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Searching for resonant HH production at CMS

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New, massive bosons could be found with the LHC. Theories with warped extra dimensions and supersymmetry predict the existence of such resonances, which for some model parameters, have a significant branching fraction to two Higgs bosons. Searches for these predicted new resonances decaying to two Higgs bosons with the CMS detector are presented. Jet substructure techniques and lepton identification are used to identify merged Higgs boson decays in the $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, and the $b\bar{b}WW^*$ final states. Exclusion limits on the product of the cross section and branching fraction for spin-0 and spin-2 resonances with mass > 0.7TeV are shown. The results are based on data collected during Run 2 of the LHC at a centre-of-mass energy of 13 TeV and include a statistical combination of the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$ channels.

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1. Resonant HH production at the LHC

Higgs boson (H) pair production could be the gateway to new physics at the CERN LHC. While this process is rare within the standard model (SM) because of destructive interference between its two leading order production diagrams, this is not the case for many extensions to the SM. In particular, there exists a broad range of theories that both address limitations of the SM and predict new bosons that decay to HH. These theories include Randall-Sundrum models of warped extra dimensions [1], for which the new bosons would be spin-0 radions or spin-2 bulk gravitons, or supersymmetry [2], which requires an extended Higgs sector.

A number of searches for such new particles have been conducted with the CMS detector [3]. These results are interpreted as searches for generic spin-0 or spin-2 particles X decaying to HH. The X resonance width is assumed to be negligible compared to the detector resolution. Only the subset of results that are optimized for particle mass $m_{\mathrm{X}} > 0.7$ TeV are reviewed here. In such high-m_{X} signal events the produced H bosons are boosted, leading to merged decays.

Three results are presented here. The first is an analyses of the $\mathrm{X} \to \mathrm{HH} \to \mathrm{b\bar{b}WW^*}$ [4] decay channel, where one W boson decays to hadrons and the other W boson decays to an electron or a muon and a neutrino. The other two are analyses of the $\mathrm{X} \to \mathrm{HH} \to \mathrm{b\bar{b}}\tau\tau$ [5], where at least one τ decays to hadrons, and the $\mathrm{X} \to \mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}}$ [6, 7] decay channels. A statistical combination of these two results [8] is also presented. All searched are performed on a data set corresponding to an integrated luminosity of 35.9 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV.

2. Event selection

The analyses of the three HH decay channels share a common event selection strategy. Events are analyzed if all final state particles from an HH decay can be associated to reconstructed objects. In all three cases, at least one merged $\mathrm{H} \to \mathrm{b\bar{b}}$ decay must be identified. The three searches then each identify a second type of Higgs boson decay.

The merged $\mathrm{H} \to \mathrm{b\bar{b}}$ decays are identified as single large-radius jets (clustered according to the anti-k_{T} algorithm with $R = 0.8$ [9, 10]) that have substructure consistent with a Higgs boson decaying to two b quarks. The "modified mass drop tagger" algorithm [11, 12], also known as the "soft drop" (SD) algorithm, with angular exponent $\beta = 0$, soft cutoff threshold $z_{\mathrm{cut}} < 0.1$, and characteristic radius $R_0 = 0.8$ [13], is applied to these jets to both identify two subjets and to obtain a groomed jet mass $m_{\mathrm{b\bar{b}}}$. These jets are also identified as likely originating from two b hadron decays. In the $\mathrm{b\bar{b}b\bar{b}}$ analysis, a dedicated double b-tagger is utilized, while the other two analyses require that the individual subjets are b tagged. The QCD multijet background is further suppressed in the $\mathrm{b\bar{b}b\bar{b}}$ analysis by placing a selection on the "N-subjettiness" ratio τ_2/τ_1 [14]. Distributions of the double-b tagger and τ_2/τ_1 are shown in Fig. 1.

For the $\mathrm{b\bar{b}b\bar{b}}$ analysis, the second type of Higgs boson decay is also $\mathrm{H} \to \mathrm{b\bar{b}}$. It is identified as either merged or separated. In the latter case, the decay is reconstructed as two b-tagged small-radius ($R = 0.4$) jets. These two jets must have an invariant mass ranging between 90–140 GeV and have angular distance separation $\Delta R < 1.5$.

The $\mathrm{H} \to \tau\tau$ decays in the $\mathrm{b\bar{b}}\tau\tau$ analysis are reconstructed as either two hadronically decaying τ leptons (τ_{h}) or a τ_{h} in addition to an isolated electron or muon. The τ_{h} are identified either as

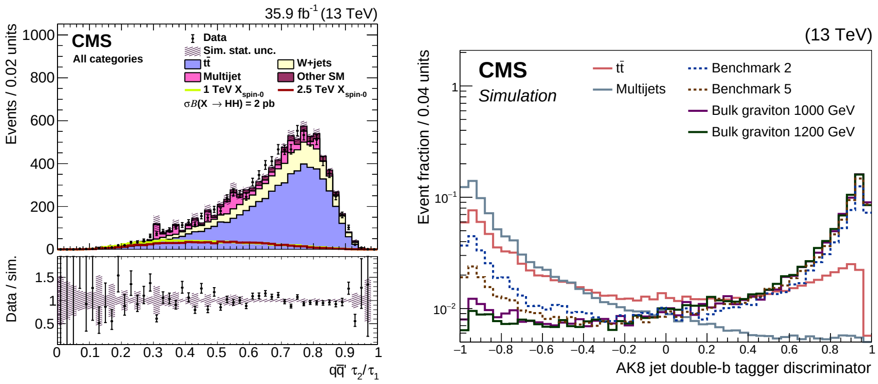

Figure 1: Discriminating variables used to identify merged boson decays. Left: τ_2/τ_1 of the merged $\mathrm{W} \to \mathrm{q\bar{q}'}$ decay in the $\mathrm{b\bar{b}WW^*}$ analysis [4]. Right: dedicated double-b tagger discriminator of the merged $\mathrm{H} \to \mathrm{b\bar{b}}$ decay in the $\mathrm{b\bar{b}b\bar{b}}$ analysis [7].

individual $R = 0.4$ jets or subjets of a large-radius jet that pass reconstruction and isolation criteria. The addition of the subjet-based τ_h identification leads to a significant increase in high-m_X signal event efficiency.

In the case of the $\mathrm{b\bar{b}WW^*}$ analysis, the $\mathrm{H} \to \mathrm{WW^*}$ decay is reconstructed as a large-radius jet and a nearby isolated lepton (electron or muon). The jet is identified as likely originating from a $\mathrm{W} \to \mathrm{q\bar{q}'}$ decay by requiring that it contains two subjets and by placing a selection on τ_2/τ_1. The lepton and jet are then combined with the missing transverse energy to fully reconstruct the Higgs boson decay. Background events with large angular separation between the two reconstructed W bosons are then removed with a selection on the boost-invariant quantity $p_\mathrm{T}\Delta R/2$. Here the p_T is that of the reconstructed Higgs boson and the angular distance is between the two W bosons.

3. Signal extraction techniques

All three searches rely on two quantities to discriminate signal events from background events: $m_{\mathrm{b\bar{b}}}$ and the invariant mass of the reconstructed X decay, m_HH. Shown in Fig. 2 for the $\mathrm{b\bar{b}WW^*}$ channel, the signal distributions have peaks in both distributions. This leads to the characterization of each analysis as a search for a peak in this two-dimensional plane over a smooth background contribution. Two background estimation methods are utilized.

The background contribution in the $\mathrm{b\bar{b}b\bar{b}}$ and $\mathrm{b\bar{b}}\tau\tau$ searches are estimated via sideband interpolation. The $m_{\mathrm{b\bar{b}}}$ distribution is first divided into a signal region near the Higgs boson mass and two background enriched sideband regions. Then the signal region background counts are estimated from the sideband data. The multijet background in the $\mathrm{b\bar{b}b\bar{b}}$ channel is modeled by interpolating the efficiency for the merged $\mathrm{H} \to \mathrm{b\bar{b}}$ jet to pass the b tagging criteria. The W/Z+jets background in the $\mathrm{b\bar{b}}\tau\tau$ channel is modeled by fitting functions to the sidebands.

In contrast, the $\mathrm{b\bar{b}WW^*}$ analysis is conducted via a maximum likelihood fit of the entire two-dimensional mass plane. Differences between data and simulation (systematic uncertainties) are included in the fit as nuisance parameters

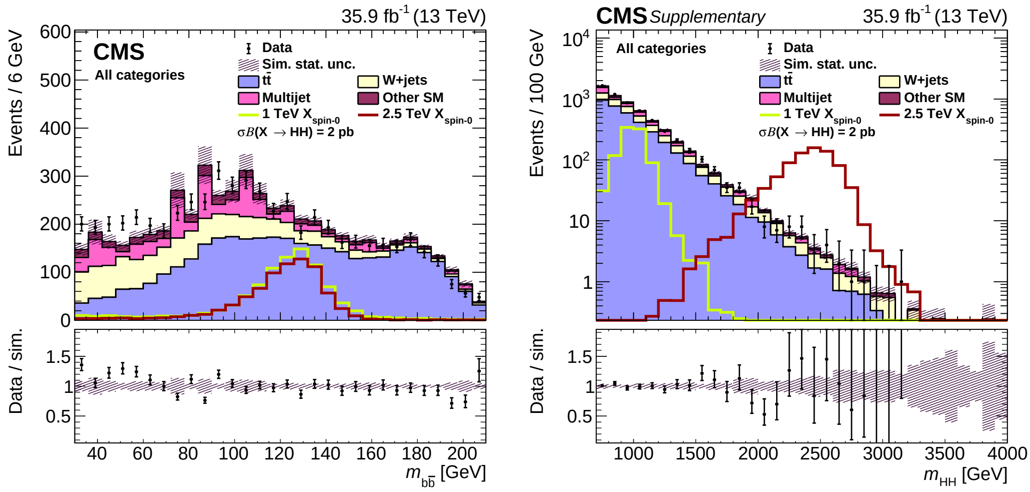

Figure 2: The two discriminating variables used to characterize signal: $m_{b\bar{b}}$ (left) and m_{HH} (right). The distributions are in $b\bar{b}WW^*$ channel [4].

4. Results and conclusion

No significant excesses are observed in any analysis. The results are interpreted as upper limits on the product of the X production cross section and the X $\rightarrow$ HH branching fraction. The $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$ results are statistically combined, resulting in approximately 33% stronger limits than those for a single channel. The 95% confidence level upper limits of this combination is shown in Fig. 3. Similarly, the limits for the $b\bar{b}WW^*$ channel are shown in Fig. 4. These are the first results for resonances decaying to this final state from the CMS Collaboration, bringing new sensitivity to this type of signal.

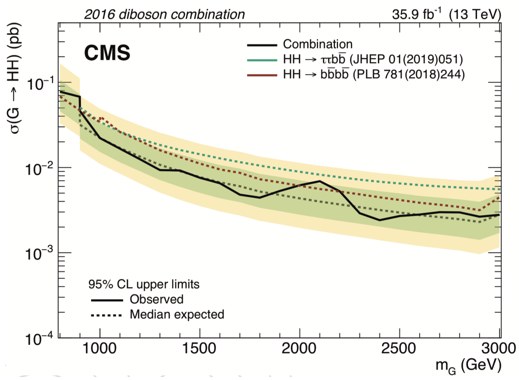

Figure 3: The 95% confidence level upper limits for spin-2 bosons as a function of bulk graviton mass m_G. Individual results for the $b\bar{b}b\bar{b}$ [7] and $b\bar{b}\tau\tau$ [5] channels are shown in addition to the combined result [8].

While no evidence of signal was observed, only a fraction of the full LHC Run 2 data set was analyzed. Future versions of these analyses that exploit the full Run 2 data set are expected to be significantly more sensitive to resonant HH production.

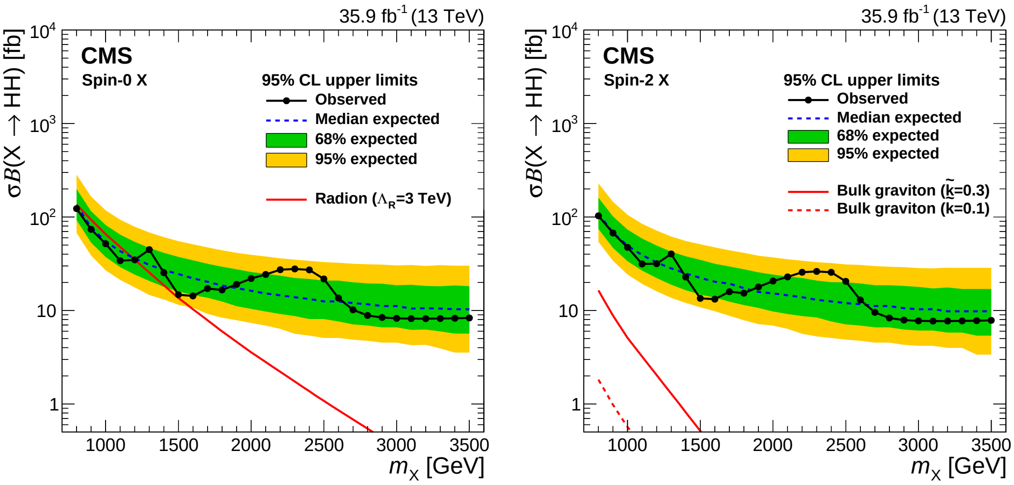

Figure 4: The 95% confidence level upper limits for spin-0 (left) and spin-2 (right) bosons as a function of m_X. These are results for the $b\bar{b}WW^*$ channel [4].

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