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Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector ☆

ATLAS Collaboration ⋆

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ABSTRACT

This Letter describes the measurement of elliptic flow of charged particles in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the ATLAS detector at the Large Hadron Collider (LHC). The results are based on an integrated luminosity of approximately 7 μb^{-1}. Elliptic flow is measured over a wide region in pseudorapidity, $|\eta| < 2.5$, and over a broad range in transverse momentum, $0.5 < p_T < 20$ GeV. The elliptic flow parameter v_2 is obtained by correlating individual tracks with the event plane measured using energy deposited in the forward calorimeters. As a function of transverse momentum, $v_2(p_T)$ reaches a maximum at p_T of about 3 GeV, then decreases and becomes weakly dependent on p_T above 7–8 GeV. Over the measured pseudorapidity region, v_2 is found to be only weakly dependent on η, with less variation than observed at lower beam energies. The results are discussed in the context of previous measurements at lower collision energies, as well as recent results from the LHC.

1. Introduction

The measurement of collective phenomena in nuclear collisions at high energies has been a subject of intensive theoretical and experimental studies. Anisotropic flow, which manifests itself as a large anisotropy in the event-by-event azimuthal angle distribution of produced particles, is generally understood to be a consequence of the spatial anisotropy of the initial energy deposition from nucleon–nucleon collisions in the overlap of the colliding nuclei. Anisotropies in the initial energy density are converted into final state momentum anisotropies via strong rescattering processes which induce pressure gradients, following the laws of relativistic hydrodynamics. Consequently, azimuthal anisotropies are sensitive to the initial state and its subsequent dynamical evolution.

Anisotropic flow is commonly studied by measuring the Fourier coefficients (v_n) of the azimuthal angle distributions of the emitted particles. The second harmonic, v_2, referred to as "elliptic flow", is the most extensively studied as it most directly relates the anisotropic shape of the overlap of the colliding nuclei to a corresponding anisotropy of the outgoing momentum distribution (for a review, see Ref. [1]). Elliptic flow has been measured over a wide range of energies, collision systems, and collision centralities by all of the RHIC heavy ion experiments [2–5] and several experiments at lower energies (see Ref. [1]). Predictions for v_2 at the LHC energy varied widely, covering all possibilities from a strong rise, no change, or even a decrease of v_2 [6] relative to lower energy collisions. Measurements of v_2 for inclusive charged-particles from the ALICE experiment [7] indicate that, integrated over p_T, it increases by about 30% from RHIC to LHC energies. However, ALICE also observed that $v_2(p_T)$ for inclusive charged particles was identical with RHIC results for the same collision centrality (or impact parameter) up to $p_T = 4$ GeV. This implies that the observed rise is driven primarily by an increase in the average transverse momentum with the higher collision energy.

In this Letter, we present a measurement of the elliptic flow of charged particles in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC. The elliptic flow is measured in the pseudorapidity region $|\eta| < 2.5$ over the full azimuthal range $0 < \phi < 2\pi$, for transverse momenta[1] $0.5 < p_T < 20$ GeV. This allows stringent tests of the applicability of hydrodynamics in the LHC energy regime, and provides information on the transition between low p_T, where hydrodynamics is expected to dominate, and higher p_T, where particle production is expected to stem from the fragmentation of jets modified by the hot, dense medium [8].

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Transverse momentum and energy are defined as $p_T = p\sin\theta$ and $E_T = E\sin\theta$, respectively.

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2. ATLAS detector and trigger

The ATLAS detector [9] is well suited for measurements of azimuthal anisotropies over a large pseudorapidity range. The relevant detectors for this analysis are the inner detector (ID) and forward calorimeter (FCal). The ID is contained within the 2 T field of a superconducting solenoid magnet, and measures the trajectories of charged particles in the pseudorapidity region $|\eta| < 2.5$ and over the full azimuthal range. The precision silicon tracking detectors consist of pixel detectors (Pixel) and a semiconductor microstrip tracker (SCT). In the "barrel" region, these are arranged on cylindrical layers surrounding the beam pipe, while in the "end-cap" regions they are mounted on disks perpendicular to the beam axis. A charged particle typically traverses three layers of the Pixel detector and four double-sided layers of the SCT. The silicon detectors are surrounded by a transition radiation tracker (TRT), composed of drift tubes and covering up to $|\eta| = 2$.

The FCal covers a pseudorapidity range $3.2 < |\eta| < 4.9$. It uses tungsten and copper absorbers with liquid argon as the active medium, with a total thickness of about 10 interaction lengths. This analysis uses the energy deposition in the entire FCal for the centrality determination, while for the reaction plane measurement only the energy deposition in the first sampling layer of the FCal (Layer 1) is used, as doing this was found to minimize the effect of fluctuations on the reaction plane measurement.

The trigger system has three stages, the first of which (Level-1) is hardware-based, while the later stages (Level-2 and Event Filter [9]) are based on software algorithms. The minimum-bias Level-1 trigger used for this analysis requires signals in either the two sets of minimum-bias trigger scintillator (MBTS) counters, covering $2.1 < |\eta| < 3.9$ on each side of the experiment, or the two zero-degree calorimeters (ZDC), each positioned at $|z| = 140$ m relative to the centre of the detector, detecting neutrons and photons with $|\eta| > 8.3$. The ZDC Level-1 trigger thresholds were set just below the single neutron peak on each side. The MBTS trigger was configured to require at least one hit above threshold from each side of the detector. A Level-2 timing requirement on signals from the MBTS was then imposed to remove beam backgrounds, while the ZDC had no further requirements beyond the Level-1 decision. The Event Filter was not needed for the minimum-bias triggering and was run in pass-through mode.

3. Event selection and reconstruction

The lead–lead data set analysed here corresponds to an integrated luminosity of approximately $L_{\text{int}} = 7\ \mu\text{b}^{-1}$. Three main event selection requirements were applied offline to reject both non-collision backgrounds and Coulomb processes, in particular highly-inelastic photonuclear events. First, an offline event selection required a time difference $|\Delta t| < 3$ ns between the positive and negative η MBTS counters as well as a reconstructed vertex in order to suppress non-collision backgrounds. Second, a coincidence of the ZDCs at forward and backward pseudorapidities was required in order to reject a variety of background processes, while maintaining high efficiency for non-Coulomb processes. Finally, in this analysis only events with a vertex with $|z_{\text{vtx}}| < 10$ cm were used. Simulations show the vertex algorithm to be essentially 100% efficient for the event sample considered here. Pile-up events, defined as additional minimum bias events in the same bunch crossing, are expected to be present at the 10^{-4} level and so are negligible. In total, approximately 4×10^7 events passed the selection criteria.

Tracks were reconstructed within the full acceptance of the inner detector. To improve the reliability of the ID track reconstruction in the tracking environment in heavy ion collisions, the track quality requirements are more stringent than those defined for proton–proton collisions [10]. Tracks are required to have at least eight hits in the SCT, at least two Pixel hits and a hit in the Pixel layer closest to the interaction point. A track must have no missing Pixel hits and at most one missing SCT hit, where such hits are expected. Finally, the transverse and longitudinal impact parameters with respect to the vertex ($|d_0|$ and $|z_0 \sin\theta|$) were each required to be less than 1 mm. These additional requirements were made to improve the purity of the track sample. The inefficiency of this selection is driven by the loss due to hadronic interactions in the detector material, which increases with $|\eta|$ [10]. This results in an additional inefficiency of approximately 15% at $|\eta| > 1$ compared to the central region of the detector.

However, the results shown here are found to be insensitive to the absolute tracking efficiency (discussed below), and the effect of the efficiency decrease at high $|\eta|$ is minimized when measurements are performed in limited transverse momentum and pseudorapidity intervals.

The tracking performance has been studied in detail by comparing data to Monte Carlo simulations based on the HIJING event generator [11] and a full GEANT4 [12] simulation of the detector [13]. In general the simulated distributions of the number of Pixel and SCT hits on tracks describe the data well, particularly after reweighting the simulated momentum distribution to account for the differences in the charged particle spectrum reconstructed in data and HIJING. Monte Carlo calculations show that the tracking efficiency for charged hadrons in this analysis is about 72% near $\eta = 0$ in central collisions, lower than in proton–proton collisions due to the more stringent requirements and the higher occupancy in the SCT. Fake tracks from random combinations of hits are generally negligible, e.g. reaching only 0.1% in $|\eta| < 0.3$ for the highest multiplicity collisions, although the rate of fake tracks increases slightly with increasing $|\eta|$.

4. Data analysis

In order to systematically select various geometries of the initial state, the data were analysed in centrality intervals defined by selections on FCal ΣE_T, the total transverse energy deposited in the FCal (always stated at the electromagnetic energy scale, which does not correct for the response of the calorimeter to hadrons). These intervals are expressed in percentiles of the total inelastic non-Coulomb lead–lead cross section (0–10%, 10–20%, ..., 70–80%) with the most central interval (0–10%) corresponding to the 10% of events with the largest FCal ΣE_T. The measured FCal ΣE_T distribution for a subset of the data (with L_{int} approximately 200 mb^{-1}), taken with a less restrictive primary trigger than used for the bulk of the data and used for the calibration procedure described below, is shown divided into centrality intervals in Fig. 1.

To establish the fraction f of the total non-Coulomb inelastic cross section selected by our trigger and event selection criteria, we have performed a convolution of FCal ΣE_T distributions measured in proton–proton data at $\sqrt{s} = 2.76$ TeV with a full Monte Carlo Glauber calculation [14]. The calculation assumes the number of effective proton–proton collisions per lead–lead event, N, scales according to the "two-component model" (from e.g. Ref. [15]). This model combines the number of participants (N_{part}, the number of nucleons which interact inelastically at least once) and the number of binary collisions (N_{coll}) as $N = (1-x)\frac{N_{\text{part}}}{2} + xN_{\text{coll}}$. In this approach, the only free parameter is x, which controls the relative contribution of N_{part} and N_{coll}. The best description of the data is found to be for $x = 0.088$. The value of f and its uncertainty is estimated by systematically varying the effect of trigger and event selection inefficiencies as well as backgrounds in the most peripheral FCal ΣE_T interval to achieve the best agreement between the

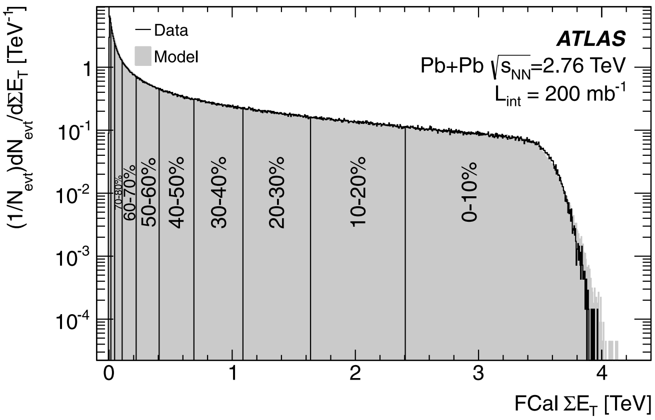

Fig. 1. Measured FCal ΣE_T distribution divided into 10% centrality intervals (black). Proton–proton data at $\sqrt{s} = 2.76$ TeV, convolved with a Glauber Monte Carlo calculation with $x = 0.088$ (grey), as described in the text.

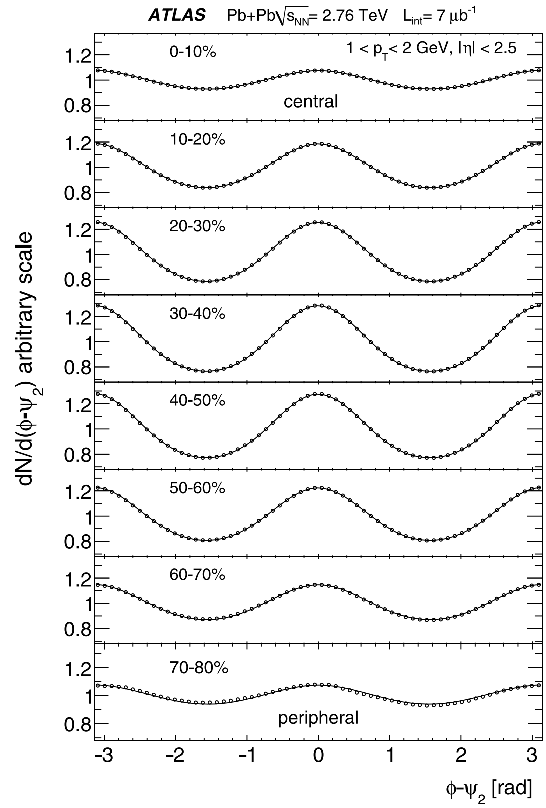

Fig. 2. Distribution of the azimuthal angle of individual tracks relative to the measured event plane, in eight centrality intervals. These distributions are meant to illustrate the observed correlation relative to the event plane, and are not used in the quantitative estimates of v_2. The curve is a fit to $1 + \sum_n 2v_n \cos(n\phi)$ up to $n = 6$.

measured and simulated distributions. Using this analysis of the FCal ΣE_T distribution, the fraction of the total cross section sampled by the trigger and event selection has been estimated to be 98%, with an uncertainty of 2%. This is similar to estimates given in a previous ATLAS publication [16]. The FCal ΣE_T ranges defined from this subsample have been found to be stable for the full data set, both by counting the number of events and by measuring the average number of reconstructed tracks in each interval. The 20% of events with the smallest FCal ΣE_T are not included in this analysis, due to the relatively large uncertainties in determining the appropriate selection criteria.

The final state momentum anisotropy can be quantified by studying the Fourier decomposition of the azimuthal angle distribution [17]:

$$E\frac{d^3N}{dp^3} = \frac{1}{p_\mathrm{T}}\frac{d^3N}{d\phi\, dp_\mathrm{T}\, dy} = \frac{1}{2\pi p_\mathrm{T}}\frac{E}{p}\frac{d^2N}{dp_\mathrm{T}\, d\eta}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]\right), \qquad (1)$$

where y, p_T and ϕ are the rapidity, transverse momentum, and azimuthal angle of final-state charged particle tracks and Ψ_n denotes the azimuthal angle of the n-th order reaction plane. In more peripheral events, Ψ_2 is close to Φ_{RP}, the reaction plane angle, defined by the impact parameter ($\vec{b}$, the vector separation of the barycentres of the two nuclei) and the beam axis (z). In more central events, Ψ_2 primarily reflects fluctuations in the initial-state configurations of colliding nucleons. This analysis was confined to the second Fourier coefficient ($n = 2$), $v_2 \equiv \langle\cos[2(\phi - \Phi_{RP})]\rangle$, where angular brackets denote an average first over particles within each event relative to the event-wise reaction plane, and then over events.

In this analysis, the $n = 2$ event plane is determined from the data on an event-by-event basis, according to the scheme outlined in Ref. [17]:

$$\Psi_2 = \frac{1}{2}\tan^{-1}\left(\frac{\sum E_{\mathrm{T},i}^{\mathrm{tower}} w_i \sin(2\phi_i)}{\sum E_{\mathrm{T},i}^{\mathrm{tower}} w_i \cos(2\phi_i)}\right), \qquad (2)$$

where sums run over tower transverse energies $E_\mathrm{T}^{\mathrm{tower}}$ as measured in the first sampling layer of the forward calorimeters, with each tower covering $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. The tower weights, $w_i = w_i(\phi_i, \eta_i)$, are used to correct for local variations in detector response. They are calculated in narrow $\Delta\eta$ slices ($\Delta\eta = 0.1$) over the full FCal η range in such a way as to remove structures in the uncorrected ϕ distributions of $E_\mathrm{T}^{\mathrm{tower}}$ in every $\Delta\eta$ slice. The final results of this analysis are found to be insensitive to the weighting, and results obtained with all $w_i = 1$ were consistent with those reported here, and well within the systematic uncertainties estimated below.

The correlation of individual track azimuthal angles with the estimated event plane is shown in Fig. 2 for tracks with $p_\mathrm{T} =$ 1–2 GeV. There is a clear sinusoidal modulation at all centralities. The modulation is largest in the 20–50% centrality intervals, and decreases for the more central and peripheral events. In the centrality intervals where the correlation is strongest, the correlation does not follow a perfect $1 + \alpha\cos(2\phi)$ form, indicating significant contributions from higher order harmonics. However, in this Letter we rely on the orthogonality of the Fourier expansion and do not extract the other coefficients. To verify that this does not bias the measurement, we have extracted v_2 from a fit containing all Fourier components v_n up to $n = 6$, and found v_2 values consistent with the results extracted below. The odd amplitudes are found to be consistent with zero, as expected when measuring odd harmonic functions relative to Ψ_2 [17].

The measured values of v_2 are generally underestimated because of the finite experimental resolution in extracting the event plane angle. The event plane resolution correction factor, R, was obtained using the subevent technique, also described in Ref. [17]. Two "subevents" are defined in each event, one each in the forward and backward η directions. For the measurement of the event plane using the FCal, the first sampling layer on the positive η side was selected as subevent "P", with a corresponding subevent "N" formed for negative η. The resolution correction for the event

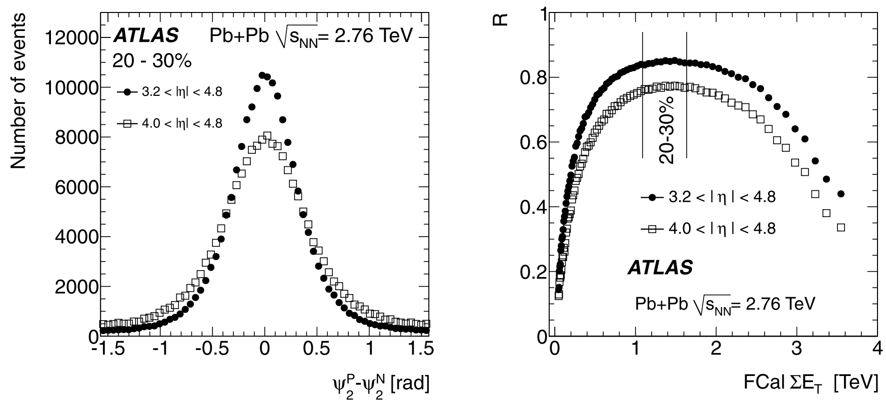

Fig. 3. (Left) Distribution of the difference between the event planes at positive and negative η obtained using Layer 1 FCal towers, both with full and half acceptance. (Right) FCal ΣE_T dependence of the resolution correction for event planes from Layer 1 FCal towers in full acceptance (full symbols) and half acceptance (open symbols).

plane measured by each subevent was calculated as a function of FCal ΣE_T according to the formula

$$R(\Sigma E_{\mathrm{T}}) = \sqrt{\langle \cos[2(\Psi_2^N - \Psi_2^P)] \rangle}, \quad (3)$$

where angular brackets denote an average over all events in a FCal ΣE_T interval. The left panel of Fig. 3 shows the distribution of the difference $\Psi_2^P - \Psi_2^N$. The right panel shows the FCal ΣE_T dependence of the resolution correction for the event plane determined using the full FCal Layer 1 as well as a reduced-acceptance version used in the systematic studies discussed below.

The final, resolution-corrected, v_2 is calculated in intervals of centrality, η and p_{T} as

$$v_2(\eta, p_{\mathrm{T}}) = \frac{1}{N_{\mathrm{tot}}^{\mathrm{trk}}} \sum_j^{\mathrm{events}} \frac{1}{R(\Sigma E_{\mathrm{T}})} \sum_i^{\mathrm{tracks}} c_i \cos[2(\phi_i - \Psi_{2,j}^{N/P})], \quad (4)$$

where $N_{\mathrm{tot}}^{\mathrm{trk}}$ denotes the total number of the reconstructed tracks in a given centrality, η and p_{T} range, and the c_i are weights similar to the w_i for tracks, designed to flatten the ϕ distribution in a small $\Delta\eta$ slice. For $\Psi_{2,j}^{N/P}$ (the event plane for event j) we take the event plane measured in the opposite η hemisphere (i.e. "P" at positive η, or "N" at negative η) to each track with azimuthal angle ϕ_i. Using the track in the opposite hemisphere maximizes the pseudorapidity gap between the reaction plane estimate and the v_2 estimate ($|\Delta\eta| > 3.2$), minimizing potential non-flow correlations between them.

The systematic uncertainty on v_2 as a function of p_{T}, η and centrality was evaluated by varying several different aspects of the analysis procedure.

- The resolution correction was changed by limiting the FCal acceptance to a smaller range in pseudorapidity.
- Tighter tracking requirements were applied (both $|d_0|$ and $|z_0 \sin\theta|$ less than 0.5 mm, instead of the nominal 1 mm requirement).
- Results were compared using negatively and positively charged tracks.
- Results were compared between v_2 measured at positive and negative pseudorapidities.
- Results were studied as a function of time during the heavy ion run.

Additional sources of systematic uncertainties were examined, including the following: Deviations from zero of $\langle \sin(2[\phi - \Psi_2]) \rangle$, which are sensitive to residual biases in the reaction plane determination and detector non-uniformities, were measured. Monte Carlo studies were performed based on HIJING, with a special procedure applied to the generated particle azimuthal angles so as to simulate elliptic flow (from Ref. [17]), with a magnitude extrapolated from RHIC data. Deviations from the flow induced at the generator level were obtained by applying the same analysis procedure to the simulated data as with real data. The event plane determined from the reconstructed tracks was also investigated as an independent cross-check on the FCal reaction plane. In this case, for the tracks with positive (negative) η the event plane determined in the negative (positive) η subevent was used. The uncertainty in the fraction of the total inelastic cross section sampled by our trigger and event selection criteria gives an overall scale uncertainty on v_2, ranging from 1% in central events up to 5% in peripheral events.

Deviations in individual contributions from the baseline results have been quantified as relative systematic uncertainties on v_2 (in percent), which are listed in Table 1 for several centrality and p_{T} intervals, all for $|\eta| < 1$. The different components have been added in quadrature and expressed as 1σ point-to-point systematic uncertainties. Note that the somewhat large increase in the scale of the uncertainties from moderate to high p_{T} can be partly attributed to the limited track statistics at high p_{T}. It should also be pointed out that the systematic uncertainties only include those associated with the measurements themselves; no attempt is made to disentangle the potential contributions from non-flow effects, since their nature is not yet fully understood.

5. Results

The top panel of Fig. 4 shows the v_2 dependence on p_{T} for eight 10% centrality intervals and for tracks with $|\eta| < 1$. It is observed that all centrality intervals show a rapid rise in $v_2(p_{\mathrm{T}})$ up to $p_{\mathrm{T}} = 3$ GeV, a decrease out to 7–8 GeV, and then a weak p_{T} dependence beyond 9–10 GeV. The same trends are also seen for $1 < |\eta| < 2$ (Fig. 4 middle) and $2 < |\eta| < 2.5$ (Fig. 4 bottom).

The pseudorapidity dependence of v_2 is shown in Fig. 5. The top row shows the centrality and η dependence of $v_2(\eta, p_{\mathrm{T}})$ for five p_{T} intervals, which characterize the trend shown in Fig. 4, and the four most-central intervals. The bottom row shows the same information for the four most peripheral intervals. It is observed that v_2 depends very weakly on η over the measured pseudorapidity region. In the two lowest p_{T} intervals, below 1.2 GeV, v_2 drops by about 5–10% over the range $|\eta| = 0$–2.4. At higher transverse momenta, a decrease on the order of few percent can be seen, although, due to the large point-to-point errors, a flat

Table 1
Principal systematic uncertainties (stated as a percentage of the value of v_2) on the v_2 measurement for three p_T intervals and two centrality intervals, all for $|\eta| < 1$.

Centrality	0–10%			40–50%		
p_T [GeV]	0.8–0.9	2.4–2.7	8–10	0.8–0.9	2.4–2.7	8–10
Smaller η acceptance of event plane determination	0.6	1.2	5.7	0.7	0.7	2.0
Residual deviation from zero of sine terms	0.7	0.6	0.4	0.5	0.7	1.2
Varying tracking cuts	0.4	0.1	1.7	0.1	< 0.1	0.2
Negative vs. positive tracks	0.5	0.3	3.3	0.3	0.1	1.6
Asymmetry with respect to η reflection	0.1	0.1	0.2	< 0.1	< 0.1	0.1
Time dependence		0.2			0.2	
Monte Carlo reconstruction	1.2	1.2	1.2	0.3	0.3	0.3
Total systematic error	1.6	1.9	6.9	1.0	1.0	2.9

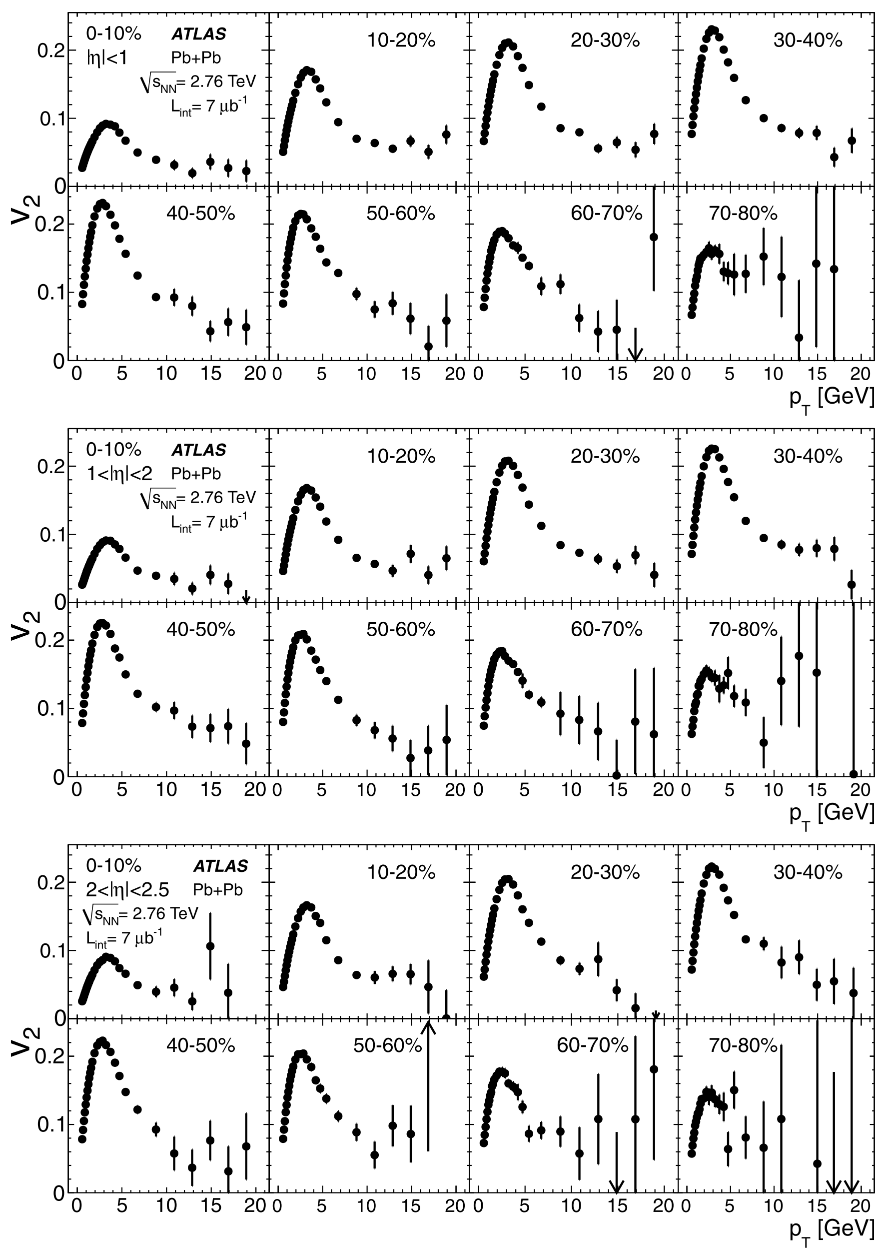

Fig. 4. Elliptic flow $v_2(p_T)$ as a function of p_T for eight 10% centrality intervals, for p_T from 0.5 to 20 GeV, and for three ranges in pseudorapidity ($|\eta| < 1$, $1 < |\eta| < 2$ and $2 < |\eta| < 2.5$). Error bars show statistical and systematic uncertainties added in quadrature. The arrows indicate where the value of v_2 does not fit within the chosen plot scale, due to large statistical fluctuations.

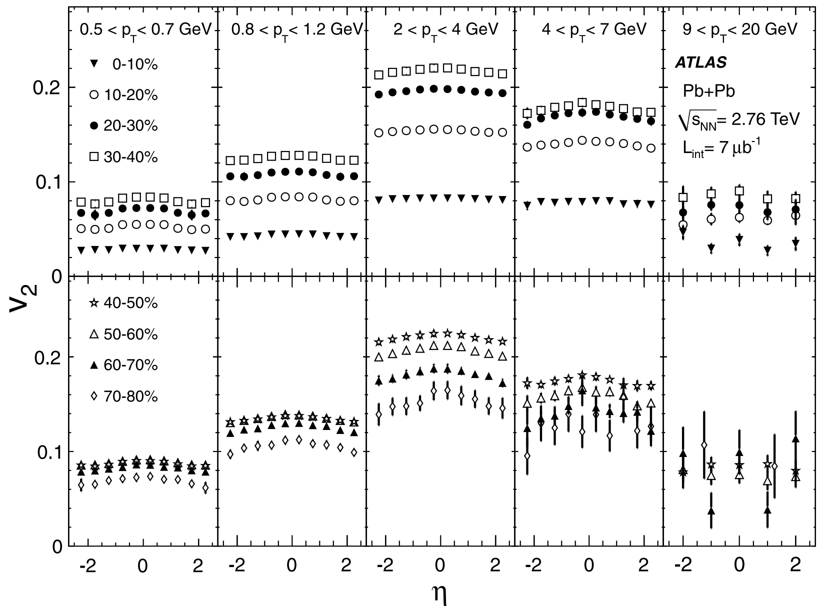

Fig. 5. Pseudorapidity dependence of $v_2(p_\mathrm{T}, \eta)$ for $0.5 < p_\mathrm{T} < 20$ GeV in five p_T intervals and 10% centrality intervals. Error bars show statistical and systematic uncertainties added in quadrature.

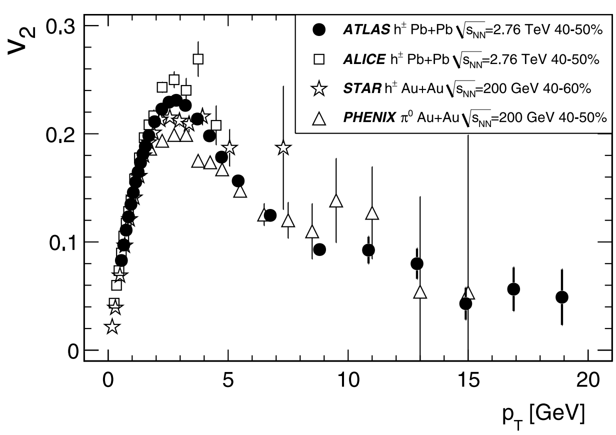

Fig. 6. v_2 vs. p_T at $|\eta| < 1$ in the 40–50% centrality interval, compared to previous experimental data: ALICE $v_2\{2\}$ [7] for inclusive charged particles, PHENIX [20] v_2 for identified π^0, and STAR data on $v_2\{2\}$ for inclusive charged particles for the 40–60% interval [19].

η dependence cannot be excluded. This is in contrast to the strong variation in $v_2(\eta)$ observed by the PHOBOS experiment at $\sqrt{s_\mathrm{NN}} = 200$ GeV [18], which drops by approximately 30% between $\eta = 0$ and $\eta = 2.5$.

Fig. 6 shows $v_2(p_\mathrm{T})$ for $|\eta| < 1$ in the 40–50% centrality interval compared to data from the LHC (ALICE, from Ref. [7]) as well as from RHIC (STAR [19] and PHENIX [20]) with a centre-of-mass energy a factor of nearly 14 lower. The ALICE and STAR data are shown for the second cumulant $v_2\{2\}$, which gives results closest to the event-plane method used in this analysis. The PHENIX data are obtained with a similar method as ATLAS, but with v_2 measured only for identified π^0 hadrons, detected through their two-photon decay mode. It is observed that all of the data sets are quite similar as a function of p_T, both at lower p_T (ALICE and STAR) and even at higher p_T, within the limited statistical precision of the PHENIX data. The observation of similar v_2 at low p_T has been noted recently [7], and has been reproduced using hydrodynamical simulations assuming the same shear viscosity to entropy density ratio but initialized at a higher energy density. However, the similarities at high p_T will require additional theoretical study to see if they are consistent with the differential energy loss of jets in the hot, dense medium.

6. Conclusions

Elliptic flow measurements in lead–lead collisions at $\sqrt{s_\mathrm{NN}} = 2.76$ TeV obtained with the ATLAS detector are presented for an integrated luminosity of approximately 7 μb^{-1}. These results represent the first measurement of v_2 over a broad range in η and p_T at the LHC energy. As a function of transverse momentum, at all $|\eta|$, v_2 rises rapidly up to $p_\mathrm{T} = 3$ GeV, decreases somewhat less rapidly out to $p_\mathrm{T} = 7$–8 GeV, and then varies weakly out to 20 GeV. Over the measured pseudorapidity region, $|\eta| < 2.5$, v_2 is found to be only weakly dependent on η, with less variation than observed at lower beam energies. Comparison of the 40–50% interval with lower energy data shows little change both at low and high p_T. These results provide strong constraints on models which aim to describe the dynamical evolution of the system created in ultra-relativistic heavy ion collisions.

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