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BSM H searches and rare H decay searches at CMS and ATLAS

Stephane Cooperstein, on behalf of the ATLAS and CMS Collaborations

Abstract

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BSM H SEARCHES AND RARE H DECAY SEARCHES

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Searches for rare Higgs boson decays and extensions of the Higgs sector beyond the standard model are key to probing the dynamics of electroweak symmetry breaking. With the large LHC Run-2 dataset, considerable progress has been made by ATLAS and CMS in probing the largely unexplored Higgs boson interactions with the lighter fermions, as well as in searching for signs of new physics in the Higgs sector with mass scales ranging from 100 MeV to several TeV. The results presented here are either brand new for this conference, or were released in the weeks just before.

1 Introduction

The extremely large datasets collected by ATLAS and CMS at the LHC are beginning to open new frontiers in our exploration of the Higgs sector. With a vast collection of candidate Higgs boson events, we have been able to probe extremely small Higgs boson couplings and to search for signs of new physics with unprecedented reach [1,2,3,4,5]. We are just getting started in experimentally probing the dynamics of mass generation for the first and second generation fermions, with the first evidence for a second generation Yukawa interaction recently achieved via a measurement of the Higgs boson decay to muons [6,7]. [a]

The results reported here were all either released for this talk, or just before the start of this conference. This is a testament to the huge effort devoted in the past years to exploring these new frontiers in the Higgs sector. Enormous progress has been made in expanding the physics reach of the data we have collected. The new search for the Higgs boson decay to charm quarks in particular has demonstrated the feasibility of measuring the charm Yukawa interaction at the LHC, a key test of electroweak symmetry breaking that until now had been thought to be impossible. In addition, several new searches for additional particles within the Higgs sector have found localized excesses over the background that, while not statistically conclusive, will be important channels to probe with the upcoming Run-3 data. Although this report highlights brand new results from CMS, both ATLAS and CMS have made extensive developments within this field in the past years.

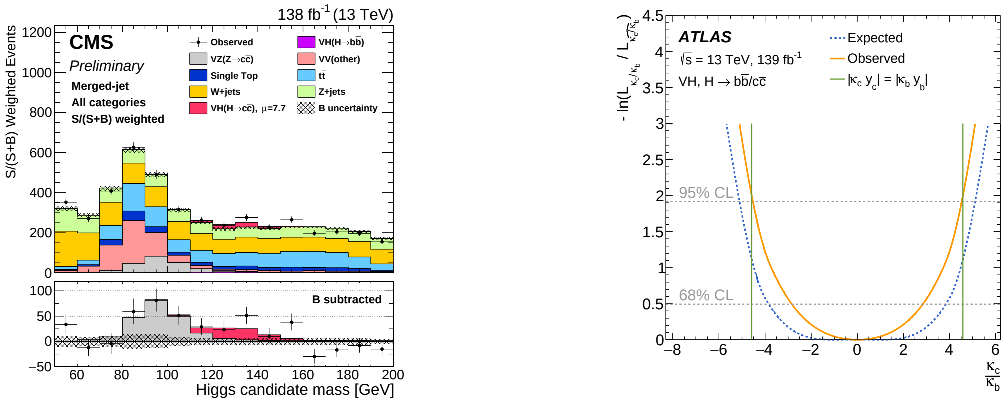

Figure 1 – Left: the reconstructed $H \to c\bar{c}$ candidate mass for the combination of merged-jet channels in the CMS $H \to c\bar{c}$ search [8]. Right: negative profile log-likelihood ratio as a function of the ratio of H-c to H-b coupling strength in the kappa framework, from the ATLAS $H \to c\bar{c}$ search [9].

2 Higgs boson decay to charm quarks

Explaining the flavor hiearchy of the Yukawa interactions is a key puzzle of the standard model, and experimentally probing the mass generation mechanism for the lighter fermions is a key test of the Yukawa sector. By measuring Higgs boson couplings with the lighter fermions, we test this hiearchy at lower scales where new dynamics can be present that would have a negligible overall effect in the Higgs boson interactions with the heaviest particles.

The search for Higgs boson decay to a charm quark-antiquark pair is extremely challenging at the LHC because of the very large multijet background and the difficulty in isolating jets originating from charm quark fragmentation. The new searches for $H \to c\bar{c}$, in the most sensitive VH production channel, demonstrate a huge effort to make the most of the Run-2 data, and pave the way for the eventual measurement of this process. Recent large improvements in charm-jet tagging in particular have made possible a measurement in this channel with Run-2 data with precision comparable to what had been recently projected for the end of the HL-LHC [8]. These developments include the first application of graph networks to jet tagging at the LHC, as well as multiple applications of multivariate regressions to discern the resonant signal with substantially better resolution. For a detailed description of the new $H \to c\bar{c}$ search from ATLAS, refer to the dedicated contribution on this topic in these proceedings. The new CMS $H \to c\bar{c}$ search is a combination of two analyses targeting different $H \to c\bar{c}$ candidate topologies - a merged-jet analysis in which the $H \to c\bar{c}$ candidate is reconstructed within a single large-radius jet, and a resolved-jet analysis in which the H candidate is reconstructed by combining two distinct charm-tagged jets.

Figure 1 (left) shows a distribution of the reconstructed $H \to c\bar{c}$ candidate mass from the CMS search. A resonant contribution from diboson events including a Z boson decay to $c\bar{c}$ ($VZ, Z \to c\bar{c}$) is clearly visible (shaded grey). The overall statistical significance of the observed $VZ, Z \to c\bar{c}$ signal is 5.7σ. This first observation of a $Z \to c\bar{c}$ decay at a hadron collider is a key validation of the charm-jet tagging algorithms, demonstrating with LHC data the reliability of the large improvements in this analysis. An upper limit of 14 (8) times the standard model expectation for $BR(H \to c\bar{c})$ is observed (expected in absence of signal). In addition, a new projection has been made for this search with $3000 fb^{-1}$ of HL-LHC data, incorporating the improvements developed for this new Run-2 analysis. The projected precision for the measurement of the Higgs-charm coupling is about 100%. The new ATLAS $H \to c\bar{c}$ search also performs a combination with the $VH, H \to b\bar{b}$ measurement channels. This provides the first exclusion of a Higgs-charm quark coupling larger than the Higgs-bottom quark coupling, as shown in Fig. 1 (right). This is a huge step forward in our path towards potentially measuring $H \to c\bar{c}$ at the LHC, and further improving this search will be an important priority in the years to come.

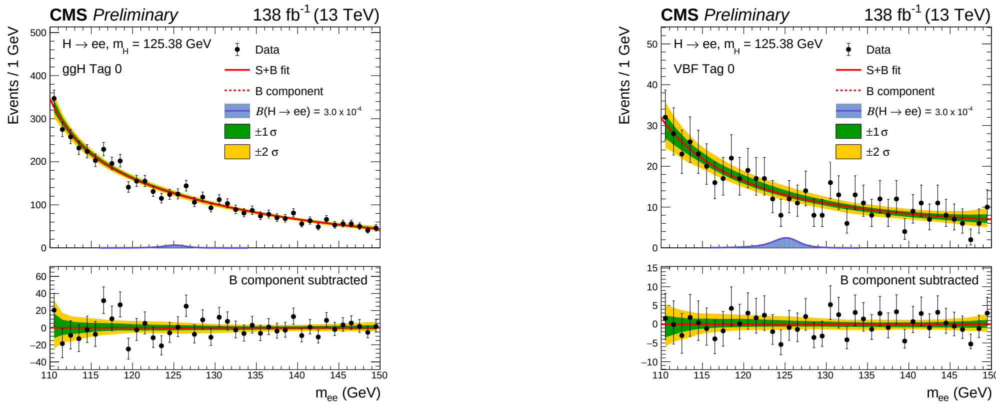

Figure 2 – Distribution of the electron-positron invariant mass in the $H \to e^+e^-$ event categories with the highest expected signal purity, for the inclusive H production channel (left) and the VBF-enriched channel (right) [10].

3 Higgs boson decay to an electron-positron pair

The search for Higgs boson decay to an electron-positron pair is the most sensitive probe of first generation Yukawa interactions at the LHC. Measuring Higgs boson interactions with first generation fermions is extremely difficult because of the very small coupling strengths, with the expected branching fraction for $H \to e^+e^-$ at the level of $5 \cdot 10^{-9}$. Any observed signal in the $H \to e^+e^-$ search at the LHC would therefore be a clear indication of new physics in the mass generation mechanism for the electron.

This new analysis searches for a resonance in the reconstructed invariant spectrum of electron-positron pairs in two channels, one targeting the inclusive Higgs boson production and one enriched in Higgs bosons produced via the vector boson fusion (VBF) mode [10]. Events are further categorized based on the output of a multivariate classifier trained to discern the $H \to e^+e^-$ signal in each channel from the Drell-Yan and $t\bar{t}$ backgrounds.

Figure 2 shows the electron-positron mass distribution in the category with the highest expected signal purity in the inclusive H production channel (left) and the VBF-enriched channel (right). No significant excess in data is observed over the expected background, and an upper limit on $BR(H \to e^+e^-)$ is set at 95% C.L. of $3 \cdot 10^{-4}$, the most stringent limit to date.

4 Search for Higgs boson decays into two merged-photon pairs

Additional (pseudo)scalar particles with Higgs-like couplings are predicted by many well-motivated extensions of the standard model Higgs sector, including the (N)MSSM and Two Higgs Doublet models. If the mass of the scalar, denoted a, is less than half the Higgs boson mass, searches via the decay of the SM-like Higgs boson ($H \to aa$) are accessible. The dominant a decay modes vary significantly depending on m_a, yielding a rich topology of experimental final states to consider. Both ATLAS and CMS have pursued a large and diverse $H \to aa$ search program beyond the scope of this summary. Figure 3 (left) shows a summary of exclusion limits in for the Two Higgs Doublet plus Singlet (2HDM+S) Type-I model from recent $H \to aa$ searches by ATLAS [12]. This report highlights a new CMS search in a previously unexplored topology, where $0.1\ \text{GeV} < m_a < 1.2\ \text{GeV}$ and each scalar decays to a pair of photons [11]. Figure 3 (middle) shows the leading order diagram for this process.

Because of the low scalar mass, the scalar is highly Lorentz-boosted and the pair of photons from the scalar decay tend to be highly collimated. The photons subsequently induce overlapping electromagnetic showers in the CMS calorimeter, which are not efficiently reconstructed using traditional resolved photon reconstruction algorithms. A dedicated end-to-end machine learning-based merged-photon reconstruction algorithm was developed, taking minimally processed detector-level information as input and therefore bypassing the traditional photon recon-

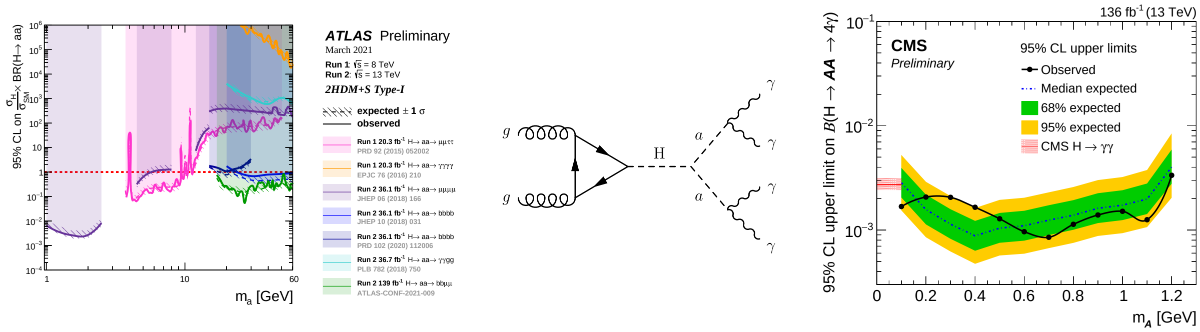

Figure 3 – Left: summary of exclusion limits for 2HDM+S Type-I models from recent ATLAS H $\rightarrow$ aa searches [12]. Middle: Leading order diagram for H decay to two scalars, each of which decay to a pair of photons. Right: 95% C.L. upper limits on the branching fraction of the SM-like H to two pairs of merged photons, as a function of scalar candidate mass [11].

struction techniques to estimate the scalar particle mass [13]. This new reconstruction approach has made possible the first search in this topology.

A data sample is selected by requiring two reconstructed merged-photon pairs, then a maximum likelihood fit is performed to a 2D template in the mass of each of the two merged-photon candidates, as estimated by the multivariate regression. No significant excess is observed in the data over the expected background, and upper limits are set on BR(H $\rightarrow$ aa $\rightarrow 4\gamma$) as a function of m_a (Fig. 3 right). Although this analysis was developed to search for a promptly decaying signature, it is also sensitive to scenarios in which the scalar decays to photons with displacements from the interaction point of up to 10 mm, with the sensitivity degrading with increasing displacement.

5 Search for additional Higgs bosons in the $\tau\tau$ final state

Searches in the $\tau\tau$ final state are a key probe of additional particles in the H sector. Although the decay to $b\bar{b}$ is generally predicted to be dominant, this final state has extremely large multijet backgrounds. Other experimentally accessible channels such as $\mu\mu$ tend to be limited by small predicted couplings. We report a new search in the $\tau\tau$ final state for additional Higgs bosons with mass ranging from 60 GeV to 3.5 TeV [14].

This result combines searches in different tau decay final states: eμ, $\mu\tau_h$, eτ_h, and $\tau_h\tau_h$, where τ_h denotes hadronic tau decays. The "low mass" channel searches for $\tau\tau$ resonances with mass less than 250 GeV and reconstructs the resonance candidate mass with likelihood-based techinques also used in H$\rightarrow \tau\tau$ measurements. The "high mass" channel instead considers resonances with mass greater than 250 GeV and searches for an enhancement over the backgrounds in the transerve mass distribution.

Events are further categorized based on the kinematic properties of the event, as well as the presence of additional b-tagged jets. Two localized excesses are observed in the data. The first excess is concentrated near 100 GeV and has a significance of 3.1σ (2.7σ considering the look-elsewhere effect within the low mass channel), while the second excess is most visible in the "no b-tag" categories of the high mass channel, with mass roughly 1.2 TeV, and has a significance of 2.8σ (2.4σ). Figure 4 shows the distribution of the fitted mass observable in a representative category from the low mass (left) and high mass (middle) channels. Note that a similar search by ATLAS did not observe an excess near 1.2 TeV, whereas the search region for resonances with mass less than 200 GeV was not considered [15].

An additional nonresonant signal interpretation, new for this analysis, is also considered. A t-channel exchange of a vector leptoquark, the dominant production channel for leptoquarks at high mass, would lead to a nonresonant enhancement in the total cross section at high $m_{\tau\tau}$. Various leptoquark models can explain the tensions observed in the lepton flavor universality

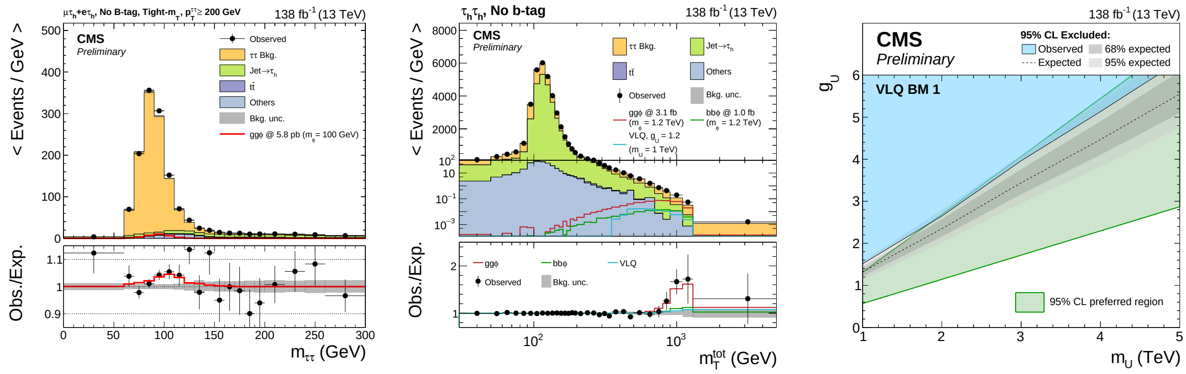

Figure 4 – Representative plots of the fitted observable in the $\tau\tau$ low mass channel (left) and the high mass channel (middle) [14]. Right: excluded parameter region for the vector leptoquark model (blue shaded region), as a function of leptoquark mass and coupling strength, compared to the region preferred by the B physics anomalies (green shaded region) [14].

tests in B meson decays performed by LHCb. The green shaded region in Fig. 4 right shows the region preferred by the B anomalies, compared to the expected and observed limits obtained from the nonresonant interpretation of this search. The model parameter space probed by this search overlaps significantly with the region preferred by the B anomalies. There is a slight excess in the data over the backgrounds, such that the observed limit is slightly weaker than expected in the absence of signal.

6 Search for additional Higgs bosons in the WW final state

The WW final state provides a complementary probe of additional particles within the Higgs sector. This new search looks for resonances with mass ranging from 115 GeV to 5 TeV, considering the final state where both W bosons decay to a neutrino and either an electron or a muon [16]. Because of the significant energy fraction carried by the neutrinos, the reconstructed mass of the dilepton pair differs significantly from the signal resonance mass. A deep neural network was developed to estimate the resonance mass from the visible decay products as well as the missing transverse energy in the event, substantially improving the reconstruction of the expected mass resonance for signal candidates. Figure 5 (left) shows the distribution of the resonance mass estimated by the neural network in a VBF-enriched selected region in the $e\mu$ channel, while Figure 5 (middle) shows the observed upper limit on the production rate times branching fraction as a function of the resonance mass.

The largest localized excess in data over the backgrounds is observed near 650 GeV, with a local (global) significance of 3.8σ (2.6σ), and concentrated in the categories targeting VBF production. Because of the large fraction of missing energy from the neutrinos, the resolution on the mass is still quite broad despite the improvement from the neural network. The excess is therefore compatible with a resonant signal with mass ranging from roughly 600 GeV to 1 TeV.

7 Search for charged Higgs in the $\tau\tau W$ final state

This new result searches for a charged Higgs boson decaying to a W boson and a SM-like Higgs boson, which then decays to a pair of taus [17]. This is the first search in this channel at the LHC, and targets charged Higgs boson production in association with a top quark. A neural network-based algorithm is used to identify fully hadronic top quark decays, and the search combines the $e\tau_h$, $\mu\tau_h$, $e\tau_h\tau_h$, and $\mu\tau_h\tau_h$ channels. Figure 5 (right) shows the expected and observed 95% C.L. upper limits on the production cross section times branching fraction of the signal as a function of the charged Higgs boson mass. No significant excess is observed in the data over the expected backgrounds.

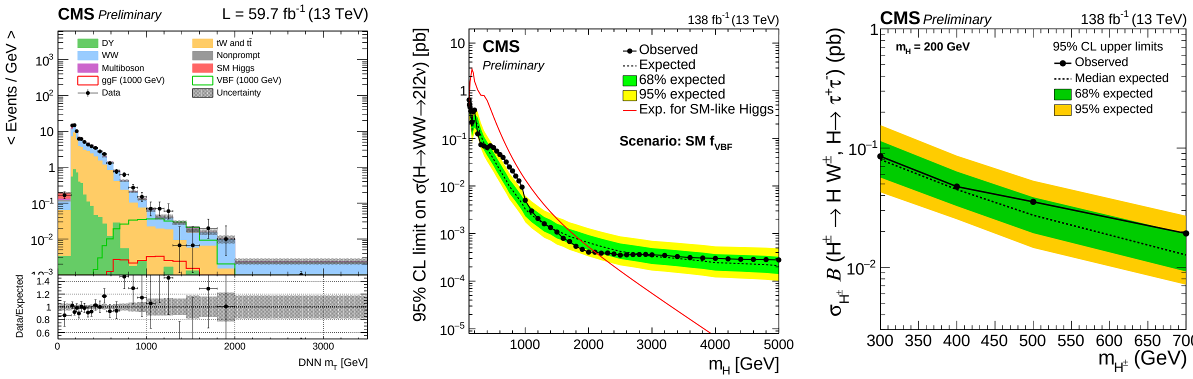

Figure 5 – Left: Predicted WW resonance mass in the VBF-enriched category of the $e\mu$ channel. Middle: 95% C.L. upper limits on cross section times branching fraction for a VBF-produced signal in the H → W$\bar{\text{W}}$ resonance search, as a function of m_H [16]. Right: upper limits on charged Higgs boson production rate times branching fraction, as a function of charged Higgs boson mass [17].

8 Summary

With the enormous datasets delivered by the LHC, we are entering a new era in the characterization of the Higgs boson. In addition to the ongoing efforts to measure the Higgs boson properties with high precision via its interactions with the heavier particles, we are beginning to probe very small Higgs boson couplings including Yukawa interactions with second generation fermions. Enormous progress has been made by ATLAS and CMS in probing the second generation Yukawa interactions with Run-2 data, paving the way for future precision measurements of the H-μ interaction and even demonstrating the possibility of measuring the Higgs interaction with the charm quark at the LHC, which had been considered impossible. We are also significantly expanding the scope of our searches for additional particles within the Higgs sector, including several new results with localized excesses observed that will be important to monitor in the coming years. The wealth of new results shown in this report demonstrate the interest in and importance of these developments in our exploration of this new frontier in the Higgs sector.

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