Centrality categorization and application to physics effects in high-energy $d + A$ collisions

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Abstract. The study of numerous physics effects in small collision systems requires a careful characterization of the event geometry. In particular, many such phenomena have a strong dependence on the impact parameter of the collision. We describe the methodology utilized by PHENIX to select centrality classes in $d + Au$ collisions via cuts on charge deposited at backward (Au-going) rapidity. The measured charge can be mapped to other geometric quantities using a Monte Carlo Glauber model. We also describe how autocorrelations between the process of interest and the backward rapidity charge introduce bias effects that alter the measurement of centrality-dependent invariant yields. Our framework provides a method to compute correction factors to account for such effects. We discuss their calculation and validation using the HIJING Monte Carlo Generator. It is found that centrality bias correction factors are small and slightly $p_T$ dependent for $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, yet an order of magnitude larger and strongly $p_T$ dependent for $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The implications of such corrections are discussed for selected physics observables and effects.

1. Introduction
Small collision systems constitute an excellent ground for the study of a wide range of physics effects. Such effects include gluon saturation, color neutralization \cite{1}, the modification of parton distribution functions in nuclei \cite{2}\cite{3} and—more recently—the open question of collective flow \cite{4, 5, 6, 7}.

Nonetheless, a prerequisite to any such study is to characterize the event geometry in terms of quantities such as the number of binary collisions $N_{\text{coll}}$, the number of participants $N_{\text{part}}$, and the impact parameter (or centrality) of the event. Not only are these values needed to calculate important quantities such as nuclear modification factors, allowing us to compare particle yields in $p + p$ and $p(d)+A$ events, but they also play a role in analyzing strongly geometry-dependent phenomena such as collective flow.

Customarily, high-energy experiments at RHIC and the LHC have determined event geometry by correlating geometric quantities with far-backward rapidity multiplicity as a physical observable. However, this correlation is biased when additional conditions are imposed on the event—such as the production of particles at midrapidity—leading to miscalculated centrality-dependent invariant particle yields.

In these proceedings, we discuss centrality categorization in $d + Au$ events, following Ref. \cite{8}. We begin by describing the methodology used by the PHENIX experiment to categorize event centrality and determine other geometric quantities from backward rapidity multiplicity measurements. We then discuss how bias effects arise for events with particle production at...
midrapidity. Afterwards, we examine the computation of bias correction factors and study their centrality and transverse momentum dependence at RHIC and LHC energies. Finally, we discuss the implications of such corrections for selected physics observables and effects.

2. Centrality Categorization in the PHENIX Experiment

The PHENIX experiment utilizes two types of detectors to determine geometry in d+Au events. Namely, a pair of beam-beam counters (BBCs) spanning the pseudorapidity range 3.0 < |η| < 3.9, and zero-degree calorimeters (ZDCs) covering |η| < 6 [9, 10]. The BBCs measure charge deposited in the Au-going direction, which can be mapped to geometric quantities following a standard Monte Carlo Glauber approach. On the other hand, the ZDCs measure the energy of spectator neutrons, which can be used to validate our geometry characterization approach.

We now describe the Monte Carlo Glauber approach [11] used to map the charge deposited in the Au-going BBC to geometric quantities, such as $N_{\text{coll}}$, $N_{\text{part}}$, and centrality. d+Au events are simulated by randomly sampling the positions of nucleons in the deuteron from the Hulthén wavefunction $\psi_d(r_{pn}) = \left(\frac{\alpha\beta}{2\pi(\alpha - \beta)^2}\right)^{1/2} \exp(-\alpha r_{pn}) - \exp(-\beta r_{pn}) r_{pn}$ (1)

where $r_{pn}$ is the inter-nucleon distance, with $\alpha = 0.228$ fm$^{-1}$ and $\beta = 1.18$ fm$^{-1}$. For the gold nucleus, we sample from a Woods-Saxon distribution $\rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}$ (2)

with parameters $R = 6.38$ fm and $a = 0.54$ fm. We assume a collision between nucleons to occur when they come within a distance of $\sqrt{\sigma_{NN}/\pi}$ of each other, with $\sigma_{NN} = 42$ mb. We are then able to count the number of wounded nucleons in each nucleus, thus obtaining $N_{\text{coll}}$ and $N_{\text{part}}$.

Once these quantities have been determined, we map them to experimental observables assuming summed charge in the Au-going BBC to be directly proportional to $N_{\text{coll}}$, with fluctuations described by a negative binomial distribution (NBD) [13, 14]:

$$\text{NBD}(x; \mu, \kappa) = \left(1 + \frac{\mu}{\kappa}\right) \frac{(\kappa + x - 1)!}{x!(\kappa - 1)!} \left(\frac{\mu}{\mu + \kappa}\right)^x.$$ (3)

The parameters $\mu$ and $\kappa$ are found by fitting the experimental BBC charge distribution. We obtain the charge deposited in the BBC by folding the Glauber $N_{\text{coll}}$ distribution, $Gl(n)$, with the NBD fluctuation response

$$P(x) = \sum_{n=1}^{N_{\text{binary}}} Gl(n) \times \text{NBD}(x; n\mu, n\kappa).$$ (4)

Centrality classes can then be established by slicing the multiplicity distribution into quantiles, as shown in the upper panel of Figure 1. We observe a good agreement between real data and the Glauber calculation, as shown in the bottom panel of Figure 1. The observed deviation from unity is due to trigger inefficiency for low charge deposition. The minimum bias trigger consists in the simultaneous detection of at least one particle in both arms of the BBC.
3. Bias Factor Corrections

In the previous section we showed how BBC multiplicity can be mapped to geometric quantities using standard Monte Carlo Glauber+NBD techniques. Once event geometry has been determined, we can calculate invariant particle yields for any given centrality selection. However, the mapping between multiplicity and geometry is biased for events where particles are produced at midrapidity, leading to the miscalculation of invariant yields. In this section we investigate the origin of the bias and how it can be corrected.

To understand the origin of the autocorrelation bias, let’s consider \( p+p \) collisions at 200 GeV, with a total inelastic cross section of 42 mb. In such case, measurements indicate that the PHENIX minimum bias trigger will fire 52 ± 4% of the time. However, this efficiency increases to 75 ± 3% for events with charge particle production at midrapidity as a result of their higher multiplicity.

Of the total inelastic \( p+p \) cross section, we find that 28 of the 42 mb come from non-diffractive collisions, with the remaining 14 mb from single and double-diffractive events [15]. Nonetheless, since diffractive events result in particle production very close to the beam line, the minimum bias trigger will be biased towards non-diffractive collisions, where particle production at midrapidity is greatest. As a result, measured invariant yields will be biased towards a larger value.

Since nucleus-nucleus collisions effectively comprise multiple \( p+p \) events, the bias effect described above will be present in \( d+Au \) events as well. In such case, there will exist a bias towards higher charge deposition in the BBC and, hence, towards larger centrality. Let’s now examine the implications for centrality-dependent yields. In the case of peripheral events, there will be a deficit of midrapidity particles as they migrate to a more central categorization, resulting in smaller measured invariant yields that need to be corrected up through multiplication by an appropriate numerical factor. On the other hand, a midrapidity particle surplus in central events requires invariant yields to be corrected down.

We use the Glauber+NBD approach to compute numerical correction factors for each centrality class. We simulate \( d+Au \) events as comprising \( N \) individual \( p+p \) collisions. Of these, we take just one to be biased toward higher multiplicity and higher trigger efficiency, with the other \( N-1 \) remaining unaffected. Biased collisions are modeled with a greater NBD contribution to BBC multiplicity in the Au-going direction, implemented by scaling the \( \mu \) and
κ parameters of the NBD by 1.55 ± 0.23, as measured in p + p data. We then take the ratio of invariant yields with and without the above bias, obtaining the correction factors shown in Table 1.

Table 1: Bias correction factors and different geometrical quantities for d+Au events at 200 GeV, as calculated with a Glauber+NBD approach.

| Centrality   | 0%-20% | 20%-40% | 40%-60% | 60%-88% |
|--------------|--------|---------|---------|---------|
| Bias Factor  | 0.94 ± 0.01 | 1.00 ± 0.01 | 1.03 ± 0.02 | 1.03 ± 0.006 |
| ⟨N_{coll}⟩  | 15.1 ± 1.0 | 10.2 ± 0.7 | 6.6 ± 0.4 | 3.2 ± 0.2 |
| ⟨N_{part}⟩  | 15.2 ± 0.6 | 11.1 ± 0.6 | 7.8 ± 0.4 | 4.3 ± 0.2 |

4. HIJING Study of the Bias Factors

The previous section described the calculation of bias correction factors for d+Au events based on the scaling of BBC multiplicity by a factor of 1.55. However, experimental data indicate a p_{T} dependence of this effect, as shown in the right panel of Figure 2. Our Glauber+NBD model does not allow for the study of this dependence. Therefore, we turn to the HIJING Monte Carlo generator [16] to examine the implications of this p_{T} dependence on our bias correction method, noting that any results will be model-dependent and not to be applied to experimental data.

4.1. Bias Factor Corrections for d+Au at 200 GeV

We assess the validity of HIJING for the study at hand by simulating p+p events at \sqrt{s_{NN}} = 200 GeV. We find the simulated minimum bias trigger efficiency to be 48%, compared to the measured value of 52 ± 4%. It is also found that the presence of midapidity particles (i.e., |\eta| < 0.35) with p_{T} > 1 GeV increases BBC multiplicity by a factor of 1.62, compared with the previously quoted value of 1.55 from data. Furthermore, Figure 2 illustrates how HIJING qualitatively reproduces the p_{T} dependence of BBC multiplicity scaling observed in data.

In order to calculate bias factor correction factors in d+Au collisions, we define 4 centrality classes (0-20%, 20-40%, 40-60% and 60-88%) using the simulated BBC multiplicity distribution. We then calculate the particle yield at midrapidity for each centrality, thus obtaining measured yields where the effect of the autocorrelation bias is expected to be present. We can isolate bias effects by determining the N_{coll} distribution for each centrality and then sorting events into centrality classes by matching these N_{coll} distributions. When particle yields are calculated in this manner, we refer to them as truth yields. Therefore, the ratio of truth to measured yields is exactly the desired bias correction factor. Table 2 shows the mean bias factors computed with HIJING for midrapidity particles with p_{T} > 1 GeV, where a good agreement is seen between HIJING and Glauber+NBD values.

The HIJING bias correction factors are shown as a function of p_{T} in left panel of Figure 3. We observe a modest p_{T} dependence of the bias factors, varying by less than 10% across p_{T}. The bias factors are seen to slightly rise in central events, and to slightly drop in peripheral events, in a manner consistent with expectations.

4.2. Bias Factor Corrections for p+Pb at 5.02 TeV

Given recent data from the LHC regarding p+Pb collisions at \sqrt{s_{NN}} = 5.02 TeV, we apply our HIJING methodology to this collision system, using charged particle multiplicity in the Pb-going direction within −4.9 < \eta < −3.1 to determine centrality.
Figure 2: (left) Simulated ratio of Au-going BBC multiplicity for $p + p$ events with particle production at midrapidity to all inelastic collisions at $\sqrt{s_{NN}} = 200$ GeV. The dashed line at 1.55 indicates the measured increase in BBC multiplicity from data. (right) Measured charge deposition in the Au-going BBC as a function of midrapidity particle $p_T$ for $p + p$ events at $\sqrt{s_{NN}} = 200$ GeV.

Table 2: Mean bias factor corrections as a function of $p_T$ for each centrality as calculated with HIJING.

| Centrality  | Mean Bias Factor Correction $1 \leq p_T < 5$ | Mean Bias Factor Correction $5 \leq p_T < 10$ | Mean Bias Factor Correction $10 \leq p_T < 15$ | Mean Bias Factor Correction $15 \leq p_T < 20$ |
|-------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| 0-20%       | 0.951 $\pm$ 0.001                          | 0.962 $\pm$ 0.001                          | 1.000 $\pm$ 0.005                          | 1.038 $\pm$ 0.020                          |
| 20-40%      | 0.996 $\pm$ 0.001                          | 1.008 $\pm$ 0.001                          | 1.010 $\pm$ 0.006                          | 0.996 $\pm$ 0.021                          |
| 40-60%      | 1.010 $\pm$ 0.001                          | 1.022 $\pm$ 0.001                          | 1.019 $\pm$ 0.007                          | 1.005 $\pm$ 0.025                          |
| 60-88%      | 1.030 $\pm$ 0.001                          | 1.026 $\pm$ 0.001                          | 0.999 $\pm$ 0.008                          | 0.991 $\pm$ 0.030                          |

As before, we begin by simulating $p + p$ events at $\sqrt{s_{NN}} = 5.02$ TeV. We find that the presence of a particle at midrapidity increases multiplicity in the Pb-going direction by 1.67.

We calculate bias correction factors for 5 centrality categories (0-20%, 20-40%, 40-60%, 60-80% and 80-100%). The results, as a function of $p_T$ are shown in Figure 3. We observe very large and $p_T$ dependent correction factors, where multi-parton interactions play a substantial role [17]. These bias factors can be contrasted with ALICE data [18], as shown in Figure 4. Bearing in mind that $Q_{pPb}$ scales as the inverse of the bias factors, we observe a good qualitative agreement between our HIJING results and the ALICE $Q_{pPb}$.

5. Application to Selected Physics Observables
In this section we present selected geometry-dependent physics observables available for study in d+Au collisions.
5.1. Transverse Energy, Charged Particle Production and Bjorken Energy Density

Transverse energy and charged particle production are examples of important centrality-dependent quantities in the study of heavy-ion collisions [19].

Figure 3: Bias factor corrections for (left) d+Au events at $\sqrt{s_{NN}} = 200$ GeV and (right) p+Pb events at $\sqrt{s_{NN}} = 5.02$ TeV.

Figure 4: $Q_{pPb}(p_T)$ for p+Pb at $\sqrt{s_{NN}} = 200$ GeV for different centrality classes in the ALICE experiment [18].
Figure 5 illustrates transverse energy and charged particle production in PHENIX for d+Au and Au + Au at $\sqrt{s_{NN}} = 200$ GeV as a function of centrality (characterized by the number of participants $N_{\text{part}}$). We observe a linear scaling of both quantities with $N_{\text{part}}$, as well as the continuity of the curve from central d+Au to peripheral Au + Au events.

The ratio of transverse energy to the overlap area between colliding nuclei corresponds to the Bjorken energy density,

$$\epsilon_{Bj} = \frac{1}{\pi R^2} \frac{dE_T}{d\eta}. \quad (5)$$

Figure 6: Bjorken energy density as a function of centrality for d+Au and Au + Au events at $\sqrt{s_{NN}} = 200$ GeV.
5.2. Collective Flow in $^3$He+Au Collisions

Recent data from RHIC (d+Au) and LHC (p+Pb) provide compelling evidence for collective flow in small systems [4, 5, 6, 7]. However, there is currently no consensus to discriminate between the effects of initial-state spatial anisotropies and those from the subsequent evolution of the medium.

$^3$He+Au collisions have been proposed as a test system whose intrinsic triangular geometry can be leveraged to disentangle initial state effects from viscous damping through comparison with systems with one and two initial hotspots [20].

The same Glauber+NBD approach used to categorize centrality in d+Au can be used to generate the initial event geometry in $^3$He+Au events. Just as the Hulthén wavefunction for the deuteron is used as input for the Glauber model, a study of $^3$He+Au requires a description of the helium wavefunction [21]. This initial geometry is then propagated with viscous hydrodynamic code [22]. As shown in Figure 7, it is observed that intrinsic initial state triangularity survives as significant final state triangular flow, even with viscous damping. This example serves to illustrate the wide applicability of our Glauber+NBD approach to characterize event geometry and compare theoretical results to experimental findings.

6. Summary

We have described the methodology used by the PHENIX experiment to categorize geometry in d+Au collisions. The method is subject to inherent bias effects arising for events with charged particle production at midrapidity, which alter the measurement of centrality-dependent invariant yields. Our framework allows for the calculation of bias correction factors to account for such effects. Simulations with the HIJING generator indicate that bias correction factors are small for d+Au events at $\sqrt{s_{NN}} = 200$ GeV, but large and substantially $pT$-dependent for p+Pb at $\sqrt{s_{NN}} = 5.02$ TeV.
References
[1] A. Accardi et al., arXiv:1212.1701.
[2] K. Eskola, H. Paukkunen, and C. Salgado, J. High Energy Phys. 04, 065 (2009)
[3] I. Helenius, K. J. Eskola, H. Honkanen, and C. A. Salgado, J. High Energy Phys. 07, 073 (2012)
[4] A. Adare et al. (PHENIX Collaboration), Phys.Rev.Lett. 111, 212301 (2013)
[5] G. Aad et al. (ATLAS Collaboration), Phys. Rev. Lett. 110, 182302 (2013).
[6] B. Abelev et al. (ALICE Collaboration), Phys. Lett. B 719, 29 (2013).
[7] S. Chatrchyan et al. (CMS Collaboration), Phys. Lett. B 718, 795 (2013).
[8] A. Adare et al. (PHENIX Collaboration), arXiv:1310.4793 (to be published).
[9] M. Allen et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 549 (2003).
[10] C. Adler et al. (STAR Collaboration), Nucl. Instrum. Methods A 499, 433 (2003).
[11] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57, 205 (2007).
[12] L. Hulthen and M. Sagawara, Handbuch der Physik 39, 14 (1957)
[13] A. Giovannini and L. Van Hove, Z. Phys. C 30, 391 (1986)
[14] T. Abbott et al. (E802 Collaboration), Phys. Rev. C 52, 2663 (1995).
[15] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. C 77, 014903 (2008).
[16] M. Gyulassy and X.-N. Wang, Comput. Phys. Commun. 83, 307 (1994).
[17] M. H. Seymour and A. Siodmok, arXiv:1307.5015.
[18] A. Morsch (ALICE Collaboration), arXiv:1309.5525.
[19] S.S. Adler et al. (PHENIX Collaboration).Phys.Rev.C 71:034908 (2005)
[20] J.L. Nagle et al., arxiv:1312.4565.
[21] J. Carlson and R. Schiavilla, Rev. Mod. Phys. 70, 743 (1998)
[22] M. Luzum and P. Romatschke, Phys.Rev.C 78, 034915 (2008), 0804.4015.