

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

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**Song-Ming Wang<sup>a,\*</sup> on behalf of the ATLAS Collaboration**

<sup>a</sup>*Academia Sinica, Institute of Physics,*

*No. 128, Section 2, Academia Road, Nangang District, Taipei City, Taiwan*

*E-mail: [smwang@phys.sinica.edu.tw](mailto:smwang@phys.sinica.edu.tw)*

The large dataset of about  $3 \text{ ab}^{-1}$  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.

*42nd International Conference on High Energy Physics (ICHEP2024)  
18-24 July 2024  
Prague, Czech Republic*

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\*Speaker



## 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  $L \sim 5 - 7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , and the average number of interactions per bunch crossing (pileup) is expected to be between 140 to 200. The machine will deliver about  $3000 \text{ fb}^{-1}$  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 Granularity 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.

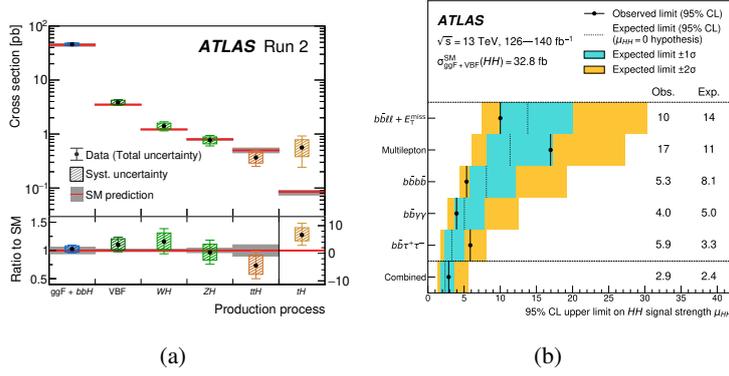
## 2. ATLAS current stand on Single- and Di-Higgs Measurements

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 ( $\tau, b, t$ ) [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  $H \rightarrow \mu^+ \mu^-$  is measured at  $2 \sigma$  significance [2], and the 95% confidence level (CL) upper limit on the observed (expected) cross section for  $VH(\rightarrow c\bar{c})$  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 ( $p_T(H)$ ) is measured at precision of  $\sim 20 - 30\%$  for  $p_T(H) < 300$  GeV, and at  $\sim 60\%$  for  $300 < p_T(H) < 650$  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 ( $\mu_{HH}$ ) for individual decay channel. The combined observed (expected) upper limit on  $\mu_{HH}$  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 ( $\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{SM}^{HHH}}$ ) 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  $3000 \text{ fb}^{-1}$ . Several systematic uncertainty scenarios are considered [6]. The most conservative scenario, “Run2” (or



**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

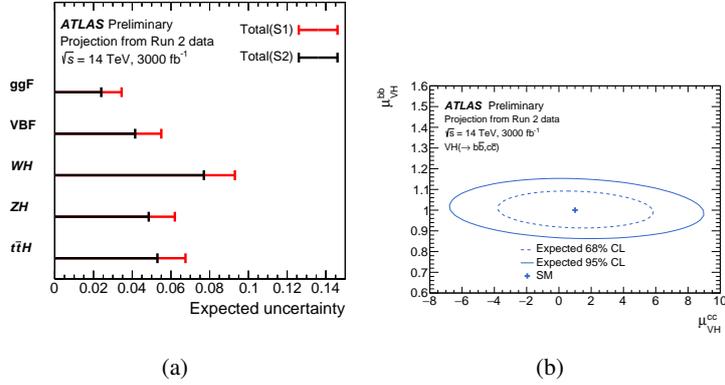
The projections for the single-Higgs boson production and couplings measurements at the HL-LHC are obtained from the extrapolation of the combined Run2 results from several production and decay measurements [7]. The Run2 analyses with final states in  $WW$ ,  $Z\gamma$ ,  $t\bar{t}H$  and  $\tau\tau$  were conducted using  $36 \text{ fb}^{-1}$  of data, and the analyses with  $\gamma\gamma$ ,  $ZZ$ ,  $VH$  ( $H \rightarrow b\bar{b}$ ) final states were performed on  $80 \text{ fb}^{-1}$  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,  $\kappa$ , are expected to have uncertainties at a few percent level. The projected uncertainties of  $\kappa_\mu$  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  $H \rightarrow \gamma\gamma$  (with  $36 \text{ fb}^{-1}$  of data) and  $H \rightarrow ZZ \rightarrow 4l$  (using  $80 \text{ fb}^{-1}$  of data) measurements. The Higgs boson transverse momentum is expected to be probed with precision of  $\sim 5\%$  at  $p_T(H) < 350 \text{ GeV}$ , and  $\sim 10\%$  at  $350 < p_T(H) < 1000 \text{ GeV}$ .

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  $m_H = 125.11 \pm 0.11 \text{ GeV}$  [9]. The projected Higgs boson mass measurement at HL-LHC, based on the extrapolation of ATLAS Run2  $H \rightarrow ZZ \rightarrow 4\mu$  results, using  $36 \text{ fb}^{-1}$  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  $H \rightarrow b\bar{b}$  and  $H \rightarrow c\bar{c}$  decay modes [10] is obtained from the extrapolation of a Run2 analysis performed on  $139 \text{ fb}^{-1}$  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  $H \rightarrow b\bar{b}$  ( $H \rightarrow c\bar{c}$ ) is  $\mu_{VH}^{bb} = 1.00 \pm 0.06$  ( $\mu_{VH}^{cc} = 1.00 \pm 3.20$ ). The likelihood scan results are shown in Figure 2(b). The expected constraint on the ratio of the modifier  $\kappa_c$  to  $\kappa_b$ , 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  $139 \text{ fb}^{-1}$ , ATLAS performed a direct search for LFV Higgs decay and set 95% CL upper limit on the branching ratios for  $B(H \rightarrow e\tau) = 0.2\%$  (0.12% expected) and  $B(H \rightarrow \mu\tau) = 0.18\%$  (0.09% expected) [11]. These results are extrapolated to the HL-LHC luminosity [12] to obtain the expected 95% CL upper limit for  $B(H \rightarrow e\tau) = 0.024^{+0.010}_{-0.017}\%$  and  $B(H \rightarrow \mu\tau) = 0.024^{+0.010}_{-0.017}\%$ . These expected limits are a factor  $\sim 3 - 5$  times improvement over the Run2 results.



**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  $\mu_{VH}^{cc}$  and  $\mu_{VH}^{bb}$  for the extrapolation of the measurement of  $VH$  ( $V = W, Z$ ) production in the  $H \rightarrow b\bar{b}$  and  $H \rightarrow c\bar{c}$  decay modes at HL-LHC [10].

## 5. Prospects for Di-Higgs Measurements

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

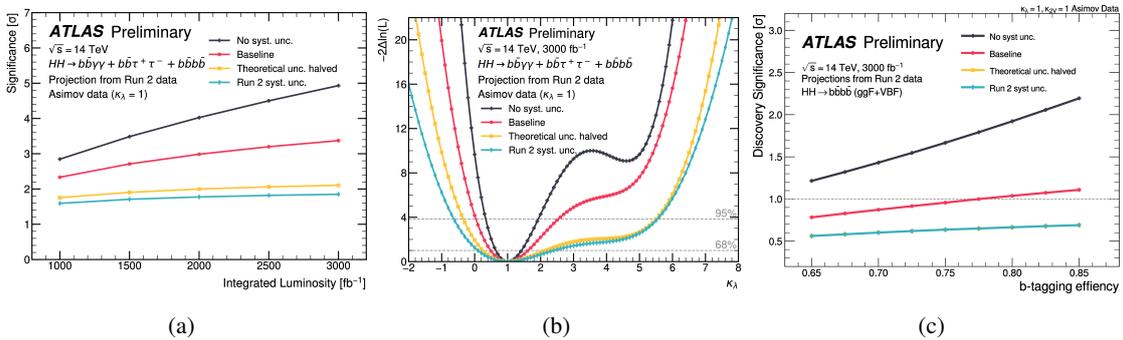
36 fb<sup>-1</sup> Run2 data [13]. The results from the new projection greatly improve over the previous projection. The ATLAS new projected combined significance reaches 3.4σ (4.9σ) compared to the previous projection of 3.0σ (3.5σ) for the baseline (no systematic uncertainty) scenario. The large improvement 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 dominating factor at high integrated luminosity.

The projection on the combined likelihood scan of the κ<sub>λ</sub> modifier for different systematic uncertainty scenarios, is shown in Figure 4(b). The expected constraint on κ<sub>λ</sub> at 65% (95%) confidence interval is 0.5 < κ<sub>λ</sub> < 1.6 (0.0 < κ<sub>λ</sub> < 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).

Uncertainty scenario	Significance [σ]				Combined signal strength precision [%]
	bbγγ	bbτ <sup>+</sup> τ <sup>-</sup>	bbbb	Combination	
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, bbγγ and bbττ search channels and combined [6]. The numbers in parantheses are from a previous ATLAS projection [13].



**Figure 4:** Projection of the combined SM HH searches in the bbbb, bbγγ and bbττ channels for (a) discovery significance and (b) likelihood scan of the κ<sub>λ</sub> modifier [6]. (c) Dependency on the b-tagging efficiency of the projected di-Higgs discovery significance [6].

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