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Accessing HH at ATLAS and CMS with the HL-LHC

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Directly measuring the Higgs self-coupling through Higgs pair production is an active area of interest for the LHC experiments, with a current limit around 10 times the Standard Model cross section per experiment. These results, exploting early Run 2 LHC data, show that a much larger dataset will be needed for discovering the Standard Model HH production process. A summary of the prospects of the sensitivity of these analyses utilizing the High-Luminosity LHC dataset is presented. Different strategies for obtaining these results are discussed, along with the most important challenges these analyses will face in the future. A combination of the ATLAS and CMS prospected sensitivities is also presented.

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1. Introduction

The LHC Higgs boson physics program has provided important insights into the Electroweak Symmetry Breaking (EWSB) sector of the Standard Model (SM). With the Higgs discovery, precision measurements on diboson channels (ZZ, WW and $\gamma\gamma$), and with the observation of the Higgs couplings to 3rd generation fermions ($t\bar{t}$, $\tau\tau$, $b\bar{b}$), the Higgs potential - and in particular, the Higgs self-coupling (λ_{HHH}) - remains one important part of the SM still inaccessible through direct probes. Deviations of the SM that can affect the shape of the Higgs potential are capable of adding significant deviations to the self-coupling modifier $\kappa_\lambda = \lambda/\lambda_{HHH}$. Directly measuring the Higgs self-coupling is of particular significance for a clear picture of the physical mechanisms behind EWSB in the SM and beyond. Such modifications are ubiquitous of beyond the SM (BSM) scenarios, and variations on the value of λ_{HHH} can have strong cosmological implications, including on the stability of the electroweak vacuum [1] and inflation [2].

One important aspect of *directly* measuring κ_λ is that it is only accessible in collider experiments through the production of pairs of Higgs boson (HH). This fact has inspired multiple searches for HH production at the LHC in several final states, depending on the decay of each Higgs boson. Direct searches for the SM HH production, however, is also a difficult task since its production cross section is small ($\sigma^{\text{FTApprox}}_{\text{NNLO}}(\kappa_\lambda = 1) = 31.05$ fb [3]) - partially due to the destructive interference between the HH production through the self-coupling diagram and the HH production through a top quark loop box diagram.

Analyses containing Higgs decays to $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ have presented the highest sensitivity to the SM HH production. They achieve high sensitivities balancing high expected signal events (with the high branching ratio of $H \to b\bar{b}$) and low background yields (by selecting *clean probes* such as photons, taus and jets containing b-hadrons). The combination of these analyses[1] with the initial Run 2 LHC data ($27 - 36$ fb^{-1}) corresponds to an observed (expected) 95% confidence level limit of 6.9 (10) times the SM cross section for ATLAS [4], and 22 (13) times the SM cross section for CMS [5].

Deviations on the κ_λ modifier also affect the kinematics of the HH system, due to the change in relative contribution of the HH production through self-coupling diagram in the interference with the top-induced diagram, which means constraints on varied κ_λ values can also be set. The ATLAS experiment observes (expects) a constraint of 95% C.L. between $-5.0\,(-5.8) < \kappa_\lambda < 12.0\,(12.0)$ [4], while for CMS, the observed (expected) constraints are of $-11.8\,(-7.1) < \kappa_\lambda < 18.8\,(13.6)$ [5]. These results indicate that the ATLAS and CMS analyses cannot be sensitive to the Higgs self-coupling with the full LHC dataset (expected to be around 350 fb^{-1}). Therefore, both experiments have investigated the capabilities of the High-Luminosity LHC (HL-LHC) project to discover this important process. In the following sections, a summary of these prospect studies will be presented.

2. HH at the HL-LHC

The HL-LHC project expects to deliver a total integrated luninosity of between 3000 fb^{-1} and 4000 fb^{-1} from mid 2027 until 2040, with a center-of-mass energy of $\sqrt{s} = 14$ TeV. This

[1]For both ATLAS and CMS, other final states contribute to this combination, such as $b\bar{b}VV^* \to b\bar{b}\ell\nu\ell\nu$ for both ATLAS and CMS, and $b\bar{b}VV^* \to b\bar{b}\ell\nu qq$, $WW^*\gamma\gamma$ and WW^*WW^* for ATLAS.

represents a two-order of magnitude increase in the dataset used for the current best constraints on the Higgs self-coupling, and a 20% increase in the SM HH production cross section. This integrated luminosity will be achieved by increasing the instantaneous luminosity currently achieved by the LHC, which represents an experimental challenge as well. Both ATLAS and CMS will undergo large-scale upgrades in order to cope with this change in environment, and in particular with the higher number of average interactions per bunch crossing (pile-up).

One key assumption of some the prospect studies that will follow is that these LHC experiments upgrades will ensure that the object reconstruction performance is not degraded with respect to Run 2. These types of studies extrapolate their current limits to the HL-LHC dataset, assuming similar detector performance, with statistical improvements for statistically-limited data-driven background estimates, for example. Other analyses, however, choose to utlize parametrized detector response and object performances which have been tuned to the expected upgraded detector simulations (including improved detector acceptances in certain cases). This strategy benefits from dedicated optimizations based on the larger dataset, many times including advanced Machine Learning-based techniques for background mitigation. A brief description of the ATLAS [6] and CMS [7] HL-LHC prospect studies in the three main channels follows below.

The $HH \to b\bar{b}b\bar{b}$ prospects analysis in ATLAS has been performed by extrapolating the early Run 2 result (27 fb^{-1}). Its main background process, multijets, is estimated directly from data with a significant systematic uncertainty that becomes a limiting factor for larger datasets. For the extrapolation procedure, the same background uncertainty is assumed pessimistically. However, results are additionally presented as a function of this uncertainty, showing that large improvements can be achieved with a more precise background estimate. The CMS $HH \to b\bar{b}b\bar{b}$ HL-LHC prospects utilizes a parametrized detector description (DELPHES) for signal and background simulation. The analysis is performed in two topologies: the *resolved* regime, in which the four jets from the HH system can be individually reconstructed as an anti-k_T R = 0.4 jet; and the *boosted* regime, in which each Higgs candidate di-jet system is reconstructed as a single large-R jet. The usage of dedicated simulation the oppotunity for a boosted decision tree (BDT) to be trained as the main discriminating variable for the resolved channel. The boosted channel is shown to be particularly useful when setting limits on BSM couplings other than κ_λ (such as large top Yukawa coupling scenarios).

Similarly to the $b\bar{b}b\bar{b}$, the $HH \to b\bar{b}\tau\tau$ prospect analyses have been performed by extrapolating early Run 2 results for ATLAS and with parametrized detector descriptions for CMS. The ATLAS analysis benefits from largely reducing statistical uncertainties on their data-driven background normalization estimates. However, this analysis is particularly affected by the available Monte Carlo simulation statistical precision - while the nominal results do not consider this uncertainty (assuming larger simulated datasets will be available in the future), a detailed study presenting its impact are performed. The CMS prospects are based on a dedicated DELPHES-based analysis, employing a neural network to discriminate signal and background in different categories based on the taus final states.

Both ATLAS and CMS $HH \to b\bar{b}\gamma\gamma$ prospect analyses use parametrized detector responses for their studies, employing ML-based algorithms for signal to background discrimination. One specificity of this final state is the importance of decreasing SM single Higgs yields in their signal regions, which will become a large and an almost-irreducible background process (for $t\bar{t}H$

production, for example). The ATLAS analysis uses a BDT to discriminate between signal, and a mix of $\gamma\gamma$+jets and SM single Higgs background, and then performs a cut-and-count analysis in the $m_{b\bar{b}\gamma\gamma}$ distribution while requiring a mass window around the Higgs peak the di-photon invariant mass distribution. The CMS analysis, on the other hand, utilizes one dedicated BDT to mitigate the SM $t\bar{t}H$ background, and another BDT trained against the $\gamma\gamma$+jets to define high signal purity categories. An extra categorization is performed on the $m_{b\bar{b}\gamma\gamma}$ distribution, in order to maximize sensitivity to κ_λ variations, and the signal extraction is performed with a parametric fit to the simulation.

A summary of the prospects results from the analyses discussed above are presented in table 1, including a combination of the ATLAs and CMS results, performed in the context of [8]. In addition to the final states discussed, CMS also provides sensitivity studies for $b\bar{b}VV^*$ and $b\bar{b}ZZ^*\,(4\ell)$ final states. Sensitivity prospects to the measurement of κ_λ have also been provided, with a combined ATLAS plus CMS expected constraint of $0.1 \leq \kappa_\lambda \leq 2.3$ at 95% C.L., to which the $m_{b\bar{b}\gamma\gamma}$ contributes the most, for both experiments, due to its sensitivity to events located at $m_{HH} < 400$ GeV (more populated for larger values of $|\kappa_\lambda|$).

	Statistical only		Statistical + Systematic	
Significances on SM HH signal	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV^*$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ^*\,(4\ell)$	-	0.37	-	0.37
Combination	3.5	2.8	3.0	2.6
	4.5		4.0	

Table 1: Summary of HL-LHC sensitivity prospects to SM HH production, assuming $\sqrt{s} = 14$ TeV and an integrated luminosity of 3000 fb^{-1}. The ATLAS plus CMS combinations were performed in the context of [8].

3. Conclusions

The prospects for the sensitivity of the ATLAS and CMS experiments to the SM HH production have been presented. These searches represent the only direct experimental probe of the Higgs self-coupling, even though precision Higgs measurements can be used to constrain κ_λ under specific theoretical assumptions. The current expected sensitivity of a combined ATLAS and CMS result is on the threshold of a discovery. While improvements on the analyses methods can be expected in the next decades, one important constraint on these results is ensuring a good experimental performance under the HL-LHC. In particular, both $HH \to b\bar{b}b\bar{b}$ and $HH \to b\bar{b}\tau\tau$ final states are heavily affected by multijet and di-tau trigger thresholds, which are expected to be increased to cope with the higher pile-up. Therefore, special attention from ATLAS and CMS must be given to their trigger and data acquisition systems to guarantee that these important events are saved and analyzed.

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