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Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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We report the first measurement of charged particle elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.2 < p_t < 5.0$ GeV/c. The elliptic flow signal v_2, measured using the 4-particle correlation method, averaged over transverse momentum and pseudorapidity is $0.087 \pm 0.002(\mathrm{stat}) \pm 0.003(\mathrm{syst})$ in the 40%–50% centrality class. The differential elliptic flow $v_2(p_t)$ reaches a maximum of 0.2 near $p_t = 3$ GeV/c. Compared to RHIC Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the elliptic flow increases by about 30%. Some hydrodynamic model predictions which include viscous corrections are in agreement with the observed increase.

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The goal of ultrarelativistic nuclear collisions is the creation and study of the quark-gluon plasma (QGP), a state of matter whose existence at high energy density is predicted by quantum chromodynamics. One of the experimental observables that is sensitive to the properties of this matter is the azimuthal distribution of particles in the plane perpendicular to the beam direction. When nuclei collide at finite impact parameter (noncentral collisions), the geometrical overlap region and therefore the initial matter distribution is anisotropic (almond shaped). If the matter is interacting, this spatial asymmetry is converted via multiple collisions into an anisotropic momentum distribution [1]. The second moment of the final state hadron azimuthal distribution is called elliptic flow; it is a response of the dense system to the initial conditions and therefore sensitive to the early and hot, strongly interacting phase of the evolution.

At RHIC large elliptic flow has been observed and is one of the key experimental discoveries [2–6]. Theoretical models, based on ideal relativistic hydrodynamics with a QGP equation of state and zero shear viscosity, fail to describe elliptic flow measurements at lower energies but describe RHIC data reasonably well [7]. Theoretical arguments, based on the AdS/CFT conjecture [8], suggest a universal lower bound of $1/4\pi$ [9] for the ratio of shear viscosity to entropy density. Recent model studies incorporating viscous corrections indicate that the shear viscosity at RHIC is within a factor of ~5 of this bound [10–13].

The pure hydrodynamic models [7,14,15] and models which combine hydrodynamics with a hadron cascade afterburner (hybrid models) [16,17] that successfully describe flow at RHIC predict an increase of the elliptic flow at the LHC ranging from 10% to 30%, with the largest increase predicted by models which account for viscous corrections [15–18] at RHIC energies. In models with viscous corrections, v_2 at RHIC is below the ideal hydrodynamic limit [12,17] and therefore can show a stronger increase with energy. In hydrodynamic models the charged particle elliptic flow as a function of transverse momentum does not change significantly [7,14], while the p_t-integrated elliptic flow increases due to the rise in average p_t expected from larger radial (azimuthally symmetric) flow. The larger radial flow also leads to a decrease of the elliptic flow at low transverse momentum, which is most pronounced for heavy particles. Models based on a parton cascade [19], including models that take into account quark recombination for particle production [20], predict a stronger decrease of the elliptic flow as a function of transverse momentum compared to RHIC energies. Phenomenological extrapolations [21] and models based on final state interactions [22] that have been tuned to describe the RHIC data predict an increase of the elliptic flow of ~50%, larger than other models. A measurement of elliptic flow at the LHC is therefore crucial to test the validity of a hydrodynamic description of the medium and to measure its thermodynamic properties, in particular, shear viscosity and the equation of state [23].

The azimuthal dependence of the particle yield can be written in the form of a Fourier series [24,25]:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)]\right), \quad (1)$$

where E is the energy of the particle, p the momentum, p_t the transverse momentum, ϕ the azimuthal angle, y the rapidity, and Ψ_R the reaction plane angle. The reaction plane is the plane defined by the beam axis z and the impact parameter direction. In general the coefficients $v_n = \langle \cos[n(\phi - \Psi_R)] \rangle$ are p_t and y dependent—therefore we

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refer to them as differential flow. The integrated flow is defined as an average evaluated with d^2N/dp_tdy used as a weight. The first coefficient, v_1, is called directed flow, and the second coefficient, v_2, is called elliptic flow.

We report the first measurement of elliptic flow of charged particles in Pb-Pb collisions at the center of mass energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV, with the ALICE detector [26–28]. The data were recorded in November 2010 during the first run with heavy ions at the LHC.

For this analysis the ALICE inner tracking system (ITS) and the time projection chamber (TPC) were used to reconstruct the charged particle tracks. The VZERO counters and the silicon pixel detector (SPD) were used for the trigger. The VZERO counters are two scintillator arrays providing both amplitude and timing information, covering the pseudorapidity range $2.8 < \eta < 5.1$ (VZERO-A) and $-3.7 < \eta < -1.7$ (VZERO-C). The VZERO time resolution is better than 1 ns. The SPD is the innermost part of the ITS, consisting of two cylindrical layers of hybrid silicon pixel assemblies covering the range of $|\eta| < 2.0$ and $|\eta| < 1.4$ for the inner and outer layer, respectively. The minimum-bias interaction trigger required at least two out of the following three conditions [29]: (i) two pixel chips hit in the outer layer of the silicon pixel detectors, (ii) a signal in VZERO-A, (iii) a signal in VZERO-C. The bunch intensity was typically 10^7 Pb ions per bunch and each beam had 4 colliding bunches. The estimated luminosity was 5×10^{23} cm^{-2} s^{-1}, producing collisions with a minimum-bias trigger at a rate of 50 Hz including about 4 Hz nuclear interactions, 45 Hz electromagnetic processes, and 1 Hz beam background.

A removal of background events was carried out off-line using the VZERO timing information and the requirement of two tracks in the central detector. A study based on Glauber model fits to the multiplicity distribution (see also [29]) in the region corresponding to 80% of the most central collisions, where the vertex reconstruction is fully efficient, allows for the determination of the cross section percentile. Only events with a vertex found in $|z| < 10$ cm were used in this analysis to ensure a uniform acceptance in the central pseudorapidity region $|\eta| < 0.8$. An event sample of 45×10^3 Pb-Pb collisions passed the selection criteria and was used in this analysis. The data are analyzed in centrality classes determined by cuts on the uncorrected charged particle multiplicity, in pseudorapidity acceptance $|\eta| < 0.8$. Figure 1 shows the uncorrected charged particle multiplicity in the TPC for these events and indicates the nine centrality bins used in the analysis.

To select charged particles with high efficiency and to minimize the contribution from photon conversions and secondary charged particles produced in the detector material, the following track requirements were applied for tracks measured with the ITS and TPC. The tracks are required to have at least 70 reconstructed space points out of the maximum 159 in the TPC and a $\langle\chi^2\rangle$ per TPC cluster ≤ 4 (with 2 degrees of freedom per cluster). Additionally, at least two of the six ITS layers must have a hit associated with the track. Tracks are rejected if their distance of closest approach to the primary vertex is larger than 0.3 cm in the transverse plane and 0.3 cm in the longitudinal direction. For the selected tracks the reconstruction efficiency and remaining contamination are estimated by Monte Carlo simulations of HIJING [30] and THERMINATOR [31,32] events using a GEANT3 [33] detector simulation and event reconstruction. The reconstruction efficiency for tracks with $0.2 < p_t < 1.0$ GeV/c increases from 60% to 70% after which it stays constant at (70 ± 5)%. The contamination from secondary interactions and photon conversions is less than 5% for $p_t = 0.2$ GeV/c and less than 1% for $p_t > 1$ GeV/c. Both the efficiency and contamination as a function of transverse momentum do not change significantly as a function of multiplicity and are therefore the same for all centrality classes.

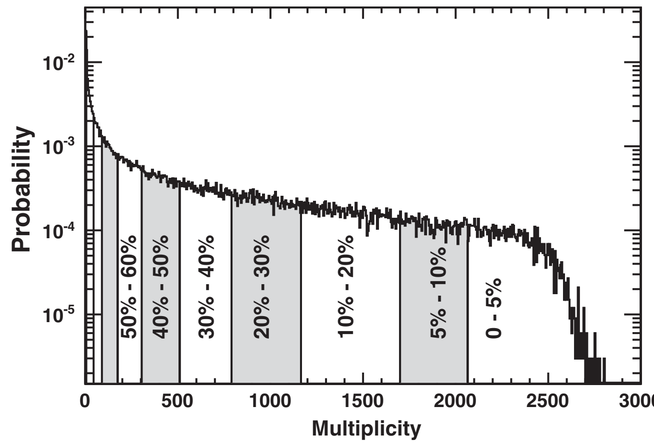

FIG. 1. The uncorrected multiplicity distribution of charged particles in the TPC ($|\eta| < 0.8$). The centrality bins used in the analysis are shown and the cumulative fraction of the total events is indicated in percent. The bins 60%–70% and 70%–80% are not labeled.

An alternative analysis was performed with tracks reconstructed using only the TPC information. For these tracks the same selections were applied except for the requirement of hits in the ITS and allowing for a larger closest distance to the primary vertex, smaller than 3.0 cm in the transverse plane and 3.0 cm in the longitudinal direction. The reconstruction efficiency for these tracks with $0.2 < p_t < 1.0$ GeV/c increases from 70% to 80% after which it stays constant at (80 ± 5)%. The contamination is less than 6% at $p_t = 0.2$ GeV/c and drops below 1% at $p_t > 1$ GeV/c. For this track selection the efficiency and contamination as a function of transverse momentum also do not depend significantly on the track density and are therefore the same for all centrality classes. The relative momentum resolution for tracks used in this analysis was better than 5%, both for the combined ITS-TPC and TPC stand-alone tracks. The results obtained from the

ITS-TPC and TPC stand-alone tracking are in excellent agreement. Because of the smaller corrections for the azimuthal acceptance, the results obtained using the TPC stand-alone tracks are presented in this Letter.

The p_t-differential flow was measured for different event centralities using various analysis techniques. In this Letter we report results obtained with 2- and 4-particle cumulant methods [34], denoted $v_2\{2\}$ and $v_2\{4\}$. To calculate multiparticle cumulants we used a new fast and exact implementation [35]. The $v_2\{2\}$ and $v_2\{4\}$ measurements have different sensitivity to flow fluctuations and nonflow effects—which are uncorrelated to the initial geometry. Analytical estimates and results of simulations show that nonflow contributions to $v_2\{4\}$ are negligible [36]. The contribution from flow fluctuations is positive for $v_2\{2\}$ and negative for $v_2\{4\}$ [37]. For the integrated elliptic flow we also fit the flow vector distribution [38] and use the Lee-Yang zeros method [39], which we denote by $v_2\{q\text{-dist}\}$ and $v_2\{\text{LYZ}\}$, respectively [40]. In addition to comparing the 2- and 4-particle cumulant results we also estimate the nonflow contribution by comparing to correlations of particles of the same charge. Charge correlations due to processes contributing to nonflow (weak decays, correlations due to jets, etc.) lead to stronger correlations between particles of unlike charge sign than like charge sign.

Figure 2(a) shows $v_2(p_t)$ for the centrality class 40%–50% obtained with different methods. For comparison, we present STAR measurements [41,42] for the same centrality from Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, indicated by the shaded area. We find that the value of $v_2(p_t)$ does not change within uncertainties from $\sqrt{s_{NN}} = 200$ GeV to 2.76 TeV. Figure 2(b) presents $v_2(p_t)$ obtained with the 4-particle cumulant method for three different centralities, compared to STAR measurements. The transverse momentum dependence is qualitatively similar for all three centrality classes. At low p_t there is agreement of $v_2(p_t)$ with STAR data within uncertainties.

The integrated elliptic flow is calculated for each centrality class using the measured $v_2(p_t)$ together with the charged particle p_t-differential yield. For the determination of integrated elliptic flow the magnitude of the charged particle reconstruction efficiency does not play a role. However, the relative change in efficiency as a function of transverse momentum does matter. We have estimated the correction to the integrated elliptic flow based on HIJING and THERMINATOR simulations. Transverse momentum spectra in HIJING and THERMINATOR are different, giving an estimate of the uncertainty in the correction. The correction is about 2% with an uncertainty of 1%. In addition, the uncertainty due to the centrality determination results in a relative uncertainty of about 3% on the value of the elliptic flow.

Figure 3 shows that the integrated elliptic flow increases from central to peripheral collisions and reaches a maximum value in the 50%–60% and 40%–50% centrality class of $0.106 \pm 0.001(\text{stat}) \pm 0.004(\text{syst})$ and $0.087 \pm 0.002(\text{stat}) \pm 0.003(\text{syst})$ for the 2- and 4-particle cumulant method, respectively. It is also seen that the measured integrated elliptic flow from the 4-particle cumulant, from fits of the flow vector distribution, and from the Lee-Yang zeros method, are in agreement. The open markers in Fig. 3 show the results obtained for the cumulants using particles of the same charge. The 4-particle cumulant results agree within uncertainties for all charged particles and for the same charge particle data sets. The 2-particle cumulant results, as expected due to nonflow, depend weakly on the charge combination. The difference is most pronounced for the most peripheral and central events.

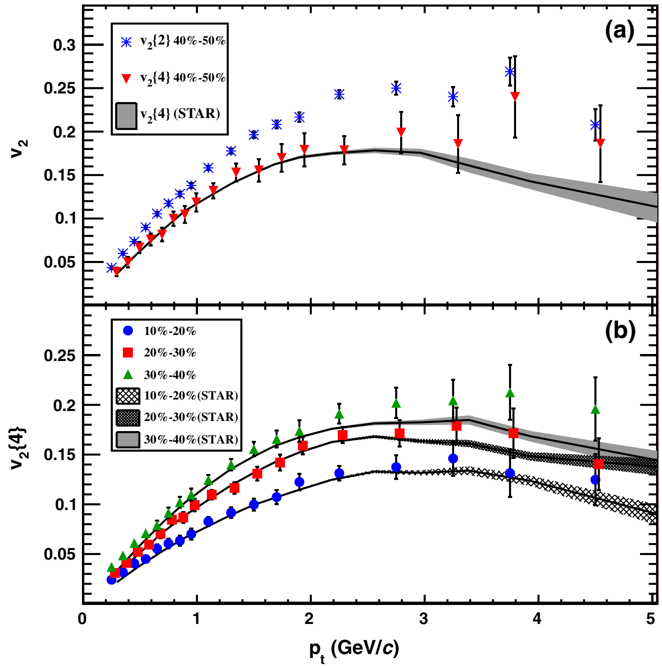

FIG. 2 (color online). (a) $v_2(p_t)$ for the centrality bin 40%–50% from the 2- and 4-particle cumulant methods for this measurement and for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. (b) $v_2\{4\}(p_t)$ for various centralities compared to STAR measurements. The data points in the 20%–30% centrality bin are shifted in p_t for visibility.

The integrated elliptic flow measured in the 20%–30% centrality class is compared to results from lower energies in Fig. 4. For the comparison we have corrected the integrated elliptic flow for the p_t cutoff of 0.2 GeV/c. The estimated magnitude of this correction is $(12 \pm 5)\%$ based on calculations with THERMINATOR. The figure shows that there is a continuous increase in the magnitude of the elliptic flow for this centrality region from RHIC to LHC energies. In comparison to the elliptic flow measurements in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, we observe about a 30% increase in the magnitude of v_2 at $\sqrt{s_{NN}} = 2.76$ TeV. The increase of about 30% is larger than in current ideal hydrodynamic calculations at LHC multiplic-

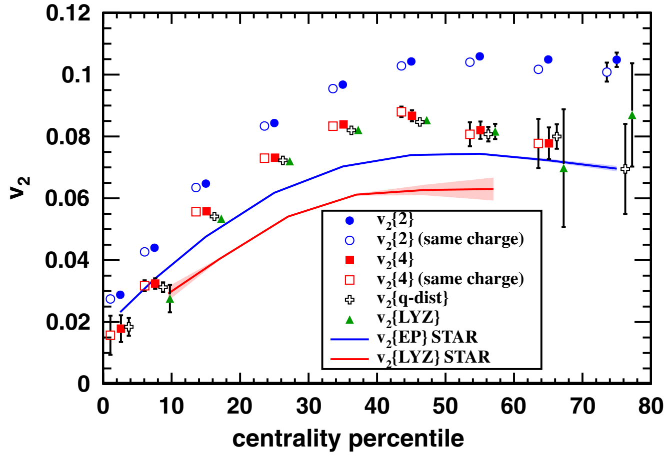

FIG. 3 (color online). Elliptic flow integrated over the p_t range $0.2 < p_t < 5.0$ GeV/c, as a function of event centrality, for the 2- and 4-particle cumulant methods, a fit of the distribution of the flow vector, and the Lee-Yang zeros method. For the cumulants the measurements are shown for all charged particles (full markers) and same charge particles (open markers). Data points are shifted for visibility. RHIC measurements for Au-Au at $\sqrt{s_{NN}} = 200$ GeV, integrated over the p_t range $0.15 < p_t < 2.0$ GeV/c, for the event plane $v_2\{\mathrm{EP}\}$ and Lee-Yang zeros are shown by the solid curves.

ities [7] but is in agreement with some models that include viscous corrections which at the LHC become less important [12,15–18].

In summary we have presented the first elliptic flow measurement at the LHC. The observed similarity at RHIC and the LHC of p_t-differential elliptic flow at low p_t is consistent with predictions of hydrodynamic models [7,14]. We find that the integrated elliptic flow increases about 30% from $\sqrt{s_{NN}} = 200$ GeV at RHIC to $\sqrt{s_{NN}} =$ 2.76 TeV. The larger integrated elliptic flow at the LHC is caused by the increase in the mean p_t. Future elliptic flow measurements of identified particles will clarify the role of radial expansion in the formation of elliptic flow.

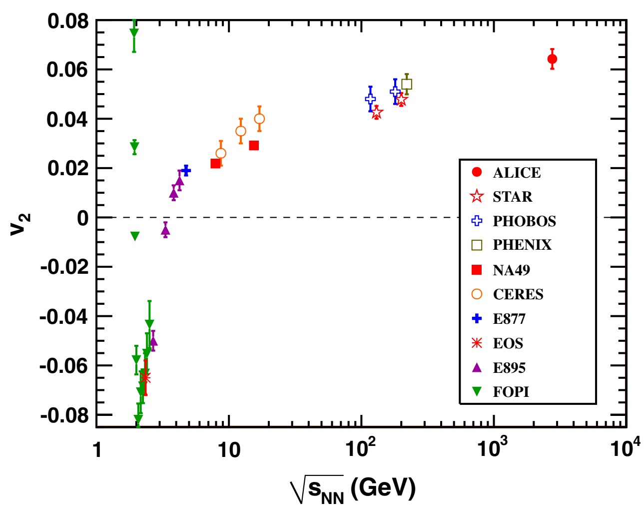

FIG. 4 (color online). Integrated elliptic flow at 2.76 TeV in Pb-Pb 20%–30% centrality class compared with results from lower energies taken at similar centralities [40,43].

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