Elliptic Flow Measurements with the PHENIX Detector

Roy A. Lacey\textsuperscript{a} for the PHENIX Collaboration\textsuperscript{*}

\textsuperscript{a}Chem. Dept., SUNY Stony Brook

Two particle azimuthal correlation functions are presented for charged hadrons produced in Au + Au collisions at RHIC ($\sqrt{s_{NN}} = 130$ GeV). The measurements allow for the determination of elliptic flow without event-by-event estimation of the reaction plane. The measured correlation functions indicate elliptic flow values ($v_2$) which show significant sensitivity to both the collision centrality and the transverse momenta of emitted hadrons.

1. Introduction

One of the important goals of current Relativistic Heavy Ion reaction studies is the creation and study of nuclear matter at high energy densities\textsuperscript{[1–4]}. Central to these studies are open questions related to the properties of high-energy-density nuclear matter, and whether or not conditions for the predicted transition to its quark gluon plasma (QGP) phase are achieved. Such a phase of deconfined quarks and gluons has been predicted to survive for $\approx 3 - 10$ fm/c in Au + Au collisions\textsuperscript{[5]} at the Relativistic Heavy Ion Collider (RHIC), and several experimental probes have been proposed for its possible detection and study\textsuperscript{[4]}. Elliptic flow is one such probe that has attracted considerable recent attention\textsuperscript{[6–11]}. \textsuperscript{*}

2. Elliptic Flow

Over a broad range of beam energies, elliptic flow can be attributed to a delicate balance between (i) the ability of a fast pressure build-up to generate a rapid transverse expansion of nuclear matter and (ii) the passage time for removal of the shadowing effect on participant hadrons by the projectile and target spectators\textsuperscript{[7,8]}. If the passage time is long compared to the expansion time, spectator nucleons serve to block the path of participant hadrons emitted toward the reaction plane, and nuclear matter is squeezed-out perpendicular to this plane giving rise to negative elliptic flow. For shorter passage times, the blocking of participant matter is significantly reduced and preferential in-plane emission or positive elliptic flow is favored because the geometry of the participant region exposes a larger surface area in the direction of the reaction plane. Thus, elliptic flow is predicted and found to be negative for beam energies $< 4$ AGeV and positive for beam energies $> 4$ AGeV \textsuperscript{[6–9]}. For RHIC energies, strong Lorentz contraction and very short

\textsuperscript{*}For the full PHENIX Collaboration author list and acknowledgements see the contribution by W.A. Zajc (K. Adecox et al.) in this volume.
passage times lead to significant reduction of shadowing effects, and positive elliptic flow is expected[6,10,11].

2.1. Azimuthal Correlation Functions

In this contribution, two-particle azimuthal correlation measurements are exploited to evaluate the elliptic flow of charged hadrons emitted in Au + Au collisions ($\sqrt{s_{NN}} = 130$ GeV) at RHIC. There are several important benefits which are afforded by these measurements. First, they circumvent the need for full azimuthal acceptance. Second, they allow the determination of elliptic flow without event-by-event estimation of the reaction plane and the associated corrections for it’s dispersion. Thirdly, these correlation measurements can serve to minimize many important systematic uncertainties (detector acceptance, efficiency, etc) which can influence the accuracy of elliptic flow measurements[13].

The colliding Au beams ($\sqrt{s_{NN}} = 130$ GeV) used in these measurements have been provided by the Relativistic Heavy Ion Collider at Brookhaven National Laboratory (BNL). Charged reaction products were detected in the east and west central arms of the PHENIX detector[1,14]. Each of these arms subtends 90° in azimuth $\phi$, and $\pm 0.35$ units of pseudorapidity $\eta$. The axial magnetic field of PHENIX (0.5 Tesla) allowed for the tracking of particles with $p_t > 200$ Mev/c in the fiducial volume of both arms. The Zero Degree Calorimeters (ZDC), were used in conjunction with the Beam-Beam Counters (BBC), to provide a trigger for a wide range of centrality (cent) selections[14].

The present data analysis is based on the use of the second Fourier coefficient, $\lambda_2 = \langle \cos (2\Delta \phi) \rangle$, to measure the anisotropy of the distribution in the azimuthal angle difference ($\Delta \phi = \phi_1 - \phi_2$) between pairs of charged hadrons[13];

$$\frac{dN}{d(\Delta \phi)} \propto [1 + 2 \lambda_1 \cos (\Delta \phi) + 2 \lambda_2 \cos (2 \Delta \phi)].$$

(1)

The value of $\sqrt{\lambda_2}$ can be identified with the second Fourier coefficient $v_2$, commonly used to quantify elliptic flow with respect to the reaction plane[13].

Following an approach commonly exploited in interferometry studies, a two-particle azimuthal correlation function can be defined as follows[3,16]

$$C(\Delta \phi) = \frac{N_{cor}(\Delta \phi)}{N_{uncor}(\Delta \phi)},$$

(2)

where $N_{cor}(\Delta \phi)$ is the observed $\Delta \phi$ distribution for charged particle or track pairs selected from the same event, and $N_{uncor}(\Delta \phi)$ is the $\Delta \phi$ distribution for particle pairs selected from mixed events. Events were selected with a collision vertex position, $-20 < z < +20$ cm, along the beam axis. Mixed events were obtained by randomly selecting each member of a particle pair from different events having similar centrality and vertex position. Event centralities were obtained by a series of cuts in the space of BBC versus ZDC analog response[1]; they reflect percentile selections of the total interaction cross section of 7.2 barns[1,14].

Figs. 1a and b show representative distributions for particle pairs obtained from the same event ($N_{cor}(\Delta \phi)$) and those obtained from mixed events ($N_{uncor}(\Delta \phi)$) respectively. The correlation function $C(\Delta \phi)$, obtained from the ratio of these two distributions (cf
Figure 1. $\Delta \phi$ distributions for charged particle or track pairs selected from the same event (a) and for particle pairs selected from mixed events (b). The resulting correlation function $C(\Delta \phi)$, obtained from the ratio of these two distributions is shown in panel (c).

Eq. 3 is shown in Fig. 1c. The correlation function shows a clear anisotropic pattern which is essentially symmetric about $\Delta \phi = 90^\circ$. Such a pattern is consistent with the features expected for in-plane elliptic flow, and serve to confirm the utility of azimuthal correlation functions for flow measurements at RHIC. The solid curve in Fig. 1 represents a fit to the correlation function following Eq. 1; it provides a measure of the magnitude of the elliptic flow via the Fourier coefficient $\sqrt{\lambda_2} = v_2$.

An important prerequisite for reliable flow extraction from PHENIX data is to establish whether or not the $\sim 180^\circ$ azimuthal coverage of the detector results in significant distortions to the correlation function. To this end, detailed simulations which take account of the detector response, acceptance and efficiency have been performed for simulated data in which specific amounts of elliptic flow were introduced. The essentially symmetric character of the correlation functions obtained from these simulations, provides a qualitative indication of the absence of distortions which could influence the reliability of the extracted flow. More quantitative evidence have been provided by Fourier fits to the correlation functions; they indicate essentially complete recovery ($\sim 90\%$) of the input $v_2$ signals.

2.2. Differential Elliptic Flow

The magnitude of the elliptic flow and the mechanism for its development are related to several aspects: (a) the geometry of the collision zone, (b) the initial baryon and energy density developed in this zone, and (c) the detailed nature of the equation of state for the created nuclear matter [10,11]. To disentangle these separate effects will undoubtedly require detailed differential elliptic flow studies. That is, $v_2(p_t)$, $v_2(cent)$, $v_2(\eta)$, etc. Initial differential flow measurements ($v_2(p_t)$, $v_2(cent)$, $v_2(p_t, cent)$) obtained with the PHENIX detector are summarized in Figs. 2; they represent the results obtained from azimuthal correlation functions for charged hadrons ($0.3 < p_t < 2.5$ GeV/c) emitted in collisions at several centralities. Figs. 2a and b show the differential flow results, $v_2(p_t)$ and $v_2(cent)$ respectively. Fig. 2c compares the differential flow, $v_2(p_t, cent)$ for
several centralities as indicated. Figs. 2a - c show relatively large differential flow values which increase with the $<p_t>$ of emitted hadrons, as well as with increasing impact parameter. These magnitudes and trends are not only consistent with the results of other flow measurements at RHIC[2,12], but are in surprisingly good qualitative agreement with hydrodynamic model calculations[10,11]. Since these calculations assume local thermal equilibrium at every space-time point in the collision zone, they are suggestive of the possibility that rapid thermalization occurs in Au + Au collisions at RHIC. Such a notion is of course important to the task of delineating the EOS and establishing whether or not QGP formation occurs at RHIC.

3. Summary

In summary, elliptic flow measurements have been made with the PHENIX detector via two-particle azimuthal correlation functions. The measurements indicate relatively large flow magnitudes (differential and integral). The differential flow $v_2(p_t)$, $v_2(cent)$ and $v_2(p_t, cent)$ are found to increase with both the $<p_t>$ of emitted hadrons, and with increasing impact parameter. The magnitude and the data trends are in good qualitative agreement with other flow measurements at RHIC[12]. They also show surprisingly good agreement with the results from hydrodynamic model calculations[10,11]. Further detailed analyses of PHENIX flow data are currently in progress and will be reported elsewhere[18].

REFERENCES
1. K. Adcox et al. (PHENIX Collaboration), Phys. Rev. Lett. 86, 3500 (2001)
2. K.H. Ackermann et al. (STAR Collaboration), Phys. Rev. Lett. 86 402 (2001).
3. B.B. Back et al. (PHOBOS Collaboration), Phys. Rev. Lett. 85 3100 (2000).
4. S. Bass et al. Proceedings of “Quark Matter 1999” (Torino, Italy, May 10 - 15, 1999), Nucl.Phys. A661 205 (1999).
5. B. Zhang, M. Gyulassy, and C.M. Ko, Phys. Lett. B 455 45 (1999).
6. J.-Y. Ollitrault, Phys. Rev. D 46 (1992) 229.
7. H. Sorge, Phys. Rev. Lett. 78 2309 (1997); *ibid.* 82 2048 (1999).
8. P. Danielewicz *et al.*, Phys. Rev. Lett. 81, 2438 (1998).
9. C. Pinkenburg *et al.*, Phys. Rev. Lett. 83, 1295 (1999).
10. D. Teaney, J. Lauret, and E.V. Shuryak, [nucl-th/ 0011058](http://arxiv.org/abs/nucl-th/0011058).
11. P. F. Kolb *et al.*, [hep-ph/0103234](http://arxiv.org/abs/hep-ph/0103234).
12. Presentations by the STAR, and PHOBOS collaborations in [17].
13. R. Lacey et al., Phys. Rev. Lett. 70, 1224 (1993).
14. See for example presentation by W. Zajc in [17].
15. A. M. Poskanzer *et al.*, Phys. Rev. C 58, 1671, (1998).
16. S. Wang et al., Phys. Rev. C44, 1091 (1991).
17. Proceedings of “Quark Matter 2001” (Stony Brook, Jan. 15-20, 2001), to appear in Nucl. Phys. A. Transparencies are available at [http://www.rhic.bnl.gov/qm2001/program.html](http://www.rhic.bnl.gov/qm2001/program.html).
18. K. Adcox *et al.* (PHENIX Collaboration), manuscript in preparation.