

## Search for heavy resonances decaying to bosons with the ATLAS and CMS detectors

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### Abstract

This document summarizes the searches for heavy resonances decaying to massive bosons at the TeV mass scale. Results are based on data corresponding to an integrated luminosity up to about 20 inverse femtobarns recorded in proton-proton collisions at  $\sqrt{s} = 8$  TeV with the ATLAS and CMS detector at the CERN LHC. The bosons coming from the resonance decay can be W, Z, or the standard model Higgs. Several final states are considered: fully leptonic, leptons plus jets, and fully hadronic final states. Techniques aiming at identifying jet substructures are used to analyze signal events in which the hadronization products from the decay of highly boosted W or Z bosons are contained within a single reconstructed jet. No significant excess above the standard model prediction is observed in data. Upper limits on the production of diboson resonances are set as a function of the resonance mass and width. These searches provide the most stringent direct limits to date on the production of these hypothesized TeV-scale resonances.

**Keywords:** Physics Beyond the Standard Model, New Resonances, LHC, CMS, Diboson, Higgs, Jet substructure

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### 1. Introduction

One century of experimental measurements and progress in theoretical physics led to an extremely compact and elegant theory of fundamental interactions between elementary particles, the standard model (SM). Its success in reproducing measurements from different experiments in energy regimes spanning over several orders of magnitude is astonishing. The relatively recent discovery of the Higgs boson (H) at the CERN Large Hadron Collider (LHC) is another confirmation of the success of the SM. Still there are several open questions which cannot be answered in the context of the SM, of which some of the most important ones are: *what is the dark matter?*, *what is the cause of the matter-antimatter asymmetry in the universe?*, *what is the reason for the large difference between the electroweak and the gravity scale?*

Looking for signs of new physics beyond the SM at the TeV scale might help to answer some of these fundamental questions. One of the most direct ways to find new physics at the TeV scale is to search for new resonances. Colliding hadrons at the highest reachable energy to possibly create and study these new massive

states has been a successful experimental approach in particle physics during the last 50 years. This document presents searches for heavy resonances decaying to SM bosons. Results are based on data corresponding to an integrated luminosity up to about 20 inverse femtobarns recorded in proton-proton collisions at  $\sqrt{s} = 8$  TeV with the ATLAS [1] and CMS [2] detectors at the CERN LHC. The bosons coming from the resonance decay can be photon, W, Z, or H. One of the main advantages of these searches is the clean experimental signature, thanks to the known properties and decay kinematics of the SM bosons. Diboson resonances are also predicted in many model of new physics beyond the SM, such as the sequential standard model extension [3], composite Higgs models [4, 5, 6], scenarios with extra dimensions [7, 8, 9, 10], Technicolor [11, 12, 13] and others.

In Section 2 we present searches for resonances that decay to pairs of SM Higgs bosons. Section 3 summarises the results of searches for resonances decaying to pairs of V bosons (where V indicates either W or Z). Results of searches for heavy resonances decaying to  $\gamma\gamma$  [14],  $W\gamma/Z\gamma$  [15], and HH/ZH in the multileptons and photons [16] final states are discussed in more

details in other proceedings of this conference (see M. Kenzie's, K. Terashi's, and O. Bondus proceedings). In Section 4 we conclude by summarizing the current status of the diboson searches at LHC and we give some prospects for future studies during the second run-phase of the LHC.

## 2. HH Resonances

Both ATLAS and CMS have searched for heavy resonances ( $X$ ) decaying to pairs of Higgs bosons in the  $X \rightarrow HH \rightarrow \gamma\gamma bb$  and  $X \rightarrow HH \rightarrow 4b$  final states. The  $\gamma\gamma bb$  channel is a powerful final state in which to search for Higgs boson pair production, thanks to the large  $H \rightarrow bb$  branching ratio ( $\sim 57\%$ ), clean diphoton trigger, excellent diphoton invariant mass resolution (about 1% for the SM Higgs), and low backgrounds. This channel is particularly important in search for resonances with mass below 500 GeV. At higher resonance masses, the 4b channel dominates the sensitivity to new physics thanks to the larger branching ratio.

### 2.1. $\gamma\gamma bb$ Channel

The ATLAS  $\gamma\gamma bb$  analysis [17] starts by requiring an  $H \rightarrow \gamma\gamma$  candidate in the event, accordingly with the standard model analysis. In addition two jets, identified as coming from hadronization of  $b$  quarks (b-jets), are required with dijet mass  $95 < m_{jj} < 135$  GeV compatible with the Higgs boson signature. Finally the mass of the  $\gamma\gamma bb$  system ( $m_{\gamma\gamma bb}$ ) is required to be consistent with the hypothesised resonance mass ( $m_X$ ). The search is performed as a counting experiment where the  $\gamma\gamma bb$  requirement varies as a function of  $m_X$ . The SM backgrounds are estimated from  $m_{\gamma\gamma}$  sidebands and events with less than 2 b-jets.

The CMS  $\gamma\gamma bb$  selection [18] is conceptually similar to the ATLAS one. A few differences in the analysis strategy are represented by the presence of two separate event categories (1 or 2 b-jets), lower requirement on jet  $p_T$  (25 GeV instead of 35-55 GeV of the ATLAS search), and the use of a shape analysis (instead of a counting experiment) in either the  $m_{\gamma\gamma}$  or the  $m_{\gamma\gamma bb}$  distribution, depending on the resonance mass tested.

The ATLAS search observes a broad excess of events compared to SM predictions at a resonance mass around 300 GeV. The event distribution does not seem consistent with the  $m_{\gamma\gamma bb}$  resolution of a narrow resonance. Figure 1 shows the upper limits on production cross section times branching ratio as a function of the resonance mass. The broad excess is visible within the  $2\sigma$  bands of the expected limit. By visual comparison with the CMS results in Figure 2 (see the dark

blue lines), after dividing the CMS limit by the factor  $BR(HH \rightarrow \gamma\gamma bb) \sim 0.2\%$  to match the y-axis scale in the two plots, we notice that the ATLAS excess seems to be excluded by the CMS constraints on the same production cross section. The CMS analysis also appear more sensitive than the ATLAS one, providing expected upper limits about 50% smaller.

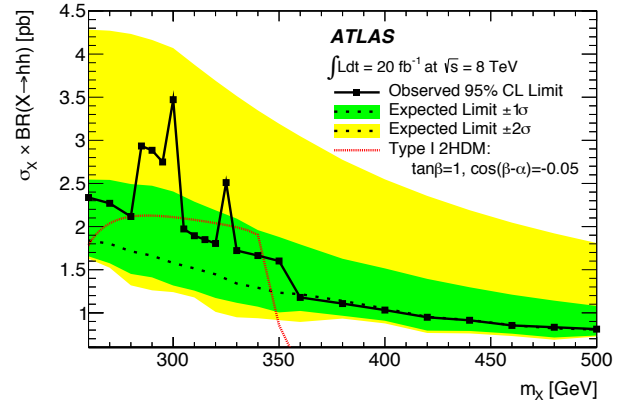


Figure 1: The ATLAS 95% CL upper limits on the cross section times branching ratio of a narrow spin-0 resonance decaying to pairs of Higgs bosons in the  $\gamma\gamma bb$  final state as a function of  $m_X$  [17].

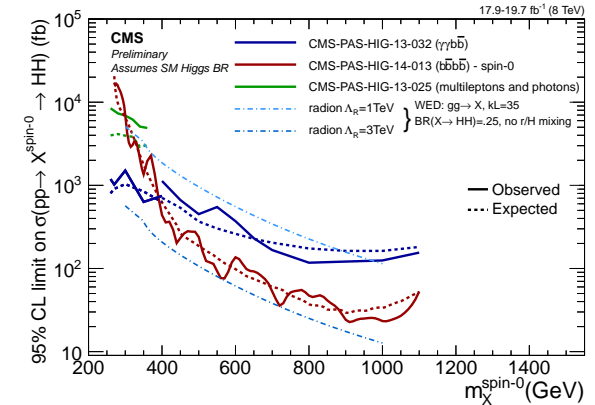


Figure 2: The expected and observed upper limit of spin-0  $X$  to  $HH$  production at 95% CLs provided by combining the searches performed by the CMS experiment looking at the 4b (HIG-14-013) [19],  $\gamma\gamma bb$  (HIG-13-032 [18]), and multileptons and photons (HIG-13-025 [16]) final states. Theoretical cross sections for the RS1-radion, with  $\Lambda_R = 1$  and 3 TeV,  $k_L = 35$ , and no radion-Higgs mixing are overlaid.

### 2.2. 4b Channel

The ATLAS  $HH \rightarrow 4b$  selection [17] requires at least 4 b-jets with  $p_T > 40$  GeV. Two unique dijets (system of two jets) are formed from the four highest- $p_T$  b-tagged

jets requiring for each dijet system a maximum angular separation between the jets ( $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 1.5$ ) and the  $p_T^{\text{dijet}} > 200$  GeV. A set of kinematic requirements are applied in order to reduce the  $t\bar{t}$  background, including a veto on extra jets in the event, as well as selections to isolate the  $t\bar{t}$  decay kinematics. After this selection, the dominant background is coming from QCD multijet events. The QCD background is estimated from data using an extrapolation from events with 2-bjets in the 4b-jet signal region. The 4b invariant mass resolution is of the order of 15% for a resonance mass of 1 TeV. No excess in data above the SM background expectation is observed. Figure 3 shows the upper limits on production cross section for a bulk graviton [8] that decays to HH in the 4b channel. The upper limits increase for resonance masses above 1 TeV; in this mass range, the Higgs bosons from resonance decay are highly boosted and their decay products are contained within a single reconstructed jet. This causes an inefficiency in the 4b selection, because it's not possible to reconstruct 4 resolved jets. Techniques aiming to solve this experimental issue will be discussed later in Section 3.1 in the context of the VV searches.

After the ICHEP2014 conference, the CMS collaboration released the results of a similar HH search in 4b final state [19]. The CMS limit is shown in Fig. 2 (red line). The sensitivities of the ATLAS and CMS analysis are comparable in the overlapping mass range between 0.5 and 1.1 TeV.

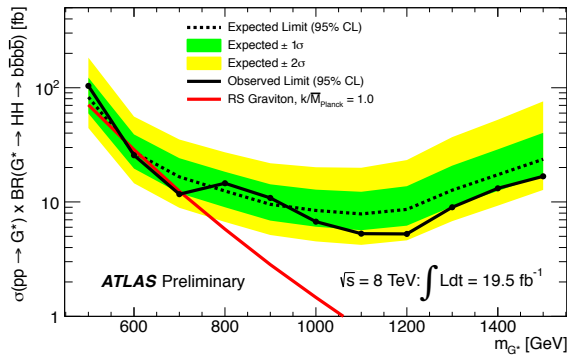


Figure 3: The ATLAS expected and observed 95% CL upper limits on  $\sigma(\text{pp} \rightarrow G_{\text{bulk}} \rightarrow \text{HH} \rightarrow 4b)$  as a function of the bulk graviton mass. Also shown is the leading-order prediction for  $\sigma(\text{pp} \rightarrow G_{\text{bulk}} \rightarrow \text{HH} \rightarrow 4b)$  as a function of the resonance mass in the bulk RS model with  $k/M_{\text{Planck}} = 1.0$  [17].

### 3. VV Resonances

There is a rich physics program on searches for VV resonances at LHC. Fully-leptonic, semi-leptonic, and

fully-hadronic final states have been considered. The Higgs boson itself is a VV resonance, and the study of these final states has covered a crucial role in its discovery. Searches for heavier partners of the Higgs are carried out in the context of the two-Higgs-doublet models [20] up to resonance masses of about 1 TeV. We'll not cover these studies in this document. We focus instead on searches for exotic neutral (WW, ZZ) and charged (WZ) resonances with masses typically beyond the TeV scale.

#### 3.1. Jet Substructure

VV final states with jets are important because of the large branching ratio of Z and W to hadrons and good jet energy resolution at high jet transverse momenta. At high mass, where the SM background is small, they exceed the sensitivity of the fully-leptonic channels. For large values of the resonance mass, the two quarks originating from the hadronically decaying W or Z bosons are highly collimated and are typically reconstructed as a single massive jet ("V jet"). The analyses presented here use the additional information from jet substructure to perform jet "V tagging" and to further suppress the SM background.

The identification of a V jet with respect to a background jet initiated from the hadronization of a quark or gluon, typically happens in two steps. In the first step, grooming algorithms (such as trimming [21], pruning [22, 23], filtering [24]) are applied to the candidate jet to remove the soft components, reducing effects of pileup (multiple pp interactions in the same bunch-crossing) and underlying event of the hard interaction. This allows to better identify the presence of substructure inside the jet. In the second step, jet declustering algorithms are applied to form subjets within the original jet, and substructure variables are built to discriminate signal from background. The most powerful variable is the jet mass: Fig. 4 shows the good separation between  $V \rightarrow qq$  jets and regular QCD background jets. The  $V \rightarrow qq$  distributions peak around the V mass (80-90 GeV) while the distributions from quark/gluon-initiated jets peak at much lower mass values. Additional variables, such as N-subjettiness [25], momentum balance [24] and others, are used in conjunction with the jet mass to improve the signal to background ratio. These methods have been validated in data using a pure sample of high  $p_T$  W bosons from  $t\bar{t}$  events. More details on the application of these techniques with the CMS and ATLAS detectors can be found at [26] and [27] respectively.

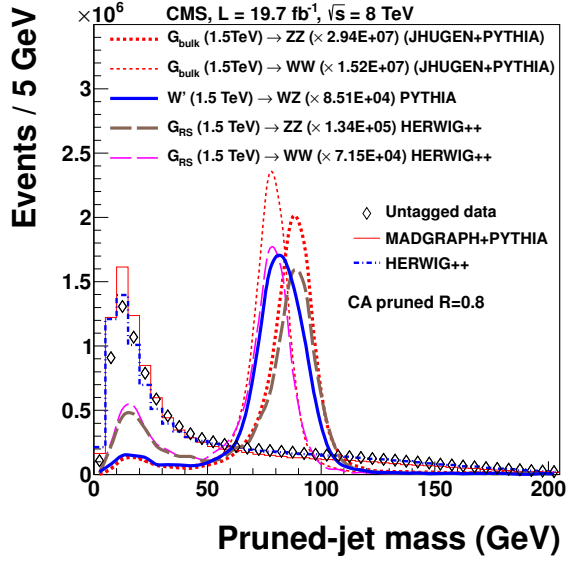


Figure 4: Distribution for pruned-jet mass in CMS data, and in simulations of signal and background events. All simulated distributions are scaled to match the number of events in data. MADGRAPH/PYTHIA and HERWIG++ refer to QCD multijet event simulations. [28]

### 3.2. Fully-Leptonic Final States

Searches for exotic charged particles decaying to  $WZ \rightarrow \ell\nu\ell\ell$ , where  $\ell$  is either an electron or a muon, have been performed in both ATLAS [29] and CMS [30]. This fully-leptonic channel is characterized by a pair of same-flavour, opposite charge, isolated leptons with high  $p_T$  and an invariant mass consistent with that of the Z boson. A third, high  $p_T$ , isolated charge leptons is also present, along with missing transverse momentum associated with the neutrino. Four channels are therefore considered:  $ee\nu e$ ,  $ee\nu\mu$ ,  $\mu\mu\nu e$ , and  $\mu\mu\nu\mu$ . The branching ratio in these final states is small (about 1.5%), but the signature is very clean. The primary background is in fact the irreducible SM WZ production. An increase in sensitivity compared to the previous results is achieved at high resonance masses by using optimised isolation criteria that successfully take into account collimated leptons from highly boosted Z bosons. The signal would appear as a bump in the  $m_{WZ}$ . In order to compute the mass, the undetectable longitudinal component of the neutrino momentum is extracted from the visible energy by using the constraint on the known W mass. With this method, the  $m_{WZ}$  resolution reaches about 10%. The CMS analysis is performed as a counting experiment after requiring that the reconstructed  $m_{WZ}$  is within an optimised range around the hypothesised resonance mass. The ATLAS analysis employs a shape analysis on the  $m_{WZ}$  spectrum. No

sign of new resonances is observed in the data. The CMS and ATLAS limits on the resonance production cross section are shown in Figures 5 and 6, respectively. Different models are tested: Sequential SM [3], Technicolor [11, 12, 13], Heavy Vector Triplet [31]. The sensitivity of the two analysis is very similar: as an example, the expected (observed) mass limit on a Sequential SM  $W'$  is 1.55 (1.47) TeV for the CMS analysis, and 1.52 (1.49) TeV for the ATLAS analysis.

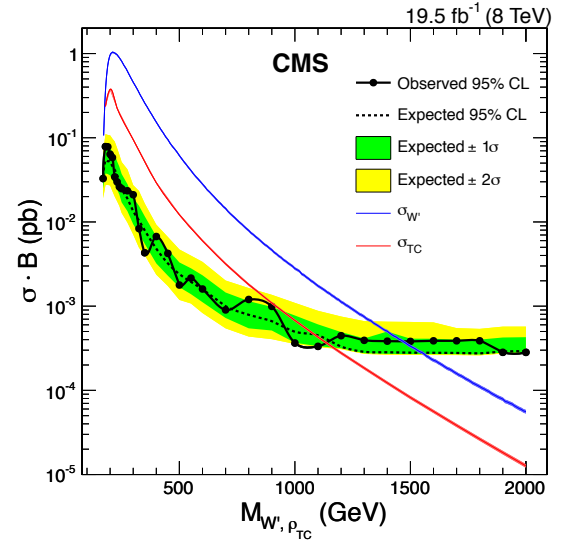


Figure 5: CMS expected and observed exclusion limit on  $\sigma \times \text{BR}(W \rightarrow 3\ell\nu)$  as a function of the WZ mass for Sequential SM  $W'$  [3] and  $\rho_{\text{Technicolor}}$  [11, 12, 13], along with the combined  $1\sigma$  ( $2\sigma$ ) statistical and systematic uncertainties depicted with the green (yellow) band.

### 3.3. Semi-Leptonic and Fully-Hadronic Final States

Final states with jets are important at high resonance mass thanks to the larger branching ratio compared to the fully-leptonic channels. The final states investigated so far are:  $ZV \rightarrow \ell\ell + V\text{-jet}$  (ATLAS [32] and CMS [33]),  $WV \rightarrow \ell\nu + V\text{-jet}$  (CMS [33]), and  $WV/ZV \rightarrow 2 V\text{-jets}$  (CMS [28]), where V can be either a W or a Z. The back-to-back topology of the two bosons from resonance decay is required in the event selection. Selection criteria are kept relatively loose in order to allow a model-independent search. Jet substructure techniques described in Section 3.1 are used to identify the hadronic decays of boosted vector bosons. In order to discriminate against multijet backgrounds, both the reconstructed jet mass, which is required to be close to the W- or Z-boson mass, and the two-prong jet substructure produced by the particle cascades of two high- $p_T$  quarks merging into one jet, are exploited. The analysis

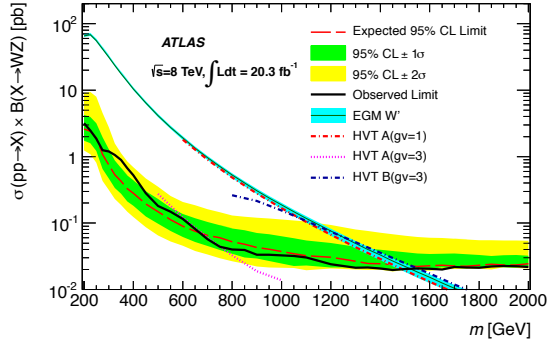


Figure 6: The ATLAS observed 95% CL upper limits on  $\sigma(pp \rightarrow X) \times \text{BR}(X \rightarrow WZ)$  as a function of the signal mass  $m$ , where  $X$  stands for the signal resonance. The expected limits are also shown together with the  $1\sigma$  and  $2\sigma$  standard deviation uncertainty bands. Theoretical cross sections for the Sequential SM  $W'$  [3] and the HVT [31] benchmark models are also shown.

strategy is a bump search in the reconstructed  $VV$  mass spectrum ( $m_{VV}$ ). Depending of the final state, the  $m_{VV}$  resolution ranges from 3% to 6% for resonance masses above  $\sim 1$  TeV.

In the semi-leptonic channels, the dominant SM background comes from  $V$ +jets processes. The  $V$ +jets background is estimated from data using events with jet mass not compatible with the  $V$  boson mass. The SM non-resonant  $VV$  production is an irreducible background, but it contributes significantly only in the tails of the  $m_{VV}$  distributions. In the  $\ell\nu$ + $V$ -jet channel, a veto to suppress  $t\bar{t}$  is also applied. The  $t\bar{t}$  and  $VV$  backgrounds are taken from simulation after correcting for differences between data and simulation in the  $V$  tagging derived from control regions in data.

In the fully-hadronic channel, the dominant background is represented by QCD multijet events. The background is estimated from data by fitting the  $m_{VV}$  distribution in the signal region with a smoothly falling function. This channel is sensitive to  $ZZ$ ,  $WW$ , and  $WZ$  resonances. Also  $qW$  and  $qZ$  resonances can be searched for using this analysis, by applying the  $V$  tagging on only one of the two leading jets.

No significant evidence of new physics beyond the standard model is observed in these searches. Figure 7 shows the limits on production cross section for the three CMS analyses in the semi-leptonic [33] and fully-hadronic [28] final states. The combination of the results is also shown under the hypothesis of a narrow bulk graviton model. In this scenario,  $\ell\nu$ + $V$ -jet is the most sensitive channel for resonance masses greater than 800 GeV. By comparing the expected limits with the observed ones, we notice a small excess in data com-

pared to background prediction in all 3 channels for a resonance mass around 1.8 TeV. The smallest discrepancy is present in the most sensitive channel, and thus dominates the overall significance of the excess (p-value around 0.1, about only  $1\sigma$ ). Figure 8 shows the limits on production cross section for the ATLAS  $\ell\ell$ + $V$ -jet analysis [32]. The sensitivity is comparable with the corresponding CMS analysis.

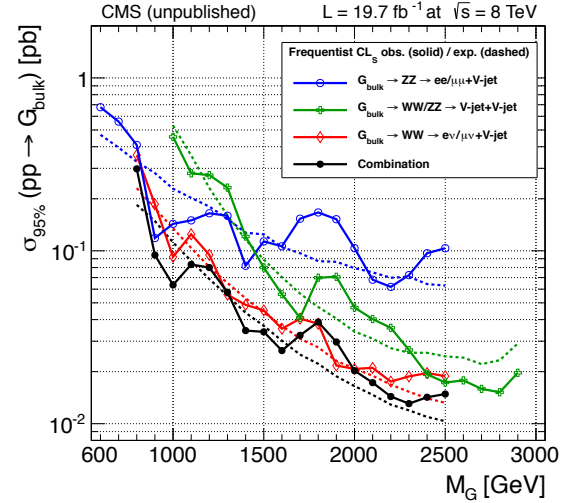


Figure 7: CMS observed (solid lines) and expected (dashed lines) 95% CL upper limit on the bulk graviton production cross section for the semi-leptonic channels [33], the all-hadronic channel [28], and their statistical combination. The combination is shown only in the mass range where at least two analyses contribute.

Some of the analyses presented above are specific to the case of a narrow bulk graviton model, but this is not the only extension of the SM predicting resonances decaying to vector bosons. We can consider narrow/wide resonances, different charge/spin hypothesis, as well as different  $V$  polarisation. The CMS semi-leptonic searches allow the reinterpretation of the results in a generic model greatly extending the versatility of the analysis. Efficiencies to reconstruct and identify a vector boson decay are provided as a function of the boson kinematics ( $\eta$  and  $p_T$ ). Upper limits on the number of signal events are also provided using a simplified event selection as a function of the resonance mass (from 600-800 GeV to 2500 GeV) and width (up to  $\Gamma/M = 40\%$ ). This allows to test a generic resonance model by comparing the expected signal yield, obtained by reweighting the generated events with the reconstruction efficiencies, with the experimental upper limits on number of signal events. More details on the use of these model-independent limits can be found in the Appendix of Ref. [33].



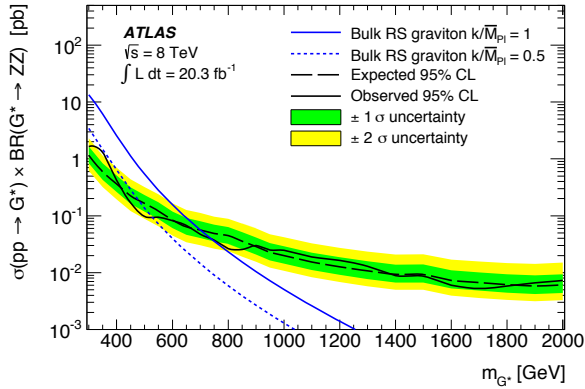


Figure 8: Observed and expected 95% CL upper limits on the cross section times branching fraction as a function of the resonance pole mass for the bulk graviton for the ATLAS  $\ell\ell+V$ -jet analysis [32]. The LO theoretical cross sections for bulk graviton production with  $k/M_{\text{Planck}} = 0.5$  and  $1.0$  are also shown.

#### 4. Conclusions and Future Prospects

We have presented the status of searches for heavy resonances at the TeV scale that decay to a pair of SM bosons, focusing on the HH and VV final states. Various theory models have been tested. Bulk gravitons with  $k/M_{\text{Planck}} = 1.0$  can be excluded at 95% confidence level (CL) up to masses of about 800 GeV. Sequential SM  $W'$  can be excluded up to about 1.8 TeV. The HVT model [31] represents an interesting benchmark for diboson searches. The method described in the paper is based on a simplified Lagrangian which reproduces a large class of explicit theory models of physics beyond the SM. The so-called “model B”, which reproduces Composite Higgs models, is particularly interesting in this context because it predicts the existence of two spin-1 resonances, one neutral ( $Z'$ ) and one charged ( $W'$ ), with approximately the same mass (within few GeV), and with primary decays in  $WW/ZH$  and  $WZ/WH$  final states, respectively. So far only the ATLAS experiment has considered this model in the context of the fully-leptonic  $WZ$  search [29]. We propose that more effort is made in future to quote limits on resonance masses and coupling parameters within this particular model; this will allow a useful comparison among the different diboson analyses as well as a direct comparison of the sensitivity between the ATLAS and CMS experiments.

Table 1 summarises the final states from the main decays of a TeV-scale resonance to a pair of SM bosons (excluding final states with photons which are not described in this document). The table also indicates which searches have been already performed at  $\sqrt{s} = 7$  and 8 TeV at the LHC in the context of the “exotic

physics” groups of ATLAS and CMS (excluding the Higgs searches to diboson final states for resonance masses below 1 TeV). Although many searches have been already performed, several final states still need to be studied. In particular  $ZH$  and  $WH$  searches for TeV scale resonances are currently missing. We expect new results on 8 TeV data analysis in the next months.

After the first run at  $\sqrt{s} = 7$  and 8 TeV, the physics program of the LHC will continue starting in Summer 2015 at  $\sqrt{s} = 13$  TeV. One of the primary physics goals will be the search for new physics in a new, unexplored energy range. There will be a large increase in sensitivity to TeV-scale resonance thanks to the larger center-of-mass-energy. We expect to exceed the current limits on production of resonances with mass greater than 2 TeV already after the first 3 weeks of data taking at  $\sqrt{s} = 13$  TeV (corresponding to about one inverse femtobarn of pp collision data). The highest priority among the diboson searches should probably be given to the semi-leptonic and fully-hadronic final states, being the most sensitive channels at high mass in the 8 TeV analyses.

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Table 1: Summary of final states from the main decays of a TeV-scale resonance to a pair of massive SM bosons. Final states indicated in red and blue has been searched for by the CMS and ATLAS experiments, respectively. It is also indicated the  $\sqrt{s}$  (in TeV) corresponding to the most recent search in the considered final state. The grey area is specular with respect to the top-left part of the table and should be ignored.

	$W \rightarrow \ell \nu$	$W \rightarrow qq$	$Z \rightarrow \ell \ell$	$Z \rightarrow \nu \nu$	$Z \rightarrow qq$	$H \rightarrow \gamma \gamma$	$H \rightarrow \tau \tau$	$H \rightarrow bb$
$W \rightarrow \ell \nu$	7	8	8	8	—	8	—	—
$W \rightarrow qq$		8	8	8	—	8	—	—
$Z \rightarrow \ell \ell$			—	—	8	8	—	—
$Z \rightarrow \nu \nu$				—	7	—	—	—
$Z \rightarrow qq$					8	—	—	—
$H \rightarrow \gamma \gamma$						—	8	8
$H \rightarrow \tau \tau$							—	—
$H \rightarrow bb$							8	8

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