Search for quark contact interactions in dijet angular distributions in *pp* collisions at √s=7 TeV measured with the ATLAS detector

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ABSTRACT

Dijet angular distributions from the first LHC pp collisions at center-of-mass energy $\sqrt{s} = 7$ TeV have been measured with the ATLAS detector. The dataset used for this analysis represents an integrated luminosity of 3.1 pb^{-1}. Dijet χ distributions and centrality ratios have been measured up to dijet masses of 2.8 TeV, and found to be in good agreement with Standard Model predictions. Analysis of the χ distributions excludes quark contact interactions with a compositeness scale Λ below 3.4 TeV, at 95% confidence level, significantly exceeding previous limits.

1. Introduction

At hadron colliders, most events with large transverse momentum (p_T) transfer occur when a constituent parton from one of the incoming hadrons scatters from a parton in the other. At high p_T, these '$2 \to 2$' scattering processes are well described within the Standard Model by perturbative Quantum Chromodynamics (QCD), the quantum field theory of strong interactions. As each high-momentum parton emerges from the collision, the subsequent parton shower and hadronization create a collimated jet of particles aligned with the direction of the original parton. In most of these collisions, two high-p_T jets emerge from the interaction. These 'dijet' events are particularly useful for measuring quantities associated with the initial interaction, such as the polar scattering angle in the two-parton center-of-mass (CM) frame, θ^*, and the dijet invariant mass, m_{jj}. Precise tests of QCD may be carried out by comparing the theoretical predictions to the experimental distributions. If discrepancies between data and QCD are found to be well beyond experimental and theoretical uncertainties, this would indicate that the QCD description needs improvement, or that a new process, not included in the Standard Model, has appeared.

This analysis focuses on dijet angular distributions, which have been shown by previous experiments [1–4] to be sensitive measures for testing the predictions of QCD and searching for new processes. Dijet angular distributions are well suited to the analysis of early LHC data, since they are little affected by the main systematic uncertainties associated with the jet energy scale (JES) and the luminosity. QCD calculations predict that high-p_T dijet production is dominated by t-channel gluon exchange, leading to angular distributions that are peaked at $|\cos\theta^*|$ close to 1. By contrast, models of new processes characteristically predict angular distributions that would be more isotropic than those of QCD.

This Letter reports on the first search with the ATLAS detector for quark contact interactions leading to modifications of dijet angular distributions in proton–proton (pp) collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV at the LHC. The data sample represents an integrated luminosity of 3.1 pb^{-1}, recorded in periods of stable collisions, through August 2010. The two distributions under study – dijet χ distributions, and dijet centrality ratios – have been used repeatedly as benchmark measures, and will be described in detail below.

The highest exclusion limits on quark contact interactions set by any previous experiment [4], for several statistical analyses, ranged from 2.8 to 3.1 TeV at 95% confidence level (CL) for the compositeness scale Λ.

2. Kinematics and angular distributions

The θ^* distribution for $2 \to 2$ parton scattering is predicted by QCD in the partonic CM frame of reference. Event by event, the momentum fraction (Bjorken x) of one incoming parton differs from that of the other, causing the partonic reference frame to be boosted relative to the detector frame by an amount which can be determined from the dijet kinematics. A natural variable

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for analysis of parton–parton interactions is therefore the rapidity, $y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$, where E is the energy and p_z, the z-component of momentum, of the given particle. The variable y transforms under Lorentz boosts along the z-direction as $y \to y - y_B = y - \tanh^{-1}(\beta_B)$, where β_B is the velocity of the boosted frame, and y_B is its rapidity boost.

The ATLAS coordinate system is a right-handed Cartesian system with the x-axis pointing to the center of the LHC ring, the z-axis following the counter-clockwise beam direction, and the y-axis going upwards. The polar angle θ is referred to the z-axis, and ϕ is the azimuthal angle about the z-axis.

Rapidity differences are boost invariant, so that under Lorentz boosts jets retain their shapes in (y, ϕ) coordinates. The pseudorapidity, $\eta = -\ln(\tan(\frac{\theta}{2}))$, approaches rapidity in the massless limit and can be used as an approximation to rapidity. The variables η and ϕ are employed in the reconstruction of jets.

The variable χ, used in the first angular distributions considered in this study, is derived from the rapidities of the two jets defining the dijet topology (y_1 and y_2). For a given scattering angle θ^*, the corresponding rapidity in the CM frame (in the massless particle limit) is $y^* = \frac{1}{2}\ln(\frac{1+|\cos\theta^*|}{1-|\cos\theta^*|})$. The variables y^* and y_B can be found from the rapidities of the two jets using $y^* = \frac{1}{2}(y_1 - y_2)$ and $y_B = \frac{1}{2}(y_1 + y_2)$. Then y^* may be used to determine the partonic CM angle θ^*. Additionally, y^* is the basis for the definition of χ: $\chi = \exp(|y_1 - y_2|) = \exp(2|y^*|)$.

The utility of the χ variable becomes apparent when making comparisons of angular distributions predicted for new processes to those of QCD. In QCD, gluon (massless, spin-1) exchange diagrams have approximately the same angular dependence as Rutherford scattering: $\mathrm{d}N/\mathrm{d}\cos\theta^* \propto 1/\sin^4(\theta^*/2)$. Evaluation of $\mathrm{d}N/\mathrm{d}\chi$ shows that this distribution is constant in χ. By contrast, the angular distributions characteristic of new processes are more isotropic, leading to additional dijet events at low χ. In QCD, subdominant diagrams also cause χ distributions to rise slightly at low χ.

The other important kinematic variable derivable from jet observables is the dijet invariant mass, m_{jj}, which is also the CM energy of the partonic system. In reconstruction, m_{jj} is found from the two jet four-vectors: $m_{jj} \equiv \sqrt{(E^{j_1} + E^{j_2})^2 - (\vec{p}^{j_1} + \vec{p}^{j_2})^2}$, where E and $\vec{p}$ are the energy and momentum of the jets. Both distributions used in this Letter are binned in this variable.

The second angular distribution considered is the dijet centrality ratio, R_C. For this analysis, the detector is divided into two pseudorapidity regions: central and non-central. R_C is defined as the ratio of the number of events in which the two highest p_T jets both fall into the central region to the number of events in which the two highest p_T jets both fall into the non-central region. For the current study, the central region is defined as $|\eta_{1,2}| < 0.7$, and the non-central region as $0.7 < |\eta_{1,2}| < 1.3$. Since new processes are expected to produce more central activity than QCD, their signal would appear as an increase in R_C above some m_{jj} threshold, with the increase being directly related to the cross section of the new signal.

R_C distributions are complementary to χ distributions by being sensitive to different regions of phase space. χ distributions are fine measures of θ^* and coarse measures of m_{jj}, while the opposite is true for R_C distributions as they can be binned more finely in m_{jj} for the given amount of data. This gives R_C distributions greater discrimination in determining mass scales associated with hypothetical signals. Ideally, when a signal is present, the two distributions together can be used to narrow the list of viable hypotheses and to establish the associated scale parameters.

The measured R_C and χ distributions include corrections for the jet energy scale but are not unfolded to account for resolution effects. They are compared to theoretical predictions processed through the detector simulation software that, similarly, includes the jet energy corrections but not resolution unfolding.

3. The ATLAS detector

The ATLAS detector [5] covers almost the whole solid angle around the collision point with layers of tracking detectors, calorimeters, and muon chambers. Jet measurements depend most strongly on the calorimeter system. The ATLAS calorimeter is segmented in intervals of pseudorapidity and ϕ to exploit the property that jet shapes are nearly boost invariant in (η, ϕ) coordinates.

Liquid argon (LAr) technology is used in the electromagnetic sampling calorimeters, with excellent energy and position resolution, to cover the pseudorapidity range $|\eta| < 3.2$. The hadronic calorimetry in the range $|\eta| < 1.7$ is provided by a sampling calorimeter made of steel and scintillating tiles. In the end-caps ($1.5 < |\eta| < 3.2$), LAr technology is also used for the hadronic calorimeters, matching the outer $|\eta|$ limits of the electromagnetic calorimeters. To complete the η coverage, the LAr forward calorimeters provide both electromagnetic and hadronic energy measurements, extending the coverage to $|\eta| = 4.9$. In ATLAS, the calorimeter (η, ϕ) granularities are 0.1×0.1 for the hadronic calorimeters up to $|\eta| < 2.5$ (except for the third layer of the tile calorimeter, which has a segmentation of 0.2×0.1 up to $|\eta| = 1.7$), and then 0.2×0.2 up to $|\eta| < 5.0$. The EM calorimeters feature a much finer readout granularity varying by layer, with cells as small as 0.025×0.025 extending to $|\eta| < 2.5$. This segmentation of the calorimeter is sufficiently fine to assure that angular resolution uncertainties in dijet analyses are negligible. In the data taking period considered approximately 187,000 calorimeter cells (98% of the total) were active for event reconstruction.

ATLAS has a three-level trigger system, with the first level (L1) being custom built hardware. The two higher level triggers (HLT) are realized in software. The HLT was not set to reject events accepted by the L1 single-jet triggers chosen for this analysis.

4. Event selection and reconstruction

In the current 3.1 pb^{-1} data sample, specific L1 jet trigger selections have been exploited for optimal analysis of the angular observables. For both observables, bins of m_{jj} are associated with distinct L1 jet trigger requirements selected to provide maximal statistics while being fully efficient, as will be detailed for χ in Section 7.

Jets have been reconstructed using the infrared-safe anti-k_t jet clustering algorithm [6] with the radius parameter $R = 0.6$. The inputs to this algorithm are clusters of calorimeter cells seeded by energy depositions significantly above the measured noise. Jet four-vectors are constructed by the vectorial addition of cell clusters, treating each cluster as an $(E, \vec{p})$ four-vector with zero mass. The jet four-vectors are then corrected, as a function of η and p_T, for the effects of hadronic shower response and detector material distributions by using a calibration scheme based on Monte Carlo (MC) studies including full detector simulation, and validated with extensive test-beam studies [7] and collision data [8].

In order to suppress cosmic-ray and beam-related backgrounds, events are required to contain at least one primary collision vertex with a position of $|z| < 30$ cm and reconstructed from at least five charged-particle tracks. Events with at least two jets are retained if the highest p_T jet (the 'leading' jet) satisfies $p_T^{j_1} > 60$ GeV and the next-to-leading jet satisfies $p_T^{j_2} > 30$ GeV. The asymmetric thresholds are required so as to avoid suppression of events where a third jet has been radiated, while the 30 GeV threshold ensures that reconstruction is fully efficient for both leading jets. Those events containing a poorly measured jet [9] with $p_T > 15$ GeV are vetoed to avoid cases where such a jet would cause incorrect identification of the two leading jets. This criterion results in a rejection rate of 0.5% in the current data sample. The two leading jets are required to satisfy quality criteria, such as being associated with in-time energy deposits in the calorimeter. To be considered as one of the two leading jets, a jet is required to be found within the pseudorapidity region $|\eta| < 2.8$, where the jet energy scale is known to highest precision.

5. Monte Carlo simulations

The Monte Carlo simulation used for the analysis presented in this Letter has the following components. The MC samples have been produced with the PYTHIA 6.4.21 event generator [10] and the ATLAS MC09 parameter tune [11], using the modified leading-order MRST2007 [12] parton distribution functions (PDF). The generated events are passed through the detailed simulation of the ATLAS detector [13], which uses GEANT4 [14] for simulation of particle transport, interactions, and decays. This yields QCD MC samples that have been smeared by detector effects for comparison with collision data. These simulated events are then subjected to the same reconstruction process as the data to produce dijet angular distributions.

As the next step, bin-by-bin correction factors (K-factors) have been applied to the angular distributions derived from MC events to account for next-to-leading order (NLO) contributions. The K-factors are derived from dedicated samples generated separately, and are defined as the ratio NLO_{ME}/PYT_{SHOW}. The NLO_{ME} sample is produced using matrix elements in NLOJET++ [15–17] and the NLO PDF from CTEQ6.6 [18]. The PYT_{SHOW} sample is produced with PYTHIA restricted to leading-order (LO) matrix elements and parton showering using the modified leading order MRST2007 PDF.

The angular distributions generated with full PYTHIA already contain various non-perturbative effects modeled by this event generator (such as multiple parton interactions and hadronization). The K-factors defined above are designed to retain these effects while adjusting for differences in the perturbative sector. Multiplying the full PYTHIA predictions of angular distributions by these bin-wise K-factors results in a reshaped spectrum which includes corrections originating from NLO matrix elements.

Over the full range of χ, the K-factors change the normalized distributions by up to 6%, with little variability from one mass bin to the other. In the case of R_C, the K-factors change the distribution by less than 1%.

The QCD predictions used for comparison to data in this Letter are the end product of the two-step procedure described above.

Other ATLAS jet studies [19] have shown that the use of different event generators and different sets of parameters for non-perturbative effects has a negligible effect on the studied observables in the phase space being considered. For the high-p_T dijet shape observables studied here, χ and R_C, differences between PDF sets were found to be consistently smaller than the uncertainty associated with the CTEQ6.6 PDF set, and are not taken into account.

6. Quark contact interaction term

The benchmark beyond-the-Standard-Model process considered in this Letter is a quark contact interaction, which may be used to model the onset of kinematic properties that would characterize quark compositeness: the hypothesis that quarks are composed of more fundamental particles. The model Lagrangian for this benchmark process is a four-fermion contact interaction [20–22], the analog of the Fermi four-fermion interaction used to describe effects of the weak interaction. The effects of the contact interaction would be expected to appear below or near a characteristic energy scale Λ. If Λ is much larger than the partonic CM energy, these interactions are suppressed by inverse powers of Λ and the quarks would appear to be point-like. The dominant effect would then come from the lowest dimensional four-fermion interactions (contact terms).

While a number of contact terms are possible, the Lagrangian in standard use since 1984 [20] is the single (isoscalar) term: $\mathcal{L}_{qqqq}(\Lambda) = \frac{\xi g^2}{2\Lambda_q^2}\bar{\Psi}_q^L\gamma^\mu\Psi_q^L\bar{\Psi}_q^L\gamma_\mu\Psi_q^L$, where $g^2/4\pi = 1$ and the quark fields Ψ_q^L are left-handed. The full Lagrangian used for hypothesis testing is then the sum of $\mathcal{L}_{qqqq}(\Lambda)$ and the QCD Lagrangian. The relative phase of these terms is controlled by the interference parameter, ξ, which is set for destructive interference ($\xi = +1$) in the current analysis. Previous analyses [4] showed that the choice of constructive ($\xi = -1$) or destructive ($\xi = +1$) interference changed exclusion limits by $\sim 1\%$.

MC samples are calculated in PYTHIA 6.4.21 using this Lagrangian, with each sample corresponding to a distinct value of Λ. Angular distributions of these samples are processed in the same fashion as QCD distributions, including the application of bin-wise K-factors.

Notably, in addition to quark compositeness, this same Lagrangian could be applied to a number of other beyond-the-Standard-Model theories (albeit with different coupling constants), so that it serves as a template for models of new processes with similar scattering distributions.

7. Kinematic criteria for angular distributions

The χ distributions described here are normalized to unit area, $(1/N_{\text{ev}})\,\mathrm{d}N_{\text{ev}}/\mathrm{d}\chi$ where N_{ev} is the number of observed events, to reduce the effects of uncertainties associated with absolute normalization.

Detector resolution effects smear the χ distributions, causing events to migrate between neighboring bins. This effect is reduced by configuring the χ bins to match the natural segmentation of the calorimeter, by making them intervals of constant $\Delta\eta$, approximating Δy. This is achieved by placing the χ bin boundaries at positions $\chi_n = \mathrm{e}^{(0.3\times n)}$, where n is the index for the lower χ boundary of the nth bin, starting with $n = 0$. In doing this, not only is the migration reduced, it is also equalized across the span of χ.

The χ distributions are divided, in turn, into intervals of dijet invariant mass, m_{jj}. For massless partons, the following approximate form shows the dependence of m_{jj} on p_T and χ: $m_{jj} = \sqrt{p_{T1}p_{T2}} \cdot \sqrt{\chi + 1/\chi - 2\cos(\Delta\phi)}$. Since m_{jj} is the CM energy of the partonic system, new processes would be expected to appear in the high mass bins. Several m_{jj} intervals are analyzed to exploit the fact that the χ distributions in low mass bins would be similar to the QCD prediction, while these distributions would be modified by new physics processes acting in high m_{jj} bins. The sensitivity to these processes depends strongly on their cross sections relative to QCD and on the number of events in the highest mass bin.

For χ distributions, events are rejected if $|y_B| > 0.75$ or $|y^*| > 1.7$. The combined criteria limit the rapidity range of both jets to $|y_{1,2}| < 2.45$. The $|y^*|$ criterion determines the maximum χ, which is 30 for this analysis. Taken together, these two criteria define a region within the space of accessible y_1 and y_2 where the acceptance is uniform to better than 1% in χ, for all mass bins. This ensures that the expected shapes of the distributions are not significantly changed by the acceptance. Also, in low mass bins, the $|y_B|$ criterion emphasizes the contribution from the matrix elements and reduces the influence of the effects of PDF convolution. In the highest m_{jj} bin, used for limit setting, the $|y_B|$ criterion reduces the sample by 16%. These kinematic cuts have been optimized through full MC simulation to assure high acceptance in all dijet mass bins.

Since event migration also occurs between bins of m_{jj}, studies of fully simulated jets are used to ensure that migration is small. This criterion, along with the requirement of a sufficient number of events, lead to m_{jj} bin boundaries of 340, 520, 800, and 1200 GeV, with no upper bound on the highest bin. As noted earlier, single-jet triggers are carefully selected for each bin to be 100% efficient. Prescaling of triggers leads to a different effective integrated luminosity in each mass bin, with the corresponding numbers being 0.12, 0.56, 2.0, and 3.1 pb^{-1} in the current data sample for the bins listed above.

Like the χ distributions, the R_C distribution has reduced sensitivity to the absolute JES. However, relative differences in jet response in η could have a significant impact on the sensitivity. Hence, for these early studies, the η range is restricted to the more central regions of the calorimeter where the JES is uniform to within 1% as determined from cross-calibration studies [8]. The R_C region has been chosen to end at a maximum of $|\eta| = 1.3$, just before the transition region between the central and end-cap calorimeters.

8. Convolution of systematic uncertainties

As mentioned before, the angular distributions have a reduced sensitivity to the JES uncertainties compared to other dijet measurements. Nevertheless, the JES still represents the dominant uncertainty for this analysis. The ATLAS JES has been determined by extensive studies [23], and its uncertainty has been tabulated in the variables η, p_T, and N_V, the number of vertices in the event. The average N_V over the full current data sample is 1.7. Typical values of the JES uncertainty in the considered phase space are between 5% and 7%. The resulting bin-wise uncertainties are up to 9% for the χ observable, and up to 7% for the R_C observable.

The dominant sources of theoretical uncertainty are NLO QCD renormalization and factorization scales, and the PDF uncertainties. The corresponding bin-wise uncertainties for normalized χ distributions are typically up to 3% for the combined NLO QCD scales and 1% for the PDF error.

Convolution of these experimental and theoretical uncertainties is done for all angular distributions through Monte Carlo pseudo-experiments (PE's). For all events in the MC sample 1000 PE's are performed, three random numbers being drawn from a Gaussian distribution for each PE. The first is applied to the absolute JES, obtained from the tabulation described above and assumed to be fully correlated across η. The second number is applied to the relative JES, extracted from the same tabulation, which depends only on η and restores the decorrelation due to η dependence of the energy scale. The third number is applied to the PDF uncertainty, provided by the CTEQ6.6 PDF error sets. In a fourth and final step, the uncertainty due to the NLO QCD renormalization (μ_R) and factorization (μ_F) scales is found by letting μ_R and μ_F vary independently between 0.5, 1 and 2 times the average transverse momentum of the two leading jets, resulting in nine samples drawn from a uniform distribution. In a given PE, the data dijet selection criteria described previously are applied.

Other sources of uncertainty have been studied in separate simulations, and have not been included in the PE's described above. As determined by in situ studies comparing data to detector simulation [24], the jet energy resolution (JER) in ATLAS evolves from 12% to 7% over the p_T range from 60 GeV to 1 TeV. To estimate the effect of JER smearing, the χ and R_C distributions were generated with and without JER variation of this magnitude, and the differences were found to be negligible. Detector angular resolution effects in ϕ and η were studied in a similar fashion, with smearing functions specific to the ATLAS calorimeter segmentation, and also found to be negligible.

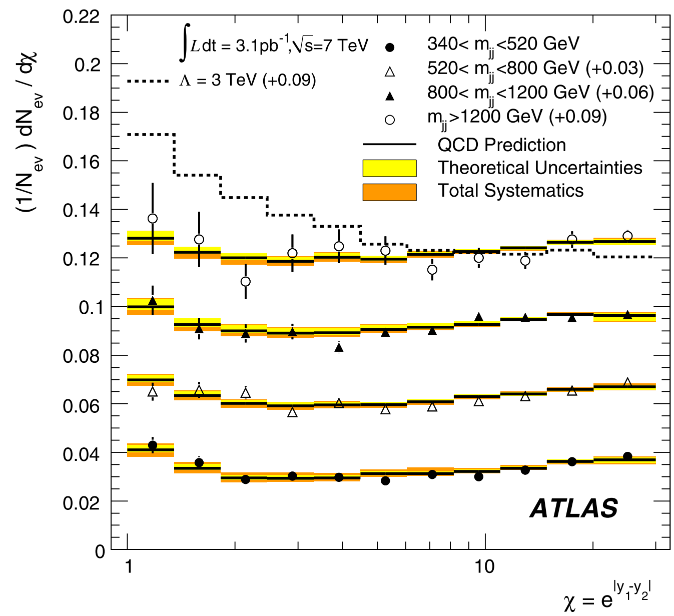

Fig. 1. The normalized χ distributions for $340 < m_{jj} < 520$ GeV, $520 < m_{jj} < 800$ GeV, $800 < m_{jj} < 1200$ GeV, and $m_{jj} > 1200$ GeV, with plotting offsets shown in parentheses. Shown are the QCD predictions with systematic uncertainties (bands), and data points with statistical uncertainties. The prediction for QCD with an added quark contact term with $\Lambda = 3.0$ TeV is shown for the highest mass bin $m_{jj} > 1200$ GeV.

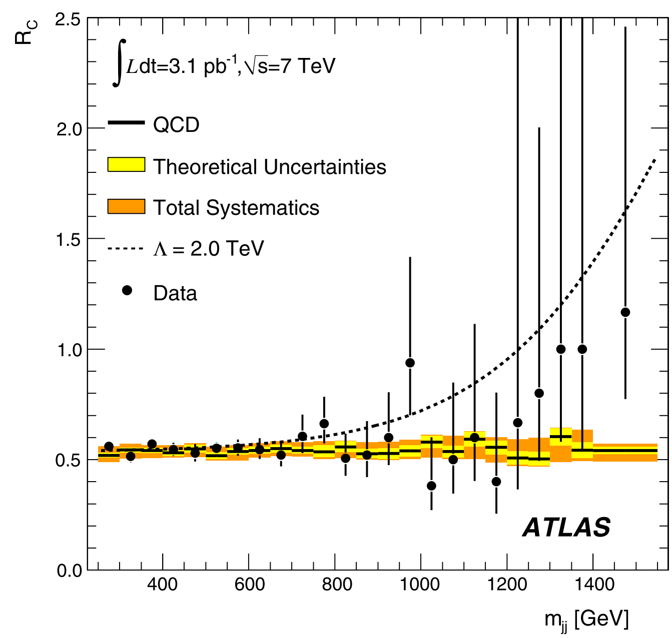

Fig. 2. Dijet centrality ratio, R_C, as a function of m_{jj}, with all events above a mass of 1400 GeV plotted in the last bin. Shown are the QCD prediction with systematic uncertainties (bands), and data points with statistical uncertainties. The prediction for QCD with an added quark contact term with $\Lambda = 2.0$ TeV is also shown.

9. Comparison of data to theory

In Fig. 1 the measured dijet χ distributions are compared to the QCD predictions, along with 1σ systematic error bands determined from the PE's, and statistical errors on the data. Fig. 2 shows the measured dijet-centrality distribution and QCD prediction. The statistical uncertainties are obtained using Poisson probabilities. In the highest mass bins, the numerator and denominator of the ratio typically contain 1 or 2 events each.

To evaluate the agreement between data and QCD in Figs. 1 and 2 a statistical significance test was performed using p-values. The p-value is the probability to obtain a fit to data further from the theoretical prediction than the observed fit, under the assumption that the QCD prediction is the correct description of physics. A chi-square goodness-of-fit is used as the test statistic, and the p-values are derived from the ensemble of PE's generated as described above, including bin-to-bin correlations due to systematic effects, but with additional statistical fluctuations. For the χ distributions shown in Fig. 1, the resulting p-value for each dijet mass bin is (from lowest to highest) 0.19, 0.11, 0.27 and 0.54, indicating good agreement with the QCD prediction. Similarly, in Fig. 2, the dijet R_C comparison has a p-value equal to 0.85, also indicating good agreement with the QCD prediction.

The best fit of the R_C distribution in Fig. 2 is obtained for a compositeness scale of 2.9 TeV. This is not statistically significant, as the QCD prediction lies within the shortest 68% confidence interval in $1/\Lambda^4$.

10. Determination of exclusion limits

Since no signal from new physics processes is apparent in these distributions, limits have been obtained on the compositeness scale Λ of quark contact interactions, based on analyses of the χ distributions. The contact term hypothesis is tested in the highest dijet mass bin in Fig. 1, which begins at $m_{jj} = 1200$ GeV. For the χ distribution in this mass bin, the parameter F_χ is defined as the ratio of the number of events in the first four χ bins to the number in all χ bins. The upper boundary of the fourth bin is at $\chi = 3.32$. This choice of the bin boundary has been determined through a MC study that varies the number of bins in the numerator, as well as the dijet mass bin, and determines the setting that maximizes the sensitivity to quark contact interactions, given the current integrated luminosity.

A frequentist analysis is employed as follows. Predictions of F_χ are obtained for a range of Λ by interpolation between distinct samples generated with different $1/\Lambda^2$ values. The QCD sample provides a bound with $\Lambda = \infty$, and additional samples are generated with Λ values of 500, 750, 1000, 1500, and 3000 GeV. A full set of PE's is made for each hypothesis to construct one-sided 95% CL intervals for F_χ, and the Neyman construction [25] is then applied to obtain a limit on Λ.

The result is shown in Fig. 3. The measured value of F_χ is shown by the dashed horizontal line. The value of F_χ expected from QCD is the solid horizontal line, and the band around it allows one to obtain the 1σ variation of the expected limit. The dotted line is the 95% CL contour of the F_χ prediction for quark contact interactions plus QCD, as a function of Λ and including all systematic uncertainties. This contour decreases as a function of Λ since, for a small Λ scale, there would be more events at low χ.

The observed limit on Λ is 3.4 TeV. This limit is found from the point where the F_χ 95% CL contour crosses the measured F_χ value. All values of Λ less than this value are excluded with 95% confidence. This corresponds to a distance scale of $\sim 6 \cdot 10^{-5}$ fm, from conversion of the limit using $\hbar c$. The expected limit, found from the crossing at the QCD prediction, is 3.5 TeV.

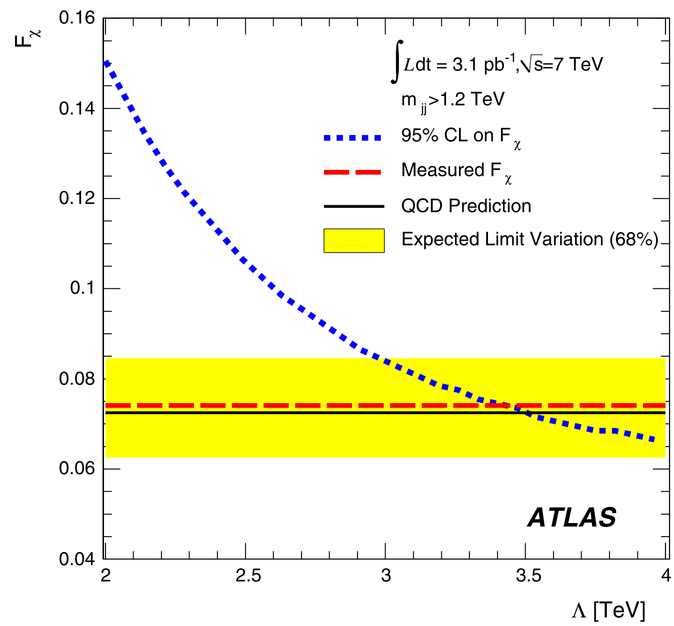

Fig. 3. The dashed horizontal line is the measured F_χ (see text) and the solid horizontal line is the QCD prediction, with a band to illustrate a 1σ variation of the expected limit. The dotted curve is the 95% CL exclusion contour for F_χ with quark contact interactions, used to set the exclusion limit on Λ.

The impact of systematic uncertainties is as follows. If all systematic uncertainties were excluded, the observed limit reported above would increase by 6% to 3.6 TeV, mainly due to the JES uncertainty. Inclusion of NLO scales and PDF uncertainties does not change the limit measurably, as shape differences arising from these are well below the statistical uncertainties.

Confirming analyses have been done using a Bayesian approach with Poisson likelihoods for all χ bins, calculated using priors flat in $1/\Lambda^2$ or $1/\Lambda^4$. These have resulted in observed exclusion limits on Λ of 3.3 TeV and 3.2 TeV, respectively, very close to the limit found in the frequentist analysis.

Similarly, an analysis has been performed to establish 95% CL limits using the dijet centrality ratio shown in Fig. 2. The likelihood for R_C is constructed as a product of likelihoods of inner and outer event counts for all mass bins, which is then analyzed with a Bayesian approach similar to that of the χ Bayesian analysis. Using priors flat in $1/\Lambda^2$ ($1/\Lambda^4$) the observed exclusion limit is 2.0 TeV (also 2.0 TeV), with an expected limit of 2.6 TeV (2.4 TeV), providing an additional benchmark for comparison with other experiments. A weaker limit than the one derived from the χ analysis is expected due to the lower η acceptance associated with the R_C observable.

11. Conclusion

Dijet angular distributions have been measured by the ATLAS experiment over a large angular range and spanning dijet masses up to 2.8 TeV. These distributions are in good agreement with QCD predictions. Using 3.1 pb^{-1} of data, quark contact interactions with a scale Λ below 3.4 TeV are excluded at the 95% CL. The sensitivity of this analysis extends significantly beyond that of previously published studies.

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