PROCEEDINGS OF SCIENCE

Searches for heavy resonances decaying into Z, W and Higgs bosons at CMS

Dennis Roy[a,*] **on behalf of the CMS Collaboration**

[a] *III. Physics Institute B, RWTH Aachen University, Otto-Blumenthal-Strasse, Aachen, Germany*

E-mail: dennis.roy@cern.ch

A summary of searches for heavy resonances with masses exceeding 1 TeV decaying into pairs of bosons is presented, performed on data produced by LHC pp collisions at $\sqrt{s} = 13$ TeV and collected with the CMS detector during 2016, 2017, and 2018. The common feature of these analyses is the boosted topology, namely the decay products of the considered bosons (both electroweak W, Z bosons and the Higgs boson) are expected to be highly energetic and close in angle, leading to a non-trivial identification of the quarks and leptons in the final state. The exploitation of jet substructure techniques allows to increase the sensitivity of the searches where at least one boson decays hadronically. Various background estimation techniques are adopted, based on data-MC hybrid approaches or relying only in control regions in data. Results are interpreted in the context of theoretical models beyond the standard model such as the Warped Extra Dimension and Heavy Vector Triplet.

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1. Introduction

Searches for high mass resonances can provide insight to exciting new physics, as these resonances can be interpreted as new particles predicted by various beyond-the-SM theories. These theories include the Two-Higgs-Doublet Model (2HDM) or Minimal Supersymmetric SM (MSSM), a Heavy Vector Triplet (HVT) or a Bulk Graviton as predicted by the Randall-Sundrum model of warped extra dimensions. This talk presents a few analyses published within the last year, studying high mass resonances decaying into a pair of bosons (di-bosons), using data collected by CMS during the Run 2 of LHC at $\sqrt{s} = 13$ TeV [1].

2. Hadronic jet reconstruction

Bosons which originate from the decay of a high mass resonance have a large Lorentz boost. This means that the boson's decay products are collimated. If it decays into a pair of jets, the collimated jets can then be reconstructed as a single "AK8" jet, which means that the Anti-k_T algorithm [2] is used for the jet reconstruction with a jet-cone size of $R = 0.8$. This approach is employed by all analyses reconstructing hadronically decaying bosons from high mass resonances. However, a few analyses also consider "resolved" categories where a boson is reconstructed using two low p_T AK4 jets, if there are no AK8 jets in an event.
The AK8 jets are groomed using soft-drop (modified mass-drop tagger) algorithm [3], removing further constituents from soft, large-angle radiation. An AK8 jet's mass is always calculated from the four-momentum of groomed jet.
The N-subjettiness τ_N [4] is used as discriminating variable for jet substructure. Specifically $\tau_{21} = \tau_2/\tau_1$ gives a measure of how likely it is that a jet is composed out of two subjets, with values near 0 indicating that the jet is very likely to have two subjets. This is used by some analyses to remove background contributions.

3. X → WW

The high mass X → WW analysis studies the di-leptonic (WW → 2l2ν) and semi-leptonic (WW → lνqq) decay channels, using an integrated luminosity of 35.9 fb^{-1} [5]. Here, an overview of the semi-leptonic channel is given.
A category specific for Vector Boson Fusion (VBF) production is defined by requiring $m_{jj} > 500$ GeV and $\Delta\eta_{jj} > 3.5$ in events with at least two additional jets, where m_{jj} and $\Delta\eta_{jj}$ represent the mass of the di-jet system using the two jets with highest transverse momentum, and the difference in pseudorapidity of the two jets, respectively. All other events are sorted into a gluon-gluon Fusion (ggF) tagged or an untagged category using a matrix element likelihood analysis (MELA) [6]. This is performed using the angular distributions of the decay products as input for MELA. Each of the three categories are further divided into a resolved and a boosted category, as explained earlier, as well as according to the flavor of the visible lepton in the final state (e/μ).
The signal region is defined applying a number of requirements, such as on the reconstructed mass of the hadronically decaying boson of 65 GeV $< m_{W,had} <$ 105 GeV. In the boosted categories, the N-subjettiness is required to be $\tau_{21} < 0.40$. The major background comes from top quark pair

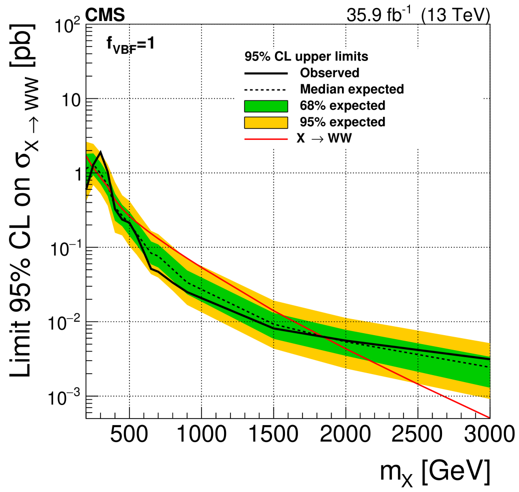

Figure 1: Upper limits at the 95 % CL on the pp → X → WW cross section for the $f_{VBF} = 1$ scenario. [5]

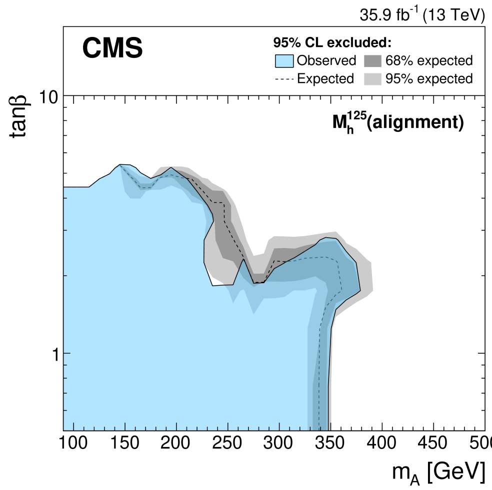

Figure 2: Expected and observed 95 % CL upper limits on tan β as a function of m_A for the M_h^{125} alignment scenario. [5]

(di-top) events and W bosons produced in association with jets (W+Jets).
The analysis considers the high mass resonance to originate from an additional electroweak singlet, where the width of the resonance is that expected from a SM-like Higgs boson at a higher mass. For signal masses above 1 TeV, the width is assumed to be half of the resonance mass. Due to these large widths, interference effects of the signal with the non-resonant WW background and the SM Higgs boson are non-negligible and are thus also taken into account.
As the analysis does not find an excess in data over the expectation, upper limits are given at 95 % CL on the cross section times branching fraction. This is done for multiple scenarios w.r.t. the considered fraction of VBF events. Figure 1 shows the limit in the case where only VBF is considered, which is able to exclude the presence of a high mass resonance up to 1800 GeV. The analysis also provides exclusion limits for various interpretations in MSSM and 2HDM scenarios (fig. 2) [7].

4. Z' → ZH

The results of an analysis studying the decay of Z', as predicted by the HVT, are presented [8]. The analysis makes use of an integrated luminosity of 137.2 fb^{-1}. The Z' decays into ZH, where the Z boson further decays into visible leptons or neutrinos, and the Higgs boson decays into a pair of b quarks.
Categories are defined for the production mode (ggF or VBF), on the decay products of the Z boson (ee, $\mu\mu$ or $\nu\nu$), and on whether the two subjets from the boosted jet from the Higgs boson being both tagged as b-jets, or at most one subjet being b-tagged. Overall, 12 categories are defined according to these criteria.
As part of the signal selection criteria, the visible di-lepton mass must be within 70 GeV $< m_{ll} <$ 100 GeV where the Z boson decay into visible leptons. Alternatively, in the Z → $\nu\nu$ categories, the transverse missing energy must fulfill $E_T^{miss} >$ 250 GeV. The mass of the AK8 jet should be within the Higgs mass range of 105 GeV $< m_J <$ 135 GeV.

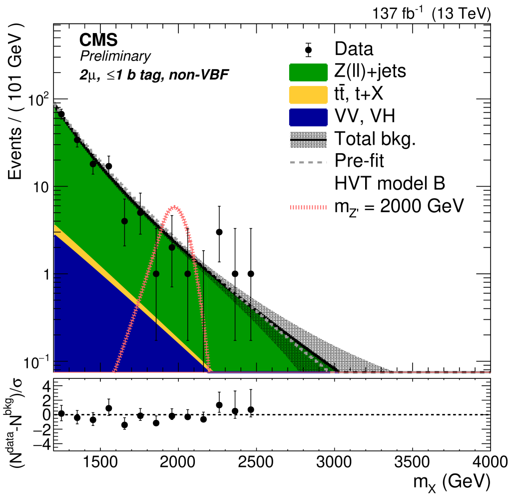

Figure 3: Event distribution of the reconstructed resonance mass in the $\mu\mu$, less than 2 b-tagged subjets and non-VBF category. [8]

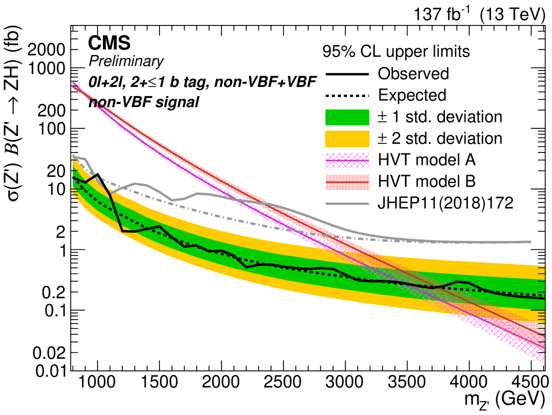

Figure 4: Observed and expected 95 % CL upper limits on the product of the cross section and branching fraction. [8]

The backgrounds in the analysis come from W or Z in association with jets (V+Jets), di-top, single top and di-boson events as well as standard model VH production. The V+Jets background is estimated from a data-driven method. Sideband regions on the mass of the AK8 jet are defined for the ranges 30 GeV $< m_J <$ 65 GeV and 135 GeV $< m_J <$ 250 GeV. The V+Jets background is estimated from these sideband regions after subtracting the top and VV contribution from data first. The V+Jets background is then normalized from the sideband region to the signal region using MC. No excess is observed over the expectation, as seen in one of the signal regions in figure 3. Upper limits on the cross section are able to exclude the HVT model A up to 3.5 TeV and the HVT model B up to 3.7 TeV (fig. 4).

5. X → VV

Lastly, an analysis searching for a high mass resonance from general di-boson decay with semi-leptonic and full hadronic final states, using an integrated luminosity of 77.3 fb^{-1}, is discussed [9]. Here the results of the all-hadronic channels are presented.

This analysis makes use of the "designed decorrelated tagger" (DDT) method [10], as it was found that the N-subjettiness τ_{21} is correlated to the mass and the p_T of the jets. Instead of τ_{21}, a new variable $\tau_{21}^{DDT} = \tau_{21} - M \cdot \rho'$ is defined, where M is a constant correlation factor and $\rho' = \log(m_J^2/p_T)$. Using τ_{21}^{DDT} instead of τ_{21} leads to a significant decrease of the mistagging rate for the same tagging efficiency.

The analysis is categorized into a high purity region ($\tau_{21}^{DDT} < 0.43$) and a low purity region ($0.43 < \tau_{21}^{DDT} < 0.79$). The event selection includes requirements on the transverse momentum of the jets of $p_T > 200$ GeV, as well as on the invariant di-jet mass of $m_{JJ} > 1126$ GeV. The major background in this analysis comes from QCD multijet events.

There is no excess observed over the expectation. Upper limits on the cross section are provided for a Bulk graviton (fig. 5) and the HVT model B (fig. 6).

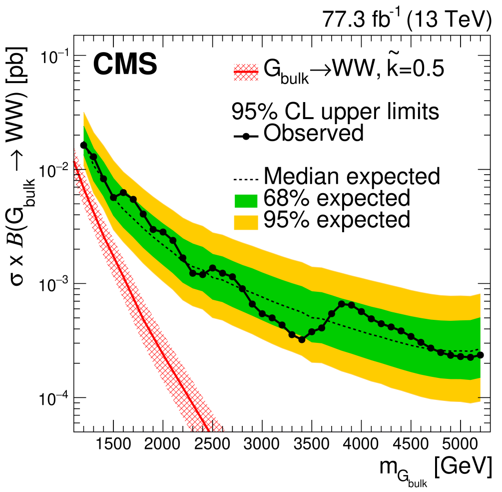

Figure 5: 95 % CL upper limits for the $G_{\text{bulk}} \to$ WW signal. [9]

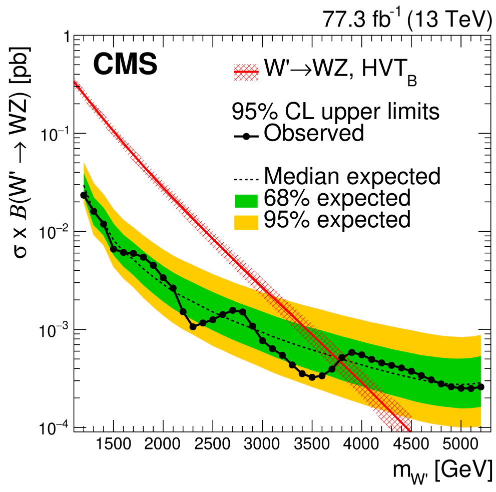

Figure 6: 95 % CL upper limits for the W' $\to$ WZ signal. [9]

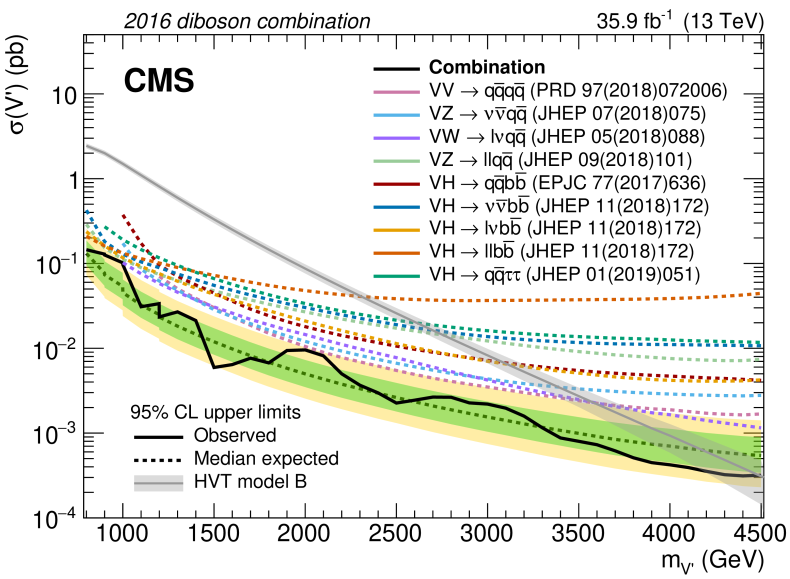

Figure 7: Observed and expected 95 % CL upper limits on cross sections as a function of the HVT triplet mass for the combination of all channels in the HVT model B. [11]

6. Conclusion

Only a few of the most recent analyses have been covered here. While there is no observation of a high mass resonance, the upper limits on signals have significantly improved with respect to those provided from Run 1 analyses. To give an example, by performing the combination of all di-boson analyses performed on the partial 2016 data set [11], the upper limit on the HVT model B using all di-boson analyses has improved to exclude a high mass resonance up to 4.5 TeV (fig. 7). A combination of analyses exploiting the full data sample collected in Run 2 will allow to extend the sensitivity of the searches even further.

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