Measurement of the properties of the SM-like Higgs boson in ATLAS and CMS

CHARGED 2018

Zirui Wang (Shanghai Jiao Tong Univ./Univ. of Michigan)

On behalf of the ATLAS and CMS Collaborations

25 Sep. 2018, Uppsala, Sweden
• Following the Higgs Boson with mass $\sim 125$ GeV discovered in 2012, more data have allowed for its properties to be measured.

• The Higgs Boson couplings to other particles are set by their masses, which determine all SM-like Higgs Boson production and decay modes including the Higgs self-coupling.

$$\mathcal{L} = -g_{Hff}f \bar{f} H + \delta_V V_\mu V_\mu \left( g_{HVV} H + \frac{g_{HHVV} H^2}{2} \right) + \frac{g_{HHH} H^3}{6} + \frac{g_{HHHH} H^4}{6}$$

$$g_{Hff} = \frac{m_f}{v}$$

$$g_{HVV} = \frac{2m_v^2}{v}$$

$$g_{HHH} = \frac{3m_H^2}{v}$$
There is an increase in production cross sections from increased center-of-mass energy.

<table>
<thead>
<tr>
<th>XS in pb</th>
<th>13 TeV</th>
<th>8 TeV</th>
<th>(\sigma_{13}/\sigma_{8})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>48.52</td>
<td>21.39</td>
<td>2.3</td>
</tr>
<tr>
<td>VBF</td>
<td>3.78</td>
<td>1.60</td>
<td>2.4</td>
</tr>
<tr>
<td>WH</td>
<td>1.37</td>
<td>0.70</td>
<td>2.0</td>
</tr>
<tr>
<td>ZH</td>
<td>0.88</td>
<td>0.42</td>
<td>2.1</td>
</tr>
<tr>
<td>bbH</td>
<td>0.49</td>
<td>0.20</td>
<td>2.4</td>
</tr>
<tr>
<td>ttH</td>
<td>0.51</td>
<td>0.13</td>
<td>3.8</td>
</tr>
<tr>
<td>tH</td>
<td>0.09</td>
<td>0.02</td>
<td>3.9</td>
</tr>
</tbody>
</table>
### SM Higgs Decay BR

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Branching Ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H\rightarrow bb$</td>
<td>58.09</td>
</tr>
<tr>
<td>$H\rightarrow WW^*$</td>
<td>21.52</td>
</tr>
<tr>
<td>$H\rightarrow gg$</td>
<td>8.18</td>
</tr>
<tr>
<td>$H\rightarrow \tau\tau$</td>
<td>6.26</td>
</tr>
<tr>
<td>$H\rightarrow cc$</td>
<td>2.88</td>
</tr>
<tr>
<td>$H\rightarrow ZZ^*$</td>
<td>2.64</td>
</tr>
<tr>
<td>$H\rightarrow \gamma\gamma$</td>
<td>0.23</td>
</tr>
<tr>
<td>$H\rightarrow Z\gamma$</td>
<td>0.15</td>
</tr>
<tr>
<td>$H\rightarrow \mu\mu$</td>
<td>0.022</td>
</tr>
</tbody>
</table>

- $H\rightarrow ZZ^*\rightarrow 4l$ (l=e, $\mu$) and $H\rightarrow \gamma\gamma$: low BR but clean signature. The excellent mass resolution is crucial for the Higgs boson mass measurement.
- $H\rightarrow WW^*$: high BR but low mass resolution.
- $H\rightarrow bb$ and $H\rightarrow \tau\tau$: high BR, low S/B and low mass resolution at LHC.
• LHC Run-1 Legacy
• Property measurement results:
  • Mass and width
  • Differential cross sections
  • Production, decay and coupling
  • Di-Higgs production and Higgs self-coupling
• Summary

Caveat: To fits the time allocated, only a selective set of results will be shown.
- **Gluon fusion** and **Vector boson fusion** production modes are observed in Run-1.
- $H \rightarrow ZZ^*$, $H \rightarrow \gamma\gamma$, $H \rightarrow WW$ and $H \rightarrow \tau\tau$ decay modes are observed in Run-1.
- Higgs boson couplings measured with ~10% - 30% precision.
- The 95% CL upper limit for $BR(\text{BSM})$ is 0.34.
The Run-1 Higgs boson mass is measured from a combination of the four results in the \( H \rightarrow ZZ^* \rightarrow 4l \) (\( l=e,\mu \)) and \( H \rightarrow \gamma\gamma \) channels for ATLAS and CMS.

- ~0.2% precision reached by Run-1 Higgs boson mass measurement.

- As for spin/parity, both CMS and ATLAS results show SM (\( J^p = 0^+ \)) is highly favored against pure alternative. (Exclude tested hypotheses with CL > 99.9%)

- Studies of width, differential distributions didn’t show deviation with SM prediction.
LHC Run-2 13 TeV:

Mass and Width of Higgs Boson
Mass measurement is performed based on $H \rightarrow ZZ^* \rightarrow 4l (l=e, \mu)$ and $H \rightarrow \gamma\gamma$ analysis channels.

To achieve the optimal calibration of photon/lepton, detailed performance studies have been performed.
Measured $m_H$:
- ATLAS+CMS Run 1 combined: $125.09 \pm 0.24$ GeV
- ATLAS Run 2 combined: $124.86 \pm 0.27$ GeV
- ATLAS Run 1+2 combined: $124.97 \pm 0.24$ GeV = $124.97 \pm 0.19 \text{(stat)} \pm 0.13 \text{(syst)}$ GeV
- CMS Run 2 $H \to ZZ^* \to 4l$: $125.26 \pm 0.21$ GeV = $125.26 \pm 0.20 \text{(stat)} \pm 0.08 \text{(syst)}$ GeV
• It is difficult to directly measure Higgs boson width (~4 MeV predicted by SM).
• The best direct limit is $\Gamma_H < 1.10 \text{ GeV} \ @ \ 95\% \ CL$ from CMS $H \rightarrow ZZ^* \rightarrow 4l$
• Indirect limit can be set from measuring the on- and off-shell signal strength in high-mass tails:

\[
\sigma_{\text{off-shell}} \propto k_{g, \text{off-shell}}^2 \cdot k_{Z, \text{off-shell}}^2 \\
\sigma_{\text{on-shell}} \propto \frac{k_{g, \text{on-shell}}^2 \cdot k_{Z, \text{on-shell}}^2}{\Gamma_H / \Gamma_{H}^{SM}} \\
\mu_{\text{off-shell}} = \frac{\sigma_{\text{off-shell}}}{\sigma_{\text{off-shell,SM}}} < 3.8 \ @ \ 95\% \ CL
\]

• ATLAS Run-1 result: $\Gamma_H < 22.7 \text{ MeV} \ @ \ 95\% \ CL$ (33.0 MeV exp.)
• The latest ATLAS Run-2 combining $H(\ast) \rightarrow ZZ(\ast) \rightarrow 4l$ and $H^* \rightarrow ZZ \rightarrow 2l2\nu$: $\Gamma_H < 14.4 \text{ MeV} \ @ \ 95\% \ CL$ (15.2 MeV exp.)
Differential cross sections measurement
• Differential cross sections measurement probe the kinematic properties of the Higgs boson, which is sensitive to new physics.

• Minimal model dependence. Measurements are corrected for detector effects. Results are reported at the particle level.

• 79.8/fb $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ result from ATLAS. 35.9/fb $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$ and $H \rightarrow bb$ from CMS.
Various differential measurements probed.

Unprecedented precision reached.

In general, results are all compatible with SM prediction.
Higgs coupling:
production and decay modes
- **Clean signature** and excellent invariant mass resolution.
- Disentangle different production modes of the signal.
- Analysis measures production rates and properties by splitting dataset into independent “categories” enhanced in a target production mode.

**ATLAS**:

\[ \text{H} \rightarrow \gamma\gamma, \mu = 1.06^{+0.14}_{-0.12} (80/\text{fb}) \]
\[ 1.06^{+0.08}_{-0.08} \text{ (stat.)} +^{0.08}_{-0.07} \text{ (exp.)} +^{0.07}_{-0.06} \text{ (th.)} \]

\[ \text{H} \rightarrow ZZ^* \rightarrow 4l, \mu = 1.19^{+0.16}_{-0.15} (80/\text{fb}) \]
\[ 1.19^{+0.12}_{-0.12} \text{ (stat.)} +^{0.06}_{-0.06} \text{ (exp.)} +^{0.08}_{-0.07} \text{ (th.)} \]

**CMS**:

\[ \text{H} \rightarrow \gamma\gamma, \mu = 1.18^{+0.17}_{-0.14} (36/\text{fb}) \]
\[ 1.18^{+0.12}_{-0.11} \text{ (stat.)} +^{0.09}_{-0.07} \text{ (exp.)} +^{0.07}_{-0.06} \text{ (th.)} \]

\[ \text{H} \rightarrow ZZ^* \rightarrow 4l, \mu = 1.05^{+0.19}_{-0.17} (36/\text{fb}) \]
\[ 1.05^{+0.15}_{-0.14} \text{ (stat.)} +^{0.11}_{-0.09} \text{ (syst.)} \]
- $H \rightarrow bb$ takes the largest BR~$58\% \rightarrow$ drives total width, constrains BSM BR allowed.
- In the most sensitive VH, $H \rightarrow bb$ analysis, both ATLAS and CMS have 3 channels (0-, 1-, 2 charged leptons from the vector boson)
- Using MVA to increase S/B in the signal region. Control regions to validate background and derive the normalizations. Shapes from MC.
- Analyses are now dominated by systematic uncertainties → Adding new data is not enough.

\[ \sim 80/\text{fb} \]
- Run-1 $VH(bb)$ ATLAS+CMS combined significance $2.6\sigma(3.7\sigma \text{ exp.})$
- Run-2 $36/\text{fb}$ evidence of $VH(bb)$: $3.5\sigma(3.0\sigma \text{ exp.})$ from ATLAS and $3.3\sigma(2.8\sigma \text{ exp.})$ from CMS.

**$H\rightarrow bb$ observation with 80/\text{fb}!**

**ATLAS:**
- $VH(bb)$ Run 1+2 combined significance $4.9\sigma(5.1\sigma \text{ exp.})$
- $H(bb)$ Run 1+2 combined significance $5.4\sigma(5.5\sigma \text{ exp.})$

**CMS:**
- $VH(bb)$ Run 1+2 combined significance $4.9\sigma(4.8\sigma \text{ exp.})$
- $H(bb)$ Run 1+2 combined significance $5.5\sigma(5.6\sigma \text{ exp.})$

$H\rightarrow bb$ measurements assume SM production cross sections.
VH production mode

- VH takes ~ 3% of the total Higgs boson production on LHC.
- Only targets leptonic decay mode for bb channel. ZZ and yy also have regions for hadronic categories.

**VH production mode observed after VH combination!**

- ATLAS combine Run-2 analyses in bb, γγ and 4l final states.
- Results assume SM Higgs boson branching fractions.
- Observation of VH production at 5.3σ (4.8σ exp.)
- Dominant contribution is from bb channel: 4.9σ.
- 1.1σ and 1.9σ contribution from 4l and γγ channel, respectively.

• ATLAS and CMS use various categories targeted for ggH/VBF production. CMS also uses 3l+4l events targeting VH
• Good agreement with SM expectation.

ATLAS:

\[ H \rightarrow WW, \mu_{ggF} = 1.21^{+0.22}_{-0.21} \] 6.3σ(5.2σ exp.)
\[ 1.21^{+0.10}_{-0.10} \text{(stat.)}^{+0.15}_{-0.15} \text{(exp.)}^{+0.13}_{-0.12} \text{(th.)} \]

\[ H \rightarrow WW, \mu_{VBF} = 0.62^{+0.37}_{-0.36} \] 1.9σ(2.7σ exp.)
\[ 0.62^{+0.30}_{-0.28} \text{(stat.)}^{+0.16}_{-0.16} \text{(exp.)}^{+0.13}_{-0.13} \text{(th.)} \]

CMS:

\[ H \rightarrow WW, \mu = 1.28^{+0.18}_{-0.17} \] 9.1σ(7.1σ exp.)
\[ 1.28^{+0.10}_{-0.10} \text{(stat.)}^{+0.11}_{-0.11} \text{(exp.)}^{+0.10}_{-0.07} \text{(th.)} \]
- ATLAS and CMS developed 3 channels targeting all possible di-tau decay modes.
- Both $\tau$ leptonic and hadronic decay modes considered.
- Both experiments observe $H \rightarrow \tau\tau$ with $> 5\sigma$. 

ATLAS:
Run-2 $4.4\sigma (4.1\sigma \text{ exp.})$
Run 1+2 $6.4\sigma (5.4\sigma \text{ exp.})$

CMS:
Run-2 $4.9\sigma (4.7\sigma \text{ exp.})$
Run 1+2 $5.9\sigma (5.9\sigma \text{ exp.})$
• Probe 2\textsuperscript{nd} generation fermions coupling. Clean experimental signature with very small BR. Large Drell-Yan background.

• Events categorized by dimuon pT, and BDT that enhances VBF contribution.

• Fitting strategy: extract a signal peak from a continuum falling background, which is similar to the $H\rightarrow\gamma\gamma$ analysis.

\begin{align*}
\text{ATLAS (Run2 80/fb):} & \quad H\rightarrow\mu\mu, \mu = 0.1^{+1.0}_{-1.1} \\
& \quad 95\% \text{ CL: } \mu < 2.1 (2.0 \text{ exp.})
\end{align*}

\begin{align*}
\text{CMS (Run1+Run2 36/fb):} & \quad H\rightarrow\mu\mu, \mu = 0.7^{+1.0}_{-1.0} \\
& \quad 95\% \text{ CL: } \mu < 2.92 (2.16 \text{ exp.})
\end{align*}
• The coupling strength through a Yukawa coupling is proportional to the mass of the fermion → **Largest coupling to top quark**
• Deviation of couplings→ **sensitive to new physics**
• Run-1 ATLAS+CMS combined ttH significance $4.4\sigma (2.0\sigma \text{ exp.})$
• **Multiple decay channels are combined** in order to reach observation.
13 TeV ttH results of different decay channels:

**ttH, \( H \rightarrow \gamma \gamma \)**
ATLAS 4.1σ (3.7σ exp., 79.8 fb)
CMS 1.4σ (1.5σ exp., 35.9 fb)

**ttH, ML(\( H \rightarrow \tau \tau, H \rightarrow WW^* \), 36/fb)**
ATLAS 4.1σ (2.8σ exp.)
CMS 3.2σ (2.8σ exp.)

**ttH, \( H \rightarrow bb \) (36/fb)**
ATLAS 1.4σ (1.6σ exp.)
CMS 1.6σ (2.2σ exp.)
**ttH production mode observed after ttH combination!**

- **ATLAS**
  - Run-2: 5.8σ (4.9σ exp.)
  - Run-1+2: 6.3σ (5.1σ exp.)

- **CMS**
  - Run-2: 4.5σ
  - Run-1+2: 5.2σ (4.2σ exp.)

---


**Phys. Rev. Lett. 120, 231801 (2018)**
Higgs coupling:
Combine all Higgs boson measurements
Combination inputs: CMS has additional ggF $H\rightarrow bb$, VH $H\rightarrow WW$, and $H\rightarrow inv.$ channels. ATLAS with $H\rightarrow ZZ$, $H\rightarrow \gamma\gamma$ and $H\rightarrow \mu\mu$ updated to 80/fb.

More channels will be covered in the following combination analysis.
• **ATLAS**: $\mu = 1.13^{+0.09}_{-0.08} = 1.13^{+0.05}_{-0.05}$ (stat. $)^{+0.05}_{-0.04}$ (exp.) $^{+0.03}_{-0.03}$ (bkg. th.)

• **CMS**: $\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}$ (stat. $)^{+0.06}_{-0.05}$ (sig. th.) $^{+0.06}_{-0.05}$ (other sys.)

• The overall production rate of the Higgs boson was measured to be in agreement with Standard Model predictions, with an uncertainty of 8%-10%

• All major production modes have been observed!
• Couplings are in an excellent agreement with the Standard Model prediction over a range covering 3 orders of magnitude in mass, from the top quark to the much lighter muons.
• The precision is better than Run1 ATLAS+CMS combination.
STXS can make Higgs measurements less model dependent than measurements during Run 1

- STXS (Simplified Template Cross Sections) splits Higgs productions into exclusive kinematic regions (Described in YR4 (Section III.2).
- Instead of performing differential measurement in clean channels only, intend for combination of all decay channels.
- Minimize the dependence on theoretical uncertainties.
ATLAS performed a combination of STXS with a fine granularity measurements for the 36.1/fb $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ channel.

- ggH measurements are in good agreement with the SM.
- Best precisions of ~20% reached

CMS combined all major decay modes: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow bb$, $H \rightarrow WW$, $H \rightarrow \tau\tau$ for STXS.

- Good agreement with SM. Best precisions of <20% reached
Di-Higgs Production and Higgs self-coupling
At $\sqrt{s} = 13$ TeV for $m_H = 125$ GeV

\[
\sigma_{gg \to HH}^{SM} = 33.53 \text{ fb} \left[ 1.0^{+4.3\%}_{-6.0\%} \text{ (scale)} \pm 2.3\% (\alpha_s) \pm 2.1\% (PDF) \pm 5\% (Th.) \right]
\]

Compared with

\[
\sigma_{gg \to H}^{SM} = 48.52 \text{ pb} \left[ 1.0^{+7.4\%}_{-7.9\%} \text{ (scale)} \pm 7.1\% \text{ (PDF+}\alpha_s) \right]
\]

• **~ 1500 difference** → Need to compromise with signal yields (BR) and S/B to select analysis channels

• Higgs self-coupling can be probed by $HH$ production at the LHC ($\lambda = \frac{m_H^2}{2v^2} \approx 0.13$ in SM)
Limit from ATLAS HH combination: $\mu < 6.7$ (10.4 exp.)
Limit from CMS HH combination: $\mu < 22$ (13 exp.)
Limit of Higgs self-coupling SF $\kappa_\lambda = \frac{\lambda_H}{\lambda_{H,SM}}$ @95% CL
  - ATLAS: $-5.0 < \kappa_\lambda < 12.1$ ($-5.8 < \kappa_\lambda < 12.0$, exp.)
  - CMS: $-11.8 < \kappa_\lambda < 18.8$ ($-7.1 < \kappa_\lambda < 13.6$, exp.)
Both CMS and ATLAS results reaches $\sim x10$ SM expected production.
The next step is to reach SM sensitivity in HL-LHC term!
• A lot of impressive Higgs results come from LHC Run 1+2
  • All major production modes have been observed.
  • Higgs coupling to 3rd generation fermions are confirmed.
  • The mass, width and couplings measurements reach unprecedented precision.
  • Di-Higgs production reaches \(~x10\) SM expected production.
• No obvious deviation from SM captured so far.
• Waiting for the full Run-2 dataset and the HL-LHC to reach a higher sensitivity to the potential new physics!
Thanks
Backup
Large Hadron Collider at CERN

LHC: 27 km, the world’s largest proton-proton collider (7-14 TeV)
Electron reconstruction efficiencies in $Z\rightarrow ee$ events as a function of transverse energy $E_T$, integrated over the full pseudo-rapidity range.

Tag-and-probe efficiency for muon reconstruction and identification in 2015 data (circles), simulation (squares), and the ratio (bottom inset) for loose muons with $p_T>20$ GeV. The statistical uncertainties are smaller than the symbols used to display the measurements.
tH production mode

- tH production cross section is small, but **sensitive to the relative sign between** $\kappa_t$ and $\kappa_V$.
- If $\kappa_t/\kappa_V < 0$, tH cross section will be larger than ttH.
- tH production mode can **directly constrain** the sign preference of $\kappa_t/\kappa_V$.

Results from CMS Run-2 36/fb combination of tH ML, tH, $H \rightarrow bb$ and ttH, $H \rightarrow \gamma\gamma$
- With the assumption that $\kappa_V = 1$, the negative sign of $\kappa_t/\kappa_V$ is excluded at **1.5σ** level.
VH production mode

- \( H \rightarrow b\bar{b} \)
- \( H \rightarrow \gamma\gamma \)
- \( H \rightarrow ZZ^* \rightarrow 4l \)

arXiv:1808.08238

arXiv:1806.00425

ATLAS-CONF-2018-018

H\(\rightarrow b\bar{b}\)

H\(\rightarrow \gamma\gamma\)

H\(\rightarrow ZZ^* \rightarrow 4l\)
• Introduce one scale factor $\kappa$ per SM particle with observable “Higgs coupling” at the LHC: $\kappa_W$, $\kappa_Z$, $\kappa_t$, $\kappa_b$, $\kappa_\mu$, $\kappa_\gamma$, $\kappa_g$, $\kappa_H$

• Use best available SM calculation for cross sections and BR, to look for deviations from the SM.

• Eg:

\[
(\sigma \times \text{BR})(gg \rightarrow H \rightarrow \gamma\gamma) \sim \frac{\kappa_g^2(\kappa_t, \kappa_b, \ldots)\kappa_H^2(\kappa_W, \kappa_t, \ldots)}{\kappa_H^2(\kappa_b, \kappa_W, \kappa_Z, \kappa_\tau, \kappa_t, \ldots)}
\]

• Can handle other production and decay vertices in a similar way (much simpler in most cases)
- from Generic kappa model:
  - 95% CL upper limit for $B_{BSM}$ from ATLAS: 0.26
  - 95% CL upper limit for $B_{inv}$ from CMS: 0.22
- Ratio coupling model will reduce the model assumptions and test the possible new physics contributions.
- Results are in agreement with SM.
• Test various alternative spin-parity options against the SM hypothesis $J^p = 0^+$ using angular and kinematic distributions in Higgs decays.
  - $H \to \gamma\gamma$ (sensitivity to $2^+$, excludes spin 1).
  - $H \to ZZ^* \to 4l$ (sensitivity to all spin/parity).
  - $H \to WW^* \to l\nu_l\nu_l$ (sensitivity to spin 1 and 2).
• Both CMS and ATLAS results show SM is highly favored against pure alternative. (Exclude tested hypotheses with CL > 99.9%)
### Significance

<table>
<thead>
<tr>
<th>Significance</th>
<th>ATLAS+CMS Run-1</th>
<th>ATLAS (36.1 – 79.8 /fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>5.4(4.6)</td>
<td>6.5(5.3)</td>
</tr>
<tr>
<td>VH</td>
<td>3.5(4.2)</td>
<td>5.3(4.8)</td>
</tr>
<tr>
<td>ttH</td>
<td>4.4(2.0)</td>
<td>5.8(5.3)</td>
</tr>
</tbody>
</table>

- Run 2 $H \rightarrow \gamma\gamma$ mass resolution: 1.4-2.1 GeV
- Run 2 $H \rightarrow ZZ^* \rightarrow 4l$ mass resolution: 1.6-2.4 GeV