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DOI
10.1103/PhysRevLett.105.252303

Publication date
2010

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):

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Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

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(Received 25 November 2010; published 13 December 2010)

By using the ATLAS detector, observations have been made of a centrality-dependent dijet asymmetry in the collisions of lead ions at the Large Hadron Collider. In a sample of lead-lead events with a per-nucleon center of mass energy of 2.76 TeV, selected with a minimum bias trigger, jets are reconstructed in fine-grained, longitudinally segmented electromagnetic and hadronic calorimeters. The transverse energies of dijets in opposite hemispheres are observed to become systematically more unbalanced with increasing event centrality leading to a large number of events which contain highly asymmetric dijets. This is the first observation of an enhancement of events with such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

DOI: 10.1103/PhysRevLett.105.252303

PACS numbers: 25.75.Bh

Collisions of heavy ions at ultrarelativistic energies are expected to produce an evanescent hot, dense state, with temperatures exceeding $2 \times 10^{12}$ K, in which the relevant degrees of freedom are not hadrons but quarks and gluons. In this medium, high-energy quarks and gluons are expected to transfer energy to the medium by multiple interactions with the ambient plasma. There is a rich theoretical literature on in-medium QCD energy loss extending back to Bjorken, who proposed to look for “jet quenching” in proton-proton collisions [1]. This work also suggested the observation of highly unbalanced dijets when one jet is produced at the periphery of the collision. For comprehensive reviews of recent theoretical work in this area, see Refs. [2,3].

Single particle measurements made by Relativistic Heavy Ion Collider experiments established that high transverse momentum ($p_T$) hadrons are produced at rates a factor of 5 or more lower than expected by assuming QCD factorization holds in every binary collision of nucleons in the oncoming nuclei [4,5]. This observation is characterized by measurements of $R_{AA}$, the ratio of yields in heavy ion collisions to proton-proton collisions, divided by the number of binary collisions. Dihadron measurements also showed a clear absence of back-to-back hadron production in more central heavy ion collisions [5], strongly suggestive of jet suppression. The limited rapidity coverage of the experiment, and jet energies comparable to the underlying event energy, prevented a stronger conclusion being drawn from these data.

The LHC heavy ion program was foreseen to provide an opportunity to study jet quenching at much higher jet energies than achieved at the Relativistic Heavy Ion Collider. This Letter provides the first measurements of jet production in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV per nucleon-nucleon collision, the highest center of mass energy ever achieved for nuclear collisions. At this energy, next-to-leading-order QCD calculations [6] predict abundant rates of jets above 100 GeV produced in the pseudorapidity region $|\eta| < 4.5$ [7], which can be reconstructed by ATLAS.

The data in this Letter were obtained by ATLAS during the 2010 lead-lead run at the LHC and correspond to an integrated luminosity of approximately $1.7 \mu b^{-1}$.

For this study, the focus is on the balance between the highest transverse energy pair of jets in events where those jets have an azimuthal angle separation $\Delta \phi = |\phi_1 - \phi_2| > \pi/2$ to reduce contributions from multijet final states. In this Letter, jets with $\Delta \phi > \pi/2$ are labeled as being in opposite hemispheres. The jet energy imbalance is expressed in terms of the asymmetry $A_J$:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta \phi > \frac{\pi}{2},$$

where the first jet is required to have a transverse energy $E_{T1} > 100$ GeV, and the second jet is the highest transverse energy jet in the opposite hemisphere with $E_{T2} > 25$ GeV. The average contribution of the underlying event energy is subtracted when deriving the individual jet transverse energies. The event selection is chosen such that the first jet has high reconstruction efficiency and the second jet is above the distribution of background fluctuations and the intrinsic soft jets associated with the collision. Dijet events are expected to have $A_J$ near zero, with deviations expected from gluon radiation falling outside the jet cone.

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as well as from instrumental effects. Energy loss in the medium could lead to much stronger deviations in the reconstructed energy balance.

The ATLAS detector [8] is well-suited for measuring jets due to its large acceptance, highly segmented electromagnetic and hadronic calorimeters. These allow efficient reconstruction of jets over a wide range in the region $|\eta| < 4.5$. The detector also provides precise charged particle and muon tracking. An event display showing the inner detector and calorimeter systems is shown in Fig. 1.

Liquid argon technology providing excellent energy and position resolution is used in the electromagnetic calorimeter that covers 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 ($1.5 < |\eta| < 3.2$), liquid argon technology is also used for the hadronic calorimeters, matching the outer $|\eta|$ limits of the electromagnetic calorimeters. To complete the $\eta$ coverage, the liquid argon forward calorimeters provide both electromagnetic and hadronic energy measurements, extending the coverage up to $|\eta| = 4.9$. The calorimeter ($\eta$ and $\phi$) granularities are $0.1 \times 0.1$ for the hadronic calorimeters up to $|\eta| = 2.5$ (except for the third layer of the tile calorimeter, which has a segmentation of $0.2 \times 0.1$ up to $|\eta| = 1.7$) and then $0.2 \times 0.2$ up to $|\eta| = 4.9$. The electromagnetic calorimeters are longitudinally segmented into three compartments and feature a much finer readout granularity varying by layer, with cells as small as $0.025 \times 0.025$ extending to $|\eta| = 2.5$ in the middle layer. In the data-taking period considered, approximately 187,000 calorimeter cells (98% of the total) were usable for event reconstruction.

The bulk of the data reported here were triggered by using coincidence signals from two sets of minimum bias trigger scintillator detectors, positioned at $z = \pm 3.56$ m, covering the full azimuth between $2.09 < |\eta| < 3.84$ and divided into eight $\phi$ sectors and two $\eta$ sectors. Coincidences in the zero degree calorimeter and luminosity measurement using a Cherenkov integrating detector were also used as primary triggers, since these detectors were far less susceptible to LHC beam backgrounds. These triggers have a large overlap and are close to fully efficient for the events studied here.

In the offline analysis, events are required to have a time difference between the two sets of minimum bias trigger scintillator counters of $\Delta t < 3$ ns and a reconstructed vertex to efficiently reject beam-halo backgrounds. The primary vertex is derived from the reconstructed tracks in the inner detector, which covers $|\eta| < 2.5$ by using silicon pixel and strip detectors surrounded by straw tubes. These event selection criteria have been estimated to accept over 98% of the total lead-lead inelastic cross section.

The level of event activity or “centrality” is characterized by using the total transverse energy ($\Sigma E_T$) deposited in the forward calorimeters (FCal), which cover $3.2 < |\eta| < 4.9$, shown in Fig. 2. Bins are defined in centrality according to fractions of the total lead-lead cross section selected by the trigger and are expressed in terms of percentiles (0%–10%, 10%–20%, 20%–40%, and 40%–100%) with 0% representing the upper end of the $\Sigma E_T$ distribution. Previous heavy ion experiments have shown a clear correlation of the $\Sigma E_T$ with the geometry of the overlap region of the colliding nuclei and, correspondingly, the total event multiplicity. This is verified in the bottom panel of Fig. 2, which shows a tight correlation between the energy flow near midrapidity and the forward $\Sigma E_T$. The forward $\Sigma E_T$ is used for this analysis to avoid biasing the centrality measurement with jets.

Jets have been reconstructed by using the infrared-safe anti-$k_t$ jet clustering algorithm [9] with the radius param-
for the cell area. The final reported four-momentum for each jet is then recalculated from the remaining energy in the cells.

The efficiency of the jet reconstruction algorithm and other event properties have been studied by using PYTHIA [10] events superimposed on HIJING events [11]. There is no parton-level interference between the PYTHIA and HIJING generated events. A GEANT4 [12] simulation models the detector response [13] to all the final state particles from the two generated events. The HIJING parameters used do not include jet quenching, but variations in flow as a function of centrality are added. It is found that jets with \( E_T > 100 \text{ GeV} \) are reconstructed with nearly 100% efficiency at all centralities.

Simulations have been used to check the overall linearity and resolution of the reconstruction with respect to the primary jet energy, assuming jet shapes similar to those found in proton-proton collisions [14]. However, the efficiency, linearity, and resolution for reconstructing jets may be poorer if the jets are substantially modified by the medium. To check the sensitivity to such effects, the jet shape, characterized here as the ratio of the “core” energy (integrated over \( \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.2 \)) to the total energy, has been studied. This ratio shows only a weak dependence on centrality, providing evidence that the high-energy jets do look approximately like jets measured in proton-proton collisions and that the energy subtraction procedure does not introduce significant biases.

After event selection, the requirement of a leading jet with \( E_T > 100 \text{ GeV} \) and \( |\eta| < 2.8 \) yields a sample of 1693 events. These are called the “jet-selected events.” The lead-lead data are also compared with a sample of 17 nb\(^{-1}\) of proton-proton collision data [14], which yields 6732 events.

A striking feature of this sample is the appearance of events with only one high \( E_T \) jet clearly visible in the calorimeter and no high \( E_T \) jet opposite to it in azimuth. Such an event is shown in Fig. 1. The calorimeter \( E_T \) and charged particle \( \Sigma p_T \) are shown in regions of \( \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.1 \), and the ratio of the maximum tower energy over the mean tower energy, greater than 5. The value \( D_{\text{cut}} = 5 \) is chosen based upon simulation studies, and the results have been tested to be stable against variations in this parameter. These average energies are subtracted layer by layer from the cells that make up each jet, scaling appropriately

\[
\Delta \eta \times \Delta \phi = 0.1 \times 0.1
\]

with the input cells weighted by using energy-density-dependent factors to correct for calorimeter noncompensation and other energy losses. Jet four-momenta are constructed by the vectorial addition of cells, treating each cell as an \((E, \mathbf{p})\) four-vector with zero mass.

The jets reconstructed by using the anti-\( k_t \) algorithm contain a mix of genuine jets and jet-sized patches of the underlying event. For each event, we estimate the average transverse energy density in each calorimeter layer in bins of width \( \Delta \eta = 0.1 \) and averaged over the azimuth. In the averaging, we exclude jets with \( D = E_T(\text{max})/(E_T) \), the ratio of the maximum tower energy over the mean tower energy, greater than 5. The value \( D_{\text{cut}} = 5 \) is chosen based upon simulation studies, and the results have been tested to be stable against variations in this parameter. These average energies are subtracted layer by layer from the cells that make up each jet, scaling appropriately

\[
D = \frac{\Sigma E_T}{\Sigma p_T}
\]

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\[
D = \frac{\Sigma E_T}{\Sigma p_T}
\]
The dijet asymmetry in peripheral lead-lead events is not problematic. The analysis was repeated first by requiring jets to be within $|\eta| < 1$ and $|\eta| < 2$, to see if there is any effect related to boundaries between the calorimeter sections, and no change to the distribution was observed. Furthermore, the highly asymmetric dijets were not found to populate any specific region of the calorimeter, indicating that no substantial fraction of produced energy was lost in an inefficient or uncovered region.

To investigate the effect of the underlying event, the jet radius parameter $R$ was varied from 0.4 to 0.2 and 0.6 with the result that the large asymmetry was not reduced. In fact, the asymmetry increased for the smaller radius, which would not be expected if detector effects are dominant. The analysis was independently corroborated by a study of “track jets,” reconstructed with inner detector tracks of $p_T > 4$ GeV using the same jet algorithms. The inner detector has an estimated efficiency for reconstructing charged hadrons above $p_T > 1$ GeV of approximately 80% in the most peripheral events (the same as that found in 7 TeV proton-proton operation) and 70% in the most central events, due to the approximately 10% occupancy reached in the silicon strips. A similar asymmetry effect is also observed with track jets. The jet energy scale and underlying event subtraction were also validated by correlating calorimeter and track-based jet measurements.

The missing $E_T$ distribution was measured for minimum bias heavy ion events as a function of the total $E_T$ deposited in the calorimeters up to about $\Sigma E_T = 10$ TeV. The resolution as a function of total $E_T$ shows the same behavior as in proton-proton collisions. None of the events in the jet-selected sample was found to have an anomalously large missing $E_T$.

The events containing high-$p_T$ jets were studied for the presence of high-$p_T$ muons that could carry a large fraction of the recoil energy. Fewer than 2% of the events have a muon with $p_T > 10$ GeV, potentially recoiling against the...
leading jet, so this cannot explain the prevalence of highly asymmetric dijet topologies in more central events.

None of these investigations indicate that the highly asymmetric dijet events arise from backgrounds or detector-related effects.

In summary, first results are presented on jet reconstruction in lead-lead collisions, with the ATLAS detector at the LHC. In a sample of events with a reconstructed jet with transverse energy of 100 GeV or more, an asymmetry is observed between the transverse energies of the leading and second jets that increases with the centrality of the collisions. This has a natural interpretation in terms of QCD energy loss, where the second jet is attenuated, in some cases leading to striking highly asymmetric dijet events. This observation is the first of an enhancement of such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

We 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 CF, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MEYS (MSMT), Czech Republic; Domske Gesellschaft für Forschung, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN-CNAF (Italy), NL-T1 (The Netherlands), PIC Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (The Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom), and in the Tier-2 facilities worldwide.

We thank CERN for the efficient commissioning and operation of the LHC. This work was supported by the Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; Romania; MES of Russia and ROSATOM, Russian Federation; INFN, Italy; Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; DNRF, DSNRC, and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS and CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; Domske Gesellschaft für Forschung, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN-CNAF (Italy), NL-T1 (The Netherlands), PIC Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (The Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom), and in the Tier-2 facilities worldwide.

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[7] 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 is defined as pointing from the collision point to the center of the LHC ring and the positive y axis points upwards. The azimuthal angle $\phi$ is measured around the beam axis, and the polar angle $\theta$ is measured with respect to the z axis. Pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$.
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