

Highlights from the ATLAS experiment at the CERN LHC

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Highlights from the ATLAS Experiment at CERN Large Hadron Collider are presented. Results shown are mostly based on the analysis of the complete 2015–2016 year dataset which corresponds to the integrated luminosity of 36 fb^{-1} taken in 13 TeV proton-proton collisions. Mainly recent measurements of Higgs boson production and decays are discussed. In addition, short summary of other results is also given.

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1. Introduction

1.1 The LHC and its physics program

The Large Hadron Collider (LHC) [1] at CERN provides proton-proton (pp) collision at the center-of-mass energy 13 TeV since 2015. Two huge multi-purpose experiments, the ATLAS [2] and CMS [3] as well as two big, but more dedicated experiments, the LHCb [4] and ALICE [5], operate at the LHC. In total, the ATLAS and CMS detectors each accumulated large amount of data corresponding to an integrated luminosity of more than 100 fb^{-1} at 13 TeV, 23 fb^{-1} at 8 TeV and 5 fb^{-1} at 7 TeV pp -collisions. The maximum instantaneous luminosity reached in 2018 is $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ which exceeds the LHC design luminosity by a factor of two.

The wide-range physics program of the LHC includes:

- tests of the Standard Model of interactions (SM) in the new energy range;
- studies of properties of recently discovered Higgs boson (h) with the mass 125 GeV [6]–[7];
- direct and indirect searches for new physics beyond the Standard Model (BSM);
- studies of heavy ion collisions;
- heavy flavour physics;
- an extraction of the parton distribution functions (PDF) in the wide kinematic range as well as precision measurements of such important SM parameters as m_W , α_S , $\sin^2 \theta_W$ etc.

Expected cross sections of different SM processes vary by many orders of magnitude from 100 mb for the total pp cross section to about 10–100 pb for the SM Higgs boson production cross section. The LHC experiments are able to measure such cross sections with high precision.

1.2 The ATLAS detector and physics

The ATLAS detector [2] is a multipurpose particle physics apparatus with forward-backward symmetric cylindrical geometry. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a straw-tube transition radiation tracker. The ID is surrounded by a thin superconducting solenoid which provides a 2 T magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic (EM) calorimetry. The electromagnetic calorimeter is divided into a central barrel and end-cap regions on either end of the detector. In the region matched to the ID ($|\eta| < 2.5^1$), it is radially segmented into three layers. The first layer has a fine segmentation in η to facilitate e/γ separation from π^0 and to improve the resolution of the shower position and direction measurements. In the region $|\eta| < 1.8$, the electromagnetic calorimeter is preceded by a presampler detector to correct for upstream energy losses. An iron-scintillator/tile calorimeter gives hadronic coverage in the central rapidity range ($|\eta| < 1.7$), while a LAr hadronic

¹ATLAS uses a right-handed coordinate system with the origin at the nominal interaction point (IP) in the centre of the detector, and the z -axis along the beam line. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, θ) are used in the transverse plane, θ being the azimuthal angle around the beam line. Observables labelled “transverse” are projected into the $x - y$ plane. The pseudorapidity is defined in terms of the polar angle θ , as $\eta = -\text{Intan}(\theta/2)$.

end-cap calorimeter provides coverage over $1.5 < |\eta| < 3.2$. The forward regions ($3.2 < |\eta| < 4.9$) are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large air-core superconducting magnets providing a toroidal field, each with eight coils, a system of precision tracking chambers, and fast detectors for triggering. The combination of all these systems provides charged particle measurements together with efficient and precise lepton and photon measurements in the pseudorapidity range $|\eta| < 2.5$. Jets and missing transverse energy, E_T^{miss} , are reconstructed using energy deposits over the full coverage of the calorimeters, $|\eta| < 4.9$.

One should note that pp -collisions at 13 TeV in the ATLAS and CMS interaction points occur with a frequency of ≈ 40 MHz, i.e. the interval between them is about 25 ns. Thanks to high LHC luminosity and large proton-proton inelastic cross section, each collision of beam bunches results, in average, to more than thirty physics events simultaneously. This effect is usually called as “pile-up” effect. Despite of such conditions, almost 95% of events triggered in the ATLAS detector are good for physics analysis.

The ATLAS collaboration has a few working groups which concentrate on the following studies:

- SM (electroweak processes, single W/Z -production, photons, hadronic jets, soft processes);
- heavy flavours and light states (charmonia, bottomonia; rare decays of B -mesons etc);
- Higgs boson (decay channels, their combination, perspectives);
- top quarks (single and pair production; measurement of the mass);
- BSM searches in many final states;
- heavy ions (ion-ion and proton-ion interactions).

Results presented in this note are mostly based on the complete 2015-2016 dataset taken at 13 TeV energy. It corresponds to the integrated luminosity 36 fb^{-1} . The summary of ATLAS results on cross section measurements of many SM processes is given in Fig.1(a). They are all in agreement with the most recent theoretical predictions, so we understand backgrounds to new physics. Further we concentrate mainly on the study of a Higgs boson production and its decays.

The note is organized as follows. Section 2 contains a brief summary of expected Higgs boson production cross sections in different mechanisms as well as branching ratios (BR) of its decay modes. In Section 3, the most sensitive bosonic decay modes of the SM Higgs boson (h), namely the $h \rightarrow ZZ^* \rightarrow 4\ell$, $h \rightarrow \gamma\gamma$ and $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ are considered; Section 4 is devoted to the $h \rightarrow b\bar{b}$ decay mode and in Section 5 the $t\bar{t}h$ production is discussed. In Section 6 BSM searches of heavy scalar higgs boson, H , are summarized. Conclusions are drawn in Section 7 together with short-term plans.

2. SM Higgs boson production and decays

The Higgs boson in the SM provides all fundamental particles with masses. Before 2012 the h boson mass was the last unknown parameter. From theoretical considerations (perturbative unitarity) $m_h \leq 1 \text{ TeV}$ is expected. The Higgs boson should have vacuum quantum numbers, i.e. zero

spin and even parity ($J^P = 0^+$). In 2003, LEP experiments put the lower bound on its mass, $m_H \geq 114.4$ GeV at the 95% confidence level (CL); smaller masses were excluded at much higher CL [9]. Theoretical analyses of electroweak precision data predicted $m_H = 94_{-24}^{+29}$ GeV, i.e. $m_h \leq 152$ GeV at the 95% CL [10]. Indeed, a new boson with a mass of 125 GeV, i.e. in-between the mentioned limits, was discovered by the ATLAS [6] and CMS [7] Collaborations at the Large Hadron Collider (LHC) six years ago.² This discovery was a great success of the SM as all measured properties of this particle were found to be compatible with the predictions for the h boson.

A search for the SM Higgs boson at the LHC is a complicated task as expected signal production cross section is $\sigma_h = \mathcal{O}(10)$ pb while background rates are much higher. Predicted σ_h at $m_h = 125$ GeV rises with the center-of-mass pp energy from ≈ 20 pb at 8 TeV to ≈ 50 pb at 13 TeV [12]. There are four main mechanisms of the SM Higgs boson production at the LHC energies: gluon fusion (ggF) via heavy-quark (mostly top) triangular loop, vector-boson fusion (VBF) where the Higgs boson is accompanied by two jets going at small polar angles, associated production with one vector boson (Vh , i.e. together with W or Z) and top-antitop fusion. The first and the last mechanisms as well as the second and the third ones have common couplings ($t\bar{t}h$ and VVh , respectively). The expected σ_h from these mechanisms are shown in Fig.1(b) as function of m_h at $\sqrt{s} = 13$ TeV together with theoretical uncertainties [12]. It is seen that the ggF mechanism dominates while rates via VBF (Vh , $t\bar{t}h$) mechanisms are ten (a few dozen) times smaller, respectively.

The expected branching ratios (BR) of the experimentally favourable decay modes are given in Table 1. Despite of 58% probability, the $h \rightarrow b\bar{b}$ channel is very difficult experimentally due to a huge background and it is not possible to see it via the ggF mechanism. However, one can try to extract the signal in the associated production of the h with a vector boson or a pair of top quarks. The $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel (here and further ℓ stands for an electron/positron or a muon) is better for searches, despite having branching ratio of only $\approx 1\%$. However, it does not allow to reconstruct a Higgs boson mass. The cleanest decay channels where this is possible are the $h \rightarrow ZZ^* \rightarrow 4\ell$ (BR $\approx 1.3 \times 10^{-4}$) and the $h \rightarrow \gamma\gamma$ (BR $\approx 2.3 \times 10^{-3}$). In the last case a signal is searched above large background. Expected signal event rates normalized to 36 fb¹ data sample collected at 13 TeV are also shown in Table 1. Here 100% detection efficiency is assumed.

3. The $h \rightarrow \gamma\gamma$, $h \rightarrow ZZ^* \rightarrow 4\ell$ and $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channels

The brief summary of the ATLAS results on the h boson measurements at 8 TeV is given in Table 2. One can see that the Higgs boson signal strength is measured with 10–50% precision, depending on the decay mode and on the production mechanism. The spin and parity of the were determined to be equal to 0^+ . No deviation from the SM is found. Below we concentrate on the results obtained at 13 TeV.

3.1 The $h \rightarrow ZZ^* \rightarrow 4\ell$ mode [20]

The $h \rightarrow ZZ^* \rightarrow 4\ell$ signature is two pairs of isolated, opposite-sign leptons. The invariant-mass distribution, $m_{4\ell}$, measured by the ATLAS experiment after the combination of all lepton cases [20]

²The CDF and D0 experiments at the FNAL Tevatron $p\bar{p}$ -collider were able to find only an evidence for the Higgs boson production at 3σ level [11].

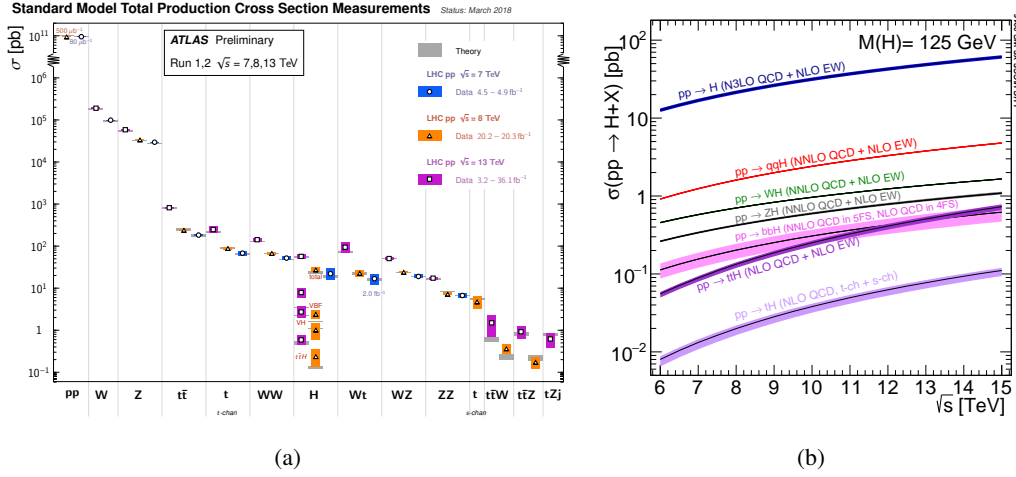


Figure 1: (a) A summary of measured cross sections of different SM processes in the ATLAS experiment [8]. (b) Predicted SM Higgs boson cross section at $m_h = 125$ GeV in different production mechanisms as function of \sqrt{s} [12].

Decay mode	BR, %	Observability in the experiment	Event rates
$h \rightarrow b\bar{b}$	57.5 ± 1.9	Mainly in Vh and tth production	≥ 24000
$h \rightarrow WW^*$	21.6 ± 0.9	Leptonic decays of both W	≈ 17000
$h \rightarrow gg$	8.56 ± 0.86	no good experimental signature	
$h \rightarrow \tau\tau$	6.30 ± 0.36	Mainly in VBF production	≈ 10000
$h \rightarrow c\bar{c}$	2.90 ± 0.35	no good experimental signature	
$h \rightarrow ZZ^*$	2.67 ± 0.11	Leptonic decays of both Z	≈ 250
$h \rightarrow \gamma\gamma$	0.228 ± 0.011	Big continuum background	≈ 5000
$h \rightarrow Z\gamma$	0.155 ± 0.014	Leptonic decays of Z	≈ 250
$h \rightarrow \mu\mu$	0.022 ± 0.001	Big continuum background	≈ 500

Table 1: Expected h branching ratios at $m_h = 125.1$ GeV as well as estimated number of events, collected at 13 TeV pp collisions (for 36 fb^{-1} data sample) assuming 100% detection efficiency (last column).

is shown in Fig. 2(a). The clear peak above a background is seen in the region around 125 GeV. The ATLAS experiment observes 95 events in the mass window 118–129 GeV with an estimated background 23.6 ± 1.6 events and an expected signal 54 events. The signal strength in the SM units, μ , is measured to be 1.28 ± 0.20 . The fiducial cross section measurement is performed and the extracted total cross section multiplied by the $\text{BR}(h \rightarrow ZZ^*)$ is 1.73 ± 0.25 pb. It agrees with the SM value of 1.34 ± 0.09 pb within 1.4σ . Fig. 2(b) shows the values of the measured fiducial cross sections in the main production modes. No deviation from the SM is observed.

3.2 The $h \rightarrow \gamma\gamma$ mode [21]

The signature of the $h \rightarrow \gamma\gamma$ decay channel is two isolated photons with an invariant mass equal to m_h . To increase the discovery potential, the ATLAS experiment subdivided events into independent categories having different expected $m_{\gamma\gamma}$ resolution and signal-to-background (S/B)

Parameter	Value	Reference	Comment
Mass	125.36 ± 0.41 GeV	[13]	125.09 ± 0.24 GeV with CMS [14]
Signal strength μ	1.18 ± 0.15	[15]	1.09 ± 0.10 with CMS [16]
μ in $h \rightarrow \gamma\gamma$ mode	$1.17^{+0.28}_{-0.26}$	[15]	5.2σ (discovery)
μ in $h \rightarrow 4\ell$ mode	$1.46^{+0.40}_{-0.34}$	[15]	8.1σ (discovery)
μ in $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ mode	$1.18^{+0.24}_{-0.21}$	[15]	6.5σ (discovery)
μ in $h \rightarrow \tau\tau$ mode	$1.44^{+0.42}_{-0.37}$	[15]	4.5σ (evidence)
μ in $h \rightarrow b\bar{b}$ mode	$0.63^{+0.39}_{-0.37}$	[15]	1.4σ
μ in ggF production	$1.23^{+0.23}_{-0.20}$	[15]	$1.03^{+0.17}_{-0.15}$ with CMS [16]
μ in VBF production	$1.23^{+0.32}_{-0.32}$	[15]	$1.18^{+0.25}_{-0.23}$ with CMS [16]
μ in Vh production	0.80 ± 0.36	[15]	$0.84^{+0.40}_{-0.38}$ with CMS [16]
μ in $t\bar{t}h$ production	1.81 ± 0.80	[15]	$2.3^{+0.7}_{-0.6}$ with CMS [16]
Spin/parity	0^+	[17]	$4\ell, \ell\nu\ell\nu, \gamma\gamma$ modes
Width	≤ 22.7 MeV (95% CL)	[18]	Off-shell $h \rightarrow WW/ZZ$
BR($h \rightarrow invisible$)	≤ 0.28 (95% CL)	[19]	WIMP searches

Table 2: Brief summary of the ATLAS results on the h boson measurements at 8 TeV.

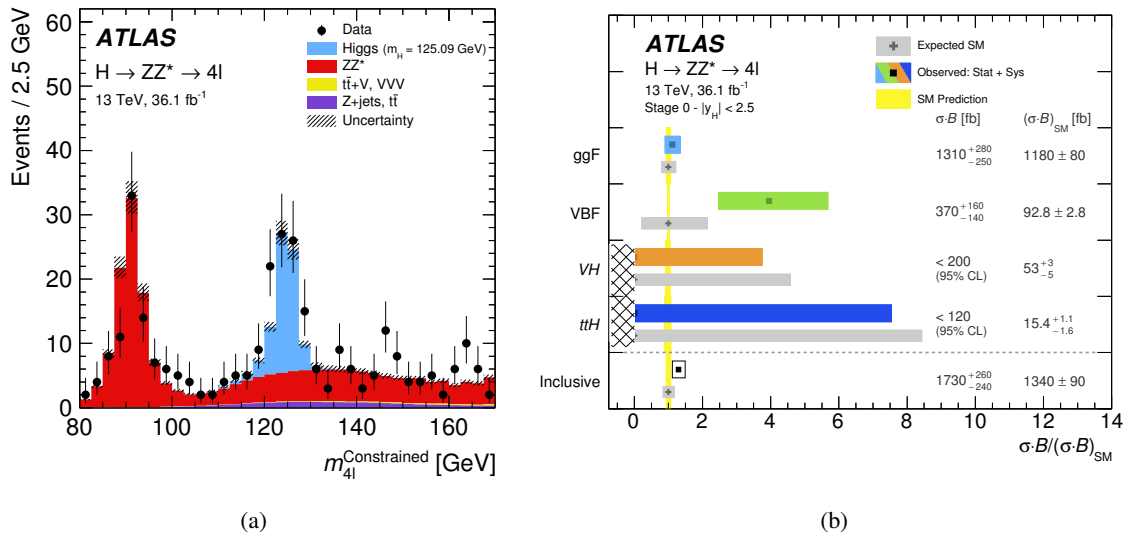


Figure 2: Results of the $h \rightarrow ZZ^* \rightarrow 4\ell$ study at 13 TeV in the ATLAS experiment [20]. (a) $m_{4\ell}$ distributions for the selected candidates compared to the background expectation in the mass range 80–170 GeV. The signal expectation for the $m_h = 125$ GeV hypothesis is also shown. (b) The measured fiducial cross sections separately in the main production modes. They are normalized to the SM predictions.

ratio and optimized for the best separation of the Higgs boson production processes. The $m_{\gamma\gamma}$ -distribution after the corresponding re-weighting is given in Fig. 3(a) together with the spectra after a background subtraction [21]. The excess of events with more than 5σ significance is clearly seen around 125 GeV. The value of the signal strength in the SM units is measured to be 0.99 ± 0.15 . Fig.3(b) shows the values of μ in the main production modes. No deviation from the SM is found.

In addition, the fiducial cross section at 13 TeV multiplied by $\text{BR}(h \rightarrow \gamma\gamma)$, defined for the kinematic range $E_T^{\gamma 1} \geq 40$ GeV, $E_T^{\gamma 2} \geq 30$ GeV, and $|\eta|^\gamma \leq 2.37$, is measured to be 55 ± 10 fb, in perfect agreement with the SM prediction of 64 ± 2 fb.

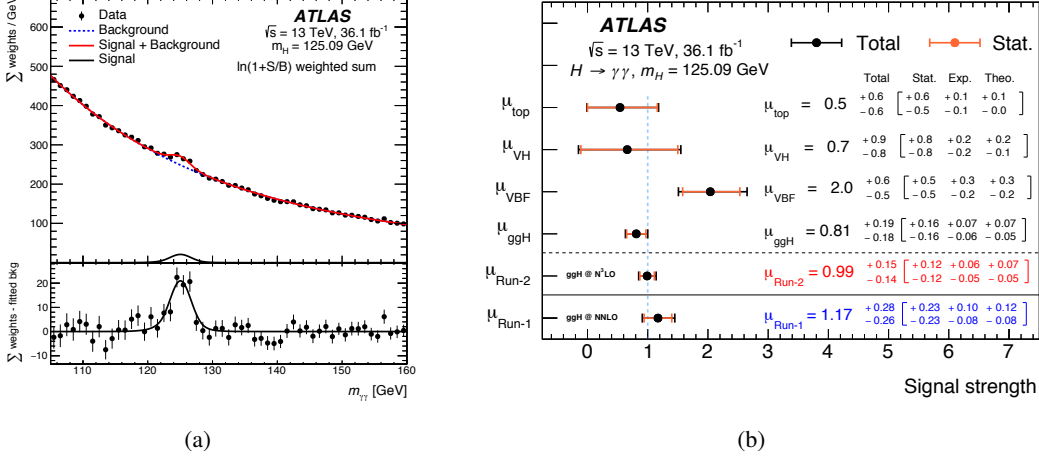


Figure 3: Results of the $h \rightarrow \gamma\gamma$ study at 13 TeV in the ATLAS experiment [21]. (a) $m_{T\gamma\gamma}$ -distribution of diphoton candidates after all selections. The result of a fit to the data with the sum of a SM Higgs boson signal (with $m_h = 125$ GeV and free signal strength) and a background is superimposed. The residuals of the data with respect to the fitted background are displayed in the lower panel. (b) The measured values of the signal strength μ in the main production modes. Also shown the values of μ measured earlier with the combined 7 and 8 TeV data.

3.3 A combination of the $h \rightarrow ZZ^* \rightarrow 4\ell$ and $h \rightarrow \gamma\gamma$ channels [22]

The results obtained for the individual channels $h \rightarrow ZZ^* \rightarrow 4\ell$ and $h \rightarrow \gamma\gamma$ are combined to extract a Higgs boson signal strength in different production mechanisms (Fig. 4(a)) and its production cross section at 13 TeV pp energy. The average signal strength is measured to be $\mu = 1.09 \pm 0.12$, in good agreement with the SM prediction. The measured h production cross section $\sigma(pp \rightarrow h + X) = 57.0^{+6.0}_{-5.9}$ (stat) $^{+4.0}_{-3.3}$ (syst) pb is compatible within 1σ with the theoretical value $55.6^{+2.4}_{-3.4}$ pb. It is obtained from fiducial measurements and also combined with older results at 7 and 8 TeV (Fig.4(b)).

3.4 The $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ mode [23]

The signature in the $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel is two isolated opposite-sign leptons (electrons or muons) and sizeable E_T^{miss} due to neutrinos so one cannot reconstruct the Higgs boson mass. Instead, its transverse mass reconstruction is possible. It is calculated as

$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{P}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}|^2}$, where $E_T^{\ell\ell} = \sqrt{|\mathbf{P}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$ and $P_T^{\ell\ell}$ ($m_{\ell\ell}$) are transverse momentum (invariant-mass) of the di-lepton system, respectively. So knowledge of a background normalization and shapes is of importance. The event sample is subdivided in accordance with the number of jets (0, 1 or ≥ 2). For the 0 and 1 jet cases the ggF mechanism is expected to be dominant while for ≥ 2 jets case signal events are mostly due to the VBF mechanism. Only the $e\mu$

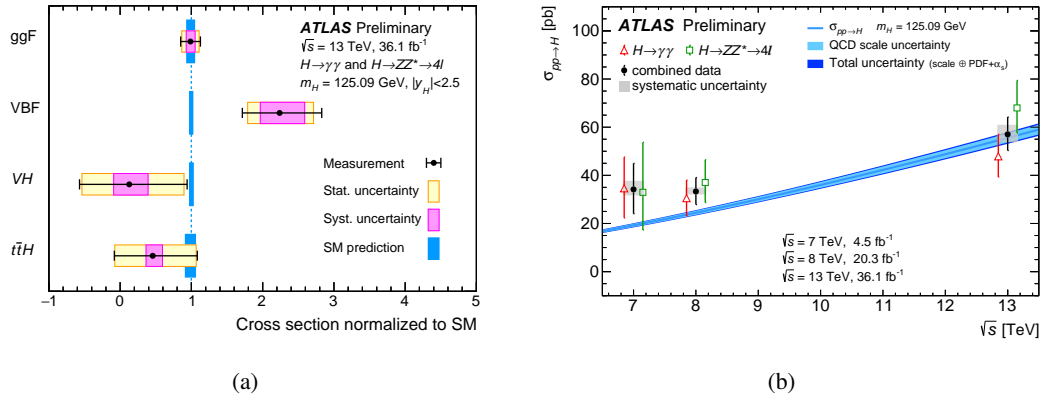


Figure 4: Results of the preliminary $h \rightarrow ZZ^* \rightarrow 4\ell$ and $h \rightarrow \gamma\gamma$ combination at 13 TeV in the ATLAS experiment [22]. (a) The measured values of the signal strength in the main production modes. (b) The measured total h boson production cross sections at 7, 8 and 13 TeV together with theoretical predictions.

final state is considered. The m_T -distribution before and after a background subtraction is shown in Fig.5(a). A clear excess of events is seen in the region 80–140 GeV. The observed (expected) signal significance at 125 GeV for the ggF h production is 6.3σ (5.2σ), respectively. The corresponding signal strength in the SM units is 1.21 ± 0.22 , and the ggF cross section multiplied by $\text{BR}(h \rightarrow WW^*)$ is measured to be $12.6 \pm 2.2 \text{ pb}$, in perfect agreement with the theoretical prediction $10.4 \pm 0.6 \text{ pb}$. The observed (expected) signal significance in the VBF production mode is 1.9σ (2.7σ), $\mu = 0.62 \pm 0.37$ and the measured cross section is $0.50 \pm 0.30 \text{ pb}$ being compatible with the expected value of $0.81 \pm 0.02 \text{ pb}$. The correlation between the measured ggF and VBF cross sections is shown in Fig.5(b).

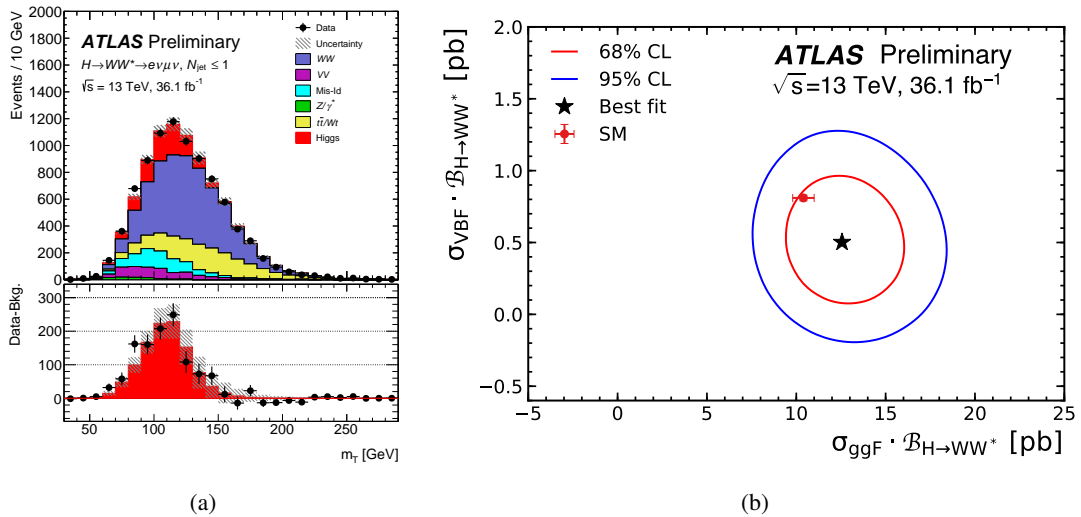


Figure 5: Results of the $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ study at 13 TeV in the ATLAS experiment [23]. (a) m_T distribution before and after a background subtraction in the case of less than two jets in an event. (b) The correlation between the measured ggF and VBF cross sections.

4. The $Vh \rightarrow b\bar{b} + X$ decay channel [24]

The $Vh \rightarrow b\bar{b} + X$ signature includes two jets originating from b -quarks with an invariant mass close to m_h . In addition, only events with tight lepton(s) and/or high E_T^{miss} depending on the Z/W final state: $Z \rightarrow \nu\nu$ (0 leptons), $W \rightarrow \ell\nu$ (one lepton) and $Z \rightarrow \ell\ell$ (two leptons) are considered. A multivariate analysis is performed to discriminate the signal from a background. The procedure is successfully tested on the $(W/Z)Z$ process with subsequent $Z \rightarrow b\bar{b}$ decay. The observed (expected) signal significance is 3.5σ (3.0σ). This corresponds to the signal strength $\mu = 1.20^{+0.42}_{-0.36}$ at 13 TeV. Fig.6(a) shows the measured μ separately in the Wh and Zh production modes. The results after the combination with the 7 and 8 TeV data are given in Fig.6(b). The combined observed (expected) significance is 3.6σ (4.0σ); the signal strength is measured to be 0.90 ± 0.27 , in agreement with the SM prediction.

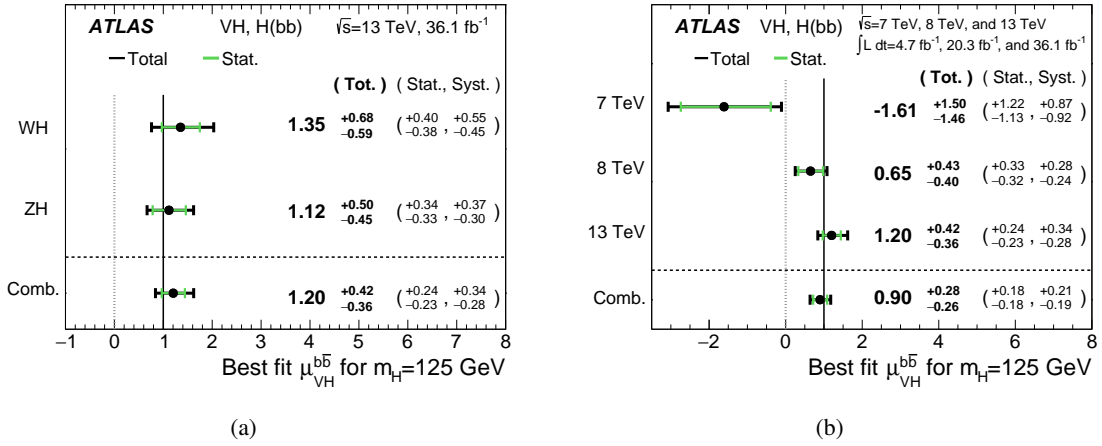


Figure 6: The observed signal strength μ in the $Vh \rightarrow b\bar{b} + X$ production mode in the ATLAS experiment [24]. (a) 13 TeV data, separately for the Wh and Zh production modes and combined result. (b) 7, 8 and 13 TeV data as well as their combination.

5. The $t\bar{t}h$ -production [25]

The $t\bar{t}h$ -production mechanism is studied using a variety of multi-lepton final states. A multivariate technique to discriminate the signal from a background is used. The measured μ is $1.6^{+0.5}_{-0.4}$ (Fig.7(a)) which corresponds to observed (expected) signal significance 4.1σ (2.8σ). After the combination with another signatures (Fig.7(b)) the measured μ is found to be 1.2 ± 0.3 [25]. The observed (expected) signal significance is 4.2σ (3.8σ).

6. Search for the Higgs boson beyond the SM at 13 TeV

The simplest model is the so-called Narrow Width Approximation (NWA) where additional high-mass Higgs boson (H) behaves as the SM Higgs boson h , except the width is fixed to be equal to 4 MeV, which is the expected width of the SM Higgs boson at $m_h = 125$ GeV. This

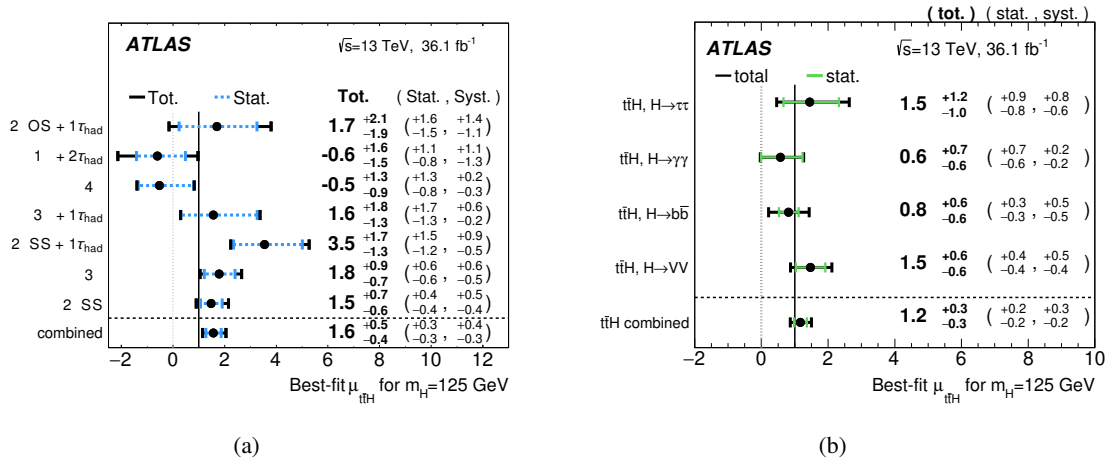


Figure 7: The observed signal strength in the $t\bar{t}h$ production mode at 13 TeV in the ATLAS experiment [25]. (a) Multi-lepton final state. (b) All final states.

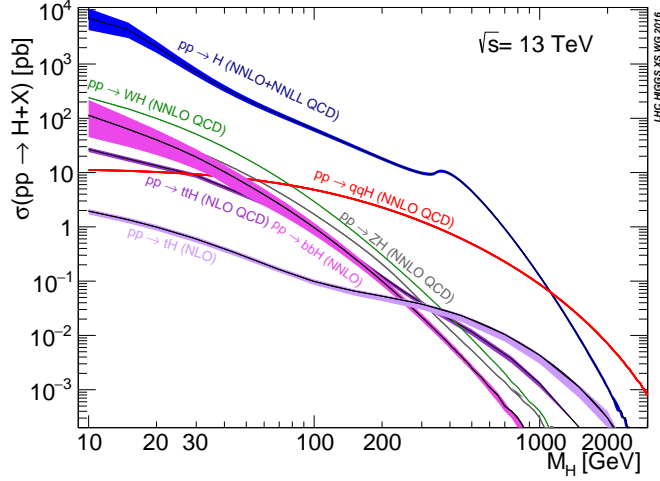
simplified model allows to produce MC samples easily. In addition, the interference of the signal with background processes can be neglected simplifying the analysis. The predictions for the Higgs boson production cross section at 13 TeV in different mechanisms are shown in Fig.8(a) as function of m_H . It is interesting to note that above 1.5 TeV mass the VBF mechanism starts to dominate. Another models contain five Higgs bosons (neutral light and neutral heavy CP-even states, h and H , one CP-odd neutral state A and two charged states, H^+ and H^-). Four masses m_h, m_H, m_A, m_{H^\pm} , mixing angle α between the light and the heavy neutral Higgs boson, and the ratio $\tan\beta$ of two vacuum expectation values are usual free parameters.

In this note only ATLAS results on heavy neutral scalar Higgs boson searches in some bosonic decay modes are covered. The interpretation is performed in the NWA framework.

Table 3 shows expected H branching ratios at $m_H = 1$ TeV as well as estimated number of events, collected at 7 TeV, 8 TeV and 13 TeV pp collisions (for 5 fb^{-1} , 20 fb^{-1} and 36 fb^{-1} data samples, respectively) assuming 100% detection efficiency. It is seen that for some of the channels considered the rates are too small at 7 and 8 TeV while they are rather big at 13 TeV.

Decay mode	BR, %	Rates at 7 TeV	Rates at 8 TeV	Rates at 13 TeV
$H \rightarrow WW \rightarrow \ell\nu\ell\nu$	$\approx 2.7\%$	≈ 2	≈ 30	≈ 500
$H \rightarrow WW \rightarrow \ell\nu q\bar{q}$	$\approx 17\%$	≈ 10	≈ 200	≈ 4000
$H \rightarrow ZZ \rightarrow 4\ell$	$\approx 0.17\%$	≈ 0.15	≈ 2	≈ 35
$H \rightarrow ZZ \rightarrow \ell\nu\nu\nu$	$\approx 1.0\%$	≈ 0.9	≈ 12	≈ 200
$H \rightarrow ZZ \rightarrow \ell\ell q\bar{q}$	$\approx 2.9\%$	≈ 2.6	≈ 35	≈ 500
$H \rightarrow ZZ \rightarrow \nu\nu q\bar{q}$	$\approx 8.5\%$	≈ 7.5	≈ 100	≈ 1700

Table 3: Expected H branching ratios at $m_H = 1$ TeV as well as estimated number of events, collected at 7 TeV, 8 TeV and 13 TeV pp collisions (for 5 fb^{-1} , 20 fb^{-1} and 36 fb^{-1} data samples, respectively) assuming 100% detection efficiency (last three columns).



(a)

Figure 8: Predicted BSM Higgs boson production cross section at 13 TeV in the NWA approach as function of m_H [12].

6.1 The $H \rightarrow \gamma\gamma$ mode [26]

The $H \rightarrow \gamma\gamma$ decay mode has a special interest because of the observation of an excess at around 750 GeV in the di-photon invariant-mass distribution both by the ATLAS and CMS experiments in the 2015 data sample [27]–[28]. In the ATLAS case, the deviation from the SM was at 3.4σ level (local significance). The ATLAS Collaboration performed a new analysis based on ten times larger dataset mostly obtained in 2016. The search mass range is 200–2700 GeV. Some 32755 events with hard photons were selected and the resulting $m_{\gamma\gamma}$ -distribution is shown in Fig. 9(a). No significant excess is observed. The resulting 95% CL upper limit on the fiducial cross section multiplied by the $\text{BR}(H \rightarrow \gamma\gamma)$ is given in Fig. 9(b).

6.2 The $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ mode [29]

The mass range between 300–3000 GeV is covered by the $H \rightarrow WW \rightarrow e\nu\mu\nu$ decay channel. Selection criteria are specially optimized for the high-mass case and a multivariate analysis is performed. Events are subdivided into ggF- and two VBF-enriched categories. No significant excess above a background is found in the search mass range (Fig. 10(a)–Fig. 10(b)). 95% CL upper limits on $\sigma_H \times \text{BR}(H \rightarrow WW)$ are established separately in the ggF and VBF production mechanisms in the framework of the NWA model. They are 6.4 pb (8 fb) at $m_H = 200$ GeV ($m_H = 4000$ GeV) in the ggF case and 1.3 pb (6 fb) at $m_H = 300$ GeV ($m_H = 3000$ GeV) in the VBF case.

7. Conclusion and short-term plans

In conclusion:

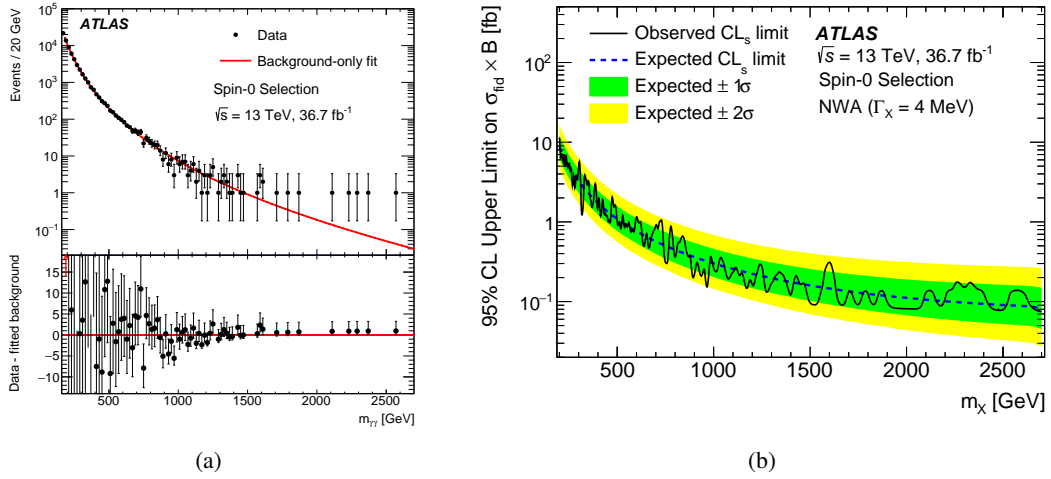


Figure 9: Results of the $H \rightarrow \gamma\gamma$ study at 13 TeV in the ATLAS experiment [26]. (a) $m_{\gamma\gamma}$ -distribution of diphoton candidates after all selections. (b) 95% CL upper limit on the fiducial cross section multiplied by the $\text{BR}(H \rightarrow \gamma\gamma)$, as a function of m_H .

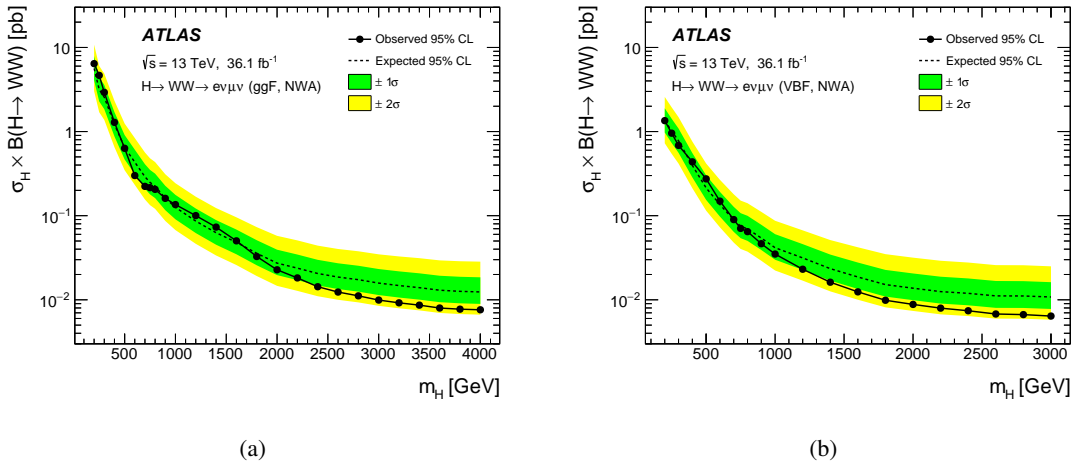


Figure 10: Results of the $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ study at 13 TeV in the ATLAS experiment [29]: 95% CL upper limits on the cross section multiplied by the $\text{BR}(H \rightarrow WW)$ as a function of m_H in two production modes. (a) ggF production mode. (b) VBF production mode.

- With 7, 8 and 13 TeV LHC data, the ATLAS Collaboration studied a lot of SM processes and measured their cross sections with high precision. All of them are in agreement with recent theoretical calculations;
- Using the same datasets, Higgs boson properties such as its couplings, mass, spin and parity were investigated. No deviation from the SM is found;
- With 36 fb^{-1} of 13 TeV LHC data, we obtained preliminary results reconfirming SM-like Higgs boson discovery in the 4ℓ and $\gamma\gamma$ modes making evidence for the $h \rightarrow b\bar{b}$ decay and

$t\bar{t}h$ -production;

- The ATLAS Collaboration also performed searches for new physics in many final states. Nothing was found yet. Strict limits on production cross sections of new particles were put;
- We plan to continue to improve existing measurements and to search for deviations from the SM with new 13-14 TeV data.

The short-term LHC and ATLAS (CMS) perspectives are the following:

- In 2018, it is expected to collect the data sample in pp collisions at 13 TeV which corresponds to 55–60 fb^{-1} integrated luminosity, so the complete ATLAS and CMS datasets will be of $\approx 150 \text{fb}^{-1}$. A lot of papers based on these samples are planned to be published;
- The LHC as well as the ATLAS and CMS experiments will be upgraded during 2019–2020 shutdown to operate at luminosities up to $3 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$;
- In 2021–2023 the run at increased energy (from 13 TeV to 14 TeV) is foreseen aiming to collect 300 fb^{-1} . More precise measurements of the h coupling and its main decay channels will be made, a discovery of new physics or strict upper limit settings on the cross section of new particles are expected. In addition, studies of rare B -meson decays and detailed investigations of ion-ion and proton-ion collisions will be continued;
- The next upgrade of the LHC and the experiments³ will be performed during 2024–2026 shutdown. After this shutdown the LHC develops into the High Luminosity stage (HL-LHC) and the general-purpose experiments should be able to work up at $7 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ luminosity. The total integrated luminosity foreseen for the HL-LHC phase is 3000 fb^{-1} .

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³The LHCb upgrade is planned to 2030.

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DISCUSSION

JULIO AURIEMMA: Could you please comment about statistical significance of the Higgs boson signal, for example, given in your slide 14?

ILYA TSUKERMAN: We checked two hypotheses:

Hypothesis 1: the observed excess of events above the background is due to the Standard Model Higgs boson;

Hypothesis 2: the observed excess is due to occasional background fluctuation.

The number of standard deviations (σ) given in the last column of Table in slide 14 corresponds to the hypothesis 2 while the measured signal strength in the SM units (second column in the mentioned table) corresponds to the hypothesis 1. You see that the quoted global signal strength of 1.18 ± 0.15 is almost within one σ compatible with unity while it is incompatible with zero (more than 10 σ deviation). This means that the observed particle is a Higgs boson.

QUESTION: What are perspectives of new physics searches at the LHC?

ILYA TSUKERMAN: New physics is not yet observed in the LHC experiments. In backup slides 71-72 which I am showing now you see summaries of ATLAS lower mass limits on different SUSY-predicted and other exotic particles and objects. If nothing will be observed, we simply put more strict limits analysing more and more experimental data.