Search for new physics in the dijet mass distribution using 1 fb-1 of pp collision data at $\sqrt{s} = 7$ TeV collected by the ATLAS detector


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Search for new physics in the dijet mass distribution using 1 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV collected by the ATLAS detector\footnote{© CERN for the benefit of the ATLAS Collaboration.}

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1. Introduction

The Standard Model (SM) description of high energy proton–proton ($pp$) collisions is based on the framework of quantum chromodynamics (QCD) in the perturbative regime, where the most energetic collisions result from the $2 \rightarrow 2$ scattering of a pair of partons (quarks or gluons). Partons emerging from the collision shower and hadronise, in the simplest case producing two jets of particles, a “dijet”, that may be reconstructed to determine the dijet invariant mass, $m_{jj}$, the mass of the two-parton system.

Previous studies of dijet mass distributions\cite{1–6} have shown that these analyses are sensitive to the highest mass scales accessible with hadronic final states. In the present study, the dijet mass distribution is examined in a search for resonances due to new phenomena localised near a given mass, employing a data-driven background estimate that does not rely on detailed QCD calculations.

In addition to new physics benchmarks used in previous ATLAS dijet analyses, namely excited quarks ($q^*$)\cite{7,8}, and axigluons\cite{9–11}, the present study includes a third hypothetical object: the colour octet scalar ($s_8$), one of many possible exotic colour resonances\cite{12}. Any of these objects could produce a peak in the dijet spectrum in the vicinity of their mass.

The present study is based on $pp$ collisions at a centre-of-mass (CM) energy of 7 TeV produced at the CERN Large Hadron Collider (LHC), measured by the ATLAS detector. This data set corresponds to an integrated luminosity of 1.0 fb$^{-1}$ recorded between March and June 2011. The most stringent limits set previously by the ATLAS Collaboration were based on the full 2010 data sample, corresponding an integrated luminosity of 36 pb$^{-1}$\cite{6}.

Excited quarks were excluded below 2.15 TeV, and axigluons below 2.10 TeV. The CMS Collaboration has recently completed a dijet resonances analysis in 1.0 fb$^{-1}$ of 2011 data, excluding excited quarks below 2.49 TeV and axigluons below 2.47 TeV, along with other limits\cite{13}.

A detailed description of the ATLAS detector is available in\cite{14}. The detector is instrumented over almost the entire solid angle around the $pp$ collision point with layers of tracking detectors, calorimeters, and muon chambers. Jet measurements are made using a finely segmented calorimeter system designed to detect the high energy jets that are the focus of this study with high efficiency and excellent energy resolution. ATLAS has a three-level trigger system, with the first level trigger (L1) being based on custom-built hardware and the two higher level triggers (HLT) being realised in software.

ATLAS uses a right-handed coordinate system with the $z$-axis along the beam pipe. The $x$-axis points 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. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta \equiv -\ln\tan(\theta/2)$. Transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.

The dijet mass, $m_{jj}$, is derived from the vectorial sum of the four-momenta of the two highest $p_T$ jets in the event. Kinematic criteria based on momentum and angular variables are applied to increase the sensitivity to centrally produced high mass resonances.

The angular distribution for $2 \rightarrow 2$ parton scattering is predicted by QCD in the CM frame of the colliding partons, which moves along the beamline due to the differing momentum fractions (Bjorken $x$) of the colliding partons. If $E$ is the jet energy and $p_z$ is the $z$-component of the jet’s momentum, the rapidity of the
jet is given by \( y \equiv \frac{1}{2} \ln \left( \frac{1 + \frac{E_T}{E}}{1 - \frac{E_T}{E}} \right) \). The rapidities of the two highest \( p_T \) jets are denoted by \( y_1 \) and \( y_2 \), and the corresponding rapidity of these partons in their mutual CM frame is \( y^* = \frac{1}{2} (y_1 - y_2) \).

2. Jet reconstruction and event selection

Individual jets are reconstructed using the anti-\( k_t \) jet clustering algorithm [15,16] with the distance parameter \( R = 0.6 \). The inputs to this algorithm are clusters [17] of calorimeter cells with energy depositions significantly above the measured noise. Jet four-momenta are constructed as the vectorial sum of clusters of cells, treating each cluster as an \(( E, \vec{p} )\) four-vector with zero mass, assuming that the corresponding particle stems from the primary vertex.

The jet four-momenta are then corrected [18] as a function of \( \eta \) and \( p_T \) for various effects, the largest of which are the hadronic shower response and detector material distribution. This is done using a calibration scheme based on Monte Carlo (MC) studies including full detector simulation and validated with extensive test-beam [19] and collision data [20–22] studies. Measured dijet mass distributions are not corrected for detector resolution, which, in terms of mass smearing, is \( \sigma_{\text{sm}} / m_{jj} \approx 5\% \) at \( m_{jj} \approx 1\tev \), drops to 4.5\% at 2\tev, and asymptotically approaches 4\% at \( m_{jj} \) of 5\tev and above.

The event selection starts with the first-level trigger, which selects events that have at least one large transverse energy deposition in the calorimeters, with the transverse energy threshold selecting events that have at least one large transverse energy deposition significantly above the measured noise. Jet four-momenta are constructed as the vectorial sum of clusters of cells, treating each cluster as an \(( E, \vec{p} )\) four-vector with zero mass, assuming that the corresponding particle stems from the primary vertex.

To achieve the highest possible effective integrated luminosity, the current data set has been recorded using a jet trigger that was usually not prescaled. The chosen trigger has a nominal jet \( p_T \) threshold of 180 GeV. After applying all other analysis cuts, \( m_{jj} \) is required to be greater than 717 GeV in order to attain a trigger efficiency of at least 99\% over the full range of the dijet mass distribution.

Events are required to have a primary collision vertex defined by at least five charged-particle tracks. Events with a poorly measured jet [23] with \( p_T \) greater than 30\% of the \( p_T \) of the next-to-leading jet are vetoed, to avoid cases where such a jet would cause incorrect identification of the two leading jets. This rejects less than 0.002\% of the events.

Additional kinematic criteria are applied, requiring that the two leading jets each satisfy \( |y_{jj}| < 2.8 \) and that the rapidity in the parton CM frame satisfies \( |y^*| < 0.6 \). These criteria favour central collisions and have been shown, based on studies of expected signals and QCD background, to optimise the analysis sensitivity.

A final selection is made to avoid the calorimeter region from \(-0.1\) to 1.5 in \( \eta \) and from \(-0.9\) to \(-0.5\) in \( \phi \), which was in large part affected by readout problems for most of the data used in these studies. Events with jets in this region are discarded. This rejects less than 0.002\% of the events.

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3. Comparing data to a smooth background

The observed dijet mass distribution after all selection cuts is shown in Fig. 1. As in the previous ATLAS studies, the \( m_{jj} \) spectrum is fit to the smooth functional form

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

where \( x = m_{jj} / \sqrt{s} \) and the \( p_i \) are fit parameters. This ansatz has been shown empirically to accurately model the steeply falling QCD dijet mass spectrum [3–6]. The \( m_{jj} \) bins are of variable width, increasing from ~ 50 to ~ 200 GeV for dijet masses from 0.85 to 4.5 TeV, respectively, to optimise the performance of the resonance search algorithm discussed in the next section.

The bottom plot of Fig. 1 shows the significance, in standard deviations, of the difference between the data and the prediction in each bin. These are purely statistical, and based on Poisson distributions. The contents of a given bin are used to determine the \( p\)-value – the probability of the background fluctuating higher than the observed excess, or lower than the observed deficit. The \( p\)-value is transformed to a significance, in terms of an equivalent number of standard deviations (the \( z\)-value). Where there is an excess (deficit) in data in a given bin, the significance is plotted as positive (negative). In mass bins with small expected number of events, where the observed number of events is similar to the expectation, the Poisson probability of a fluctuation at least as high (low) as the observed excess (deficit) can be greater than 50\%, as a result of the asymmetry of the Poisson distribution. Such bins present no statistical interest and, for simplicity, bars are not drawn for them.

To determine the degree of consistency between data and the fitted background, the \( p\)-value of the fit is obtained by calculating the \( \chi^2 \) from the data, and comparing this result to the \( \chi^2 

4. Search for resonances

As a more sensitive test, the BUMPHunter algorithm [24,25] is used to establish the presence or absence of a resonance in the dijet mass spectrum. To optimise the sensitivity of this algorithm, the \( m_{jj} \) binning strategy is to establish a minimum width for resonances to be considered physical. To this end, the relatively narrow \( q^2 \) \( m_{jj} \) template from full MC simulation [26], described below for subsequent studies, has been used to establish the binning. If the width of the resonance is defined as \( \pm 1\sigma \), the greatest sensitivity at the minimum width is achieved by setting the bin width to \( 1\sigma \), half the resonance width. The final result of this procedure is that the variable bin sizes are typically 6.5\% to 7.0\% of \( m_{jj} \), in width, somewhat wider than detector resolution due to the finite natu-
eral width of $q^*$, which varies between about 3% and 3.5% of the $q^*$ mass.

In the current implementation, the BUMPHEUR algorithm searches for the signal window with the most significant excess of events above background. Starting with a two-bin window, the algorithm increases the signal window and shifts its location until all possible bin ranges, up to half the mass range spanned by the data, have been tested. The most significant departure from the smooth spectrum (“bump”) is defined by the set of bins that have the smallest probability of arising from a background fluctuation assuming Poisson statistics.

The BUMPHEUR algorithm accounts for the so-called “look elsewhere effect” (or “trials factor effect”) [27] by performing a series of pseudoexperiments to determine the probability that random fluctuations in the background-only hypothesis would create an excess as significant as the one observed anywhere in the spectrum. Variable width binning reduces the penalty due to this effect, while retaining sensitivity.

To prevent any new physics signal from biasing the background estimate, if the biggest local excess from the background fit has a p-value smaller than 0.01, this region is excluded and a new background fit is performed. No such exclusion is needed for this data set.

The most significant discrepancy identified by the BUMPHEUR algorithm in the observed dijet mass distribution reported in Fig. 1 is a 2-bin excess in the interval 1.16 to 1.35 TeV. The probability of observing such an excess or larger somewhere in the spectrum, Variable width binning reduces the penalty due to this effect, while retaining sensitivity.

In the absence of any observed significant discrepancy from the zero-signal hypothesis, the Bayesian method documented in [6] is used to set 95% credibility-level (CL) upper limits. Bayesian credibility intervals are set by defining a posterior probability density constant in all positive values of signal strength, $A$. The effect of the jet energy resolution and the jet energy scale (JES) are included. The systematic uncertainty on the JES is taken from the 2010 data [18]. The JES uncertainty shifts resonance peaks by less than 4%. The luminosity and of the jet energy scale (JES) are included. The systematic uncertainty on the JES is taken from the 2010 data [18].

The observed limits on $s_8$ are less strict than the corresponding $q^*$ limits, in part because the $s_8$ signal is much wider than $q^*$. Much of this width increase is due to final state radiation, which is larger for gluon-jets than for quark-jets. In the initial state, the initial state for $s_8$ production contains gluons, which have small parton density at high mass. Thus, $s_8$ are much more likely to be off-mass-shell than $q^*$.
to Gaussian probability distributions and convolving them with the Bayesian posterior probability distribution. Credibility intervals are then calculated numerically from the resulting convolutions. No uncertainties are associated with the theoretical model of new physics, as in each case the model is a benchmark that incorporates a specific choice of model parameters, of PDF set, and of MC tune. Previous ATLAS studies have already explored the impact of different MC tunes and PDF sets on the $q^*$ theoretical prediction [4].

In 2011, the instantaneous luminosity has risen to a level where corrections must be made for multiple $pp$ collisions occurring in the same bunch crossing ("pileup"), whose presence affects the measurement of calorimeter energy depositions associated with the hard-scattering event under study. All simulated samples used in this analysis include a Poisson distributed number of MC minimum bias events added to the hard interaction to account for "in-time" pileup caused by additional collisions in the same bunch crossing. Further account must be taken of "out-of-time" pileup originating from collisions in bunches preceding or following the one of interest, due to the long response time of the liquid argon calorimeters. With the 50 ns bunch spacing in the LHC for these data, up to 12 preceding bunches and 1–2 following bunches contribute to out-of-time pileup. Although the conditions modelled in MC are realistic, they may not perfectly match the data due to bunch train structure and instantaneous luminosity variations in the LHC. The MC events are therefore reweighted to remove these residual differences. Following this procedure the pileup description in MC is sufficiently good that no additional uncertainty on the JES is required for jets with $p_T > 100$ GeV.

The resulting limits are shown in Fig. 2. For excited quarks, the acceptance $A$ ranges from 37 to 51% for $m_{q^*}$ varying from 0.8 to 5.0 TeV, and is never lower than 47% above masses of 1.1 TeV. The main impact on the acceptance comes from the rapidity requirements. Using the theoretical prediction for $q^*$ production described above, the expected mass limit at 95% CL is 2.81 TeV, and the observed limit is 2.99 TeV.

The axigluon results are obtained from the $\sigma \times A$ limits determined from the $q^*$ analysis. The axigluon theoretical prediction is derived from the cross section provided by CalcHEP at each simulated mass, $m$, within the restricted mass range 0.7m to 1.3m, after applying the kinematic selections. Using the axigluon theoretical $\sigma \times A$ thus defined, the expected axigluon mass limit at 95% CL is 3.07 TeV, and the observed limit is 3.32 TeV. This method has been confirmed by full simulation of axigluon samples at three mass points, showing that the differences between parton level and full simulation are negligible compared to the effects of other uncertainties.

Fig. 2(b) shows the limits on the accepted cross section $\sigma \times A$ for colour octet scalar resonances. The expected mass limit at 95% CL is 1.77 TeV, and the observed limit is 1.92 TeV. Since the colour octet scalar cross section decreases much more rapidly with $m$ than those for excited quark and axigluon production, the resulting limits are considerably lower.

For all three models used in these studies, if systematic uncertainties had not been included the exclusion limits would be approximately 60 GeV higher.

7. Model independent limit setting

In addition to specific theoretical models, limits are set to a collection of hypothetical signals that are assumed to be Gaussian-distributed in $m_{jj}$ with mean ($m_{cl}$) ranging from 0.9 to 4.0 TeV and standard deviation ($\sigma_{cl}$) from 5% to 15% of the mean.

Systematic uncertainties are treated using the same methods as applied in model dependent limit setting. The only difference for the Gaussian analysis arises from the decay of the dijet final state not being simulated. In place of this, it is assumed that the dijet signal distribution is Gaussian in shape, and the JES is adjusted by modelling it as an uncertainty of 4% in the central value of the Gaussian signal.

The resulting limits on $\sigma \times A$ for the Gaussian template model are shown in Fig. 3. Relative to previous studies [6] they are substantially improved in the region above 900 GeV. These results may be utilised to set limits on new physics models beyond those considered in these studies, using the procedure described in Appendix A.
Fig. 3. The 95% CL upper limits on $\sigma \times A$ for a simple Gaussian resonance decaying to dijets as a function of the mean mass, $m_G$, for four values of $\sigma_G/m_G$, taking into account both statistical and systematic uncertainties.

Table 1
The 95% CL mass limits for the models of new physics examined in this study. They have been obtained with Bayesian analyses and include systematic uncertainties.

<table>
<thead>
<tr>
<th>Model</th>
<th>95% CL limits (TeV)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excited quark $q^*$</td>
<td>2.81</td>
<td>2.99</td>
<td></td>
</tr>
<tr>
<td>Axigluon</td>
<td>3.07</td>
<td>3.32</td>
<td></td>
</tr>
<tr>
<td>Colour octet scalar</td>
<td>1.77</td>
<td>1.92</td>
<td></td>
</tr>
</tbody>
</table>

Table 2
The 95% CL upper limit on $\sigma \times A$ [pb] for the Gaussian “model-independent” scenario. The symbols $m_G$ and $\sigma_G$ are, respectively, the mean mass and standard deviation of the Gaussian.

<table>
<thead>
<tr>
<th>$m_G$ (GeV)</th>
<th>$\sigma_G/m_G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>0.69 0.83 0.99 1.9</td>
</tr>
<tr>
<td>950</td>
<td>0.67 0.84 1.1 2.2</td>
</tr>
<tr>
<td>1000</td>
<td>0.63 0.82 1.2 2.2</td>
</tr>
<tr>
<td>1050</td>
<td>0.61 0.76 1.1 1.9</td>
</tr>
<tr>
<td>1100</td>
<td>0.53 0.73 1.0 1.6</td>
</tr>
<tr>
<td>1150</td>
<td>0.51 0.67 0.93 1.4</td>
</tr>
<tr>
<td>1200</td>
<td>0.50 0.62 0.83 1.1</td>
</tr>
<tr>
<td>1250</td>
<td>0.48 0.58 0.73 0.89</td>
</tr>
<tr>
<td>1300</td>
<td>0.43 0.51 0.58 0.61</td>
</tr>
<tr>
<td>1350</td>
<td>0.39 0.41 0.42 0.47</td>
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<tr>
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<td>0.24 0.27 0.31 0.33</td>
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<tr>
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<tr>
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<tr>
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</tr>
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<td>1800</td>
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<td>1850</td>
<td>0.055 0.062 0.081 0.10</td>
</tr>
<tr>
<td>1900</td>
<td>0.054 0.062 0.076 0.10</td>
</tr>
<tr>
<td>1950</td>
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<td>2000</td>
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<tr>
<td>3000</td>
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</tr>
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</tr>
<tr>
<td>3400</td>
<td>0.005 0.006 0.007 0.007</td>
</tr>
<tr>
<td>3600</td>
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</tr>
<tr>
<td>3800</td>
<td>0.005 0.005 0.006 0.006</td>
</tr>
<tr>
<td>4000</td>
<td>0.004 0.005 0.005 0.005</td>
</tr>
</tbody>
</table>

8. Conclusion

The dijet mass spectrum measured by the ATLAS experiment has been examined in a search for resonances from new phenomena, using 1.0 fb$^{-1}$ of 7 TeV pp collision data taken in 2011. The observed distribution, which extends up to masses of $\approx$ 4 TeV, is in agreement with a smooth function representing the SM expectation. No evidence for the production of new resonances is found. 95% CL mass limits using Bayesian methodology have been set in the context of several models of new physics, as summarized in Table 1. For excited quarks and axigluons, the current results exceed the limits obtained by ATLAS with the 2010 data by approximately one TeV. Exclusion limits on colour octet scalar resonances have been established for the first time in ATLAS. The limits reported in this Letter are the most stringent to date.

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Appendix A. Setting limits on new models

The following procedure is appropriate for resonances that are approximately Gaussian near the core, and with tails that are well below the background. For convenience, the results of Fig. 3 are provided in Table 2.

(1) For a MC sample generated with the mass of the hypothetical new particle set to $M$, compute an initial acceptance including the branching ratio into dijets. Then apply the kinematic cuts on the parton $p_T$ and $|y^*$| used in this analysis. (2) Approximate the reduction of acceptance due to the calorimeter (temporary) readout problem by eliminating events where a parton enters the
region $-0.1$ to $1.5$ in $\eta$, and $-0.9$ to $-0.5$ in $\phi$. (Indicatively, the acceptance of $q^*$ is reduced by a factor 0.92.) (3) Smeared the signal mass distribution to reflect the detector resolution. In the absence of a better detector simulation tool, use the mass resolution given in Section 2, which is derived from full ATLAS simulation. (4) Since a Gaussian signal shape has been assumed in determining the limit, any long tails in the reconstructed $m_{jj}$ should be removed in the sample under study. The recommendation (based on optimization using $q^*$ templates) is to retain events with $m_{jj}$ between $0.8M$ and $1.2M$. The mean mass, $m$, of this truncated signal should be calculated. (5) The fraction of MC events surviving the first four steps determines the modified acceptance, $A$. (6) From Table 2 select $m_C$ so that $m_C = m$. If the exact value of $m$ is not among the listed values of $m_C$, check the limit for the two values of $m_C$ that are directly above and below $m$, and use the larger of the two limits to be conservative. (7) To retain enough of the information in the full signal template, and at the same time reject tails that would invalidate the Gaussian approximation, the following truncation procedure is recommended. For this mass point, choose a value of $\sigma_C/m_C$ such that the width $2\sigma_C$ is well contained in the (truncated) mass range. For the $q^*$ a good choice is empirically found to be $\sigma_C = (1.2M - 0.8M)/5$. This $\sigma_C$ corresponds to a Gaussian distribution contained within the truncation interval [0.8M, 1.2M], since the interval [0.8M, 1.2M] corresponds to $[m_C - 2.5\sigma_C, m_C + 2.5\sigma_C]$.

For the $q^*$ case a good choice is $\sigma_C = (1.2M - 0.8M)/5$ so that 95% of the Gaussian spans $4 \times (0.4/5)M$. Use this value to pick the closest $\sigma_C/m_C$ value, rounded up to be conservative. (8) Compare the tabulated 95% CL upper limit corresponding to the chosen $m_C$ and $\sigma_C/m_C$ values to the $\sigma \times A$ obtained from the theoretical cross section of the model multiplied by the acceptance defined in step (5) above.

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