Measuring mid-rapidity multiplicity in PHOBOS

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Abstract. Several techniques have been developed by PHOBOS for measuring the multiplicity of charged particles produced in Au + Au collisions. We will discuss one of these techniques (the ‘Tracklet’ method) which utilizes two-hit tracks which intersect at the reconstructed collision vertex position. The physics that comes from these measurements can give valuable insight into the underlying mechanisms of particle production over a center of mass energy range of $\sqrt{s_{NN}} = 19.6$ GeV to the maximum RHIC energy of $\sqrt{s_{NN}} = 200$ GeV.

1. Introduction
The measurement of charged particle multiplicity in relativistic heavy ion collisions is very important. Measurement as a function of collision centrality is even more so, as theoretical models predict different evolutions with the collision geometry, depending on the particle production dynamics they employ. Particles emitted in the central two units of pseudorapidity, $|\eta| < 1$, have more transverse than longitudinal momentum and, in this region, particle production was expected (in part) to follow not only a trend of increasing multiplicity with...
Figure 1. Phobos detector setup for the 2000-2001 Au+Au run. The inset shows an enlarged view of the detector configuration closest to the interaction point with the Top Vertex detector planes visible and part of the Spectrometer and Octagon detectors.

the number of participating nucleons, but also with the number of binary \((p+p)\) like collisions. It is then possible, by studying the variation of multiplicity at mid-rapidity with centrality, to distinguish between model calculations that employ this assumption and those which do not.

PHOBOS has previously reported results from \(\sqrt{s_{NN}} = 19.6\) to 200 GeV for mid-rapidity yields as function of centrality [1, 2, 3]. In this paper, the analysis technique and results are discussed using data from \(\sqrt{s_{NN}} = 19.6\) and 200 GeV. These data have been completely reanalysed using new centrality determination methods [4].

2. Vertex Tracklets

Four different methods have been developed by PHOBOS to measure charged particle multiplicity. The one presented here, called the Vertex Tracklet method, is used to measure the multiplicity at mid-rapidity \((|\eta| < 1)\) and derives its name from the Vertex detector used in the analysis. This detector is a compact silicon pad detector, situated close to the PHOBOS interaction point. The primary design purpose of this detector is to reconstruct the event vertex (the \(x, y, z\) coordinates of the collision position) to high precision in \(z\). The \(z\)-axis lies along the beam direction and \(y\) is vertical. The PHOBOS detector configuration is shown in figure 1.
Figure 2. Schematic drawing of the four Vertex detector planes. The layers above the beam pipe are known as Top Vertex, these below as Bottom Vertex. The Vertex detector consists of $4 \times 2048$ Si channels in total.

Figure 3. Schematic presentation of the Top Vertex detector layers. The Inner Vertex layer is chosen as the Seed layer, the Outer Vertex layer is chosen as the Search layer. A tracklet is formed from the two hits if the combination points back to the reconstructed event vertex and satisfies conditions on $\Delta \eta$ and $\Delta \phi$.

Figure 2 shows a schematic drawing of the Vertex detector. The detector consists of 4 horizontal planes, two placed approximately 5 and 11 cm above the beam pipe (Top Vertex) and two placed (symmetrically) below the beam pipe (Bottom Vertex). The Inner layers, closest to the beam pipe, are finely segmented, each having 2048 Si channels with dimensions $0.47 \times 12.0mm^2$. The Outer layers consist of the same number of channels, although wider than the Inner ($0.47 \times 24.0mm^2$), each pad covers the same $\Delta \phi$. More information about the Vertex and other detectors can be found in [5].

A Vertex tracklet consists of a two-hit combination formed from hits in Outer and Inner Vertex layers (Top or Bottom), pointing back to the reconstructed vertex (see figure 3). $\eta$ and $\phi$ for all hits are calculated using the reconstructed event vertex. One of the planes is chosen to be a Seed layer, the other is chosen as a Search layer. For each hit from the Seed layer all possible combinations of hits from the Search layer are considered. If the difference in $\eta$ and $\phi$ of the two-hit combination (tracklet residuals) is less than 0.04 and 0.3 respectively, the combination is retained, see for example figure 4. If, for a given seed hit, there is more than one combination that satisfies the above conditions, the combination with smallest difference in $\eta$ is retained. The requirement of smaller $\Delta \eta$ is due to the finer segmentation of the sensors along the $z$-axis. The next step in the reconstruction process searches for tracklets sharing hits in the Search layer. Only the tracklet with the smallest $\Delta \eta$ is retained in this case.

Reconstructed tracklets can be divided into two categories: those which correspond to real primary tracks, and those created from random combinations. The latter have to be subtracted to determine the true multiplicity. For a given total number of hits in the Vertex detector, the number of random tracklets should be the same. The number of hits in data is the same for Top and Bottom Vertex detectors. Rotating the Inner Vertex by $180^\circ$ around the $z$-axis in software and performing the tracklet reconstruction procedure as described above allows the combinatorial background to be determined. The same procedure was used for both data and Monte Carlo (MC) studies using HIJING [6] and a full GEANT [7] simulation of the detector.

The charged particle multiplicity is determined by reconstructing tracklets using the Top and Bottom Vertex layers, subtracting the combinatorial background tracklets and then finally correcting this number for the geometrical acceptance and efficiency of the detector. This final correction, called “$\alpha$”, corrects for the azimuthal acceptance of the detector, tracklet reconstruction efficiency and weak decays from neutral strange particles. It is found to depend
Figure 4. Tracklet residual for $\Delta \eta$ shown for data at 19.6 GeV for 80-100 hits in the Vertex detector. The vertical lines show the final cut ($\pm 0.04$) on the measured difference in $\eta$ for the two hits forming the tracklet. The data are integrated over many events.

Figure 5. Illustration of the centrality determination. Curves represent the pseudorapidity distribution for 200 and 19.6 GeV for the top 25% of the inelastic cross-section. Boxes represent the regions in pseudorapidity space used to measure centrality (see text).

3. Centrality determination

The centrality determination method for 19.6 and 200 GeV $Au + Au$ collisions is illustrated in figure 5 where charged particle pseudorapidity distributions are shown for the top 25% of the inelastic cross-section. The centrality determination for 200 GeV is based on the energy deposited in two scintillator Paddle counters, which cover $3.2 < |\eta| < 4.5$ (regions (b) in figure 5). For 19.6 GeV collisions, the geometry of the events was determined using a signal proportional to the number of hits in the silicon Octagon detector in region (d). The region (d) was calculated as the Paddle pseudorapidity coverage scaled by the ratio of beam rapidities ($y_{19.6}^{beam} / y_{200}^{beam} \approx 0.561$).

Having two different methodologies (energy deposited in a scintillator or silicon detector) at different energies to find the centrality posed questions regarding the comparison of results obtained for the two energies. To check the importance of the details of the centrality determination on the final results, two mid-rapidity methods were also used to check for systematic effects, regions (a) and (c). The results presented here, utilize the mid-rapidity centrality determination from Octagon detector (regions (a) and (c)). Results obtained with regions (b) and (d) yielded consistent results.

The use of two centrality methods also allows a close examination of the necessary requirement of a monotonic dependence of the number of participating nucleons, $N_{part}$, and the particle multiplicity used as a centrality measure. The rate of increase in multiplicity is known to be different in different regions of pseudorapidity. Thus, for a given centrality measure, the
Figure 6. Centrality dependence of the mid-rapidity yields, normalized by the number of participating pairs of nucleons. Also shown are the HIJING (dashed line) and Saturation Model (solid line) predictions. Within the scope of the systematic errors, neither model can be ruled out. Data as reported in [3].

The measured pseudorapidity density per participant pair is presented in figure 6 as a function of centrality. The results for 200 GeV data are shown as closed circles and represent the top 50% of the inelastic cross-section. The result for 19.6 GeV is shown as closed squares, for the top 40% of the inelastic cross-section. The data are restricted to the central and mid-central collisions, with the centrality ranges as quoted above, due to a vertex efficiency that falls well below 100% for the most peripheral data. The systematic errors for the Vertex tracklets are estimated to be 7.5% for each energy. The error ellipses in the figure represent 90% C.L. and include estimated errors in the determination of $\langle N_{\text{part}} \rangle$. The open squares at $\langle N_{\text{part}} \rangle=2$ correspond to the measured multiplicity for $p+p$ inelastic collisions from the UA5 collaboration (for 200 GeV) and interpolated multiplicity for $p+p$ collisions from ISR measurements (for 19.6 GeV) [8, 9]. Both reference points have been chosen to match our pseudorapidity coverage of $|\eta| < 1$.

One immediate conclusion which can be made is that the normalized multiplicity in $Au+Au$ collisions is higher than the corresponding values for the inelastic $p(\bar{p})+p$ collisions. A comparison of the results with HIJING [6] and KLN Saturation Model [10, 11] for the two energies has also been made (figure 6). The HIJING predictions are shown as dashed lines and the solid lines are the calculations from a Saturation Model. Taking into account the large systematic errors of the data measurements, neither of the models can be conclusively ruled out. One observation is that the Saturation Model calculations follow the data trend more closely than those of HIJING.
An additional way to study the differences between the measured pseudorapidity density per participant pair, as a function of centrality, is to take the ratio of the two data sets, as shown in figure 7. The approach has the advantage that most of the systematic errors on the individual measurements cancel in the ratio. The reason for this is due to the analysis that was performed with the same method (Vertex tracklets), for the same detector and carefully matched centrality determination. Due to the difference in the fraction of measured inelastic cross-sections, the ratio is presented only for the top 40%. Errors on the ratio are calculated as the combined 1-σ statistical and systematic errors.

Five factors contribute to the final error on the ratio:

(i) $R_\alpha$ - uncertainty due to the overall acceptance and efficiency of the detector.
(ii) $R_\beta$ - systematic error from the combinatorial background.
(iii) $R_{N_{\text{part}} - N_{\text{part est}}}$ estimation uncertainty.
(iv) $R_{N_{\text{rec}}}$ - Statistical and systematic uncertainties from counting statistics.
(v) $R_{\text{TrigEff}}$ - Uncertainty from the estimation of the overall detector triggering efficiency.

$R_\alpha$ has two main contributions, the overall acceptance of the Vertex detector and the tracklet finding efficiency. Geometrical acceptances for the two datasets are identical as the data were taken back-to-back with the same apparatus and overall beam conditions. Errors from the efficiency may not precisely cancel in the ratio, as the main contribution is due to the decays of neutral strange particles. The relative yield of these particles is not the same at each energy. $R_\alpha$ is estimated to be 2%. The combinatorial background was found to be the same at both energies, as expected from MC studies. The main contribution here comes from the uncertainty in the measured $y$-position of the collision vertex and was estimated as $R_\beta = 0.4\%$ for each energy. $R_{N_{\text{part}}}$ includes uncertainties from MC simulations of the detector response as well as Glauber Model calculations. These effects should cancel in the ratio, leaving only an error of 0.4% from the uncertainty in the measured nucleon-nucleon cross-sections at both energies. For the most central collisions, counting statistics contribute about one-half the total error. $R_{N_{\text{rec}}}$ is estimated to be 2.2% on the ratio for each centrality bin. The final uncertainty comes from the estimation of the trigger efficiency, which has a cumulative effect as one moves from central to mid-central collisions. $R_{\text{TrigEff}}$ is therefore a centrality dependent factor, varying smoothly from 0% for the most central collisions to 6% for the mid-central.

The final, 1-σ, systematic and statistical errors on the ratio for the two data sets are centrality dependent. By adding all factors, described above, in quadrature, the final error is 3% for central and 7% for mid-central events.

For the same fixed fraction of cross-section, $\langle N_{\text{part}} \rangle$ is different for the two energies. For this reason, the ratio was calculated in two distinct ways. First, the result presented with closed squares in figure 7 (Au+Au 1) is obtained by averaging the individual $\langle N_{\text{part}} \rangle$ values. Second, the ratio (Au+Au 2), open squares, is formed by completely reanalyzing the data with a new centrality determination, which varies the percentile of cross-section bin width in an iterative fashion in order to ensure the same, fixed $\langle N_{\text{part}} \rangle$ for the two energies. These two ways of performing the ratio yield consistent results, and show no systematic effect due to the specific centrality determination. Furthermore, the slopes for both ratios are consistent with zero within the errors, showing no centrality dependence on the ratio $R_{200/19.6}$ for the top 40% of the inelastic cross-section. The most probable mean value found for the Au+Au for fixed cross-section bins case is $R_{200/19.6} = 2.03 \pm 0.02 \pm 0.05$ [3].

HIJING predictions for the ratio of the two data sets, dashed line in figure 7, give a rapid increase in mid-rapidity multiplicity with centrality. The predictions of the Saturation Model are shown with a solid line and the expectations are for flatter centrality dependence as observed in data.
Figure 7. Ratio of the mid-rapidity pseudorapidity charged particle density per participant pair versus $\langle N_{\text{part}} \rangle$ for 200 and 19.6 GeV. Closed squares correspond to the fixed cross-section centrality determination, open squares are for the fixed $\langle N_{\text{part}} \rangle$ case (see text). Curves give various calculations. The ratio of the inelastic $p(p) + p$ collision data is shown as closed circle at $N_{\text{part}} = 2$. Vertical error bars represent combined $1 - \sigma$ statistical and systematic uncertainties. Data as reported in [3].

This is not the only result from PHOBOS, which exhibits a “geometry scaling”. The equivalent result for 130 and 200 GeV data gives a value of $R_{200/130} = 1.14 \pm 0.01 \pm 0.05$ [1] for the top 50% of the inelastic cross-section, again independent of centrality. Additionally, figure 8 illustrates that the total charge $N_{\text{tot}}$ per participant pair as a function of $\langle N_{\text{part}} \rangle$ is independent of centrality for $\sqrt{s_{\text{NN}}} = 19.6, 130$ and 200 GeV, for $|\eta| < 5.4$ [12].

5. Conclusions
PHOBOS has measured the charged-particle pseudorapidity density at mid-rapidity for Au+Au collisions at 200 and 19.6 GeV. The Vertex tracklet method, along with new centrality determinations, allows for a consistent comparison of the results at these two energies. Potential systematic effects on physics measurements due to the pseudorapidity range used in deriving the collision centrality have been studied using the two methods at each energy.

For each of the energies presented, an increase in particle production per participant pair for Au+Au data compared to that of $p(p) + p$ collisions (at the same energy) is observed.

The ratio of the multiplicities measured at the two energies has significantly reduced errors as compared to the individual measurement. The ratio of the measured yields for the top 40% of the inelastic cross-section gives a simple, centrality independent, scaling factor between the two energies. The expected increase with collision energy of the contribution from hard-processes, which should scale with the number of binary collisions, is not present over the wide range in collision energies studied here.
Figure 8. Total charge, scaled by the number of participating pairs, versus $\langle N_{\text{part}} \rangle$ for 200 (circles), 130 (triangles) and 19.6 GeV (squares) AuAu collisions. The corresponding $p(p)+p$ measurements/extrapolations for each energy are plotted at $N_{\text{part}} = 2$. The vertical error bars represent the 90% C.L. limits, the shaded bands represent the systematic error due to the $N_{\text{part}}$ calculations.

Acknowledgments
This work was partially supported by U.S. DOE Grants DE-AC02-98CH10886, DE-FG02-93ER40820, DE-FC02-94ER40818, DE-FG02-94ER40865, DE-FG02-99ER41099, and W-31-109-ENG-38, by U.S. NSF grants 9603486, 0072204, and 0245011, by Polish KBN Grant 1-P03B-062-27(2004-2007), and by NSC of Taiwan Contract NSC 89-2112-M-008-024.

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