PROCEEDINGS OF SCIENCE

Beyond Standard Model Higgs boson searches

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The discovery of the Higgs boson at the Large Hadron Collider (LHC) is one of the major achievements of the ATLAS and CMS collaborations. Important questions on the nature of this new boson and on possible extensions of the scalar sector of the Standard Model have been tested by both the ATLAS and CMS collaborations with a vast variety of searches performed at a centre-of-mass energy of 7 TeV and 8 TeV (LHC Run 1). New searches, surpassing the Run 1 sensitivities, have been performed by the LHC collaborations with the proton proton collision data collected in 2015 at a centre-of-mass energy of 13 TeV. Two examples, the searches for $A/H \to \tau\tau$ and $H \to hh$, have been selected for a detailed description in these proceedings.

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1. Introduction

One of the major achievements by the ATLAS [1] and CMS [2] collaborations during the Run1 data taking at a centre-of-mass energy of 8 TeV at the Large Hadron Collider (LHC) is the discovery of a scalar particle, with a mass of approximately 125 GeV, and properties consistent with the Higgs boson predicted in the Standard Model (SM). An important question is whether this new particle is the SM Higgs boson or part of an extended Higgs sector. One interesting approach to answer this question is to search for additional scalars. For the first LHC collision data provided at a centre-of-mass energy of 13 TeV and recorded by the ATLAS and CMS detectors, the collaborations have performed many searches that are motivated by a variety of models beyond the SM. The simplest extensions of the SM involve the addition of a singlet or a doublet field, known as Electroweak Singlet Models (EWS) and Two-Higgs-Doublet Models (2HDM), respectively. Many searches are motivated by these extensions and benchmarks within specific related models, such as the Minimal Supersymmetric Standard Model (MSSM). To a good approximation, the phenomenology of the Higgs sector in the MSSM is described entirely by two parameters: the mass of one of the Higgs bosons and the ratio of the vacuum expectation values, $\tan\beta$. Models in which both an additional singlet and doublet field are added in the Higgs sector have been proposed, and benchmarks in the Next to Minimal Supersymmetric Standard Model (NMSSM) have motivated several additional searches at the LHC. Finally extension with triplets fields has been searched by both the ATLAS and the CMS collaborations.

In these proceedings we present some of the searches performed with the 13 TeV data, which are performed with an integrated luminosity of 3.2 fb^{-1} and up to 2.3 fb^{-1} with the ATLAS [3, 4, 5, 6, 7] and CMS [8, 9, 10] detectors, respectively. In particular, we will focus on the searches of new scalar bosons in the MSSM benchmarks. Both the wide variety of searches and the precise measurement of the Higgs boson couplings performed with an integrated luminosity of 20 fb^{-1} at $\sqrt{s}$ =8 TeV by the ATLAS [11] and the CMS [12, 13, 14, 15] collaborations put stringent limits on the MSSM parameter space. In Fig. 1 is shown the Run1 results by ATLAS and CMS collaborations [16, 17]. Among the new searches performed with the 13 TeV data, the $A/H \to \tau\tau$ and the $H \to hh$ are particularly intriguing and already able to investigate regions of the MSSM parameter space not covered before. For this reason, these proceedings will focus on these two searches.

2. Search for neutral Higgs bosons $H/A \to \tau\tau$

For extensions of the Higgs sector containing two Higgs doublets, the couplings of the heavy Higgs bosons to down-type fermions can be enhanced with respect to the SM for large $\tan\beta$ values. These results in increased branching fractions to τ (and μ) leptons and b quarks, as well as a higher cross section for Higgs boson production in association with b-quarks. This has motivated a variety of searches in $\tau\tau$, bb and $\mu\mu$ final states at the LHC -Run1 [12, 13, 18, 19, 20] with no indication of an excess over the expected SM background.

The Run-2 search for neutral Higgs bosons decaying to τ leptons is performed in three channels by the ATLAS collaboration[3]: the $\tau_e\tau_{\text{had}}$ channel where one τ decays leptonically to an electron and neutrinos and the other hadronically (to hadrons and a neutrino), the $\tau_\mu\tau_{\text{had}}$ channel where the leptonically decaying τ produces a muon and neutrinos, and the $\tau_{\text{had}}\tau_{\text{had}}$ channel where

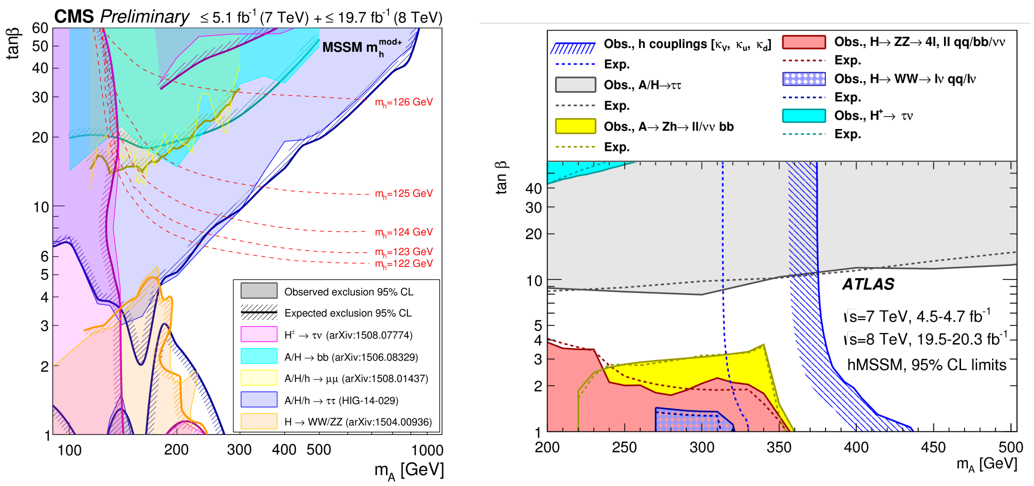

Figure 1: Run1 $m_A - tan\beta$ exclusion plane by (left) CMS experiment and (right) ATLAS experiment.

both τ leptons decay hadronically. In addition to the previous three channels, the CMS collaboration extended the search in the $\tau_e\tau_\mu$ channel in which both τ's decay leptonically [21]. In addition, the CMS collaboration divided the events into two categories based on the number of b-tagged jets: events with exactly zero b-tagged jets and events with at least one b-tagged jet.

2.1 τ_{had} reconstruction

The reconstruction and the identification of hadronic decays of τ leptons are critical aspects for the searches of neutral Higgs bosons H/A. The hadronic decays of τ leptons are predominantly characterised by the presence of one or three charged particles, accompanied by a neutrino and possibly neutral pions. In ATLAS, as reported in Ref. [22], the reconstruction of the visible decay products of the hadronic decays of τ starts with jets reconstructed from calorimeter clusters using the anti-kt algorithm with a radius of $\Delta R = 0.4$ [23]. The τ_{had} candidate must have energy deposits in the calorimeters in the range $|\eta| < 2.5$, with the transition region between the barrel and end-cap calorimeters ($1.37 < |\eta| < 1.52$) excluded, have a transverse momentum greater than 20 GeV, one or three associated tracks and an electric charge of ± 1. A multivariate Boosted Decision Tree (BDT) based identification is used to reject backgrounds from jets, using shower shape and track multiplicity properties. An additional dedicated likelihood-based veto is used to reduce the number of electrons misidentified as τ_{had}. In the ATLAS analysis, two τ_{had} identification selections are used: "loose" and "medium" with efficiencies for true τ_{had} objects of about 65% and 55%, respectively. In CMS, hadronically decaying τ leptons are reconstructed using the hadron-plus-strips algorithm [24]. The algorithm considers candidates with one charged pion and up to two neutral pions, or three charged pions, and is seeded by a jet. The neutral pions decay rapidly into two photons, and they are reconstructed as "strips" of electromagnetic particles, formed from energy depositions in the electromagnetic calorimeter ECAL. The τ decay mode is reconstructed by combining the charged hadrons with the ECAL strips. The τ_{had} candidate must have $|\eta| < 2.3$ and a transverse momentum greater than 20 GeV for the $\tau_e\tau_{\text{had}}$ and $\tau_\mu\tau_{\text{had}}$ channels, while $|\eta| < 2.1$ and $p_{\text{T}} > 40$ GeV for the $\tau_{\text{had}}\tau_{\text{had}}$ channel. The τ_{had} candidates that are also compatible with muons or electrons are rejected. Jets originating from the hadronization of quarks and gluons are suppressed by requiring the $\tau_{\rm had}$ candidate to be isolated, where the isolation variable is computed using a multivariate (MVA) approach [24].

2.2 The $\tau_{\rm had}\tau_{\rm had}$, $\tau_e\tau_{\rm had}$, $\tau_\mu\tau_{\rm had}$ and $\tau_e\tau_\mu$ channels

In the $\tau_{\rm had}\tau_{\rm had}$ channel, multi-jet events form the dominant background, and they are estimated using a data-driven techniques by both collaborations, with a fake-factor method in ATLAS, and with events in data with slightly looser isolation conditions compared to the the signal regions in CMS. These events are then weighted by the extrapolation factor from the nominal selection to this control region as measured in data events with $\tau_{\rm had}$ candidate having the same charge. Events from other processes with a jet misidentified as a $\tau_{\rm had}$, such as W+jets and top-quark backgrounds, are taken from simulation and, in ATLAS, corrected using fake rates measured from data. Events with correctly identified $\tau_{\rm had}$ are taken from simulation, with additional derived data/MC corrections.

In the $\tau_e\tau_{\rm had}$ and $\tau_\mu\tau_{\rm had}$ channels, the background is composed by processes involving jets misidentified as $\tau_{\rm had}$ (multi-jet, W+jets), processes with electrons misidentified as a $\tau_{\rm had}$ ($Z/\gamma \to ee$), and backgrounds with a correctly identified $\tau_{\rm had}$ ($Z/\gamma \to \tau\tau$ or $t\bar{t} \to W^+W^-b\bar{b} \to l\tau_{\rm had}\nu\bar{\nu}b\bar{b}$). To suppress the W+jets backgrund, a cut to reject events with transverse mass $m_{\rm T}(l, E_{\rm T}^{\rm miss})$ (where l is the electron or the muon, and $E_{\rm T}^{\rm miss}$ is the missing transverse momentum) compatible with the W boson are used by both the collaborations. Backgrounds from all processes that involve jets misidentified as $\tau_{\rm had}$ are estimated simultaneously in a data-driven method. For W+jets, the measurement is performed in a region identical to the signal region, but with reversed cut on $m_{\rm T}(l, E_{\rm T}^{\rm miss})$. The multi-jet background is measured in a region defined by inverting the isolation requirement of the electron or muon by the ATLAS collaboration, and by inverting the requirement on the relative charge of the $\tau_{\rm had}$ with respect to the electron or to the muon by the CMS collaboration. Events with electrons misidentified as a $\tau_{\rm had}$ are suppressed by the ATLAS collaboration with a veto of events with the mass $m(\tau_{\rm had}, l)$ in the Z boson mass window, 80 GeV $< m(\tau_{\rm had}, l) <$ 110 GeV, while the CMS collaboration uses a veto of events containing a pair of opposite sign electrons or muons passing slightly looser identification and isolation conditions. Backgrounds with a correctly identified $\tau_{\rm had}$ are taken from simulation, with additional derived data/MC corrections.

Finally, for the $\tau_e\tau_\mu$ channel studied by the CMS collaboration, the contribution from W+jets is small and taken from MC. Events with same sign (e,μ) are used after subtracting the other backgrounds for the multi-jet estimate. All the other backgrounds are taken from simulation, with additional derived data/MC corrections.

The transverse invariant mass of the ditau candidate pair, $m_{\rm T}(\tau_1, \tau_2)$, is used to search for a possible signal contribution on top of the expected backgrounds by the CMS collaboration, while ATLAS used the total transverse mass, defined as $m_{\rm T}^{tot} = \sqrt{m_{\rm T}^2(\tau_1,\tau_2) + m_{\rm T}^2(\tau_1, E_{\rm T}^{\rm miss}) + m_{\rm T}^2(\tau_2, E_{\rm T}^{\rm miss})}$. The results of both collaborations show an observed event yield compatible with the expected event yield from SM processes, within uncertainties. The $m_{\rm T}(\tau_1, \tau_2)$ and $m_{\rm T}^{tot}$ distributions for representative signal regions are shown in Fig. 2.

2.3 Results

The final results are provided both as limits on the cross section times branching ratio as well as a model-dependent limits on various MSSM benchmark models. The limits for all channels

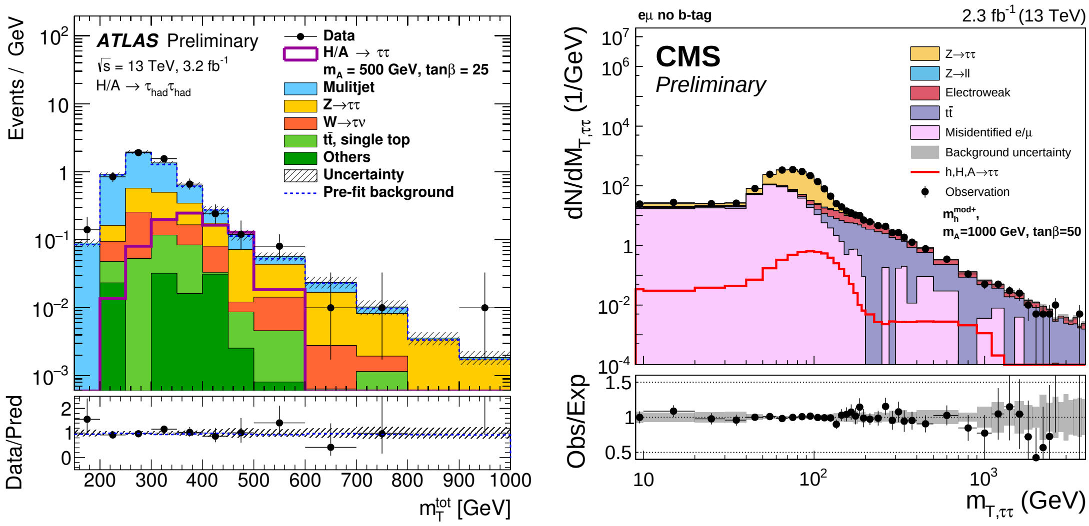

Figure 2: (Left) Post–fit plot of the total transverse mass distribution in f the $\tau_{\rm had}\tau_{\rm had}$ channel by the ATLAS collaboration. (Right) Post–fit plot of the transverse mass distribution in the no b–tag category of the $\tau_e\tau_\mu$ channel by the CMS collaboration.

combined are shown in Fig. 3 and Fig. 4 for the gluon fusion and b-associated production methods respectively, while Fig. 5 shows the expected and observed 95% CL upper limits on tanβ as a function of m_A in the MSSM m_h^{mod+} scenario, and the comparison with the LHC Run1 results. Already with the limited statistics recorded in 2015, the sensitivity exceeds the 8 TeV result for $m_H > 750$ GeV for ATLAS and $m_H > 350$ GeV for CMS.

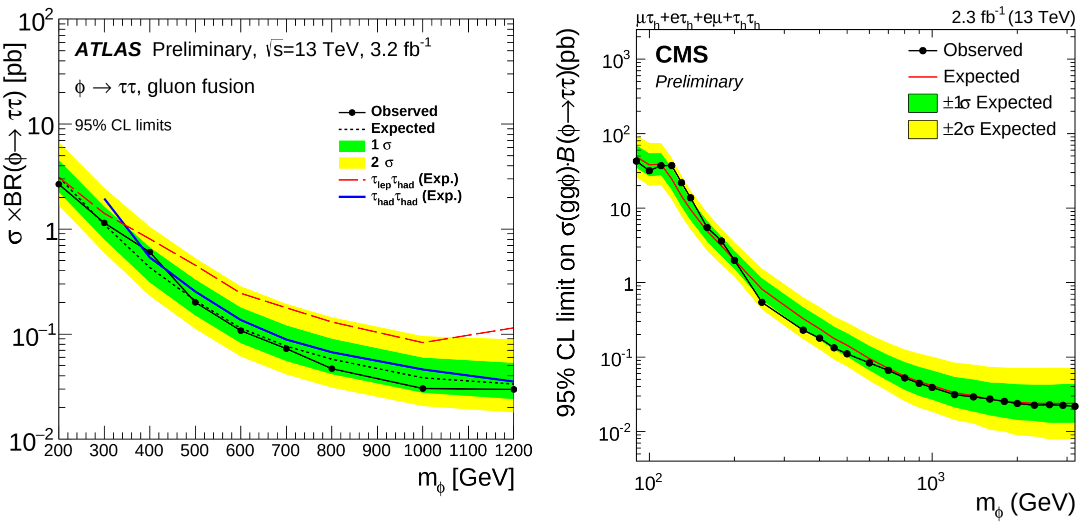

Figure 3: Observed and expected 95% CL upper limits on the product of cross section and the branching fraction $\sigma(pp \to \phi) \times B(\phi \to \tau\tau)$ obtained by the ATLAS collaboration (left) and by the CMS collaboration (right) for the gluon-gluon fusion production.

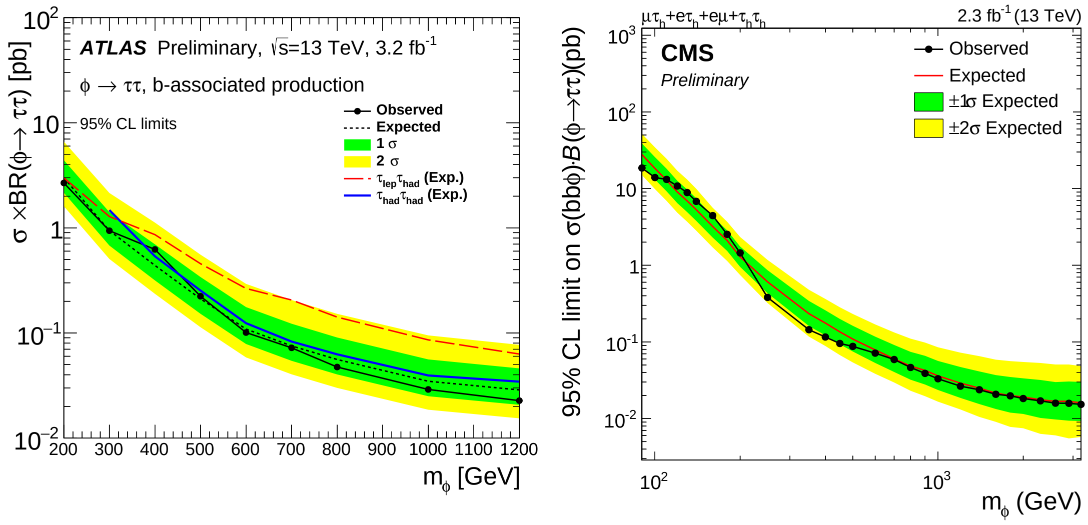

Figure 4: Observed and expected 95% CL upper limits on the product of cross section and the branching fraction $\sigma(pp \to \phi) \times B(\phi \to \tau\tau)$ obtained by the ATLAS collaboration (left) and by the CMS collaboration (right) for the b-associated production.

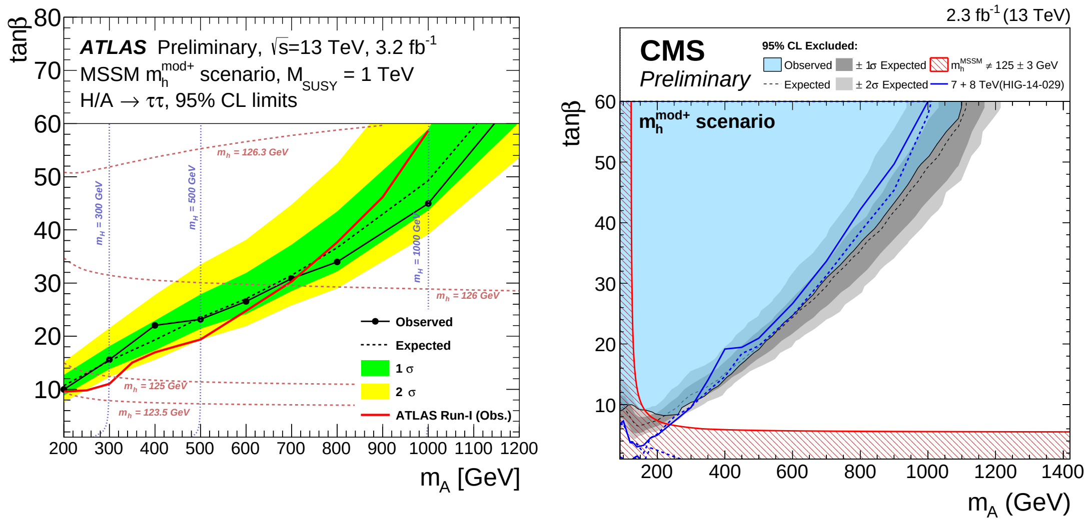

Figure 5: The expected and observed 95% CL upper limits on tanβ as a function of m_A in the MSSM m_h^{mod+} scenario for ATLAS (left) and CMS (right).

3. Search for Higgs boson pair production

The Higgs boson pair production could be used to investigate both the SM and the BSM scenarios.
Searches for *non-resonant hh* production give information on the trilinear coupling present in the SM Higgs potential fields; the same searches could spot out discrepancies with respect to the SM λ_{hhh} introduced by anomalous couplings and new physics.
Similar searches in the *resonant* regime could be used to explore the BSM world; new particles, introduced by extensions in the $\mathscr{L}_{SM}$, could decay in a couple of Higgs SM like boson (Di-Higgs). The experience acquired during the 8 TeV data taking period at LHC for SM Higgs search is used for seek different final state configuration of the Di-Higgs.

In this paragraph an overview of the latest *resonant* results, provided by ATLAS and CMS experiment for 13 TeV collision, will be presented. Both collaborations have produced results with 8 TeV data [25][26] in many Di-Higgs decay configurations as shown in Fig. 6.

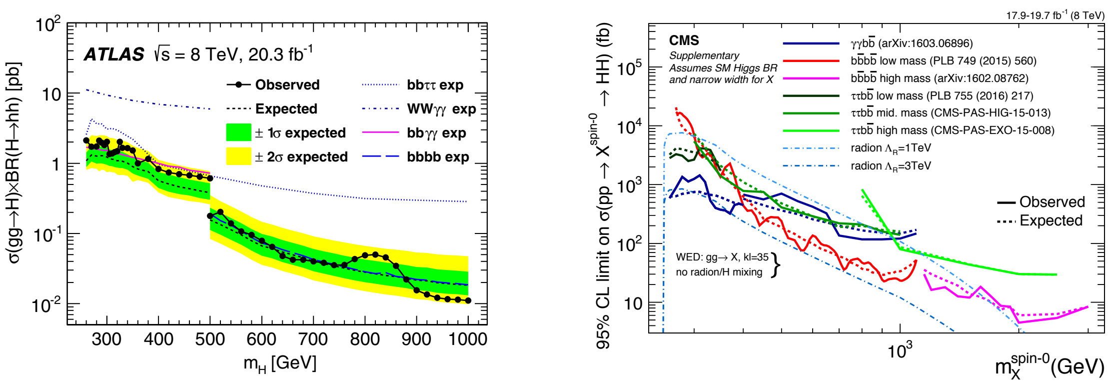

Figure 6: (left) ATLAS combination Higgs boson pair production in the $hh \to bb\tau\tau$, $\gamma\gamma WW^*$, $\gamma\gamma bb$, $bbbb$ channels with 8 TeV data, (right) CMS observed and expected 95% CL upper limits on the product of cross section and the branching fraction $\sigma(gg \to X) \times B(X \to hh)$ obtained by different analyses assuming spin-0 hypothesis.

3.1 $H \to hh \to bbbb$ channel

The Higgs boson decay mode in b quarks has the highest branching ratio, this imply that a Di-Higgs final state, with each Higgs dacaying into a b pair, it's the most prominent one between the others. Although search of this kind of final state should take into account the overwhelming multi-jet background that could limit the sensitivity of the channel with respect to other finale states.

ATLAS and CMS collaborations analysis scan a mass range 260 GeV $< m_H <$ 3000 GeV, particularly CMS cover from 260 GeV to 1200 GeV and ATLAS from 500 GeV to 3000 GeV. Both analysis have different strategy for different m_H ranges: low-mass region (260 GeV $< m_H <$ 400 GeV), medium-mass ragion (400 GeV $< m_H <$ 1200 GeV), boosted region (1200 GeV $< m_H <$ 3000 GeV). The categorisation is chosen to maximise to significance of the analysis.

The results are shown in Fig. 7.

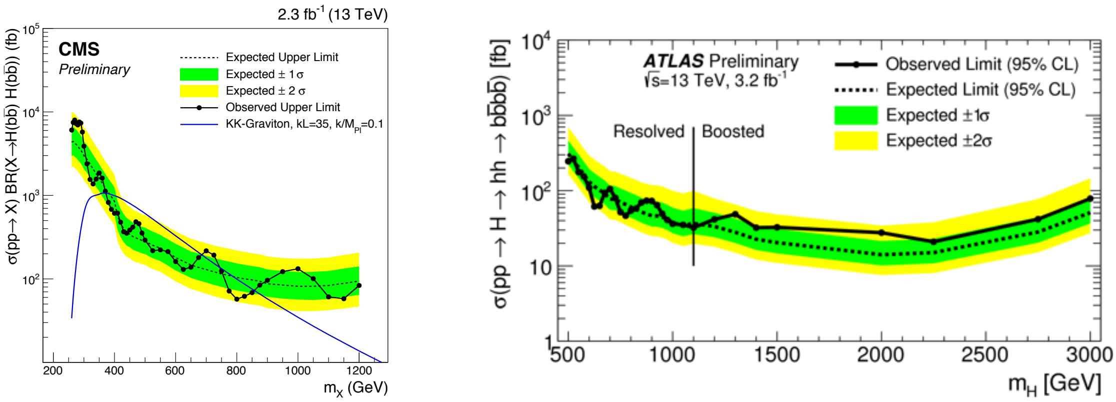

Figure 7: (left) CMS: The observed and expected upper limits on the cross section for a spin-2 resonance $H \to hh \to bbbb$ at a 95% confidence level using data corresponding to an integrated luminosity of $2.3 fb^{-1}$ at 13 TeV using the asymptotic CL_S method, (right) ATLAS: The expected and observed upper limit for $pp \to H \to hh \to bbbb$ with fixed $\Gamma_H = 1$ GeV, at the 95% confidence level .

3.2 $H \to hh \to bb\gamma\gamma$ channel

The $bb\gamma\gamma$ final state is particularly promising for the DiHiggs search, as it benefits from the large branching fraction of the $h \to bb$ decay and the clean di-photon signal, due to high $m_{\gamma\gamma}$ resolution, on top of a smooth continuum di-photon background from multi-jet and multi-photon SM processes.

The analysis performed by ATLAS collaboration scans masses in the range 275 GeV $< m_H <$ 400 GeV. A counting approach is adopted in order to estimate the number of signal and background events.

Observed and expected 95% CL upper limits are shown in Fig. 8.

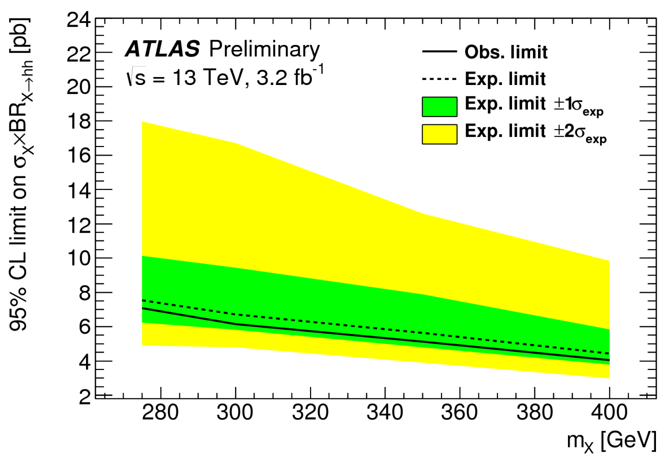

Figure 8: Observed and expected 95% CL upper limits on $\sigma(pp \to H) \times BR(H \to hh)$

3.3 $H \to hh \to bb\tau\tau$ channel

The $bb\tau\tau$ channel can exploit the presence of the τ leptons to suppress the multi-jet background.

The analysis performed by CMS collaboration scans a 260 GeV $< m_H <$ 900 GeV and combine three different $\tau\tau$ final state: $\mu\tau_h$, $e\tau_h$ and $\tau_h\tau_h$, where τ_h stands for the hadronic decays of a τ. The finale m_H shape is constructed using a dedicated kinematic fit procedure.

Observed and expected 95% CL upper limits are shown in Fig. 9.

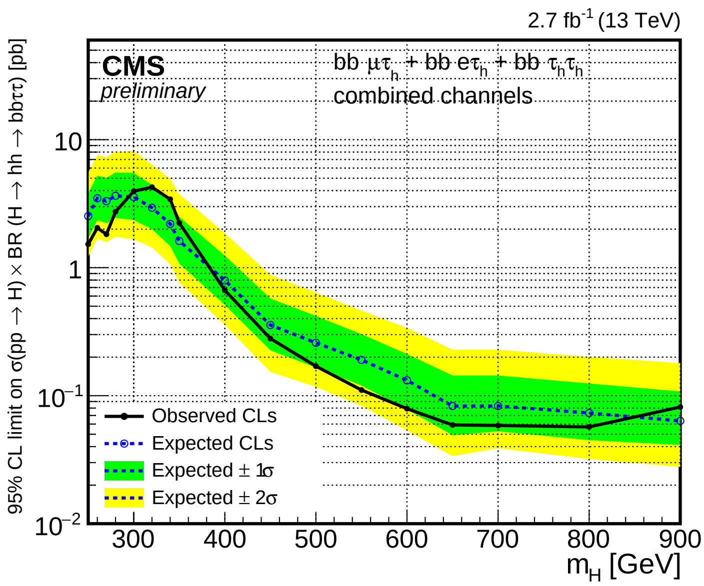

Figure 9: Observed and expected 95% CL upper limits on $\sigma(pp \to H) \times BR(H \to hh \to bb\tau\tau)$ from the combination of the three channels as a function of the mass of the resonance m_H

3.4 $H \to hh \to bbWW$ channel

The search for resonant Higgs pair production, $H \to hh$, where one of the h decays as $h \to bb$, and the other as $H \to WW \to l\nu l\nu$ (where l is either an electron or a muon) is performed by CMS collaboration using LHC proton-proton collision data at 13 TeV. The analysis focuses on the invariant mass distribution of the b-jet pair, searching for a resonant-like excess compatible with the h boson mass in combination with a boosted decision tree discriminant based on kinematic information. The dominant background is tt production with smaller contributions from Drell-Yan and single top processes. Fig. 10 shows the result obtained.

3.5 Results

Results for Di-Higgs resonant searches at 13 TeV don't show presence of a new resonance decaying in two SM Higgs bosons. Exclusion limits are set for all the different final states.

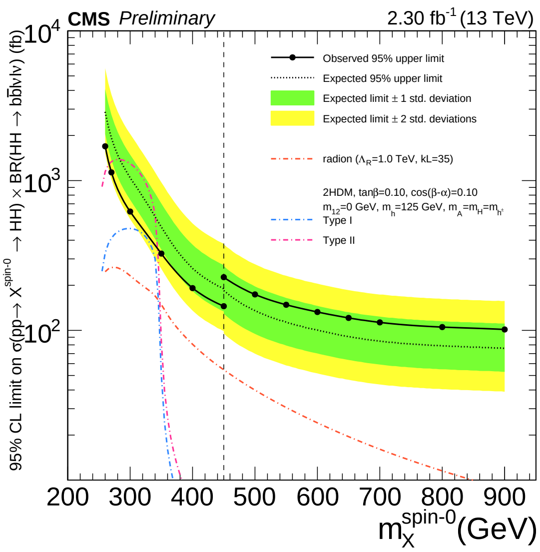

Figure 10: Observed and expected 95% CL upper limits on $\sigma(pp \to H) \times BR(H \to hh \to bbl\nu l\nu)$

4. Conclusions

The discovery of a scalar boson at the LHC strengthened the interest for searches of extension of the scalar sector of the Standard Model. A vast variety of searches have been performed by the ATLAS and CMS collaboration, using the data collected during the Run 1. Thanks to proton-proton collisions at a center of mass energy of 13 TeV, the data collected in 2015 allowed the LHC collaborations to extend the reach in sensitivity in the searches for Higgs bosons beyond the SM. Searches for additional Higgs bosons performed so far have shown consistency with the SM predictions, although the data that will be collected in the next few years can enlighten the nature of the Higgs sector.

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