Centrality determination using the Glauber model in Xe–Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV

ALICE Collaboration

Abstract

This document describes the methods used by the ALICE Collaboration for determining the centrality of Xe–Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV at the LHC within the Glauber model. The half-density radius $R$ and the diffusivity $a$ describing the Xe-129 nucleus with a 2-parameter Fermi distribution have been derived from a recent electron scattering measurement for the Xe-132 nucleus. The deformation parameter $\beta$ has been derived by an interpolation between measured deformation parameters for the even-$A$ Xe isotopes. The inelastic nucleon-nucleon cross-section at $\sqrt{s_{\text{NN}}} = 5.44$ TeV has been estimated by interpolation of pp data at different center-of-mass energies. The particle multiplicity per nucleon-nucleon collision has been parameterized by a negative binomial distribution (NBD) and a number of independently emitting sources (ancestors) given by a linear combination of $N_{\text{part}}$ and $N_{\text{coll}}$. The NBD parameters $\mu$ and $k$ and the ancestor parameter $f$ are then obtained by a fit to the amplitude distribution measured in the V0, which is a detector comprised of two scintillator arrays. Finally, the mean number of participants and collisions and the mean nuclear thickness function are derived for sharp centrality cuts in the simulated V0 amplitude distribution. These values are compared with those obtained by defining centrality classes with sharp cuts in impact parameter. In general the numbers of participants are very similar between both approaches for 0-80% centrality, while they differ considerably for the most peripheral 80-100% class. Finally, to put our results in a wider context, Glauber calculations based on alternative particle production models are used and the results are compared with the pseudorapidity density of charged particles per participant pair measured by ALICE in Xe–Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV.

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*See Appendix B for the list of collaboration members
1 Introduction

The Large Hadron Collider provided for the first time Xe–Xe collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.44$ TeV during a pilot run in October 2017. The size of this collision system bridges the gap between pp, p–Pb on one hand and Pb–Pb on the other hand, with $A = 129$ for xenon and $A = 208$ for lead.

In ALICE, events are selected according to the signal amplitude in a pair of scintillator arrays called V0 [1]. Centrality-related properties such as the average number of participant nucleons $N_{\text{part}}$ and the average number of nucleon-nucleon collisions $N_{\text{coll}}$ are calculated using a Glauber Monte Carlo model [2]. The same model allows for the calculation of the average nuclear overlap function $T_{AA}$ which is defined as the ratio between the average $N_{\text{coll}}$ and the inelastic nucleon-nucleon cross-section, and is needed in order to obtain e.g. the nuclear modification factors for the yields of (un)identified particles and jets.

In the following we report on the centrality determination in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using the ALICE standard method. Section 2 describes the Glauber Monte Carlo method and the input data used for Xe–Xe. Section 3 describes how the deformation of the Xe-129 nucleus is taken into account. Section 4 describes the Negative Binomial Distribution (NBD) - Glauber fit to the measured V0 amplitude distribution and presents the main results, i.e. $N_{\text{part}}$, $N_{\text{coll}}$ and $T_{AA}$ for Xe–Xe in several centrality classes. Section 5 explores different particle production models such as the core-corona approach and single quark scattering. A summary is given in Section 6. Tables with results for $N_{\text{part}}$, $N_{\text{coll}}$ and $T_{AA}$ are given in Appendix A.

2 The Glauber Monte Carlo

The Glauber Monte Carlo model is used to describe nuclear collisions as a superposition of binary nucleon-nucleon interactions and determine geometrical quantities ($N_{\text{part}}$, $N_{\text{coll}}$) for event samples classified from experimentally measured observables. The standard method used by the ALICE Collaboration is described in Ref. [2] and relies on the implementation given in Refs. [3, 4].

The first step in the Glauber Monte Carlo is to prepare a model of the two nuclei by defining the position of the nucleons in each nucleus stochastically. The nucleon position in the colliding nuclei is determined by the nuclear density function, typically modeled by the functional form (modified Woods-Saxon or 2-parameter Fermi distribution):

$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}$$

The half-density parameter $R$ and the diffuseness parameter $a$ have been derived from a recent electron scattering measurement [5] for the Xe-132 nucleus, rescaled by $(129/132)^{1/3}$, leading to $R = 5.36 \pm 0.1$ fm and $a = 0.59 \pm 0.07$ fm. The modifications needed to describe the deformation of the Xe-129 nucleus will be described in detail in the next section.

In the Monte Carlo procedure the radial coordinate of a nucleon is randomly drawn from the distribution $4\pi r^2 \rho(r)$ and $\rho_0$ is determined by the overall normalization condition $\int \rho(r) d^3r = A$. We require a hard-sphere exclusion distance of $d_{\text{min}} = 0.4$ fm between the centers of the nucleons, i.e. no two nucleons inside the nucleus are less than $d_{\text{min}}$ apart. The hard-sphere exclusion distance, characteristic of the range of the repulsive nucleon-nucleon force, is not known experimentally and thus is varied by 100% ($d_{\text{min}} = 0.4 \pm 0.4$ fm) for the evaluation of systematic uncertainties.

The second step is to simulate a nuclear collision. The impact parameter $b$ is randomly selected from the geometrical probability distribution $dP/db \sim b$ up to a maximum $b_{\text{max}} > 2R$. The maximum value of the impact parameter $b_{\text{max}}$ is chosen large enough to simulate collisions until the interaction probability
Centrality determination using the Glauber model in Xe–Xe at $\sqrt{s_{\text{NN}}} = 5.44$ TeV

<table>
<thead>
<tr>
<th>N</th>
<th>A</th>
<th>$B(E2)$ $\uparrow (b^2)$</th>
<th>$\beta$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>124</td>
<td>0.96 ± 0.06</td>
<td>0.212 ± 0.007</td>
<td>[8]</td>
</tr>
<tr>
<td>72</td>
<td>126</td>
<td>0.77 ± 0.025</td>
<td>0.188 ± 0.003</td>
<td>[8, 9]</td>
</tr>
<tr>
<td>74</td>
<td>128</td>
<td>0.817 ± 0.016</td>
<td>0.192 ± 0.002</td>
<td>[10] recomputed</td>
</tr>
<tr>
<td>76</td>
<td>130</td>
<td>0.65 ± 0.05</td>
<td>0.169 ± 0.007</td>
<td>[8]</td>
</tr>
<tr>
<td>78</td>
<td>132</td>
<td>0.46 ± 0.03</td>
<td>0.141 ± 0.005</td>
<td>[8, 11]</td>
</tr>
<tr>
<td>80</td>
<td>134</td>
<td>0.312 ± 0.021</td>
<td>0.115 ± 0.004</td>
<td>[12]</td>
</tr>
<tr>
<td>82</td>
<td>136</td>
<td>0.201 ± 0.008</td>
<td>0.0914 ± 0.0018</td>
<td>[13]</td>
</tr>
</tbody>
</table>

Table 1: Values of the nuclear transition probability $B(E2) \uparrow$ and of the deformation parameter $\beta$ for even-$A$ isotopes of Xe.

becomes zero. This is particularly important for the calculation of the total cross section. The nucleus-nucleus collision is treated as a sequence of independent binary nucleon-nucleon collisions, i.e. the same cross section is used for all successive collisions. Two nucleons from different nuclei are assumed to collide if the relative transverse distance between centers is less than the distance corresponding to the inelastic nucleon-nucleon cross section $d < \sqrt{\sigma_{\text{NN}}^{\text{inel}}}/\pi$.

The number of collisions $N_{\text{coll}}$ and the number of participants $N_{\text{part}}$ are determined by counting, respectively, the binary nucleon collisions and the nucleons that experience at least one collision. The geometric nuclear overlap function $T_{\text{XeXe}}$ is then calculated as $T_{\text{XeXe}} = N_{\text{coll}}/\sigma_{\text{NN}}^{\text{inel}}$, and represents the effective nucleon luminosity in the collision process.

For nuclear collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV, we use $\sigma_{\text{NN}}^{\text{inel}} = 68.4 \pm 0.5$ mb [6], estimated by interpolation of pp data at different center-of-mass energies and from cosmic rays, and subtracting the elastic scattering cross section from the total cross section.

The total Xe–Xe cross section is calculated as $\sigma_{\text{XeXe}} = N_{\text{coll}}(N_{\text{coll}} \geq 1)/N_{\text{coll}}(N_{\text{coll}} \geq 0) \times \pi b_{\text{max}}^2$, i.e. the geometrical value corrected by the fraction of events with at least one nucleon-nucleon collision. We obtain $\sigma_{\text{XeXe}} = 5.7 \pm 0.2$ b.

3 Deformation of the xenon isotopes

The simplest parameterization of a deformed nucleus is described (see e.g. [7]) with a single deformation parameter $\beta$, namely by $R(\theta) = R_0(1 + \beta Y_{20}(\theta))$, where $R_0$ is the average radius and $Y_{20} = \frac{1}{4} \sqrt{\frac{5}{\pi}} (3 \cos^2 \theta - 1)$ is the spherical harmonic with $\ell = 2$ and $m = 0$ (also known as the Legendre polynomial of degree 2 in cos $\theta$). This is the axially symmetric case with no dependence on the azimuthal angle $\varphi$.

The nuclear transition probability $B(E2) \uparrow$ is defined for even-even nuclei as the transition probability from the $0^+$ ground state to the first-excited $2^+$ state and is measured experimentally in a model-independent way. The deformation parameter $\beta$ (often called $\beta_2$) can be related to this transition probability by the formula [8]: $\beta = \frac{4\pi}{3} \frac{\langle B(E2) \uparrow \rangle}{e^2}$, where the transition probability is given in units of $e^2b^2$ (squared electron charge times squared barns) and $R_0$ is taken to be 1.2A$^{1/3}$ fm.

In various nuclear deformation models the relation between the deformation parameters of the nuclear potential, generally a set of parameters $\beta_{lm}$ (see par. 2.2.3 and formula (38) in [14]), and the transition probability is more complicated. Ref. [7] for example gives formula (5): $\frac{\langle B(E2) \uparrow \rangle}{e^2} = \frac{4\pi}{3} \frac{\langle B(E2) \uparrow \rangle}{e^2}$, where the added quadratic term in $\beta$ is related to the expression of the quadrupole moment $Q_0$ in the Finite-Range Droplet Model (FRDM), see formula (17) in [8].
Table 2: Values of the deformation parameters \( \beta_2 \), \( \beta_3 \) and \( \beta_4 \) from a recent version of the FRDM model [14] for isotopes of Xe; the experimental values for even-\( A \) isotopes from Table 1 are reported in the last column.

<table>
<thead>
<tr>
<th>N</th>
<th>A</th>
<th>( \beta_2 )</th>
<th>( \beta_3 )</th>
<th>( \beta_4 )</th>
<th>Exper. ( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>124</td>
<td>0.229</td>
<td>0.000</td>
<td>-0.018</td>
<td>0.212 ± 0.007</td>
</tr>
<tr>
<td>71</td>
<td>125</td>
<td>0.217</td>
<td>0.000</td>
<td>-0.007</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>126</td>
<td>0.195</td>
<td>0.000</td>
<td>0.002</td>
<td>0.188 ± 0.003</td>
</tr>
<tr>
<td>73</td>
<td>127</td>
<td>0.172</td>
<td>0.000</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>128</td>
<td>0.173</td>
<td>0.000</td>
<td>-0.001</td>
<td>0.192 ± 0.002</td>
</tr>
<tr>
<td>75</td>
<td>129</td>
<td>0.162</td>
<td>0.000</td>
<td>-0.003</td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>130</td>
<td>-0.125</td>
<td>0.000</td>
<td>-0.018</td>
<td>0.169 ± 0.007</td>
</tr>
<tr>
<td>77</td>
<td>131</td>
<td>-0.125</td>
<td>0.000</td>
<td>-0.029</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>132</td>
<td>-0.125</td>
<td>0.000</td>
<td>-0.029</td>
<td>0.141 ± 0.005</td>
</tr>
<tr>
<td>79</td>
<td>133</td>
<td>0.053</td>
<td>0.000</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>134</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.115 ± 0.004</td>
</tr>
<tr>
<td>81</td>
<td>135</td>
<td>0.032</td>
<td>0.000</td>
<td>-0.012</td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>136</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.0914 ± 0.0018</td>
</tr>
</tbody>
</table>

An early review of experimental results on the transition probability and on the deduced deformation parameter \( \beta \) for even-\( A \) isotopes of Xe is given in [7]. A more recent review of \( B(E2) \uparrow \) for 328 nuclides is given in [8]. The Nuclear Data Sheets reviews for \( A = 134 \) [12] and for \( A = 136 \) [13] adopts more recent measurements of the transition probability with respect to ref. [8].

Table 1 summarizes the deformation parameters \( \beta \) that we consider reliable for even-\( A \) isotopes of Xe from \( A = 124 \) to \( A = 136 \). In two cases we have retained the \( \beta \) values given in [8], for \( A = 124 \), since the more recent review [15] uses apparently only one of the 3 measurements quoted in [8], and furthermore reports incorrectly the corresponding \( B(E2) \uparrow \) result for \( A = 130 \), since the review [16] does not give any reference for the \( \beta \) value quoted. In another case, namely \( A = 128 \), we have recomputed the weighted average from the 5 values of \( B(E2) \uparrow \) reported in [10].

The most recent ENSDF evaluation for \( A = 129 \) isobars [17] does not report a deformation parameter \( \beta \) for Xe, since experimentally \( B(E2) \uparrow \) is not defined for odd-\( A \) isotopes. Hence we must resort to interpolation using the even-\( A \) isotopes parameters, and later we will compare the interpolated value with a model.

Using only the two closer isotopes 128 and 130, the interpolated value for Xe-129 is about 0.18. Considering that we have recomputed the value of \( \beta \) for \( A = 128 \), we attribute an \( \text{rms} \) (root mean square) uncertainty of 0.02 to this value. So we will use the following experimentally-based deformation parameter estimate for Xe-129: \( \beta = 0.18 \pm 0.02 \).

Ref. [8] provided a comparison between experimental adopted values of \( B(E2) \uparrow \) (see Table I) with predictions from several models (see Table III). For Xe in particular (see Fig. IV at page 29) the model which came closer to data was the SSANM (Single-Shell Asymptotic Nilsson Model). The FRDM model (Finite-Range Droplet Model, version of 1992) reproduced well \( B(E2) \uparrow \) data for Xe-124 and Xe-126 but underpredicted those for higher mass isotopes. With respect to ref. [8], the updated experimental values presented in Table I do not change substantially the decreasing trend for \( \beta \) going from \( A = 124 \) to \( A = 136 \); but of course models have evolved in the mean time.

Recently a new, improved calculation with the FRDM model, namely the FRDM(2012) edition, has been

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1This is probably due to a typographical error in the original article PRC 57 (1998) 632, compare Table Ib with Fig. 5.
2The \( \beta \) value given by the reference does not match, being 5% higher, the weighted average of the original measurements.
3Evaluated Nuclear Structure Data File, a database maintained by the National Nuclear Data Center at Brookhaven National Laboratory.
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published \cite{14}. The 10 model constants have been optimized through a fit to ground-state masses of 2149 nuclei with $A$ ranging from 16 to 265. For nuclei with $N \geq 65$, the error on the mass is 0.35 MeV. The nuclear deformation is modeled with the perturbed spheroid parameterization (see par. 2.2.1) through parameters $\varepsilon_2$, $\varepsilon_3$, $\varepsilon_4$ and $\varepsilon_{6}$, from which the derived parameters (see par. 2.2.3) $\beta_2$ (similar to $\beta$ in the simplest parameterization), $\beta_3$, $\beta_4$ and $\beta_6$ are obtained. The deformation parameters are listed for each isotope, including those with even $Z$ and odd $N$, in the table at the end of \cite{14}.

Table 2 presents the $\beta$ parameters for the relevant Xe isotopes (from pages 118-119 of \cite{14}) as well as the experimental values of $\beta$ from table 1. The $\beta_A$ parameter is negligible except for Xe-124 (-0.006) and Xe-133 (0.001), hence it is not reported in table 2.

The agreement of the FRDM(2012) model with data has improved with respect to the version of 1992, but the heavier isotopes 134 and 136 are still predicted to be spherical. Isotopes 130, 131 and 132 are predicted to be prolate (negative $\beta_2$) rather than oblate. The prediction of $\beta_2$ for $A = 128$ is in fair agreement with experiment, while the absolute value of the prediction for $A = 130$ is 26% lower than experiment. The prediction of $\beta_2$ for Xe-129 is 0.162, which compares well with the interpolated experimental value $0.18 \pm 0.02$ quoted above.

It has been shown \cite{18} that when describing a deformed nucleus using an expansion in spherical harmonics (typically with $Y_{20}$ and $Y_{40}$ terms) one cannot use directly the mean radius ($R_0$) and diffuseness ($a$) parameters derived from electron scattering experiments in the Woods-Saxon distribution. Instead, $R_0$ and $a$ must be re-optimized (for given $\beta_2$ and $\beta_3$ values) in order to be consistent both with electron scattering data and $B(E2) \uparrow$ data. In the case of U-238, with $\beta_2 = 0.2863$, the change in $R_0$ and especially in $a$ is sizeable (respectively, +1% and -30%).

In the case of Xe-129, however, we have found that the recalculated Woods-Saxon parameters are only slightly different from the original ones: $a$ and $R_0$ change by less than 1%. So in the following we will adopt the original Woods-Saxon parameters for Xe-129 as given in Sect. 2.

To summarize, we describe the Xe-129 nucleus with the single deformation parameter $\beta_2$, therefore neglecting higher order terms, together with the Woods-Saxon parameters presented in the previous section.

\section*{4 The NBD-Glauber fit}

The Glauber Monte Carlo determines, for an event with a given impact parameter $b$, the corresponding $N_{\text{part}}$ and $N_{\text{coll}}$. The particle multiplicity per nucleon-nucleon collision is parameterized by a negative binomial distribution (NBD):

\[ P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \cdot \frac{(\mu/k)^n}{(\mu/k+1)^{n+k}}, \]

which gives the probability of measuring $n$ particles, where $\mu$ is the mean multiplicity and $k$ quantifies the variation of multiplicity.

To apply this model to any nuclear collision with a given $N_{\text{part}}$ and $N_{\text{coll}}$ value we define the ancestors $N_{\text{ancestors}}$, i.e. independently emitting sources of particles. The number of ancestors is parameterized by $N_{\text{ancestors}} = f \cdot N_{\text{part}} + (1-f) \cdot N_{\text{coll}}$. This is inspired by two-component models \cite{19,20}, however other assumptions can be made leading to a different parameterization, e.g. a power-law function of $N_{\text{part}}$, $N_{\text{coll}}$, motivated by the approximately linear scaling observed in soft processes, or a power-law function of $N_{\text{coll}}$, expected for a superposition of binary nucleon-nucleon collisions, in hard processes. These alternative assumptions will be considered in Sect. 5.

For every Glauber Monte Carlo event, the NBD is sampled $N_{\text{ancestors}}$ times to obtain the averaged simulated V0 amplitude for this event, which is proportional to the number of particles hitting the scintillators.
Fig. 1: Upper panel: Distribution of the sum of amplitudes in the V0 scintillators. The distribution is fitted with the NBD-Glauber model, shown as a line. A few centrality class examples are indicated in the figure. The inset shows a zoom of the most peripheral region. Lower panel: Ratio of the V0M data distribution by the distribution obtained from the NBD fit.

The V0 amplitude distribution is simulated for an ensemble of events and for various values of the NBD parameters \( \mu, k \), and the \( N_{\text{ancestors}} \) parameter \( f \). A minimization procedure is applied to find the parameters which result in the smallest \( \chi^2 \), also shown in Fig. 1. The fit is performed for V0 amplitudes large enough so that the purity of the event sample (no contamination from electromagnetic processes) and the efficiency of the event selection are both 100%. In practice we remove from the fit the most peripheral 90-100% class. We note that the high multiplicity tail, which is quite sensitive to fluctuations and the detector resolution not implemented in the model, is not perfectly well described.

Table A.1 reports the mean number of participants \( \langle N_{\text{part}} \rangle \) and collisions \( \langle N_{\text{coll}} \rangle \), and the mean nuclear thickness function \( \langle T_{\text{XeXe}} \rangle \) for centrality classes defined by sharp cuts in the simulated V0 distribution. The standard deviation of these distributions is a measure of the magnitude of the dispersion of the quantities. The systematic uncertainties on the mean values are obtained by independently varying the parameters of the Glauber model within their estimated uncertainties and repeating the NBD-Glauber fit. Figure 2 shows the resulting variations of \( N_{\text{part}} \) and \( N_{\text{coll}} \) for Xe–Xe collisions at \( \sqrt{s_{\text{NN}}} = 5.44 \) TeV. The total systematic uncertainty reported in Table A.1 was obtained by adding all deviations observed in Fig. 2 in quadrature. Table A.2 shows for comparison the geometrical values obtained for centrality classes defined by sharp cuts in impact parameter, denoted by \( \langle N_{\text{part}}^{\text{geo}} \rangle \) and \( \langle N_{\text{coll}}^{\text{geo}} \rangle \). In general the values of \( \langle N_{\text{part}}^{\text{geo}} \rangle \) and \( \langle N_{\text{mult}} \rangle \) are very similar in 0-80%, while they differ by over 60% for the most peripheral 80-100%.

It was already discussed in detail (see e.g. [21]) that whenever multiplicities are small, as for instance in p–Pb, fluctuations may have a significant impact in event selection, so that a centrality classification based on multiplicity may select a sample of nucleon-nucleon collisions which is biased compared to a sample defined by cuts on the impact parameter \( b \). This selection bias can be quantified using the Glauber fit itself. Figure 3 shows the ratio between the average multiplicity per average participant (or ancestor) and the average multiplicity \( \mu \) of the NBD, as a function of centrality. In p–Pb collisions the ratio differs from unity for all centralities with large deviations for the most central and most peripheral collisions. In Pb–Pb collisions, where multiplicity fluctuations at fixed \( b \) are small compared to total multiplicity,
Fig. 2: Sensitivity of $N_{\text{part}}$ (top) and $N_{\text{coll}}$ (bottom) to variations of parameters in the Glauber Monte Carlo model of Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. The first 9 centrality classes are 10% wide, while the 10% most central one is divided in 4 parts. The gray band represents the standard deviation of $N_{\text{part}}$ and $N_{\text{coll}}$ respectively. It is scaled by a factor 0.1 for visibility.
Fig. 3: Multiplicity fluctuation bias quantified as the mean multiplicity per $\langle N_{\text{ancestors}} \rangle / \mu$ from the NBD-Glauber MC in p–Pb, Xe–Xe and Pb–Pb calculations. The centrality estimator described in this document is indicated by V0M. For p–Pb collisions, other estimators indicated by V0A, V0C and CL1 are also shown, see [21] for details.

The ratio deviates from unity only for the most peripheral collisions. The Xe–Xe collisions have larger relative fluctuations than in Pb–Pb collisions and therefore a larger multiplicity bias, in between the one for Pb–Pb and that of p–Pb (both evaluated with the V0M centrality estimator), although closer to Pb–Pb. When selecting event classes using impact parameter $b$ intervals, there is no deviation from unity, as expected.

5 Mechanism of particle production

In this section different particle production models are compared with the pseudorapidity density of charged particles per participant pair measured [22] by ALICE in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV.

5.1 $N_{\text{part}}$ and $N_{\text{coll}}$ functions

The charged particle multiplicity as a function of the number of participants $N_{\text{part}}$ was fitted with three different parameterizations:

- a two-component model: $dN_{\text{ch}}/d\eta \propto f \cdot N_{\text{part}} + (1 - f) \cdot N_{\text{coll}}$;
- a power-law function of $N_{\text{part}}$: $dN_{\text{ch}}/d\eta \propto N_{\text{part}}^\alpha$;
- a power-law function of $N_{\text{coll}}$: $dN_{\text{ch}}/d\eta \propto N_{\text{coll}}^\beta$. 
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The functions were originally fitted to the Pb–Pb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. For the Xe–Xe data only the absolute normalisation was adjusted. The parameters, namely the relative fraction of particles produced proportional to $N_{\text{part}}$ and $N_{\text{coll}}$, or the exponent of the power-law functions, were fixed to the value obtained in Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [2], which in turn are found to be consistent with what one obtained with RHIC and SPS data [23, 24].

5.2 Core-Corona

Following the simple approach proposed in [25], which aims at describing relativistic heavy-ion collisions with a superposition of particle emission from thermal (core) and direct sources (corona), the participating nucleons $N_{\text{part}}$ in the Glauber Monte Carlo are separated in those which scatter only once, $N_{\text{core}}$, and the rest, $N_{\text{corona}}$. The multiplicity can then be fitted with the sum of those contributions, $M_{\text{pp}} N_{\text{corona}} + M_{\text{core}} N_{\text{core}}$, where $M_{\text{pp}}$ is the multiplicity measured in inelastic pp [26] and $M_{\text{core}}$ is a fit parameter to scale the core fireball contribution. The fractions of core and corona contributions are shown in Fig. 4 for Pb–Pb and Xe–Xe.

5.3 Constituent quarks

Following [27], developed along the line of [28], we have also performed a Glauber calculation based on single quark scattering. Constituent quarks are located around nucleon centers with distribution

$$\rho(r) = \rho_0^{\text{proton}} \exp(-a \cdot r)$$

(3)

where $a = 4.27$ fm$^{-1}$ is derived from the $\text{rms}$ charge radius of the proton. We used the often employed $N_q = 3$ for three constituent quarks as the effective number of partonic degrees of freedom, as well as
\[ N_q = 5 \]. In case of \( N_q = 3 \) the radial distribution is modified to maintain the proton center of mass at zero and the desired radial distribution as explained in [29]. The effective q-q inelastic scattering cross section is set to 20.38 (9.76 mb) for \( N_q = 3 \) (\( N_q = 5 \)), respectively, adjusted to reproduce the 68.4 mb nucleon-nucleon inelastic cross section at 5.44 TeV. Note that the number of participant quarks \( N_{q\text{part}} \) as determined by the Glauber calculation has been divided by \( \mu = \langle N_{q\text{part}} \rangle \) in pp collisions which is 3.5 (4.3) for \( N_q = 3 \) (\( N_q = 5 \)).

5.4 Discussion

In Fig. 5 we compare the multiplicity per participant pairs in Xe–Xe collisions at \( \sqrt{s_{NN}} = 5.44 \) TeV with the three different parameterizations for particle production presented above. Pb–Pb data and fits are shown as well. While no unique physics conclusion can be drawn from such fits, the results suggest that geometrical considerations are sufficient to provide a good description of particle production across different colliding systems and beam energies. Also a scaling with the number of participants that scatter more than once, \( N_{\text{core}} \) (defined above), is shown. The curve qualitatively follows the trends observed in the data, although not in details. The figure also shows the multiplicity per participant quark (triangles), calculated with the single-quark scattering model, as a function of \( N_{\text{part}} \). The multiplicity seems to scale well with the number of participating constituent quarks, as already observed in...
the results of PHENIX [30, 31] which suggested that the identical shape of the distribution indicates a nuclear-geometrical effect, well represented in terms of constituent quark participants.

6 Summary

We have used a Glauber Monte Carlo method (extending the ALICE standard method) to determine centrality-related properties \(N_{\text{part}}, N_{\text{coll}}\) and \(T_{AA}\) of event samples selected by an experimentally accessible quantity which is the V0 amplitude. We have applied this method to the special case of Xe–Xe collisions, in order to classify collisions obtained in a short run which took place in fall 2017 at the LHC. The Xe-129 deformed nucleus has been described by a 2-parameter Fermi function with parameters derived from recent electron scattering measurements on Xe-132, modulated by a spherical harmonics with a deformation parameter derived from interpolation from Xe isotopes with a similar mass number. The mean number of participants and collisions and the mean nuclear thickness function have been calculated for centrality classes defined with sharp cuts in the simulated V0 amplitude. The calculated quantities are useful to study physics observables for each centrality class in Xe–Xe collisions as a function of the number of participants and collisions and to compute the nuclear modification factors. We have performed Glauber calculations with different particle production models, namely power-law functions in \(N_{\text{part}}\) or \(N_{\text{coll}}\), a core-corona approach and a constituent quark approach. The multiplicity per participant pair or per participant quark in Pb–Pb and Xe–Xe collisions at LHC energies is rather well described by the different approaches used.

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The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Universidade Federal do Rio Grande do Sul (UFRGS), Financiadora de Estudos e Projetos (Finep) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil; Ministry of Science & Technology of China (MSTC), National Natural Science Foundation of China (NSFC) and Ministry of Education of China (MOEC) , China; Ministry of Science and Education, Croatia; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the Carlsberg Foundation and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l’Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Science, Indonesia; Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi and Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology ,
References


Centrality determination using the Glauber model in Xe–Xe at $\sqrt{s_{NN}} = 5.44$ TeV


## A Tables

<table>
<thead>
<tr>
<th>Centrality</th>
<th>(\langle N_{\text{part}}\rangle)</th>
<th>(\sigma) (sys.)</th>
<th>(\langle N_{\text{coll}}\rangle)</th>
<th>(\sigma) (sys.)</th>
<th>(\langle T_{\text{XeXe}}\rangle)</th>
<th>(\sigma) (sys.)</th>
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<tbody>
<tr>
<td>0-2.5 %</td>
<td>242.3</td>
<td>7.7</td>
<td>1.3</td>
<td>1012</td>
<td>75</td>
<td>57</td>
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<td>229.2</td>
<td>10.1</td>
<td>1.7</td>
<td>885.9</td>
<td>63</td>
<td>50</td>
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<td>2.0</td>
<td>782.8</td>
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<td>48</td>
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<td>11.8</td>
<td>1.8</td>
<td>691.8</td>
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<td>948.9</td>
<td>93</td>
<td>53</td>
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<td>737.3</td>
<td>73</td>
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<tr>
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<td>1.6</td>
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<tr>
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<tr>
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<td>2.7</td>
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<td>17.44</td>
<td>5.2</td>
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<tr>
<td>70-75%</td>
<td>12.25</td>
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<td>1.0</td>
<td>11.54</td>
<td>3.8</td>
<td>1.5</td>
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<tr>
<td>75-80%</td>
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<td>2.3</td>
<td>0.65</td>
<td>7.502</td>
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<tr>
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<td>0.42</td>
<td>4.775</td>
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<td>0.47</td>
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<tr>
<td>85-90%</td>
<td>4.143</td>
<td>1.4</td>
<td>0.23</td>
<td>2.91</td>
<td>1.3</td>
<td>0.16</td>
</tr>
<tr>
<td>90-95%</td>
<td>2.814</td>
<td>0.94</td>
<td>0.12</td>
<td>1.744</td>
<td>0.85</td>
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<td>95-100%</td>
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<td>0.42</td>
<td>0.033</td>
<td>1.148</td>
<td>0.4</td>
<td>0.033</td>
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Table A.1: Geometric properties \(\langle N_{\text{part}}, N_{\text{coll}}, T_{\text{XeXe}}\rangle\) of Xe–Xe collisions at \(\sqrt{s_{\text{NN}}} = 5.44\) TeV for centrality classes defined by sharp cuts in the V0M multiplicity distribution, simulated with an NBD-Glauber Monte Carlo calculation. Mean values, standard deviations (\(\sigma\)) and systematic uncertainties are obtained as explained in the text.
Table A.2: Comparison of the $\langle N_{\text{geo}}^{\text{geo}} \rangle$ (sharp cuts in impact parameter) and $\langle N_{\text{mult}}^{\text{geo}} \rangle$ (sharp cuts in V0 multiplicity) values for Xe–Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV. Also $N_{\text{coll}}$ and $T_{\text{XeXe}}$ values in both calculations are listed.
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Centrality determination using the Glauber model in Xe–Xe at $\sqrt{s_{\text{NN}}}=5.44$ TeV
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