Searching for Exotics: Heavy resonances with the
ATLAS detector

Simon Viel, on behalf of the ATLAS Collaboration
University of British Columbia - TRIUMF, Vancouver, Canada
E-mail: sviel@cern.ch

Abstract. Many theories that go beyond the Standard Model predict the existence of new
heavy resonances decaying into pairs of particles. This review summarizes a wide collection
of recent results from the ATLAS experiment at the Large Hadron Collider on searches for
resonances decaying into various combinations of charged leptons, neutrinos, jets from gluons or
light quarks, top quarks, photons and heavy gauge bosons. Limits are set on a variety of theories
beyond the Standard Model used as benchmarks, among them Kaluza-Klein, Randall-Sundrum
and ADD models with extra dimensions, as well as Grand Unified Theories and Technicolour.

1. Introduction
Resonances decaying into pairs of particles have played a very significant role in the development
of particle physics, and are an important place to look for phenomena beyond the Standard
Model (SM). This review summarizes several searches for such new particles, conducted using
proton-proton collision data at a centre-of-mass energy of 7 TeV or 8 TeV recorded with
the ATLAS detector [1] at the Large Hadron Collider (LHC). Since no significant excess is
observed over expectations from SM processes, limits are set at the 95% confidence level (CL)
on resonances decaying into jets from light quarks or gluons, charged leptons (including taus),
neutrinos, top quarks, photons or heavy gauge bosons.

The searches are signature-based, and interpreted in terms of theories beyond the Standard
Model, used as benchmarks.1 The Sequential Standard Model (SSM), where new gauge bosons
W'_{SSM} and Z'_{SSM} only differ from the SM W and Z by their mass, is commonly used for this
purpose. Better theoretically motivated are the additional gauge bosons W' and Z' which arise
from Grand Unified Theories (GUT), for example with E_6 as the unifying gauge group, or in
parametrizations such as the Minimal Z' models. Another class of models postulates extra
dimensions of space in an attempt to solve the hierarchy problem, and these theories predict
new resonances such as Kaluza-Klein (KK) modes of the graviton in ADD models, excited
gravitons (G*) or KK gluon modes (g_{KK}) in Randall-Sundrum (RS) models, or KK modes of
other gauge bosons (γ_{KK}, Z_{KK}) in TeV⁻¹ models. Other possible solutions to the hierarchy
problem, including Technicolour and theories with chiral bosons (W*, Z*), predict resonances
that may be observed at the LHC, and likewise other theories beyond the SM predict excited
fermions, colour-octet scalars, string resonances, torsion resonances, quantum black holes, etc.
Some searches can also be interpreted in terms of effective four-fermion contact interactions.

1 Theoretical references can be found in the respective experimental works cited.
2. The ATLAS detector

The analyses described in this review collectively make use of all the detector systems that constitute the ATLAS detector. The inner detector (ID), used to reconstruct charged particle tracks and vertices, consists of silicon pixels, silicon strips and transition radiation detectors, covering $|\eta| < 2.5$ in pseudorapidity. It is immersed in a homogeneous solenoidal magnetic field, which allows to measure the momentum of charged particles using track curvature. The calorimeters, responsible for the reconstruction of particle showers, are made of liquid argon and lead in the electromagnetic (EM) part, while the hadronic part is composed of scintillating tiles and iron in the central region and liquid argon, copper and tungsten in the forward region. Outside the calorimeter, toroid magnets provide the field for the muon spectrometer (MS), which consists of resistive-plate and thin-gap trigger chambers, and three sets of drift tubes and cathode strip chambers allowing for the reconstruction of muon tracks with high precision.

3. Dijet resonances

Collisions at the LHC often result in a pair of jets of particles with high transverse momentum ($p_T$), and such events can reach the highest energies accessible at the LHC. Jets in ATLAS are reconstructed using the anti-$k_t$ clustering algorithm with the distance parameter $R = 0.6$, and their energy is measured in the calorimeters. The dijet invariant mass, $m_{jj}$, is calculated from the four-momenta of the two highest-$p_T$ central jets passing the selection criteria, and the resulting spectrum from data is fitted with a smooth function:

$$f(x) = p_1(1 - x)^{p_2}x^{p_3} + p_4 \ln x,$$

where $x = m_{jj}/\sqrt{s}$ and the $p_i$ are fitting parameters, to obtain the background estimate.

The dijet invariant mass distribution obtained using 13 fb$^{-1}$ of data collected in 2012 at $\sqrt{s} = 8$ TeV is shown along with the corresponding background estimate in Figure 1. Limits are set on excited quarks ($q^*$), excluding masses above 3.84 TeV at the 95% CL, as well as on the cross section times acceptance ($\sigma \times A$) of Gaussian signal shapes, as shown in Figure 2.

The analysis performed using the full dataset taken in 2011 at $\sqrt{s} = 7$ TeV, set limits on a wider range of hypothetical resonances decaying into dijets: colour octet scalars, $W'_{SSM}$ and string resonances, in addition to excited quarks. In addition, an angular analysis was performed and data were shown to be consistent with QCD NLO simulations. Limits were therefore set on the scale of four-quark contact interactions, and on the quantum gravity scale for a quantum black hole signal in six additional space-time dimensions.

4. Dilepton resonances

Searches for resonances decaying into pairs of high-energy electrons and muons rely on accurately measuring the final-state leptons. Electron candidates are identified using clusters in the electromagnetic calorimeter associated with inner detector tracks, while muon candidates are combined tracks from the independent inner detector and muon spectrometer measurements.

The main experimental challenge for this analysis in the muon channel is to ensure a good momentum measurement. Muon momenta are measured using the curvature of the associated tracks due to the magnetic field. At high momentum, tracks are very straight, and the resolution is dominated by the intrinsic curvature resolution. Therefore, only the best-aligned chambers of the muon spectrometer can be used for this analysis, and muons are required to pass stringent hit requirements in both the ID and the MS. Impact parameter and track isolation requirements suppress muons from cosmic rays and QCD jets, then evaluated to be negligible in this channel.

In the electron channel, the main challenge is particle identification: quality cuts on the shape of the energy deposit, inner detector hits and calorimeter isolation are needed to distinguish genuine high-energy electrons from QCD jets and converted photons. Data-driven strategies are employed to estimate the remaining background due to these sources.

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Pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$, while $\varphi$ is the azimuthal angle.
Figure 1. Reconstructed dijet mass distribution with statistical uncertainties, fitted with a smooth functional form. The bin-by-bin significance of the data-fit difference is shown in the lower panel. [3]

Figure 2. The 95% CL upper limits on $\sigma \times A$ for Gaussian signal shapes as a function of the mean mass $m_G$, for three values of the relative standard deviation $\sigma_G/m_G$. [3]

The dilepton invariant mass spectra obtained using 6 fb$^{-1}$ of data taken in 2012 at $\sqrt{s} = 8$ TeV [5] are shown in Figure 3. The dominant background to this search is the SM $Z/\gamma^*$ production and decay into dileptons, followed by contributions from diboson processes and top quark pairs. Background from these sources is estimated using Monte Carlo (MC) simulations. The sum of all background contributions is normalized to the data on the $Z$ peak.

Figure 3. Dielectron (left) and dimuon (right) invariant mass distributions after final selection, compared to the stacked sum of all expected backgrounds, with three example $Z_{SSM}$ signals overlaid. The bin width is constant in log $m_\ell^+\ell^-$. [5]

This analysis sets limits on $Z'$ from the SSM and $E_6$ GUT, excluding $Z'_{SSM}$ with masses below 2.49 TeV at the 95% CL. Limits on further models were set using data collected in 2011 at $\sqrt{s} = 7$ TeV [6]: RS $G^*$, $Z_{KK}$, $Z^*$, Technicolour, torsion resonances and Minimal $Z'$ models. A non-resonant search was also performed using the integral of the dilepton spectrum [7], setting limits on the scale of $\ell\ellqq$ contact interactions, as well as on the string scale in the ADD model.
5. Diphoton resonances
Photons in ATLAS are measured primarily using the EM calorimeter, but the inner detector helps to identify photon conversions, by determining whether charged particle tracks come directly from the primary collision vertex or from a subsequent decay. Requirements on the shower width and energy distribution, as well as a tight calorimeter isolation requirement help distinguish photons from jets. As well, an ambient energy correction is applied to remove contributions to the photon energy measurement from the underlying event and pile-up.

The invariant mass distribution of diphoton events is shown in Figure 4, for the analysis using data taken at $\sqrt{s} = 7$ TeV in 2011 [8]. The dominant, irreducible background in this search is $\gamma\gamma$ production from the SM, estimated from MC simulations. Reducible backgrounds due to events with one or more jets mis-identified as a photon are estimated using a data-driven technique.

Limits at the 95% CL are set on the RS $G^*$ in combination with the results in the dilepton channel at $\sqrt{s} = 7$ TeV, in the plane of $k/T$ versus $M_{G^*}$, are presented in Figure 5.

![Figure 4](image1.png)
**Figure 4.** Observed invariant mass distribution of diphoton events. The SM background expectation and two expected signal examples are superimposed. The bin-by-bin significance of the difference between data and predicted background is shown in the lower panel. [8]

![Figure 5](image2.png)
**Figure 5.** Expected and observed limits from the combination of $G^* \rightarrow \gamma\gamma/ee/\mu\mu$ channels, interpreted in the plane of $k/T$ versus graviton mass. The region above the curve is excluded at the 95% CL. [8]

6. Resonances decaying into a lepton and a neutrino
Neutrinos leave ATLAS undetected, but their production can be inferred via the presence of missing transverse momentum ($E_T^{\text{miss}}$). In the search for resonances decaying into a neutrino and exactly one high-$p_T$ muon or electron, $E_T^{\text{miss}}$ is combined with the lepton momentum to form the transverse mass ($m_T$):

$$m_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos \varphi_{\ell\nu})},$$

where $\varphi_{\ell\nu}$ is the angle between the $p_T$ and $E_T^{\text{miss}}$. The lepton measurement is especially important in this channel, because any mis-measurement also biases the $E_T^{\text{miss}}$, and therefore has a double impact on $m_T$. The selected leptons satisfy stringent identification and quality requirements.

The resulting $m_T$ spectra with the complete dataset taken in 2011 at $\sqrt{s} = 7$ TeV [9] are shown in Figure 6. The main background to this search is SM $W$ production and decay in the leptonic channel, and also $Z/\gamma^*$ where one of the two final state leptons is not reconstructed, as well as diboson processes, top quark pairs and single top. All of the above are estimated from MC simulation, and contributions from mis-identified QCD jets are estimated from the data.
Limits at the 95% CL are set on $W_{SSM}'$ excluding masses below 2.55 TeV, as well as on $W^*$ excluding masses below 2.42 TeV.

![Figure 6](image)

Figure 6. Spectra of $m_T$ for the electron (left) and muon (right) channels, with three example $W_{SSM}'$ signals overlaid. The bin width is constant in log $m_{\ell^+\ell^-}$. [9]

7. Resonances decaying into a pair of weak bosons

7.1. $WW \to \ell\nu\ell\nu$

Searches looking for exactly two oppositely-charged high-$p_T$ electrons or muons and large $E_{\text{miss}}$ are sensitive to the production of RS $G^*$ decaying into $W$ boson pairs. In addition to the original RS model, one of its extensions, the bulk RS model, is considered in this search because there the decay probability of the new boson $G^*_{\text{bulk}}$ in light fermion and photon channels is small and the coupling to heavy particles such as $W$, $Z$, Higgs bosons and top quarks is strongly enhanced.

The observable in this search is defined as follows, with $p_{\ell i}$ the momentum of the $i$th lepton:

$$m_{WW}^T = \sqrt{\left(\sum_{i=1}^{2} p_{\ell i}^x + E_{T\text{miss}}^x\right)^2 - \left(\sum_{i=1}^{2} p_{\ell i}^y + E_{T\text{miss}}^y\right)^2 - \left(\sum_{i=1}^{2} p_{\ell i}^z + E_{T\text{miss}}^z\right)^2}$$

and the resulting distributions with data collected in 2011 at $\sqrt{s} = 7$ TeV [10] show good agreement with expectations from the SM. Reducible backgrounds are suppressed using dedicated cuts: requiring that the invariant mass of the two leptons in the event be higher than 106 GeV reduces the contribution from $Z/\gamma^*$, and a $b$-tag veto helps reject top quark events. These two sources of background are estimated from simulation, and the estimates are validated using dedicated control regions. For $m_{WW}^T > 300$ GeV, the predicted backgrounds are obtain from fits to the MC samples. This analysis sets limits excluding, both for $k/M_{Pl}$ = 0.1, $G^*$ masses below 1.23 TeV and $G^*_{\text{bulk}}$ masses below 0.84 TeV, at the 95% CL.

7.2. $ZW$ or $ZZ \to \ell\ellqq$

In the $\ell\ellqq$ decay channel, 7.2 fb$^{-1}$ of data taken at $\sqrt{s} = 8$ TeV in 2012 are analyzed to look for a resonant excess in the diboson mass spectrum [11]. Two final states are considered: while the jets from many $W$ and $Z$ hadronic decays can be resolved, in events with high invariant mass the gauge bosons are highly boosted and hadronic decays merge into a single large jet.

To obtain the background prediction, data in each of these two event selections are fitted using the same function as in the dijet analysis: $f(x) = p_1(1-x)p_2x^p_3x^p_4\ln x$, with $x = m_{lljj}/\sqrt{s}$ or $x = m_{llj}/\sqrt{s}$ depending on the selection, and the results are shown in Figure 7. Limits are set excluding $G^*_{\text{bulk}}$ for $k/M_{Pl} = 1.0$ for masses below 0.88 TeV, at the 95% CL.
8. Third-generation searches

Analyses looking for new processes decaying into third-generation particles are complementary to their light-flavour counterparts. For example, some extensions of the standard model proposed to explain the high mass of the top quark predict new gauge bosons that couple preferentially to third-generation fermions. All results in this section were obtained using the complete dataset collected in 2011 at $\sqrt{s} = 7$ TeV [12, 13, 14, 15].

8.1. Ditau resonances

The identification of hadronic tau decays is performed using Boosted Decision Trees, trained to discriminate against QCD jets using shower shape and tracking identification variables.

The search for ditau resonances has the same backgrounds as the dilepton analysis, and is carried out by counting events above thresholds in $m^\text{tot}_T$, defined as

$$m^\text{tot}_T = \sqrt{2p^\text{T}T_1 C + 2E^\text{miss}_T p^\text{T}_T C_1 + 2E^\text{miss}_T p^\text{T}_T C_2},$$  \hspace{1cm} (3)$$

where $C = 1 - \cos(\Delta \varphi)$, with $\Delta \varphi$ the angle between the two visible tau decay products, and $C_1$ and $C_2$ are defined analogously for the angles between the respective decay products and $E^\text{miss}_T$.

Four decay channels are considered, depending on the combinations of hadronic ($\tau_{\text{had}}$) or leptonic ($\tau_e$ or $\tau_{\mu}$) tau decays. The $m^\text{tot}_T$ spectra obtained are shown in Figure 8 [12]. This analysis sets limits on the cross-section of a new resonance times its branching fraction to tau lepton pairs, with $Z^\prime_{\text{SSM}}$, used as a benchmark, excluded for masses below 1.4 TeV.

8.2. Ditop resonances in the fully hadronic channel

Forty-six percent of top quark pair ($t\bar{t}$) events have both top quarks decaying in the hadronic channel, and novel hadronic top-tagging techniques allow a search for resonances decaying into $t\bar{t}$. Two complementary algorithms are used: the HEPTopTagger tests the substructure of jets with a large distance parameter $R = 1.5$ and is effective in identifying top quarks with $p^\text{T}_T > 200$ GeV, while the Top Template Tagger matches the observed energy deposits of jets with $R = 1.0$ to a large set of possible patterns of energy deposits from simulated hadronic top quark decays, in order to reject jets from light quarks and gluons, and is optimized for top quarks with $p^\text{T}_T > 450$ GeV.

In addition to $t\bar{t}$ production from the SM, there is a background contribution from QCD multijets, which is evaluated from data. Figure 9 shows the resulting $t\bar{t}$ invariant mass distributions [13]. Limits at the 95% CL are set excluding $g_{KK}$ for masses between 0.70 and 1.62 TeV, as well as a leptophobic $Z^\prime$ boson for masses between 0.70 and 1.00 TeV and between 1.28 and 1.32 TeV.
Figure 8. Spectra of $m_{\text{tot}}$ for each channel: (a) $\tau_{\text{had}}\tau_{\text{had}}$, (b) $\tau_{\mu}\tau_{\text{had}}$, (c) $\tau_{e}\tau_{\text{had}}$ and (d) $\tau_{e}\tau_{\mu}$, with an example $Z'_{\text{SSM}}$ signal overlaid. The signal mass point closest to the $Z'_{\text{SSM}}$ exclusion limit in each channel is chosen and is indicated in parentheses in the legend in units of GeV. The uncertainty on the total estimated background (hatched) includes only the statistical uncertainty from the simulated samples. The visible decay products of hadronically decaying taus are denoted by $\tau_{\text{had-vis}}$. [12]

Figure 9. Distributions of the $t\bar{t}$ invariant mass in the fully hadronic channel, for the HEPTopTagger with a $Z'$ signal (left) and for the Top Template Tagger with a $g_{KK}$ signal (right). [13]

8.3. Ditop resonances in the semi-leptonic channel

The analysis looking for resonances decaying into $t\bar{t} \rightarrow \ell\nu b + jjb$, where $\ell = e$ or $\mu$, makes use of two event selections. In the "resolved" selection, jets in the event are assigned to either top quark using a $\chi^2$ algorithm, while the "boosted" selection requires one jet with $R = 1.0$, interpreted as a hadronic top decay, and a $b$-tagged jet close to the lepton ($\sqrt{\Delta\eta^2 + \Delta\phi^2} < 1.5$). Additional requirements are applied on $m_{T}$ and $E_{T}^{\text{miss}}$ to reduce the QCD multijet background.

The $t\bar{t}$ invariant mass spectrum observed in this analysis [14] is in good agreement with the SM, hence 95% CL limits are set excluding $g_{KK}$ for masses below 1.7 TeV and a leptophobic $Z'$ for masses below 1.9 TeV.
8.4. Resonances decaying into a top quark and a light quark

Finally, a search for resonances decaying into a light quark and a top quark decaying leptonically is carried out to probe models proposed to explain the top quark forward-backward asymmetry \( (A_{FB}) \) anomaly from the Tevatron experiments. This analysis makes use of the semi-leptonic \( t \bar{t} \) selection and requires at least one additional jet, for a total of one lepton and at least 5 jets. A likelihood test is performed to assign jets to one of the top quarks in the event, and the additional jets forming the highest jet-top mass \( (m_{tj}) \) and jet-anti-top mass \( (m_{\bar{t}j}) \) are considered.

The \( m_{tj} \) and \( m_{\bar{t}j} \) spectra [15] are consistent with SM expectations and limits on new colour-singlets \( (W') \) or colour-triplets \( (\phi) \) are shown in Figure 10. The parameter space favoured by the Tevatron \( A_{FB} \) and \( \sigma_{t\bar{t}} \) measurements is notably almost completely ruled out by this result.

![Figure 10](image-url)  

**Figure 10.** Expected and observed 95% CL upper limits on the colour-singlet \( (W') \) and colour-triplet \( (\phi) \) model cross-sections. The region favoured by the Tevatron \( A_{FB} \) and \( \sigma_{t\bar{t}} \) measurements is shown as the dark band. [15]

9. Conclusion

To summarize, no significant excess above expectations from the Standard Model has been observed in searches for heavy resonances carried out by the ATLAS collaboration at the LHC. Limits are set on a variety of resonances decaying into combinations of charged leptons, neutrinos, gauge bosons, top quarks and jets, and these limits are interpreted in the context of theoretical models used as benchmarks such as \( Z' \), \( W' \), Randall-Sundrum \( G^* \) and many others.

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