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Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC

The ATLAS Collaboration
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A search for new heavy particles manifested as resonances in two-jet final states is presented. The data were produced in 7 TeV proton-proton collisions by the Large Hadron Collider (LHC) and correspond to an integrated luminosity of 31.5 nb⁻¹ collected by the ATLAS detector. No resonances were observed. Upper limits were set on the product of cross section and signal acceptance for excited-quark (q*) production as a function of q* mass. These exclude at the 95% CL the q* mass interval 0.30 < m_q* < 1.26 TeV, extending the reach of previous experiments.

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Two-jet (dijet) events in high-energy proton-proton (pp) collisions are usually described in the Standard Model (SM) by applying quantum chromodynamics (QCD) to the scattering of beam-constituent quarks and gluons. Several extensions beyond the SM predict new heavy particles, accessible at LHC energies, that decay into two energetic partons. Such new states may include an excited composite quark q*, exemplifying quark substructure [1-3]; an axigluon predicted by chiral color models [4, 5]; a flavour-universal color-octet coloron [6, 7]; or a color-octet techni-p meson predicted by models of excited-quark production as a function of q* mass. These exclude at the 95% CL the q* mass interval 0.30 < m_q* < 1.26 TeV, extending the reach of previous experiments.

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Events with at least two jets were retained if the highest \( p_T \) jet (the "leading" jet) satisfied \( p_T^{1} > 80 \) GeV and the next-to-leading jet satisfied \( p_T^{2} > 30 \) GeV; this ensured that the data sample had high and unbiased trigger and jet reconstruction efficiencies. Those events containing a poorly measured jet with \( p_T > 15 \) GeV were vetoed to prevent cases where a jet was incorrectly identified as one of the two leading jets [23]; this affected the event selection by less than 0.5%. The two leading jets were required to satisfy several quality criteria [23] and to lie outside detector regions where the jet energy was not yet measured in an optimal way, such as the interval \( 1.3 < |\eta^{\text{jet}}| < 1.8 \). Finally, both jets were required to be in the pseudorapidity region \( |\eta^{\text{jet}}| < 2.5 \), and their pseudorapidity difference was required to satisfy \( |\eta^{\text{jet1}} - \eta^{\text{jet2}}| < 1.3 \). These cuts, which suppress high-mass SM multijet background, were determined by performing an optimization of the potential signal from \( q^* \) decays (using a \( q^* \) mass of 1 TeV) compared with the SM background. There were 132,433 candidates that satisfied these requirements.

The final event sample was selected by requiring the dijet invariant mass to satisfy \( m^{jj} > 200 \) GeV in order to eliminate any potential kinematic bias in the \( m^{jj} \) distributions from the selection requirements on the jet candidates. There were 37,805 events in this sample, which formed the \( m^{jj} \) distribution shown in Fig. 1.

MC signal events were generated using the excited-quark \((qg \rightarrow q^*)\) production model [2, 3]. The excited quark \( q^* \) was assumed to have spin \( 1/2 \) and quark-like couplings, relative to those of the SM \( SU(2) \), \( U(1) \), and \( SU(3) \) gauge groups, of \( f = f' = f_s = 1 \), respectively. The compositeness scale \( \Lambda \) was set to the \( q^* \) mass. Signal events were generated using PYTHIA [24] 6.4.21, a leading-order parton-shower MC generator, with the modified leading-order MRST2007 [25] parton distribution functions (PDFs) and with the renormalization and factorization scales set to the mean \( p_T \) of the two leading jets. PYTHIA was also used to decay the excited quarks to all possible SM final states, which were dominantly \( qg \) but also \( qW, qZ \), and \( qY \). The MC samples were produced [26] using the ATLAS MC09 parameter tune [27] and a GEANT4-based detector simulation [28].

Figure 1 shows the predicted signals for \( q^* \) masses of 500, 800, and 1200 GeV, after all selection cuts. The signal acceptance \( \mathcal{A} \), which included reconstruction and trigger efficiencies near 100%, was found to range from \( \sim 31\% \) for \( m_{q^*} = 300 \) GeV to \( \sim 48\% \) for \( m_{q^*} = 1.7 \) TeV [29]. The choice of dijet mass binning was motivated by the dijet mass resolution of the signal. The predicted experimental width ranged from \( \sigma_{m^{jj}}/m^{jj} \sim 11\% \) at \( m_{q^*} = 300 \) GeV to \( \sigma_{m^{jj}}/m^{jj} \sim 7\% \) at \( m_{q^*} = 1.7 \) TeV and was dominated by the detector energy resolution.

The background shape was determined by fitting the observed spectrum with the function [16]

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

where \( x = m^{jj}/\sqrt{s} \) such that \( f(1) = 0 \) and \( f(0) \rightarrow +\infty \), and \( p_{1,2,3,4} \) are free parameters. The \( x^{p_4} \ln x \) factor was included to describe the high-\( m^{jj} \) part of the spectrum. The function in Eqn. 1 has been shown to fit the \( m^{jj} \) observable well in PYTHIA, HERWIG, and next-to-leading-order (NLO) perturbative QCD predictions for \( pp \) collisions at \( \sqrt{s} = 1.96 \) TeV [16]. Studies using PYTHIA and the ATLAS GEANT4-based detector simulation were performed to demonstrate that the smooth and monotonic form of Eqn. 1 describes QCD-predicted dijet mass distributions in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV. There is good agreement between the MC prediction and the fitted parametrization in Eqn. 1, as evidenced by a \( \chi^2 \) per degree of freedom of 27/22 over the dijet mass range \( 200 < m^{jj} < 1900 \) GeV.

The results of fitting the data with Eqn. 1 are shown in Fig. 1. The presence or absence of detectable \( m^{jj} \) resonances in this distribution was determined by performing several statistical tests of the background-only hypothesis. A suite of six tests was employed: the BumpHunter [30], the Jeffreys divergence [31], the Kolmogorov-Smirnov test, the likelihood, the Pearson \( \chi^2 \), and the TailHunter statistic [32]. The agreement of the data with the background-only hypothesis of a smoothly varying and monotonic distribution was determined for each statistic by calculating the \( p \)-value for the data using \( 10^3 \) pseudo-spectra drawn from Poisson variations seeded by the results of the fit of Eqn. 1 to the data. The \( p \)-value of the background-only hypothesis is defined as the fraction of pseudo-experiments that result in a value of the same statistic greater than the value of the same statistic found by the fit to the data. The results of all six tests were consistent with the conclusion that the fitted parametrization described the observed data distribution well, with \( p \)-values in excess of 51%. These observations supported the background-only hypothesis.

In the absence of any observed discrepancy with the zero-signal hypothesis, a Bayesian approach was used to set 95% credibility-level (CL) upper limits on \( \sigma \cdot \mathcal{A} \) for hypothetical new particles decaying into dijets with \( |\eta^{\text{jet}}| < 2.5 \). For each of the test masses (indexed by \( \nu \) corresponding to the excited-quark \( q^* \) predictions, a likelihood function \( L_{\nu} \) was defined as a product of Poisson factors computed for each bin \( i \) of the \( m^{jj} \) distribution:

\[
L_{\nu}(d|b_{\nu}, s) \equiv \prod_i \frac{[b_{\nu i} + s_{\nu i}(\nu)]^{d_i} d_i!}{d_i!} e^{-b_{\nu i} + s_{\nu i}(\nu)},
\]

where \( d_i \) is the observed number of data events in bin \( i \), \( b_{\nu i} \) is the background in bin \( i \) obtained as described below; and \( s_{\nu i}(\nu) \) is the predicted signal added in bin \( i \) by the signal template; the latter was normalized to the total number of predicted signal events \( s = \sum_i s_{\nu i}(\nu) \). For
The data (D) dijet mass distribution (filled points) fitted using a binned background (B) distribution described by Eqn. 1 (histogram). The predicted $q^*$ signals [2, 3] for excited-quark masses of 500, 800, and 1200 GeV are overlaid, and the bin-by-bin significance of the data-background difference is shown.

Each $\nu$, the backgrounds in the bins $b_{\nu i}$ were evaluated from a simultaneous five-parameter fit of the signal and background distributions to ensure that the background determination would not be biased by the presence of any signal. The four background parameters were those in Eqn. 1; the fifth parameter consisted of the normalization of the predicted $\nu^{th} q^*$ signal template. To avoid acceptance bias, the lowest $q^*$ test mass used was 300 GeV. For every $q^*$ mass, Eqn. 2 was computed for a range of possible signal yields, $s$, and the resulting likelihood function was multiplied by a flat prior in $s$ to give a posterior probability density in $s$. The 95% probability region was then determined by integration of the posterior probability distribution. This Bayesian technique was found to yield credibility intervals that corresponded well with the true number of signal events. The Bayesian technique was found to be unbiased by the presence of any signal. The background fit, integrated luminosity, and JER were incorporated as nuisance parameters into the likelihood function in Eqn. 2 and then marginalized by numerically integrating the product of this modified likelihood, the prior in $s$, and the priors corresponding to the nuisance parameters to arrive at a modified posterior probability distribution. In the course of applying this convolution technique, the JER was found to make a negligible contribution to the overall systematic uncertainty.

Figure 2 depicts the resulting 95% CL upper limits on $\sigma \cdot A$ as a function of the $q^*$ resonance mass after incorporation of systematic uncertainties. Linear interpolations between test masses were used to determine where the experimental bound intersected with a theoretical prediction to yield a lower limit on allowed mass. The corresponding observed 95% CL excited-quark mass exclusion region was found to be $0.30 < m_{q^*} < 1.26$ TeV using MRST2007 PDFs in the ATLAS default MC09 tune. Table I shows the results obtained using CTEQ6L1 [37] and CTEQ5L [38] PDF sets. The variations in the observed limit associated with the error eigenvectors of a CTEQ PDF set were found to be smaller than the spread displayed in Table I. The excluded regions were $\sim 30$ GeV greater when only statistical uncertainties were taken into account. The expected limits corresponding to the data sample were computed using an analogous approach, but replacing the actual data with pseudo-data generated by random fluctuations around the smooth function described by fitting the data with Eqn. 1; these are shown in Fig. 2, with a resulting expected $q^*$ mass exclusion region of $0.30 < m_{q^*} < 1.06$ TeV using MRST2007 PDFs. As indicated in Table I, the two other PDF sets yielded similar results, with expected exclusion regions extending to near 1 TeV. An indication of the dependence of the $m_{q^*}$ limits on the theoretical prediction for the $q^*$ signal was obtained by simultaneously varying both the renormalization and factorization scales by factors of 0.5 and 2, which was tantamount to modifying the predicted cross section by approximately $\pm 20\%$. This changed the observed MRST2007 limit of 1.26 TeV to 1.32 TeV and 1.22 TeV, respectively.

In conclusion, a model-independent search for new heavy particles manifested as mass resonances in dijet final states was conducted using a 315 nb$^{-1}$ sample of 7 TeV proton-proton collisions produced by the LHC and recorded by the ATLAS detector. No evidence of a resonance structure was found and upper limits at the 95% CL were set on the products of cross section and signal
TABLE I. The 95% CL lower limits on the allowed $q^*$ mass obtained using different PDF sets.

<table>
<thead>
<tr>
<th>MC Tune</th>
<th>PDF Set</th>
<th>Observed Mass Limit [TeV]</th>
<th>Expected Mass Limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC09 [27]</td>
<td>MRST2007 [25]</td>
<td>1.26</td>
<td>1.28</td>
</tr>
<tr>
<td>MC09' a</td>
<td>CTEQ6L1 [37]</td>
<td>1.20</td>
<td>1.23</td>
</tr>
<tr>
<td>Perugia0 [39]</td>
<td>CTEQ5L [38]</td>
<td>1.22</td>
<td>1.25</td>
</tr>
</tbody>
</table>

$^a$ The MC09' tune is identical to MC09 except for the PYTHIA parameter PARP(82)$= 2.1$ and use of the CTEQ6L1 PDF set.

FIG. 2. The 95% CL upper limit on $\sigma \cdot A$ as a function of dijet resonance mass (black filled circles). The black dotted curve shows the expected 95% CL upper limit and the light and dark yellow shaded bands represent the 68% and 95% credibility intervals of the expected limit, respectively. The dashed curves represent excited-quark $\sigma \cdot A$ predictions for different MC tunes, each using a different PDF set.

acceptance for hypothetical new $q^*$ particles decaying to dijets. These data exclude at the 95% CL excited-quark masses from the lower edge of the search region, 0.30 TeV, to 1.26 TeV for a standard set of model parameters and using the ATLAS default MC09 tune [27]. This result extends the reach of previous experiments and constitutes the first exclusion of physics beyond the Standard Model by the ATLAS experiment. In the future, such searches will be extended to exclude or discover additional hypothetical particles over greater mass ranges.

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[19] For the specific qq final state, the product of branching fraction and acceptance ranged from ~28% to ~40% for m∗ = 300 GeV and m∗ = 1.7 TeV, respectively.

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