Search for Resonances Decaying into Top Quark Pairs Using Fully Hadronic Decays in $pp$ Collisions with ATLAS at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

Abstract

A search for heavy resonances decaying into top quark pairs is presented. Proton–proton collision events recorded with the ATLAS detector at the Large Hadron Collider running at a centre-of-mass energy of 7 TeV corresponding to an integrated luminosity of 4.7 fb$^{-1}$ are used. The $t\bar{t}$ events are reconstructed by selecting two top quarks in their fully hadronic decay modes which are reconstructed using the Cambridge/Aachen jet finder algorithm with a radius parameter of 1.5. The substructure of the jets is analysed using the HEPTopTagger algorithm to separate top quark jets from those originating from gluons and lighter quark jets. The jets are also required to be associated with a $b$-tagged jet of smaller radius. The invariant mass spectrum of the data is compared to the Standard Model prediction, and no evidence for resonant production of top quark pairs is found. The data are used to set upper limits on the cross section times branching ratio for resonant $t\bar{t}$ production in two models at 95% confidence level. Leptophobic $Z'$ bosons with masses between 700 and 1300 GeV and Kaluza–Klein–Gluons with masses between 700 and 1500 GeV are excluded at the 95% confidence level.
1 Introduction

Many models of new physics beyond the Standard Model (SM) predict resonances in the TeV mass range which decay primarily into top-antitop quark pairs and can be produced in $pp$ collisions at the Large Hadron Collider (LHC). This note reports a search for such phenomena where both top quarks are reconstructed in their fully hadronic final states and have high transverse momentum ($p_T$). In these boosted events the decay products of each top quark are collimated and merge into one jet with large invariant mass.

Most of the previous searches considered only cases where in one or both of the top quark decays, the intermediate $W$-boson decays leptonically and hence the top quark decays result in one or two leptons, missing energy from the neutrinos, and jets in the final state [1–7]. The requirement of a well-identified and isolated charged lepton and missing transverse energy rejects a large fraction of background from multijet production. However, difficulties arise in these final states when the top quark decay particles are collimated, since leptons from the top quark decay are no longer isolated and thus backgrounds with lepton candidates originating from hadronic jets are hard to distinguish from the signal.

An alternative approach is to consider final states in which both top quarks produced with high momentum decay hadronically, and their decay products are found in a cone around the top quark flight direction. Such searches require the top quarks to have $p_T$ in excess of 200-300 GeV and require rejection of the large background of gluon, light quark and $b$-jets. The CMS Collaboration employed this technique in a recent study [8]. In the present note the HEPTopTagger algorithm [9] is used to identify hadronic top quark decays and to reconstruct the top quark momentum. The invariant mass distribution of the $t\bar{t}$ pairs is examined for evidence of resonances.

Two specific models that predict resonances of different masses $m$ with narrow and broad decay widths $\Gamma$ are considered: leptophobic topcolor $Z'$ bosons with $\Gamma/m = 1.2\%$ [10] and Kaluza-Klein (KK) gluons with $\Gamma/m = 15.3\%$ [11,12]. Recent results by the ATLAS Collaboration [7,13] exclude $Z'$ bosons (KK gluons) with masses between 0.5 and 1.2 TeV (0.5 and 1.5 TeV). The CMS Collaboration obtained similar results [8,14,15] ranging up to 1.5 TeV (2.0 TeV) for narrow (broad) $t\bar{t}$ resonances.

This note is organised as follows: Section 2 describes the ATLAS detector and Section 3 summarises the data samples and Monte Carlo (MC) event generators used in the analysis. The event selection and the definition of the reconstructed objects are given in Section 4. The HEPTopTagger algorithm is described in Section 5. Estimations of the background and systematic uncertainties are given in Section 6 and Section 7, respectively. In Section 8 the resulting di-top invariant mass spectrum and exclusion limits are presented.

2 ATLAS Detector

The ATLAS detector [16] at the LHC covers nearly the entire solid angle around the proton–proton collision point. The inner tracking detector (ID) comprises a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker, providing tracking capability within $|\eta| < 2.5$. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by liquid-argon (LAr) electromagnetic sampling calorimeters with high granularity. An iron-scintillator tile calorimeter provides hadronic energy measurements in the central rapidity range ($|\eta| < 1.7$). The end-cap and forward regions, covering $1.37 < |\eta| < 4.9$, are instrumented with LAr calorimetry for both electromagnetic

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1In the following “top quark” refers to both the top quark and its anti-particle.

2ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(r,\phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. Distances in $(\eta,\phi)$ space are given as $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$.
and hadronic energy measurements. The calorimeter system is surrounded by a muon spectrometer incorporating three superconducting toroid magnet assemblies.

A three-level trigger system is used to select the events for this analysis. The level-1 trigger is implemented in hardware and uses a subset of the detector information to reduce the rate to at most 75 kHz. This is followed by two software based trigger levels that together reduce the event rate to approximately 400 Hz.

3 Data and Monte Carlo Samples

The analysis is performed using data collected from March to November 2011 with a centre-of-mass energy of $\sqrt{s} = 7$ TeV and corresponding to an integrated luminosity of $4.7 \pm 0.1 \text{ fb}^{-1}$ \cite{17, 18}. With the increasing instantaneous luminosity of the LHC, the average number of simultaneous proton–proton interactions per beam crossing (pile-up) increased from about 6 to 17 during the data taking period. The data pile-up conditions are included in the Monte Carlo simulation.

The backgrounds to a resonant signal in this channel consist of irreducible SM $t\bar{t}$ production and QCD multijet production. SM $t\bar{t}$ production is simulated using the MC@NLO v3.41 generator \cite{19, 20} with CT10 parton density functions (PDFs) \cite{21}. Final state parton showers are simulated and hadronised using the HERWIG v6.5 \cite{22} program in association with the JIMMY underlying event model \cite{23}. A $t\bar{t}$ production cross section of 166.8 pb is used, evaluated at approximate next to next to leading order in QCD using HATHOR version 1.2 Monte Carlo program \cite{24}, employing the MSTW2008 90\% NNLO PDF sets \cite{25}, incorporating PDF+$\alpha_s$ uncertainties according to the MSTW prescription \cite{26}.

The remaining backgrounds, dominated by multijet events and also including other small backgrounds like W+jets, are estimated from data in signal-depleted control regions and are referred to as QCD multijet (QCD for short) background in the following. For cross-checks PYTHIA \cite{27} dijet simulated samples are used. Simulated signal samples for the $pp \rightarrow Z' \rightarrow t\bar{t}$ process are generated using PYTHIA v6.421 with MSTW2008 PDFs \cite{25}. Kaluza–Klein gluons are generated with MADGRAPH v4.4.51 \cite{28} with CTQ6L1 PDFs \cite{29} and the parton showers are simulated with PYTHIA. Possible interference effects between the $t\bar{t}$ signal and the SM $t\bar{t}$ continuum are not taken into account.

The generated events are passed through a full GEANT4 \cite{30} based simulation of the ATLAS detector \cite{31} and then processed with the same reconstruction algorithms used for the $pp$ collision data events.

4 Event Selection and Object Reconstruction

The events are selected with online triggers that require either the transverse energy ($E_T$) of at least one jet (anti-$k_T$ algorithm \cite{32} with a distance parameter $R = 0.4$) to fulfill $E_T > 100$ GeV and the scalar sum of all jets to fulfill $\sum E_T > 350$ GeV ($> 400$ GeV for later data-taking periods) or at least five jets with $E_T > 30$ GeV. The use of the combined single jet and $\sum E_T$ is very useful for boosted events since it does not rely on the precise topology of the decay (which may change due to the splitting and merging of jets) but mainly on the total energy deposited in the calorimeter. The high-multiplicity trigger is used to increase the efficiency at low $m_{t\bar{t}}$ where the top decay products can also be reconstructed individually. The events are required to have a primary event vertex with at least 5 tracks with $p_T > 0.4$ GeV. In the case of multiple primary vertex candidates the primary vertex is the vertex with the largest $\sum p_T^2$ of the tracks associated with it.

The analysis uses various jet finder algorithms and radius parameters to reconstruct top quark candidates and to suppress background. These jets are formed from topological calorimeter clusters \cite{33, 34} using the FastJet software \cite{35, 36}. The clusters are calibrated using the local cluster weighting method.
(LCW \cite{37}), and only clusters with positive energy are used. The events are required to contain at least two jets with $p_T > 200$ GeV at the LCW scale and $|\eta| < 2.5$, reconstructed with the Cambridge/Aachen (C/A) algorithm \cite{38} with a distance parameter of $R = 1.5$ (called “fat jets”). Each of these fat jets is subjected to the HEPTopTagger algorithm (explained in detail in the following section), which, by applying kinematic cuts, either rejects the jet as being incompatible with hadronic top quark decay or selects it as a top quark candidate and assigns a four-momentum to it. To ensure a high reconstruction efficiency only top quark candidates with $p_T > 200$ GeV are considered in the following. At least two top quark candidates per event are required and the di-top invariant mass $m_{\bar{t}t}$ is constructed from the four-momenta of the two leading $p_T$ top quark candidates.

To further suppress background events in which multiple light quark and/or gluon jets satisfy the kinematic HEPTopTagger requirements, the MV1 $b$-tagging algorithm is used \cite{39}. This neural network-based algorithm uses the output weights of impact parameter, secondary-vertex and decay-topology based $b$-tagging algorithms as input. The nominal $b$-tagging efficiency is 70% with a rejection factor of about 140 for light jets with $p_T > 20$ GeV.

Candidate $b$-quark jets are defined by using the anti-$k_t$ algorithm with a distance parameter $R = 0.4$ and each calorimeter jet is calibrated to the energy scale corresponding to hadronic jets \cite{34}. These $b$-jets must satisfy the requirements $p_T > 25$ GeV and $|\eta| < 2.5$, and more than 75% of the transverse momentum of the tracks associated with the jet must be carried by tracks with $p_T > 0.5$ GeV associated with the primary vertex. These anti-$k_t$ jets are used to apply quality cuts that reject events which suffer from instrumental failures and non-collision backgrounds (cosmics, beam gas, beam halo) \cite{40}. To be considered for $b$-tagging the jets additionally need to be within a cone of radius $\Delta R = 1.4$ around the axis of one of the fat jets. At least two $b$-candidates per event are required.

The selected event sample is made complementary to samples used in searches for $t\bar{t}$ resonances in the lepton+$jets$ and di-lepton channels by rejecting events which contain at least one isolated electron (with $p_T > 25$ GeV) or muon candidate (with $p_T > 20$ GeV).

5 The HEPTopTagger Algorithm

The HEPTopTagger \cite{9} is designed to reconstruct hadronically decaying top quarks that are sufficiently boosted that their decay products lie inside a single fat jet. If the substructure of the fat jet is found to be compatible with hadronic top quark decay a top quark four-momentum is reconstructed.

The HEPTopTagger operates on a fat jet that has been constructed using the Cambridge/Aachen jet finder and the same finder is employed inside the tagger to cluster the fat jet constituents into subjets. In \cite{41} it was found that, compared with the $k_T$ and SISCone \cite{42} jet finders, C/A provides the best signal efficiency and background rejection in the presence of underlying event activity for taggers like the HEPTopTagger. In the following the term “fat jet” will refer to the (unfiltered) C/A jet before the HEPTopTagger procedure is applied, and “top-quark candidate” to the object resulting from the HEPTopTagger procedure. The HEPTopTagger procedure itself is referred to as “top-tagging”.

The main steps of the algorithm are described in the following; for a detailed description see \cite{9}. A graphical illustration of the algorithm can be found in \cite{43}. In a first phase, the input fat jet is broken down into subjets from the hard process with masses below 50 GeV. These subjets form the basis of the substructure analysis. All combinations of three subjets (referred to as ‘triplets’ in the following) are then tested for compatibility with hadronic top quark decay. This is done as follows: First, a so-called filtering step is introduced to remove contributions from the underlying event and pile-up: jets are formed from all calorimeter clusters of the triplet jets with a radius parameter equal to half of the smallest pair-wise distance between the triplet jets (but at most 0.3), and only the five hardest reconstructed jets are kept. The constituents of those five jets are re-clustered exclusively into three jets. All subjets are calibrated to the particle level. Then, by imposing requirements on invariant mass ratios, the three subjets are tested
for compatibility with being the products of the hadronic top quark decay. If the mass ratio requirements are met, the top quark candidate is obtained by summing the four-momenta of the subjets. The invariant mass $m_t$ of the top quark candidate is required to lie in the range from 140 to 210 GeV, otherwise this triplet is discarded. If a top quark candidate is found in more than one triplet, only the one with its mass closest to the measured $[44]$ top mass of 172.3 GeV is used.

The performance of the HEPTopTagger has been studied extensively $[43]$ using ATLAS pp collision data and simulated events.

Figure 1 shows the effect of pile-up on the reconstructed top candidate mass for data and simulated $t\bar{t}$ events as a function of the average number of interactions per bunch-crossing. No systematic shift of the mass with increased pile-up is observed within the statistical uncertainties.

The total selection efficiency together with its statistical uncertainty is given in Table 1 for different $Z'$ and KK gluon mass points, where the top quarks are decayed hadronically. The inefficiency is dominated by the top-tagging and $b$-tagging inefficiencies which vary as a function of the top and bottom quark momenta and is bounded by

$$\varepsilon_{\text{b-tag.}, \text{max.}} \cdot \varepsilon_{\text{top-tag.}, \text{max.}} \approx 10\%$$

where $\varepsilon_{\text{b-tag.}, \text{max.}}$ is the maximal $b$-tagging efficiency of 80 % and $\varepsilon_{\text{top-tag.}, \text{max.}}$ the maximal top-tagging efficiency of 40 %. The highest efficiency of 6.4% is obtained in the case of a $Z'$ mass of 1.3 TeV.

The reconstructed di-top invariant mass for different $Z'$ and KK gluon masses is shown in Figure 2.

6 Background Estimates

To estimate the background contribution, control regions are used that are defined by loosening the requirements on the number of top quark candidates found in the event and on the number of fat jets that are associated with $b$-tagged jets. As outlined in Table 2 six classes of events are defined, depending on the numbers of top quark candidates and $b$-tagged jets. Regions E and F contain the events with at least two $b$-tags, with region E (F) additionally containing one (two) top quark candidate(s). Region F constitutes the signal region.
Table 1: Efficiency for selecting $Z'$ and Kaluza-Klein gluons that decay into hadronically decaying $\bar{t}t$ pairs. All uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Sample</th>
<th>efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'(500 \text{ GeV})$</td>
<td>$0.05 \pm 0.01 %$</td>
</tr>
<tr>
<td>$Z'(800 \text{ GeV})$</td>
<td>$3.19 \pm 0.08 %$</td>
</tr>
<tr>
<td>$Z'(1000 \text{ GeV})$</td>
<td>$5.26 \pm 0.10 %$</td>
</tr>
<tr>
<td>$Z'(1300 \text{ GeV})$</td>
<td>$6.36 \pm 0.12 %$</td>
</tr>
<tr>
<td>$Z'(1600 \text{ GeV})$</td>
<td>$6.13 \pm 0.11 %$</td>
</tr>
<tr>
<td>$Z'(2000 \text{ GeV})$</td>
<td>$5.05 \pm 0.10 %$</td>
</tr>
<tr>
<td>$Z'(3000 \text{ GeV})$</td>
<td>$3.70 \pm 0.08 %$</td>
</tr>
<tr>
<td>KK gluon(700 GeV)</td>
<td>$1.92 \pm 0.14 %$</td>
</tr>
<tr>
<td>KK gluon(800 GeV)</td>
<td>$2.83 \pm 0.17 %$</td>
</tr>
<tr>
<td>KK gluon(1000 GeV)</td>
<td>$4.57 \pm 0.22 %$</td>
</tr>
<tr>
<td>KK gluon(1300 GeV)</td>
<td>$5.73 \pm 0.25 %$</td>
</tr>
<tr>
<td>KK gluon(1600 GeV)</td>
<td>$5.31 \pm 0.24 %$</td>
</tr>
<tr>
<td>KK gluon(2000 GeV)</td>
<td>$5.07 \pm 0.23 %$</td>
</tr>
</tbody>
</table>

Table 2: The classes of events used to validate the performance of the HEPTopTagger, and to calculate the data-driven background prediction for QCD jets. The numbers in parentheses are the estimated $\bar{t}t$ purities in each region, given by the expected number of events arising from SM $\bar{t}t$ production divided by the number of observed events in that region.

<table>
<thead>
<tr>
<th></th>
<th>1 top-tag</th>
<th>$\geq 2$ top-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>no $b$-tag</td>
<td>A (0.3%)</td>
<td>B (2.7%)</td>
</tr>
<tr>
<td>1 $b$-tag</td>
<td>C (3.5%)</td>
<td>D (26.9%)</td>
</tr>
<tr>
<td>$\geq 2$ $b$-tags</td>
<td>E (13.9%)</td>
<td>F (73.7%)</td>
</tr>
</tbody>
</table>

The contributions of SM $\bar{t}t$ production to all regions are estimated using the simulated sample and validated with data in region E: the top candidate mass distribution in data, shown in Figure 3, is fit with the sum of $\bar{t}t$ template (simulated events in region E) and the QCD background template (taken from the data distribution in region C after subtracting the expected $\bar{t}t$ contribution) to extract the $\bar{t}t$ background fraction, exploiting the contrasting shapes predicted by the simulated SM samples. The result of the fit in region E is shown in Figure 3. The ratio of the fitted $\bar{t}t$ event yield compared to the predicted yield is $1.12 \pm 0.11$ with the uncertainty being the statistical uncertainty of the template fit. This ratio is always implicitly used for the normalization of the $\bar{t}t$ sample in the following (i.e. in the determination of the QCD background and in figures), unless stated otherwise. The resulting SM $\bar{t}t$ yield in signal region F is estimated to be 957 events.

The QCD background is estimated by exploiting the fact that the number of $b$-tags and the number of top-tags are uncorrelated for this background. The shape of the QCD background for a given variable (e.g. $m_{\bar{t}t}$) is estimated by the weighted average of the distribution of that variable in regions B and D, normalized by the yields in regions A and C, i.e.

$$
\frac{dn_F}{dm_{\bar{t}t}} = \left(\frac{1}{n_A} \frac{dn_B}{dm_{\bar{t}t}} + \frac{1}{n_C} \frac{dn_D}{dm_{\bar{t}t}}\right) \cdot \frac{n_F}{2}
$$

where $n_i$ is the number of events in region $i$. In all regions the expected $\bar{t}t$ background is subtracted; this introduces an anti-correlation between these two background sources. The resulting estimate for the total
Figure 2: Reconstructed di-top invariant mass $m_{t\bar{t}}$ for $Z'$ (left) and Kaluza-Klein gluon (right) benchmark models of different mass values. For all models, $\sigma(pp \rightarrow Z'/KKgluon) \times BR(Z'/KKgluon \rightarrow t\bar{t})$ is fixed to 1 pb and an integrated luminosity of 4.7 fb$^{-1}$ is assumed.

Figure 3: The distribution of the top quark jet candidate mass in region E for data, the templates for QCD and $t\bar{t}$ production and the result of the template fit.

The number of QCD events in the signal region is 320. To show that the QCD and $t\bar{t}$ background predictions describe the data and to illustrate that the HEPTopTagger identifies top quark jets effectively, Figure 4 shows comparisons of predicted and observed control distributions, namely the fat jet mass (4(a)), the top quark candidate mass (4(b)), the fat jet $p_T$ (4(c)), the top quark candidate $p_T$ (4(d)) and the substructure variables $m_{23}/m_{12}$ (4(e)) and $\arctan(m_{13}/m_{12})$ (4(f)). In these ratios $m_{123}$ is the invariant mass of all three subjets, $m_{12}$ is the invariant mass of the two leading $p_T$ subjets, etc. The ratios are used to determine if a candidate is compatible
with a hadronic top quark decay. For example \( m_{23}/m_{123} \approx m_{W^{\text{true}}}/m_{t^\text{true}} \approx 0.47 \) indicates that the sub-leading and sub-sub-leading \( p_T \) subjet are the decay products of the W boson whereas the two peaks in Figure 4 correspond to the other two possible combinations.

The data and background predictions agree well for all distributions.

7 Systematic Uncertainties

The following systematic uncertainties are considered and propagated to the predicted \( m_{t\bar{t}} \) distributions. The uncertainty on the \( b \)-tagging efficiency \([39][45][47]\) is evaluated by re-weighting events according to \( \pm 1 \) standard deviation shifts in the tagging efficiency and fake rate for \( b \)-jets, \( c \)-jets, and light quark jets and gluons. The \( b \)-tagging efficiency reaches a maximum at \( p_T \approx 100 \text{ GeV} \) and then falls at higher \( p_T \). The \( b \)-tagging efficiency uncertainty in the region \( p_T < 200 \text{ GeV} \) is determined directly from the data using muon-tagged \( b \)-jet candidates \([39]\). An additional systematic uncertainty of 11% (12%) is considered for \( p_T = 200 - 300 \text{ GeV} \) (\( p_T > 300 \text{ GeV} \)) based on detailed studies of the impact on the \( b \)-tag efficiency of possible deficiencies in the modeling of tracks on the \( b \)-tagging efficiency.

The jet energy scale uncertainty is fully correlated between subjets and fat jets and has been estimated to be 3.5%. The PDF eigenvector approach is applied to determine the sensitivity of the resulting invariant mass distribution to the PDF uncertainties. The envelope of the CT10, \\( M_{\text{STW}2008} \) and \\( N_{\text{STW}2008} \) NLO PDF sets are used in this procedure \([48]\). The uncertainty on the integrated luminosity is 1.8% \([17][18]\).

The impact of the choice of \( t\bar{t} \) generator, QCD initial and final state radiation (ISR/FSR) and parton shower models on the shape of the \( m_{t\bar{t}} \) distribution for the \( t\bar{t} \) sample are evaluated by comparing two different simulated samples each. The differences between the distributions are symmetrised and taken as the systematic uncertainty. The variations considered are:

- **\( t\bar{t} \) generator:** a PowHeg simulated \([49]\) sample and an Mc@NLO simulated sample, both using the HERWIG fragmentation and hadronisation models.
- **ISR/FSR:** two AcerMC simulated \([50]\) samples with two different PYTHIA tunes for the simulation of ISR/FSR.
- **Parton shower model:** two PowHeg simulated samples, one where the HERWIG and one where the PYTHIA parton shower and hadronization model is used.

The normalisation of the \( t\bar{t} \) contribution is allowed to vary between \( +100\% \) and \( -50\% \). This arbitrarily large uncertainty is chosen because the \( t\bar{t} \) normalisation is constrained directly in the fit to the data and the initial normalisation of 957 events is only used as input to the fit. All other uncertainties are considered to only influence the shape of the \( m_{t\bar{t}} \) distribution for this sample.

There is no additional uncertainty added for the modelling of variables in the HEPTopTagger as all uncertainties on the input objects (such as the JES) are fully propagated and additionally the substructure variables shown in Figures 4(e) and (f) and \([43]\) agree very well between data and prediction.

The trigger efficiency was compared between data and simulation and found to agree well. In particular the uncertainty on the jet energy scale, which affects the trigger efficiency in the simulation, covers any differences such that no additional uncertainty on the trigger efficiency is considered.

The QCD background is estimated in a data-driven procedure that includes subtraction of the predicted SM \( t\bar{t} \) contribution as described in Section 6. The systematic uncertainties on the \( t\bar{t} \) contribution are propagated to the QCD estimate. An additional uncertainty on the QCD background is obtained by comparing the two possible independent di-top invariant mass \( m_{t\bar{t}} \) predictions given by eliminating either the term depending on \( n_B \) or \( n_D \) and the factor of \( \frac{1}{2} \) in Equation 2 and taking the maximum per-bin variation as the systematic uncertainty.
Figure 4: Distributions of the fat jet mass (a), the top quark candidate mass (b), the fat jet $p_T$ (c) and top quark candidate $p_T$ (d) and the top quark candidate substructure variables $m_{23}/m_{123}$ (e) and $\text{arctan}(m_{13}/m_{12})$ (f) in signal region F. The $p_T$ and mass distributions are shown for the leading candidate, the substructure variables are presented for all candidates. The data, the simulated tt sample, the QCD contribution as estimated from data and a hypothetical $Z'$ signal sample are shown.
Figure 5: Distribution of the di-top invariant mass $m_{t\bar{t}}$ using a linear (left) and logarithmic scale (right) in the signal region. The data, the simulated $t\bar{t}$ sample, the QCD sample estimated from data and a hypothetical $Z'$ signal sample with $M_{Z'} = 1$ TeV are shown.

The following systematic uncertainties affect the yield of signal events: $b$-tagging, jet energy scale, PDF uncertainty and luminosity uncertainty. The resulting total uncertainty on the signal yield is $\approx 20\%$ and is dominated by the $b$-tagging and jet energy scale uncertainties.

8 Results

In the signal region 1281 events are observed in the data. The $t\bar{t}$ background is estimated to result in 957 $\pm$ 190(stat.+syst.) events. The QCD background estimated from data yields 320 $\pm$ 42(stat.+syst.) events. Figure 5 shows the di-top invariant mass distribution for the data, the expected background and a hypothetical $Z'$ sample in the signal region. No excess over the SM expectation is observed.

As no signal is found, 95% confidence level (C.L.) upper limits on the production cross section times branching ratio to $t\bar{t}$ final states for each model considered are set using a Bayesian approach [51].

The limits are determined for resonance masses ranging from 0.5 to 3.0 TeV as a function of $m_{t\bar{t}}$. The systematic uncertainties are treated as nuisance parameters with Gaussian prior distributions reflecting their uncertainty and are then marginalised to set confidence intervals.

To estimate the $a$ priori sensitivity for this search, background-only pseudo-experiments are randomly drawn from the background prediction. All nuisance parameters are allowed to vary in a manner consistent with their prior distributions for each pseudo-experiment.
Table 3: Relative change of the expected limit on the production cross section times branching fraction for a hypothetical $Z'$ boson mass of 1.3 GeV, due to neglecting individual systematic uncertainties. All non-listed uncertainties result in changes smaller than 1%.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>b-tagging eff.</th>
<th>$t\bar{t}$ normal.</th>
<th>Jet energy scale</th>
<th>$t\bar{t}$ parton shower</th>
<th>$t\bar{t}$ generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rel. change of limit</td>
<td>15.9%</td>
<td>9.3%</td>
<td>3.5%</td>
<td>3.1%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

Figure 6: Expected and observed limits on the production cross section times branching fraction $\sigma \times BR$ versus the di-top invariant mass for a $Z'$ boson (a) and for Kaluza-Klein gluons (b). The red bands are the model predictions including theoretical uncertainties. The $Z'$ boson cross section is calculated at LO but multiplied by 1.3 to account for expected higher order corrections. For the KK gluon the LO cross section is used.

The median of the distribution is chosen to represent the expected limit. The ensemble of limits is also used to define the 68% and 95% confidence level envelope of limits as a function of resonance mass.

To illustrate the effect of the different sources of systematic uncertainties Table 3 shows the relative change of the expected cross section times branching fraction limit if one uncertainty is neglected for a hypothetical $Z'$ boson mass of 1.3 GeV.

Figures 6(a) and (b) show the 95% C.L. exclusion limits on the cross section times branching ratio for the two models.

These are interpreted as mass limits by comparing the cross section limits to theoretical cross section predictions from specific benchmark models. The theoretical cross section for the bulk Randall-Sundrum model (RS) [52] and the $Z'$ model are calculated with ПУТНИЯ v8.1 [53], and ПУТНИЯ v6.421, respectively. In the case of the $Z'$ boson cross sections, an additional K-factor of 1.3 is applied to account for NLO effects [54]. The expected and observed mass limits are shown in Table 4.

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3The left-handed ($g_{L}$) and right-handed ($g_{R}$) couplings to quarks in this model are: $g_{L} = g_{R} = -0.2g_{s}$ for light quarks including charm, where $g_{s} = \sqrt{4\pi \alpha_{s}}$; $g_{L} = 1.0g_{s}$; $g_{R} = -0.2g_{s}$ for bottom quarks; and $g_{L} = 1.0g_{s}$; $g_{R} = 4.0g_{s}$ for the top quark.
Table 4: Expected and observed exclusion regions on the $Z'$ boson mass and on the KK gluon mass in the Randall-Sundrum model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Observed Mass Limit (TeV)</th>
<th>Expected Mass Limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptophobic $Z'$</td>
<td>0.7 &lt; $m_{Z'}$ &lt; 1.3</td>
<td>0.6 &lt; $m_{Z'}$ &lt; 1.1</td>
</tr>
<tr>
<td>RS KK gluon</td>
<td>0.7 &lt; $m_{g_{KK}}$ &lt; 1.5</td>
<td>0.7 &lt; $m_{g_{KK}}$ &lt; 1.5</td>
</tr>
</tbody>
</table>

9 Conclusions

A search for massive resonances ($Z'$, Kaluza-Klein gluons) decaying into $t\bar{t}$ pairs in the fully-hadronic final state is presented, using the full 4.7 fb$^{-1}$ data set collected with the ATLAS detector during the 2011 proton–proton run of the LHC at a centre-of-mass energy of 7 TeV. The HEPTopTagger technique is used to reconstruct top quarks in their hadronic decay mode for moderately boosted top quarks with transverse momenta above 200 GeV.

The reconstructed $m_{t\bar{t}}$ spectrum is compared to a prediction for SM $t\bar{t}$ production and the background from massive jets from QCD processes. No evidence for resonant $t\bar{t}$ production is found. $Z'$ bosons with masses between 700 and 1300 GeV and Kaluza-Klein gluons between 700 and 1500 GeV are excluded.

References


[8] CMS Collaboration, Search for anomalous $t\bar{t}$ production in the highly-boosted all-hadronic final state, arXiv:1204.2488 [hep-ex]. Submitted to JHEP.


