

DIRECTED FLOW OF IDENTIFIED CHARGED PARTICLES FROM THE RHIC BEAM ENERGY SCAN*

YADAV PANDIT

for the STAR Collaboration

Kent State University, Kent, OH 44240, USA

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We present the STAR measurements of directed flow, v_1 , for $\pi^\pm$, $K^\pm$, protons and antiprotons, as well as for all detected charged particles in Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV as a function of transverse momentum, rapidity and centrality. Results are compared to the predictions from transport models.

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1. Introduction

The RHIC Beam Energy Scan (BES) is mainly focused on a search for the QCD critical point and the 1st-order phase boundary in the QCD phase diagram. In the year 2010, the STAR experiment at RHIC took data for the beam energies $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV as a first phase of the BES program. Analysis of the collected data for various observables sensitive to the phase transition and critical point continues for the successful accomplishment of the program.

Directed flow, v_1 , is the first harmonic coefficient in the azimuthal distribution of the particles with respect to the reaction plane,

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

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 [1]. Both hydrodynamic and nuclear transport models [2,3]

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indicate that directed flow is a sensitive signature for the phenomena related to the possible phase transition specially in the BES region [4]. In particular, the shape of $v_1(y)$ may exhibit flatness at midrapidity due to a strong, tilted expansion of the source giving rise to anti-flow or a 3-rd flow [5] component. If the tilted expansion is strong enough, it can cancel and reverse the motion in the bounce-off direction and results in a negative $v_1(y)$ slope at midrapidity, potentially producing a wiggle like structure in $v_1(y)$. A wiggle for baryons is a possible signature of a phase transition between hadronic matter and quark-gluon plasma (QGP), although QGP is not the only possible explanation [5, 6, 7]. If strong but incomplete baryon stopping is assumed together with positive space-momentum correlations caused by transverse radial expansion, then a wiggle structure might be explained even in a hadronic system [8].

2. Methods and analysis

In this paper, we report v_1 measurements by the STAR experiment from $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV Au + Au collisions. Data were taken from Run 10 (2010). The STAR Time Projection Chamber (TPC) [9] was used as the main detector for charged particle tracking at midrapidity and Forward Time Projection Chambers (FTPCs) were used for charged particle tracking at forward rapidities. The centrality was determined by the number of tracks from the pseudorapidity region $|\eta| < 0.5$. Two Beam Counters covering $3.3 < |\eta| < 5.0$ were used to reconstruct the first order event plane for this analysis. The pseudorapidity gap between BBC and TPC suppresses the non-flow effects. We analyzed minimum bias events with the following conditions: event vertex radius $\sqrt{V_x^2 + V_y^2} < 2.0$ cm, where V_x and V_y are the vertex positions along the x and y directions, respectively, and V_z within 70, 50 and 30 cm of the center of the detector at 7.7, 11.5 and 39 GeV respectively. Tracks are also required to have transverse momenta $p_T > 0.2$ GeV/ c , pass within 3 cm of the primary vertex, have at least 15 space points in the main TPC acceptance ($|\eta| < 1.0$) or 5 space points in the case of tracks in the FTPC acceptance ($2.5 < |\eta| < 4.0$), and we require the ratio of the number of actual space points to the maximum possible number of space points to be greater than 0.52. Protons and antiprotons up to 2.8 GeV/ c and $\pi^\pm$ and $K^\pm$ up to 1.6 GeV/ c in transverse momentum were identified based on specific energy loss in the TPC and the time-of-flight information from multi-gap resistive plate chamber TOF detectors in combination with the momentum.

3. Results

Beam energy and centrality dependence of directed flow of charged particles as a function of pseudorapidity and transverse momentum has been previously reported [11]. Fig. 1 (left panel) shows charged hadron v_1 as a function of η scaled by the corresponding beam rapidity (y_{beam}) and right panel as a function of $\eta - y_{\text{beam}}$ for Au + Au Collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 39, 62.4$ and 200 GeV for 30–60% central collisions. The new results reported here are the charged hadron $v_1\{\text{BBC}\}$ in Au + Au collisions for 30–60% centrality at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV. We observe an approximate beam energy scaling behavior of directed flow [12], also observed at SPS energies [13].

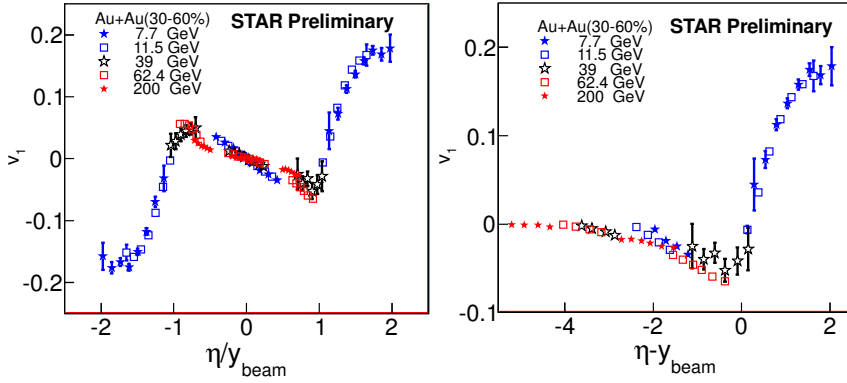


Fig. 1. The left panel shows charged hadron v_1 as a function of η scaled by y_{beam} for Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 39, 62.4$ and 200 GeV for 30–60% central collisions. The right panel shows charged hadron v_1 as a function of $\eta - y_{\text{beam}}$. The results for 62.4 and 200 GeV are for 30–60% centrality, previously reported by STAR [10].

Fig. 2 shows directed flow v_1 of identified particles proton, antiproton, $\pi^\pm$ and $K^\pm$ as a function of rapidity for from Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV. We observe the differences in v_1 for protons and antiprotons.

In Fig. 3, proton v_1 as a function of rapidity (y) for central (0–10%), mid-central (10–40%) and peripheral (40–80%) collisions at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV are compared to the UrQMD model prediction. A sign change in proton slope going from central to peripheral collisions is observed. UrQMD is qualitatively consistent with the data but does not predict the right magnitude at these energies. AMPT (default) model calculation is similar to UrQMD results.

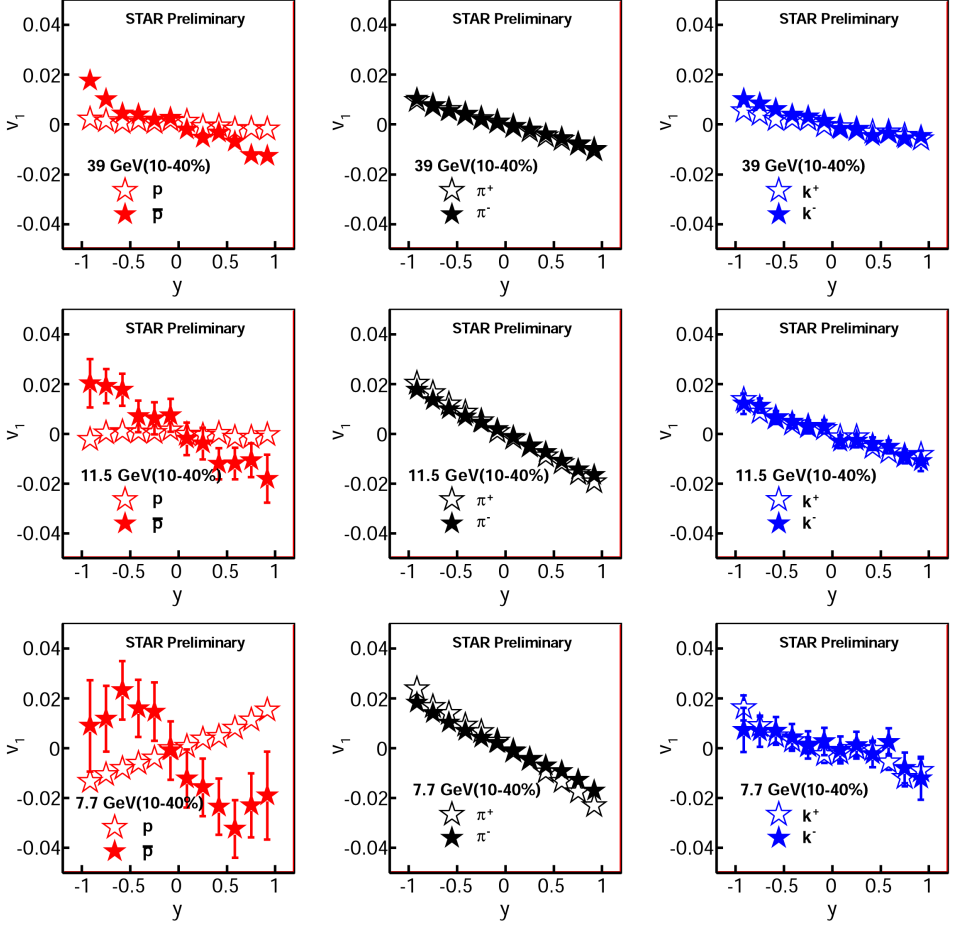


Fig. 2. The top, middle and bottom row of panels show directed flow v_1 as a function of rapidity for positive and negative hadrons from Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV respectively with proton, antiproton, $\pi^\pm$ and $K^\pm$ shown in the first, second and last column of panels for mid-central (10–40%) collisions.

In Fig. 4, proton and antiproton slope $F = dv_1/dy'$ around midrapidity is plotted as a function of collision energy, where y' is the scaled rapidity, defined as $y' = y/y_{\text{beam}}$. Values for the slope of $v_1(y')$ are extracted via a polynomial fit of the form $Fy' + Cy'^3$. The proton slope decreases rapidly with increasing energy, changes its sign to negative between 7.7 and 11.5 GeV, and remains small and negative up to 200 GeV. In contrast, the antiproton slope, which was not reported by the NA49 or E895 collaborations, remains always negative in the measured $\sqrt{s_{NN}}$ range from 7.7 to 200 GeV.

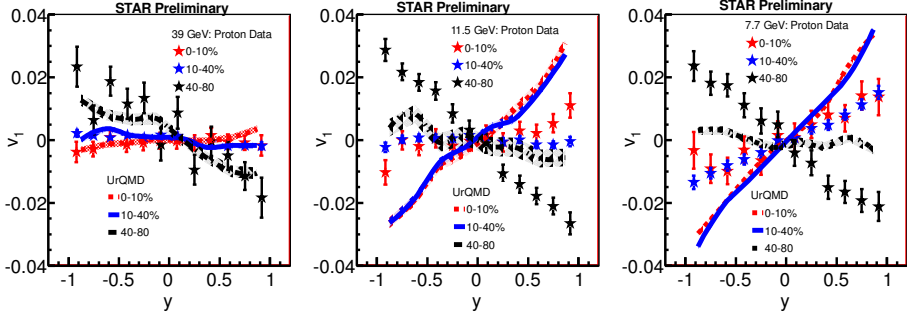


Fig. 3. Centrality dependence of directed flow of protons as a function of rapidity, y . Results are compared with the UrQMD model calculations.

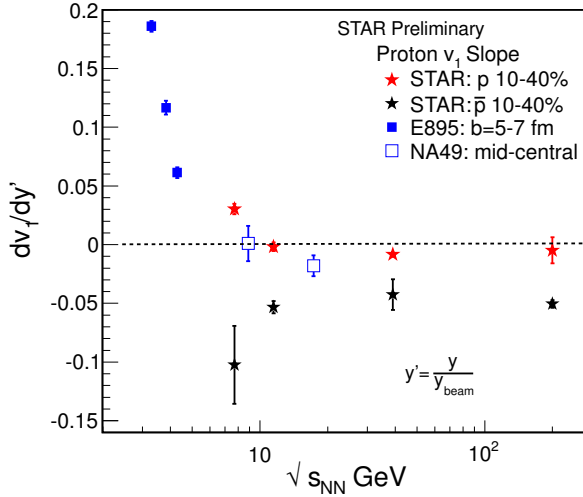


Fig. 4. Proton and antiproton slope dv_1/dy' at midrapidity as a function of beam energy. Antiproton data are not available from NA49 and E895.

4. Summary and outlook

In this paper, we present STAR results for directed flow as a function of transverse momentum, pseudorapidity and centrality for Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV. Our findings demonstrate that $v_1(\eta/y_{\text{beam}})$ shows a beam energy scaling behavior, though not perfect, that has already been established at higher RHIC energies. Difference in directed flow of protons and antiprotons is observed. For mid-central collisions (10–40%), the $\pi^\pm$, $K^\pm$, and antiprotons have a negative dv_1/dy' at midrapidity, but proton dv_1/dy' at 7.7 GeV becomes positive. The proton $v_1(y')$ slope decreases rapidly with increasing energy up to 7.7 GeV. Its sign changes to negative

between 7.7 and 11.5 GeV, and remains small and negative at 11.5, 17.3, 39 and 200 GeV. However, antiproton slope is always negative in the measured range from 7.7 GeV to 200 GeV. Tested models do not predict the right magnitude of directed flow but UrQMD and AMPT (default) qualitatively follow some of the features shown by the data. The beam energy scan at RHIC will continue in the future to map in more detail the interesting energy range between 11.5 and 39 GeV. Hence results from 19.6 GeV and 27 GeV, which were collected in 2011, will provide further important information to the observed beam energy dependence of the directed flow.

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