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Searches for a high-mass Higgs boson in the ZZ and WW decay channels with the CMS detector

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Abstract

Searches for a high-mass Higgs boson decaying into WW and ZZ channels have been carried out using data collected at centre-of-mass energies of 7 and 8 TeV at the LHC collider, corresponding to integrated luminosities of about 5 fb^{-1} and 20 fb^{-1}, respectively. Many different final states have been considered and upper limits on the Higgs boson production cross section have been derived. The results are interpreted in a BSM model containing an additional electroweak singlet.

Keywords: Particle Physics, Higgs boson, Resonance, Electroweak Singlet, CMS Collaboration,

1. Introduction

The standard model (SM) of electroweak interactions [1, 2, 3], the most complete theory describing the interactions between fundamental particles, has been successfully tested during several decades. Its last prediction, the existence of a scalar particle, the Higgs boson (h), associated with the field responsible for spontaneous electroweak symmetry breaking [4, 5, 6, 7, 8, 9], seems to have been confirmed by the observation of a new boson, whose properties match those expected for a SM Higgs, with a mass of approximately 125 GeV$/c^2$, as reported by the ATLAS and CMS Collaborations [10, 11].

The observation of such a boson is consistent with the theoretical constraint coming from the unitarization of diboson scattering at high energies [12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. However, there is still a possibility that the newly discovered particle has no connection or partial connection to the electroweak symmetry breaking mechanism [22, 23]. This includes several popular scenarios, as it is the case of general two-Higgs-doublet models (for a review see [24, 25]) or models in which the SM Higgs boson mixes with a heavy electroweak singlet [26], which predict the existence of additional resonances at high mass, with couplings similar to the SM Higgs boson.

Here we report on searches performed at CMS of a SM-like Higgs boson at high mass, assuming the properties predicted by the SM. The $H \to WW$ and $H \to ZZ$ decay channels are used for a mass range of $145 < m(H) < 1000$ GeV$/c^2$. Additionally, we interpret the results in the heavy electroweak singlet scenario, where the heavy resonance also contributes to electroweak symmetry breaking, and has similar properties to the SM Higgs boson with modifications to its width and allowing for non-SM-like Higgs decay modes.

These searches are performed using the data collected by the CMS experiment at centre-of-mass energies of 7 and 8 TeV at the LHC collider, corresponding to integrated luminosities of about 5 fb^{-1} and 20 fb^{-1}, respectively. Several final states has been considered, in order to exploit the capabilities of the CMS detector to identify different types of particles and measure their kinematical properties. These are used to reconstruct the diboson final states that may hint to the existence of a new Higgs-like boson.

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the X axis pointing to the centre of the LHC ring, the

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Y axis pointing up (perpendicular to the plane of the LHC ring), and the Z axis along the counterclockwise-beam direction. The polar angle θ is measured from the positive Z axis, and the azimuthal angle ϕ is measured in the X–Y plane. All angles in this document are presented in radians. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, which provides a magnetic field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass-scintillator hadron calorimeter. A quartz-fibre Cherenkov calorimeter extends the coverage to $|\eta| < 5.0$. Muons are measured in gas-ionisation detectors embedded in the steel magnetic-flux return yoke. The first level of the CMS trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than 3 μs, using information from the calorimeters and muon detectors. The high level trigger processor farm decreases the event rate from 100 kHz delivered by the first level trigger to a few hundred hertz, before data storage. A full description of the CMS apparatus is available elsewhere [27].

The following two sections give a detailed description of the analysis and their results. Afterwards, we discuss the combination and the future plans for these searches.

2. Searches in the *WW* decay channel

When looking for a high-mass Higgs-like, the most prominent and clean decays are those given by two weak bosons. Even with an extension of the SM, we expect those decays to be present if the new massive object is somehow involved in the breakdown of the electroweak symmetry.

Additionally, if the new particle is also involved in conserving the unitarity of the boson-boson scattering, the coupling to WW is perfectly motivated and would give rise to the search decay.

In this case, the cleanest channel is the fully leptonic, given by $H \to WW \to l\nu l\nu$ where the two charged leptons are identified with the detector components and the neutrinos are reconstructed by the imbalance in transverse momentum (the so-called, "missing ET", E_T^{miss}). The dominant background in this final state is given by the continuous production of WW, with some contributions from top-quark production and from events passing the selection due to misidentified leptons, i.e. W+jets. Contribution from Drell-Yan production of leptons is strongly suppressed due to the E_T^{miss} requirements.

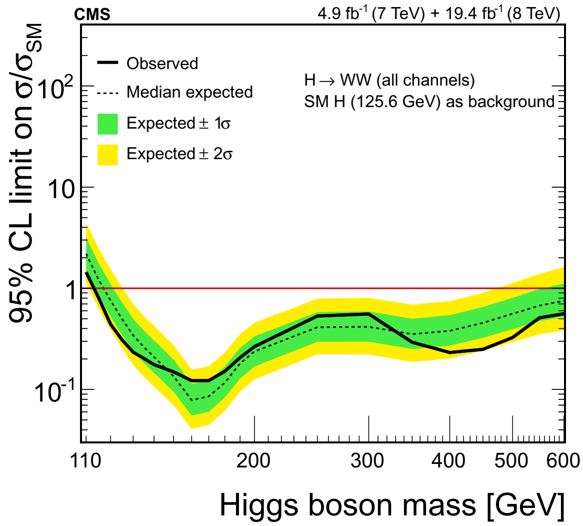

Figure 1: Observed (black line) and expected (dashed line with uncertainty colour bands) limit for the $H \to WW$ channel in the fully leptonic channel. The limit is set on the cross section normalised to the expectation of a SM Higgs of the hypothetical mass.

CMS has performed this search [28] by using the full Run I dataset mentioned before. The analysis exploits the kinematic differences between the expected signal and the backgrounds. Due to the presence of neutrinos in the final state, the complete mass is not reconstructed, but variables related to the leptons and those of the E_T^{miss} are used in the discrimination.

Additionally, to maximise the sensitivity of the search, the final events are classified in all possible forms, mostly in jet multiplicities, what allows to enhance the contributions from different production channels. This is very relevant since some properties of the produced particle are available from the way the particle is produced, that for a Higgs-like particle are classified in three types: gluon-gluon fusion via a quark-loop, vector-boson fusion and associated production with a SM particle, mostly a weak boson or a top quark, due to the higher couplings to them.

The expected background describes very well the obtained distributions in data and no hint for a new particle beyond the $h(125)$ boson has been observed. Figure 1 shows the observed limit as a function of the hypothetical mass of the new boson H. The limit is presented in terms of the expected cross section for a Higgs boson of such a mass. The plot also includes the expected limit and the uncertainty bands for the background-only hypothesis, which in this case also includes the events expected for the already-observed Higgs at 125 GeV/c^2.

It should be noted that although the fully leptonic channel is clean and with high final sensitivity, it presents a limitation in the acceptance due to the reduced branching fraction of the W boson into leptons. To account for this, and extend the sensitivity to higher masses, it is necessary to include the hadronic decays.

The semi-leptonic channel given by $H \rightarrow WW \rightarrow l\nu jj$, covered using the full Run I dataset [29], makes use of the hadronic branching fraction of the W at the cost of increasing the QCD-induced background. For this analysis, the main subject is the understanding of the W+jets background that is hugely dominating. In order to reduce it, the analysis requires to make use of topological quantities. Specifically, the invariant mass of the two jets is used to reduce the presence of dijet production in addition to the W boson. Furthermore, the sideband regions of the used W resonance peak are used to reduce the uncertainties on the estimation of such W+dijet background.

In addition to the $W \rightarrow jj$ resonance, this final state allows a second handle to separate the Higgs boson signal: since there is only one neutrino in the final state, it is possible to obtain a complete reconstruction of the WW mass, by using the mass of the leptonic W boson as input to constrain the Z component of the neutrino momentum. With the full reconstruction of the mass, the Higgs signal would appear as a resonant excess of the four-body reconstructed mass distribution, which yields a cleaner distinction with respect to the continuous background.

All these properties are used in the analysis to obtain a result that does not show any significant deviation with respect to the expected background. As in the previous case the analysis set a competitive limit on the production cross section of Higgs-like bosons. In this case the sensitivity decreases very rapidly for $m(H) \gtrsim 500$ GeV$/c^2$ because for higher masses the transverse momentum of the W bosons is too large and the boosted decay products tends to be merged, making difficult the reconstruction of two separated jets.

In order to account for this effect and extend the sensitivity beyond $m(H) = 600$ GeV$/c^2$, a specific reconstruction is needed in which a single broad jet is reconstructed for the hadronic W boson [30]. Due to the kinematic properties of the collisions at the LHC, many tools to tag jets as boosted W bosons have been developed in recent years. The basic method used here reconstructs internal structures (*subjets*) inside the broad jets and using their kinematical properties identifies whether the jet is a candidate to be a boosted W boson or not.

This kind of strategy has been proven to be much more powerful than the usage of jet algorithms of smaller radius. Once the jets are identified as possible W boson candidates, the analysis is performed as in the usual semi-leptonic analysis described above. The obtained limit is presented in Fig. 3, where we observe that the sensitivity is of the order of 1-3 times the expected cross section for a SM Higgs boson up to 1 TeV$/c^2$. It should be remarked that without the specific merged-jet reconstruction, the acceptance would be so low that the sensitivity would be negligible for those high masses.

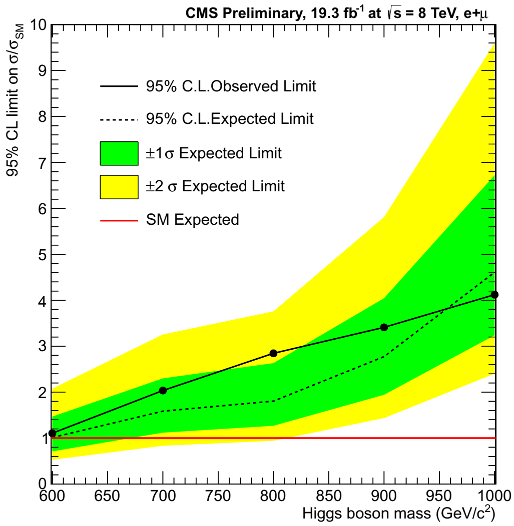

Figure 2: Observed (black line) and expected (dashed line with uncertainty colour bands) limit for the $H \rightarrow WW$ channel in the semi-leptonic channel including a highly-boosted W-tagged jet. The limit is set on the cross section normalised to the expectation of a SM Higgs of the hypothetical mass.

3. Searches in the ZZ decay channel

If we are expecting a possible new Higgs boson to be involved in the electroweak-symmetry breaking mechanism, it should also couple to the Z boson in addition to the W boson. Therefore decays to ZZ states are also expected and have been investigated in order to get a complete picture of the possible resonance and also to enhance the sensitivity to it.

In the case of ZZ the golden channel is the fully leptonic decay, as it happens with the $h(125)$ boson. This is the cleanest channel due to the reduced background, practically given by the continuous production of ZZ. On the other hand this channel has the limitation of the low acceptance because of the reduced branching fraction of the Z boson into charged leptons. This limits the obtained sensitivity, but on the other hand, the four-lepton final state provides also the ideal situation to study the properties of a new resonance, so this channel will be fundamental in case that a new high-mass resonance is found, even if it is not providing the largest sensitivity with the current data sample.

The analysis performed by CMS [31] searches for a possible resonance in the tail of the four-lepton invariant mass, with a selection based on dilepton pairs coming from on-shell Z bosons. Since the final state is so clean, it is possible to make use of all the possible final states and classify the events accordingly to the topology. Even making use of the fact that the full final state is reconstructed, which allows to enhance the sensitivity based on the kinematic properties expected from a scalar particle decaying into the well-known Z bosons.

The sensitivity is very high for the low-end of the spectrum, and it gets worse at the mass increases. In order to account for this limitation, the search for a new resonance decaying into ZZ has been extended by requiring one of the bosons to decay into neutrinos. In this final state, ll+E_T^{miss}, the larger branching fraction into neutrinos allow to increase the acceptance by more than a factor of two, at the cost of having a less clean final state due to the loss in information from the undetected neutrinos.

The analysis [32] takes also advantage of the fact that the higher the mass of the resonance, the more boosted the produced Z are. This makes a cleaner reconstruction of a final state when one of the Z is invisible. Due to this, it provides the highest sensitivity to such kind of resonance in the high end of the spectrum.

As it is the case of all the analyses previously described, this study also makes use of the different topologies, which provide information about the production mode and differences with respect to the expected background, mostly given by Drell-Yan production with additional jets, in which the E_T^{miss} is mostly given by mismeasured energies of the hadrons or leptons in the event or by the presence of neutrinos produced in the decays of hadrons.

Fig. 3 shows the 95% confidence level limit obtained in the analysis, for which no hint of any new resonance has been observed. The observed limit, in good agreement with the expectation from the background-only hypothesis, is able to exclude the presence of a SM-like Higgs resonance up to 900 GeV/c^2.

The results of this analysis has also been interpreted in terms of a search for a partner of the $h(125)$ boson within the electroweak singlet model [26]. In this model, the couplings of the two Higgs bosons are modified by a factor, that is C for the low-mass $h(125)$ and C' for the high mass state H. In order to conserve uni-

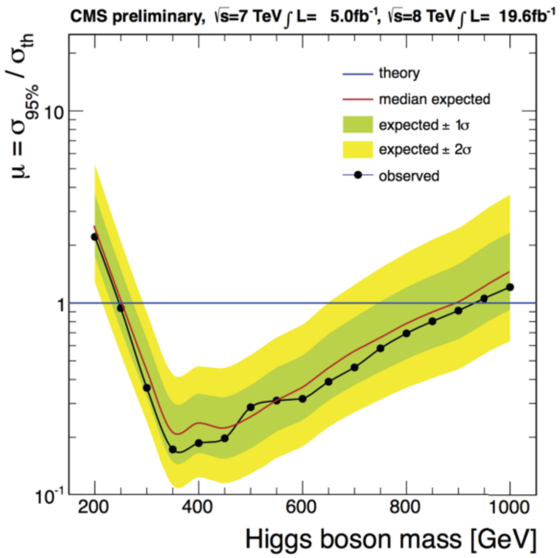

Figure 3: Observed (black line) and expected (dashed line with uncertainty colour bands) limit for the $H \to ZZ$ channel in the dilepton+E_T^{miss} channel. The limit is set on the cross section normalised to the expectation of a SM Higgs of the hypothetical mass.

tarity, these factors satisfy the condition $C^2 + C'^2 = 1$, which introduces a correlation between the properties of the two states.

One of the results obtained in this interpretation is shown in Fig. 4, which presents the excluded parameter space in the plane for C' and $m(H)$. It includes the exclusion area coming from the measurements of the properties of the $h(125)$, since the most SM-like is such Higgs boson, the less likely is the presence of an additional state. It should be noticed however that the direct search is much more sensitive, at least for not very high masses of the unknown state.

In addition to the leptonic decays, the semi-leptonic channel $H \to ZZ \to lljj$ has been also been considered in the search for a high-mass state. As in the case of the W, the Z predominantly decays into hadrons and this can be exploited to increase the acceptance for a possible signal. Again the cost is the increase in the background from the presence of dijet production in addition to a Z boson. The performed analysis [33] has taken this into account and has made use of all the handles to enhance the sensitivity to a possible signal.

In the case of the this decay chain, all final-state elements are reconstructed, allowing to use similar discrimination variables to those described for the WW case described above, with the advantage that no constraint is needed to infer any parameter. Additionally, the search for $H \to ZZ \to lljj$ has used the fact that we are looking for a scalar particle decaying into spin-1 bosons in order to build an angular-based discriminant which is used to reduce the background contamination.

Another difference between the expected signal events and the background is the larger presence of b-quark jets. It is well known that the Z boson decays into b quarks with a sizable branching fraction, much larger than the probability of getting b-quark from QCD-induced processes, in which the production of gluons dominates. This characteristic is used in the analysis by the mean of b-tagging which allows to select jets that has a large probability of having been originated by a b quark. The number of such jets is then taken as a classification variable and event in the final selection are divided into categories according to that quantity. This enhances further the sensitivity to a possible signal and the obtained result excludes a Higgs-like boson in the 290 – 600 GeV$/c^2$ range

The current result stop the search around 600 GeV$/c^2$ because of the loss in sensitivity due to the merging to of two jets into one for very high masses of the hypothetical particle, as it was the case in the WW semi-leptonic analysis described above. In the case of ZZ a specific reconstruction to identify boosted Z bosons is required here by analysing the internal structure of broad jets produced back-to-back to a Z boson. In addition to the strategy followed in the W boson case, the possibility of b-tagging the subjets is also a handle that is exploited for the Z-boson tagging of the jets. This extension of the analysis is already planned for the future update of this channel.

4. Combination of the results

Although all the channels shown before have a good sensitivity to the presence of a new resonance, the combination of the results is able to increase the reach of the conclusions obtained from the data sample.

For this reason, the plan is to combine all of these results as has been done in the past. The combinations, as the last one performed for the ZZ channels shown in Fig. 5, allows to take advantage of the differences in sensitivity obtained in the several final states.

The plot in the figure shows the obtained combined limit and the comparison to the expected limit with the associated uncertainty. For comparison, the observed limit from the several analysis are also shown, and they show that the combination does not only benefit from its larger statistical power, but also from the complementarity of the several searches looking at different final states.

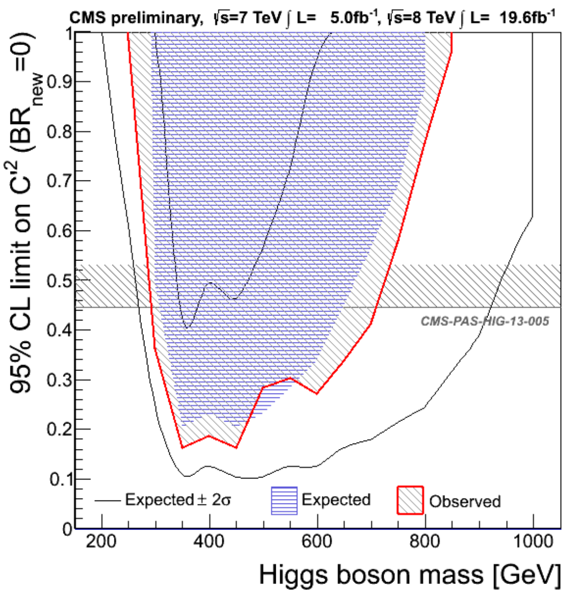

Figure 4: Observed (red line around hatched area) and expected (blue area) limit obtained in the context of the electroweak-singlet model from the $H \to ZZ$ channel in the dilepton+E_T^{miss} channel. The limit is set on the plane defined by the C' parameter and the hypothetical mass of the search partner. For comparison, the indirect limit from the constraint in the properties of the $h(125)$ boson is also shown.

5. Conclusions and prospects

After the observation of the particle having a mass of about 125 GeV$/c^2$ the searches of similar bosons is strongly motivated. Several extensions of the standard model suggest the existence of such bosons that would be partners of the one already found and their detection may provide the first step towards the physics beyond the standard model.

The report summarises the effort by CMS to look for a possible high-mass Higgs-like particle decaying into dibosons. Currently no hint of such particle has been observed and the results are used to extend the current limits on searches of Higgs-like bosons within the SM-like benchmark or other models. An effort to combine all the results using the full Run I is on-going and expected to provide a clear picture before the beginning of the Run II of the LHC in 2015.

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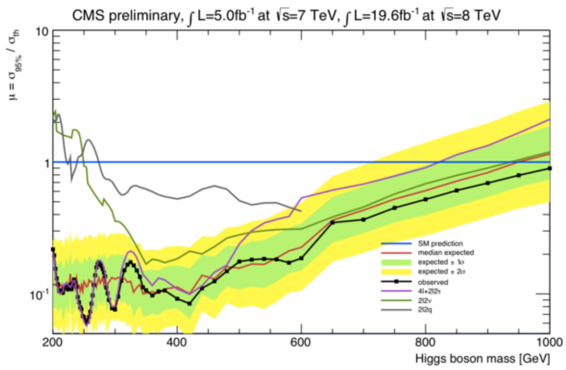

Figure 5: Observed (black line with squares) and expected (red line with uncertainty colour bands) limit for the combination of all the $H \to ZZ$ searches. The limit is set on the cross section normalised to the expectation of a SM Higgs of the hypothetical mass. For comparison, the observed limits from the several channels are also shown.

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