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Search for heavy resonances in the $\ell\ell qq$ final state in pp collisions at $\sqrt{s} = 13$ TeV with ATLAS

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Abstract. A search for heavy resonances decaying to a pair of Z bosons is performed using proton–proton collision data produced at $\sqrt{s} = 13$ TeV and recorded by the ATLAS detector at the LHC. The data correspond to an integrated luminosity of 3.2 fb^{-1}. Diboson resonant production is expected in several Standard Model extension scenarios. The ZZ decay mode considered corresponds to one Z boson decaying to a pair of charged leptons and the other decaying to a pair of quarks. No evidence for the production of resonances decaying to a ZZ pair is observed. Upper bounds on the production cross sections at $\sqrt{s} = 13$ TeV times their decay branching ratios to ZZ pairs are derived for a heavy Higgs boson and a spin–2 Randall-Sundrum graviton scenario.

1 Introduction

This note presents a search for heavy resonances decaying to a pair of Z bosons [1]. The ZZ decay mode considered corresponds to one Z boson decaying to a pair of electrons or muons and the other decaying to a pair of quarks. The data used were collected with the ATLAS detector [2] during 2015 at the LHC in proton–proton collisions at a centre-of-mass energy of 13 TeV and correspond to an integrated luminosity of 3.2 fb^{-1}. Heavy ZZ resonances are predicted in several extensions of the Standard Model (SM) such as models with extra Higgs bosons [3, 4], the extended gauge model [5] and warped extra-dimension models [6]. The heavy resonances are modeled using a neutral CP–even spin–0 Higgs boson with SM–like couplings, as well as a spin–2 graviton G*. The gluon-gluon fusion process, gg→H or G*, is used to model the production of both ZZ resonances.

2 Event classification

The online selection of $ZZ \rightarrow \ell\ell qq$ events was based on a selection of various single-electron or single-muon triggers with quality and isolation requirements dependent on the E_T (electron) and p_T (muon) thresholds. The E_T thresholds for electrons were 24, 60 and 120 GeV, while the p_T thresholds for muons were 20 and 50 GeV.

The two leptons from one leg of the ZZ decay are required to be of same flavour, isolated and pass 'loose' identification criteria while at least one of the two is additionally required to fullfill 'medium' selection criteria. The dilepton invariant mass is required to be in the range of 83–99 GeV

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for electrons and wider for muons, 76–106 GeV, in order to accomodate effects of degraded muon momentum resolution at high-p_T. Events with more than two 'loose' leptons are vetoed.

The reconstruction of the Z→ qq is performed via two exclusive and complementary approaches due to the potentially highly boosted system of the decay. Therefore the object and event selections in the two cases differ. The two strategies are outlined in following sections.

2.1 Resolved selection

Two separate jets (jj) are reconstructed. Candidate events are further categorized based on the number of b-tagged jets; events with two b-tagged jets (tagged category) and events with fewer than two b-tagged jets (untagged category). The selection highlights of the resolved channel are listed below:

- At least 2 jets with $|\eta| < 2.5$.
- Leading jet $p_T \geq 60$ GeV.
- Subleading jet $p_T \geq 25$ GeV.
- Dijet invariant mass in the range $70 \leq m_{jj} \leq 105$ GeV.
- A p_T-balance cut defined as $\sqrt{p_T^2(\ell\ell) + p_T^2(jj)}/m_{\ell\ell jj} > 0.5$, applied only to the untagged category.

2.2 Merged selection

This case comprises of heavy resonances decaying to Z bosons producing a highly boosted system where the two fermions are emitted within a small opening angle in the laboratory frame. The hadronization of the quarks coming from the Z boson in this case produces two partially overlapping jets reconstructed as a single jet. These large-R jets are reconstructed with the anti-k_T algorithm and radius parameter $R = 1.0$, in the rapidity range $|\eta| < 2.0$.

The leading p_T large-R jet in the event, denoted with J, is assumed to originate from the hadronic Z decay and the event selection requires that the following criteria are satisfied:

- Leading jet $p_T \geq 200$ GeV.
- $p_T(\ell\ell)/m_{\ell\ell J} > 0.3$.
- J is tagged as a Z boson in a 2-step process:

  1. A p_T-dependent requirement on the jet substructure variable $D_2^{(\beta=1)}$, which is the ratio of the energy correlation functions of subjets [7].
  2. The large-R jet mass m_J is required to be in a window of ±15 GeV around 93.4 GeV, the expected value for the Z boson mass based on MC simulations. This requirement is $\sim 68\%$ efficient for the signals studied [1].

The Merged channel has priority over the Resolved channel in the event selection flow. In Table 1 the data and MC yields for both signal and backgrounds after full selection are given for the three non overlappig signal regions (SR).

Table 1. Data and MC yields after full selection.

Process	Merged analysis	Resolved analysis	
		untagged category	tagged category
Z+jets	185 ± 9	4130 ± 50	204 ± 16
Diboson	17.3 ± 3.5	143 ± 14	23.2 ± 3.3
Top quark	1.5 ± 0.6	113 ± 10	151 ± 6
Total background	203 ± 11	4380 ± 50	378 ± 15
Data	201	4484	373
H (750 GeV)	12.9 ± 3.2	7.3 ± 2.1	2.03 ± 0.33
G^* (750 GeV)	15 ± 4	7.9 ± 2.3	2.0 ± 0.4

3 Large-R jets and substructure

In the merged channel, jet-substructure techniques are used to identify the qq pair, reconstructed as a single large-radius jet. The jets are groomed to reduce the effect of pileup and other sources of noise on the resolution. The chosen grooming technique is the trimming algorithm. Trimming takes the original constituents of the jet, reclusters them using the k_t algorithm with a smaller distance parameter and produces a collection of subjets used to recompute the large-R jet energy and momentum. The decision to reject or keep the subjet is based on its p_T. If the ratio of the jet p_T over the original jet p_T is above a certain threshold (f_{cut}) the subjet is kept. The trimming parameters optimised for this search are $R_{subjet} = 0.2$ and $f_{cut} = 5\%$.

Figure 1 illustrates the steps needed to produce a trimmed jet out of the initial large-R jet.

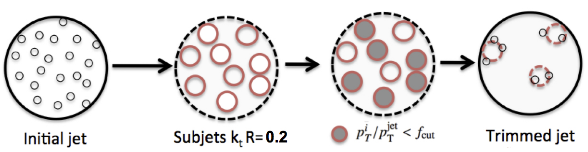

Figure 1. Schematic view of jet grooming technique using the trimming algorithm.

4 Background estimation

A summary of the sources of background and their contribution to each of the three above defined event categories is shown in Figure 2. Background events from Z+jets, diboson and top-quark processes are expected with the Z+jets being the dominant one. The multijet background is estimated to be negligible. The distribution of the $m_{\ell\ell jj}$ and $m_{\ell\ell J}$ variables, for events passing the resolved or merged selections respectively, are used as final discriminants for the signal against the background, which is expected to exhibit a smooth trend for all sources.

The estimation of the background is based both on Monte Carlo (MC) simulation and on data-driven techniques. In all cases, the shapes of kinematic variables are taken from MC simulations. Background from Z+jets and top events are estimated from four control regions (CR) enriched each in one or two of the main backgrounds.

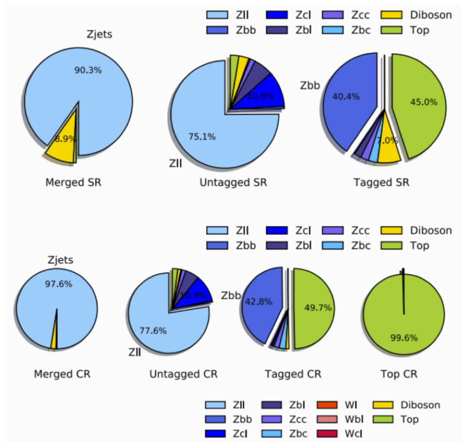

Figure 2. Breakdown of contributions to SR and CR from background sources.

Z+jets CR are defined using the side-bands of the m_J distribution for the merged analysis and the side-bands of the m_{jj} distribution for the resolved analysis. All other selections are kept the same as for the SR definition.

For the merged analysis, the leading large-R jet is required to have its mass value outside the 15 GeV Z boson mass window. For the resolved analysis, a requirement of $50 < m_{jj} < 70$ GeV or $105 < m_{jj} < 150$ GeV is applied.

Top-quark production is a significant background in the tagged category of the resolved analysis. Its contribution is normalised using a top-quark control region where events are selected requiring two different-flavour leptons with invariant mass between 76 and 106 GeV, plus two b-tagged jets with their invariant mass in the range [50,150] GeV.

Diboson production, mainly ZZ and WZ processes, are estimated completely from MC simulations. The compatibility of the data with the hypothesis of a heavy resonance is tested with a simultaneous maximum likelihood fit to the binned distributions of $m_{\ell\ell jj}$ or $m_{\ell\ell J}$ in the three signals and the four control regions devised to contrain the normalization of the main background processes. Systematic uncertainties and their correlations are taken into account in the fit through nuisance parameters.

Figure 3 shows the invariant mass distributions of the ZZ decay products in the three Z+jets and one top-quark control regions in the data. Fit results in scale factors, with respect to the MC predictions, of 1.03 ± 0.15 for Z+jets of the merged analysis, 0.92 ± 0.07 for Z + jj of the resolved analysis, 1.40 ± 0.14 for Z + bb of the resolved analysis, and 1.03 ± 0.07 for top-quark in the tagged category of the resolved analysis.

5 Results

The data are found to be consistent with the background expectations and no evidence for heavy resonance production is observed. Figure 4 shows upper limits at 95% CL on the production cross section of the heavy resonance times its branching ratio to ZZ derived for H→ZZ and $G^\star$ → ZZ as a function of the resonance mass. The observed (expected) limits range from 5.6 (3.3) pb at 300 GeV to 0.21 (0.11) pb at 1000 GeV for the heavy Higgs boson and from 0.62 (0.52) pb at 500 GeV to 0.20 (0.11) pb at 1000 GeV for the graviton. Limits are derived also for gg→H→ZZ production of Higgs

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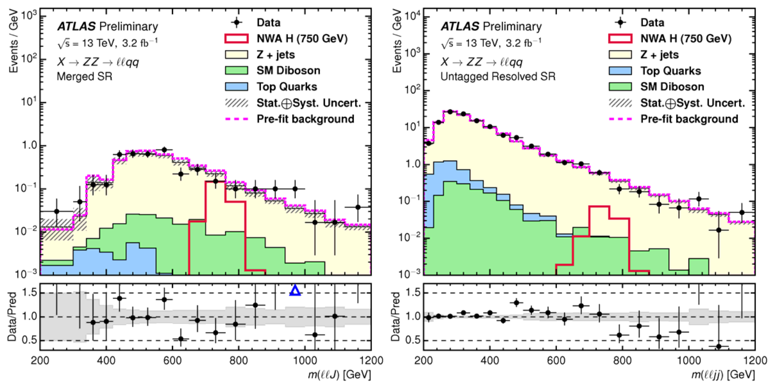

Figure 3. Post-fit of $m_{\ell\ell J}$ and $m_{\ell\ell jj}$ distributions [1].

bosons with a narrow width and three different values of the width: 5%, 10%, and 15% of the Higgs boson mass.

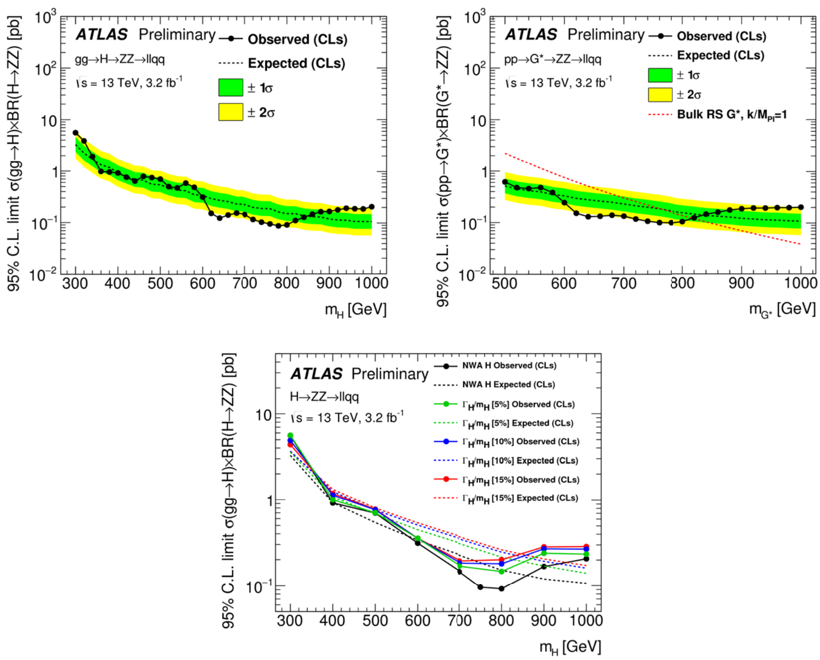

Figure 4. Observed and expected 95% CL upper limits on the production cross section of a heavy resonance at $\sqrt{s}$ = 13 TeV times its decay branching ratio to a Z boson pair for H→ZZ (left) and G* → ZZ (middle) as functions of the resonance mass, combining the merged and resolved analyses. The observed and expected upper limits for gg→H→ZZ production of Higgs bosons with a narrow width (black) and three different values of the width: 5% (green), 10% (blue), and 15% (red) of the Higgs boson mass [1].

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