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

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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

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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 LHC and correspond to an integrated luminosity of 315 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% C.L. 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 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 contribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.

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rected for the effects of calorimeter noncompensation and inhomogeneities by using transverse-momentum ($p_T$) and $\eta$-dependent calibration factors based on Monte Carlo (MC) corrections and validated with extensive test-beam and collision-data studies [20,22]. The $m^{jj}$ observable was computed without unfolding jets to hadrons or partons.

In order to suppress cosmic-ray and beam-related backgrounds, events were required to contain at least one primary collision vertex, defined by at least five reconstructed charged-particle tracks, each with a position, when extrapolated to the beam line, of $|z| < 10$ cm. Events with at least two jets were retained if the highest $p_T$ jet (the “leading” jet) satisfied $p_T^j > 80$ GeV and the next-to-leading jet satisfied $p_T^{j_2} > 30$ 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 $1.3 < |\eta^{jet}| < 1.8$. Finally, both jets were required to be in the pseudorapidity region $|\eta^{jet}| < 2.5$, and their pseudorapidity difference was required to satisfy $|\eta^{j_1} - \eta^{j_2}| < 1.3$. These cuts, which suppress high-mass SM multijet background, were determined by performing an optimization of the potential signal from $q^*\rightarrow q'g$ 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 by using the excited-quark ($qg \rightarrow q^* g$) production model [2,3]. The excited quark $q^*$ was assumed to have spin 1/2 and quarklike 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 ($A$) was set to the $q^*$ mass. Signal events were generated by 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 $gg$ but also $gW, gZ, \text{and } q\gamma$. The MC samples were produced [26] by 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 ($A$), 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 $x \equiv m^{jj}/\sqrt{s}$, 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 Eq. (1) has been shown to fit the $m^{jj}$ observable well in PYTHIA, HERWIG, and next-to-leading-order 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 Eq. (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 Eq. (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 Eq. (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 Eq. (1) to the data. The $p$ value of the background-only hypothesis is defined as the fraction of pseudoexperiments that result in a value of the given 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 (C.L.) 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:

$$L_{\nu}(d \mid b_{\nu}, s) = \prod_i \frac{(b_{\nu i} + s_i(\nu))^{d_i}}{d_i!} e^{-[b_{\nu i} + s_i(\nu)]},$$

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 $s_i(\nu)$ is the predicted signal added in bin $i$ by the signal template; the latter was normalized to the total number of predicted signal events $s = \sum s_i(\nu)$. For each $\nu$, the background 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 Eq. (1); the fifth parameter consisted of the normalization of the predicted $\nu^{\text{th}}$ $q^*$ signal template. To avoid acceptance bias, the lowest $q^*$ test mass used was 300 GeV. For every $q^*$ mass, Eq. (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 frequentist confidence intervals. This was verified by performing a series of pseudoexperiments to determine, by way of a standard frequentist calculation, the coverage, or the fraction of times that the 95% Bayesian credibility interval contained the true number of signal events.

The dominant sources of systematic uncertainty, in decreasing order of importance, were the absolute jet energy scale, the background fit parameters, the integrated luminosity, and the jet energy resolution (JER). The jet energy scale uncertainty was quantified as a function of $p_T$ and $\eta^{\text{jet}}$, with values in the range 6%–9% [20,33,34]. The jet calibration relied on the MC simulation of the response of the ATLAS detector; its uncertainty was constrained by varying the ATLAS simulation and from in situ information. The systematic uncertainty on the determination of the background was taken from the uncertainty on the parameters resulting from the fit of Eq. (1) to the data sample. The uncertainty on $\sigma \cdot \mathcal{A}$ due to integrated luminosity was estimated to be ±11% [35]. The JER uncertainty was treated as uniform in $p_T$ and $\eta^{\text{jet}}$ with a value of ±14% on the fractional $p_T$ resolution of each jet [36]. The effects of jet energy scale, background fit, integrated luminosity, and JER were incorporated as nuisance parameters into the likelihood function in Eq. (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% C.L. upper limits on $\sigma \cdot \mathcal{A}$ as a function of the $q^*$ resonance mass after incorporation of systematic uncertainties. Linear interpolations...
random fluctuations around the smooth function described
sample were computed by using an analogous approach
account. The expected limits corresponding to the data
greater when only statistical uncertainties were taken into

Table I shows the results obtained by using CTEQ6L1
MC09 tune. Table I presents the results obtained by using CTEQ6L1 [37] and CTEQ5L [39] 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 by using an analogous approach
but replacing the actual data with pseudodata generated by
random fluctuations around the smooth function described
by fitting the data with Eq. (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 simultane-ously 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 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 re-
corded by the ATLAS detector. No evidence of a resonance
structure was found, and upper limits at the 95\% C.L. were
set on the products of cross section and signal accept-
ance for hypothetical new \( q^* \) particles decaying to dijets. These
data exclude at the 95\% C.L. 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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\[
\begin{array}{lllll}
\text{MC tune} & \text{PDF set} & \text{Observed mass limit [TeV]} & \text{Expected mass limit [TeV]} \\
\hline
\text{MC09} & \text{MRST2007} & 1.26 & 1.28 & 1.06 \\
\text{MC09} & \text{CTEQ6L1} & 1.20 & 1.23 & 0.99 \\
\text{Perugia0} & \text{CTEQ5L} & 1.22 & 1.25 & 1.00 \\
\end{array}
\]

\(^a\)The MC09\(^a\) tune is identical to MC09 except for the PYTHIA [24] parameter PARP(82) = 2.1
and use of the CTEQ6L1 PDF set.
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[19] The ATLAS reference system is a Cartesian right-handed coordinate system, with the nominal collision point at the origin. The anticlockwise beam direction defines the positive z axis, while the positive x axis points from the collision point to the center of the LHC ring and the positive y axis points upward. The angles \( \phi \) and \( \theta \) are the azimuthal and polar angles, respectively. The pseudorapidity is defined as \( \eta = - \ln \tan(\theta/2) \) and rapidity is defined as \( y = \frac{1}{2} \ln(E + p_z)/(E - p_z) \), where E is the energy and \( p_z \) is the longitudinal component of the momentum along the beam direction.
[29] For the specific \( gg \) final state, the product of branching fraction and acceptance ranged from \( \sim 2\% \) to \( \sim 40\% \) for \( m_\gamma \sim 300 \text{ GeV} \) and \( m_\gamma \sim 1.7 \text{ TeV} \), respectively.

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