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# Higgs Boson Measurements and Extended Scalar Sector Searches in Bosonic Final States

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Searches for additional Higgs-like bosons in the H to WW and H to ZZ decay channels are reported, for boson masses in the range $145 < m_{\mathrm{H}} < 1000$ GeV. The results are based upon proton-proton collision data samples at $\sqrt{s} = 8$ and 13 TeV, recorded by the CMS experiment at the LHC. Several final states of the WW and ZZ decays are analyzed. Upper limits for the search for a heavy BSM resonance and the combined upper limits at 95% confidence level on the products of the cross section and branching fraction. These data are also used to constrain the SM Higgs boson total decay width, finding observed and expected limits at the 95% confidence level (CL).

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## 1. Introduction

The strategies developed by the CMS experiment [1] at CERN LHC for searches and studies of the Standard Model (SM) Higgs boson may also be applied to searches for higher mass Higgs-like scalar bosons. Searches for bosonic decays of such particles include a pair of Z bosons decaying in the four lepton ($4\ell$) and two lepton plus two jet ($\ell\ell qq$) final states, or a pair of W bosons decaying in the two lepton, two neutrino final state ($2\ell2\nu$). In addition to these searches, a search for off-shell Higgs production is performed in the $4\ell$ channel, which depends on the Higgs boson width.

## 2. Four Lepton Final State

Four lepton final state results build upon the strategy of measuring the SM Higgs decays to four leptons as reported in [2]. Electrons or muons in same-flavour, opposite-sign pairs are required. Electrons (muons) are required to have a minimum transverse momentum $p_{\mathrm{T}}$ of 7 (5) GeV, and pseudorapidity $\eta$ less than 2.5 (2.4). Further, the leading lepton must have $p_{\mathrm{T}} > 20$ GeV and the second $p_{\mathrm{T}} > 10$ GeV. In order to recover final state radiation, photons close to the leptons may be included in the overall Z candidates if they satisfy requirements described in [3].

Non-resonant $ZZ$ production is the primary background; this is irreducible and the mass distribution is predicted from simulation. Reducible backgrounds include Z+jets and top quark pairs, which are measured from control regions. Kinematic discriminants are used to select events for signal extraction. The primary discriminant is $\mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}}$, which uses kinematic information that fully describes the four lepton system in order to separate signal and background. Further discriminants are used to identify VBF and other production mechanisms.

### 2.1 Higgs Width Measurement

The high mass spectrum can be used to constrain off-shell production, which is dependent on the Higgs boson width. On the assumption of SM branching ratios and no additional particles affecting the ratio of on-shell and off-shell production, this gives a the 95% CL limit on the width of 41 MeV, compared with the predicted SM width of about 4 MeV. If only candidates with masses near to on-shell are used, the 95% CL limit is 3.9 GeV, illustrating the strong dependence on the assumptions for the fit using the full mass range. In Fig. 1, the log likelihood test statistic is shown as a function of Higgs mass and width for both cases; note the very different scale between the fit using off-shell information (left) and on-shell only (right).

### 2.2 Extended Scalar Search

High mass data from the four lepton analysis is also used to put constraints on additional Higgs-like resonances decaying to Z pairs. The limits are shown in Fig. 2. Limits are shown for a range of widths; at left the limits are shown allowing the fraction of events produced in the VBF mode to vary, at right only VBF production is assumed to contribute.

## 3. High Mass Resonance Search in $\ell\ell qq$ State

A high-mass scalar decaying to Z boson pairs may also be seen in the case when one Z boson decays leptonically and the other hadronically.[4] For the hadronic Z, the two resulting jets may

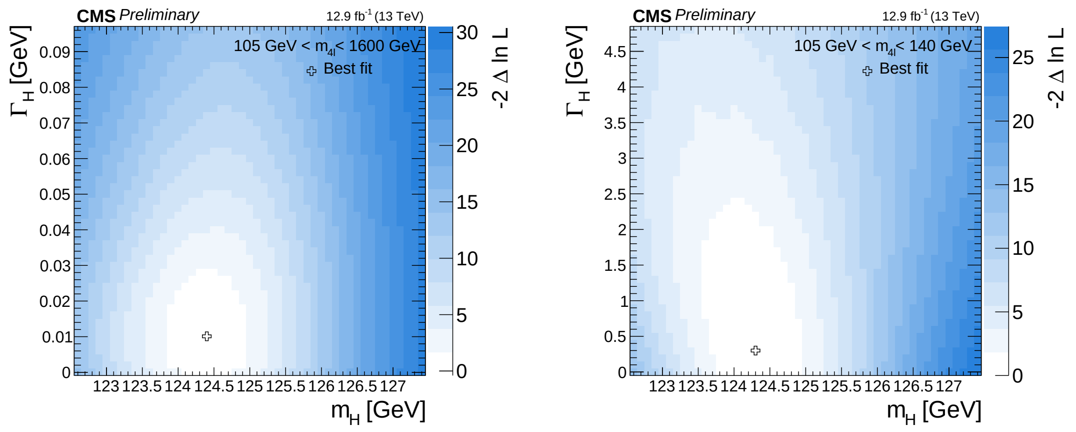


**Figure 1:** Log likelihood test statistic as a function of Higgs mass and width. At left, both on shell and off shell mass ranges are used, and it is assumed that only SM particles appear in loops and SM branching ratios are correct; at right, only the on shell mass range is used. Note the different y-axis scale. [2]

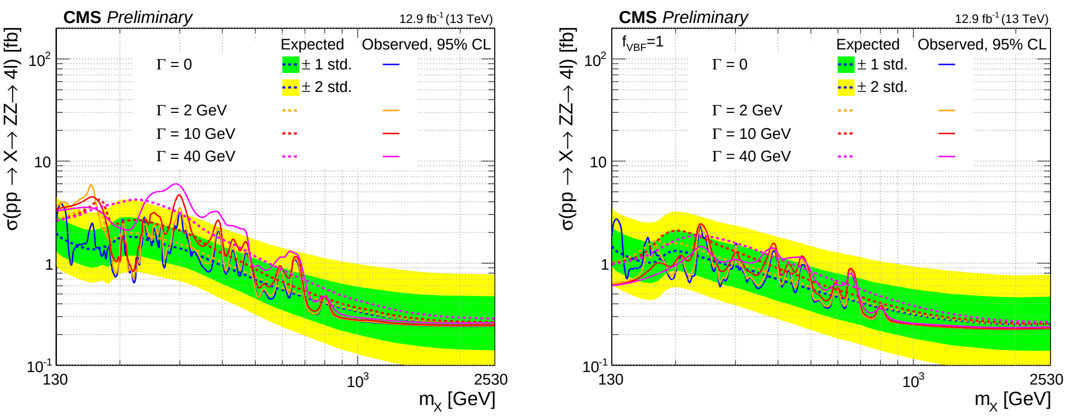


**Figure 2:** Limits set on additional Higgs-like resonances decaying to Z boson pairs, as a function of mass. At left, the fraction of VBF production is allowed to vary in the fit; at right it is fixed to 100%. Expected and observed limits are shown for a range of resonance widths. [2]

either be close together or well-separated, depending on the Z boson $p_T$. In the search reported in [4], events with two opposite sign, same flavor leptons with leading (subleading) $p_T$ above 40 (24) GeV are selected; these are combined to a leptonic Z candidate which is required to have $p_T >$ 100 GeV. A hadronic Z candidate is then formed either from two separate jets with reconstructed from the anti-$k_t$ algorithm [5] with R = 0.4, applied to particle flow candiates [6] as identified by the CMS detector, or else from a single merged jet with R = 0.8. In the merged jet case cuts are applied to the pruned mass and compatibility with the 2-jet hypothesis is required. The efficiency for the selection in simulation, as a function of resonance mass, is shown on the left side of Figure 3. Above 1 TeV, the acceptance is dominated by the merged category.

Events are split into mutually exclusive categories: first, a kinematic discriminant is used to determine if there are additional jets compatible with a VBF-like configuration; second, if the two jets forming the Z candidate are both b-tagged; third, the remaining untagged events. For each of six distributions, corresponding to merged and resolved Z candidates and the three categories, background rates are estimated using sidebands in the hadronic Z candidate mass, and a signal fit performed. An example distribution for the untagged case is shown at right in Fig. 3. No new high-mass scalar is observed in the fit; limits on the cross section for such a scalar times its branching ratio into Z pairs are shown in Fig. 4.

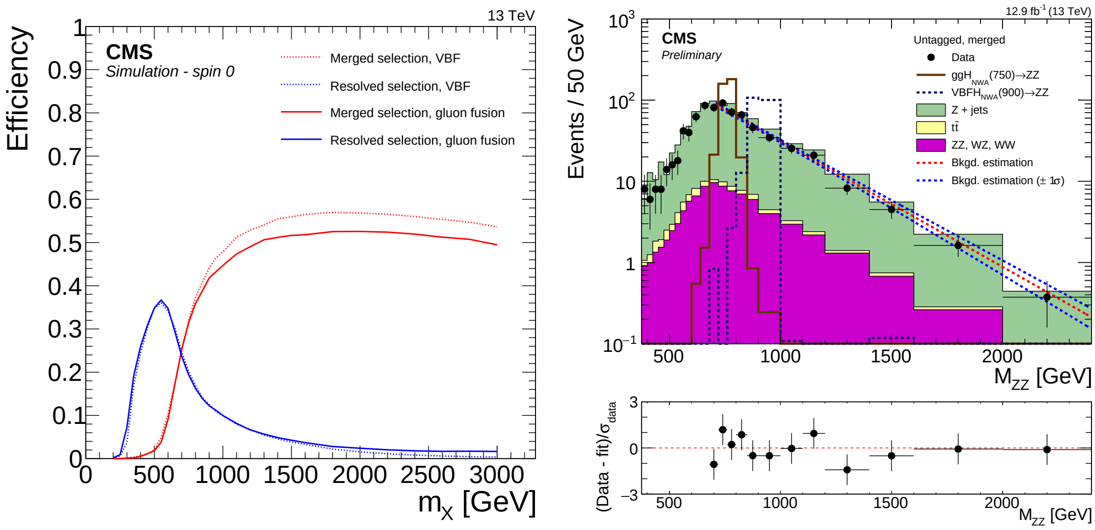


**Figure 3:** At left, the efficiency of the analysis selection for $X \to ZZ \to \ell\ell qq$, determined as a function of resonance mass, for the spin 0 case. The merged (resolved) jet selection efficiency is shown in blue (red). Solid and dotted lines indicated gluon fusion and VBF production. At right, an example distribution is shown for the merged selection in the untagged category. Black points are data, open histograms are simulated signal samples for particular mass points and production modes as indicated, stacked histograms are simulated SM background, and dotted lines are data-driven background estimates from sidebands. [4].

## 4. Higg Mass Resonance Search in $2\ell 2\nu$ State

A searched is performed for a spin 0 resonance decaying into W pairs using 2.3 $\text{fb}^{-1}$ of data [7]. Exactly one electron and one muon with $p_T > 20$ GeV are required. Decays of W pairs via tau leptons are rejected through a cut on the transverse mass ($m_T$). Events from leptonic decays of single top and top pair production are rejected by vetoing b-tagged jets.

The $m_T$ distribution for top background is estimated from a control region defined by requiring b-tagged jets. $W\gamma^*$ and DY $\to \tau\tau$ background shapes in $m_T$ are taken from simulation, with overall normalization taken from control regions defined by requiring 3 leptons for $W\gamma^*$ and cutting on transverse mass and $m_{\ell\ell}$ for DY $\to \tau\tau$. Backgrounds with leptons from jets are estimated by relaxing the lepton isolation cut in data. Simulation is used to estimate di-boson and tri-buson backgrounds, for both shape and normalization.

Final signal and yields, along with continuum $WW$ background, are extracted by a fit to $m_T$, for $m_T > 100$ GeV, in 0-jet, 1-jet and VBF-tagged categories, with examples shown in Fig. 5. No excess is observed and limits are set for several signal width hypotheses, as shown in Fig. 6.

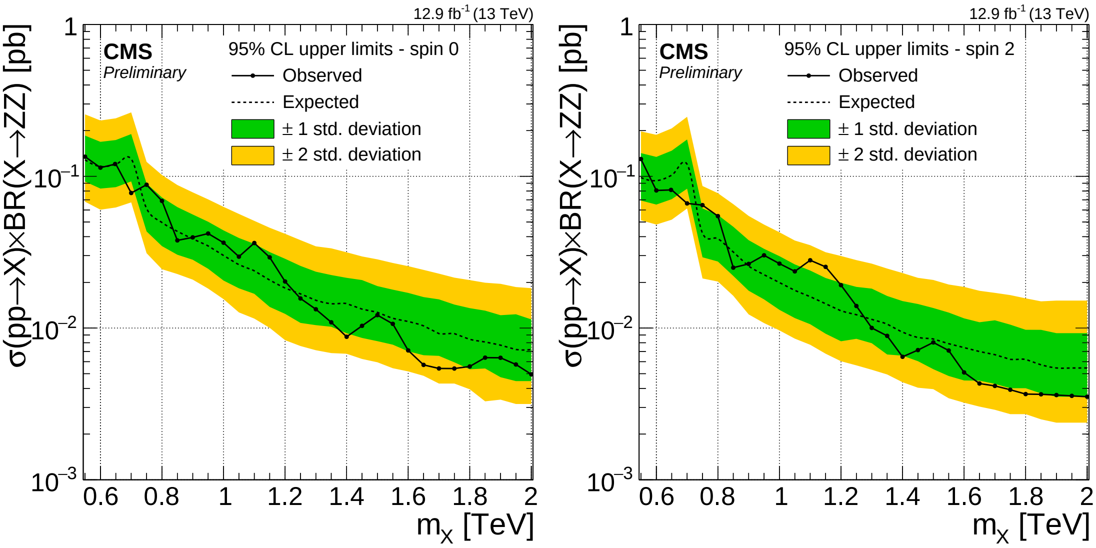


**Figure 4:** At left (right), limits on the production of a spin 0 (spin 2) scalar times its branching ratio into ZZ [4].

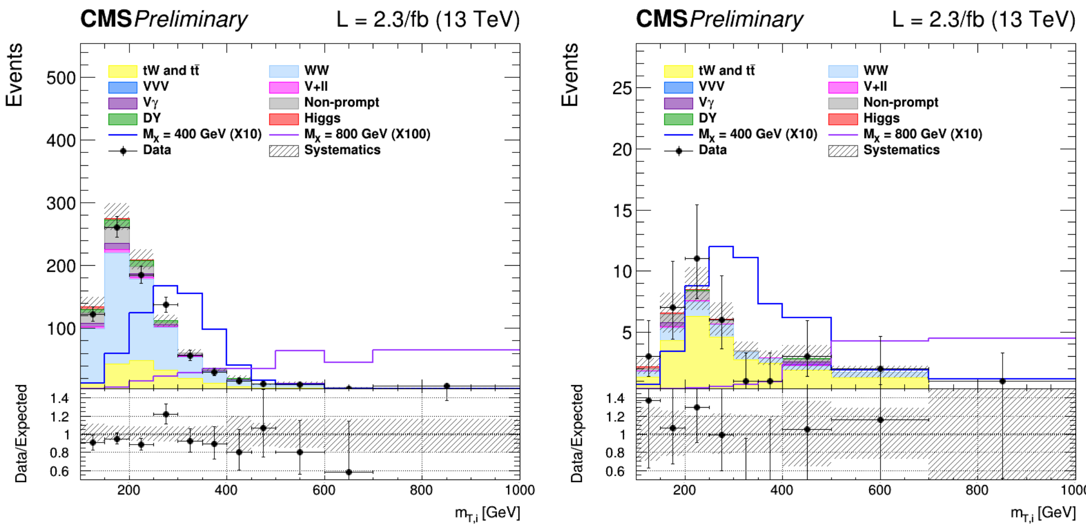


**Figure 5:** Example transverse mass distributions for the 0-jet (VBF tagged) events are shown at left (right). Lines illustrate two signal hypotheses, stacked histograms SM backgrounds, and points the signal region data [7].

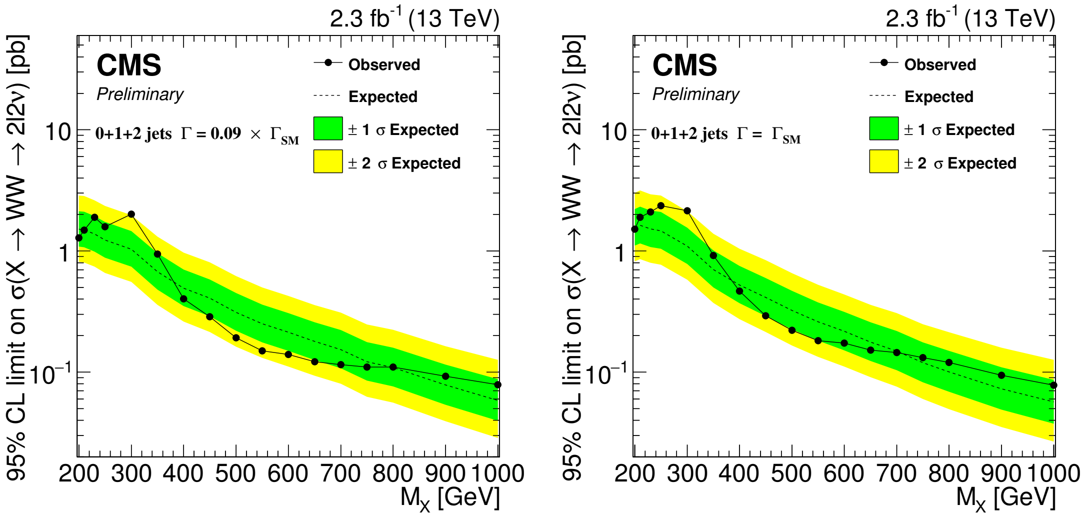


**Figure 6:** Limits are set on the cross section for a new resnonance times its branching ratio to WW, depending on the assumed signal width. At left (right), an example is shown with an assumed width of 0.09 (1.0) times the width a SM Higgs would have at the given mass [7].

## 5. Conclusions

Using the high mass data and techniques from Higgs boson analyses, searches for high mass resonances decaying to W and Z boson pairs have been performed. No excesses are seen. Analysis of the high mass spectrum allows off-shell Higgs boson production to be studied, and upper limits are set on the Higgs boson width, assuming SM branching ratios and no additional particles affecting the ratio of on-shell to off-shell production.

## References

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