

**Centrality categorization for  $R_{p(d)+A}$  in high-energy collisions**

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High-energy proton- and deuteron-nucleus collisions provide an excellent tool for studying a wide array of physics effects, including modifications of parton distribution functions in nuclei, gluon saturation, and color neutralization and hadronization in a nuclear environment, among others. All of these effects are expected to have a significant dependence on the size of the nuclear target and the impact parameter of the collision, also known as the collision centrality. In this article, we detail a method for determining centrality classes in  $p(d) + A$  collisions via cuts on the multiplicity at backward rapidity (i.e., the nucleus-going direction) and for determining systematic uncertainties in this procedure. For  $d + Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV we find that the connection to geometry is confirmed by measuring the fraction of events in which a neutron from the deuteron does not interact with the nucleus. As an application, we consider the nuclear modification factors  $R_{p(d)+A}$ , for which there is a bias in the measured centrality-dependent yields owing to auto correlations between the process of interest and the backward-rapidity multiplicity. We determine the bias-correction factors within this framework. This method is further tested using the HIJING Monte Carlo generator. We find that for  $d + Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV, these bias corrections are small and vary by less than 5% (10%) up to  $p_T = 10$  (20) GeV/ $c$ . In contrast, for  $p + Pb$  collisions at  $\sqrt{s_{NN}} = 5.02$  TeV we find that these bias factors are an order of magnitude larger and strongly  $p_T$  dependent, likely attributable to the larger effect of multiparton interactions.

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## I. INTRODUCTION

Proton- and deuteron-nucleus collisions provide an excellent tool for studying a variety of nuclear effects. For example, there are important modifications to parton distribution functions (PDFs) in nuclei, which are strongly dependent on  $x$  and  $Q^2$  [1,2]; the low- $x$  partons have a wavelength longer than the extent of large nuclei and thus saturation effects are expected to scale with the nuclear thickness. Modifications of particle yields owing to color neutralization and hadronization within the target nucleus are elucidated by their path-length dependence through the target [3]. Furthermore, studies in deep inelastic scattering (DIS) average over the geometry of a given nuclear target, and studies of the geometric dependence of nuclear modifications are restricted to varying the nuclear target atomic number  $A$ . In proton- or deuteron-nucleus collisions, there has been a significant effort to characterize the geometry in individual collisions in terms of the impact parameter or the number of binary collisions ( $N_{\text{coll}}$ ). Being able to characterize the geometry of the collision allows for the comparison of  $p + p$  and  $p(d) + A$  yields through physics quantities, such as the nuclear modification factor  $R_{p(d)+A}$ ,

$$R_{p(d)+A} = \frac{dN^{p(d)+A}/dy}{\langle N_{\text{coll}} \rangle dN^{pp}/dy}, \quad (1)$$

where  $dN^{p(d)+A}/dy$  and  $dN^{pp}/dy$  are the invariant yields in  $p(d) + A$  and  $p + p$  collisions, respectively. Therefore, being able to precisely determine the geometric properties of the collision is critical to understanding these nuclear effects.

Recent data taken with  $p + Pb$  collisions at the Large Hadron Collider (LHC) and new analysis of  $d + Au$  collision

data at Relativistic Heavy Ion Collider (RHIC) indicate possible collective flow effects with an important geometric dependence [4–7]. These measurements further highlight the need to characterize the geometry in individual collisions and for future measurements with different collision species.

At lower energies, “gray tracks” (named for their appearance in emulsion experiments) from spectator nucleons have been utilized for characterizing geometry [8–10]. At RHIC and the LHC, the categorization has been done with backward rapidity multiplicity and not with spectator nucleons. This general method has been utilized by all RHIC experiments in numerous observables over the past decade. In this paper we describe in detail a method for characterizing  $p(d) + A$  collisions.

The geometry correlation with backward-rapidity multiplicity is biased when an additional condition on the event is included, for example, the production of a midrapidity particle. We describe a procedure for correcting the  $p(d) + A$  centrality-dependent particle yields for this autocorrelation bias. Because high-statistics  $p(d) + A$  data are available with yields extending to high transverse momentum ( $p_T$ ), it is also important to study the dependence of these bias-correction factors on the  $p_T$  of the produced particle. We utilize measurements in  $p + p$  collisions to study the correlation of backward-rapidity multiplicity with the presence of a high- $p_T$  midrapidity particle. We discuss this method in the context of the PHENIX experiment, though this method is applicable in any collider experiment with a far-backward particle detector. In addition, we test this method utilizing the HIJING MC generator for both  $d + Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV and  $p + Pb$  collisions at  $\sqrt{s_{NN}} = 5.02$  TeV.

The paper is organized as follows. Section II discusses the detectors used by the PHENIX experiment to characterize the geometry of the collision, which gives context to the specific tests detailed later in the paper. Sections III–VII describe the general methodology for centrality categorization.

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Section III describes the method, Sec. IV details the cross checks with neutron-tagged events, and Secs. VI and VII provide the derivation and systematic uncertainties of various geometric quantities, as well as the bias-factor corrections to the measured yields. Section VIII details the calculation of the bias factors using the HIJING MC generator and comparisons to those obtained in previous sections with our Glauber + negative-binomial-distribution (Glauber + NBD) procedure. Section IX summarizes the findings.

## II. EXPERIMENT

To characterize the geometry of  $d + \text{Au}$  collisions at  $\sqrt{s_{NN}} = 200$  GeV, the PHENIX experiment uses beam-beam counters (BBCs) covering the pseudorapidity range  $3.0 < |\eta| < 3.9$  and zero-degree calorimeters (ZDCs) covering  $|\eta| > 6$ . Both detectors are described in detail in Refs. [11,12].

Each BBC is an array of 64 Čerenkov counters around the beam pipe and is positioned 1.44 m upstream and downstream of the nominal vertex location. Each counter is composed of 3 cm of quartz coupled to a mesh-dynode photomultiplier tube. Although the BBC charge is calibrated to a minimum-ionizing charged particle [11], approximately 50% of the hits are the result of scattering particles from outside the nominal pseudorapidity acceptance of the BBC or of photon conversions (e.g., in the beryllium beam pipe). The information from the BBC is used to determine the event timing, vertex position, and centrality.

The two ZDCs are hadronic calorimeters that measure spectator neutrons. They are located 18 m from the interaction point and comprise optical readout fibers between tungsten plates. At the top RHIC energy of 100 GeV/nucleon, neutrons evaporated from the spectator remnants of the collision are emitted within 1 mrad from the colliding-beam direction. Charged fragments and the noninteracted primary beam are bent by deflecting magnets to much larger angles. The ZDC thus measures the total neutron energy within a small cone and thus provides the number of spectator neutrons from the interacting nucleus.

## III. CENTRALITY CATEGORIZATION METHOD

The PHENIX experiment selects centrality categories in  $d + \text{Au}$  collisions based on the summed charge measured in the BBC in the Au-going direction. To determine the mapping from the measured charge to various geometric quantities such as the number of binary collisions, we employ a standard MC-Glauber model. The general procedure for such calculations in heavy ions is described in Ref. [14]. On an event-by-event basis, the transverse positions of all nucleons in the deuteron and gold nucleus are selected from the Hulthén wave function and a Woods-Saxon distribution, respectively. The deuteron is described by a Hulthén wave function,

$$\psi_d(r_{pn}) = \left[ \frac{\alpha\beta(\alpha + \beta)}{2\pi(\alpha - \beta)^2} \right]^{1/2} \frac{(e^{-\alpha r_{pn}} - e^{-\beta r_{pn}})}{r_{pn}}, \quad (2)$$

with  $\alpha = 0.228 \text{ fm}^{-1}$  and  $\beta = 1.18 \text{ fm}^{-1}$  [13]. The square of this wave function determines the probability distribution for the distance between the proton and neutron within the

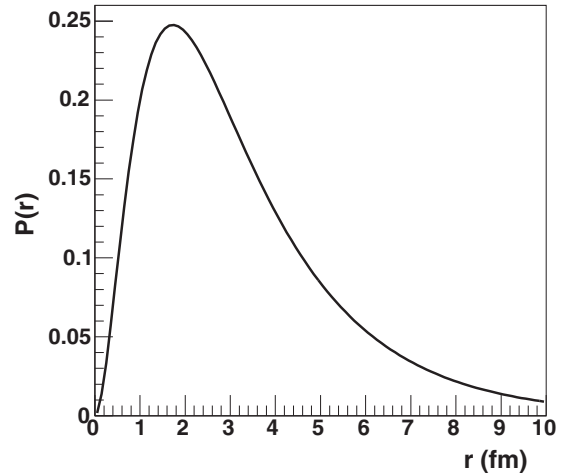


FIG. 1. Probability density distribution for the proton-neutron distance in the deuteron given by the square of the Hulthén wave function [13].

deuteron, as shown in Fig. 1. For the gold nucleus, we use the Woods-Saxon density distribution,

$$\rho(r) = \frac{\rho_0}{1 + e^{\frac{r-R}{a}}}, \quad (3)$$

with radius  $R = 6.38$  fm and diffuseness parameter  $a = 0.54$  fm. We utilize a nucleon-nucleon inelastic cross section of 42 mb. Variation of these values and the inclusion of a hard-core repulsive potential are utilized in the determination of systematic uncertainties described later. On an event-by-event basis, the nucleon positions are determined at random (weighted with the respective probability distributions), an impact parameter is selected, and the nucleon-nucleon collisions are calculated. A nucleon-nucleon collision occurs if the distance between two nucleons is less than  $\sqrt{\sigma_{NN}/\pi}$ . A single  $d + \text{Au}$  event is shown in Fig. 2, where both nucleons from

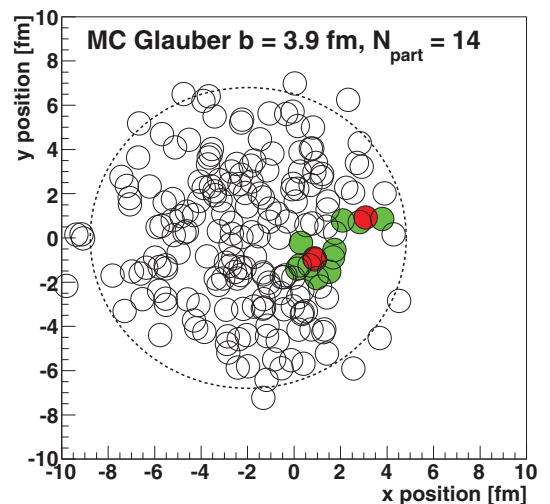


FIG. 2. (Color online) MC-Glauber event display for a single  $d + \text{Au}$  collision. All nucleons are shown as open circles and nucleons with at least one inelastic collision are highlighted as solid circles.

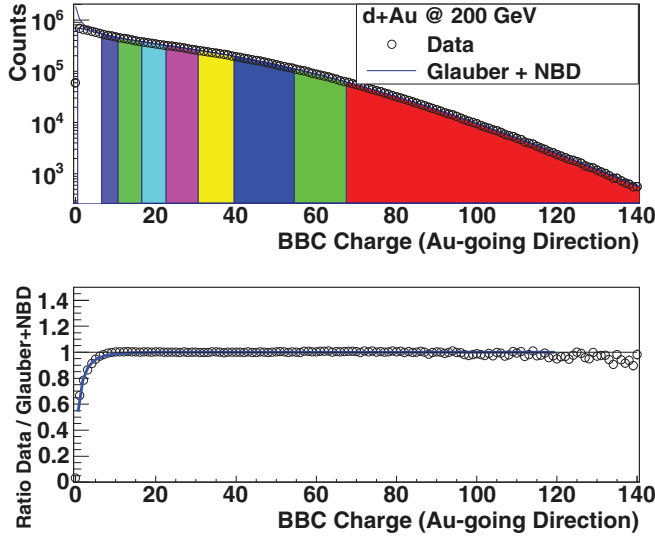


FIG. 3. (Color online) (a) Real-data  $d + \text{Au}$  BBC Au-going direction charge distribution is shown as open points and Glauber + NBD calculation as a histogram. Shown as different color regions are the centrality selections of 0%–5%, 5%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, 50%–60%, 60%–70%, and 70%–88%. (b) The ratio of real data to Glauber + NBD calculation. The line is a fit to the experimental trigger efficiency turn-on curve.

the deuteron, shown as red circles, have inelastic collisions and the nucleons from the gold nucleus, shown as green circles, with at least one inelastic collision are highlighted. Once the participating nucleons are determined in a given event, one has full information on the number of participating nucleons, the number of binary collisions, and the spatial position and overlap of all participating nucleons.

To relate these MC-Glauber quantities to geometric parameters, they must be mapped to an experimental observable. The PHENIX experiment has used as the experimental observable the charge measured in the BBC in the Au-going direction covering pseudorapidity  $-3.9 < \eta < -3.0$ . The minimum-bias (MB) trigger requirement is the coincidence of one or more hits in both the BBC in the Au-going direction and the BBC in the  $d$ -going direction. The experimental distribution of the BBC Au-going charge corresponding to this MB trigger sample is shown with open circles Fig. 3(a).

At this point we make the hypothesis that the BBC Au-going charge is proportional to the number of binary collisions in an individual  $d + \text{Au}$  collision, with fluctuations in the contribution from each binary collision described by the NBD, which is parametrized by the mean  $\mu$  and a positive exponent  $\kappa$ :

$$\text{NBD}(x; \mu, \kappa) = \left(1 + \frac{\mu}{\kappa}\right) \frac{(\kappa + x - 1)!}{x!(\kappa - 1)!} \left(\frac{\mu}{\mu + \kappa}\right)^x. \quad (4)$$

NBD distributions have been utilized for fitting particle multiplicities (see, for example, Refs. [15,16]), in part owing to the fact that randomly sampling from  $n$  NBD( $\mu, \kappa$ ) distributions results in an NBD distribution with NBD( $n\mu, n\kappa$ ). The fluctuations contained in the NBD relate to both the variation in the number and the distribution of particles produced and also

to fluctuations in the number of particles resulting in charge in the BBC detector. One then folds the Glauber distribution of the number of binary collisions [Gl( $n$ )], normalized per event, with the NBD response using

$$P(x) = \sum_{n=1}^{N_{\text{binary}}(\text{max})} \text{Gl}(n) \times \text{NBD}(x; n\mu, n\kappa), \quad (5)$$

where  $x$  is the BBC charge.

The two NBD parameters  $\mu$  and  $\kappa$  are fit to the experimental distribution for BBC charge greater than 20. At low BBC charge there will be an expected deviation between the calculation and data owing to the inefficiency of the MB trigger requirement (including at least one hit in the  $d$ -going BBC). The result of the best fit yields values  $\mu = 3.03$  and  $\kappa = 0.46$  and is shown as a histogram in Fig. 3(a). The ratio of the data to the Glauber + NBD calculation is shown in Fig. 3(b) and shows very good agreement for BBC charge greater than 10. We have also considered the possibility that the Au-going charge is proportional to the number of Au participants, rather than the number of binary collisions. We get an equally good fit to the data, and the difference in the extracted geometric quantities (detailed later) is included in the quoted systematic uncertainty.

We have fit the deviation at low charge to determine the MB trigger efficiency turn-on curve. The integrated results indicate that the MB trigger fires on  $88\% \pm 4\%$  of the Glauber determined 2.19-b inelastic  $d + \text{Au}$  cross section. The PHENIX experiment has separately measured the MB trigger sample cross section. The deuteron dissociation cross section  $\sigma(d \rightarrow p + n)$  is theoretically well calculated as  $1.38 \pm 0.01$  b and thus combining this with the measured ratio of MB to dissociation cross section, one obtains the MB cross section of  $1.99 \pm 0.10$  b [17]. When combined with the 88% trigger efficiency, this yields a total inelastic cross section of  $2.26 \pm 0.10$  b, in agreement with the previous value.

In  $p + p$  collisions there is always one binary collision. The NBD parameters determined above are consistent within uncertainties with the mean BBC multiplicity in  $p + p$  collisions. However, an exact comparison of the full distribution is challenging because the MB trigger significantly biases the distribution. Utilizing clock triggers (random triggers with no detector requirement) has the difficulty of background contamination from beam-gas interactions and beam-beam collisions outside the nominal PHENIX  $z$ -vertex range ( $-30 \text{ cm} < z < +30 \text{ cm}$ ).

For each centrality bin we can apply the identical event selection and trigger turn-on curve on the Glauber + NBD calculation, thus determining the distribution of the number of binary collisions (number of nucleon-nucleon inelastic collisions). The results corresponding to the nine centrality quantiles 0%–5%, 5%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, 50%–60%, 60%–70%, and 70%–88% are shown in Fig. 4.

#### IV. NEUTRON-TAGGED CROSS CHECK

As an additional test, we checked the validity of our geometry selection method using neutron-tagged events. Owing to the large size of the deuteron, there is a significant probability for

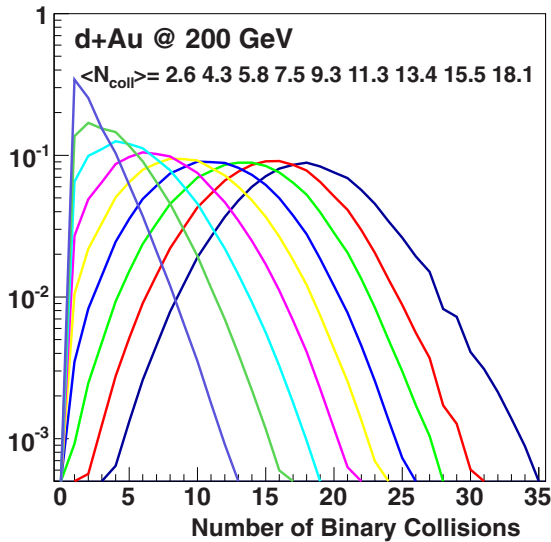


FIG. 4. (Color online) Extracted distribution of the number of binary collisions in each of the nine centrality quantiles (from right to left): 0%–5%, 5–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, 50%–60%, 60%–70%, and 70%–88%.

the neutron (proton) from the deuteron to miss the Au nucleus (i.e., have no inelastic interaction with any target nucleon), while the proton (neutron) does interact. These “ $p$ ” + Au and “ $n$ ” + Au interactions have been studied and are detailed in Ref. [18]. In the “ $p$ ” + Au case, the method employed is to measure the spectator neutron energy in the PHENIX ZDC in the deuteron-going direction. The ZDC energy distribution in  $d + \text{Au}$  MB events is shown in Fig. 5. The distribution is only for events where energy above threshold is deposited in the ZDC, and therefore the majority of events, i.e., those where there is no spectator neutron, are not included. One observes a clear single neutron peak with a mean energy

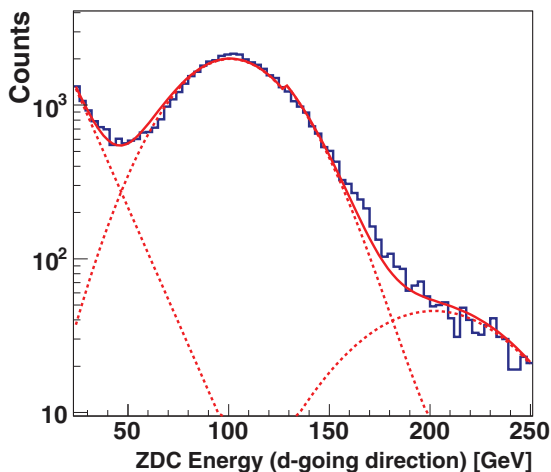


FIG. 5. (Color online) ZDC energy distribution in the deuteron-going direction for MB  $d + \text{Au}$  collisions. The data are well described by an exponential background component, a single spectator neutron peak, and a much smaller contribution from two neutrons owing to double interactions.

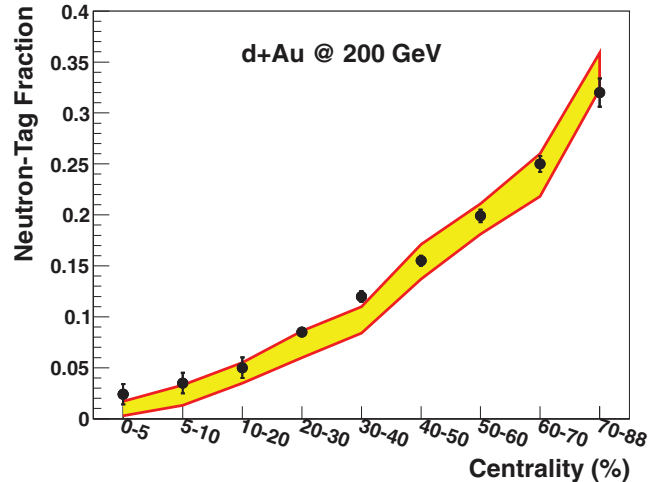


FIG. 6. (Color online) Data points are the measured fraction of events where there is a spectator neutron from the deuteron projectile. In comparison, the yellow band is the MC-Glauber result with systematic uncertainties.

of 100 GeV (the expected beam energy) and a resolution width of approximately 28 GeV. Additionally, there is a low energy background component that is well described by an exponential. Last there is a contribution from two neutrons. The two-neutron contribution comes from double interactions where the additional neutron results from an independent inelastic  $d + \text{Au}$  interaction or a  $d + \text{Au}$  photodisintegration reaction.

We select events with a spectator neutron with a ZDC energy cut of 60–180 GeV, which captures 96% of the single neutron peak. We estimate a 2%–3% contribution from the exponential background. These effects tend to cancel and we apply no net correction to the spectator neutron event yield and apply a  $\pm 3\%$  systematic uncertainty on this yield. The double interaction contribution (i.e., the two-neutron peak yield) depends on the instantaneous luminosity and the “centrality” category of selected  $d + \text{Au}$  events. Accounting for these double interaction contributions as detailed in the next section, we determine from data the probability of a spectator neutron from a single  $d + \text{Au}$  inelastic interaction in the nine centrality selections, as shown in Fig. 6. The error bars reflect systematic uncertainties from accounting for double interaction contributions between the different data sets (dominant in central events) and from the neutron tagging efficiency (dominant in peripheral events). The yellow band corresponds to the MC-Glauber calculated values and the systematic uncertainties in that calculation from a full set of parameter variations, discussed in detail in the next section. The agreement between data and calculation is good and gives us confidence in the geometric modeling of the collisions.

## V. DOUBLE INTERACTION STUDY

Figure 7 shows the BBC Au-going charge distribution in MB  $d + \text{Au}$  events (upper curves) and the distribution in the subset of events where there is a single neutron spectator present (lower curves). The lowest curve (blue) in each set

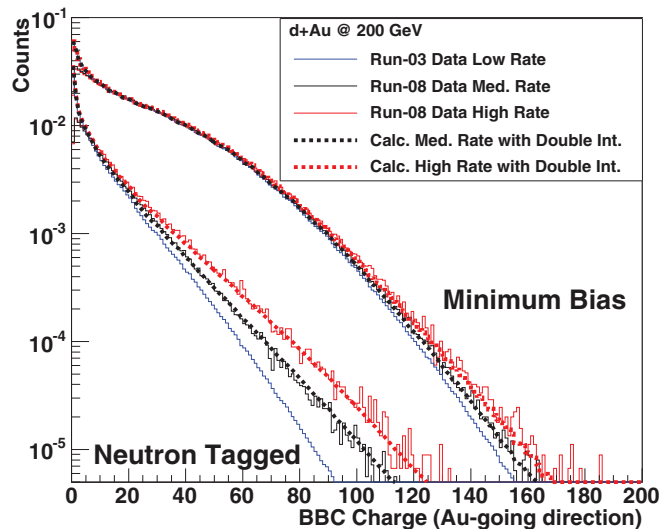


FIG. 7. (Color online) Data distributions for the BBC charge (in the Au-going direction) from low-luminosity data recorded in 2003 [18], medium-luminosity data from early in 2008, and high-luminosity data from late in 2008. The upper set of curves are for MB  $d + Au$  interactions and the lower set of curves feature the additional requirement of a neutron spectator from the deuteron. The differences in the distributions are the result of contributions from double interactions. The results of a calculation of these contributions with input rates relevant to match the medium- and high-luminosity 2008 data are also shown.

is from low-luminosity  $d + Au$  data collected in 2003 [18]. The middle curve (black) and upper curve (red) are from medium- and high-luminosity data collected in the 2008  $d + Au$  running, respectively. The highest luminosities achieved correspond to BBC trigger rates of order 300 kHz, where the probability of a second inelastic interaction within the same crossing approaches a few percent. Although the probability is low, the case of two inelastic interactions occurring in the same crossing results in the sum of their respective BBC Au-going charge, and thus a higher probability for a falsely identified  $d + Au$  central event. In the high-luminosity category and for the most central 5% of interactions, the double interaction contribution is approximately 13%.

The difference in BBC distributions is even more pronounced between data taken at different luminosities for the neutron spectator sample. The reason is that a central, high-BBC-multiplicity event has a small probability to have a neutron spectator, because both nucleons from the deuteron are typically occluded by the Au nucleus. Thus, the probability of two interactions, one with high multiplicity and no spectator neutron and one low multiplicity with a spectator neutron, dominates. In addition, the second interaction may be a photodissociation reaction that results in no BBC multiplicity contribution and just the neutron striking the ZDC. Using a Weizsacker-Williams approach, the photodissociation  $d + Au$  cross section is calculated to be 1.38 b [19].

We employ a simple model to account for all these contributions. The 2003 distributions shown in Fig. 7 are from very-low-luminosity data [18], where double interactions are

negligible. Thus, we use these distributions as from strictly single interactions. For the 2008 medium rate data sample, the BBC coincidence rate without any collision vertex selection was measured with the PHENIX data acquisition scalers and is approximately 100–150 kHz. Thus, the probability for two interactions occurring in the same 106-ns bunch crossing is  $100\text{--}150\text{ kHz}/9.4\text{ MHz} = 1.0\%\text{--}1.5\%$ . The rates are approximately 2.5–3.0 times higher for the 2008 high-luminosity data-taking period. Using these rates as input, we calculate the probability of two inelastic collisions and their resulting summed BBC charge. We also calculate the probability of one inelastic collision with no spectator neutron and a second interaction (inelastic or photodisintegration) with a resulting neutron. We then sum the different relative single and double interaction contributions. We find best agreement with the MB data distributions with a double interaction probability of 1.5% (3.5%), and the results are shown as the thick black (red) lines, which simultaneously match the MB and neutron-tagged real-data samples.

The BBC Au-going charge distribution shown in Fig. 3 is from a low-luminosity run in 2008. The centrality quantiles are determined on a run-by-run basis and thus the highest luminosity runs will have some influence from the double interaction contamination. In the central 0%–20% sample the contamination is very small for both the 2003 and 2008 luminosities. Only in the most central 0%–5% sample, where the contamination can reach as high as 13% at the highest luminosities, does this become a real concern and further checks become necessary. For example, an analysis of low- $p_T$  correlations [4] using the 0%–5% sample, checked explicitly the robustness of the result using subsets of low and high luminosity and found good agreement between the two.

## VI. GEOMETRY CHARACTERIZATION AND SYSTEMATIC UNCERTAINTIES

At this point, with the mapping of BBC charge to MC-Glauber, we determine several geometric properties from the MB  $d + Au$  sample, such as  $N_{\text{part}}$ ,  $N_{\text{coll}}$ , and eccentricity, in each centrality selection. We note that an additional requirement of a particular particle at midrapidity will bias this geometric mapping owing to autocorrelations with the backward rapidity multiplicity. We correct for this effect separately as discussed in the next section. To determine the systematic uncertainty on these geometric properties, we vary the input parameters and rerun the entire NBD parameter fit and trigger efficiency turn-on curve determination. The following variations are considered.

- (i) We vary the nucleon-nucleon inelastic cross section from the default value of 42 mb down to 39 mb and up to 45 mb.
- (ii) We vary the Woods-Saxon Au nucleus parameters. The alternate set No. 1 has a radius = 6.65 fm and diffusiveness = 0.55 fm. The alternate set No. 2 has a radius = 6.25 fm and diffusiveness = 0.53 fm. These are compared to the default values of radius = 6.38 fm and diffusiveness = 0.54 fm.

- (iii) We include a hard-core repulsive potential with an exclusion radius  $r = 0.4$  fm in the Glauber model selection of nucleon positions in the Au nucleus. The hard-core potential prevents nucleons from occupying the same space.
- (iv) We consider the possibility that the BBC Au-going direction charge is not simply proportional to the number of binary collisions, but instead is proportional to the number of binary collisions to the power  $\alpha$ . We consider values of  $\alpha = 0.95$  and  $\alpha = 1.05$ . These values of  $\alpha$  result in a change in particle production per binary collision from peripheral events to central events of order 10%–15% and are at the extreme of consistency with the centrality dependence of the charge multiplicity.
- (v) We run the real data to Glauber + NBD comparison by default for the  $z$ -vertex range  $|z| < 5$  cm. We include comparisons with the extremes in the  $z$ -vertex selection of 25 to 30 cm and  $-25$  to  $-30$  cm. The BBC acceptance varies slightly with the change in the collision  $z$  vertex and, owing to the centrality-dependent asymmetric rapidity distribution of charged particles [20], the variation is different for extreme positive and negative vertices.

As an example, the variations in the mean number of binary collisions as the inputs are individually changed are shown with different colors in Fig. 8. The largest change in the number of binary collisions results when the value for  $\sigma_{NN}$  is varied. In a similar manner, changing the Woods-Saxon parameters creates a more (less) dense nucleus and moves the  $\langle N_{\text{coll}} \rangle$  values for all centralities up (down). The simplistic inclusion of a hard-core repulsive potential between nucleons results in the largest absolute shift from central to peripheral as it moves nucleons away from the core of the nucleus. Changes in the scaling of the multiplicity ( $\alpha$ ) and the  $z$ -vertex range fit result in very modest changes over all centralities.

We then consider 81 different scenarios with combinations of these variations and rerun the entire procedure. The mean and the root mean square (rms) of these 81 variations yield the final quoted value and systematic uncertainty. These values

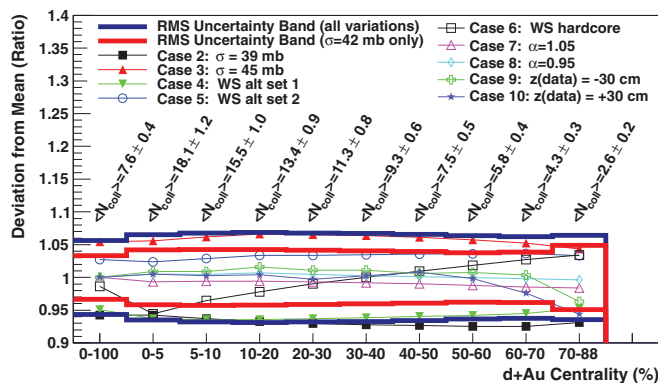


FIG. 8. (Color online) The variation relative to the mean  $N_{\text{coll}}$  value for variations in the input assumptions for the MC-Glauber extraction. The final mean and rms systematic uncertainties are shown in Table I.

are also shown in Fig. 8. The black band is the fractional rms uncertainty. The red band is the fractional rms uncertainty but without the variation in the nucleon-nucleon cross section of 42 mb. When calculating quantities, such as the nuclear modification factor  $R_{d+\text{Au}}$ , this uncertainty cancels, because the same value appears in determining the  $p + p$  cross section in the denominator. The same procedure of 81 variations was applied in calculating the neutron spectator fraction shown earlier in Fig. 6.

We have applied the identical procedure to other interesting geometric quantities and calculated the mean value and systematic uncertainty for the nine centrality selections, plus the integral over all centralities, corresponding to 0%–100% of the  $d + \text{Au}$  inelastic cross section. We quote the mean number of binary collisions  $\langle N_{\text{coll}} \rangle$ , the total number of participating nucleons  $\langle N_{\text{part}} \rangle$ , the number of participating nucleons from the Au nucleus  $\langle N_{\text{part}}[\text{Au}] \rangle$ , and the number of participating nucleons from the deuteron  $\langle N_{\text{part}}[d] \rangle$ . We also know the spatial distribution in the transverse plane of all the participants and can thus calculate different geometric quantities. The eccentricity  $\varepsilon_2$  and higher moments are calculated as

$$\varepsilon_n = \frac{\sqrt{\langle r^2 \cos(n\phi) \rangle^2 + \langle r^2 \sin(n\phi) \rangle^2}}{\langle r^2 \rangle}, \quad (6)$$

where  $n$  is the  $n$ th moment of the spatial anisotropy calculated relative to the mean position. The averages are taken over the spatial distribution of participating nucleons from the MC-Glauber calculation. We also calculate often-used quantities, including the spatial overlap area,

$$S = 4\pi \sqrt{\langle x^2 \rangle \langle y^2 \rangle - \langle xy \rangle^2}, \quad (7)$$

and

$$\bar{R} = \frac{1}{\sqrt{1/\langle x^2 \rangle + 1/\langle y^2 \rangle}}, \quad (8)$$

where these quantities are calculated in a frame rotated to align with the second-order participant plane. We have performed these geometric calculations assuming

- (i) an equal weighting for each participating nucleon at the pointlike center position (pt-like),
- (ii) an equal weighting for each participating nucleon with the spatial distribution of a Gaussian with  $\sigma = 0.4$  fm (Gauss-like),
- (iii) an equal weighting for each participating nucleon with a spatial distribution of a uniform disk with  $R = 1$  fm (disklike), and
- (iv) with a weighting determined randomly from our NBD calculations for each participating nucleon with a spatial distribution of a uniform disk with  $R = 1$  fm (disk-nbd).

Note that the systematic uncertainty quoted on each quantity includes the 81 variations in our standard calculation and does not include any uncertainty related to the assumption used in each of the given four cases above. All of these results are given in Table I.



TABLE I. Different physical quantities characterizing  $d + \text{Au}$  collisions, and the bias-factor corrections, for nine PHENIX centrality bins.

	0%–100%	0%–5%	5%–10%	10%–20%	20%–30%
Bias-factor correction	$0.889 \pm 0.003$	$0.91 \pm 0.01$	$0.940 \pm 0.007$	$0.966 \pm 0.008$	$0.99 \pm 0.01$
$\langle N_{\text{coll}} \rangle$	$7.6 \pm 0.4$	$18.1 \pm 1.2$	$15.5 \pm 1.0$	$13.4 \pm 0.9$	$11.2 \pm 0.8$
$\langle N_{\text{part}} \rangle$	$8.6 \pm 0.4$	$17.8 \pm 1.2$	$15.6 \pm 1.0$	$14.1 \pm 0.8$	$11.9 \pm 0.7$
$\langle N_{\text{part}}[\text{Au}] \rangle$	$7.0 \pm 0.4$	$15.8 \pm 1.2$	$13.6 \pm 1.0$	$12.2 \pm 0.8$	$10.0 \pm 0.7$
$\langle N_{\text{part}}[d] \rangle$	$1.62 \pm 0.01$	$1.97 \pm 0.02$	$1.96 \pm 0.02$	$1.91 \pm 0.02$	$1.88 \pm 0.03$
$\langle \epsilon_2 \rangle$ (pt-like)	$0.70 \pm 0.01$	$0.63 \pm 0.04$	$0.64 \pm 0.02$	$0.64 \pm 0.02$	$0.63 \pm 0.02$
$\sqrt{\langle \epsilon_2^2 \rangle}$ (pt-like)	$0.75 \pm 0.01$	$0.67 \pm 0.04$	$0.68 \pm 0.02$	$0.68 \pm 0.02$	$0.68 \pm 0.02$
$\langle \epsilon_2 \rangle$ (Gauss-like)	$0.453 \pm 0.007$	$0.54 \pm 0.04$	$0.54 \pm 0.02$	$0.53 \pm 0.02$	$0.51 \pm 0.02$
$\langle \epsilon_2 \rangle$ (disklike)	$0.390 \pm 0.007$	$0.49 \pm 0.04$	$0.50 \pm 0.02$	$0.48 \pm 0.02$	$0.47 \pm 0.02$
$\langle \epsilon_2 \rangle$ (disk-nbd)	$0.415 \pm 0.008$	$0.50 \pm 0.04$	$0.51 \pm 0.02$	$0.50 \pm 0.02$	$0.49 \pm 0.02$
$\langle S \rangle$ (ptlike)	$4.36 \pm 0.24$	$8.0 \pm 0.8$	$7.6 \pm 0.4$	$7.2 \pm 0.4$	$6.8 \pm 0.4$
$\langle S \rangle$ (Gauss-like)	$7.04 \pm 0.24$	$10.8 \pm 0.8$	$10.4 \pm 0.8$	$10.0 \pm 0.4$	$9.6 \pm 0.4$
$\langle S \rangle$ (disklike)	$8.56 \pm 0.24$	$12.0 \pm 0.8$	$12.0 \pm 0.8$	$11.6 \pm 0.4$	$11.2 \pm 0.4$
$\langle S \rangle$ (disk-nbd)	$6.96 \pm 0.2$	$10.8 \pm 0.8$	$10.4 \pm 0.4$	$10.0 \pm 0.4$	$9.2 \pm 0.4$
$\langle \bar{R} \rangle$ (pt-like)	$0.28 \pm 0.01$	$0.45 \pm 0.02$	$0.43 \pm 0.02$	$0.42 \pm 0.02$	$0.40 \pm 0.02$
$\langle \bar{R} \rangle$ (Gauss-like)	$0.449 \pm 0.008$	$0.55 \pm 0.02$	$0.55 \pm 0.02$	$0.53 \pm 0.01$	$0.52 \pm 0.01$
$\langle \bar{R} \rangle$ (disklike)	$0.513 \pm 0.007$	$0.61 \pm 0.02$	$0.60 \pm 0.01$	$0.59 \pm 0.01$	$0.58 \pm 0.01$
$\langle \bar{R} \rangle$ (disk-nbd)	$0.455 \pm 0.006$	$0.57 \pm 0.02$	$0.56 \pm 0.01$	$0.54 \pm 0.01$	$0.53 \pm 0.01$
$\langle \epsilon_3 \rangle$ (pt-like)	$0.311 \pm 0.004$	$0.26 \pm 0.02$	$0.28 \pm 0.02$	$0.30 \pm 0.01$	$0.31 \pm 0.01$
$\langle \epsilon_3 \rangle$ (Gauss-like)	$0.174 \pm 0.004$	$0.19 \pm 0.01$	$0.20 \pm 0.01$	$0.21 \pm 0.01$	$0.208 \pm 0.008$
	30%–40%	40%–50%	50%–60%	60%–70%	70%–88%
$\langle N_{\text{coll}} \rangle$	$1.01 \pm 0.02$	$1.03 \pm 0.02$	$1.050 \pm 0.003$	$1.07 \pm 0.06$	$1.1 \pm 0.1$
$\langle N_{\text{part}} \rangle$	$9.3 \pm 0.6$	$7.5 \pm 0.5$	$5.8 \pm 0.4$	$4.2 \pm 0.3$	$2.6 \pm 0.2$
$\langle N_{\text{part}}[\text{Au}] \rangle$	$10.5 \pm 0.6$	$8.7 \pm 0.5$	$7.1 \pm 0.4$	$5.7 \pm 0.4$	$3.9 \pm 0.3$
$\langle N_{\text{part}}[d] \rangle$	$8.7 \pm 0.6$	$7.0 \pm 0.5$	$5.5 \pm 0.4$	$4.1 \pm 0.3$	$2.6 \pm 0.3$
$\langle N_{\text{part}}[d] \rangle$	$1.82 \pm 0.04$	$1.70 \pm 0.03$	$1.62 \pm 0.03$	$1.55 \pm 0.06$	$1.30 \pm 0.03$
$\langle \epsilon_2 \rangle$ (pt-like)	$0.63 \pm 0.02$	$0.63 \pm 0.03$	$0.66 \pm 0.02$	$0.71 \pm 0.02$	$0.80 \pm 0.02$
$\sqrt{\langle \epsilon_2^2 \rangle}$ (pt-like)	$0.68 \pm 0.02$	$0.67 \pm 0.03$	$0.71 \pm 0.02$	$0.76 \pm 0.02$	$0.84 \pm 0.02$
$\langle \epsilon_2 \rangle$ (Gauss-like)	$0.49 \pm 0.02$	$0.45 \pm 0.03$	$0.44 \pm 0.02$	$0.43 \pm 0.02$	$0.39 \pm 0.01$
$\langle \epsilon_2 \rangle$ (disklike)	$0.44 \pm 0.01$	$0.40 \pm 0.03$	$0.38 \pm 0.02$	$0.36 \pm 0.02$	$0.31 \pm 0.01$
$\langle \epsilon_2 \rangle$ (disk-nbd)	$0.47 \pm 0.02$	$0.44 \pm 0.03$	$0.43 \pm 0.02$	$0.39 \pm 0.02$	$0.33 \pm 0.01$
$\langle S \rangle$ (pt-like)	$6.0 \pm 0.4$	$4.8 \pm 0.4$	$4.00 \pm 0.36$	$2.8 \pm 0.4$	$1.64 \pm 0.02$
$\langle S \rangle$ (Gauss-like)	$8.8 \pm 0.4$	$7.6 \pm 0.4$	$6.64 \pm 0.36$	$5.6 \pm 0.4$	$4.32 \pm 0.24$
$\langle S \rangle$ (disklike)	$10.0 \pm 0.4$	$9.2 \pm 0.4$	$8.12 \pm 0.36$	$7.2 \pm 0.4$	$5.72 \pm 0.24$
$\langle S \rangle$ (disk-nbd)	$8.44 \pm 0.36$	$7.2 \pm 0.4$	$6.4 \pm 0.4$	$5.48 \pm 0.36$	$4.28 \pm 0.2$
$\langle \bar{R} \rangle$ (pt-like)	$0.37 \pm 0.02$	$0.33 \pm 0.02$	$0.29 \pm 0.02$	$0.23 \pm 0.02$	$0.14 \pm 0.01$
$\langle \bar{R} \rangle$ (Gauss-like)	$0.50 \pm 0.01$	$0.47 \pm 0.01$	$0.44 \pm 0.01$	$0.41 \pm 0.01$	$0.370 \pm 0.007$
$\langle \bar{R} \rangle$ (disklike)	$0.56 \pm 0.01$	$0.53 \pm 0.01$	$0.50 \pm 0.01$	$0.48 \pm 0.01$	$0.440 \pm 0.006$
$\langle \bar{R} \rangle$ (disk-nbd)	$0.50 \pm 0.01$	$0.48 \pm 0.01$	$0.44 \pm 0.01$	$0.42 \pm 0.01$	$0.371 \pm 0.007$
$\langle \epsilon_3 \rangle$ (pt-like)	$0.35 \pm 0.01$	$0.37 \pm 0.02$	$0.38 \pm 0.02$	$0.36 \pm 0.02$	$0.29 \pm 0.02$
$\langle \epsilon_3 \rangle$ (Gauss-like)	$0.214 \pm 0.009$	$0.21 \pm 0.01$	$0.193 \pm 0.008$	$0.17 \pm 0.01$	$0.129 \pm 0.009$

In addition, many PHENIX results have been categorized in four centrality selections. For completeness, we list those in Table II.

## VII. BIAS-FACTOR CORRECTIONS

At this point we can calculate the invariant yield of a given particle for a given centrality selection and correlate that with the geometric quantification described above. In this section to take into account the autocorrelations between the presence of a particular particle and the backward-rapidity multiplicity, we look for additional corrections to the previous Glauber + NBD model. This correction can then be multiplied by the invariant yield, of  $\pi^0$  at midrapidity (for example), to give

an accurate match to the quantities derived in the previous section.

Here we discuss a specific autocorrelation bias in  $p + p$  collisions at  $\sqrt{s_{NN}} = 200$  GeV. The PHENIX experiment has measured that inelastic  $p + p$  reactions, corresponding to the 42-mb cross section, fire the BBC trigger  $52\% \pm 4\%$  of the time. In contrast, a  $p + p$  collision with a midrapidity-produced pion, charged hadron, or  $J/\psi$  fires the trigger  $75\% \pm 3\%$  of the time. The simple reason is that the multiplicity in these events is higher. The  $p + p$  42-mb inelastic cross section can be thought of as having three distinct contributions [18]:

- (i) nondiffractive collisions with 28 mb,
- (ii) single-diffractive collisions with 10 mb, and
- (iii) double-diffractive collisions with 4 mb.

TABLE II. Different physical quantities characterizing  $d + \text{Au}$  collisions and the bias-factor corrections for four PHENIX centrality bins.

	0%–20%	20%–40%	40%–60%	60%–88%
Bias-factor correction	$0.94 \pm 0.01$	$1.00 \pm 0.01$	$1.03 \pm 0.02$	$1.03 \pm 0.06$
$\langle N_{\text{coll}} \rangle$	$15.1 \pm 1.0$	$10.2 \pm 0.7$	$6.6 \pm 0.4$	$3.2 \pm 0.2$
$\langle N_{\text{part}} \rangle$	$15.2 \pm 0.6$	$11.1 \pm 0.6$	$7.8 \pm 0.4$	$4.3 \pm 0.2$
$\langle N_{\text{part}}[\text{Au}] \rangle$	$13.3 \pm 0.8$	$9.3 \pm 0.6$	$6.2 \pm 0.4$	$3.0 \pm 0.2$
$\langle N_{\text{part}}[d] \rangle$	$1.95 \pm 0.01$	$1.84 \pm 0.01$	$1.65 \pm 0.02$	$1.36 \pm 0.02$

A PYTHIA 6.2 MC simulation of  $p + p$  collisions coupled with a GEANT modeling of the BBC yields triggers efficiencies of  $72\% \pm 1\%$ ,  $7\% \pm 1\%$  and  $32\% \pm 1\%$  for each process respectively. Single- and double-diffractive collisions produce particles dominantly near the beam rapidity and thus have a small probability for particle production in the BBC acceptance of  $3.0 < |\eta| < 3.9$  and an even smaller probability at midrapidity. The BBC trigger is therefore biased to the nondiffractive collisions, which have larger particle production at midrapidity. Thus, in the  $p + p$  case when one measures the number of midrapidity particles per event, one is including 75% of the particles in the numerator and 52% of the overall events in the denominator. A similar effect will be present in  $d + \text{Au}$  peripheral collisions, resulting in a measured invariant yield that is also biased to a larger value.

There is a competing bias effect in  $d + \text{Au}$ . Because the multiplicity is higher in  $p + p$  events with a midrapidity particle, there will be a bias in  $d + \text{Au}$  towards higher charge in the Au-going BBC and thus towards larger centrality. For peripheral events this will lead to an undercounting of midrapidity particles, because they will migrate to more midcentral categorization. This will result in a bias in peripheral  $d + \text{Au}$  events to a smaller measured invariant yield (i.e., one that needs to be corrected up). In central  $d + \text{Au}$  events, one will have the opposite effect (i.e., migration of additional midrapidity particles into this category) and the yield in such events will need to be corrected down.

To calculate these bias-factor corrections, we assume that a binary collision that produces a midrapidity particle in a given  $d + \text{Au}$  event has a larger NBD contribution to the BBC Au-going direction charge. From  $p + p$  MB and clock-trigger data, we determine this additional charge to be consistent with scaling both the NBD parameters  $\mu$  and  $\kappa$  up by a multiplicative factor of  $1.55 \pm 0.23$ . One can also think of this in terms of an event with a hard scattering having a larger overall multiplicity in the underlying event by this factor. For this simple estimate, we assume the following:

- (i) in an event with  $N$  binary collisions, the one with a hard scattering is biased to higher multiplicity and higher trigger efficiency;
- (ii) the increase in the BBC charge measured in  $p + p$  is applicable for this one binary collision in a  $d + \text{Au}$  event; and
- (iii) the other  $N - 1$  binary collisions are unaffected.

We then calculate the invariant yield with and without this bias in the Glauber + NBD framework and determine the bias-factor corrections.

These bias-factor corrections can then be applied to physical quantities, such as  $R_{d+\text{Au}}$  using

$$R_{d+\text{Au}} = \frac{c dN^{d+\text{Au}}/dy}{\langle N_{\text{coll}} \rangle dN^{pp}/dy}, \quad (9)$$

where  $c$  is the bias-factor correction. The 0%–100% centrality integrated correction is a special case. Because the PHENIX MB trigger covers only 88% of the  $d + \text{Au}$  inelastic cross section, the correction is used as

$$R_{d+\text{Au}}(0\%–100\%) = \frac{c dN^{d+\text{Au}}/dy(0\%–88\%)}{\langle N_{\text{coll}} \rangle dN^{pp}/dy}. \quad (10)$$

We again employ the 81 variations in the Glauber + NBD parameters and determine the best bias-factor corrections and their systematic uncertainties, as shown in Fig. 9.

For the more commonly used PHENIX four centrality bins, the correction factors are given in Table II. For the 0%–100% category, the correction factor is  $0.89 \pm 0.01$ . In the most central  $d + \text{Au}$  category, there is no trigger efficiency bias effect (i.e., such events always fire the trigger) and the multiplicity bias leads to an overcounting of particles in this category (hence, a downward correction factor). In the most peripheral  $d + \text{Au}$  category, there is a balancing of the two effects. Calculated separately, the trigger bias correction is 0.89 and the centrality bias correction is 1.16, yielding an overall correction of 1.03 and a larger systematic uncertainty than for the other centralities.

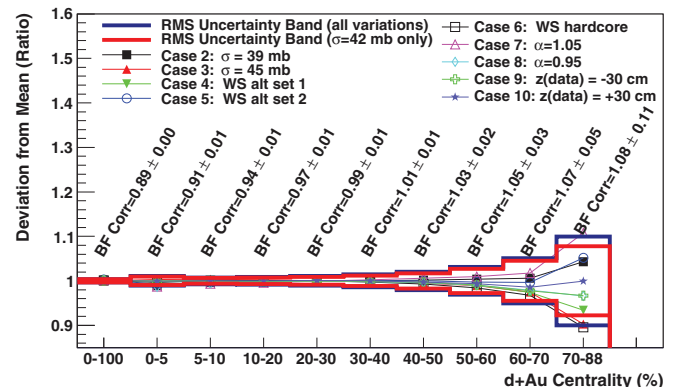


FIG. 9. (Color online) Multiplicative bias-factor corrections and their systematic uncertainties as a function of collision centrality.

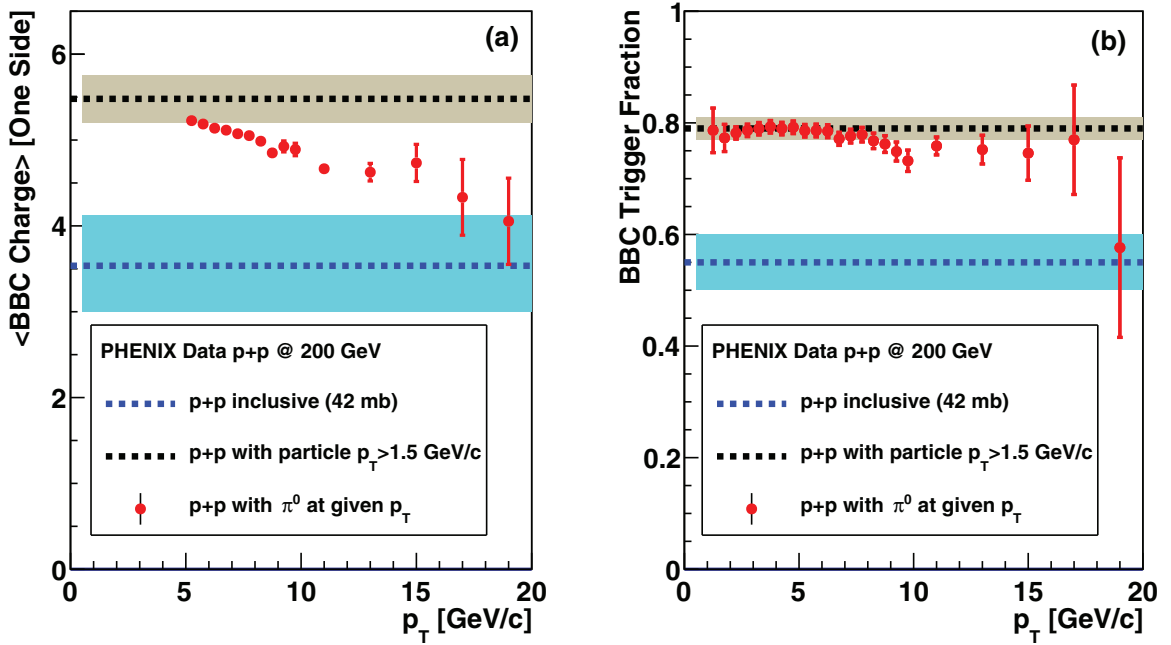


FIG. 10. (Color online) (a) Shown as a dashed blue line is the mean BBC charge on one side for inclusive  $p + p$  interactions, corresponding to  $\sigma_{\text{inelastic}} = 42$  mb. The systematic uncertainty is shown as a band. Shown as a dashed black line is the mean BBC charge on one side when a midrapidity charged hadron with  $p_T > 1.5$  GeV/c is in coincidence. The red points are the mean BBC charge when there is a  $\pi^0$  measured with a  $p_T$  as indicated by the  $x$  axis. (b) The same quantities as before, but for the fraction of interactions that fire the BBC coincidence trigger. The bias-factor corrections were originally calculated in 2003 with inputs that the BBC trigger fires on  $52\% \pm 4\%$  of inclusive inelastic  $p + p$  interactions corresponding to 42 mb and  $75\% \pm 3\%$  of inelastic  $p + p$  interactions with a charged hadron of  $p_T > 1.5$  GeV/c. For the 2008 analysis, the BBC thresholds were adjusted and the most accurate determination indicates that the BBC trigger fires on  $55\% \pm 5\%$  of inclusive inelastic  $p + p$  interactions corresponding to 42 mb and  $79\% \pm 2\%$  of inelastic  $p + p$  interactions with a charged hadron of  $p_T > 1.5$  GeV/c, as shown above. The  $\pi^0$  points shown above are from data taken with these thresholds adjusted. These differences result in negligible changes to the bias-factor correction values used.

#### A. Transverse-momentum dependence of bias-factor corrections

The above calculation of the bias-factor corrections was based essentially on two input values:

- (i) the 75% probability of the BBC-MB trigger to fire when a particle is detected at midrapidity in  $p + p$  collisions and
- (ii) the increase in BBC multiplicity by 1.55 when a particle is detected at midrapidity in conjunction with a BBC-MB trigger firing.

The previous discussion regarding the bias introduced by the presence of a particular particle may depend on the type of particle and its transverse momentum and rapidity. The fraction of  $p + p$  events with a specific particle present that fire the BBC trigger is 75%, as measured experimentally with midrapidity  $\pi^0$ , midrapidity charged hadrons, and forward rapidity  $J/\psi$ . Detailed PYTHIA studies indicate that, within our cited uncertainties, all particles produced at midrapidity down to  $p_T \sim 0.2$  GeV/c and also quarkonia and charm decay muons over a broader rapidity range  $-2.2 < y < 2.2$  give a similar bias, because the origin is a common bias towards nondiffraction collisions. However, these studies were limited to transverse momentum values less than 9 GeV/c [21].

High-statistics results for neutral pions indicate a change in these values at much higher  $p_T$ , as shown in Fig. 10. These

values are determined from  $p + p$  data taken in 2006 utilizing a photon trigger with and without the coincidence on the BBC-MB trigger. There is always an increase in the mean multiplicity in events with a neutral pion compared to MB  $p + p$  events; however, that value decreases by approximately 20% for particles near  $p_T \approx 15\text{--}20$  GeV/c compared with lower  $p_T$ , as shown in the left panel of Fig. 10. The trigger efficiency shows a very slight decrease for the highest  $p_T$  measured, as shown in the right panel of Fig. 10.

As a simple estimate of the change in bias-factor corrections for these high- $p_T$  particle invariant yields, we can repeat the procedure from the previous section, replacing the values of 75% with 70% and the increased multiplicity factor of 1.55 with 1.25, as overestimates for neutral pions with  $p_T \approx 15$  GeV/c. Changing these factors results in a bias factor correction for central (i.e., 0%–20%)  $d + \text{Au}$  events of 0.97 (compared with the previous value of  $0.94 \pm 0.01$ ). This result makes sense in that there is slightly less centrality shifting bias, because the increased multiplicity is reduced. Also, because there are a large number of binary collisions (of order 15), the bias from just one binary collision leaving the other  $N - 1$  unmodified, yields only a small change. In considering the peripheral category (i.e., 60%–88% centrality bin), it is interesting to look first at the two bias contributions separately. The trigger part of the bias-factor correction is now 1.07 (compared with the previous value of 1.16) and

the centrality shifting bias correction is now 0.90 (compared with the previous value of 0.89). The overall combined bias correction becomes 0.96 (compared with the previous value of  $1.03 \pm 0.06$ ). These results are slightly outside of the rms systematic uncertainties quoted on these bias-factor corrections.

One might hypothesize about the origin of this  $p_T$  dependence and posit that it relates to using up more energy at midrapidity, thus yielding a decrease in particles at backward rapidity, or a change in the rapidity distribution itself. It is also unclear that the other  $N - 1$  binary collisions are uncorrelated with the process in the one binary collision, producing the midrapidity high- $p_T$  particle. This motivates a full HIJING MC study where we know the true invariant yields and can determine (albeit in a model-dependent way) the actual bias-factor corrections owing to autocorrelations. The goal of this HIJING study is not to correct the experimental data in a model-dependent way, but rather to gain some insight into the centrality and bias-correction method.

### VIII. HIJING STUDY

The HIJING MC generator [22] has been established as a useful tool for the study of hard-scattering processes and the underlying event in  $p + p$  and  $A + A$  collisions over a wide range of collision energies.

#### A. Centrality bias-factor corrections for $d + Au$ at $\sqrt{s_{NN}} = 200$ GeV

Prior to carrying out the bias-factor study, we need to define a set of selection cuts to make a close comparison with the experimental results. First, we model the PHENIX BBC response and trigger selection by examining the number of particles within the same pseudorapidity acceptance  $3.0 < |\eta| < 3.9$ . A full GEANT simulation of the BBC response on HIJING events is computationally prohibitive, because we examine tens of billions of HIJING events to study the  $p_T$  dependence of the bias-factor corrections.

The PHENIX MB trigger is modeled requiring at least one particle in each of the BBC regions. We find that for  $p + p$  collisions at  $\sqrt{s_{NN}} = 200$  GeV, the percentage of HIJING events satisfying the PHENIX MB trigger requirement is 48% compared with the experimentally measured value of  $52\% \pm 4\%$ . For HIJING-simulated  $d + Au$  collisions, the trigger requirement is met by 83% of events compared with the previously cited value of  $88\% \pm 4\%$ . For  $d + Au$  collisions, we divide the simulated HIJING BBC multiplicity distribution into centrality selections following the same procedure used on experimental data. In the HIJING case, we can examine the centrality selected events for the true number of binary collisions. The mean and rms  $\langle N_{\text{coll}} \rangle$  values from HIJING are given in Table III. These values are in reasonable agreement with those given earlier as determined from experimental data and the Glauber + NBD fit. The slight difference in the 60%–88% category is potentially attributable to the differences in trigger efficiencies previously noted. The rms values are somewhat smaller from HIJING, which may be attributable to the lack of a complete simulation of the BBC detector response.

TABLE III. Mean  $N_{\text{coll}}$  and rms values for each centrality.

Centrality (%)	HIJING		Glauber + NBD	
	$\langle N_{\text{coll}} \rangle$	rms	$\langle N_{\text{coll}} \rangle$	rms
0–20	15.0	4.1	$15.1 \pm 1.0$	4.9
20–40	10.1	3.5	$10.2 \pm 0.7$	4.2
40–60	6.3	3.0	$6.6 \pm 0.4$	3.6
60–88	2.8	2.0	$3.2 \pm 0.2$	2.3

In HIJING the requirement of a midrapidity (i.e.,  $|\eta| < 0.35$ ) particle with  $p_T > 1$  GeV/ $c$  in  $p + p$  collisions increases the BBC multiplicity by a factor of 1.62 (compared with 1.55 as measured with experimental data) and increases the probability to satisfy the BBC-MB trigger requirement to 62% (compared with  $75\% \pm 3\%$  as measured with experimental data). The trigger difference may be attributable to the specific handling of single and double diffractive events within HIJING. With these differences kept in mind, we proceed to calculate the bias-factor corrections within HIJING.

First, we separate HIJING  $d + Au$  events into four centrality selections (0%–20%, 20%–40%, 40%–60%, 60%–88%) by the simulated BBC multiplicity in the Au-going direction. Using the generator-level truth information for these events, we determine the distribution of  $N_{\text{coll}}$  for each centrality. We then calculate the yield of particles at midrapidity per event within each centrality selection, as is done with the experimental data. We refer to this as the HIJING “measured” yield. Separately, using the truth information on the number of binary collisions, we sort all HIJING events into the four centrality bins to exactly match the  $N_{\text{coll}}$  distributions determined from the “measured” selection. We calculate the yield of particles at midrapidity per event using this truth information, not the multiplicity of the event. We refer to this yield as the HIJING “truth” yield. The only difference between the HIJING “measured” and “truth” yields results from the autocorrelation between the midrapidity particle production and the multiplicity measured in the Au-going direction. Therefore, the ratio of “truth” to “measured” is exactly the bias-correction factor. The HIJING bias-factor corrections for midrapidity particles with  $p_T > 1$  GeV/ $c$  are shown in Table IV. The uncertainties shown are statistical only. For comparison, we again include the experimentally determined bias-factor corrections from the Glauber + NBD procedure. The correction factors are in agreement within uncertainties with those derived from Glauber + NBD.

With a large statistical sample of HIJING  $p + p$  and  $d + Au$  events, we can also examine the  $p_T$  dependence of these bias-factor corrections. Figure 11 shows the HIJING  $p + p$  mean multiplicity in the BBC for events which contain a particle at midrapidity with a given  $p_T$ , as a ratio relative to all inelastic  $p + p$  collisions. The results indicate a decrease of the multiplicity for higher  $p_T$  particles at midrapidity, in qualitative agreement with that shown earlier in  $p + p$  experimental data. Following the same procedure outlined above for determining the HIJING “measured” and “truth” yields, as well as the same centrality definitions, we calculate the bias-factor corrections as a function of the  $p_T$  of the midrapidity particle. The results are shown in Fig. 12. These values are integrated

TABLE IV. Mean bias-factor corrections as a function of  $p_T$  for each centrality as calculated with HIJING and comparison with reference Glauber + NBD values.

Centrality (%)	Glauber + NBD	HIJING $1 \leq p_T < 5$	HIJING $5 \leq p_T < 10$	HIJING $10 \leq p_T < 15$	HIJING $15 \leq p_T < 20$
0–20	$0.94 \pm 0.01$	$0.951 \pm 0.001$	$0.962 \pm 0.001$	$1.000 \pm 0.005$	$1.038 \pm 0.020$
20–40	$1.00 \pm 0.01$	$0.996 \pm 0.001$	$1.008 \pm 0.001$	$1.010 \pm 0.006$	$0.996 \pm 0.021$
40–60	$1.03 \pm 0.02$	$1.010 \pm 0.001$	$1.022 \pm 0.001$	$1.019 \pm 0.007$	$1.005 \pm 0.025$
60–88	$1.03 \pm 0.06$	$1.030 \pm 0.001$	$1.026 \pm 0.001$	$0.999 \pm 0.008$	$0.991 \pm 0.030$

over wider  $p_T$  selections and are tabulated in Table IV. These bias-correction factors vary by less than 5% (10%) up to  $p_T = 10(20)$  GeV/c in all four centrality categories. There is a slight increase in the bias-factor correction in central events and a slight decrease in the bias-factor correction in peripheral events, both in agreement with our simple estimate from the experimental  $p + p$  data values. Though these results are HIJING model specific, the agreement of the bias correction factors and their very modest  $p_T$  dependence are noteworthy. There are other models that make different assumptions regarding the relationship between binary collisions and geometry and therefore may give different results; for example, see Ref. [23].

### B. Centrality bias-factor corrections for $p + \text{Pb}$ at $\sqrt{s_{NN}} = 5.02$ TeV

Given the recent  $p + \text{Pb}$  collision data at  $\sqrt{s_{NN}} = 5.02$  TeV at the LHC, it is interesting to apply the identical procedure using HIJING at this higher energy. In this case, we use the particle multiplicity within  $-4.9 < \eta < -3.1$  as the simulated detector acceptance in the Pb-going direction for determining centrality quantiles. From HIJING  $p + p$  events at 5.02 TeV, we

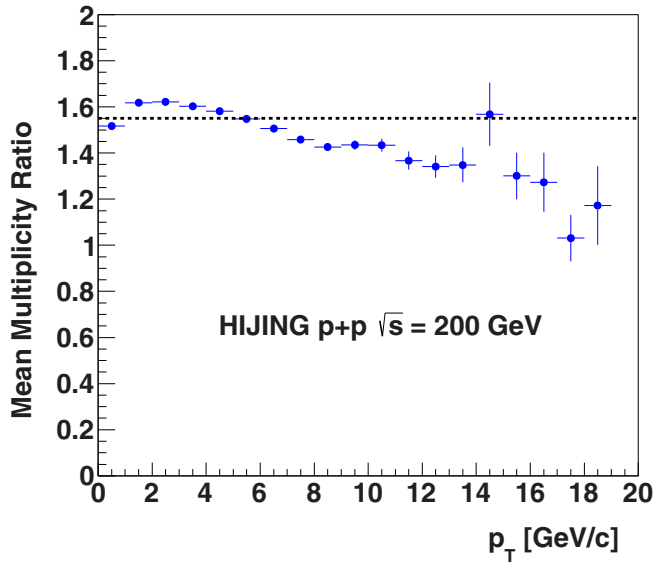


FIG. 11. (Color online) The ratio of the mean multiplicity at  $-3.9 < \eta < -3.0$  in triggered events with a particle with a given  $p_T$  produced at midrapidity to all inelastic  $p + p$  collisions from HIJING at  $\sqrt{s_{NN}} = 200$  GeV. The dashed line at 1.55 represents the mean reference value measured in the data.

find that the presence of a midrapidity particle increases the Pb-going multiplicity by a factor of approximately 1.67 and with a significant dependence on the  $p_T$  of the midrapidity particle, as shown in Fig. 13.

The requirement of one particle in the forward and backward acceptance for these HIJING  $p + \text{Pb}$  events has a nearly 100% efficiency. Thus, we divide the  $p + \text{Pb}$  events into five centrality categories 0%–20%, 20%–40%, 40%–60%, 60%–80%, and 80%–100%. The bias-factor corrections thus are expected to only include the centrality migration effect and no effect from the trigger autocorrelation bias. The resulting bias-factor corrections as a function of  $p_T$  are shown in Fig. 14. The HIJING calculations indicate very large correction factors in the most peripheral selection and with a substantial  $p_T$  dependence, particularly over the range  $1 < p_T < 10$  GeV/c.

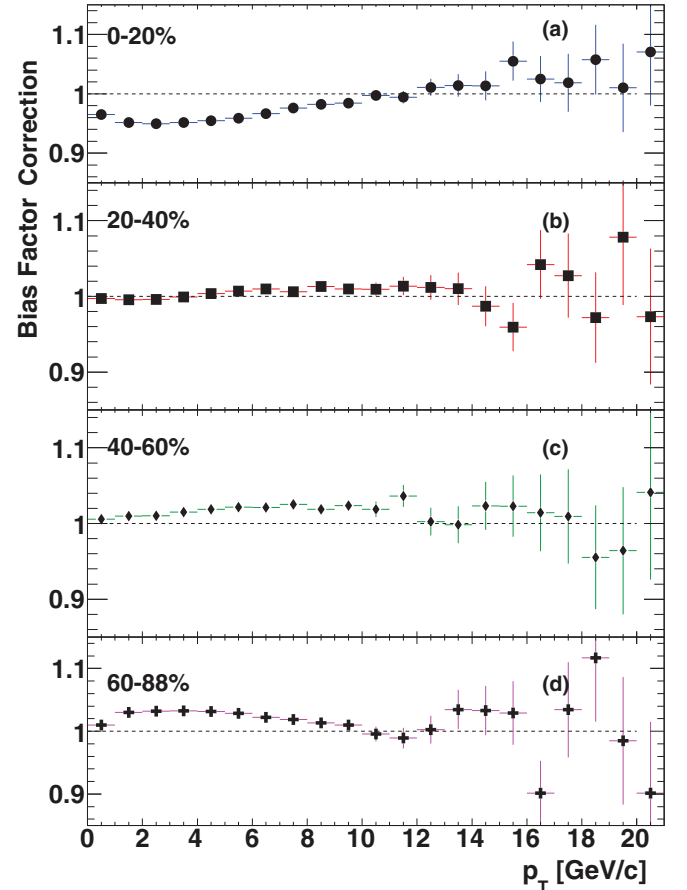


FIG. 12. (Color online) Bias-factor corrections as a function of  $p_T$  for HIJING  $d + \text{Au}$  events at  $\sqrt{s_{NN}} = 200$  GeV.

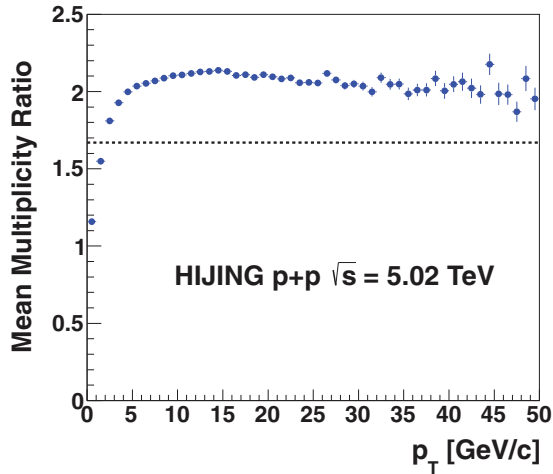


FIG. 13. (Color online) The ratio of the mean multiplicity at  $-4.9 < \eta < -3.1$  in triggered events with a particle with a given  $p_T$  produced at midrapidity to all inelastic  $p + p$  collisions from HIJING at  $\sqrt{s_{NN}} = 5.02$  TeV. The dashed line corresponds to the inclusive mean multiplicity ratio.

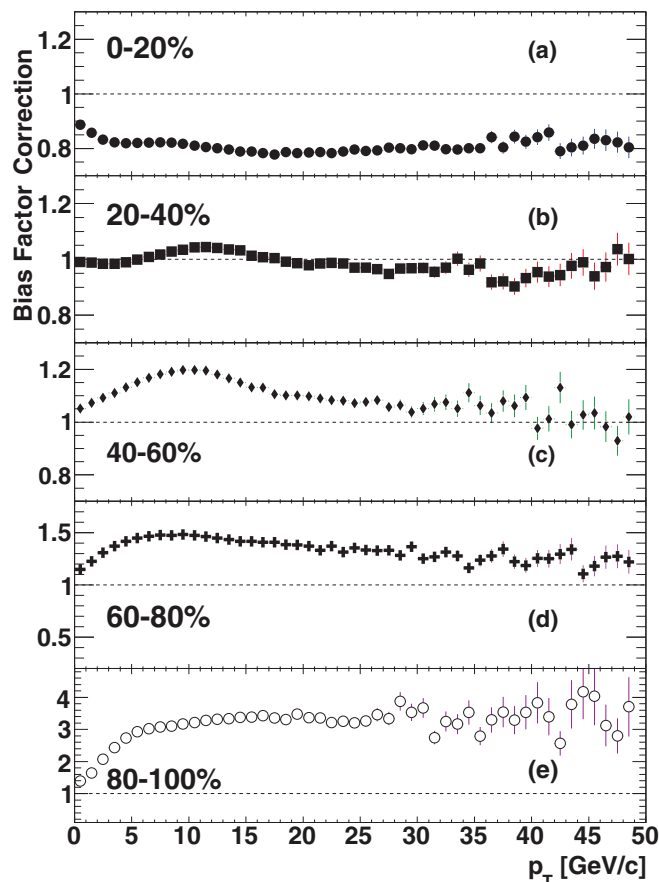


FIG. 14. (Color online) Bias-factor corrections as a function of  $p_T$  for HIJING  $p + Pb$  events at  $\sqrt{s_{NN}} = 5.02$  TeV. Correction factors for each centrality are plotted with different vertical scales to better illustrate the magnitude of the effect.

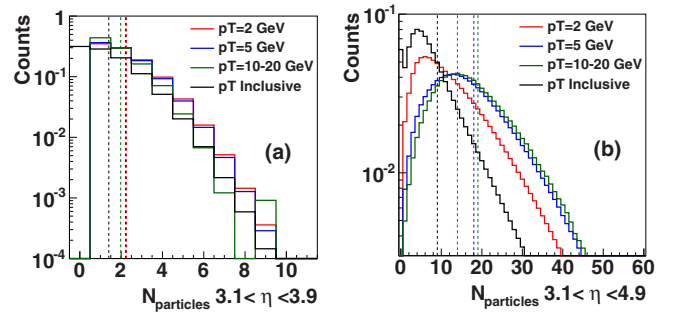


FIG. 15. (Color online) Multiplicity distribution at  $-4.9 < \eta < -3.0$  for HIJING  $p + p$  events for (a)  $\sqrt{s} = 200$  GeV at RHIC and (b)  $\sqrt{s} = 5.02$  TeV at the LHC. Dashed lines indicate the mean values of each distribution.

This means that the HIJING “measured” yield at  $p_T = 5$  GeV/c would be more than a factor of two lower than the truth value.

### C. HIJING discussion

The bias factors extracted from HIJING in  $p + Pb$  collisions at  $\sqrt{s_{NN}} = 5.02$  TeV are an order of magnitude larger than those in  $d + Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV. When comparing the  $p + Pb$  and  $d + Au$  results, it should be noted that in the most peripheral class, the  $d + Au$  case only extends down to 88% owing to the trigger efficiency and part of the centrality migration bias is canceled by the trigger bias. Figure 15 compares the HIJING  $p + p$  multiplicity distribution in the backward acceptance for different selections on the  $p_T$  of a midrapidity particle. One observes only a modest dependence on the  $p_T$  of the midrapidity particle for RHIC energies, and a large dependence for LHC energies. This autocorrelation directly translates into the large calculated bias-factor corrections.

The HIJING results follow the same trends previously observed in  $p + \bar{p}$  collisions at the Tevatron from  $\sqrt{s} = 300$  GeV to 1.96 TeV [24–26] and in  $p + p$  collisions at the LHC from  $\sqrt{s} = 900$  GeV to 7.0 TeV [27–29], as detailed in Ref. [30]. At the highest LHC energies, the increased multiplicity of the underlying event as the particle  $p_T$  value increases from 1 to 10 GeV/c is well described in terms of multiparton interactions (MPIs) [30]. At the lowest Tevatron energy of 300 GeV, the underlying event is relatively unchanged for  $p_T$  values from 2 GeV/c and above owing to the much lower hard-scattering cross section and thus the smaller influence from multiparton interactions.

The effect of MPI at RHIC and LHC energies can be investigated within HIJING. According to HIJING, the mean number of hard scatterings per nucleon-nucleon binary collision is 0.24 in  $d + Au$  at 200 GeV, but 1.36 in  $p + Pb$  at 5.02 TeV. This highlights the strong  $\sqrt{s}$  dependence of the effect.

The HIJING calculations also include another effect that will result in deviations from binary scaling, but is not an autocorrelation effect. Figure 16 shows the number of hard scatterings per nucleon-nucleon collision as a function of  $N_{coll}$ . Peripheral  $p(d) + A$  events have individual binary collisions geometrically biased towards larger impact parameters, i.e.,

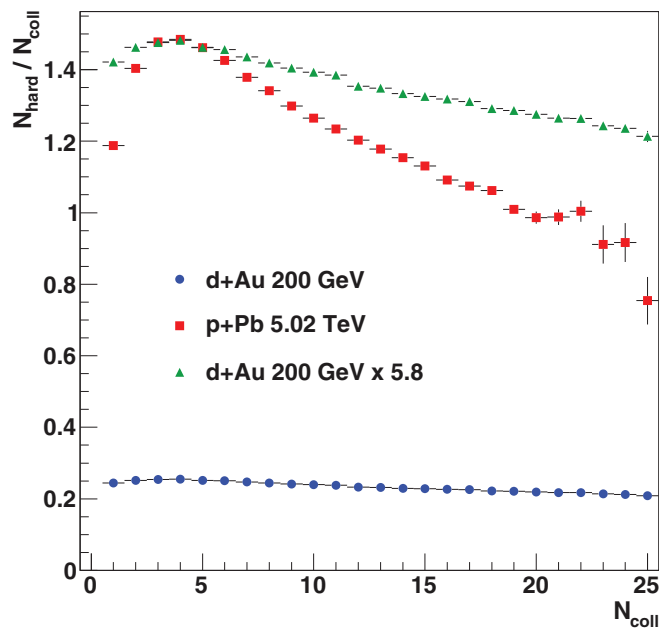


FIG. 16. (Color online) A comparison of the MPI effect in HIJING for  $d + Au$  and  $p + Pb$  collisions at 200 GeV and 5.02 TeV, respectively. Plotted is the number of hard scatterings ( $N_{\text{hard}}$ ) divided by the number of nucleon-nucleon collisions ( $N_{\text{coll}}$ ) as a function of  $N_{\text{coll}}$ .

with less overlap between the nucleons, within the constraint  $b < \sqrt{\sigma_{NN}}/\pi$ . HIJING has a geometric overlap dependence to the hard-scattering probability. This effect is significantly larger in  $p + Pb$  collisions at  $\sqrt{s_{NN}} = 5.02$  TeV [31]. Additionally, the decrease for more central events may be an energy-conservation effect, which is also smaller for  $d + Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV, because the binary scatters are split between two projectile nucleons. It is unclear that one should attempt to correct for this in constructing  $R_{p(d)+A}$ . In either case the effects are small for  $d + Au$  at  $\sqrt{s_{NN}} = 200$  GeV.

The results of the HIJING study shows that the bias effects are small with little  $p_T$  dependence in  $d + Au$  at  $\sqrt{s_{NN}} = 200$  GeV, and that these bias factors are primarily attributable to the trigger bias toward nondiffractive collisions. However, in  $p + Pb$  collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, the bias factors are large and dominated by the effects of multiparton interactions.

## IX. SUMMARY

We have presented a detailed description of centrality determination in  $p(d) + A$  collisions. This method has been utilized by PHENIX in the analysis of  $d + Au$  collision data recorded in 2008. Using a Glauber-MC calculation coupled with a simulation of the charge deposited

in the Au-going BBC we are able to determine geometric quantities associated with different centrality selections. Using this model, we also calculate the fraction of events in each centrality class with a spectator neutron and find good agreement with the measured data. Utilizing the same formalism we also describe a calculation of the bias-factor corrections associated with this centrality determination. Using HIJING, we present a study of the  $p_T$  dependence of these bias-factor corrections. We find that they exhibit a modest  $p_T$  dependence at  $\sqrt{s_{NN}} = 200$  GeV, in agreement with those derived with the Glauber model and used in earlier PHENIX publications. Repeating the HIJING study for  $p + Pb$  collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, we find significantly larger centrality bias factors, exhibiting a strong  $p_T$  dependence that may result in part from the much higher contribution from multiparton interactions. Additional experimental checks are needed, at both energies, of  $p + A$  collisions with different  $A$  to further study these effects.

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