Precision Measurements in the Higgs Sector at ATLAS and CMS

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A concise review of precision measurements in the Higgs sector of the Standard Model (SM) of particle physics is given using ATLAS and CMS data. The results are based on LHC Run-2 data, taken between 2015 and 2018. Impressive progress has been made since the discovery of the Higgs boson in 2012 for measuring all major production and decay modes. Good agreement with the SM predictions was observed in all measurements.

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1. Introduction

The Higgs boson of the SM is produced at the Large Hadron Collider (LHC) at CERN in different production modes. They are given below together with the numbers of expected Higgs boson events for 140 fb$^{-1}$ corresponding to the complete Run-2 data set:

- gluon-gluon fusion (ggF), 6.9M events,
- vector boson fusion (VBF), 520k events,
- vector boson associated production (VH), 320k events, and
- top-top Higgs (ttH) production, 70k events.

The decay branching ratios of the Higgs boson in the SM are given in Table 1.

Table 1: SM Higgs boson decay branching ratios.

<table>
<thead>
<tr>
<th>$H \rightarrow$</th>
<th>$\ell \ell$</th>
<th>$\gamma \gamma$</th>
<th>$\mu \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$ (%)</td>
<td>58</td>
<td>21</td>
<td>6.3</td>
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ATLAS [1] and CMS [2] measured the Higgs boson properties as outlined in the following sections.

2. Higgs boson mass and width

The Higgs boson mass has been determined by ATLAS $m_H = 124.97 \pm 0.24$ GeV [3] and CMS $m_H = 125.26 \pm 0.20(stat) \pm 0.08(syst)$ GeV [4]. Indirect limits on the Higgs boson width are set at 95% CL by ATLAS $\Gamma_H < 14.4$ MeV [5] and CMS $\Gamma_H < 9.16$ MeV [6].

3. Higgs boson couplings to bosons

3.1 $H \rightarrow \gamma \gamma$

ATLAS and CMS measured the coupling $H \rightarrow \gamma \gamma$. ATLAS obtains for 79.8 fb$^{-1}$ data, ggF, VBF, VH and ttH production a $\sigma \times B$ value consistent with the SM expectation [7]. Using 36.9 fb$^{-1}$ data, CMS measured the total Higgs boson production cross-section $\sigma_{tot} = 61.1 \pm 6.0(stat) \pm 3.7(syst)$ pb based on a combination of the $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ$ channels, which is consistent with the SM value $\sigma_{tot}^{SM} = 55.6 \pm 2.5$ pb [8].

3.2 $H \rightarrow ZZ$

A clear signal over background is observed for $H \rightarrow ZZ \rightarrow 4l$ for 79.8 fb$^{-1}$ data [7] and 137.1 fb$^{-1}$ data [9]. For the ggF production, the $\sigma \times B$ measurement has an uncertainty of about 15%. The measurement is consistent with the SM expectation.
3.3 $H \rightarrow WW$

In the $H \rightarrow WW$ analyses, the following results are obtained for ggF production $\sigma \times B = 11.4^{+1.2}_{-1.1}(\text{stat})^{+1.4}_{-1.3}(\text{theo.syst})\times 1.1(\text{exp.syst})$ pb, which is consistent with the SM expectation $10.4 \pm 0.6$ pb. For VBF production $\sigma \times B = 0.5^{+0.24}_{-0.22}(\text{stat}) \pm 0.10(\text{theo.syst})\times 0.13(\text{exp.syst})$ pb, which is also consistent with the SM expectation of $0.81 \pm 0.02$ pb [10].

4. Higgs boson couplings to fermions

4.1 $H \rightarrow \tau\tau$

In combined ATLAS and CMS data (LHC Run-1), the observation (expectation) was $5.5 (5.0)$ st. dev. [11]. ATLAS Run-1 and 36 fb$^{-1}$Run-2 data led to $6.4 (5.4)$ st. dev. [12]. In ggF production, the measurement is $3.1 \pm 0.1(\text{stat})\pm 0.16(\text{syst})$ pb, compared to the SM expectation of $3.05 \pm 0.13$ pb.

For VBF production, the measurement is $0.28 \pm 0.09(\text{stat})\pm 0.09(\text{syst})$ pb, compared to the SM value $0.237 \pm 0.006$ pb. Similar results are obtained by CMS for 35.9 fb$^{-1}$ data [13], leading to $4.9 (4.7)$ st. dev. and $5.9 (5.9)$ st. dev. when combined with Run-1 data.

Stage-1 simplified template cross-sections are based on about 77.4 fb$^{-1}$ data, taken 2015-2017 [14]: $\sigma \times B(\rightarrow \tau\tau) = 2.56 \pm 0.48(\text{stat}) \pm 0.34(\text{syst})$ pb, $\sigma(gg \rightarrow H, bbH) \times B(\rightarrow \tau\tau) = 1.11 \pm 0.81(\text{stat}) \pm 0.78(\text{syst})$ pb, and $\sigma(VBF) \times B(\rightarrow \tau\tau) = 0.34 \pm 0.08(\text{stat}) \pm 0.09(\text{syst})$ pb.

The CP invariance of the Higgs boson coupling to vector bosons has been tested in the VBF $H \rightarrow \tau\tau$ process in 36.1 fb$^{-1}$ data. No evidence of CP violation is observed, consistent with the SM expectation [15].

4.2 $H \rightarrow bb$

This is a difficult channel due to large backgrounds, despite the large branching ratio (58%). The most sensitive production mode is VH. Further searches using ggF, VBF, and ttH give 5.4 (5.5) st. dev. [16]. Stage-1 simplified template cross-sections times $H \rightarrow bb$ branching were reported [17].

Dedicated searches in ttH, VBF, ggH, and VH production modes led to 5.6 (5.5) st. dev. and $\mu = 1.04 \pm 0.20$, where $\mu$ is defined as the ratio of the measurement to the SM prediction [18].

4.3 ttH

Atoll-2 139 fb$^{-1}$ data-set was analysed for $ttH(\rightarrow \gamma\gamma)$ [20]. Separate event selections are applied corresponding to the decay modes of the top quarks (hadronic and leptonic). Templates from top mass distributions were constructed in $tt\gamma\gamma$, $\gamma\gamma$, and $ttH$ simulations in order to decompose the continuum background by a template fit to the data.

The CMS observation with 2016 data was 5.2 (4.2) st. dev. (combined $bb$, multilepton, $\gamma\gamma$, ZZ channels) [21], including 2017 data, the analysis of $ttH(\rightarrow \gamma\gamma)$ resulted in $\mu = 1.7^{+0.6}_{-0.5}$ [22].

In the $ttH$ multilepton channels with $\ell = e$ or $\mu$, and $\tau$(hadronic decay) $\mu = 0.96^{+0.34}_{-0.31}(1.00^{+0.30}_{-0.27})$ for 35.9 fb$^{-1}$ (2016 CMS data) was obtained [22]. For 41.5 fb$^{-1}$ (2017 ATLAS data) 3.2 (4.0) st. dev. was achieved [23]. In an analysis of $ttH$ and $ttW$ production in multilepton final states using 80 fb$^{-1}$, ATLAS measured the $ttH$ signal with 1.8 (3.1) st. dev. above the SM background [24].
The $ttH(H \to bb)$ fully hadronic, single-lepton and double-lepton final states were analysed by CMS, leading to 3.7 (2.6) st. dev. [25].

4.4 $H \to \mu\mu$

As the SM $B(H \to \mu\mu) = 0.022\%$ is very small, currently, only limits are set at 95% CL on $\mu = \sigma \times B(H \to \mu\mu)/\sigma \times B(H \to \mu\mu)_{SM} < 2.1\%$ (2.0) by ATLAS [26] and < 2.9 (2.2) by CMS [27].

5. Simplified template cross-sections STXS

STXS was proposed at the Les Houches’15 workshop and by the LHC Higgs boson cross-section working group. The goal was having a common format for ATLAS, CMS and theory, in particular, 1) to measure cross-sections per production modes (ggF, VBF, VH, $ttH$) in different phase space, signal templates $p_T(H)$, $p_T(V)$, etc, reducing model dependency and maximizing sensitivity to BSM effects, and 2) to combine different decay channels in order to increase sensitivity.

A combination of the main channels was performed with STXS stage-1 [28]. In STXS, several channels contribute to different kinematic regions of the same production mode, e.g., VH dominated by $H \to bb$ in high $p_T(V)$, while $gg$ and $ZZ^*$ are relevant at low $p_T(V)$. No significant deviations from SM predictions in any kinematic region were observed, and the p-value with respect to the SM hypothesis is 0.80.

The experimental selection efficiency and background rates can be quite different, and also Multi Variate Analysis (MVA) techniques can be used to separate signal and background. The goal is to balance experimental precision and theory uncertainty. A combination of various decay channels was performed with 35.9 fb$^{-1}$ [29]. For STXS stage-1, ggH and VBF bins using $H \to \gamma\gamma$ based on 77.4 fb$^{-1}$ were used [30]. Ten ggH and three VBF parameters were defined, leading to the result that good agreement with the SM predictions was obtained.

6. Differential Higgs boson decay cross-sections

Differential Higgs boson decay cross-sections have been measured for several modes, e.g., $H \to \gamma\gamma$ with ATLAS data [31] and $H \to \gamma\gamma, ZZ, 4\ell, bb$ combined modes with CMS data [8].

7. Rare Higgs boson decays

Further SM Higgs boson decay modes can be in reach with growing LHC data sets. Current limits at 95% CL are:

- $\mu = \sigma \times B(H \to Z\gamma)/\sigma \times B(H \to Z\gamma)_{SM} < 6.6\%$ (4.4) [32], and
- $\mu = \sigma_{HZ} \times B(H \to cc)/\sigma_{HZ} \times B(H \to cc)_{SM} < 110\%$ (150) [33].

The four-muon final state is experimentally clean containing only very small SM background [34], however, the expected SM branching fractions are several orders of magnitude below the sensitivity limits at 95% CL:
• \(B(H \rightarrow J/\psi J/\psi) < 1.8 \cdot 10^{-3} \) (obs), \(< (1.8^{+0.2}_{-0.1}) \cdot 10^{-3} \) (exp), and
• \(B(H \rightarrow \Upsilon \Upsilon) < 1.4 \cdot 10^{-3} \) (obs), \(< (1.4 \pm 0.1) \cdot 10^{-3} \) (exp).

Anomalous couplings were also searched for [6].

8. Higgs boson decays into invisible particles

A motivation for this search was given by Patt and Wilczek, “Higgs-field portal into hidden sectors” [35]. There are indirect constraints from coupling fits, and direct constraints from searches for Higgs bosons decaying into invisible particles. Three separate ATLAS searches were performed: \(V(had)H(inv)\), \(Z(lep)H(inv)\) and \(VBF H(inv)\), with the result \(B(H \rightarrow inv) < 0.26 \) (0.17) at 95% CL, assuming SM production cross-section [36].

For CMS, the dominant backgrounds are \(Z(\nu\nu)+jets\) and \(W(\ell\nu)+jets\), extrapolated from 2-lepton sideband, and from 1-lepton sideband, respectively. The VBF production channel is most sensitive. 2016 VBF-only data led to \(B(H \rightarrow inv) < 0.33 \) (0.25) at 95% CL.

About 25% improvement in sensitivity is obtained by adding VH and ggH channels, thus \(B(H \rightarrow inv) < 0.26 \) (0.20) at 95% CL (13 TeV data), and \(B(H \rightarrow inv) < 0.19 \) (0.15) using 7, 8, 13 TeV data [37]. ttH limits on invisible decays are also set at 95% CL \(B(H \rightarrow inv) < 0.46(0.48) \) [38].

9. Combination

The ATLAS results of the measurements from several production and decay modes were combined taking their uncertainties into account [28]. The result is expressed as a comparison to the SM expectation \(\mu = 1.11^{+0.09}_{-0.08}\). Thus, the combined result is compatible with the expectation from the SM.

10. Higgs boson production modes (ggF, VBF, VH, ttH)

All major Higgs boson production modes are observed (> 5 st. dev.) based on 79.8 fb\(^{-1}\) data, assuming SM branching ratios [28]:

• ggF, VBF (6.5 st. dev.),
• VH (5.3 st. dev.), and
• ttH (5.8 st. dev.).

There are only small correlations between production modes, and the results are consistent with the SM expectations. Similar results are obtained by a CMS data combination [29].

Cross-sections are measured for VBF versus ggF. Individual and combined decay modes are in agreement with the SM expectation [28]. A generic parametrization of the measured couplings with respect to the SM was performed for \(\lambda(tg)\) contributing through ggF loop, as compared to ttH, and \(\lambda(yZ)\) contributing to the \(H \rightarrow \gamma\gamma\) loop, as compared to \(H \rightarrow ZZ\) decays. The results are also in agreement with SM expectations.

For 137 fb\(^{-1}\) data in the \(H \rightarrow ZZ \rightarrow 4\ell\) channel (\(\ell = e \) or \(\mu\)), the cross-section measurement is \(\sigma = 2.73^{+0.22}_{-0.22}(stat) + 0.24(syst)\) fb, which is consistent with the SM expectation 2.76 ± 0.14 fb [9]. Differential cross-sections versus \(p_T(H)\), \(H\) rapidity, and the number of jets were also studied.
11. Single-top-Higgs production tH, Higgs boson pair-production HH

The single-top-Higgs production $tH (H \rightarrow WW, ZZ, \tau\tau, bb)$ was searched for. A combination with $ttH$ and $H \rightarrow \gamma\gamma$ could give sensitivity to the absolute values of the top quark Yukawa coupling and the Higgs boson coupling to vector bosons $g_{HV}$, and uniquely, to their relative sign. The SM-like signal favours a $\kappa_t = 1.0$ over $\kappa_t = -1.0$ by $> 1.5$ st. dev. [39]. ATLAS sets a limit on $HH \rightarrow bbVV, bbbb, bb\tau\tau, bb\gamma\gamma < 6.7 (10.4) \times SM$ at 95% CL. CMS obtained a limit $HH \rightarrow bbVV, bbbb, bb\tau\tau, bb\gamma\gamma < 22.2 (12.8) \times SM$ at 95% CL [40].

12. Relation of coupling and fermion mass

An interpretation of the results is given in the $\kappa$-framework as a function of the particle mass, assuming only SM contributions to the total width [28, 29]. Figure 1 shows the linearity as expected from the Higgs boson theory for ATLAS and CMS. Under the assumption that new physics affects only the Higgs boson self-coupling, the best fit value of the coupling modifier is $\kappa_\lambda = 4.6^{+3.2}_{-3.8}$, excluding values outside the interval $-2.3 < \kappa_\lambda < 10.3$ at 95% CL, while the expected excluded range assuming the SM predictions is $-5.1 < \kappa_\lambda < 11.2$ [41].

Figure 1: Left [28]: Reduced coupling-strength modifiers $\kappa_F m_F/v$ for fermions ($F = t, b, \tau, \mu$) and $\sqrt{\kappa_V m_V}/v$ for weak gauge bosons ($V = W, Z$) as a function of their masses $m_F$ and $m_V$, respectively, and the vacuum expectation value of the Higgs field $v = 246$ GeV. The SM prediction for both cases is also shown (dotted line). The black error bars represent 68% CL intervals for the measured parameters. For $\kappa_\mu$ the light error bars indicate the 95% CL interval. The coupling modifiers $\kappa_F$ and $\kappa_V$ are measured assuming no BSM contributions to the Higgs boson decays, and the SM structure of loop processes such as $gg \rightarrow H, H \rightarrow \gamma\gamma$ and $H \rightarrow gg$. The lower inset shows the ratios of the values to their SM predictions. Right [29]: Result of the phenomenological $(M, \epsilon)$ fit overlayed with the resolved $\kappa$-framework model.
13. Conclusions and Outlook

In conclusion, LHC Run-2 operation was very successful. Observations of the couplings Higgs to tau leptons, Higgs to bottom quarks, and Higgs to top quarks were reported. Sensitivity to the coupling Higgs to muon leptons is approaching. Most inclusive measurements are established. The focus is now on differential measurements and combinations of all main LHC Higgs boson production modes. So far, all Higgs boson properties are in agreement with the SM expectations.

The outlook for LHC Run-2 data analysis is towards a complete analysis of the LHC Run-2 data set (about 140 fb$^{-1}$ per experiment), a more detailed understand of the data to increase the measurement precision, and a combination of ATLAS and CMS results to increase sensitivities further. LHC Run-3 is anticipated to add 300 fb$^{-1}$ (2021 to 2023 data-taking), and HL-LHC is approved for 3000 fb$^{-1}$ (2026-) for a new era of measurements with higher precision. Overall there is a strong and approved LHC programme for new discoveries and further precision measurements.

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