On the azimuthal flow of protons in the heavy ion collisions at 2-4 GeV

Азимутальный поток протонов в столкновениях тяжелых ионов при энергиях 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.

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Introduction

The strongly interacting matter produced in heavy ion collisions at beam 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 [?, ?]. This level of compression is achieved due to the presence of the colliding nuclei remnants

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known as spectators [?]. We can estimate the time at which the accelerated nuclei interpenetrate 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 nuclei [?]. 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) [?]:

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

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. This 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.

The analysis is based on the HADES data for Ag+Ag collisions at E_{kin} = 1.23A and 1.58A GeVcollected in 2019. The results were obtained in 2021 while in the HADES Collaboration and were not changed since.

Results

Shown in the left plot of the fig. 1 is the 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. The directed flow v_1 was initially calculated as a function of center-of-mass rapidity y_cm and then fitted with the linear function $v_1 = a_0 + a_1 \times y_{cm}$ in mostly the backward-rapidity range. The coefficient a_1 is extracted as a slope value in each centrality class. The cubic ansatz $v_1 = a_0 + a_1 \times y_{cm} + a_3 \times y_{cm}^3$ was tested as well in a wider rapidity window and no significant difference was observed. The systematical errors correspond to effects not related to initial asymmetry of the collision (see [?, ?]). We can see that the $dv_1/dy|_{y_{cm}=0}$ for collisions of Au+Au and Ag+Ag at the same

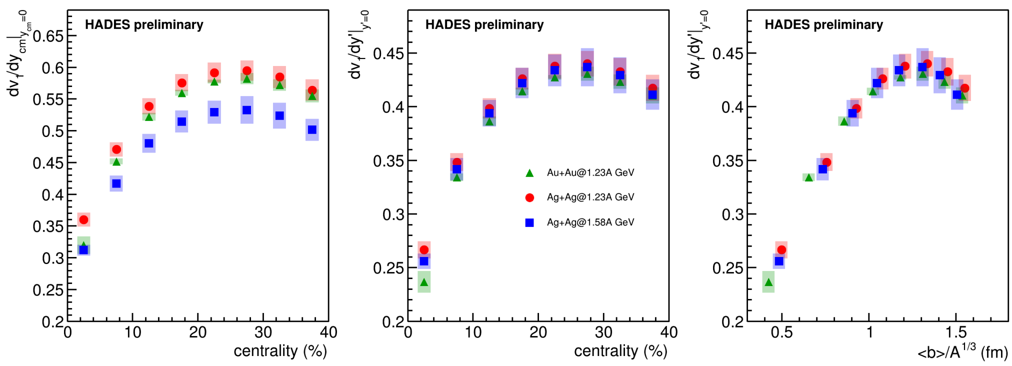

Fig. 1. Left: Directed flow slope of protons $dv_1/dy|_{y_{cm}=0}$ at center-of-mass rapidity $y_{cm} = 0$ as a function of centrality of the collision; Center: Directed flow slope of protons $dv_1/dy|_{y'=0}$ scaled on the beam rapidity as a function of centrality of the collision; Right: Directed flow 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).

energy are in an agreement within the systematical error. On the contrary, the results for the directed flow slope of protons in Ag+Ag collisions at higher kinetic energy is noticeably lower. The directed flow slope of protons $dv_1/dy|_{y'=0}$ scaled on the beam rapidity as a function of centrality of the collision is shown in the center plot of the fig. 1. The center-of-mass rapidity is normalized on the beam rapidity $y' = y_{cm}/y_{beam}$ such as projectile and target rapidities are equal to ± 1. This transformation simplified the directed flow slope dependence on centrality and the results for all three data-sets are in agreement within the systematic error except for the central-most collisions. In the right plot of the fig. 1 the beam-rapidity-scaled $dv_1/dy|_{y'=0}$ is shown as a function of of the mean impact parameter divided over the cubic root of mass number of colliding nuclei. The mean impact parameter was calculated for each centrality class of the collision and then normalized to be a representative value of the geometry of the collision despite the difference in the colliding nuclei size. The normalization was applied with the idea that the radius of the nuclei is proportional to the cubic root of the mass number $r \propto A^{1/3}$. 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.

The directed flow slope of protons $dv_1/dy|_{y=0}$ as a function of collision energy $\sqrt{s_{NN}}$is shown in 2. The results for E895 are taken from [**?**], for the STAR-FXT from [**?**] and FOPI measurements from [**?**]. 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 GeVand $p_T > 0.35$ GeV at E_{kin}=1.58A GeV. The points for Au+Au at E_{kin}=1.23A GeVand Ag+Ag at E_{kin}=1.23A and 1.58A GeVfollow the world data trend.

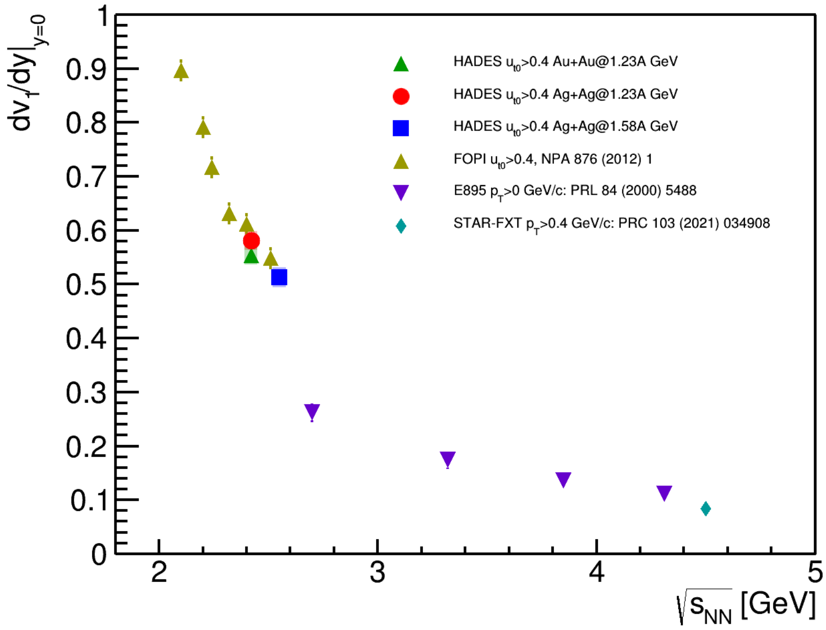

Fig. 2. The directed flow slope of protons $dv_1/dy|_{y=0}$ as a function of collision energy $\sqrt{s_{NN}}$: comparison with the world data. The results were taken from: the E895 experiment [?], the STAR-FXT program [?] and the FOPI measurements [?].

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 GeVand 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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