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Study of Electromagnetic Effect by Charged-dependent Directed Flow in Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV using STAR at RHIC

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In non-central heavy-ion collisions, it is predicted that an initial strong but transient magnetic field ($\sim 10^{18}$ Gauss) can be generated. The charge-dependent directed flow (v_1) can serve as the probe to detect this initial magnetic field. In addition, v_1 of several identified hadron species with different constituent quarks will help to disentangle the role of produced and transported quarks. In this proceedings, we present the measurements of v_1 for $\pi^{\pm}$, $K^{\pm}$, $p(\bar{p})$ in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of transverse momentum, rapidity, and centrality. The difference of v_1 slope ($\Delta \mathrm{d}v_1/\mathrm{dy}$) between protons and anti-protons is observed and is studied as a function of centrality. While the contribution from transported quarks can give positive $\Delta \mathrm{d}v_1/\mathrm{dy}$, the electromagnetic field is predicted to give negative $\Delta \mathrm{d}v_1/\mathrm{dy}$. The significant negative $\Delta \mathrm{d}v_1/\mathrm{dy}$ of protons in peripheral collisions is consistent with the prediction from initial strong magnetic field in heavy-ion collisions.

Keywords: heavy-ion collisions; directed flow; electromagnetic effect; transported-quark.

PACS numbers:

1. Introduction

A collision of two ultra-relativistic nuclei forms a strongly interacting matter called the Quark-Gluon Plasma (QGP).[4] Anisotropic flow is quantified by Fourier coefficients of particle's distribution in azimuthal angle measured with respect to the reaction plane. The first coefficient of Fourier expansion is termed as directed flow (v_1),[5]

$$v_1 = \langle cos(\phi - \Psi_R) \rangle, \quad (1)$$

where ϕ denotes the azimuthal angle of an outgoing particle and Ψ_R is the orientation of the reaction plane defined by the beam axis and the impact parameter vector. The rapidity-odd component of directed flow v_1(y) has been argued to be sensitive to initial strong electromagnetic (EM) fields.[3]

In the early stages of the collisions, an ultra strong magnetic field is expected to be created (eB $\sim m_{\pi}^2$ at top Relativistic Heavy Ion Collider (RHIC) energy).[6]

This magnetic field is generated by the incoming spectator protons in the collision, and may be captured if the medium produced has finite electric conductivity. As the spectator protons recede from the collision zone the produced magnetic field decays with time. This time-varying magnetic field induces an electric field due to the Faraday effect. The Lorentz force results in an electric current perpendicular to expansion velocity of medium and magnetic field, akin to the classical Hall effect. The interplay of competing Faraday and Hall effects can influence the v_1. In other words, EM fields are expected to drive positively-charged and negatively-charged particles in opposite ways, leading to a splitting of v_1(y).[3]

UrQMD calculations[8] at RHIC energies have shown that the transported protons and the spectator nucleons have the same sign of v_1 and hence they have a positive v_1 slope ($dv_1/dy > 0$) at the mid-rapidity. On the other hand, produced protons and anti-protons can have negative v_1 ($dv_1/dy < 0$) slope due to contribution other than transported quarks, e.g. the tilted source.[7] This results in a positive splitting between protons and anti-protons [$\Delta dv_1/dy = dv_1/dy(p) - dv_1/dy(\bar{p}) > 0$]. Therefore, transport will affect the splitting between any particle and anti-particle pairs having transported quark content, e.g splitting between $\pi^+(u\bar{d})$ and $\pi^-(d\bar{u})$, and also between $K^+(u\bar{s})$ and $K^-(\bar{u}s)$. Finally, the interplay between EM field and transported quark effect determines the sign and magnitude of splitting between particle and anti-particle pairs.

2. Method and Analysis

This analysis uses Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV, collected by Solenoidal Tracker at RHIC (STAR) during 2018. Details about the event cuts and track selections can be found in Ref.[9] In this analysis, the first order event plane angle is determined using Zero Degree Calorimeter (ZDC).[10] The description of measuring v_1 using the ZDC event plane can be found in Ref.[9] The Time Projection Chamber (TPC)[11] was used for charged-particle tracking within pseudorapidity $|\eta| < 1$, with full 2π azimuthal coverage. After the vertex selection, we analysed about 1.7 billion Ru+Ru events and 1.8 billion Zr+Zr events. Centrality is defined from the number of charged particles detected by the TPC within $|\eta| < 0.5$. The directed flow analyses were carried out on tracks that have transverse momenta, $p_T > 0.2$ GeV/c for $\pi^{\pm}$ and $K^{\pm}$, and $p_T > 0.4$ GeV/c for $p(\bar{p})$. The tracks should pass a requirement to be within 3 cm of distance of closest approach (DCA) to the primary vertex (V_z), and have at least 15 space points (N_{hits}) in the main TPC acceptance. $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ are identified based on the truncated mean value of the track energy loss ($\langle dE/dx \rangle$) in the TPC and we select $|n\sigma| < 2$ ($n\sigma = \frac{1}{\sigma_R} ln(\langle dE/dx \rangle / \langle dE/dx \rangle_{[\pi/K/p]}$, σ_R is the $\langle dE/dx \rangle$ resolution). To ensure the purity of identified particles, we select particles with momentum smaller than 2 GeV/c for protons, and 1.6 GeV/c for pions and kaons. The time-of-flight detector (TOF)[12] was used to improve the particle identification and we select particles within mass-square (m^2) range, -0.01 $< m^2 <$ 0.1 ((GeV/c^2)^2) for pions, 0.2 $< m^2 <$ 0.35

((GeV/c^2)^2) for kaons and $0.8 < m^2 < 1.0$ ((GeV/c^2)^2) for protons.

The systematic uncertainties of the v_1 measurements are calculated by varying DCA, V_z, N_{hits}, $n\sigma$ etc. within a reasonable maximum range. The absolute difference ($|\Delta_i|$) between default cut with the cut variation is taken as systematic uncertainty. In addition, the absolute difference between the $v_1(y)$ slopes between forward and backward rapidities is also considered as a source of systematic uncertainty. The final systematic error is the quadrature sum of the systematic errors from all the sources, which are calculated as $|\Delta_i|/\sqrt{12}$ assuming uniform probability distribution.

3. Results

Figure 1 presents $v_1(y)$ for protons and anti-protons in Au+Au collisions at $\sqrt{s_{NN}} = 27$ and 200 GeV and isobar collisions at $\sqrt{s_{NN}} = 200$ GeV in the centrality range of 50–80%. Linear fits within -0.8 $< y <$ 0.8 (solid lines) that passing through (0, 0) is used to extract the slope ($\Delta dv_1/dy$). We observe a significant negative slope of proton and antiproton difference in the peripheral collisions which is inline with the prediction of dominance of the Faraday/Coulomb effect over the Hall and transported-quark effects, as transported quarks only provide positive contributions to the proton $\Delta dv_1/dy$.[8] The extracted $\Delta dv_1/dy$ values for each particle species using the same linear-function fit are plotted as a function of centrality and is presented in Fig. 2 for $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ in Au+Au at $\sqrt{s_{NN}} = 27$ and 200 GeV and isobar collisions at $\sqrt{s_{NN}} = 200$ GeV.

It is clear from Fig. 2 that $\Delta dv_1/dy$ for protons shows decreasing trend, i.e positive to negative when going from central to peripheral collisions. The electromagnetic effect is weak in central collisions due to the lack of spectator protons. Therefore, the transported-quark effect can contribute to the positive v_1 splitting. Towards the peripheral collisions the electromagnetic effect can be dominant and we see a sign change of $\Delta dv_1/dy$. The solid curve represented in the figure shows the quantitative calculation of electromagnetic-field contributions to the proton $\Delta dv_1/dy$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.[2] Similar decreasing trend of $\Delta dv_1/dy$ is also observed for K^+ and K^-, but less significant compared to protons. This could be due to the fact that kaons have lower mean transverse momentum ($\langle p_T \rangle$) than protons and hence weaker electromagnetic field effects.[2]

The v_1 splitting between π^+ and π^- is consistent with zero within uncertainty at $\sqrt{s_{NN}} = 200$ GeV. The transported quarks should give negative $\Delta dv_1/dy$ between π^+ and π^-. Also, the electromagnetic effect gives negative $\Delta dv_1/dy$. Since π^+ and π^- numbers are almost symmetric at the top RHIC energy, the transported-quark effect is negligible. The electromagnetic effect can be diluted from neutral resonance decay. At $\sqrt{s_{NN}} = 27$ GeV, we can see a small negative $\Delta dv_1/dy$ at peripheral collisions which can have both transported-quark and electromagnetic effect.

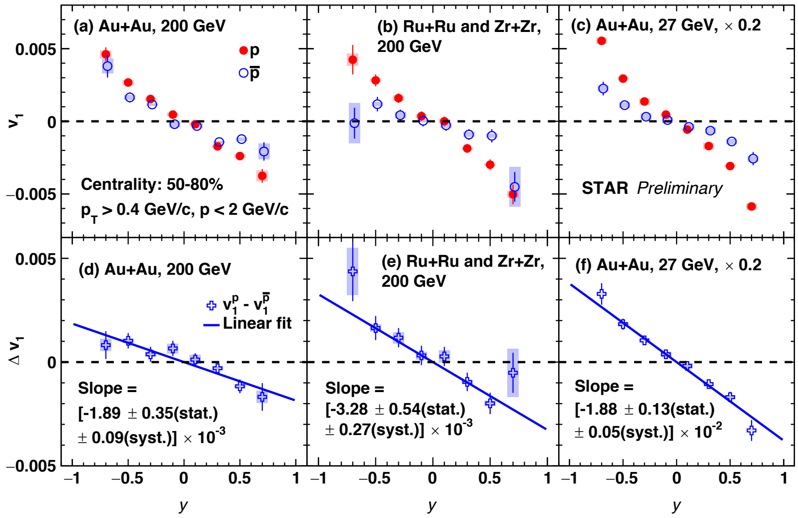

Fig. 1. Directed flow of protons and anti-protons and their difference ($v_1^p - v_1^{\bar{p}}$) as a function of rapidity for Au+Au collisions at $\sqrt{s_{NN}} = 27$ and 200 GeV, and Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV for 50-80 % centrality.[1] The systematic uncertainties are indicated with shaded bands and the slopes are obtained with linear fits (solid lines).

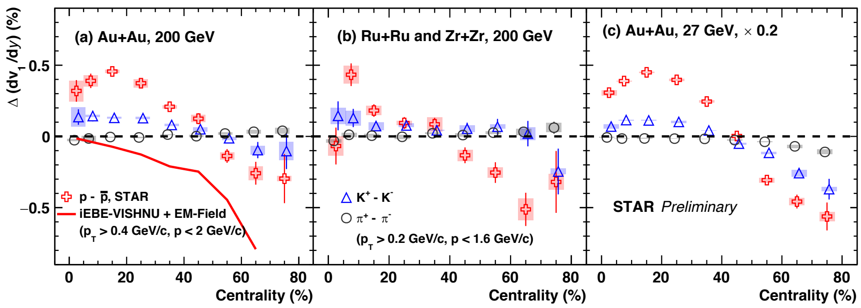

Fig. 2. Slope difference ($\Delta dv_1/dy$) between positively and negatively charged pions, kaons and protons as a function of centrality for Au+Au collisions at $\sqrt{s_{NN}} = 27$ and 200 GeV and isobar collisions at $\sqrt{s_{NN}} = 200$.[1] The systematic uncertainties are represented by shaded bands. The solid line is the electromagnetic field prediction for v_1 splitting between protons and anti-protons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.[2]

4. Summary and Outlook

The study of charged-dependent v_1 can provide information about transported quark and electromagnetic (Hall, Faraday, and Coulomb etc.) effects in heavy-ion collisions. We have presented the v_1 measurements of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ for Au+Au collisions at $\sqrt{s_{NN}} = 27$ and 200 GeV, and Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} =$

200 GeV. The splitting between protons and anti-protons changes sign from positive value in central collisions to negative value in peripheral collisions. The positive value of $\Delta dv_1/dy$ in central collisions could be accommodated by transported quark contribution where as significant negative $\Delta dv_1/dy$ in peripheral collisions is consistent with expectation from dominance of Faraday/Coulomb effects over Hall effect.

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