Di-Higgs production and Higgs boson self-coupling at the HL-LHC with the ATLAS detector.

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Summary

The physics plan for the Higgs physics studies at the high-luminosity phase of the LHC starting in 2026 is well defined in the Report produced by the ATLAS and CMS communities [1]. We present here how the ATLAS-IN2P3 team plans to organise towards the measurement of the Higgs self-coupling, one of the key goals of this program.

1. Introduction

The discovery in 2012 of a new particle, H(125), with properties compatible with those of the Higgs boson of the standard model (SM) represents a milestone for particle physics. The SM provides a complete description of all high energy experimental results. The Higgs mechanism and the resulting Higgs boson are key ingredients of this model. The discovery of this last missing piece predicted by the SM is the culmination of several decades of coordinated experimental efforts.
Despite its success, the SM may only describe the low-energy limit of a more complex fundamental physics. Among the shortcomings of the SM are the facts that it does not describe the dark matter content of the universe and that it does not include sufficient sources of CP violation to explain the matter-antimatter asymmetry of the present Universe. In addition to the failure to explain these and other experimental observations, the SM suffers from conceptual imperfections. For example, the Higgs potential is postulated in an ad hoc manner, and no plausible explanations for its origin are given.
Many of these issues are related to the couplings of the Higgs to itself, labelled λ_{HHH}, and to the other fields. For example, CP violation appears in the coupling of the Higgs field to fermions, and the coupling of the Higgs field to itself arises from the Higgs potential.
The ability to experimentally study, at the HL-LHC, the couplings of the Higgs boson to itself and to the other fields therefore gives us a new, powerful tool to make progress on today's pressing

questions in particle physics. The HL-LHC is the major project of particle physics for the next twenty years to come.

Among these studies, the measurement of the Higgs self-coupling is particularly fundamental because this is the only way to experimentally reconstruct the Higgs potential in a model-independant way. The most sensitive method to measure the self-coupling is by measuring the production rate and kinematics of the di-Higgs production. Its production cross-section is three orders of magnitude smaller than that of a single Higgs boson, making it a long-term study.

2. Expected results at HL-LHC

The prospective studies of physics with the HL-LHC data were performed as part of a complete effort between the theory community and the ATLAS and CMS collaborations. The experimental performance of object reconstruction, identification and efficiency under high-luminosity conditions was assessed, based on the Technical Design Reports of the upgrades for the HL-LHC phase which were produced in the past two years. A common exercise between the two collaborations was made to estimate the associated uncertainties.

IN2P3 teams were highly involved in the $HH \rightarrow b\bar{b}\gamma\gamma$ channel analysis, both on the performance side (photon energy resolution, b-tagging) and by introducing a new analysis method, allowing to increase the discovery potential of this channel from 1 to 2 standard deviations [2]. It was shown that, combining the most sensitive channels ($b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$), the expected significance to observe the di-Higgs process was greatly increased with respect to the previous studies in 2014, going from an expected significance of around 2 standard deviations by combining the two experiments to 4 standard deviations [1], and 3 standard deviations for the ATLAS experiment alone [2]. The hypothesis of a vanishing self-coupling could be rejected at 95% CL, and the trilinear coupling itself could be measured with a precision of 50%, as illustrated in Figure 1. This whole exercise illustrates perfectly that this measurement will be possible only by a continuous understanding and improvement of the detector performance, and by using new ideas for the analysis.

It should be noted that this measurement will remain the most precise until indirect constraints with the high-energy phase of the next generation of electron-positron Future Colliders around 2050, or direct constraints with the hadronic phase of the FCC [3].

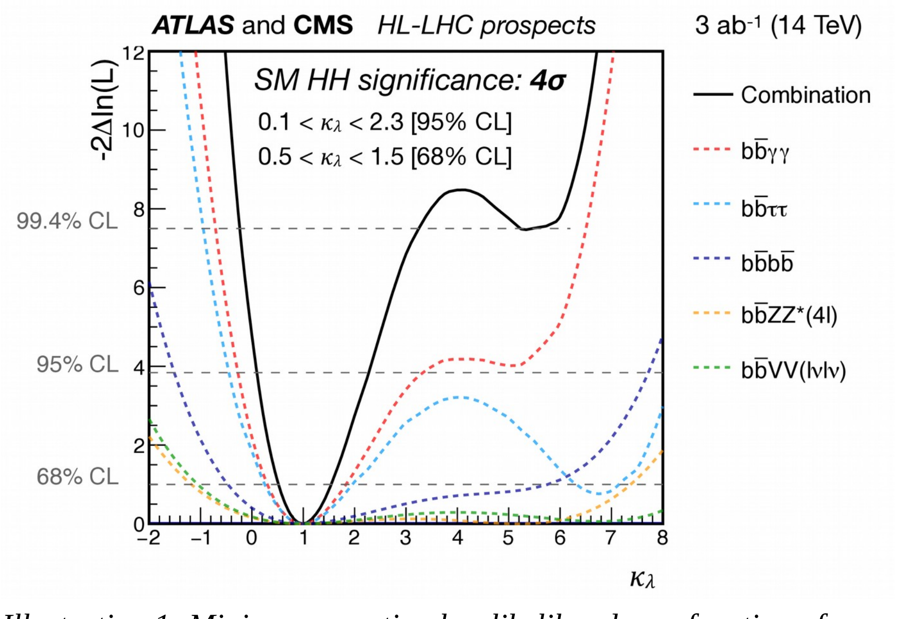

Illustration 1: Minimum negative-log-likelihood as a function of $\kappa_\lambda=\lambda_{HHH}/\lambda_{HHH}^{SM}$, calculated by performing a conditional signal+background fit to the background and SM signal. [1]

3. Global roadmap for Run 3 and HL-LHC

The current 95% CL expected limit on the di-Higgs production cross-section is 10 times the predicted SM cross-section, using a quarter of the integrated luminosity collected by the ATLAS experiment during the Run 2 of the LHC (2015-2018) [4]. The dataset is expected to double during Run 3 (2021-2023) to reach a total of 300 fb^{-1} of collected data, with a similar to slightly higher pile-up.
We have already been highly involved in the $HH \rightarrow b\bar{b}\gamma\gamma$ analysis channel [5], one of the three channels with highest sensitivity, with two members being responsible for the Run-2 analysis [6]. We have also started to participate to the multilepton channel, using techniques developed for the $t\bar{t}H$ analysis with similar final state.

Such involvement is expected to continue during Run 3 for the $HH \rightarrow b\bar{b}\gamma\gamma$ analysis. Several improvements of the selections are foreseen, in particular the use of Deep Neural Networks or of the Matrix Element Method. In order to use those refined techniques a good understanding of the background processes is necessary. That is why we plan to measure the diphoton + two (b-)jets SM process, to better understand the flavour composition in data and the description of the kinematic variables by the current NLO generators. The single-Higgs process is also an important background to the analysis. We plan to measure the $Z(\rightarrow \bar{b}b)H(\rightarrow \gamma\gamma)$ and ggF+2 b-jets processes, which could be detected with a 2 standard deviation significance with the dataset collected during Run 3.

We will also start to be involved in the $HH \rightarrow b\bar{b}\tau\tau$ channel during Run 3, which is also one of the channels with the highest sensitivity. Several analysis improvements are already foreseen, in particular in the background assessment with data driven techniques and the use of Deep Neural Networks for the signal extraction.

In general the $Z(\rightarrow \bar{b}b)H(\rightarrow \gamma\gamma$ or $\rightarrow \tau\tau)$ measurement is a benchmark to test the analysis strategy, as was done for the $VH(\rightarrow \bar{b}b)$ analysis in Run 1 and Run 2, and initial studies have started already. An evidence of this process could be reached by the end of Run 3.
The combined analysis with the single Higgs boson processes will also be exploited, in the context of Effective Field Theory, in order to constraint the Higgs couplings parameters using both the di-Higgs and single-Higgs measurements [5]. Those indirect constraints on λ_{HHH} through the single-Higgs couplings will limited on the long term since they are more affected by systematic uncertainties, but will still be competitive until the end of Run 3.

We also plan to work on the detector and object performance to achieve the goals of the Technical Design Reports for HL-LHC. The ATLAS-IN2P3 teams already have a recognised expertise in the energy resolution and identification of photons, and in b-jet tagging, linked to the construction and knowledge of the electromagnetic calorimeter and pixel inner detector. This expertise will be extended thanks to the extensive participation to the upgrades for the HL-LHC phase, in particular in the design and construction of the future Inner Tracker. New tracking strategies will be developed, for example for the photon conversion reconstruction, the b-tagging algorithms or the track-vertex association for τ leptons. The di-Higgs production being a rare process, it will be important to achieve high-efficiency selections. This work has already started with several members having responsibilities in the preparation of the HL-LHC phase and will continue until the beginning of the HL-LHC phase in 2026 and during the commissionning of the upgraded detectors.

4. Deliverable and personpower

A continuous and significant effort is necessary on the analysis side to achieve or surpass the expected results for the di-Higgs production and self-coupling measurements.

The Run 3 period will be a good opportunity to involve students in SM measurements of the main background processes, and to start new methods for the differents analyses. The systematic uncertainties will still have a limited impact at that time. It will also be necessary to maintain our skills in photon and b-tagging performance, in measurements and improvement of the selections. It should be noted that the building of the HL-LHC upgraded detectors will also happen during that time.

A large involvement will be needed on the commissioning of the detector starting from the Long Shutdown 3 of the LHC in 2024, including tracking performance to be used for the reconstruction of photon conversions, b-tagging and τ-tagging.

Run-3 (2021-2023)	LS 3 (2024-2025)	HL-LHC (2026-2037)	
HH → $b\bar{b}\gamma\gamma$ analysis			
HH → $b\bar{b}\tau\tau$ analysis			
SM background measurements			
Z(→bb)H(→γγ or →ττ) measurement			
egamma: preparation		egamma: commissioning	egamma: performance
b-tagging: preparation		b-tagging: commissioning	b-tagging: performance
τ-tagging: preparation		τ-tagging: commissioning	τ-tagging: performance

5. References

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[4] *Combination of searches for Higgs boson pairs in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, The ATLAS Collaboration, arXiv:1906.02025

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