CENTRALITY MEASUREMENTS IN THE PHOBOS EXPERIMENT*

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The methods of centrality measurements in the PHOBOS experiment are presented. The precision and uncertainties in centrality determination are discussed.

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1. Introduction

In the study of high energy heavy ion interactions the centrality of the collision describing the geometry of the collision region, plays an important role. It is defined by the impact parameter, b; the smaller is the impact parameter, the more central is the collision. Other parameters, which vary with the impact parameter, are also used to characterize the centrality of the collision. For non-zero impact parameters not all nucleons inside the nucleus will participate in the collision. This observation led to the formulation of the so-called "participant–spectator" model, in which only nucleons in the region of geometrical overlap of colliding nuclei participate in the collision, while other nucleons are spectators. The number of participating nucleons, $N_{\rm part}$, is customarily used in the studies of high energy nucleus–nucleus collisions at RHIC. Note that neither b nor $N_{\rm part}$ are directly measurable quantities. Therefore in order to define centrality, an experimental observable must be chosen that correlates with the impact parameter or the number of participants.

2. Centrality in models of nuclear interactions

A detailed definition of centrality parameters can be obtained within the Glauber model formalism [1] which considers nuclear interaction as a superposition of independent collisions between participating nucleons. The basic parameters of this model, the value of nucleon–nucleon cross-section and parameters of the Wood–Saxon density of nucleons inside the nucleus, are taken from experiments.

Within the Glauber model one can calculate correlations between centrality of the collision, as represented by impact parameter, b, the number of participating nucleons, $N_{\rm part}$ and the number of nucleon–nucleon collisions, $N_{\rm coll}$ [2]. A distribution of impact parameter in collisions of Au ions, shown in Fig. 1, demonstrates that only small fraction of collisions is characterized by small impact parameters. This means that in order to study these central collisions one needs to develop efficient and precise methods of centrality determination event by event.

Most current models describing nuclear interactions use Glauber formalism to calculate initial geometry of the system $(N_{\rm part}, N_{\rm coll}, b)$. Then, the predictions for the density of particle production are obtained either by assuming an independent superposition of nucleon–nucleon collisions [3, 4] or using different scaling hypotheses [5]. In some models, the calculated initial conditions are used as input to more sophisticated Monte Carlo interaction models, which can take into account novel physics effects predicted to occur at high energy and/or parton density.

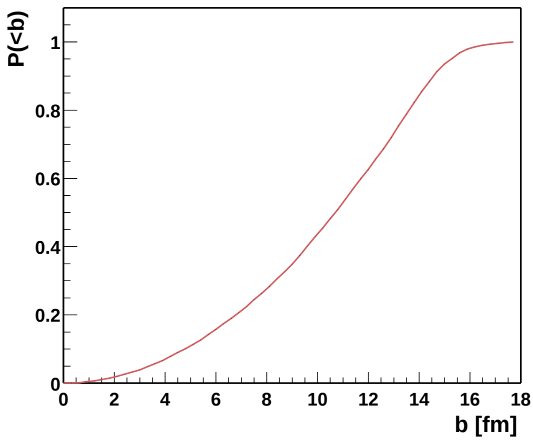

Fig. 1. Distribution of impact parameter, b, in Au + Au collisions.

The importance of centrality dependent measurements becomes obvious when one looks at a variety of model predictions for particle production at mid-rapidity, shown in Fig. 2. In this figure different model predictions

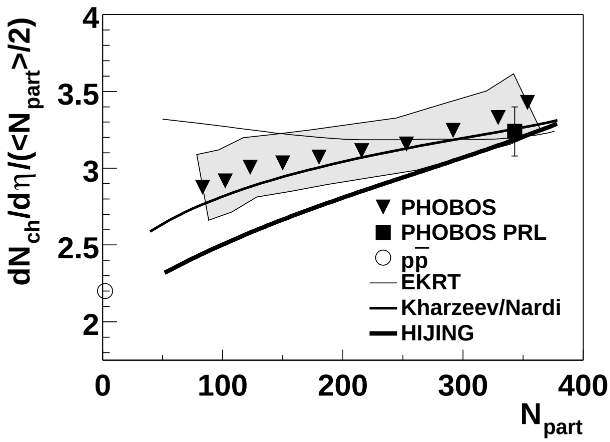

Fig. 2. $N_{\rm part}$ dependence of charged particle density at mid-rapidity normalized per pair of participating nucleons. The shadowed band indicates the combined systematic and statistical error for PHOBOS data. Model calculations are shown by solid lines of different width.

[3, 4, 6] are compared with the results obtained in the PHOBOS experiment [7]. Experimentally measured scaled particle densities $dN/d\eta/\langle N_{\rm part}/2\rangle$, rise with increasing centrality of the collision, here measured by $N_{\rm part}$. On the other hand, model predictions either show a slight decrease [6] or an increase

of particle densities [3,4] which in some models (*e.g.* HIJING) is much faster than that observed in the data. So in order to test these different ideas, it is crucial to make precise measurements of centrality and centrality dependent quantities.

3. Precision of centrality determination

Precision of centrality measurements is influenced by several factors. One of them is associated with the choice of the analyzed event samples. In general there are two ways to vary the volume of interacting nuclear matter:

(1) by changing mass of colliding nuclei and studying properties of inclusive samples of these collisions, and

(2) by selecting events with different centrality from a single sample of inclusive nucleus–nucleus collisions. The properties of event samples obtained in these two ways are shown in Figs. 3 and 4.

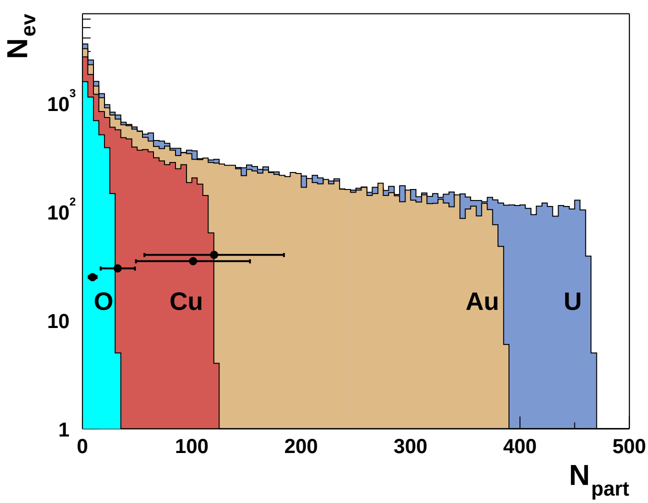

Fig. 3. Distributions of the number of participating nucleons for inclusive samples of symmetric collisions of ions of different size. The average and RMS values are indicated by points and horizontal bars.

As one can see, by changing size of colliding nuclei one can indeed change the average number of participating nucleons, $N_{\rm part}$, but the average $\langle N_{\rm part}\rangle$ is low and the distribution has a large spread of $N_{\rm part}$ values due to a mixture of events with different centralities. The second method of event selection is very efficient, providing samples of events with distinctly different centrality properties, reaching also $N_{\rm part}$ values far beyond the range available in the

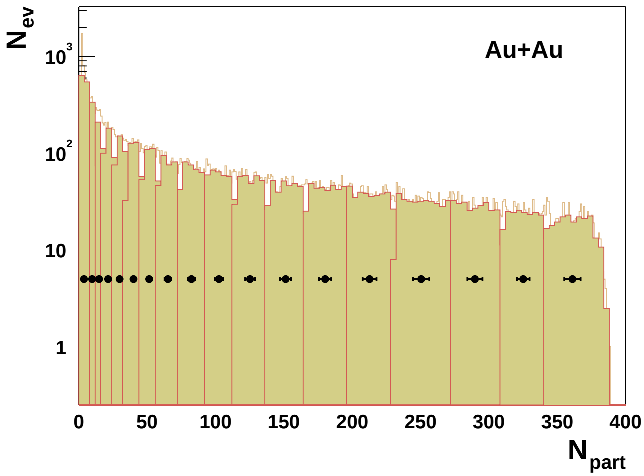

Fig. 4. Distribution of the number of participating nucleons for sub-samples of events selected from the inclusive sample of Au + Au collisions by N_{part} centrality cuts. The average and RMS values for each sub-sample are shown.

first method. It is, however, more sensitive to the theoretical and experimental uncertainties of calculating centrality properties for these samples of selected events, as it will be discussed later.

Another factor that influences the precision of centrality measurements is related to the uncertainties in the Glauber model. Examples of such differences are shown in Fig. 5, where the results for the ratio of average N_{part} obtained from different versions of Glauber calculations to the value obtained from HIJING Monte Carlo model are shown for different centralities. It is known [8] that the "optical" approximation used routinely in analytical Glauber calculations is not correct in the case of collisions of heavy ions. In contrast, the method of Monte Carlo calculations avoids approximations used in analytical calculations and delivers correct results. As it is seen in Fig. 5, where the MC results are indicated by points around a constant value of 1, and where points from analytical Glauber calculations with several different sets of parameters lie below, the difference between these two approaches may exceed a value of 10% already for moderately peripheral collisions. Uncertainties in Glauber model parameters describing nucleon density distribution, lead to differences of the order of 2% and are much smaller than those from "optical" approximation.

It is important to keep track of these uncertainties, especially when comparing results in which different methods of N_{part} calculations were used. One should always make sure that trivial sources of discrepancies are eliminated first, before going into conclusions about physics effects.

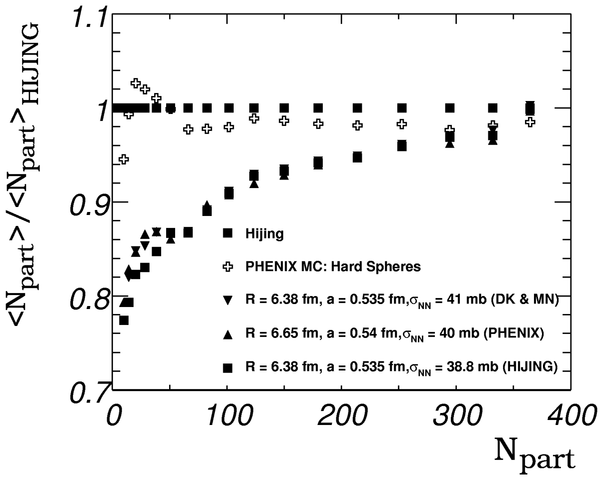

Fig. 5. Dependence of the ratio of average value of $N_{\rm part}$ obtained from different applications of the Glauber model to the average $N_{\rm part}$ from HIJING MC model on $N_{\rm part}$. HIJING and PHENIX MC represent Monte Carlo approach, while the points for three sets of (R, a, σ_{NN}) parameters are from analytical Glauber calculations.

4. Centrality determination in the PHOBOS experiment

In the experiment it is not possible to directly measure impact parameter, b, which defines the centrality of a collision. Experimentally measured observables are typically related to the number of participating or spectator nucleons, the quantities which are in turn correlated with the impact parameter of a collision.

The number of spectator nucleons can be obtained from the measurements of the total mass or energy of the nuclear spectator remnant. These measurements are possible in fixed target experiments, but difficult in the collider experiments. This is due to the fact that nuclear spectator fragments are emitted in the direction of the colliding nuclei, thus stay inside the beam pipe and are not available for measurements. At RHIC collider, all heavy ion experiments are equipped with the identical Zero Degree Calorimeters located ± 18 m from the nominal interaction point, behind the magnets deflecting charged particles. Therefore, they can detect only a small fraction of all spectators, the neutrons, which follow a straight line trajectory all the way downstream to the calorimeter.

Another way of measuring centrality is by estimating the number of participating nucleons. This number is strongly correlated with the total transverse energy, or the multiplicity of produced particles. In PHOBOS we measure particle production in a limited range of $3 < |\eta| < 4.5$ using scintillator Paddle detectors (see [9]), more details on the Paddle signal processing can be found in [7]. The amplitude of the signal in these detectors is the main parameter used to classify events according to their centrality in the PHOBOS experiment.

In Fig. 6 we show the correlation between the Paddle signal and the total number of hits registered in the PHOBOS silicon detectors covering almost a full phase space. The latter quantity is proportional to the total number of produced particles which, in turn, increases with increasing centrality of the collision. An additional proof that the Paddle signal is a good measure of centrality comes from the observed anti-correlation between signals in Paddle and in ZDC detectors, shown in Fig. 7. This anti-correlation is

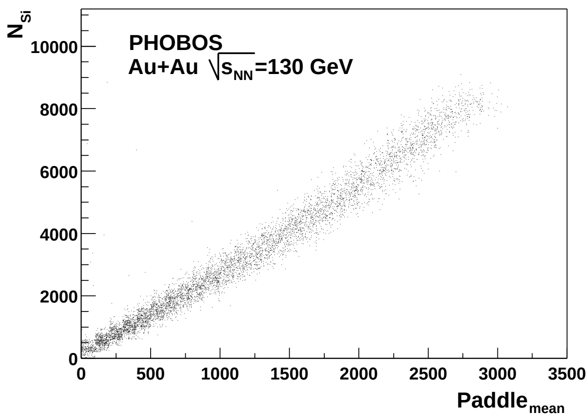

Fig. 6. Positive correlation between signal in Paddle detectors and the total number of hits in PHOBOS silicon detectors.

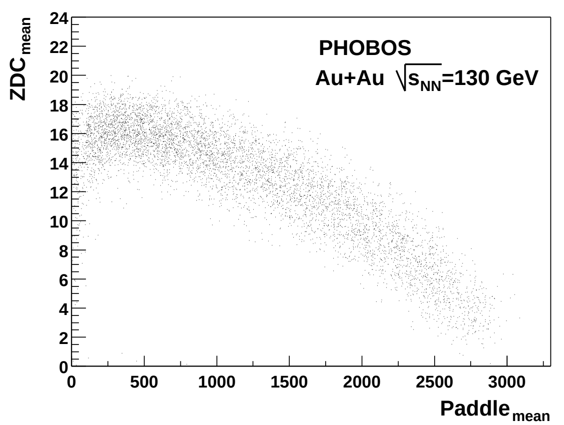

Fig. 7. An anti-correlation between signal in Paddle detectors and ZDC.

a consequence of a trivial relationship $N_{\rm spect} = A - N_{\rm part}$, where $N_{\rm part}$ is correlated with the signal in Paddle detector, while $N_{\rm spect}$ is correlated with the ZDC signal. The anti-correlation is clearly seen over a wide range of measured signals, except for the most peripheral collisions, for which most of the spectator neutrons are bound in charged fragments and escape the detection in ZDC calorimeters.

The further steps in experimental centrality determination involve detailed modeling of experimental signals followed by estimation of the value of centrality parameters, *e.g.* $N_{\rm part}$, for samples obtained by making selection cuts on the measured signals.

In the PHOBOS experiment we use MC simulations based on the HIJING event generator and the GEANT simulations of the detector response to correlate the signals in the Paddle and ZDC detectors with the centrality parameters. In the case of ZDC detectors only the signals from the 50% of most central collisions are modeled, due to the lack of a reliable model for describing the process of nuclear fragmentation. The distributions of the simulated signals agree well with the measured Paddle and ZDC signals. The final estimate of the centrality parameters is obtained by dividing up the inclusive signal distributions for both data[1] and MC into percentage cross-section bins. For MC, the centrality parameters are known for each event, which allows to associate paddle signal for each percentage cross-section slice with a corresponding $N_{\rm part}$ or $N_{\rm coll}$ distribution. The properties of centrality parameters obtained for the simulated data are then applied to samples selected from real data.

5. Precision of experimentally determined centrality parameters

Since centrality is not directly measured in the experiment, but only indirectly deduced using models of the measured signals, which are correlated with centrality only to a certain degree, additional sources of errors and biases are introduced. They influence the determination of the mean value and the width of the distribution of a given centrality parameter. In Fig. 8, the average values of the number of participating nucleons are compared for percentage cross-section cuts applied to the impact parameter, $N_{\rm part}$ and Paddle signal distributions. It can be seen that the average number of participating nucleons is not sensitive to the selection of the centrality related quantity. On the contrary, as shown in Fig. 9 the width of the $N_{\rm part}$ distribution changes strongly for different quantities used for centrality selection. In particular the width of $N_{\rm part}$ distributions is largest in samples obtained by cuts on the value of signals in ZDC, due to the weak correlation between

[1] The measured distribution was corrected for the missing fraction of cross-section, due to the trigger inefficiency [7]

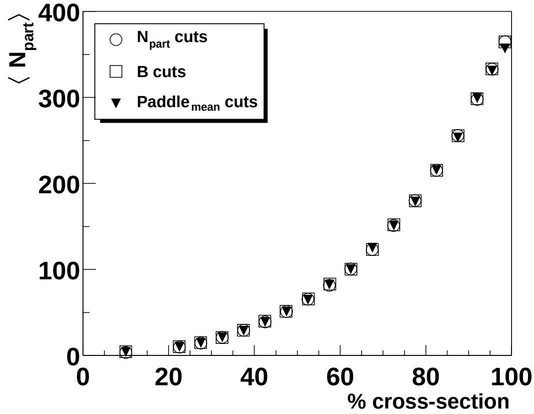

Fig. 8. Comparison of average value of $N_{\rm part}$ for samples obtained by cuts on different centrality related quantities.

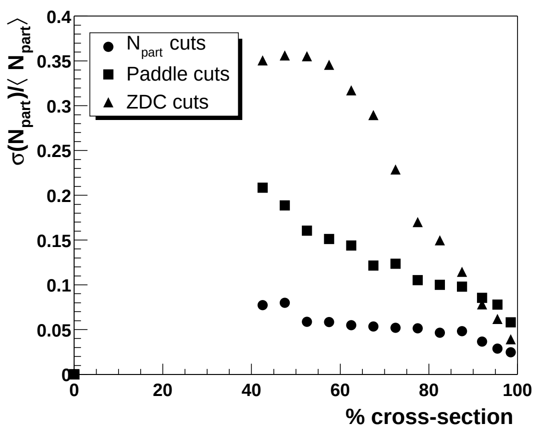

Fig. 9. Comparison of the width of $N_{\rm part}$ distributions for samples obtained by cuts on different centrality related quantities.

the number of neutrons measured in ZDC and the total number of spectator nucleons in the collision.

A large contribution to the systematic error in the experimental estimation of centrality comes from the uncertainty in the fraction of the inelastic cross-section actually measured in the experiment. A direct estimation of this fraction from the number of events experimentally registered is not possible due to the uncertainties regarding precise value of the total cross-section in Au + Au interactions at RHIC energies. In PHOBOS, the measured fraction of inelastic cross-section has been estimated at the level of 97% with systematic uncertainty of 3%, from the comparison of occupancy in Paddle counters with MC simulated distribution. The global uncertainty at this level proved to be the largest component of the experimental systematic error. The comparison of the magnitude of systematic errors coming from the biases in the experimental method of centrality determination and the global uncertainty of the measured cross-section as a function of centrality is shown in Fig. 10. The total systematic error exceeds the value of 7% at $N_{\rm part} < 70$. Therefore the analysis of the data in PHOBOS was limited to 45% of the most central events where $N_{\rm part} > 70$.

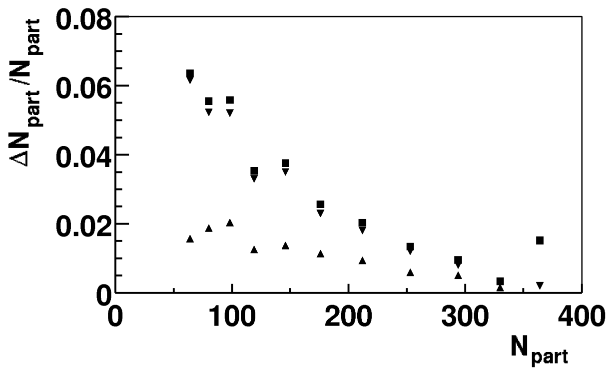

Fig. 10. Relative systematic errors of the number of participating nucleons $N_{\rm part}$ as a function of centrality. The two components of systematic errors coming from the uncertainty in the absolute value of the cross-section measured and from the bias of experimental method are shown by, down and up, triangles, respectively. The total value of systematic error as a function of centrality is shown by square points.

6. Summary

Systematic studies of the centrality dependence of various observables in high energy heavy-ion collisions are necessary in order to understand physics phenomena in dense and hot nuclear matter. These studies require precision measurements of the centrality parameters such as $N_{\rm part}$ or $N_{\rm coll}$. It has been shown that large variation in the centrality parameters and their relatively accurate estimates can be achieved by selecting sub-samples of events from the inclusive sample measured for a given collision system.

The uncertainties in the particular application of the Glauber formalism affect the estimate of the centrality parameters. Especially, the analytical calculations of the parameters, based on the optical approximation of the Glauber model, should be avoided since they provide incorrect results for the heavy ion collisions.

The precision of experimental estimates of the centrality parameters is mainly limited by the uncertainty in the measured fraction of inelastic cross-section. The biases in the estimate of the mean values of centrality parameters, due to the choice of experimental signal for centrality selection cuts and imperfections in the signal simulations, are correspondingly small. They, however, affect the width of the distribution of the centrality parameters, and should be taken into account particularly in model predictions.

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