ATL-PHYS-PROC-2014-093
07 August 2014

Studies of Higgs Boson Properties in Future LHC Runs

Hideki Okawa
On behalf of the ATLAS and CMS Collaborations
Brookhaven National Laboratory, Upton, New York, USA

A Higgs boson has been discovered with the Run 1 data collected at the Large Hadron Collider (LHC). Future LHC and High Luminosity LHC (HL-LHC) data will allow precise measurements of the Higgs couplings and searches for rare events and additional Higgs bosons in the high mass region. Measurements of the Higgs pair-production and self-coupling are also of great importance. With these precision measurements, underlying physics beyond the Standard Model could be discovered.

1 Introduction

The ATLAS [1] and CMS [2] experiments at the Large Hadron Collider (LHC) [3] at CERN have discovered a Higgs boson [4,5] in 2012, and future data are awaited to further understand the property of the Higgs boson and to search for physics beyond the Standard Model (BSM).

The LHC is currently in the first Long Shutdown (LS1), and machine commissioning for the next run of data-taking will start in early 2015. Collisions will resume with an initial bunch spacing of 50 ns, changing to 25 ns soon after, at the center of mass energy of 13 TeV and eventually 14 TeV. The expected luminosity between 2015 to 2018 is about 1.6×10^{34} cm^{-2}s^{-1}, surpassing the initial design luminosity of 1×10^{34} cm^{-2}s^{-1}, and the ATLAS and CMS detectors are expected to each collect about 75 to 100 fb^{-1} of proton-proton collision data. The LHC injector will be upgraded during the second Long Shutdown (LS2), and the luminosity will increase to about 2×10^{34} cm^{-2}s^{-1}, resulting in about 300 fb^{-1} of data by 2022. During the third Long Shutdown (LS3), the upgrade will be done for the High Luminosity LHC (HL-LHC), and the luminosity will be enhanced to about 5×10^{34} cm^{-2}s^{-1}, which is five times higher than the initial LHC design. About 3000 fb^{-1} of data will be collected with a decade of HL-LHC operation.

The upcoming dataset will allow precision measurements of the Higgs couplings and searches for BSM productions and decays (e.g. invisible) of the Higgs boson, CP-violation in the Higgs-sector, and additional Higgs bosons. These studies are summarized in these proceedings. The pair production of Higgs bosons and their self-coupling could also be measured with the HL-LHC.

2 Projections with Future LHC

Integrated luminosities of 300 fb^{-1} and 3000 fb^{-1} are considered as benchmarks for the 14 TeV LHC and HL-LHC studies. The average number of proton-proton interactions per bunch crossing over the data taking period is assumed to be 60 and 140 for the two scenarios.

For the ATLAS studies, dedicated Monte Carlo (MC) samples at the generator level are used with response functions applied to consider the expected detector and object performance for the benchmark conditions [6,7]. Full simulation is used to extract response functions for jets

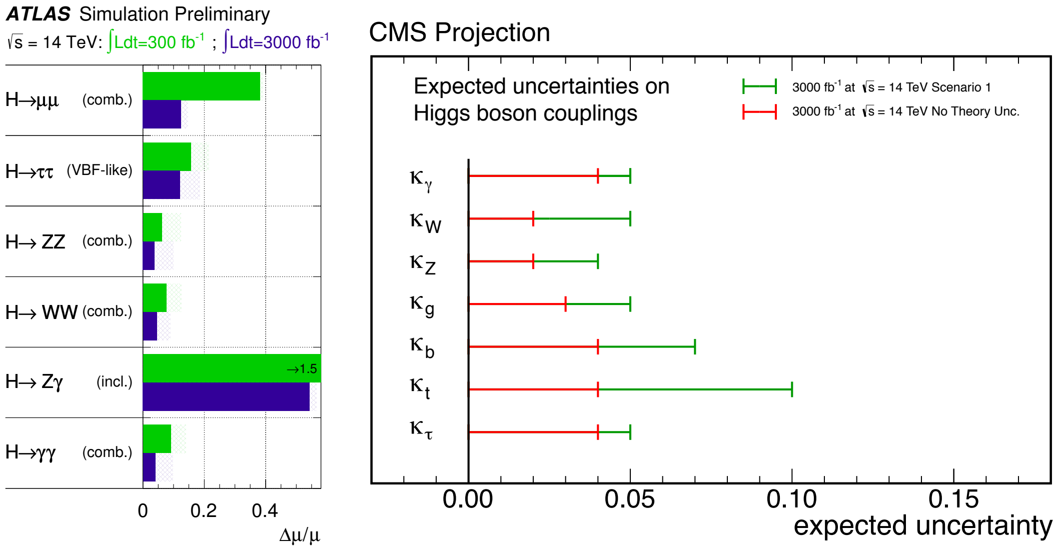

Figure 1 – The expected precision of measuring the signal strength for the Higgs decay channels at the ATLAS experiment (left) [10], and Higgs couplings at the CMS experiment (right) [8].

and missing transverse momentum. In some cases, such as the $H \to W^{\pm}W^{(*)\mp}$ projection, the results from the 7 and 8 TeV analyses are extrapolated to 300 and 3000 fb^{-1} considering the cross sections at 14 TeV.

For the CMS studies, the 7 and 8 TeV analysis results are extrapolated to 300 and 3000 fb^{-1}, assuming the same detector and trigger performance.

Regarding systematic uncertainties, CMS considered two scenarios [8], where for the first scenario (Scenario 1) the same size of theory and experimental uncertainties are considered as Run 1, and for the second scenario (Scenario 2), the theory uncertainties are reduced by 50% and the experimental uncertainties are scaled by the square root of the integrated luminosity. For the ATLAS studies, the uncertainties are assumed to be the same as the Run 1 analyses. Some uncertainties for data-driven background estimates (e.g. in the $ZH \to \ell^+\ell^-$+invisible analysis) are scaled with the square root of the integrated luminosity.

3 Precision Measurements of the Higgs Boson

With 3000 fb^{-1} of HL-LHC data, the $H \to ZZ^{(*)} \to 4\ell$ channel provides clean signatures for all the production modes: gluon-gluon fusion, vector boson fusion, VH and $t\bar{t}H$. Such a large dataset also allows to observe more than 100 signal events from the $t\bar{t}H, H \to \gamma\gamma$ [9,10], which is sensitive to the top Yukawa coupling from both the production and the decay patterns. The HL-LHC data also provides sensitivities to the SM rare decays such as $H \to \mu^+\mu^-$, which could be observed with 7σ significance. The expected significance for $H \to Z\gamma$ with 3000 fb^{-1} is 2.1σ.

The signal strength of the main channels, $H \to \gamma\gamma$, $H \to ZZ^{(*)}$, $H \to W^{\pm}W^{(*)\mp}$, $H \to \tau^+\tau^-$, $H \to b\bar{b}$ could be measured by each experiment to an accuracy of about 5% (10%) without (with) theory uncertainties. Assuming the SM value for the total width of the Higgs boson, the Higgs couplings can be extracted from the measured $\sigma \times$ BR to the similar accuracy, namely about 2–4% (4–10%) without (with) theory uncertainties, as shown in Figure 1. Measuring the couplings with such a high precision is very important, because in many BSM models, the couplings deviate from the SM expectation by 6–10% [11].

4 Searches for BSM Decays

4.1 Invisible Higgs Decay

As the best upper limit on the total decay width of the Higgs boson is still several times larger than the SM expectation [12], the presence of BSM decays of the Higgs boson cannot be excluded. An invisible decay of the Higgs boson to weakly interacting particles such as dark matter is a promising scenario. The constraint on such a BSM decay could be provided by both direct searches and coupling measurements. With the HL-LHC data, the upper limit on BR($H \to$ inv.) is expected to reach below 10% from each of the direct and indirect searches, starting to cover interesting regions of phase space for various BSM models, such as supersymmetry.

4.2 Top-quark Decays to Higgs Boson

The $t\bar{t}$ process provides opportunities to search for flavor-changing neutral currents in top-quark decays. With the presence of BSM physics, BR($t \to cH$) could significantly be enhanced from the SM value of 3 $\times 10^{-15}$. In such a final state, the invariant masses of $\gamma\gamma$, $\gamma\gamma j$ and $W(\to l\nu, jj)j$ offer clean signatures to search for the rare process [13]. The expected limit reaches BR($t \to cH$)=1.2–1.4$\times 10^{-4}$ with 3000 fb^{-1}.

5 CP-Mixing due to Multiple Higgs Bosons

The presence of multiple Higgs bosons and CP-violation can lead to the 125 GeV Higgs boson to be an admixture of a CP-scalar and -pseudoscalar states. Such an admixture provides a new source of CP-violation beyond the SM. The most precise test could be performed with the $H \to ZZ^{(*)} \to 4\ell$ final state. ATLAS uses eight-dimensional kinematic fits to extract couplings of the CP-even and CP-odd components, whereas CMS adopts the Matrix Element likelihood approach. The ATLAS and CMS experiments are expected to obtain upper limits on the fraction of the CP-odd contributions f_{a_3} of 0.15 (0.037) and 0.13 (0.04) respectively [8,14] with 300 (3000) fb^{-1}.

6 BSM Heavy Higgs Bosons

Two scenarios are investigated for the heavy Higgs bosons: (1) additional electroweak (EW) singlet case and (2) Two Higgs Doublet Model (2HDM).

The first scenario considers the presence of an additional singlet with mass m_H, which couples to the bosons and fermions as the SM Higgs boson. Coupling strength is reduced by a set of common scale factors (κ_h, κ_H) for the SM Higgs boson (denoted as "h") and the heavy Higgs boson ("H"). There is a unitarity constraint between the scale factors: $\kappa_h^2 + \kappa_H^2 = 1$.

The second scenario considers the case where the SM Higgs sector is extended by another doublet. The 2HDM is a generic model with six parameters: four Higgs boson (h, H, A, $H^{\pm}$: CP-even, CP-even, CP-odd, charged) masses, $\tan\beta$, and the mixing angle α of h and H. Four model types are considered, and Type-II includes the minimal supersymmetric standard model (MSSM).

6.1 Coupling Studies for Additional Higgs bosons

The coupling measurements from the $H \to \gamma\gamma$, $ZZ^{(*)} \to 4\ell$, $W^{\pm}W^{(*)\mp} \to \ell^{\pm}\nu\ell^{\mp}\nu$, $\tau^+\tau^-$, $Z\gamma$, $\mu^+\mu^-$ channels can be used to constrain the contributions from BSM physics [15]. The scale factor for another EW singlet could be excluded at the level of $\kappa_H < 0.35$ (0.31) with 300 fb^{-1} and $\kappa_H < 0.31$ (0.25) with 3000 fb^{-1} with (without) the theory uncertainties. Figure 2 (left) [16] shows the expected exclusion of the Type-II 2HDM in the plane of $\cos(\beta - \alpha)$ and $\tan\beta$.

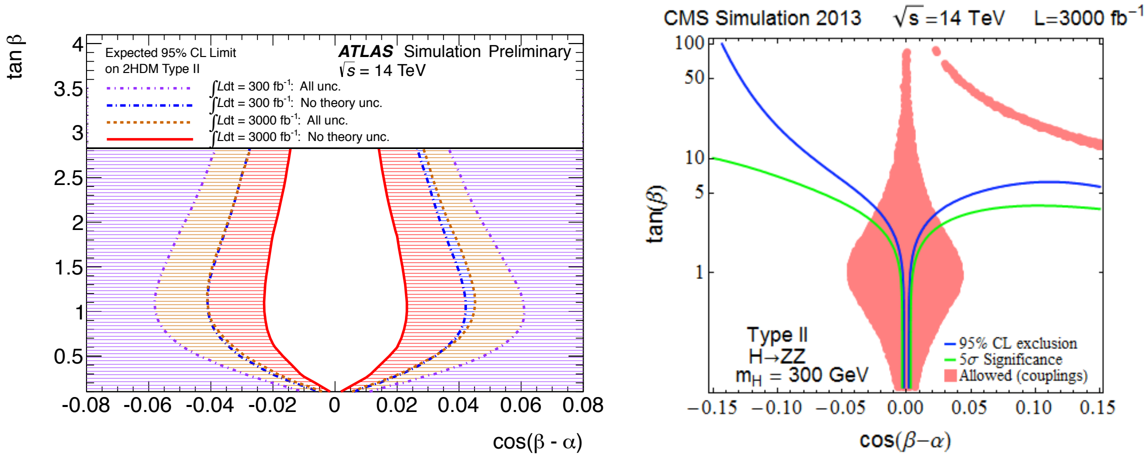

Figure 2 – The expected exclusions of the Type-II 2HDM in the plane of $\tan\beta$ and $\cos(\beta - \alpha)$ using the coupling measurements in ATLAS (left) [15], and direct search in the $H \to ZZ^{(*)} \to 4\ell$ channel in CMS (right) [17].

6.2 Direct Searches for Additional Higgs Bosons

The decay patterns of the heavy Higgs bosons depend highly on $\tan\beta$ and their masses. Thus, it is important that various search channels are investigated in parallel. The $H \to ZZ^{(*)} \to 4\ell$ and $A \to Zh \to \ell^+\ell^- b\bar{b}$ are examples of promising channels for low $\tan\beta$ cases and provide complementary sensitivities to the coupling studies as shown in Figure 2 (right) [17].

7 Conclusions

Future LHC and HL-LHC data will allow precise measurements of the Higgs couplings. A deviation from the SM expectation would indicate the presence of physics beyond the SM. Searches for rare events and for additional Higgs bosons in the high mass region could be possible. Measurements of the Higgs pair-production and self-coupling are also of great importance. With these precision measurements, underlying physics beyond the Standard Model could be discovered.

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