Directed flow at midrapidity in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions

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We analyze published data from the ALICE Collaboration in order to obtain the first extraction of the recently-proposed rapidity-even directed flow observable $v_1$. An accounting of the correlation due to the conservation of transverse momentum restores the factorization seen by ALICE in all other Fourier harmonics and thus indicates that the remaining correlation gives a reliable measurement of directed flow. We then carry out the first viscous hydrodynamic calculation of directed flow, and show that it is less sensitive to viscosity than higher harmonics. This allows for a direct extraction of the dipole asymmetry of the initial state, providing a strict constraint on the non-equilibrium dynamics of the early-time system. A prediction is then made for $v_1$ in Au-Au collisions at RHIC.

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I. INTRODUCTION

Azimuthal correlations between particles emitted in heavy-ion collisions are a useful observable to probe the behavior of these systems [1]. Specifically, one measures the Fourier coefficient [2]

$$V_{n\Delta} \equiv \langle \cos n \Delta \phi \rangle,$$

(1)

where $\Delta \phi$ is the relative azimuthal angle between a pair of particles, and $\langle \cdots \rangle$ denotes an average over pairs and collisions. The long-range part of this correlation (defined by a rapidity gap between the pair) is mostly generated by collective, anisotropic flow of the strongly-coupled matter created in the collision [3].

The most studied Fourier component is $V_{2\Delta}$ [4–6], corresponding to elliptic flow [7]. Recently it was realized that event-by-event fluctuations [2], generate a whole series of harmonics. This has triggered detailed analyses of $V_{n\Delta}$ for $n = 3–6$ [8–13].

Neglected in these analyses is the first Fourier harmonic $V_{1\Delta}$. The observed $V_{1\Delta}$ is smaller than $V_{2\Delta}$ and $V_{3\Delta}$ [3, 10], and receives a sizable contribution from global momentum conservation [14, 15] which makes its interpretation less straightforward. Fluctuations are expected to create a dipole asymmetry in the system [16], and it is also possible for intrinsic (“non-flow”) pair correlations to factorize [22]. However, flow is currently the only known mechanism that produces a factorized correlation in the range of transverse momentum studied here (the bulk of particles). This factorization has been tested in Pb-Pb collisions at the Large Hadron Collider (LHC) [10, 12]: this is done by fitting the left-hand side of Eq. (2), which is a $N \times N$ symmetric matrix for $N$ bins in $p_T$, with the right-hand side of Eq. (2), using the $N$ values of $v_n(p_T)$ as fit parameters. The ALICE collaboration has shown that, while the data do factorize for $n > 1$, this factorization breaks down for $n = 1$ [10]. This is not surprising since there is expected to be an additional long-range correlation induced by momentum conservation that only affects the

II. DIRECTED FLOW FROM DIHADRON CORRELATIONS

The standard picture of heavy-ion collisions is that an approximately thermalized fluid is created, which eventually breaks up into particles. Particles are emitted independently in each event, with an azimuthal distribution that fluctuates from event to event. This yields a two-particle correlation which factorizes into the product of two single-particle distributions [21]:

$$V_{n\Delta}(p_T^t, p_T^a) = v_n(p_T^t)v_n(p_T^a),$$

(2)

where the superscripts $t$ and $a$ refer to trigger and associated particles that can be taken from different bins in transverse momentum, and $v_n(p_T)$ is the anisotropic flow coefficient. Note that it is possible for the event-averaged correlation to not factorize even if independent emission holds in each event [21], and it is also possible for intrinsic (“non-flow”) pair correlations to factorize [22]. However, flow is currently the only known mechanism that produces a factorized correlation in the range of transverse momentum studied here (the bulk of particles). This factorization has been tested in Pb-Pb collisions at the Large Hadron Collider (LHC) [10, 12]: this is done by fitting the left-hand side of Eq. (2), which is a $N \times N$ symmetric matrix for $N$ bins in $p_T$, with the right-hand side of Eq. (2), using the $N$ values of $v_n(p_T)$ as fit parameters. The ALICE collaboration has shown that, while the data do factorize for $n > 1$, this factorization breaks down for $n = 1$ [10]. This is not surprising since there is expected to be an additional long-range correlation induced by momentum conservation that only affects the
The first harmonic [14]. The constraint that all transverse momenta add up to 0 yields a back-to-back correlation between pairs, which increases linearly with the transverse momenta of both particles. This correlation adds to the correlation from flow: \[ V_{1\Delta}(p_T^f, p_T^s) = v_1(p_T^f) v_1(p_T^s) - k p_T^f p_T^s. \] (Note that the nonflow correlation also factorizes in this particular case [22], but the sum does not.) Table I compares the quality of the fit to \( V_{1\Delta} \) using Eq. (2) or (3). Adding one single fit parameter \( k \) tremendously increases the quality of the fit for all centrality windows. We have checked that the values of the fit parameters depend little on the \( p_T \) window. However, the quality of the fit decreases as higher \( p_T \) particles are included, as observed for other harmonics [10]. Nevertheless, we include the entire range of values as a systematic uncertainty in Table I, varying the lower \( p_T \) cutoff from 0.25–0.75 GeV, and the upper cutoff from 2.5–15.0 GeV. Similarly, we use this procedure to estimate a systematic uncertainty in \( v_1 \) (see Fig. 2 below).

Next, we check whether the value of \( k \) from the fit is compatible with the value expected from momentum conservation. Assuming for simplicity that momentum conservation is the only source of correlation, one obtains [14] \( k = \langle \sum p_T^2 \rangle^{-1} \), where the sum runs over all particles emitted in one event, and angular brackets denote an average over events in the centrality class. Since experiments measure only charged particles in a restricted phase-space window, only a rough estimate of this quantity can be made, by extrapolating from existing data. We have used the preliminary identified particle \( p_T \) spectra from ALICE at midrapidity [23], and extrapolated them outside the \( p_T \) acceptance of the detector using Levy fits [24]. In order to extrapolate to all rapidities, we have assumed for simplicity that \( p_T \) spectra are independent of rapidity, and we have used the total charged multiplicity estimated by the ALICE collaboration [25]. Neutral particles were taken into account assuming isospin symmetry, and the contribution of particles heavier than nucleons was neglected.

The resulting estimate is shown in the last column of Table I. The fit result in general has the correct size and increases with % centrality, as expected. The centrality dependence is steeper than expected from our rough estimate, however — the fit value is larger than the estimated value for the most peripheral bin, while it is significantly smaller for central collisions. We cannot explain this, but overall the agreement is reasonable, and a discrepancy in \( k \) of this size has a very small effect on the extracted directed flow; the extracted directed flow curves with \( k \) fixed to the estimated values were also included in the systematic error band in \( v_1 \), but only have a small effect on the two most central bins.

It has been suggested that the correlation from momentum conservation could be larger than our estimate because of approximate conservation of transverse momentum within smaller subsystems of the entire collision system—specifically rapidity slices of roughly unit extent [26, 27]. However, we see no evidence here for such an enhancement.

Thus, by taking into account the only obvious non-flow correlation, the factorization seen in higher harmonics is restored, and we can take the resulting \( v_1(p_T) \) as a reliable measurement of directed flow \( v_1 \) (presented in Fig. 2 below).

### III. RESULTS OF HYDRODYNAMIC CALCULATIONS

Relativistic viscous hydrodynamics has been shown to successfully reproduce \( v_n \) for \( n = 2, 3, 4 \) [25]. Here, we present the first viscous hydrodynamic calculation for directed flow, \( v_1 \). In hydrodynamics, \( v_1 \) and the corresponding event-plane angle \( \Psi_1 \) are defined by \( v_1 e^{i\Psi_1} \equiv \langle e^{i\varphi} \rangle \), where angular brackets denote an average over the momentum distribution at freeze-out [29]. A collision of identical nuclei at mid-rapidity has \( \varphi \rightarrow \varphi + \pi \) symmetry except for fluctuations, hence \( v_1 \) at mid-rapidity is solely due to event-by-event fluctuations in the initial state.

In event-by-event ideal hydrodynamic calculations, \( v_1 \) was found [13] to be approximately proportional to the dipole asymmetry of the system \( \varepsilon_1 \) defined as [16]

\[ \varepsilon_1 = \frac{\langle r^2 e^{i\varphi} \rangle}{\langle r^3 \rangle}. \]

where \( \{ \cdots \} \) denotes an average value over the initial energy density after recentering the coordinate system \( \langle r e^{i\varphi} \rangle = 0 \). Here, in order to make a systematic study, we use a smooth, symmetric density profile which we deform to introduce a dipole asymmetry of the desired size and orientation. Specifically, our calculation is a \( 2+1 \) dimensional viscous hydrodynamic calculation which uses as initial condition the transverse energy density \( \langle \epsilon(r, \phi) \rangle \) profile from an optical Glauber model [30], which is deformed in a way analogous to the previous study of \( v_3 \) and higher harmonics in Ref. [31]:

\[ \epsilon(r, \phi) \rightarrow \epsilon \left( r \sqrt{1 + \delta \cos(\phi - \Phi_1)}, \phi \right), \]
where $\delta$ is a small parameter. Both $v_1$ and $\varepsilon_1$ are proportional to $\delta$ for $\delta \ll 1$. For noncentral collisions, $v_1$ depends mildly on the orientation of the dipole asymmetry $\Phi_1$ with respect to the impact parameter. Our results are averaged over $\Phi_1$.

Fig. 1 presents the ratio $v_1/\varepsilon_1$ as a function of the transverse momentum $p_T$ for central collisions. Unlike higher-order harmonics, which are usually positive for all $p_T$, $v_1$ changes sign. The reason is that the net transverse momentum of the system is zero by construction, which implies $\langle p_T v_1(p_T) \rangle = 0$: low-$p_T$ particles tend to flow in the direction opposite to high-$p_T$ particles.

The harmonics $v_n$ tend to probe smaller length scales with increasing $n$, and as a result are expected to have an increasing sensitivity to viscosity. Our results show that, indeed, $v_1$ is less sensitive to viscosity than $v_2$ and higher harmonics [28, 31]. This insensitivity to viscosity combined with the approximate proportionality $v_1 \propto \varepsilon_1$ provides a unique opportunity to place a direct constraint on the dipole asymmetry of the early-time system.

In a realistic Pb-Pb collision, $\varepsilon_1$ varies from event to event. The contribution of directed flow to $V_1\Delta$ scales like $\varepsilon_1^2$. Therefore the experimentally measured $v_1$ scales like the root-mean-square (rms) value of $\varepsilon_1$ in the centrality bin. As we shall see below, there is a wide range of predictions for this quantity. With these new data we can now quickly discern which ones are compatible with experiment by identifying an allowed range of values for the rms dipole asymmetry.

Fig. 2 displays $v_1$ versus $p_T$ extracted from ALICE correlation data using Eq. (3). The magnitude and $p_T$ dependence of $v_1$ are similar at LHC and at RHIC [17], and the mild centrality dependence, reminiscent of $v_2$ [3, 9], is expected since both are generated purely from fluctuations in the initial state.

The $p_T$ dependence of $v_1$ in LHC data bears a striking resemblance to that predicted by hydrodynamics, Fig. 1. In a given centrality window and for a given value of the viscosity, one can tune the value of the dipole asymmetry $\varepsilon_1$ in the hydrodynamic calculation so as to obtain reasonable agreement with data. If one chooses to match data at the lowest $p_T$, calculation overpredicts data at high $p_T$. Conversely, if one matches data at high $p_T$, calculation underpredicts data at low $p_T$. The corresponding values of $\varepsilon_1$ can be considered upper and lower bounds on the actual value.

The values of $\eta/s$ (the ratio of shear viscosity to entropy density) implied by comparisons of elliptic flow data to hydrodynamic calculations all lie in the range $0 < \eta/s < 0.24$ [30, 33, 34]. Assuming that $\eta/s$ lies in this range, we can extract an allowed range for the dipole asymmetry, using the extremal values of $\eta/s$ and $\varepsilon_1$ that still give a reasonable fit to data. (The extremal curves used are shown in Fig. 2.

Fig. 3 displays the allowed values of $\varepsilon_1$ as a function of centrality, together with the rms $\varepsilon_1$ from various Monte-Carlo models of initial conditions. The allowed range assuming $0.08 < \eta/s < 0.16$, representing the most common values extracted from $v_2$ data, are also shown in a darker band, to illustrate the small effect of viscosity. Both the order of magnitude and the centrality dependence of $\varepsilon_1$ from Monte-Carlo models resemble the allowed values from LHC data. However, there are significant differences between the models. LHC data already exclude DIPSY [35] above 10% centrality, and the Phobos Glauber model [39] as well as a recent improved mckt model with KNO fluctuations [35] over the entire
Note, however, that since hydrodynamics is expected to be more reliable at low transverse momentum, the actual value of $\varepsilon_1$ is most likely to lie very close to our upper bound. Thus it is possible that the two models with the largest dipole asymmetry may only need a slight tuning to achieve a correct value, while the value from the others may in fact be too low. We prefer here to be conservative in our claimed region of allowed values and leave it to future study for more stringent conclusions.

Models such as those presented here do not in general predict a significant change in dipole asymmetry with collision energy. By extracting a best value of $\varepsilon_1$ from these LHC data combined with hydrodynamic calculations of lower energy collisions, we can make predictions for Au-Au collisions at RHIC assuming little change in the average dipole asymmetry in a centrality bin. Since the change of $\varepsilon_1$ with collision energy predicted by each current Monte Carlo model is much smaller than the range spanned by the various models, this prediction is more reliable than any obtained by assuming a particular model for the initial conditions. These are presented in Fig. 4. The value of $\varepsilon_1$ at LHC is obtained by taking the best fit to the experimental $v_1$ for $p_T < 1.5$ GeV/c, which is the range where hydrodynamics agrees best with data [29]. Our calculations use $\eta/s = 0.16$ both at LHC and at RHIC, but the extrapolation from LHC to RHIC depends very weakly on the assumed value of $\eta/s$ [30].

These predictions are compatible with the attempted extraction of $v_1$ [17] from a much more limited set of correlation data at 20–60% centrality released by the STAR collaboration, but a dedicated analysis by one of the experimental collaborations at RHIC will allow for a much more precise test, including centrality dependence.

IV. CONCLUSIONS

We have shown that the first Fourier component of the two-particle azimuthal correlation measured at LHC, $v_{1\Delta}$, can be explained by collective flow, much in the same way as higher harmonics, after the correlation from momentum conservation is accounted for. We have thus obtained the first measurement of directed flow, $v_1$, at midrapidity at the LHC. This experimental result was compared with the first viscous hydrodynamic calculation of directed flow. $v_1$ was found to have a weaker dependence on viscosity than $v_2$ and $v_3$, which allows for the first time a tight constraint to be placed directly on the geometry and fluctuations of the early-time system, and which rules out certain current theoretical models. The extracted values of the dipole asymmetry of the initial conditions then allow for predictions to be made for directed flow at midrapidity in lower-energy collisions at RHIC, which were presented.

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