Directed flow at the STAR-BES (phase I) energies

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The anisotropic distribution of azimuthal angles (ϕ) of charged hadrons can be used to explore a collective behavior of the intermediate fireball produced under extreme thermodynamic conditions in high-energy collisions between two heavy-nuclei. The ϕ-distribution can be decomposed into a Fourier series as [1],

$$\frac{dN_{ch}}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\{n(\phi - \Psi_{RP})\} \quad (1)$$

The n^{th} order flow-coefficient v_n is given by,

$$v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle \quad (2)$$

The averaging $\langle\ \rangle$ runs over all events and all particles considered. The first Fourier coefficient (v_1), known as the directed flow, measures the total amount of in-plane transverse flow. Ψ_{RP} denotes the azimuthal angle of the reaction plane that cannot be accessed in real experiments. One can replace Ψ_{RP} with Ψ_1, the first order event-plane angle [1], and then calculate v_1^{obs} as,

$$v_1^{obs} = \langle \cos[(\phi - \Psi_1)] \rangle \quad (3)$$

The v_1^{obs}-value should then be corrected by the event plane resolution [2] as,

$$v_1\{EP\} = \frac{v_1}{\sqrt{2\left\langle \cos(\Psi_1^A - \Psi_1^B) \right\rangle}} \quad (4)$$

that is estimated after dividing an event into two sub-events A and B. Here Ψ_1^A and Ψ_1^B are the first order event plane angles of the respective sub-events [1]. We have studied the rapidity (y) dependence of $v_1\{EP\}$ and its slope at mid-rapidity $dv_1\{EP\}/dy|_{(y=0)}$ against the nucleon-nucleon center of mass energy $\sqrt{s_{\rm NN}}$. STAR experimental results [3, 4] are compared with the UrQMD (v-3.4)) [5] as a baseline prediction. Charged hadrons falling within $3.3 < |\eta| < 5.0$ are used to determine Ψ_1 [3], whereas charged hadrons falling within $1.0 < \eta < 3.3$ and $-3.3 < \eta < -1.0$, respectively, are used to determine Ψ_1^A and Ψ_1^B. Rapidity dependence of $v_1\{EP\}$ for different hadron species produced in $(10-40)\%$ central Au+Au collisions are shown in FIG. 1. One can see that $v_1\{EP\}$ is quite small valued in the mid-rapidity region and distributed anti-symmetrically about $y = 0$. It is comparatively larger valued in the fragmentation regions, especially at smaller $\sqrt{s_{\rm NN}}$. Conventionally for normal $v_1 > 0$) flow $(v_1 \cdot y) > 0$, and $(v_1 \cdot y) < 0$. Pions, kaons and anti-protons exhibit antiflow at all $\sqrt{s_{\rm NN}}$ considered. In contrast, protons show normal flow at lower $\sqrt{s_{\rm NN}}$, that with increasing $\sqrt{s_{\rm NN}}$ turns into antiflow.

As the shape of $v_1(y)$ curves provide crucial information about the early stage dynamics of a high-energy heavy-ion collision, we measure $dv_1\{EP\}/dy|_{(y=0)}$ and plot them against $\sqrt{s_{\rm NN}}$ in FIG. 2. In order to find out the slope, a linear fit over $|y| < 0.8$ has been performed. Apart from the external factors like $\sqrt{s_{\rm NN}}$, the slope of $v_1(y)$ also depends upon collision centrality, target-projectile rapidity gap, space-momentum correlation and degree of baryon stopping [6]. In both simulation and experiment $dv_1\{EP\}/dy|_{(y=0)}$ is negative for pions, kaons and anti-protons, and gradually approaches zero with increasing $\sqrt{s_{\rm NN}}$. Except for K^+ the magnitude of $dv_1\{EP\}/dy|_{(y=0)}$ obtained from the UrQMD simulation for $\sqrt{s_{NN}} \leq 11.5$ GeV are much larger than the experimental value. At relatively lower $\sqrt{s_{\rm NN}}$, the sideward expansion of the intermediate fireball is obstructed by the spectator nucleons. Therefore, sufficient

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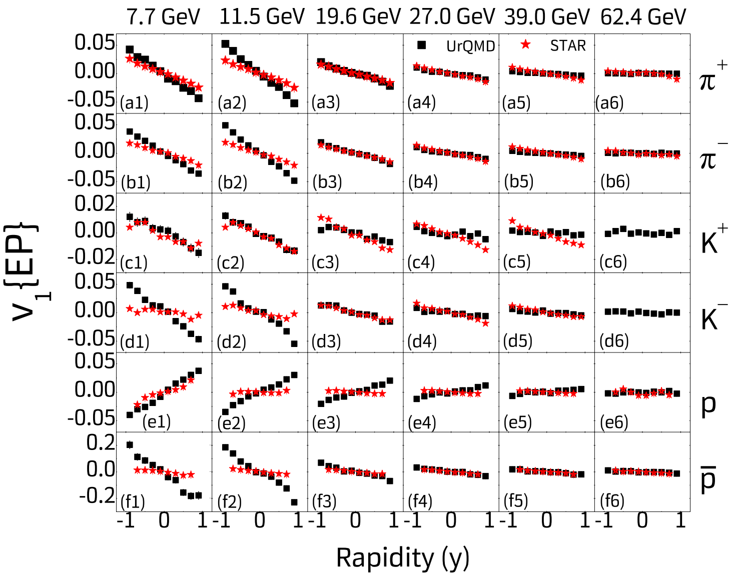

FIG. 1: Rapidity dependence of v_1 for $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ produced in $(10-40)\%$ central Au+Au collisions at $\sqrt{s_{\rm NN}} = 7.7 - 62.4$ GeV. The experimental data points are taken from [3, 4].

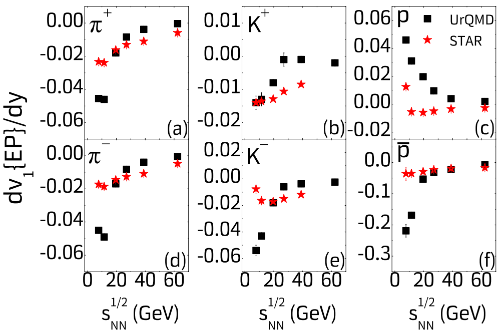

FIG. 2: Collision energy dependence of the $dv_1\{EP\}/dy_{(y=0)}$ near mid-rapidity for $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ produced in in $(10-40)\%$ central Au+Au collisions. STAR results are taken from [3, 4].

space is not available before the flow can fully develop, leading to a negative v_1. With an increase in $\sqrt{s_{\rm NN}}$ this obstruction is reduced and the magnitude of $dv_1\{EP\}/dy|_{(y=0)}$ gradually decreases. A minimum in the slope for p and K^- observed in the experimental data may be considered as a signature of a first order transition between deconfined and hadronic phases. On the other hand, UrQMD simulation results are qualitatively different, in which we do not find any non-monotonic behavior of $dv_1\{EP\}/dy|_{(y=0)}$.

References

[1] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C **58**, 1671 (1998).

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

[3] P. Shanmuganathan (for the STAR Collaboration), Nucl. Phys. A **956**, 260 (2016).

[4] L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. Lett. **112**, 162301 (2014).

[5] S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998).

[6] R. J. M. Snellings, N. Sorge, S. A. Voloshin, F.Q. Wang and N. Xu, Phys. Rev. Lett. **84**, 2803 (2000).