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Prospects for Higgs and di-Higgs measurements at the ATLAS experiment

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Abstract

The large dataset of about 3000 fb^{-1} that will be collected at the High Luminosity LHC (HL-LHC) will be used to measure Higgs boson processes in detail. This large dataset will also provide sensitivity to di-Higgs processes and will allow for the improvement of the constraints on the Higgs boson self coupling. Studies based on current ATLAS analyses using LHC Run 2 data have been carried out to understand the expected precision and limitations of the Higgs and di-Higgs measurements at the HL-LHC. This paper presents the ATLAS prospects for Higgs and di-Higgs results at the HL-LHC.

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1 Introduction

The Higgs boson (H) was discovered at the Large Hadron Collider (LHC) in 2012, by the ATLAS [1] and CMS collaborations [2,3]. In the Standard Model (SM) [4–10] all the Higgs boson couplings are defined once the value of its mass is known. After the Higgs boson discovery, a vast programme of measurements of its properties was launched and it is currently ongoing using the LHC Run 2 data. From the combination of ATLAS and CMS measurements [11], the measured value of the Higgs boson mass is 125.09 ± 0.21 (stat.) ±0.11 (syst.) GeV. All current measurements of the Higgs boson couplings are so far consistent with the SM predictions for this value of the mass within the measurements uncertainties [12].

However, the SM is not complete and leaves many open questions. There are many alternative beyond the SM (BSM) theories that make various different predictions for the properties of one or more Higgs bosons. Therefore, precise measurements in the Higgs sector are a high priority for the future programme of particle physics as it is very important to probe the compatibility of the measured values of the Higgs boson properties to the SM predictions with increased precision.

In order to be able to increase the precision of the Higgs properties measurements more data will need to be collected. An upgrade programme of the LHC [13] and of the experiments is planned in several phases to achieve this goal, as shown in Figure 1. During the High-Luminosity LHC (HL-LHC) run, the LHC is expected to provide pp collisions at the nominal centre-of-mass energy of 14 TeV, with a peak instantaneous luminosity of 5 to 7 $\times 10^{-34}$ cm^{-2}s^{-1} and it is expected to deliver 3000 to 4000 fb^{-1} of data, i.e. 10 times more than the integrated luminosity of the LHC Runs 1-3 combined.

Studies based on the ATLAS Higgs and di-Higgs analyses using LHC Run 2 data have been carried out to understand the expected precision and limitations of these measurements at the HL-LHC.

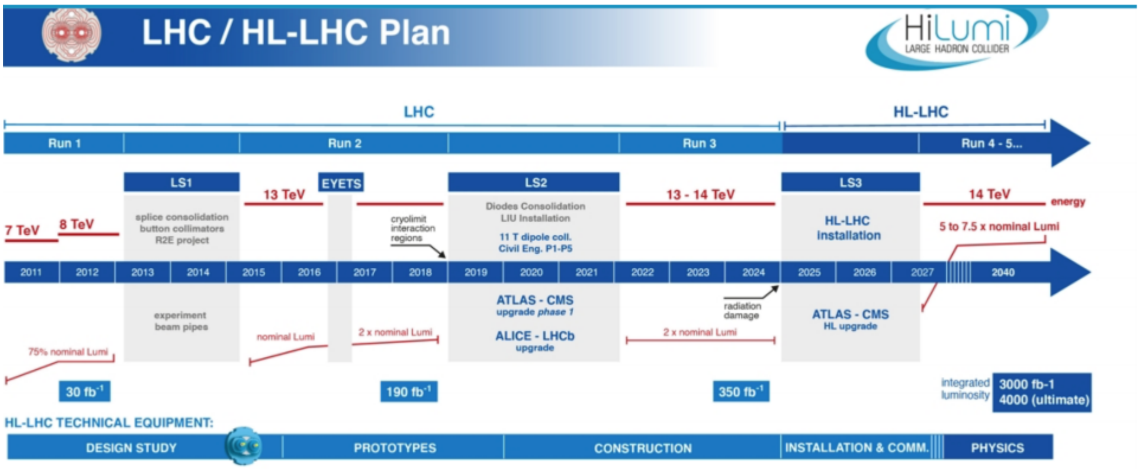


Figure 1: LHC upgrade programme [13].

2 ATLAS detector upgrade

The HL-LHC run will be a challenging collision environment, with new conditions of operation for the detectors. The instantaneous luminosity will increase by a factor 2-4 compared to Run 3 and the mean number of interactions per bunch-crossing will reach 200.

To maximise the physics outcome of this LHC run, the ATLAS experiment will need to maintain or improve object reconstruction efficiency and resolution on their measured properties and reduce the fake rates even in an collision environment with more pile-up jets. To be able to reach the physics goal set for the HL-LHC the ATLAS detector has to be upgraded.

The ATLAS detector upgrade consists of an upgrade of readout electronics, replacement of some elements of sub-detectors using most recent technologies, extension of angular coverage in the forward region and an upgrade of trigger and data acquisition systems to sustain higher rate of interactions without sacrificing efficiency. New Front-End (FE) electronics and new read-out systems will be installed in the calorimeters [14, 15] to allow for the read-out of higher resolution objects at the trigger level. The inner tracking detector will be replaced with a new all-silicon Inner Tracker (ITk) [16, 17], increasing the coverage up to a pseudorapidity of $|\eta| = 4$. A new detector, the high-granularity timing detector [18] will be installed in the forward region, which is expected to improve separation between close-by vertices of multiple interactions. New muon chambers will be installed in the inner barrel region [19] to increase the coverage at the trigger level. The Trigger and Data Acquisition (TDAQ) system will be upgraded and re-designed to sustain the higher rate [20], exploiting the higher granularity information available from the upgraded detector, with hardware selection output at 1 MHz and software selection output at 10 kHz.

3 Higgs prospects

Prospects for the Higgs measurements at the HL-LHC were performed to evaluate the expected precision of the Higgs couplings measurements and of the Higgs differential cross section measurements, described in Section 3.1 and Section 3.2 respectively.

3.1 Higgs couplings

Prospects for the Higgs couplings measurements are based on extrapolations of the ATLAS Run 2 Higgs couplings analyses performed using data collected in 2015 and 2016, corresponding to 36 fb^{-1}, for the WW, $Z\gamma$, ttH and $\tau\tau$ analyses and data collected in 2015, 2016 and 2017, corresponding to 80 fb^{-1}, for the $\gamma\gamma$, ZZ, and VH with $H \to bb$ and $H \to \mu\mu$ analyses [23].

Two scenarios were considered for assumptions on the systematic uncertainties: a conservative scenario (S1) using the Run 2 values of the systematic uncertainties and an ultimate scenario (S2) where the systematic uncertainties were reduced based on estimates of ultimate performance for experimental uncertainties and applying a factor of two reduction of the theoretical uncertainties.

The expected precision of the measurement of the Higgs global signal strength for the S1 (S2) systematic scenario is:

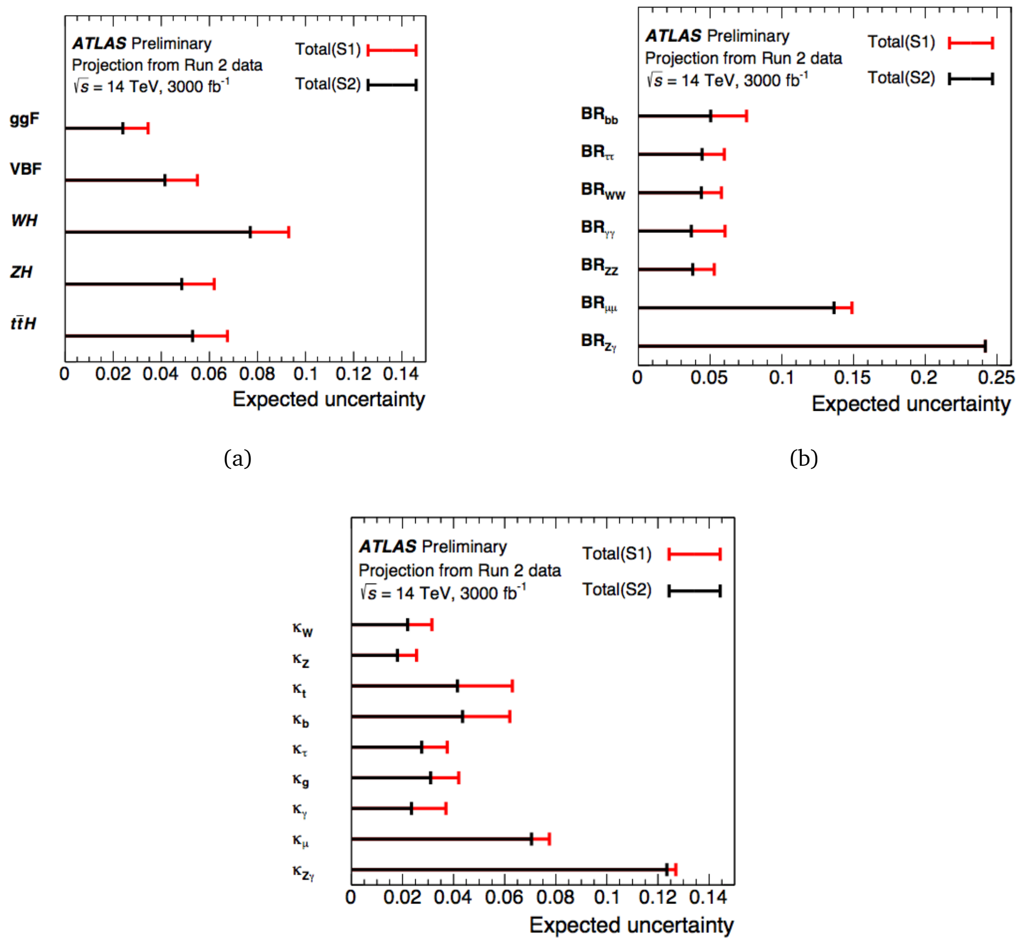
$$\begin{aligned} \mu &= 1.000\,^{+0.038}_{-0.037}\,\left(^{+0.025}_{-0.024}\right) \\ &= 1.000 \pm 0.006\,(\text{stat}) \pm 0.016\,(0.013)\,(\text{exp})\,^{+0.030}_{-0.028}\,\left(^{+0.017}_{-0.017}\right)(\text{sig})\,^{+0.016}_{-0.015}\,\left(^{+0.010}_{-0.010}\right)(\text{bkg})\,, \end{aligned} \tag{1}$$

showing that a precision of a few % is expected to be reached, dominated by the systematic uncertainties with an important impact of the theoretical uncertainties on signal.

Figure 2 illustrates the expected uncertainty on the measurements of the cross sections for the ggF, VBF, WH, ZH and ttH production modes normalised to their SM predictions assuming SM branching fractions, the expected uncertainty on the branching ratio measurements for the $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, $\mu\mu$ and $Z\gamma$ decay channels normalised to their SM predictions assuming SM production cross section and the expected uncertainty on the measurement of each Higgs boson coupling modifier per particle type with effective photon, gluon and $Z\gamma$ couplings, for the two systematic uncertainties scenarios S1 and S2. These results show that a precision of few %, dominated by systematic uncertainties, is expected to be reached on all Higgs production modes cross sections as well as on all the Higgs branching ratios and on all the Higgs coupling parameters,. The only exceptions are the branching ratios of the $\mu\mu$ and $Z\gamma$ decay channels for which a 15-20% precision is expected and the μ and $Z\gamma$ couplings for which a 10% precision is expected, dominated by statistical uncertainties.

3.2 Higgs differential cross sections

Prospects for the Higgs differential cross section measurements are based on extrapolations of the ATLAS Run 2 Higgs differential cross sections analyses performed using the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels, and are presenting the expected results on four observables, p_T^H, $|y^H|$, N_{jets}, P_T^{j1} [24]. The extrapolations are based on the analyses using data collected in 2015 and 2016, corresponding to 36 fb^{-1}, with the exception of the p_T^H observable in $H \to ZZ^* \to 4\ell$ where the measurement based on data collected in 2015, 2016 and 2017, corresponding to 80 fb^{-1}, is used.



(a) (b)

(c)

Figure 2: Expected uncertainty on the measurements of the cross sections for the ggF, VBF, WH, ZH and ttH production modes normalised to their SM predictions assuming SM branching fractions (a), the expected uncertainty on the branching ratio measurements for the $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, $\mu\mu$ (b) and $Z\gamma$ decay channels normalised to their SM predictions assuming SM production cross section and the expected uncertainty on the measurement of each Higgs boson coupling modifier per particle type with effective photon, gluon and $Z\gamma$ couplings (c), for the two systematic uncertainties scenarios S1 (red) and S2 (black) [23].

As for the prospects for the Higgs couplings measurements, also for the prospects for the Higgs differential cross section measurements two uncertainty scenarios S1 and S2 were considered.

The differential cross sections in the total phase space extrapolated to the full HL-LHC luminosity for the combination of the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels for the Higgs boson transverse momentum p_T^H is shown in Figure 3. In the low-medium p_T regime, up to 350 GeV, a precision of about 5% is expected for S1 and 4% for S2, with about equal contributions from statistical and systematic uncertainties. In the large p_T regime, between 350 GeV and 1000 GeV, a precision of about 8% is expected, dominated by the statistical uncertainties.

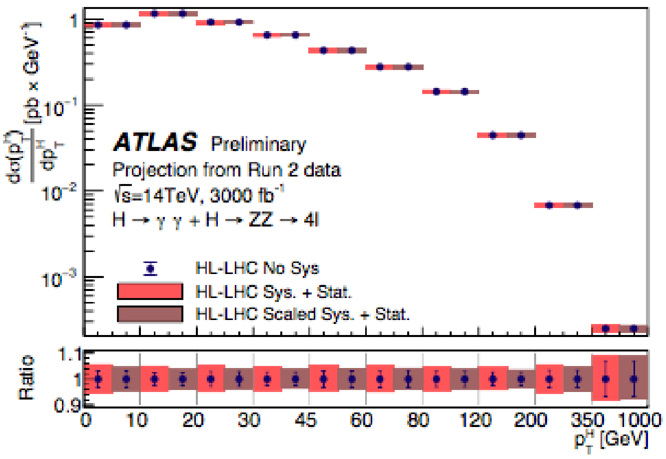


Figure 3: Differential cross sections in the total phase space extrapolated to the full HL-LHC luminosity for the combination of the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels for the Higgs boson transverse momentum p_T^H. For each point both the statistical (error bar) and total (shaded area) uncertainties are shown. Two scenarios are shown: one with the current Run 2 systematic uncertainties and one with reduced systematic uncertainties [24].

4 Di-Higgs prospects

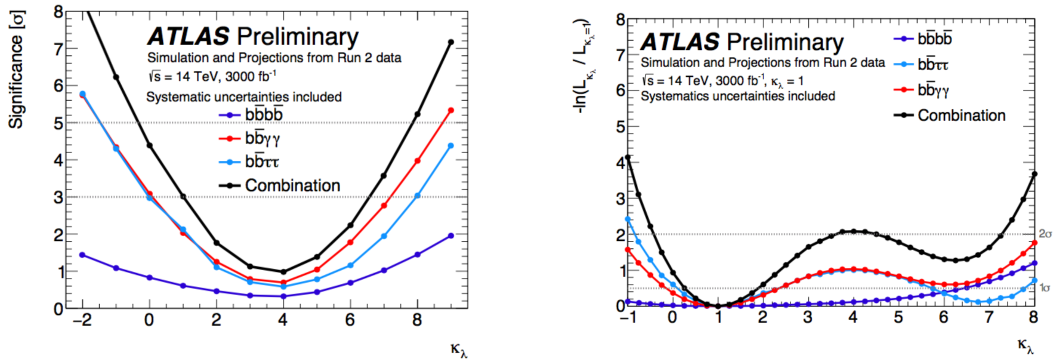
Prospects for the di-Higgs measurements at the HL-LHC are performed using the $bbbb$, $bb\tau\tau$ and $bb\gamma\gamma$ decay channels [25]. Prospects in the $bbbb$ and $bb\tau\tau$ channels are obtained from extrapolations of the ATLAS Run 2 analyses using data collected in 2015 and 2016, corresponding to 36 fb^{-1}, while the prospects in the $bb\gamma\gamma$ channel are obtained from a dedicated new analysis performed using simulations at 14 TeV. The expected results include the expected significance for the di-Higgs signal and the exclusion limit on the Higgs-self coupling modifier κ_λ.

The expected significance for the di-Higgs signal as a function of κ_λ and the expected negative natural logarithm of the ratio of the maximum likelihood for κ_λ to the maximum likelihood for $\kappa_\lambda = 1$ (SM) are shown in Figure 4. The expected significance for the di-Higgs SM signal observation is 3σ from the combination of the three channels. The Higgs self coupling modifier is expected to be constrained at 95% C.L. in the interval $-0.4 \leq \kappa_\lambda \leq 7.3$.

5 Conclusion

The prospects for Higgs and di-Higgs measurements at the HL-LHC are promising. The estimates show that the HL-LHC will provide a great opportunity for Higgs precision measurements, allowing to reach few percent precision of the Higgs couplings measurements and allowing for new rare processes to become accessible. The observation of $H \to \mu\mu$ and $H \to Z\gamma$ decays and the evidence of HH production will be possible.

Major progress is also expected by improving objects reconstruction and identification performance, reducing systematic uncertainties (experimental and theoretical) and improving analysis techniques. These will provide further improvements in addition to the luminosity increase considered in the prospects studies.



(a) (b)

Figure 4: Expected significance for the di-Higgs signal as a function of κ_λ (a) and expected negative natural logarithm of the ratio of the maximum likelihood for κ_λ to the maximum likelihood for $\kappa_\lambda = 1$ (SM) (b) [25].

Acknowledgements

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