Study of thermal vorticity and hyperon polarization in heavy-ion collisions at intermediate energies

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in collaboration with

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ICNFP-2023, OAC, Kolymbari, Crete, Greece, 10.07 – 23.07.2023

MOTIVATION

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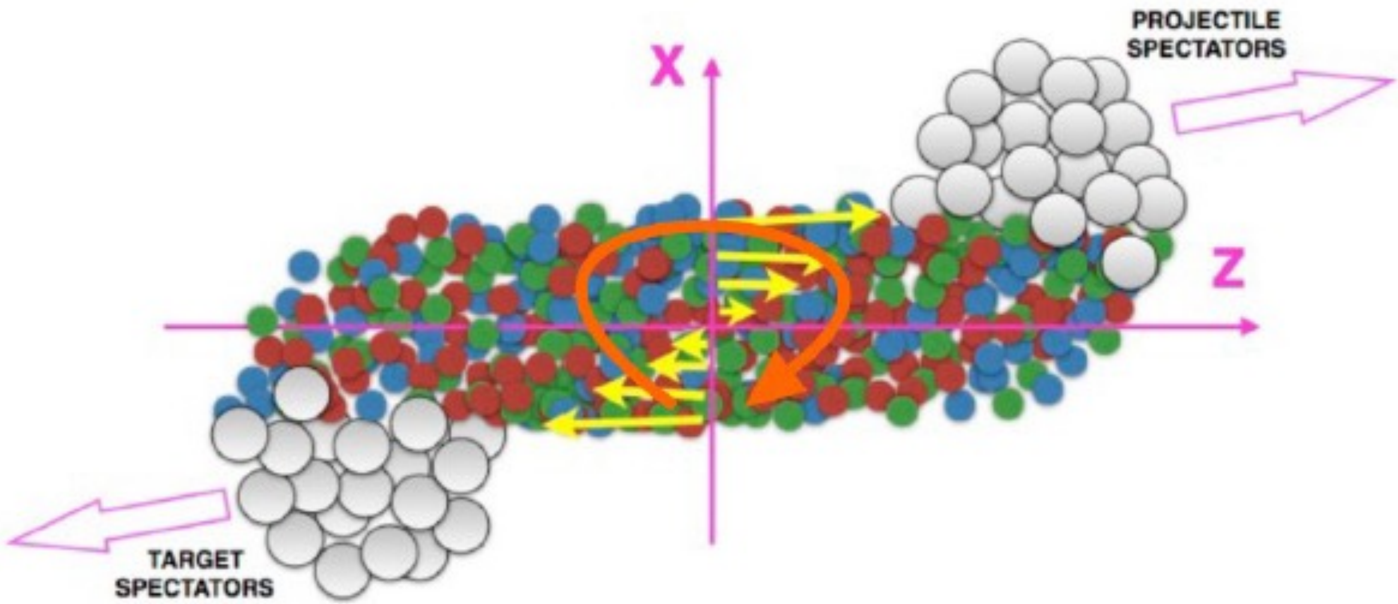
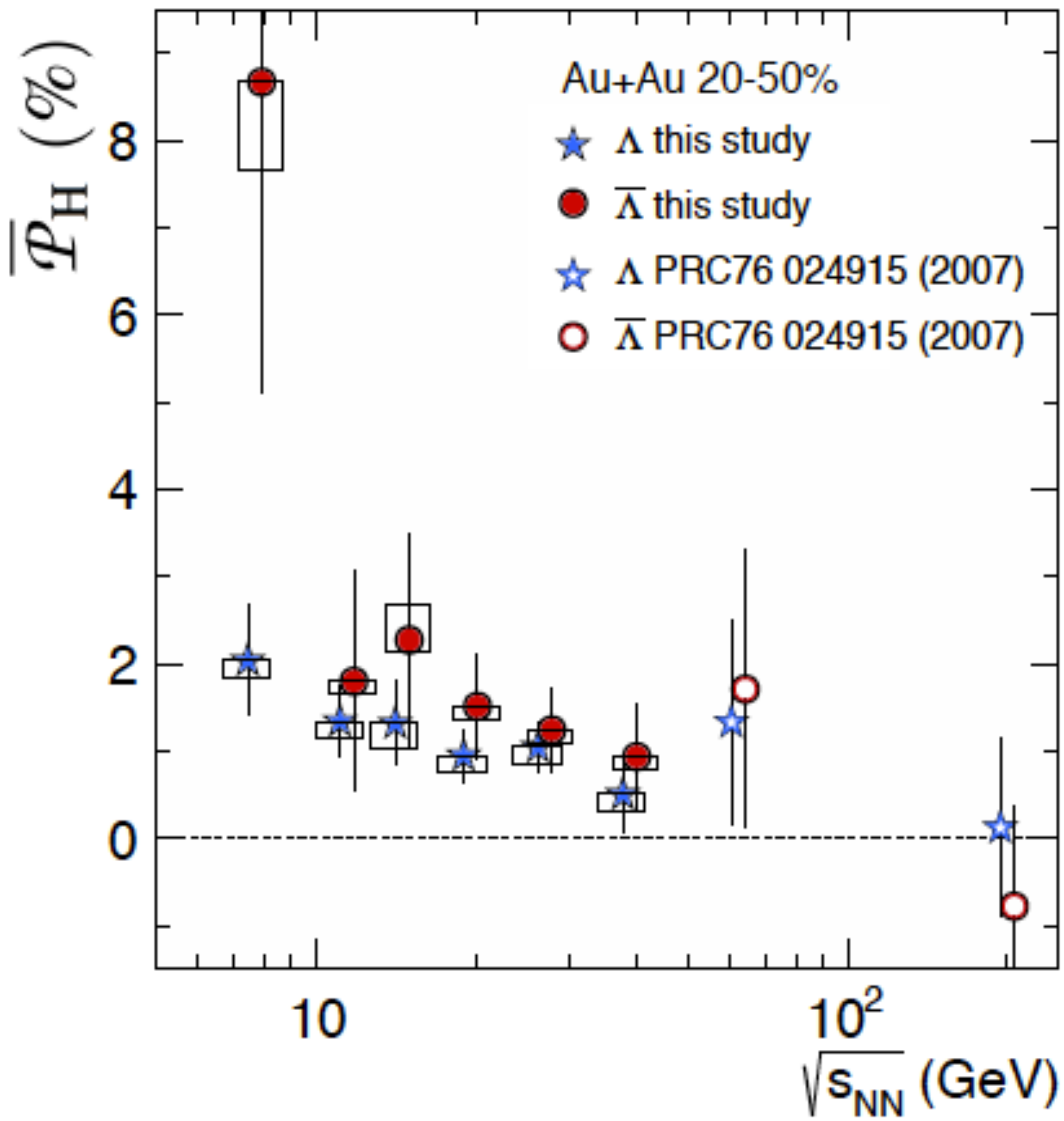


In non-central collisions, the initial collective longitudinal flow velocity depends on x:

$$\omega_y = \frac{1}{2}(\nabla \times v)_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$

MOTIVATION

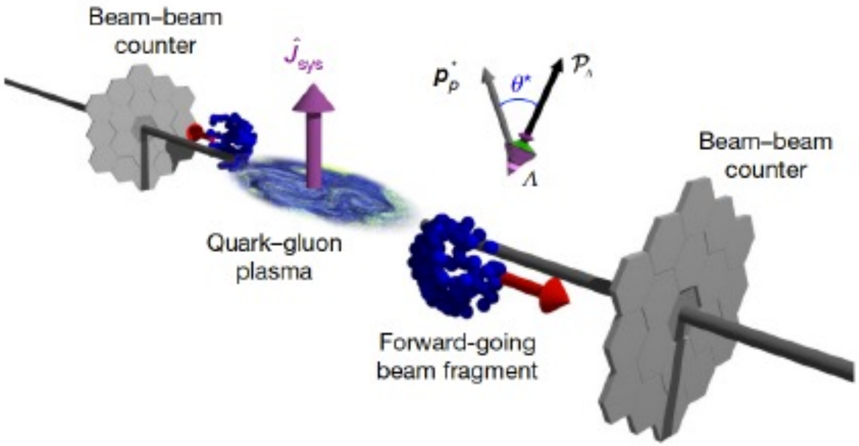


"The discovery of global Lambda polarization in non-central heavy ion collisions opens new directions in the study of the hottest, least viscous - and now, most vortical - fluid ever produced in the laboratory."

STAR Collaboration, Nature 548 (2017) 62

MEASUREMENT OF Λ POLARIZATION

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]

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 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)]

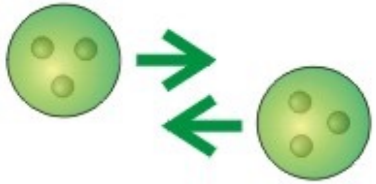
MODELS AT OUR DISPOSAL

TRANSPORT MODEL: UrQMD

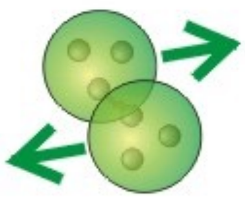
- Represents a Monte Carlo method for the time evolution of the various phase space densities of particle species.
- Based on the covariant propagation of all hadrons on classical trajectories, stochastic binary scatterings, resonance and string formation with their subsequent decay.
- Provides the solution of the relativistic Boltzmann equation.
- The collision criterion (black disk approximation):
  $d < d_0 = \sqrt{\sigma_{tot}(\sqrt{s}, \mathrm{type})/\pi}$
- 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]

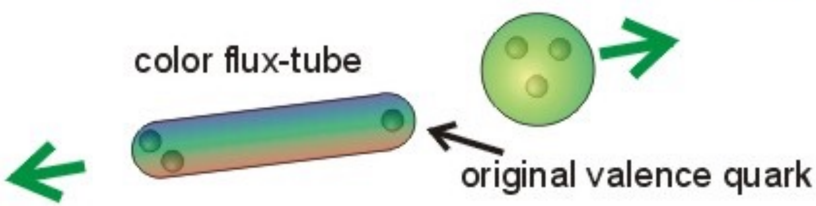
PARTICLE PRODUCTION VIA STRINGS IN URQMD



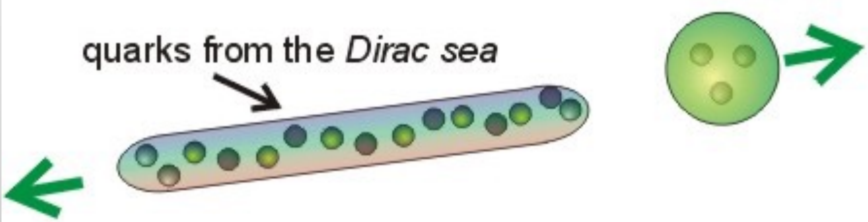
- in high energy collisions hadrons can be excited into *strings*
- a *color flux-tube* is formed by pulling one valence quark away from the remaining ones in the hadron



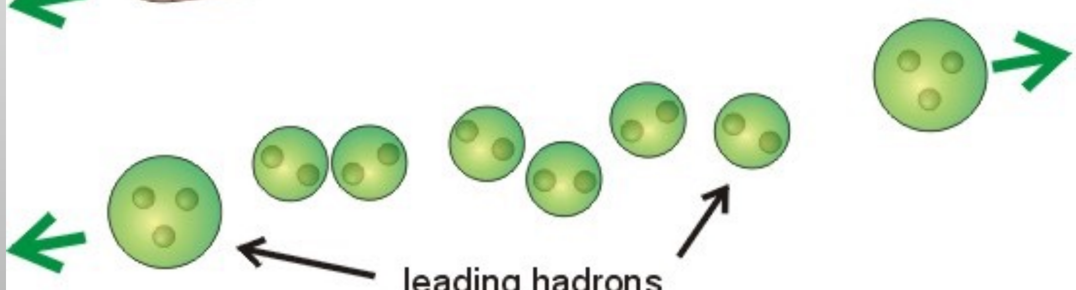
- if the color-field increases beyond a critical value (defined by the *string-tension*), spontaneous quark-antiquark creation from the *Dirac sea* occurs (*Schwinger mechanism*)



- 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

Steffen A. Bass

STATISTICAL MODEL OF IDEAL HADRON GAS

input values → output values

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

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

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

Multiplicity →

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

Energy →

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

Pressure →

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

Entropy density →

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

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:

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

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

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

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

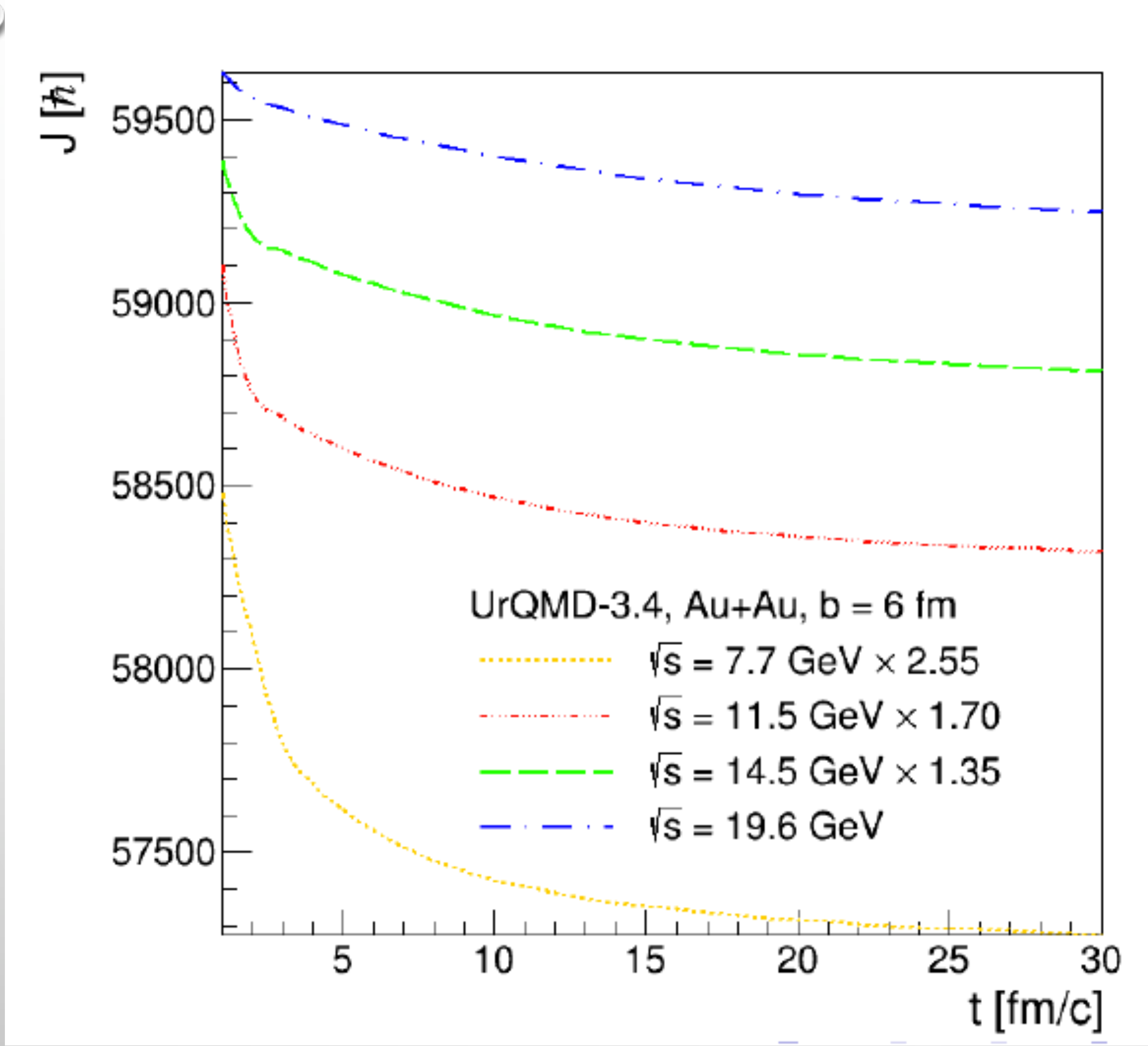
Minuit2 numerical minimizer

Output:
T, μ_B, μ_S

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

RESULTS

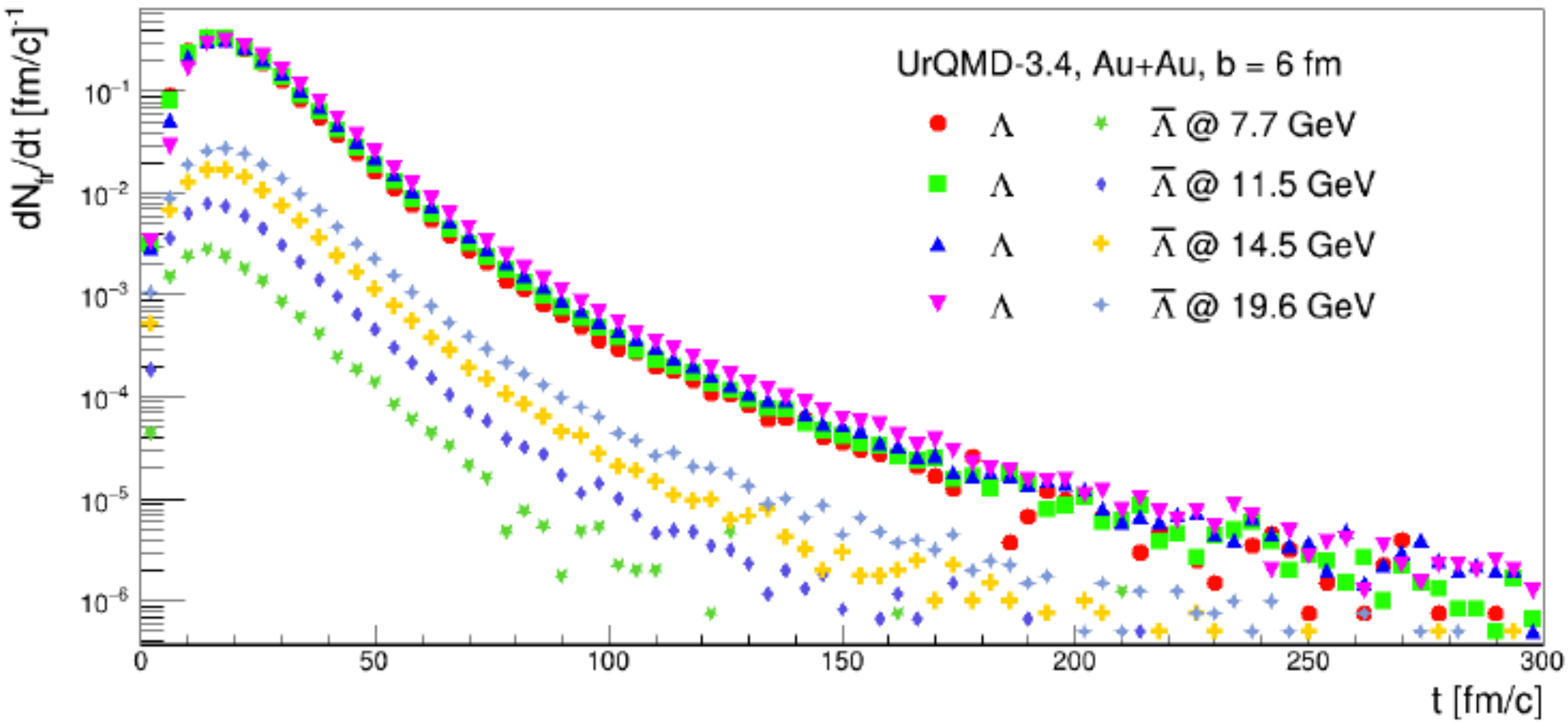
ANGULAR MOMENTUM



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

L.B. et al, Symmetry 13 (2021) 10, 1852

FREEZE-OUT OF HYPERONS

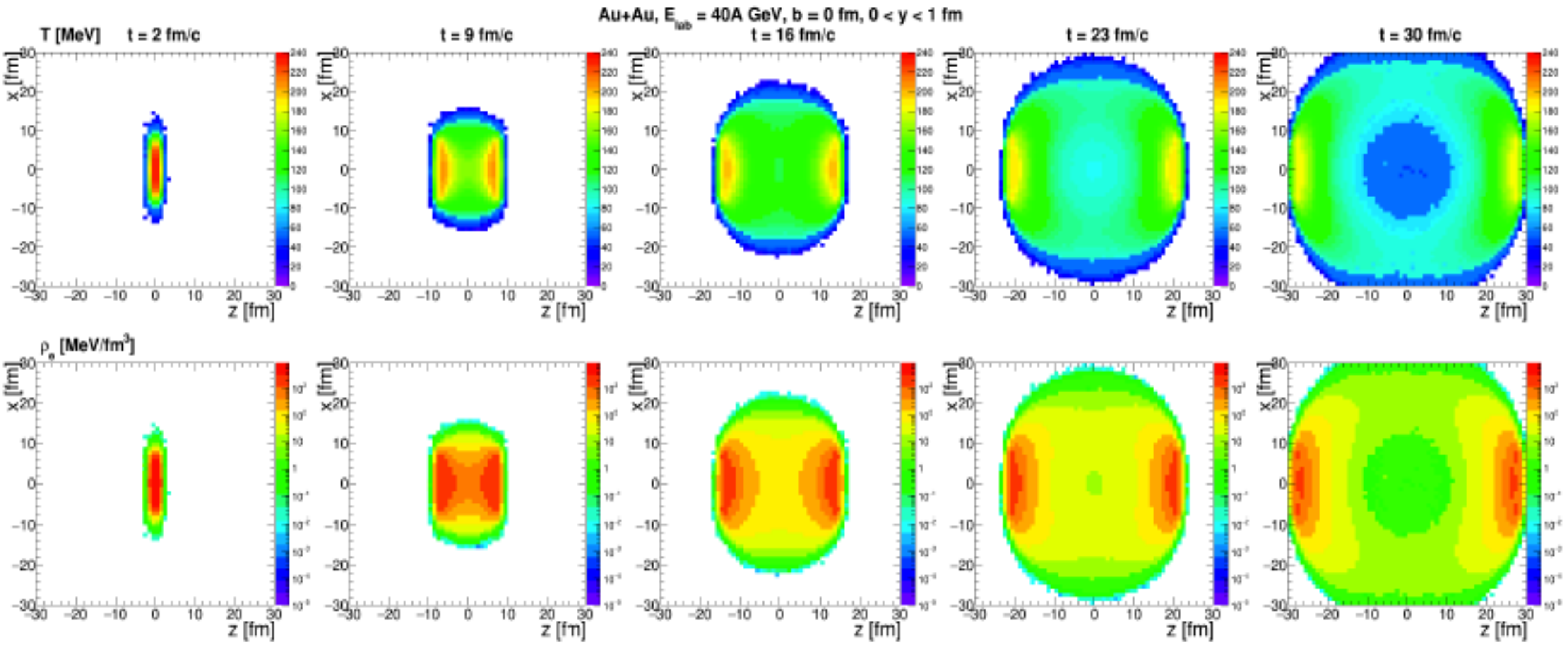


Λ's and $\bar{\Lambda}$'s with $|y| < 1$ and $0.2 < p_t < 3$ GeV/c were analyzed.

$\sqrt{s}$ [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

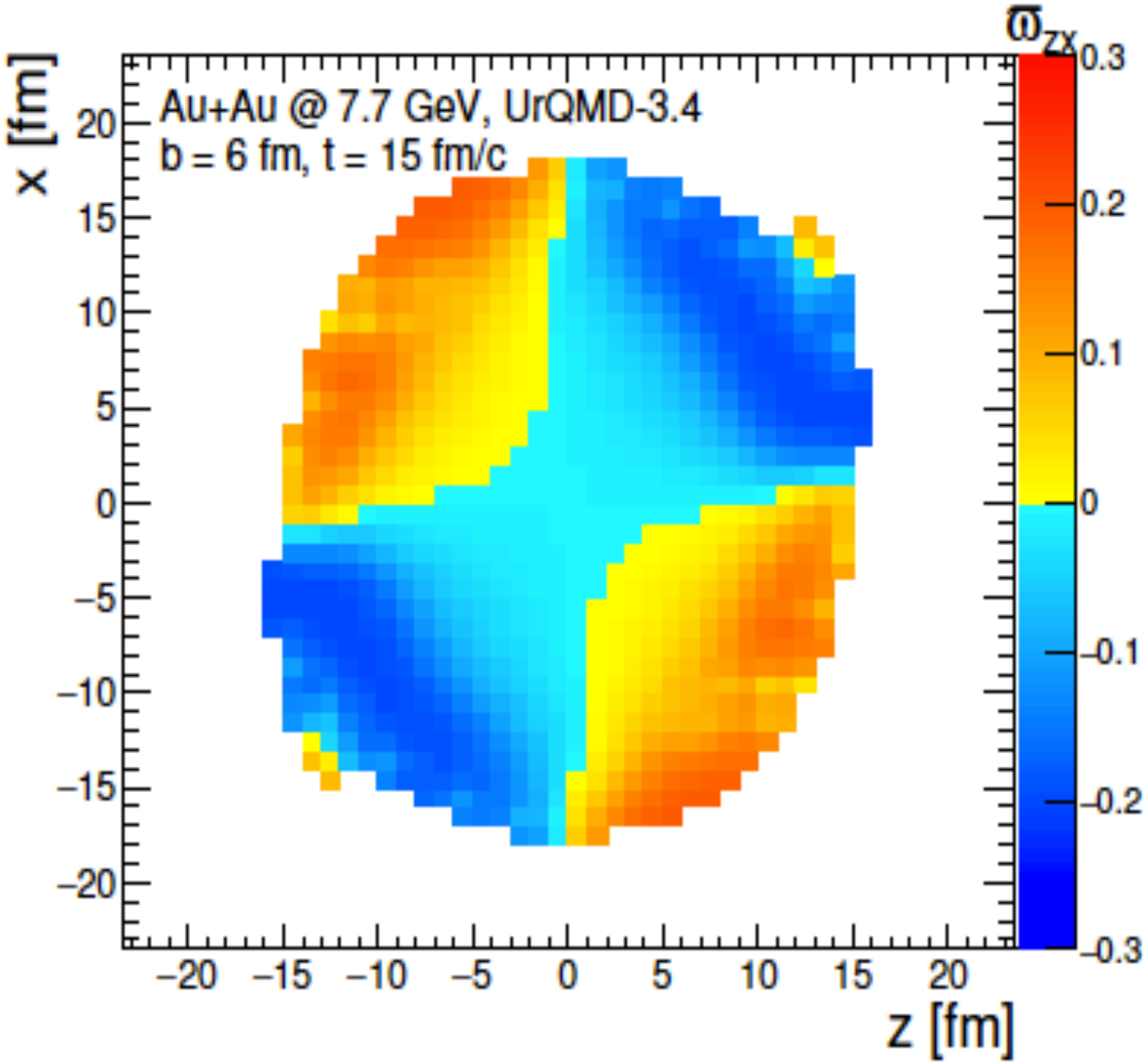
EVOLUTION OF TEMPERATURE AND ENERGY DENSITY

L.B. et al, Symmetry 13 (2021) 10, 1852



Neither energy density nor temperature is uniformly distributed within the expanding hot and dense nuclear matter

THERMAL VORTICITY IN THE REACTION PLANE

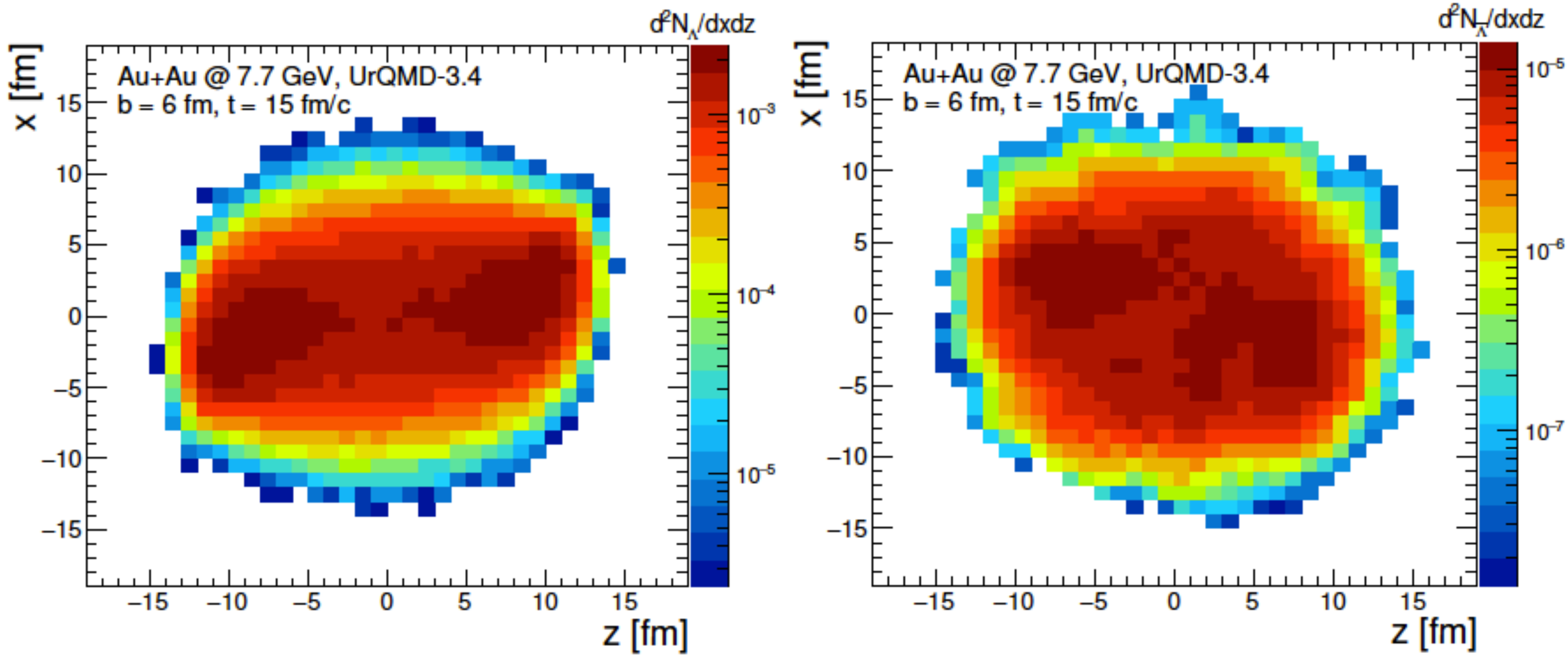


O. Vitiuk, L.B., E. Zabrodin, PLB 803 (2020) 135298

Thermal vorticity component ω_{zx} has a quadruple structure in the reaction plane. It is stable in time, but its magnitude decreases because of the system expansion. At intermediate energies, first and third quadrants are connected in the central area which has a small negative vorticity. This connection part becomes smaller with increasing energy of heavy ion collisions.

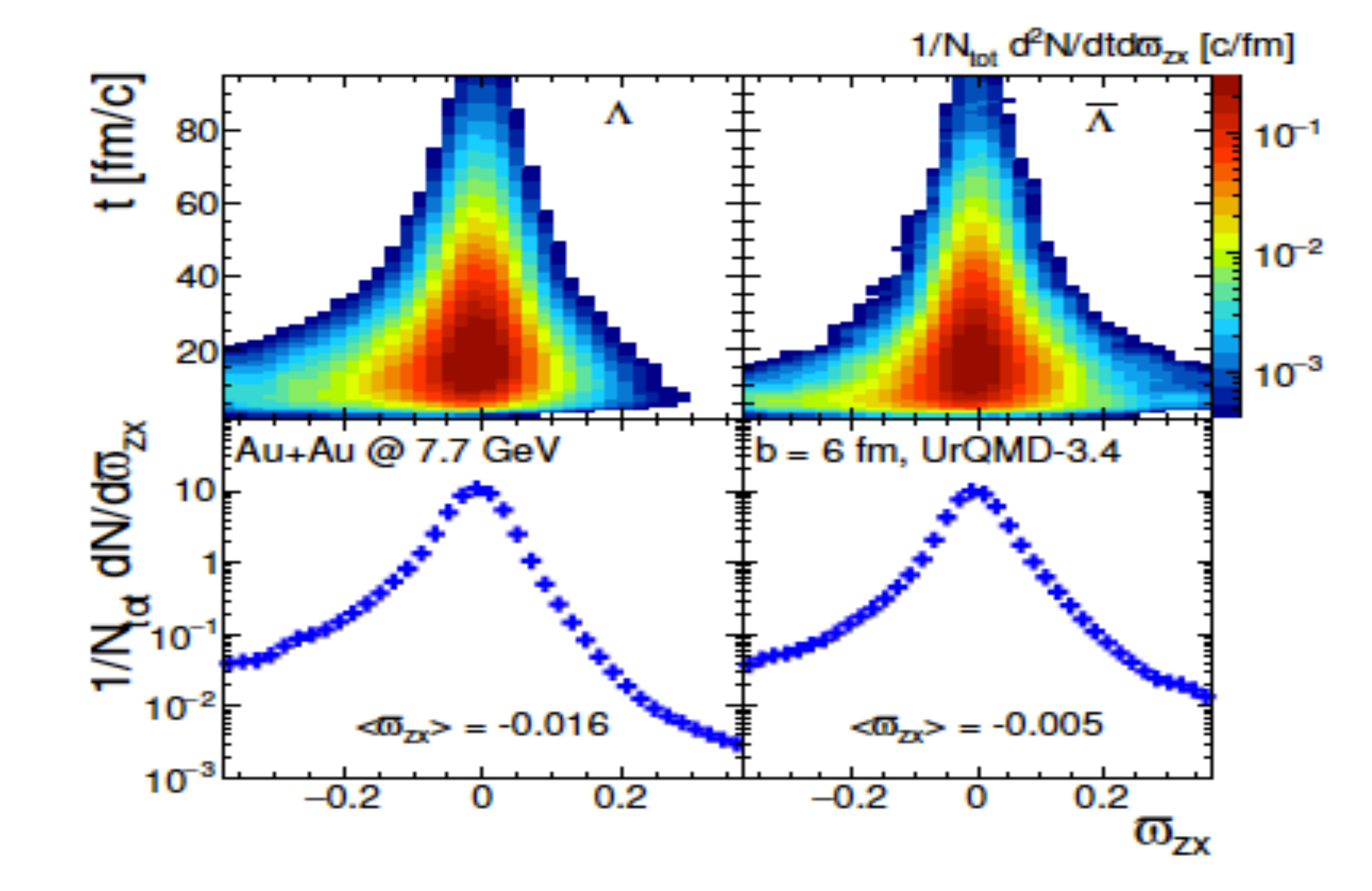
SPATIAL DISTRIBUTION OF Λ AND ANTI-Λ

O. Vitiuk, L.B., E. Zabrodin,
PLB 803 (2020) 135298



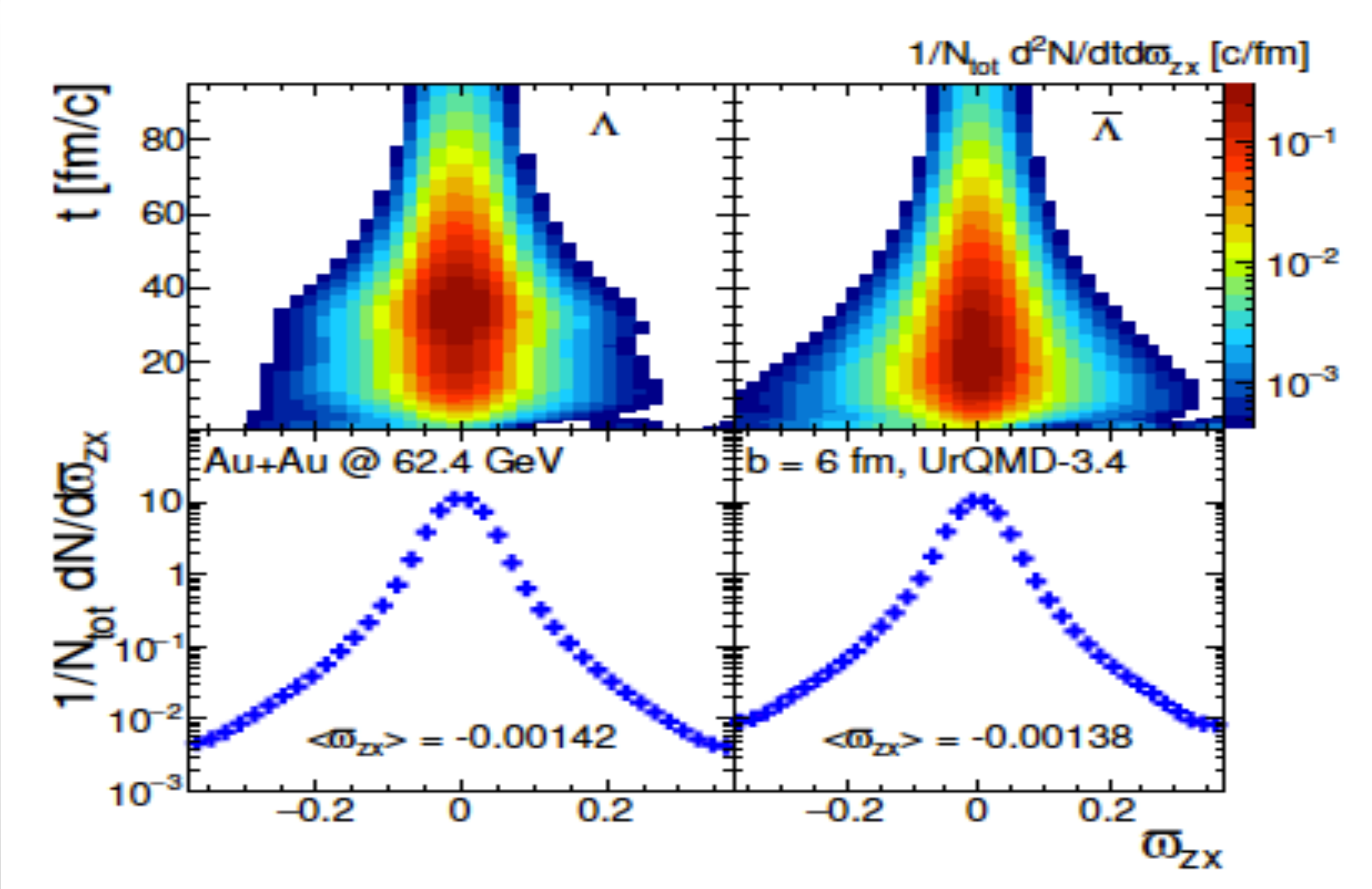
At $\sqrt{s} = 7.7\ GeV$ Λ are mostly located near hot and dense regions and $\bar{\Lambda}$ are distributed more uniformly near system center.

DEPENDENCE ON COLLISION ENERGY



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

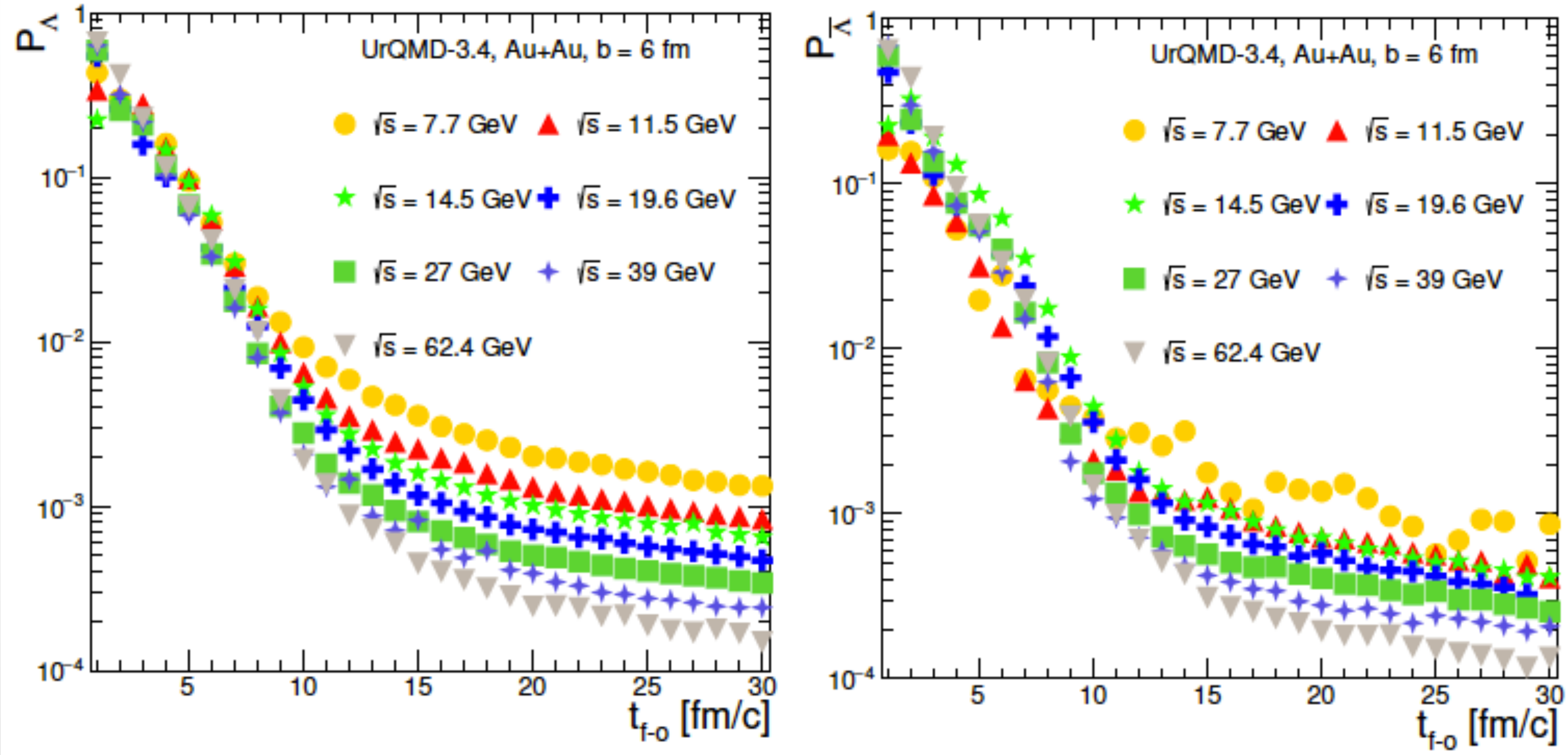
DEPENDENCE ON COLLISION ENERGY



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

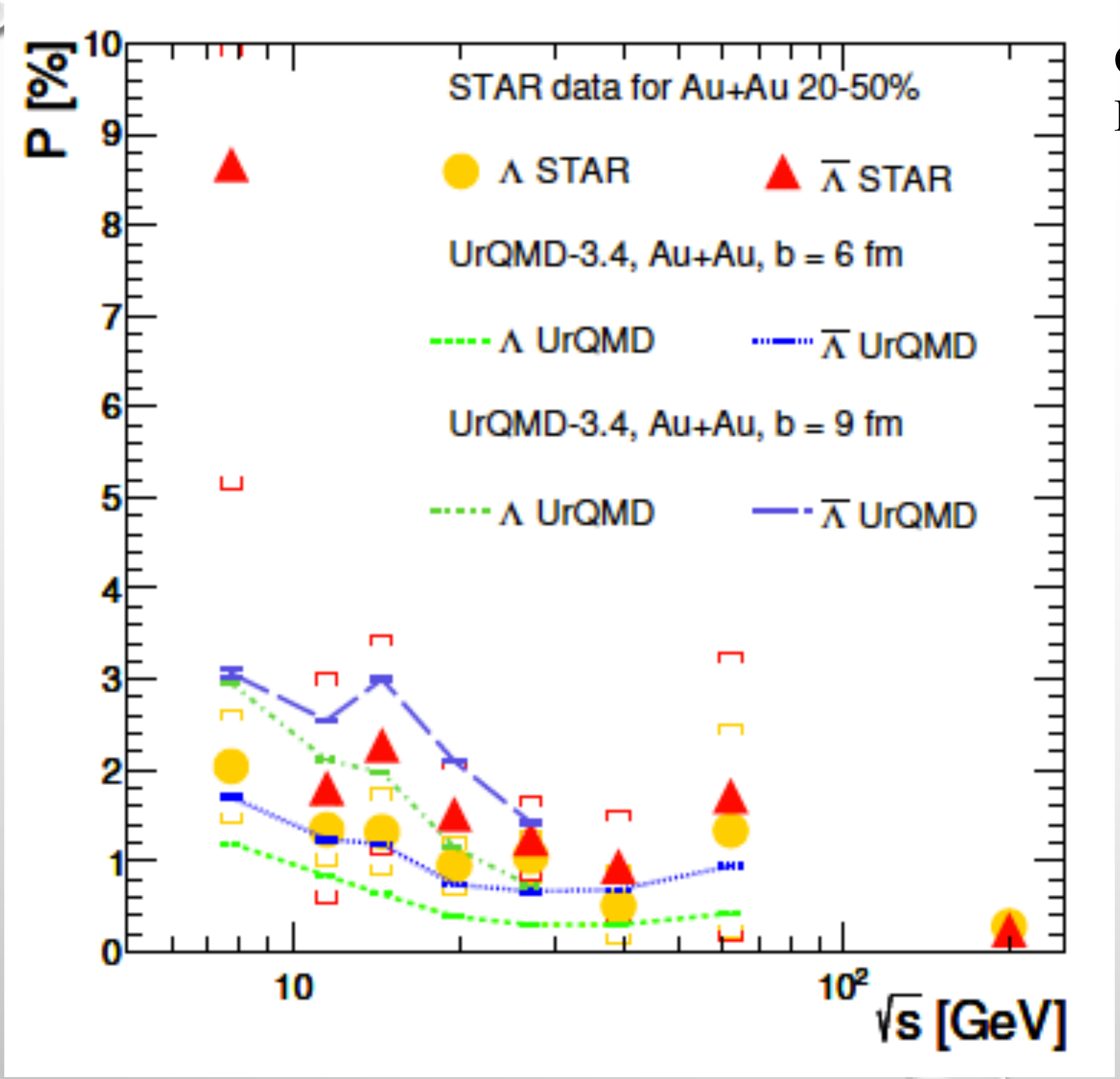
POLARIZATION OF Λ AND ANTI-Λ

O. Vitiuk, L.B., E. Zabrodin, PLB 803 (2020) 135298



Polarization of both hyperons decreases with time. At the initial stage, they are mainly formed in hot and dense areas with high polarization. Later on polarization of newly formed hyperons rapidly drops

ENERGY DEPENDENCE OF Λ AND ANTI-Λ POLARIZATION



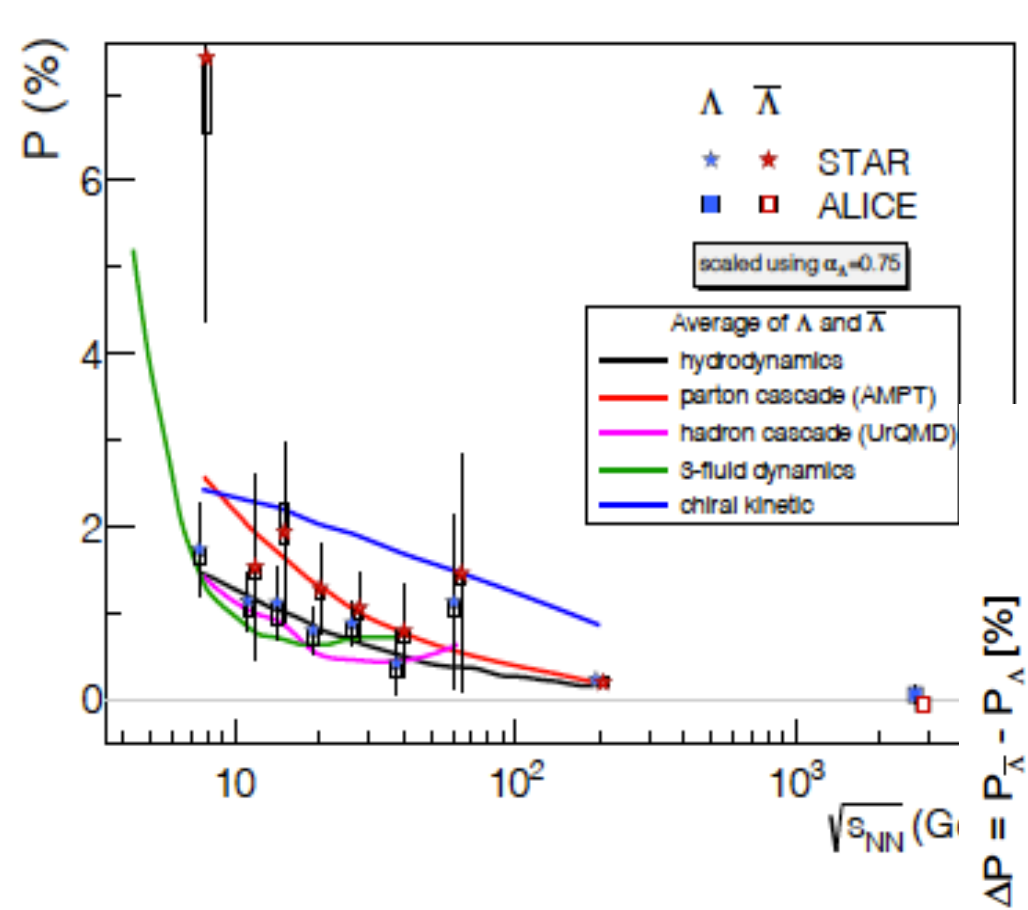
O. Vitiuk, L.B., E. Zabrodin, PLB 803 (2020) 135298

Difference in global polarization of both hyperons arises from

(1) different spatio-temporal distributions of Λ and anti-Λ
(2) different thermal vorticity in the freeze-out regions

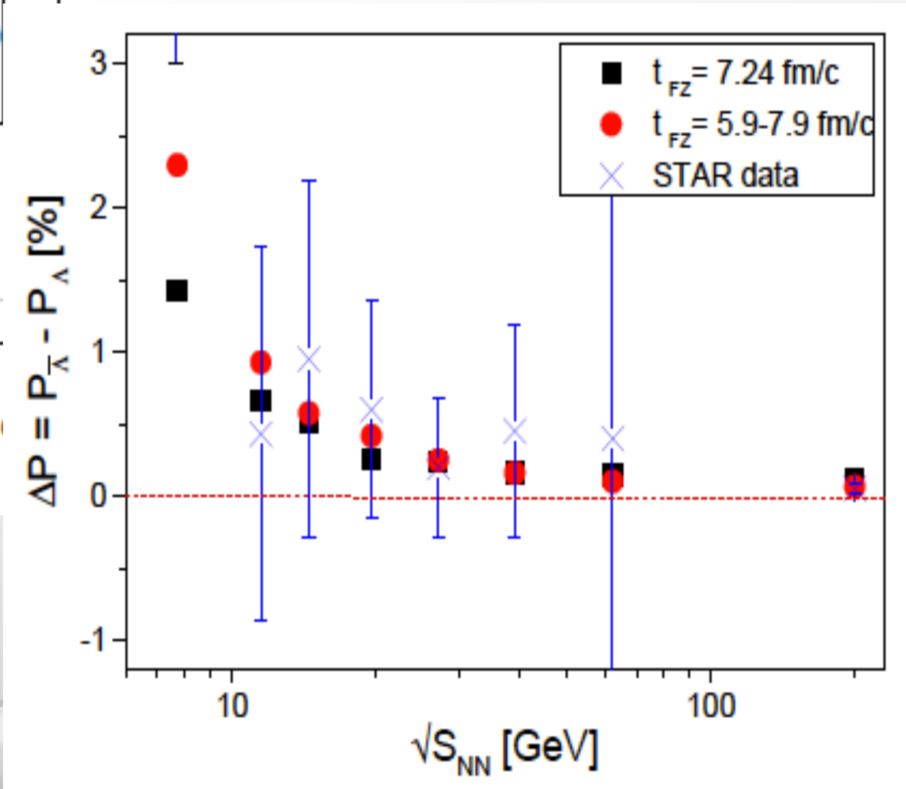
Data: STAR Collab., PRC 98 (2018) 014910

OTHER MODELS



The idea of different FO can be employed in other models also

Y.Xie, G.Chen, L.P.Csernai, EPJC 81 (2021) 12

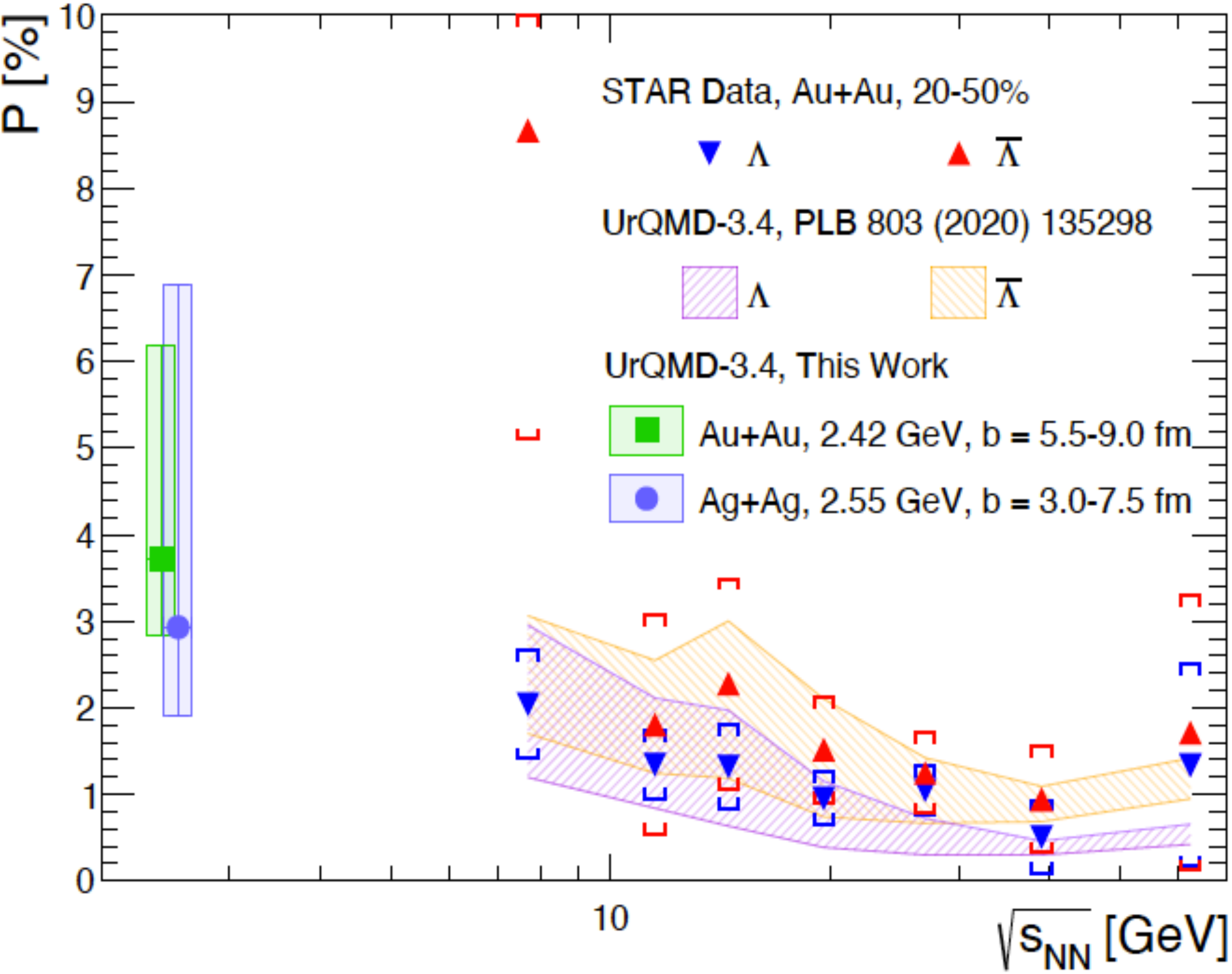


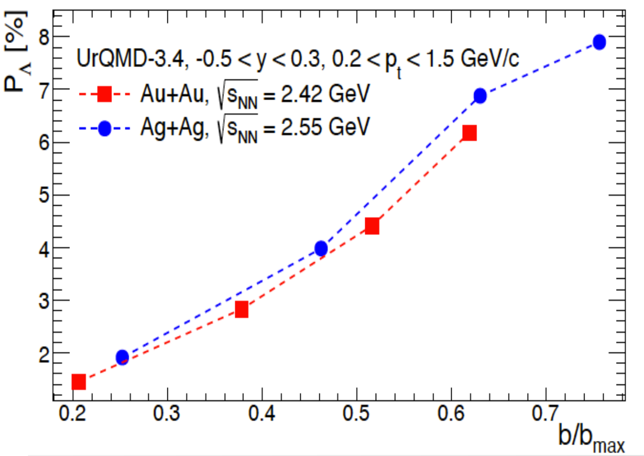
F.Becattini and M.A.Lisa, Ann. Rev. Nucl. Part. Sci. 70 (2020) 395

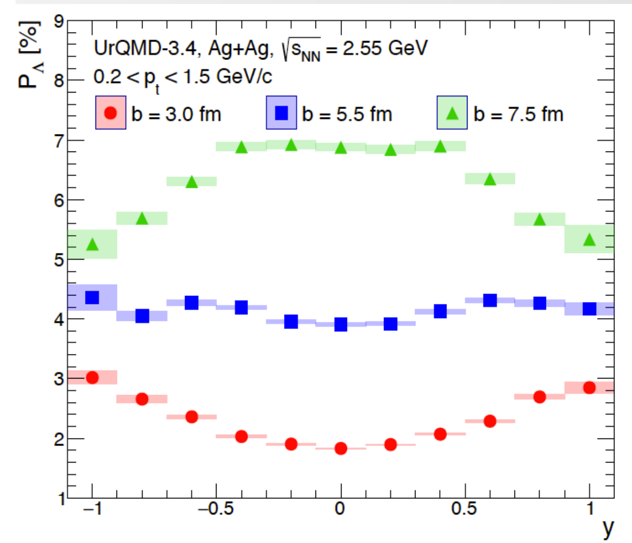
ENERGY DEPENDENCE OF Λ AND ANTI-Λ POLARIZATION

Request from HADES Collaboration:

Provide model predictions for Λ and anti-Λ polarization in (i) Ag+Ag @ 2.55 GeV and (ii) Au+Au @ 2.42 GeV for given centrality and kinematic windows

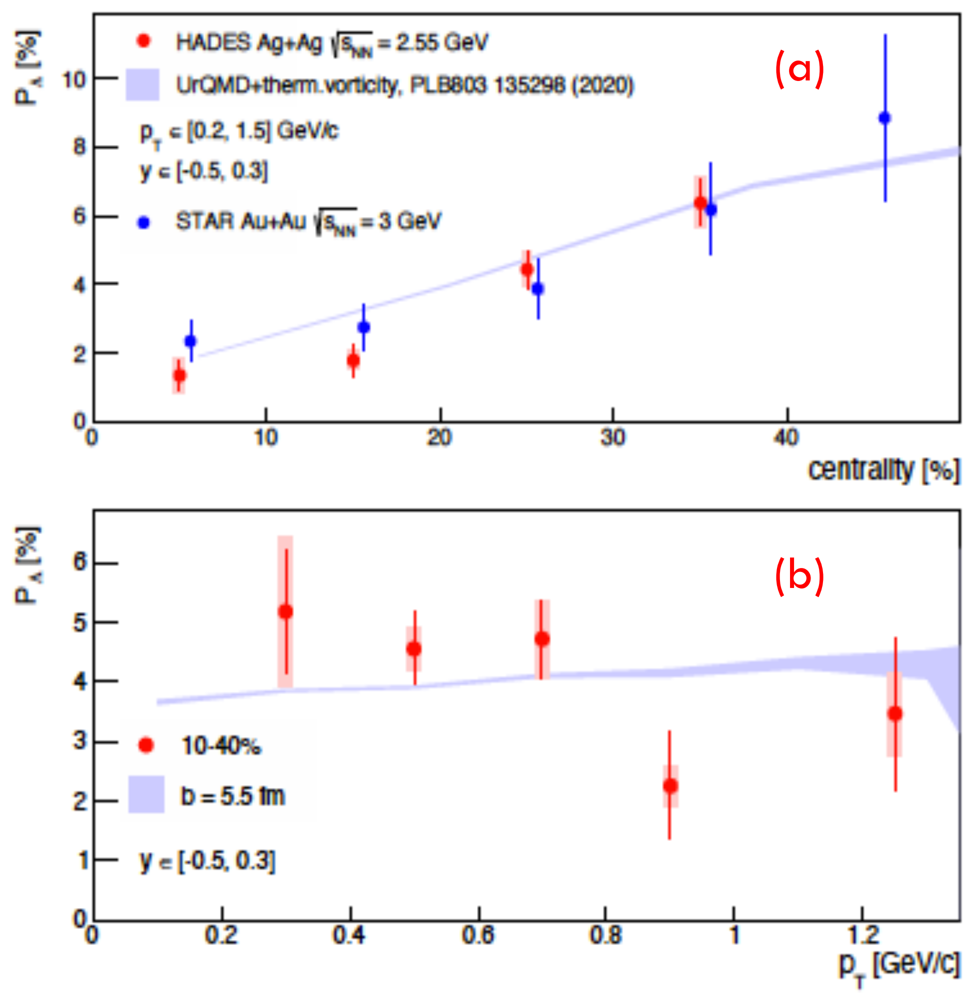


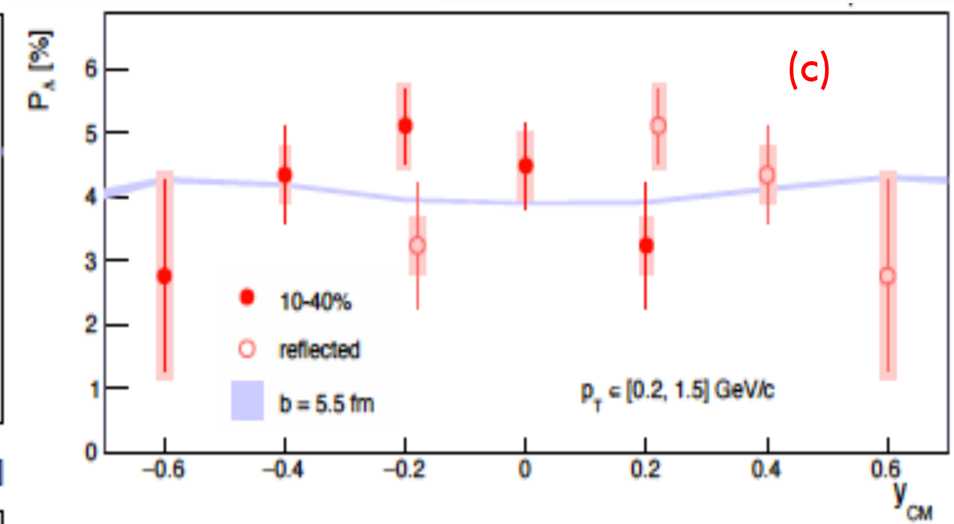




COMPARISON WITH THE DATA

HADES Collab., PLB 835 (2022) 137506





Global polarization of Λ as function of centrality (a), transverse momentum (b), and rapidity (c) in Ag+Ag collisions at $\sqrt{s} = 2.55$ GeV

"The agreement is remarkable …" (PLB 835, 137506)

CONCLUSIONS

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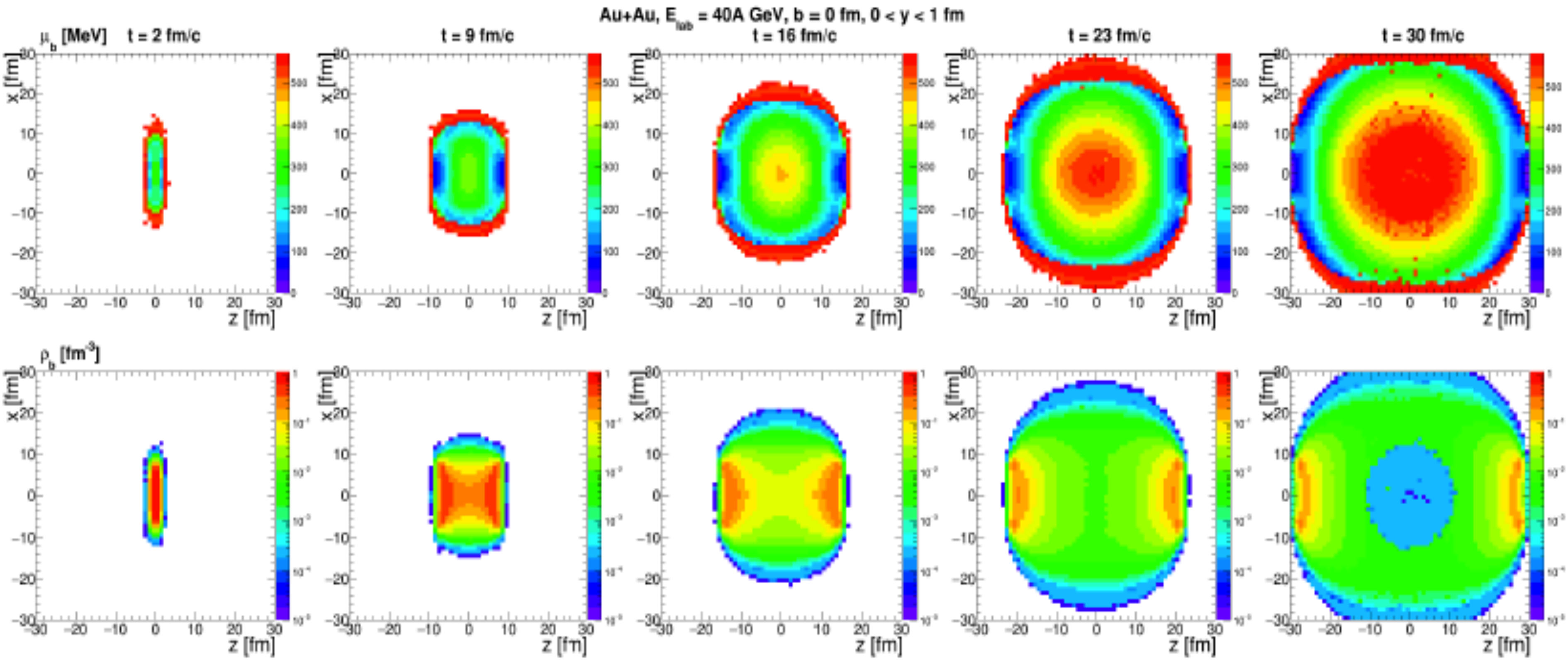
1. Thermal vorticity in non-central heavy ion collisions, Au+Au and Ag+Ag, was studied at √s = 2,4 --19,6 GeV within the framework of UrQMD model
2. Quadruple structure of ω_{zx} was obtained
3. The magnitude of vorticity dependence on time and energy of colliding nuclei is studied
4. Self-consistent method for calculation of Λ-polarization in microscopic transport model is developed
5. The distribution of Λ and anti-Λ is different in space, their freeze-out distributions are (slightly) different in time, therefore these hyperons are emitted from regions with different vorticity

THANK YOU FOR YOUR ATTENTION !

EVOLUTION OF BARYON CHEMICAL POTENTIAL AND DENSITY



EVOLUTION OF STRANGENESS CHEMICAL POTENTIAL AND STRANGENESS DENSITY