Title
Search for new particles in two-jet final states in 7 TeV proton-proton collisions with the ATLAS detector at the LHC

Permalink
https://escholarship.org/uc/item/26r925zj

Journal
Physical Review Letters, 105(16)

ISSN
0031-9007

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Publication Date
2010-10-11

DOI
10.1103/PhysRevLett.105.161801

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Peer reviewed
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 models [4,5], a flavor-universal color-octet coloron [6,7], or a color-octet techni-$\rho$ meson predicted by models of extended technicolor and top-color-assisted technicolor [8–11].

Particularly sensitive to such new objects is the dijet invariant mass observable, defined as $m^{ij} = \sqrt{(E_i + E_j)^2 - (p_i + p_j)^2}$, where $E$ and $p$ are the jet energy and momentum, respectively. Several experiments have examined $m^{ij}$ distributions in search of new resonances [12–17]; recently, 1.13 fb$^{-1}$ of $p\bar{p}$ collision data at the Fermilab Tevatron collider have excluded the existence of excited quarks $q'$ with mass $260 < m_{q'} < 870$ GeV [16]. This Letter reports the first search by the ATLAS experiment [18] at the LHC for such massive particles in pp collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV, based on a data sample corresponding to an integrated luminosity of 315 nb$^{-1}$. The analysis presented here focused on a search for excited quarks because of the accessible predicted cross section [2,3] for such particles and the benchmark nature of the model that allows limits on the acceptance times cross section to be set for resonant states with intrinsic widths narrower than the experimental resolution.

The analysis technique consisted of a model-independent search for a dijet mass resonance on top of a smooth and rapidly falling spectrum and relied on the measured $m^{ij}$ distribution to estimate the background level to this new possible signal. In the absence of an observed new physics signal, upper limits were determined on products of cross section ($\sigma$) and signal acceptance ($\mathcal{A}$) for several $q'$ test masses for a standard set of model parameters.

The ATLAS detector [18] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near $4\pi$ coverage in solid angle [19]. The overall layout of the detector is dominated by its four superconducting magnet systems, which comprise a thin solenoid surrounding inner tracking detectors and three large toroids with an eightfold azimuthal symmetry.

The calorimeters, which are surrounded by an extensive muon system, are of particular importance to this analysis. In the pseudorapidity region $|\eta| < 3.2$, high-granularity liquid-argon (LAr) electromagnetic sampling calorimeters are used. An iron-scintillator tile calorimeter provides hadronic coverage in the range $|\eta| < 1.7$. The end-cap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements.

The data sample was collected during stable periods of 7 TeV pp collisions using a trigger configuration requiring the lowest-level hardware-based calorimeter jet trigger to satisfy a nominal transverse energy threshold of 15 GeV [20]. This trigger had an efficiency greater than 99% for events with at least one jet with transverse energy higher than 80 GeV.

Jets were reconstructed by using the anti-$k_T$ jet clustering algorithm [21] with a radius parameter $R = 0.6$. The inputs to this algorithm were clusters of calorimeter cells seeded by cells with energy significantly above the measured noise. Jet four-vectors were constructed by performing a four-vector sum over these cell clusters, treating each as an $(E, \vec{p})$ four-vector with zero mass. These were cor-
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 $p_T^l > 80$ GeV and the next-to-leading jet satisfied $p_T^l > 30$ 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 less than 0.5%. The two leading jets were required to satisfy

$$p_T > 80 \text{ GeV}$$

and collision-data studies [20,22]. The $m^{jj}$ distribution shown in Fig. 1. The predicted signals for $q^*W$, $q^*Z$, and $q^*\gamma$ are free parameters. The $x^{p_{\text{inj}}}$ 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 $p\bar{p}$ 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 $p\bar{p}$ 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

$$f(x) = p_1(1 - x)p_2x^{p_3} + p_4^{\text{inj}},$$

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 $x^{p_{\text{inj}}}$ factor was included to describe the high-$m^{jj}$ part of the spectrum. 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]
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 $10^3$ pseudospectra 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 values in excess of 51%. These observations supported the background-only hypothesis.

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 $\eta$, 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 $\eta$ 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
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% C.L. excited-quark mass exclusion region was found to be $0.30 < m_{q^*} < 1.26$ TeV by using MRST2007 PDFs in the ATLAS default MC09 tune. Table I shows 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 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 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% C.L. were set on the products of cross section and signal acceptance 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.

We deeply thank everybody at CERN involved in operating the LHC in such a superb way during this initial high-energy data-taking period. We acknowledge equally warmly all the technical and administrative staff in the collaborating institutions without whom ATLAS could not be operated so efficiently. We acknowledge the support of ANPCyT, Argentina; Yerevan Physics Institute, Armenia; ARC and DEST, Australia; Bundesministerium für Wissenschaft und Forschung, Austria; National Academy of Sciences of Azerbaijan; State Committee on Science and Technologies of the Republic of Belarus; CNPq and FINEP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; NSFC, China; COLCIENCIAS, Colombia; Ministry of Education, Youth and Sports of the Czech Republic, Ministry of Industry and Trade of the Czech Republic, and Committee for Collaboration of the Czech Republic with CERN; Danish National Science Research Council and the Lundbeck Foundation; European Commission, through the ARTEMIS Research Training Network; IN2P3-CNRS and CEA-DSM/IRFU, France; Georgian Academy of Sciences; BMBF, DFG, HGF and MPG, Germany; Ministry of Education and Religion, through the EPEAEK program PYTHAGORAS II and GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT, Japan; CNRST, Morocco; FOM and NWO, The Netherlands; The Research Council of Norway; Ministry of Science and Higher Education, Poland; GRICES and FCT, Portugal; Ministry of Education and Research, Romania; Ministry of Education and Science of the Russian Federation and State Atomic Energy Corporation ROSATOM; JINR; Ministry of Science, Serbia; Department of International Science and Technology Cooperation, Ministry of Education of the Slovak Republic; Slovenian Research Agency, Ministry of Higher Education, Science and Technology, Slovenia; Ministerio de Educación y Ciencia, Spain; The Swedish Research Council, The Knut and Alice Wallenberg Foundation, Sweden; State Secretariat for Education and Science, Swiss National Science Foundation, and Cantons of Bern and Geneva, Switzerland; National Science Council, Taiwan; TAEK, Turkey; The Science and

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<tr>
<th>MC tune</th>
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<th>Observed mass limit [TeV]</th>
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<td>MC09$^a$</td>
<td>CTEQ6L1 [37]</td>
<td>1.20</td>
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<td>Perugia0 [38]</td>
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$^a$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.
Technology Facilities Council and The Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

[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 Φ and θ are the azimuthal and polar angles, respectively. The pseudorapidity is defined as η = −ln[tan(θ/2)] and rapidity is defined as y = 1/2 ln[(E + pₓ)/(E − pₓ)], where E is the energy and pₓ 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 ~28% to ~40% for mg = 300 GeV and mgq = 1.7 TeV, respectively.

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