Using multiplicity as a fractional cross-section estimation for centrality in PHOBOS

Richard S Hollis\textsuperscript{6} for the PHOBOS Collaboration

B B Back\textsuperscript{1}, M D Baker\textsuperscript{2}, M Ballintijn\textsuperscript{4}, D S Barton\textsuperscript{2}, R R Betts\textsuperscript{6},
A A Bickley\textsuperscript{7}, R Bindel\textsuperscript{7}, W Busza\textsuperscript{4}, A Carroll\textsuperscript{2}, Z Chai\textsuperscript{2},
M P Decowski\textsuperscript{4}, E García\textsuperscript{6}, T Gburek\textsuperscript{3}, N George\textsuperscript{2}, K Gulbrandsen\textsuperscript{4},
C Halliwell\textsuperscript{8}, J Hamblen\textsuperscript{8}, M Hauer\textsuperscript{2}, C Henderson\textsuperscript{4}, D J Hofman\textsuperscript{6},
R S Hollis\textsuperscript{6}, R Holyński\textsuperscript{3}, B Holzman\textsuperscript{2}, A Iordanova\textsuperscript{6}, E Johnson\textsuperscript{8},
J L Kane\textsuperscript{4}, N Khan\textsuperscript{8}, P Kulchin\textsuperscript{4}, C M Ku\textsuperscript{6}, W T Lin\textsuperscript{5}, S Manly\textsuperscript{8},
A C Mignerey\textsuperscript{7}, R Nouri\textsuperscript{2},\textsuperscript{6}, A Olszewski\textsuperscript{3}, R Pak\textsuperscript{2}, C Reed\textsuperscript{4},
C Roland\textsuperscript{4}, G Roland\textsuperscript{4}, J Sagerer\textsuperscript{6}, H Seals\textsuperscript{2}, I Sedykh\textsuperscript{2}, C E Smith\textsuperscript{6},
M A Stankiewicz\textsuperscript{2}, P Steinberg\textsuperscript{2}, G S S Stephens\textsuperscript{4}, A Sukhanov\textsuperscript{2},
M B Tonjes\textsuperscript{7}, A Trzupek\textsuperscript{3}, C Vale\textsuperscript{4}, G J van Nieuwenhuizen\textsuperscript{4},
S S Vaurynovich\textsuperscript{4}, R Verdier\textsuperscript{1}, G I Veres\textsuperscript{4}, E Wenger\textsuperscript{1}, F L H Wolfs\textsuperscript{8},
W Bosiek\textsuperscript{3}, K Woźniak\textsuperscript{3} and B Wosiek\textsuperscript{4}

\textsuperscript{1} Argonne National Laboratory, Argonne, IL 60439-4843, USA
\textsuperscript{2} Brookhaven National Laboratory, Upton, NY 11973-5000, USA
\textsuperscript{3} Institute of Nuclear Physics PAN, Kraków, Poland
\textsuperscript{4} Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA
\textsuperscript{5} National Central University, Chung-Li, Taiwan
\textsuperscript{6} University of Illinois at Chicago, Chicago, IL 60607-7059, USA
\textsuperscript{7} University of Maryland, College Park, MD 20742, USA
\textsuperscript{8} University of Rochester, Rochester, NY 14627, USA

E-mail: rholli3@uic.edu

Abstract. Collision centrality is a valuable parameter used in relativistic nuclear physics which relates to geometrical quantities such as the number of participating nucleons. PHOBOS utilizes a multiplicity measurement as a means to estimate fractional cross-section of a collision event-by-event. From this, the centrality of this collision can be deduced. The details of the centrality determination depend both on the collision system and collision energy. Presented here are the techniques developed over the course of the RHIC program that are used by PHOBOS to extract the centrality. Possible biases that have to be overcome before a final measurement can be interpreted are discussed.

1. Introduction
The determination of well defined geometrical control parameters in nuclear collisions affords the ability of a cross-reference between the various experiments, without concern about the details of the individual experiments. Further, various measured quantities (e.g. the charged
particle multiplicity) have been found to be sensitive to the collision geometry. Specifically, the overall yield of particles grows with the number of nucleons participating in a given collision. Unfortunately, access to this geometrical information is not directly available and must be deduced from a combination of experimentally measured quantities and Monte-Carlo simulations.

The methodology of the centrality determination takes a well defined form, with four distinct procedures to be followed before the final physics analysis can be performed. In this paper, the methodology will be discussed from the perspective of the PHOBOS √sNN = 200 GeV Au + Au data, as well as the low multiplicity environment of the √sNN = 200 GeV d + Au collision system. Considerations for other collision energies are also discussed. These procedures begin with the event selection, efficiency estimations, careful selection of phase-space for the percentage of cross-section determination and finally Monte-Carlo simulations which are used to estimate the geometrical parameters of the collision. Also presented is a discussion of effects of centrality induced biases on the d + Au dataset. The final remarks will concern physics results in the context of centrality.

2. Centrality Terms and Definitions

The collision centrality can be defined by using one of many geometrical parameters. The most common is the number of nucleons that participate in any one collision, commonly referred to as Npart. This, as with many geometrical variables, is defined using the results of Glauber model calculations [1]. Other geometrical variables include the impact parameter, usually denoted as b, and the number of binary collisions, Ncoll. The results of a Glauber model calculation of these quantities is shown in figure 1, displaying in the left panel Npart and Ncoll as a function of impact parameter, and in the right panel the evolution of Ncoll vs Npart for the different energies run at RHIC.

The percentage of the total collision cross-section indicates the fraction of data relative to all possible collision geometries, or impact parameters, corrected for triggering inefficiencies. Specifically, this term is used to denote the fraction of data within a centrality bin, for example the 0–6% most central (largest number of participating nucleons) or 35–45% (semi-peripheral).

3. Analysis Outline - Au + Au Collisions at √sNN = 200 GeV

In this section, the full methodology is explored in the context of the 200 GeV Au + Au dataset. The basic philosophy of the centrality determination, however, is the same for each collision energy and collision system measured at PHOBOS.

3.1. Event Selection

The single most important step in the centrality determination is to ensure that the event sample is free from non-collision events and events outside a usable vertex region, relative to the detector. In order to impose a minimal bias on the dataset at the level of triggering, data is recorded from a wide vertex region of ≈ 6m, which includes the possibility of down-stream Beam-Gas collisions. The trigger consists a pair of symmetrically located large area scintillator arrays covering 3.2 < |η| < 4.5, known as the “Paddles” (refer to [2] for a complete description of the PHOBOS detector). Each paddle array consists of 16 slats. To remove the non collision events, the Paddles’ timing and energy signals are calibrated and then cuts are applied offline to narrow the vertex region to the centre of the PHOBOS detector.

3.2. Efficiency Determination

The next step in the process is to estimate the total efficiency of the dataset. Event triggering requirements impose a small inefficiency for peripheral events. In order to produce results in
Figure 1. Glauber Monte-Carlo simulations of geometrical quantities for Au + Au collisions. The left panel shows $N_{\text{part}}$ and $N_{\text{coll}}$ as a function of the impact parameter. The right panel illustrates the expectation of the increasing number of binary collisions with the centre of mass energy. The energies shown are the four RHIC energies run over the course of the heavy-ion program.

bins of total inelastic cross-section, the efficiency has to be determined in order to estimate the amount of missing cross-section. For the $Au + Au$ data the estimation of the efficiency comes from the analysis of the total number of Paddle slats hit in both data and Monte-Carlo. Figure 2 shows the resulting distributions for data and Monte-Carlo. A plateau is found to exist in both distributions, roughly between 15 and 22 paddle slats hit. This region allows a normalisation factor to be calculated between the two distributions such that the missing cross-section in data can be estimated. For a trigger configuration of at least one Paddle slat hit in each array, the total efficiency is estimated to be $97 \pm 3\%$ at the full RHIC energy.

3.3. Pseudorapidity Region
Particle production varies widely depending on the region of phase space. Figure 3 shows the $dN/d\eta$ distributions for the top 25\% of the inelastic cross-section for $\sqrt{s_{NN}} = 19.6$ and 200 GeV $Au + Au$ collisions. In the central region in $\eta$ space, the most particles are produced. The two main factors that should be considered for the choice of pseudorapidity region are the integral of the yield in a region of $\eta$ and the evolution of this yield with centrality. This statement may seem somewhat circular, but there exists an important cross-check in the data alone that can support this decision.

In non-central nuclear collisions one distinguishes the participants (nucleons in the overlap volume of the collision) and the spectators. By definition the spectators do not collide and produce particles that would be detected in PHOBOS. These protons and neutrons (either single or bound in nuclear fragments) continue on their original trajectory until the steering magnet sweeps away protons (and nuclear fragments). The neutrons continue undeviated and impact on the Zero-Degree Calorimeters, strategically placed for this purpose, $\pm 18m$ from the nominal interaction point. As a collision becomes more central, there are fewer and fewer spectators, and therefore fewer neutrons to be detected in the ZDCs. From this, an important piece of information can be derived. Figure 4 shows the strong anti-correlation observed between the
Figure 2. Estimation of the event selection efficiency in $\sqrt{s_{NN}} = 200$ GeV $Au + Au$ collisions. Data and simulations of the Paddle counter response each have a plateau which is used to normalise the distributions and estimate the missing cross-section due to the trigger inefficiency.

Figure 3. The pseudorapidity density distribution for $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV (lightest band) and 19.6 GeV. The region (a) indicates the region of the Paddle trigger counters, the region used as the centrality determination at $\sqrt{s_{NN}} = 200$ GeV. Region (b) illustrates the extent of the Silicon Octagon detector, from which a signal is used for the 19.6 GeV centrality estimate.

Figure 4. (Anti) correlation of the Paddle Counters (Paddle Mean) and the Zero Degree Calorimeters (ZDC Sum).

signal from the ZDCs (ZDC Sum), proportional to the number of spectator neutrons, and the energy signals from the Paddle counters (Paddle Mean).
The signal in the chosen region of pseudorapidity, in this case the “Paddle Mean”, is then divided into percentile bins of inelastic cross-section (corrected for the event selection efficiency). This defines the Centrality of the collision.

3.4. Monte-Carlo Simulations
The final step in the process is the estimation of the number of participants, \( N_{\text{part}} \), and other control parameters. Using HIJING [3] and a full GEANT [4] simulation of the PHOBOS detector, a monotonic relation with the (known) number of participants and the simulated Paddle Mean signal must be demonstrated to exist. Non-monotonicity means the region (of \( \eta \)) cannot be used for this purpose. Figure 5a illustrates this for the correlation between \( N_{\text{part}} \) and Paddle Mean, with different shading denoting the percentile bins (in the Monte-Carlo). Figure 5b shows the projection of the correlation onto the \( N_{\text{part}} \) axis. Distinct peaks are observed for each bin and the mean of this distribution is associated with the same percentile bin in data and Monte-Carlo.

![Figure 5. (a) Monte-Carlo simulation of the Paddle counters correlated with the given number of participants. (b) represents the projection from (a) onto the \( N_{\text{part}} \) axis for percentile of cross-section bins determined from the Paddle counters.](image)

4. Centrality Determination of Other Systems
PHOBOS has taken data at five energies (\( \sqrt{s_{NN}} = 19.6, 56, 62.4, 130 \) and 200 GeV). For all energies the centrality determination uses the same detailed techniques with the exception of the 19.6 GeV data. Figure 3 shows how the 200 and 19.6 GeV datasets differ in terms of charged-particle pseudorapidity density distributions. The most significant observation, in the context of the centrality determination, is the width of these distributions (in \( \eta \)-space). The positioning of the Paddle counters is illustrated as regions (a) in the figure. Consequently, at the lowest RHIC energy the particle density in the Paddle counters is too small to ensure viability of the centrality determination from the Paddle signals.

A new technique, using a quantity proportional to the charge liberated in the central barrel Octagon detector was developed, \( EOct \), region (b) in figure 3. The design of the Octagon is such that particles impinging these detectors can pass through several pads on one sensor,
dependent on the angle (or $\eta$). For particles passing through more material, more charge is liberated so, to balance the weighting of hits in various parts of the detector, an angle correction has to be applied. For this, a vertex position is required, imposing a harsh centrality bias on the peripheral (low multiplicity) data, for which the vertex finding is necessarily inefficient. A shape matching technique between the corresponding data and Monte-Carlo distributions was employed to estimate the efficiency. For further details see [5, 6].

The very low multiplicity $d + Au$ dataset posed several problems in constructing the centrality. The definition of the event selection had to be suitably modified to take into account the effect of a worse timing resolution in the Paddle counters. Instead of relying primarily on signals from these trigger detectors, as in the case of $Au + Au$ collisions, the event selection was made with a high efficiency vertex reconstruction algorithm. As for the 19.6 GeV, a shape matching technique between data and Monte-Carlo, with the same variable (EOct) was employed to estimate the efficiency. The choice of pseudorapidity regions and biases related to the centrality determination for $d + Au$ collisions are the subject of section 5.

The outlined centrality determination methods provided PHOBOS with a dataset covering a factor of ten in energy and geometrical reach from about 2 upto 350 participating nucleons. Physics results that have been produced benefit substantially from knowledge of the collision geometry, providing the tool by which to test our theoretical understanding of nuclear collisions. Centrality tests performed on the various $Au + Au$ datasets (by using different $\eta$ regions for the centrality variable) resulted in consistency well within the reported systematic errors [5].

The same consistency checks in the $d + Au$ data resulted in substantial differences in the final pseudorapidity density shape, a fact that had to be overcome before the results could be finalised.

5. Centrality Determination Biases in $d + Au$ Collisions at $\sqrt{s_{NN}} = 200$ GeV

Auto-correlation biases between centrality determination signals and physics measurements become extremely important in low multiplicity environments. Small fluctuations in the centrality variable, both real and detector induced, are washed-out by the large yield of particles for high multiplicity data. In lower multiplicity data, the centrality variable can be more strongly influenced by similar effects as the yields are not large enough to dilute fluctuations. With a large acceptance detector, covering $|\eta| < 5.4$, a systematic study of auto-correlation biases can be performed in both data and Monte-Carlo. The first step is to establish independent regions of pseudorapidity for determining the percentile of cross-section bins.

Five methods were established using the multiplicity array of the Octagon and Ring detectors. The signals coming from these detectors were divided into different pseudorapidity regions, with some overlap allowed. These regions are shown as shaded bands in figure 6. This figure also illustrates the possible pitfalls of low multiplicity centrality determination, if careful studies are not used to guide the final centrality analysis. $EOct$ (top), from the central region of particle production, shows a large bias for both central (enhancement) and peripheral (reduction) data over that of the input Monte-Carlo. Similar effects are seen in $E_{AuHem}$ (measuring particles going in the direction of the Au nucleus), $E_{dHem}$ (particles going in the deuteron direction) and the total charge liberated in the Octagon and Ring detectors, $ETot$. With the centrality determined from pseudorapidity region $ERing$, little or no bias is produced for any of the bins in percentile of cross-section studied. To add further confidence that $ERing$ is performing the same in data as in the Monte-Carlo studies, ratios of measured $dN/d\eta$ distributions with different centrality methods relative to that obtained using $ERing$ method were made and found to be consistent with the same ratios for Monte-Carlo simulations.

The minimum bias distribution reported in [7] employed all five methods to reconstruct an inelastic pseudorapidity density distribution. In this case, the data were divided into 10 bins of equal fraction of inelastic cross-section. The reconstructed data for each bin were then simply added together and scaled by the number of bins (10). The equal weighting for each bin takes
Figure 6. HIJING Monte-Carlo simulations of $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, for peripheral (left column) and central (right column) events as defined by the five centrality methods (open symbols). The original HIJING (truth values) for these centrality regions are also shown as solid symbols. The pseudorapidity region used for each centrality variable is shown as the shaded region for the respective plots.
into account the inefficiencies in the most peripheral bins when summing together. Summing all the events without binning causes a \( \approx 15\% \) increase in the measured minimum bias distribution, whereas we find less than \( \approx 2.5\% \) bias with this technique. Even with the substantially different centrality dependences, the resulting distributions from each of the centrality methods were found to be consistent [7].

Correcting for any biases in the centrality determination is important when comparing the results at different energies or different collision systems. The analysis of lower energy hadron+nucleus data showed that the total charged particle multiplicity scales with the number of participants. In the \( d + Au \) data, a much larger range of \( N_{\text{part}} \) can be explored with the single system, see [8, 9]. Ranging from 2.7 to 15.5 participants, the observation holds with the total multiplicity equals approximately \( 0.5 \times N_{pp} \times N_{\text{part}} \). To illustrate this, figure 7 compares PHOBOS data scaled by the corresponding \( p + p \) data versus \( N_{\text{part}} \) to that of lower energy \( h + A \) data. This result gives further credence to the centrality determination methodology and to the choice of ERing as the one with the least bias.

![Figure 7](image)

**Figure 7.** Total integrated yield of charged particles in \( d + Au \) collisions, compared to lower energy hadron+nucleus data. Data from [9].

6. Conclusions
PHOBOS has measured the collision centrality for a variety of systems, from \( \sqrt{s_{NN}} = 19.6 \) to 200 GeV \( Au + Au \) collisions to the much smaller \( d + Au \) system. A consistent set of procedures has been developed to enable the centrality to be estimated. The biases of these different techniques have been examined in these systems and consistency cross-checks have been performed to find the most appropriate centrality variable. Total charged particle yields derived from \( d + Au \) collisions, have been found to scale with the number of participants, as also found in lower energy data.

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References

[1] Glauber R J 1959 in *Lectures in Theoretical Physics*, edited by W E Brittin and L G Dunham (Interscience, N.Y), Vol. 1 315
[2] Back B B et al 2003 *Nucl. Instum. Methods* A 499 603
[3] Gyulassy M and Wang X N 1994 *Comput. Phys. Commun.* 83 307
[4] GEANT 3.21, CERN Program Library, Geneva
[5] Back B B et al 2004 *Phys. Rev* C 70 021902(R)
[6] Iordanova A et al *These Proceedings*
[7] Back B B et al 2004 *Phys. Rev. Lett.* 93 082301
[8] Nouicer R et al 2004 *J. Phys.* G 30 S1133 and references therein
[9] Back B B et al *Preprint* nucl-ex/0409021