Vorticity structure and helicity separation in heavy-ion collision.

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Introduction

The experimental evidences for polarization of hyperons in heavy-ion collisions found by STAR collaboration attracted recently much attention.
The studies of polarization are often performed in the framework of approach exploring local equilibrium thermodynamics and hydrodynamical calculations of vorticity.
There is another approach to polarization. The so-called axial vortical effect being the macroscopic manifestation of axial anomaly leads to induced axial current of strange quarks which may be converted to polarization of **Λ**-hyperons.
The effect is proportional to vorticity and helicity of the strong interacting medium, and, in particular, to helicity separation effect discovered in the kinetic Quark-Gluon-String Model(QGSM) and confirmed in PHSD model. This helicity separation effect receives the significant contribution $\sim \vec{v}_y \vec{\omega}_y$ from the transverse component of velocity and vorticity. It is easily explained by the same signs of transverse vorticities in the "upper" and "lower" (w.r.t. reaction plane) half-spaces, combined with the opposite signs of velocities. At the same time, even larger contribution of longitudinal components of velocity and vorticity $\sim \vec{v}_z \vec{\omega}_z$ implies the appearance of the "quadrupole" structure of longitudinal vorticity, recently found in the hydrodynamical approach.

Vorticity and Vortex sheet

There are several definitions of vorticity. We will use the relativistic kinetic vorticity:

$$\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)\,, \qquad (1)$$

where u_ν is a relativistic four-vector of the velocity field.

$$u_\nu(t, \vec{x}) = \gamma(1, \vec{v}(t, \vec{x}))\,, \quad \gamma(t, \vec{x}) = \frac{1}{\sqrt{1 - \vec{v}^{\,2}(t, \vec{x})}} \qquad (2)$$

We will use the term t_c to determine the relative position of the nuclei from each other. $t = 0$ means that the nuclei began to overlap and $t = t_c$ means that they completely passed each other $(z(t = t_c) = 2R/\gamma)$.
If $t \sim 2t_c$ (depending on the energy $\sqrt{s}$), a vortex sheet begins to form on the boundary of the fireball. It is observed both in the QGSM and in the PHSD -model.

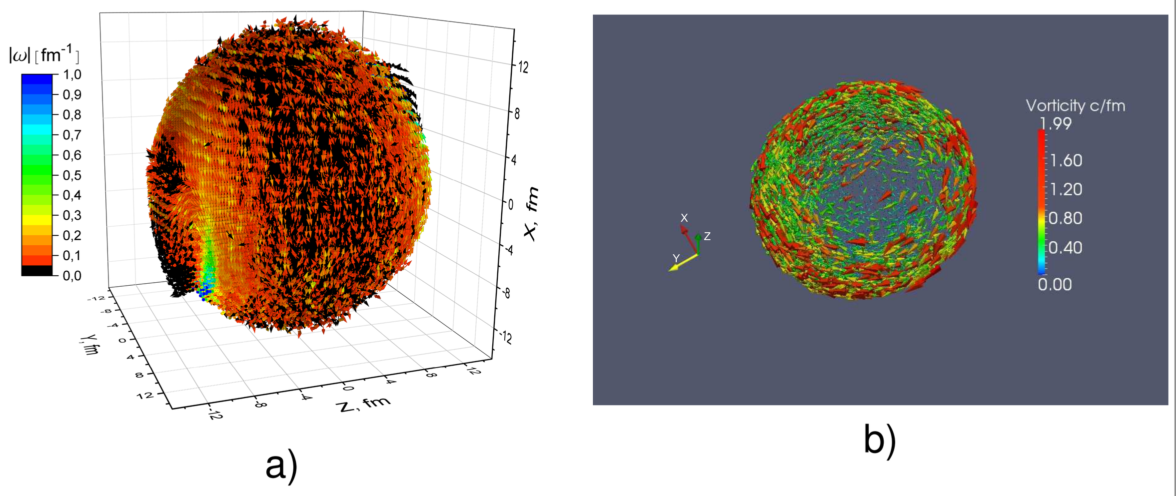

Figure: 1. Vortex sheet in PHSD a) and QGSM b).

Vorticity formation

The quadrupole structure of vorticity is clearly observed in the planes xy and zy. In the xz plane, it is visible only inside the fireball.

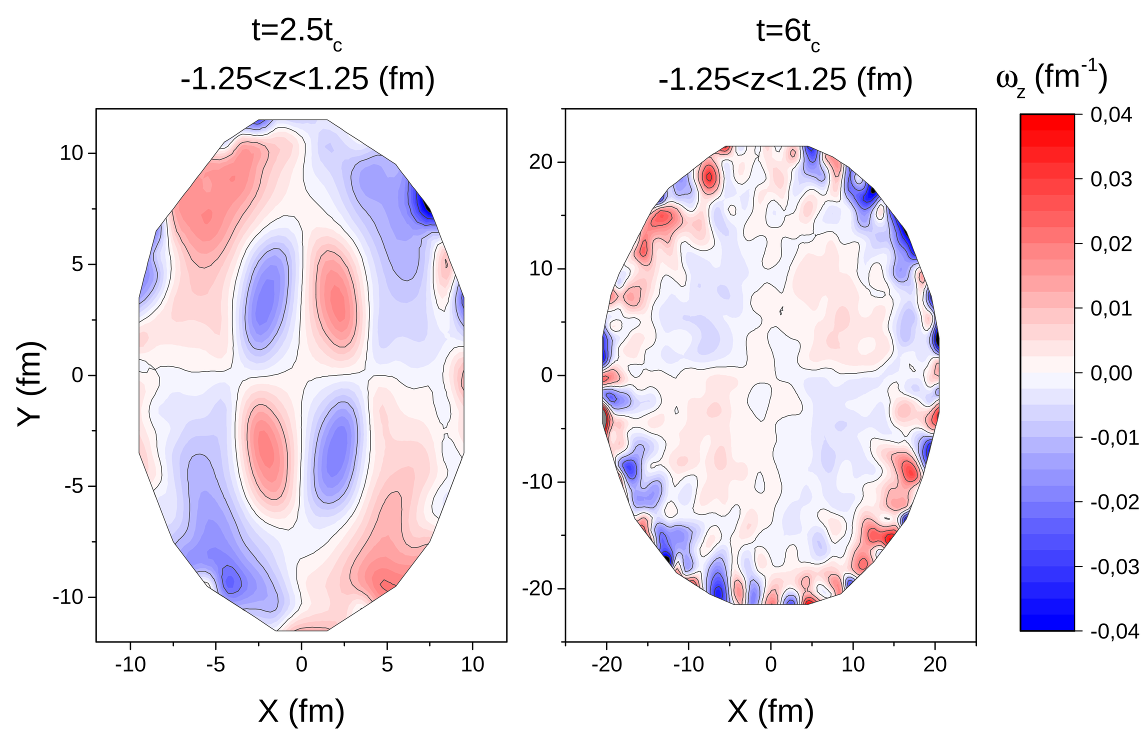

Figure: 2. Relativistic vorticity in Au+Au ($\sqrt{s} = 7.7$ GeV), $t = 2.5t_c$ and $t = 6t_c$ in XY plane.

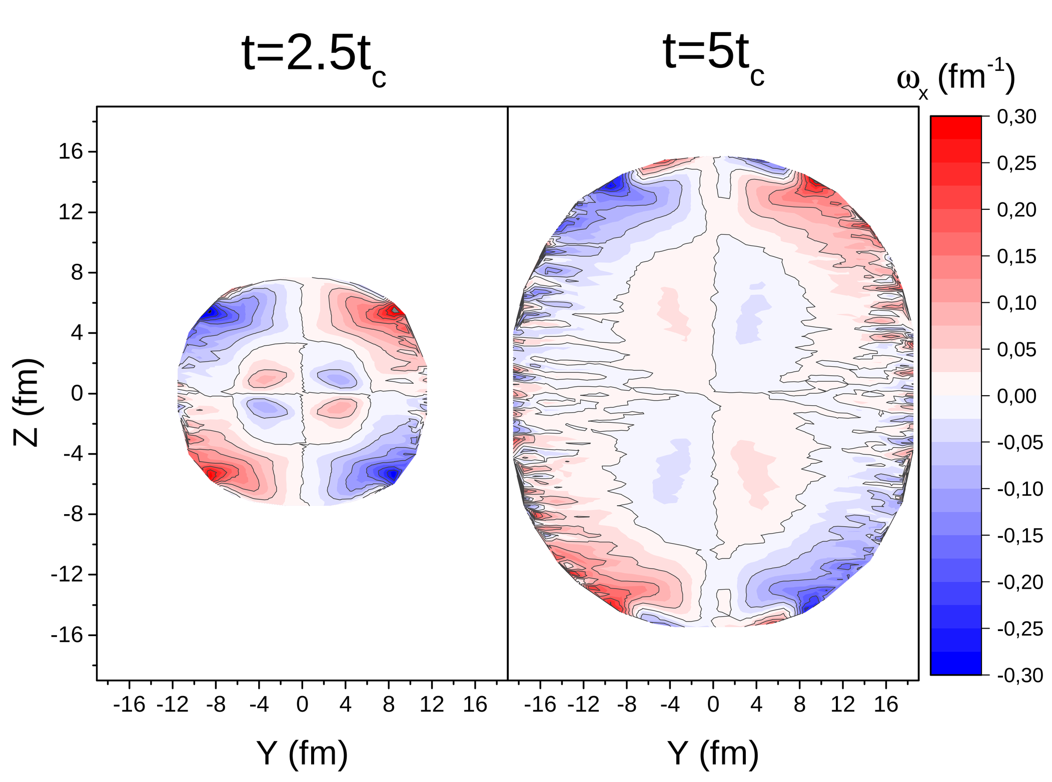

Figure: 3. Relativistic vorticity in Au+Au ($\sqrt{s} = 7.7$ GeV), $t = 2.5t_c$ and $t = 5t_c$ in YZ plane.

In the case of relativistic vorticity, γ-factor has a significant influence on the fireball boundaries, strengthening the vortex sheet.

Vorticity formation

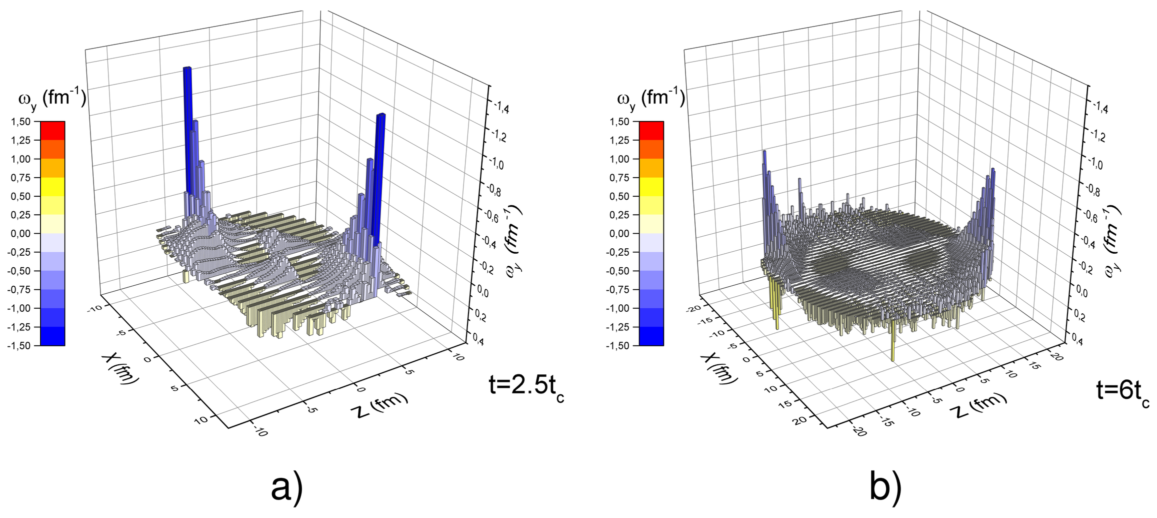

Figure: 4. Relativistic in Au+Au ($\sqrt{s} = 7.7$ GeV), $t = 2.5t_c$ a) and $t = 6t_c$ b) in ZX plane.

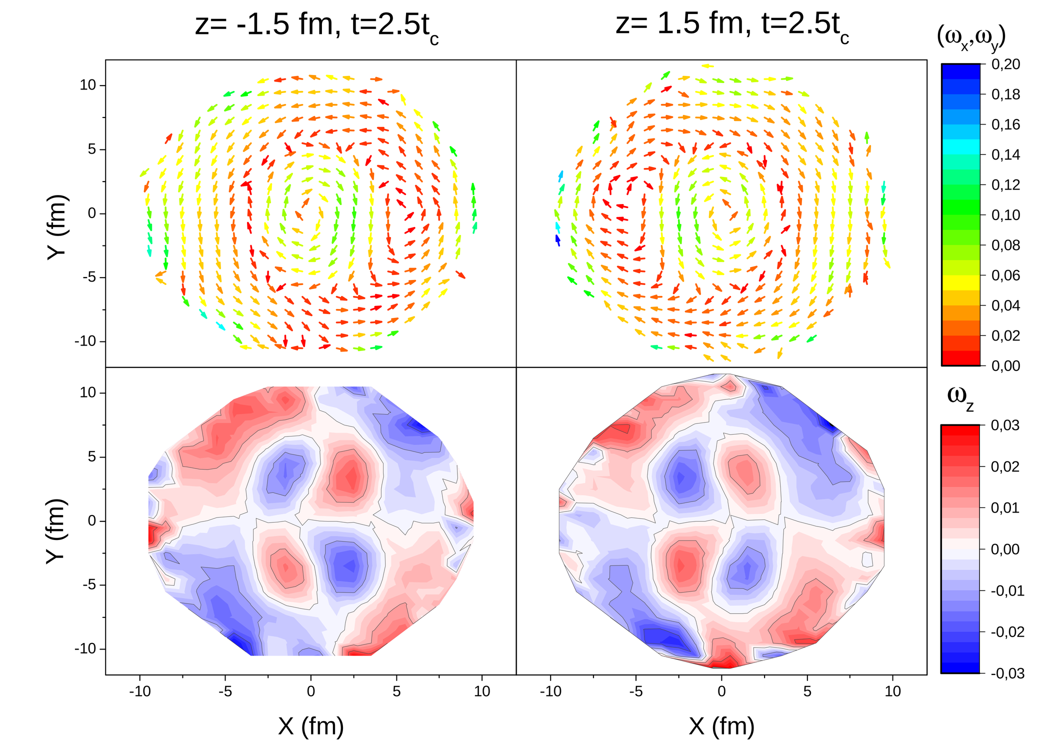

Figure: 5. Relativistic transvers vorticity (ω_x, ω_y) in Au+Au ($\sqrt{s} = 7.7$ GeV), $t = 2.5t_c$ - first row. And ω_z, where $z = + - 1.5$ fm - second row.

As can be seen, the quadrupole structure is observed inside the fireball and on the border with the spectators(XY and ZY planes). In sum, they give a mirror quadrupole structure.

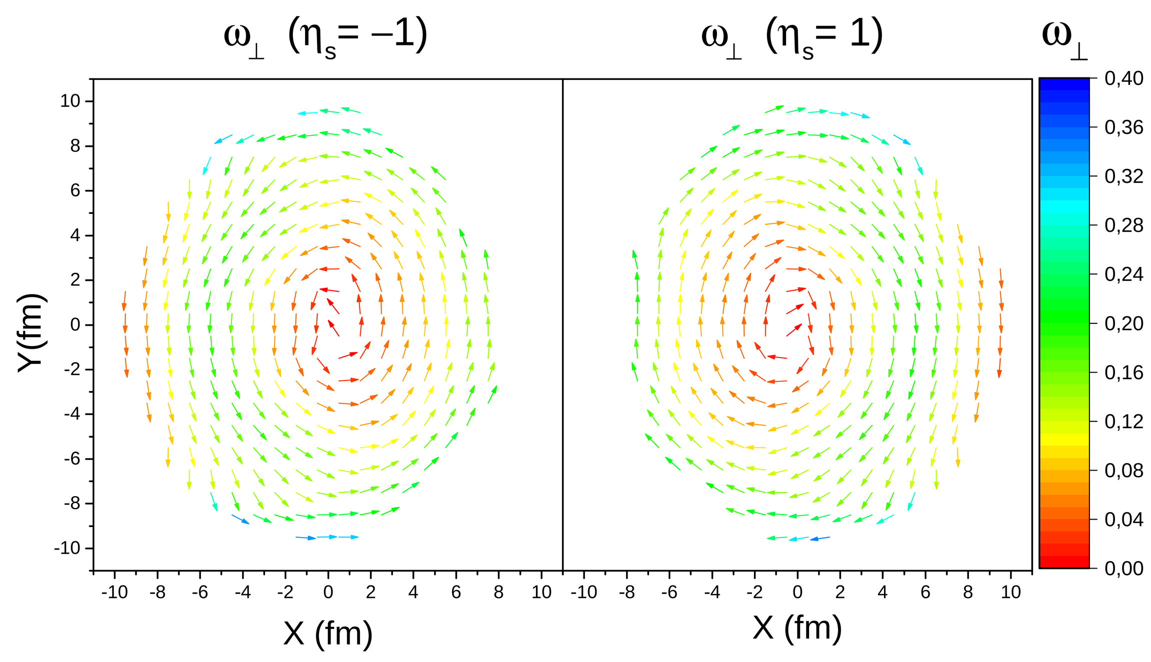

Figure: 6. The distribution of the transverse vorticity $\omega_\perp = (\omega_x, \omega_y)$ in the transverse plane at longitudinal position $\eta_s = -1$ (left) and $\eta_s = 1$ (right) at time $t = 3t_c$, b= 5 fm ($\sqrt{s} = 7.7$ GeV).

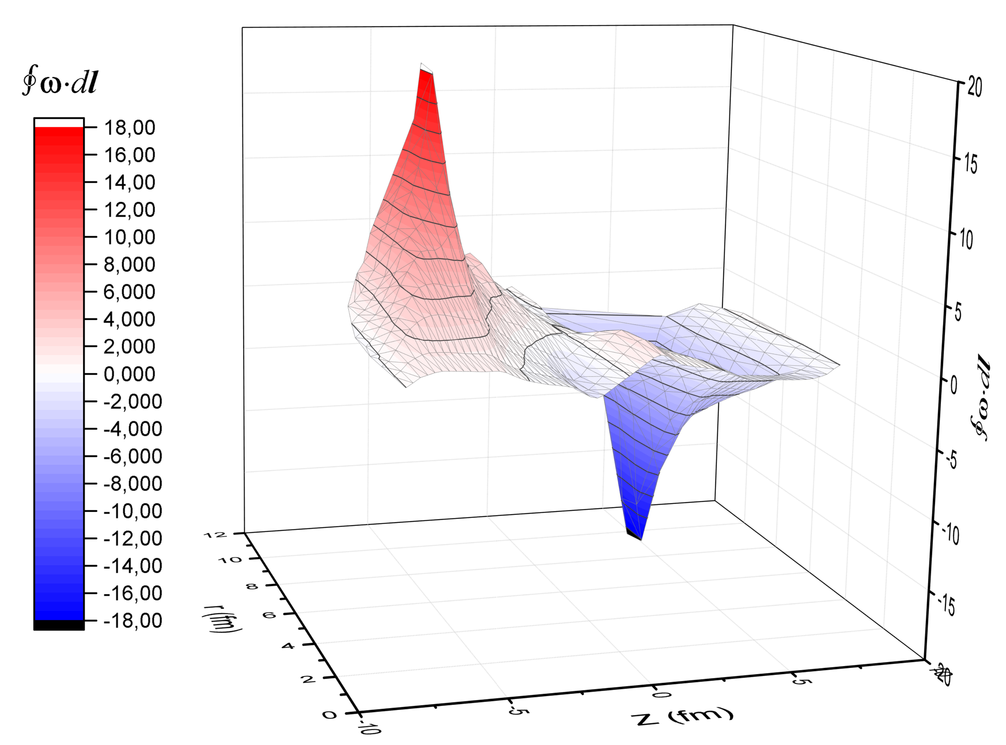

Figure: 7. The distribution of the Circulation of ω depending on Z and r at $t = 2.5t_c$.

Fragmentation of the quadrupole structure occurs closer to the center of the fireball.

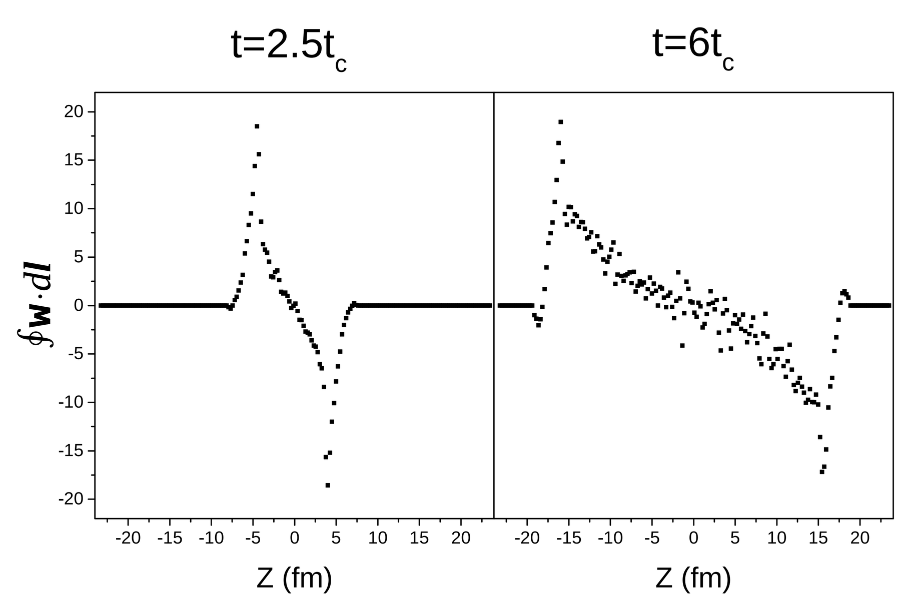

Figure: 8. Circulation of ω (at boundary of fireball) depending on Z.

Helicity separation.

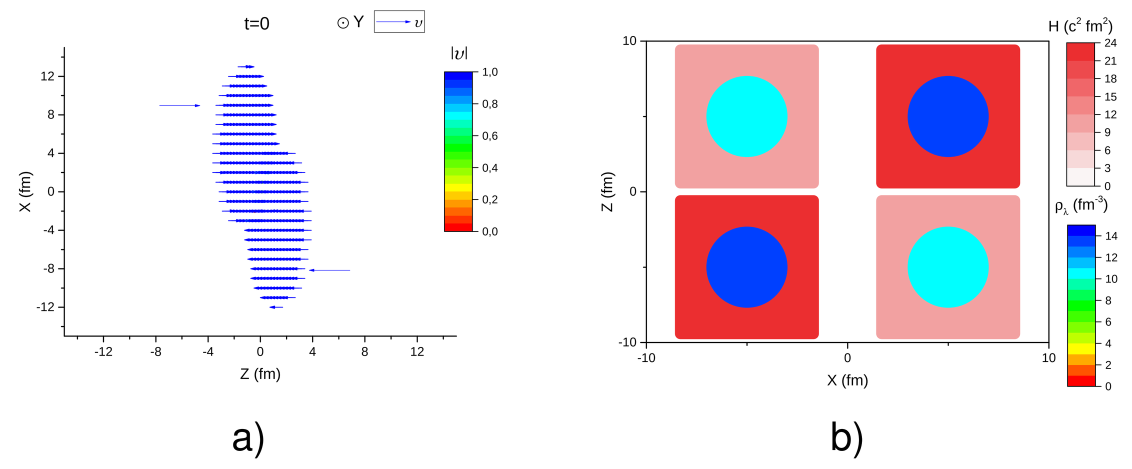

Figure: 9. Field of velocity at $t = 0t_c$ PHSD a) and distribution of helicity and λ-hyperons in octans($y < 0$) b).

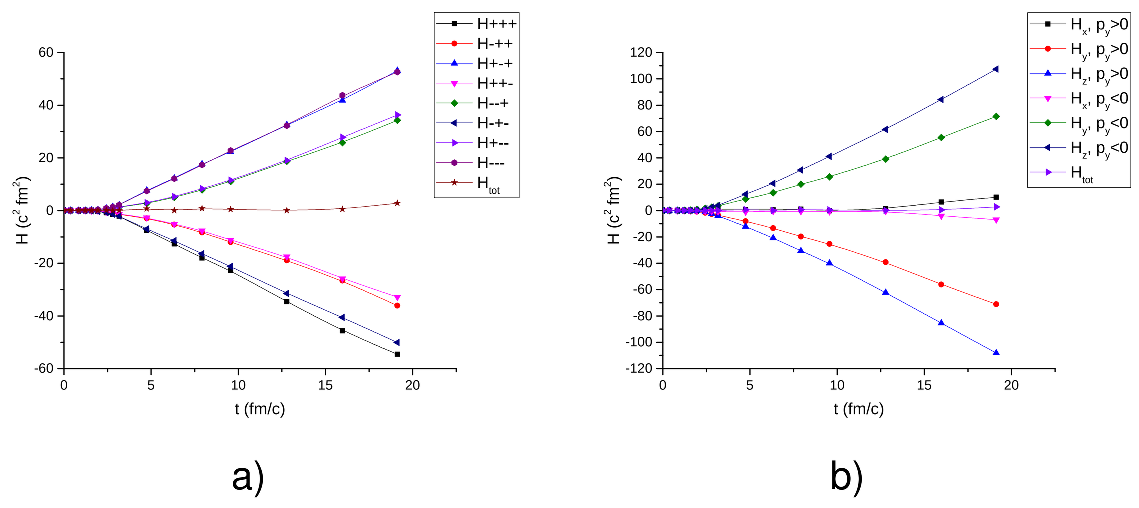

Figure: 10. a) Helicity (H ($fm^2\ c^2$)) separation relative to spatial octants (impact parameter $b = 7$ fm). +++ means that integration is in octant $x > 0$, $y > 0$, $z > 0$ and – – – - $x < 0$, $y < 0$, $z < 0$ respectively. b) Helicity (H ($fm^2\ c^2$)) separation relative to y- component of momentum (impact parameter $b = 7$ fm).

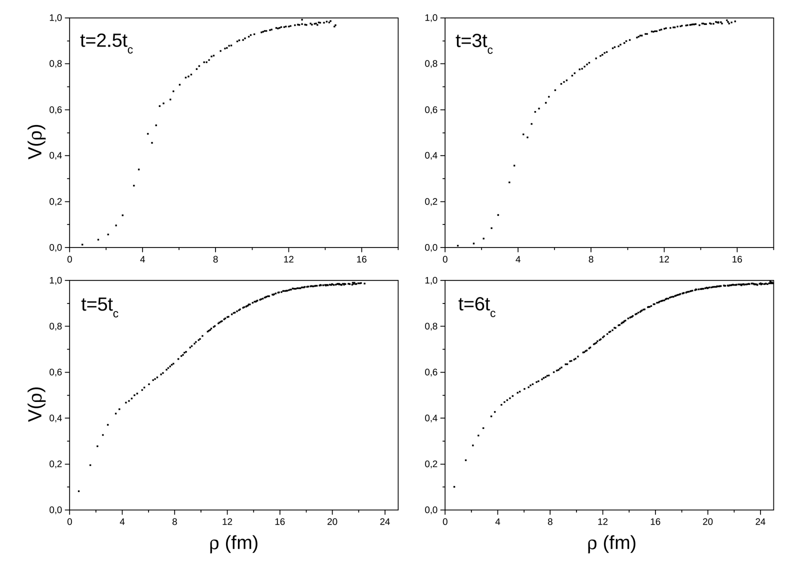

Figure: 11. Velocity dependence on distance to fireball center b(=7 fm).

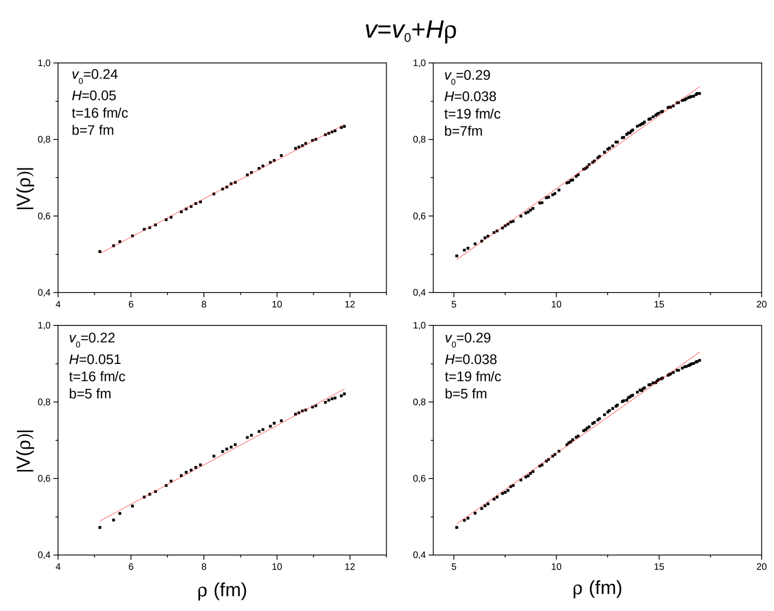

Figure: 12. Linear velocity domain as a Hubble law.

Polarization.

We performed the numerical simulations in QGSM model (PHSD in progress).
The $\bar{\Lambda}$ polarization is emerging due to the polarization of $\bar{s}$–quarks, which has the same sign, as the axial current and charge are C-even operators. The magnitude of the $\bar{\Lambda}$ is larger as the same axial charge is distributed between the polarizations of the smaller number of particles.