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 ($\int dt = 36 \text{pb}^{-1}$) 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.

PACS numbers: 13.87.Ce, 12.38.Qk

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 $p_T$. Decorrelations 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.

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 $\int dt = (36 \pm 4) \text{pb}^{-1}$. The $\Delta \phi$ distribution is normalized by the inclusive dijet cross section, $\sigma$, integrated over the same phase space. This construction minimizes experimental and theoretical uncertainties. Previous measurements of $\Delta \phi$ from the D0 and CMS collaborations are extended here to higher jet $p_T$ values.

Jets are reconstructed using the anti-$k_t$ algorithm (implemented with FASTJET) 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). 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, $p_T^{\text{max}}$, and the jet with the second-highest $p_T$ in the event. There are nine analysis regions in $p_T^{\text{max}}$, where the lowest region is bounded by $p_T^{\text{max}} > 110$ GeV and the highest region requires $p_T^{\text{max}} > 800$ GeV. Only jets with $p_T > 100$ GeV and $|y| < 2.8$, where $y$ is the jet rapidity, 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 $\pm 3\%$ (at fixed factorization scale). The cross sections, measured over the range $\pi/2 \leq \Delta \phi \leq \pi$ and normalized independently for each analysis region, are compared with expectations from a pQCD calculation 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 $\alpha_s$ is the strong coupling constant.

The angular decorrelation is sensitive to multijet configurations such as those produced by event generators like SHERPA, which matches higher-order tree-level pQCD diagrams with a dipole parton-shower model. Samples for $2 \to 2 - 6$ jet production are combined using an improved CKKW matching scheme. The progression of the parton shower is vetoed to avoid double counting of emissions. Event generators such as PYTHIA and HERWIG 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.

The ATLAS detector 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 ($\eta$) and $\phi$ segmentations of
sets of triggered events with different integrated luminos-
ities are selected by a single trigger with a given
energy 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 luminos-
ity are considered: 2.3 pb$^{-1}$ for $110 < p_T^{\text{max}} \leq 160$ GeV,
9.6 pb$^{-1}$ for $160 < p_T^{\text{max}} \leq 260$ GeV, and 36 pb$^{-1}$ for
$p_T^{\text{max}} > 260$ GeV. Events are also required to have
a reconstructed primary vertex within 15 cm in $z$ of
the center of the detector; each vertex had $> 5$ asso-
ciated tracks. The inputs to the anti-$k_t$ jet algorithm
are clusters of calorimeter cells seeded by cells with en-
ergy that is significantly above the measured noise [3].
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 $\eta$-dependent calibration [7]
based on the detector simulation and validated with ex-
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 $p_T > 100$ GeV. There are 146788 events in
the data sample, 85 of which have at least five jets with
$p_T > 100$ GeV. Also shown is the PYTHIA sample with
MRST 2007 LO PDF [23] and ATLAS MC09 underly-
ing event tune [24], processed through the full detector
simulation and normalized to the number of events in
the sample, lie within $\pm 9\%$ of unity. The leading sources
of systematic uncertainty on the normalized cross sec-

FIG. 1. The $\Delta \phi$ distribution for $\geq 2$, $\geq 3$, $\geq 4$, and $\geq 5$ jets
with $p_T > 100$ 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 $p_T^{\text{max}}$ regions. Overlaid on the data (points) are re-
sults 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 sub-
sequent figures. The theory uncertainties are indicated by the
hatched regions. Different bins in $p_T^{\text{max}}$ are scaled by multi-

licative factors of ten for display purposes. The region near
the divergence at $\Delta \phi \to \pi$ is excluded from the calculation.

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-

the calorimeters are sufficiently fine to ensure that an-
gular 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 satis-
fied a minimum transverse energy ($E_T$) requirement
were recorded for further analysis. The events in each $p_T^{\text{max}}$
range are selected by a single trigger with a given $E_T$
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simulation and normalized to the number of events in
the sample, lie within $\pm 9\%$ of unity. The leading sources
of systematic uncertainty on the normalized cross sec-
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 \(\pi\) and \(\pi/2\), respectively, and correspond to the
analysis region with the smallest statistical uncertainty (160 < \(p_T^{\text{max}}\) ≤ 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 \(p_T^{\text{max}}\) analysis regions as a function of \(\Delta \phi\) in Fig. 2. As \(p_T^{\text{max}}\) increases, and the probability for the emission of a hard third jet is reduced, the fraction of events near \(\pi\) becomes larger. Overlaid on the data are the results from a NLO pQCD \([\mathcal{O}(\alpha_s^3)]\) calculation, NLOJET++ \([10]\) with fastNLO \([25]\) and using the MSTW 2008 PDF \([8]\).

The factorization and renormalization scales are set to \(p_T^{\text{max}}\) 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 \([8]\), NNPDF 2.0 \([26]\), and CTEQ 10 \([27]\), and are combined with the uncertainties resulting from an \(\alpha_s\) variation of ±0.004; the \(\alpha_s\) 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 \(\Delta \phi \rightarrow \pi\) 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 < \(p_T^{\text{max}}\) < 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 \(\Delta \phi \rightarrow \pi\); 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 \(p_T^{\text{max}}\) 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 ($\mathcal{L} dt = 36 \text{ pb}^{-1}$) collected by the ATLAS collaboration during the 2010 run of the LHC. Expectations from NLO pQCD \([O(\alpha_s^3)]\) and those of several event generators successfully describe the general characteristics of our measurements, including the increasing slope of the $\Delta \phi$ distribution with $p_T^{\text{max}}$ 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.

We wish to thank CERN for the efficient commissioning and operation of the LHC during this initial high-energy data-taking period as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; CMS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

[8] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Rapidity is defined as $y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z}\right)$, where $E$ is the energy and $p_z$ is the longitudinal component of the momentum along the beam direction.

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