Combination of couplings of the Higgs boson by the ATLAS experiment with Run 1 data

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On behalf of the ATLAS collaboration

ICNFP2015, Crete, Greece
August 23-30, 2015
**SM Higgs production and decay at LHC**

\[ \sigma(pp \rightarrow H+X)\ [pb] \]

- ggH
- VBF
- VH

\[ \sqrt{s} = 8 \text{ TeV} \]

- m\(_{H}\): fundamental parameter of the SM with no expected value
- Expected limit: somewhere below ~1 TeV

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ICNFP2015 Conference
**Higgs boson mass measurement**

- Input for testing SM Higgs coupling structure

**ATLAS** $m_H$ measurement using $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ decay channels.

**Mass measurement method**

Simultaneously fit of mass spectra for ten categories and at 7 and 8TeV.

**Signal modeling**

Crystal Ball + Gaussian

**Background modeling and estimation**

- Fit to diphoton mass distribution in the data.
- Exponential functional of first/second-order polynomial

**Main systematics:**

Photon energy scale uncertainties

Result from $H \rightarrow \gamma\gamma$

$m_H = 125.98 \pm 0.50$ GeV

$= 125.98 \pm 0.42(\text{stat.}) \pm 0.28(\text{syst.})$ GeV
Higgs boson mass measurement - Input for testing SM Higgs coupling structure

Mass measurement method

2D fit to $m_{4\ell}$ and $\text{BDT}_{ZZ^*}$ output

- Multivariate discriminant $\text{BDT}_{ZZ^*}$: reduce impact from main background $ZZ^*$

Variables used in training

$\rho_{T,4\ell}, \eta_{4\ell}, D_{ZZ^*} = \ln \left( \frac{|M_{\text{sig}}|^2}{|M_{ZZ^*}|^2} \right)$

Result from $H \rightarrow ZZ^* \rightarrow 4\ell$

$m_H = 124.51 \pm 0.52 \, \text{GeV}$

**Combined mass measurement result**

- **Model independent measurement**: Signal strength for $\gamma\gamma$ and $4l$, $\mu_{\gamma\gamma}$ and $\mu_{4l}$, allowed to vary independently.

- Compatibility of the measurements in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ channels at $2\sigma$ level

Signal strength definition

\[
\mu = \frac{\sigma \times BR}{(\sigma_{SM} \times BR_{SM})}
\]

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ATLAS Combined measurement

\[
m_H = 125.36 \pm 0.41 \text{ GeV} \\
   = 125.36 \pm 0.37(\text{stat.}) \pm 0.18(\text{syst.}) \text{GeV}
\]

**Talk by Prof Pascal VANLAER link**

ATLAS+CMS combined measurement

\[
m_H = 125.09 \pm 0.24 \text{ GeV} \\
   = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{GeV}
\]

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**PRL114,191803(2015)**
Combined mass measurement result

No significant correlation between the two fitted variables observed confirming the model-independence of the mass measurement.

**Direct limit on the total width**

**Method:** limit set from the observed width of the invariant mass peak

**Signal model:**
- $H \to \gamma\gamma$: Convolution of detector resolution with a non relative Breit-Wigner distribution
- $H \to ZZ \to 4l$: per-event resolution model

**Observed 95% CL upper limit on the width:**
- $H \to \gamma\gamma$: 5.0 GeV
- $H \to ZZ \to 4l$: 2.6 GeV

**Talk by Prof Pascal VANLAER link**
Indirect limit on the total width from off-shell Higgs boson measurement

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**ATLAS**

$H \to ZZ^* \to 4l$

$s= 7$ TeV: $Ldt = 4.5$ fb$^{-1}$

$s= 8$ TeV: $Ldt = 20.3$ fb$^{-1}$

- Expected, $\mu=1.0$, $m_H=125$ GeV
- Observed

Measurement of the Higgs boson production and decay rates and coupling strength

Measured at ALTAS combined mass of 125.36 GeV

The study combines the following specific analysis:

- $H \rightarrow \gamma\gamma, ZZ^*, WW^*, Z\gamma, b\bar{b}, \tau\tau$ and $\mu\mu$ decay channels.
- Searches for $t\bar{t}H$ production (talk by Yang Qin Link)
- Measurements of off-shell Higgs boson production (Talk by Prof Pascal VANLAER link)
**Rate measurements**

Assuming a multiplier common to all decay modes

combined measurement of signal strengths compatible with SM expectation

\[ p\text{-value} = 18\% \]

Combined result:

\[
\mu = 1.18^{+0.15}_{-0.14}
\]

\[ = 1.18 \pm 0.10 \text{(stat.)} \pm 0.07 \text{(syst.)}^{+0.08}_{-0.07} \text{(theo.)} \]

**arXiv:1507.04548**
**Decouple different Higgs production modes**

**arXiv:1507.04548**

- Assuming SM Higgs decay branching ratio
  
  \[ \mu_{ggF} = 1.23^{+0.23}_{-0.20} \]
  
  \[ \mu_{VBF} = 1.23 \pm 0.32 \]
  
  \[ \mu_{VH} = 0.80 \pm 0.36 \]
  
  \[ \mu_{ttH} = 1.81 \pm 0.80 \]

- Compatibility of the SM hypothesis at 1\(\sigma\) level

**Total measured Higgs production cross sections**

\[ \sigma_H(7 \text{ TeV}) = 22.1^{+7.4}_{-6.0} \text{ pb} \]
\[ = 22.1^{+6.7}_{-5.3} \text{ (stat.)}^{+2.7}_{-2.3} \text{ (syst.)}^{+1.9}_{-1.4} \text{ (theo.) pb} \]

\[ \sigma_H(8 \text{ TeV}) = 27.7 \pm 3.7 \text{ pb} \]
\[ = 27.7 \pm 3.0 \text{ (stat.)}^{+2.0}_{-1.7} \text{ (syst.)}^{+1.2}_{-0.9} \text{ (theo.) pb} \]

**Theoretical predictions**

- 7TeV: 17.4 \(\pm\) 1.6 pb
- 8TeV: 22.3 \(\pm\) 2.0 pb
**Boson and fermion-mediated production processes**

Higgs production processes:

- Fermion mediated: $\mu_{\text{ggF}+ttH}^f \equiv (\mu_{\text{ggF}}^f = \mu_{ttH}^f)$
- Boson mediated: $\mu_{\text{VBF}+VH}^f \equiv (\mu_{\text{VBF}}^f = \mu_{VH}^f)$

Result consistent with the SM expectation

\[
R_{YY} = 0.56^{+0.66}_{-0.45},
R_{ZZ^*} = 0.18^{+1.20}_{-0.52},
R_{WW^*} = 1.47^{+0.80}_{-0.54},
R_{\tau\tau} = 0.81^{+2.19}_{-0.49},
R_{bb} = 0.33^{+1.03}_{-0.25},
R_{\text{Combined}} = 0.96^{+0.43}_{-0.31}
\]

\[
\sigma_{\text{VBF}+VH}/\sigma_{\text{ggF}+ttH} = \frac{\sigma_{\text{VBF}+VH}}{\sigma_{\text{ggF}+ttH}}_{\text{SM}}
\]

Relative production cross section $R$

Higgs decay branching ratios cancel

\[
\mu_{\text{VBF}+VH}^f = \frac{\sigma_{\text{VBF}+VH}/\sigma_{\text{ggF}+ttH}}{\sigma_{\text{VBF}+VH}/\sigma_{\text{ggF}+ttH}}_{\text{SM}} = \frac{\mu_{\text{VBF}+VH}}{\mu_{\text{ggF}+ttH}} \equiv R_{ff}
\]

arXiv:1507.04548
Unlike most other measurements the inclusive theory uncertainties are not part of this measurement. Hence if theory prediction changes, this measurement will stay more valid.
Framework for coupling-strength measurements

- Leading order tree-level motivated framework with assumptions:
  - Signal observed in different channels originate from a single resonance $m_H \sim 125.36$ GeV
  - Narrow width approximation.
  - Lagrangian tensor structure: SM hypothesis $J^\text{CP} = 0^{++}$

Yield for the production and decay $i \rightarrow H \rightarrow f$ parametrized in terms of coupling scale factors scaling the SM cross sections and widths

\[
\sigma \cdot B(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \left( \kappa_i^2 \kappa_f^2 \right)
\]

Coupling scale factors:

- $\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$ (Production)
- $\kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}}$ (Decay)
- $\kappa_H^2 = \frac{\sum \Gamma_f}{\sum \Gamma_f^{SM}}$ (Total width)

- Higgs boson width $\Gamma_H$ not experimentally constrained to a meaningful precision at the LHC:
  - No assumptions on $\Gamma_H$: Ratios of coupling strength can be measured
  - Make assumption on $\Gamma_H$: absolute coupling strengths can be measured.
**Fermion versus boson coupling**

Assuming only SM contributions to the total width

\[ \kappa_Y^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t \]

\( \kappa_F - \kappa_V \) relative sign sensitivity from W- and t-loop in \( H \to \gamma \gamma \)

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**ATLAS**

- \( \sqrt{s} = 7 \text{ TeV}, 4.5-4.7 \text{ fb}^{-1} \)
- \( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
- \( m_H = 125.36 \text{ GeV} \)

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**Negative solution strongly disfavored at \(~4\sigma\)**

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Change in sign of the chosen profiled solution of \( \kappa_F \)

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**[arXiv:1507.04548]**
**BSM contributions in loop vertices and to the total width allowing modified couplings to SM particles**

\[
\Gamma_H(\kappa_j, \text{BR}_{i,u.}) = \frac{\kappa_H^2(\kappa_j)}{(1 - \text{BR}_{i,u.})} \Gamma_{H}^{\text{SM}}
\]

Constraints on the total width:

\(\kappa_V < 1\): Higgs boson should solve the unitarity problem in vector boson scattering, valid in a wide class of BSM models.

\(\kappa_{\text{on}} = \kappa_{\text{off}}\): coupling strength in off-shell Higgs boson production identical to those for on-shell Higgs boson production

Compatibility with SM hypothesis

\(\kappa_V < 1\): 96%

\(\kappa_{\text{on}} = \kappa_{\text{off}}\): 64%

arXiv:1507.04548
Probing relations within the fermion coupling sector

- Motivation: Many extensions of the SM contain: (e.g. certain Two-Higgs-Doublet Models)
- different coupling strengths of the Higgs boson to up-type and down-type fermions.

Probe up- and down type fermion symmetry

Probe quark and lepton symmetry

- different coupling strengths of the Higgs boson to leptons and quarks

ATLAS

\[ \begin{align*}
\lambda_{du} &= \frac{\kappa_d}{\kappa_{du}} \\
\lambda_{\ell q} &= \frac{\kappa_{\ell}}{\kappa_{\ell q}}
\end{align*} \]

Compatibility with the SM hypothesis: 51%
Evidence of Higgs coupling to down-type fermions: 4.5\(\sigma\)

arXiv:1507.04548

\[ \begin{align*}
\lambda_{du} &= \frac{\kappa_d}{\kappa_{du}} \\
\lambda_{\ell q} &= \frac{\kappa_{\ell}}{\kappa_{\ell q}}
\end{align*} \]

Compatibility with the SM hypothesis: 53%
Evidence of Higgs coupling to lepton: 4.4\(\sigma\)
Mass dependence

Generic model of tree-level coupling factors, with assumptions that no BSM contributions to loop-induced process and to total width.

Compatibility with the SM hypothesis: 57%

Reduced coupling-strength scale factors

\[ y_{V,i} = \sqrt{\kappa_{V,i}} \frac{g_{V,i}}{2v} = \sqrt{\kappa_{V,i}} \frac{m_{V,i}}{v} \]

\[ y_{F,i} = \kappa_{F,i} \frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i} \frac{m_{F,i}}{v} \]

**ATLAS**

\[ \sqrt{s} = 7 \text{ TeV}, 4.5-4.7 \text{ fb}^{-1} \]

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

— Observed

— SM Expected

**arXiv:1507.04548**
Most model-independent determination of coupling-strength scale factors that is currently possible.

Ratios of scale factors:

$$\lambda_{ij} = K_i / K_j, \ K_{ij} = K_i \cdot K_j / K_H$$

Compatibility with the SM hypothesis: 73%

$$\lambda_{wz}$$ measurement in excellent agreement with the prediction of SU(2) custodial symmetry.

Parameter boundaries:

- $$\kappa_{gZ} = 1.18 \pm 0.16$$
- $$\lambda_{Zg} = 1.09^{+0.26}_{-0.22}$$
- $$\lambda_{WZ} \in [-1.04, -0.81] \cup [0.80, 1.06]$$
- $$\lambda_{tg} \in [-1.70, -1.07] \cup [1.03, 1.73]$$
- $$\lambda_{bZ} = 0.60 \pm 0.27$$
- $$\lambda_{rZ} = 0.99^{+0.23}_{-0.19}$$

(95% CL) $$\lambda_{\mu Z} < 2.3$$

(95% CL) $$\lambda_{(Z\gamma)Z} < 3.2$$

$$\sqrt{s} = 7 \text{ TeV}, 4.5 - 4.7 \text{ fb}^{-1}$$

$$\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$$

Parameter value

$$m_H = 125.36 \text{ GeV}$$

arXiv:1507.04548
Conclusion

Using LHC run-1 pp collision dataset collected by ATLAS detector:

- Combined measurement of Higgs boson mass
  \[ m_H = 125.36 \pm 0.41 \text{ GeV} = 125.36 \pm 0.37(\text{stat.}) \pm 0.18(\text{syst.}) \text{GeV} \]

- Combined measured signal yield normalized to SM expectation
  \[ \mu = 1.18^{+0.15}_{-0.14} \]

- The observed Higgs boson production and decay rates interpreted in a leading-order coupling framework. The observed data found to be compatible with the SM expectations for all models considered.

Expect more precise measurements in Run 2.

Effective field theory approach with consistent calculations of higher order corrections and including CP-odd coupling, promising for future precision measurements.
Thank you!
References


arXiv:1507.04548, Submitted to EPJC: Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at $\sqrt{s} = 7$ and 8 TeV in the ATLAS experiment