Elliptic Flow in Au+Au Collisions at RHIC

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Abstract. Elliptic flow is an interesting probe of the dynamical evolution of the dense system formed in the ultrarelativistic heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC). The elliptic flow dependences on transverse momentum, centrality, and pseudorapidity were measured using data collected by the PHOBOS detector, which offers a unique opportunity to study the azimuthal anisotropies of charged particles over a wide range of pseudorapidity. These measurements are presented, together with an overview of the analysis methods and a discussion of the results.

Collisions of Au nuclei at the Relativistic Heavy Ion Collider (RHIC) are the most energetic nucleus-nucleus collisions ever achieved in a laboratory, allowing for the study of the properties of nuclear matter under extreme conditions. In order to characterize the medium created in the Au+Au collisions at RHIC, it is necessary to establish that the particles in the system undergo enough reinteractions to reach a state of thermal equilibrium. Only in such a state may the evolution of the medium be described in terms of thermodynamical quantities. Elliptic flow is one of the experimental observables than can help resolve this question. It

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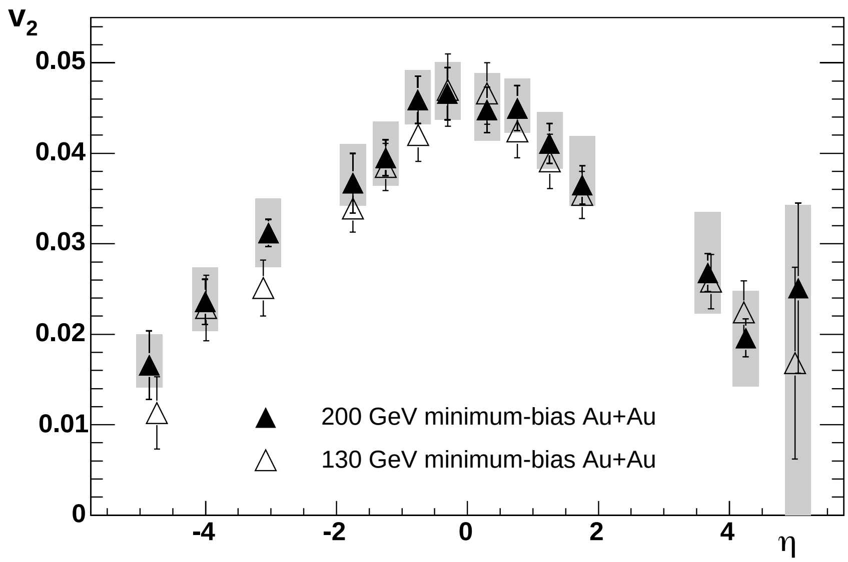

Figure 1. Pseudorapidity dependence of v_2 for charged hadrons in minimum bias Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV (open triangles) [1] and 200 GeV (solid triangles) [2]. The gray boxes around the 200 GeV data points represent the systematic errors.

originates in non-central collisions, where due to the incomplete overlap of the nuclei, the region of overlap is not azimuthally symmetric. If the medium happens to behave collectively, this initial asymmetry will give rise to pressure gradients that change with the azimuthal angle and will modify the angular distribution of the produced particles. Elliptic flow, or v_2, measures the amplitude of the azimuthal anisotropy in the observed particle distributions, and a strong signal suggests that such pressure gradients occurred early in the evolution of the system.

Two analysis methods are employed in PHOBOS for the measurement of flow. The hit-based analysis method, described in [1], was first used for the analysis of 130 GeV data, providing results on the centrality and pseudorapidity dependence of v_2. For the analysis of 200 GeV data, the same method was applied without changes. The pseudorapidity dependence of v_2 for minimum bias charged hadrons at both energies is shown in figure 1. At the startup of RHIC, the expectation was that the pseudorapidity dependence of v_2, if any existed, should be weak. This result, showing a strong dependence, was very surprising at the time and still poses a challenge to theoretical models. In order to further investigate the topic of elliptic flow, a new method which uses tracks in the PHOBOS spectrometer, was developed and applied to the 200 GeV data [2]. That method extends the previous measurements, and offers an independent verification of the hit-based analysis results.

The PHOBOS detector is based on silicon pad technology. Several detector systems are used for measurements based on hits (single layer detectors), or based on tracks (multiple-layer vertex detector and spectrometer). The two spectrometer arms are placed inside a dipole magnetic field of 2 T, to allow for momentum measurements. The single layer detectors provide a wide pseudorapidity coverage, with the octagonal multiplicity detector covering the range $|\eta| < 3.2$ (for collisions at the nominal interaction point), and two sets of three silicon ring detectors covering a more forward region: $3.0 < |\eta| < 5.4$. In these detectors, the passage of particles is recorded by their energy deposition in the silicon (a "hit"). A more detailed

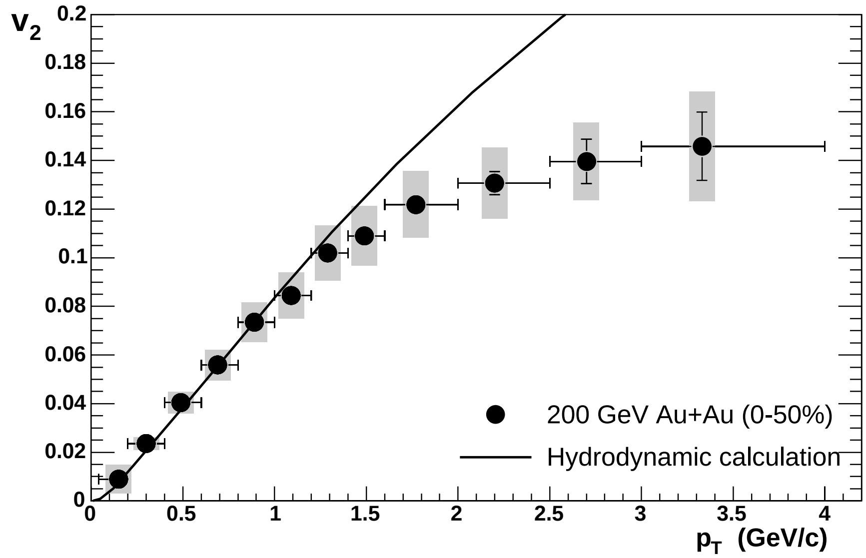

Figure 2. Elliptic flow of charged hadrons, measured as a function of transverse momentum, for the most central 50% of the 200 GeV Au+Au cross-section [2]. The gray boxes show the systematic uncertainty. The pseudorapidity range of this measurement is $0 < \eta < 1.5$. The line corresponds to a hydrodynamical model calculation [6].

description of the PHOBOS detector system can be found in [3].

The experimental trigger is provided by two sets of scintillator detectors, the paddle counters, located on each side of the interaction region, along the beam line. Additionally, a vertex trigger was given by two sets of Čerenkov detectors. The vertex trigger was crucial in obtaining the data set used by the hit-based analysis, which requires events with collision vertices centered at $z = -34$ cm, where z is the beam axis.

The new track-based method determines v_2 by correlating the azimuthal angles of tracks reconstructed in the spectrometer with the event plane measured using the multiplicity detector. Unlike the hit-based analysis, the track-based method uses events with vertices near the nominal interaction region, in order to maximize the track acceptance in the spectrometer. Within this vertex range (-8 cm$< v_z <$10 cm), the central region of the octagon detector is not azimuthally symmetric, due to 4 gaps designed to let particles in the spectrometer and vertex detectors' acceptances to go through without traversing additional material. Therefore, in order to have full azimuthal acceptance for the event plane determination, only parts of the detector further away from the nominal interaction region, which have no gaps, were used. Following the strategy outlined in [4], two subevents of equal multiplicity, and symmetric over pseudorapidity, are employed to determine both the event plane and its resolution. A detailed description of this analysis method can be found in [5].

Figure 2 shows the measured transverse momentum dependence of the elliptic flow amplitude in the range $0 < \eta < 1.5$, for events in the top 50% centrality. A curve representing a hydrodynamical model prediction [6], for the same event class and phase space cuts, is also shown. The v_2 is seen to grow almost linearly as a function of transverse momentum, up to $p_T \sim 1.5$ GeV/c, and then it appears to saturate at a value of about 0.14. This shape of the $v_2(p_T)$ curve has been observed previously, both for charged hadrons and identified particles (see, for example: [7, 8, 9, 10]).

The contribution of non-flow effects to experimental measurements of v_2 has been discussed extensively [11, 12, 13, 14]. In this analysis, the expectation is that by determining the event plane using two well separated sub-events, which are also separated from the pseudorapidity region where v_2 is being measured, the contribution of such non-flow effects should be noticeably reduced, particularly those originating from short range two-particle correlations. By comparing the result of figure 2 with results from reference [13], obtained using reaction plane and 2 and 4-particle cumulant methods, it is seen that the PHOBOS result shows best agreement with the STAR result obtained with the 4-particle cumulant method, implying that the PHOBOS result is indeed less sensitive to non-flow effects.

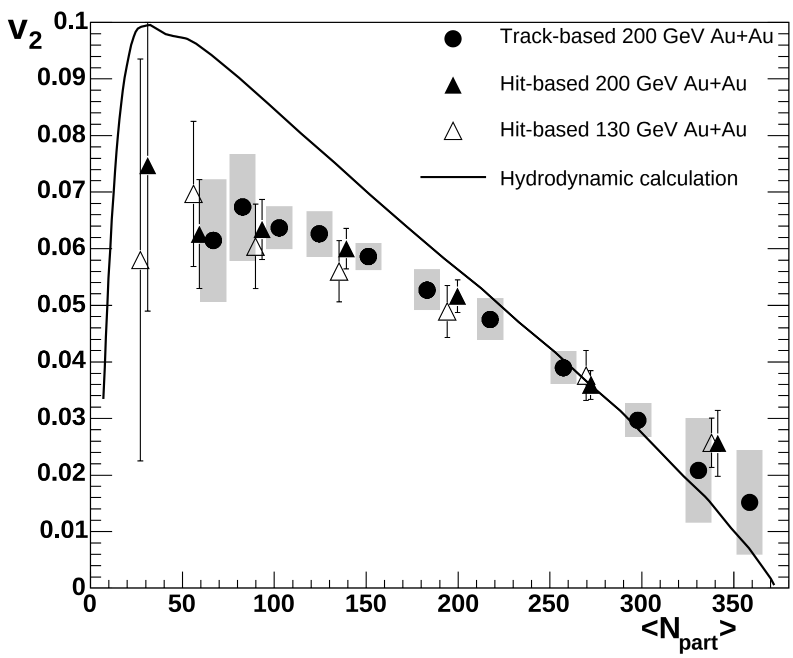

Figure 3. Centrality dependence of the elliptic flow, for $|\eta| < 1$, shown as a function of the number of participants N_{part} [2]. The closed circles represent the result of the track-based method, and the closed triangles show the result of the hit-based method, both for collisions at 200 GeV. The open triangles show the previously obtained result from the hit-based method at 130 GeV [1]. The gray boxes represent the systematic uncertainties for the track-based method. The line shows a hydrodynamical calculation at $\sqrt{s_{NN}} = 200$ GeV [6].

The results for the centrality dependence of v_2, obtained with both analysis methods, are compared in figure 3. Also included in the figure is the result for 130 GeV, previously obtained with the hit-based method [1]. A very good agreement between the two methods is seen. The curve shown in the figure corresponds to the same hydrodynamical model mentioned previously.

The shape of $v_2(\eta)$ for three centrality classes ("peripheral": $25 - 50\%$, "mid-central": $15 - 25\%$, "central": $3 - 15\%$) is shown in figure 4, with results from both analysis methods. The agreement between the two methods, within their range of overlap, is very good. The general features of the shape are common to the three centrality classes, and resemble that of the minimum bias result from figure 1.

Figure 5 shows $v_2(\eta)$ for the same three centrality regions, but with the hit-based and

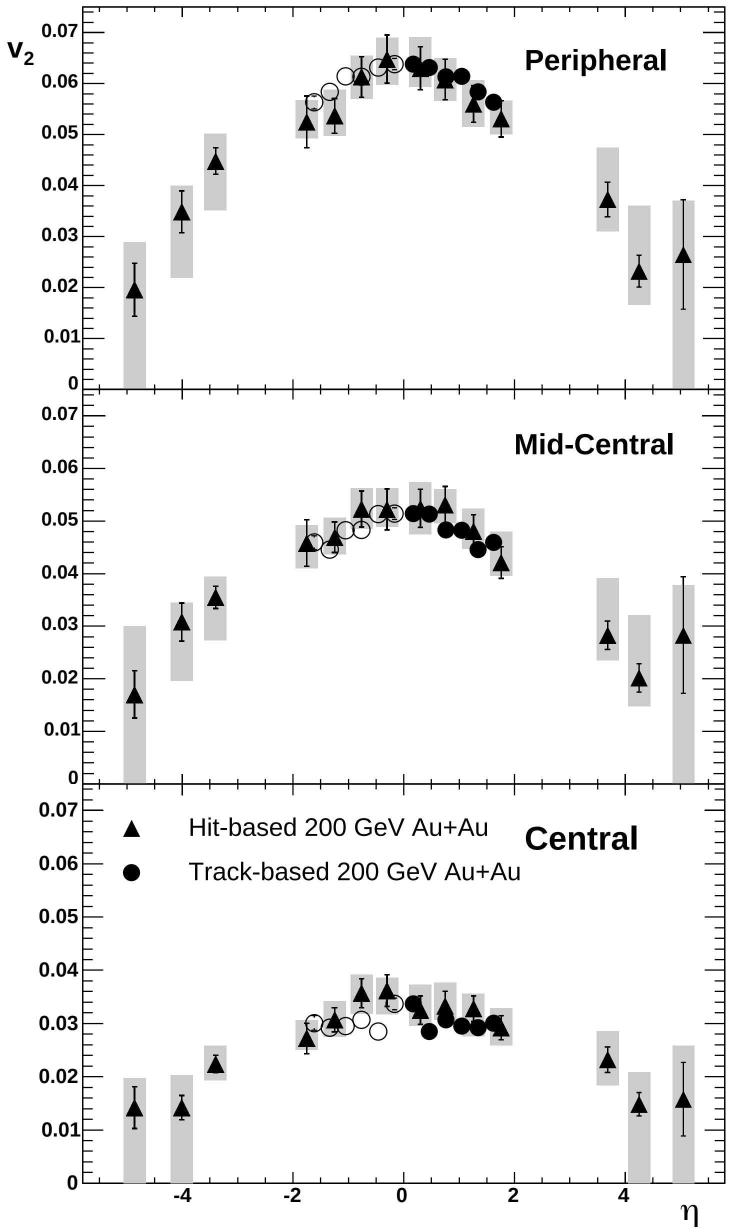

Figure 4. Elliptic flow of charged hadrons measured as a function of pseudorapidity [2], for three centrality classes: $25-50\%$, $15-25\%$ and $3-15\%$, respectively from top to bottom (top is peripheral, bottom is central). The hit-based method results are represented by triangles, and the track-based results are shown by circles, with open circles representing a reflection of the results about mid-rapidity. The gray boxes indicate the systematic errors for the hit-based method results.

track-based methods' results combined. Given that these methods employ different detectors and techniques, they are taken as independent, and as such, it is assumed when combining the results that their errors are not correlated. The combination procedure is detailed in [2]. At least for the semi-peripheral collisions, it is clearly seen that the decrease of v_2 with η starts already near mid-rapidity. The shape of the measured pseudorapidity dependence of v_2 appears to change only by a scale factor as centrality increases, but a flattening of the shape

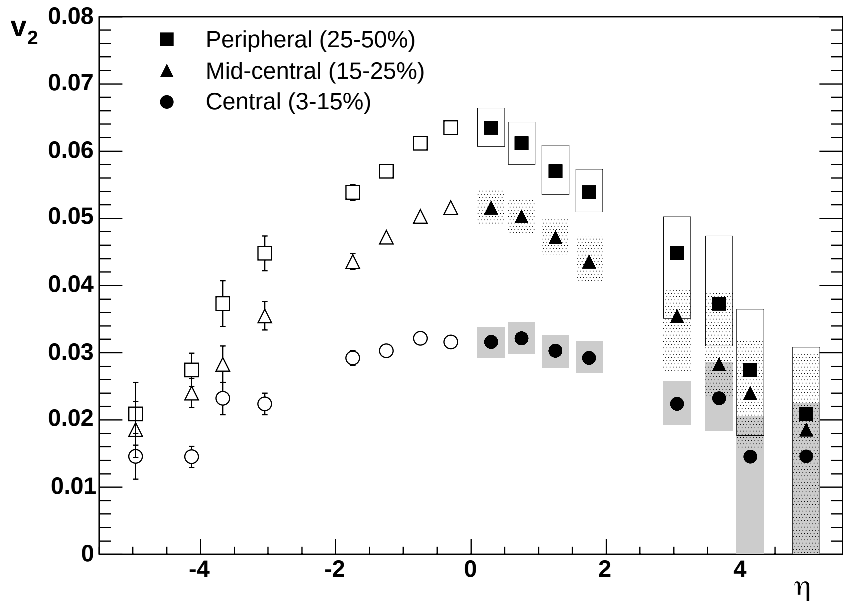

Figure 5. Pseudorapidity dependence of the charged hadron elliptic flow for 3 centrality regions ($25-50\%$ squares, $15-25\%$ triangles, $3-15\%$ circles), for 200 GeV Au+Au collisions [2]. The results for positive η were obtained by reflecting the hit-based measurements about mid-rapidity, and then combining them with the track-based measurements. The systematic errors are shown as boxes for $\eta > 0$, and the statistical errors are shown for the reflected points (open symbols) at negative η.

for the most central bin studied cannot at present be ruled out.

Another recent result obtained by PHOBOS [15], with a hit-based method similar to the one mentioned above, used data sets at four different RHIC beam energies to compare the pseudorapidity dependence of the elliptic flow within the context of limiting fragmentation. The results, presented in figure 6, are shown as a function of η', which is the value of the pseudorapidity when shifted by the beam rapidity. It is seen that the elliptic flow at all four energies studied appears to be independent of energy in η', displaying limiting fragmentation throughout the entire range of η'. This is another surprising feature of elliptic flow results at RHIC, given that particle production in the limiting fragmentation region is thought generally to be distinct from that at midrapidity, but in this case there is no evidence for two separate regions in any of the four energies analyzed.

In conclusion, the PHOBOS collaboration has presented an ensemble of measurements of charged hadron elliptic flow, including a unique measurement of the pseudorapidity dependence of v_2 over a large range for several beam energies. Both $v_2(p_T)$ and $v_2(N_{part})$ are well described by hydrodynamical models, within their range of applicability (i.e., mid-central to central collisions, and p_T up to about 1 GeV). However, no model to date has been able to reproduce the shape of $v_2(\eta)$. The results presented here for the centrality and energy dependence of this shape provide additional input that may give further insight into this issue.

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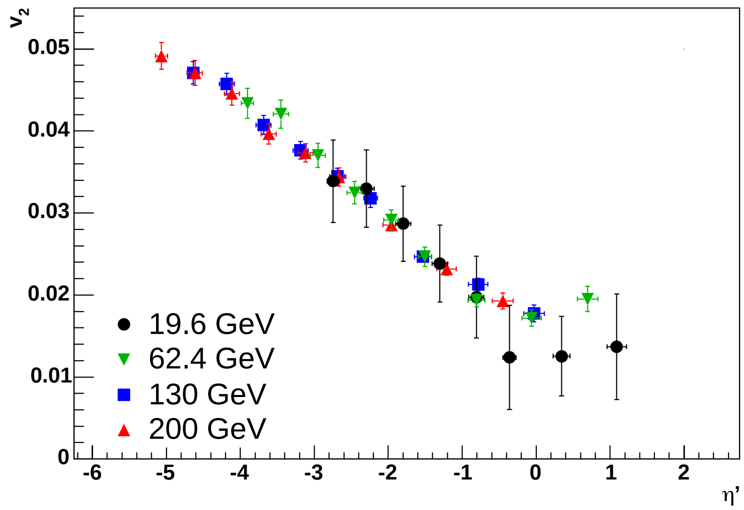

Figure 6. Elliptic flow in Au+Au collisions for four beam energies, averaged over centrality (0-40%), and show as a function of $\eta' = |\eta| - y_{beam}$ [15]. The error bars represent the statistical errors only.

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