Flow and non-flow correlations from four-particle multiplets in STAR

A. H. Tang for the STAR collaboration

Abstract. Elliptic flow results are presented for Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV in RHIC. This signal is investigated as a function of transverse momentum, rapidity and centrality. Results from four-particle correlation analysis, which can filter out contributions to the flow signal from correlations unrelated to the event reaction plane ("non-flow"), are presented and compared to the conventional method, in which non-flow effects are treated as part of the systematic uncertainty.

INTRODUCTION

Flow describes the azimuthal momentum distribution with respect to the reaction plane of particle emission from non-central heavy-ion collisions [1, 2]. The initial spatial deformation due to geometry and the pressure developed early in the collision causes azimuthal momentum-space anisotropy. The measurement of flow can help provide insight into the evolution of this early stage of a relativistic heavy-ion collision. Elliptic flow is characterized by the second harmonic coefficient $v_2$ of an azimuthal Fourier decomposition of the momentum distribution [3, 4, 5], and has been observed and extensively studied in Au + Au collisions from subrelativistic energies on up to RHIC. At RHIC energies, elliptic flow is inferred to be a relative enhancement of emission in the plane of the reaction, and provides information about the early-time thermalization achieved in the collisions [6].

Sideward and elliptic flow are widely studied phenomena with a well-understood relationship to the event reaction plane [1, 2]. Generally speaking, large values of flow observables are considered signatures of hydrodynamic behavior, while smaller flow signals can have alternative explanations. Furthermore, there are several possible sources of azimuthal correlations which are unrelated to the reaction plane, examples include correlations caused by resonance decays or dijets, by HBT or Coulomb effects, by momentum conservation, etc. In the present type of study, it is not necessary to distinguish between the various possible effects in this overall category, and their combined effect is known as "non-flow" correlations.

Conventional flow analyses are equivalent to averaging over correlation observables constructed from pairs of particles, and there is no requirement for each event to contribute more than one pair. When such analyses are applied to relativistic nuclear collisions where particle multiplicities can be as high as a few thousand, the possible new information contained in higher multiplets remains untapped. A previous study of high-order flow effects focused on measuring the extent to which all fragments contribute to the observed flow signal [7]. Given that flow analyses based on pair correlations are sensitive to both flow and non-flow effects, the present work investigates correlation observables constructed from particle quadruplets, and it is assumed that non-flow effects contribute at a negligible level to the quadruplet correlation.

This study presents STAR (Solenoidal Tracker At RHIC) data from Au + Au running at $\sqrt{s_{NN}} = 130$ GeV during summer 2000. Details of the detector in its year-one configuration can be found elsewhere [8, 6]. The present analysis is based on 120k events corresponding to a minimum bias trigger. Events with a primary vertex beyond 1 cm radially from the center of the beam or 75 cm longitudinally from the center of the Time Projection Chamber (TPC) were excluded. Within the selected events, tracks were included if all five of the following conditions were satisfied: they passed within 2 cm of the primary vertex, they had at least 15 space points in the TPC, the ratio of the number of space points to the expected maximum number of space points was above 0.52, pseudorapidity $|\eta| < 1.3$, and $0.1 < p_t < 2.0$ GeV/$c$. The above cuts are essentially the same as used in the previous STAR studies of elliptic flow [6, 9].
TWO- AND FOUR-PARTICLE CORRELATION METHODS

The conventional flow analysis methods [10, 3, 5] are based on measurement of the correlation between particle pairs, and in past analyses where the non-flow contribution was of concern, it was estimated independently. In the first study of elliptic flow in STAR [6], the non-flow effect from jets and resonances was estimated by assuming that they contribute to the second harmonic at the same level as to the first harmonic, and this established an upper limit on the non-flow contribution to the reported $v_2$ signal. This limit played a role in determining the systematic error on the published measurements.

The cumulant [11, 12, 13, 14, 15] and generating function approach offers a formal and convenient way to study flow and non-flow contributions systematically. In this method [14], the cumulant to order four is defined by

$$\langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle \equiv \langle e^{in(\phi_1+\phi_2-\phi_3)}\rangle - \langle e^{in(\phi_1-\phi_3)}\rangle \langle e^{in(\phi_2-\phi_4)}\rangle - \langle e^{in(\phi_1-\phi_4)}\rangle \langle e^{in(\phi_2-\phi_3)}\rangle,$$

(1)

where the double angle bracket notation represents the cumulant expression shown explicitly on the right-hand side, $\phi$ is the measured azimuthal angle for an individual particle, and the $n$ is the harmonic whose coefficient is being studied. The cumulant $\langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle$ involves only pure four-particle correlations since the two-particle correlations among the quadruplets have been explicitly subtracted away.

In the presence of flow, the cumulant [14] becomes

$$\langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle = -v_n^4 + O\left(\frac{1}{M^4} + \frac{v_n^2}{M^2}\right),$$

(2)

where $M$ is the multiplicity of the events. The cumulant to higher orders and the corresponding generalization of the above can also be determined. Likewise, the cumulant of order two reduces to the equivalent of a pair correlation analysis of the conventional type. Statistical uncertainties associated with a cumulant analysis increase with increasing order. We find that statistics from STAR year-one data are adequate for this preliminary study of the 4th-order cumulant, but it is not yet feasible to investigate orders higher than four using available STAR data.

An alternative approach to distinguishing flow and non-flow contributions to $v_2$ is to partition each event into four subevents randomly.

$$\langle Q_1 Q_2 Q_3 Q_4^* - 2 Q_1 Q_2^* \rangle^2 = \langle v_n^4 \rangle - 2 \langle v_n^2 \rangle^2,$$

(3)

where the vector $Q_j$ is the summation of $e^{in\phi}$ for all tracks in subevent $j$ divided by the multiplicity for that subevent. This method can be implemented to estimate the non-flow effect, and yields results that are consistent with those from the cumulant approach. However the statistical error from four subevent method is relatively large since it uses only a fraction of all possible quadruplets.

Figure 1 shows $v_2$ as a function of $p_t$ for events whose centrality lies between 0.26 and 0.34 on the scale of charged particle multiplicity $n_{ch}$ normalized by maximum observed charged particle multiplicity, $n_{max}$. Figure 1 demonstrates that the two pair correlation methods — conventional $v_2$ and the 2nd-order cumulant $v_2$ are consistent with each other, as required. The 4th-order cumulant $v_2$ is systematically lower than the other two calculations, verifying that non-flow effects contribute to the conventional $v_2$ analysis [5, 16, 17]. When this comparison is repeated for central events and again for peripheral events, the statistical error on the 4th-order cumulant $v_2$ becomes bigger, but the same pattern can be observed.

The observed $v_2$ as a function of pseudorapidity (not shown) is almost flat within $|\eta| < 1.3$ for the same three methods, and again, the quadruplet calculation lies below the two $v_2$ observables based on pair correlations.

The integrated $v_2$ as a function of centrality is shown in Fig. 2. The circles show the conventional $v_2$, with the reported systematic uncertainty [18] represented by the asymmetric error bars. The statistical error for the conventional method is smaller than the symbol size. The crosses show the 4th-order cumulant $v_2$, which is consistent within statistical uncertainties with the expectation that $v_2$ corrected for non-flow effects should lie at or within the systematic uncertainties reported for the previous conventional $v_2$ measurements [6]. It is clear that non-flow effects are present at all centralities, and their size is largest for peripheral collisions, as expected [14].

In order to test the reliability of the cumulant results, various simulated events have been processed via the same analysis procedure as the data. The results for simulated events are shown in Figs. 4 and 5. Nine data sets were produced, each having 10k simulated events of constant multiplicity $n_{ch} = 500$, with $v_2 = 0.10$. Then, a simple non-flow effect consisting of embedded back-to-back track pairs was introduced at various levels ranging up to 80 embedded pairs per simulated event. Figure 4 illustrates that the 4th-order cumulant $v_2$ always recovers the input 10% $v_2$, while the $v_2$ from the pair correlation analysis methods can only recover the correct input if non-flow pairs are not
FIGURE 1. $v_2$ as a function of transverse momentum for events with charged particle multiplicity near the middle of the observed range (see text). The circle, triangle and cross represent $v_2$ from the conventional method, from the 2nd-order cumulant method, and from the 4th-order cumulant method, respectively.

Figure 5 reports results of a similar test, except that here, the number of embedded pairs was constant at 50 per event, while the imposed input level of elliptic flow was varied. Again, it is seen that the reconstructed $v_2$ from the 4th-order cumulant analysis agrees with the input elliptic flow, while the other two methods are biased towards overestimating the true $v_2$ flow signal.

CONCLUSION

It is concluded that quadruplet correlation analyses can reliably separate flow and non-flow correlation signals. The cumulant approach applied to the year-one STAR data reported in this work has demonstrated some advantages over the previous alternative approaches for treating non-flow effects. In particular, the cumulant approach is sufficiently flexible that we have now chosen to present $v_2$ measurements corrected for non-flow effects, in contrast to the earlier analyses where the non-flow contribution was partly removed and partly quantified by the reported systematic uncertainties. On the other hand, a 4th-order cumulant analysis is subject to larger statistical errors than a conventional pair correlation analysis of the same data set. In the case of year-one data from STAR, the intrinsic advantages of a higher-order analysis are offset by the increased statistical errors, but in the case of the forthcoming higher statistics running in 2001 and beyond, a higher-order analysis will provide a clear advantage.

It is observed that non-flow correlations are present in $\sqrt{s_{NN}} = 130$ GeV Au + Au events throughout the studied region $|\eta| < 1.3$ and $0.1 < p_t < 2.0$ GeV/c, and are present at all centralities. The largest contribution from non-flow correlations is found among peripheral collisions.

ACKNOWLEDGMENTS

We thank Nicolas Borghini and Jean-Yves Ollitrault for helpful discussions and advice.
FIGURE 2. $v_2$ as a function of centrality, where centrality is characterized by charged particle multiplicity $n_{ch}$ divided by the maximum observed charged particle multiplicity, $n_{max}$. The circle and cross represent conventional $v_2$ and the 4th-order cumulant $v_2$, respectively.

REFERENCES

1. Reisdorf, W., and Ritter, H.G., Annu. Rev. Nucl. Part. Sci. 47, 663 (1997).
2. Herrmann, N., Wessels, J.P., and Wienold, T., Annu. Rev. Nucl. Part. Sci. 49, 581 (1999).
3. Ollitrault, J.-Y., Phys. Rev. D 46, 229 (1992).
4. Voloshin, S., and Zhang, Y., Z. Phys. C 70, 665 (1996).
5. Poskanzer, A.M., and Voloshin S.A., Phys. Rev. C 58, 1671 (1998).
6. STAR collaboration, Ackermann, K.H. et al., Phys. Rev. Lett. 86, 402 (2001).
7. Jiang, J. et al., Phys. Rev. Lett. 68, 2739 (1992).
8. STAR collaboration, Ackermann, K.H. et al., Nucl. Phys. A661, 681c (1999).
9. STAR collaboration, Adler, K.H. et al., nucl-ex/0107003, (2001).
10. Danielewicz, P. et al., Phys. Rev. C 38, 120 (1988).
11. Biyajima, M., Prog. Theor. Phys. 66, 1378 (1981).
12. Liboff, R. L., Kinetic Theory Prentice Hall, Englewood Cliffs, New Jersey (1994).
13. Eggers H. C., Lipa P., Carruthers P. and Buschbeck, B., Phys. Rev. D 48, 2040 (1988).
14. Borghini, N., Dinh, P. M., and Ollitrault, J.-Y., Phys. Rev. C 63, 054906 (2001).
15. Borghini, N., Dinh, P. M., and Ollitrault, J.-Y., nucl-th/0105040 (2001).
16. Dinh, P. M., Borghini, N., and Ollitrault, J.-Y., Phys. Lett. B 477, 51 (2000).
17. Borghini, N., Dinh, P. M., and Ollitrault, J.-Y., Phys. Rev. C 62, 034902 (2000).
18. Snellings, R. et al., STAR collaboration, Quark Matter, (2001).
FIGURE 3. Reconstructed $v_2$ for simulated events as a function of number of embedded back-to-back track pairs. The horizontal dashed line marks the level of the true elliptic flow $v_2 = 0.10$, as imposed on the simulated events. The circles, triangles and crosses represent $v_2$ from the conventional method, from the 2nd-order cumulant method, and from the 4th-order cumulant method, respectively. The statistical error is smaller than the symbol size.

FIGURE 4. Reconstructed $v_2$ versus input $v_2$, with a dashed line to mark the “input = output” diagonal. The circles, triangles and crosses represent $v_2$ from the conventional method, from the 2nd-order cumulant method, and from the 4th-order cumulant method, respectively.
