On the scaling properties of the directed flow of protons in Au+Au and Ag+Ag collisions at the beam energies of 1.23A and 1.58A GeV

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In the relativistic heavy ion collisions at the collision energies of a few GeV the strongly interacting matter is created at high baryon densities and relatively low temperatures. Azimuthal anisotropy of the produced particles provides a valuable insight into the properties of this form of matter. In this work, we discuss the scaling properties of directed flow of protons with system size as well as the collision energy.

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Introduction

Relativistic heavy-ion collisions at $\sqrt{s_{\mathrm{NN}}} = $ 2-5 GeV produce strongly interacting QCD matter with temperatures between 60 and 110 MeV, and a net-baryon density 2–5 times larger than the nuclear saturation density [1,2]. Several beam energy scan experiments are investigating matter under such conditions: STAR experiment at RHIC ($\sqrt{s_{\mathrm{NN}}} = $ 3-5.2 GeV) [3], BM@N experiment at Nuclotron ($\sqrt{s_{\mathrm{NN}}} = $ 2.4-3.5 GeV) [4] , HADES experiment at SIS-18 ($\sqrt{s_{\mathrm{NN}}} = $ 2.4-2.55 GeV) [5] and HIAF experiment at IMP ($\sqrt{s_{\mathrm{NN}}} = $ 2–4 GeV) [2]. It is possible to place limits on the EOS of dense baryonic matter by comparing the observables from heavy ion collision experiments with theoretical predictions [6]. One of such observables is the azimuthal collective flow of produced hadrons, which can be can be quantified by Fourier coefficients $v_n = \langle \cos[n(\varphi - \Psi_R)] \rangle$ [7] in the expansion of the particle azimuthal distribution relative to the reaction plane given by the angle Ψ_R:

$$dN/d\phi \propto 1 + \sum_{n=1} 2v_n \cos(n(\varphi - \Psi_R)), \qquad (1)$$

where φ is the azimuthal angle of a particle and n is the order of the harmonic [7]. The dominant and most studied signals in the energy range $2 < \sqrt{s_{\mathrm{NN}}} < 5$ GeV are the directed (v_1) and elliptic (v_2) flows [7–13]. Recently the HADES experiment at SIS18 has reported the first measurements of the higher order (v_3, v_4, v_5, v_6) flow coefficients of protons in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 2.4$ GeV [13]. Their amplitude is significantly smaller when compared

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to that of v_1 and v_2. In this energy regime the passage time and the expansion time are comparable, and the anisotropic flow is strongly affected by the presence of cold spectators. The passage time t_{pass}, at which the accelerated nuclei interpenetrate each other, can be estimated as

$$t_{pass} = \frac{2R}{\sinh y_{beam}}, \quad (2)$$

where R is the radius of the colling nuclei and y_{beam} is the beam rapidity. For Au+Au collisions at $2 < \sqrt{s_{\rm NN}} < 5$ GeV, the t_{pass} decreases from 30 fm/c to 5 fm/c. If the passage time is long compared to the expansion time, spectator nucleons serve to block the path of produced hadrons emitted towards the reaction plane. The passage time depends on collision energy and on the size of the colliding system. Therefore, the study of the system size dependence of anisotropic flow may help to estimate the participant-spectator contribution and improve our knowledge of EOS of symmetric nuclear matter.

In this work, we present the study of the scaling properties of v_1 of protons in Au+Au collisions at $\sqrt{s_{NN}}$=2.4 GeV (1.23 A GeV), Ag+Ag collisions at $\sqrt{s_{NN}}$=2.4 GeV (1.23 A GeV) and 2.55 GeV (1.58 A GeV). The v_1 results are based on the analysis of HADES data collected by the experiment in 2019 and were presented by author at FAIR-NICA-2021 workshop. In addition we provide the comparison of the measured v_1 of protons with results of analysis of Jet AA Microscopic transport model (JAM) events [14–16]. The nuclear mean field is simulated based on the relativistic version of the QMD model (RQMD.RMF) [16]. The JAM approach with the (RQMD.RMF) model has been found to reproduce the directed and integral elliptic flow data at $2.3 < \sqrt{s_{NN}} < 8$ GeV simultaneously with the parameter set MD2 [16]. We used the same version of JAM model and set of parameters.

1. System size and energy dependence of v_1 of protons: Ag+Ag vs Au+Au

Figure 1 shows the directed flow v_1 of protons in Au+Au collisions at the beam energy of 1.23A GeV (solid triangles) and Ag+Ag collisions at the beam energies of 1.23A (solid circles) and 1.58A GeV (solid boxes) as a function of center-of-mass rapidity y_{cm} (left) and transverse momentum p_T (right). The solid symbols denote the preliminary HADES results. The values of v_1 of protons are very close to each other for Au+Au and Ag+Ag collisions at beam energy of 1.23A GeV. In contrast, the magnitude of the proton directed flow produced in Ag+Ag collisions at higher beam energy of 1.58A GeV is noticeably lower. The lines in Figure 1 represent the v_1 of protons obtained from the analysis of JET AA Microscopic Transportation Model (JAM) [14–16] model events. We have used the version JAM 1.9 [16] with hard momentum-dependent EOS (MD2, K_0 = 380 MeV), see Table I from Ref. [16]. Comparing the preliminary HADES data with the that from JAM model shows that the model can roughly capture the overall magnitude and trend of the measured v_1 signal as a function of center-of-mass rapidity

y_{cm} for both colliding systems. However it fails to describe the shape of the proton v_1 dependence on transverse momentum p_T.

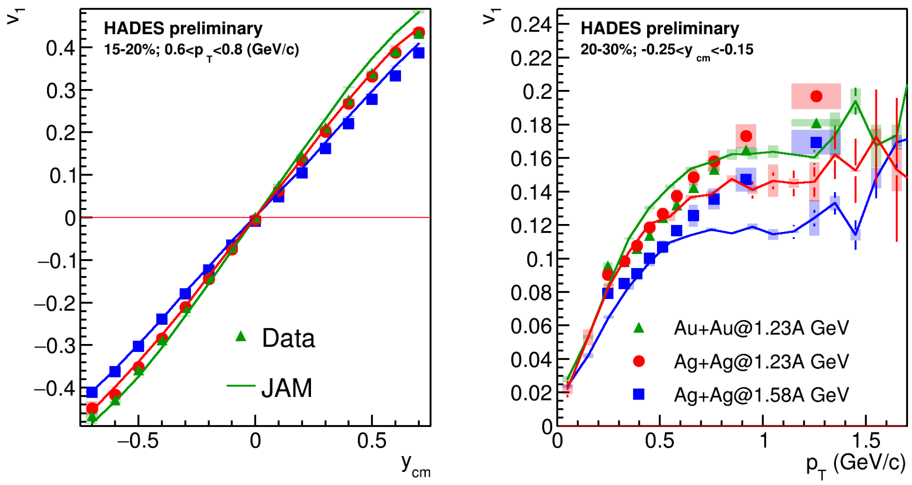

Fig. 1. Directed flow v_1 of protons in Au+Au collisions at the beam energy of 1.23A GeV (solid triangles) and Ag+Ag collisions at the beam energies of 1.23A (solid circles) and 1.58A GeV (solid boxes) as a function of (left) center-of-mass rapidity, y_{cm}; (right) transverse momentum p_T. The solid symbols denote the preliminary HADES results. Lines denote the results for JAM model with hard momentum dependent mean-field EOS MD2 (K_0 = 380 MeV).

The directed (v_1) flow at mid-rapidity can be quantified by its slope $dv_1/dy|_{y=0}$. It is is determined as the linear term, $dv_1/dy|_{y=0} = a_1$, of a cubic ansatz $v_1(y) = a_0 + a_1\, y + a_3\, y^3$ which has been fitted to the measured $v_1(y)$ data points. The left part of Figure 2 shows the centrality dependence of the slope of v_1 of protons at midrapidity $dv_1/dy_{cm}|_{y_{cm}=0}$ for the case if one use the center-of-mass rapidity $y = y_{cm}$. The slope $dv_1/dy_{cm}|_{y_{cm}=0}$ decreases with increasing the collision energy. In this energy range, the anisotropic flow is strongly affected by the presence of cold spectators due to sizable passage time (see Eq. 2). The observed change in the slope $dv_1/dy_{cm}|_{y_{cm}=0}$ can be attributed to the reduction of the shadowing effects by the spectator matter due to decrease in the t_{pass}. The rapidity dependence of v_1 of protons becomes less complicated if one uses the scaled rapidity $y' = y_{cm}/y_{beam}$, see middle panel of Figure 2. Scaled beam rapidity in the center-of-mass frame is always is equal to $y' = \pm 1$ The scaled rapidity ($y' = y_{cm}/y_{beam}$) dependence of v_1 may reflect the partial scaling of v_1 with t_{pass} in this energy range. To compare flow results for different colliding systems, it was suggested to use the scaled impact parameter b_0, defined by $b_0 = b/b_{max}$, taking $b_{max} = 1.15(A_P^{1/3} + A_T^{1/3})$ fm [17]. Since we study the symmetric colliding systems ($A_T = A_P = A$) we use mean impact parameter $\langle b \rangle$ at corresponding centrality class normalized to a cubic root of colliding ion mass number $\langle b \rangle / A^{1/3}$. The right panel of Figure 2 shows the slope $dv_1/dy'|_{y'=0}$ as a function of $\langle b \rangle / A^{1/3}$. Figure 2 shows, that the use of the scaled variables

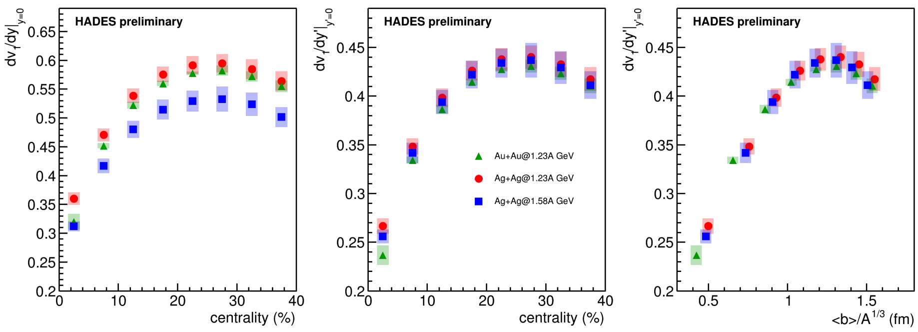

Fig. 2. The centrality dependence of the slope of v_1 of protons at midrapidity $dv_1/dy|_{y=0}$: (left) the center-of-mass rapidity y_{cm}, (middle) for the scaled rapidity $y' = y_{cm}/y_{beam}$ and (right) for the scaled rapidity $dv_1/dy'|_{y'=0}$ as a function of mean impact parameter at corresponding centrality class normalized to cubic root of colliding ion mass number.

may simplify the comparison of v_n results for different colliding systems and collision energies.

The left part of Figure 3 shows the p_T-dependence of v_1 of protons (with $-0.25 < y_{cm} < -0.15$) for 20-25% central Ag+Ag and Au+Au collisions. The p_T-dependence of v_1 of protons divided by the value of the slope $dv_1/dy|_{y=0}$ is presented in the right panel of Figure 3. It shows that the shape of $v_1(p_T)$ is very similar for Ag+Ag and Au+Au collisions.

2. Summary

In summary, we have presented the findings of the study on the scaling properties of the directed flow of protons v_1 in Au+Au at the beam energy of 1.23A GeV and Ag+Ag at the beam energies of 1.23A and 1.58A GeV. It is observed that by using scaled variables like rapidity divided by the beam rapidity $y' = y_{cm}/y_{beam}$ and relative impact parameter in each centrality class $< b > /A^{1/3}$, the dependence of v_1 on colliding system size and beam energy may be significantly reduced. This leads to the conclusion that the proton directed flow at these energies is strongly affected by the presence of cold spectators due to passage time comparable with the expansion time. Additionally, a similarity is observed in a shape of proton v_1 dependence on transverse momentum p_T.

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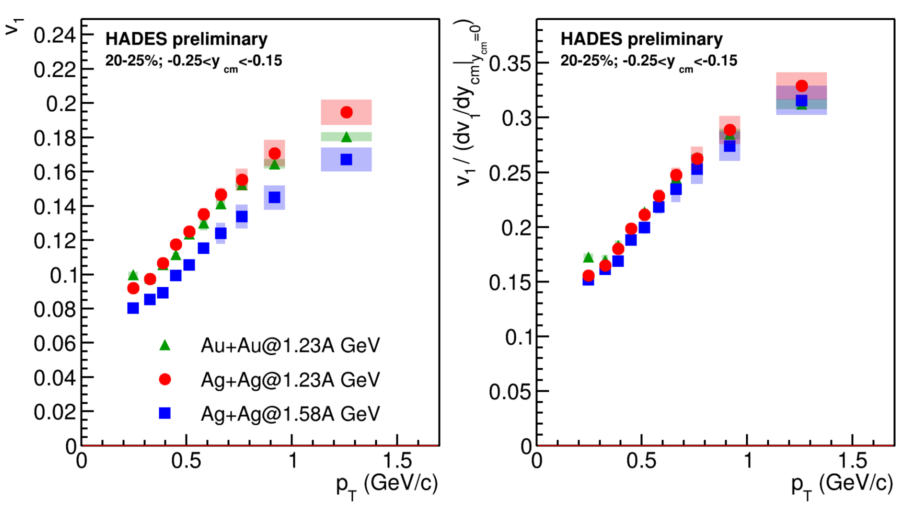

Fig. 3. (left) p_T dependence of v_1 of protons (with $-0.25 < y_{cm} < -0.15$) for 20-25% central Ag+Ag and Au+Au collisions. (right) p_T dependence of v_1 of protons divided by the value of the slope $dv_1/dy|_{y=0}$.

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