Features of triangular flow of strange and non-strange hadrons at LHC

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Abstract. Triangular flow of strange and non-strange hadrons in Pb+Pb collisions at LHC energies is studied within the HYDJET++ model, which combines hard processes in a hot and dense partonic medium with parametrized hydrodynamics. Together with an extensive table of resonances, this circumstance enables us to investigate (i) the interplay between hard and soft processes and (ii) between jets and final-state interactions. Jets are found to be the main reason for violation of the NCQ scaling for $v_3$ at LHC, whereas decays of resonances improve the scaling fulfillment. Comparison with the experimental data is performed.

1. Introduction

Anisotropic flow of secondary particles and quenching of jets, traversing the hot and dense medium, are among the few signals especially sensitive to creation of quark-gluon plasma (QGP) in ultra-relativistic heavy-ion collisions. These two phenomena are usually considered separately as a soft and a hard signal, respectively. In previous studies \cite{1, 2, 3} we pointed out that the interplay between the soft hydro-like processes and the jets might have important consequences for the particle anisotropic flow at transverse momentum $p_T \geq 1$ GeV/$c$. For our analysis the HYDJET++ model \cite{4, 5} was employed. The model relies on parametrized ideal hydrodynamics with more than 360 possible hadronic states and resonances, including charmed hadrons, after the chemical freeze-out accompanied by treatment of hard jets propagating in the QGP. In the last case both collisional and radiative energy losses are taken into account \cite{6}. Below we focus on implementation of the anisotropic flow components in HYDJET++.

The angular distribution of hadrons in the azimuthal plane is decomposed in the Fourier series as \cite{7}

\begin{align}
E \frac{d^3N}{d^3p} &= \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos \{ n(\phi - \Psi_n) \} \right], \\
v_n &= \langle \cos \{ n(\phi - \Psi_n) \} \rangle,
\end{align}

(1)

(2)
with $p_T$, $y$ and $\phi$ being the transverse momentum, the rapidity and the azimuthal angle of a particle, respectively. $\Psi_n$ is the angle of the reaction plane of $n$-th harmonic, and the coefficients $v_n$ are dubbed directed flow ($v_1$), elliptic flow ($v_2$), triangular flow ($v_3$), and so forth. Experiments show that $v_1$ is extremely weak in heavy-ion collisions at LHC, therefore, we concentrate on $v_2$ and $v_3$. To take into account both ellipticity and triangularity of the initial state, resulting into appearance of corresponding flow harmonics in the particle momentum distribution, HYDJET++ utilizes the following typical parametrizations of the freeze-out hypersurface of the fireball produced in a collision of two similar nuclei with the impact parameter $b$.

$$R(b, \phi) = R_{\text{ell}}(b, \phi) \{1 + \epsilon_3(b) \cos [3(\phi - \Psi_3)] \} \quad (3)$$

$$R_{\text{ell}}(b, \phi) = R_{\text{fo}}(b) \frac{\sqrt{1 - \epsilon^2(b)}}{\sqrt{1 + \epsilon(b) \cos 2\phi}} \quad (4)$$

Here $R_{\text{fo}}(0)$ is the model parameter that determines the scale of the fireball transverse size at freeze-out, and two spatial anisotropy parameters, $\epsilon(b)$ and $\epsilon_3(b)$, are responsible for emergence of elliptical and triangular anisotropy, respectively. Our aim is to investigate the influence of hard processes and final-state interactions on the triangular flow of both strange and non-strange hadrons.

2. Results

**Interplay of soft processes and jets.** Lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with centrality $0 \leq \sigma/\sigma_{\text{geo}} \leq 50\%$ are considered. As shown in [8, 9], HYDJET++ provides a good quantitative description of the triangular flow of charged particles within the indicated centrality range, but $v_3$ of hadronic species was not studied yet. Partial triangular flows of $p + \bar{p}$, $\pi^\pm$, $K^\pm$ and $\Lambda + \bar{\Lambda}$ in collisions with centrality $20 - 30\%$ are shown in Fig. 1. Here the plot (a) displays the resulting $v_3$ of particle species as a function of transverse momentum $p_T$, whereas the plots (b) and (c) show, respectively, the triangular flow generated separately in hydro-module and jet-module of the program. The combination of these two processes helps one to understand the origin of the hump-like structure of total $v_3(p_T)$ distributions and also breaking of the mass ordering. Indeed, in pure hydro calculations presented in the middle window $v_3(p_T)$ grows almost linearly at $0.5 \leq p_T \leq 4$ GeV/c, and meson triangular flow is stronger than the baryon one. Although hadrons produced from the fragmentation of jets should carry zero anisotropic flow, they can develop a weak $v_3$ at $p_T \geq 3$ GeV/c because of the well-known jet quenching process. The
reason of the flow falloff at $p_T \geq 2 \text{ GeV}/c$ and simultaneous breaking of the mass ordering is as follows. At small and intermediate transverse momenta spectra of particles are dominated by hadrons produced in soft processes. At higher $p_T$ the spectra are dominated by hadrons from jets. The latter carry weak $v_3$, therefore the total signal drops. The transverse momentum, at which the crossing between soft and hard parts of particle spectrum takes place, increases with rising mass of the particles, thus resulting in crossing of meson and baryon branches of $v_3(p_T)$ at $p_T \geq 2.5 \text{ GeV}/c$.

Figure 2 presents the ratio $v_3^{1/3}(p_T)/v_2^{1/2}(p_T)$ calculated in four centrality bins in comparison with the ATLAS data. The model results and the data agree within the error bars. The ratio seems to be insensitive to transverse momentum in the interval $1 \leq p_T \leq 6 \text{ GeV}/c$, however, the separate ratios of individual contributions of directly produced particles, decays of resonances and jets, such as $v_3^{1/3}(\text{hydro})(p_T)/v_2^{1/2}(\text{hydro})(p_T)$, reveal the dependence on $p_T$, see [10].

**Figure 2.** Ratio $v_3^{1/3}/v_2^{1/2}$ for different centralities in comparison with ATLAS data.

**Figure 3.** $v_3(p_T)$ of directly produced hadrons (open symbols) and the same spectra after the feeddown from resonances (full symbols).

**Final-state interactions: decays of resonances.** Partial $v_3(p_T)$ spectra of only directly produced particles, which are frozen at the freeze-out hypersurface or decoupled from jets, are shown in Fig. 3 together with the spectra obtained after the decays of resonances. The reaction centrality is 20 − 30%. One may note that decays of resonances modify the distributions of all hadrons in a similar way - the maximum of the spectrum increases, and its position is shifted to a bit higher transverse momenta. The most increase is observed for charged pions. In contrast, charged kaons and $\Lambda + \bar{\Lambda}$ demonstrate just moderate rise of their $v_3(p_T)$-maxima of about 15%.

**Number-of-constituent-quark (NCQ) scaling.** The idea behind is to use the $kE_T = m_T - m_0$ dependence of $v_3$ rather than the $p_T$ one, and to divide both $v_3$ and $kE_T$ of a hadron on its number of valence quarks. The distribution functions of elliptic flow of identified hadrons were found nearly coinciding at $kE_T \leq 1 \text{ GeV}$ at RHIC [11, 12]. Since then this phenomenon is called NCQ scaling. Worsening of NCQ scaling at LHC was predicted in [1] and observed later in [13]. Let us analyse the $v_3/n_q$ distributions in HYDJET++ presented in Fig. 4. Top plots show the $v_3/n_q$ of charged pions, charged kaons, (anti)protons and (anti)Lambdas separately for (a) directly produced hadrons, (b) hadrons produced in soft processes and in decays of resonances, and (c) final distributions where all processes are taken into account. The bottom row displays the ratios of distributions to that of (anti)protons. The NCQ scaling of triangular flow certainly
Figure 4. $v_3/n_q(k_{ET}/n_q)$ distributions for (a) directly produced particles, (b) particles produced in hydro-like processes with resonance decays, and (c) all particles. Bottom windows present the ratios to the $p + \bar{p}$ distribution.

holds for hydro-produced hadrons, and decays of resonances make the agreement between the spectra even better by increasing the $p_T$-yields of mesons at $p_T \geq 2.5$ GeV/c. Hadrons from the jets, in contrast, lead to worsening of the scaling.

3. Conclusions
The influence of the interplay between soft and hard processes and final-state interactions on the triangular flow of identified hadrons is studied in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV within the HYDJET++ model. Hadrons emitted by jets dominate the hard part of particle spectrum, thus causing the drop of resulting triangular flow at high transverse momenta, because these hadrons develop almost zero flow. Decays of resonances increase the maxima of $v_3(p_T)$ distributions and shift it to higher $p_T$ values. The number-of-constituent-quark scaling for particle $v_3$ is observed for hadrons produced in soft processes. Hadrons originated from the jet fragmentation carry almost no flow, therefore, the NCQ scaling of $v_3/n_q(k_{ET}/n_q)$ is worsening.

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