Impact of initial granularity on the collective flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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Abstract. The Parton-Hadron-String-Dynamics (PHSD) transport model is used to study the influence of initial state granularity of the interacting system on flow observables in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for different centralities. While the flow coefficients $v_2$, $v_3$, $v_4$ and $v_5$ are reasonably described in comparison to the data from the ALICE Collaboration for different centralities within the default setting, no essential sensitivity is found with respect to the initial state granularity even for very central collisions where the flow coefficients are dominated by the size of initial state fluctuations. We attribute this lack of sensitivity to the low interaction rate of the degrees-of-freedom in this very early phase of order $\sim 0.3$ fm/c which is also in common with the weakly interacting color glass condensate (CGC) or glasma approach.

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1. Introduction

Ultra-relativistic nucleus-nucleus collisions allow to study strongly interacting QCD matter under extreme conditions in 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 couple of fm/c [1, 2]. Due to the non-perturbative and non-equilibrium nature of relativistic nuclear reaction systems, their theoretical description is based on a variety of effective approaches ranging from hydrodynamic models with different initial conditions [3, 4, 5, 6, 7, 8, 9, 10, 11, 12] to various kinetic approaches [13, 14, 15, 16, 17, 18, 19, 20, 21] or different types of hybrid models [22, 23, 24, 25, 26, 27, 28, 29]. In the latter hybrid approaches the initial state models are followed by an ideal or viscous hydro phase which after hadronic freeze-out is followed up by a hadronic cascade simulation.

The actual question addressed in this study is whether the initial state granularity of the colliding zone leaves its traces in the collective flow coefficients $v_n$. A color glass condensate (CGC) [30] is expected to lead to sizeably larger fluctuations in the initial energy density as compared to the Glauber model that incorporates fluctuations on the nucleon scale. A similar question has been addressed in the ideal or viscous hydro calculations by the authors of Refs. [31, 32, 33, 34, 35, 36, 37] which have found some sensitivity with respect to higher moments $v_n$.

In the ideal or viscous hydro calculations the initial conditions – at some finite starting time of the order of 0.3 to 0.5 fm/c – have to be evaluated either in terms of the (standard) Glauber model or other initial state scenarios like in the IP-glasma model [31, 32] or the CGC approach, respectively. Differences between the different initial state assumptions and dynamical evolutions thus have to be expected. The applicability of ideal or viscous hydrodynamic models to proton-nucleus reactions for low multiplicity events, however, is very much debated. This also holds for hybrid models as long as they employ a hydro phase. To our knowledge only microscopic transport approaches allow to bridge the gap from p-p to p-A and A-A collisions in a unique way without introducing additional (and less controlled) parameters.

We recall that the flow harmonics $v_n$ for the azimuthal angular distribution of hadrons have been found to be sensitive to the early stage of the nuclear interaction and in particular to their fluctuations. Indeed, the detailed heavy-ion analysis in Ref. [38] shows that Monte Carlo CGC approaches (MC-CGC) systematically give a larger initial eccentricity than Glauber models. However, it is unclear to what extent such properties of the CGC formalism are robust with respect to extended correlations. Also, studies of higher harmonics – as presented in [2] by the PHENIX or ALICE collaborations – do not clearly favor the CGC or Glauber assumptions for the initial state of the collision. The first LHC data on the bulk particle production in Pb-Pb collisions are in good agreement with improved CGC expectations but they are also compatible with Monte Carlo event generators [1, 39].
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The complexity of heavy-ion collisions is reduced essentially in the case of proton-nucleus collisions due to the expected dominance of the initial state effects over final state effects. Recently, we have performed a microscopic transport study of p-Pb collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV and compared our results to the first preliminary ALICE measurement at the LHC of the charged particle pseudorapidity distributions from Ref. [40] for pseudorapidity $|\eta| < 2$ for different multiplicity bins of charged particles $N_{ch}$ [11]. However, these differential pseudorapidity densities do not allow for firm conclusions on the initial state configuration since independent approaches compare reasonably well, too: the saturation models employing coherence effects [42, 43, 44] or the two-component models combining perturbative QCD processes with soft interactions [45, 46]. On the other side, a sizeable difference in the mean transverse momentum of particles $\langle p_T \rangle$ versus the pseudorapidity $\eta$ with opposite slopes in $\eta$ on the projectile side is found within the CGC framework relative to hydrodynamical or transport calculations [41].

We here explore the sensitivity of the initial state granularity on the collective flow coefficients $v_n$ and related quantities in Pb-Pb interactions at the collision energy $\sqrt{s_{NN}} = 2.76$ TeV within the parton-hadron-string-dynamics (PHSD) transport approach [21] which has been properly upgraded to LHC energies with respect to a more recent PYTHIA 6.4 implementation [11]. After a brief reminder of the PHSD approach and generic results for transverse momentum spectra and flow coefficients $v_n(p_T)$ for central and mid-central Pb-Pb collisions in comparison to available data in Sec. 2 we present the actual results for $v_n(p_T)$ for very central Pb-Pb collisions employing different granularities in Sec. 3. We conclude our findings in Sec. 4.

2. PHSD @ LHC

The PHSD model is a covariant dynamical approach for strongly interacting systems formulated on the basis of Kadanoff-Baym equations [47] 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 [48]. 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. [47, 48]). 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. [48]; model results and their comparison with experimental observables for heavy-ion collisions from the lower super-proton-synchrotron (SPS) to relativistic-heavy-ion-collider (RHIC) energies can be found in Refs. [21, 49, 50, 51] including electromagnetic probes such as $e^+e^-$ or $\mu^+\mu^-$ pairs [52] or real photons [53].
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2.1. Extensions @ LHC

To extend the PHSD model to higher energies than $\sqrt{s_{NN}} = 200$ GeV at RHIC, the PYTHIA 6.4 generator [54] has been additionally implemented for initial nucleon collisions at LHC energies [41]. For the subsequent (lower energy) collisions the standard PHSD model [21] is applied (including PYTHIA v5.5 with JETSET v7.3 for the production and fragmentation of jets [55], i.e. for $\sqrt{s_{NN}} \leq 500$ GeV [55]). In this way all results from PHSD up to top RHIC energies are regained and a proper extension to LHC energies is achieved. At $\sim \sqrt{s_{NN}} = 500$ GeV both PYTHIA versions lead to very similar results. In PYTHIA 6.4 we use the Innsbruck pp tune (390) which allows to describe reasonably the p-p collisions at $\sqrt{s_{NN}} = 7$ TeV in the framework of the PHSD transport approach (cf. Fig. 1 in [41]). The overall agreement with LHC experimental data for the distribution in the charged particle multiplicity $N_{ch}$, the charged particle pseudorapidity distribution, the transverse momentum $p_T$ spectra and the correlation of the average $p_T$ with the number of charged particles $N_{ch}$ is satisfactory. Also a variety of observables from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compare quite well with the experimental observations [41].

Figure 1. Mean $p_T$ results for p-p, p-Pb and Pb-Pb collisions from the PHSD transport approach in comparison to the ALICE experimental data from Ref. [56]. Note the different invariant energies for p-p, p-Pb and Pb-Pb collisions.

The first (homework) question to answer is whether the PHSD approach still works at LHC energies for nucleus-nucleus collisions although the invariant energy is higher by about a factor of 13.8 than at the top RHIC energy. In Fig. 1 we compare the mean $p_T$ as a function of charged multiplicity $N_{ch}$ in p-p reactions at $\sqrt{s_{NN}} = 7$ TeV, p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from the PHSD to the experimental data from Ref. [56]. Note that for low multiplicities ($N_{ch} < 5$) the mean $p_T$ is almost independent on energy whereas the increase with $N_{ch}$ sizeably
Granularity test of the initial conditions in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV depends on $\sqrt{s_{NN}}$ (see also Ref. [56]). Nevertheless, the agreement between data and calculations (within the statistical accuracy) is encouraging. In this case, however, only very peripheral Pb-Pb collisions are probed.

2.2. $p_T$-spectra for central Pb-Pb

![Figure 2. Transverse momentum spectra from PHSD in comparison to the results of the ALICE Collaboration for all charged particles [57, 58] (solid line) as well as for charged pions [59] (dashed line).](image)

We continue with the transverse momentum spectra for central Pb-Pb reactions at $\sqrt{s_{NN}} = 2.76$ TeV (0-5% centrality) which are compared in Fig. 2 with results of the ALICE Collaboration for all charged particles [57, 58] (PHSD: black solid line) as well as for charged pions [59] (PHSD: dashed blue line). Note that except for the upgrade in the PYTHIA version no additional parameters or changes have been introduced in the PHSD that had been employed before in Refs. [21, 49, 50, 51, 52, 53] from lower SPS up to top RHIC energies. In this respect the approximate reproduction of the midrapidity $p_T$ spectra for central collisions over 7 orders of magnitude in Fig. 2 is quite remarkable.

2.3. Differential flow results for Pb-Pb

Whereas the transverse charged single-particle spectra compare quite well with the experimental observation the question remains for the collective behavior of the system. In this respect the flow coefficients $v_2$, $v_3$, $v_4$ and $v_5$ of all charged particles from PHSD are shown in Fig. 3 as a function of $p_T$ for the centralities 0-5% (upper part) and 30-40% (lower part) in comparison to the ALICE data from Ref. [60]. The PHSD results for $v_2(p_T)$, $v_3(p_T)$ and $v_4(p_T)$ compare reasonably up to about 3.5 GeV/c whereas at higher transverse momenta the statistics is insufficient to draw robust conclusions. This also
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Figure 3. The flow coefficients $v_2$, $v_3$, $v_4$ and $v_5$ of all charged particles as a function of $p_T$ for the centralities 0-5% (upper part) and 30-40% (lower part). The ALICE data have been taken from Ref. [60]. Note the different scales for the $v_n$-axis on the upper and lower plots!

holds for the flow coefficient $v_5$ which still is in line with the data within error bars. It is quite remarkable that the collective behavior is reproduced not only for semi-central collisions (lower part) but also for 0-5% central collisions (upper part) that are more sensitive to the initial fluctuations [23].

These tests indicate that the 'soft' physics at LHC in central A-A reactions is very similar to the top RHIC energy regime although the invariant energy is higher by more than an order of magnitude. Furthermore, the PHSD approach seems to work from lower SPS energies up to LHC energies for p-p, p-A as well as A-A collisions, i.e. over a range of more than two orders in $\sqrt{s_{NN}}$. 
3. Probing the initial granularity with PHSD

Having established that the PHSD approach gives results for single particle spectra as well as collective flow coefficients roughly in line with experimental observation at LHC energies we now may come to the central question of this study and address the impact of the initial granularity on the collective flow in central Pb-Pb collisions. As discussed in Ref. [51] especially the triangular flow $v_3$ is sensitive to the initial fluctuations in the energy density since the average over an ensemble of events at the same centrality is shape symmetric with vanishing $v_3$. Earlier studies e.g. in Refs. [23, 26] have shown that the elliptic flow $v_2$ in semi-peripheral reactions is dominated by the geometry and less by the initial state fluctuations, however, central collisions do show a sensitivity to these fluctuations. The same arguments hold for $v_4$ which is roughly $\sim v_2^2$ (cf. Fig. 10 of Ref. [51]).

In order to illustrate the local fluctuations in the density we show in Fig. 4 (l.h.s.) the transverse ‘particle’ density at a time $t = 3.5 \times 10^{-3}$ fm/c after contact of the nuclei for a Pb-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV and impact parameter $b = 8$ fm in the default PHSD approach (open red circles) which is comparable to a Monte Carlo Glauber distribution. At this time the two Pb-nuclei have almost passed through each other, however, the initial kinetic energy in violent nucleon-nucleon interactions – as described by PYTHIA 6.4 – is converted to a large extent to new degrees-of-freedom (denoted shortly as partons). This transverse ‘lumpy parton’ distribution shows separable and overlapping clusters which in beam (z-)direction have the shape of string-like configurations (see r.h.s. of Fig. 4). Very similar ‘lumpy’ initial conditions
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have been presented in Refs. [33, 34, 36] and propagated in time by ideal or viscous hydrodynamics. In PHSD this 'parton' distribution is stored on a grid with cell-size $\Delta x = \Delta y, \Delta z = \Delta x/\gamma_{cm}$ where optionally the cell width $\Delta x$ is chosen between 0.2 fm and 1 fm (depending on the question of interest). The actual distributions are point-like and smeared by a Gaussian of width $\sigma$ from 0.2 fm to 1 fm in order to achieve particle/energy distributions of different (lower) granularity. However, in order to simulate a distribution of even higher granularity – as expected for glasma initial conditions [33, 34] – a different strategy has been adopted: a) by means of widely used cluster algorithms, in particular in statistical physics [61] where we can identify 'clusters' of particles, evaluate the total 'cluster' energy and the center of the 'cluster' position; b) in a second more phenomenological scenario the transversal vectors of all 'particles' in the cluster relative to the center of the cluster are multiplied by a common factor $d < 1$ which keeps the 'cluster' position unchanged, however, increases the energy density when evaluated on a fine grid. The full dotted points in Fig. 4 give an example of the algorithm when increasing the granularity by a factor of about three.

Some note of caution has to be added here with respect to the interpretation of 'particles'. Due to the Heisenberg uncertainty relation the energy density at $t \approx 3.5 \times 10^{-3}$ fm/c cannot be specified as being due to 'particles' since the latter may form only much later on a timescale of their inverse transverse mass (in their rest frame). More specifically, a jet at midrapidity with transverse momentum $p_T = 100$ GeV/c is expected to appear at $t \approx 2 \cdot 10^{-3}$ fm/c while a soft parton with transverse momentum $p_T \sim 0.5$ GeV should be formed after $t \approx 0.4$ fm/c. At this time, however, the energy density $\epsilon$ is lower by more than a factor of 100 due to the dominant longitudinal expansion. The question, if these degrees-of-freedom in the early time are coherent gluon fields (glima), perturbative gluons or virtual $q\bar{q}$ pairs is presently open. In Ref. [41] it has been argued that a color glass condensate might be identified by the rapidity dependence of the $p_T$ of charged particles in p-Pb reactions while in Ref. [62] the splitting of the directed flow for hadrons of opposite charge in mid-central and peripheral collisions of asymmetric systems (e.g. Cu-Au) has been advocated as a signal for the early presence of electric charges (i.e. quarks and antiquarks).

In order to exclude any effect from geometry on the flow coefficients we now consider very central Pb-Pb collisions with impact parameter $b = 0$ at $\sqrt{s_{NN}} = 2.76$ TeV and perform an event-by-event analysis. We study two cases: i) standard PHSD evolution with MC Glauber initial condition which leads to parton distribution as shown in Fig. 4 with red empty dots; ii) we artificially increase the granularity of the parton distribution at $t \approx 3.5 \times 10^{-3}$ fm/c by a shift of the cluster transverse vectors as explained before in the scenario b) and shown in Fig. 4 by black solid dots. The results for the flow coefficients $v_2, v_3$ and $v_4$ are shown in Fig. 5 as a function of transverse momentum $p_T$ (upper part) and pseudorapidity $\eta$ (lower part). Here the default PHSD calculations are displayed by the dotted lines while the solid lines result from the same number of events with higher granularity. Within the statistical accuracy achieved we find no apparent sensitivity to the initial state granularity. Our calculations are in line with the viscous
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Figure 5. Flow coefficients $v_2$, $v_3$ and $v_4$ as a function of $p_T$ (upper part) and $\eta$ (lower part) for $b=0$ collisions of Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV. The results for increased granularity (solid lines) are compared with results from the standard PHSD (MC Glauber) initial distributions (dotted lines).

hydro results from Gale et al. [32] for $v_2$ and $v_3$ while higher moments $v_n$ show are more pronounced sensitivity in the hydro calculations which, however, are out of reach for the microscopic PHSD studies.

The reason for the insensitivity to the initial state granularity is essentially due to fact that the system in the very early stage is almost collision-less since only formed partons – with a ‘dressed’ propagator – interact in PHSD. This is demonstrated explicitly for a central Pb-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV for $b = 0$ fm in Fig. 6 where the partonic interaction rate from PHSD is displayed as a function of time $t$ from contact. It is clearly seen that the interaction rate is very low for about 0.2 fm/c; during this time
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the local clusters have increased in transverse diameter by about 0.6 fm such that the density/energy distributions between the default and squeezed initial conditions become similar. This phase of low interaction rate is also assumed in the CGC model and thus is common with PHSD.

4. Conclusions

In this study the parton-hadron-string dynamics (PHSD) approach has been employed in the LHC energy range for Pb-Pb collisions as well as p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. We find that this approach works also reasonably for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with respect to charged particle spectra as well as collective flow coefficients $v_2, v_3, v_4$ and $v_5$ for different centralities with a quality comparable to that achieved at RHIC energies before [21, 49, 50, 51, 52, 53]. Our finding implies that the ‘soft’ physics in Pb-Pb collisions at the LHC and Au-Au interactions at the top RHIC energies – despite a factor of $\sim 14$ in $\sqrt{s_{NN}}$ – is very similar and in line with the dynamical quasiparticle model (DQPM) that defines the parton properties for PHSD in equilibrium. This finding is common with earlier studies using viscous hydro approaches with varying initial conditions [63].

The particular question addressed in this study has been the dependence of the collective flow observables to the initial state fluctuations in the parton density or energy density. The PHSD calculations have shown no sensitivity to the initial state granularity for the flow harmonics $v_2$ to $v_4$ which can be traced back to the low interaction rate in the initial nonequilibrium stage in PHSD ($\sim 0.3$ fm/c) where effects from different granularities are already washed out to some extent. This is different from hydro calculations with varying granularity that instantly start to convert fluctuations in coordinate space to collective modes in momentum space. The low interaction rate
Granularity test of the initial conditions in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in this very early phase in PHSD is common with the CGC concept and thus does not allow to disentangle or determine the effective degrees-of-freedom in this 'pre-hydro' phase.

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References

[1] The BRAHMS Collaboration 2005 *Nucl. Phys. A* **757** 1;
The PHOBOS Collaboration 2005 *Nucl. Phys. A* **757** 28;
The STAR Collaboration 2005 *Nucl. Phys. A* **757** 101;
The PHENIX Collaboration 2005 *Nucl. Phys. A* **757** 184
[2] Schutz Y and Wiedemann U A (ed) 2011 Proc. of the 22nd Int. Conf. on Ultra-Relativistic NucleusNucleus Collisions (Annecy, France, 2328 May 2011) *J. Phys. G: Nucl. Part. Phys.** 38** 120301
[3] Huovinen P et al 2001 *Phys. Lett.* **B** 503 58
[4] Kolb P F, Huovinen P, Heinz U and Heiselberg H 2001 *Phys. Lett.* **B** 500 232
[5] Teaney D, Lauret J and Shuryak E V 2001 *Phys. Rev. Lett.* **86** 4783
[6] Hirano T and Tsuda K 2002 *Phys. Rev. C* **66** 054905
[7] Kolb P F and Rapp R 2003 *Phys. Rev. C* **67** 044903
[8] Huovinen P 2004 *QuarkGluon Plasma 3* ed R C Hwa and X-N Wang (Singapore: World Scientific)
Kolb P F and Heinz U W 2004 *QuarkGluon Plasma 3* ed R C Hwa and X-N Wang (Singapore: World Scientific)
[9] Romatschke P and Romatschke U 2007 *Phys. Rev. Lett.* **99** 172301
[10] Song H and Heinz U W 2008 *Phys. Rev. C** 77** 064901
[11] Luzum M and Romatschke P 2008 *Phys. Rev. C** 78** 034915
[12] Schenke B, Jeon S and Gale C 2010 *Phys. Rev. C** 82** 014903
[13] Geiger K and Müller B 1992 *Nucl. Phys. B** 369** 600
[14] Molnár D and Gyulassy M 2000 *Phys. Rev. C** 62** 054907
[15] Bass S, Müller B and Srivastava D 2003 *Phys. Lett. B** 551** 277
[16] Arsene I C et al 2007 *Phys. Rev. C** 75** 034902
[17] Plumari S, Puglisi A, Scardina F and Greco V 2012 *Phys. Rev. C** 86** 054902
[18] Cassing W and Bratkovskaya E L 1999 *Phys. Rep.** 308** 65
[19] Lin Z W, Ko C M, Li B A, Zhang B and Pal S 2005 *Phys. Rev. C** 72** 064901
[20] Xu Z and Greiner C 2005 *Phys. Rev. C** 71** 064901
Xu Z and Greiner C 2007 *Phys. Rev. C** 76** 024911
Xu Z and Greiner C 2010 *Phys. Rev. C** 81** 054901
[21] Cassing W and Bratkovskaya E L 2009 *Nucl. Phys. A** 831** 215
Bratkovskaya E L et al 2011 *Nucl. Phys. A** 856** 162
[22] Nonaka C and Bass S A 2007 *Phys. Rev. C** 75** 014902.
[23] Petersen H and Bleicher M 2010 *Phys. Rev. C** 81** 044906.
[24] Qin G-Y, Petersen H, Bass S A and Miller B 2010 *Phys. Rev. C** 82** 064903.
[25] Song H, Bass S A and Heinz U 2011 *Phys. Rev. C** 83** 024912.
Granularity test of the initial conditions in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

[26] Petersen H, Coleman-Smith C, Bass S A and Wolpert R 2011 J. Phys. G: Nucl. Part. Phys. 38 045102
[27] Petersen H, Bhattacharya V, Bass S A and Greiner C 2011 Phys. Rev. C 84 054908
[28] Petersen H, la Placa R and Bass S A 2012 J. Phys. G 39 055102
[29] Song H, Bass S A, Heinz U, Hirano T, and Shen C S 2011 Phys. Rev. Lett. 106 192301
Song H, Bass S A, Heinz U, Hirano T, and Shen C S 2012 Phys. Rev. Lett. 109 139904 (erratum)
[30] Gelis F, Iancu E, Jalilian-Marian J and Venugopalan R 2010 Annu. Rev. Nucl. Part. Sci. 60 463
Iancu E and Venugopalan R 2003 QuarkGluon Plasma ed R Hwa and X N Wang (Singapore: World Scientific)
Weigert H 2005 Prog. Part. Nucl. Phys. 55 461
[31] Schenke B, Tribedy P and Venugopalan R 2012 Phys. Rev. C 86 034908
[32] Gale C, Jeon S, Schenke B, Tribedy P, and Venugopalan R 2013 Phys. Rev. Lett. 110 012302
[33] Schenke B, Tribedy P, and Venugopalan R 2012 Phys. Rev. Lett. 108 252301
[34] Bzdak A, Schenke B, Tribedy P, and Venugopalan R 2013 Phys. Rev. C 87 064906
[35] Schenke B, Tribedy P and Venugopalan R 2014 Phys. Rev. Lett. 113 102301
[36] Werner K, Karpenko I, Pierot T, Bleicher M and Mikhailov K 2010 Phys. Rev. C 82 044904
[37] Werner K, Guiot B, Karpenko I and Pierot T 2014 Phys. Rev. C 89 064903
[38] Albacete J L 2011 J. Phys. G: Nucl. Part. Phys. 38 124006
[39] ATLAS Collaboration 2013 J. High Energy Phys. 11 183
[40] Abelev B et al (ALICE Collaboration) 2013 Phys. Rev. Lett. 110 032301
[41] Konchakovski V P, Cassing W and Toneev V D 2014 J. Phys. G 41 105004
[42] Dumitru A, Kharzeev D E, Levin E M and Nara Y 2012 Phys. Rev. C 85 044920
[43] Tribedy P and Venugopalan R 2012 Phys. Rev. Lett. B 710 125
[44] Albacete J L, Dumitru A, Fujii H and Nara Y 2013 Nucl. Phys. A 897 1
[45] Barnafoldi G G, Barrette J, Gyulassy M, Levai P and Topor Pop V 2012 Phys. Rev. C 85 024903
[46] Xu R, Deng W-T and Wang X-N 2012 Phys. Rev. C 86 051901
[47] Juchem S, Cassing W and Greiner C 2004 Phys. Rev. D 69 025006
Juchem S, Cassing W and Greiner C 2004 Nucl. Phys. A 743 92
[48] Cassing W 2009 Eur. Phys. J. Spec. Top. 168 3
Cassing W 2007 Nucl. Phys. A 795 70
[49] Toneev V D, Voronyuk V, Bratkovskaya E L, Cassing W, Konchakovski V P and Voloshin S A 2012 Phys. Rev. C 85 034910
[50] Konchakovski V P, Bratkovskaya E L, Cassing W, Toneev V D and Voronyuk V 2012 Phys. Rev. C 85 011902
[51] Konchakovski V P, Bratkovskaya E L, Cassing W, Toneev V D, Voloshin S A and Voronyuk V 2012 Phys. Rev. C 85 044922
[52] Linnyk O, Cassing W, Manninen J, Bratkovskaya E L and Ko C M 2012 Phys. Rev. C 85 024910
Linnyk O, Bratkovskaya E L, Ozvenchuk V, Cassing W and Ko C M 2011 Phys. Rev. C 84 054917
Linnyk O, Cassing W, Manninen J, Bratkovskaya E L, Gossiaux P B, Aichelin J, Song T and Ko C M 2013 Phys. Rev. C 87 014905
[53] Linnyk O, Cassing W, and Bratkovskaya E L 2014 Phys. Rev. C 89 034908
Linnyk O, Konchakovski V P, Cassing W and Bratkovskaya E L 2013 Phys. Rev. C 88 034904
[54] Sjostrand T, Mrenna S and Skands P Z 2006 J. High Energy Phys. 05 026
[55] Bengtsson H-U and Sjostrand T 1987 Comput. Phys. Commun. 46 43
[56] Abelev B B et al. [ALICE Collaboration] 2013 Phys. Lett. B 727 371
[57] Abelev B B et al. [ALICE Collaboration] 2013 Phys. Lett. B 720 52
[58] Abelev B B et al. [ALICE Collaboration] 2013 Eur. Phys. J. C 73 2662
[59] Abelev B B et al. [ALICE Collaboration] 2014 Phys. Lett. B 736 196
[60] Aamodt K et al. [ALICE Collaboration] 2011 Phys. Rev. Lett. 107 032301
Granularity test of the initial conditions in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

[61] E. Luitjen, Introduction to cluster Monte Carlo algorithms, Lect. Notes Phys. 703 13 (2006).
[62] Voronyuk V, Toneev V D, Voloshin S A, and Cassing W, arXiv:1410.1402 [nucl-th]
[63] Song H, Bass S A and Heinz U 2011 Phys. Rev. C 83 054912
    Song H, Bass S A and Heinz U 2013 Phys. Rev. C 87 014902
    Song H, Bass S A and Heinz U 2014 Phys. Rev. C 89 034919