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

G. Aad et al. (The ATLAS Collaboration)∗

Collisions of heavy ions at ultra-relativistic energies are expected to produce an evanescent hot, dense state, with temperatures exceeding two trillion kelvins, 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 RHIC experiments established that high transverse momentum (pT) hadrons are produced at rates a factor of five 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. Di-hadron 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 RHIC. This letter provides the first measurements of jet production in lead-lead collisions at √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 |η| < 4.5 [7], which can be reconstructed by ATLAS.

The data in this paper were obtained by ATLAS during the 2010 lead-lead run at the LHC and correspond to an integrated luminosity of approximately 1.7 µb⁻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, Δφ = |φ₁ − φ₂| > π/2 to reduce contributions from multi-jet final states. In this letter, jets with Δφ > π/2 are labeled as being in opposite hemispheres. The jet energy imbalance is expressed in terms of the asymmetry A_J,

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} > \frac{\pi}{2} \]

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, 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 (EM) and hadronic calorimeters. These allow efficient reconstruction of jets over a wide range in the region |η| < 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 (LAr) technology providing excellent energy and position resolution is used in the electromagnetic calorimeter that covers the pseudorapidity range

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[The ATLAS Collaboration]
FIG. 1: Event display of a highly asymmetric dijet event, with one jet with $E_T > 100$ GeV and no evident recoiling jet, and with high energy calorimeter cell deposits distributed over a wide azimuthal region. By selecting tracks with $p_T > 2.6$ GeV and applying cell thresholds in the calorimeters ($E_T > 700$ MeV in the electromagnetic calorimeter, and $E > 1$ GeV in the hadronic calorimeter) the recoil can be seen dispersed widely over azimuth.

$|\eta| < 3.2$. 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 $\eta$ coverage, the LAr forward calorimeters provide both electromagnetic and hadronic energy measurements, extending the coverage up to $|\eta| = 4.9$. The calorimeter ($\eta,\phi$) 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 EM 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 using coincidence signals from two sets of Minimum Bias Trigger Scintillator (MBTS) 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 LUCID luminosity detectors 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 MBTS 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 (ID), which covers $|\eta| < 2.5$ 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 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 mid-rapidity 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 using the infrared-safe anti-$k_t$ jet clustering algorithm [9] with the radius parameter $R = 0.4$. The inputs to this algorithm are “towers” of calorimeter cells of size $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ with the input cells weighted using energy-density dependent factors to correct for calorimeter non-compensation and other energy losses. Jet four-momenta are constructed by the vectorial addition of cells, treating each cell as an $(E, \vec{p})$ four-vector with zero mass.

The jets reconstructed 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 azimuth. In the averaging, we exclude jets with $D = E_T(max)/(E_T)$, the ratio of the maximum tower energy over the mean tower energy, greater than 5. The value $D_{cut} = 5$ is chosen
FIG. 2: (top) Distribution of uncorrected $\Sigma E_T$ in the Forward Calorimeter (FCal). Bins in event activity or “central­ity” are indicated by the alternating bands (see text for de­tails) and labeled according to increasing fraction of lead-lead total cross section starting from the largest measured $\Sigma E_T$.

(bottom) Correlation of uncorrected $\Sigma E_T$ in $|\eta| < 3.2$ with that measured in the FCal (3.2 < $|\eta|$ < 4.9).

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 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 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 $E_T > 100$ 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 $\sqrt{\Delta y^2 + \Delta \phi^2} < 0.2$) 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 $E_T > 100$ 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 $\Delta y \times \Delta \phi = 0.1 \times 0.1$. Inspection of this event shows a highly asymmetric pair of jets with the particles recoiling against the leading jet being widely distributed in azimuth.

To quantify the transverse energy balance between jets in these events, we calculate the dijet asymmetry, $A_J$, in different centrality bins between the highest $E_T$ (leading) jet and the highest $E_T$ jet in the opposite hemisphere (second jet). The second jet is required to have $E_T > 25$ GeV in order to discriminate against background from the underlying event. This excludes around 5% of the jet selected events in the most central 40% of the cross section, and accepts nearly all of the more peripheral events.

The dijet asymmetry and $\Delta \phi$ distributions are shown in four centrality bins in Fig. 3, where they are compared with proton-proton data and with fully-reconstructed HI­JING+PYTHIA simulated events. The simulated events are intended to illustrate the effect of the heavy ion back­ground on jet reconstruction, not any underlying physics process. The dijet asymmetry in peripheral lead-lead events is similar to that in both proton-proton and simulated events; however, as the events become more central, the lead-lead data distributions develop different char­acteristics, indicating an increased rate of highly asym­metric dijet events. The asymmetry distribution broad­ens; the mean shifts to higher values; the peak at zero asymmetry is no longer visible; and for the most cen­tral events a peak is visible at higher asymmetry values.
FIG. 3: (top) Dijet asymmetry distributions for data (points) and unquenched HIJING with superimposed PYTHIA dijets (solid yellow histograms), as a function of collision centrality (left to right from peripheral to central events). Proton-proton data from $\sqrt{s} = 7$ TeV, analyzed with the same jet selection, is shown as open circles. (bottom) Distribution of $\Delta \phi$, the azimuthal angle between the two jets, for data and HIJING+PYTHIA, also as a function of centrality.

Numerous studies have been performed to verify that the events with large asymmetry are not produced by backgrounds or detector effects. Detector effects primarily include readout errors and local acceptance loss due to dead channels and detector cracks. All of the jet events in this sample were checked, and no events were flagged as problematic. The analysis was repeated first requiring both 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 ID tracks of $p_T > 4$ GeV using the same jet algorithms. The ID 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 can not 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.

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* Full author list given at the end of the article in Appendix.
[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 $\eta = -\ln(\tan(\theta/2))$.
143 SLAC National Accelerator Laboratory, Stanford, California 94309, United States of America
144 Comenius University, Faculty of Mathematics, Physics & Informatics\(^{(a)}\), Mlynska dolina F2, SK - 84248 Bratislava; Institute of Experimental Physics of the Slovak Academy of Sciences, Dept. of Subnuclear Physics\(^{(b)}\), Watsonova 47, SK - 04353 Kosice, Slovak Republic
145 \(^{(a)}\)University of Johannesburg, Department of Physics, PO Box 524, Auckland Park, Johannesburg 2006; \(^{(b)}\)School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, Johannesburg, South Africa, South Africa
146 Stockholm University: Department of Physics\(^{(a)}\), The Oskar Klein Centre\(^{(b)}\), AlbaNova, SE - 106 91 Stockholm, Sweden
147 Royal Institute of Technology (KTH), Physics Department, SE - 106 91 Stockholm, Sweden
148 Stony Brook University, Department of Physics and Astronomy, Nicolls Road, Stony Brook, NY 11794-3800, United States of America
149 University of Sussex, Department of Physics and Astronomy Pevensey 2 Building, Falmer, Brighton BN1 9QH, United Kingdom
150 University of Sydney, School of Physics, AU - Sydney NSW 2006, Australia
151 Institute of Physics, Academia Sinica, TW - Taipei 11529, Taiwan
152 Technion, Israel Inst. of Technology, Department of Physics, Technion City, IL - Haifa 32000, Israel
153 Tel Aviv University, Raymond and Beverly Sackler School of Physics and Astronomy, Ramat Aviv, IL - Tel Aviv 69978, Israel
154 Aristotle University of Thessaloniki, Faculty of Science, Department of Physics, Division of Nuclear & Particle Physics, University Campus, GR - 54124, Thessaloniki, Greece
155 The University of Tokyo, International Center for Elementary Particle Physics and Department of Physics, 7-3-1 Hongo, Bunkyo-ku, JP - Tokyo 113-0033, Japan
156 Tokyo Metropolitan University, Graduate School of Science and Technology, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan
157 Tokyo Institute of Technology, Department of Physics, 2-12-1 O-Okayama, Meguro, Tokyo 152-8551, Japan
158 University of Toronto, Department of Physics, 60 Saint George Street, Toronto M5S 1A7, Ontario, Canada
159 TRIUMF\(^{(a)}\), 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3; \(^{(b)}\)York University, Department of Physics and Astronomy, 4700 Keele St., Toronto, Ontario, M3J 1P3, Canada
160 University of Tsukuba, Institute of Pure and Applied Sciences, 1-1-1 Tennoudai, Tsukuba-shi, JP - Ibaraki 305-8571, Japan
161 Tufts University, Science & Technology Center, 4 Colby Street, Medford, MA 02155, United States of America
162 Universidad Antonio Narino, Centro de Investigaciones, Cra 3 Este No.47A-15, Bogota, Colombia
163 University of California, Irvine, Department of Physics & Astronomy, CA 92697-4575, United States of America
164 INFN Gruppo Collegato di Udine\(^{(a)}\), ICP\(^{(b)}\), Strada Costiera 11, IT-34014, Trieste; Università di Udine, Dipartimento di Fisica\(^{(c)}\), via delle Scienze 208, IT - 33100 Udine, Italy
165 University of Illinois, Department of Physics, 1110 West Green Street, Urbana, Illinois 61801, United States of America
166 University of Uppsala, Department of Physics and Astronomy, P.O. Box 516, SE -751 20 Uppsala, Sweden
167 Instituto de Física Corpuscular (IFIC) Centro Mixto UVEG-CSIC, Apdo. 22085 ES-46071 Valencia, Dept. Física At. Mol. y Nuclear; Dept. Ing. Electrónica; Univ. of Valencia, and Inst. de Microelectrónica de Barcelona (IMB-CNMCSCIC) 08193 Bellaterra, Spain
168 University of British Columbia, Department of Physics, 6224 Agricultural Road, CA - Vancouver, B.C. V6T 1Z1, Canada
169 University of Victoria, Department of Physics and Astronomy, P.O. Box 3055, Victoria B.C., V8W 3P6, Canada
170 Waseda University, WISE, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan
171 The Weizmann Institute of Science, Department of Particle Physics, P.O. Box 26, IL - 76100 Rehovot, Israel
172 University of Wisconsin, Department of Physics, 1150 University Avenue, WI 53706 Madison, Wisconsin, United States of America
173 Julius-Maximilians-University of Würzburg, Physikalisches Institute, Am Hubland, 97074 Würzburg, Germany
174 Bergische Universität, Fachbereich C, Physik, Postfach 100127, Gauss-Strasse 20, D- 42097 Wuppertal, Germany
175 Yale University, Department of Physics, PO Box 208121, New Haven CT, 06520-8121, United States of America
176 Yerevan Physics Institute, Alikharian Brothers Street 2, AM - 375036 Yerevan, Armenia
177 Centre de Calcul CNRS/IN2P3, Domaine scientifique de la Doua, 27 bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France
\(^{a}\) Also at LIP, Portugal