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Higgs rare decays at ATLAS and CMS

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More than a decade has passed since the start of the operation of the Large Hadron Collider at CERN and the discovery of the Higgs boson by the ATLAS and CMS Collaborations. The so far observed Higgs boson decay modes cover around 90% of the total Higgs boson width. The rare and yet unobserved Higgs boson decay channels could potentially be affected by the new physics, beyond the Standard Model. It is then crucial to search for these experimentally challenging decay modes in order to have a more complete characterisation of the Higgs boson physics sector. This was enabled with LHC Run 2 data having both increase in the Higgs production rate, with increased energy, and also the increase in the recorded luminosity. Both ATLAS and CMS have refined and advanced their analysis techniques, contributing further to increase in Higgs analyses sensitivity.

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1. Introduction

The discovery of the Higgs boson by the ATLAS [1] and CMS [2] Collaborations at CERN Large Hadron Collider (LHC) in 2012 is one of the most important events in the history of particle physics [3–5]. In recent years, observation of the leading Higgs boson decay modes has covered more than 90% of the total width. However, there are still rare, yet unseen and experimentally very challenging decay modes of the Higgs boson to be observed, that could potentially be affected and altered by the new physics, beyond the Standard Model (SM). A more complete characterisation of the Higgs boson physics sector will be made possible by searching for these rare decay modes of the Higgs boson. In the LHC Run 2, the Higgs boson production rate has increased due to higher centre-of-mass energy and also higher luminosity, with respect to the LHC Run 1. Many analysis techniques used by ATLAS and CMS Collaborations were improved, enhancing signal sensitivity.[1]

2. Higgs boson decay to pair of muons

Searches for Higgs boson decays into a pair of muons were performed by the ATLAS and CMS Collaborations [6, 7]. This is the most experimentally sensitive probe of the Higgs boson interaction with the second generation fermions at the LHC. In the SM, the Higgs boson branching fraction into a pair of muons is 2.18×10^{-4} for Higgs boson mass of 125 GeV, with a signal appearing as a narrow peak in the di-muon invariant mass spectrum, on top of the falling background composed mostly from Drell-Yan, $t\bar{t}$ and diboson events. The analyses performed by the ATLAS and CMS Collaborations used multivariate analysis techniques to extract the Higgs$\rightarrow \mu\mu$ signal, with different number of categories in main Higgs boson productions modes. In all event categories, both at ATLAS and CMS, the dimuon invariant mass spectrum was used as discriminating variable, except in the vector boson fusion (VBF) channel at CMS, where a deep neural network (DNN) was used to extract the signal. The signal strength that is the product of cross section and branching fraction relative to the SM expectation measured by ATLAS is 1.2 ± 0.6 as shown in Figure 1. This corresponds to an observed (expected) significance over the background-only hypothesis of 2.0 (1.7) standard deviations. The CMS Collaboration reported the first evidence of Higgs couplings to muons, having measured the signal strength of $1.19^{+0.44}_{-0.42}$, as shown in Figure 2, which corresponds to an observed (expected) signal significance of 3.0 (2.5) standard deviations.

3. Higgs boson decay to Z boson and photon

The ATLAS and CMS Collaborations have searched for the Higgs boson decay to Z boson and photon [8, 9], a rare decay mode occurring via loop-induced diagrams. In the analysis by the ATLAS Collaboration there were six event categories constructed, based on the lepton flavour and kinematical properties of the event. The BDT is trained to separate the VBF production mode from other Higgs production modes. It is used to define VBF-enriched category of events with at least two jets. The observed (expected) signal significance is found to be 2.2 (1.2) standard deviations, respectively. The upper limit on the production cross section times branching ratio was found to be

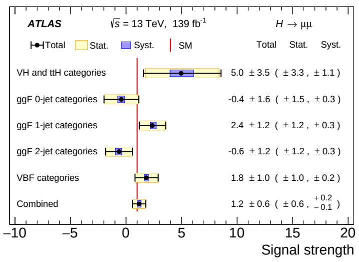

Figure 1: The best-fit values of the signal strength parameters for the five major groups of categories (ttH+VH, ggF 0-jet, 1-jet, 2-jet, and VBF), together with the combined value. [6]

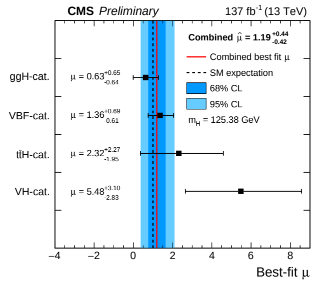

Figure 2: Signal strength modifiers measured for m_H= 125.38 GeV in each production category (black), compared to the result of the combined fit (red) and SM expectation (grey) [7].

3.6 times the SM expectation, at the 95% confidence level. The best-fit value for the signal yield normalised to the SM prediction is $2.0^{+1.0}_{-0.9}$. The weighted $Z\gamma$ invariant mass ($m_{Z\gamma}$) distribution of events satisfying the $H \to Z\gamma$ selection in data is shown in Figure 3. The CMS Collaboration has searched for the Higgs boson decaying to Z boson and photon, with Z boson decaying to a pair of electrons or muons. All Higgs production modes were considered and eight mutually exclusive event categories were constructed. The best fit value of the signal strength for m_H = 125.38 GeV is measured at 2.4±0.9. The observed (expected) limits on the cross section times branching ratio were found to be 4.1 (1.9), respectively. An excess of events over the background-only hypothesis with a significance of 2.7 standard deviations, where 1.2 standard deviations were expected, is reported. The upper limit on the signal strength at the 95% confidence level is presented in Figure 4.

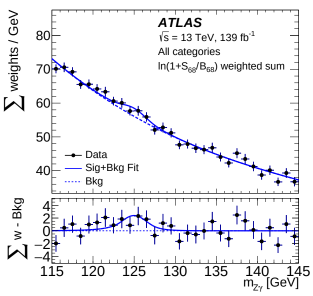

Figure 3: Weighted $Z\gamma$ invariant mass ($m_{Z\gamma}$) distribution of events satisfying the $H \to Z\gamma$ selection in data [8].

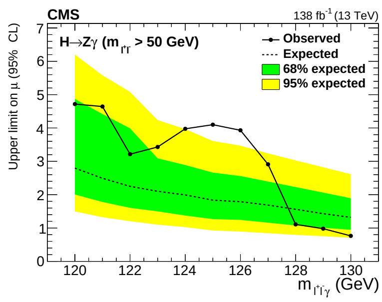

Figure 4: Upper limit (95% CL) on the signal strength (μ) relative to the SM prediction, as a function of the Higgs boson mass. [9].

4. Higgs boson decay to pair of charm quarks

The Higgs boson decay to pair of charm quarks has a relatively small branching ratio of 2.89% and also a very large background from multijet events. Besides that, tagging of charm jets is challenging to perform at the LHC. The analyses performed by the CMS and ATLAS collaborations study the VH production mode. In the analysis performed by CMS, two event topologies were considered: the so-called "merged-jet" topology with $p_T(H)$ > 300 GeV, where the two jets are reconstructed as one merged jet, and the "resolved-jet" topology where the two c-tagged jets are reconstructed separately [10]. At CMS, for the merged jet topology, a c-jet tagger using the DNN algorithm ParticleNet [11] was applied, yielding an improvement of a factor of 4 to 7 in the rejection of other jet flavors when compared to the previously used DeepAK15 discriminant [12, 13]. The analyses at both ATLAS and CMS use event categories with either zero, one or two leptons. The ATLAS Collaboration uses two discriminants based on multivariate algorithms to tag either b-hadrons or c-hadrons [14]. The efficiency to tag c-jets was measured in simulation events ($t\bar{t}$) to be 27% and b-jet and light jet misidentification rates was measured to be 8% and 16%, respectively. In the ATLAS analysis, the categories were made based on the vector boson transverse momentum and the number of jets and c-tagged jets. The invariant mass of the two c-tagged jets was used in a likelihood fit to extract the signal. The analysis strategy was validated by the diboson measurement, that yielded with a signal strength of $1.1^{+0.23}_{-0.21}$ corresponding to an observed (expected) significance of 2.6 (2.2) standard deviations for the VZ production (where Z$\rightarrow$ cc), and 3.8 (4.6) observed (expected) for the VW production (where $W \rightarrow cq$), of which the latter represents an evidence for the $VW \rightarrow cq$ decay. At CMS, the Higgs boson candidate invariant mass was fitted in the merged-jet analysis, while a BDT discriminant was trained for the usage in the resolved-jet analysis. An observed (expected) signal significance in the VZ production (where $Z \rightarrow cc$) of 4.4 (4.7) standard deviations was reported in the merged-jet topology, while 3.1 (3.3) standard deviations was obtained for the resolved-jet case. The two analyses led to a signal strength of $1.01^{+0.23}_{-0.21}$, corresponding to an observed (expected) signal significance of 5.7 (5.9) standard deviations and it is the first observation of the $Z \rightarrow cc$ process at hadron collider. The observed (expected) upper limits at 95% confidence level on the VH production cross section times the $H \rightarrow cc$ branching fraction are 31 (26) times the SM expectation for the ATLAS, and 7.60 (14.4) times the SM expectations for the CMS analysis, as shown in Figures 5 and 6, respectively.

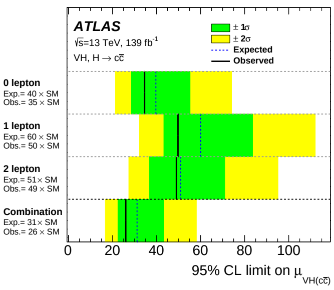

Figure 5: The observed and expected 95% CL upper limits on the cross-section times branching fraction normalised to its SM prediction [10].

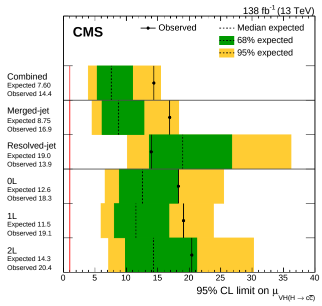

Figure 6: The 95% CL upper limits on $\mu_{VH(H\rightarrow cc)}$. Green and yellow bands indicate the 68/95% intervals on the expected limits [14].

5. Conclusion

Studies of rare Higgs boson decays are essential to probe the Higgs sector and search for indirect new physics, beyond SM. The first evidence of Higgs couplings to muons was reported by the CMS Collaboration, without any deviations from the SM. Most stringent limits on many rare Higgs decay modes were extracted. Further improvements are expected in Run 3 of the LHC.

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