Identified Particle Spectra and Anisotropic Flow in an Event-by-Event Hybrid Approach in Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

Hannah Petersen

Department of Physics, Duke University, Durham, North Carolina 27708-0305, United States

The first results from heavy ion collisions at the Large Hadron Collider for charged particle spectra and elliptic flow are compared to an event-by-event hybrid approach with an ideal hydrodynamic expansion. This approach has been shown to successfully describe bulk observables at RHIC. Without changing any parameters of the calculation the same approach is applied to Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). This is an important test if the established understanding of the dynamics of relativistic heavy ion collisions is also applicable at even higher energies. Specifically, we employ the hybrid approach with two different equations of state and the pure hadronic transport approach to indicate sensitivities to finite viscosity. The centrality dependence of the charged hadron multiplicity, \( p_T \) spectra and differential elliptic flow are shown to be in reasonable agreement with the ALICE data. Furthermore, we make predictions for the transverse mass spectra of identified particles and triangular flow. The eccentricities and their fluctuations are found to be surprisingly similar to the ones at lower energies and therefore also the triangular flow results are very similar. Any deviations from these predictions will indicate the need for new physics mechanisms responsible for the dynamics of heavy ion collisions.

PACS numbers: 25.75.-q,24.10.Lx,24.10.Nz

Recently, the first results from heavy ion collisions at \( E_{cm} = 2.76A \text{ TeV} \) have been published by the ALICE collaboration [1]. To study strongly interacting matter at high temperatures has been the goal of the relativistic heavy ion program at the Relativistic Heavy Ion Collider (RHIC) since more than a decade. The 10 times higher beam energies at the Large Hadron Collider (LHC) allow for the investigation of the dynamical evolution of nucleus-nucleus collisions that have been established in Au+Au collisions at \( E_{cm} = 200A \text{ GeV} \) in a different kinematic range [2]. It is especially interesting, if the matter still behaves as a almost perfect liquid or if the quark gluon plasma becomes more viscous by going to higher temperatures [3–5].

Hybrid approaches that are based on hydrodynamics for the hot and dense stage of the evolution that is coupled to hadronic transport approaches to describe the successive decoupling of the matter have been very successful in describing the properties of the bulk matter that is created at RHIC [6–13] and LHC [14–15]. Within the last year, full-event-by-event hydrodynamic approaches [16–21] have become more favorable because it has turned out that the effect of initial state fluctuations on final flow observables needs to be studied in a consistent way to draw quantitative conclusions for e.g. the value of the shear viscosity.

It is important to apply well-established approaches for the dynamical evolution of heavy ion reactions at RHIC to the higher energy collisions at LHC without tuning parameters to investigate how good the energy dependence is described by a specific model. Differences between the experimental data and the theoretical calculations imply the need for new physics concepts to be applied. To understand the bulk evolution at LHC energies is a prerequisite for all further detailed studies of e.g. jet quenching and energy loss or electromagnetic probes [22–23].

In this manuscript a event-by-event hybrid approach based on the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) transport approach with an embedded (3+1) dimensional ideal hydrodynamic evolution is applied to lead-lead collisions at LHC energies. First, a comparison to the available experimental data on charged particle multiplicities, \( p_T \) spectra and elliptic flow is carried out with the exact same parameter set that has been applied at RHIC energies. Then, transverse mass spectra and triangular flow for identified particles are predicted. To compare the amount of initial state fluctuations, the probability distributions of coordinate space eccentricities are compared to their corresponding values at RHIC.

Let us start with a short description of the hybrid approach that has been developed for SPS energies [18] and recently successfully applied to gold-gold collisions at the highest RHIC energy [24–26]. The early non-equilibrium evolution is described by the UrQMD approach [27–28], where the two lead nuclei are initialized according to Wood-Saxon profiles followed by binary interactions of the nucleons. The main contribution to the particle production at high energies is achieved by string excitation and fragmentation where for the hard collisions (momentum transfer \( Q > 1.5 \text{ GeV} \)) are treated by PYTHIA [29–31].

At the so called starting time of \( t_{\text{start}} = 0.5 \text{ fm} \) the particle distributions are transferred to energy, momentum and net baryon density distributions by representing each particle with a three-dimensional Gaussian distribution (width \( \sigma = 1 \text{ fm} \)) that is Lorentz-contracted along the beam direction. During the following ideal relativistic one fluid evolution [32–33] two different equations of state are employed, one representing a hadron gas (HG-EoS) and one including a cross-over deconfinement phase transition based on a chiral approach (DE-EoS) [34–35]. The transition back to the hadronic transport approach
happens on a constant proper time hypersurface, where the Cooper-Frye equation is applied on transverse slices of thickness $\Delta z = 0.1 - 0.2 \text{ fm}$ that have cooled down below an energy density of $5\epsilon_0 \approx 730 \text{ MeV/fm}^3$. This approach provides the full final phase space distributions of the produced particles for each event and can be compared to the pure transport approach by turning off the hydrodynamic evolution which allows for a qualitative study of viscous effects.

The first observable to look at is the charged particle multiplicity at midrapidity. In Fig. 1 the calculation of the centrality dependent multiplicity scaled by the number of participants (estimated in a Glauber approach) is shown. The hadronic transport approach UrQMD provides a reasonable description of the multiplicity. For central collisions the predictions published in [37] are right on top of the ALICE data while with decreasing centrality the number of charged particles is a little lower than in the data. This fair agreement with the data hints to the fact that the main particle production can be described by the initial binary nucleon-nucleon interactions treated by PYTHIA. The hydrodynamic evolution does not affect the particle production. Since ideal hydrodynamics implies an isentropic expansion this means that the charged particle multiplicity is determined in the initial state and by the final resonance decays.

For the following calculations of spectra and collective flow four different centrality classes have been chosen that match the ones applied by the ALICE collaboration as they are listed in the following table:

| Centrality class | Impact parameter range |
|------------------|------------------------|
| 0-5%             | $b < 3 \text{ fm}$     |
| 5-10%            | $b = 3 - 5 \text{ fm}$ |
| 10-20%           | $b = 5 - 7 \text{ fm}$ |
| 20-40%           | $b = 7 - 10 \text{ fm}$|

The transverse momentum spectrum for charged particles in the mentioned centrality classes are compared to experimental data in the most central bin (see Fig. 2). The main difference between the hybrid and the transport calculation is in the slopes of the spectra. As expected the hydrodynamic evolution leads to a purely exponential $p_T$ dependence which describes the data until $p_T < 3 \text{ GeV}$ very well. At higher transverse momenta the power law tail from hard processes becomes important for a good agreement with the measured values. In the range from 4 to 6 GeV the non-equilibrium description exemplified by the UrQMD calculation provides a better description of the experimental data.

In Fig. 3 predictions for the transverse mass spectra at midrapidity of pions, kaons and protons are presented. The pion spectra are very similar to the charged particle spectra since they represent the major fraction of the newly produced particles in the collision. Kaons are strange mesons and protons are chosen because they have a higher mass and are baryonic degrees of freedom. The general features of the transverse mass spectra are similar to the ones observed at RHIC and imply a col-
FIG. 3: (Color online) Transverse mass spectra of negative pions (top), positive kaons (middle) and protons (bottom) for four different centralities calculated in the hybrid approach with two different equations of state.

Collective radial velocity that drives all the particle species. The two different equations of state lead to very similar results with the deconfinement transition having a little steeper slope due to the more rapid expansion due to the higher pressure in the quark gluon plasma phase.

After proving a rather successful agreement with basic quantities like the multiplicity and transverse momentum spectrum the next step is to look at anisotropic flow observables. The elliptic flow has been calculated with respect to the reaction plane by averaging over all charged particles in all events to be compared to the ALICE measurement that relies on the four-particle cumulant method in two centrality bins. Fig. 4 shows a good agreement between the hybrid calculations and the data, especially between $p_T=0.8-2.5$ GeV. In the very low transverse momentum region the hybrid approach underpredicts the data which has been observed in other calculations as well [14]. At higher $p_T$ again the influence of hard processes needs to be taken into account.

To quantify the shape of the initial conditions employed for the hydrodynamic calculation and its event-by-event fluctuations Fig. 5 shows the probability distribution of the coordinate space asymmetry characterized by the eccentricity and the triangularity as defined in [25]. The initial $c_n$ coefficients have been calculated in each event and the normalized probability distribution is plotted for two different centrality bins.

For central collisions the mean value and the shape of the distributions are very similar for the participant eccentricity and the triangularity since both of them are mainly generated by fluctuations. For more peripheral collisions the eccentricity is influenced by a large geometry component due to the ellipsoidal shape of the initial state in the transverse plane. Therefore, the mean eccentricity is larger and the fluctuations increase leading to a wider distribution, whereas the triangularity stays smaller and the distribution has a smaller width.

Since the triangularity has been introduced because of its sensitivity to initial state fluctuations the higher multiplicity at LHC energies triggers the expectations that the fluctuations become smaller compared to RHIC energies. In Fig. 5 the triangles and diamonds depict the eccentricity and triangularity calculation from UrQMD initial conditions for Au+Au collisions at $E_{cm} = 200$ A GeV. Surprisingly, the $c_n$ distributions match almost exactly the ones at LHC energies for the two similar cen-
hybrid approach for four different centrality classes of Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared in two centrality bins to the corresponding results of the UrQMD transport approach.

Finally in Fig. 7 predictions for the transverse momentum dependence of triangular flow for charged particles in the four different centrality classes are made. There is a weak centrality dependence, but overall the different curves from the hybrid calculation look very similar qualitatively. Since the calculation with the deconfinement phase transition leads to very similar results, only the hadron gas result is shown in this figure to reduce the number of lines displayed. To investigate the effect of a finite viscosity during the expansion the calculation is compared to the pure UrQMD result. Within the very viscous hadronic transport approach the pressure gradients are too small to transfer the initial coordinate space asymmetry to a final state momentum space asymmetry. For impact parameters up to $b = 5$ fm the result is consistent with zero and even for very peripheral event the result is negligible especially in the low transverse momentum region where most of the particles are. This leads to the conclusion that a finite triangular flow measurement is a strong indication for almost ideal hydrodynamic behavior during the hot and dense evolution of the heavy ion reaction.

To summarize we have presented a comparison of bulk observables measured in Pb+Pb collisions at $E_{cm} = 2.76A$ TeV to a state-of-the-art event-by-event hybrid
description. Employing the same parameters as have been used for Au+Au collisions at RHIC a reasonably good agreement for the multiplicity, transverse momentum spectra and elliptic flow is achieved. One can conclude that the basic assumptions about the major ingredients that are needed to describe the dynamic evolution of heavy ion reactions do not have to be revised at LHC energies.

With a non-equilibrium initial state, an ideal hydrodynamic evolution and a hadronic afterburner predictions for identified particle transverse mass spectra and elliptic as well as triangular flow are made. The initial state fluctuations quantified by the probability distribution of the initial eccentricity and triangularity are very similar at LHC and RHIC energies within the UrQMD approach. A large viscosity during the evolution results in almost negligible higher harmonic coefficients, so the triangular flow measurement at LHC will provide a robust confirmation of the almost ideal hydrodynamic expansion.

Acknowledgements

We are grateful to the Open Science Grid for the computing resources. The author thanks Dirk Rischke for providing the 1 fluid hydrodynamics code. H.P. acknowledges a Feodor Lynen fellowship of the Alexander von Humboldt foundation. This work was supported in part by U.S. department of Energy grant DE-FG02-05ER41367. H.P. thanks Jan Steinheimer for help with the extension of the equation of state, Guangyou Qin for providing the Glauber calculation of the number of participants and Steffen A. Bass and Berndt Müller for fruitful discussions.

[1] K. Aamodt et al. [ALICE Collaboration], Phys. Rev. Lett. 106, 032301 (2011) [arXiv:1012.1657 [nucl-ex]].
[2] K. Aamodt et al. [ALICE Collaboration], Phys. Lett. B 696, 30 (2011) [arXiv:1012.1004 [nucl-ex]].
[3] K. Aamodt et al. [The ALICE Collaboration], arXiv:1011.3914 [nucl-ex].
[4] K. Aamodt et al. [The ALICE Collaboration], Phys. Rev. Lett. 105, 252301 (2010) [arXiv:1011.3916 [nucl-ex]].
[5] N. Armesto et al., J. Phys. G 35, 054001 (2008) [arXiv:0711.0974 [hep-ph]].
[6] M. Luzum, Phys. Rev. C 83, 044911 (2011) [arXiv:1011.5173 [nucl-th]].
[7] H. Niemi, G. S. Denicol, P. Huovinen, E. Molnar and D. H. Rischke, arXiv:1101.2442 [nucl-th].
[8] H. Song, S. A. Bass and U. W. Heinz, arXiv:1103.2380 [nucl-th].
[9] R. A. Lacey, A. Taranenko, N. N. Ajitanand and J. M. Alexander, Phys. Rev. C 83, 031901 (2011) [arXiv:1011.6328 [nucl-th]].
[10] S. A. Bass and A. Dumitru, Phys. Rev. C 61, 064909 (2000) [arXiv:nucl-th/0001033].
[11] D. Teaney, J. Lauret and E. V. Shuryak, arXiv:nucl-th/0110037.
[12] T. Hirano, U. W. Heinz, D. Kharzeev, R. Lacey and Y. Nara, Phys. Lett. B 636, 299 (2006) [arXiv:nucl-th/0511046].
[13] C. Nonaka and S. A. Bass, Phys. Rev. C 75, 041902 (2007) [arXiv:nucl-th/0607018].
[14] T. Hirano, P. Huovinen and Y. Nara, arXiv:1012.3955 [nucl-th].
[15] B. Shenke, S. Jeon and C. Gale, arXiv:1102.0575 [hep-ph].
[16] R. Andrade, F. Grassi, Y. Hama, T. Kodama and O. J. Socolowski, Phys. Rev. Lett. 97, 202302 (2006) [arXiv:nucl-th/0608067].
[17] B. M. Tavares, H. J. Drescher and T. Kodama, Braz. J. Phys. 37, 41 (2007) [arXiv:hep-ph/0702224].
[18] H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C 78, 044901 (2008) [arXiv:0806.1605 [nucl-th]].
[19] H. Holopainen, H. Niemi and K. J. Eskola, Phys. Rev. C 83, 034901 (2011) [arXiv:1007.0365 [hep-ph]].
[20] K. Werner, I. Karpenko, T. Pierog, M. Bleicher and K. Mikhailov, Phys. Rev. C 82, 044904 (2010) [arXiv:1004.0805 [nucl-th]].
[21] B. Shenke, S. Jeon and C. Gale, Phys. Rev. Lett. 106, 042301 (2011) [arXiv:1009.3243 [hep-ph]].
[22] T. Renk, H. Holopainen, R. Paatelainen and K. J. Eskola, arXiv:1103.5308 [hep-ph].
[23] H. Holopainen, S. Rasanen and K. J. Eskola, arXiv:1104.5371 [hep-ph].
[24] H. Petersen, T. Renk and S. A. Bass, Phys. Rev. C 83, 014916 (2011) [arXiv:1008.3846 [nucl-th]].
[25] H. Petersen, G. Y. Qin, S. A. Bass and B. Muller, Phys. Rev. C 82, 044901 (2010) [arXiv:1008.0625 [nucl-th]].
[26] H. Petersen, C. Coleman-Smith, S. A. Bass and R. Wolpert, J. Phys. G 38, 045102 (2011) [arXiv:1012.4629 [nucl-th]].
[27] S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998) [Prog. Part. Nucl. Phys. 41, 225 (1998)] [arXiv:nucl-th/9803035].
[28] M. Bleicher et al., J. Phys. G 25, 1859 (1999) [arXiv:hep-ph/9909407].
[29] H. Petersen, M. Bleicher, S. A. Bass and H. Stocker, arXiv:0805.0567 [hep-ph].
[30] B. Nilsson-Almqvist and E. Stenlund, Comput. Phys. Commun. 43, 387 (1987).
[31] T. Sjostrand, Comput. Phys. Commun. 82, 74 (1994).
[32] D. H. Rischke, S. Bernard and J. A. Maruhn, Nucl. Phys. A 595, 346 (1995) [arXiv:nucl-th/9504018].
[33] D. H. Rischke, Y. Pursun and J. A. Maruhn, Nucl. Phys. A 595, 383 (1995) [Erratum-ibid. A 596, 717 (1996)] [arXiv:nucl-th/9504021].
[34] J. Steinheimer, V. Dexheimer, H. Petersen, M. Bleicher, S. Schramm and H. Stoecker, Phys. Rev. C 81, 044913 (2010) [arXiv:0908.3009 [hep-ph]].
[35] J. Steinheimer, S. Schramm and H. Stoecker, arXiv:0909.4421 [hep-ph].
[36] H. Petersen, J. Steinheimer, M. Bleicher and H. Stocker, J. Phys. G 36, 055104 (2009) [arXiv:0902.4860 [nucl-th]].
[37] M. Mitrovski, T. Schuster, G. Graf, H. Petersen and M. Bleicher, Phys. Rev. C 79, 044901 (2009) [arXiv:0812.2041 [hep-ph]].