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ATLAS Searches for VH, HH, VV, V+γ and $\gamma\gamma$ Resonances

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The discovery of a Higgs boson at the Large Hadron Collider motivates searches for physics beyond the Standard Model in channels involving coupling to the Higgs boson. A search for massive resonances decaying into couples of bosons is described. The considered final states are: HH, VH, VV, $V\gamma$ and $\gamma\gamma$ with V indicating either the W or the Z boson. Final states with different number of leptons or photons and where, in many cases, at least one Higgs decays into a b-quark pair are studied using different jet reconstruction techniques which allow to optimize the signal acceptance for low or high Higgs boson transverse momentum. The most recent diboson resonance searches using LHC Run 2 data are described.

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1. Introduction

With the discovery of the Higgs boson by the ATLAS [1] and CMS [2] experiments in 2012, the Standard Model (SM) is now complete, yet unanswered questions are still present. For this reason, one of the goals of particle physics research at the LHC is to find new hints on physics Beyond the Standard Model (BSM). Diboson resonances with masses of the order of few TeV are a promising signature for direct searches for new physics since they are predicted by many BSM models such as Extended Gauge Models (EGM) [3], Warped Extra Dimensions [4], Technicolor models [5], Extra/Composite Higgs [6, 7]. Given the wide variety of BSM models, the searches are designed to be sensitive to a large range of signatures and to a broad phase space. Those searches must remain as general as possible and not being sensitive to the parameters specific to a given theory observing only the invariant mass of the diboson system. The presence of a new particle is then searched as a peak arising over a smooth background.

Few benchmark models are chosen to test the analysis performances against different models. Limits on cross-sections as a function of the particle mass are obtained in the framework of three representative benchmark models: the Randall-Sundrum graviton [4], the Heavy Vector Triplet (HVT) [8] and the additional Higgs [6, 7]. The Randall-Sundrum model introduces a warped extra dimension to solve the hierarchy problem. It predicts the existence of various new particles among which there are excited states of the bulk graviton that appear as spin-2 neutral particles with mass of the order of few TeV. A second model often used as benchmark is the Heavy Vector Triplet, that envisages the presence of three additional spin-1 particles degenerated in mass: a charged particle and its antiparticle, $W^{'\pm}$ and a neutral particle $Z^{'}$. This triplet arises in a variety of models therefore an effective Lagrangian in which the coupling between the SM boson and the HVT (g_h) is considered as a parameter of the model is used. Two values of the coupling g_h are tested: $g_h = 1$ (Model A) favours coupling to fermions, $g_h = 3$ (Model B), favoring coupling to SM bosons. The last benchmark model considered predicts an additional Higgs boson, that is a neutral scalar particle, with mass of the order of few TeV.

2. Jet topologies and experimental techniques

All models include the existence of new particles with mass $O(\text{TeV})$ therefore the bosons, candidate decay products of these particles, must have high transverse momenta. This is particularly relevant when the final state is reconstructed through the hadronic decays of the bosons (W, Z or H). In this case the angular separation (ΔR) of the two quarks emerging from the boson decay can be roughly described by $\Delta R \approx \frac{2\times M_B}{p_{\mathrm{T}}{}^B}$ where M_B and $p_{\mathrm{T}}{}^B$ are the mass and the transverse momenta of the parent boson (B=W, Z, H). Two kinematic phase spaces are defined based on the value of the p_{T}^B:

- a resolved regime where the two decay products are identified as two separate anti-k_t jet with a radius parameter of 0.4;
- a boosted regime where the two decay products are identified as an unique anti-k_t jet with a radius parameter of 1.0, often called large-R jet or J.

In the merged regime, the large cone size used to reconstruct the boson decay products gives rise to a large contamination by soft particles (pile-up, underlying event, ...) that are rejected using the trimming technique [1]. Once this jet cleanup is performed, then boson identification techniques can be applied to the large-*R* jet. In the case of an Higgs boson double *b*-tagging algorithms are used ($BR(H \to b\bar{b}) \approx 67\%$).

For gauge bosons, substructure techniques exploit the two and three point correlation functions between energy deposits in the jet using a variable named D_2, which can identify the two prong substructure characteristic of gauge boson originated jets.

3. Analysis strategies and results

This section reports the most relevant points and the main results of a selected set of di-boson analysis which constitute, at this time, the most updated analysis for the VV, VH, HH, $V+\gamma$ and $\gamma\gamma$ searches. The full description of each analysis can be found in the reference papers. These analysis are performed using data collected with the ATLAS detector [9] at $\sqrt{s} = 13$ TeV with an integrated luminosity that differs for each particular analysis and that will be indicated in each paragraph.

$\boldsymbol{VV' \to qq'q''q'''}$; $\int \mathscr{L} dt = 15.5\,\mathrm{fb}^{-1}$ - The $VV \to qq'q''q'''$ [10] fully hadronic final state is the one that better populates the high mass di-boson spectrum due to its high branching fraction. The drawback of choosing a fully hadronic final state is the presence of a large multi-jet background. The strategy to improve the signal to background ratio is based on three criteria:

- the analysis is performed only in the merged regime that is the two candidate bosons are reconstructed as two large-*R* jets with high p_T thresholds ($p_\mathrm{T} > 450$ GeV and $p_\mathrm{T} > 200$ GeV respectively);
- the high jet p_T thresholds rejects a large part of the soft multi-jet background. ;
- jet substructure techniques are used for boson identification;
- event level selections are applied to require large angular separation and momentum balance of the two jets.

After all the selection criteria the QCD multi-jet background shape on the m_{JJ} can be modeled with a double polynomial fitted in signal region. Limits are set using the modified CL_S approach [11]. This analysis excludes the presence of Model-A HVT (Model-B) in the regions 1200 GeV $\leq m_{W'} \leq$ 1900 GeV (1200 GeV $\leq m_{W'} \leq$ 3000 GeV) for the charged resonance and 1100 GeV $\leq m_{Z'} \leq$ 1800 GeV (1200 GeV $\leq m_{Z'} \leq$ 1900 GeV) for the neutral component. An example of limits on the production cross section of HVT charged current is reported in Figure 1.

$\boldsymbol{VH \to q\bar{q}(')b\bar{b}}$; $\int \mathscr{L} dt = 36.1\,\mathrm{fb}^{-1}$ - As for the previous search, also for the $VH \to q\bar{q}(')b\bar{b}$ final state [12] the high QCD multi-jet background is reduced performing the analysis only in the merged regime. In this case the analysis is performed categorizing the signal in four regions, namely WH 1 *b*-tag, WH 2 *b*-tag, ZH 1 *b*-tag and ZH 2 *b*-tag. The M_{JJ} multi-jet background

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[1] The trimming algorithm used in these analyses uses k_t sub-jets with a radius parameter of 0.2 and a p_T cut of 5%

shape is obtained from the 0 b-tag sample reweighting the M_{JJ} spectrum to account for kinematic differences with respect to the 1, 2 b-tag samples as obtained from the MC. The normalization of each distribution is obtained using the sideband regions. This analysis excludes the Model-A HVT (Model-B) in the regions 1100 GeV $\leq m_{WH} \leq$ 2400 GeV (1100 GeV $\leq m_{WH} \leq$ 2500 GeV) for the charged resonance and 1100 GeV $\leq m_{ZH} \leq$ 1480 GeV, 1700 GeV $\leq m_{ZH} \leq$ 2350 GeV (1100 GeV $\leq m_{ZH} \leq$ 2600 GeV) for the neutral component. The highest tension found in data is in the 3.0 TeV region and has a local significance of 3.3σ and a global significance of 2.2σ.

$\boldsymbol{HH \rightarrow b\bar{b}b\bar{b}}$; $\int \mathscr{L} dt = 13.3\,\mathrm{fb}^{-1}$ - The search in the $HH \rightarrow b\bar{b}b\bar{b}$ final state [13] is performed both in the boosted and merged regimes. In each regime the signal is categorized on the base of the number of b-tags (2, 3, 4). This categorization allows to increase the analysis sensitivity. The multi-jet background is estimated using data-driven techniques and it accounts for roughly the 85% of the total background. This estimation is performed defining three non-overlapping regions based on the value of the masses of the two Higgs boson candidates (Figure 2). The three lines on Figure 2 indicate the signal, sideband and control regions. The 2, 3, 4 b-tag control regions are used to reweight the 0-btag sample to account for kinematic differences with respect to the 2, 3, 4 b-tag samples. The obtained reweighted samples are used as multi-jet p.d.f. The full background shape is obtained summing this multi-jet p.d.f. to the p.d.f. of other backgrounds extracted from MC samples. The total background distribution is then obtained fitting the obtained distribution in sideband and signal regions simultaneously. This analysis has excluded the presence of Randall-Sundrum Bulk gravitons for 360 GeV $\leq m_{G^*} \leq$ 860 GeV.

$\boldsymbol{Z\gamma \rightarrow \ell\ell\gamma}$; $\int \mathscr{L} dt = 13.3\,\mathrm{fb}^{-1}$ - The search for new resonances in the $Z\gamma$ channel [14] is performed in the fully leptonic final state. The analysis examines two final states: $X \rightarrow Z\gamma \rightarrow e^+e^-\gamma$ and, $X \rightarrow Z\gamma \rightarrow \mu^+\mu^-\gamma$. The Z selection is performed requiring $m_{\ell\ell} \in m_Z \pm 15$ GeV and selecting the Z candidate with the highest transverse momentum. The signal is parameterised using a double sided Crystal-Ball; the width and mass of the peak are fixed using a simulated sample of additional scalar bosons decaying into leptons+γ. The signal width is larger for the $\mu\mu\gamma$ final state than in the $ee\gamma$ one, as an example for a signal of mass $M_X = 2.5$ TeV the signal width is expected to be $\sigma(M_X) = 15$ GeV (0.6%) in the $e^+e^-\gamma$ channel while it is $\sigma(M_X) = 35$ GeV (1.4%) in the $\mu^+\mu^-\gamma$ channel. The background is parameterised using a double polynomial fitted to data in the signal region. No significant excess is found and, the largest deviation from the background only hypothesis is found for $M_X = 268$ GeV with a local significance of 2.2σ.

$\boldsymbol{\gamma\gamma}$; $\int \mathscr{L} dt = 15.4\,\mathrm{fb}^{-1}$ - The latest update on the search for scalar diphoton resonances [15] includes only the spin-0 resonance selection. In this analysis the two photons are required to be well isolated and to pass tight identification criteria based on a likelihood. Furthermore, the two photons are expected to have similar values of transverse energies (E_T) therefore it is required that $E_\mathrm{T} > 0.4(0.3)M_{\gamma\gamma}$ for the leading (subleading) photon. The signal is parameterised using a double sided Crystal-Ball; in this case the mass and the width of the signal are left floating and limits are set as a function of the two parameters. The background is parametrized with a double polynomial. The 3.2fb^{-1} collected during 2015 were re-analyzed with an improved photon reconstruction algorithm and the largest excess is observed at $M_X = 730$ GeV with a local significance of 3.4σ and a width equal to 8%. The largest excess in the 2015+2016 dataset is observed at $M_X = 1600$ GeV, with a local significance of 2.4σ local in narrow width approximation (width fixed to 400 MeV). In the $700 - 800$ GeV mass range, the largest excess for the complete 2015+2016 dataset is instead observed at $M_X = 710$ GeV with a local significance of 2.4σ for a relative width 10%. The compatibility between the 2015 and the 2016 data has been evaluated and was found to be at the level of 2.7σ in the hypothesis of $M_X = 730$ GeV.

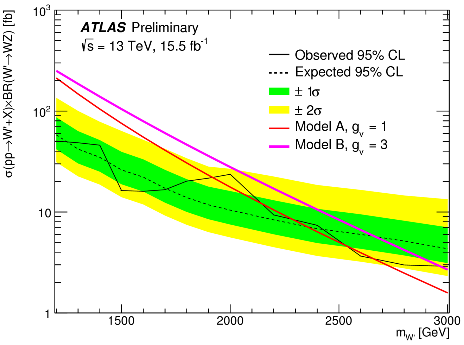

Figure 1: Limits on $\sigma \times BR$ for the charged signal selection ($WZ \to qq'q''q'''$) [10] as a function of $M_{W'}$. The black solid (dashed) line represents the observed (expected) limit. The green and yellow bands give respectively the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties of the expected limits. The predicted production cross-sections are shown in the magenta (HVT Model-B) and red (HVT Model-A) solid line.

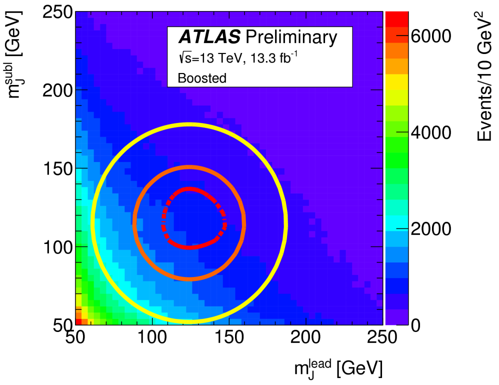

Figure 2: Signal (dashed red line), sideband (yellow line) and control (orange line) region definition for the boosted regime of $HH \to b\bar{b}b\bar{b}$ analysis [13]. The jet mass distributions for the leading (m_J^{lead}) and subleading boson candidates (m_J^{subl}) is shown.

4. Conclusion

A brief summary of the most recent searches obtained by the ATLAS collaboration in the diboson final states was presented. The analysis teams are exploitng the available luminosity to refine their results and to push the exclusion boundaries towards the high mass/low cross section regime. Improvements on the exclusion limits will also take advantage of the unprecedented luminosity of ≈ 100 fb^{-1} available at the end of the LHC Run 2.

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