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Measurement of Dijet Azimuthal Decorrelations in pp Collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

Azimuthal decorrelations between the two central jets with the largest transverse momenta are sensitive to the dynamics of events with multiple jets. We present a measurement of the normalized differential cross section based on the full dataset ($\int\mathcal{L}\,dt = 36\,\mathrm{pb}^{-1}$) acquired by the ATLAS detector during the 2010 $\sqrt{s} = 7$ TeV proton-proton run of the LHC. The measured distributions include jets with transverse momenta up to 1.3 TeV, probing perturbative QCD in a high energy regime.

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The production of events containing high transverse-momentum (p_{T}) jets is a key signature of quantum chromodynamic (QCD) interactions between partons in pp collisions at large center-of-mass energies ($\sqrt{s}$). The Large Hadron Collider (LHC) opens a window into the dynamics of interactions with high-p_{T} jets in a new energy regime of $\sqrt{s} = 7$ TeV. QCD predicts the decorrelation in the azimuthal angle between the two most energetic jets, $\Delta\phi$, as a function of the number of partons produced. Events with only two high-p_{T} jets have small azimuthal decorrelations, $\Delta\phi \sim \pi$, while $\Delta\phi \ll \pi$ is evidence of events with several high-p_{T} jets. QCD also describes the evolution of the shape of the $\Delta\phi$ distribution, which narrows with increasing leading jet p_{T}. Distributions in $\Delta\phi$ therefore test perturbative QCD (pQCD) calculations for multiple jet production without requiring the measurement of additional jets. Furthermore, a detailed understanding of events with large azimuthal decorrelations is important to searches for new physical phenomena with dijet signatures, such as supersymmetric extensions to the Standard Model [1].

In this Letter, we present a measurement of dijet azimuthal decorrelations with jet p_{T} up to 1.3 TeV as measured by the ATLAS detector, beyond the reach of previous colliders. The normalized differential cross section $(1/\sigma)(d\sigma/d\Delta\phi)$ is based upon an integrated luminosity $\int\mathcal{L}\,dt = (36 \pm 4)\ \mathrm{pb}^{-1}$ [2]. The $\Delta\phi$ distribution is normalized by the inclusive dijet cross section, σ, integrated over the same phase space. This construction minimizes experimental and theoretical uncertainties. Previous measurements of $\Delta\phi$ from the D0 [3] and CMS [4] collaborations are extended here to higher jet p_{T} values.

Jets are reconstructed using the anti-k_{t} algorithm [5] (implemented with FASTJET [6]) with radius $R = 0.6$, and the jet four-momenta are constructed from a sum over its constituents, treating each as an $(E, \vec{p})$ four-vector with zero mass. The anti-k_{t} algorithm is well-motivated since it is infrared-safe to all orders, produces geometrically well-defined cone-like jets, and is used for pQCD calculations (from partons), event generators (from stable particles), and the detector (from energy clusters [7]). The azimuthal decorrelation, $\Delta\phi$, is defined as the absolute value of the difference in azimuthal angle between the jet with the highest p_{T} in each event, $p_{\mathrm{T}}^{\max}$, and the jet with the second-highest p_{T} in the event. There are nine analysis regions in $p_{\mathrm{T}}^{\max}$, where the lowest region is bounded by $p_{\mathrm{T}}^{\max} > 110$ GeV and the highest region requires $p_{\mathrm{T}}^{\max} > 800$ GeV [7]. Only jets with $p_{\mathrm{T}} > 100$ GeV and $|y| < 2.8$, where y is the jet rapidity [8], are considered. The two leading jets that define $\Delta\phi$ are required to satisfy $|y| < 0.8$, restricting the measurement to a central y region where the momentum fractions (x) of the interacting partons are roughly equal and the experimental acceptance for multijet production is increased. In this region where $0.02 \lesssim x \lesssim 0.14$, the parton distribution function (PDF) uncertainties are typically $\pm3\%$ (at fixed factorization scale) [9]. The cross sections, measured over the range $\pi/2 \le \Delta\phi \le \pi$ and normalized independently for each analysis region, are compared with expectations from a pQCD calculation [10] that is next-to-leading order (NLO) in three-parton production. The perturbative prediction for the cross section is $\mathcal{O}(\alpha_s^4)$, where α_s is the strong coupling constant.

The angular decorrelation is sensitive to multijet configurations such as those produced by event generators like SHERPA [11], which matches higher-order tree-level pQCD diagrams with a dipole parton-shower model [12]. Samples for $2 \to 2-6$ jet production are combined using an improved CKKW matching scheme [13]. The progression of the parton shower is vetoed to avoid double counting of emissions. Event generators such as PYTHIA [14] and HERWIG [15] use $2 \to 2$ leading order pQCD matrix elements matched with phenomenological parton-cascade models to simulate higher-order QCD effects. Such models have been successful at reproducing other QCD processes measured by the ATLAS collaboration [7, 16].

The ATLAS detector [17, 18] consists of an inner tracking system surrounded by a thin superconducting solenoid providing a 2T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer based on large superconducting toroids. Jet measurements depend most heavily on the calorimeters. The electromagnetic calorimeter is a lead liquid-argon (LAr) detector with an accordion geometry. Hadron calorimetry is based on two different detector technologies, with scintillator tiles or LAr as the active medium, and with either steel, copper, or tungsten as the absorber material. The pseudorapidity (η) [8] and ϕ segmentations of

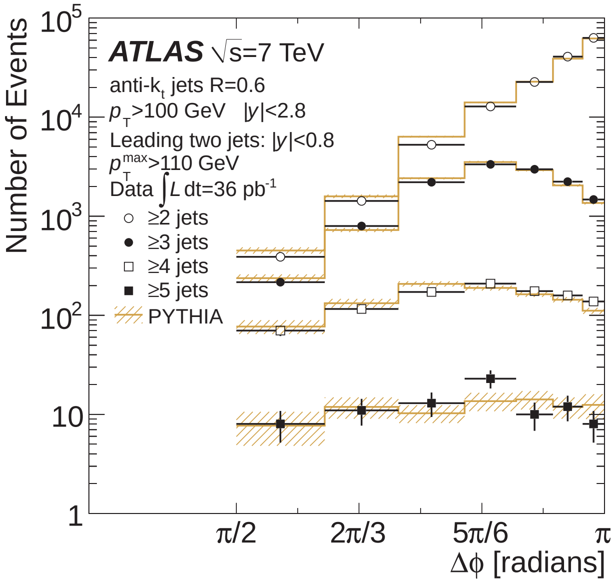

FIG. 1. The $\Delta\phi$ distribution for ≥ 2, ≥ 3, ≥ 4, and ≥ 5 jets with $p_{\mathrm{T}} > 100$ GeV. Overlaid on the calibrated but otherwise uncorrected data (points) are results from PYTHIA processed through the detector simulation (lines). All uncertainties are statistical only.

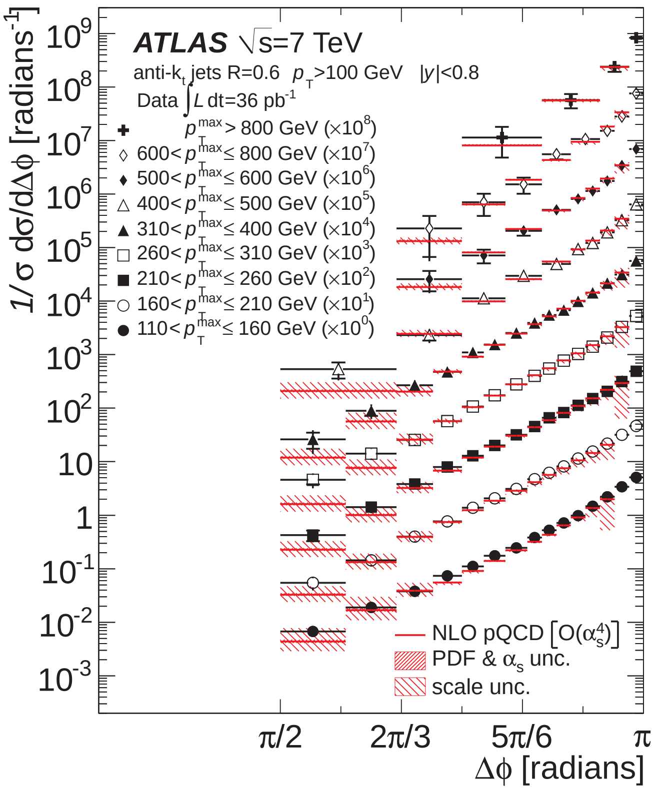

FIG. 2. The differential cross section $(1/\sigma)(d\sigma/d\Delta\phi)$ binned in nine $p_{\mathrm{T}}^{\max}$ regions. Overlaid on the data (points) are results from the NLO pQCD calculation. The error bars on the data points indicate the statistical (inner error bar) and systematic uncertainties added in quadrature in this and subsequent figures. The theory uncertainties are indicated by the hatched regions. Different bins in $p_{\mathrm{T}}^{\max}$ are scaled by multiplicative factors of ten for display purposes. The region near the divergence at $\Delta\phi \to \pi$ is excluded from the calculation.

the calorimeters are sufficiently fine to ensure that angular resolution uncertainties are negligible compared to other sources of systematic uncertainty.

A hardware-based calorimeter jet trigger identified events of interest; the decision was further refined in software [17, 18]. Events with at least one jet that satisfied a minimum transverse energy (E_{T}) requirement were recorded for further analysis. The events in each $p_{\mathrm{T}}^{\max}$ range are selected by a single trigger with a given E_{T} threshold, and the lower end of the range is chosen above the jet p_{T} at which that trigger is $\approx 100\%$ efficient. Three sets of triggered events with different integrated luminosity are considered: $2.3\,\mathrm{pb}^{-1}$ for $110 < p_{\mathrm{T}}^{\max} \leq 160$ GeV, $9.6\,\mathrm{pb}^{-1}$ for $160 < p_{\mathrm{T}}^{\max} \leq 260$ GeV, and $36\,\mathrm{pb}^{-1}$ for $p_{\mathrm{T}}^{\max} > 260$ GeV [2]. Events are also required to have a reconstructed primary vertex within 15 cm in z of the center of the detector; each vertex had ≥ 5 associated tracks. The inputs to the anti-k_{t} jet algorithm are clusters of calorimeter cells seeded by cells with energy that is significantly above the measured noise [7]. Jets reconstructed in the detector, whether in data or the GEANT4-based simulation [19, 20], are corrected for the effects of hadronic shower response and detector-material distributions using a p_{T}- and η-dependent calibration [7] based on the detector simulation and validated with extensive test-beam [17] and collision data [21] studies. Jets likely to have arisen from detector noise or cosmic rays are rejected [22].

The resulting $\Delta\phi$ distribution is shown in Fig. 1 for jets with $p_{\mathrm{T}} > 100$ GeV. There are 146788 events in the data sample, 85 of which have at least five jets with $p_{\mathrm{T}} > 100$ GeV. Also shown is the PYTHIA sample with MRST 2007 LO* PDF [23] and ATLAS MC09 underlying event tune [24], processed through the full detector simulation and normalized to the number of events in the data sample. Two- and three-jet production primarily populates the region $2\pi/3 < \Delta\phi < \pi$ while smaller values of $\Delta\phi$ require additional activity such as soft radiation or more jets in an event. Fig. 1 illustrates that the decorrelation increases when a third high-p_{T} jet is also required. Events with additional high-p_{T} jets widen the overall distribution.

The measured differential $\Delta\phi$ distributions in data are corrected in a single step with a bin-by-bin unfolding method [7] to compensate for trigger and detector inefficiencies and the effects of finite experimental resolutions. These correction factors, evaluated using the PYTHIA sample, lie within $\pm 9\%$ of unity. The leading sources of systematic uncertainty on the normalized cross sec-

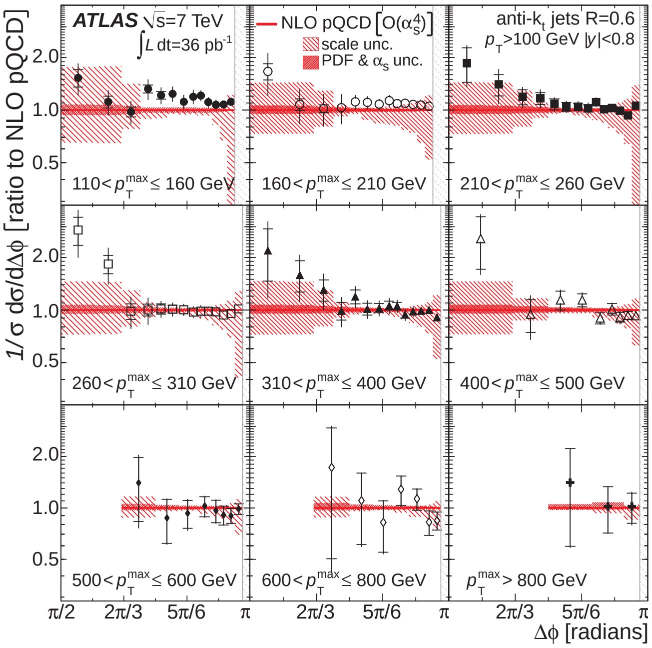

FIG. 3. Ratio of the differential cross section $(1/\sigma)(d\sigma/d\Delta\phi)$ measured in data with respect to expectations from NLO pQCD (points). The theory uncertainties are indicated by the hatched regions. The region near the divergence at $\Delta\phi \to \pi$ is excluded from the comparison.

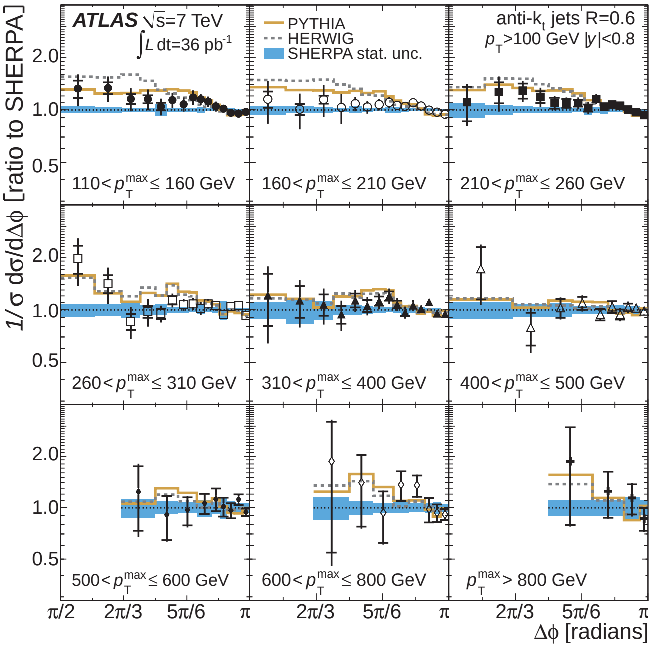

FIG. 4. Ratio of the differential cross section $(1/\sigma)(d\sigma/d\Delta\phi)$ measured in data with respect to the result from SHERPA (points). The shaded region indicates the SHERPA statistical uncertainty. Predictions from PYTHIA and HERWIG, also in ratio to SHERPA, are displayed as lines.

tion are the jet energy scale calibration $(2-17\%)$ [7], the bin-by-bin unfolding method $(1-19\%)$, and the jet energy and position resolutions $(0.5-5\%)$. The ranges in parentheses represent the magnitude of the uncertainties near π and $\pi/2$, respectively, and correspond to the analysis region with the smallest statistical uncertainty ($160 < p_T^{\max} \leq 210$ GeV). Uncertainties due to multiple pp interactions in the same beam crossing ($< 0.8\%$ on the cross section for all analysis regions) are included in the evaluation of the jet energy scale uncertainties.

The normalized differential cross section is shown for each of the nine $p_T^{\max}$ analysis regions as a function of $\Delta\phi$ in Fig. 2. As $p_T^{\max}$ increases, and the probability for the emission of a hard third jet is reduced, the fraction of events near π becomes larger. Overlaid on the data are the results from a NLO pQCD [$\mathcal{O}(\alpha_s^4)$] calculation, NLOJET++ [10] with fastNLO [25] and using the MSTW 2008 PDF [9]. The factorization and renormalization scales are set to $p_T^{\max}$ and are varied independently up and down by a factor of two to determine the scale uncertainties. The scale uncertainties are larger between $\pi/2 < \Delta\phi < 2\pi/3$ where the pQCD calculation is effectively leading order in four-parton production. The PDF uncertainties are treated as the envelope of the 68% CL uncertainties from MSTW 2008 [9], NNPDF 2.0 [26], and CTEQ 10 [27], and are combined with the uncertainties resulting from an α_s variation of ± 0.004; the α_s contributions dominate. The calculation is corrected for non-perturbative effects due to hadronization and the underlying event [28, 29]; the correction is smaller than 3%. The fixed-order calculation fails near $\Delta\phi \to \pi$ where soft processes dominate and contributions from logarithmic terms are enhanced. Figure 3 displays the ratio of the cross section with respect to the NLO calculation. In most regions, the theory is consistent with the data. However, the prediction in the range $110 < p_T^{\max} < 160$ GeV is relatively low in the central region of $\Delta\phi$ where the scale uncertainties are small.

The data are also compared with predictions from SHERPA, PYTHIA, and HERWIG in Fig. 4. The leading-logarithmic approximations used in these event generators' parton-shower models effectively regularize the divergence at $\Delta\phi \to \pi$; all three provide a good description of the data in this region. In the region $\pi/2 < \Delta\phi < 5\pi/6$, where multijet contributions are significant, this observable distinguishes between the three generators. SHERPA, which explicitly includes higher-order tree-level diagrams, performs well in most $\Delta\phi$ and $p_T^{\max}$ regions. Having phenomenological parameters that have been adjusted to previous ATLAS measurements, PYTHIA [28] and HERWIG [24] also describe the data.

In summary, we present a measurement of dijet azimuthal decorrelations in events produced in pp collisions at $\sqrt{s} = 7$ TeV. The normalized differential cross sections are based on the full dataset ($\int\mathcal{L}\,dt = 36\,\mathrm{pb}^{-1}$) collected by the ATLAS collaboration during the 2010 run of the LHC. Expectations from NLO pQCD [$\mathcal{O}(\alpha_s^4)$] and those of several event generators successfully describe the general characteristics of our measurements, including the increasing slope of the $\Delta\phi$ distribution with $p_{\mathrm{T}}^{\mathrm{max}}$ and the shape near $\Delta\phi \sim \pi/2$ where events with multiple jets make a considerable contribution. Our data, which include jets with p_{T} values that significantly exceed earlier measurements, explore QCD in a new kinematic region.

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