# *Transport model approach to Lambda and anti-Lambda polarization in heavy-ion collisions*

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*IHEP Protvino, 09-13.11.2020*

Based on publications:

1. O.Vitiuk, L.Bravina, E.Z.,

Phys. Lett. B 803 (2020) 135298

2. O.Vitiuk, L.Bravina, E.Z., A.Sorin, O.Teryaev,

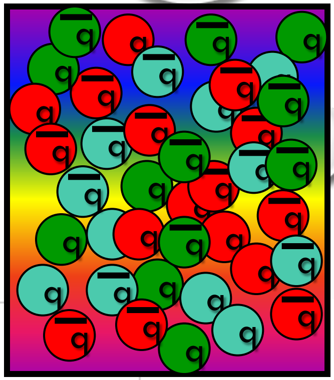
Springer Proc. in Physics 250 (2020) 429

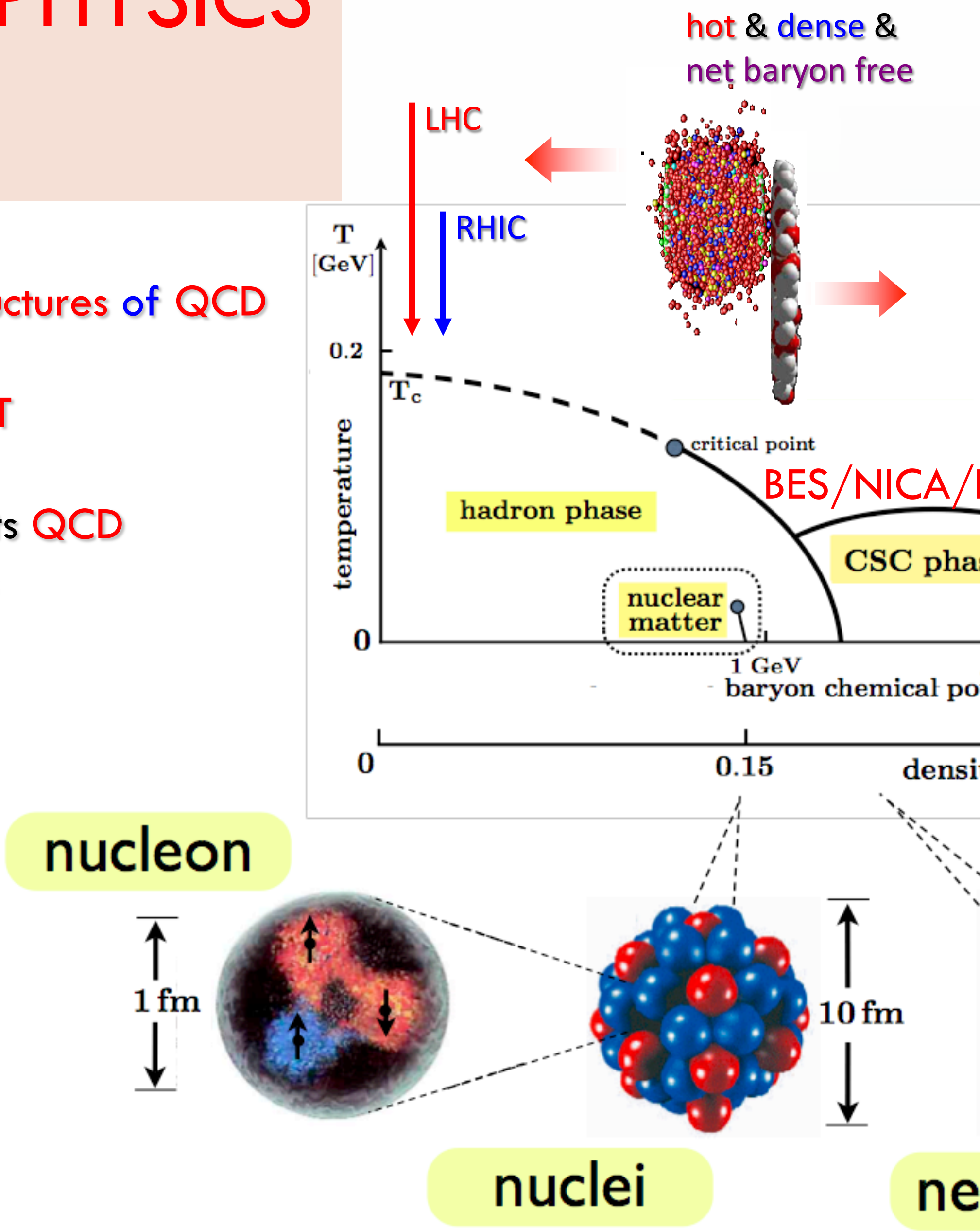
# INTRODUCTION

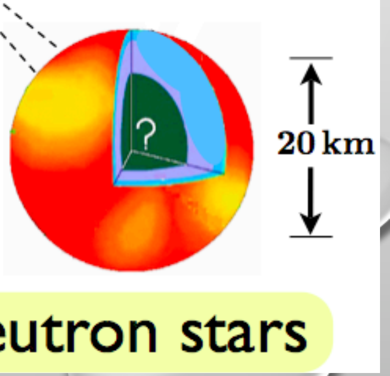
# HEAVY ION PHYSICS

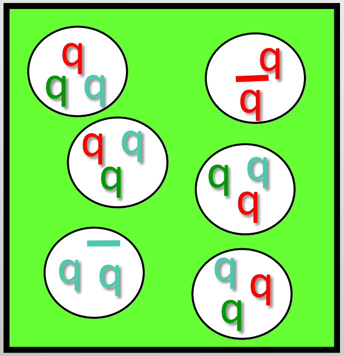
Exploring Phases and Structures of QCD phase diagram

- High temperature T
- High density ε
- Many-body aspects QCD
- Vacuum properties

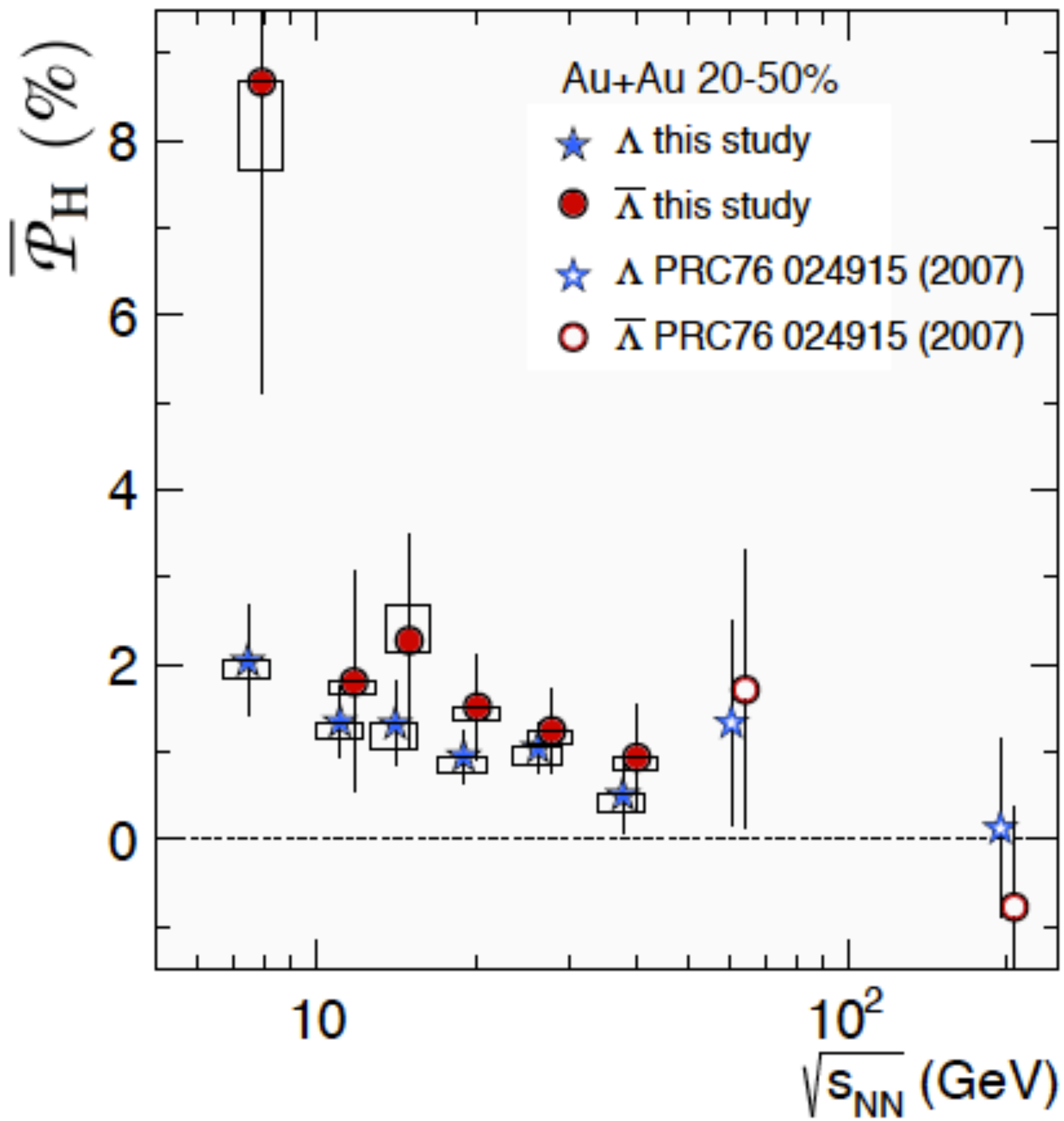


# MOTIVATION

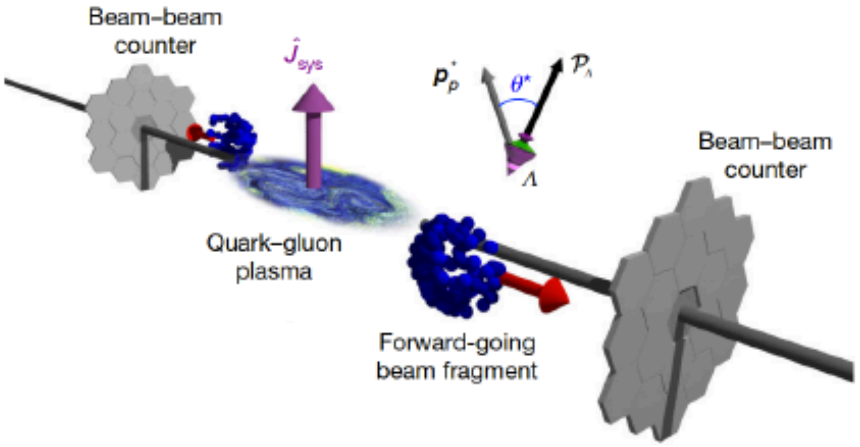



"The discovery of global Lambda polarization in non-central heavy ion collisions opens new directions in the study of the hottest, least viscous - and now, most vortical - fluid ever produced in the laboratory."

STAR Collaboration, Nature 548 (2017) 62

# Measurement of Lambda Polarization

$\Lambda$ 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 $\Lambda$.




If $\theta^*$ is the angle between the daughter proton momentum $\Lambda$ 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]

# Thermal Vorticity and Polarization

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

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

with $\beta^{\mu} = u^{\mu}/T$ being the inverse-temperature four-velocity. The number density of $\Lambda$'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 $\Lambda$'s energy, momentum, and mass, respectively.The spin vector of $\Lambda$ 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)]

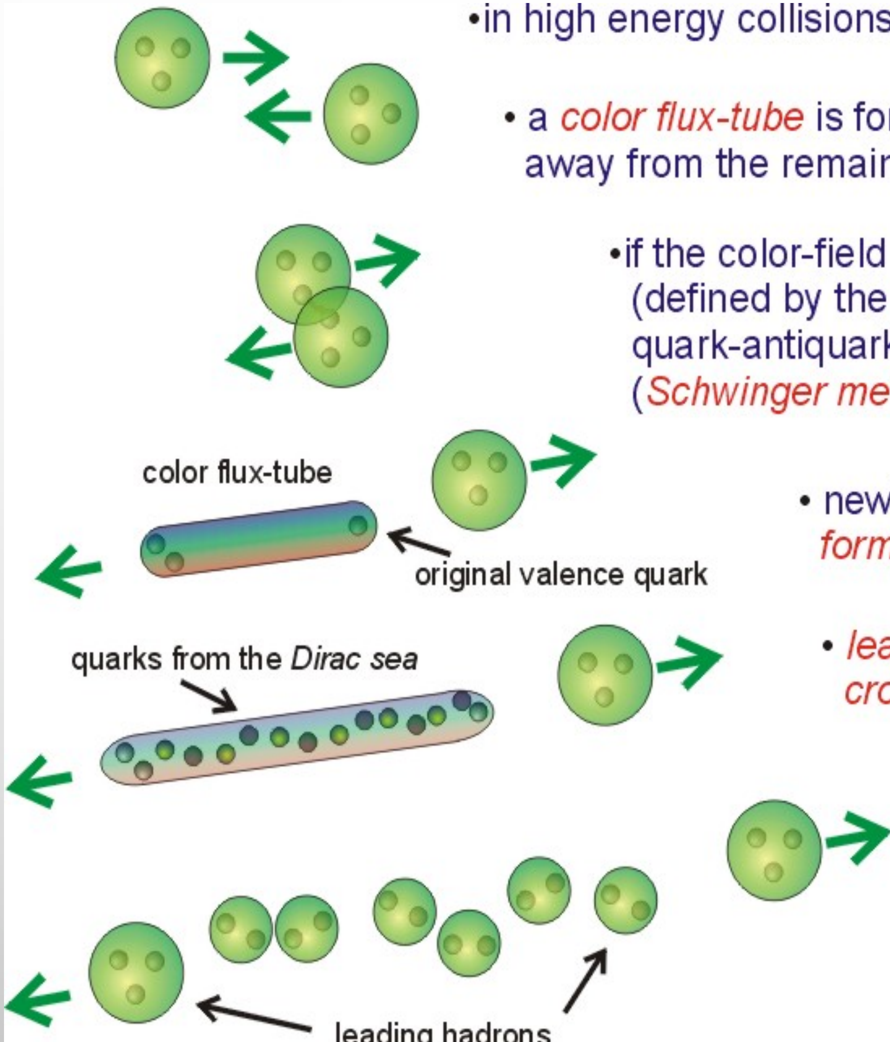
# MODELS AT OUR DISPOSAL

# Microscopic Transport Model 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]

# INITIAL PARTICLE PRODUCTION IN URQMD




- in high energy collisions hadrons can be excited into *strings*
- a *color flux-tube* is formed by pulling one valence quark away from the remaining ones in the hadron
- if the color-field increases beyond a critical value (defined by the *string-tension*), spontaneous quark-antiquark creation from the *Dirac sea* occurs (*Schwinger mechanism*)
- newly created (anti-)quarks require a *formation time* to form hadrons
- *leading hadrons* interact with *reduced cross sections* during their formation time
- *newly created hadrons* have *zero cross section* during their formation time

# STATISTICAL MODEL OF IDEAL HADRON GAS

input values                                        output values

$$\varepsilon^{\mathrm{mic}} = \frac{1}{V}\sum_i E_i^{\mathrm{SM}}(T, \mu_{\mathrm{B}}, \mu_{\mathrm{S}}),$$

$$\rho_{\mathrm{B}}^{\mathrm{mic}} = \frac{1}{V}\sum_i B_i \cdot N_i^{\mathrm{SM}}(T, \mu_{\mathrm{B}}, \mu_{\mathrm{S}}),$$

$$\rho_{\mathrm{S}}^{\mathrm{mic}} = \frac{1}{V}\sum_i S_i \cdot N_i^{\mathrm{SM}}(T, \mu_{\mathrm{B}}, \mu_{\mathrm{S}}).$$

Multiplicity

$$N_i^{\mathrm{SM}} = \frac{V g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 f(p, m_i)dp,$$

Energy

$$E_i^{\mathrm{SM}} = \frac{V g_i}{2\pi^2\hbar^3}\int_0^\infty p^2\sqrt{p^2+m_i^2}\, f(p, m_i)dp$$

Pressure

$$P^{\mathrm{SM}} = \sum_i \frac{g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 \frac{p^2}{3(p^2+m_i^2)^{1/2}}\, f(p, m_i)dp$$

Entropy density

$$s^{\mathrm{SM}} = -\sum_i \frac{g_i}{2\pi^2\hbar^3}\int_0^\infty f(p, m_i)\,[\ln f(p, m_i) - 1]\, p^2 dp$$

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

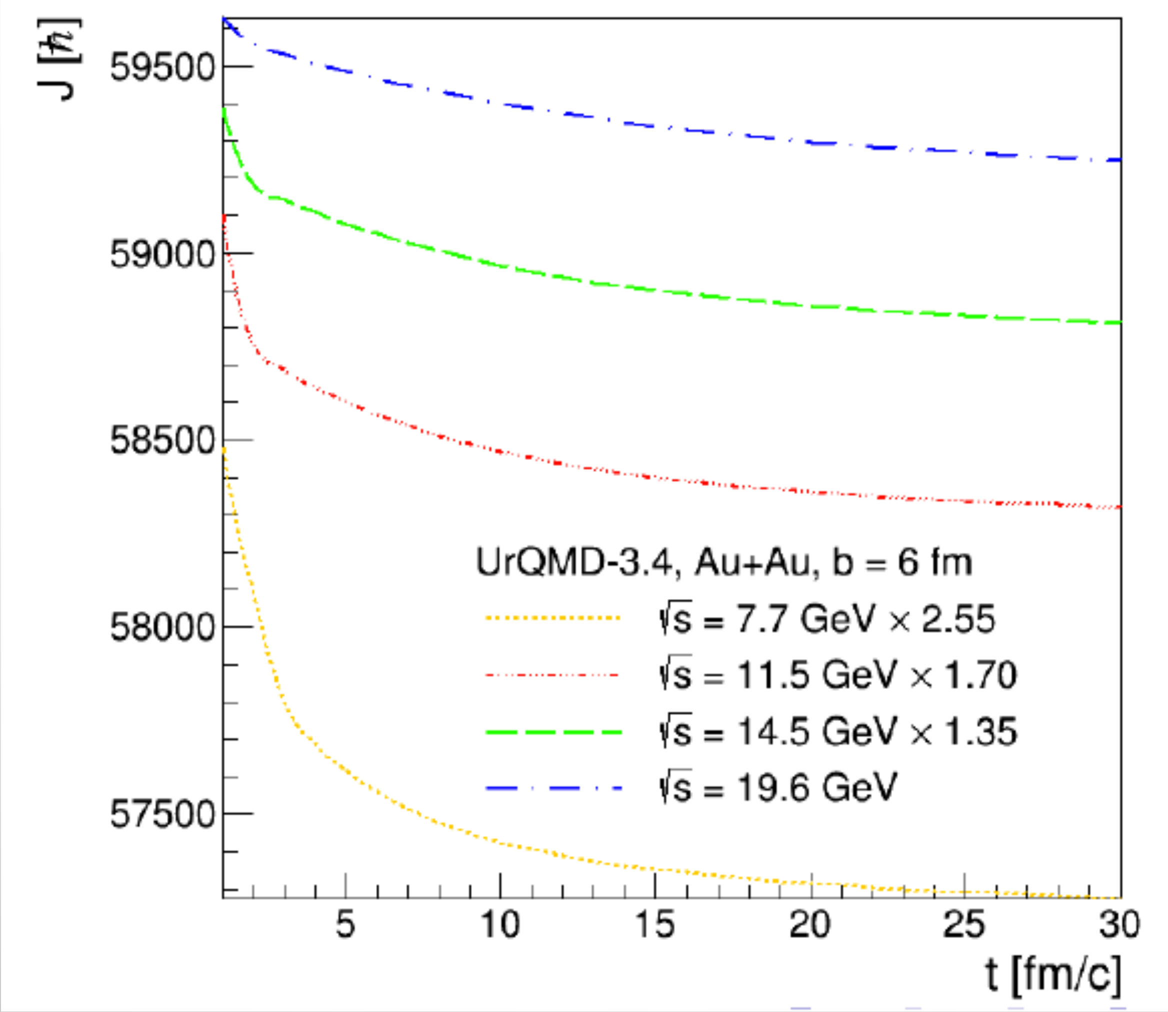
Output:

$T, \mu_B, \mu_S$

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

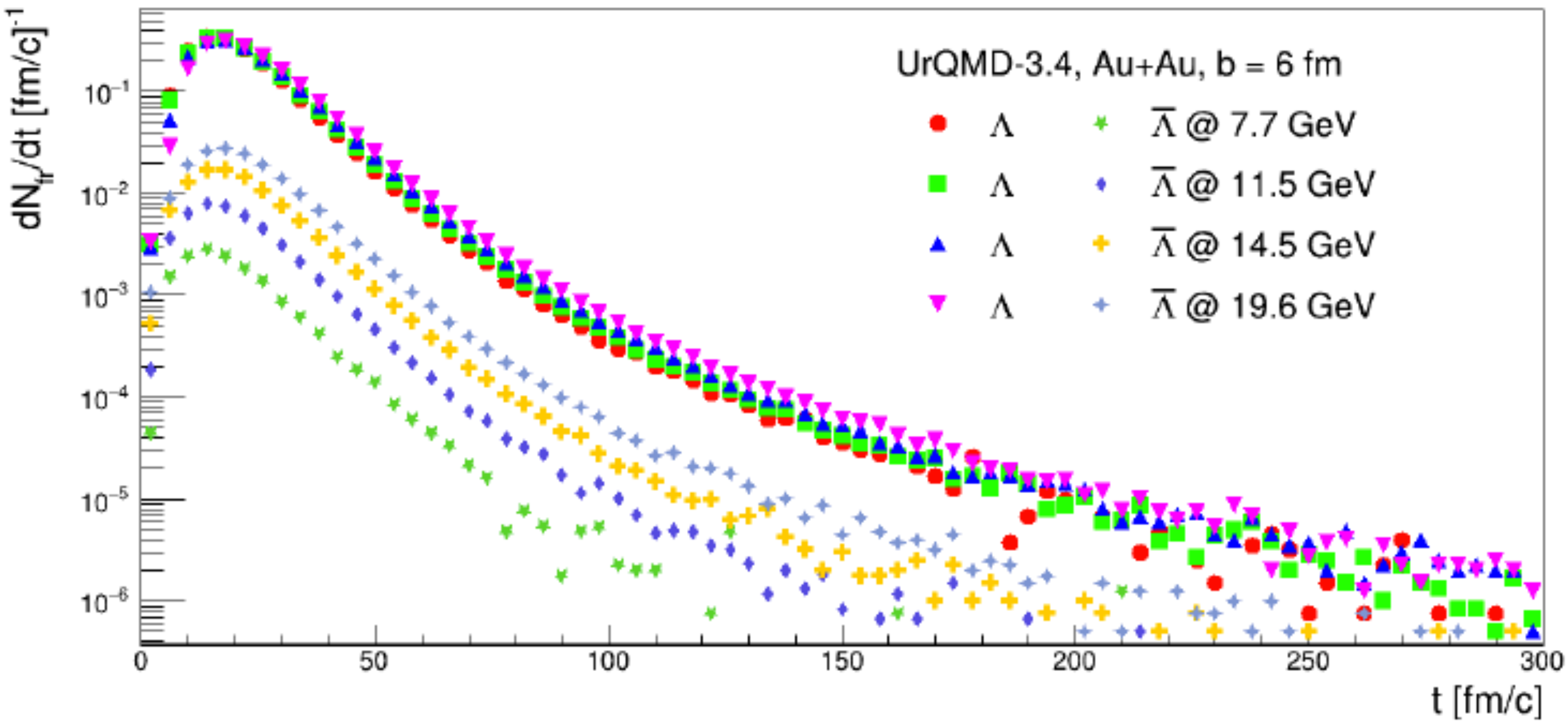
# RESULTS

# ANGULAR MOMENTUM




Angular momentum is not conserved
at early stage of the collision because of inelastic collisions (especially, in decays of strings).
However, maximum deviation does not exceed 2%.

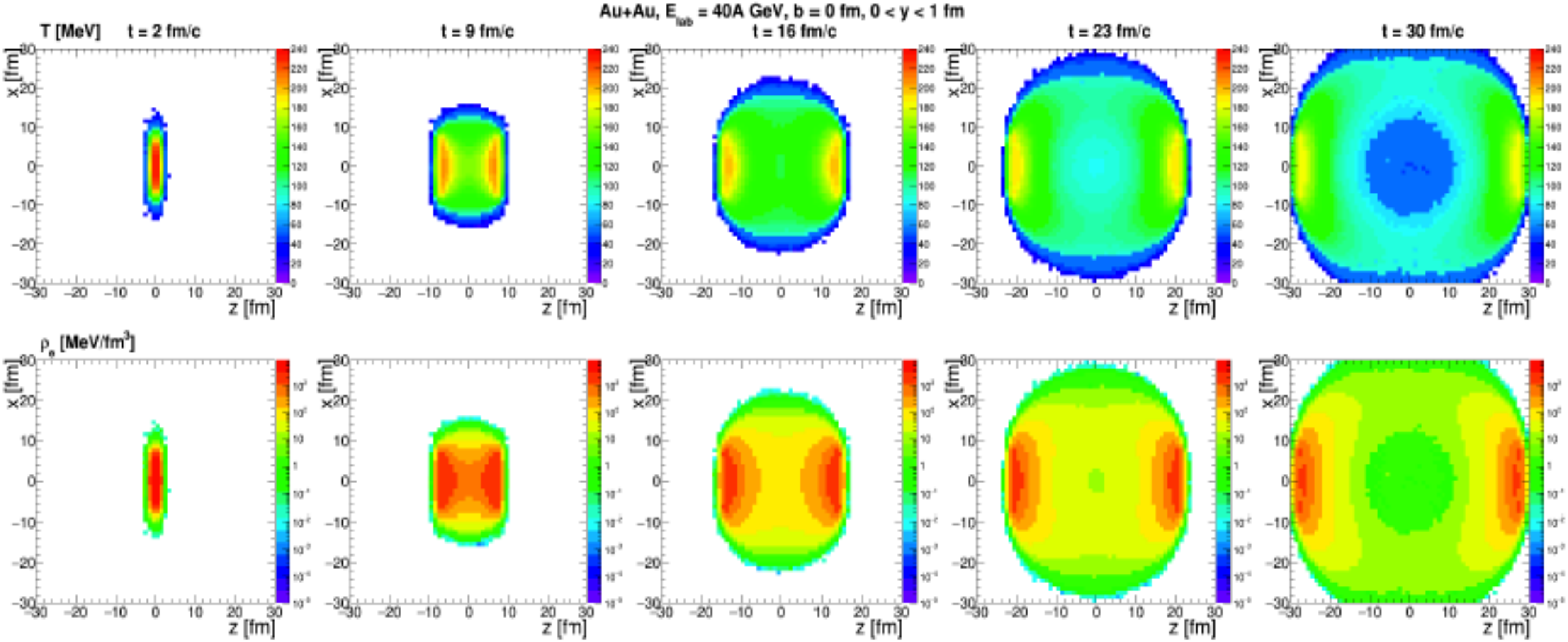
# FREEZE-OUT OF HYPERONS



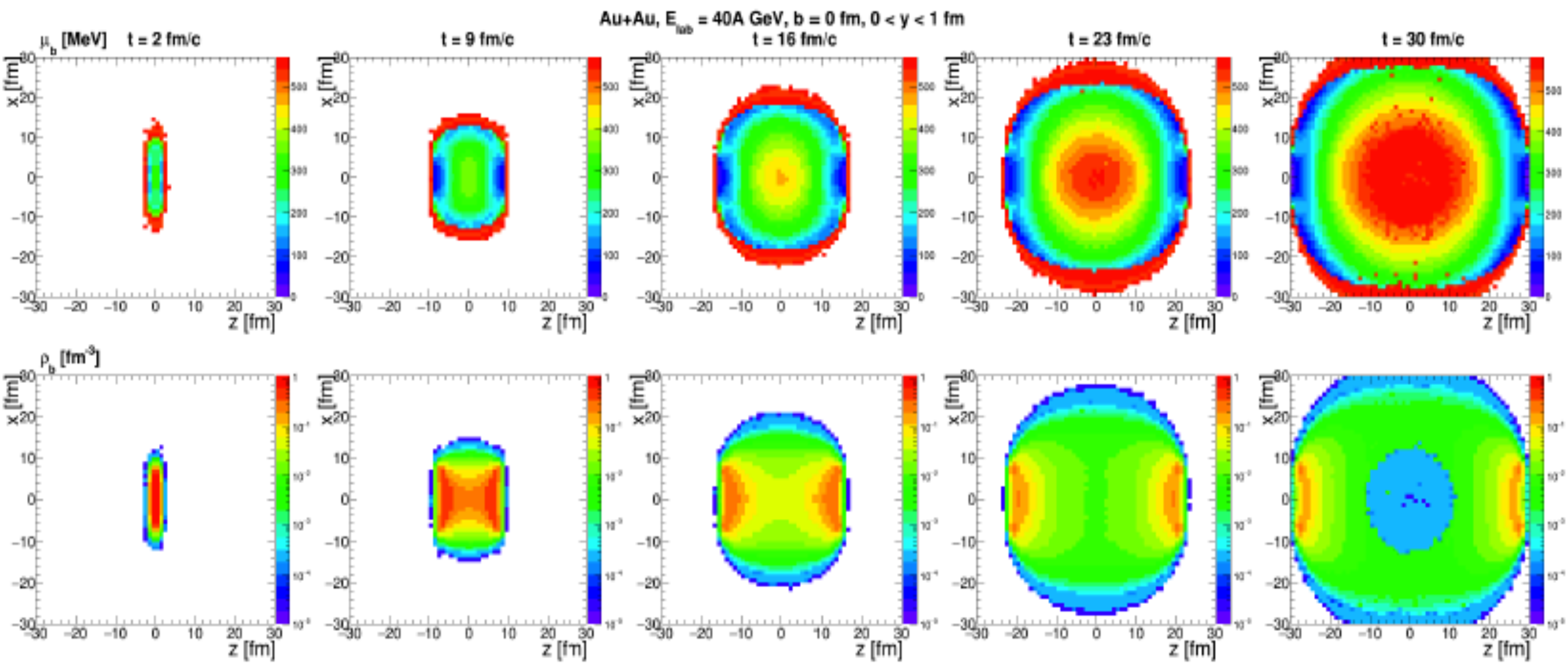

Λ's and $\bar{\Lambda}$'s with $|y| < 1$ and $0.2 < p_t < 3$ GeV/c were analyzed.

| $\sqrt{s}$ [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 |

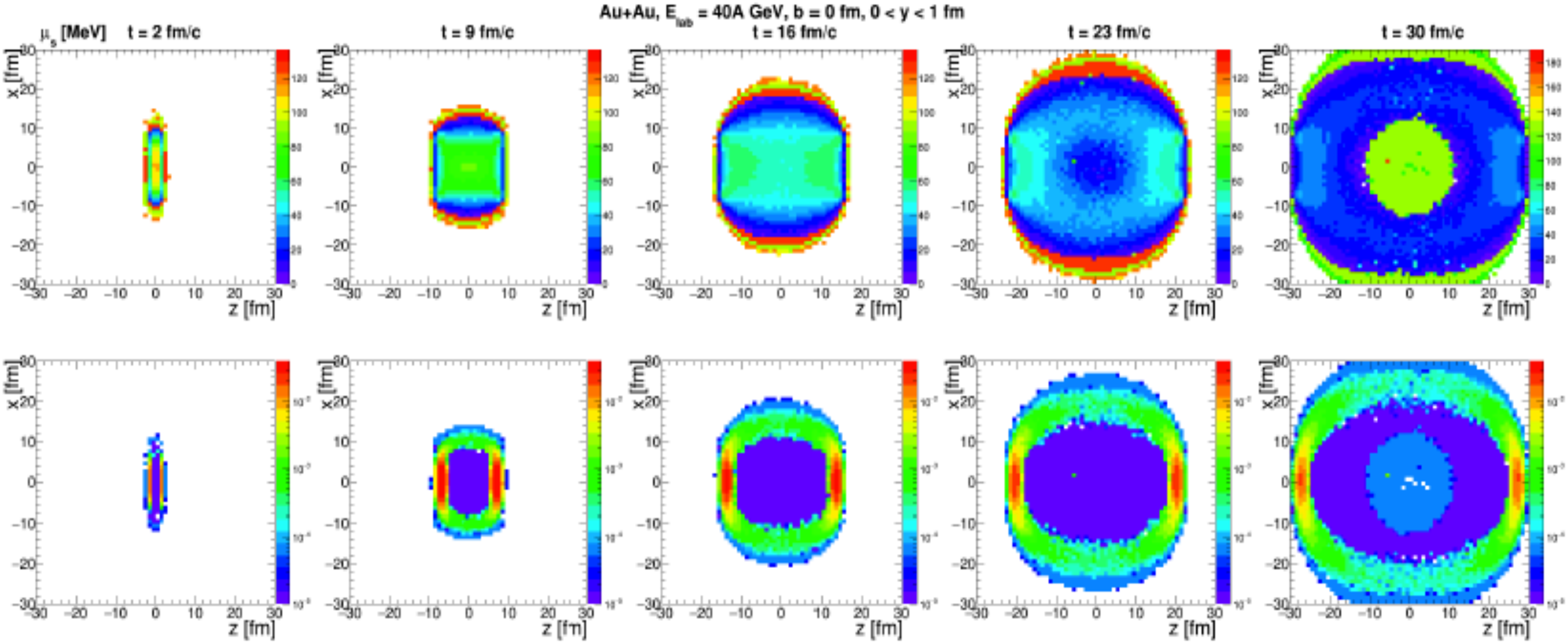
# EVOLUTION OF TEMPERATURE AND ENERGY DENSITY



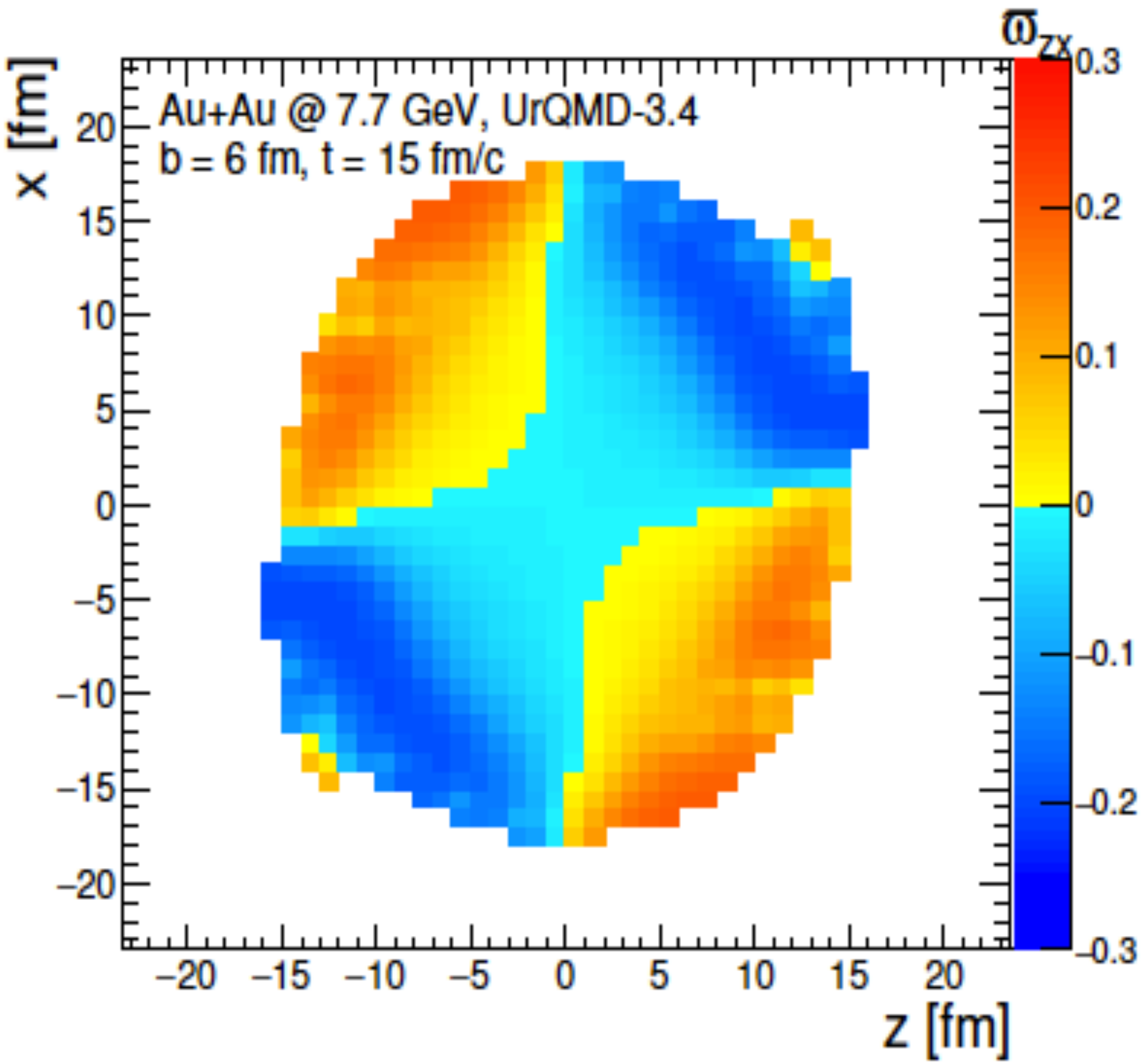
# EVOLUTION OF BARYON CHEMICAL POTENTIAL AND BARYON DENSITY



# EVOLUTION OF STRANGENESS CHEMICAL POTENTIAL AND STRANGENESS DENSITY

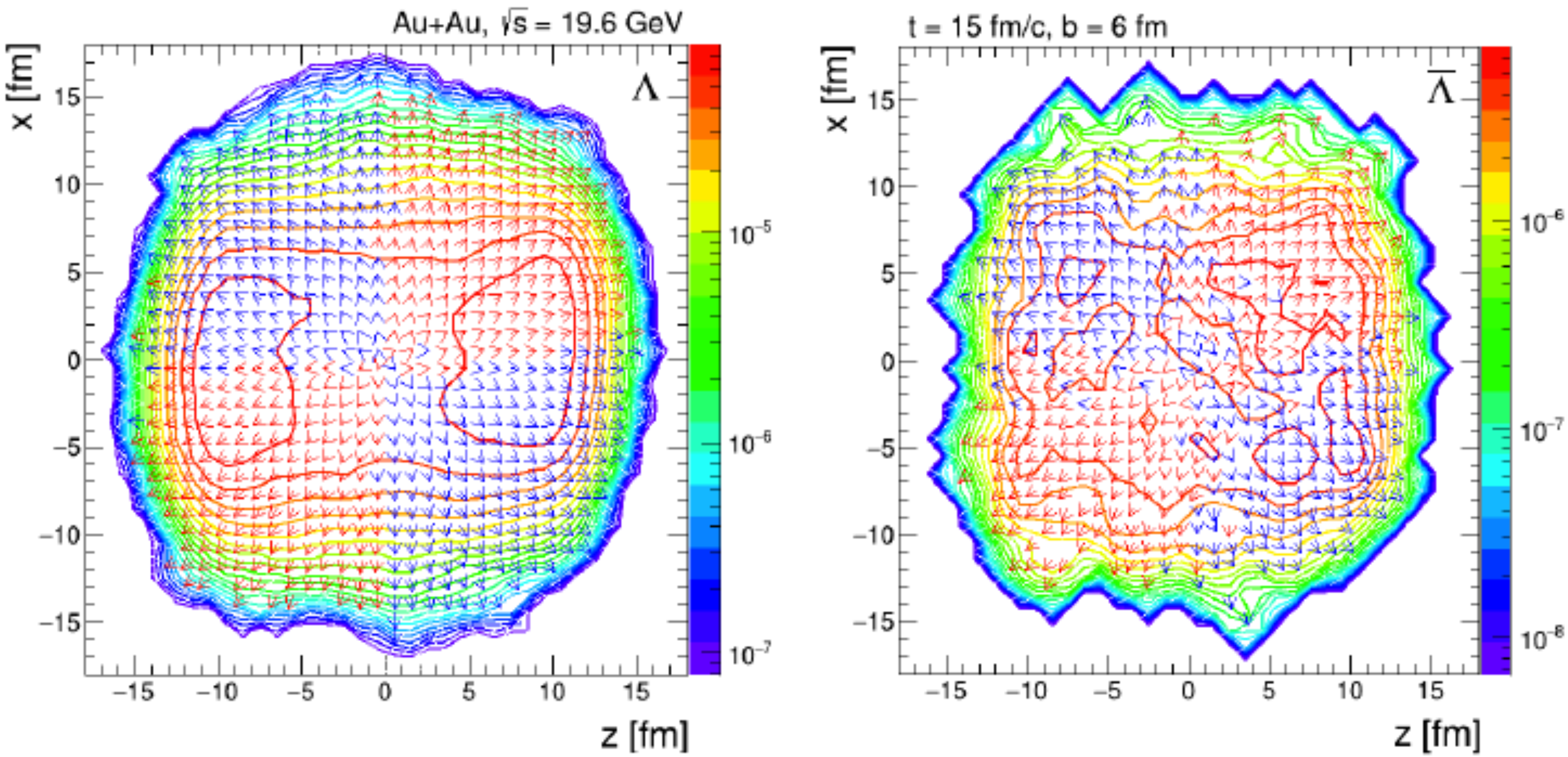


# THERMAL VORTICITY IN REACTION PLANE



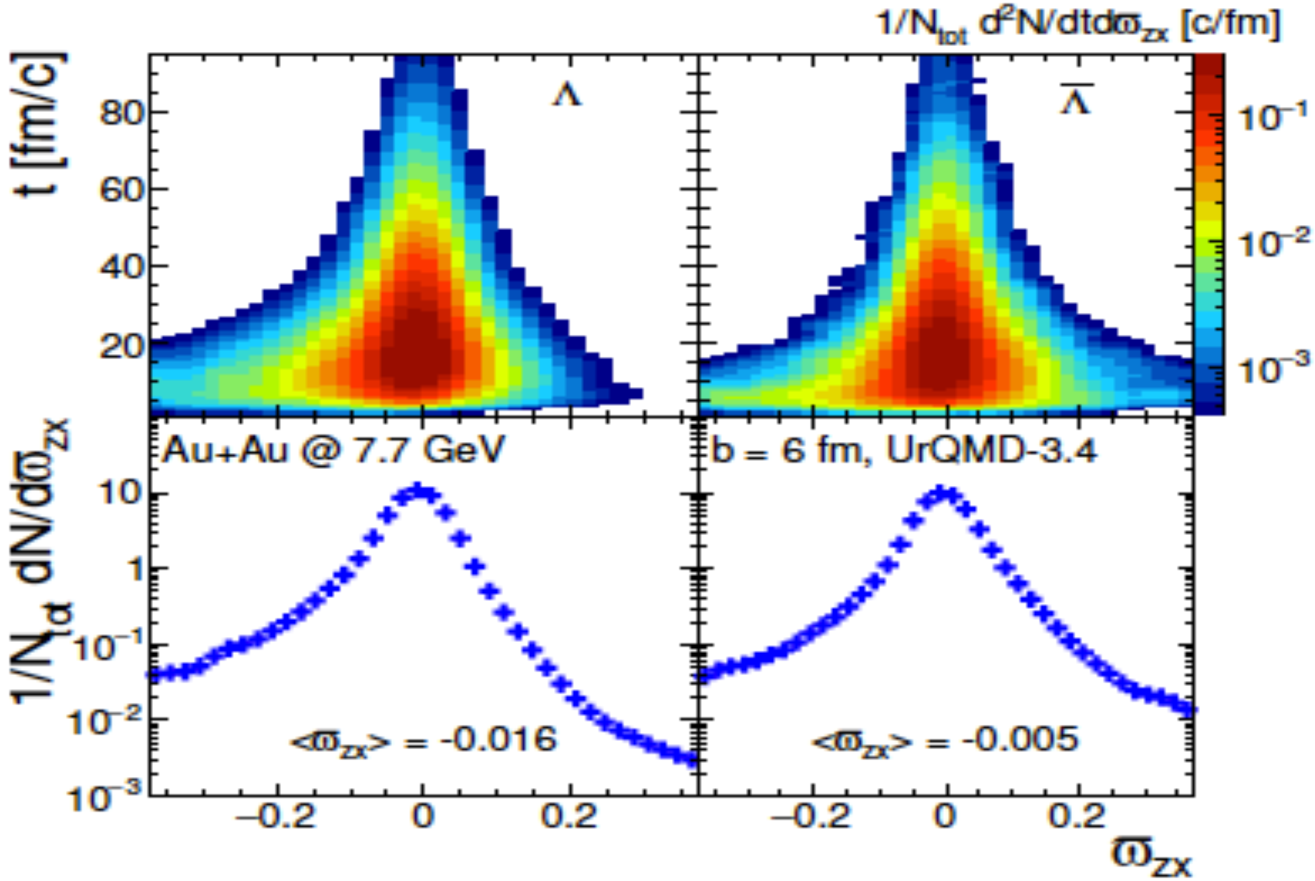

Thermal vorticity component $\varpi_{zx}$ has quadruple-like structure in reaction plane which is stable in time but magnitude decreases due to system expansion. First and third quadrant are connected with central region which has small negative vorticity. This connection part becomes smaller when energy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

# SPATIAL DISTRIBUTION OF (ANTI-)LAMBDAS



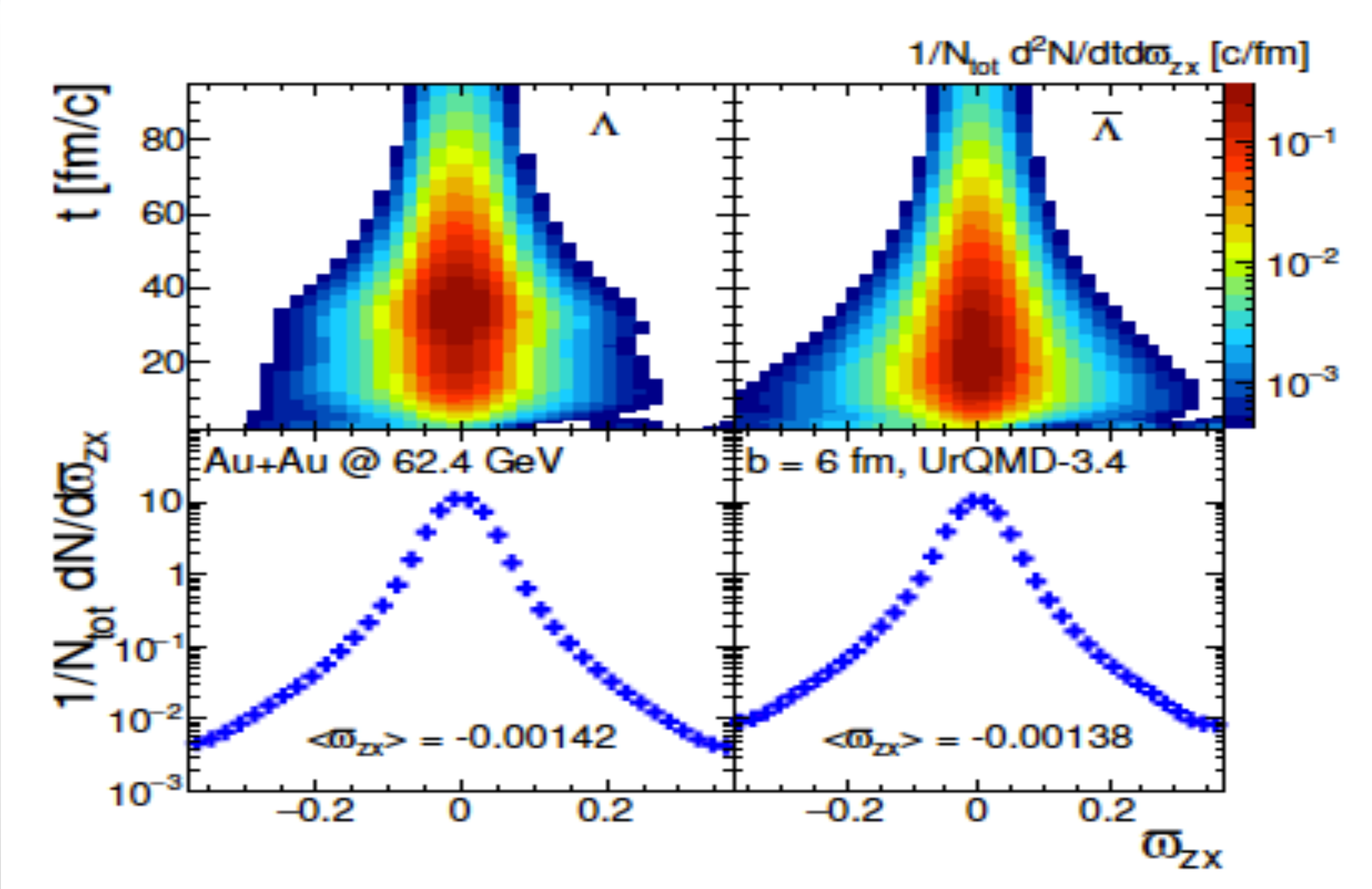

At $\sqrt{s} = 19.6 GeV$ $\Lambda$ are mostly located near hot and dense regions and $\bar{\Lambda}$ are distributed more uniformly near system center.

# EMISSION OF LAMBDAS AND ANTILAMBDAS



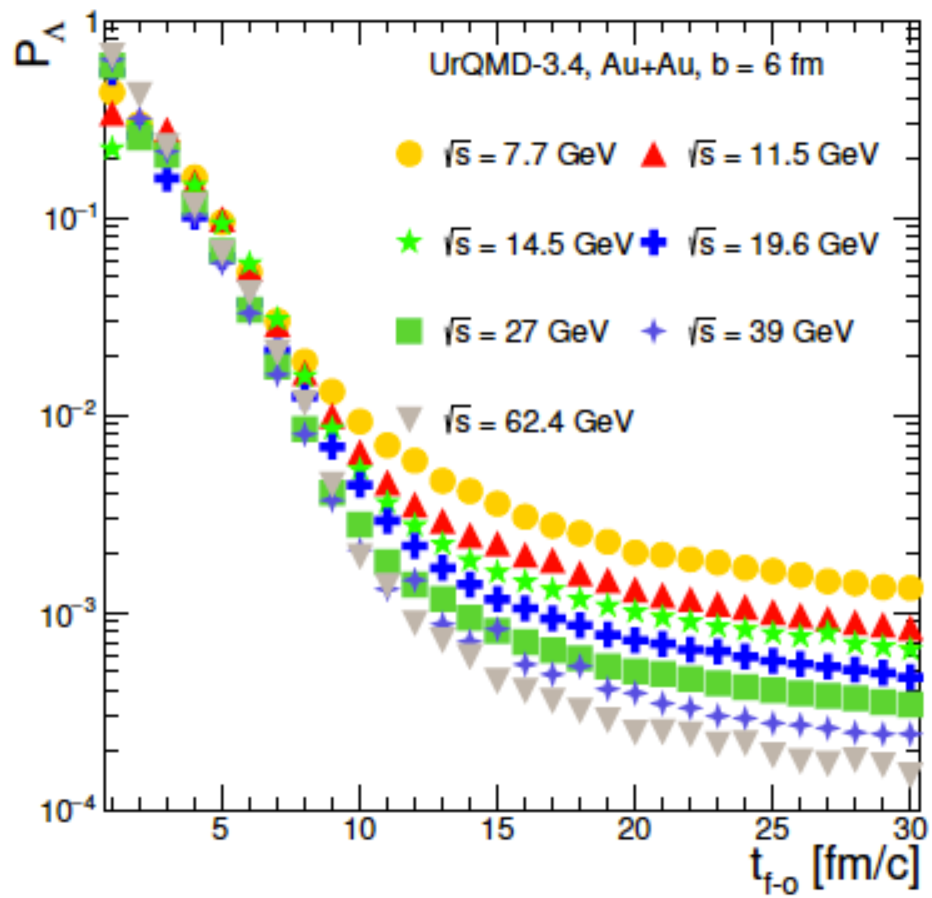

At $\sqrt{s} = 7.7 GeV$ $\Lambda$ and $\bar{\Lambda}$ are mainly emitted from regions with small negative vorticity, thus they should have non-zero positive polarization. $\bar{\Lambda}$ has mean value of $\varpi_{zx}$ with larger magnitude than $\Lambda$

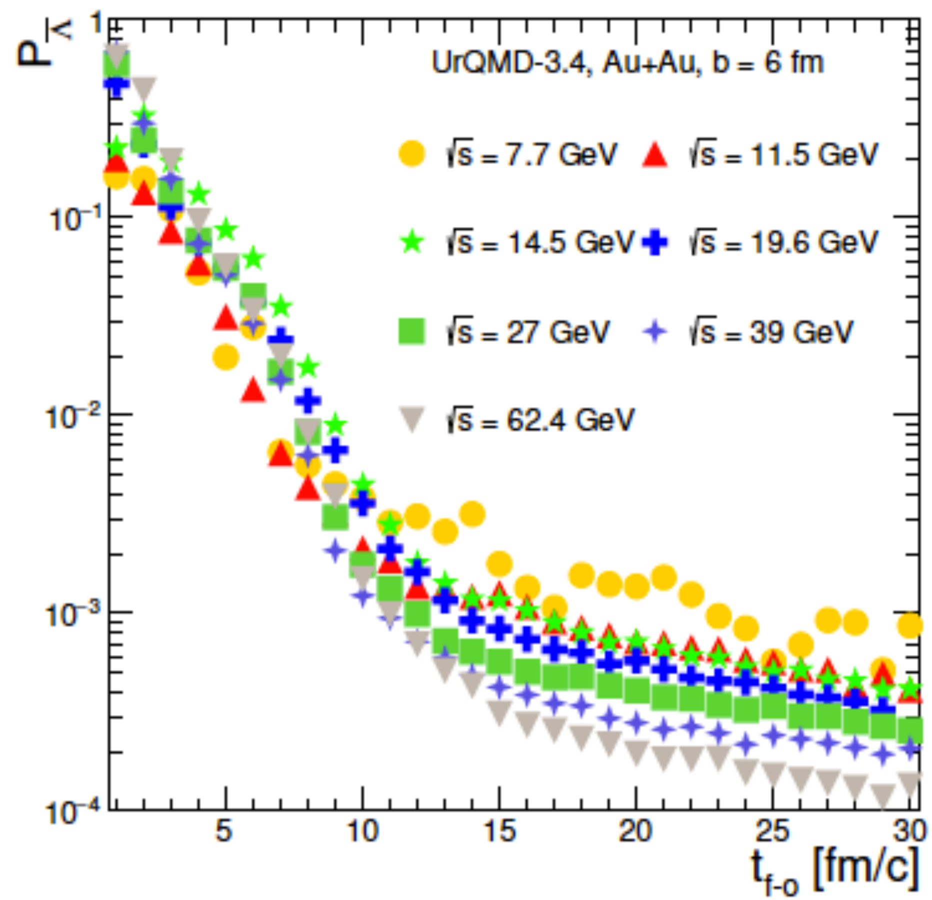
# EMISSION OF LAMBDAS AND ANTILAMBDAS




At $\sqrt{s} = 62.4$ GeV $\Lambda$ and $\bar{\Lambda}$ are also mainly emitted from regions with small negative vorticity, but distributions are more symmetric and wide.

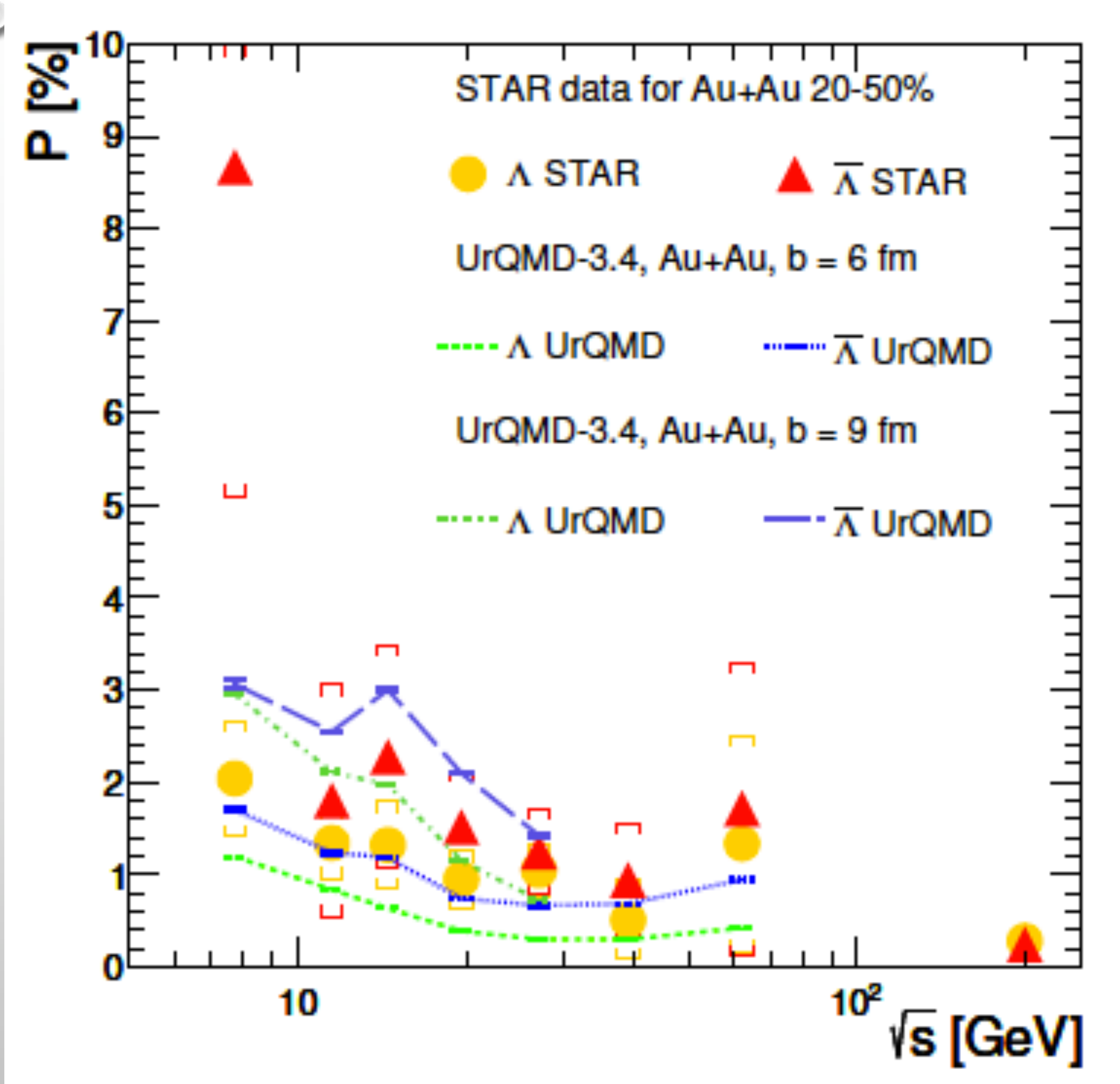
# POLARIZATION OF (ANTI-)LAMBDAS




Polarization of both hyperons decreases with time. At the early stages Lambdas are formed preferably in the hot and dense regions with high polarization. Polarization of (anti-)Lambdas formed after t = 10 fm/c is close to zero.

# ENERGY DEPENDENCE OF GLOBAL POLARIZATION OF (ANTI-)LAMBDAS



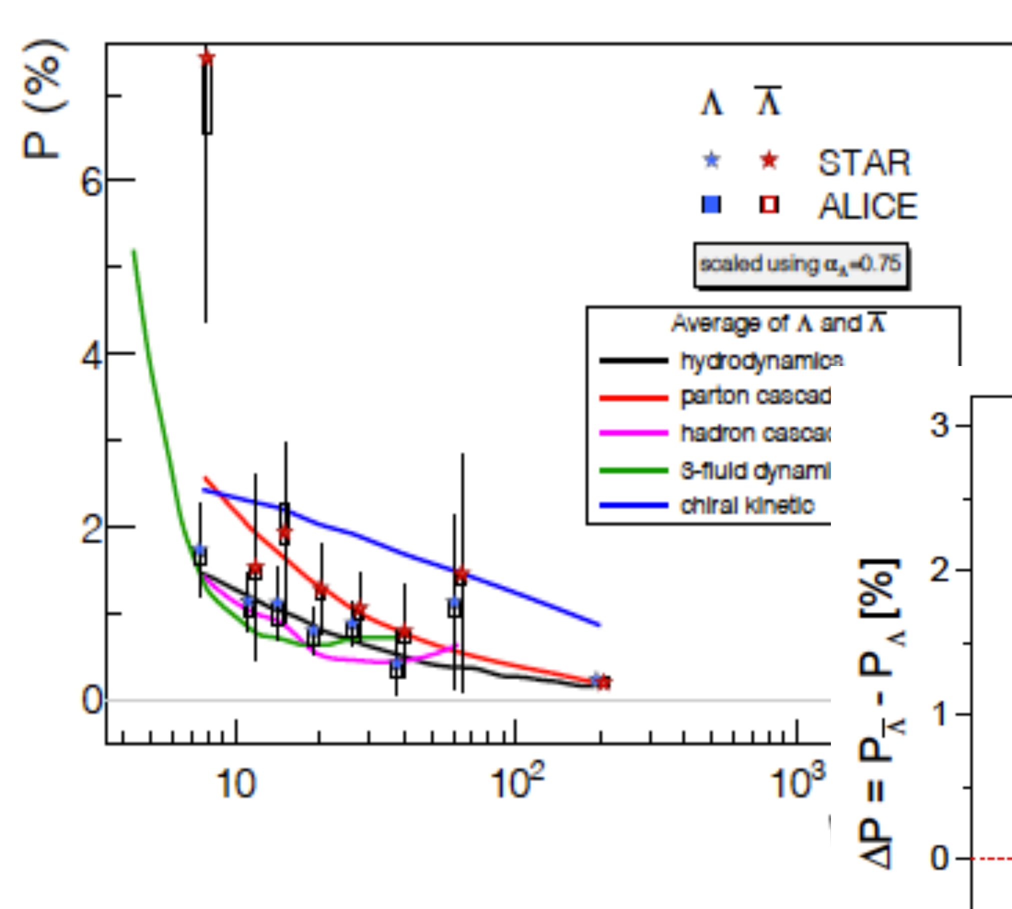

The difference between the global polarization of both hyperons originates

(i) from different space-time distributions of Lambdas and anti-Lambdas and

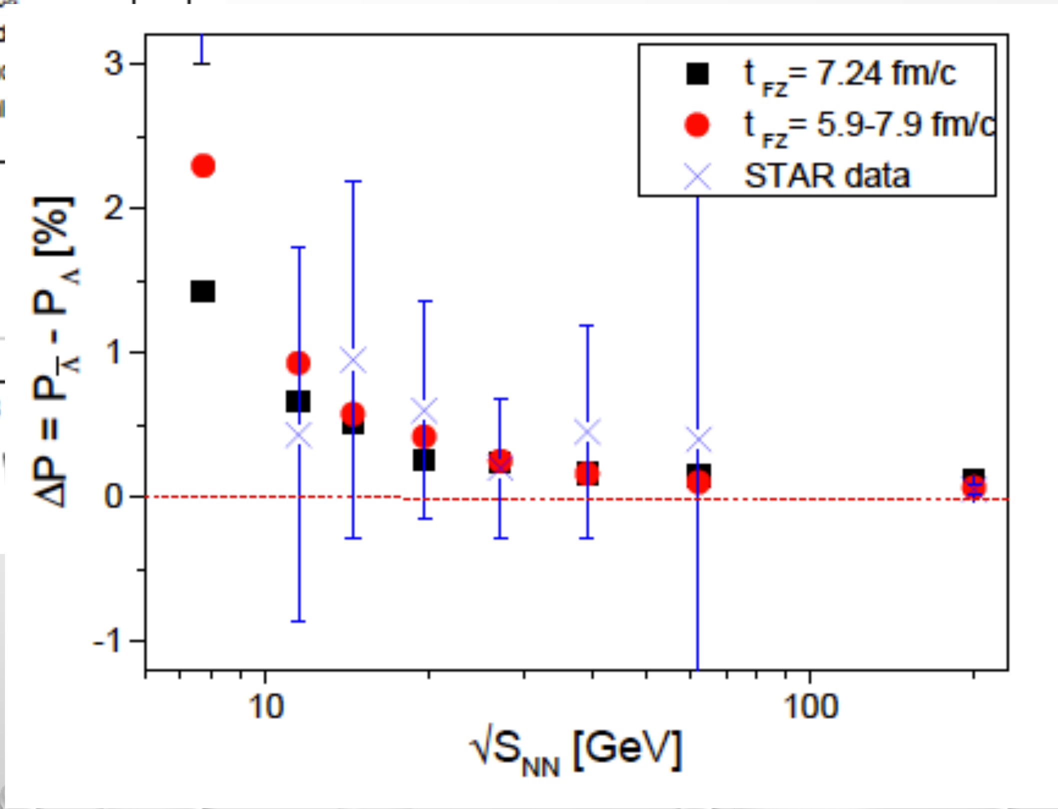
(ii) from the different freeze-out conditions of both hyperons wrt thermal vorticity field.

Data are from PRC 98 (2018) 014910

# OTHER APPROACHES:




However, our idea is quite reasonable, e.g., Y.Xie, G.Chen, L.P.Csernai, arXiv:1912.00209




F.Becattini and M.A.Lisa, arXiv:2003.03640

# 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 $\varpi_{zx}$ vorticity is obtained.
- Magnitude of vorticity dependence on time and energy is studied.
- Method for calculation of $\Lambda$ polarization in transport model is developed.
- Freeze-out of $\Lambda$ and $\bar{\Lambda}$ is different in space and time, thus they are emitted from parts of system with different vorticity.

# THANK YOU !