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 production cross-sections \[^1\] and the numbers of expected Higgs boson events for 140 fb\(^{-1}\) corresponding to the complete Run-2 data set:

- gluon-gluon fusion (ggF), 48.58 pb, 6.80M events,
- vector boson fusion (VBF), 3.783 pb, 530k events,
- vector boson associated production (WH+ZH), \((1.415 + 0.8915)\) pb, 323k events, and
- top-top Higgs (ttH) production, 0.507 pb, 71k events.

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

| \(H \to\) | \(bb\) | \(WW^*\) | \(\tau\tau\) | \(ZZ^*\) | \(\gamma\gamma\) | \(\mu\mu\) |
|---------|-------|---------|---------|---------|--------|--------|
| B (%)   | 58    | 21      | 6.3     | 2.6     | 0.23   | 0.022  |

ATLAS \[^2\] and CMS \[^3\] 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 \[^4\] and CMS \(m_H = 125.35 \pm 0.15\) GeV \[^5\]. Indirect limits on the Higgs boson width are set at 95% CL by ATLAS \(\Gamma_H < 14.4\) MeV \[^6\] and CMS \(\Gamma_H < 9.16\) MeV \[^7\].

3. Higgs boson couplings to bosons

3.1 \(H \to \gamma\gamma\)

ATLAS and CMS measured the coupling \(H \to \gamma\gamma\). ATLAS obtains for 79.8 fb\(^{-1}\) data, ggF, VBF, VH and ttH production a \(\sigma \times B\) value consistent with the SM expectation \[^8\]. Using 36.9 fb\(^{-1}\) data, CMS measured the total Higgs boson production cross-section \(\sigma_{\text{tot}} = 61.1 \pm 6.0\) (stat) \pm 3.7 (syst) pb based on a combination of the \(H \to \gamma\gamma\) and \(H \to ZZ\) channels, which is consistent with the SM value \(\sigma_{\text{tot}}^{\text{SM}} = 55.6 \pm 2.5\) pb \[^9\].

3.2 \(H \to ZZ\)

A clear signal over background is observed for \(H \to ZZ \to 4l\) for 79.8 fb\(^{-1}\) ATLAS data \[^8\] and 137.1 fb\(^{-1}\) CMS data \[^10\]. 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 ATLAS $H \rightarrow WW$ analyses, the following results are obtained for ggF production $\sigma \times B = 11.4^{+1.2}_{-1.3} (\text{stat})^{+1.2}_{-1.3} (\text{theo, syst})^{+1.4}_{-1.3} (\text{exp, syst})$ pb, which is consistent with the SM expectation $10.4 \pm 0.6$ pb. For VBF production $\sigma \times B = 0.5^{+0.24}_{-0.22} (\text{stat}) \pm 0.10 (\text{theo, syst})^{+0.12}_{-0.13} (\text{exp, syst})$ pb, which is also consistent with the SM expectation of $0.81 \pm 0.02$ pb [11].

4. Higgs boson couplings to fermions

4.1 $H \rightarrow \tau \tau$

In combined ATLAS and CMS data (LHC Run-1), the observation (expectation)$^1$ was 5.5 (5.0) st. dev. [12]. ATLAS Run-1 and 36 fb$^{-1}$ Run-2 data led to 6.4 (5.4) st. dev. [13]. In ggF production, the measurement is $3.1 \pm 0.1$ (stat) $^{+0.16}_{-0.13}$ (syst) pb, compared to the SM expectation of $3.05 \pm 0.13$ pb. For VBF production, the measurement is $0.28 \pm 0.09$ (stat) $^{+0.11}_{-0.09}$ (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 [14], 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 (STXS) [15] are based on about 77.4 fb$^{-1}$ CMS data, taken 2015-2017: $\sigma(pp \rightarrow H) \times B(H \rightarrow \tau \tau) = 2.56 \pm 0.48$ (stat) $\pm 0.34$ (syst) pb, $\sigma(gg \rightarrow H, bbH) \times B(H \rightarrow \tau \tau) = 1.11 \pm 0.81$ (stat) $\pm 0.78$ (syst) pb, and $\sigma(VBF) \times B(H \rightarrow \tau \tau) = 0.34 \pm 0.08$ (stat) $\pm 0.09$ (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$^{-1}$ ATLAS data. No evidence of CP violation is observed, consistent with the SM expectation [16].

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, and combined ATLAS Run-1 and 79.8 fb$^{-1}$ Run-2 data yield a sensitivity of 5.4 (5.5) st. dev. [17]. Stage-1 simplified template cross-sections times $H \rightarrow bb$ branching were reported [18]. Dedicated CMS 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 the signal strength $\mu$ is defined as the ratio of the measured cross-section to the SM prediction [19].

4.3 $ttH$

$ttH$ observation in ATLAS has 5.8 (4.9) st. dev. [20] and in CMS has 5.2 (4.2) st. dev. [19]. The full Run-2 139 fb$^{-1}$ data-set was analysed for $ttH(H \rightarrow \gamma \gamma)$ [21]. 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 $tt\gamma\gamma$, $\gamma\gamma$+jets, 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) [22], including 2017 data, the analysis of $ttH(H \rightarrow \gamma \gamma)$ resulted in $\mu = 1.7^{+0.6}_{-0.5}$ [23].

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 [23]. For 41.5 fb$^{-1}$ (2017 ATLAS data) 3.2 (4.0) st. dev. was achieved [24]. 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 [25].

$^1$The expected significance is given in parenthesis throughout the article.
The $ttH(H \rightarrow bb)$ fully hadronic, single-lepton and double-lepton final states were analysed by CMS, leading to 3.7 (2.6) st. dev. [26].

4.4 $H \rightarrow \mu\mu$

As the SM $B(H \rightarrow \mu\mu) = 0.022\%$ is very small, currently, only limits are set at 95% CL on $\mu = \sigma(pp \rightarrow H) \times B(H \rightarrow \mu\mu) / \sigma(pp \rightarrow H)_{SM} \times B(H \rightarrow \mu\mu)_{SM} < 2.1$ (2.0) by ATLAS [27] and $< 2.9$ (2.2) by CMS [28].

5. Simplified template cross-sections STXS

STXS was proposed at the Les Houchesâ’Z15 workshop and by the LHC Higgs boson cross-section working group. The goal was to have a common format for ATLAS, CMS and theory, in particular, 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 to combine different decay channels in order to increase sensitivity.

An ATLAS combination of the main channels was performed with STXS stage-1 [29]. In STXS, several channels contribute to different kinematic regions of the same production mode, e.g., VH dominated by $H \rightarrow bb$ in high $p_T(V)$, while $gg$ and $ZZ^{'}$ are relevant at low $p_T(V)$. No significant deviation from SM predictions in any kinematic region was observed, and the p-value with respect to the SM hypothesis is 0.80.

A CMS combination of various production modes and decay channels was performed with $35.9 \text{ fb}^{-1}$ [30]. A first CMS measurement of STXS stage-1 regions in the diphoton channel was performed, covering the gluon fusion (ggH) and vector boson fusion (VBF) production modes. For STXS stage-1, ggH and VBF bins using $H \rightarrow \gamma\gamma$ based on $77.4 \text{ fb}^{-1}$ were analysed [31]. Ten ggH and three VBF parameters were defined, depending on the number of jets and $p_T(H)$. For each of the thirteen signal parameters, the measured cross-section was compared with the SM prediction, and good agreement was obtained.

6. Differential Higgs boson decay cross-sections

Differential Higgs boson decay cross-sections have been measured for several modes, e.g., $H \rightarrow \gamma\gamma$ with ATLAS data [32] and $H \rightarrow \gamma\gamma, ZZ, 4\ell, bb$ combined modes with CMS data [9].

7. Rare Higgs boson decays

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

- $\mu = \sigma(pp \rightarrow H) \times B(H \rightarrow Z\gamma) / \sigma(pp \rightarrow H) \times B(H \rightarrow Z\gamma)_{SM} < 6.6$ (4.4) [33], and
- $\mu = \sigma_{HZ} \times B(H \rightarrow cc) / \sigma_{HZ} \times B(H \rightarrow cc)_{SM} < 110$ (150) [34].

The four-muon final state is experimentally clean containing only very small SM background [35], however, the observed (expected) CMS limits are far from the expected SM rates. The limits at 95% CL are:
- $B(H \rightarrow J/\psi J/\psi) < 1.8 \cdot 10^{-3}$ (obs), $< (1.8^{+0.2}_{-0.1}) \cdot 10^{-3}$ (exp), and
- $B(H \rightarrow YY) < 1.4 \cdot 10^{-3}$ (obs), $< (1.4 \pm 0.1) \cdot 10^{-3}$ (exp).

Anomalous couplings were also searched for [7].

8. Higgs boson decays into invisible particles

A motivation for this search was given by Patt and Wilczek, âditorâHiggs-field portal into hidden sectorsâditor [36]. 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 $B(H \rightarrow \text{inv}) < 0.26 (0.17)$ at 95% CL, assuming SM production cross-section [37].

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 the most sensitive one. 2016 VBF-only data led to $B(H \rightarrow \text{inv}) < 0.33 (0.25)$ at 95% CL.

About 25% improvement in sensitivity is obtained by adding VH and ggH channels, thus $B(H \rightarrow \text{inv}) < 0.26 (0.20)$ at 95% CL (13 TeV data), and $B(H \rightarrow \text{inv}) < 0.19 (0.15)$ using 7, 8, 13 TeV data [38]. $ttH$ limits on invisible decays are also set at 95% CL $B(H \rightarrow \text{inv}) < 0.46 (0.48)$ [39].

9. Combination

The ATLAS results of the measurements from several production and decay modes were combined taking their uncertainties into account [29]. 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$^{-1}$ ATLAS data, assuming SM branching ratios [29]:

- 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 [30].

Cross-sections are measured for VBF versus ggF. Individual and combined decay modes are in agreement with the SM expectation [29]. 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 $\lambda(\gamma Z)$ 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 $\sigma = 2.73^{+0.23}_{-0.22}$ (stat) $^{+0.24}_{-0.19}$ (syst) fb, which is consistent with the SM expectation 2.76$\pm$0.14 fb [10]. 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. [40]. ATLAS sets a limit on \( HH \rightarrow bbbb, bb\tau\tau, bb\gamma\gamma < 6.7 \times (10.4) \times \text{SM at 95\% CL} \). CMS obtained a limit \( HH \rightarrow bbVV, bbbb, bb\tau\tau, bb\gamma\gamma < 22.2 \times (12.8) \times \text{SM at 95\% CL} \) [41].

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 [29, 30]. 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 \(-5.1 < \kappa_\lambda < 11.2\) [42].

![Figure 1:](image)

**Figure 1**: Left (ATLAS result) [29]: 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 \( v = 246 \text{ GeV} \). 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 assuming the SM structure of loop processes such as \( gg \rightarrow H, H \rightarrow \gamma\gamma \) and \( H \rightarrow gg \). The lower panel shows the ratios of the values to their SM predictions. Right (CMS result) [30]: Result of the phenomenological \( (M, \varepsilon) \) fit is also overlaid with the resolved \( \kappa \)-framework model.
13. Conclusions and Outlook

In conclusion, LHC Run-2 operation was very successful. Observations of the Higgs to tau coupling, Higgs to bottom coupling, and Higgs to top coupling were reported. Sensitivity to the Higgs to muon coupling is approaching. After establishing these inclusive measurements, 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 understanding 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$^{-1}$ (during the 2021 to 2023 data-taking), and HL-LHC is approved for 3000 fb$^{-1}$ (expected to start delivering data in 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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