Higgs boson measurements at ATLAS

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A comprehensive set of Higgs boson measurements has been performed in $pp$ collisions produced by the Large Hadron Collider at centre-of-mass energies of 7 and 8 TeV, and the results combined between the ATLAS and CMS experiments. Recent results from ATLAS at a centre-of-mass energy of 13 TeV are consistent with expectations. With more data available, additional Higgs boson processes are on the cusp of observation, while measured processes promise improved precision.

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1. Introduction

Since the discovery of the Higgs boson in 2012, the Large Hadron Collider (LHC) has produced more than ten times more Higgs bosons. These bosons have been measured with increasing precision by the ATLAS and CMS experiments, which have also provided first evidence of the rarer production and decay processes. These proceedings first review the Higgs mechanism, then present the recent Higgs boson measurements, and finally discuss searches for rare Higgs boson processes. The focus is on results from the ATLAS experiment [1].

2. The Higgs mechanism

In a quantum field theory, a scalar field can be represented by a complex number with dimensions of mass at each point in spacetime. The symmetry of the equations of motion under a particular gauge group transformation means that physical processes depend only on the magnitude of the field and not on its phase. The equations of motion can be derived from the Lagrangian of the scalar field, which can be represented as

\[ \mathcal{L}(\phi) = \frac{1}{2} (D_\mu \phi^* D^\mu \phi + \mu^2 \phi^* \phi) - \lambda (\phi^* \phi)^2 - \frac{1}{4} F_{\mu
u} F^{\mu\nu}, \tag{2.1} \]

where \( \phi \) is the scalar field, \( D_\mu \) is the covariant derivative, \( F_{\mu\nu} \) is the gauge field strength, and \( \lambda \) and \( \mu \) are real-valued parameters. If both \( \lambda \) and \( \mu \) are positive then the potential has a minimum at \( \phi^* \phi = \mu^2 / (2 \lambda) \). For the Higgs field this value is 246 GeV, and quantized oscillations about this minimum correspond to the physical Higgs boson. Because the covariant derivatives contain the gauge field, a non-zero magnitude of the scalar field corresponds to a potential term quadratic in the gauge field. This term results in massive gauge bosons.

Massless gauge bosons have spin projections of \( \pm 1 \), while a massive gauge boson can also have a spin projection equal to 0. The acquisition of this additional degree of freedom can be made explicit by choosing a gauge coordinate system where the scalar field has zero phase at every point in spacetime:

\[
\begin{align*}
\phi' &= e^{\imath \epsilon/\phi_0} \phi \\
A'_\mu &= A_\mu + \frac{1}{\epsilon \phi_0} \partial_\mu \epsilon,
\end{align*}
\tag{2.2}
\]

where \( \phi_0 \) is the vacuum expectation value of the scalar field, \( A_\mu \) is the gauge field, and \( \epsilon \) is the spacetime-dependent phase of a particular coordinate system of the scalar field. The removed phase of the scalar field appears as a spin-0 component on the gauge field.

3. Higgs boson measurements

The increasing energy and luminosity of the LHC has resulted in progressively increasing Higgs boson yields. These yields are shown in Table 1 for a Higgs boson mass of 125.09 GeV and the current integrated luminosity collected by ATLAS. More than 2 million Higgs bosons have been produced, though the majority of the events are not measurable because of the overwhelming strong production of \( b\bar{b} \) pairs.
Table 1: The yields for various measured production processes and decay channels measured at the LHC.

<table>
<thead>
<tr>
<th>Process</th>
<th>Produced events ($\times 10^3$)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg → H</td>
<td>75</td>
<td>7 TeV</td>
</tr>
<tr>
<td>qq → Hqq</td>
<td>5.5</td>
<td>8 TeV</td>
</tr>
<tr>
<td>q̅q → VH</td>
<td>4.1</td>
<td>13 TeV</td>
</tr>
<tr>
<td>q̅q/gg → t̅tH</td>
<td>0.4</td>
<td>8 TeV</td>
</tr>
</tbody>
</table>

The final combined ATLAS and CMS results with $\sqrt{s} = 7$ and 8 TeV data [2] are shown in Fig. 1, expressed as a ratio $\mu$ of the measured cross section to the Standard Model prediction. The ratios can be recast as coupling multipliers $\kappa$ to the Higgs boson interaction terms in the Lagrangian. If the measured multipliers are equal to one, the interaction strength has the mass dependence predicted by the SM. Figure 2 shows the consistency of the measurements with the predictions as a function of particle mass.

The first Higgs boson cross section measurements at $\sqrt{s} = 13$ TeV have been performed in its decays to ZZ* and γγ. Figure 3 shows the expected increase in production cross section in the
**Figure 2:** Combinations of Higgs boson coupling multipliers $\kappa_F$ (to fermions) or $\kappa_V$ (to gauge bosons) with the ratios of particle mass to the Higgs vacuum expectation value $v$ [2].

**Figure 3:** The measured Higgs boson production cross sections in its decays to $\gamma\gamma$ and $ZZ^*$ bosons, and the two decay channels combined. The production cross section as a function of energy (left) and for each production and decay process (right) are shown [3]. Ratios to the SM cross sections are not given so that the uncertainties on the measurements can be separated from those on the predictions. Future measurements will subdivide the cross sections into various kinematic regions to produce “simplified template cross sections”.

Measurements of the Higgs-boson interactions with third-generation quarks are important. The coupling strength between Higgs bosons and top quarks can be inferred from the measurement
Figure 4: The ratio of measured cross sections to SM predictions for $ttH$ production in various decay channels, as well as their combination at $\sqrt{s} = 13$ TeV [4]. For comparison the combined result at $\sqrt{s} = 7$ and 8 TeV is also shown.

of gluon fusion production, which is consistent with the SM prediction. However, to ensure that the gluon fusion process does not contain non-SM contributions, a direct measurement of the $ttH$ coupling is required, through $ttH$ production. The combined measurement at $\sqrt{s} = 7$ and 8 TeV showed a factor of 2 excess over the SM prediction (Fig. 1), though it corresponds to a $< 2\sigma$ deviation. A combined measurement from ATLAS at $\sqrt{s} = 13$ TeV [4] shows a somewhat smaller and less significant excess (Fig. 4). The sensitivity to a possible non-SM rate will continue to increase as more data are collected.

The largest branching fraction of the Higgs boson is to $b$-quark pairs; a small change in this fraction has a substantial impact on other decay rates. The most promising process for measuring this decay is in $VH$ production. Evidence for this production and decay was observed at the Tevatron and the $\sqrt{s} = 7$ and 8 TeV combination has more than $2\sigma$ significance, with the measured rate somewhat lower than expected (Fig. 1). A first measurement at $\sqrt{s} = 13$ TeV from ATLAS has been performed [5], with the result again showing a lower rate than expected but with larger uncertainties than the combination (Fig. 5).

To add sensitivity to the $H \rightarrow b\bar{b}$ decay channel, ATLAS has performed a first probe for this decay in vector-boson fusion production [6]. To reduce background from gluon-initiated jets, a photon is required in the event in addition to two $b$-quark jets and two forward jets resulting from the vector-boson radiation (Fig. 6). The analysis constructs a discriminant to separate signal from background using a boosted decision tree (BDT). The inputs to the BDT are the invariant mass and pseudorapidity separation of the forward jets; the width of the forward jets; the centrality of the photon between the jets; and the presence of low-$p_t$ jets (near the selection threshold). As a first step, the presence of $Z$-boson production is tested, with an expected significance of $1.3\sigma$; the expected significance of Higgs boson production is $0.4\sigma$. The observations are consistent with expectations, demonstrating a sufficient understanding of the background to contribute to an $H \rightarrow b\bar{b}$ measurement with more data.
The overall consistency of the measured and predicted Higgs-boson decays to gauge bosons motivates a more detailed study of these channels. Differential measurements of the production kinematics improve sensitivity to non-SM processes, particularly in regions of high momentum transfer. First measurements have been performed in the $ZZ^{*}$ and $\gamma\gamma$ decay channels in $\sqrt{s} = 7$ and 8 TeV data; new measurements in the $\gamma\gamma$ channel study kinematic distributions such as the jet multiplicity and $p_T$ of the Higgs boson candidate using $\sqrt{s} = 13$ TeV data (Fig. 7) [7]. Additionally, measurements of Higgs boson decays to $WW^{*}$ bosons have been recently performed with $\sqrt{s} = 8$ TeV data (Fig. 8) [8].

The constraints on new physics imposed by differential measurements can be quantified using an effective field theory (EFT) [9] containing dimension-6 operators in the Lagrangian suppressed by factors of $\sim v^2/\Lambda^2$, where $v$ is the Higgs vacuum expectation value and $\Lambda$ is the energy scale.
of physics beyond the Standard Model. Constraints on the coefficients of these operators $c_i$ have been determined using differential measurements of $H \rightarrow \gamma\gamma$ production at $\sqrt{s} = 8$ TeV, as shown in Fig. 9 [10].

Within the context of an EFT one can test for the existence of dimension-6 operators that describe CP-violating interactions between the Higgs and gauge bosons. The relative angles of the final-state jets in vector-boson fusion can be used to probe these operators. Using the full information from the matrix element, an “optimal observable” can be defined that quantifies the contribution of the interference between the CP-violating and SM matrix elements, relative to the...
Figure 9: Left: The set of measured differential distributions for Higgs bosons decaying to two photons, compared to the SM prediction and to models with additional dimension-6 terms in the Lagrangian. Right: Constraints on the values of two dimension-6 operator coefficients [10].

Figure 10: Left: The set of measured differential distributions for Higgs bosons decaying to two photons, compared to the SM prediction and to models with additional dimension-6 terms in the Lagrangian. Right: Constraints on the values of two dimension-6 operator coefficients [11].

square of the SM matrix element. This observable has been studied by ATLAS in vector-boson fusion with the Higgs boson decaying to tau-lepton pairs (Fig. 10) [11]. The coefficient of the CP-violating operator is constrained to be between -0.11 and 0.05 at 68% confidence level if the contribution from new physics has a scale equal to the $W$ boson mass.

4. Higgs boson searches

There are many rare Higgs boson production and decay processes predicted by the Standard
Table 2: The yields for various production processes and decay channels not yet measured at the LHC.

<table>
<thead>
<tr>
<th>Process</th>
<th>Produced events</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow HH$</td>
<td>32, 210, 1300</td>
<td>$\sigma &lt; 29\sigma_{SM}$</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>130, 750, 3200</td>
<td>$\sigma &lt; 11\sigma_{SM}$</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>18, 110, 440</td>
<td>$\sigma &lt; 3.5\sigma_{SM}$</td>
</tr>
<tr>
<td>$H \rightarrow J/\psi\gamma$</td>
<td>0.2, 1.2, 5.0</td>
<td>$\sigma &lt; 540\sigma_{SM}$</td>
</tr>
<tr>
<td>$H \rightarrow $</td>
<td>0.2, 1.1, 4.7</td>
<td>$\sigma &lt; 610\sigma_{SM}$</td>
</tr>
</tbody>
</table>

Model that have yet to be observed. In many cases these provide the only access to the couplings described by the Lagrangian. An overview of the yields of a number of rare processes is given in Table 2.

A particularly important process is Higgs boson pair production, which gives the most direct access to the Higgs boson self-coupling. This self-coupling arises from the $\lambda (\phi^* \phi)^2$ term in the Lagrangian in Eq. 2.1 that gives rise to a non-zero vacuum expectation value in the SM. Due to destructive interference between the self-coupling Feynman diagram and the diagram with the two Higgs bosons radiated by the top quarks in the loop, the rate for Higgs boson pair production is very small in the SM; however, non-SM contributions can significantly affect the rate. Searches for this process are challenging because of the low rate and the large number of possible decay channels. ATLAS searches at $\sqrt{s} = 8$ TeV in the decays to $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $\gamma\gamma b\bar{b}$, and $\gamma\gamma WW^*$ have set upper limits of 63, 160, 220, and 1150, respectively, on the ratio of the production cross section to the SM prediction [12]. New results at $\sqrt{s} = 13$ TeV in the $b\bar{b}b\bar{b}$ [13], $\gamma\gamma b\bar{b}$ [14], and $\gamma\gamma WW^*$ [15] channels give corresponding limits of 29, 120 and 750, respectively. Distributions from the $b\bar{b}b\bar{b}$ and $\gamma\gamma b\bar{b}$ channels are shown in Fig. 11. In the $b\bar{b}b\bar{b}$ channel, the sensitivity to $HH$ production is primarily at high invariant mass of the Higgs-boson pair, where the diagram with two radiated Higgs bosons dominates. The $\gamma\gamma b\bar{b}$ channel is sensitive over the full region of invariant mass but has lower statistical sensitivity due to the low branching ratio of the Higgs boson to a photon pair.

The next Higgs boson process within reach in the next few years is its decay to muon pairs. Such a measurement would provide the first verification that the second generation fermions follow the same mass generation mechanism as those of the third generation. A recent search from ATLAS at $\sqrt{s} = 13$ TeV divided the data into six regions with different gluon-fusion purity, and into a vector-boson fusion region [16]. The dimuon mass distribution in the vector-boson fusion region is shown in Fig. 12.

Testing the Higgs-boson interactions with second-generation quarks is more challenging. One strategy is to search for decays to quark-antiquark mesons in association with a photon. However, this decay is dominated by the splitting of an off-shell photon in $H \rightarrow \gamma\gamma^*$ decays rather than the direct Higgs-quark-quark coupling. Nonetheless a constraint can be made on the coupling by searching for decays to a meson and a photon. Recent ATLAS searches have constrained the cross section for Higgs boson production and decay to $J/\psi \gamma$ [17] ($\phi\gamma$ [18]) to be less than 540 (610) times the SM prediction, using $\sqrt{s} = 8$ (13) TeV data.
Figure 11: Left: The invariant mass of the pair of Higgs-boson candidates in events with four jets identified to originate from $b$-quarks [13]. Right: The invariant mass of two photons in events containing two $b$-quark jets [14].

Figure 12: The invariant mass distributions of muon pairs in events consistent with the vector-boson fusion production of a Higgs boson [16].
5. Summary

The prolific production of Higgs bosons at the LHC allows a rich experimental program of Higgs boson measurements. Production and decay processes with the highest rate have been used to study the production of Higgs bosons in detail. With the continued increase in collisions, rarer processes involving interactions that have never been observed will become accessible to the experiments. Current searches lay the groundwork for these potential observations, and have recently begun with data at the record centre-of-mass energy of $\sqrt{s} = 13$ TeV. Given that only $\sim 1\%$ of the expected number of collisions have been produced, there is much to look forward to in Higgs boson measurements and searches at the LHC.

References

[8] ATLAS Collaboration, “Measurement of fiducial differential cross sections of gluon-fusion production of Higgs bosons decaying to $WW^{\ast} \rightarrow e\nu\mu\nu$ with the ATLAS detector at $\sqrt{s} = 8$ TeV,” J. High En. Phys. 08 (2016), 104.
[12] ATLAS Collaboration, “Searches for Higgs boson pair production in the $hh \to b\bar{b}\tau\tau, \gamma\gamma WW^*, \gamma\gamma bb, b\bar{b}bb$ channels with the ATLAS detector,” Phys. Rev. D 92, 092004 (2015).


