

Recent Results in Higgs Physics

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These proceedings report on recent results of the Higgs physics by ATLAS and CMS at the Large Hadron Collider. All Run 2 analysis results are based on the full Run 2 dataset, corresponding to an integrated luminosity of approximately 140 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$. Various measurements of Higgs properties: mass, width, couplings, cross sections and self-coupling are performed. First Run 3 Higgs cross section measurement is obtained using 2022 data, corresponding to approximately 30 fb^{-1} at the $\sqrt{s} = 13.6 \text{ TeV}$. No significant deviation from the Standard Model on the Higgs boson properties is observed.

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1. Introduction

In 2012, ATLAS and CMS discovered a Higgs boson [1, 2] at the Large Hadron Collider (LHC) [3]. The discovery of the Higgs boson filled the last particle predicted by the Standard Model (SM). At the same time, this discovery opens many questions not solved in the SM. The Higgs sector is the most vulnerable in the SM. 15 parameters out of 19 in the SM are related to the Higgs sector. ATLAS [4] and CMS [5] have measured Higgs boson properties in Run 1, and Run 2. There are several extraordinary achievements during Run2: the observation of the Higgs boson production in association with a top quarks [6, 7], the observation of the Higgs boson decaying into a pair of bottom quarks [8, 9], the evidence of the interaction between Higgs boson and muon [10, 11], and the evidence of Higgs boson decaying into $\ell\ell\gamma$ [12].

These proceedings report the highlight of the recent Higgs boson property measurements using full Run 2 dataset corresponding to roughly 140 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ collected by the ATLAS and CMS experiments and using Run 3 dataset of 2022 at $\sqrt{s} = 13.6 \text{ TeV}$ collected by the ATLAS experiment [13].

2. Higgs mass measurement

ATLAS measures Higgs boson mass using $H \rightarrow \gamma\gamma$ channel which has excellent mass resolution due to precise photon energy scale and resolution calibrations. However, they were still the dominant systematic uncertainties for the mass measurement in the previous analysis [14]. ATLAS improves the calibration method of the photon energy scale and resolution, in particular, in-situ calibration using $Z \rightarrow ee$ events providing a significant reduction of the systematic uncertainties [15]. The systematic uncertainty of photon calibration is reduced by a factor of four. The measured Higgs boson mass is $125.17 \pm 0.11(\text{stat.}) \pm 0.09(\text{syst.}) \text{ GeV}$ in Run 2 dataset and $125.22 \pm 0.11(\text{stat.}) \pm 0.09(\text{syst.}) \text{ GeV}$ combined with Run 1 dataset [14]. ATLAS combined mass measurement of $H \rightarrow \gamma\gamma$ with that of the $H \rightarrow ZZ^* \rightarrow 4\ell$ which provides another best mass measurement because of the excellent lepton energy and momentum calibration [16]. The mass measurement of two channels and their combinations is summarised in the left of Figure 1. All measurements are in good agreement, and the combined Higgs mass is measured to be $125.11 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.}) \text{ GeV}$.

3. Higgs width measurement

ATLAS and CMS measure the Higgs boson total width from off-shell and on-shell signal strength using $H \rightarrow ZZ^*$ decay mode in gluon-fusion (ggF) and VBF processes. The on-shell measurement depends on the Higgs total width from the Higgs propagator term. On the other hand, the off-shell measurement does not depend on the Higgs total width. In the off-shell phase space, the $gg \rightarrow H \rightarrow ZZ$ diagram destructively interferes with the $gg \rightarrow ZZ$ diagram in the leading-order in ggF. With the large interference effect, the off-shell signal strength can be measured. CMS (ATLAS) observe the significance of non-zero off-shell Higgs boson signal strength by $3.6(3.3) \sigma$ and the CMS result is shown in the right of Figure 1. The off-shell signal strength is measured to be $0.62^{+0.68}_{-0.45} (1.1^{+0.7}_{-0.6})$ for CMS (ATLAS). As stated above, the off-shell signal strength is expressed as

$\mu_{\text{off-shell}} \sim \kappa_g^2 \kappa_Z^2$ and the on-shell signal strength is expressed as $\mu_{\text{on-shell}} \sim \kappa_g^2 \kappa_Z^2 \frac{\Gamma_H^{\text{SM}}}{\Gamma_H}$, where κ_g (κ_Z) represent the couplings between Higgs boson and gluon (Z boson) normalised to the SM prediction. Assuming the couplings are the same in on-shell and off-shell processes, Higgs boson total width Γ_H can be measured by $\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} \Gamma_H^{\text{SM}}$. The observed Higgs total width is $3.2^{+2.4}_{-1.7}$ ($4.5^{+3.3}_{-2.5}$) MeV for CMS (ATLAS), which is consistent with the SM Higgs total width, 4.1 MeV [17–20].

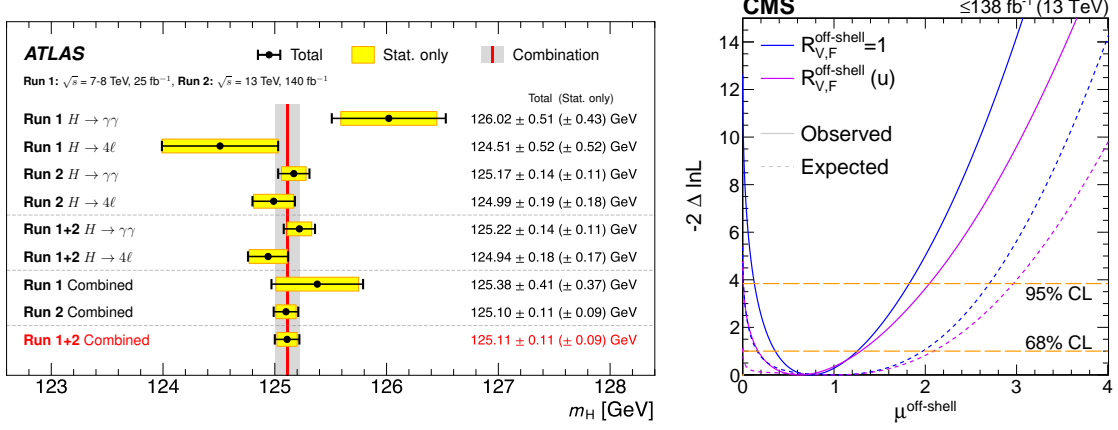


Figure 1: (Left) A summary of the Higgs boson mass measurement of the individual $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ and the combination of two channels [14]. (Right) The likelihood profile as a function of the off-shell signal strength, $\mu_{\text{off-shell}}$ [19].

4. Higgs coupling and cross-section measurements

The measurements of couplings between the Higgs boson and the SM particles and non-SM particles are one of the most important Higgs properties measurements because many BSM models indicate the deviations from the SM. ATLAS and CMS measure the couplings in various production and decay modes which covers different couplings in the different phase spaces. The combined measurement of all productions and decay modes provides the most sensitive and comprehensive information on the couplings. Figure 2 shows the results of coupling measurement using κ -framework [21]. ATLAS and CMS have similar precision on the κ parameters, which are coupling strength modifiers normalized by the coupling predicted by the SM. The precision for $\kappa_{W/Z}, \kappa_\gamma, \kappa_g, \kappa_\tau$ reaches 6-8% level, κ_t, κ_b precision is approximately 10%, κ_μ precision is 20% and $\kappa_{Z\gamma}$ precision is 40% level [22, 23]. ATLAS also shows the limit on the branching fraction of invisible decay ($B_{\text{inv.}}$) and other undetected decay (B_u) modes in Figure 2.

ATLAS measures the cross section using the simplified template cross section (STXS) framework [24]. The STXS defines the bins of kinematic regions for each production process. Figure 3 (left) shows the STXS measurements in 36 different phase space bins. The higher statistics of the dataset and the combination of various production and decay modes make the STXS measurement more sensitive to the BSM. Figure 3 (right) shows the constraint of Wilson coefficients of linearised SMEFT [25] using the combined STXS measurements [22]. The agreement with the SM expectation is 94.5% in the p -value.

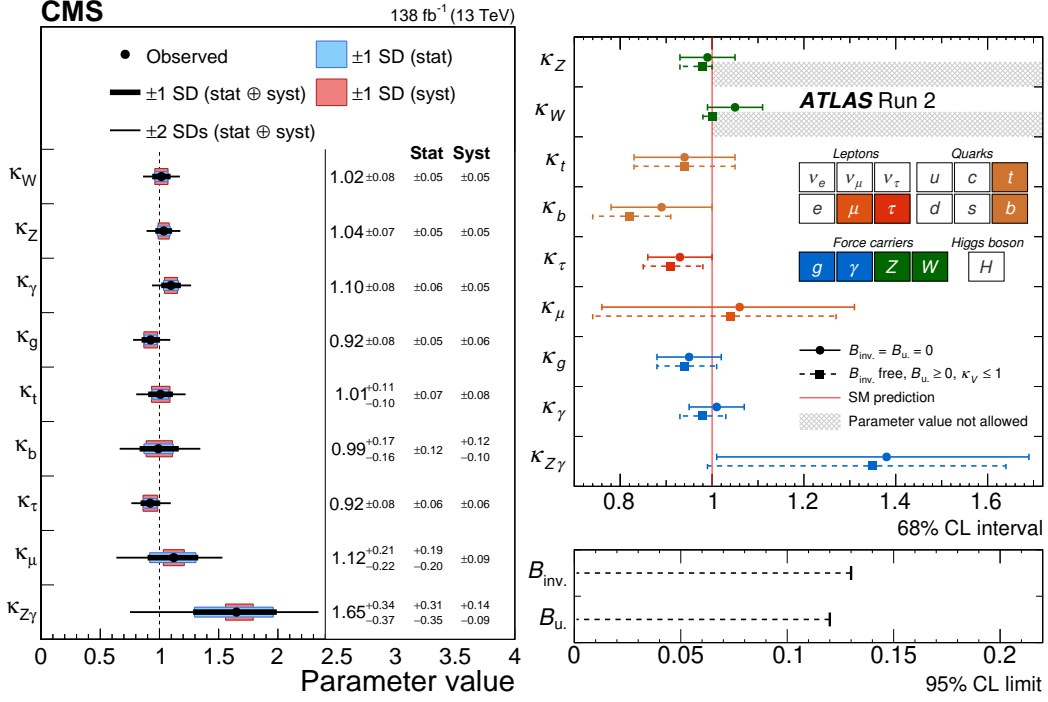


Figure 2: (Left) The combined coupling measurement and their uncertainties per particle and effective couplings of the photon, $Z\gamma$ and gluon assuming $B_{inv.} = B_u = 0$ is shown [23]. (Right) In addition to that scenario, ATLAS also shows another scenario assuming $\kappa_V \leq 1$, $B_u \geq 0$ and $B_{inv.}$ is free floated. The lower panel shows the 95% CL upper limits on $B_{inv.}$ and B_u . [22].

CMS updates the property measurements of $t\bar{t}H$ and tH production processes using the full Run 2 dataset. A fully hadronic channel is newly analyzed in addition to the semi-leptonic and di-leptonic channels of $t\bar{t}$ decay and an artificial neural network is used to separate signal and background in all channels. The observed signal strength is $\mu_{t\bar{t}H} = 0.33^{+0.26}_{-0.26}$, corresponding to the observed signal significance of 1.3σ with an expectation of 4.1σ [26]. Figure 4 (left) shows the simultaneous measurement of $\mu_{t\bar{t}H}$ and μ_{tH} . The best fit values of $\mu_{t\bar{t}H}$ and μ_{tH} are 0.35 and -3.83 , respectively [26].

ATLAS searches for new rare associated production of Higgs and W bosons via vector boson fusion which is sensitive to the relative sign of the Higgs boson coupling of W and Z bosons. Figure 4 (middle) shows confidence intervals in the $\kappa_Z - \kappa_W$ plane. The negative scenario of the relative sign of the κ_Z and κ_W is excluded with significance of greater than 8σ [27].

ATLAS and CMS perform the combination of individual measurements of rare $Z\gamma$ decay modes. The observed individual signal strength is $\mu_{Z\gamma} = 2.0^{+1.0}_{-0.9}$ ($2.4^{+1.0}_{-0.9}$) for ATLAS (CMS) analyses [28, 29]. Figure 4 (right) shows the $Z\gamma$ mass distribution of events from all ATLAS and CMS analysis categories. The events are weighted by the $\ln(1 + S/B)$ of their categories, where S and B are the observed signal and background yields in the range $120 < m_{Z\gamma} < 130$ GeV. The signal strength in the combined measurement is $\mu_{Z\gamma} = 2.2 \pm 0.7$. The observed (expected) local significance with null hypothesis corresponds to 3.4σ (1.6σ) [30]. The combined measurement provides the first evidence of the rare $Z\gamma$ decay modes. The p -value for the compatibility with the

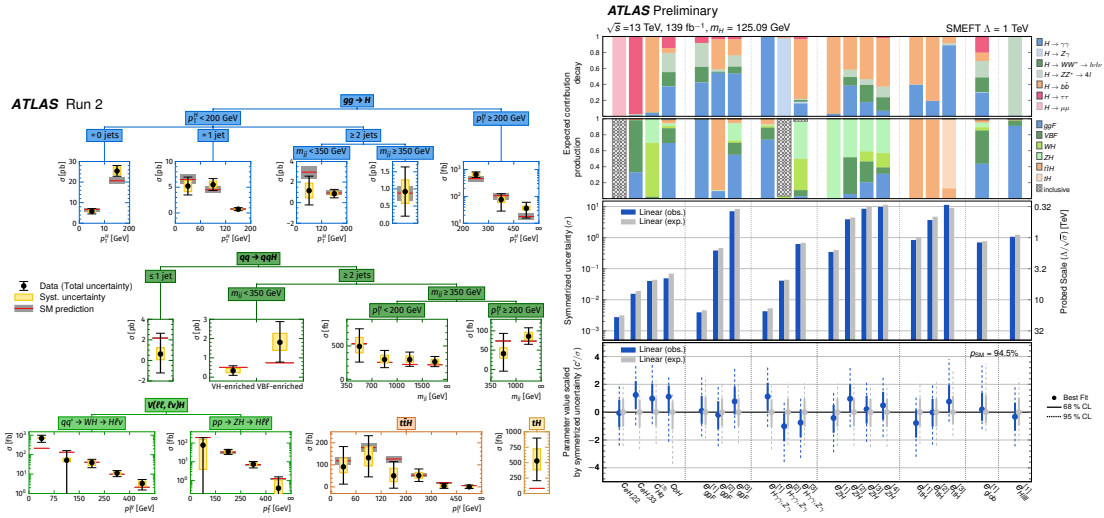


Figure 3: (Left) The observed and predicted Higgs boson production cross section in the different STXS bins [22]. (Right) The comparison of the observed and expected SMEFT parameters with a linearised model is shown in the bottom panel. The middle panel shows the 68% uncertainties on each parameter. The top panel shows the expected contribution of each production and decay mode [25].

SM is about 6%, and the observed local significance with respect to the SM is 1.9σ level.

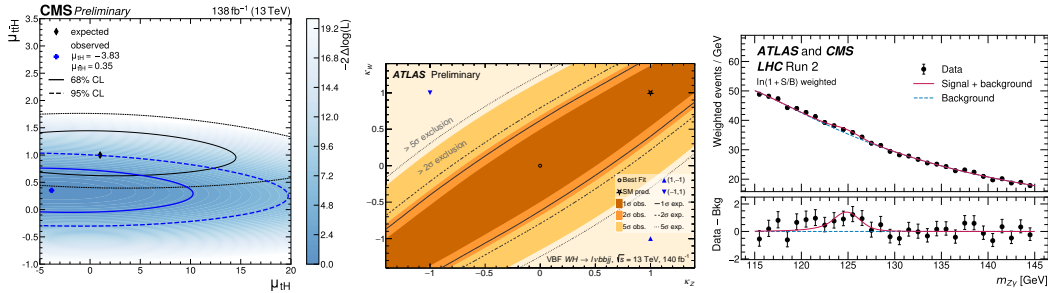


Figure 4: (Left) Simultaneous measurement of μ_{tH} and μ_{tH} [26]. (Middle) Simultaneous fit results of κ_W and κ_Z . The colored contours indicate the observed allowed regions in each significance [27]. (Right) The $Z\gamma$ mass distribution of events from all ATLAS and CMS analysis categories. The events are weighted by $\ln(1 + S/B)$ in each category [30].

5. New measurements using boosted topology

CMS has recently developed the reconstruction method using machine learning techniques for boosted Higgs boson which decays into a pair of bottom quarks. In the high- p_T^H topology, two b -quarks from the Higgs decay are reconstructed as the one large-radius jet. DEEPDOUBLEBvL-v2 (DDB) multivariate jet tagger [31] is applied to the gluon-fusion (ggF) and VBF events to improve the discrimination of Higgs candidates and QCD background and enhance the signal significance. Figure 5 shows the soft drop jet mass [33] distribution for ggF and VBF categories [32]. The

signal strength for the VBF process is measured to be $5.0^{+2.1}_{-1.8}$, which corresponds to the observed (expected) significance of 3.0σ (0.9σ). For the ggF process, the signal strength is measured to be $2.1^{+1.9}_{-1.7}$, which corresponds to the observed (expected) significance of 1.2σ (0.9σ).

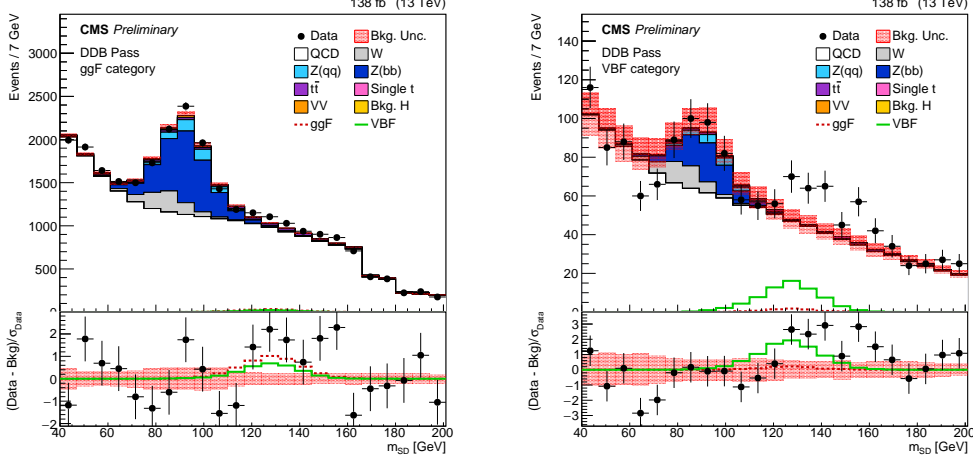


Figure 5: Soft-drop mass [33] distributions in ggF (left) and VBF (middle) categories [32].

6. Higgs pair production

The Higgs self-coupling measurement is one of the biggest goals of the LHC physics program since various BSM models indicate the deviation from the SM. The Higgs self-interaction is directly accessible via Higgs boson pair (HH) production. However, the HH production cross section is more than 1000 times lower than the single Higgs production cross section and very rare production at the LHC. Also, the Higgs boson self-interaction contributes to other processes via next-to-leading order EW corrections [34]. ATLAS and CMS search for the HH production process using various decay modes in ggF and VBF. Three main decay modes: $bb\gamma\gamma$, $bb\tau\tau$, $4b$, are the most sensitive to the self-coupling measurement and their results are combined in ATLAS. The observed (expected) upper limit on the double Higgs signal strength is set to 2.4 (2.9) at 95% CL. The observed values of $-2 \ln(\Lambda)$ as a function of κ_λ are shown in Figure 6 (left) for the single-Higgs and double-Higgs analyses, and their combination. The combined observed (expected) constraints on κ_λ are $-0.4 < \kappa_\lambda < 6.3$ ($-1.9 < \kappa_\lambda < 7.6$) at 95% CL [34]. The observed and expected upper limit on VBF HH production cross section as a function of the quartic VVHH coupling modifier κ_{2V} are shown in Figure 6 (right). The constraint on κ_{2V} is in the range of 0.67 to 1.38. CMS excluded $k_{2V} = 0$ with a significance of 6.6σ [23].

7. First Run3 Higgs cross section measurements at 13.6 TeV

ATLAS measures inclusive and fiducial Higgs boson production cross-section in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ [35] using approximately 30 fb^{-1} of pp collision data at a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. The $m_{\gamma\gamma}$ and $m_{4\ell}$ distributions are shown in Figure 7 (right) and (middle).

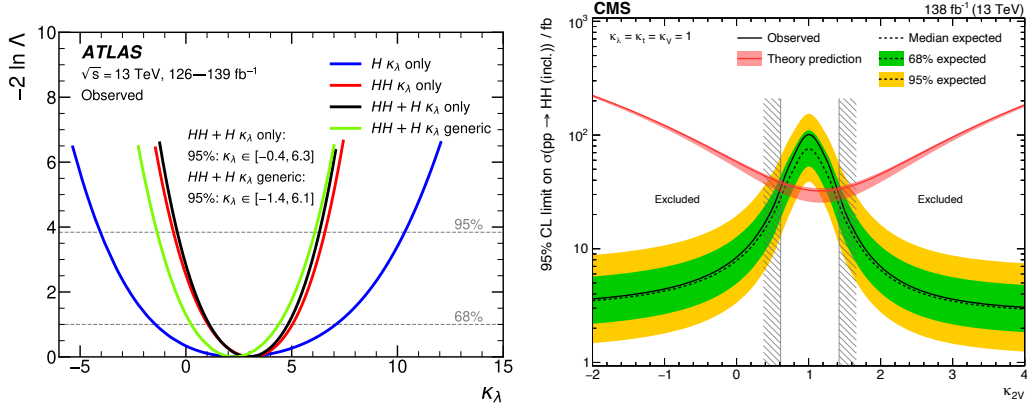


Figure 6: (Left) Observed values of the test statistic ($-2\ln(\Lambda)$) as a function of κ_λ parameter for the single-Higgs (blue) and double-Higgs (red) analysis, and their combinations in the scenarios assuming all other couplings fixed to unity (black), and assuming $\kappa_t, \kappa_b, \kappa_V$ and κ_τ are free floated [34]. (Right) Expected and observed 95% CL upper limit on the HH production cross section as a function of κ_{2V} [23].

The total Higgs boson production cross-section at $\sqrt{s} = 13.6$ TeV is measured to be 67_{-11}^{+12} pb for $H \rightarrow \gamma\gamma$ channel and 46 ± 12 pb for $H \rightarrow ZZ \rightarrow 4\ell$. The two measurements are compatible with a p -value of 20%. The total Higgs boson production cross-section combined with two channels is measured to be 58.2 ± 8.7 pb as shown in Figure 7 (right). All measurements are in good agreement with the SM prediction, 59.9 ± 2.6 pb.

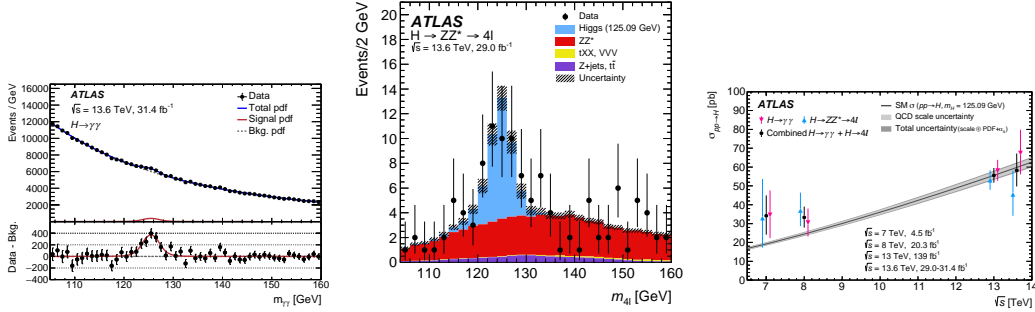


Figure 7: (Left) $m_{\gamma\gamma}$ distribution. (Middle) $m_{4\ell}$ distribution. (Right) The observed total cross section for each centre-of-mass energy from ATLAS Run 1, Run 2, and Run 3. The SM predictions and their uncertainties are shown as a function of centre-of-mass energy [35].

8. Conclusion

High statistics of the full Run 2 dataset collected by ATLAS and CMS at the LHC and improvement of the analysis techniques significantly improve the precision of Higgs boson property measurements. The precision of Higgs mass measurement reached less than 0.1%. The major couplings of Higgs boson are measured by less than 10% level. Higgs measurements for the rare

production processes and decay modes are accessible. ATLAS and CMS have evidence of rare decay mode, $H \rightarrow Z\gamma$ by 3.4σ . The measurement of STXS and differential cross sections in the corner of phase spaces which is more sensitive to the BSM is doable due to large statistics and development of the boosted Higgs reconstruction techniques. The sensitivity of the Higgs pair production is improved dramatically during Run 2 and constrains to κ_λ in the wide range. Furthermore, the first Run3 inclusive Higgs boson production cross section is measured by ATLAS and it is consistent with the SM prediction.

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