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

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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.

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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 $\sqrt{s_{\text{NN}}} = 2.76$ 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 $A_J$:

$$A_J = \frac{E_{T_1} - E_{T_2}}{E_{T_1} + E_{T_2}}, \quad \Delta \phi > \frac{\pi}{2}, \quad (1)$$

where the first jet is required to have a transverse energy $E_{T_1} > 100$ GeV, and the second jet is the highest transverse energy jet in the opposite hemisphere with $E_{T_2} > 25$ 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 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 parame-

![FIG. 1 (color online). 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 the azimuth.](image-url)
The averaging, we exclude jets with \( \Sigma E_T^{D} \) of width \( \Delta \eta \times \Delta \phi \), with that measured in the FCal (\( \Sigma E_T^{D} \)). Bins in event activity or centrality are indicated by \( \Sigma \Sigma E_T^{D} > 100 \text{ GeV} \) and \( \Sigma E_T^{D} > 3 \). From the largest measured \( \Sigma E_T \), the ratio of the maximum tower energy over the mean tower energy, greater than 5. The value \( \frac{\Sigma \Sigma E_T^{D}}{\Sigma E_T^{D}} \) is corrected to that measured in the FCal (3.2 \( \eta \) < 4.9) with that measured in the FCal (3.2 \( \eta \) < 4.9). These average energies are subtracted layer by layer to increase the fraction of lead-lead total cross section starting from the largest measured \( \Sigma E_T \).

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 \( E_T > 25 \text{ GeV} \) 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 in-
FIG. 3 (color online). (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, are 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.

...tended 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 (asymmetries larger than 0.6 can exist only for leading jets substantially above the kinematic threshold of 100 GeV transverse energy). The $\Delta\phi$ distributions show that the leading and second jets are primarily back-to-back in all centrality bins; however, a systematic increase is observed in the rate of second jets at large angles relative to the recoil direction as the events become more central.

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 by 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 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 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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