Intercomparison of flow measurements at RHIC experiments

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Abstract. The measurements of collective flow effects in particle production have provided invaluable insights on the transport properties of the strongly interacting matter produced in relativistic heavy-ion collisions at RHIC. The detailed comparison of flow measurements from PHENIX and STAR experiments at RHIC have been presented and discussed. For elliptic flow v_2 of charged hadrons from Au+Au collisions at 200 GeV the two data sets overlap excellently for centralities > 20%, they increasingly diverge at small centralities, with a 30% difference between STAR an PHENIX in the 0-5% centrality bin. For v_3 values the agreement is much worse and coming from the difference in STAR measurements. More investigations are needed to understand the reason for such differences.

1. Introduction

Ultra-relativistic heavy ion collisions offer the opportunity to study the strongly interacting matter under extreme conditions. In nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) with energies up to $\sqrt{S_{NN}} = 200$ GeV and at the Large Hadron Collider (LHC) at energies of $\sqrt{S_{NN}} = 2.76$ TeV, nuclear matter is heated to temperatures up to 200-500 MeV. At these high energies quantum chromodynamics predict a cross-over transition to a new state of matter, so called quark-gluon plasma (QGP) [1]. The most important observables supporting the discovery of the QGP are the high values of elliptic flow and the suppression of high p_T hadrons that can be explained within assuming a strongly coupled quark-gluon liquid to be formed [2].

The collective expansion, also called flow, originates from the initial pressure gradients in the created hot and dense matter. These pressure gradients transform the initial spatial deformations and inhomogeneities of the created matter into momentum anisotropies of the final state particle production, which are experimentally characterized by so-called flow harmonics v_n [3]. Anisotropic flow can probe the properties of the system created in heavy-ion interactions, such as the equation of state (EoS) and transport coefficients like the shear viscosity to the entropy density ratio (η/s).

Every physical quantity which can be experimentally measured is important for a verification of a theory and therefore should be obtained properly. A good measurement should be reproducible; in particular, it should be done in such a way that one can easily compare results from different experiments, using different detectors.

2. Flow analysis methods

There are several methods to measure the magnitude of the flow signal v_n. The various methods have different sensitivities to non-flow effects and v_n fluctuations. Non-flow refers to correlations between particles which are independent of the initial geometry of the collision system, such as resonance decays, HBT correlations, final state interactions and jets.

- *Event Plane method*
  The Event Plane (EP) method [5] uses the anisotropic flow itself to determine the event plane. Within this method, one first identifies the event plane angle (Ψ_n) in each event using a specific detector at forward rapidity and then calculates the correlation of particles near mid rapidity as $v_n = \langle cos[n(\phi - \Psi_n)]\rangle/Res\{\Psi_n\}$, where $Res\{\Psi_n\}$ is the event plane resolution factor. Note that detectors evaluating Ψ_n and detectors measuring the azimuthal angle of the particle ϕ should have the rapidity gap to suppress the auto- and non-flow correlations. Two-particle cumulant method based on the similar idea.

- *The 4-particle cumulant method*
  The advantage of the cumulant method is that the multi-particle cumulant removes the contribution of non-flow correlations from lower-order correlations [6]. The flow contribution can be obtained by subtracting the 2-particle correlation from the 4-particle correlation.

- *Lee-Yang Zero (LYZ) method*
  As opposed to the four-particle cumulant method which is sensitive to the correlations of four particles, LYZ method [7] is sensitive to the correlations of all the particles. Thus it is supposed to remove non-flow correlations to all orders.

Event-by-event fluctuations of v_n affect each method of measurement differently. The event plane and two-particle cumulant methods have a positive contribution while the multi-particle methods (4-particle cumulant and LYZ) have a negative contribution. As a result of fluctuations, an event-plane measurement of v_n yields an ambiguous measure lying somewhere between the event-averaged mean value $\langle v_n \rangle$ and the root-mean-square value $\langle v_n^2 \rangle^{1/2}$. Where exactly depends on the event plane resolution $Res\{\Psi_n\}$, which strongly depends on the experimental setup.

3. Comparison of PHENIX and STAR flow results

An important step toward reducing the systematic uncertainty associated with flow measurements at RHIC, is a detailed comparison of differential flow results $v_n(p_T, \text{centrality})$ obtained by STAR and PHENIX collaborations.
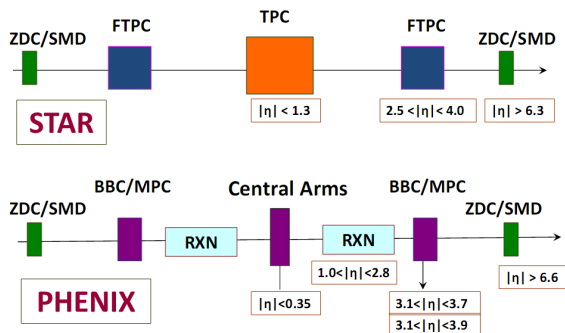

Figure 1. The pseudo-rapidity η acceptance of the PHENIX and STAR detectors used for event-plane reconstruction, along with the mid-rapidity detectors used for charged hadron measurements.

The flow measurements in the PHENIX collaboration were performed using the EP method, where one correlate the azimuthal angles ϕ of the charged tracks in the PHENIX central arms ($|\eta| \leq 0.35$) with the azimuth of the estimated n-order event plane Ψ_n, determined via

hits in the two beam-beam counters (BBCs), reaction plane hodoscopes (RXNs) and zero-degree calorimeters (ZDCs). The respective η coverage for these event-plane detector pairs are: $1.0 < |\eta_{RXN}| < 2.8$, $3.1 < |\eta_{BBC}| < 3.9$ and $|\eta_{ZDC}| > 6.5$, see figure 1. The event centrality is determined by using the total charge deposited in the BBCs.

The STAR collaboration uses both: multi-particle methods (4-particle cumulant and LYZ method) and EP method. In EP method, one correlate the azimuthal angles ϕ of the charged tracks reconstructed in the STAR Time Projection Chamber (TPC) ($|\eta| < 1.0$) with with the azimuth of the estimated n-order event plane Ψ_n, determined via tracks in TPC ($|\eta_{TPC}| < 1.0$) and FTPC ($2.5 < |\eta_{FTPC}| < 4.0$), hits in ZDCs ($|\eta_{ZDC}| > 6.5$), see figure 1. The centrality determination is based on the number of charged tracks in the TPC with track quality cuts. To suppress non-flow effects for EP measurements using TPC one apply $\Delta\eta$ gap between tracks used for EP construction and tracks used for the measurements of v_n.

In order to make proper comparison for EP method we should use the event plane detectors with the same η coverage and similar event plane resolution. This is the case for STAR/PHENIX ZDC/SMD and for STAR FTPC/PHENIX BBC. Unfortunately, we have only one colliding system and one beam energy for the proper comparison of the published elliptic flow (v_2) results between STAR and PHENIX: the v_2 values of charged hadrons from Cu+Cu collisions at $\sqrt{S_{NN}} = 200$ GeV obtained using the EP from STAR FTPC [9] and PHENIX BBC [10]. Figure 2 compares the centrality dependence of the ratio of v_2 obtained using EP from STAR FTPC and PHENIX BBC for four bins in p_T. The difference between two data sets are less than 5-10% within a typical systematic uncertainty of the measurements of 5%. So even with the similar $\Delta\eta$-gap and event plane resolution there are some differences between two experiments.
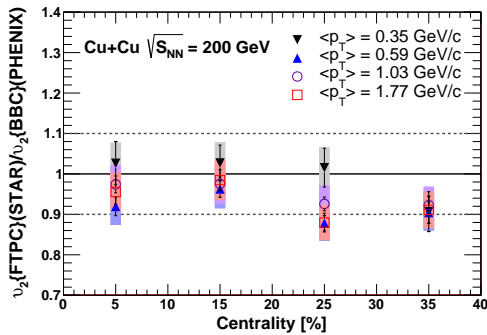

Figure 2. Centrality dependence of the ratio of STAR $v_2(p_T)$ values [9] obtained using EP from STAR FTPC to the v_2 values [10] obtained using EP from PHENIX BBC. The data are for charged hadrons from Cu+Cu collisions at $\sqrt{S_{NN}} = 200$ GeV. The 5% systematic errors are shown.
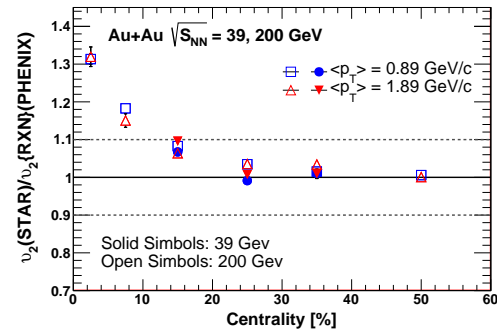
Figure 3. Centrality dependence of the ratio of STAR $v_2(p_T)$ values obtained using EP from STAR TPC to the v_2 values obtained using EP from PHENIX RXN. The data are for charged hadrons from Au+Au collisions at $\sqrt{S_{NN}} = 39$ and 200 GeV.

However, it is hard to make proper comparison for the v_2 measurements of charged hadrons emerged from Au+Au collisions at $\sqrt{S_{NN}} = 200$ GeV. This is the reference point for the Beam Energy Scan program at RHIC and for comparison with LHC results. Here we can make the comparison between v_2 results obtained using the PHENIX EP RXN ($1.0 < |\eta_{RXN}| < 2.8$) and STAR TPC EP with $\Delta\eta > 0.5$. The open symbols from figure 3 shows the centrality dependence of the ratio of STAR $v_2(p_T)$ values to the v_2 values obtained from PHENIX for charged hadrons at $\sqrt{S_{NN}} = 200$ GeV. While the two data sets overlap excellently for centralities $> 20\%$, they

increasingly diverge at small centralities, with a 30% difference between STAR an PHENIX in the 0-5% centrality bin. The PHENIX EP measurements are less affected by non-flow effects due to larger $\Delta\eta$ gap. However, it is hard to explain the difference by non-flow effects only as we see the same difference between STAR and PHENIX results for Au+Au collisions at $\sqrt{S_{NN}}$ = 39 GeV. The excess of the STAR over the PHENIX data is almost uniform in p_T and could be explained by a small shift in the centrality definitions between the experiments.

Figure 4 compares υ_3 values obtained with STAR TPC and FTPC event plane detectors to PHENIX RXN EP υ_3 measurements. One can see a huge difference (40-50%) between TPC and FTPC data and $< 10\%$ difference between STAR TPC to PHENIX RXN results on the other hand. To understand this enormous difference between STAR results more comparisons should be made, e.g. for the elliptic flow between FTPC and TPC EP.
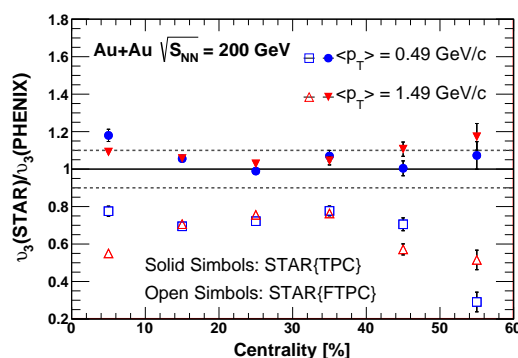

Figure 4. The centrality dependence of the ratio of the υ_3 values of STAR{TPC}(solid) and STAR{FTPC}(open) to the PHENIX $\upsilon_3(p_T)$ points fit for the two p_T bins at $\sqrt{S_{NN}} = 200$ GeV Au+Au collisions. The points are extracted from [11].

4. Conclusion

The comparison of flow measurements from PHENIX and STAR experiments was presented and discussed. The divergences between experimental values are present for every kind of juxtaposition. Precise comparisons require careful attention to the details of each of various measurements, and this will be important in the future when trying to extract more precise quantitative information from experimental data.

Acknowledgments

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