Measurement of properties of the Higgs-like boson in diboson channels on ATLAS

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Large Hadron Collider Physics, Barcelona, Spain
May 13, 2013
Outline

• Motivation & overview

• Measurement of resonance mass
  - $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$
  - combination

• Measurement of signal strength
  - $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow l\ell\ell$
  - signal strengths in different production modes
    - For coupling combinations, see G. Facini’s talk in *Higgs 2* parallel session

• Spin/CP ($J^P$) discrimination
  - $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow l\ell\ell$
    - combination

• Summary & outlook
Motivation & overview

• We have found a new boson in the search for the SM Higgs
• So far confirmed it in the 3 bosonic decay channels: $\gamma\gamma$, $ZZ$ and $WW$
• We can already start measuring its properties in these channels
  - mass, couplings, signal strengths in various production modes: measure and compare to expectations from SM
  - $J^P$ quantum numbers: compare expected kinematics of $J^P = 0^+$ signal with those of non-SM hypotheses
• The LHC has given us enough data during 2011-12 to start making fairly strong statements
  - $4.6-4.8$ fb$^{-1}$ at 7 TeV, $20.7$ fb$^{-1}$ at 8 TeV
Measurement of resonance mass
Mass from high-resolution channels

- Use mass $m_H$ as the parameter of interest in likelihood, fit to data
  - signal strength $\mu (=\sigma/\sigma_{SM})$ is a free parameter

- Best-fit mass

  $H \rightarrow \gamma\gamma$: \[ m_H = 126.8 \pm 0.2 \text{(stat)} \pm 0.7 \text{(syst)} \text{ GeV} \]

  $H \rightarrow ZZ \rightarrow 4l$: \[ m_H = 124.3^{+0.6}_{-0.5} \text{(stat)}^{+0.5}_{-0.3} \text{(syst)} \text{ GeV} \]
Mass: combination of $\gamma\gamma$, $4l$ channels

- From combined fit: $m_H = 125.5 \pm 0.2\text{(stat)} \pm 0.5\text{(syst)}$ GeV

- Mass difference $\Delta m_H(\gamma\gamma - 4l) = 2.3^{+0.6}_{-0.7}\text{(stat)} \pm 0.6\text{(syst)}$ GeV

- What is the probability that both channels see the same resonance?
  
  $\text{prob}(\Delta m_H = 0) = 1.5\% (2.4\sigma)$ using ensemble tests
Measurement of signal strengths
Overall signal strength $\mu (=\sigma/\sigma_{\text{SM}})$ at 126.8 GeV: $1.65 \pm 0.24\text{(stat)}^{+0.25}_{-0.18}\text{(syst)}$

Compatibility with SM expectation: $2.3\sigma$

At combined mass of 125.5 GeV, $\mu : 1.6 \pm 0.3$

Signal strength is high in all production modes, although consistent with SM expectation in VBF and associated production modes

- can imply presence of new particles in decay loop
**H → ZZ → 4l**

- Overall signal strength $\mu$ at 124.3 GeV: $1.7^{+0.5}_{-0.4}$
- At 125.5 GeV, $\mu : 1.5 \pm 0.4$

**Signal strength by production mode at $m_H = 124.3$ GeV**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$\mu_{ggF+ttH} \times B/B_{SM}$</th>
<th>$\mu_{VBF+VH} \times B/B_{SM}$</th>
<th>$\mu_{VBF+VH} / \mu_{ggF+ttH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured value</td>
<td>$1.8^{+0.8}_{-0.5}$</td>
<td>$1.2^{+3.8}_{-1.4}$</td>
<td>$0.7^{+2.4}_{-0.3}$</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**

- $\sqrt{s} = 7$ TeV: $\int Ldt = 4.6$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV: $\int Ldt = 20.7$ fb$^{-1}$

**ATLAS Preliminary**

- $H \rightarrow ZZ \rightarrow 4l$
- $\mu_{VBF+VH} / \mu_{ggF+ttH} = 0.7^{+2.4}_{-0.3}$
$H \rightarrow WW \rightarrow l\nu l\nu$

**ATLAS-CONF-2013-030**

- Overall signal strength $\mu$ at 125 GeV: $1.01 \pm 0.31$
- Excellent agreement with SM!

**Signal strength by production mode at $m_H = 125.0$ GeV**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$\mu_{ggF} x B/B_{SM}$</th>
<th>$\mu_{VBF+VH} x B/B_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured value</td>
<td>$0.82 \pm 0.24$(stat) + 0.28(syst)</td>
<td>$1.66 \pm 0.67$(stat) + 0.42(syst)</td>
</tr>
</tbody>
</table>
Spin/CP discrimination
H → ZZ → 4l

ATLAS-CONF-2013-013

• 4 charged leptons → most sensitive channel for J^P discrimination

• 6 J^P hypotheses tested: 0^+, 0^−, 1^+, 1^−, 2^+, 2^−

• 2^+ can produced via ggF or qq annihilation
  - agnostic to production model → do analysis for 5 gg/qq → 2^+ fractions in interval [0, 1]

• Boosted Decision Trees (BDTs) used to maximize sensitivity

<table>
<thead>
<tr>
<th>BDT analysis</th>
<th>CL_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>tested J^P for an assumed 0^+</td>
<td>tested 0^+ for an assumed J^P</td>
</tr>
<tr>
<td>observed</td>
<td>observed*</td>
</tr>
<tr>
<td>0^-</td>
<td>p_0</td>
</tr>
<tr>
<td>1^+</td>
<td>p_0</td>
</tr>
<tr>
<td>1^-</td>
<td>p_0</td>
</tr>
<tr>
<td>2^+_m</td>
<td>p_0</td>
</tr>
<tr>
<td>2^-</td>
<td>p_0</td>
</tr>
</tbody>
</table>

• 0^- excluded at 97.8% CL

• All 2^+ hypotheses excluded at >83% CL

• SM hypothesis favored in all cases
• $J^P = 0^+ \text{ vs } 2^+$ discrimination analysis

• Five $2^+$ production models tested, and data does not prefer any of them

• In both channels, data agree closely with SM signal hypothesis
Combination of $J^P = 0^+ \, \nu s \, 2^+$ analyses

ATLAS-CONF-2013-040

<table>
<thead>
<tr>
<th>$f_{qq}$</th>
<th>Spin-2 assumed exp. $p_0(J^P = 0^+)$</th>
<th>Spin-0 assumed exp. $p_0(J^P = 2^+)$</th>
<th>obs. $p_0(J^P = 0^+)$</th>
<th>obs. $p_0(J^P = 2^+)$</th>
<th>$CL_s(J^P = 2^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>3.4 $\cdot$ 10^{-3}</td>
<td>9.4 $\cdot$ 10^{-5}</td>
<td>0.82</td>
<td>0.4 $\cdot$ 10^{-5}</td>
<td>0.2 $\cdot$ 10^{-4}</td>
</tr>
<tr>
<td>75%</td>
<td>1.0 $\cdot$ 10^{-2}</td>
<td>1.1 $\cdot$ 10^{-3}</td>
<td>0.82</td>
<td>3.7 $\cdot$ 10^{-5}</td>
<td>2.1 $\cdot$ 10^{-4}</td>
</tr>
<tr>
<td>50%</td>
<td>1.5 $\cdot$ 10^{-2}</td>
<td>3.5 $\cdot$ 10^{-3}</td>
<td>0.85</td>
<td>9.1 $\cdot$ 10^{-5}</td>
<td>6.0 $\cdot$ 10^{-4}</td>
</tr>
<tr>
<td>25%</td>
<td>6.8 $\cdot$ 10^{-3}</td>
<td>2.4 $\cdot$ 10^{-3}</td>
<td>0.81</td>
<td>1.0 $\cdot$ 10^{-4}</td>
<td>5.3 $\cdot$ 10^{-4}</td>
</tr>
<tr>
<td>0%</td>
<td>1.6 $\cdot$ 10^{-3}</td>
<td>6.1 $\cdot$ 10^{-4}</td>
<td>0.65</td>
<td>1.4 $\cdot$ 10^{-4}</td>
<td>4.0 $\cdot$ 10^{-4}</td>
</tr>
</tbody>
</table>

All 2$^+$ models excluded at >99.9% CL

Data look very SM Higgs-like
Measurement of properties of new boson in ATLAS using Run I dataset presented

- current focus is on bosonic decay channels: $\gamma\gamma$, $ZZ$ and $WW$

Mass from combination of $\gamma\gamma$, $ZZ$ channels:

$$125.5 \pm 0.2 \text{(stat)} \pm 0.5 \text{(syst)} \text{GeV}$$

- error on mass already <1%, and systematically limited

Overall signal strength in $WW$ channel very SM-like; high in $ZZ$, but still statistically limited

- Signal strength in $\gamma\gamma$ channel is high, consistent w/ SM expectation at 2.3$\sigma$

Spin/CP analyses done in all 3 channels

- $J^P = 2^+$ excluded at >99.9\% CL, $J^P = 0^-$ and $1^{+)/−}$ excluded at >94\% CL

This boson is looking very SM-like, but confirmation in fermionic channels crucial (D. Jamin’s talk in this session)
Backup
Systematic uncertainties in $H \rightarrow ZZ \rightarrow 4l$

- **Mass measurement**
  - Decay modes involving electrons ($4e$, $2e2\mu$): electron energy scale uncertainty is main contributor
    - 0.4% (0.2%) on measured mass in $4e$ ($2e2\mu$)
  - Decay modes involving muons ($4\mu$, $2\mu2e$): muon momentum scale, resolution uncertainty are main contributors
    - 0.2% (0.1%) on measured mass in $4\mu$ ($2\mu2e$)

- **Signal strength measurement**
  - Decay modes involving electrons: electron ID and reco efficiency
    - at $m_{4l} = 125$ GeV, impact is 9.4% in $4e$, 8.7% in $2e2\mu$, 2.4% in $2\mu2e$
  - Decay modes involving muons: muon ID and reco efficiency
    - impact is 0.8% in $4e$, 8.7% in $2e2\mu$, 2.4% in $2\mu2e$
Systematic uncertainties in $H \rightarrow \gamma\gamma$

Table 5: Summary of the impact of systematic uncertainties on the signal yields for the analysis of 8 TeV data.

<table>
<thead>
<tr>
<th>Systematic uncertainties</th>
<th>Value(%)</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>±3.6</td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>±0.5</td>
<td></td>
</tr>
<tr>
<td>Photon Identification</td>
<td>±2.4</td>
<td></td>
</tr>
<tr>
<td>Isolation</td>
<td>±1.0</td>
<td></td>
</tr>
<tr>
<td>Photon Energy Scale</td>
<td>±0.25</td>
<td></td>
</tr>
<tr>
<td>Branching ratio</td>
<td>±5.9% - ±2.1% ($m_H = 110 - 150$ GeV)</td>
<td>Asymmetric Log-normal</td>
</tr>
<tr>
<td>Scale</td>
<td>ggF: 7.2</td>
<td>VBF: +0.2</td>
</tr>
<tr>
<td></td>
<td>_7.8</td>
<td>_0.2</td>
</tr>
<tr>
<td></td>
<td>ZH: +1.6</td>
<td>ttH: +3.8</td>
</tr>
<tr>
<td></td>
<td>_1.5</td>
<td>_9.3</td>
</tr>
<tr>
<td>PDF+$\alpha_s$</td>
<td>ggF: 7.5</td>
<td>VBF: +2.6</td>
</tr>
<tr>
<td></td>
<td>_6.9</td>
<td>_2.7</td>
</tr>
<tr>
<td></td>
<td>ZH: ±3.6</td>
<td>ttH: ±7.8</td>
</tr>
<tr>
<td>Theory cross section on ggF</td>
<td>Tight high-mass two-jet: ±48</td>
<td>Log-normal</td>
</tr>
<tr>
<td></td>
<td>Loose high-mass two-jet: ±28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low-mass two-jet: ±30</td>
<td></td>
</tr>
</tbody>
</table>
Table 13: Leading uncertainties on the signal strength $\mu$ for the combined 7 and 8 TeV analysis.

<table>
<thead>
<tr>
<th>Category</th>
<th>Source</th>
<th>Uncertainty, up (%)</th>
<th>Uncertainty, down (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>Observed data</td>
<td>+21</td>
<td>−21</td>
</tr>
<tr>
<td>Theoretical</td>
<td>Signal yield ($\sigma \cdot B$)</td>
<td>+12</td>
<td>−9</td>
</tr>
<tr>
<td>Theoretical</td>
<td>$WW$ normalisation</td>
<td>+12</td>
<td>−12</td>
</tr>
<tr>
<td>Experimental</td>
<td>Objects and DY estimation</td>
<td>+9</td>
<td>−8</td>
</tr>
<tr>
<td>Theoretical</td>
<td>Signal acceptance</td>
<td>+9</td>
<td>−7</td>
</tr>
<tr>
<td>Experimental</td>
<td>MC statistics</td>
<td>+7</td>
<td>−7</td>
</tr>
<tr>
<td>Experimental</td>
<td>$W+$ jets fake factor</td>
<td>+5</td>
<td>−5</td>
</tr>
<tr>
<td>Theoretical</td>
<td>Backgrounds, excluding $WW$</td>
<td>+5</td>
<td>−4</td>
</tr>
<tr>
<td>Luminosity</td>
<td>Integrated luminosity</td>
<td>+4</td>
<td>−4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>+32</strong></td>
<td><strong>−29</strong></td>
</tr>
</tbody>
</table>
Probability of background-only hypothesis

\( \gamma \gamma: 7.4\sigma \)

\( ZZ: 6.6\sigma \)

\( WW: 3.8\sigma \)
Best-fit $\mu$ vs mass

- Poor mass resolution in $H \rightarrow WW \rightarrow ll\nu\nu$
- Agreement with $\gamma\gamma$ and $ZZ$ within 95% CL
$\mu_{ggF+ttH}, \mu_{VBF+VH}$

- Combination yields $>3\sigma$ evidence for VBF production of resonance
Spin discrimination in $H \rightarrow \gamma\gamma$

The two sets of points correspond to the subtraction of the different profiled bkg shapes in the case of the conditional $0^+$ and $2^+$ fits. The expected PDFs for the two cases are overlain. The cyan band shows the systematics on bkg modeling.
Spin discriminants in $H \rightarrow WW \rightarrow l\nu l\nu$
Bkg-subtracted BDT distributions in $H \rightarrow WW \rightarrow lvlv$
Spin toy distributions in $H \rightarrow WW \rightarrow l\nu l\nu$

$f_{qq} = 0$

$f_{qq} = 0.25$

$f_{qq} = 0.5$

$f_{qq} = 0.75$

$f_{qq} = 1$
Spin analyses: statistical treatment

- Same statistical methodology used in individual channels and in combination
  - Likelihood defined with the fraction of $J^P = 0^+$ signal as the parameter of interest $\varepsilon$
    
    $$
    \mathcal{L}(\varepsilon, \theta) = \prod_{i}^{N_{\text{bins}}} P(N_i|\varepsilon \cdot S_{i}^{0+}(\theta)) \cdot (1 - \varepsilon) S_{i}^{2+}(\theta) \cdot B_i(\theta) \times \prod_{j}^{N_{\text{sys}}} \mathcal{A}(\tilde{\theta}_j|\theta_j)
    $$
  
  - Since have no knowledge of $2^+_m$ production cross-section, signal strength $\mu$ is a floating parameter in fit
  
  - The test statistic $q$ is defined as a ratio of likelihoods
    
    $$
    q = \ln \frac{L(\varepsilon = 1, \tilde{\theta}_{\varepsilon=1})}{L(\varepsilon = 0, \tilde{\theta}_{\varepsilon=0})}
    $$
  
  - Distributions of test statistic obtained using toy MC
    
    - in toy generation, number of signal and bkg events in each channel is estimated from a fit to data, with all nuisance parameters profiled
Spin analyses: $p$-values and $\text{CL}_s$

For illustration

Spin-2 rejection test:
- obtain expected $p$-value by integrating over tail of the blue ($2^+$) distribution to the right of the median of the red ($0^+$) distribution
- obtain observed $p$-value by integrating over same tail, but this time to the right of the observed test statistic (black vertical line)

Spin-0 rejection test similar, with the direction of integration reversed

- To avoid spurious exclusion of a hypothesis owing to fluctuations in data, normalize $p$-value using a $\text{CL}_s$ approach

$$\text{CL}_s(J^P = 2^+) = \frac{p_0(J^P = 2^+)}{1 - p_0(J^P = 0^+)}$$
The 2\(^+\) model

- The amplitude for the interaction of a general spin-2 particle with gauge bosons is:

\[
A(X \to VV) = \Lambda^{-1} \left[ 2g^{(2)}_{1,\mu\nu} f^{*1,\alpha}_1 f^{*2,\nu}_\alpha + 2g^{(2)}_{2,\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu_\alpha} f^{*2,\nu_\beta} + g^{(2)}_3 \frac{q_\beta \tilde{q}_\alpha}{\Lambda^2} t_{\beta\nu} \left( f^{*1,\mu}_1 f^{*2,\mu}_\alpha + f^{*2,\mu}_1 f^{*1,\mu}_\alpha \right) + g^{(2)}_4 \frac{q^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha}_\beta f^{*2(2)}_{\alpha\beta} \\
+ m^2_V \left( 2g^{(2)}_5 t_{\mu\nu} \epsilon^*_1 \epsilon^*_2 \epsilon^\nu_1 \epsilon^\alpha_2 + 2g^{(2)}_6 \frac{\tilde{q}^\alpha q_\alpha}{\Lambda^2} t_{\mu\nu} \left( \epsilon^*_1 \epsilon^* \epsilon^\nu_1 - \epsilon^*_1 \epsilon^* \epsilon^\nu_2 \right) + g^{(2)}_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^*_1 \epsilon^*_2 \right) \\
+ g^{(2)}_8 \frac{q_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha}_1 f^{*2(2)}_{\alpha\beta} + g^{(2)}_9 t_{\mu\alpha} \tilde{q}^\alpha \epsilon^{\mu_\rho} \epsilon^*_1 \epsilon^*_2 q^{\sigma} + g^{(2)}_{10} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon^{\mu_\rho} \epsilon^{\nu_\sigma} q^{\rho_\sigma} \left( \epsilon^*_1 \epsilon^*_2 (q \epsilon^*_1) + \epsilon^*_1 \epsilon^*_2 (q \epsilon^*_1) \right) \right] 
\]


- At least 10 couplings \(\rightarrow\) large number of possible models depending on which couplings are non-zero

- In our case, all 3 channels use a simplified scenario
  - for \(gg\) production of \(2^+\), all couplings except \(g_I\) are zero, with \(g_I = 1\)
  - for bosonic decays, \(g_I = g_5 = 1\), all other couplings zero
  - for \(qq\) production, only \(\rho_I = 1\) in Eq. 10 in above reference
• 4 charged leptons $\rightarrow$ most sensitive channel for $J^P$ discrimination

• 6 $J^P$ hypotheses tested: $0^+$, $0^-$, $1^+$, $1^-$, $2^+$, $2^-$

• $2^+$ can produced via $ggF$ or $qq$ annihilation
  - agnostic to production model $\rightarrow$ do analysis for $5 \, gg/qq \rightarrow 2^+$ fractions in interval $[0, 1]$

• Selected events in range $115 < m_{4l} < 130$ GeV used

• Boosted Decision Trees (BDTs) trained to maximize sensitivity
  - $\Phi, \theta_1, \theta_2, m_{12}, m_{34}$ used to train BDT for $0^+$ vs $0^-$ discrimination
  - for other hypotheses, $\Phi_1$ and $\theta^*$ used in addition

$H \rightarrow ZZ \rightarrow 4l$
$H \rightarrow ZZ \rightarrow 4l$ (cont’d)

- $0^{-}$ excluded at 97.8% CL
- All $2^{+}$ hypotheses excluded at $>83\%$ CL
- SM signal hypothesis is strongly favored in all cases
Spin: $H \rightarrow \gamma\gamma$

- $J^P = 0^+ \text{ vs } 2^+$ discrimination analysis

- Five $2^+$ production models tested, as in ZZ channel

- Two variables used to separate signal from bkg, and to test $J^P$ hypotheses:
  - $\gamma\gamma$ invariant mass, $m_{\gamma\gamma}$
  - polar angle distribution of photons with respect to $z$-axis of Collins-Soper frame, $|\cos\theta^*|$

- Only 8 TeV data used

- $2^+$ hypothesis with 100% $gg$ fraction rejected at >99% CL

- Data prefer SM signal hypothesis
Spin: $H \rightarrow WW \rightarrow lvlv$

- $J^p = 0^+ \, vs \, 2^+$ discrimination analysis

- 2 BDTs trained
  - one BDT to separate $0^+$ signal from bkg, the other to separate $2^+$ signal from bkg
  - 2D BDT output fit to data

- Training variables: $\Delta \phi_{ll}$, $m_{ll}$, $p_{Tll}$, $m_T$

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

- Different lepton flavor, 0-jet channel used
  - only 8 TeV data used at this point

- $2^+$ hypothesis rejected at 95% CL or better in all cases

- As in the other two channels, data prefer SM signal hypothesis

<table>
<thead>
<tr>
<th>$f_{qq}$</th>
<th>1-CLs ($2^+_m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>0.99</td>
</tr>
<tr>
<td>75%</td>
<td>0.99</td>
</tr>
<tr>
<td>50%</td>
<td>0.98</td>
</tr>
<tr>
<td>25%</td>
<td>0.97</td>
</tr>
<tr>
<td>0%</td>
<td>0.95</td>
</tr>
</tbody>
</table>