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

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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 talk will present the prospects for Higgs and di-Higgs results with the ATLAS detector at the HL-LHC.

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1. Introduction

After the Higgs boson discovery in 2012, a vast program was launched by the ATLAS experiment [1] to measure the Higgs boson properties using the data samples collected during the Run1 and Run2 data taking. However larger data sample is needed for precision measurements to check the compatibility with the Standard Model (SM) predictions, and to detect any hint of new physics. The High-Luminosity LHC (HL-LHC) is expected to start colliding proton-on-proton beams at $\sqrt{s} = 13.6 - 14$ TeV in 2029. The peak instantaneous luminosity will be at $L \sim 5 - 7 \times 10^{34}$ cm^{-2}s^{-1}, and the average number of interactions per bunch crossing (pileup) is expected to be between 140 to 200. The machine will deliver about 3000 fb^{-1} of integrated luminosity for the HL-LHC program. The high instantaneous luminosity and high pileup will pose challenging conditions to ATLAS and thus require improvements in many areas of the experiment. The improvements include new muon chambers in the barrel region, an entire new all-silicon inner tracking detector (ITK) with coverage up to $|\eta| = 4$, a precision timing detector (High Graularity Timing Detector (HGTD)) at both end cap regions, upgrades of the calorimeter and muon detector readout electronics, and upgrade of the trigger and data acquisition system to handle the high trigger rates.

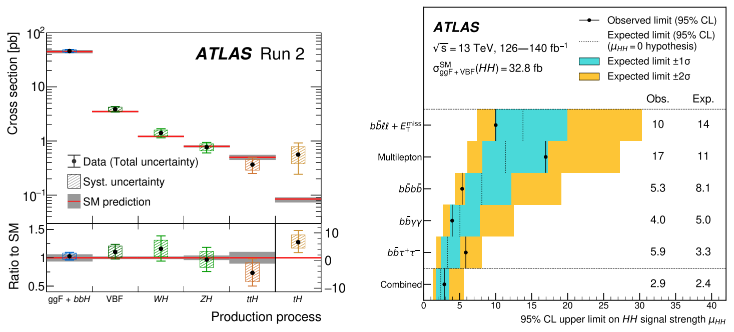
2. ATLAS current stand on Single- and Di-Higgs Measurements

With Run1 and Run2 data, ATLAS has observed the main single-Higgs boson production channels (gluon fusion (ggF), vector-boson fusion (VBF), W and Z associated production (VH), and top pair associated production (ttH)), as shown in Figure 1(a), and observed couplings to gauge bosons ($\gamma\gamma$, WW, ZZ) and third generation fermions (τ,b,t) [2]. The productions, decays and coupling measurements are at the level of O(10%) precision for the best channels. For the couplings to the second generation fermions, the $H \to \mu^+\mu^-$ is measured at 2 σ significance [2], and the 95% confidence level (CL) upper limit on the observed (expected) cross section for $VH(\to c\bar{c})$ is 11.3 (10.4) times the SM prediction [3]. Several differential cross sections of the Higgs boson kinematic features have also been probed. The Higgs boson transverse momentum ($p_{\mathrm{T}}(H)$) is measured at precision of $\sim 20 - 30\%$ for $p_{\mathrm{T}}(H) < 300$ GeV, and at $\sim 60\%$ for $300 < p_{\mathrm{T}}(H) < 650$ GeV [4].

The di-Higgs boson (HH) production is searched by ATLAS in several decays channels using the Run2 data, Figure 1(b) shows the 95% CL upper limits on the HH signal strength (μ_{HH}) for individual decay channel. The combined observed (expected) upper limit on μ_{HH} is 2.9 (2.4) in the absence of the HH signal. The expected upper limit is 3.4 in the SM case ($\mu_{HH} = 1$) [5]. The Higgs self-coupling modifier ($\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$) is constrained at 95% in the interval of $-1.2 < \kappa_\lambda < 7.2$ ($-1.6 < \kappa_\lambda < 7.2$) observed (expected).

3. ATLAS Projections to HL-LHC

The projections on the performance of the single-Higgs and di-Higgs measurements at the HL-LHC are carried out by conducting detailed simulations to access the performance of the upgraded detector and the HL-LHC conditions, and either extrapolating the existing results or using parametric simulations to perform full re-optimization of the analyses. The projections assume a center-of-mass energy $\sqrt{s} = 14$ TeV and a total integrated luminosity of 3000 fb^{-1}. Several systematic uncertainty scenarios are considered [6]. The most conservative scenario, "Run2" (or



(a) (b)

Figure 1: (a) Observed and predicted single-Higgs boson production cross-sections [2]. (b) Observed and expected 95% CL upper limits on the signal strength for inclusive ggF and VBF HH production in several decay channels, and their statistical combination [5].

"S1"), uses the Run2 uncertainties and assume the higher pileup effects will be compensated by the detector upgrades. The "Theoretical uncertainties halved" scenario uses the Run2 uncertainties, but reduce the theory uncertainties by half. The "Baseline" (or "S2") scenario, assumes theory uncertainties to be half of Run2, no simulation statistical uncertainties, statistical uncertainties scaled by $1/\sqrt{L}$ (L is the integrated luminosity), luminosity uncertainty at 1%, and the uncertainties due to detector limitations remain unchanged or are revised according to the simulation studies of the upgraded detector. The "No systematic uncertainties" only considers statistical uncertainty.

4. Prospects for Single-Higgs Measurements

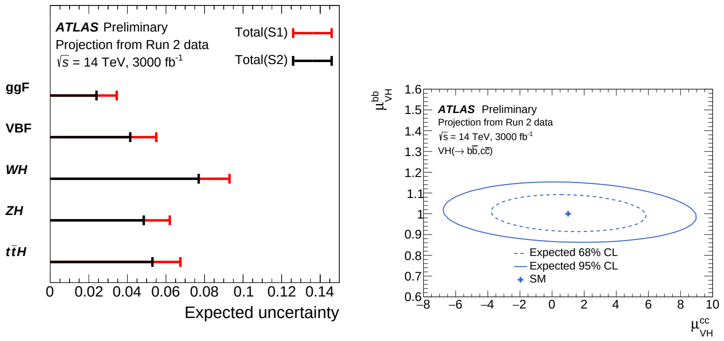
The projections for the single-Higgs boson proudction and couplings measurements at the HL-LHC are obtained from the extrapolation of the combined Run2 results from several production and decay measurements [7]. The Run2 analyses with final states in WW, $Z\gamma$, $t\bar{t}H$ and $\tau\tau$ were conducted using 36 fb^{-1} of data, and the analyses with $\gamma\gamma$, ZZ, VH ($H \to b\bar{b}$) final states were performed on 80 fb^{-1} of data. The precision of the projected measurement of the production cross sections, as shown in Figure 2(a), are less than 10%, with $\sim 2-3$% for ggF production, and $\sim 8-9$%, for WH associated production. Most coupling modifiers, κ, are expected to have uncertainties at a few percent level. The projected uncertainties of κ_μ and $\kappa_{Z\gamma}$ are at the level of $\sim$ 10%, as the measurements will be dominated by statistical uncertainties.

Several differential cross section measurements are extrapolated to the HL-LHC luminosity [8]. The extrapolations are based on Run2 $H \to \gamma\gamma$ (with 36 fb^{-1} of data) and $H \to ZZ \to 4l$ (using 80 fb^{-1} of data) measurements. The Higgs boson transverse momentum is expected to be probed with precision of $\sim$ 5% at $p_T(H) < 350$ GeV, and $\sim$ 10% at $350 < p_T(H) < 1000$ GeV.

The Higgs boson mass is a significant physical quantity as all the properties of the Higgs boson can be defined once its mass is known. The most recent measurement of the Higgs boson mass from ATLAS is $m_H = 125.11 \pm 0.11$ GeV [9]. The projected Higgs boson mass measurement at HL-LHC, based on the extrapolation of ATLAS Run2 $H \to ZZ \to 4\mu$ results, using 36 fb^{-1} of data, will have a total uncertainty that varies from 52 MeV to 33 MeV, depending on the considered uncertainty scenarios [7].

The HL-LHC prospect for the measurement of VH ($V = W, Z$) production in the $H \to b\bar{b}$ and $H \to c\bar{c}$ decay modes [10] is obtained from the extrapolation of a Run2 analysis performed on 139 fb^{-1} data sample. The analyses on these two decay modes are combined by performing a fit to their signal and control regions simultaneously and allowing both signal strengths to float. The uncertainties between the two analyses are mostly treated as uncorrelated. The expected best fit signal strength for VH production with $H \to b\bar{b}$ ($H \to c\bar{c}$) is $\mu^{bb}_{VH} = 1.00 \pm 0.06$ ($\mu^{cc}_{VH} = 1.00 \pm 3.20$). The likelihood scan results are shown in Figure 2(b). The expected constraint on the ratio of the modifier κ_c to κ_b, obtained from the fit, is $|\kappa_c/\kappa_b| < 2.7$ at 95% CL.

Lepton flavour violation (LFV) in Higgs boson decay is predicted in several beyond the Standard Model (BSM) models. Using the full Run2 data of 139 fb^{-1}, ATLAS performed a direct search for LFV Higgs decay and set 95% CL upper limit on the branching ratios for $B(H \to e\tau) = 0.2\%$ (0.12% expected) and $B(H \to \mu\tau) = 0.18\%$ (0.09% expected) [11]. These results are extrapolated to the HL-LHC luminosity [12] to obtain the expected 95% CL upper limit for $B(H \to e\tau) = 0.024^{+0.010}_{-0.017}\%$ and $B(H \to \mu\tau) = 0.024^{+0.010}_{-0.017}\%$. These expected limits are a factor $\sim 3-5$ times improvement over the Run2 results.



(a) (b)

Figure 2: (a) Expected uncertainty on the cross section measurements of ggF, VBF, WH, ZH and $t\bar{t}H$ production channels normalized to the SM predictions, assuming the SM branching fractions [7]. (b) Two dimension scan of the simultaneous fit to μ^{cc}_{VH} and μ^{bb}_{VH} for the extrapolation of the measurement of VH ($V = W, Z$) production in the $H \to b\bar{b}$ and $H \to c\bar{c}$ decay modes at HL-LHC [10].

5. Prospects for Di-Higgs Measurements

ATLAS has analyzed its full Run2 data sample (139 fb^{-1}) in the search for di-Higgs production in several different decay channels. The results from the most sensitive decay channels ($HH \to b\bar{b}b\bar{b}$, $HH \to b\bar{b}\gamma\gamma$, $HH \to b\bar{b}\tau^+\tau^-$) are extrapolated to project the reach of di-Higgs search at the HL-LHC [6]. The $HH \to b\bar{b}b\bar{b}$ channel has the highest signal decay branching fraction ($\sim$ 33%) among the different HH decay modes, however the analysis suffers from large multi-jet background. The $HH \to b\bar{b}\gamma\gamma$ channel has clean final state signature but has small signal decay branching fraction ($\sim$ 0.3%). The $HH \to b\bar{b}\tau^+\tau^-$ channel has moderate background contribution and has moderate signal decay branching fraction ($\sim$ 7%).

The projected discovery significance for the three individual search channels and combined, are shown in Figure 3 for different uncertainty scenarios. In the table, the numbers in parantheses are the expected significance from a previous ATLAS projection to the HL-LHC that is based on

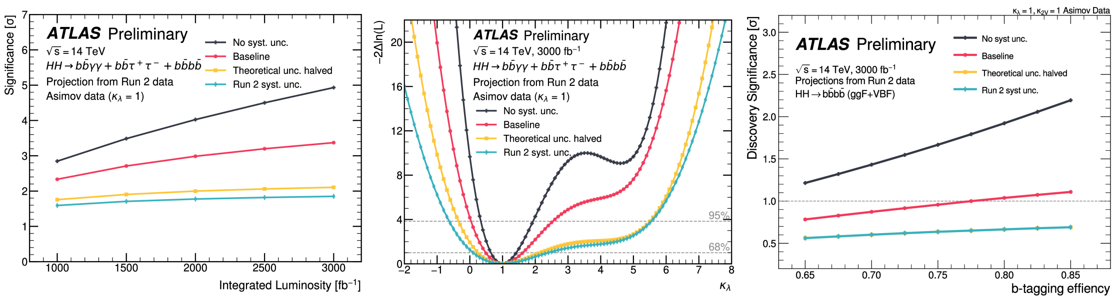
36 fb^{-1} Run2 data [13]. The results from the new projection greatly improve over the previous projection. The ATLAS new projected combined significance reaches 3.4σ (4.9σ) compared to the previous projection of 3.0σ (3.5σ) for the baseline (no systematic uncertainty) scenario. The large improvement in the projected discovery significance are mainly due to the advancement of the physics objects (e.g. γ, e, μ, τ and $b-$jet) reconstruction and identification, and the analysis methods. Figure 3 also shows the uncertainty of the new projected combined signal strength. The expected precision of the combined signal strength is ~ 33% (~ 22%) for the baseline (no systematic uncertainty) scenario. Figure 4(a) shows the projected discovery significance as a function of the integrated luminosity for different uncertainty scenarios of the the combined analysis. Systematic uncertainties become a dominanting factor at high integrated luminosity.

The projection on the combined likelihood scan of the κ_λ modifier for different systematic uncertainty scenarios, is shown in Figure 4(b). The expected constraint on κ_λ at 65% (95%) confidence interval is $0.5 < \kappa_\lambda < 1.6$ ($0.0 < \kappa_\lambda < 2.5$) for the baseline scenario.

At the HL-LHC, systematic uncertainties are expected to be the limiting factor in the di-Higgs search. The search sensitivity will be driven by the theoretical uncertainties of the di-Higgs production cross section and the cross section of the single-Higgs production with b-jets, modelling of the background sources, and the performance of the physics object reconstruction and identification. The dependency on the b-tagging efficiency of the projected di-Higgs discovery significance is shown in Figure 4(c).

	Significance [σ]				Combined signal
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	strength precision [%]
No syst. unc.	2.3 (2.1)	4.0 (2.5)	1.8 (1.4)	4.9 (3.5)	−21/+22
Baseline	2.2 (2.0)	2.8 (2.1)	0.99 (0.61)	3.4 (3.0)	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

Figure 3: Projected discovery significance of SM HH production for the $bbbb$, $bb\gamma\gamma$ and $bb\tau\tau$ search channels and combined [6]. The numbers in parantheses are from a previous ATLAS projection [13].



(a) (b) (c)

Figure 4: Projection of the combined SM HH searches in the $bbbb$, $bb\gamma\gamma$ and $bb\tau\tau$ channels for (a) discovery significance and (b) likelihood scan of the κ_λ modifier [6]. (c) Dependency on the b-tagging efficiency of the projected di-Higgs discovery significance [6].

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References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *Journal of Instrumentation* **3** 08 S08003, https://dx.doi.org/10.1088/1748-0221/3/08/S08003.

[2] ATLAS Collaboration, *A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery*, *Nature* **607**, (2022) 52-59.

[3] ATLAS Collaboration, *Measurements of WH and ZH Higgs production with decays into bottom quarks and direct constraints on the charm Yukawa coupling with 13 TeV collisions in the ATLAS detector*, ATLAS-CONF-2024-010, https://cds.cern.ch/record/2905263

[4] ATLAS Collaboration, *Measurement of the total and differential Higgs boson production cross-sections at $\sqrt{s}$ = 13 TeV with the ATLAS detector by combining the $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ decay channels*, *JHEP* **05**, (2023) 028.

[5] ATLAS Collaboration, *Combination of Searches for Higgs Boson Pair Production in pp Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector*, *Phys. Rev. Lett.* **133**, (2024) 101801.

[6] ATLAS Collaboration, *HL-LHC prospects for the measurement of Higgs boson pair production in the $b\bar{b}b\bar{b}$ final state and combination with the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ $b\bar{b}$ final states at the ATLAS experiment*, ATL-PHYS-PUB-2022-053, https://cds.cern.ch/record/2841244

[7] ATLAS Collaboration, *Projections for measurements of Higgs boson cross sections, branching ratios, coupling parameters and mass with the ATLAS detector at the HL-LHC*, ATL-PHYS-PUB-2018-054, https://cds.cern.ch/record/2652762

[8] ATLAS Collaboration, *Prospects for differential cross-section measurements of Higgs boson production measured in decays to ZZ and $\gamma\gamma$ with the ATLAS experiment at the High-Luminosity LHC*, ATL-PHYS-PUB-2018-040, https://cds.cern.ch/record/2649879

[9] ATLAS Collaboration, *Combined Measurement of the Higgs Boson Mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ Decay Channels with the ATLAS Detector Using $\sqrt{s}$ = 7, 8, and 13 TeV pp Collision Data*, *PRL* **131**, 251802 (2023).

[10] ATLAS Collaboration, *Extrapolation of ATLAS sensitivity to $H \to b\bar{b}$ and $H \to c\bar{c}$ decays in VH production at the HL-LHC*, ATL-PHYS-PUB-2021-039, https://cds.cern.ch/record/2788490

[11] ATLAS Collaboration, *Searches for lepton-flavour-violating decays of the Higgs boson into $e\tau$ and $\mu\tau$ in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector*, *JHEP* **07**, (2023) 166.

[12] ATLAS Collaboration, *Searches of lepton-flavour-violating decays of the Higgs bosons with the ATLAS detector at the HL-LHC*, ATL-PHYS-PUB-2022-054, https://cds.cern.ch/record/2841245

[13] ATLAS Collaboration, *Measurement prospects of the pair production and self-coupling of the Higgs boson with the ATLAS experiment at the HL-LHC*, ATL-PHYS-PUB-2018-053, https://cds.cern.ch/record/2652727