV
• Two isolated, opposite charged leptons ($p_T > 40$ GeV) and $E_T^{\text{miss}}$; no mass peak
• Only different lepton-flavor ($e\mu \nu$) used
• Event categories: 0jet, 1jet, ≥2jet(VBF)
• Top and WW backgrounds normalized to data control regions
• $M_T$ is used as the discriminating variable

\[ m_T = \left( (E_T^{\ell \ell} + E_T^{\text{miss}})^2 - |p_T^{\ell \ell} + E_T^{\text{miss}}|^2 \right)^{1/2} \text{ with } E_T^{\ell \ell} = \left( |p_T^{\ell \ell}|^2 + m_{\ell \ell}^2 \right)^{1/2} \]
**H->WW->lνl′ν′**

Analysis performed using two different assumptions on Higgs width:

- **SM Higgs width and lineshape**
- **Fixed 1GeV wide BW lineshape**

Motivated by h(126) mixing with EW singlet model

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**ATLAS Preliminary**

H→WW→eνμν, SM width

<table>
<thead>
<tr>
<th>Lineshape</th>
<th>Production mode</th>
<th>$m_H = 300$ GeV</th>
<th>$m_H = 600$ GeV</th>
<th>$m_H = 1$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM-like</td>
<td>ggF</td>
<td>250</td>
<td>34</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>VBF</td>
<td>40</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>NWA</td>
<td>ggF</td>
<td>230</td>
<td>32</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>VBF</td>
<td>39</td>
<td>12</td>
<td>10</td>
</tr>
</tbody>
</table>

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H→WW→lνqq′

- Analysis performed for mass range [600-1000] GeV; large branching ratio due to hadronic decay of W
- Single isolated μ(e) with p_T>30(35) GeV, large E_T^{miss}
- A jet containing the entire hadronic decay of W
  - W bosons are highly boosted (required p_T>200 GeV)
  - Jet substructure techniques are used in identifying the hadronic W

The highest p_T jet by Cambridge-Aachen clustering algorithm (R=0.8) selected as hadronic W.

Jet pruning algorithm improves separation between signal and background.
$H \rightarrow WW \rightarrow l\nu qq'$

$M(l\nu J)$ reconstructable

1.1(4.2) times SM for 600(1000)GeV
Generic BSM benchmark to start with: minimal extension of SM

A new, heavy Higgs boson mixes with h(126)
  - Reduction of the h(126) couplings wrt SM by $C$
  - Heavy Higgs couplings wrt SM: $C'$
  - Unitarity implies: $C^2 + C'^2 = 1$

The heavy Higgs may decay to new states: $BR_{\text{new}}$ (e.g. H->hh)

Signal strength and width of the heavy Higgs
  - $\mu' = C'^2 (1 - BR_{\text{new}})$; $\Gamma' = C'^2 \Gamma_{\text{SM}} / (1 - BR_{\text{new}})$
  - Current studies focus on the case $\Gamma' \leq \Gamma_{\text{SM}}$
Assumed $BR_{\text{new}}=0$

CMS-PAS-HIG-13-014
$(5.0+19.6\,\text{fb}^{-1})$

Limits on signal strength for various values of $C'$ as a function of $m_H$

Limits on $C'^2$ as a function of $m_H$
H→ZZ→2l2ν

mH=400 GeV

Limits on signal strength as a function of width vs BR$_{\text{new}}$ (left) or $C'^2$ vs BR$_{\text{new}}$ (right)
Assumed $\text{BR}_{\text{new}} = 0$

Limits on cross sections for various values of $C'^2$ as a function of $m_H$ (left) or $\text{BR}_{\text{new}}$ (right)

CMS-PAS-HIG-13-008
(19.3 fb$^{-1}$)

Higgs mass, $600 \text{ GeV/c}^2$

CMS Preliminary, 19.3 fb$^{-1}$ at $\sqrt{s} = 8 \text{ TeV, e+e-}$

Friday, July 26, 2013
Summary

- Searches for heavy SM-like Higgs boson in $H \rightarrow ZZ$ and $H \rightarrow WW$ decay channels have been presented.
- The analyses use up to 25 fb$^{-1}$ $pp$ collision data recorded by ATLAS and CMS at LHC in 2011 and 2012.
- No excess above SM background expectations is observed.
- Presence of a SM Higgs boson is excluded up to $O(1)$ TeV.
- Results are also re-interpreted as a search for a heavy narrow EW singlet; a sizable region of parameter space has been excluded.
Backup

**ATLAS 2011**

$H \rightarrow ZZ \rightarrow ll\nu\nu$

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

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

- Observed
- Expected
- $\pm 1\sigma$
- $\pm 2\sigma$

$m_{H}$ [GeV]
\[ dS_{\text{NNLO}} = K(m) \, dS \]
\[ dS_{\text{corr}} = dS_{\text{NNLO}} + (K(m))^n \, dI, \quad n = 0, 0.5, 1 \]

**NNLO K factors from G. Passarino**
Table 2: Event selection used in the analysis. The preselection applies to all final states. In the $N_{\text{jet}} \geq 2$ final state, the rapidity gap is the $y$ range spanned by the two leading jets.

<table>
<thead>
<tr>
<th>Category</th>
<th>0-jet</th>
<th>1-jet</th>
<th>$\geq$2-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>An isolated electron and an isolated muon, with opposite charge, each with $p_T &gt; 40$ GeV, $m_{\ell\ell} &gt; 10$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missing transverse momentum</td>
<td>$E_{T,\text{rel}}^{\text{miss}} &gt; 25$ GeV</td>
<td>$E_{T,\text{rel}}^{\text{miss}} &gt; 25$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 20$ GeV</td>
</tr>
<tr>
<td>General selection</td>
<td></td>
<td>$N_{b\text{-jet}} = 0$</td>
<td>$N_{b\text{-jet}} = 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_T^{\text{jet}} &lt; 45$ GeV</td>
<td>$p_T^{\text{jet}} &lt; 45$ GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Z/\gamma^* \rightarrow \tau\tau$ veto</td>
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</tr>
<tr>
<td>VBF topology</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow \ell\nu\ell\nu$ topology</td>
<td>$m_{\ell\ell} &gt; 50$ GeV</td>
<td>$m_{\ell\ell} &gt; 50$ GeV</td>
<td>$m_{\ell\ell} &gt; 50$ GeV</td>
</tr>
<tr>
<td></td>
<td>$\Delta\eta_{\ell\ell} &lt; 1.0$</td>
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<td>$\Delta\eta_{\ell\ell} &lt; 1.0$</td>
</tr>
</tbody>
</table>
Higgs experimental mass resolution

<table>
<thead>
<tr>
<th>Channel</th>
<th>mH resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ \to 4l$</td>
<td>1-2%</td>
</tr>
<tr>
<td>$ZZ \to 2l2\nu$</td>
<td>~10%</td>
</tr>
<tr>
<td>$ZZ \to 2l2q$</td>
<td>3%</td>
</tr>
<tr>
<td>$WW \to l\nu l\nu$</td>
<td>~20%</td>
</tr>
<tr>
<td>$WW \to l\nu q\bar{q}$</td>
<td>~15%</td>
</tr>
</tbody>
</table>