Higgs Property Measurement with ATLAS

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Observation of a new Particle (2012.7.4)!

Is it the SM Higgs?

- Verify the new observed particle
  - Spin-0 particle
    - Spin-1: excluded by $H \rightarrow \gamma\gamma$
    - Spin-2: look at angular correlations

- CP-nature
  - SM Higgs CP-even, extended Higgs sectors has CP-odd or mixed states
  - Look at angular correlations

- Couplings
  - Gauge / Yukawa couplings $\rightarrow g_{vH}, g_{fH} \propto m$
  - Unitarity in $W_L W_L$ scattering $\rightarrow g_{WWH} \propto m_W$
  - Higgs self-couplings, determine shape of Higgs potential via trilinear and quartic couplings, $V = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 + $ constant
ATLAS Combined Results

Discovery of a particle with a local significance of 5.9σ.

Channel | Fitted $m_H$ | Observed | Expected
---------|--------------|-----------|-----------
$H \rightarrow \gamma\gamma$ | 126.5 GeV | 4.5σ | 2.5σ |
$H \rightarrow ZZ^* \rightarrow 4l$ | 125.0 GeV | 3.6σ | 2.7σ |
$H \rightarrow WW^* \rightarrow l_\nu l_\nu$ | 125.0 GeV | 2.8σ | 2.3σ |
**Combined** | **126.0 GeV** | **5.9σ** | **4.9σ** |
ATLAS Combined Results

- $H \rightarrow bb, \tau\tau$ and $WW^*$ analyses have been updated using 13 fb$^{-1}$ data collected at 8 TeV in 2012.
- Higgs decays to $\gamma\gamma$, $ZZ^*$ and $WW^*$ are established, but $H \rightarrow bb, \tau\tau$ still lack of statistics to draw definitive conclusion.

Best-fit signal strength: $\mu = 1.3 \pm 0.3$

Best-fit Higgs mass $m_H$: $126.0 \pm 0.4$ (stat) $\pm 0.4$ (syst) GeV
- **Observation of \( H \rightarrow \gamma\gamma \) excludes spin-1**

- **Higgs has two types of couplings**
  - “Gauge” couplings (to bosons)
  - Yukawa couplings (to fermions)

- **Explore tension between SM value and observation from different Higgs production modes:**  \( \mu_{VBF+VH} \) vs. \( \mu_{ggF+ttH} \)
Model independent coupling studies which are directly related to experimental observables.

2D contour: $\mu_{VBF+VH}$ vs. $\mu_{ggF+ttH}$

$H \rightarrow ZZ^* \rightarrow 4l$ has low statistics and uses inclusive analysis.

The signal strength ratios cancel the branching ratios of different channels so that the results can be compared directly.
Assumptions (LHC HXSWG, arXiv:1209.0040):

- The signal observed in different channels originate from a single narrow resonance with mass near 125 GeV.
- The width of the assumed Higgs boson near 125 GeV is neglected, hence the signal cross section can be decomposed in the following for all channels:

\[(\sigma \cdot \text{BR}) (i\bar{i} \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}\]

- Only modifications of couplings strengths are taken into account, while the tensor structure of the couplings is assumed to be same as in the SM prediction (CP-even scalar). [ATLAS-CONF-2012-127]
Depending on the benchmark model, $\kappa_g$, $\kappa_\gamma$ and $\kappa_H$ are either functions of other couplings or independent parameters.

Notation for $gg \rightarrow H \rightarrow \gamma\gamma$

\[
(\sigma \cdot \text{BR})(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{ggF} \cdot \frac{\Gamma_{\gamma\gamma}}{\Gamma_H}
\]

\[
\frac{\sigma_{ggF}^{\text{SM}}}{\sigma_{ggF}^{\text{SM}}} = \kappa_g^2 \\
\frac{\Gamma_{\gamma\gamma}^{\text{SM}}}{\Gamma_{\gamma\gamma}^{\text{SM}}} = \kappa_\gamma^2 \\
\frac{\Gamma_H^{\text{SM}}}{\Gamma_H^{\text{SM}}} = \kappa_H^2
\]

\[
= \kappa_g^2 \sigma_{\text{SM}}(gg \rightarrow H) \cdot \frac{\kappa_\gamma^2}{\kappa_H^2} \cdot \text{BR}_{\text{SM}}(H \rightarrow \gamma\gamma)
\]

fixed
No BSM particle contributions to $gg \rightarrow H$, $H \rightarrow \gamma\gamma$ and the total width. Two coupling scale factors $\kappa_F$ for fermions and $\kappa_V$ for bosons,

$$\kappa_F = \kappa_t = \kappa_b = \kappa_{\tau}$$

$$\kappa_V = \kappa_W = \kappa_Z$$

68% CL intervals

$$\kappa_F \in [-1.0, -0.7] \cup [0.7, 1.3]$$

$$\kappa_V \in [0.9, 1.0] \cup [1.1, 1.3]$$

Same as above, but without the assumption on the total width

$$\lambda_{FV} = \frac{\kappa_F}{\kappa_V}, \quad \kappa_{VV} = \kappa_V \cdot \kappa_V / \kappa_H$$

68% CL intervals

$$\lambda_{FV} \in [-1.1, -0.7] \cup [0.6, 1.1]$$

$$\kappa_{VV} = 1.2^{+0.3}_{-0.6}$$
Probing custodial symmetry of the W/Z Coupling

- Similar to previous benchmark model, but $\kappa_V \rightarrow \kappa_W$ and $\kappa_Z$, so there are three free parameters $\kappa_W$, $\kappa_Z$ and $\kappa_F$. Identical couplings scale factors for the W and Z are required within tight bounds by SU(2) custodial symmetry and $\rho$ parameter.

- The VBF process is parametrized with $\kappa_W$ and $\kappa_Z$ according to the Standard Model.

\[
\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 1.07^{+0.35}_{-0.27}
\]
In many extensions of the SM, the couplings of the light Higgs boson to up-type and down-type fermions differ ($|\lambda_{du}|$).

The measurement is dominated by channels where we don’t observe an excess, $H\to bb (\mu=-0.4 \pm 1.1)$ and $H\to \tau\tau (\mu=0.7 \pm 0.6)$. 

\begin{itemize}
  \item \textbf{ATLAS Preliminary}
  \item $\sqrt{s} = 7\text{TeV}, \int L dt = 4.8 \text{ fb}^{-1}$
  \item $\sqrt{s} = 8\text{TeV}, \int L dt = 5.8-5.9 \text{ fb}^{-1}$
  \item exp. $-2 \ln \Lambda(\lambda_{du})$
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  \item exp. $-2 \ln \Lambda(\lambda_{lq})$
\end{itemize}

95\% CL
\[ \lambda_{du} \in [-2.0, 1.8] \]
\[ \lambda_{du} = \frac{k_d}{k_u} \]

95\% CL
\[ \lambda_{lq} \in [-2.1, 2.1] \]
\[ \lambda_{lq} = \frac{k_l}{k_q} \]
For $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ vertices, effective scale factors $\kappa_\gamma$ and $\kappa_g$ are introduced (two free parameters). Non-SM particles can contribute to $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ loops or in new final states.

Using only SM contributions to total width and $\kappa_i = 1$ for all SM particles.

\[
\begin{align*}
\kappa_g &= 1.1^{+0.4}_{-0.2} \\
\kappa_\gamma &= 1.2^{+0.3}_{-0.2}
\end{align*}
\]

$68\%$ CL

$-2 \ln \Lambda(\kappa, \kappa_g) < 2.3$

$-2 \ln \Lambda(\kappa_\gamma, \kappa_g) < 6.0$

Compatibility $35\%$

$\Gamma_H = \frac{\kappa_H^2 (\kappa_i)}{(1 - BR_{inv, undet})} \Gamma_{SM}^H$

$BR_{inv, undet.} < 0.68$
A new Higgs-like particle was observed on July 4, 2012

Mass: $m_H = 126.0 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV}$

Signal strength: $\mu = 1.3 \pm 0.3$

Higgs decays to $\gamma\gamma$, $ZZ^*$ and $WW^*$ (gauge coupling) are established, but $H \rightarrow bb$, $\tau\tau$ (Yukawa coupling) still lack of statistics to draw definitive conclusion.

The spin-1 is excluded due to observation of $H \rightarrow \gamma\gamma$.

Uncertainties of couplings parameters $\sim$20-30%, no significant deviations from the SM couplings are observed.

Please stay tuned!
<table>
<thead>
<tr>
<th>Higgs Boson Decay</th>
<th>Subsequent Decay</th>
<th>Sub-Channels</th>
<th>$\int L , dt$</th>
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<tbody>
<tr>
<td>$H \rightarrow ZZ^{(*)}$</td>
<td>$4\ell$</td>
<td>${4e, 2e2\mu, 2\mu2e, 4\mu}$</td>
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<td>$H \rightarrow \gamma\gamma$</td>
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<td>$H \rightarrow \tau\tau$</td>
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<td>${e\mu\otimes 0\text{-jet}} \oplus {\ell\ell\otimes 1\text{-jet, 2-jet, boosted, } VH}$</td>
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<td>$VH \rightarrow Vbb$</td>
<td>$Z \rightarrow \nu\nu$, $W \rightarrow \ell\nu$, $Z \rightarrow \ell\ell$</td>
<td>$E_{\text{miss}}^{\nu}\in{120 - 160, 160 - 200, \geq 200 , \text{GeV}} \otimes {2\text{-jet, 3-jet}}$, $p_T^{W}\in{&lt; 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 , \text{GeV}}$, $p_T^{\ell}\in{&lt; 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 , \text{GeV}}$</td>
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**2012 $\sqrt{s} =$8 TeV**

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**Best-fit Higgs mass:**

$m_H = 126 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV}$

**Best-fit signal strength:**

$\mu = 1.4 \pm 0.3$
Higgs Boson Production at LHC

Gluon-gluon fusion $gg \rightarrow H$ and vector-boson fusion $qq \rightarrow qqH$ are dominant processes.

@125 GeV: $\sigma_{ggH} = 19.5$ pb, $\sigma_{VBF} = 1.6$ pb, $\sigma_{WH} = 0.70$ pb, $\sigma_{ZH} = 0.39$ pb, $\sigma_{ttH} = 0.13$ pb

$\Rightarrow$ ~230k events in 2011+2012 samples
Higgs Boson Decay

Higgs decay branching ratio at $m_H=125$ GeV

- $\bar{b}b$: 57.7% (huge QCD background)
- $WW^*$: 21.5% (easy identification in di-lepton mode, complex background)
- $\tau\tau$: 6.3% (complex final states with $\tau$ leptonic and/or hadronic decays)
- $ZZ^*$: 2.6% (“gold-plated”, clean signature of 4-lepton, high S/B, excellent mass peak)
- $\gamma\gamma$: 0.23% (excellent mass resolution, high sensitivity)

Higgs boson production rate: 1 out of $10^{12}$ collision events
Higgs Boson Width

- **Strong mass dependent**
  \[ \Gamma_H = 3.5 \text{ MeV } @ \text{120 GeV} \]
  \[ 1.4 \text{ GeV } @ \text{200 GeV} \]
  \[ 8.4 \text{ GeV } @ \text{300 GeV} \]
  \[ 68.0 \text{ GeV } @ \text{500 GeV} \]

- At low mass region (<200 GeV), detector resolution dominates mass resolution.

- At high mass, intrinsic width becomes dominant.

\[ \Gamma_H \approx \frac{3G_F M_H^3}{16\pi\sqrt{2}} \]

\[ \approx 500 \text{ GeV} \cdot \left( \frac{M_H}{1 \text{ TeV}} \right)^3 \]
Higgs Boson Decays

The decay properties of the Higgs boson are fixed, if the mass is known:

\[ \Gamma(H \rightarrow f\bar{f}) = N_C \left( \frac{G_F}{4\sqrt{2}\pi} \right) m_f^2 (M_H^2) M_H \]

\[ \Gamma(H \rightarrow VV) = \delta_V \left( \frac{G_F}{16\sqrt{2}\pi} \right) M_H^3 \left( 1 - 4x + 12x^2 \right) \beta_V \]

where: \( \delta_Z = 1, \delta_W = 2, x = M_V^2 / M_H^2, \beta = \text{velocity} \)

\[ \Gamma(H \rightarrow gg) = \frac{G_F}{36\sqrt{2}\pi} \frac{\alpha_s^2(M_H^2)}{M_H^3} \left[ 1 + \left( \frac{95}{4} - \frac{\tau N_f}{6} \right) \frac{\alpha_s}{\pi} \right] \]

\[ \Gamma(H \rightarrow \gamma\gamma) = \frac{G_F}{128\sqrt{2}\pi} \frac{\alpha_s^2}{M_H^3} \left[ \frac{4}{3} N_C e_t^2 - 7 \right]^2 \]

Higgs Boson:

- it couples to particles proportional to their masses
- decays preferentially in the heaviest particles kinematically allowed