Latest Higgs physics results with the ATLAS detector

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This report presents the investigations on the recently discovered scalar boson by the ATLAS experiment at the CERN Large Hadron Collider. The latest results fully exploit the data collected during LHC Run 1 to measure the properties of the new boson and within the current sensitivity confirm the identification of this particle with the Higgs boson of the Standard Model.

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1. Introduction

The 4th of July 2012 the ATLAS¹ and CMS² experiments, operating at the CERN Large Hadron Collider (LHC), announced the observation of a new boson with a mass close to 125 GeV. The discovery^{3,4} was based on about 5 fb⁻¹ collected at $\sqrt{s} = 7$ TeV in 2011 and 5 fb⁻¹ collected at $\sqrt{s} = 8$ TeV in 2012 by each experiment. At the time of the discovery the excess was significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ^* , although there was already a clear indication also in the WW^* channel. By the end of 2012 each of the experiments accumulated more than ~ 20 fb⁻¹ of high quality data at $\sqrt{s} = 8$ TeV which were used to consolidate this result, increasing the excess significance and the number of investigated channels thus shifting from discovery to measurements of the properties of the new particle.

This talk does not cover the details of the extraordinary performance of the accelerator and of the ATLAS experiment in 2012, nor the many technical and experimental issues, like the increasing pile-up of multiple collisions, which were

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successfully faced and overcome by the first analyses. It rather summarizes the most recent results of the ATLAS experiment from the final analysis of Run 1 data (collected in 2011 and 2012), focusing on the mature analyses developed during the Long Shutdown 1 of LHC (2013 and 2014) and comparing the properties of the new particle with Standard Model (SM) expectations for the Higgs boson.

2. Production and Decay of the Standard Model Higgs Boson

The Higgs boson couples both to fermions and to bosons and the couplings depend linearly on the fermionic masses and quadratically on the bosonic masses. These properties dictate the relative weight of the possible production modes at LHC. The most relevant ones are⁵:

- the gluon-gluon fusion (ggF) mechanism which, due to the lack of direct couplings of the Higgs boson to gluons, is mediated by a top-quark dominated loop, thanks to the mass dependence of the fermionic couplings. This process for $\sqrt{s} = 8$ TeV has a cross section of ~ 19 pb.
- the vector boson fusion (VBF) mechanism, which depends on the coupling of the Higgs boson to the W and Z bosons, with a cross section of ~ 1.6 pb at the 8 TeV center-of-mass energy.
- the VH associate production, where a weak boson $V = W$ or Z , produced by the electroweak interaction of a quark and an anti-quark, radiates a Higgs boson. The cross section at 8 TeV is ~ 1.1 pb.
- the associate production with a heavy $q\bar{q}$ pair, dominated by the heaviest pair, $t\bar{t}$, with a cross section of 0.13 pb ($t\bar{t}H$).

The Higgs boson then decays to pairs of massive weak bosons, or to pairs of fermions, or to not directly-coupled final states through fermionic or bosonic loops. The latter are dominated by top quark or W bosons, which are the most massive objects of each category and can lead to gluon pairs (only through a top loop), $\gamma\gamma$ or $Z\gamma$ (with both contributions). The partial width of each decay channel depends on the mass of the involved particles, both through the coupling strength and the available phase space in the final state. The phase space contributions strongly depend on the Higgs boson mass which dictates the available decay channels. Therefore both the total width and the decay branching ratios (BR) depend strongly on the Higgs boson mass. For a 125 GeV Higgs boson the main decay channels are $b\bar{b}$, with a BR of $\sim 58\%$, and WW^* , with a BR of $\sim 22\%$.⁵ However these channels are not the easiest ones from an experimental point of view.

3. Decay Channels

Pros and cons of the main decay channels of the Higgs boson are illustrated in Table 1, in terms of BR, sensitivity to the different production modes, expected number of events, signal over background ratio (S/B) and mass resolution.

Table 1. Comparison between the Higgs boson decay channels. Here $\ell = e$ or μ . A mass of 125 GeV is assumed.

Decay	BR	Production Modes	Run 1 Expected Yield	S/B	Mass Resolution
$\gamma\gamma$	0.0023	ALL	~ 450	0.03	1–2%
$ZZ^* \rightarrow 4\ell$	$0.026 \times (2 \times 0.034)^2$	ALL	~ 20	1.6	1–2%
$WW^* \rightarrow \ell\nu\ell\nu$	$0.21 \times (2 \times 0.11)^2$	ALL	~ 500	0.15	20%
$\tau\tau$	0.063	ALL	~ 300	0.01–0.30	
$b\bar{b}$	0.58	VH, ttH	~ 400	0.01–0.10	
$Z\gamma$	0.0015	ggF			
$\mu\mu$	0.00022	ggF, VBF			
<i>invisible</i>	absent in SM	ggF, VBF, VH			

4. Mass

From Table 1 the best mass resolution is provided by the ZZ^* to charged leptons and $\gamma\gamma$ decays. The lower statistics available in the former channel is compensated by its higher purity and both channels can be used to provide a precise measurement of the Higgs boson mass. After a careful calibration of photons, electrons and muons energy-scales, the mass of the Higgs boson is derived from a combined fit to the reconstructed invariant mass spectra of the decay channels $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ as described in Ref. 6: $m_H = 125.36 \pm 0.37(\text{stat.}) \pm 0.18(\text{syst.})$ GeV. These measurements have been combined with similar ones from the CMS Collaboration to obtain the LHC mass measurement:⁷ $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV. The four measurements from the two channels and from the two experiments agree well with each other within less than two standard deviations.

5. Width

The expected width for a SM Higgs boson with a mass of 125 GeV is only ~ 4 MeV, which is three orders of magnitude below the experimental resolution of the channels discussed above. There is therefore no direct access to a width measurement and alternative approaches are needed to test its compatibility with the SM.

One approach is to set constraints on the off-shell Higgs boson signal strength, using ZZ and WW high mass final states, which can be combined with observed on-shell yields and then turned into limits on Γ_H/Γ_H^{SM} . This is done in Ref. 8 under the assumptions that the relevant Higgs boson couplings are independent of the energy scale of the Higgs boson production and that the same K-factors apply to signal and backgrounds. The result translates into an observed (expected) 95% CL upper limit on the Higgs boson total width of 22.7 (33.0) MeV.

The search for non SM decays or for deviations in the measured branching ratios with respect to SM is related to the width measurement. The search for invisible Higgs boson decays belongs to the former class of searches and it is performed either studying the recoil of W or Z bosons against an invisibly decaying hypothesized Higgs boson,^{9,10} or tagging the Higgs boson produced through VBF exploiting the

two forward-jets signature.¹¹ The latter analysis sets an upper limit at 95% CL on the invisible branching ratio of a 125 GeV Higgs boson at 29%.

6. Quantum Numbers

In order to establish the spin and parity quantum numbers of the 125 GeV boson, a number of hypotheses alternative to the SM assignment ($J^P = 0^+$) are tested against the SM one constructing appropriate test statistics, allowing also for deviations in the couplings to fermions and vector bosons with respect to the SM expectation.¹² All models alternative to the SM are excluded at more than 99.9% confidence level. Moreover the decays to ZZ^* and WW^* , and then to 4ℓ and $\mu\nu e\nu$ respectively, allow to investigate the tensor structure of the HVV interaction vertex which, under the spin-0 hypothesis, does not show any deviations from SM.

7. Signal Strength

For each investigated final state a signal strength parameter μ is defined as the ratio between the measured product of cross section times the BR and the expected SM one.

7.1. Main decay channels

In all the analyses different event categories are defined with a twofold purpose:

- (i) enhance the sensitivity by separating classes of events with different signal over background ratios;
- (ii) extract, whenever possible, information on the different production mechanisms, exploiting the categories defined under the different decay signatures.

Profile likelihood fits are then used to globally extract signal and nuisance parameters for each single channel^{13–17} and their combination. Of particular relevance are the evidence for the decay to $\tau\tau$ which is the first direct evidence of the Yukawa coupling to fermions¹⁶ and the first evidence for the VBF mechanism, achieved in the WW^* channel.¹⁸

7.2. Rare decays

Searches have been performed also on decay channels for which, with the first 25 fb^{-1} , ATLAS is not expected to be sensitive to the SM yield, like $h \rightarrow \mu\mu$ ¹⁹ and $h \rightarrow Z\gamma$,²⁰ setting mass dependent upper limits on the signal strength.

7.3. $t\bar{t}H$ production mode

The rare production mode $t\bar{t}H$ is particularly interesting since it gives direct access to the largest Yukawa coupling, the one for the top quark. It has been searched for

in three different final states:

- $H \rightarrow b\bar{b}$, where few hundred events are expected but S/B is only few percent;²¹
- H to multi-leptons (through WW^* , $\tau\tau$ and ZZ^* decays), where O(10) events are expected but S/B $\sim 10\%$;²²
- $H \rightarrow \gamma\gamma$, where O(1) event is expected and S/B $\sim 20\%$.²³

All three searches so far set upper limits at 95% CL on μ .

7.4. Combined results

Figure 1 summarizes the signal strength measured in each channel and the combined one.²⁴ It is possible to extract the signal strength parameters for the different production modes from the combined fit, assuming SM branching ratios for the Higgs boson decay and profiting of the categorization of events. This results in the values summarized in Fig. 2.

Introducing scale factors parametrizing possible deviation from the SM couplings, it is possible to interpret the results within different scenarios²⁵ and extract

Fig. 1. The observed signal strengths and uncertainties for different Higgs boson decay channels and their combination for $m_H = 125.36 \text{ GeV}$. Higgs boson signals corresponding to the same decay channel are combined together for all analyses, assuming SM values for the cross-section ratios of different production processes. The best-fit values are shown by the solid vertical lines. The total $\pm 1\sigma$ uncertainties are indicated by green shaded bands, with the individual contributions from the statistical uncertainty (top), the total (experimental and theoretical) systematic uncertainty (middle), and the signal theoretical uncertainty (bottom) on the signal strength shown as horizontal error bars. From Ref. 24.

Fig. 2. The best-fit signal-strength values of different production modes determined from the combined fit to the $\sqrt{s}=7$ and 8 TeV data. The inner and outer error bars correspond to 68% CL and 95% CL intervals. Total uncertainties combining statistical, experimental and theoretical systematic uncertainties are shown. The fit assumes the SM values of the Higgs boson decay branching ratios for $m_H = 125.36$ GeV. From Ref. 24.

constraints on such models. The results presented in Ref. 24 appear well compatible with SM expectations.

8. Cross Section

The total and differential cross sections for the production of the Higgs boson in pp interactions have been measured from $\gamma\gamma$ and ZZ^* candidates and are summarized in Ref. 26. The total cross sections measured in the two decay channels are perfectly compatible and their combined value is $\sigma = 33.0 \pm 5.3(\text{stat.}) \pm 1.6(\text{syst.})$ pb. The systematic uncertainty includes the uncertainty on the Higgs boson mass, on the relative contributions of the different production modes, the acceptance variations due to the choice of parton density functions (PDF) and to the missing higher-order corrections, see Ref. 26 for more details. The central value of the ggF cross section, obtained subtracting a 3.0 ± 0.1 pb contribution for the other production modes,⁵ is above the most recent theory SM predictions, although statistically in agreement, both for:

- next-to-next-to-leading order (NNLO) in QCD with threshold resummation accurate to next-to-next-to-leading logarithms (NNLL), see Ref. 5;
- and next-to-next-to-next-leading order (N³LO), see Refs. 27–30.

Differential cross sections are studied both to check for distortions possibly induced by new phenomena and to investigate if the mild excess observed in the total cross section is localized to specific kinematic regions. Differential distributions in inclusive and exclusive jet multiplicity bins, transverse momentum (p_T^H) and rapidity (y^H) of the Higgs boson, and transverse momentum of the leading jet in the event (p_T^{j1}), are compared to various theoretical predictions and, within the still limited statistics, no deviations are observed. The p -values quantifying the compatibility between the measured cross sections and the predictions range from

Fig. 3. Normalized cross-section shapes for inclusive Higgs boson production measured by combining the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels. The measured variables are, from left to right, the Higgs boson transverse momentum p_T^H and its rapidity y^H , and the transverse momentum of the leading jet p_T^{j1} . The 0–30 GeV bin of the p_T^{j1} distribution corresponds to events without jets above 30 GeV. Various ^{31–37} theoretical predictions are presented, using the same bin widths as the measurement. Events simulated with NNLOPS and MG5_aMC@NLO are interfaced with PYTHIA8³⁸ for parton showering. From Ref. 26.

2% to 26%, and for the shapes from 8% to 88%. Figure 3 presents the measured cross-section shapes compared to predictions normalized to the data.

9. Summary and Outlook

Progress in Higgs boson physics did not stop over the Long Shutdown 1 of LHC. Significant steps were made in refining the analyses which led to the discovery of the new particle and the first tests of its characteristics. The $\sim 25 \text{ fb}^{-1}$ of data collected in Run 1 have been fully exploited and ATLAS is now ready to investigate the Higgs boson properties at the higher energies of Run 2. In the new Run, just started, ATLAS expects to collect ten times more integrated luminosity than in Run 1. The increased center-of-mass energy will push up the different Higgs boson production cross sections by factors ranging between 2.1 and 2.6 for the majority of the production channels and reaching 4.7 for $t\bar{t}H$. Top quark related backgrounds will scale up by a similar factor.

References

1. ATLAS Collaboration, *JINST* **3**, S08003 (2008).
2. CMS Collaboration, *JINST* **3**, S08004 (2008).
3. ATLAS Collaboration, *Phys. Lett.* **B716**, 1 (2012).
4. CMS Collaboration, *Phys. Lett.* **B716**, 30 (2012).
5. LHC Higgs Cross Section Working Group, S. Dittmaier, C. Mariotti, G. Passarino and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, arXiv:1101.0593 (2011).
6. ATLAS Collaboration, *Phys. Rev.* **D90**, p. 052004 (2014).
7. ATLAS and CMS Collaborations, *Phys. Rev. Lett.* **114**, 191803 (2015).
8. ATLAS Collaboration, *Eur. Phys. J.* **C75**, 335 (2015).
9. ATLAS Collaboration, *Eur. Phys. J.* **C75**, 337 (2015).

10. ATLAS Collaboration, *Phys. Rev. Lett.* **112**, 201802 (2014).
11. ATLAS Collaboration, *Search for an Invisibly Decaying Higgs Boson Produced via Vector Boson Fusion in pp Collisions at $\sqrt{s} = 8$ TeV using the ATLAS Detector at the LHC*, ATLAS-CONF-2015-004 (Mar, 2015), <http://cds.cern.ch/record/2002121>.
12. ATLAS Collaboration, *Study of the Spin and Parity of the Higgs Boson in Diboson Decays with the ATLAS Detector*, arXiv:1506.05669 (2015).
13. ATLAS Collaboration, *Phys. Rev. D* **90**, 112015 (2014).
14. ATLAS Collaboration, *Phys. Rev. D* **91**, 012006 (2015).
15. ATLAS Collaboration, *JHEP* **08**, 137 (2015).
16. ATLAS Collaboration, *JHEP* **04**, 117 (2015).
17. ATLAS Collaboration, *JHEP* **01**, 069 (2015).
18. ATLAS Collaboration, *Phys. Rev. D* **92**, 012006 (2015).
19. ATLAS Collaboration, *Phys. Lett. B* **738**, 68 (2014).
20. ATLAS Collaboration, *Phys. Lett. B* **732**, 8 (2014).
21. ATLAS Collaboration, *Eur. Phys. J. C* **75**, 349 (2015).
22. ATLAS Collaboration, *Phys. Lett. B* **749**, 519 (2015).
23. ATLAS Collaboration, *Phys. Lett. B* **740**, 222 (2015).
24. ATLAS Collaboration, *Measurements of the Higgs Boson Production and Decay Rates and Coupling Strengths Using pp Collision Data at $\sqrt{s} = 7$ and 8 TeV in the ATLAS Experiment*, arXiv:1507.04548 (2015).
25. LHC Higgs Cross Section Working Group, S. Heinemeyer, C. Mariotti, G. Passarino and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, arXiv:1307.1347 (2013).
26. ATLAS Collaboration, *Phys. Rev. Lett.* **115**, 091801 (2015).
27. C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog and B. Mistlberger, *Phys. Lett. B* **737**, 325 (2014).
28. C. Anastasiou, S. Buehler, F. Herzog and A. Lazopoulos, *JHEP* **12**, 058 (2011).
29. C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog and B. Mistlberger, *JHEP* **03**, 091 (2015).
30. C. Anastasiou, C. Duhr, F. Dulat, F. Herzog and B. Mistlberger, *Phys. Rev. Lett.* **114**, 212001 (2015).
31. D. de Florian, G. Ferrera, M. Grazzini and D. Tommasini, *JHEP* **06**, 132 (2012).
32. M. Grazzini and H. Sargsyan, *JHEP* **09**, 129 (2013).
33. K. Hamilton, P. Nason, E. Re and G. Zanderighi, *JHEP* **10**, 222 (2013).
34. R. Frederix and S. Frixione, *JHEP* **12**, 061 (2012).
35. J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli and M. Zaro, *JHEP* **07**, 079 (2014).
36. T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert and J. Winter, *JHEP* **02**, 007 (2009).
37. S. Hoeche, F. Krauss and M. Schonherr, *Phys. Rev.* **D90**, 014012 (2014).
38. T. Sjostrand, S. Mrenna and P. Z. Skands, *Comput. Phys. Commun.* **178**, 852 (2008).