Directed flow measurements from STAR

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Abstract. STAR measurements of $v_1$ for identified particles for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are presented. A negative $v_1$ slope is observed for pions, protons, antiprotons and kaons ($K^0_S$) in 10-70% central collisions. For pion $v_1$ slope, the comparison between the current result and available models (RQMD, UrQMD, AMPT, QGSM and hydro model with a tilted source) is made. In 5-30% central collisions, surprisingly sizable difference between $v_1$ of protons and antiprotons is observed. The centrality and energy dependence of proton $v_1$ are also presented. The charged hadron $v_1$ for Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4$ GeV is measured and compared with results obtained previously.

1. Introduction and Motivation
At RHIC, it is expected that the Quark-Gluon Plasma (QGP) can be created in the laboratory by colliding heavy ions at high energies. In a relativistic heavy ion collision, two nuclei are smashed together at near light-speed, and the collision produces thousands of particles due to the tremendous amount of energy deposited. In order to characterize the collision, anisotropic flow is used to describe the emission pattern, with respect to the reaction plane, of out-going particles. Anisotropic flow is quantified by Fourier coefficients of particle’s distribution in azimuthal angle measured with respect to the reaction plane [1]. The first coefficient of such Fourier expansion is regarded as directed flow, and is evaluated by

$$ v_1 = \langle \cos(\phi - \Psi_1) \rangle / Res(\Psi_1), $$

where $\phi$ denotes the azimuthal angle of outgoing particles, and $\Psi_1$ is the azimuthal angle of the reconstructed first-order event plane. A correction factor, namely the first-order event plane resolution ($Res(\Psi_1)$), is applied here to take into account the smearing between the reconstructed event plane and the true reaction plane [1]. To calculate the event plane resolution, we first calculate the correlation between two sub-event planes reconstructed in different $\eta$ windows (details in Ref. [2, 3]), then calculate the full event plane resolution according to Eq. 11 in Ref. [1].

Directed flow ($v_1$) describes the side-splash of particles away from the mid-rapidity [4] and it probes the early dynamics of the system in relativistic heavy-ion collisions. The shape of the directed flow as function of rapidity for identified particles is sensitive to the equation of state (EOS) and may carry a phase transition signal [5]. It is argued that directed flow, as a function of rapidity, may exhibit a flatness at mid-rapidity due to a strong, tilted expansion of the source.
Such tilted expansion gives rise to anti-flow [6] (or a 3rd flow component [7]). The anti-flow is perpendicular to the source surface, and is in the opposite direction to the bouncing-off motion of nucleons. If the tilted expansion is strong enough, it can even overcome the bouncing-off motion and results in a negative $v_1(y)$ slope at mid-rapidity, potentially producing a wiggle-like structure in $v_1(y)$. Although these calculations are made for collisions at SPS energies, yet the origination of the negative slope is the strong expansion of a tilted source, which is also relevant at top energies at RHIC. Indeed the hydrodynamic calculation with a tilted source as the initial condition [8] can give the similar negative $v_1(y)$ slope as that found in data. A wiggle structure for nucleons is also found in the Relativistic Quantum Molecular Dynamics (RQMD) model [9], and it is attributed to the baryon stopping together with the positive space-momentum correlation. In this picture, no phase transition is needed, and pions also exhibit a wiggle because that the shadowing effect causes pions and nucleons to flow in opposite directions.

To distinguish between the baryon stopping and the anti-flow associated with a phase transition, it is desirable to measure the $v_1(y)$ for identified particles and their slope around mid-rapidity.

2. Dataset and cuts

In total 54 million events for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are used in this study, all taken with a minimum-bias trigger by the STAR experiment during the RHIC run 2007. Event cuts and track selections can be found in Ref. [10]. In this analysis, the event plane angle $v_1$ is determined from the sideward deflection of spectator neutrons measured by STAR’s Shower Maximum Detectors at Zero Degree Calorimeters (ZDCSMD), which are located close to beam rapidity and have the minimum contribution from non-flow. The description of measuring $v_1$ using the ZDCSMD event plane can be found in [2, 3].

There are about 420k events used in the analysis of $v_1$ for Cu + Cu collisions at $\sqrt{s_{NN}} = 22.4$ GeV. STAR’s Beam Beam Counters (BBCs) [11] are used to reconstruct the first order event plane at this energy. BBCs are scintillator annuli mounted around the beam pipe beyond the east and west pole-tips of the STAR magnet at about 375 cm from the center of the nominal interaction region (IR). They have a $\eta$ coverage of 3.8 < |$\eta$| < 5.2 and a full azimuthal (2\$\pi$) coverage. For $v_1$ study in the Time Projection Chamber (TPC) [12] region (|$\eta$| < 1.3), the full event plane is combined from the east BBC and west BBC event planes. However, for $v_1$ study in the FTPC region (2.5 < |$\eta$| < 4.2), only the east (west) BBC event plane, which is located at the backward (forward) pseudorapidity, is used to study $v_1$ in the forward (backward) FTPC. This is to avoid the possible self-correlation due to the overlap in $\eta$ between the FTPC and the BBC coverage. The self-correlation arises when using particles from the same $\eta$ region that is used to reconstruct the event plane to study flow, and it should be avoided in any flow studies. Errors presented in figures are statistical.

3. Directed flow results

In the left panel of Fig. 1, $v_1(y)$ of pions, kaons ($K_0^0$), protons and antiprotons are presented for centrality 10-70%. Following convention, the sign of spectator $v_1$ in the forward region is chosen to be positive, to which the measured sign of $v_1$ for particles of interest is only relative. Fitting with a linear function, slopes are $-0.15 \pm 0.05$($\%$), $-0.46 \pm 0.06$($\%$), $-0.27 \pm 0.01$($\%$), $-0.02 \pm 0.11$($\%$) and $-0.17 \pm 0.02$($\%$) for protons, antiprotons, pions, charged kaons and $K_0^0$, respectively. The $v_1(y)$ slope for the three produced particle species (pions, kaons ($K_0^0$) and antiprotons) are found negative at mid-rapidity, which is consistent with the anti-flow picture. In particular $K_0^0$ are less sensitive to the nucleon shadowing effect due to the small kaon/nucleon cross section, yet they show negative slope. This is again in favor of the anti-flow picture. However, surprisingly it is observed that $v_1(y)$ of protons exhibits a clearly flatter shape than that of antiprotons. This feature cannot be explained by the anti-flow alone and will be discussed later in this paper. In the right panel of Fig. 1, pions $v_1(y)$ at mid-rapidity is plotted.
Figure 1. Left panel: Pions, kaons ($K^0_S$), protons and antiprotons $v_1$ as a function of rapidity for 10-70% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The dashed lines presented the linear fit (see text for detail). Right panel: model calculations of pion $v_1(y)$ (or $v_1(\eta)$, for the QGSM model only) for minimum-bias events for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Pions $v_1(y)$ measurement from the left panel is re-plotted for comparison. QGSM* model presents the basic Quark-Gluon String model with parton recombination [15]. Hydro* model presents the hydrodynamic expansion from a tilted source [8].

Together with five model calculations, namely, RQMD [9], UrQMD [13], AMPT [14], QGSM with parton recombination [15], and hydrodynamic calculation with a tilted source [8]. Many model calculations either predict wrong sign of pions $v_1$ or wrong magnitude. The calculation that assumes a hydrodynamic expansion starting from a tilted source, which is a characteristic of anti-flow, describes the data best.

Figure 2. Directed flow vs. rapidity for protons (circles), antiprotons (squares) and charged pions (stars) for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, for centrality 5%-30%(left panel) and 30%-80%(right panel). Dashed and dotted lines are linear fits of $v_1(y)$ for protons and antiprotons, respectively.

Fig. 2 shows $v_1(y)$ for protons, antiprotons and charged pions for different collision centralities. Fitting with a linear function, in 5-30% central collisions, the slope is $-0.06 \pm 0.06(\%)$ and $-0.50 \pm 0.08(\%)$ for protons and antiprotons, respectively; while in 30-80% central collisions, it is $-0.40 \pm 0.07(\%)$ and $-0.48 \pm 0.09(\%)$, respectively. Negative $v_1$ slope for protons and
antiprotons is observed at mid-rapidity in 30-80% centrality. A sizable difference in \( v_1(y) \) slope is seen in 5-30% central collisions but not much is seen in 30-80% central collisions.

![Figure 4](image1.png)

**Figure 4.** Protons \( v_1(y') \) slope (\( dv_1/dy' \)) at mid-rapidity as a function of center of mass collision energy, where \( y' = y/y_{beam} \).

The centrality dependence of \( v_1 \) at mid-rapidity is studied further in Fig. 3, in which \( v_1(y) \) slope is plotted as a function of centrality for protons, antiprotons and charged pions. Two observations are noteworthy to be mentioned: i) If the difference between \( v_1 \) of protons and antiprotons is caused by the anti-flow alone, then such difference is expected to be accompanied by strongly negative \( v_1 \). In data, the large difference between protons and antiprotons \( v_1 \) slopes is seen in 5-30% centrality, while strongly negative \( v_1 \) slope is found for protons, antiprotons and charged pions in a different centrality (30-80%), and ii) the hydrodynamics model with tilted source (which is a characteristic of anti-flow), while correctly predicts the pions \( v_1(y) \) slopes, does not predict the difference in \( v_1(y) \) between particle species [16]. Both observations suggest that additional mechanism is needed to explain the centrality dependence of the difference between the \( v_1(y) \) slopes of protons and antiprotons.

In Fig. 4, protons \( v_1(y') \) slope \( F = (dv_1/dy') \) around mid-rapidity is plotted as a function of collision energy, where \( y' = y/y_{beam} \). Values for the \( v_1(y') \) slope are extracted via a polynomial fit of the form \( Fy' + Cy'^3 \). At low energies, a different slope, that is, the slope of \( \langle p_x(y') \rangle \) in stead of \( v_1(y) \), has been measured for protons by the E877 [18] and the E895 [17] Collaboration. The \( d(p_x)/dy' \) decreases steadily with increasing beam energy over the E877 and the E895 energy range. The similar trend is shown in Fig. 4 with \( v_1(y) \) slope for protons. The slope decreases rapidly with increasing energy, reaching zero around \( \sqrt{s_{NN}} = 9 \text{ GeV} \). It changes its sign to negative around \( \sqrt{s_{NN}} = 17 \text{ GeV} \), as shown by the NA49 measurement. The E877 result is not included in this plot because no \( dv_1/dy' \) from the E877 experiment is available. With previous measurements, which include only one point above \( \sqrt{s_{NN}} = 9 \text{ GeV} \), one cannot conclude if protons \( v_1 \) slope continues to decrease or stays close to zero when energy increases. The addition of the data point from RHIC indicates that protons \( v_1 \) slope remains close to zero at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). Judging over a broad energy range, the transition of the protons \( v_1 \) slope sign from positive to negative happens around \( \sqrt{s_{NN}} = 9 \text{ GeV} \), interestingly, it coincides with the energy vicinity where \( \langle k^+/(\pi^+) \rangle \) exhibits a horn [19].

Fig. 5 shows the charged hadron \( v_1 \) result for Cu+Cu collisions for the centrality 0-60% at \( \sqrt{s_{NN}} = 22.4 \text{ GeV} \). The result is compared to published results for \( \sqrt{s_{NN}} = 62.4 \) and 200 GeV in centrality 30-60% [2]. When viewed in \( \eta/y_{beam} \) frame, a comment trend is observed for all energies in the range of \( \eta/y_{beam} < 1 \).
4. Summary
In summary, STAR’s measurement of directed flow of pions, kaons ($K^0_S$), protons and antiprotons for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are presented. In 10-70% central collisions, $v_1(y)$ slopes of pions, kaons ($K^0_S$) and antiprotons are found mostly negative around mid-rapidity. Sizable difference is seen between $v_1$ of protons and antiprotons in 5-30% central collisions. Comparison to models (RQMD, UrQMD, AMPT, QGSM with parton recombination, hydrodynamics with a tilted source) are made. It is found that hydrodynamic calculation with a tilted source gives the most reasonable description of $v_1(y)$ slope for pions. However, it does not predict the difference between protons and antiprotons $v_1$ [16]. Anti-flow can explain the negative $v_1(y)$ slope while it alone has difficulties in explaining the centrality dependence of the difference between the $v_1(y)$ slopes of protons and antiprotons. The $v_1$ results at 22.4 GeV from Cu + Cu collisions are presented, it is consistent with the published results for Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV and $\sqrt{s_{NN}} = 200$ GeV.

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References
[1] Poskanzer A M and Voloshin S A 1998 Phys. Rev. C 58 1671
[2] Abelev B I et al. (STAR Collaboration) 2008 Phys. Rev. Lett. 101 252301
[3] Chen J (for the STAR Collaboration) 2008 J. Phys. G 35 044072
[4] Sorge H 1997 Phys. Rev. Lett. 78 2309
[5] Stöcker H 2005 Nucl. Phys. A 750 121
[6] Brachmann J, Sofi S, Dumitru A, Stöcker H, Mahruhn J A, Greiner W, Bravina L V and Rischke D H 2000 Phys. Rev. C 61 024909
[7] Csernai L P and Röhrich D 1999 Phy. Lett. B 458 454
[8] Bozek P and Wyskiel I 2010 Phys. Rev. C 81 054902
[9] Snellings R J, Sorge H , Voloshin S, Wang F Q and Xu N 2000 Phys. Rev. Lett 84 2803
[10] Tang A (for the STAR Collaboration) 2010 J. Phys.: Conference Series 230 012018
[11] Bieser F S et al. 2003 Nucl. Instrum. Method A 499 766
[12] Anderson M et al. 2003 Nucl. Instrum. Methods A 499 659
[13] Bleicher M and Stöcker H 2002 Phys. Rev. B 526 309
[14] Chen J Y, Zuo J X, Cai X Z, Liu F, Ma Y G and Tang A H 2010 Phys. Rev. C 81 014904
[15] Bleiche J, Buraun G, Faessler A and Fuchs C 2007 Phys. Rev. C 81 024912
[16] Piotr Bozek 2010 private communication.
[17] Liu H et al. (E895 Collaboration) 2000 Phys. Rev. Lett. 84 5488
[18] Barrette J et al. (E877 Collaboration) 1997 Phys. Rev. C 56 3254; Barrette J et al. (E877 Collaboration) 1997 Phys. Rev. C 55 1420
[19] Afanasiev S V et al. (NA49 Collaboration) 2002 Phys. Rev. C 66 054902; Alt C et al. (NA49 Collaboration) 2008 Phys. Rev. C 77 024903; Alt C et al. (NA49 Collaboration) 2006 Phys. Rev. C 73 044910; Anticic T et al. (NA49 Collaboration) 2004 Phys. Rev. C 69 024902