Directed flow in Au+Au collisions at $\sqrt{s_{NN}} = 62.4 $ GeV

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We present the directed flow \( \langle v_1 \rangle \) measured in Au+Au collisions at \( \sqrt{s_{NN}} = 62.4 \) GeV in the mid-pseudorapidity region \( |\eta| < 1.3 \) and in the forward pseudorapidity region \( 2.5 < |\eta| < 4.0 \). The results are obtained using the three-particle cumulant method, the event plane method with mixed harmonics, and for the first time at the Relativistic Heavy Ion Collider (RHIC), the standard method with the event plane reconstructed from spectator neutrons. Results from all three methods are in
good agreement. Over the pseudorapidity range studied, charged particle directed flow is in the direction opposite to that of fragmentation neutrons.

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Directed flow in heavy-ion collisions is quantified by the first harmonic \( v_1 \) in the Fourier expansion of the azimuthal distribution of produced particles with respect to the reaction plane \( \hat{z} \). It describes collective sideward motion of produced particles and nuclear fragments and carries information on the very early stages of the collision \( \hat{z} \). The shape of \( v_1(y) \) in the central rapidity region is of special interest because it might reveal a signature of a possible Quark-Gluon Plasma (QGP) phase \( \hat{z} \) [3, 4, 10-12].

At AGS and SPS energies, \( v_1 \) versus rapidity is an almost linear function of rapidity \( y \). Often, just the slope of \( v_1(y) \) at midrapidity is used to define the strength of directed flow. The sign of \( v_1 \) is by convention defined as positive for nucleons in the projectile fragmentation region. At these energies, the slope of \( v_1(y) \) at midrapidity is observed to be positive for protons, and significantly smaller in magnitude and negative for pions \( \hat{z} \). The opposite directed flow of pions is usually explained mostly with opposite sign to the protons, but somewhat diffused due to higher thermal velocities for pions. Similar UrQMD calculations \( [10] \) predict no wiggle for pions in the central rapidity region with a negative slope at midrapidity as observed at lower collision energies.

At RHIC, most of the detectors cover the central rapidity region where the directed flow signal is small and the analysis procedures easily can be confused by azimuthal correlations not related to the reaction plane orientation, the so-called non-flow effects. Only recently have the first \( v_1 \) results been reported by the STAR Collaboration \( [12] \) and preliminary results by the PHOBOS Collaboration \( [13] \). In \( [12] \), the shape of \( v_1 \) in the region on either side of midrapidity is poorly resolved due to large statistical errors. This shortcoming arose from having only about 70,000 events from the Forward Time Projection Chambers (FTP\( C \)s) \( [14] \) during their commissioning in the RHIC run II period (2002).

In this paper, we present directed flow measurements in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). Results are obtained by three different methods, namely, the three-particle cumulant method \( (v_1(3)) \) \( [12] \), the event plane method with mixed harmonics \( (v_1\{\text{EP}_{1}, \text{EP}_{2}\}) \) \( [14] \), and the standard method \( [1] \) with the first-order event plane reconstructed from neutral fragments of the incident beams \( (v_1\{\text{ZDC-SMD}\}) \) [14]. According to the standard method \( [1] \), directed flow can be evaluated by

\[
v_1\{\text{Standard}\} = \langle \cos(\phi - \Psi_1) \rangle / \text{Res}(\Psi_1) \tag{1}\]

where \( \phi \) and \( \Psi_1 \) denote the azimuthal angle of the particle and the first-order event plane, respectively, and \( \text{Res}(\Psi_1) = \langle \cos(\Psi_1 - \Psi_{\text{RP}}) \rangle \) represents the resolution of the first-order event plane. In the three-particle cumulant method \( [12] \), the flow is evaluated from

\[
\langle \langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle \rangle = \langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle \\
-\langle \cos(\phi_a + \phi_b) \rangle \langle \cos(-2\phi_c) \rangle \\
-\langle \cos(\phi_a) \rangle \langle \cos(\phi_b - 2\phi_c) \rangle \\
-\langle \cos(\phi_b) \rangle \langle \cos(\phi_a - 2\phi_c) \rangle \\
+2\langle \cos(\phi_a) \rangle \langle \cos(\phi_b) \rangle \langle \cos(-2\phi_c) \rangle \\
= v_{1,a}v_{1,b}v_{2,c} \tag{2}\]

where on the r.h.s. of the first equality, the first term is a three-particle correlation and the other terms are to isolate the genuine three-particle correlation from spurious correlations induced by detector effects. Subscripts \( a, b \) and \( c \) denote three different particles. This method was used in the first \( v_1 \) publication at RHIC \( [12] \). The event plane method with mixed harmonics \( [14] \) utilizes the second-order event plane from the TPC, \( \Psi_{\text{TPC}} \), and two first-order event planes from random subevents in
the FTPCs, $\Psi_1^{\text{FTPC}}$ and $\Psi_2^{\text{FTPC}}$. It measures

$$v_1\{\text{EP}_1,\text{EP}_2\} = \frac{\langle \cos (\phi + \Psi_1^{\text{FTPC}} - 2\Psi_2^{\text{FTPC}}) \rangle}{\sqrt{\langle \cos (\Psi_1^{\text{FTPC}} + \Psi_2^{\text{FTPC}} - 2\Psi_2^{\text{FTPC}}) \rangle \cdot \text{Res}(\Psi_2^{\text{FTPC}})}}$$

where the emission angle of the particle $\phi$ is correlated with the first-order event plane $\Psi_1^{\text{FTPC}}$ of the random subevent (made of tracks of both FTPCs) which does not contain the particle. $\text{Res}(\Psi_2^{\text{FTPC}})$ represents the resolution of the second-order event plane measured in the TPC [16]. Both the cumulant method and the event plane method with mixed harmonics offer enhanced suppression of non-flow effects, including correlations due to momentum conservation, compared with the standard method (in which the event plane is reconstructed for the same harmonics and in the same rapidity region where the event anisotropy is measured). In the present study, the procedures to obtain $v_1\{3\}$ and $v_1\{\text{EP}_1,\text{EP}_2\}$ are essentially the same as in Ref. [12]. In the third method,

| Centrality | Event plane resolution |
|------------|------------------------|
| 70% − 80%  | 0.179 ± 0.005          |
| 60% − 70%  | 0.185 ± 0.004          |
| 50% − 60%  | 0.176 ± 0.005          |
| 40% − 50%  | 0.167 ± 0.005          |
| 30% − 40%  | 0.138 ± 0.006          |
| 20% − 30%  | 0.110 ± 0.008          |
| 10% − 20%  | 0.081 ± 0.010          |

TABLE I: The resolution of the first-order event plane [1] provided by the ZDC-SMDs, as determined from the sub-event correlation between east and west SMDs. The errors in the table are statistical.

the reaction plane was determined from the sideward deflection of spectator neutrons ("bounce-off") [5], measured in the Zero Degree Calorimeters (ZDCs) [17]. This is the first report from RHIC of flow results with the event plane reconstructed from spectator fragments. Five million minimum-bias events were used in this study for each of the three analyses, and all the errors presented are statistical. Cuts used in the TPC ($|\eta| < 1.3$) [15] and FTPC ($2.5 < |\eta| < 4.0$) analyses are the same as listed in Table II of Ref. [10], except that the vertex $z$ cut is from −30 to 30 cm. The centrality definition, based on the raw charged particle TPC multiplicity with $|\eta| < 0.5$, is the same as used previously [16].

In the Fall of 2003, STAR installed Shower Maximum Detectors (SMDs) sandwiched between the first and second modules of each existing STAR ZDC at $|\eta| > 6.3$. Each SMD consists of two plastic scintillator planes, one of 7 vertical slats and another of 8 horizontal slats. The two SMDs provide event-by-event information on the transverse distribution of energy deposition of the spectator neutrons. The weighted center of the energy distribution determines the event plane vector on each side. The combination of the east and west event plane vectors provides the full event plane and the event plane resolution is obtained from the correlation of the two event plane vectors in the standard way. The $v_1\{\text{ZDC-SMD}\}$ should have minimal contribution from non-flow effects due to the large rapidity gap between the spectator neutrons used to establish the reaction plane and the rapidity region where the measurements were performed. The resolution, as defined in [11], of the first-order event plane reconstructed using the ZDC-SMDs is listed in Table III.

The centrality ranges of Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV where the three $v_1$ methods work are slightly different: $v_1\{3\}$ fails at centralities less than 5% and centralities greater than 70%, because the four particle cumulant $v_2\{4\}$, which is a necessary ingredient for measuring $v_1\{3\}$, is not measurable in those regions possibly due to large $v_2$ fluctuations; $v_1\{\text{ZDC-SMD}\}$ fails for centrality less than 10% because of insufficient event plane resolution in central collisions. Figure [4] shows charged
FIG. 2: (color online) $v_1$ versus rapidity for protons and pions. The charged particle $v_1(\eta)$ is plotted as a reference. The different upper end of the $p_t$ range for protons and pions is due to different limits of the $dE/dx$ identification method. The solid and dashed lines are results from linear fits described in the text. All results are from analyses using the reaction plane reconstructed by the ZDC-SMD, $v_1$ (ZDC-SMD). The plotted errors are statistical only, and systematic effects are discussed in the text.

AMPT [19], RQMD [2], and UrQMD [20] model calculations for the same centrality of Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV are also shown in Fig. 11. Most transport models, including AMPT, RQMD and UrQMD, underpredict elliptic flow ($v_2$) at RHIC energies, and we now report that they also underpredict the charged particle $v_1(\eta)$ within a unit or so of mid-pseudorapidity, but then come into good agreement with the data over the region $2.5 < |\eta| < 4.0$. While the magnitude of $v_1$ for charged particles increases with the magnitude of pseudorapidity below $|\eta| \sim 3.8$ for centralities between 10% and 70%, our results are compatible with the peak in $|v_1|$ lying in the $|\eta|$ region predicted by all three models, namely, 3.5 to 4.0.

No apparent wiggle structure, as discussed above, is observed within our acceptance. Throughout our pseudorapidity acceptance, charged particles on a given side of $\eta=0$ flow in the opposite direction to the fragmentation neutrons on that side. This is consistent with the direction expected in the “anti-flow” scenario [3] but it is also the same direction as measured for pions at lower energies that is usually related to the pion shadowing by nucleons. Assuming that the charged particle flow at beam rapidity is dominated by protons, one would conclude that over the entire pseudorapidity range $v_1(\eta)$ changes sign three times. However, this does not prove the existence of the wiggle structure for protons and pions separately. Measurements of directed flow of identified particles could be more informative in this respect. In STAR, particle identification is feasible only in the main TPC, which covers the pseudorapidity region $|\eta| < 1.3$. In this region, the RQMD model predicts very flat $v_1(\eta)$ for pions and a clear wiggle structure, with negative slope $dv_1/d\eta$ at mid-pseudorapidity for protons at $\sqrt{s_{NN}} = 62.4$ GeV. (The relatively strong wiggle for pions reported in Ref. 10 is developed only at higher collision energies.) To maximize the magnitude of the possible slope, we select the centrality interval 40% to 70%, where flow anisotropies normally are at their peak. The result is shown in Fig. 2. With the current statistics, we observe that pion flow is very similar to that of charged particles, with the slope at midrapidity $dv_1/d\eta$ about $-0.0074 \pm 0.0010$, obtained from a linear fit over the region $|\eta| < 1.3$ (dashed line). For protons, the slope $dv_1/d\eta$ is $-0.025 \pm 0.011$ from a linear fit in $|\eta| < 0.6$ (solid line). At present, STAR’s statistics for baryons are rather small compared with the statistics for all charged particles, and our best estimates of the fitted slope are such that a negative baryon slope with comparable magnitude to the RQMD prediction is not decisively ruled out. For the identified particles, the influence of the particle identification procedures on the flow values for pions and protons may be a source of errors. By default we eliminate particles $3\sigma$ away from the expected TPC energy loss for the relevant particle type. When we tightened the cut to $2\sigma$ instead of $3\sigma$, we found that for 40%–70% most central events, the

This article discusses the analysis of directed flow measurements using two-particle correlations. It highlights the importance of systematic uncertainties and the role of different models in predicting elliptic flow ($v_2$). The text examines the behavior of $v_1(\eta)$ for charged particles, noting that while model predictions are generally consistent, the results are compatible with the peak in $|v_1|$ lying within the region predicted by all three models. It also touches on the challenges in identifying baryons and the influence of particle identification procedures on flow measurements.
$v_1\{\text{ZDC-SMD}\}$ of pions is reduced by less than 10% while the proton $v_1\{\text{ZDC-SMD}\}$ stays constant within errors.

Figure 3 shows $v_1$ of charged particles as a function of $\eta$ for different centralities. We do not observe an onset of any special feature in the pseudorapidity dependence of $v_1$ at any centrality. Preliminary $v_1(\eta)$ results from PHOBOS for centrality 0 to 40% are consistent with our data at the same centrality except that $|v_1(\eta)|$ from PHOBOS has its peak at $|\eta|$ of about 3 to 3.5, while STAR’s $|v_1(\eta)|$ peaks at $|\eta|$ about 3.8 or higher. A significant change in particle abundances below STAR’s transverse momentum acceptance cut (0.15 GeV/c) might account for some or all of this difference in the $|v_1|$ peak position.

The transverse-momentum dependence of $v_1$ is shown in Fig. 4. Since $v_1(\eta,p_t)$ is asymmetric about $\eta = 0$, the integral of $v_1(\eta,p_t)$ over a symmetric $\eta$ range goes to zero. We change $v_1(\eta,p_t)$ of particles with negative $\eta$ into $-v_1(-\eta,p_t)$, and integrate over all $\eta$. Due to the small magnitude of the $v_1$ signal close to mid-pseudorapidity ($|\eta| < 1.3$), only the averaged $v_1(p_t)$ over centralities 10%–70% is shown. For $2.5 < |\eta| < 4.0$, the $v_1$ signal is large enough to be resolved for different centrality regions. The poor $p_t$ resolution for higher $p_t$ in FTPCs limits the $p_t$ range to below 1 GeV/c for $2.5 < |\eta| < 4.0$. For all centralities and pseudorapidity regions, the magnitude of $v_1$ is observed to reach its maximum at $p_t \approx 1$ GeV/c for $|\eta| < 1.3$ and at $p_t \approx 0.5$ GeV/c for $2.5 < |\eta| < 4.0$.

| Centrality | Impact parameter (fm) |
|------------|-----------------------|
| 70% – 80%  | $12.82 \pm 0.62 - 0.67$ |
| 60% – 70%  | $11.89 \pm 0.67 - 0.52$ |
| 50% – 60%  | $10.95 \pm 0.58 - 0.52$ |
| 40% – 50%  | $9.91 \pm 0.47 - 0.42$ |
| 30% – 40%  | $8.71 \pm 0.52 - 0.31$ |
| 20% – 30%  | $7.36 \pm 0.47 - 0.26$ |
| 10% – 20%  | $5.72 \pm 0.32 - 0.21$ |
| 5% – 10%   | $4.08 \pm 0.16 - 0.21$ |
| 0 – 5%     | $2.24 \pm 0.07 - 0.14$ |

TABLE II: The correspondence between centrality and impact parameter.

Note that from its definition, $v_1(p_t)$ must approach zero as $p_t$ approaches zero. The centrality dependence of $p_t$-integrated $v_1$ is shown in Fig. 5. The values of the impact
strongly with centrality than in the region closer to mid-
fragmentation \cite{25}. Figure 6 presents
beam energies \cite{12, 23, 24}, a pattern known as limiting
beam rapidity appears unchanged over a wide range of
tra and flow) as a function of rapidity distance from
port the limiting fragmentation hypothesis in the region

determination of the reaction plane from the bounce-off
of charged particle directed flow in Au+Au collisions at
\sqrt{s_{NN}} = 62.4 \text{ GeV}. The analysis has been performed us-
ing three different methods and the results agree very
well with each other. One of the methods involves the
determination of the reaction plane from the bounce-off
of fragmentation neutrons, the first measurement of this
type at RHIC. This method provides measurements of di-
rected flow that are expected to have negligible system-
atic uncertainty arising from non-flow effects. In addi-
tion, these measurements provide a determination of the
sign of v_1. In this way, we conclude that charged particles
in the pseudorapidity region covered by the STAR TPC
and FTPCs (up to |\eta| = 4.0) flow in the opposite direc-
tion to the fragmentation nucleons with the same sign of
\eta. The p_t-dependence of v_1 saturates above p_t ≈ 1 \text{ GeV/c}
in the mid-pseudorapidity region and p_t ≈ 0.5 \text{ GeV/c}

parameter were obtained using a Monte Carlo Glauber calculation \cite{22}, listed in Table II. As expected, v_1 de-
creases with centrality. It is seen that v_1 in the more for-
ward pseudorapidity region 2.5 < |\eta| < 4.0 varies more
strongly with centrality than in the region closer to mid-
pseudorapidity (|\eta| < 1.3).

It has been observed that particle emission (both spec-
tra and flow) as a function of rapidity distance from
beam rapidity appears unchanged over a wide range of
beam energies \cite{12, 23, 24}, a pattern known as limiting
fragmentation \cite{25}. Figure 4 presents v_1 results in the
projectile frame for three beam energies. In this frame,
zero on the horizontal axis corresponds to beam rapid-
ity for each of the three beam energies. The data sup-
port the limiting fragmentation hypothesis in the region
−2 < y - y_{beam} < 1.

In summary, we have presented the first measurements of charged particle directed flow in Au+Au collisions at
\sqrt{s_{NN}} = 62.4 \text{ GeV}. The analysis has been performed us-
ing three different methods and the results agree very
well with each other. One of the methods involves the
determination of the reaction plane from the bounce-off
of fragmentation neutrons, the first measurement of this
type at RHIC. This method provides measurements of di-

FIG. 4: (color online) The upper panel shows v_1{3} versus p_t measured in the main TPC (|\eta| < 1.3), for centrality 10%–
70%. The lower panel shows v_1{3} versus p_t measured by
the Forward TPC (2.5 < |\eta| < 4.0), for different centralities.
Note the different scales on both axes for the two panels. The
differential directed flow of particles with negative \eta has been
changed in sign as stated in the text. The plotted errors are
statistical.

FIG. 5: (color online) Directed flow of charged particles as
a function of impact parameter for the mid-pseudorapidity
region (|\eta| < 1.3, with the left vertical scale) and the forward
pseudorapidity region (2.5 < |\eta| < 4.0, with the right vertical
scale). The differential directed flow of particles with negative
\eta has been changed in sign as stated in the text. The plotted
errors are statistical.

FIG. 6: (color online) Charged particle v_1 for Au+Au colli-
sions (10%–70\%) at 200 GeV \cite{12} (open stars) and 62.4 GeV
(solid stars), as a function of \eta−y_{beam}. Also shown are results
from NA49 \cite{7} (circles) for pions from 158\,A GeV midcentral
(12.5%–33.5\%) Pb+Pb collisions as a function of y − y_{beam}.
The 62.4 GeV and 200 GeV points are averaged over the pos-
itive and negative rapidity regions. All results are from anal-
yses involving three-particle cumulants, v_1{3}. The plotted
errors are statistical.
in the forward pseudorapidity region. Over the pseudorapidity range studied, no sign change in the slope of charged-particle $v_1$ versus pseudorapidity is observed at any centrality. The centrality dependence of $v_1$ in the region of $2.5 < |\eta| < 4.0$ is found to be stronger than what is observed closer to mid-pseudorapidity. The rapidity dependence of $v_1$ provides further support for the limiting fragmentation picture.

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