Combined coupling measurements of the Higgs-like boson with the ATLAS detector using up to 25 fb$^{-1}$ of proton-proton collision data. The ATLAS Collaboration.

Abstract

This note presents an update of the measurements of the properties of the newly discovered boson using the full $pp$ collision data sample recorded by the ATLAS experiment at the LHC for the channels $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ(\ast) \rightarrow 4\ell$ and $H \rightarrow WW(\ast) \rightarrow \ell\nu\ell\nu$, corresponding to integrated luminosities of up to 4.8 fb$^{-1}$ at $\sqrt{s}=7$ TeV and 20.7 fb$^{-1}$ at $\sqrt{s}=8$ TeV. The combination also includes results from the $H \rightarrow \tau\tau$ and $H \rightarrow b \bar{b}$ channels based on $pp$ collision data corresponding to an integrated luminosity of up to 4.7 fb$^{-1}$ at $\sqrt{s}=7$ TeV and 13 fb$^{-1}$ at $\sqrt{s}=8$ TeV. The combined signal strength is determined to be $\mu = 1.30 \pm 0.13$ (stat) $\pm 0.14$ (sys) at a mass of 125.5 GeV. The cross section ratio between vector boson mediated and gluon (top) initiated Higgs boson production processes is found to be $\mu_{VBF} + VH/\mu_{ggF} + t\bar{t}H = 1.2 \pm 0.7^{-0.5}$, giving more than 3$\sigma$ evidence for Higgs-like boson production through vector-boson fusion. Measurements of relative branching fraction ratios between the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ(\ast) \rightarrow 4\ell$ and $H \rightarrow WW(\ast) \rightarrow \ell\nu\ell\nu$ channels, as well as combined fits testing the fermion and vector coupling sector, couplings to $W$ and $Z$ and loop induced processes of the Higgs-like boson show no significant deviation from the Standard Model expectation.

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Talk Overview

Introduction
i. Higgs Boson Production and decay
ii. The ATLAS detector and the LHC
iii. Combined **Mass measurements** from $H \rightarrow \gamma\gamma$ & $H \rightarrow ZZ^*$

Properties
iv. Combining **Coupling measurements** for all search channels
v. **Combined** Spin analysis from $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, $H \rightarrow WW^*$
vi. **Differential Cross sections** from $H \rightarrow \gamma\gamma$

Summary
vii. Conclusions & Outlook

[ATLAS-CONF-2013-072] [ATLAS-CONF-2013-040]

New: [Mass paper – to be submitted]
i.a Higgs Boson Production

Existence of Higgs field essential for mass generation of Weak vector bosons + quarks & leptons in Standard Model

Spontaneous symmetry breaking in Higgs Mechanism produces new scalar particle: the Higgs boson

In *pp* collisions Higgs Boson produces via $gg \rightarrow H$, VBF, $ZH$, $WH$ & $ttH$

Cross section for various $m_H$ at $\sqrt{s} = 8$ TeV:
i.b Higgs Boson Decay & Discovery

Higgs Boson decays after $10^{-10} - 10^{-13}$ ps into other SM particles

Branching fractions for Higgs decay:

![Graph showing branching fractions for Higgs decay](image)

ATLAS Search Channels

* $H \rightarrow b\bar{b}$ for $VH$
* $H \rightarrow \tau^+\tau^-$
* $H \rightarrow \mu^+\mu^-$
* $H \rightarrow \gamma\gamma$
* $H \rightarrow Z\gamma$
* $H \rightarrow WW^{(*)}$
* $H \rightarrow ZZ^{(*)}$

July 4th 2012: ATLAS and CMS announced discovery of new boson

Searches overview: (see talk of Doug Schouten); Coupling & Spin compatible with SM Higgs boson
ii. ATLAS Detector & Large Hadron Collider

**ATLAS** is multipurpose detector

focus: Higgs, EW, BSM, B physics

Multilayered EM & Hadronic calorimeter
excellent Tracking & Muon detection

**Very successful 2011 & 2012 run period:**

![Graph showing total integrated luminosity from 2011 to 2012](image)

- **2011, \( \sqrt{s} = 7 \text{ TeV} \)**
  - Delivered: 5.46 fb\(^{-1}\)
  - Recorded: 5.08 fb\(^{-1}\)
  - Physics: 4.57 fb\(^{-1}\)

- **2012, \( \sqrt{s} = 8 \text{ TeV} \)**
  - Delivered: 22.8 fb\(^{-1}\)
  - Recorded: 21.3 fb\(^{-1}\)
  - Physics: 20.3 fb\(^{-1}\)

24.9 fb\(^{-1}\) integrated luminosity good for physics
iii.a New! Combined mass measurements for $H \to \gamma\gamma$ & $H \to ZZ^*$

Much improved EM cluster energy correction via MVA regression & more accurate geometry

→ Largely improved resolution for $H \to \gamma\gamma$.

Energy scale & resolution extracted from reference process: $Z \to ee$

Good data & sim. agreement after corrections

linearity and extrapolation to photons checked with other leptonic reference processes and $Z \to \ell\ell\gamma$ events.

Large effort reduced systematic uncertainties in $H \to \gamma\gamma$ by more than a factor of two
iii.b New! Combined mass measurements for $H \rightarrow \gamma \gamma$ & $H \rightarrow ZZ^*$

Two measurements w/ good mass resolution:

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

| Higgs Mass [GeV] | $H \rightarrow \gamma \gamma$ | $H \rightarrow ZZ^* \rightarrow 4\ell$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Old calibration</td>
<td>125.98 ± 0.42 ± 0.28</td>
<td>124.51 ± 0.52 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>126.8 ± 0.2 ± 0.7</td>
<td>124.3 +0.6 +0.5 −0.5 −0.3</td>
</tr>
</tbody>
</table>

First error is statistical, second systematic.

Combine both measurements under the assumption of a single resonance:

Profile likelihood for combination

$$\Lambda(m_H) = \frac{\mathcal{L}(m_H)}{\mathcal{L}(\hat{m}_H)}$$

with the full likelihood contours from the individual measurements in $m_H$ & $\mu$, taking into account correlated systematics.
iii.c Combining Mass measurements from $H \to \gamma\gamma$ & $H \to ZZ^*$

**Combined mass maximising test statistics:**

$$m_H = 125.36 \pm 0.37 \pm 0.18 \text{ GeV}$$

Old calibration $125.5 \pm 0.2^{+0.5}_{-0.6} \text{ GeV}$

To test the consistency between both measurements a modified test statistic can be used.

$$\Delta m_H = m_H^{\gamma\gamma} - m_H^{4\ell}$$

$$\Delta m_H = 1.47 \pm 0.67 \pm 0.28 \text{ GeV}$$

Old calibration $2.3^{+0.6}_{-0.7} \pm 0.6 \text{ GeV}$

Compatibility with $\Delta m_H$ of the level of 4.9\% (2.0\sigma)

Assuming non-gaussian uncertainties for the 3 principal systematic uncertainties ($Z \to ee$ calibration/extrapolation, material upstream & energy scale of presampler detector) improves compat. to 11\%. 
iv.a Combining Coupling measurements

Signal strength combination from

\[ H \rightarrow \gamma \gamma, \ H \rightarrow ZZ^* \rightarrow 4\ell, \ H \rightarrow WW^* \rightarrow \ell\nu\ell\nu \]

\[ VH \rightarrow Vb\bar{b}, \ H \rightarrow \tau\tau \]

Can combine all measurements under the assumption of a single resonance:

\[ \Lambda(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})} \]

Profile likelihood for combination

Coupling strength \( \mu = \sigma^{\text{measured}} / \sigma^{\text{SM}} \)

\[
\begin{array}{c|c|c|c}
 & H \rightarrow \gamma \gamma & H \rightarrow ZZ^* \rightarrow 4\ell & H \rightarrow WW^* \rightarrow \ell\nu\ell\nu \\
\hline
\mu & 1.6 \pm 0.3 & 1.4 \pm 0.4 & 1.0 \pm 0.3 \\
\hline
VH \rightarrow Vb\bar{b} & 0.2 \pm 0.7 & 1.4 \pm 0.5 \\
\end{array}
\]

Evaluated at \( m_H = 125.5 \text{ GeV} \)

Plots: Transverse mass \( m_T = \left( E_T^{\ell\ell} + E_T^{\text{miss}} \right)^2 - |p_T^{\ell\ell} + E_T^{\text{miss}} | \right)^{1/2} \) distributions for \( H \rightarrow WW^* \rightarrow \ell\nu\ell\nu \)
### iv.b Combining Coupling measurements

**Combined signal strength results for \( \mu \) and \( \mu_{VBF+VH}/\mu _{ggF+ttH} \):**

<table>
<thead>
<tr>
<th>ATLAS Prelim. ( m_H = 125.5 ) GeV</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \gamma \gamma ) ( \mu = 1.57^{+0.33}_{-0.28} )</td>
<td>( \pm 1\sigma ) on ( \mu )</td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* \rightarrow 4l ) ( \mu = 1.44^{+0.40}_{-0.35} )</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow WW^* \rightarrow l\nu\nu ) ( \mu = 1.00^{+0.32}_{-0.29} )</td>
<td></td>
</tr>
<tr>
<td>Combined ( H \rightarrow \gamma \gamma, ZZ^<em>, WW^</em> ) ( \mu = 1.35^{+0.21}_{-0.20} )</td>
<td></td>
</tr>
<tr>
<td>( W,Z \rightarrow b\bar{b} ) ( \mu = 0.2^{+0.7}_{-0.6} )</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow \tau \tau ) (8 TeV data only) ( \mu = 1.4^{+0.5}_{-0.4} )</td>
<td></td>
</tr>
<tr>
<td>Combined ( H \rightarrow b\bar{b}, \tau \tau ) ( \mu = 1.09^{+0.36}_{-0.32} )</td>
<td></td>
</tr>
</tbody>
</table>

Overall signal production strength: \( \mu = 1.30^{+0.18}_{-0.17} \)

Evidence for VBF+VH: \( \mu_{VBF+VH}/\mu _{ggF+ttH} = 1.4^{+0.7}_{-0.5} \)
iv.c Combining Coupling measurements

Projection in $\mu_{VBF+VH} - \mu_{ggF+ttH}$ plane:

Coupling ratio for VBF production only: $\frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.4^{+0.5}_{-0.4} + 0.3$

→ Evidence at 4.1σ for VBF production!
**iv.d Combining Coupling measurements**

More detailed study on the Higgs coupling can be done via *leading order tree-level motivated* framework.

Assumptions:

i. **Single resonance** at $m_H = 125.5$ GeV

ii. **Narrow width approximation** holds, i.e. rates of the process $i \rightarrow H \rightarrow f$ are given by

$$\sigma \cdot B = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

with $\Gamma_H$ the Higgs width, and $\Gamma_f$ the partial width of the $H \rightarrow f$ transition, and $\sigma_i$ the cross section for $i \rightarrow H$ production.

iii. **No modifications in the tensor structure** of the SM Lagrangian, i.e. **Higgs is $0^+$**

**Free parameters in the framework:** coupling scale factors $\kappa_j^2$ ratio of measured over SM cross section times partial decay width, $\kappa_H^2$ the total Higgs width, or double ratios of the coupling scale factors $\lambda_{ij} = \kappa_i / \kappa_j$.

E.g. the effective couplings of $gg \rightarrow H \rightarrow \gamma\gamma$ can be written as

$$\frac{(\sigma \cdot B)^{\text{meas}}}{(\sigma \cdot B)^{\text{SM}}} = \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$
iv.e Combining Coupling measurements

Selection of benchmark models with focus on different observables:

<table>
<thead>
<tr>
<th>Model</th>
<th>Probed couplings</th>
<th>Parameters of interest</th>
<th>Functional assumptions</th>
<th>Example: $gg \to H \to \gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Couplings to fermions and bosons</td>
<td>$\kappa_V, \kappa_F$</td>
<td>$\sqrt{\sqrt{\sqrt{\sqrt{}}}}$</td>
<td>$\kappa_F^2 \cdot \kappa_V^2 (\kappa_F, \kappa_V)/\kappa_H^2 (\kappa_F, \kappa_V)$</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$\lambda_{FV}, \kappa_V$</td>
<td>$\sqrt{\sqrt{\sqrt{\sqrt{}}}}$</td>
<td>$\kappa_V^2 \cdot \lambda_{FV}^2 \cdot \kappa_V^2 (\lambda_{FV}, \lambda_F, \lambda_{FV}, 1)$</td>
</tr>
<tr>
<td>3</td>
<td>Custodial symmetry</td>
<td>$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$</td>
<td>$\sqrt{\sqrt{\sqrt{\sqrt{}}}}$</td>
<td>$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_V^2 (\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>$\lambda_{WZ}, \lambda_{FZ}, \lambda_{YZ}, \kappa_{ZZ}$</td>
<td>$\sqrt{\sqrt{\sqrt{\sqrt{}}}}$</td>
<td>$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{YZ}^2$</td>
</tr>
<tr>
<td>5</td>
<td>Vertex loops</td>
<td>$\kappa_g, \kappa_\gamma$</td>
<td>$\sqrt{\sqrt{\sqrt{\sqrt{}}}}$</td>
<td>$\kappa_g^2 \cdot \kappa_\gamma^2 / \kappa_H^2 (\kappa_g, \kappa_\gamma)$</td>
</tr>
</tbody>
</table>

The ticks correspond to a certain fixed functional dependence – more details in backup

**Model 1:** One coupling factor for fermions and one coupling factor for bosons: $\kappa_F, \kappa_V$

**Model 2:** Removing the constraint on the Higgs boson width (i.e. that the measured partial widths have to saturate the total width) only the ratio $\lambda_{FV} = \kappa_F / \kappa_V$ and $\kappa_{VV} = \kappa_V^2 / \kappa_H$ can be measured.

<table>
<thead>
<tr>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_F = 0.99^{+0.17}_{-0.15}$</td>
<td>$\lambda_{FV} = 0.86^{+0.14}_{-0.12}$</td>
</tr>
<tr>
<td>$\kappa_V = 1.15^{+0.08}_{-0.08}$</td>
<td>$\kappa_{VV} = 1.28^{+0.16}_{-0.15}$</td>
</tr>
</tbody>
</table>

Compatibility of SM with both model fits: **10%**.
iv.f Combining Coupling measurements

SM custodial symmetry: \( W \) \& \( Z \) couple identically to Higgs, i.e. \( \lambda_{WZ} = \kappa_W / \kappa_Z = 1 \)

**Model 3 \& 4:** \( H \rightarrow VV \) \& \( i \rightarrow H \rightarrow VV \)

information; Model 4 also includes degrees of freedom for a potential BSM to \( H \rightarrow \gamma\gamma \)

\begin{align*}
\text{Model 3} & \quad \lambda_{WZ} = 0.94^{+0.14}_{-0.29} \\
\text{Model 4} & \quad \lambda_{WZ} = 0.80 \pm 0.15
\end{align*}

Compatibility of SM with Model 4: 21%.

Calculated using full 7D covariance between determined values.

**Model 5:** Result for \( \kappa_g \) \& \( \kappa_\gamma \):

\begin{align*}
\kappa_g & = 1.08^{+0.15}_{-0.13} \\
\kappa_\gamma & = 1.19^{+0.15}_{-0.12}
\end{align*}

Compatibility of SM with fit: 9%.

Calculated using full 2D covariance between determined values.
Spin & CP can be inferred by angular correlation of Higgs decay products:

Channels used for combination: \( H \rightarrow \gamma\gamma \) 
\( H \rightarrow ZZ^* \), \( H \rightarrow WW^* \).

Hypothesis test: Spin 0\(^-\) (SM) versus Spin 2\(^+\)

Test spin 2 admixture of leading order \( q\bar{q} \rightarrow X \) 
& \( gg \rightarrow X \) production: \( f_{q\bar{q}} \)

Entire Spin 2\(^+\) configuration space excluded at 99.9% \( CL_s \).
Differential cross section measurements from \( H \rightarrow \gamma\gamma \)

**Analysis Idea Illustrated**

Simultaneous unbinned Likelihood fit in \( m_{\gamma\gamma} \)

**Unfolding**

* Unfold yields into cross sections using **bin-by-bin** correction factors
* Truth fiducial definition chosen to closely match experimental selection.
  → Minimizes model dependence.

**Measured 7 variables:** Higgs \( p_T \) and rapidity, \( \cos \Theta^* \), \( N_{\text{jets}} \), leading jet \( p_T \), \( p_T^{H+jj} \), \( \Delta \phi_{jj} \)
Higgs $p_T$, helicity angle, and $N_{\text{jets}}$ compared with HRes, Powheg+Py8, HJ Minlo+Py8

Compatibility with SM predictions:

P-value based on $\chi^2$ using full experimental + theory covariance

| $N_{\text{jets}}$ | $p_T^{\gamma\gamma}$ | $|y^{\gamma\gamma}|$ | $|\cos(\theta^*)|$ | $p_T^{j_1}$ | $\Delta\phi_{jj}$ | $p_T^{\gamma\gamma jj}$ |
|------------------|----------------------|--------------------|---------------------|-------------|----------------|----------------|
| POWHEG           | 0.54                 | 0.55               | 0.38                | 0.69        | 0.79           | 0.42           |
| MINLO            | 0.44                 | –                  | –                   | 0.67        | 0.73           | 0.45           |
| HRES             | 1.0                  | 0.39               | 0.44                | –           | –              | –              |

* Statistical limited at this point
→ Good agreement with SM predictions.
vi.a Conclusion

* **New:** Combination of precision mass measurement from $H \rightarrow \gamma \gamma$ & $H \rightarrow ZZ^*$:

\[
m_H = 125.36 \pm 0.37 \pm 0.18 \text{ GeV}
\]

New calibration reduces tension between both channels.

* **Overall signal production strength** combining $H \rightarrow \gamma \gamma$, $H \rightarrow ZZ^*$, $H \rightarrow WW^*$, $VH \rightarrow Hb\bar{b}$, $H \rightarrow \tau\tau$: (with old calibration and mass)

\[
\mu = 1.30^{+0.18}_{-0.17}
\]

Observed coupling compatible with SM Higgs

* **VBF coupling strength from combination:**

\[
\mu_{\text{VBF}} / \mu_{\text{ggF+ttH}} = 1.4^{+0.5+0.4}_{-0.4-0.3}
\]

→ Evidence of $4.1\sigma$ for VBF production of Higgs
vi.b Conclusion

* Results with *leading order* tree-level motivated framework:

**Assumptions** Single resonance, $0^+$, narrow width approx.

* 5 models with focus on different observables:
  1/2 Couplings to Fermions & Bosons
  3/4 Custodial Symmetry
  5 Vertex loops

→ All determined couplings compatible with the SM (p-values ranging from 12-20%)

* Differential cross section measurements from $H \rightarrow \gamma \gamma$

* 7 observables studied, e.g. Higgs $p_T$ and helicity angle

→ All measured distributions compatible with the SM.

---

**ATLAS** Preliminary

$m_H = 125.5 \text{ GeV}$

<table>
<thead>
<tr>
<th>Model: $\kappa_{\psi}, \kappa_F$</th>
<th>$\kappa_F = 1.15^{+0.08}_{-0.08}$</th>
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<th>$\pm 1\sigma$</th>
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<td>$p_{SM}=10%$</td>
<td></td>
<td></td>
<td>2.6</td>
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<table>
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<tr>
<th>Model: $\lambda_{FV}, \lambda_{WZ}, \kappa_F$</th>
<th>$\lambda_{FV} = 0.86^{+0.14}_{-0.12}$</th>
<th>$\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$</th>
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<tr>
<th>Model: $\lambda_{WZ}, \lambda_{FF}, \kappa_{\psi}$</th>
<th>$\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$</th>
<th>$\lambda_{FF} \in [-1.48,-0.99] \cup [0.99,1.50]$</th>
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<tr>
<th>Model: $\lambda_{wq}, \lambda_{qg}, \kappa_{\psi}$</th>
<th>$\lambda_{wq} \in [-1.24,-0.81] \cup [0.78,1.15]$</th>
<th>$\lambda_{qg} \in [-1.24,-0.81] \cup [0.78,1.15]$</th>
<th>$\pm 1\sigma$</th>
<th>$\pm 2\sigma$</th>
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<td>$p_{SM}=15%$</td>
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<th>Model: $\kappa_{\psi}, \kappa_{g}$</th>
<th>$\kappa_g = 1.08^{+0.15}_{-0.13}$</th>
<th>$\kappa_{g} = 1.19^{+0.15}_{-0.12}$</th>
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<td>2.9</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model: $\kappa_{\psi}, \kappa_{x_{\psi}}, B_{\psi}$</th>
<th>$B_{\psi} \leq 0.41$</th>
<th>$\pm 1\sigma$</th>
<th>$\pm 2\sigma$</th>
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</table>
Updated coupling analysis paper in preparation

Updated differential & fiducial cross section paper in preparation

Other interesting results out, like low- & high-mass search for additional narrow resonances [ATLAS-CONF-2014-031]

We are in the transition period from discovery to more precise measurements. Very exciting conditions for LHC Run period 2.

Slight **Paradigm shift ongoing:** unfolded differential distributions will make it possible for outsiders to test our understanding of the Higgs boson

Thank you
Backup