Study of Higgs boson production in the WW decay channel at the LHC

Tatjana Lenz

on behalf of the ATLAS and CMS collaborations

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Rencontres du Vietnam
4th July 2012 - the discovery of a new particle

ATLAS and CMS today:
- ~2.5x larger data set
- reduced experimental uncertainties
- new exclusive analyses - event categories targeting specific production modes

WW channel:
- large branching ratio
- clear signature
- but no mass peak

<table>
<thead>
<tr>
<th>Production</th>
<th>mass range</th>
<th>luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>110-600</td>
<td>4.9/19.6</td>
</tr>
<tr>
<td>VBF</td>
<td>110-600</td>
<td>4.9/12.1</td>
</tr>
<tr>
<td>WH, W→ℓν</td>
<td>110-200</td>
<td>4.9/19.6</td>
</tr>
<tr>
<td>new VH, V→jj</td>
<td>110-300</td>
<td>4.9/19.6</td>
</tr>
<tr>
<td>ATLAS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF</td>
<td>110-200</td>
<td>4.9/20.7</td>
</tr>
<tr>
<td>VBF</td>
<td>110-200</td>
<td>4.9/20.7</td>
</tr>
<tr>
<td>new VH, 3l or 4l</td>
<td>110-200</td>
<td>4.9/20.7</td>
</tr>
<tr>
<td>new high mass</td>
<td>260-1000</td>
<td>20.7</td>
</tr>
</tbody>
</table>
$H ightarrow WW \rightarrow \mu\nu\nu\nu$ candidate
Higgs to $WW\rightarrow\ell\nu\ell\nu$ CMS

- exactly two opposite sign iso. leptons (e,\(\mu\)) and large MET
- cuts on $m_{ll}$, $p_T(ll)$, Z-peak veto, b-jet veto, $Z/\gamma^*$ rejection using MVA
- split in categories:
  - jet multiplicity: 0j, 1j, 2j
  - separated in same (SF) and opposite (DF) flavour
- challenging backgrounds:
  - data-driven methods for reducible bkg: $tt/tW$, $W+jets$, $Z\rightarrow ll$, $Z\rightarrow \tau\tau$
  - $WZ/ZZ$, $V+\gamma^*$ from MC
- $WW$ fit to data in sidebands
- analysis categories:
  - 0j, 1j DF category: 2D shape analysis
  - 0j, 1j SF category: $m_H$ dependent cuts on $\Delta\phi(ll)$, $p_T(l_{max})$, $p_T(l_{min})$, $m_{ll}$, $m_T$
  - VBF category: 2 or 3 jets (2 jets with $p_T > 30$ GeV), no jets in the gap $|\Delta\eta(jj)|>3.5$ and $m_{jj}>500$ GeV
Higgs to $WW \rightarrow \ell\nu\ell\nu$ CMS

0j, 1j DF category: 2D shape analysis

$M_H = 125$ GeV

CMS preliminary $L = 19.5$ fb$^{-1}$ (8TeV)

signal, 0j

background, 0j

Data - Background
CMS preliminary $L = 19.5$ fb$^{-1}$ (8TeV)

0j

Additional SM Higgs-like boson excluded in the mass range 128 - 600 GeV at 95% CL.

4.0 (5.1) obs. (exp.) significance at 125 GeV
test spin-2 resonance which couples to WW through minimal couplings (100% gg production)

WW final state can’t be fully reconstructed but use other spin-sensitive variables:

Δϕ(ll), Mll, mT

DF only, all jet bins

build a maximum likelihood fit like in the standard analysis but for both models - SM and spin-2 model

use test statistic q to quantify the consistency of data to the two models

\[ q = -2 \ln \left( \frac{L_{2+}}{L_{0+}} \right) \]

exclusion of the spin-2 hypothesis at 86% CL in favour of SM
VH, H→WW→2l2ν and V→jj

- same event preselection as 0/1 jet analysis plus:
  - two central jets with pT > 30 GeV and |η|<2.5, Δφ(ll,jj) < 165°, 65<m(jj)<105 GeV
  - 30% VH, 60% ggH and 10% VBF at 125 GeV
  - mH dependent cuts on ΔR(ll), mll, mT
  - 95% CL on σ/σSM at 125 GeV: 5.0(4.2) obs(exp)

WH, H→WW→2l2ν and W→lv

- look for 3 isolated leptons (e,µ) and large trans. miss. energy
- two categories according to the presence of an OSSF pair or not
- shape based approach based on ΔR(l+l-)
- 95% CL on σ/σSM at 125 GeV: 3.3(3.0) obs(exp)
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET

$H \rightarrow WW \rightarrow e\nu\mu\nu + 2 \text{ jets}$
Higgs to $WW\rightarrow l\nu l\nu$ ATLAS

- single e, $\mu$ triggers
- lepton $p_T > 25, 15$ GeV
- jet $p_T > 25$ GeV, $30$ GeV for $|\eta| > 2.5$
- relative MET $> 25$ GeV

$$E_T^{\text{miss}} = \begin{cases} E_T^{\text{miss}} & \text{if } \Delta \phi \geq \pi/2 \\ E_T^{\text{miss}} \times \sin \Delta \phi & \text{if } \Delta \phi < \pi/2 \end{cases}$$

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW\rightarrow l\nu l\nu$</td>
<td>irreducible</td>
<td>norm. to data</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>jet fakes lepton</td>
<td>data driven</td>
</tr>
<tr>
<td>$V\gamma(*)$</td>
<td>photon conversion</td>
<td>MC</td>
</tr>
<tr>
<td>$tt$</td>
<td>not identified 2 b-jets</td>
<td>norm. to data</td>
</tr>
<tr>
<td>$Wt$</td>
<td>not identified b-jet</td>
<td>norm. to data</td>
</tr>
<tr>
<td>$Z\rightarrow \tau\tau$</td>
<td>real missing energy</td>
<td>norm. to data</td>
</tr>
<tr>
<td>$ZZ\rightarrow l\nu l\nu$</td>
<td>irreducible</td>
<td>MC</td>
</tr>
<tr>
<td>$WZ$</td>
<td>lose lepton</td>
<td>MC</td>
</tr>
</tbody>
</table>

- $ggF$ category $(0j+1j)$: Higgs spin-0 and V-A decays $\Rightarrow$ collinear leptons
- $D\Phi_{ll} < 1.8$, $P_{Tll} > 30$ GeV, $M_{ll} < 50$ GeV
VBF category(2+j):
- require b-veto and two forward jets
- $\Delta Y_{jj} > 2.8$, $M_{jj} > 500$ GeV

split in ee, $\mu\mu$, $e\mu$ and $\mu e$

0jet, 1jets and $\geq$2jets channels

binned likelihood fit of

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - |p_T^{\ell\ell} + E_T^{miss}|^2}$$

ATLAS

$\mathcal{L} = 7$ TeV, $L_{int} = 4.6$ fb$^{-1}$
$\gamma \rightarrow WW^{*} \rightarrow 4\ell$, $W W^{*} \rightarrow 4f$

$H \rightarrow WW^{*} \rightarrow e\mu \nu \nu$

$Obs. \quad m_{h} = 125.5$ GeV

$m_{T}$ [GeV]

- $H \rightarrow WW^{*} \rightarrow e\mu \nu \nu$
- SM Higgs boson $m_{h} = 125$ GeV
- ggF $m_{T}$ = 125 GeV
- $T \rightarrow WW$
- $Z_{t}$
- $W+$jets
- Single Top
- Other VV
- $W+$jets
- Bkg.

Limited mass resolution

VBF

0j+1j $\ell\ell$ fit in 2 bins of $M_{ll}$
Higgs to $WW\rightarrow\ell\ell\ell\ell$ ATLAS

**HIGH MASS SEARCH:**
- Based on the previous analysis but:
  - Lepton $p_T > 40$ GeV
  - Only DF, all jet bins

### VH Channel:
- WH, ZH production in 3l, 4l channels
- 95% CL on $\sigma/\sigma_{SM}$ is 7.2(3.6) obs(exp)

**ATLAS Preliminary**

<table>
<thead>
<tr>
<th>significance ($\sigma$)</th>
<th>VH</th>
<th>$H\rightarrow WW^{(*)}$ [6]</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected</td>
<td>0.7</td>
<td>3.7</td>
<td>3.8</td>
</tr>
<tr>
<td>observed</td>
<td>2.0</td>
<td>3.8</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**SM Width**

$260 < m(H) < 642$ GeV

**ATLAS CONF-2013-067**
Higgs to WW Spin ATLAS

- same preselection like in the $H\rightarrow WW$ rate analysis but 0 jet, $e\mu$-channel only
- looser cuts on metrel, $p_T(ll)$, $M(ll)$, $\Delta\phi(ll)$
- train separate BDTs on 4 variables: $p_T(ll)$, $M(ll)$, $\Delta\phi(ll)$ and $m_T$
- $J=0^+,1^-,1^+$ and $2^+$ vs all backgrounds
- study test statistic of $J=0^+$ vs others

$q = -2 \ln(L_{2+}/L_{0+})$

- spin-$2^+$ excluded at at least 95%CL
- spin-$1^+$ at 92% CL
- spin-$1^-$ at 98% CL

http://arxiv.org/abs/1307.1432
Summary

- a Higgs boson seen beyond any doubts in all three bosonic channels
- evidence in the WW channel
- looks more and more like a SM Higgs boson
- no evidence for additional Higgs bosons at higher or lower mass

http://arxiv.org/abs/1307.1427

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>$m_H = 125.5$ GeV</th>
<th>$\sigma^{(\text{stat})}$</th>
<th>$\sigma^{(\text{sys})}$</th>
<th>$\sigma^{(\text{theo})}$</th>
<th>Total uncertainty $\pm 1\sigma$ on $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$\mu = 1.55^{+0.33}_{-0.28}$</td>
<td>$0.03$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>Low $p_T$</td>
<td>$\mu = 1.6^{+0.05}_{-0.04}$</td>
<td>$0.05$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>High $p_T$</td>
<td>$\mu = 1.7^{+0.07}_{-0.06}$</td>
<td>$0.06$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>$Z'$ jet high mass (VBF)</td>
<td>$\mu = 1.9^{+0.05}_{-0.04}$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>VH categories</td>
<td>$\mu = 1.3^{+0.12}_{-0.11}$</td>
<td>$0.09$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>$H \to ZZ^* \to 4l$</td>
<td>$\mu = 1.43^{+0.40}_{-0.35}$</td>
<td>$0.14$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>VBF+VH-like categories</td>
<td>$\mu = 1.2^{+0.16}_{-0.09}$</td>
<td>$0.09$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>Other categories</td>
<td>$\mu = 1.45^{+0.43}_{-0.39}$</td>
<td>$0.35$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>$H \to WW^* \to lvlv$</td>
<td>$\mu = 0.99^{+0.31}_{-0.28}$</td>
<td>$0.21$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>0+1 jet</td>
<td>$\mu = 0.82^{+0.33}_{-0.28}$</td>
<td>$0.09$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>2 jet VBF</td>
<td>$\mu = 1.4^{+0.07}_{-0.06}$</td>
<td>$0.5$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>Comb. $H \to \gamma\gamma, ZZ^<em>, WW^</em>$</td>
<td>$\mu = 1.33^{+0.21}_{-0.18}$</td>
<td>$0.11$</td>
<td>$0.15$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
</tbody>
</table>

CMS Preliminary

CMS-PAS-HIG-13-005

$\sqrt{s} = 7$ TeV, $L \leq 5.1$ fb$^{-1}$  $\sqrt{s} = 8$ TeV, $L \leq 19.6$ fb$^{-1}$
BACKUP
Higgs to $WW \rightarrow \ell \ell \nu \nu$ CMS

$M_H = 125$ GeV

CMS preliminary $L = 19.5$ fb$^{-1}$ (8 TeV)

Data - Background

CMS preliminary $L = 19.5$ fb$^{-1}$ (8 TeV)

standard selection for 2D fit

CMS-PAS-HIG-13-003
Higgs to $WW\rightarrow l\nu l\nu$ CMS

signal strength, CMS preliminary, $L = 24.4\text{ fb}^{-1}$

- SF 1-jet 7 TeV
- SF 0-jet 7 TeV
- DF 1-jet 7 TeV
- DF 0-jet 7 TeV
- SF 1-jet 8 TeV
- SF 0-jet 8 TeV
- DF 1-jet 8 TeV
- DF 0-jet 8 TeV

Best Fit $\sigma/\sigma_{SM}$
Higgs to WW ATLAS

VBF SF and DF

http://arxiv.org/abs/1307.1427