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Vorticity evolution in hydrodynamical expansion of the fireball

A. Reina Ramírez,[a,*] **V.K. Magas,**[a] **L.P. Csernai,**[b,c] **L. Bravina**[d] **and E. Zabrodin**[d]

[a] *Departament de Fisica Quantica i Astrofisica and Institut de Ciencies del Cosmos University of Barcelona, 08028-Barcelona, Spain*

[b] *Institute of Physics and Technology, University of Bergen, Allegaten 55, 5007 Bergen, Norway*

[c] *Frankfurt Institute for Advanced Studies (FIAS) Ruth-Moufang-Str. 1, 60438, Frankfurt am Main, Germany*

[d] *Department of Physics, University of Oslo P.O. Box 1048 Blindern, N-0316 Oslo, Norway*

E-mail: areinara50@alumnes.ub.edu, vladimir@fqa.ub.edu

Relativistic Heavy Ion Collisions allow to create ultra hot and dense systems, where a phase transition from hadronic matter to quark-gluon matter is expected to occur. Nowadays the progress of experimental techniques allows to analyze these collisions on an event-by-event basis, and the most advanced theoretical simulations are performed within the so-called hybrid models, where different stages of the reaction are each simulated with the most suitable theoretical approach. Our group also uses such a hybrid approach – initial stages are simulated with Generalized Effective String Rope Model [1], then the system expansion is simulated using 3+1D Particle-in-Cell relativistic hydrodynamical module, which is later coupled to SMASH hadron cascade [2, 3]. However, in this presentation I want to concentrate on the results of the first two modules related to the production and further evolution of the vorticity in relativistic flow. Results at different collision energies and reaction centralities will be presented, and we shall verify whether the helicity conservation law, recently propose in [4], is satisfied in our simulations.

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Relativistic Heavy Ion Collisions provide the opportunity to study the fundamental properties of matter at extreme temperatures and densities. Facilities including the Relativistic Heavy-Ion Collider (RHIC) at BNL or the Large Hadron Collider (LHC) at CERN realize such collisions, each focused on a particular energy range of interest. This make possible to explore the QCD phase diagram and look for the signatures of the phase transition and critical end point.

In this work, we introduce a modular hybrid approach for simulating heavy ion reactions at RHIC Beam Energy Scan range $\sqrt{S_{NN}} = 27.0 - 200.0$ GeV. Our hybrid model is still being tested at the moment of writing this paper, and thus the presented results are preliminary. Nevertheless, these can be used, for example, to study the influence of different initial states on experimental observables and the vorticity evolution during the hydrodynamical stage of the collision.

We employ four main modules in order to simulate the relativistic heavy ion collision. The physics behind each of these modules is rather different, therefore each of them is simulated with the most suitable theoretical approach. The whole evolution in our model looks like follows: initial state (IS), relativistic hydrodynamic expansion with EoS, which allows for QGP-hadron matter phase transition [5], particlization (realized using CORNELIUS algorithm [6] to determine particlization hypersurface based on following condition for the rest frame energy density $e_{par} = 732$ MeV/fm^3, and then applying the so called SMASH-hadron-sampler algorithm [7, 8], which statistically generates hadrons on a particlization hypersurface in correspondence with all conservation laws) and, finally, afterburner, realized with SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) code [2, 3], a relativistic hadronic transport approach including all well-established hadrons up to a mass of ~ 2 GeV as degrees of freedom.

The hydrodynamic phase we can describe either with vHLLE, a 3+1 dimensional viscous relativistic hydrodynamic code working in (τ, η) coordinates [9], or with Particle-in-Cell (PIC), an ideal relativistic hydrodynamic program working in (t, z) coordinate space [10]. Correspondingly, the IS is need either at some constant initial proper time τ or at some constant time t.

The initial state, which is the most difficult part for simulation, spreads out from just before the nuclei make first contact till the moment than our system reaches local equilibrium. Currently we make use of two different initial states: the state-of-the-art SMASH IS at constant τ hypersurface, and the Generalized Effective String-Rope Model (GESRM) IS at constant t.

The state-of-the-art SMASH IS is calculated using the same SMASH transport code in the high energy density regime and later realizing the so called "fluiditation" process [8]. The GESRM [1] describes fluctuating initial states of relativistic heavy ion collisions through the implementation of the Glauber Monte Carlo approach on the Effective String Rope Model [11], a 1D Bjorken based effective model which takes into account the baryon recoil by formation of chromo-electric string fields.

Thus, we can compare two rather different simulations for the Au+Au collision at 31.2+31.2 GeV/nucl energy with the impact parameter $b = 7$ fm (this reaction was measured at RHIC@BNL): GESRM+PIC hydro+SMASH - this initial state is tried in the full simulation for the first time; and SMASH+vHLLE+SMASH - which is known to reproduce well experimental data in the RHIC energy region [8]. Of course, we intent to couple these modules respecting all the conservation laws, however in practice there are some errors related to intermodule coupling, both on numerical and physical levels, for example the particlization procedure has an unsolved problem of negative Cooper-Frey contributions [6]. In the case of SMASH+vHLLE+SMASH these errors have been studied in Ref. [8] and are rather small (<8%), while for GESRM+PIC hydro+SMASH our analysis shows bigger errors, which can reach 15-20%.

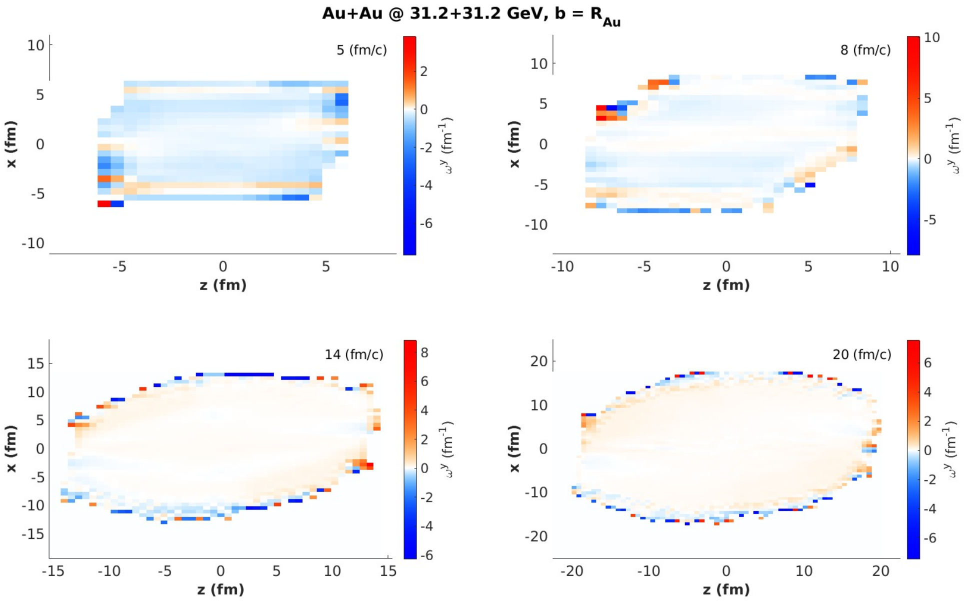

Figure 1: Y-component of relativistic vorticity in the reaction plane.

It is known that the GESRM IS generates a rather large initial flow vorticity [1]. The flow vorticity is interesting and important, because it is responsible polarization of emitted particles, what was recently confirmed by the experiments data from STAR collaboration on global polarization of $\Lambda(\bar{\Lambda})$ hyperons at non-zero impact parameter in Au+Au collisions [12]. In Fig. 1 we show the further vorticity evolution within the PIC hydro code. We have checked that the helicity conservation law, recently propose in [4], is not followed in our hydro simulation. The reason is that it is derived under the streak condition of ideal fluid, i.e. with zero viscosity, however, the PIC hydro algorithm generates numerical viscosity [13], which violates the equations of Ref. [4].

To convert fluid into particles we construct a 3D hypersurface by means of Cornelius algorithm [6]. This particlization hypersurface is built at given critical energy density, for which the matter is supposed to be on hadronic phase. Figure 2 shows particlization hypersurfaces in the reaction plane. Once the particlization hypersurface has been closed we apply SMASH-hadron-sampler algorithm, based on Ref. [6], to sample the fluid into particles, and these particle spectra are used as initial conditions for further afterburner evolution.

Figure 2 clearly demonstrates that IS has a very important, fundamental, effect on for the hydrodynamical evolution of the fireball. Comparing the particlization hypersurfaces for two above mentioned simulations, we can see that the SMASH IS simulation follows more a Bjorken transparency scenario, and consequently the hadrons are generated effectively by two sources moving in positive and negative beam directions; while GESRM IS simulation is more based on stopping (Landau's scenario) and correspondingly the hadrons are mostly produced from the one stopped source.

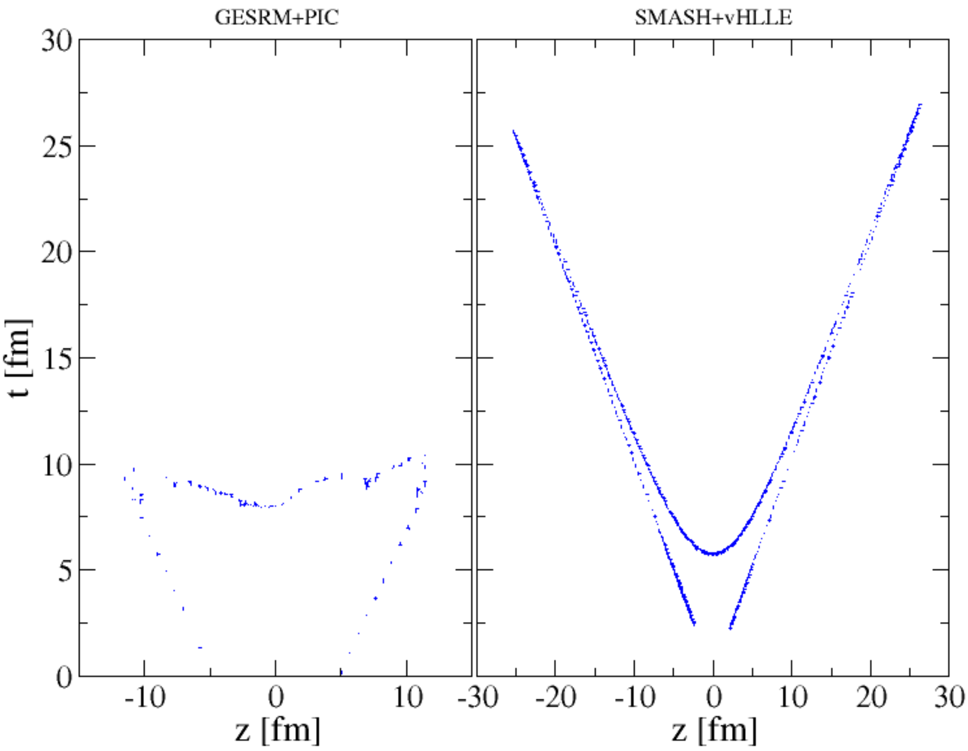

Figure 2: Particlization hypersurface (e_{par} = 732 MeV/fm^3 left plot and e_{par} = 500 MeV/fm^3 right plot) from different hybrid approaches.

The later observation plays a very important role in the overall particle production in the collision. Figure 3 shows the dN/dy spectra for different hadrons. In all the cases we can see the same effect: although the overall energy and baryon and electric charges of the produced particles are the same (with the accuracy of the simulation) GESRM IS simulation produces more particles with less average momenta, while the SMASH IS simulation, which are in good agreement with the experimental spectra [8], produce less particles of all types but with a higher average momenta, and thus the distributions are lower, but wider.

Summarizing our preliminary results (not all of these were discussed in these Proceedings due to limited space) we can say that the GESRM+PIC hydro+SMASH hybrid model is doing a reasonable job with elliptic flow and has some interesting features related to vorticity production, but, at the moment, it overshoots experimental data on the production of different hadron species and do not agree with the width of experimental dN/dy distributions. The work is in progress.

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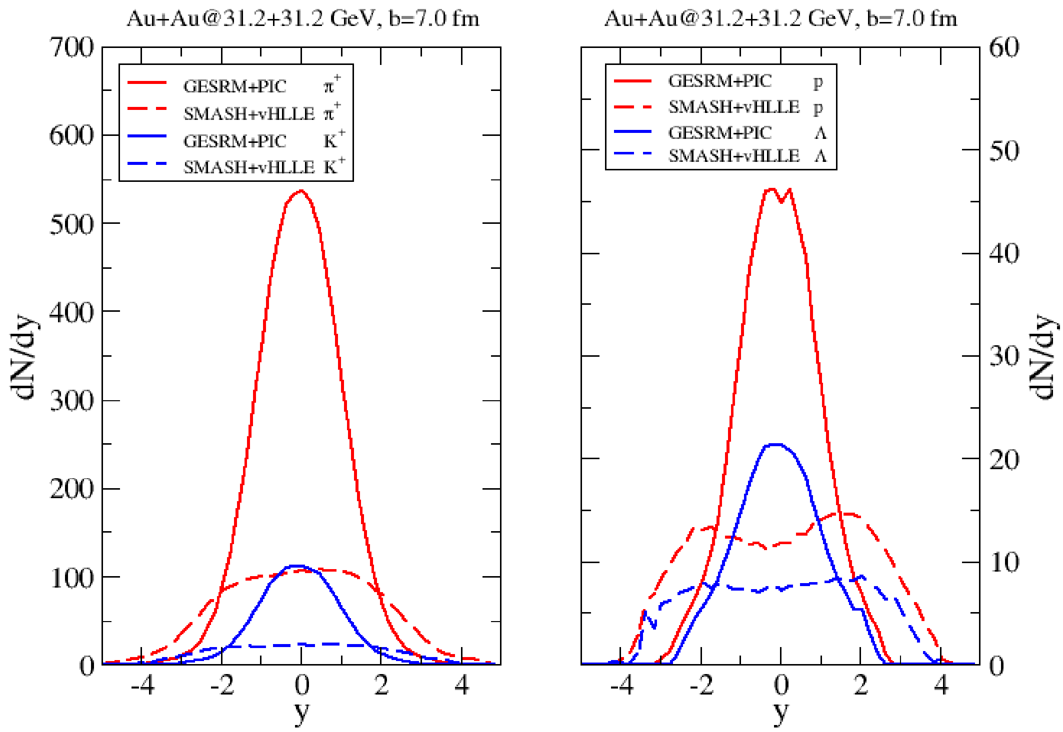

Figure 3: Comparison of dN/dy spectra for π^+, K^+, p and Λ.

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