Higgs boson results from ATLAS

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On behalf of the ATLAS collaboration
The Higgs particle was the missing cornerstone of the SM and is responsible for the masses of elementary particles.

**Born on 4th of July 2012:**

- Higgs-like boson at ~125GeV
- $5.9\sigma$ @ATLAS, $5\sigma$ @CMS (PLB, 716, 2012)

**October 2013:** Nobel prize to Englert and Higgs

**A new era of particle physics — measure the properties of the new particle:**

- mass, couplings and differential cross-sections, spin, CP, width ...
The Large Hadron Collider

The LHC Run 1

\[ \sqrt{s} = 7 \text{ TeV} \]
\[ \sim 5 \text{ fb}^{-1} \text{ at 7 TeV} \]
\[ \sim 20 \text{ fb}^{-1} \text{ at 8 TeV} \]

Delivered Luminosity [fb]

- 2010 pp \( \sqrt{s} = 7 \text{ TeV} \)
- 2011 pp \( \sqrt{s} = 7 \text{ TeV} \)
- 2012 pp \( \sqrt{s} = 8 \text{ TeV} \)

4th July seminar and ICHEP

95% (90%) of recorded (delivered) luminosity was good for physics analysis

Challenges with high luminosity
Higgs production at the LHC

- ~500K Higgs bosons produced in the ATLAS detector
Higgs production at the LHC

- ~500K Higgs bosons produced in the ATLAS detector
- only one in ~$10^{10}$ events will be a Higgs boson.
Higgs production at the LHC

- ~500K Higgs bosons produced
- only one in $\sim 10^{10}$ events will be a Higgs boson.
Higgs decays

Higgs BR + Total Uncert
- Dominant: bb (57%)
- ττ channel (6.3%)
- γγ channel (0.2%)
- WW channel (22%)
- ZZ channel (3%)
- cc channel (3%)
- Zγ channel (0.2%)

Main discovery channels with excellent mass resolution

approximate event yield after selection

450 H → γγ
σ(m_H) ~ 1-2%
S/B ~ 3%

20 H → ZZ*(4l)
σ(m_H) ~ 1-2%
S/B ~ 1.6

500 H → WW*(2l2ν)
σ(m_{T,H}) ~ 20%
S/B ~ 15%
Higgs decays

\[ H \rightarrow \gamma\gamma \]
exp. yield \( \sim 450 \)
\( \sigma(m_H) \sim 1-2\% \)
S/B \( \sim 3\% \)

\[ H \rightarrow ZZ^*(4l) \]
exp. yield \( \sim 20 \)
\( \sigma(m_H) \sim 1-2\% \)
S/B \( \sim 1.6 \)

\[ H \rightarrow WW^*(2l2\nu) \]
exp. yield \( \sim 500 \)
\( \sigma(m_{T,H}) \sim 20\% \)
S/B \( \sim 15\% \)

\[ H \rightarrow \tau\tau \]
exp. yield \( \sim 300 \)
\( \sigma(m_H) \sim 10-20\% \)
S/B \( \sim 1-30\% \)

\[ H \rightarrow bb \]
exp. yield \( \sim 400 \)
\( \sigma(m_H) \sim 10-20\% \)
S/B \( \sim 1-10\% \)

Higgs field serves as the source of mass generation in the fermion sector through the Yukawa interaction.
## Panorama of Higgs analysis

<table>
<thead>
<tr>
<th>Channel</th>
<th>ggF</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma\gamma)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(ZZ^*(4l))</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(WW^*(llll))</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(\tau\tau)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(bb)</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Z\gamma)</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\mu\mu)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
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<tr>
<td>invisible</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass</th>
<th>CP</th>
<th>X-sec.</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>✓</td>
<td>✓</td>
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<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

**Experimental Strategy:**

- Investgate a large number of final states with dedicated event categories to separate different production modes (and to increase overall significance).
- Probe different kinds of the Higgs properties.
Higgs property measurement

- Higgs Mass Measurement
- Coupling measurement
- Higgs invisible search
- Off-Shell behaviour
- Higgs Boson quantum numbers
- Fiducial and Differential cross section measurements
The free and fundamental parameter of the SM Higgs sector

Linked to Higgs properties, including the potential self-coupling.
Uncertainty is estimated by fixing all the 146 constrained parameters into individual contributions, processes or groups of them, the hypothesized number of dilepton categories are defined to have low yield since the production modes. In all cases, for illustration purposes, the sum of the 7-TeV and 8-TeV data is shown in Figs. as a single value. Positive and negative uncertainty contributions are reported where the statistical uncertainties are estimated by finding the points in the spectrum where the difference between the total and statistical uncertainties is approximately symmetric around the best fit value of the parameter. The total systematic uncertainty is given by the quadratic sum of the individual curve uncertainties, each event is weighted according to the expected signal-to-background ratio for the relevant category and data points. The local significance is found to be measured at 125.4 GeV. The background component of the fit is shown with the signal plus background model when the Higgs boson mass is fixed at 125.4 GeV. The background model, the categories with low expected yields are held constant at 1, thus treating them effectively as backgrounds.

The total uncertainty for production process \( \mu \) is estimated by finding the points where the resulting uncertainties in quadrature from the total and statistical uncertainties are estimated by fixing the 123 (23) constrained nuisance parameters associated with experimental (theoretical) uncertainties. The \( m_H \) and \( m_\gamma \) are set to 125.4 GeV and the signal strength categories are defined to have low yield since the production modes. In all cases, for illustration purposes, the sum of the 7-TeV and 8-TeV data is shown in Figs. as a single value. Positive and negative uncertainty contributions are reported where the statistical uncertainties are estimated by finding the points in the spectrum where the difference between the total and statistical uncertainties is approximately symmetric around the best fit value of the parameter.

The total systematic uncertainty is given by the quadratic sum of the individual curve uncertainties, each event is weighted according to the expected signal-to-background ratio for the relevant category and data points. The local significance is found to be measured at 125.4 GeV. The background component of the fit is shown with the signal plus background model when the Higgs boson mass is fixed at 125.4 GeV. The background model, the categories with low expected yields are held constant at 1, thus treating them effectively as backgrounds.
**H → ZZ* → 4l**

Run Number: 204769  
Event Number: 82599793  
Date: 2012-06-10, 13:12:52 CET  

**H → ZZ* → 4μ**
Higgs Mass

- Statistics dominated measurement.
- Systematic uncertainties dominated by energy/momentum calibration of photons ($H\to\gamma\gamma$) and electrons/muons ($H\to ZZ^*(4l)$)
- Compatibility of the four measurement masses $O(10\%)$
- Individual measurement compatible with $\sim2\sigma$

**First ATLAS and CMS Combination:** $m_H=125.09\pm0.21\text{(stat.)}\pm0.11\text{(sys.)}\text{GeV}$
Higgs Boson Couplings

- Predicted for all SM particles for a given Higgs mass.
- Determine Higgs boson phenomenology & experimental signatures.
- Sensitive to BSM phenomena coupling to Higgs sector.

- A straightforward consistency/deviation strategy is based on signal strength measurements in different production and decay modes:
  - The signal strength ($\mu$) is defined as the ratio between the measured Higgs yield and the SM prediction.

$$\mu = \frac{N_{\text{measured}}}{N_{\text{SM}}} = \frac{\sigma \times BR}{(\sigma \times BR)_{\text{SM}}}$$
H→γγ and H→ZZ*(4l)

**ATLAS** Preliminary

m_H = 125.36 GeV

### Input measurements

<table>
<thead>
<tr>
<th>μ</th>
<th>± 1σ on μ</th>
</tr>
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<tbody>
<tr>
<td>m_H (GeV)</td>
<td></td>
</tr>
<tr>
<td>125.4</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>H → γγ</th>
<th>Overall: μ = 1.17^{+0.27}_{-0.27}</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF: μ = 1.32^{+0.38}_{-0.38}</td>
<td></td>
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<tr>
<td>VBF: μ = 0.8^{+0.7}_{-0.7}</td>
<td></td>
</tr>
<tr>
<td>WH: μ = 1.0^{+1.6}_{-1.6}</td>
<td></td>
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<tr>
<td>ZH: μ = 0.1^{+0.7}_{-0.1}</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>H → ZZ*</th>
<th>Overall: μ = 1.44^{+0.40}_{-0.33}</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF+tH: μ = 1.7^{+0.5}_{-0.4}</td>
<td></td>
</tr>
<tr>
<td>VBF+VH: μ = 0.3^{+0.6}_{-0.9}</td>
<td></td>
</tr>
</tbody>
</table>

√s = 7 TeV, 4.5-4.7 fb⁻¹

√s = 8 TeV, 20.3 fb⁻¹

### Signal strength (μ)

<table>
<thead>
<tr>
<th>4l selection</th>
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<tbody>
<tr>
<td>H → ZZ* → 4l</td>
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</table>

<table>
<thead>
<tr>
<th>4l selection</th>
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<tbody>
<tr>
<td>H → ZZ* → 4l</td>
</tr>
</tbody>
</table>

### obs.(exp.) Significance

<table>
<thead>
<tr>
<th>H→γγ</th>
<th>5.2σ(4.6σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H→ZZ*(4l)</td>
<td>8.1σ(6.2σ)</td>
</tr>
</tbody>
</table>
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and no jets

**Longitudinal view**

**Transverse view**

Run 189483, Ev. no. 90659667
Sep. 19, 2011, 10:11:20 CEST

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and no jets

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**Longitudinal view**

**Transverse view**

Run 189483, Ev. no. 90659667
Sep. 19, 2011, 10:11:20 CEST
H → WW*(2l2ν)

- obs.(exp.) significance: 6.1σ(5.8σ)
- **Evidence for VBF** with obs.(exp.) significance of 3.2σ(2.7σ): Crucial to measure VH couplings in tree level processes
- Systematic (in particular theoretical uncertainty) play a very important role
  - N-jet categorization and VBF total cross section

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
<th>Plot of error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Data statistics</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>Signal regions</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Profiled control regions</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Profiled signal regions</td>
<td>-</td>
<td>-</td>
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<tr>
<td>MC statistics</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Theoretical systematics</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>Experimental systematics</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>0.23</td>
<td>0.21</td>
</tr>
</tbody>
</table>

\[ \mu = 1.09^{+0.23}_{-0.21} = 1.09^{+0.16}_{-0.15} \text{(stat.)}^{+0.17}_{-0.14} \text{(syst.)} \]
\[ \mu_{ggF} = 1.02^{+0.29}_{-0.26} = 1.02 \pm 0.19 \text{(stat.)}^{+0.22}_{-0.18} \text{(syst.)} \]
\[ \mu_{VBF} = 1.27^{+0.53}_{-0.45} = 1.27^{+0.44}_{-0.40} \text{(stat.)}^{+0.30}_{-0.21} \text{(syst.)} \]
- **H → ττ**: include all τ decays
  - obs.(exp.) significance: 4.5σ(3.4σ)
  - **Evidence for Higgs-Yukawa coupling** as predicted in the SM.
- **H→bb**: due to overwhelming multi-jet backgrounds, need additional signature from exclusive production modes.
  - Signal: (W/Z)H with H→bb and V leptonic decay.
  - obs.(exp.) significance: 1.4σ(2.6σ)
Searches for Rare Higgs Boson Production & Decays

❖ Searches for rare production modes
  • ttH (direct access to top-Higgs Yukawa coupling)

❖ Searches for rare SM decays
  • $H \rightarrow \mu \mu$ (probe 2nd generation lepton coupling)
  • $H \rightarrow Z \gamma$ (probe loop decay)
$ttH(H\rightarrow\gamma\gamma)$
The results are compatible with the SM expectation and dominated by statistical uncertainties.
H→μμ and H→Zγ Searches

<table>
<thead>
<tr>
<th>95% CL upper limit on signal strength (μ)</th>
<th>observed</th>
<th>expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>H→μμ</td>
<td>7.0</td>
<td>7.4</td>
</tr>
<tr>
<td>H→Zγ</td>
<td>11</td>
<td>9</td>
</tr>
</tbody>
</table>

- Searches are statistically limited
- Clear sign that Higgs boson does not couple universally to leptons (260×SM for H→μμ given the observed evidence of H→ττ)
Summary of signal strength measurement

- All measurements of signal strength consistent with 1:
  - combined precision ~13%, theory uncertainty non-negligible
### Summary of signal strength measurement

<table>
<thead>
<tr>
<th>ATLAS Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H = 125.36$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$H \rightarrow \gamma\gamma$</th>
<th>$\mu = 1.17^{+0.28}_{-0.26}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>$\mu = 1.46^{+0.40}_{-0.34}$</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>$\mu = 1.18^{+0.24}_{-0.21}$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>$\mu = 0.63^{+0.39}_{-0.37}$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$\mu = 1.44^{+0.42}_{-0.37}$</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>$\mu = -0.7^{+3.7}_{-0.7}$</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$\mu = 2.7^{+4.5}_{-4.5}$</td>
</tr>
<tr>
<td>Combined</td>
<td>$\mu = 1.18^{+0.15}_{-0.14}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sqrt{s} = 7$ TeV, $4.5-4.7$ fb$^{-1}$</th>
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</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 8$ TeV, $20.3$ fb$^{-1}$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>$-1$</th>
<th>$0$</th>
<th>$1$</th>
<th>$2$</th>
<th>$3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal strength ($\mu$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Re-parametrisation with the ratios to ggF(production) and WW(decay): |

$$ R_{i/ggF} = \frac{\sigma_i/\sigma_{ggF}}{[\sigma_i/\sigma_{ggF}]_{SM}} $$

$$ \rho_{f/WW^*} = \frac{BR_f/BR_{WW^*}}{[BR_f/BR_{WW^*}]_{SM}} $$

<table>
<thead>
<tr>
<th>$\mu_{ggF}$</th>
<th>$1.15^{+0.28}_{-0.24}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{WW^*}$</td>
<td></td>
</tr>
<tr>
<td>Ratio of cross sections</td>
<td>Best-fit value</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>$R_{VBF/ggF}$</td>
<td>$1.00^{+0.46}_{-0.34}$</td>
</tr>
<tr>
<td>$R_{VH/ggF}$</td>
<td>$1.33^{+0.94}_{-0.68}$</td>
</tr>
<tr>
<td>$R_{ttH/ggF}$</td>
<td>$1.90^{+1.12}_{-0.86}$</td>
</tr>
</tbody>
</table>

- All measurements of signal strength consistent with 1:
  - combined precision ~13%, theory uncertainty non-negligible
Higgs boson coupling scale factors

- **Assumptions:**
  - Single state, spin 0 and CP-even.
  - Narrow-width approximation: \((σ \cdot BR) (ii \rightarrow H \rightarrow ff) = \frac{σ_{ii} \cdot Γ_{ff}}{Γ_{H}}\)

- **Methodology:** parametrise deviations with coupling scale factors \(\{κ_x\}\)

\[ \mu_f = \frac{κ_V^2}{κ_H^2} \]

\[ Γ_H(κ_j, BR_{i,u.}) = \frac{κ_H^2(κ_j)}{(1 - BR_{i,u.})} Γ_{SM}^H \]

- **Two fundamental options:**
  - Allow undetected/invisible decays (κ_H free) or only SM decays
  - Allow BSM particles in the loops or resolve the loop assuming SM field only
Scalar coupling deviations framework

<table>
<thead>
<tr>
<th>Production</th>
<th>Loops</th>
<th>Interference</th>
<th>Expression in terms of fundamental coupling strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(ggF) )</td>
<td>( \checkmark )</td>
<td>( b-t )</td>
<td>( \kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b )</td>
</tr>
<tr>
<td>( \sigma(VBF) )</td>
<td></td>
<td></td>
<td>( \sim 0.74 \cdot \kappa_t^2 + 0.26 \cdot \kappa_Z^2 )</td>
</tr>
<tr>
<td>( \sigma(WH) )</td>
<td></td>
<td></td>
<td>( \sim \kappa_t^2 )</td>
</tr>
<tr>
<td>( \sigma(qg \rightarrow ZH) )</td>
<td></td>
<td></td>
<td>( \sim \kappa_t^2 )</td>
</tr>
<tr>
<td>( \sigma(gg \rightarrow ZH) )</td>
<td>( \checkmark )</td>
<td>( Z-t )</td>
<td>( \kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_t^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_t \kappa_t )</td>
</tr>
<tr>
<td>( \sigma(bbH) )</td>
<td></td>
<td></td>
<td>( \sim \kappa_b^2 )</td>
</tr>
<tr>
<td>( \sigma(ttH) )</td>
<td></td>
<td></td>
<td>( \sim \kappa_t^2 )</td>
</tr>
<tr>
<td>( \sigma(gb \rightarrow WtH) )</td>
<td></td>
<td>( W-t )</td>
<td>( \sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_w^2 - 2.41 \cdot \kappa_t \kappa_w )</td>
</tr>
<tr>
<td>( \sigma(qb \rightarrow tHq') )</td>
<td></td>
<td>( W-t )</td>
<td>( \sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_w^2 - 5.96 \cdot \kappa_t \kappa_w )</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Partial decay width</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_{bb} )</td>
</tr>
<tr>
<td>( \Gamma_{WW} )</td>
</tr>
<tr>
<td>( \Gamma_{ZZ} )</td>
</tr>
<tr>
<td>( \Gamma_{\tau\tau} )</td>
</tr>
<tr>
<td>( \Gamma_{\mu\mu} )</td>
</tr>
<tr>
<td>( \Gamma_{\gamma\gamma} )</td>
</tr>
<tr>
<td>( \Gamma_{Z\gamma} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total decay width</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_H )</td>
</tr>
<tr>
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</table>

Input analyses to the combinations: \( H \rightarrow \gamma\gamma, ZZ, WW, \tau\tau, bb, \mu\mu, Z\gamma \) and constraint on \( ttH \) and off-shell Higgs productions
Higgs Boson Coupling measurement

- Scaling coupling to fermions (κ_F) and vector bosons (κ_V):
  - All decay channels converging around SM expectation.

- Other benchmarks models:
  - different options on the loops and decays
  - custodial symmetry of W and Z
  - coupling to up/down-type fermions
  - coupling ratios

Couplings very consistent with SM predictions

**Best Fit values:**

\[
\begin{align*}
\kappa_V &= 1.09^{+0.07}_{-0.07} \\
\kappa_F &= 1.11^{+0.17}_{-0.15}
\end{align*}
\]
Higgs Boson Coupling measurement

- Most general benchmark scenario with the consideration of all potential $\kappa$-scale factors:

![Graph showing fits for generic models and benchmark scenarios](Image)

**ATLAS Preliminary**

- $\sqrt{s} = 7$ TeV, $4.5 - 4.7$ fb$^{-1}$
- 68% CL:
  - $k_V < 1$
  - $k_{Z} = 1$
  - $k_{t} = 1$
  - $k_{b} = 1$
  - $k_{\tau} = 1$
  - $k_{\mu} = 1$
  - $k_{y} = 1$
  - $k_{g} = 1$
  - $k_{Z} = 1$
- $95%$ CL:
  - $k_{Z} = 1$
  - $k_{t} = 1$
  - $k_{b} = 1$
  - $k_{\tau} = 1$
  - $k_{\mu} = 1$
  - $k_{y} = 1$
  - $k_{g} = 1$
  - $k_{Z} = 1$

- $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- 68% CL:
  - $k_{V} < 1$
  - $k_{Z} = 1$
  - $k_{t} = 1$
  - $k_{b} = 1$
  - $k_{\tau} = 1$
  - $k_{\mu} = 1$
  - $k_{y} = 1$
  - $k_{g} = 1$
  - $k_{Z} = 1$
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  - $k_{Z} = 1$
  - $k_{t} = 1$
  - $k_{b} = 1$
  - $k_{\tau} = 1$
  - $k_{\mu} = 1$
  - $k_{y} = 1$
  - $k_{g} = 1$
  - $k_{Z} = 1$

**ATLAS Preliminary**

- $\sqrt{s} = 7$ TeV, $4.5 - 4.7$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

**Measurements very compatible with SM prediction**
Invisible Higgs Searches

With the assumption of SM coupling to known SM particle:

- **VBF:** \( \text{Br}(H \rightarrow \text{inv}) < 0.29(0.35) @ 95\% \text{ CL} \)
- **ZH, Z \rightarrow \text{ee/} \mu\mu:** \( \text{Br}(H \rightarrow \text{inv}) < 0.75(0.62) @ 95\% \text{ CL} \)
- **VH, V \rightarrow qq:** \( \text{Br}(H \rightarrow \text{inv}) < 0.78(0.86) @ 95\% \text{ CL} \)
- **Combination** between \( Zh \rightarrow ll + \text{MET} \) and indirect measurement:
  \( \text{Br}(H \rightarrow \text{inv}) < 0.37(0.39) @ 95\% \text{ CL} \)

- In “Higgs portal” models, limits on \( \text{Br}(H \rightarrow \text{inv}) \) can be translated to constraints on coupling \( \lambda(h, \text{WIMP}) \), then re-parametrized to scattering cross section \( \sigma_{\chi-N} \).

- Tight constraint on the DM at the low mass region

*Combination with the indirect measurement of different channels with coupling scenario
Off-Shell Behaviour and the Higgs Boson Width

- Measurement of the off-shell signal strength in $H \rightarrow WW$ and $H \rightarrow ZZ$.

- With the combination between on-shell and off-shell analysis:
  - Assuming the on-shell couplings are the same as the off-shell couplings, the coupling measurements can be reinterpreted as the **constraints on $\Gamma_H$**.
  - Assuming SM Higgs width, it can be reinterpreted as the **constraints on off-shell and on-shell coupling ratio** $\mu_{\text{off-shell}}/\mu_{\text{on-shell}}$. 

\[
\mu_{\text{off-shell}} = \mu_{\text{on-shell}} \times \frac{\Gamma_H}{\Gamma_H(SM)}
\]
Off-Shell signal strength and the Higgs Boson Width Limit

expressed as a function of unknown K-factor ratio:

- Assuming the unknown \( gg \to VV \) k-factor is equal to signal k-factor:
  - \( \mu_{\text{off-shell}} < 6.2 \ (8.1) \) obs(exp) at 95%CL
  - \( \Gamma_H < 22.7 \ (33.0) \) MeV obs(exp) at 95%CL

- Direct Higgs width measurement at 95%CL:
  - \( H \to \gamma\gamma: \quad \Gamma_H < 5.0(6.2) \) GeV
  - \( H \to ZZ: \quad \Gamma_H < 2.6(6.2) \) GeV
Higgs Boson Quantum Numbers

Clear SM prediction for Higgs Boson quantum Numbers: $J^{pc}=0^{++}$

- All alternative hypotheses excluded to more than 99% CL: non-SM spin-0 models and spin-2 models with universal and non-universal coupling to fermions and bosons.

- Tensor structure of the HVV interaction in the spin-0 hypothesis is investigated.

- Higgs boson very SM-like: small non-SM admixture not yet excluded!
Fiducial and Differential cross section measurement

- Measurement designed as **model independent** as possible.
- Direct **comparison with theoretical predictions** at particle level.
- A wide and diverse range of physical phenomena to be probed:
  - Higgs boson kinematics, Jet activity, VBF-sensitive variables, Spin-CP sensitive variables

**H→ZZ**

PLB 738 (2014)

**H→γγ**

JHEP 09 (2014)

- Dominated by statistical uncertainties
- Broadly in line with the theoretical expectations
Inclusive pp→H cross section

\[ \sigma_{pp\rightarrow H} = 33.0 \pm 5.3 \text{ (stat)} \pm 1.6 \text{ (syst)} \text{ pb} \]

The measurement are comparable to the prediction
Summary: What have we learned?

- Higgs mass determined to 0.2%
- Higgs signal strength \(\sim 1\), determined to 15%
- Higgs couplings tested for many scenarios and assumptions (consistent with SM), the combination between ATLAS and CMS is coming soon.
- Many non-Spin-0 and CP-odd hypotheses excluded
- Differential cross-section measurement at 8TeV

Higgs boson is so far very consistent with SM predictions, but still statistically limited.
LHC/HL-LHC Plan

\( \sqrt{s} = 13 \text{ TeV} \)
- bunch spacing 25 ns
- \( \mathcal{L} \sim 1.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
- Pile Up \sim 40

\( \sqrt{s} = 14 \text{ TeV} \)
- LHC injector upgrade
- \( \mathcal{L} \sim 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
- Pile Up \sim 60

New interaction region layout
- Crab cavity
- luminosity levelling
  - \( \mathcal{L} \sim 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
  - Pile Up \sim 140

\[ s = 13 \text{ TeV} \]
\[ s = 14 \text{ TeV} \]
\[ \mathcal{L} \sim 1.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]
\[ \mathcal{L} \sim 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]
\[ \mathcal{L} \sim 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]
Prospect of Higgs Boson coupling

- Offer a comprehensive physics programme
  - Expected to establish: $H \rightarrow bb$, $ttH$, $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$
  - $3000 \text{fb}^{-1}$ offers physics significance better than $300 \text{fb}^{-1}$
  - Theory uncertainties become dominant for many key processes
LHC Run2 is underway, more results to come very soon!

proton-proton collisions at 13 TeV