# Generation of Higher Flow Harmonics in Pb+Pb Collisions at LHC in HYDJET++ model

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**Abstract.** The observed particle distributions in Pb+Pb collisions at LHC are under investigation. Monte Carlo simulations of the azimuthal anisotropy i.e. flow, and transverse momentum spectra provide insights in hadron genesis and in medio scattering. Simulations are made using the HYDJET++ model, which is based on parameterization of soft processes and generation of hard physics. The second and third event planes are implemented, thus generating the second and third order flows which are believed to provide the largest part of the observed azimuthal distribution. The elliptic and triangular flows are simulated in good agreement with experimental data for ($p_T < 3.5$) GeV/c and centralities $0 - 50\%$, along with the associated transverse momentum spectra, which also displays a high degree of precision. Also, flow projections are investigated, which further differentiates the observables. These simulations can be further elaborated upon, thus investigating multiparticle and multiplane (nonlinear) correlations.

## 1. Introduction

The particle distributions in relativistic heavy ion collisions are under investigation. Particle spectra provide information regarding fundamental processes such as hadronization, phase transitions; and *in medio* scattering [1–4]. In addition to the particle spectra; the azimuth is a direct observable which carries coherence information related to *in praegressus* processes. In present paper, the main topic is the yield anisotropy. The azimuthal part of the observed momentum distribution is commonly presented as the Fourier expansion [5, 6]

$$E\frac{d^3N}{d^3p} = \frac{1}{\pi}\frac{d^2N}{dp_T^2dy}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n\left(\phi - \Psi_n\right)\right]. \tag{1}$$

Here, $\phi$ and $\Psi_n$ are the particle azimuth and the n$^{\text{th}}$ event plane angle. The total momenta is p and the transverse momenta and rapidity are denoted by $p_T$ and y. The energy is denoted by E. From (1); the particle azimuth is characterized by the Fourier coefficients $v_n$, i.e. *flow*. The flow displays characteristics depending on order n and is to a large part determined by the initial conditions, which are characterized by *eccentricity* ($\epsilon$), with initial state event plane $\phi_n$ and transverse radius r,

$$\epsilon_n = -e^{-i\phi_n}\frac{\langle r^n e^{i\phi}\rangle}{\langle r^n\rangle}. \tag{2}$$

The eccentricity thus corresponds by the order n to the flow terms in (1).

## 2. Method

The investigation of azimuthal anisotropy begins with the simulation of the first two modes: $v_2$ and $v_3$; which provides the foundation for the azimuthal part [7] of (1). In present model, i.e. HYDJET++ [8–10], the expanding fireball is modulated by *in medio* collisions [11–13] and radiation [14, 15]. Also, shadowing effects [16] are accounted for. In addition; hydro dynamical processes are parameterized on freeze-out hyper surfaces of the expanding fireball [17, 18]; and forms in superposition with hard particles the simulated distributions. In order to simulate the azimuthal anisotropy; the fireball transverse radius "R"

$$R\,(b,\phi) = R_f\,(b)\,\frac{\sqrt{1-\epsilon^2(b)}}{\sqrt{1+\epsilon(b)\cos 2\phi}}, \tag{3}$$

is modulated in terms of azimuth $\phi$ and the impact-parameter dependent model-eccentricity $\epsilon(b)$; with $R_f$ as the fireball RMS radius. Also, the linear transverse rapidity profile, and thus the particle velocity are modulated in terms of a second model parameter $\delta\,(b)$. The modulation of the transverse velocity $u^T$ is

$$u^x = \sqrt{1+\delta\,(b)}\sinh\tilde{\rho_u}\cos\phi, \quad u^y = \sqrt{1-\delta\,(b)}\sinh\tilde{\rho_u}\sin\phi, \tag{4}$$

where the transverse rapidity is further modulated by event plane angles, e.g. $\tilde{\rho_u} = \tilde{\rho_u}(\Psi_3)$.

## 3. Results

The investigation of evolutionary processes is done by relating different projections of the azimuthal anisotropy and particle spectra, thus investigating in-collisional processes. The simulations are array run on the UiO cluster ABEL [1] with an ATLAS setting and compared to available experimental projections. First; the transverse momentum spectra are simulated for unidentified particles and displayed with experimental data in addition to a hydro dynamical projection (Fig.1). The simulated particle spectra are seen to agree with experimental data [19]

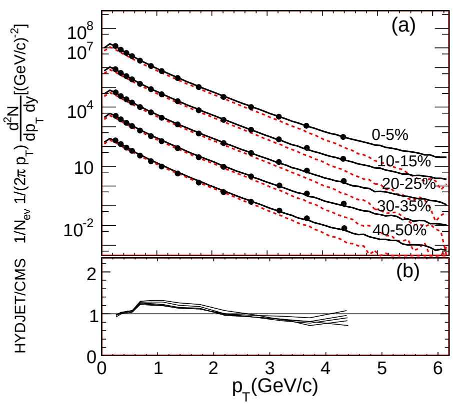


**Figure 1.** Transverse momentum spectra for unidentified particles (——) and hydro dynamical particles (- - - -). Particle spectra are simulated for:$\sigma/\sigma_{geo} = 0-5\%$; $\sigma/\sigma_{geo} = 10-15\%$; $\sigma/\sigma_{geo} = 20-25\%$; $\sigma/\sigma_{geo} = 30-35\%$; and $\sigma/\sigma_{geo} = 40-50\%$. Experimental data [19] are denoted by ●. Comparison between experimental data and simulations in the lower pane.

[1] The Abel cluster is owned by the University of Oslo and the Norwegian metacenter for High Performance Computing (NOTUR); and operated by the Department for Research Computing at USIT, the Oslo University IT-Department.

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for all simulated centralities. The hydro dynamical projection displays thermal characteristics for the soft transverse momentum regime. In contrast; the power law characterized fragmentation regime is observed for the transverse momentum regime 2 GeV/c $\leq p_T$.

Further, the ratios of the sixth order triangular- and elliptic factorizations are investigated. Agreement with experimental data is seen for the regime $p_T \leq 3.5$ GeV/c in Fig.2 (a). Deviations are seen for central collisions; although qualitative behaviour is seen to be reproduced. The magnitude of the ratio is here seen as strongly centrality dependent due to the rising ellipticity (coherency), which provides for a suppressed ratio. The flow is more prominent in the triangular plane for the soft transverse momentum regime; and for higher transverse momentum ($\sim 2$ GeV/c), the elliptic plane provides coherency, thus depressing the ratio. This depression is seen to depend on centrality and thus the level of fragmentation. The higher transverse momentum regime (2.5 GeV/c$\leq p_T$ GeV/c) displays a rising trend; thus moving toward a triangular-like flow. The hydro dynamical projection of the $v_3^2/v_2^3$ ratio of Fig.2 (b) displays a ratio which is

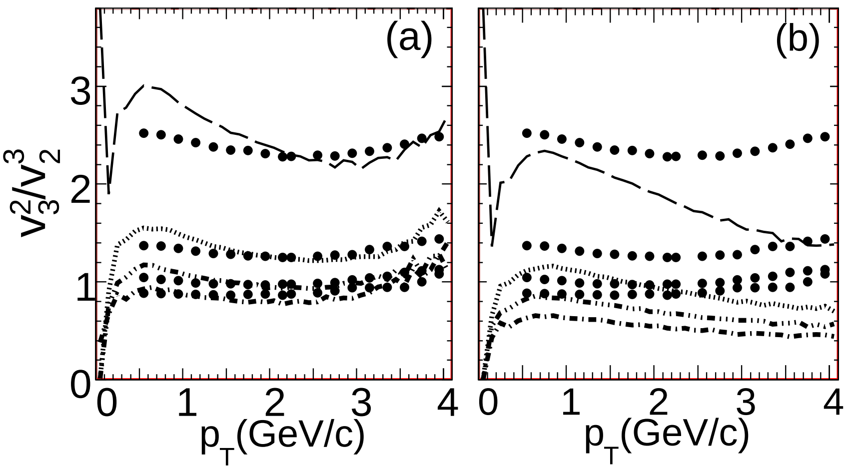


**Figure 2.** Ratio $v_3^2/v_2^3$ for unidentified- (a); and *hydro dynamical* particles (b). Experimental data for inclusive particles are included for comparison [20] and are denoted by ●. Simulations are made for: $\sigma/\sigma_{geo} = 10 - 20\%$ (— — —); $\sigma/\sigma_{geo} = 20 - 30\%$ (······); $\sigma/\sigma_{geo} = 30 - 40\%$ (— · · —); and $\sigma/\sigma_{geo} = 40 - 50\%$ (— · —).

differentiated in transverse momentum; thus not displaying scaling. From the hydro dynamical projection; hard processes are now seen to contribute to the approximate scaling; thus, the elliptic plane is seen to provide coherency for the hydro dynamical evolution. Also from the plots; the ratio is seen to be less dependent on hydrodynamics for more peripheral hits, thus deviating from scaling to a lesser degree.

## 4. Discussion and Conclusion

The finer coherence dependent structure observed in flow, makes flow a main observable of heavy ion collisions in combination with the particle spectra. The azimuthal anisotropy provides information regarding initial conditions, *in medio* processes; and hadronization processes. The agreement with experimental spectra for the soft regime, using a parameterized Cooper-Frye freeze-out [17, 18], is high (Fig.1). The postulated extensive hydrodynamics provides an exponential hydrodynamic projection; which is calculated on the fireball freeze-out hyper surfaces. The agreement between simulations and experimental data for the high transverse momentum regime works in favour of the present model which implements jet production by hard vertex production in the PYTHIA model [21]; which is subsequently quenched by the PYQUEN [8, 9] part of HYDJET++. The flow ratio under investigation, in Fig.2, displays momentum space characteristics, thus carrying information regarding particle production mode. From the plots, the jets are seen to provide for the fluctuating triangular plane; thus, the ratio displays sensitivity to fluctuations and jets. Also, the ratios dependence on production mode is seen to be connected to initial geometry, thus suppressed by the coherent elliptic plane. Relatively, the ratio is seen to be more dependent on fragmentation for peripheral hits. In conclusion: through the simulated azimuthal anisotropy and particle spectra; *in medio* scattering is seen to provide greater medium effects in central collisions in contrast to the more fragmentation characterized peripheral collisions. Thus, media properties and processes are manifesting themselves in the simulations which are related to the laboratory observables.

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