Directed flow, Vorticity and Λ Polarization in HIC

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Outline

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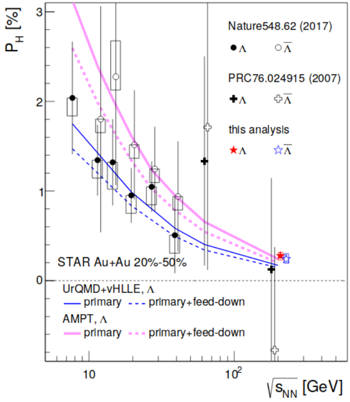
- How to measure?
- How to calculate?

2 Models which were used

3 Results

4 Conclusions

Introduction



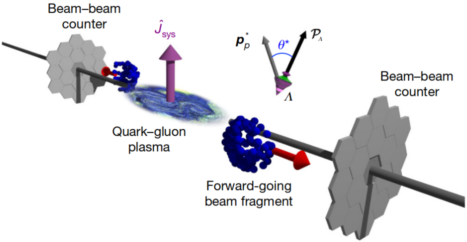
[Phys. Rev. C 98 (2018) 14910]

- Very simple idea: *Peripheral collisions* → *Angular momentum* → *Global polarization*. But still not clear mechanism of transition of angular momentum to spins.
- A new outlook, forcing us to rethink the foundations of relativistic hydrodynamics and kinetic theory in a fully quantum framework.

Thus it is important to find out if vorticity really exists in different models and calculate related quantities such as polarization.

How to measure?

Λ and $\bar{\Lambda}$ hyperons are "self-analyzing". That is, in the weak decay $\Lambda \to p + \pi^-$, the proton tends to be emitted along the spin direction of the parent Λ.



If θ^* is the angle between the daughter proton momentum Λ polarization vector in the hyperon rest frame, then:

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_H |\vec{P}_H| \cos\theta^*) \quad \to \quad P_H = \frac{8}{\pi\alpha_H} \sin(\phi_p^* - \Psi_{RP})$$

[Nature 548 (2017) 62]

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   - How to measure?
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Thermal Approach

In local thermal equilibrium, the ensemble average of the spin vector for spin-1/2 fermions with four-momentum p at space-time point x is obtained from the statistical-hydrodynamical model as well as the Wigner function approach and reads

$$S^\mu(x,p) = -\frac{1}{8m}\,(1-n_F)\,\epsilon^{\mu\nu\rho\sigma}\,p_\nu \varpi_{\rho\sigma}(x),$$

where the thermal vorticity tensor is given by

$$\varpi_{\mu\nu} = \frac{1}{2}\,(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu)\,,$$

with $\beta^\mu = u^\mu/T$ being the inverse-temperature four-velocity. The number density of Λ's is very small so that we can make the approximation $1 - n_F \simeq 1$ Therefore:

$$S^\mu(x,p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}\,p_\nu \varpi_{\rho\sigma}(x).$$

By decomposing the thermal vorticity into the following components,

$$\boldsymbol{\varpi}_T = (\varpi_{0x}, \varpi_{0y}, \varpi_{0z}) = \frac{1}{2}\left[\nabla\left(\frac{\gamma}{T}\right) + \partial_t\left(\frac{\gamma\mathbf{v}}{T}\right)\right],$$

$$\boldsymbol{\varpi}_S = (\varpi_{yz}, \varpi_{zx}, \varpi_{xy}) = \frac{1}{2}\nabla\times\left(\frac{\gamma\mathbf{v}}{T}\right),$$

Equation can be rewritten as

$$S^0(x,p) = \frac{1}{4m}\mathbf{p}\cdot\boldsymbol{\varpi}_S, \quad \mathbf{S}(x,p) = \frac{1}{4m}\left(E_p\boldsymbol{\varpi}_S + \mathbf{p}\times\boldsymbol{\varpi}_T\right),$$

where E_p, $\mathbf{p}$, m are the Λ's energy, momentum, and mass, respectively.The spin vector of Λ in its rest frame is denoted as $S^{*\mu} = (0, \mathbf{S}^*)$ and is related to the same quantity in the c.m. frame by a Lorentz boost. Finally:

$$P = \frac{\langle\mathbf{S}^*\rangle\cdot\mathbf{J}}{|\langle\mathbf{S}^*\rangle||\mathbf{J}|},$$

[F. Becattini et al, Phys. Rev. C 95, 054902 (2017)]

UrQMD

- Represents a Monte Carlo method for the time evolution of the various phase space densities of particle species.
- Based on the covariant propagation of all hadrons on classical trajectories, stochastic binary scatterings, resonance and string formation with their subsequent decay.
- Provides the solution of the relativistic Boltzmann equation.
- The collision criterion (black disk approximation):
  $d < d_0 = \sqrt{\sigma_{tot}(\sqrt{s}, \text{type})/\pi}$
- 55 baryons and 32 mesons are included. All antiparticles and isospin-projected states are implemented.
- Cross sections are taken from PDG.
- Resonances are implemented in Breit–Wigner form.

[S. A. Bass et al, Prog. Part. Nucl. Phys. 41 (1998) 255-369,
M. Bleicher et al, J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859-1896]

Statistical model

Input from UrQMD:

$$\varepsilon_{UrQMD} = \frac{1}{V}\sum_i E_i$$

$$\rho_{B_{UrQMD}} = \frac{1}{V}\sum_i B_i$$

$$\rho_{S_{UrQMD}} = \frac{1}{V}\sum_i S_i$$

Stat. Physics:

$$\varepsilon_{stat} = \sum_i \varepsilon_i(T, \mu_B, \mu_S)$$

$$\rho_{B_{stat}} = \sum_i B_i n_i(T, \mu_B, \mu_S)$$

$$\rho_{S_{stat}} = \sum_i S_i n_i(T, \mu_B, \mu_S)$$

$$\chi^2 = \frac{(\varepsilon_{UrQMD} - \varepsilon_{stat})^2}{\sigma_\varepsilon^2} + \frac{(\rho_{B_{UrQMD}} - \rho_{B_{stat}})^2}{\sigma_{\rho_B}^2} + \frac{(\rho_{S_{UrQMD}} - \rho_{S_{stat}})^2}{\sigma_{\rho_S}^2}$$

Minuit2 numerical minimizer

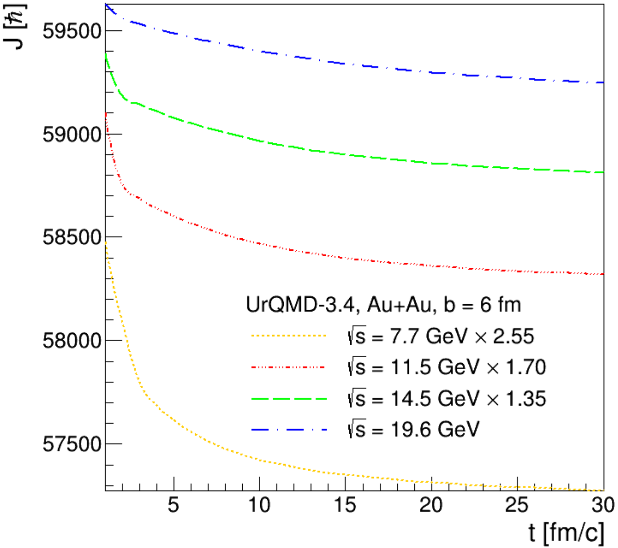
Output:

T, μ_B, μ_S

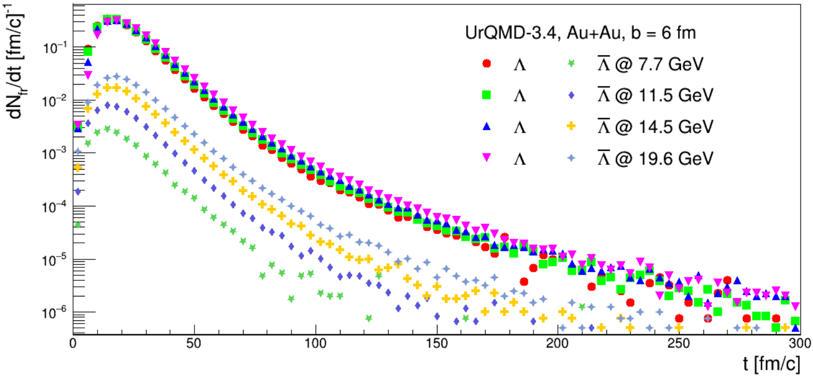
[L. Bravina et al, Phys. Rev. C60 (1999) 024904]

Angular momentum

Angular momentum does not conserve on early stage due to inelastic collisions (especially through the decays of strings). But, maximum deviation is only $\simeq 2\%$



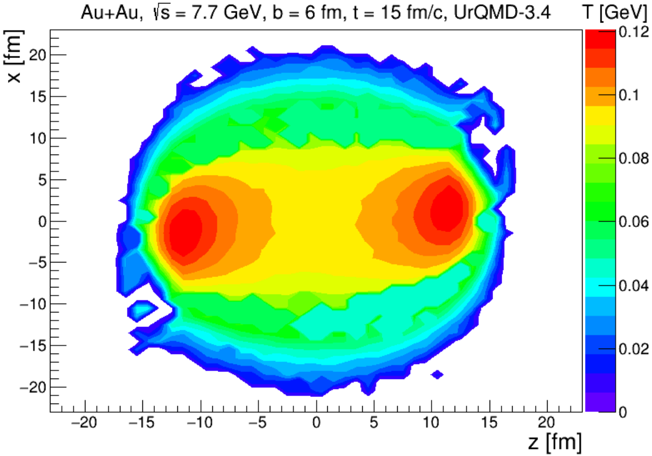
Freeze-out



Λ's and $\bar{\Lambda}$'s with $|y| < 1$ and $0.2 < p_t < 3$ GeV/c were analyzed.

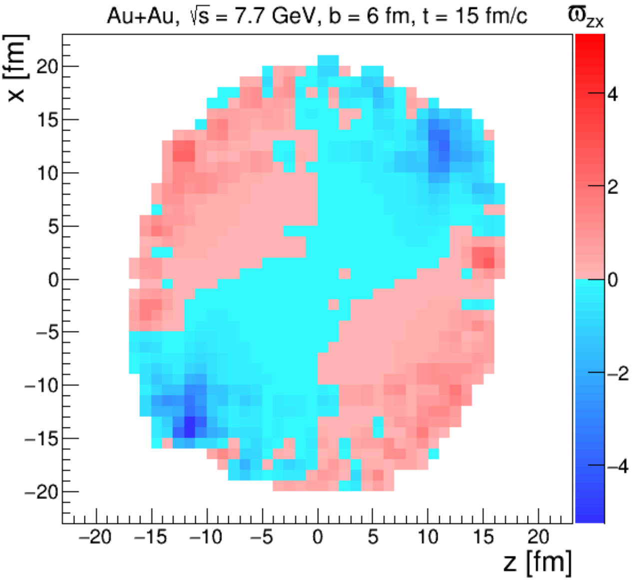
$\sqrt{s}$ [GeV]	7.7	11.5	14.5	19.6
Mean freeze-out time Λ [fm/c]	21.3009	21.9568	23.066	24.3462
Mean freeze-out time $\bar{\Lambda}$ [fm/c]	19.7806	21.0302	21.959	23.1288

Proper Temperature



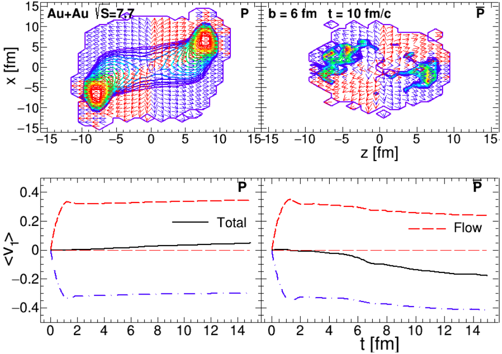
Temperature extracted with statistical model is not uniform. There are two main regions. More hot regions with T $\simeq 100 MeV$ are connected to dense spectators. The other part is related to fireball with temperature $\simeq 60 MeV$.

Thermal vorticity in reaction plane



Thermal vorticity component ϖ_{zx} has quadruple-like structure in reaction plane which is stable in time but magnitude decreases due to system expansion. First and third quadrant are connected with central region which has small negative vorticity. This connection part becomes smaller when energy increases.

Space distribution of Lambdas



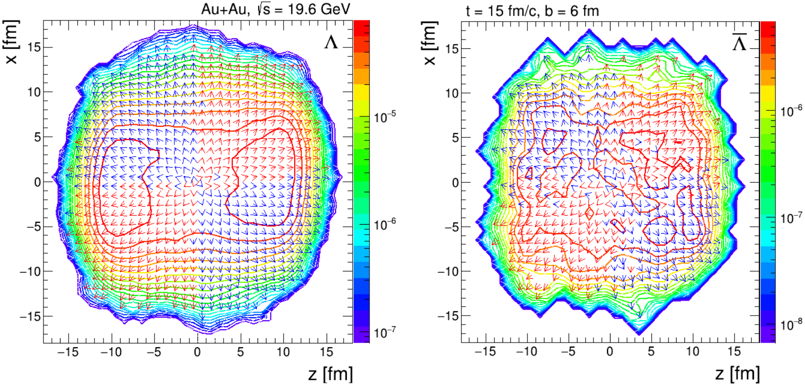
At low energies Λ and $\bar{\Lambda}$ are produced and emitted from the same regions as protons and antiprotons respectively. Λ's are concentrated also near hot and dense spectators, whereas $\bar{\Lambda}$'s are mostly produced in central region.

Mean flow is calculated as:

$$< v_1 >= \int sign(y) v_1(y) \frac{dN^{par}}{dy} dy / \int \frac{dN^{par}}{dy} dy$$

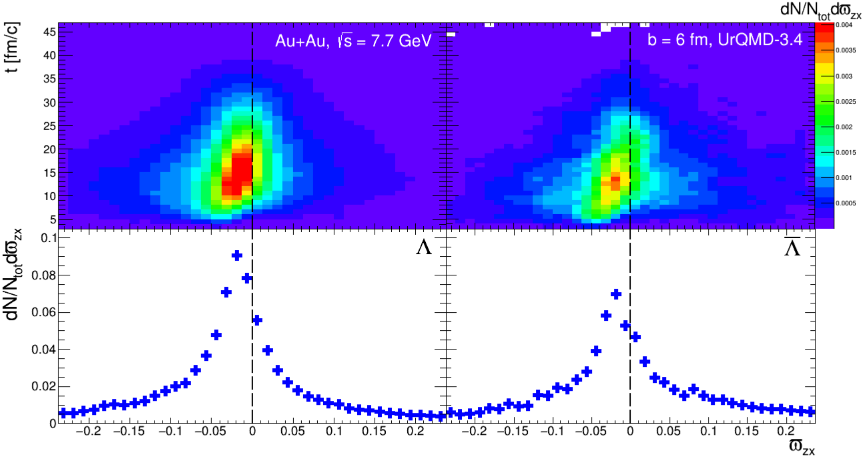
Collective velocities are shown on the picture to demonstrate that particles which have positive product of velocities $v_x v_z$ produce normal component of flow and particles with $v_x v_z < 0$ produce anti-flow component of directed flow. [Bravina et al, EPJ Web of Conferences 191, 05004 (2018)]

Space distribution of Lambdas



At $\sqrt{s} = 19.6 GeV$ Λ are mostly located near hot and dense regions and $\bar{\Lambda}$ are distributed more uniformly near system center.

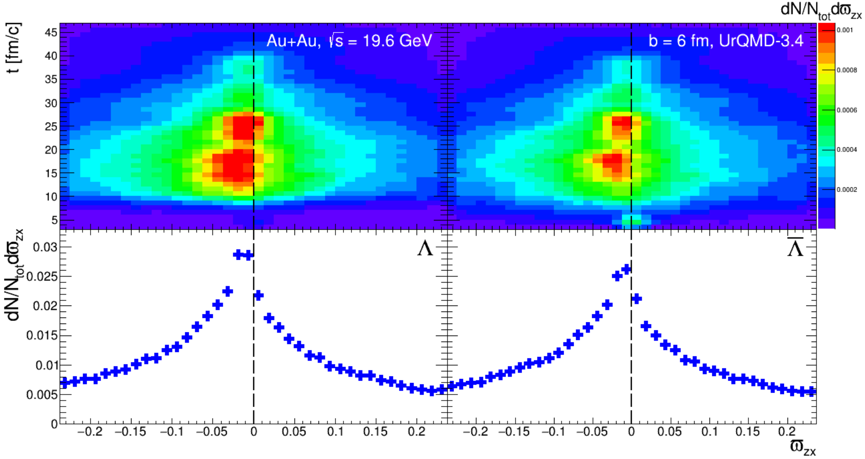
Emission of Λ and $\bar{\Lambda}$



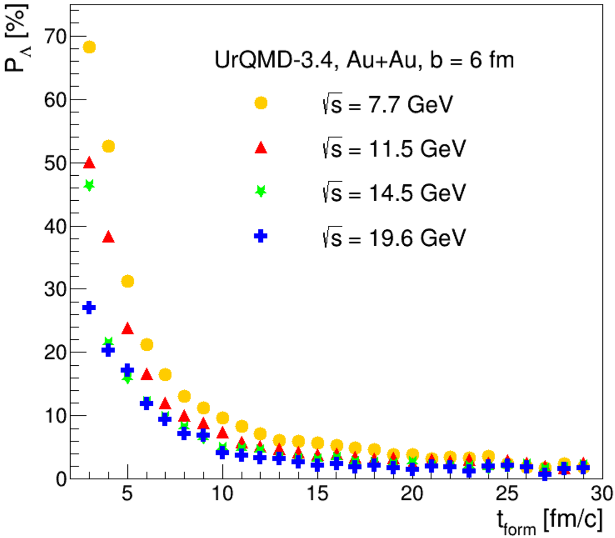
At $\sqrt{s} = 7.7 GeV$ Λ and $\bar{\Lambda}$ are mainly emitted from regions with small negative vorticity, thus they should have non-zero positive polarization. $\bar{\Lambda}$ has mean value of ϖ_{zx} with larger magnitude than Λ ($\simeq -0.04$ and $\simeq -0.017$ respectively).

Emission of Λ and $\bar{\Lambda}$

At $\sqrt{s} = 19.6 GeV$ Λ and $\bar{\Lambda}$ are also mainly emitted from regions with small negative vorticity, but distributions are more symmetric and wide. Thus mean values of ϖ_{zx} for Λ and $\bar{\Lambda}$ drop ($\simeq -0.009$ and $\simeq -0.011$ respectively).

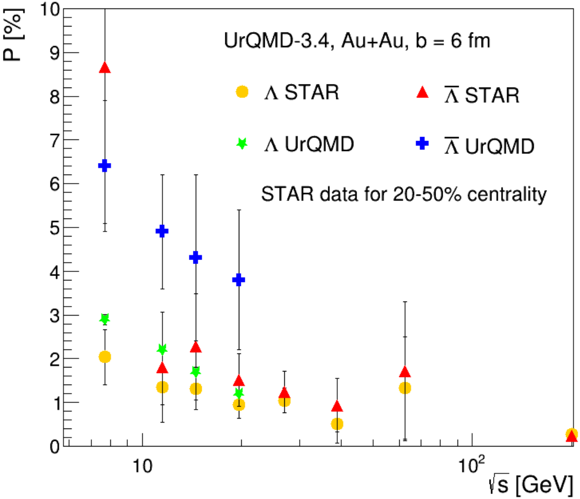


Polarization time evolution



Polarization of Λ hyperon decreases with time. At the beginning lambdas are preferably formed in hot and dense regions with high polarization. But later lambdas are formed uniformly in fireball and average polarization is almost zero.

Polarization energy dependency



Polarization of Λ and $\bar{\Lambda}$ decreases with energy as in the experiment.
Λ's global polarization agrees well with experimental data. $\bar{\Lambda}$ polarization has right energy dependence.

STAR data from [Phys. Rev. C 98 (2018) 14910]

Conclusions

- Thermal vorticity was calculated in Au+Au (b = 6 fm) collisions at BES energies $\sqrt{s} = 7.7 - 19.6\ GeV$ within the UrQMD model.
- Quadruple structure of ϖ_{zx} vorticity is obtained.
- Magnitude of vorticity dependence on time and energy is studied.
- Method for calculation of Λ polarization in transport model is developed.
- Freeze-out of Λ and $\bar{\Lambda}$ is different in space and time, thus they are emitted from parts of system with different vorticity.
- Λ and $\bar{\Lambda}$ global polarization is calculated at energies $\sqrt{s} = 7.7 - 19.6\ GeV$ and compared with experimental data.

Conclusions

- The global polarization is jointly determined by the space-time distribution of Λ and the thermal vorticity field. The larger global polarization at lower collision energies is due to more Λ's produced in the negative-vorticity region at lower energies because of slow expansion rate. This means that the magnitude of vorticity does not decrease too much.
- Difference in global polarization of Λ and $\bar{\Lambda}$ is naturally explained by the difference in space-time distributions of Λ and $\bar{\Lambda}$ and different freeze-out with respect to the thermal vorticity field.