On the azimuthal flow of protons in the heavy ion collisions at $\sqrt{s_{NN}}$=2-4 GeV
Азимутальный поток протонов в столкновениях тяжелых ионов при энергиях $\sqrt{s_{NN}}$=2–4 ГэВ

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Одной из основных целей экспериментов по столкновениям тяжелых ионов является изучение свойств сильно взаимодействующей материи, возникающей в области перекрытия сталкивающихся ионов в различных состояниях. При относительно низкой энергии в несколько ГэВ на пару нуклонов созданная материя может характеризоваться высокими барионными плотностями и относительно низкими температурами. Азимутальная анизотропия, возникающая при столкновении адронов, несёт ценную информацию о свойствах вещества в области перекрытия. В этой работе мы представляем результаты свойств масштабирования направленного потока протонов в зависимости от энергии столкновения, а также размера системы. Кроме того, приведено сравнение полученных результатов с теоретическими моделями.

One of the main goals of the heavy ion collisions experiments is studying the properties of strongly interacting matter created at different states in the overlap region of two intercepting ions. At a relatively low energy of several-GeV per nucleon pair created matter can be characterized by high net baryon densities and relatively low temperatures. The azimuthal anisotropy or produced in the collision hadrons is a valuable probe of the properties of the matter within the overlap region. In this work we present the observation of the scaling properties of the directed flow of protons on energy of the collision as well as the system size. We also elaborate on the directed flow of protons dependence on the geometry of the collision.

PACS: 44.25.+f; 44.90.+c

Introduction

The strongly interacting matter produced in heavy ion collisions at collision energies of $\sqrt{s_{NN}}$=2-4 GeV is characterized by the net baryon densities of 2-5 times greater than the nuclear saturation density [1, 2]. This level of compression is achieved due to the presence of the colliding nuclei remnants

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known as spectators [3]. We can estimate the time it took the accelerated nuclei to penetrate each other (t_{pass}), as

$$t_{pass} = \frac{2R}{\sinh y_{beam}}, \tag{1}$$

where R is the radius of the colliding nuclei and y_{beam} is the beam rapidity. In non-central collisions the overlap region of two colliding nuclei is asymmetric. Via the interaction of the constituents of the matter within the overlap region as well as cold spectator matter this asymmetry transforms into azimuthal anisotropy of the produced particles [4]. This anisotropy can be quantified by decomposing the azimuthal angle distribution in a Fourier series with respect to plane spanned on vectors of beam direction and impact parameter (reaction plane) [5]:

$$\rho(\phi - \Psi_{RP}) = \frac{1}{2\pi}(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_{RP})), \tag{2}$$

where ϕ is the azimuthal angle of particle momentum and Ψ_{RP} is the reaction plane. The coefficients of the decomposition v_n are defined as follows:

$$v_n = \langle \cos n(\phi - \Psi_{RP}) \rangle, \tag{3}$$

where the angle brackets denote the averaging over all particles in the collision as well as all collisions. The coefficients of the first and second orders — v_1 and v_2 — are usually referred to as directed flow and elliptic flow, respectively. The v_1 and v_2 signals are dominant in low energy heavy ion collisions and are sensitive probes of the properties of the matter created within the overlap region. The experimental measurements of the flow harmonics can lay a constraints on the macroscopic properties of the matter existing for the brief moments in the collision. In this work, we discuss the results of the measurements of v_1 of protons in Ag+Ag collisions at $\sqrt{s_{NN}}$=2.4 GeV (E_{kin}=1.23 AGeV) and 2.55 GeV (E_{kin}=1.58 AGeV), presented by the author at FAIR-NICA workshop in 2021. The preliminary results are based on the analysis of HADES data collected by the experiment in 2019. The detailed comparison with v_1 results for Au+Au collisions at $\sqrt{s_{NN}}$= 2.4 GeV (E_{kin}=1.23 AGeV) will be presented.

Results

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 $v_1(y) = a_1\, y + a_3\, y^3$ which has been fitted to the measured $v_1(y)$ data points. The left part of Fig. 1 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 systematical errors correspond to effects not related to initial asymmetry of the collision (see [6,7]). The slope

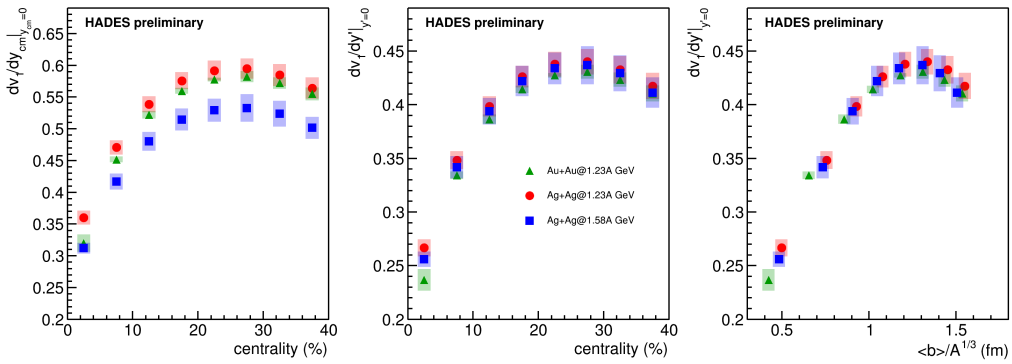

Fig. 1. Left: Directed flow slope of protons $dv_1/dy|_{y_{cm}=0}$ at center-of-mass rapidity $y_{cm} = 0$ as a function of centrality of the collision; Center: Directed flow slope of protons $dv_1/dy|_{y'=0}$ scaled on the beam rapidity as a function of centrality of the collision; Right: Directed flow slope of protons $dv_1/dy|_{y'=0}$ scaled on the beam rapidity as a function of the mean impact parameter divided over the cubic root of mass number of colliding nuclei $\langle b\rangle/A^{1/3}$ (relative impact parameter of the collision).

$dv_1/dy|_{y_{cm}=0}$ for the collision of Au+Au and Ag+Ag at the same energy is consistent with the systematic error. 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 t_{pass}. 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 $y' = y_{cm}/y_{beam}$, since for the colliding beams one then always has $y'_{beam} = \pm 1$ in the center-of-mass frame, see middle panel of Fig 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. The slope results for all three data-sets are in agreement within the systematic error except for the central-most collisions. 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 [10]. 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 Fig. 1 shows the slope $dv_1/dy'|_{y'=0}$ as a function of $\langle b\rangle/A^{1/3}$. The scaled directed flow slope of protons $dv_1/dy|_{y'=0}$ shows the same dependency on the relative impact parameter of the collision $\langle b\rangle/A^{1/3}$ in all three cases. Figure 1 shows, that the use of the scaled variables may simplify the comparison of v_n results for different colliding systems and collision energies.

The directed flow slope of protons $dv_1/dy|_{y=0}$ as a function of collision energy $\sqrt{s_{NN}}$ is shown in Fig. 2. The v_1 results for E895 experiment are taken from [8], for the STAR-FXT program from [9] and FOPI experiment results

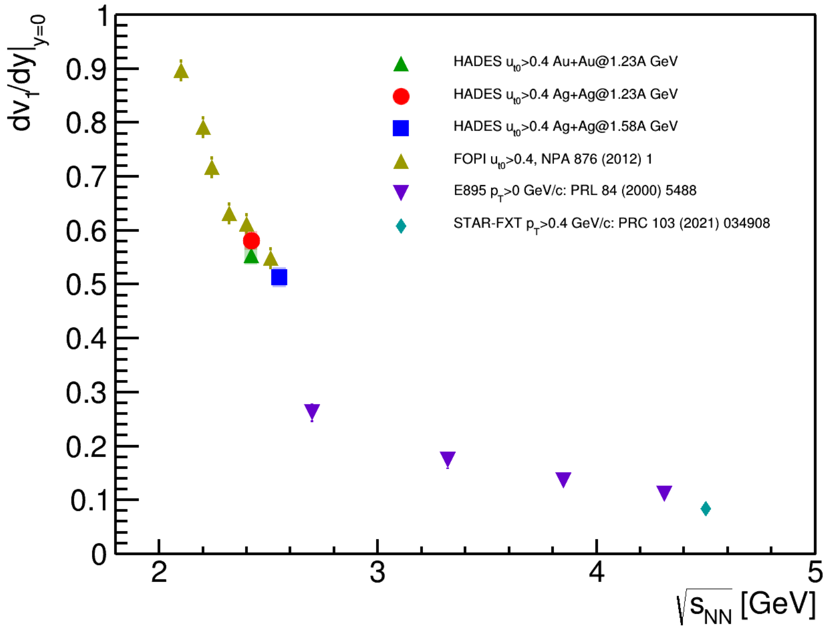

Fig. 2. The directed flow slope of protons $dv_1/dy|_{y=0}$ as a function of collision energy $\sqrt{s_{NN}}$: comparison with the world data. The results were taken from: the E895 experiment [8], the STAR-FXT program [9] and the FOPI measurements [10].

from [10]. The values are presented without the scaling on the beam rapidity and the FOPI-similar momentum criteria ($u_{t0} > 0.4$) is applied, which corresponds to the $p_T > 0.3$ GeV at $E_{kin} = 1.23A$ GeV and $p_T > 0.35$ GeV at E_{kin}=1.58A GeV. The points for Au+Au at E_{kin}=1.23A GeV and Ag+Ag at E_{kin}=1.23A and 1.58A GeV follow the world data trend for v_1.

Summary

The results for the directed flow slope of protons at midrapidity $dv_1/dy|y = 0$ are presented as a function of centrality and relative impact parameter of the collision for Au+Au at E_{kin}=1.23A GeV and Ag+Ag at E_{kin}=1.23A and 1.58A GeV. Scaling the results on the beam rapidity reduces the dependency of $dv_1/dy|y = 0$ on the energy of the collision. Scaled directed flow slope of protons $dv_1/dy'|y' = 0$ shows the same dependency on the relative impact parameter of the collision in all three data-sets. The obtained results for $dv_1/dy|y = 0$ follow the existing world data trend as a function of collision energy.

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