PROCEEDINGS OF SCIENCE

Simulation of Hadronic Triangular Flow in Heavy-Ion Collisions

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Study of triangular flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV was performed using HYDJET++ Monte Carlo model. The model combines description of hard scatterings in hot and dense partonic medium with the treatment of soft processes represented by parametrized hydrodynamics. The interplay between jet production and hydrodynamics, as well as the influence of the resonance decays on the triangular flow in AA collisions at RHIC and LHC were studied. It was found that the decays of resonances increase the magnitude of the $v_3(p_T)$ distribution at $p_T \geq 1$ GeV$/c$ and shift its maximum to higher transverse momenta. Resonances also drive the v_3 toward the NCQ scaling fulfilment, whereas jets cause the scaling violation at the LHC.

53rd International Winter Meeting on Nuclear Physics,
26-30 January 2015
Bormio, Italy

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1. Anisotropic flow of particles

The hadronic collective flow is one of the most pronounced signatures of QGP produced in ultrarelativistic heavy ion collisions at the RHIC and at the LHC. Hydrodynamical calculations have shown that the spatial anisotropy of the initial overlap zone of the nucleus-nucleus collisions is transferred into the final state momentum anisotropic flow. The invariant differential cross section can be expanded into a Fourier series w. r. t. reaction plane Ψ_R:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_T\mathrm{d}p_T\mathrm{d}y}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\varphi-n\Psi_R\right)\right)$$

$$v_n = \langle\cos\left(n\phi-n\Psi_R\right)\rangle$$

where p_T stands for transverse momentum, y denotes rapidity and φ represents azimuthal angle of the particle [1]. At high energies the elliptic flow, defined as the second Fourier coefficient v_2, dominates the Fourier expansion for semi-peripheral and peripheral collisions. With collisions centrality, the contribution of the third Fourier coefficient, triangular flow v_3, becomes more pronounced due to the spatial initial state fluctuations.

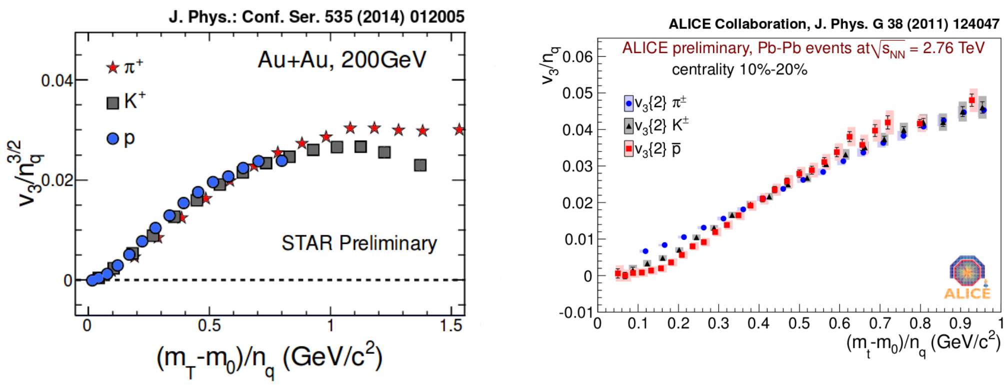
Measurement of flow can, among other, yield information about the characteristics of medium created in collisions. Elliptic flow measured at RHIC suggests creation of ideal liquid with very low viscosity [2]. Triangular flow can unveil new information in such measurements as it enables comparison of multiple parameters depending on viscosity [3].

Number-of-constituent-quark scaling (NCQ) is a prominent feature of elliptic flow at RHIC energies [4]. In other words, all quarks at given p_T carry the same flow independently on the system they are bound in, suggesting that flow is formed at partonic level. Because jets are significantly more abundant and energetic at the LHC than at the RHIC, NCQ scaling is broken at LHC energies. Recent studies have shown that triangular flow scales at the RHIC as $v_3/n_q^{3/2}$ [5], see Fig. 1a. The ALICE experiment investigated scaling v_3/n_q [6] as shown in Fig. 1b. As in the case of v_2, the scaling is broken.

2. HYDJET++

HYDJET++ [7] is a Monte Carlo heavy-ion event generator composed of two independent parts. The soft part of the model is represented by parametrized relativistic hydrodynamics, describing a transition from hot and dense lump of partonic substance to a freeze-out hypersurface on which the partons are generated. The hard part containing jets deals with binary collisions at given impact parameter b. Partons with transverse momenta $p_T > p_T^{min}$ are further evolved further medium, while the rest are hadronised and included in the soft component.

The interplay of the two parts yields realistic shapes of flow distributions. The soft part of distributions is dominated by the hydro-driven soft component, resulting in rise of the distribution and observed mass ordering. The subsequent fall-off resulting in crossing of meson and baryon branches is caused by jets being gradually more prominent with higher p_T.

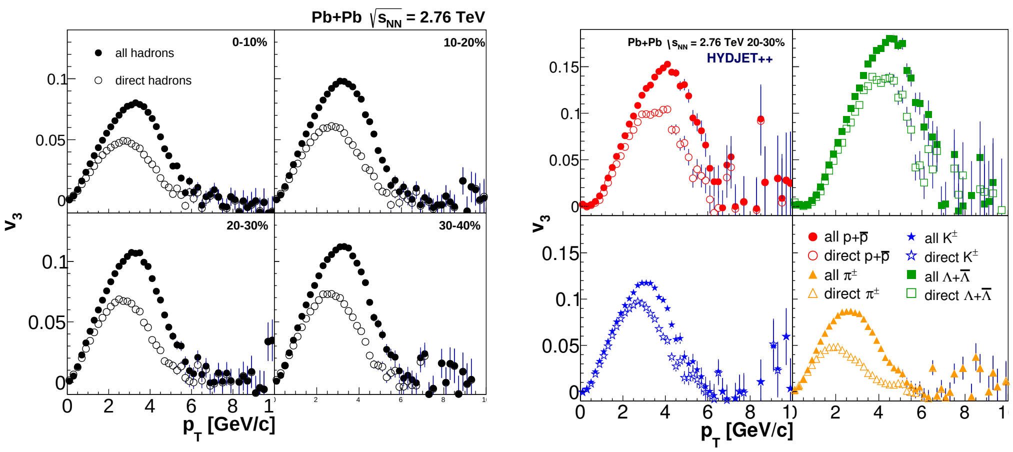


(a) (b)

Figure 1: (a) Number-of-constituent-quark scaling $v_3/n_q^{3/2}$ vs (kE_T/n_q) in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [5]. (b) v_3/n_q vs (kE_T/n_q) in Pb+Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV at centrality 10-20% [6].

3. Triangular flow at the LHC

We have studied the effect of final-state interactions on triangular flow in Pb+Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV. Comparison between the flow distributions of direct hadrons, i. e. hadrons produced directly from the medium, and all hadrons recorded in the event is shown in Fig. 2a.



(a) (b)

Figure 2: Pb+Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV in HYDJET++. (a) Triangular flow for all hadrons (full circles) and for directly produced hadrons (open circles). (b) Triangular flow of protons (red circles), lambdas (green squares), charged kaons (blue stars) and charged pions (yellow triangles). Full symbols denote flow of all particles produced in the event, open symbols show flow of direct particles only.

HYDJET++ describes the LHC data quite successfully [8]. Triangular flow of charged particles changes rather weakly with centrality, which is in agreement with experimental data [3]. The magnitude of flow in maximum is significantly increased by decays of resonances, the maximum is also shifted into higher p_T by about 10% of the original value. Fig 2b portrays the comparison of direct and total flow distribution at 20-30% centrality window for different hadron species separately, namely protons, lambdas, kaons and pions. The effect of resonance decays is strongest in case of the lightest particles, i. e. pions, while heavier particles such as lambdas are only marginally affected.

Preliminary results from LHC suggest that the NCQ scaling for v_3 is broken [6]. Scaling $v_3/n_q(kE_T/n_q)$ and its changing due to resonance decays has been studied. According to HYDJET++ calculations, shown in Fig. 3, the scaling seems to be broken indeed. However the decays of resonances drive the distributions towards scaling fulfilment.

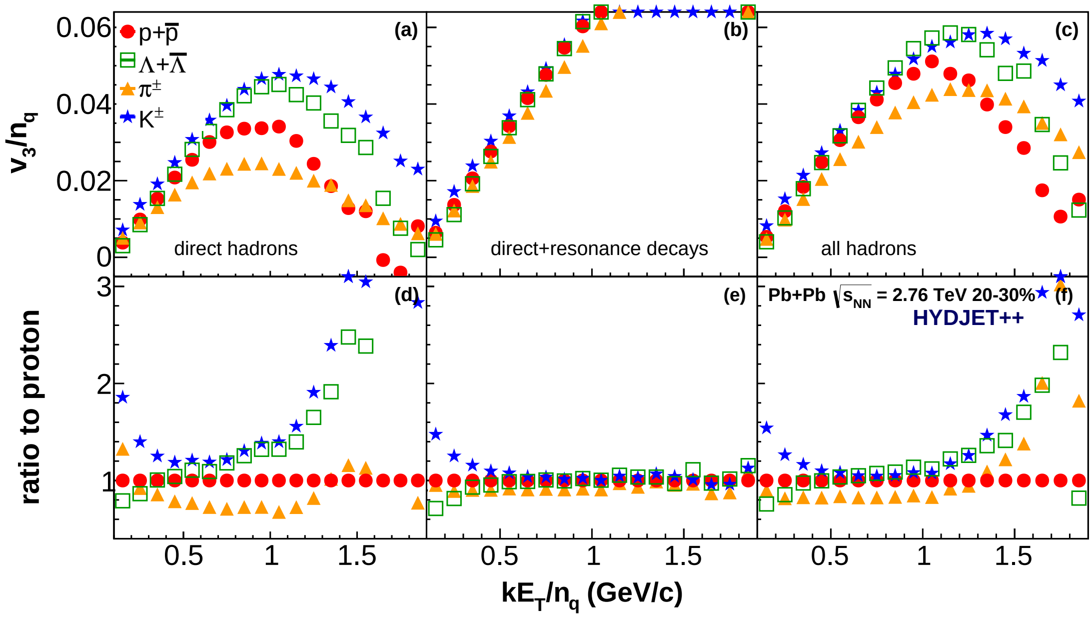


Figure 3: v_3/n_q vs kE_T/n_q in Pb+Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV in HYDJET++. (a) Direct hydro+jets , (b) direct+from decays of resonances and (c) total distributions for protons (red circles), lambdas (green open squares), charged kaons (blue stars) and charged pions (yellow triangles). (d), (e) and (f) show the respective three distributions divided by the corresponding proton distribution.

4. Triangular flow at the RHIC

Triangular flow at RHIC energies has been also investigated. v_3 of protons, charged kaons and charged pions in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is displayed in Fig. 4. While the proton and pion distributions agree rather well with STAR data [5], the kaons manifest much stronger flow in HYDJET++. Where STAR saw blurring of the meson and baryon branch, HYDJET++ shows a strict branching.

This also affects the results for NCQ scaling observation, see Fig. 5. As in the case of LHC, the direct distributions at RHIC display no scaling behaviour (a, c). Only by counting in the decays of resonances, one obtains a reasonable scaling scenario (b, d).

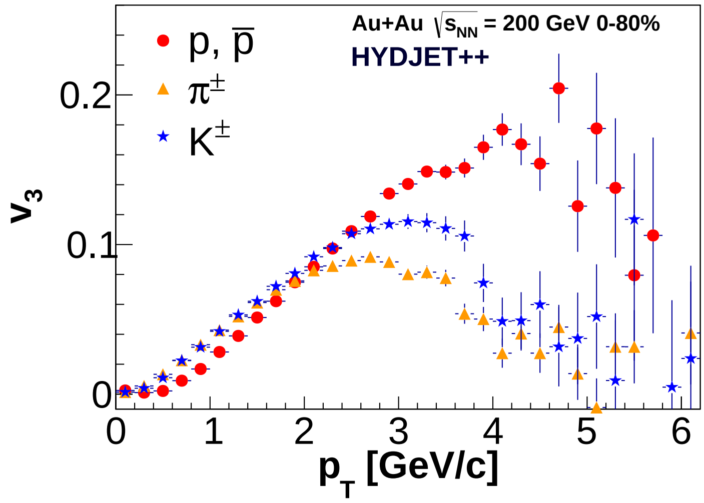


Figure 4: Triangular flow distributions $v_3(p_T)$ for protons (red circles), charged kaons (blue stars) and charged pions (yellow triangles) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in HYDJET++.

5. Conclusions

HYDJET++ provides a good description of triangular flow in relativistic heavy-ion collisions. Resulting shape of distributions comes naturally from the interplay of hydrodynamics and jets. The model enables study of final-state-interaction effects on flow distributions.

Influence of resonance decays on triangular flow at LHC and at RHIC energies was investigated. Decays change significantly the shape of the distribution by increasing the amplitude in the maximum and by its shift to higher p_T region. Resonances also drive flow towards NCQ scaling behaviour. Scaling is still broken at LHC energies, this effect is attributed to the energetic jets

Acknowledgement

This work was supported by the grant of the Grant Agency of Czech Republic n.13-20841S, by the Grant Agency of the Czech Technical University in Prague, grant No. SGS13/215/OHK4/3T/14, and by the European social fund within the framework "Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague", CZ.1.07/2.3.00/30.0034.

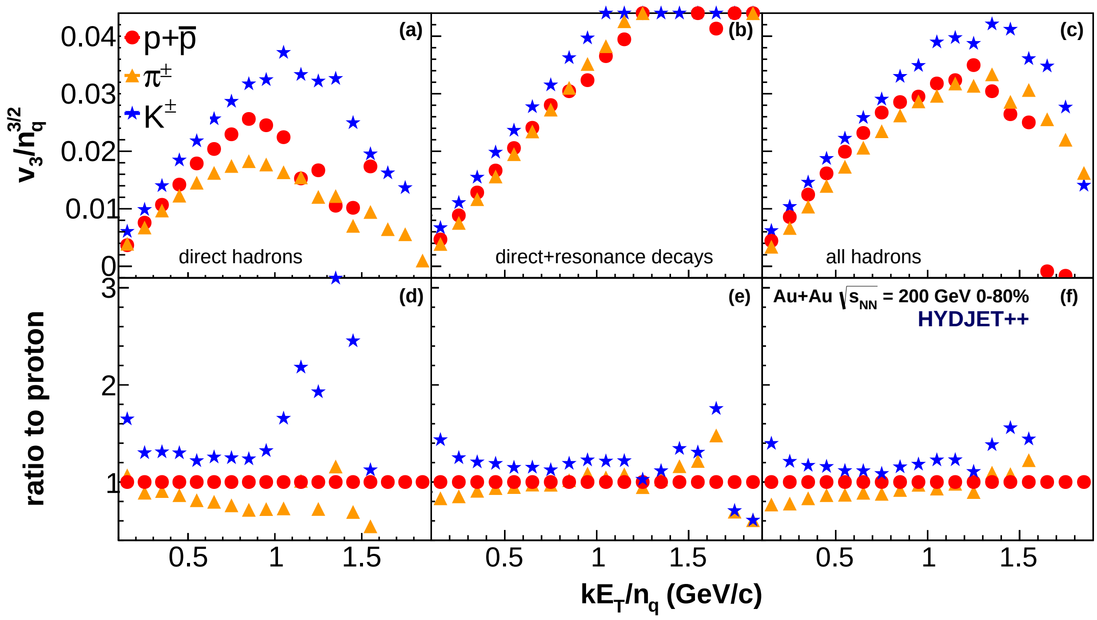


Figure 5: v_3/n_q vs kE_T/n_q in Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV in HYDJET++. (a) Direct hydro+jets , (b) direct+from decays of resonances and (c) total distributions for protons (red circles), kaons (blue stars) and pions (yellow triangles). (d), (e) and (f) show the respective three distributions divided by the corresponding proton distribution.

References

[1] S. Voloshin and Y. Zhang, Z. Phys. C 70 (1996) 665.

[2] M. Gyulassy and L. McLerran, Nucl. Phys. A 750 (2005) 30.

[3] K. Aamodt *et al.* (ALICE Collaboration), Phys. Rev. Lett. 107 (2011) 032301.

[4] A. Adare *et al.* (PHENIX Collaboration), Phys. Rev. Lett. 98 (2007) 162301.

[5] X. Sun (for STAR Collaboration), J. Phys.: Conf. Ser. 535 (2014) 012005.

[6] M. Krzewicki (for ALICE Collaboration), J. Phys. G 38 (2011) 124047.

[7] I. P. Lokhtin *et al.*, Comp. Phys. Comm. 180 (2009) 779.

[8] L. Bravina *et al.* Eur. Phys. J. C74 (2014) 2807.