Proton-nucleus collisions at LHC energy in the Monte Carlo model

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A Monte Carlo model, initially developed for soft pp and AA collisions at high energy, is applied for proton-lead interaction at the LHC energy. Elementary collisions are implemented at the partonic level and do not involve the usual Glauber’s supposition of independent nucleon-nucleon collisions. The average number of participating nucleons and charged multiplicity in p-Pb collisions were calculated and compared with the predictions of Glauber model and experimental data. It was demonstrated that taking into account the energy conservation results in the number of participating nucleons considerably lower than in the Glauber approach. Different ways of centrality in determination in pA are discussed and the influence of the methods of centrality definition on mean observables and their variances is studied.

1. INTRODUCTION

After three years of successful operation of the LHC as proton-proton and lead-lead collider the first pilot run of proton-lead collisions was held on 12-13 September 2012 [1], followed by longer one-month running period in 2013. The statistics, collected at the first run, was enough to provide physical results [2–4]. The first measurements, performed at the LHC, are related to the multiplicity studies and involve also centrality selection [4]. In the present work two aspects, related to these studies, multiplicity and centrality, are discussed within the Monte-Carlo model [5, 6] and further predictions are made.

The first result, obtained by the ALICE Collaboration – mean pseudorapidity density of charged particles in NSD p-Pb collisions at 5.02 TeV – found at the level of 16.81 ± 0.71. The normalization of the result to the number of participants (N_{part}) was performed and the corresponding normalized value 2.14 ± 0.17 was found to be less than the multiplicity in pp collisions at the same energy (which is 2.6, see fig. 2 in [2]). Note that the number of

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participant nucleons was not extracted from the data, but calculated using Glauber model [7] (similarly to RHIC experiments), while alternative experimental approaches was used by earlier experiments, such as the measurement of the number of net baryons [8] or ZDC and Veto calorimeters [9].

The use of Glauber model is criticized [6, 10, 11], as it over-predicts the multiplicity yields in AA collisions and the consistency can be achieved only by parameters fitting, different at each colliding system and energy. In several models behind Glauber the decrease of the number of binary nucleon collisions \( N_{\text{coll}} \) in AA compared to Glauber model was found [6, 10]. Similar effects are predicted also by the Gribov-Glauber approach [12] and models with gluon shadowing [13]. Due to the fact that in pA collisions \( N_{\text{part}} = N_{\text{coll}} + 1 \), the value of \( N_{\text{part}} \) could be also affected by this issues, and we check this in the present model.

2. MONTE CARLO MODEL

The present model is based on the partonic picture of nucleons interaction. The initial positions of the nucleons are distributed according to Woods-Saxon: 
\[
\rho(r) = \frac{\rho_0}{1 + \exp((r-R)/d)},
\]
with parameters \( R = 6.63 \text{ fm}, d = 0.545 \text{ fm} \). Each nucleon consist of a set of partons (valence quark, diquark and quark-diquark pairs), distributed in transverse plane with Gauss distribution relative to the center of nucleon with mean-square radius \( r_0 \). For each parton the appropriate momentum fraction is assigned, according to the exclusive distributions [5], accounting energy and angular momentum conservation in the initial state of a nucleon.

Quark-diquark and quark-antiquark pairs form set of dipoles. Interaction probability amplitude of two dipoles with transverse coordinates \((r_1, r_1')\) and \((r_2, r_2')\) is given by [14, 15]:
\[
f = \frac{\alpha_S^2}{8} \ln^2 \left( \frac{(r_1 - r_1')^2(r_2 - r_2')^2}{(r_1 - r_2')^2(r_2 - r_1')^2} \right).
\]
Note, that two dipoles interact more probably, if the ends are close to each other, and (others equal) if they are wide. After taking into account confinement effects, one gets [14, 15]:
\[
f = \frac{\alpha_S^2}{2} \left[ K_0 \left( \frac{|r_1 - r_1'|}{r_{\text{max}}} \right) + K_0 \left( \frac{|r_2 - r_2'|}{r_{\text{max}}} \right) - K_0 \left( \frac{|r_1 - r_2'|}{r_{\text{max}}} \right) - K_0 \left( \frac{|r_1 - r_1'|}{r_{\text{max}}} \right) \right]^2,
\]
where \( K_0 \) is modified Bessel function. \( \alpha_S \) here is an effective coupling constant, \( r_{\text{max}} \approx 0.2 - 0.3 \text{ fm} \) – confinement scale, the exact values are turned to describe experimental data.
The charged multiplicity is calculated in the approach of colour strings, taking into account their finite rapidity width and interactions due to non-zero transverse radius of string $r_{str}$ (string fusion) [16, 17], with introducing a lattice in the transverse plane [18, 19].

Important feature of the present model is that every parton can interact with other one only once, forming a pair of quark-gluon strings, hence, producing particles, contrary to Glauber supposition of constant nucleon cross section. A nucleon is participating in the collision if at least one of it’s partons collides with other from the proton.

Parameters of the model are constrained from the pp data on the total inelastic cross section and charged multiplicity in wide energy range (from ISR to LHC) [20, 21]. Additional requirement was the consistent description of the multiplicity in minimum bias p-Pb and Pb-Pb collisions at the LHC energy [2, 22]. The remaining freedom in the parameters selection is used as the systematic uncertainty of the results.

Most of the results were obtained with the following parameters:

$$r_0 = 0.6 \text{ fm}, \quad \alpha_S = 0.4, \quad r_{\text{max}}/r_0 = 0.5, \quad r_{str} = 0.2 \text{ fm}, \quad \mu_0 = 1.152,$$

where $\mu_0$ is mean charged multiplicity from one single string per rapidity unit.

3. RESULTS

3.1. $N_{\text{part}}$ and multiplicity

In the framework of the present model we performed the calculations for p-Pb collisions at $\sqrt{s} = 5.02$ TeV. The mean number of the participant nucleons in p-Pb collisions is shown at Figure 1 and compared to the calculations in Glauber model. The distribution of $N_{\text{part}}$ is shown at Figure 2. $N_{\text{part}}$ in the present model is found to be considerable less than in Glauber case, forming a plateau at central collisions.

In order to clarify the reason of this difference, we implemented so-called “polygamous” version of the model. In this artificial variant we allowed the partons to interact several times, forming the strings and produce particles. Note, that in this case the same energy, belonging to a parton, can go to the particle production several times, breaking the energy conservation.

The number of participants in “plogamy” model (Fig. 2) is found very close to the Glauber results. This demonstrates that the accounting of the energy conservation is the
reason of decrease of $N_{\text{part}}$ in our non-Glauber approach.

Note, that similar decrease of $N_{\text{part}}$ in pA compared to Glauber is found also in several other models, that are aimed to describe consistently pp, pA and AA collisions, such as Modified Glauber [10, 11], where the energy conservation is implemented in effective way, and AMPT [23], which include gluon shadowing and collective effects. Also such signatures were found in the experimental studies [8], when the approach, based on the number of net baryons, was used for the determination of $N_{\text{part}}$: some discrepancy between geometrical models and experimental data was observed only for non-symmetrical colliding systems, although the difference was accounted as systematic error in the data.

Taking all this into account one may suggest to pay more attention, or even reconsider the use of Glauber normalization of the multiplicity yields in experimental studies, at least for non-symmetrical colliding systems.

At Figure 3 the prediction of multiplicity distribution, calculated in the present model, is shown. The mean value – 16.5 – is consistent with experiment [2]. The predicted non-monotonic shape would be interesting to compare with future measurements.

3.2. Centrality classes

We performed also the calculation of centrality dependence of the multiplicity in p-Pb collisions. Centrality is always determined as a fraction of some variable among the whole distribution. We used four centrality estimators: impact parameter, number of participants, multiplicity signal in off-central rapidity region (“vzero”) and multiplicity in $|\eta| < 0.5$ itself. The “vzero” signal is emulated as a sum of charged multiplicities in rapidity windows: $(3.0; 5.0)+(-3.6; -1.6)$, which is approximately the coverage of the ALICE detector V0 [24]. We selected five classes of 20% centrality width.

The results on the multiplicity mean values (Figure 4) show noticeable discrepancy between several methods. One concludes that the difference between central and peripheral collisions depends on how much the estimator is correlated to the observable. That leads that the relation of centrality in pA collisions to “geometrical” properties is not straightforward, and proper accounting of the method of the centrality determination should be performed in order to compare model predictions with experiment and even between several experiments.

At Figure 4 (right) the variance of the number of charged particles in several central-
ity classes is shown. The values and the behavior is quite different for several centrality estimators. Assuming that the model “vzero” method would approximate the real ALICE experimental centrality determination, this result can be compared with the further measurements.

4. CONCLUSIONS

It was demonstrated, that taking into account the energy conservation in the model leads to considerable decrease of the mean number of the participants compared to the Glauber model.

The study of several methods of the centrality selection showed, that there is valuable difference between the mean multiplicity between methods. Clearly, the way, how the centrality classes are determined, should be always taken into account while comparison the results between several experiments and between models and experiment.

It seems that the “geometric” treatment of the centrality is less relevant in pA collisions, since the true value of impact parameter is never known in the real experiment, but relation between it and observables is not straightforward.

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**Table 1.** Summary of the results for NSD p-Pb collisions at 5.02 TeV

| MC Model | Glauber and experiment [2] |
|----------|-----------------------------|
| $\langle N_{\text{part}} \rangle = 6.2 \pm 0.6$ | $\langle N_{\text{part}} \rangle = 7.9 \pm 0.6$ |
| $\langle dN/d\eta \rangle = 16.5 \pm 0.5$ | $\langle N_{\text{part}} \rangle = 16.81 \pm 0.71$ |
| $\langle dN/d\eta \rangle / \langle N_{\text{part}} \rangle |_{pA} = 2.66 \pm 0.04$ | $\langle dN/d\eta \rangle / \langle N_{\text{part}} \rangle |_{pA} = 2.14 \pm 0.17$ |
| $\langle dN/d\eta \rangle / \langle N_{\text{part}} \rangle |_{pp} = 2.58$ | $\langle dN/d\eta \rangle / \langle N_{\text{part}} \rangle |_{pp} = 2.58$ |
Figures

Figure 1. Mean number of participant nucleons as a function of impact parameter. Results of the present MC model and Glauber model for p-Pb collisions at $\sqrt{s} = 5.02$ TeV.

Figure 2. Distribution of $N_{\text{part}}$ in p-Pb collisions at $\sqrt{s} = 5.02$ TeV, calculated in the default, “polygamous” MC model and Glauber model.
Figure 3. Charged multiplicity distribution in the rapidity window $|\eta|<0.5$ for p-Pb collisions at 5.02 TeV, calculated in the MC model.

Figure 4. Multiplicity in $|\eta| < 0.5$ (left) and its variance (right) in p-Pb collisions at 5.02 TeV as function of centrality, obtained in MC model using several centrality estimators: impact parameter, number of participants, multiplicity detector (“vzero”) and multiplicity itself in this window.
Figure captions

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