I. INTRODUCTION

Ultrarelativistic nucleus-nucleus collisions provide an opportunity for exploring strongly interacting QCD matter under extreme conditions which is the ultimate goal of heavy-ion experiments at the relativistic heavy-ion collider (RHIC) and the large hadron collider (LHC). The experiments at the RHIC and the LHC have demonstrated that a stage of partonic matter is produced in these reactions which is in an approximate equilibrium for a few fm/c [1, 2]. Due to the non-perturbative and non-equilibrium nature of relativistic nuclear reaction systems, their theoretical description is based essentially on a variety of effective models ranging from hydrodynamic models with different initial conditions [3–12] to various kinetic approaches [13–19]. However, a commonly accepted and complete picture is still lacking and precise data from the RHIC and LHC are expected to clarify the situation.

The actual questions addressed in this study are twofold: i) how to disentangle nuclear modification effects due to initial state and final state interactions and ii) does the initial state of colliding nuclei behaves like a superposition of its constituents or as a coherent gluon field as predicted in the color glass condensate (CGC) framework [21].

The different phenomenological models that successfully describe data include coherence effects in the initial state which can be identified at the level of the wave function and also at the level of primary particle production. A complete, QCD-based, dynamical description of the coherence effects is provided within the color glass condensate concept (cf. the reviews [20]). Here, gluon shadowing is taken into account through nonlinear renormalization group equations, i.e. the BK-JIMWLK evolution of classical Yang-Mills equations. They also imply the emergence of a dynamical transverse momenta.

The Parton-Hadron-String-Dynamics (PHSD) transport model is employed for p+Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) and compared to recent experimental data from the LHC as well as to alternative models. We focus on the question of initial state dynamics, i.e. if the initial state might be approximated by a superposition of independent nucleon-nucleon collisions or should be considered as a coherent gluon field as predicted within the color glass condensate (CGC) framework. We find that the PHSD approach provides correlations between the charged particle multiplicity at midrapidity and the number of participant nucleons very close to results from the CGC and differs substantially from results calculated with Glauber initial conditions. However, a difference is found between the PHSD approach and CGC models with respect to the rapidity dependence of the average transverse momentum. Accordingly, related measurements at LHC should allow to prove or disprove the presence of coherent colour fields in the initial phase of the collisions.

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sentially in the case of proton-nucleus collisions owing to the expected dominance of the initial state effects. Recently, the first preliminary ALICE measurement of the charged particle pseudorapidity density has been reported \[22\] for \(|p| < 2\) in p-Pb collisions at a nucleon-nucleon center-of-mass energy \(\sqrt{s_{NN}} = 5.02\) TeV. The measurement is compared to two sets of particle production models that describe similar measurements for other collision systems: the saturation models employing coherence effects \[20, 28\] and the two-component models combining perturbative QCD processes with soft interactions \[29, 30\]. A comparison of the model calculations with the data shows that the results are model-dependent and predict the measured multiplicity values only within 20%. Accordingly, the restrictions imposed by the measured minimal bias pseudorapidity spectra \(dN_{ch}/d\eta\) are not enough to disentangle different models for the very early interaction stage of ultrarelativistic collisions. A large set of various characteristic predicted in the compilation \[31\] for p-Pb collisions at 5.02 TeV is still waiting for a proper analysis/comparison.

A rigorous test of color coherence in proton-nucleus collisions at the LHC energy has been proposed recently in Ref. \[32\]. The idea of this proposal is based on the fact that the observed mean multiplicity of charged particles \(\langle N_{ch}\rangle\) linearly depends on the number of participants \(N_{\text{part}}\) within the wounded nucleon model (WNM) of independent nucleon-nucleon scatterings, \(\langle N_{ch}\rangle \sim N_{\text{part}}\), while in the CGC models this dependence is logarithmic, \(\langle N_{ch}\rangle \sim \ln N_{\text{part}}\). For a small number of participants, \(N_{\text{part}} \lesssim 10\), the mean multiplicities calculated in both approaches practically coincide (in agreement with experiment) but for \(N_{\text{part}} \sim 25\) they differ by almost a factor of two \[32\]. Such large numbers of participant are possible at the LHC energy of 5.02 TeV in p-Pb collisions. Furthermore, as pointed out in Ref. \[33\] there should be a sizeable difference in the mean transverse momentum of particles versus the pseudorapidity \((p_T)(\eta)\) with opposite slopes in \(\eta\) on the projectile side within the CGC framework relative to hydrodynamical calculations due the saturation scale in the CGC.

Following these suggestions we here study the charged particle multiplicities and related quantities in p-Pb interactions at the collision energy \(\sqrt{s_{NN}} = 5.02\) TeV within the parton-hadron-string-dynamics (PHSD) transport approach \[12\] which has been properly upgraded to LHC energies with respect to a more recent PYTHIA implementation (Sec. II). Predictions for various observables and their correlations are given in Sec. III which are also compared to available data as well as to results from CGC saturation models. We conclude our findings in Sec. IV.

II. PHSD @ LHC

The PHSD model is a covariant dynamical approach for strongly interacting systems formulated on the basis of Kadanoff-Baym equations \[34\] or off-shell transport equations in phase-space representation, respectively. In the Kadanoff-Baym theory the field quanta are described in terms of dressed propagators with complex selfenergies. Whereas the real part of the selfenergies can be related to mean-field potentials (of Lorentz scalar, vector or tensor type), the imaginary parts provide information about the lifetime and/or reaction rates of time-like particles \[35\]. Once the proper (complex) selfenergies of the degrees of freedom are known, the time evolution of the system is fully governed by off-shell transport equations (as described in Refs. \[34, 37\]). This approach allows for a simple and transparent interpretation of lattice QCD results for thermodynamic quantities as well as correlators and leads to effective strongly interacting partonic quasiparticles with broad spectral functions. For a review on off-shell transport theory we refer the reader to Ref. \[33\]; model results and their comparison with experimental observables for heavy-ion collisions from the lower super-proton-synchrotron (SPS) to RHIC energies can be found in Refs. \[19, 36, 37\] including electromagnetic probes such as e⁻e⁻ or \(\mu^+\mu^-\) pairs \[38\]. We mention that the PHSD model takes into account some kind of coherent effects with respect to QCD showers since it includes corrections to the leading-log picture – denoted as coherence effects – that lead to an ordering of subsequent emissions in terms of decreasing angles.

To adjust the PHSD model to higher energies than \(\sqrt{s_{NN}} = 200\) GeV at RHIC, we have additionally implemented the PYTHIA 6.4 generator \[39\] for initial nucleon collisions at LHC energies. For the subsequent (lower energy) collisions the standard PHSD model \[19\] is applied. In PYTHIA 6.4 we use the Perugia tune (324) without color recombination which allows to describe reasonably the p-p collisions at 7 TeV in the framework of the PHSD transport approach (cf. Fig. 1). The overall agreement with LHC experiment data for the charged particle multiplicity \(N_{ch}\) and the transverse momentum \(p_T\) is satisfactory, however, the distributions increasingly deviate for \(N_{ch} \gtrsim 45\) and \(p_T \gtrsim 4.5\) GeV, respectively, although the correlation \(< p_T(N_{ch}) >\) is acceptable. Furthermore, PYTHIA 6.4 (tune 324) reproduces correctly the shape of the pseudorapidity distribution in the pseudorapidity range \(-3 \lesssim \eta \lesssim 3\) but slightly (\(< 10\%\)) overestimates the absolute yield. Note that these distributions are perfectly described in the CGC model with the special tuning described in Ref. \[28\]. We point out, furthermore, that the \(N_{ch}\) and \(dN_{ch}/d\eta\) distributions have been measured by different collaborations, ALICE \[40\] and CMS \[41\], respectively.

Although PYTHIA 6.4 includes some elements of coherence in the creation of particles (by string fusion, string fragmentation, quasiparticle spectral densities etc.) it deviates substantially from the early interaction stage in the CGC approach \[20\]. We mention that initial state fluctuations in hydro calculations are usually imposed by independent Glauber model simulations or MC-KLN initial conditions \[43\], respectively. Initial con-
ditions very similar to the Glauber model are included by default in the PHSD transport approach, however, with an essential difference: the energy-momentum conservation is fulfilled exactly in every collision such that the entire dynamics conserves four-momentum as well as all discrete conservation laws. We recall that the PHSD approach has been tested successfully for collective flows $v_1, v_2, v_3$ and $v_4$ in nucleus-nucleus collisions from lower super-proton-synchrotron (SPS) up to RHIC energies [36] where especially the uneven flow coefficients are sensitive to the initial state fluctuations.

It has been argued, furthermore, that in high energy p-A collisions the Glauber model should be corrected to account for the fact that between successive interactions the incoming proton is off-shell [44] and fluctuates in size. In addition, event-to-event fluctuations in the configuration of the incoming proton can change its effective scattering cross section [45–47]. The concept of hadronic cross-section fluctuations incorporates the physics of color transparency and color opacity into the dynamics of relativistic nuclear collisions. In order to evaluate the impact of these fluctuations of the projectile proton, a modified version of the Glauber Monte Carlo, referred to as ‘Glauber-Gribov’ MC, is implemented additionally in the PHSD. Following Refs. [45–47], the probability distribution of total cross sections $\sigma_{tot}$ is taken to be

$$ P_h(\sigma_{tot}) = a_h \frac{\sigma_{tot}}{\sigma_{tot} + \sigma_0} \exp \left( -\frac{(\sigma_{tot}/\sigma_0 - 1)^2}{\Omega^2} \right). \quad (1) $$

Here, $a_h$ is a normalization constant, $\Omega$ controls the width of the $P_h(\sigma_{tot})$ distribution, and $\sigma_0$ determines $\langle \sigma_{tot} \rangle$. Estimates of $\Omega$ have been provided in [47] for center-of-mass energies of 1.8, 9, and 14 TeV. We use two interpolations of these values that for $\sqrt{s_{NN}} = 5.02$ TeV results in $\Omega = 0.55$ or $\Omega = 1.01$ which enhances the influence of fluctuations. The elastic fraction of the total cross-section in (1) is taken to be constant [47], $\sigma_{NN} = \lambda \sigma_{tot}$, so the probability distribution for $\sigma_{NN}$ is given by $P_H(\sigma_{NN}) = (1/\lambda)P(\sigma_{NN}/\lambda)$. 

FIG. 1: Comparison of the PYTHIA 6.4 results with LHC experimental data for p-p collisions at $\sqrt{s_{NN}} = 7$ TeV: (a) $N_{ch}$ distributions [40], (b) $dN_{ch}/d\eta$ distribution [41], (c) $p_T$-spectra [41] and (d) mean $p_T$ vs. $N_{ch}$ [42]. The CGC results in (b) are taken from Ref. [28].
III. PROPERTIES OF P-PB COLLISIONS

A. Energy density in a single p-Pb event

The energy density $\epsilon$ in local cells from PHSD is presented in Fig. 2 in the transverse $(x-y)$ plane (a) as well as the reaction $(x-z)$ plane (b) for a single p-Pb event at $\sqrt{s_{NN}} = 5.02$ TeV. The time of this event ($t = 0.002$ fm/c) corresponds to the moment when the proton has passed the Lorentz contracted nucleus.

The maximal energy density $\epsilon \sim 10^5$ GeV/fm$^3$ in the p-Pb reaction is extremely high and quite comparable with that in heavy-ion collisions at the LHC energy for local cells due to fluctuations of the initial conditions in PHSD. Note that the formed high energy density "tube" is strongly Lorentz contracted along the collision axis $z$ and is reminiscent of the energy density in a 'string'.

![Diagram](image1)

FIG. 2: $x-y$ (a) and $x-z$ (b) projections of the energy density in a single p-Pb event at the time when the proton-remnant has passed through the Pb-nucleus. The region occupied by the Pb nucleus is also shown by the shaded area.

B. Charged particle multiplicities and their distributions

With the elementary p-p collisions in the PHSD being adjusted at LHC energies we now proceed with observ-

![Diagram](image2)

FIG. 3: Probability distribution of the participant number and number of charged particles at midrapidity (a) and its different projections in (b) and (c). The WNM and CGC calculations are taken from [32] while simulations in the Glauber-Gribov approximation stem from [49].
ables and correlations from p-Pb collisions. In Fig. 4(a) we present the probability distribution in the participant number $N_{part}$ and the number of charged hadrons at midrapidity $N_{ch}(\eta = 0)$ as well as the different projections for p-Pb (5.02 TeV) in (b) and (c). In this figure it was assumed that the charged particles are distributed according to negative binomial distributions. As is seen from Fig. 3 the number of charged particles at midrapidity correlates with the number of participants, $N_{ch}(\eta = 0) \sim N_{part}$, however, with a large dispersion in both quantities. If this 2D distribution is integrated over the number of charged particles, the $P(N_{part})$ distributions for various models are compared in Fig. 3(b) and 3(c). For $N_{part} \gtrsim 15$, the Gribov-Glauber (GG) distributions (calculated in the WNM) increasingly overshoot the standard Glauber (G) result [53] and this difference reaches an order of magnitude in the case of $N_{part} \gtrsim 30$ while all evaluated distributions practically coincide for low numbers of participants, $N_{part} \lesssim 15$. In contrast to the Glauber or Gribov-Glauber Monte Carlo simulations we find no dramatic enhancement in the distribution when taking into account the cross section fluctuations in the PHSD (PHSD-GG): the $P(N_{part})$ distribution is close to the standard Glauber result (Fig. 3(b)). The noted difference is seen in the correlation $N_{ch}/d\eta(\eta = 0)$ vs. $N_{part}$. Both the standard Glauber and CGC results are presented and supporting the results of Ref. [52]. However, the two versions of the PHSD model, with and without cross section fluctuations, predict that the multiplicity dependence turns out to be very close to the CGC result and is only weakly sensitive to the parameter $\Omega$ for the size of fluctuations in the cross section. The reason of such multiplicity suppression is the energy-momentum conservation in PHSD which on average results in a decrease of particle multiplicity in subsequent collisions as compared to the primary interaction. This is directly confirmed by a decrease of the energy density distribution in the longitudinal direction in Fig. 4(b).

A wide distribution is also observed in the number of participants or in the number of charged particles at midrapidity for a given impact parameter $b$, see Fig. 4. The solid lines in this figure show the mean values $\langle N_{part} \rangle$ and $\langle dN_{ch}/d\eta \rangle$, respectively. In contrast to nucleus-nucleus collisions, these mean quantities are almost independent of the impact parameter for central and semi-central collisions, $b \lesssim (4-5)$ fm. This fact should have been expected since the size of the projectile-proton is noticeably smaller than that of the target nucleus. From these results it follows that an event selection with respect to the number of participants or charged particles refers to a large range in impact parameter.

C. Rapidity distribution

The pseudorapidity distributions of charged particles from p-Pb minimum bias collisions at $\sqrt{s_{NN}} = 5.02$ TeV are compared with the experiment data [23] in Fig. 5. The data are displayed in the laboratory system which is shifted with respect to the nucleon-nucleon center-of-mass by $y_{cm} = -0.465$. The results of two versions of the parton-hadron string dynamics model (PHSD and PHSD-GG) differ only for backward-emitted particles and both versions are rather close to the measured data. Note that there are no modifications in the PHSD except the extensions pointed out in Sec. II which implies that p-p, p-A and A-A collisions are consistently described from low SPS to LHC energies (within 10%).

The CGC predictions, performed earlier for the upcoming p-Pb run at the LHC, are plotted in the same figure [28]. This result is based on the Balitsky-Kovchegov (BK) equation [48] which is the large-$N_c$ limit of non-linear renormalization group equations such as the (outlined-above) BK-JIMWLK hierarchy [20] tested with respect to e+p data. The inclusion of running coupling corrections to the evolution kernel of the BK equation
(rcBK model) made it possible to describe various data at high energies in terms of solutions of the rcBK equation [50] and turned out in the best agreement among the compilation of CGC saturated models in Ref. [28]. An astonishing result is that the CGC and PHSD results almost coincide. Note that this minimum-bias distribution corresponds to the mean charged particle multiplicity at the given value of pseudorapidity $\eta$. However, event fluctuations of $dN_{ch}/d\eta$ are very large as demonstrated in Fig. 5(b). Thus, the study of minimum-bias $dN_{ch}/d\eta$ does not allow to disentangle the initial state concepts described within the PHSD and CGC approaches.

Let us, furthermore, consider pseudorapidity distributions for fixed high-multiplicity events. Such distributions for different centrality bins were measured recently by the ATLAS collaboration [49]. Experimentally the centrality was defined according to the selected bins in the transverse energy. However, the PHSD (PYTHIA 6.4) model does not well reproduce the tail of the p-p transverse energy distribution. So, we define bins in $N_{ch}$ keeping the same percentage of the number of selected events as in [49] (the bin partition is shown in Fig. 6(a) and the relative contribution of different centralities is given in the legend in Fig. 6(b)). In this figure the PHSD results are based on $10^6$ simulated events.

As is seen from Fig. 6 the PHSD model correctly reproduces the shape of the $dN_{ch}/d\eta$ distributions and its variation with centrality, in particular the increase with centrality of the forward-backward asymmetry between the directions of the proton-beam and Pb-target. For centralities higher than 20% (see Fig. 6(a)) the model quantitatively agrees with the ATLAS data but for higher
multiplicities it progressively underestimates the particle yield which essentially can be traced back to the underestimation of high multiplicity events in PYTHIA 6.4 (cf. Fig. 1). The centrality sample of 40-60% with the maximal number of charged particles at the maximum of the distribution is about 75, while the PHSD predicts by ~ 10 particles less. Nevertheless, the agreement is not so bad taking into account the experimental error bars.

D. Transverse momentum spectra

The transverse momentum characteristics for charged particles from the PHSD are compared with the ALICE data in Fig. 7. In the measured range $0.5 < p_T < 10$ GeV/c the yield changes by 7 orders of magnitude in a general agreement with experiment [51]. The deviations by about factor of three are observed in the momentum range $p_T \gtrsim 2$ GeV/c (see Fig. 7(a)). These deviations are reflected in the dependence of the mean transverse momentum on the number of charged particles (Fig. 7(b)), which is below the measured data by about 0.05 GeV/c. We note that there is practically no sensitivity to fluctuations in the initial $NN$ cross sections.

A remarkable difference in observables between the predictions of the saturated CGC and hydro models has been noted in Ref. [33]. Based on general arguments, it was shown that in the case of the CGC the mean transverse momentum slightly grows with increasing rapidity due to the increasing saturation momentum of the nucleus (see Fig. 8). On the contrary, the $\langle p_T \rangle_y / \langle p_T \rangle_{y=0}$ in the hydrodynamic framework decreases due to the decreasing number of particles. The collective expansion scenario cannot lead in a simple way to an increase of the average transverse momentum on the proton side $y > 0$ [33]. The PHSD model predicts the $\langle p_T \rangle_y / \langle p_T \rangle_{y=0}$ distribution rather close to the hydrodynamic models; cross section fluctuations have no essential influence on this result. It would be of great interest to check experimentally this clear difference in the $\langle p_T \rangle_y / \langle p_T \rangle_{y=0}$ distribution due to different initial state concepts.

IV. CONCLUSIONS

In this study the parton-hadron-string dynamics (PHSD) approach has been extended to the LHC energy range by implementing the PYTHIA 6.4 generator to describe adequately initial hadron interactions in the TeV energy range and to take into account additionally fluctuations of nucleon-nucleon cross sections. The model quite successfully reproduces observables of p-Pb collis-
sions at $\sqrt{s_{NN}} = 5.02$ TeV, including those for high multiplicity events. The calculated PHSD results have been confronted with predictions from saturation CGC models in order to disentangle the inherent assumptions with respect to the initial state conditions and dynamics. We have found the decisive test of color coherence in the initial state in ultrarelativistic p-Pb collisions (as proposed in [32]) turned out to be not conclusive. The proposal had been based on wounded-nucleon model (WNM) estimates of the fraction of high multiplicity events. However, the WNM does not take into account the energy-momentum conservation law and therefore overestimated this fraction. Our results within the dynamical PHSD calculations are only slightly above the CGC predictions and cross section fluctuations practically do not influence the observables investigated. Accordingly, the considered quantities, – multiplicity, transverse momentum, their distributions and correlations, – do not allow for a firm conclusion on the presence (or absence) of a color glass condensate in a nucleus at 5.02 TeV.

However, we have found that it is more promising to measure the $\langle p_T \rangle_y / \langle p_T \rangle_{y=0}$ distribution (suggested in [33]) to get a more conclusive result since our PHSD calculations provide results very close to hydro calculations with a slope opposite to the CGC models.

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