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FLOW COMPONENTS AND INITIAL STATE CM FLUCTUATIONS*

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At the LHC, the strong collective flow is observed in Pb+Pb collisions, as shown by the azimuthal correlations in the transverse-momentum distributions of the produced particles. We calculate flow components in a relativistic fluid dynamical model at constant time freeze out (FO) for massless equilibrated post FO pion gas. Our results indicate that at the LHC the v_1 flow is expected to peak at forward rapidities, at the same side and direction as the projectile residue. The effect of initial state center-of-mass rapidity fluctuations is taken into account. In order to better study the transverse-momentum flow dependence, we suggest a new "symmetrized" $v_1^{\rm S}$ function; and we also propose a new method to disentangle global v_1 flow from the contribution generated by the random fluctuations in the initial state. The result is sensitive to the global initial state, where different parameterizations exist.

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The strong elliptic flow effect was indicated by the LHC heavy ion experiments [1]. This effect exceeded the results obtained by the former lower energy measurements. Strong equilibration and thermalization phenomenon was expected to arise in the collisions. The directed flow v_1 was also measured by ALICE six months later [2].

RHIC and LHC results indicate that the flow has two origins [2, 3]: *(i)* the global collective (GC) flow correlated with the reaction plane of the event (EP), and *(ii)* the random fluctuation (RF) flow of all v_n varieties, where the corresponding symmetry axes (*e.g.*, for v_1 and v_3) have no correlation with the reaction plane EP, instead they are observed with respect to a participant plane (PP) event-by-event (EbE) [4,5]. The participant planes are different for the neighboring flow harmonics.

Here, we discuss the behavior of the first type, *(i)*, of these flow phenomena, the GC flow, which is the weakest at RHIC and LHC energies. We will also discuss, how to separate the global v_1 flow, from the one produced by EbE RFs of the initial state, *(ii)*. Fluctuations, which do not follow the required symmetries can be removed, but this may not be sufficient. If we know the general features of fluctuations, this may help. If we know the features of some well defined disturbing effects, we might exploit this to our advantage.

Collective global flow in non-central collisions leads to the asymmetric azimuthal distributions, quantified by the functions $v_n(y, p_{\rm t})$ in the expansion

$$\frac{d^3N}{dy dp_{\rm t} d\phi} = \frac{1}{2\pi}\frac{d^2N}{dy dp_{\rm t}}\left[1 + 2v_1(y,p_{\rm t})\cos(\phi) + 2v_2(y,p_{\rm t})\cos(2\phi) + \cdots\right] , \tag{1}$$

where y is the rapidity, $p_{\rm t}$ is the transverse momentum, and ϕ is the azimuthal angle in the transverse plane with respect to the impact parameter vector, $\vec{b}$. The observed large $v_2(p_{\rm t})$ has important consequences. It indicates that QGP is strongly interacting and, at the same time, it also indicates that QGP is a nearly perfect fluid with minimal shear viscosity at the phase transition point [6, 7].

In a recent perfect-fluid dynamical model calculation [8], with small numerical viscosity and dissipation (see Fig. 1), we have shown that the energy density distribution in the reaction plane, 6–8 fm/c after the formation of fluid dynamics, is strongly rotated with respect to the initial configuration, due to the large initial angular momentum, so that the direction of strongest transverse expansion points to $\Theta = 75^\circ (255^\circ)$. Thus, the upward moving matter is moving now forward and the downward moving matter backward, in contrast to what happens at RHIC and SPS energies. The substantial angular momentum is most visible at large impact parameters, $b > 0.6\, b_{\rm max}$, or for centrality exceeding 50%.

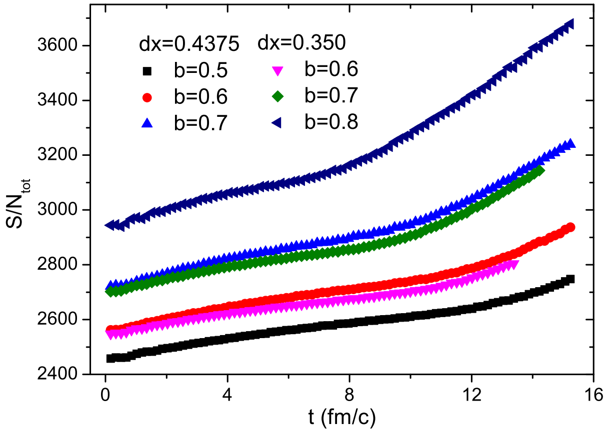

Fig. 1. The entropy per baryon estimated in the fluid-dynamics (FD) model with the cell sizes $dx = 0.4375$–0.35 fm, and different impact parameters $b = 0.5$–$0.8\, b_{\max}$. The value of entropy per baryon increases with larger cells, because the numerical viscosity is larger in bigger cells. At late stages ($t > 8$–$10\,\mathrm{fm}/c$) the matter is dilute; in a large part of the volume the pressure vanishes and the applicability of the FD approach gradually ceases.

In the simplest approach, we assume a constant time FO hypersurface. The transition from pre FO QGP to post FO ideal massless pion Jüttner gas is calculated according to the method described in Ref. [9], satisfying the conservation laws. In this way, for each fluid cell, i, we obtain a post FO flow velocity, $\vec{v}^i = (\vec{v_{\rm t}}^i, v_z^i)$, and temperature, T^i, as parameters of the gas. We calculate the flow observables from the contribution of these post FO contributions cell by cell.

The flow parameters, for example v_2, can be calculated from the final post FO distribution by the Cooper–Frye formula. Assuming a constant time FO hypersurface, we obtain simple expressions for final observables, following the arguments of Refs. [10, 11]. Thus the expression for the transverse momentum dependence of the flow is

$$v_n\left(p_\perp\right) = \frac{\sum\limits_{i=1}^{N} V_i A_i B\left(i, m_\perp^i\right) I_n\left(\gamma^i v_\perp^i p_\perp / T_i\right) \cos n\phi_0^i}{\sum\limits_{i=1}^{N} V_i A_i B\left(i, m_\perp^i\right) I_0\left(\gamma^i v_\perp^i p_\perp / T_i\right)}\,, \tag{2}$$

where

$$A_i = \frac{1}{(2\pi\hbar)^3} \exp\left(\frac{\mu^i}{T}\right) = \frac{n_i}{4\pi m^2 T_i K_2(m/T_i)}\,,$$

μ^i is the chemical potential of the given particle type in the cell i, n_i is the density in the cell, u_i^μ is a cell flow 4-velocity: $u_i^\mu = \gamma^i(1, v_x^i, v_y^i, v_z^i) = \gamma^i(1, \boldsymbol{v}_\perp^{\boldsymbol{i}}, v_z^i)$, $m_\perp^2 = m^2 + p_\perp^2$, and T_i is a temperature of the given cell. Furthermore,

$$B(m_\perp) = \frac{2m_\perp}{\sqrt{1-v_z^2}} K_1\left(\frac{\gamma m_\perp\sqrt{1-v_z^2}}{T}, \frac{\gamma m_\perp}{T}\right) - \frac{2m_\perp|v_z|e^{-\frac{\gamma p_\mathrm{t}}{T}}}{1-v_z^2}\,,$$

where $K_n(z,w) = \frac{2^n n!}{(2n)!} z^{-n} \int_w^\infty dx(x^2 - z^2)^{n-1/2} e^{-x}$ is the modified Bessel function of the second kind.

The calculated $v_2(p_\mathrm{t})$ distributions are similar to the experimental trends both in the magnitude and the centrality dependence. The p_t-dependence is also similar, especially at the smaller centralities.

As v_1 is an antisymmetric function of y, the y-integrated $v_1(p_\mathrm{t})$ value must vanish. In our calculation this is realized to an accuracy better than 10^{-16}. Considering this obvious asymmetry, we propose to construct a symmetrized function, v_1^S, reversing the $\vec{p}_\mathrm{t}$ direction of backward going $(y < 0)$ particles. In this way, we get a non-vanishing $v_1^\mathrm{S}(p_\mathrm{t})$ function, which will be less sensitive to the initial state fluctuations,

$$v_1^\mathrm{S}(p_\perp) = \frac{\sum\limits_i^{\text{cells}} 2D\left(\vec{v}^{\,i}, T^i, p_\perp\right) I_1\left(\gamma^i v_\mathrm{t}^i p_\perp / T^i\right) \cos\left(\phi_0^i\right)}{\sum\limits_i^{\text{cells}} B\left(\vec{v}^{\,i}, T^i, p_\perp\right) I_0\left(\gamma^i v_\mathrm{t}^i p_\perp / T^i\right)}\,, \tag{3}$$

where $D(\vec{v}, T, p_\perp) = e^{-\gamma p_\perp / T} \frac{v_z}{1-v_z^2} \frac{T}{\gamma}$. The $v_1^\mathrm{S}(p_\perp)$ parameter calculated in this way is shown in Fig. 2.

The ALICE team has made a symmetry analysis of the v_1 flow components. The *even* and *odd* rapidity combinations gave almost identical $v_1(p_\mathrm{t})$ distributions [2], indicating that the global azimuthal symmetry does not influence the measured data, thus the measured azimuthal asymmetry must originate from random initial fluctuations. These results were based on data with 0–80% centrality percentage, where the central and semi-central collisions may show azimuthal fluctuations, which originate exclusively from random fluctuations. However, we can gain information about the p_t dependence of the global directed flow, if we repeat the same analysis, *i.e.*, we make separation into *even* and *odd* components, for the $v_1^\mathrm{S}(p_\mathrm{t})$ function introduced above in Eq. (3).

We have also evaluated the rapidity dependence of the v_1 flow component. Due to the sufficiently strong rotation of the initial state at the present LHC energy, the earlier "anti-flow" peak rotates forward, before the expansion overwhelms the rotation effect, and so the v_1 flow peak appears at small, but forward rapidities.

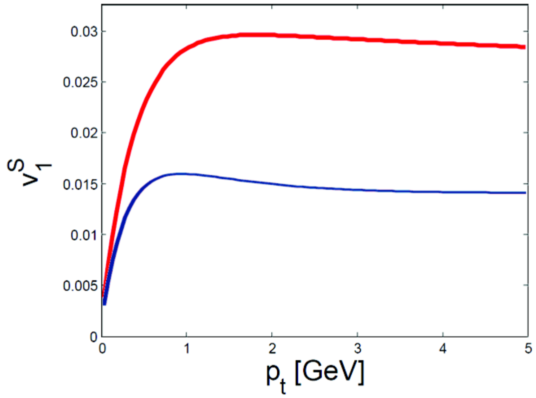

Fig. 2. The $v_1^{\rm S}$ parameter calculated for the ideal massless pion Jüttner gas, *versus* the transverse momentum $p_{\rm t}$ for $b = 0.5\,(0.7)\,b_{\rm max}$ at the FO time $t = 10\,(8)$ fm/c, shown as the thin/blue (thick/red) line. The magnitude of $v_1^{\rm S}$ is increasing with the impact parameter and it is about 3% at $b = 0.7\,b_{\rm max}$.

The calculated v_1 parameter *versus* the rapidity y is shown in Fig. 3. As we can see the v_1 is relatively large and easily measurable in the experimental rapidity range $|y| \leq 0.8$, reaching a peak of 26% at $y = \pm 0.5$. The most important change with respect to the similar simulations for RHIC [13] is that the v_1 now peaks in forward direction, *i.e.*, the positive (negative) peak appears now at positive (negative) rapidity.

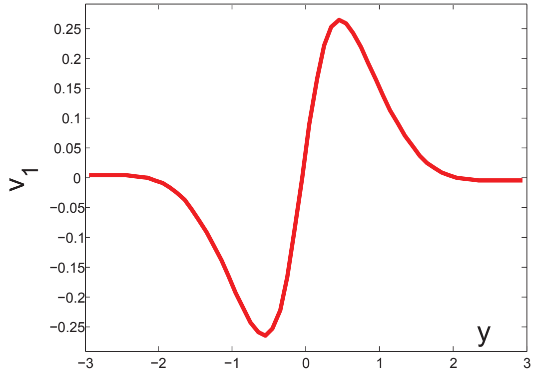

Fig. 3. The v_1 parameter calculated for ideal massless pion Jüttner gas *versus* the rapidity y for $b = 0.7 b_{\rm max}$ at $t = 8$ fm/c FO time. The curve represents semi analytical calculations. The v_1 peak appears at positive rapidity, in contrast to lower energy calculations and measurements. This is a consequence of the stronger rotation of the expanding system at higher beam energy.

At lower energies, in the same FD model calculations we obtained that the v_1 peaks in the backward direction (*3rd-flow component*) [12, 13], with a magnitude of about 5% and 2–3% for 158 and $65+65A$ GeV energies, respectively. The position of the peaks also moved from $|y| \approx 1.5$ to $|y| \approx 0.5$ with the energy increasing from SPS to RHIC. Experimentally, the 3rd-flow component was indeed measured at these energies [12, 14], although the peak values were smaller. Especially at the RHIC energies, where the highest values were $v_1 \approx 0.6\%$ and 0.2% for for $65+65$ and $100{+}100A$ GeV energies, respectively. The peaks appeared at $|y| \approx 1$ around the far end of the acceptance of the central TPC. Thus, at RHIC the v_1 magnitude was about 5 times smaller than the FD prediction. Also, the move towards the more central rapidities was weaker in the experiment than in FD calculations.

The reason for such a disagreement is the effect of initial state fluctuations, which may be decisive in the case of v_1 due to the sharp change around $y = 0$.

Initial state fluctuations may arise from the event-to-event fluctuations of nucleon positions in the transverse, participant plane. Fluctuations may also arise from individual nucleon–nucleon collisions in an event, so that even if a projectile nucleon is within the transverse domain of participants, it may not collide with any of the target nucleons, and may not become a participant. The effect of these fluctuations on different flow component has been recently analyzed, see for example [15, 16].

In both cases, the experimental cuts on the rapidity range lead to an increase of the asymmetry. Now, it should not be forgotten that $v_2(p_{\rm t})$ and $v_1^{\rm S}(p_{\rm t})$, constructed from the observables within the limited rapidity range, will be affected by the initial CM rapidity fluctuations. One can expect that the $v_1^{\rm S}(p_{\rm t})$ will be very much reduced, because, as we have seen, the CM rapidity fluctuations smooth out the strong v_1 peaks at central rapidities and strongly reduce the v_1 magnitude to be integrated up.

Interestingly, the initial $y_{\rm CM}$-fluctuations lead to some increase of the elliptic flow, $v_2(p_{\rm t})$, putting it in a reasonable agreement with the ALICE data [1], see Fig. 4 and, please, note that no fine-tuning was done. At the same time, $y_{\rm CM}$-fluctuations strongly reduce $v_1^{\rm S}(p_{\rm t})$. Thus, we predict for the LHC the $v_1^{\rm S}(p_{\rm t})$ flow parameters to be about 0.5–1%.

Other works have addressed the directed flow problem at RHIC energies [17, 18]. In these works, the initial state was not obtained from a dynamical model but these were parameterizations based on some assumptions. The initial flow velocity distributions were taken to be longitudinal Bjorken scaling flow solutions, identical at each point of the transverse plane. The transverse mass distribution was determined based on the Glauber model, while the longitudinal distribution was parametrized in different ways and this determined the angular momentum of the of the initial configuration.

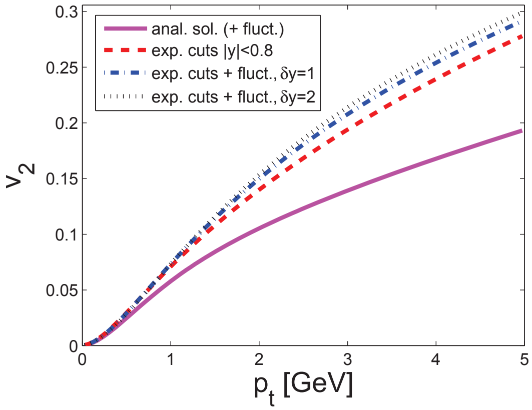

Fig. 4. The v_2 parameter calculated for ideal massless pion Jüttner gas, *versus* the transverse momentum $p_{\rm t}$ for $b = 0.7 b_{\rm max}$, at $t = 8\,{\rm fm}/c$ FO time. The magnitude of v_2 is comparable to the observed v_2 at 40–50% centrality. See the text for more explanations of different curves.

Both models gave a forward peaking directed flow for RHIC energies (where the experiments observed the anti-flow). In Ref. [18] this initial state was "tilted", and this could already reproduce the experimental anti-flow. The problem is that these parametrized states can hardly be reproduced in dynamical models starting from the pre-collision space-time configuration.

Our FD simulations of the LHC heavy ion collisions suggest that the collective directed flow $v_1(y)$ and a newly introduced $v_1^{\rm S}(p_{\rm t})$ function can and should be measured [19], although these are strongly suppressed due to initial state $y_{\rm CM}$-fluctuations (see Fig. 2). For the first time in hydrodynamical calculations we see that the v_1 global flow can change the direction to forward, in contrast to what happened at lower energies. This is a result of our tilted and moving initial state [20], in which the effective "angular momentum" from the increasing beam momentum is superseding the expansion driven by the pressure. We have also proposed a new method to distinguish contributions to $v_1(p_{\rm t})$ from global flow *(i)* and from random fluctuations in the initial state *(ii)*. The method is based on $v_1^{\rm S}(p_{\rm t})$ function.

REFERENCES

[1] K. Aamodt *et al.* [ALICE Collaboration], *Phys. Rev. Lett.* **105**, 252302 (2010).

[2] R. Snellings [ALICE Collaboration], *J. Phys. G* **38**, 124013 (2011);
I. Shelyuzenkov [ALICE Collaboration], *J. Phys. G* **38**, 124167 (2011);

G. Eyyubova [ALICE Collaboration], poster at the 22nd International Conference on Ultra-Relativistic Nucleus–Nucleus Collisions (Quark Matter 2011), Annecy, France, May 23–28, 2011.

[3] B.I. Abelev *et al.* [STAR Collaboration], *Phys. Rev. Lett.* **101**, 252301 (2008).

[4] N. Borghini, P.M. Dinh, J.Y. Ollitrault, *Phys. Rev.* **C64**, 054901 (2001); J. Schukraft, presentation at the 22nd International Conference on Ultra-Relativistic Nucleus–Nucleus Collisions (Quark Matter 2011), Annecy, France, May 23–28, 2011.

[5] B. Schenke *et al.*, *J. Phys. G* **38**, 124169 (2011).

[6] P.K. Kovtun, D.T. Son, A.O. Starinets, *Phys. Rev. Lett.* **94**, 111601 (2005).

[7] L.P. Csernai, J.I. Kapusta, L.D. McLerran, *Phys. Rev. Lett.* **97**, 152303 (2006).

[8] L.P. Csernai, V.K. Magas, H. Stöcker, D.D. Strottman, *Phys. Rev.* **C84**, 024914 (2011).

[9] Yun Cheng *et al.*, *Phys. Rev.* **C81**, 064910 (2010).

[10] L.P. Csernai *et al.*, *Nucl. Phys.* **A834**, 261c (2010).

[11] P. Huovinen *et al.*, *Phys. Lett.* **B503**, 58 (2001).

[12] L.P. Csernai, D. Röhrich, *Phys. Lett.* **B458**, 454 (1999).

[13] B. Bäuchle *et al.*, *J. Phys. G* **34**, s1077 (2007).

[14] G. Wang *et al.* [STAR Collaboration], *J. Phys. G* **34**, s1093 (2007).

[15] F.G. Gardim *et al.*, *Phys. Rev.* **C83**, 064901 (2011).

[16] G.Y. Qin, H. Petersen, S.A. Bass, B. Mueller, *Phys. Rev.* **C82**, 064903 (2010); H. Petersen *et al.*, *Phys. Rev.* **C84**, 054908 (2011), [`arXiv:1105.0340v2 [nucl-th]`]

[17] A. Adil, M. Gyulassy, *Phys. Rev.* **C72**, 034907 (2005).

[18] P. Bozek, I. Wyskiel, *Phys. Rev.* **C81**, 054902 (2010).

[19] D. Röhrich [ALICE Collaboration], private communication.

[20] V.K. Magas, L.P. Csernai, D.D. Strottman, *Phys. Rev.* **C64**, 014901 (2001); *Nucl. Phys.* **A712**, 167 (2002).