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Prospects for Single- and Di-Higgs Measurements at the HL-LHC with ATLAS

Tulin Mete[a,*]**, on behalf of the ATLAS Collaboration**

[a] *Academia Sinica, Institute of Physics,*
No.128, Section 2, Academia Rd, Nangang District, Taipei City, Taiwan

E-mail: Tulin.Varol@cern.ch

The large dataset of about 3 ab^{-1} that will be collected at the High Luminosity LHC (HL-LHC) will be used to measure Higgs boson processes in detail. Studies based on current analyses have been carried out to understand the expected precision and limitations of these measurements. The large dataset will also allow for better sensitivity to di-Higgs processes and the Higgs boson self coupling. This proceeding presents the prospects for Higgs and di-Higgs results with the ATLAS detector at the HL-LHC.

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*Speaker

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1. Introduction

The High-Luminosity LHC (HL-LHC), which is expected to be operational from the beginning of 2029, aims to provide 20 times the dataset delivered so far, ultimately delivering 3000 fb^{-1} of integrated luminosity at $\sqrt{s}$ = 14 TeV. However, that would also lead to a more challenging data taking environment, with up to 200 additional interactions per bunch crossing, and up to an order of magnitude larger radiation dose. In order to cope with these challenges, the ATLAS detector [1] will have a set of upgrades, including the installation of all-silicon inner tracker (ITk) with coverage up to $|\eta|$ = 4, High Granularity Timing Detector (HGTD) in the forward region, new muon chambers in the inner barrel region, as well as some replacements for calorimeter front-end systems. An upgrade is also planned for TDAQ off-detector electronics, in order to have an output rate of 1 MHz from L0 hardware trigger, and an output rate of 10 kHz from the Event Filter.

The ATLAS Collaboration is continuously developing its physics program for the HL-LHC. The prospect studies of the HL-LHC performance carried out by the ATLAS Collaboration are highlighted in the CERN Yellow Report from European Strategy for Particle Physics (2019) [2], and feature in the Snowmass White Paper (2022) [3]. One of the major components of this program would be more detailed studies of Higgs boson properties. This proceeding highlights the projections of single- and di-Higgs measurements at the HL-LHC with the ATLAS detector, by discussing the expected sensitivities for these measurements.

2. ATLAS HL-LHC Projection Strategies

For the extrapolations, a HL-LHC scenario corresponding to a dataset of 3000 fb^{-1} of pp collisions at $\sqrt{s}$ = 14 TeV, is considered. A baseline scenario for estimating systematic uncertainties of the extrapolation from Run 2 measurements (often referred to as "YR18 systematics uncertainties" scenario) is devised. In this scenario, most of the experimental uncertainties are scaled down with the square root of the integrated luminosity. Statistical uncertainties in measurements are reduced by a factor of $1/\sqrt{\mathrm{L}}$, where L is the projection integrated luminosity divided by that of the reference Run 2 analysis. Uncertainties related to the limited number of simulated events are neglected assuming sufficiently large simulation samples will be available at that time. Assuming there will be improvements to theoretical predictions, theoretical uncertainties are halved with respect to current values. The uncertainty in the integrated luminosity of the data sample is taken as 1%, which is expected as a result of a better understanding of the calibration methods, and making use of the new capabilities of the upgraded detectors. Uncertainties on analysis methods are left unchanged, assuming that harsher HL-LHC conditions will be compensated by improvements of analysis methods.

3. Prospects for Single- and Di-Higgs Measurements at the HL-LHC

3.1 Prospects for Measurement of the CP Nature and Spin of the Higgs Boson

The Standard Model (SM) predicts the Higgs boson to be scalar with no CP-violating interactions. The existence of a CP-odd contribution in the Higgs boson couplings would be a hint for physics beyond the SM. The extrapolation of these measurements for the HL-LHC scenario

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[2, 4] are based on the measurement of the $H\tau\tau$ coupling with 36.1 fb^{-1} of $\sqrt{s}$ = 13 TeV data. Contributions from CP-violating interactions between the Higgs boson and τ leptons are described by a single mixing angle parameter ϕ_τ ($\phi_\tau = 0$ for pure scalar coupling, $\phi_\tau = \pi/2$ for pure pseudoscalar coupling). The mixing parameter can be probed experimentally in the $H \rightarrow \tau\tau$ decays via the correlations of the τ leptons' spins. The τ decays via $\tau^\pm \rightarrow \rho^\pm \nu_\tau \rightarrow \pi^\pm \pi^0 \nu_\tau$ are analysed in this study, since these decays allow for the construction of an observable that is sensitive to the CP-violating phase.

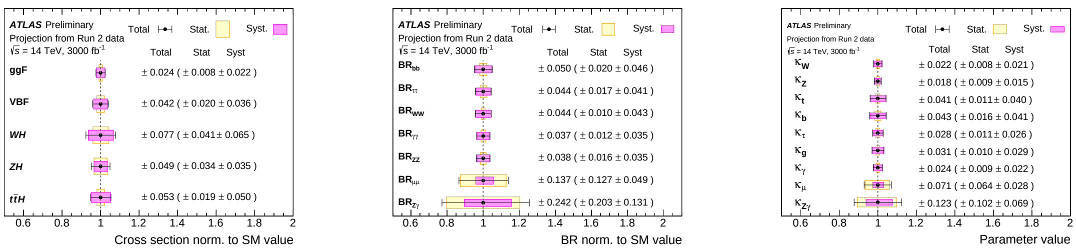
In this analysis, scenarios with different π resolutions are considered, since the precision of the π^0 reconstruction is expected to have a strong effect in the analysis. The uncertainties include only the statistical uncertainties of the expected data sample. This study shows that pseudo-scalar hypothesis is excluded at 95% confidence level (CL) even with 1.5 times the nominal π^0 resolution, and the CP-violating phase could be measured at 68% CL within a statistical precision of approximately $\pm$18 and $\pm$33 degrees assuming the nominal or twice as large the π^0 resolution.

3.2 Prospects for Measurements of Higgs Boson Cross-Section and Coupling Modifiers

The projection studies performed for measurements of Higgs boson cross-sections [2, 5] are extrapolated from the Run 2 analysis results, where the analyses with final states in $WW, Z\gamma, t\bar{t}H, \tau\tau$ are conducted using 36 fb^{-1} of data, and the studies in remaining channels $\gamma\gamma, ZZ, VH$ with $H \rightarrow b\bar{b}$ and $\mu\mu$ are performed using 80 fb^{-1} of data at $\sqrt{s}$ = 13 TeV. All extrapolated single-channel results are combined to compute cross-sections per production mode and branching ratios (BR).

The production modes studied in the analysis are gluon-gluon fusion (ggF), vector-boson fusion (VBF), Higgs boson production in association with a vector boson (VH), and Higgs boson production in association with a top-antitop quark pair ($t\bar{t}H$) or a single top quark (tH).

The expected uncertainties on the production cross-sections and branching ratios, for the HL-LHC, are shown in Figure 1a and Figure 1b. These results are calculated assuming YR18 systematic uncertainties scenario. For this scenario, all production mode cross-section measurements are limited by systematic uncertainties.



(a) (b) (c)

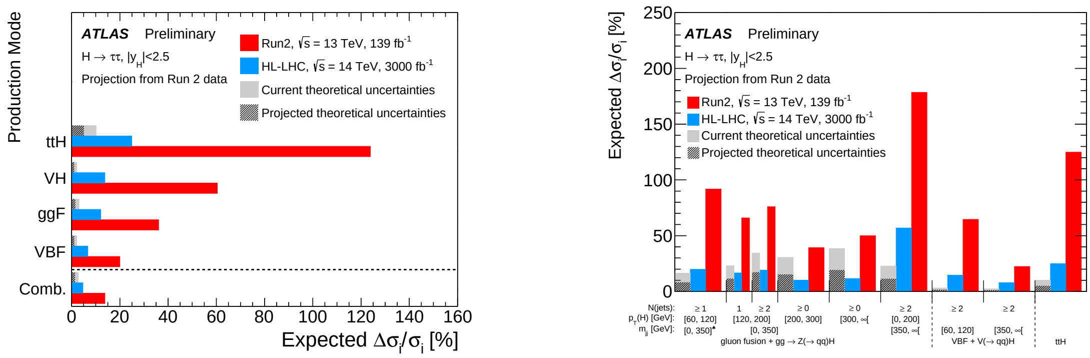
Figure 1: (a) Expected result for the measured cross-sections for each production mode, normalised to their SM predictions assuming SM branching ratios, with YR18 systematic scenario. (b) Expected result for the measured branching ratios for each decay channel, normalised to their SM predicted production cross-section, with YR18 systematic scenario. (c) Expected result for the measurement of each Higgs boson coupling modifier per particle type with effective photon, gluon and $Z\gamma$ couplings, with YR18 systematic scenario and without BSM contribution to the Higgs boson total width. The black bars, yellow boxes and pink boxes show the total, statistical and systematic uncertainties, respectively. For more details see [5].

These results are also interpreted for Higgs boson coupling modifiers κ, which are multiplicative factors applied to the Higgs boson couplings to the SM particles, shown by $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau$ and κ_μ. Couplings κ_g for the ggF vertex, κ_γ for the $H\gamma\gamma$ vertex and $\kappa_{Z\gamma}$ for the $HZ\gamma$ vertex are expressed either in terms of more fundamental factors, as mentioned earlier, or kept as effective modifiers. Results with the total, statistical, and systematic uncertainties are shown in Figure 1c. No BSM contribution to the Higgs boson total width is considered for results shown here.

3.3 Prospects for the Inclusive $H \to \tau\tau$ Cross-Section

The extrapolation to assess the expected sensitivity of $H \to \tau^+\tau^-$ cross-section measurements [3, 6] is performed using the results obtained with 139 fb^{-1} of data at $\sqrt{s}$ = 13 TeV. Results are provided for the inclusive $H \to \tau^+\tau^-$ cross-section, as well as four main Higgs boson production cross-sections (ggF, VBF, VH and $t\bar{t}H$). Their kinematic dependence is also studied and presented within the Simplified Template Cross-Section (STXS) framework. The obtained results indicate that a precision of 5% for the $H \to \tau^+\tau^-$ cross-section measurement could be achieved at the HL-LHC. The projected precisions of the measurements of ggF, VBF, VH and $t\bar{t}H$ productions are 11%, 7%, 14%, 24%, respectively. The dominant uncertainties expected at the HL-LHC for each production mode measurement are shown in Figure 2a along with their Run 2 counterparts.

Projected measurements in the STXS framework are shown in Figure 2b. The most sensitive measurements for the Higgs boson production, in a given momentum range possible at the HL-LHC, are expected to be obtained for the ggF + $gg \to Z(\to qq)H$ cross-section in events with Higgs boson transverse momentum between 200-300 GeV (above 300 GeV), with an uncertainty of 10% (11%).



(a) (b)

Figure 2: (a) Expected precisions of the ggF, VBF, VH and $t\bar{t}H$ production measurements via the $H \to \tau^+\tau^-$ decay mode for the HL-LHC and Run 2. (b) Expected precision of the various STXS $H \to \tau^+\tau^-$ measurements for the projected HL-LHC and Run 2. For more details see [6].

3.4 Prospects for Sensitivity to $H \to b\bar{b}$ and $H \to c\bar{c}$ Decays in VH Production

The expected sensitivity of the measurements of Higgs boson decays into $b\bar{b}$ and $c\bar{c}$ at the HL-LHC [3, 7] is estimated by extrapolating the results obtained using 139 fb^{-1} of data at $\sqrt{s}$ = 13 TeV. The associated production of a Higgs boson with either a W or a Z boson, where the

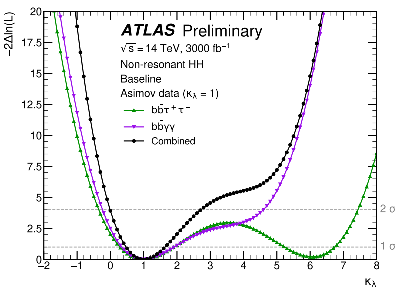
Higgs boson decays into $b-$ or $c-$ quarks and the W or Z boson decays leptonically, are studied. Two analyses are combined by performing a fit to the $VH, H \to b\bar{b}$ and $VH, H \to c\bar{c}$ regions simultaneously and allowing both signal strengths to float. Uncertainties between the two analyses are mostly treated as uncorrelated. The expected best fit signal strengths at the HL-LHC are obtained as $\mu_{VH}^{b\bar{b}} = 1.00 \pm 0.06$ and $\mu_{VH}^{c\bar{c}} = 1.00 \pm 3.20$. A fit is also performed to κ modifiers, which results in an expected constraint of $|\kappa_c/\kappa_b| < 2.7$ at 95% CL.

3.5 Prospects for Sensitivity of Higgs Boson Pair Production

One of the major goals of the HL-LHC is to measure the Higgs boson self-coupling (λ_{HHH}), which is accessible at tree level in HH production and at loop level in single-H production. The dominant HH production mode at the LHC is the ggF ($\sigma_{ggF}^{HH} = 36.69$ fb at $\sqrt{s} = 14$ TeV at NNLO), and it is then followed by the VBF production mode ($\sigma_{VBF}^{HH} = 2.055$ fb at $\sqrt{s} = 14$ TeV at N3LO QCD). The latest prospects for Higgs boson pair production studies at ATLAS at the HL-LHC [3, 8] are assessed through extrapolation of the measurements using 139 fb^{-1} of $\sqrt{s} = 13$ TeV data, from the combination of separate analysis in $b\bar{b}\tau^+\tau^-$ [9] and $b\bar{b}\gamma\gamma$ [10] final states. The projected significance and the precision on the measured signal strength in the SM hypothesis are shown in Figure 3a for four different uncertainty scenarios. These measurements show that the Higgs self-coupling could be measured with an expected significance of 3.2σ considering the baseline scenario. This demonstrates an improvement compared to the previous projections [11, 12], where the corresponding significance was calculated as 2.9σ, despite the fact that previous projections also included $b\bar{b}b\bar{b}$ channel in the combination. This is due to the fact that the updated results contain substantial improvements such as the analysis methods, τ reconstruction identification and b-tagging methods. Effects of κ_λ on VBF processes were also introduced in the updated results. Likelihood scans of the single and combined searches in the baseline systematic scenario are shown in Figure 3b. After the combination, the 1σ confidence intervals (CI) on κ_λ are [0.5, 1.6] in the baseline scenario and [0.6, 1.5] without systematic uncertainties. These results also show an improvement compared to the previous projections, from which a 1σ CI for κ_λ is expected to be [0.25, 1.9] ([0.4, 1.7]) with (without) systematic uncertainties. Latest results could further be improved with the future addition of the $b\bar{b}b\bar{b}$ channel to the combination.

Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	4.6	$-23/+23$
Baseline	2.2	2.8	3.2	$-31/+34$
Theoretical unc. halved	1.1	1.7	2.0	$-49/+51$
Run 2 syst. unc.	1.1	1.5	1.7	$-57/+68$

(a)



(b)

Figure 3: (a) The projected significance and the precision on the measured signal strength in the SM hypothesis shown for four uncertainty scenarios. (b) Likelihood distributions as a function of κ_λ for the $HH \to b\bar{b}\tau^+\tau^-$, $HH \to b\bar{b}\gamma\gamma$ and their combination. For more details see [8]

4. Summary

The HL-LHC will provide a great opportunity to study the Higgs boson properties in more detail. The ATLAS Collaboration have carried out projection studies to estimate the expected precision and limitations on the measurements of these properties. Results already indicate that the Higgs self-coupling can be measured with an expected significance of 3.2σ in the baseline scenario.

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