RECENT HIGGS BOSON RESULTS FROM THE LHC

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Abstract
A collection of Higgs boson property measurements from ATLAS and CMS collaboration based on LHC Run1 dataset is presented. In addition, recent results on Higgs physics from LHC Run2 are summarized.

1 Introduction
The ATLAS and CMS collaborations announced on July 4th 2012 the discovery of a new particle in the SM Higgs searches. The properties of this new particle have been studied by both collaborations, confirming its identity as a Higgs boson with a mass of about $m_H = 125$ GeV. Its decays, production modes and couplings have been studied, and its spin and parity properties have been tested and compared with SM expectations. In the SM, the Higgs boson is produced at LHC predominantly via gluon-fusion process ($\sigma \sim 19.5$ pb at $\sqrt{s} = 8$ ...
TeV) followed by vector boson fusion ($\sigma \sim 1.6$ pb at $\sqrt{s} = 8$ TeV), associated production with a vector boson ($\sigma \sim 1.1$ pb at $\sqrt{s} = 8$ TeV) and associated production with a $t\bar{t}$ pair. At $m_H = 125$ GeV, the main Higgs boson decay channels are into $b\bar{b}$ (branching fraction 57.7%), $\tau\tau$ (6.3%), $WW^*$ (21.5%), $ZZ^*$ (2.6%) and $\gamma\gamma$ (0.23%). The production cross sections increase by about a factor 2.2 at $\sqrt{s} = 13$ TeV compared to the 8 TeV, with exception of the associate production with a $t\bar{t}$ pair, which experience a gain of almost a factor 4.

2 Run1 Highlights

2.1 Higgs boson mass and width measurements

Both ATLAS and CMS performed a mass measurement of the Higgs boson exploiting the channels with the best mass resolution (1-2%): the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell(\ell = e, \mu)$. The mass measurements of each experiment as well as the combination, are shown in Figure 1. The combined mass of the Higgs boson is $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$. The dominant systematic uncertainty is related to the scale uncertainty on the electron, photons and muons. The compatibility of the four measurements is tested using the likelihood ratio and the resulting $p-$value is 10%.

In the SM, the predicted width for a $m_H = 125$ GeV Higgs boson is $\Gamma_H = 4.07$ MeV. A direct upper limit of $\Gamma_H < 1.7$ GeV at 95% CL on the total width

Figure 1: Summary of Higgs boson mass measurements from the individual analyses of ATLAS and CMS and from the combined analysis.

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In the SM, the predicted width for a $m_H = 125$ GeV Higgs boson is $\Gamma_H = 4.07$ MeV. A direct upper limit of $\Gamma_H < 1.7$ GeV at 95% CL on the total width
has been set by CMS using the invariant mass distribution of the diphoton and four leptons final states. CMS also set a lower limit of \( \Gamma_H > 3.5 \cdot 10^{-9} \) MeV at 95% CL by measuring the lifetime of the Higgs boson in the ZZ channel. An indirect constraint can be obtained by the ratio between on-shell and off-shell production of the Higgs boson under the strong assumption that the ratio of coupling constants remains invariant at the low and high \( m_{VV} \) values. The indirect limit from ATLAS is \( \Gamma_H < 22.7 \) MeV (33 MeV expected) at 95% CL \(^2\) while from CMS is \( \Gamma_H < 13 \) MeV (26 MeV expected) at 95% CL \(^3\).

2.2 Measurement of the coupling properties of the Higgs boson

Both the experiments published at the end of Run1 analyses targeting to the measurement of the Higgs boson production rate in several combinations of production and decay modes \(^4\), \(^5\). All these measurements have been combined together to probe the coupling properties of the Higgs boson \(^6\). More than 600 experimental categories contribute to the combination. Each category can receive contributions from different processes and can bring information about different couplings. Different signal strength parametrizations can be chosen with the limitation that single analysis channels are always only sensitive to the product of production cross sections and the decay branching ratios. Only combining them, the different production and decay modes can be partially disentangled. The signal strength modifier parametrization measure the observed signal yield relative to the SM expectation and it is defined as

\[
\mu_i^f = \frac{\sigma_i \cdot BR_i^f}{(\sigma_{i,SM} \cdot BR_{i,SM}^f)} = \mu_i \cdot \mu_f
\]

where \( \mu_i \) and \( \mu_f \) are multiplicative scale factors to the SM expectations from signal events produced via process \( i \) and decaying to final state \( f \). Figure 2 shows the results of fits using two signal strength parametrizations, in which either all production cross sections are fixed to their SM values \(^2(a)\) or alternatively all decay BRs are fixed to their SM value \(^2(b)\). The compatibility with the SM expectations is at the level of 60% and 24% respectively. Under the above assumptions, a significance of more than 5\( \sigma \) is obtained for the VBF production mode and \( \tau\tau \) decay, and the evidence of associate production of the Higgs boson with a vector boson (W or Z) is also observed. It is also possible to scale all production and decay modes with a single signal strength parameter \( \mu \) and, in this case, the combined ATLAS-CMS measurement is

\[
\mu = 1.09 \pm 0.07(\text{stat})^{+0.09}_{-0.08}(\text{syst}) \quad (1)
\]
Figure 2: Best fit results for the production (a) and decay (b) signal strengths for the combination of ATLAS and CMS data. The results from each experiment are also shown. The error bars indicate the 1σ (thick lines) and 2σ (thin lines) intervals. (c) Fit results for two parametrizations allowing BSM loop couplings ($\kappa_V \leq 1$ or $BR_{BSM}=0$).

In addition, the results can be interpreted in a LO framework \(^7\) ($\kappa$ framework) in which coupling modifiers are introduced to parametrize possible deviations from the SM predictions of the Higgs boson couplings to SM bosons and fermions. Since the width of the Higgs boson is unknown, an additional assumption needs to be done. Two possible constraints are either $\kappa_V \leq 1$ or $BR_{BSM}=0$. The former is satisfied by several theoretical extensions of the SM while the latter does not allow for invisible or undetected decays or modifications to BR which are not measured directly. The two results are shown in figure 2(c).

2.3 Spin and Parity studies

In the SM the Higgs boson has spin zero and even CP value ($J^{PC} = 0^{++}$) and a deviation from this will be a sign of BSM physics. The $J = 1$ is excluded from the decay in two photons. Various spin and parity models have been studied by using the angular and kinematic distributions in decays of the Higgs to dibosons without taking into account the measured rates to minimize the model dependence of the results. The ratio of profiled likelihoods for the SM and the alternative hypothesis is used as test statistics, its distribution for the SM and alternative hypothesis is evaluated on pseudo-experiments and the $CL_s$ is used.
to assess the level of exclusion of the alternative model. The analyses combine
the information from $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow \ell\ell\nu\nu$, and in the case
of the ATLAS experiment also $H \rightarrow \gamma\gamma$. Figure 4 shows the distribution of the
test statistics for the SM Higgs boson and alternative models for ATLAS and
CMS 8, 9. The alternative non-SM hypotheses with are excluded at more
than 99% confidence level.

![Figure 3](image)

Figure 3: Distribution of the test statistics for the SM Higgs boson and alter-
native models from ATLAS (a) and CMS (b).

3 First results with 2015 LHC Run2 collision data.

During 2015 both ATLAS and CMS experiments collected their first data at
$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$ and 2.8 fb$^{-1}$ respectively. Given the still limited amount
of data, the sensitivities for the SM Higgs boson analyses were still lower with
respect to Run1. On the other hand, the searches for new heavy particles
started to be already competitive with respect to the Run1 results thanks to
the gain in the parton luminosities.

3.1 SM Higgs into dibosons

Figure 4(a) shows the Higgs boson cross-section measurement performed by
ATLAS as function of the center of mass energy of the LHC proton proton
collisions obtained with a combination of the $ZZ$ and $\gamma\gamma$ final states 10). The
statistical uncertainty on the 13 TeV measurements is still the dominant uncer-
tainty. A 3.4σ significant measurement (assuming SM yields) was expected but
the observation yield to 1.4σ. The compatibility with the SM has been quantified at the 1.3σ level. Also CMS performed first measurements using collision data at √s = 13 TeV. Figure 4(b) shows the distribution of m_{4ℓ} measured by CMS while figure 4(c) the fiducial cross section measurement performed in the H → ZZ^* → 4ℓ channel as a function of √s.

![Graphs showing distributions and cross sections](image)

Figure 4: Combined H → ZZ^* → 4ℓ and H → γγ cross section measured by ATLAS as function of √s. (b) CMS distribution of the four-lepton invariant mass measured with 2.8 fb^{-1} of data at √s = 13 TeV and (c) the measured fiducial cross section as a function of √s in the H → ZZ^* → 4ℓ channel.

3.2 Heavy resonance searches in the diboson final states

Several ATLAS and CMS analyses have been designed to exploit the big potential of the first LHC collisions at √s = 13 TeV in the search for BSM physics in the diboson final states like: sequential Standard Model (Z' and W', J = 1), Randall-Sundrum graviton (RS G^*, J = 2), Bulk RS graviton (Bulk G^*, J = 2), HVT Model, extended Higgs sectors (J = 0). The strategy is common to most of the analyses and consists in the search for an excess in the m_{VV} spectra over a smooth background, which is usually fit using functions or predicted with MC simulations. In addition, for resonances decaying into W and Z bosons, boosted topologies of the jets coming from the hadronic vector boson decays are extensively investigated. In all the searches, no significant excess was found, with the exception of the resonance search in the γγ final state. ATLAS experiment observed the largest deviation from background only hypothesis at about m_{γγ} =750 GeV with global (local) significance of 2.0σ (3.9σ) for a J = 0 hypothesis with Γ_X=45 GeV and of 1.8σ (3.6σ) for a J = 2 hy-
pothesis with \( \Gamma_X = 6\% m_X \) \(^{12}\). The compatibility with the background-only hypothesis as a function of the assumed mass \( m_X \) and relative width \( \Gamma_X/m_X \) for the ATLAS analysis, optimized for a spin-0 resonance search, is shown in Figure 5(a). CMS experiment observed the largest deviation from background only hypothesis at about \( m_{\gamma\gamma} = 760 \) GeV with global (local) significance of \(< 1.0\sigma \) (2.8\( \sigma \) for \( J=0 \) and 2.9\( \sigma \) for \( J=2 \)) with a preference for a narrow signal \(^{13}\). These results are shown in figure 5.

Figure 5: (a) Compatibility with the background-only hypothesis as a function of the assumed mass \( m_X \) and relative width \( \Gamma_X/m_X \) for the ATLAS analysis optimized for a spin-0 resonance search. (b) Observed \( m_{\gamma\gamma} \) spectra by CMS for the events with both photons in the ECAL barrel detector. (c) Observed CMS background-only \( p \)-value for spin-0 narrow resonances as a function of \( m_{\gamma\gamma} \) from the combined analysis of the 8 and 13 TeV data. The results for the 8 and 13 TeV data sets are also shown separately.

4 Conclusions

The LHC Run 1 physics program has been very successful and both ATLAS and CMS started their era of the Higgs boson properties measurements after its discovery in summer 2012. The results of these studies, performed by the two experiments using about 25 fb\(^{-1} \) of proton-proton collision data at \( \sqrt{s} = 7 \) and 8 TeV, are consistent with the Standard Model expectations within the uncertainties.

The LHC Run2 started in 2015 at \( \sqrt{s} = 13 \) TeV and about 3 fb\(^{-1} \) have been delivered to ATLAS and CMS. Preliminary results on the Higgs boson physics
at this center of mass energy have been obtained by the two experiments and, with the ~30 fb$^{-1}$ expected at the end of 2016, it will be possible to improve the precision of most of the current Higgs boson related measurements. Although no high-mass Higgs boson nor other exotic resonance has been found yet, the collected luminosity at $\sqrt{s} = 13$ TeV during 2015 allows already to set limits more stringent than those obtained in Run1. The 750 GeV mild excess in the $\gamma\gamma$ channel is quite intriguing and, already with the data expected by August 2016, ATLAS and CMS experiments will be able to determine the origin of this excess observed with 2015 data.

References

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