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Search for New Phenomena in Dijet Angular Distributions in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV Measured with the ATLAS Detector

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A search for new phenomena in LHC proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV was performed with the ATLAS detector using an integrated luminosity of 17.3 fb^{-1} . The angular distributions are studied in events with at least two jets; the highest dijet mass observed is 5.5 TeV. All angular distributions are consistent with the predictions of the standard model. In a benchmark model of quark contact interactions, a compositeness scale below 8.1 TeV in a destructive interference scenario and 12.0 TeV in a constructive interference scenario is excluded at 95% C.L.; median expected limits are 8.9 TeV for the destructive interference scenario and 14.1 TeV for the constructive interference scenario.

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The search for an internal structure of fermions and new forces that might govern that structure is a major goal of modern particle physics. The most powerful probes are scattering experiments with large momentum transfer. Collisions of protons at the Large Hadron Collider (LHC) resulting in two energetic jets of particles (dijets) provide the largest momentum transfer currently available, and therefore the deepest probe.

The angular distribution of jets relative to the beam axis in events with high dijet invariant mass (m_{jj}) provides stringent tests of perturbative quantum chromodynamics (QCD) as well as theories of new phenomena. QCD calculations predict that dijet production, dominated by t -channel gluon exchange in the kinematic region of proton-proton (pp) collisions at the LHC, features steeply falling m_{jj} distributions and angular distributions peaked at $|\cos(\theta^*)| = 1$, where θ^* is the polar scattering angle in the two-parton center-of-mass frame. New phenomena, such as strong gravity [1,2] or new interactions [3–6] typically predict angular distributions which are more isotropic.

Previous studies of dijet angular distributions, at the CERN SPS [7,8], the FNAL Tevatron [9,10], the CERN LHC at $\sqrt{s} = 7$ TeV [11–16], and by the CMS Collaboration at $\sqrt{s} = 8$ TeV [17], have reported results consistent with the standard model (SM). This Letter reports on studies of dijet angular distributions in pp collisions at $\sqrt{s} = 8$ TeV in data with an integrated luminosity of 17.3 fb^{-1} collected with the ATLAS detector in 2012.

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A detailed description of the ATLAS detector is published elsewhere [18]. The detector is instrumented over almost the entire solid angle around the pp collision point, with layers of tracking detectors, calorimeters, and muon detectors.

The jets are measured using a calorimeter system composed of different detector types covering different regions in η [19] and depth. The electromagnetic calorimeter is composed of liquid-argon sampling calorimeters, using lead as an absorber, and is split into a barrel ($|\eta| < 1.475$) and two end caps ($1.375 < |\eta| < 3.2$). The hadronic calorimeter is divided into a barrel and two extended barrels ($|\eta| < 1.75$), and two endcaps ($1.5 < |\eta| < 3.2$). The barrel and extended barrels are sampling calorimeters with steel as absorber and scintillator tiles as the active medium, while the hadronic end caps are liquid-argon calorimeters with copper as the absorber. In the very forward regions ($3.1 < |\eta| < 4.9$) there are liquid argon calorimeters with copper and tungsten absorbers.

The data are selected using a trigger that requires a single high- p_T [19] jet above one of eight thresholds, ranging from 25 to 220 GeV. Because of the high rate of jets at lower p_T , only a fraction of the events from the lower seven thresholds are stored.

Individual jets are reconstructed using the anti- k_r jet clustering algorithm [20,21] with radius parameter $R = 0.6$. The inputs to this algorithm are clusters [22] of calorimeter cells with energy depositions significantly above the noise. Jet four-momenta are constructed by the vectorial addition of clusters of cells, treating each cluster as a four-momentum with zero mass. The jet four-momenta are then corrected to the jet energy scale [23] as a function of η and p_T for various effects, the largest of which are the hadronic shower response, detector material distribution, and pileup events [24]. This is done using a calibration scheme based on samples of simulated events and validated with test-beam [25] and collision data [22] studies.

The rapidity of a jet is defined as $y = \frac{1}{2} \ln[(E + p_z)/(E - p_z)]$, where E is the jet energy and p_z is the momentum component along the beam axis [19]. The scattering angle between two jets can be expressed using the variable $\chi = e^{|y_1 - y_2|} = e^{2|y^*|}$, where y_1 and y_2 are the rapidities of the two jets, and $y^* = \frac{1}{2}(y_1 - y_2)$. The rapidity boost of the dijet system with respect to the center of mass of the colliding protons is calculated as $y_B = \frac{1}{2}(y_1 + y_2)$.

For each trigger, the event is required to have a jet with p_T sufficient to achieve a trigger efficiency greater than 99.5%. For the lowest (highest) threshold trigger, this corresponds to $p_T > p_T^{\min} = 47(333)$ GeV. Events are required to have at least two jets, each with $p_T > 50$ GeV; the dijet system, defined as the two jets with largest p_T , is required to have $|y^*| < 1.7$, $|y_B| < 1.1$, and $m_{jj} > 600$ GeV (where the m_{jj} requirement avoids the kinematic bias in the angular distributions introduced by the minimum p_T requirement).

The detector covers the angular range $|y^*| < 1.7$, corresponding to $\chi < 30$. This interval is divided into 11 bins, with boundaries at $\chi_n = e^{(0.3 \times n)}$ for $n = 0$ to 10, approximating the segmentation of the calorimeter in $\Delta\eta$. The data are further binned coarsely in m_{jj} with the expectation that low- m_{jj} bins are dominated by QCD processes and that signals associated with new physics would be found in higher dijet invariant mass bins. The bin edges are chosen to optimize the expected sensitivity to the model of contact interactions. The highest dijet mass observed is 5.5 TeV.

The SM predictions are estimated using the PYTHIA8 [26] v8.160 event generator with the AU2 [27] underlying-event tune and the CT10 [28] parton distribution functions (PDF). The simulated events are propagated through a detector simulation [29] that uses the GEANT4 [30] simulation package. Pileup conditions vary as a function of the instantaneous luminosity and are taken into account by overlaying simulated minimum-bias events generated with PYTHIA8 onto the hard-scattering process such that the observed distribution of the average number of interactions per bunch crossing is reproduced. The same reconstruction and event selection are applied to the simulated events and the data.

The PYTHIA8 calculations are primarily to leading order (LO) in QCD with simulation of higher-order contributions included in the shower modeling. Events generated by PYTHIA8 are reweighted using a correction factor calculated based on the ratio of the next-to-leading-order (NLO) cross-section calculation from NLOJET++ [31–33] v4.1.2 to the LO+shower calculation from PYTHIA8:

$$K(\chi, m_{jj}) = \frac{\sigma_{\text{NLO}}(\chi, m_{jj})^{\text{NLOJET++}}}{\sigma_{\text{LO+shower}}(\chi, m_{jj})^{\text{Pythia8}}}.$$

The K factors decrease with χ and thus modify the shape of the angular distributions; the impact ranges from a few percent at low m_{jj} to approximately 15% for the highest

m_{jj} region. Additional processes accounting for electro-weak (EW) effects not included in PYTHIA8 (virtual weak boson exchange and Sudakov-type logarithms) are included as EW corrections [34]. The effect is most pronounced at high m_{jj} and low χ , and the correction factors range from unity at low m_{jj} to 0.98–1.12 in the highest m_{jj} region. The EW corrections and the NLO K factors are applied as a function of χ and m_{jj} to the PYTHIA8 prediction.

Figure 1 shows the distributions of the data as a function of χ . The distribution in each m_{jj} region is normalized to unity, as the sensitivity to new phenomena is due to the angular distribution rather than normalization. The predicted SM distributions are also shown in Fig. 1 and describe the data well. The EW corrections substantially improve the agreement of the SM prediction with data at high m_{jj} , as can be appreciated from the comparison of the

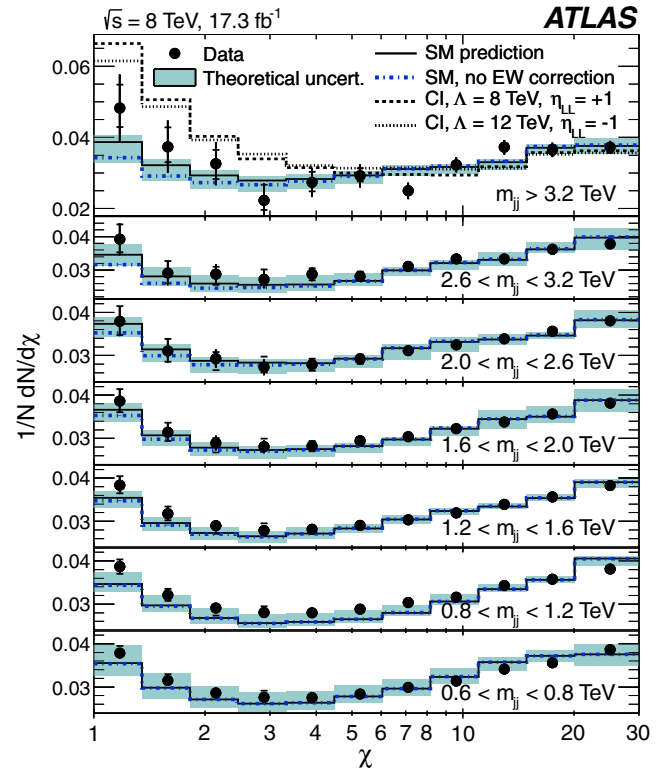


FIG. 1 (color online). Distributions of the dijet angular variable χ for several regions of dijet invariant mass m_{jj} . Shown are the data (dots), SM predictions (solid lines) with uncertainties, and predictions for a benchmark theory of new contact interactions with a left-chiral color-singlet coupling with constructive (dotted, $\eta_{LL} = +1$ and $\Lambda = 12$ TeV) or destructive (dashed, $\eta_{LL} = -1$ and $\Lambda = 8$ TeV) interference with the SM processes. Also shown is the impact of the electroweak (EW) corrections described in the text. The error bars on data represent the experimental and statistical uncertainties added in quadrature, with a tick representing experimental uncertainties only. The theoretical uncertainties are displayed as a shaded band around the SM prediction.

predictions with and without these corrections shown in Fig. 1.

Models of quark compositeness are probed by searching for evidence of new interactions between quarks at a large characteristic energy scale, Λ . At energies below this scale, the details of the new interaction and potential mediating particles can be integrated out to form a four-fermion contact interaction model [5,6] described by an effective field theory:

$$L_{qq} = \frac{2\pi}{\Lambda^2} [\eta_{LL}(\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma^\mu q_L) + \eta_{RR}(\bar{q}_R \gamma_\mu q_R)(\bar{q}_R \gamma^\mu q_R) + 2\eta_{RL}(\bar{q}_R \gamma_\mu q_R)(\bar{q}_L \gamma^\mu q_L)], \quad (1)$$

where the quark fields have L and R chiral projections and the coefficients η_{LL} , η_{RR} , and η_{RL} turn on and off various interactions.

In this Letter, a contact interaction (CI) model with a left-chiral color-singlet coupling ($\eta_{LL} = \pm 1$) is used as a benchmark model, as many other models of new phenomena have similar predictions for the dijet scattering angle χ at large m_{jj} . Interference of the signal model with the SM process $q\bar{q} \rightarrow q\bar{q}$ is also included.

Event samples were simulated with both QCD and contact interactions, taking interference into account and using the same event generator, underlying-event tune, and PDF as for the SM simulations. Events were generated for both constructive and destructive interference with $\Lambda = 7$ TeV and $\Lambda = 10$ TeV. The $\Lambda = 7$ TeV sample is then used for extrapolation to other values of Λ , using the fact that the interference term is proportional to $1/\Lambda^2$ and the pure CI cross section is proportional to $1/\Lambda^4$. This procedure is validated with the $\Lambda = 10$ TeV sample. As with the QCD prediction, a K -factor correction is computed to correct the PYTHIA LO + shower prediction to a NLO calculation. Calculations at NLO are provided by CIJET [35] v1.0.

Uncertainties in the SM and signal predictions include theoretical uncertainties and experimental uncertainties on the measured angular distributions. Theoretical uncertainties in the SM and signal predictions are due to the choice of PDF, renormalization and factorization scales, choice of event generator, as well as statistical uncertainties due to limited simulation sample sizes. The impact of the uncertainty in the PDF is estimated using NLOJET++ with three different PDFs: CT10, MSTW2008 [36], and NNPDF23 [37]. These uncertainties are negligible ($< 1\%$), as the choice of PDF largely impacts the total cross section rather than the angular distributions. The uncertainty due to the choice of renormalization and factorization scales were estimated by varying those independently up and down by a factor two in NLOJET++. The resulting uncertainty varies with m_{jj} and χ , rising to 4% at the smallest χ values at high m_{jj} . The uncertainty due to the choice of generator is

estimated by comparing the predictions from the NLO generator POWHEG [38] v1.0 with those of PYTHIA8 with K factors applied. The largest uncertainty due to choice of generator is at the lowest m_{jj} values, where it approaches 20%, while for the highest m_{jj} values and smallest χ , it ranges from 10% to 14%. The uncertainty due to the choice of the showering model is estimated through comparison of POWHEG samples showered and hadronized with PYTHIA8 v8.175 to HERWIG [39] v6.520.2 samples using JIMMY [40,41] v4.31. The largest value of this uncertainty is less than 1% at the highest m_{jj} values and smallest values of χ . Finally the statistical uncertainties on the K factors due to limited simulation sample size are small and set to 1%.

The experimental uncertainty is dominated by the η dependence of the jet energy scale calibration. This uncertainty varies from approximately 15% at small values of χ for the highest m_{jj} values, to a few percent at lower m_{jj} values and higher χ values. The uncertainty in the beam energy is found to introduce a negligible contribution. The total uncertainty at the lowest χ , highest m_{jj} amounts to 20%, decreasing to a few percent at high χ . The total theoretical and experimental uncertainties are shown in Fig. 1.

The p value for the SM hypothesis is (0.25) 0.30 for the (second) highest m_{jj} bin. In the absence of significant deviations from the SM prediction, upper bounds on CI contributions are calculated using a one-sided profile likelihood ratio and the CL_s technique [42,43], evaluated using the asymptotic approximation [44] on events with $m_{jj} > 3.2$ TeV; the validity of asymptotic approximation was confirmed using toy simulations. These bounds exclude a compositeness scale below 8.1 TeV in a destructive interference scenario and below 12.0 TeV in a constructive interference scenario. The median expected limits are 8.9 (14.1) TeV for the destructive (constructive) interference scenario.

In summary, dijet angular distributions have been measured by the ATLAS experiment in 17.3 fb^{-1} of 8 TeV pp collisions at the LHC. Over a wide angular range and dijet invariant mass spectrum, the data are well described by QCD predictions at NLO. A model of quark compositeness is used as a benchmark for theories of new phenomena that include new forces and mediating particles; such theories predict deviations at small values of χ . A compositeness scale below 8.1 (12.0) TeV in a destructive (constructive) interference scenario is excluded at 95% confidence level, similar to results from the CMS Collaboration [17] and representing a significant enhancement in sensitivity relative to the previous limit (at 7.6 TeV for destructive interference) from the ATLAS Collaboration [11].

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