Prospects On Standard Model And Higgs Physics At The HL-LHC

Aleandro Nisati$^{1,a)}$

$^{1}$ Istituto Nazionale di Fisica Nucleare, P.le Aldo Moro 2; Rome, 00185 (I);  
on behalf of the ATLAS and CMS collaborations  

$a)$Corresponding author: aleandro.nisati@cern.ch  
on behalf of the ATLAS and CMS Collaborations

Abstract. The luminosity upgrade of LHC, HL-LHC, will provide a large statistics data set that allows precision measurements of the 125 GeV Higgs boson properties. In particular, couplings to elementary fermions and bosons will be measured at the level of a few % accuracy. Searches for Higgs boson pair production and BSM effects in the vector boson scattering, of primary importance in the investigations of the electroweak symmetry breaking mechanism, also represent a crucial point in the HL-LHC physics programme.

Introduction

The discovery of the 125 GeV Higgs boson with the ATLAS and CMS detectors at the Large Hadron Collider (LHC) [1, 2, 3] opens a new era in particle physics. Current data indicate consistency of this new particle with the Higgs boson predicted by Standard Model (SM).

Direct searches of new particles and new phenomena at the 13-14 TeV LHC are of paramount importance. In particular, searches for possible partners of this newly discovered object are mandatory.

The presence of this boson in nature, and the knowledge of its mass, $m_H$ [4] ($m_H = 125.09 \pm 0.21 \text{(stat)} \pm 0.11 \text{(scale)} \pm 0.02 \text{(other)} \pm 0.01 \text{(theory)}$), was the only fundamental parameter missing to completely set the SM structure. We just entered a new era where precision tests are now needed in order to “discover” possible deviations from the SM theory.

The list below summarises the most important milestones of the understanding of 125 GeV Higgs boson sector:

- Observation of the Higgs decay $H \to \tau^+\tau^-$ in ATLAS and CMS independently;
- Observation of the vector boson fusion (VBF) and VH production mode (Higgs boson produced in association with a $W$ or $Z$ vector boson);
- Study of the Higgs boson differential production cross sections;
- Observation of the Higgs boson production mode $t\bar{t}H$, crucial for direct measure of the Higgs-top Yukawa coupling;
- Search for rare decay modes, particularly $H \to \mu^+\mu^-$;
- Measurement of the individual Higgs boson couplings to elementary fermions and bosons by the combination of all available rate measurements;
- Searches for double Higgs boson production.

Deviations from Standard Model Higgs boson couplings predicted by several BSM models can be as large as few $\%$, up to $\sim 10\%$. An example of this study is available in Ref. [5].

This paper presents and discusses the results of preliminary Higgs and electroweak sector studies with the ATLAS and CMS detectors simulated in the planned upgrade configuration at the HL-LHC [6].
The ATLAS and CMS upgrades

Current ATLAS [7][8] and CMS [9] detectors have been designed to operate with a pile-up level of $\mu_{pu} \sim 23$ proton-proton events (pp) per bunch crossing (bx), in average. We expect them to continue performing an excellent job with pile-up level up to about 50 pp/bx. The much larger level of pile-up expected at HL-LHC, $\mu = 140 - 200$ pp/bx, does require detector upgrades [10, 11]. In particular, the Inner Detector of ATLAS and CMS will undergo a complete replacement with a new system, fully based on pixel and silicon-strip technologies.

Different projection studies of physics reach at HL-LHC have been made by independently by ATLAS and CMS collaborations.

In ATLAS, the performance of individual physics objects (leptons, photons, jets, missing transverse energy and heavy-flavour jets) has been studies with full simulation Monte Carlo (MC) events in the severe environmental pile-up conditions of HL-LHC, and the results have been parametrized with simple *smearing functions* of the momentum in space of the considered object. Then, Monte Carlo events at particle level have been processed applying the effects described by the smearing functions. The physics analysis has then been performed.

In CMS, extrapolations of 8 TeV (Run 1) analyses to 14 TeV and high-luminosity have been performed under two scenarios: 1) assuming the same systematic uncertainties found in Run 1, and 2) assuming theoretical uncertainties reduced by a factor 2 and experimental uncertainties scaling with $\sqrt{L}$, where $L$ is the integrated luminosity.

**FIGURE 1.** ATLAS invariant mass distribution of the two isolated photons in the final state on the ttH 1-lepton category [23]. Small statistics background simulation samples are replaced by toy Monte Carlo generated distributions from exponential fits.

**Higgs boson couplings**

Most of the run-1 Higgs boson analyses performed in run-1 have been considered in the projection studies at HL-LHC. This allowed to probe all production modes

- gluon-gluon fusion (ggF)
- vector boson fusion (VBF)
- production in association with $W$ and $Z$ bosons (VH)
- coupling in the associated $t\bar{t}$ production)

and the decay modes:

- $H \to \gamma\gamma$
- $H \to ZZ^* \to 4l$
- $H \to WW^* \to lvlv$
- $H \to \tau^+\tau^-$
- $H \to bb$

as well as the rare decay modes $H \to Z\gamma$ and $H \to \mu^+\mu^-$ [12, 13, 14].

The final states $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ are particularly important for probing the top quark Yukawa coupling, thanks to the excellent mass resolution possible in these decay modes. Assuming 3000 fb$^{-1}$, a signal yield of 35 events is predicted by SM in the $H \to ZZ^* \to 4l$ channel with ATLAS. The very low background rate allows the
signal strength to be measured with an accuracy of about 20%. A better accuracy can be achieved with the channel $H \to \gamma\gamma$, see also figure 1. Similar results are found in the CMS analysis.

The search for rare Higgs boson decays is one of the strongest points of the HL-LHC physics programme. In particular, the Higgs decay mode $H \to \mu^+\mu^-$ allows direct study of the coupling to second generation leptons and tests lepton non-universality in the Higgs boson sector. Preliminary and conservative ATLAS studies have indicated that the signal strength can be measured with an accuracy of 20% (including theory uncertainty). More recent CMS studies indicate that it is possible to improve this measurement to $\sim 10\%$ [15] (neglecting theory systematic uncertainties). The precision measurement of muon leptons makes the channel $H \to \mu^+\tau^-$ a very interesting benchmark for lepton-flavour violation searches in the Higgs sector. The search for the $H \to Z\gamma$ decay mode at HL-LHC has also been examined.

If produced with Standard Model rates, this signal can be seen with a significance of about four standard deviations, still assuming a data sample of 3000 fb$^{-1}$.

The projected results from the various production and decay modes can be combined to extract the Higgs boson couplings within the so-called $\kappa$-framework; see references [1, 2] for details. The analysis can be done under different assumptions. In the most generic models, either no assumptions are made on the total width and only coupling ratios can be measured, or the assumption of no BSM Higgs boson decay modes is made, so that the natural width is fully constrained by SM decays. Detailed tables on the findings of this combination in ATLAS and in CMS are available here [12, 13, 14]. Table 1 reports a concise summary of the results in the case of the model dependent scenario.

<table>
<thead>
<tr>
<th>Coupling modifier</th>
<th>$L=300$ fb$^{-1}$</th>
<th>$L=3000$ fb$^{-1}$</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{WZ}, \kappa_Y$</td>
<td>6</td>
<td>3</td>
<td>down-quark type</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>12</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>15</td>
<td>7</td>
<td>top-quark Yukawa coup.</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>10</td>
<td>5</td>
<td>lepton coup.</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>22</td>
<td>7</td>
<td>2$^{nd}$ generation</td>
</tr>
</tbody>
</table>

The interpretation of data from SM processes in the context of the 2HDM model are reported by ATLAS in Ref. [16].

**Higgs boson pair production**

After the observation of the Higgs boson and the accurate measurement of its physics properties, the next important step would be the determination of the shape of the Higgs potential. Among the measurements which need to be performed, the analysis of the Higgs self-coupling in processes where the Higgs boson is produced in pairs is of utmost importance. A review paper on this subject is available in Ref. [17]. Furthermore, in many BSM implementations the HH production rate is much larger than the Standard Model predictions. Hence, double-Higgs production represents one of the most interesting portals to new physics.

Preliminary studies of Higgs boson pair production at HL-LHC are also available [15, 18, 19]. The SM HH production cross section at HL-LHC is predicted to be $\sim 40$ fb. So, the overall production in 3000 fb$^{-1}$ is of the order of 120,000 Higgs boson pairs. However, the rate of Higgs boson final states that can be fully reconstructed and where at least one of the two Higgs bosons decays in high-resolution channels is very low. The decay channel $HH \to \gamma\gamma$ is the only of this category possible at HL-LHC, given its yield of less than 320 events expected assuming SM production.

If detector acceptance and analysis cuts are taken into account, both ATLAS and CMS select about 9 signal events with a background contamination of about 50 events. The signal significance that can be obtained is smaller than 2 standard deviations with 3000 fb$^{-1}$ of data. Figure 2 shows the findings from the CMS simulation study. This result can be improved by combining as many other channels as possible, even if with lower individual significances. For example, CMS studies indicate that 1.9 standard deviations can be reached combining the $\gamma\gamma$ and $\tau\tau$ final states. If the findings of two experiments are also combined, a significance of about three standard deviations is at reach.
In the Standard Model the Higgs boson is the only particle responsible for avoiding unitarity violation of the $V V$ ($V=W,Z$) production cross section scattering at high energy. It is of paramount importance of confirming this process experimentally. In fact, other mechanisms are also possible in BSM models, and they would bring to anomalous rates in this scattering process induced by the presence of objects not predicted by SM.

Early studies at HL-LHC have been performed by ATLAS [20] and CMS [21]. In this context, scenarios for anomalous quartic gauge couplings (aQGC) have been also investigated. Recent studies have been made public by ATLAS [22]. It has been shown that the high integrated luminosity data sample that can be collected at HL-LHC increases the discovery potential for tensor operator’s coefficients by more than a factor two to three.

A Standard-Model-like Higgs boson has been discovered in 2012. Its mass has been measured to be $125.09 \pm 0.24$ GeV. This particle was the only missing piece in the Standard Model, that now can be considered a complete theory of particles and fields.

A data sample of 300 fb$^{-1}$ at the LHC will allow the exclusion of strong deviations of the new object properties from those predicted for the SM Higgs boson.

A complete investigation of the physics properties of this object will require the search for rare decays and rare processes, Higgs self-coupling and CP violation effects, as well as the reduction of experimental and theoretical systematic uncertainties. The HL-LHC data sample can provide the requires statistics to measure the Higgs boson couplings to elementary fermions and bosons with an overall accuracy in the range 1%-4%. Finally, the high-luminosity LHC extends the searches for beyond-SM particles, and it offers the required data to study the properties of new particles if found in the LHC data.

REFERENCES

[10] A. Canepa, These proceedings.