JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin Laboratory of High Energy Physics

# FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Study of vorticity and helicity according to model data from SMASH in Au+Au collisions $\sqrt{s_{NN}} = 11.5$ GeV

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# 1 Abstract

We study the structure of votricity and hidrodynamic helisity fields in non-central heavy ion collisions. Using the Simulating Many Accelerated Strongly-interacting Hadrons (SMASH) model we perform the numerical simulations of Au+Au collisions at energy $\sqrt{s_{NN}} = 11.5$ GeV. In this research velocity, vorticity and helicity was calculated using different definitions of cell velocity.

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# 2 Introduction

The high-energy heavy-ion collisions provides us unique opportunity to study strongly interacting matter in laboratory. In peripheral high energy heavy ion collisions the system has a large angular momentum in the direction perpendicular to the reaction plane [1]. After the collision, part of total angular momentum is saved in the quark-gluon plasma. This fraction of the angular momentum is manifested as a shift in the longitudinal momentum density and it has been shown in hydrodynamical computation that this leads to a large shear and vorticity [2]. In hydrodynamics, the vorticity represents the local angular velocity, and it leads to interesting effects. For example may occur phenomena like rotation [3], or even turbulence [4] [5]. Also the large angular momentum may show itself in the polarization of secondary produced particles [6].

# 3 Basic concepts and methodology

## 3.1 Velocity and vorticity

We start our studies with the structure of velocty and vorticity fields. We will consider these values as the average for all particles in a given phase volume.

Mathematically the velocity field can be defined as double sum over the particles in phase volume and over all simulated collisions: [7]

$$\vec{v}(x, y, z, t) = \frac{\sum_i \sum_j \vec{P}_{ij}}{\sum_i \sum_j E_{ij}} \tag{1}$$

where $\vec{P}_{ij}$ and $\sum_j E_{ij}$ are the momentum and full energy of particle i in the collision j, respectively.

Another way of calculating velocity field is to sum particle velocities:

$$\vec{v}(x, y, z, t) = \sum_i \sum_j \frac{\vec{P}_{ij}}{E_{ij}} \tag{2}$$

Unlike in classical hydrodynamics, where vorticity is defined as:

$$\omega = \nabla \times \vec{v} \tag{3}$$

several vorticities can be defined in relativistic hydrodynamics according to different physical conditions [6].

## 3.2 Helicity

Helicity is a pseudoscalar characteristic of vorticity:

$$H = \int dV (\vec{v} * \vec{\omega}) \tag{4}$$

that is associated with a number of interesting phenomena in hydrodynamics and plasma physics, such as turbulent Dynamo and Lagrangian chaos [7]. It is the extent to which corkscrew-like motion occurs

# 4 The SMASH model

## 4.1 Model overview

SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) model, created in 2018, is based on hadronic transport approach. This approach have been successfully applied to describe the dynamical evolution of heavy ion collisions since many years. The goal of model is to provide baseline calculations with hadronic vacuum properties to identify signals of the phase transition to the quark-gluon plasma.All information about the model can be read [8].

The main advantage of microscopic transport approach is that the full phase-space information of all particles is available at all times. Model uses the most well-established hadronic states from the Review of Particle Properties [9] with their corresponding decays and cross sections.

It constitutes an effective solution of the relativistic Boltzmann equation with binary interactions. Most interactions proceed via resonance excitation and decay at lower energies or string excitation and fragmentation at higher energies.

## 4.2 Event generating

For all calculations SMASH-1.6 has been used.

Was generated $10^6$ of Au+Au collisions at energy $\sqrt{s_{NN}} = 11.5$ GeV with time $t < 20fm/c$ after collision and time step $\delta t = 1fm/c$. The impact parameter is in range from 0 to 10 with "quadratic" distribution - use areal input sampling (the probability of an input parameter range is proportional to the area corresponding to that range $sP(b) = b * db$).

Potentials was off. Fermi motion was set frozen. Calculation Frame used center of velocity.

# 5 Velocity and vortisity fields

## 5.1 Velocity weighting

To make the distribution of particles more uniform in coordinates and in momenta, a Gauss weighting was made. At fig. 1 the three plane projection of the cell velocity (1) for all particles with no weighting at time $t = 10fm/c$. This is projections from 3d plot, and they sum all slices (near less than 40). So we the values are more than 1. However at 1 slice this distribution looks like 1 right down figure. So velocity lowers to the center.

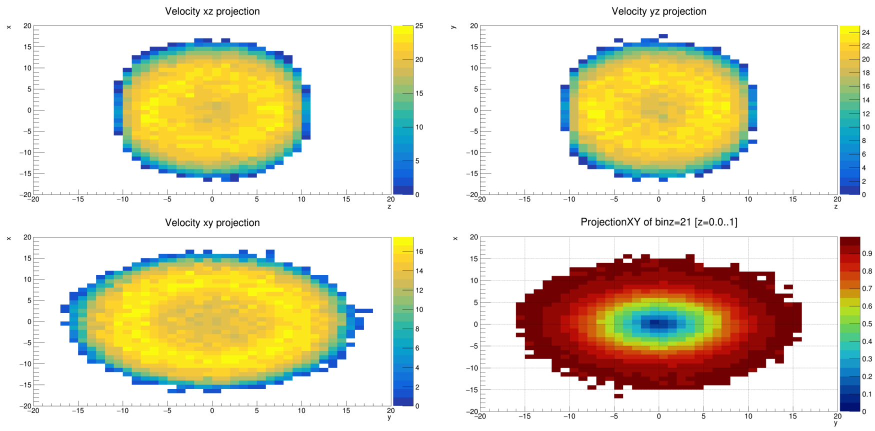


Figure 1: The three plane projection of not weighted velocity at t=10fm/c and right bottom 1 slice XY projection, z=0-1 fm/c.

The same was made for weighted particles. As we can see at fig 2 weighted velocity is smoother. This means that it is less susceptible to random fluctuations. And when we will calculate the derivatives numerically, the values will be more even and accurate.

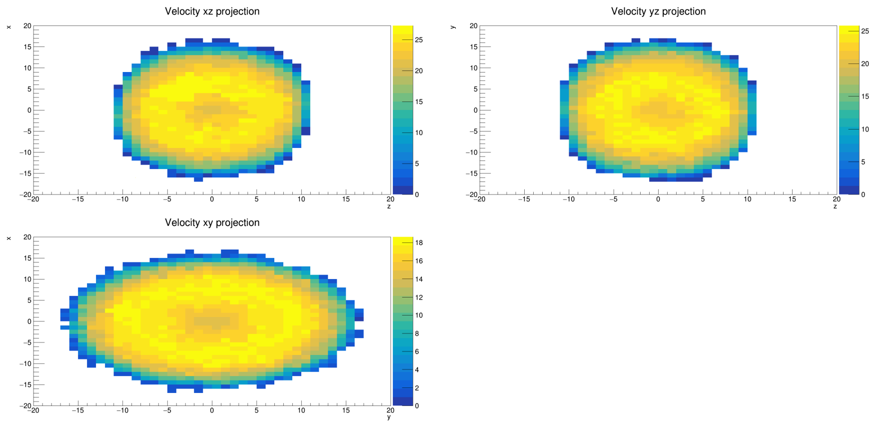


Figure 2: The 3 plane projections of weighted velocity at t=10fm/c

## 5.2 Vorticity calculation

The vorticity was calculated using discrete partial derivatives. We use numerical differentiation by three nodes, where possible, and differentiation by two nodes was used at the edges.

At the figure 3 is shown vorticity projection in reaction plane at y from 0 to 1 fm/c. We can see the quadrupole-like structure. The upper figures show the vorticity values. While the bottom only it sign. It can be seen that in the center of the structure its value tends to 0. At the borders, since the derivative is calculated less accurately and, possibly, there are few particles, we observe strong fluctuations. The vorticity cells with values more than 0.1 were excluded, because they are observed only at the borders in a small number of cells.

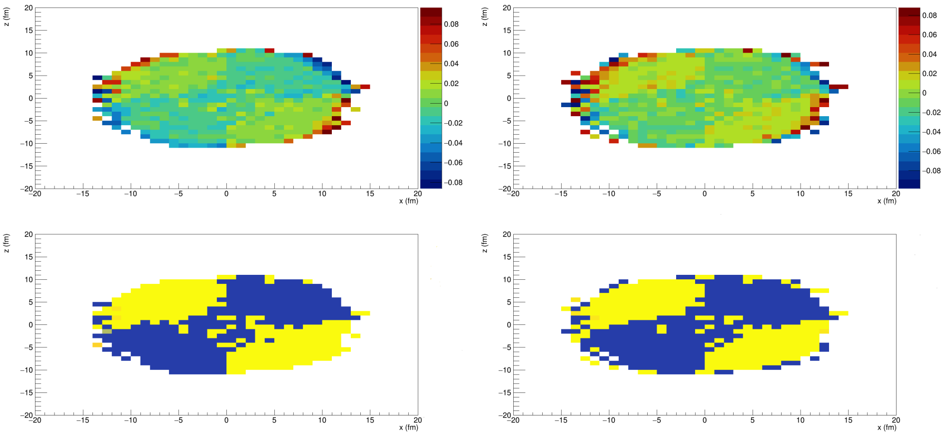

Figure 3: Vorticity projection in reaction plane. Used different methods of calculation velocity: Right (1), Left (2). Top is projection, bottom is sign: blue - negative, yellow - positive

The figure 4 contains all vorticities, but we can't see the quadrupole-like structure. And some big values near the border.That changes sing from cell to cell and must be taken more accurate.

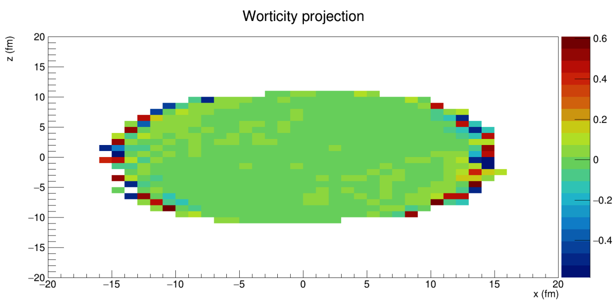


Figure 4: Vorticity projection in reaction plane. First method of finding velocity.

Than we made ratio for this two methods for all cells, and for cells with vorticity $< 0.1$. As shown in figure 5 , for cells with any vorticity, the values diverge greatly, near 50%, while for cells with a value less than 0.1 they coincide within 2%. However This means that the methodology of calculating the vorticity strongly affects the boundaries and almost does not differ in the center. This effect is also possible due to a change in the method of calculating the derivative from three nodes to two at any coordinate.

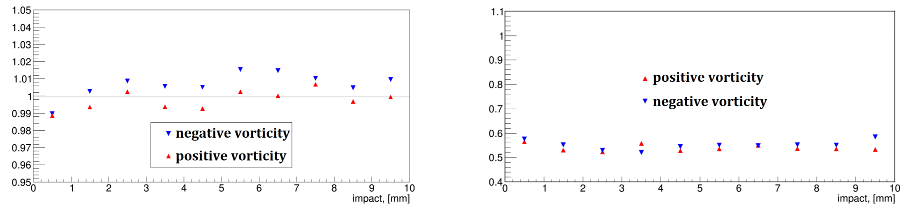


Figure 5: Vorticity ratio for 2 differen methods (2)/(1) with all cells (right) and only with vorticity less than 0.1 (left).

## 5.3 Helicity separation

For each impact parameter helicity was calculated for cells with positive and negative speeds separately. Because the sum helicity is near 0.

As shown at fig 6 helicity is not zero and changes the sign with the sign of the velocity y component calculated with (1).

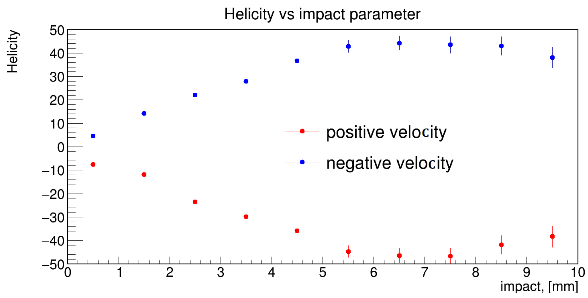


Figure 6: Helicity separation with positive and negative velocity

Also we compared the values obtained for helicity, depending on the method for determining the velocity. As it can be seen from the figure 7, the values obtained by method (1) are slightly larger than those obtained by the (2). With impact parameter $< 1$ mm the values are very different, since very central collisions occur.

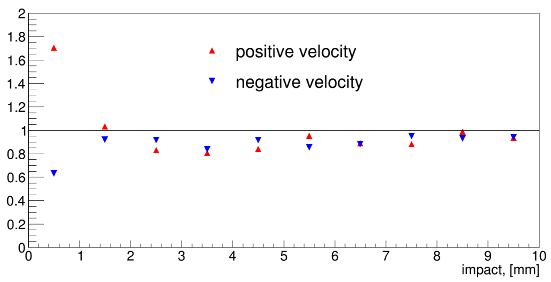


Figure 7: Helicity ratio for 2 different methods of calculating velocity.

# 6 Conclusion

At this analysis we calculated the following physical quantities within SMASH model: velocity, vorticity and hydrodinamical helicity. All valies was calculated for all particles. Was used two different definitions for velocity, that has some differences in final values. Also particle weighting makes distribution more smooth, which leads to more accurate values of the derivative.

During the analysis were shown quadrupole-like structure of vorticity in reaction plane and helicity sign changes with velocity, two methods works practically the same for low vorticities, and has some differences with huge values.

# 7 References

## References


[1] F. Becattini, F. Piccinini and J. Rizzo, Phys. Rev. C77,024906 (2008).

[2] L. P. Csernai, V. K. Magas, D. J. Wang, Phys. Rev. C87, 034906 (2013)

[3] L.P.Csernai, V.K.Magas, H.Stocker, and D.D.Strottman, Phys. Rev. C84, 024914 (2011)

[4] L.P. Csernai, D.D. Strottman and Cs. Anderlik, Phys.Rev. C85, 054901 (2012).

[5] S. Floerchinger and U.A. Wiedemann, JHEP 11, 100(2011); and J. Phys. G 38, 124171 (2011)

[6] E. Gourgoulhon, EAS Publ. Ser.21(2006) 43

[7] M. Baznat, K. Gudima, A. Sorin and O. Teryaev, Phys. Rev. C **88** (2013) no.6, 061901 doi:10.1103/PhysRevC.88.061901 [arXiv:1301.7003 [nucl-th]].

[8] J. Weil *et al.*, Phys. Rev. C **94** (2016) no.5, 054905 doi:10.1103/PhysRevC.94.054905 [arXiv:1606.06642 [nucl-th]].

[9] M. Tanabashi et al. (Particle Data Group) Phys. Rev. D 98, 030001 – Published 17 August 2018