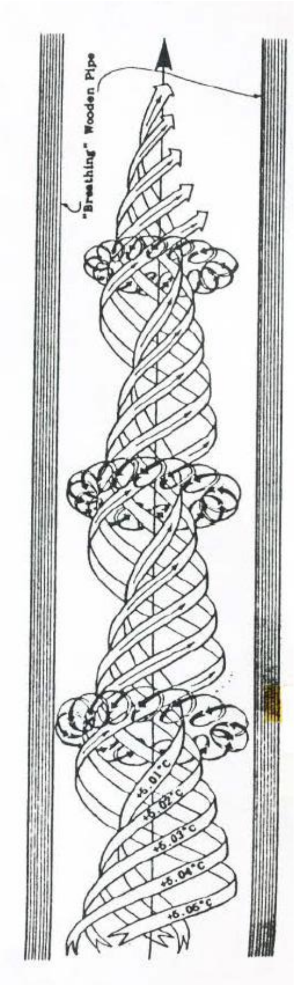
Helicity and vorticity in heavy-ion collisions and hyperon polarization



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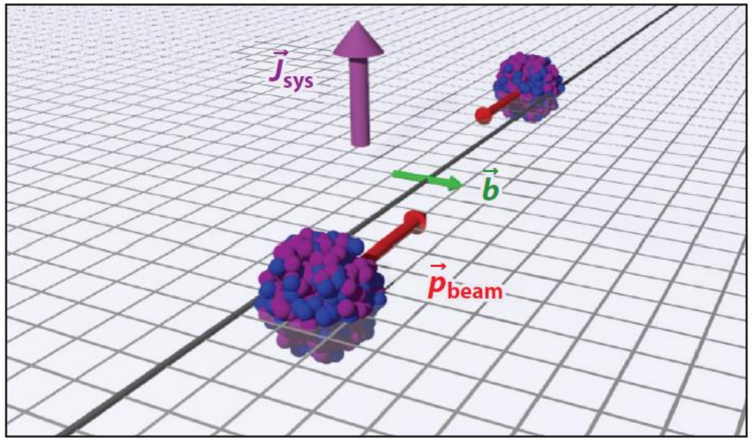
Particles **2023** (2023) 373
arXiv:2305.10792 [nucl-th

Origin of global polarization in collective processes



Initial angular momentum of colliding nuclei

$$\vec{l} = \frac{\vec{L}}{A} = \pm\vec{e}_y \frac{b}{2}\sqrt{s_{NN} - 4m_N^2}$$

angular momentum per nucleon

for $\sqrt{s_{NN}} = 2.5\,\mathrm{GeV}$ $\quad \boldsymbol{l} \approx 42\hbar(b/10\,\mathrm{fm})$

for $\sqrt{s_{NN}} = 11\,\mathrm{GeV}$ $\quad \boldsymbol{l} \approx 275\hbar(b/10\,\mathrm{fm})$

Mechanism of angular-momentum transfer from orbital one to spin

In equilibrium! density matrix

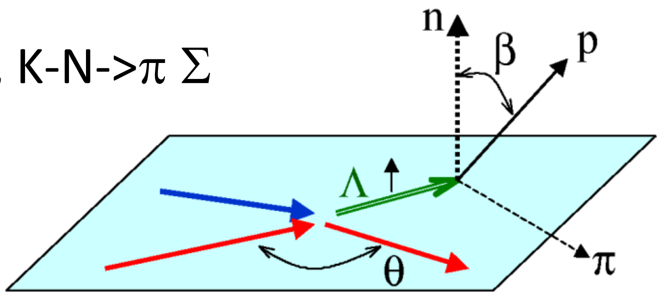
$$\hat{\rho} = \frac{1}{Z}\exp\left[-\frac{\hat{H}}{T} + \frac{\boldsymbol{\omega}(\hat{\boldsymbol{L}} + \hat{\boldsymbol{S}})}{T}\right]$$

spin ***S*** and angular moment ***L*** operators

hydrodynamic **vorticity** $\boldsymbol{\omega} = \mathrm{rot}\,\boldsymbol{v}$

elementary processes

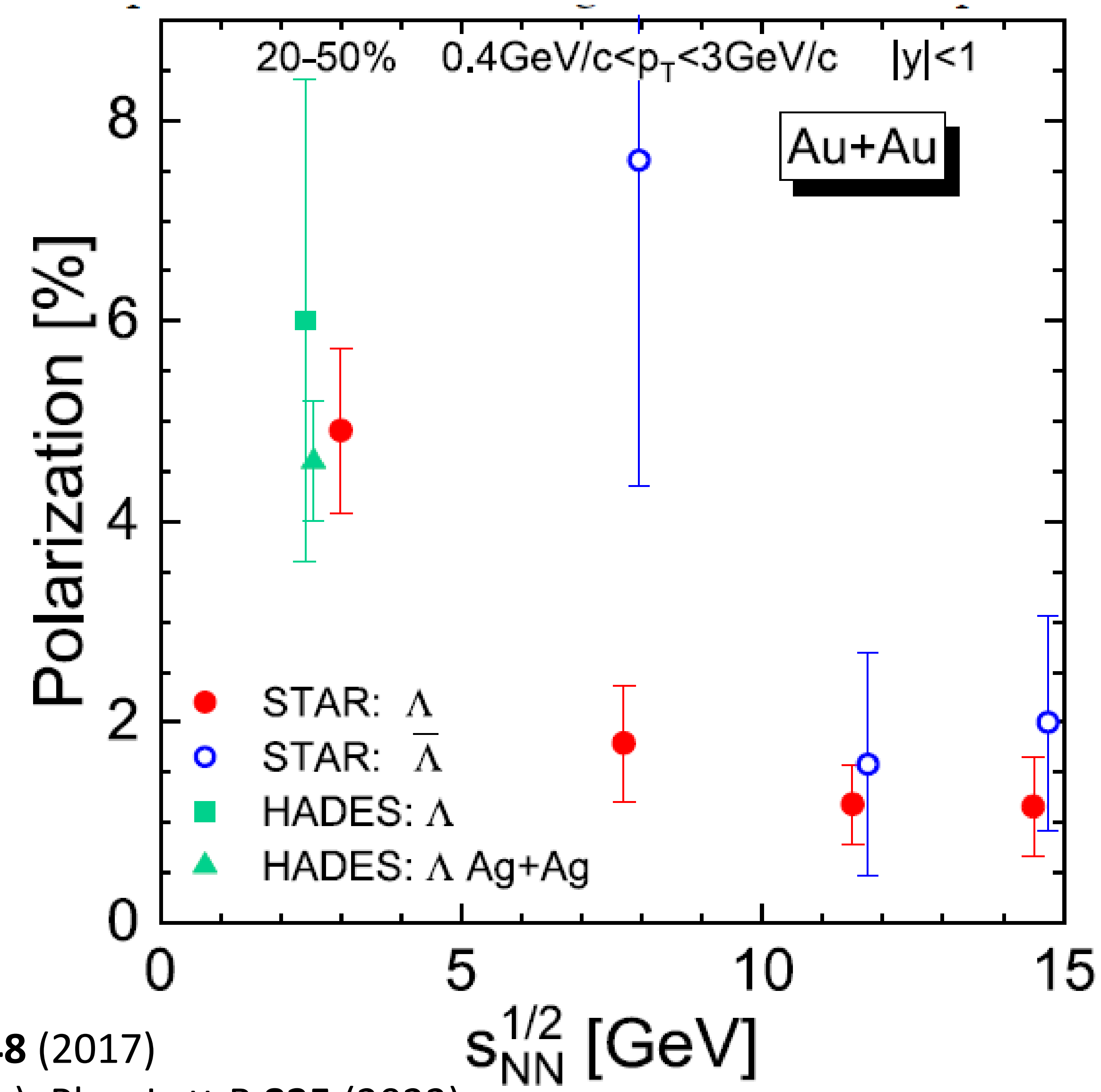
Hadronic scattering, e.g., K- N-> π Λ, K-N->π Σ



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}\cos\beta} = \Big(1 + P_H(\cos\theta)\,\cos\beta\Big)\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}$$

interference of s- and p-waves

● The experimental data of global Λ and anti-Λ polarization



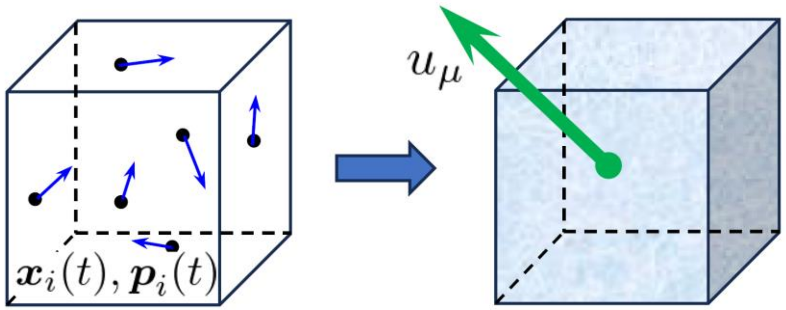
Λ – anti-Λ splitting in global polarization

L. Adamczyk et al., Nature **548** (2017)
R.A.Yassine et al. (HADES Coll.), Phys.Lett.B **835** (2022)

● Setup

The Parton-Hadron-String Dynamic model: the generalized off-shell transport equations, Dynamical Quasi-Particle Model (for partons), FRITIOF Lund (strings breaking) PYTHIA and JETSET (jet production and fragmentation), Chiral Symmetry Restoration,

Kinetics → **fluidization** → hydrodynamic quantities



Fluidization criterion:
cells with ε > 0.05 GeV/fm^3.
Spectators do not form fluid!

$$u_\mu T^{\mu\nu} = \varepsilon\, u^\nu$$

$$u^\mu = \gamma(1, \boldsymbol{v})$$

$$T^{\mu\nu} = \sum_{a,i_a} \frac{p^\mu_{i_a}(t)\, p^\nu_{i_a}(t)}{p^0_{i_a}(t)} \Phi\left(\boldsymbol{x}, \boldsymbol{x}_{i_a}(t)\right)$$

Φ − smearing function

Spectator separation:
$||y_{spectator}| - y_{beam}| \leq 0.27$

Fermi motion

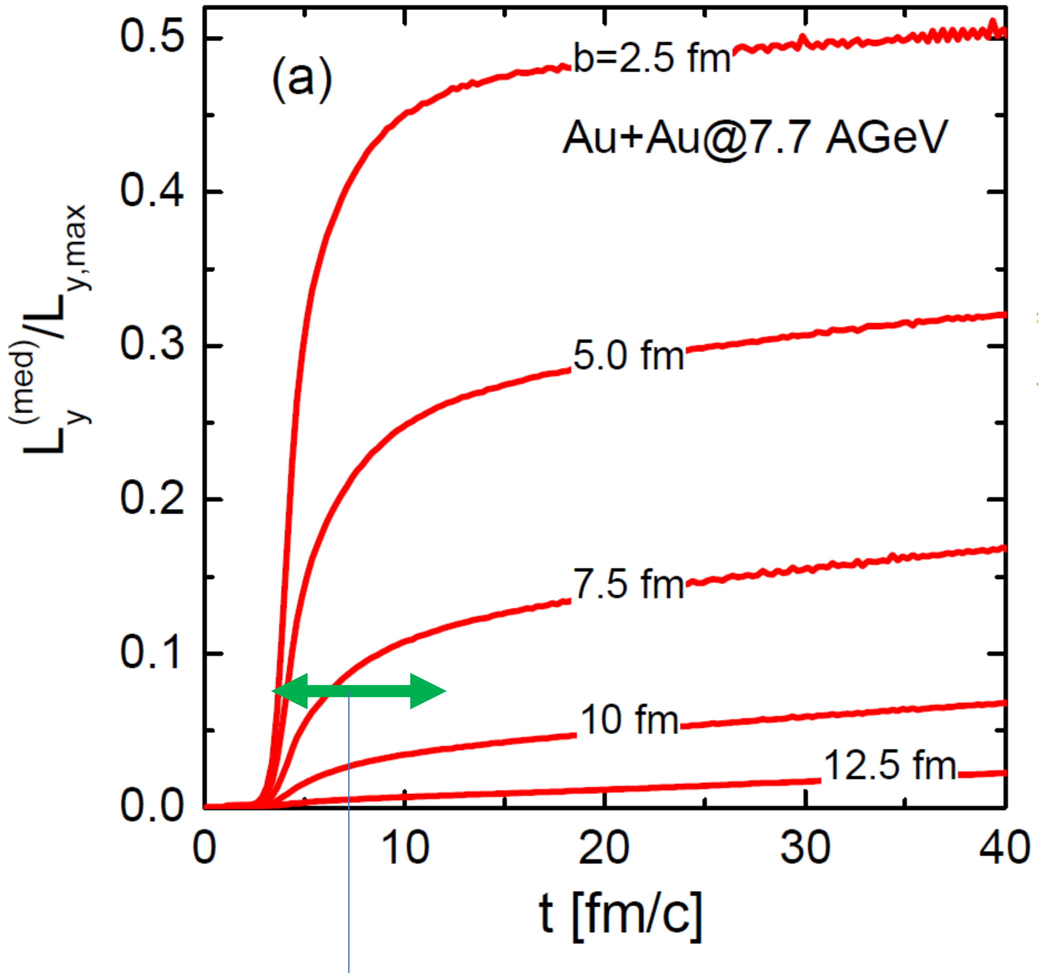
$$J^\mu_B = \sum_{a,i_a} B_{i_a} \frac{p^\mu_{i_a}(t)}{p^0_{i_a}(t)} \Phi\left(\boldsymbol{x}, \boldsymbol{x}_{i_a}(t)\right) \qquad n_B = u_\mu J^\mu_B$$

$$\varepsilon, n_B \longrightarrow \textbf{EoS} \longrightarrow T(\varepsilon, n_B)$$

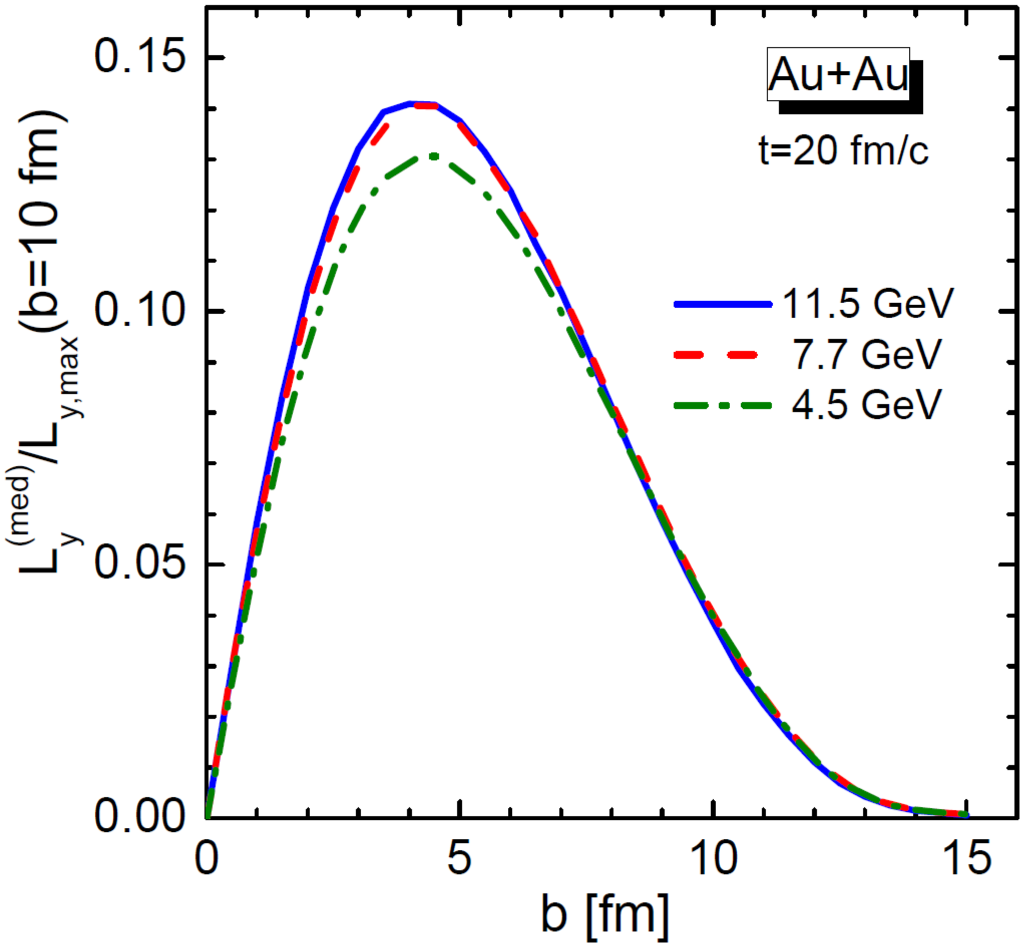
Angular momentum transfer

Small b: L is small but large fraction of it can be transferred
Large b: L is big but nuclear overlap is small and less L is transferred

Transferred angular momentum distribution depends weakly on the collision energy

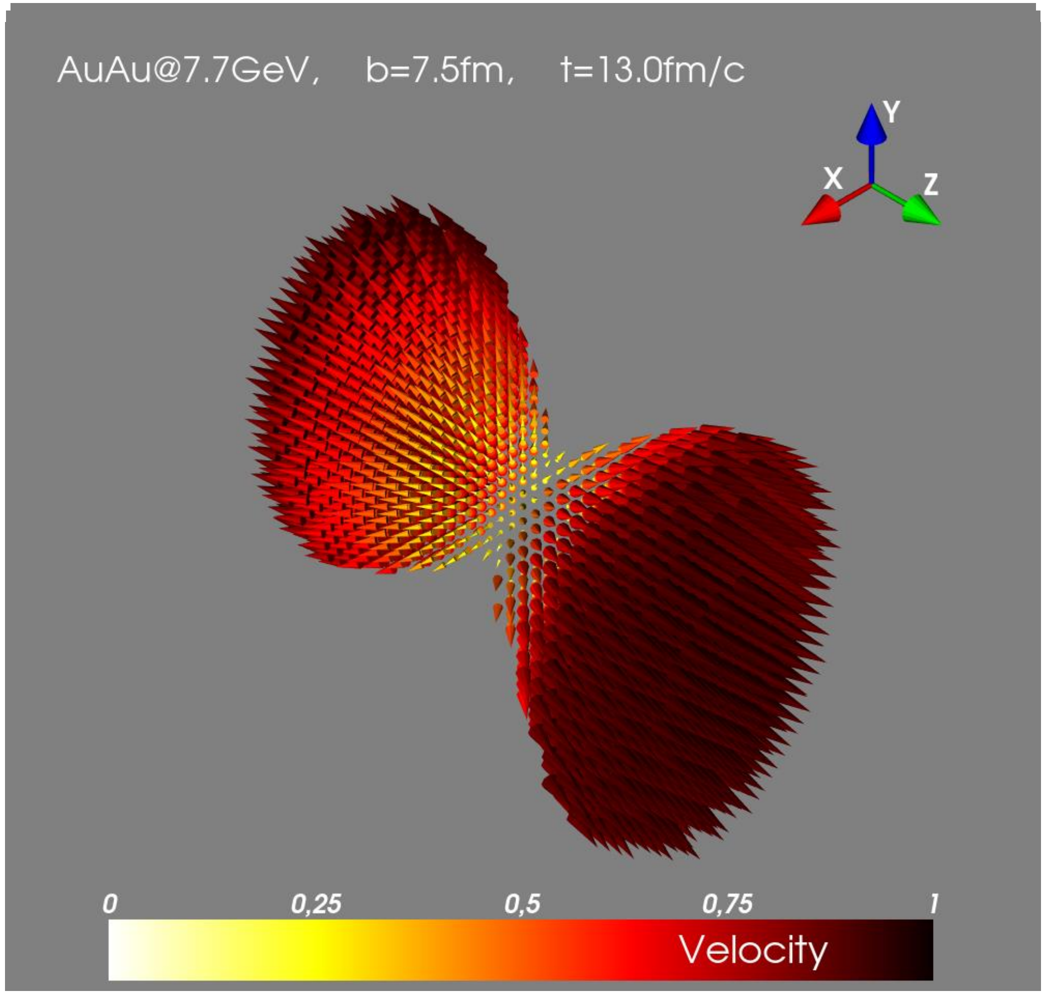


transition time scale ~10fm/c



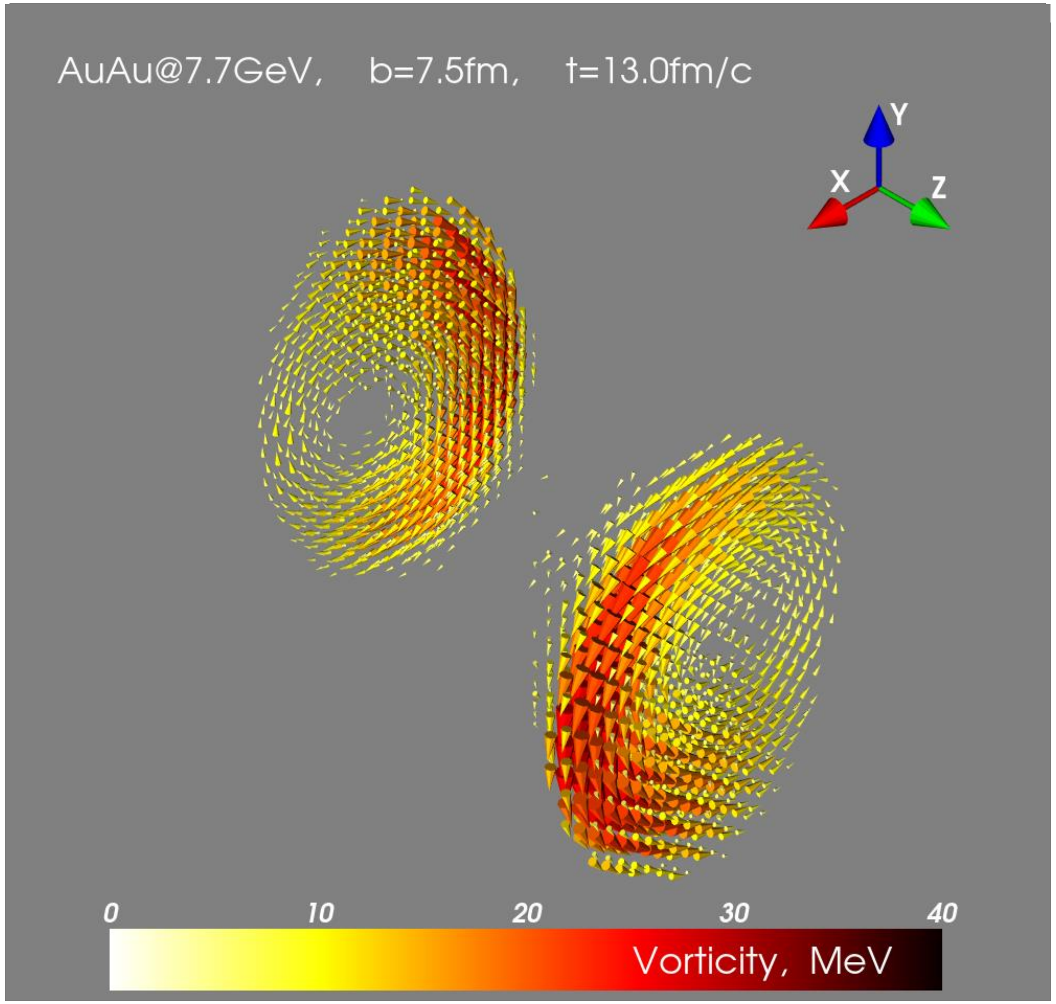
similar dependence was derived in [Becattini, Piccinini, Rizzo, PRC77 (2008)]

Velocity and vorticity fields



Hydrodynamic velocity field

$$\varepsilon > 0.05\,\mathrm{GeV/fm^3}$$
$$\boldsymbol{v} \approx \boldsymbol{v}_{\mathrm{Hubble}} = (\alpha_T\, x, \alpha_T\, y, \alpha_z\, z)$$

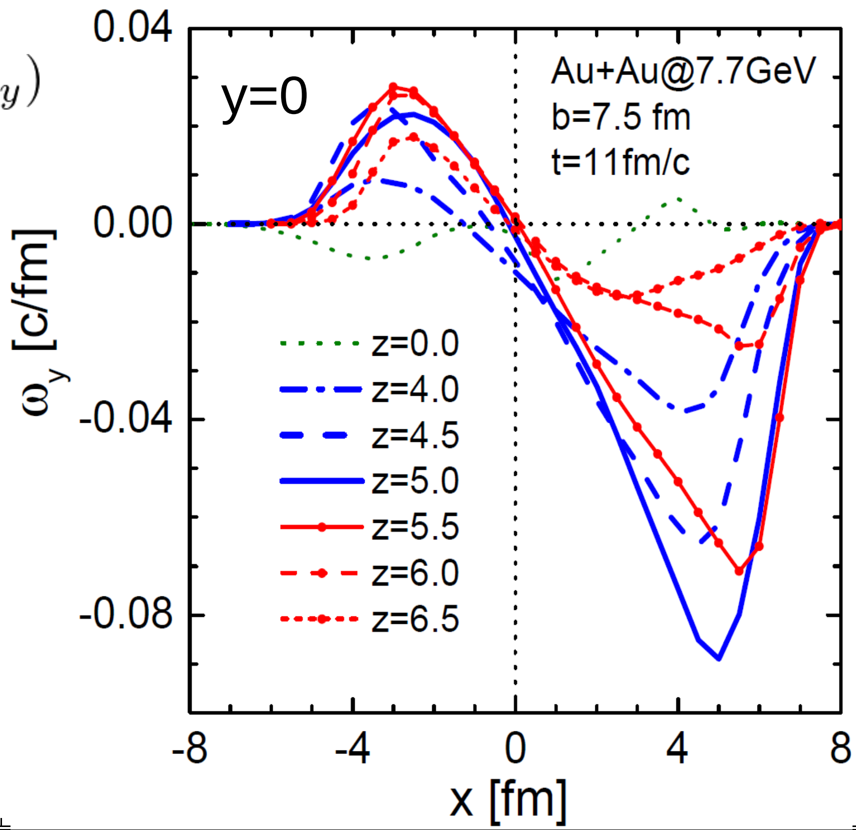


Hydrodynamic vorticity field

Vorticity field (ω_x, ω_y)

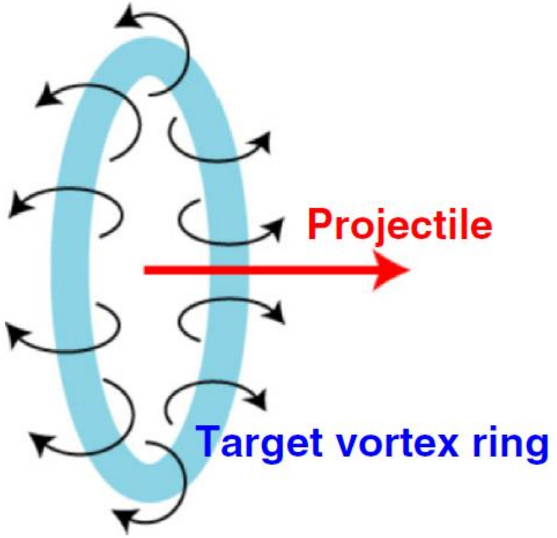
Au+Au @ 7.7 GeV

b=7.5 fm

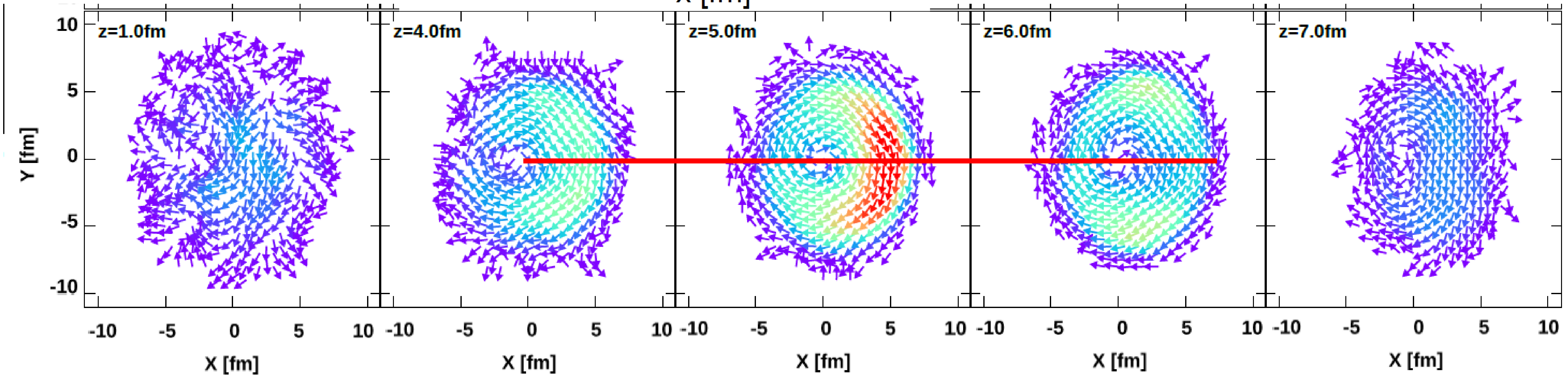


Yu.B. Ivanov, A.A. Soldatov predicted in [PRC97 (2018)] within the 3-fluid hydro model the formation of vortex rings

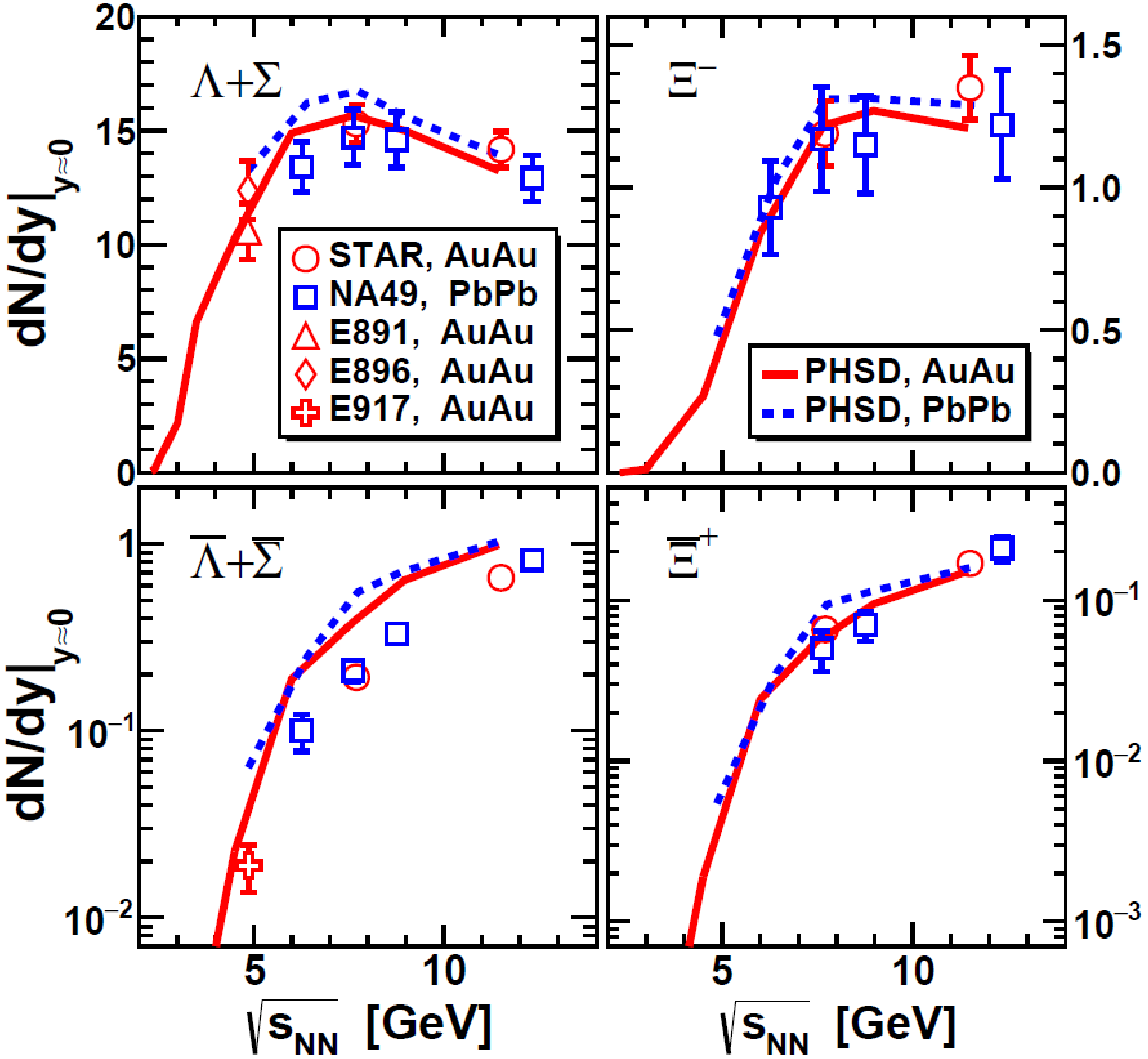
Vortex ring



t=11 fm/c



Hyperon and Anti-hyperon production



Ω ant $\overline{\Omega}$ multiplicities

Exp: NA49 PRL 94 (2005) 192301

central Pb+Pb collisions at energy 40AGeV

$\sqrt{s_{NN}} = 8.77\,\mathrm{GeV}$

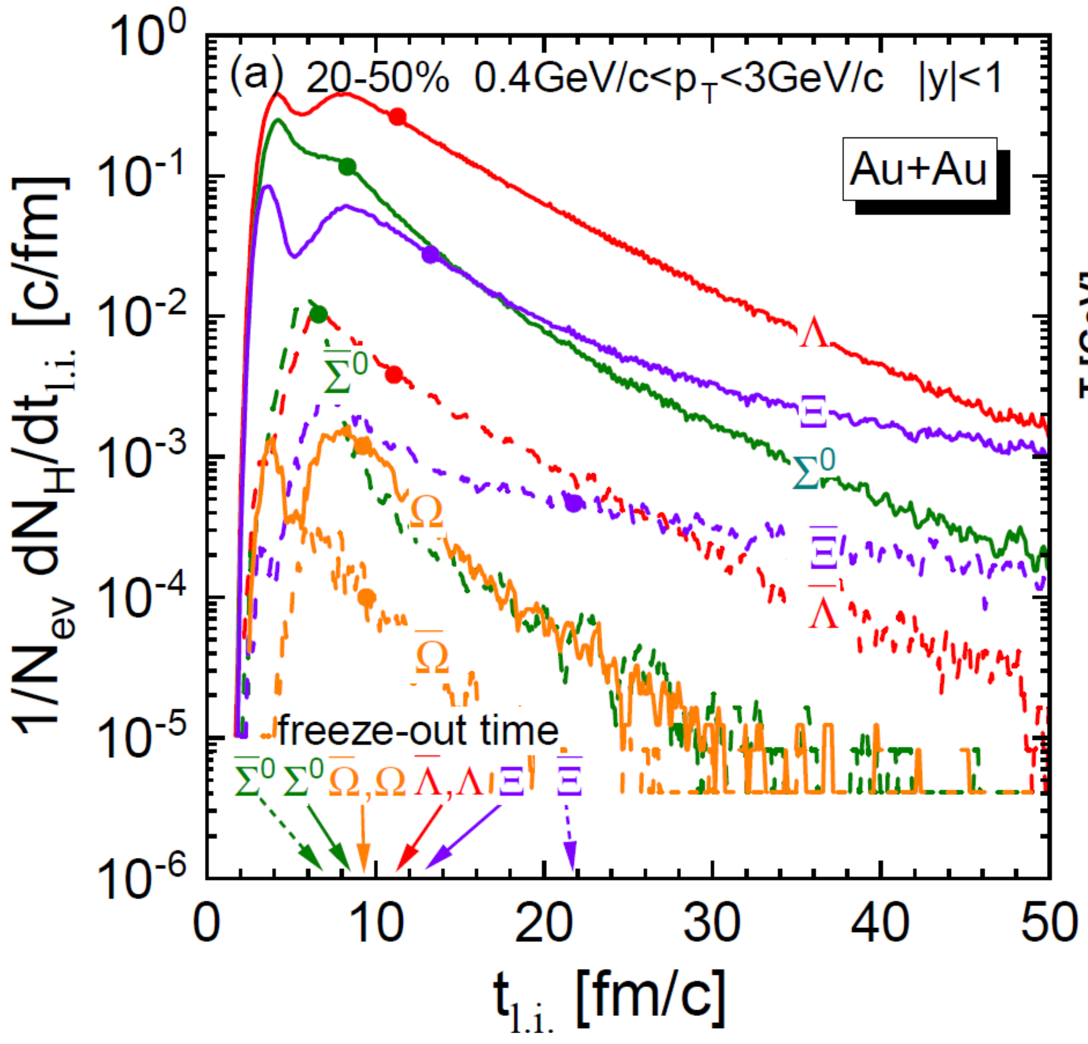
$$M^{(\mathrm{exp})}_{\Omega+\overline{\Omega}} = 0.14 \pm 0.05$$

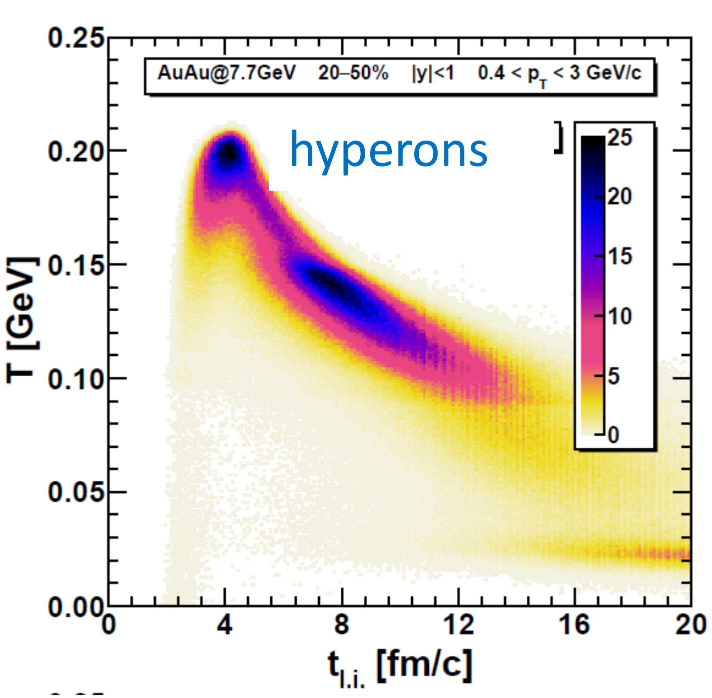
Theory:

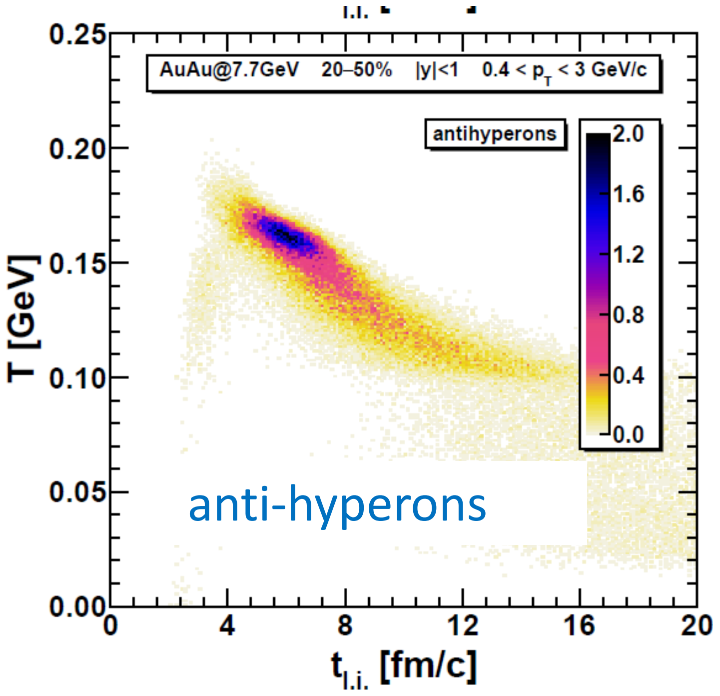
$$M_{\Omega} = 0.123\,, \quad M_{\overline{\Omega}} = 0.018$$

Dynamics of hyperon production

We store the time marker for each 'newly-created' particle. After the completion of a code run, we can look at survived hyperons and obtain the distribution of the time of the last interaction, $t_{\rm l.i.}$ (TLI).



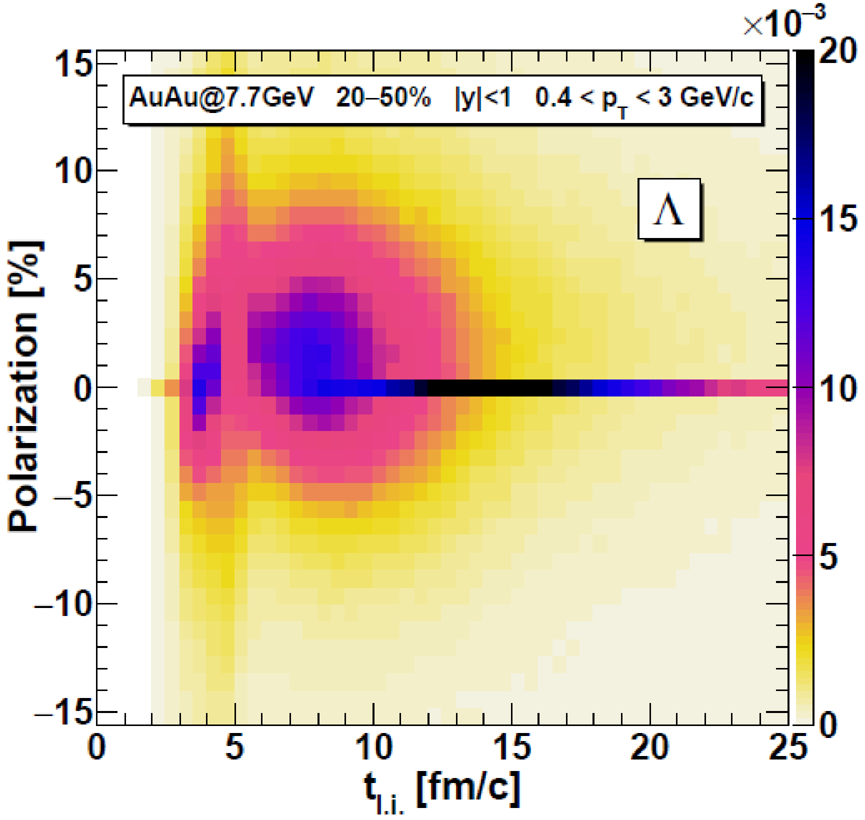


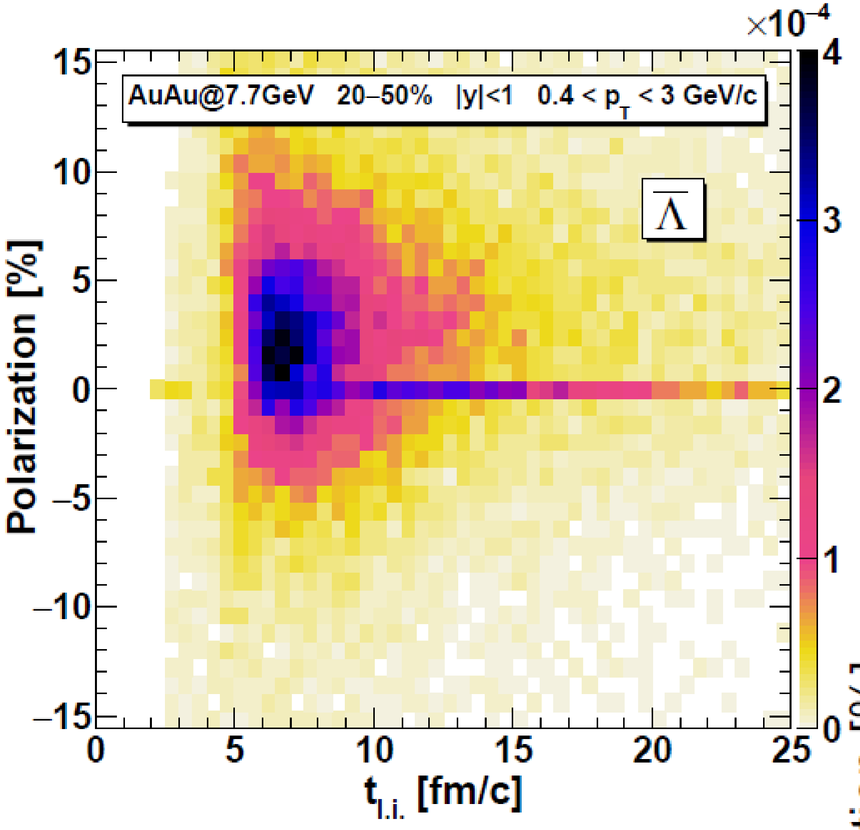


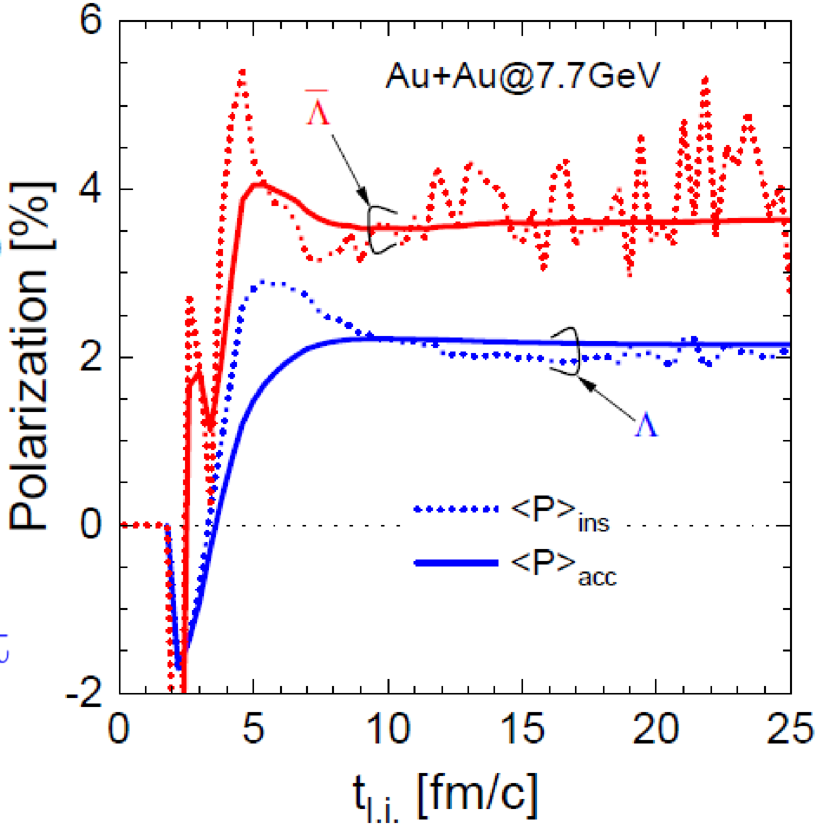
Two main sources for hyperons and only one for antihyperons.

Different thermodynamic conditions for particles and antiparticles→ different polarization!

Polarization source







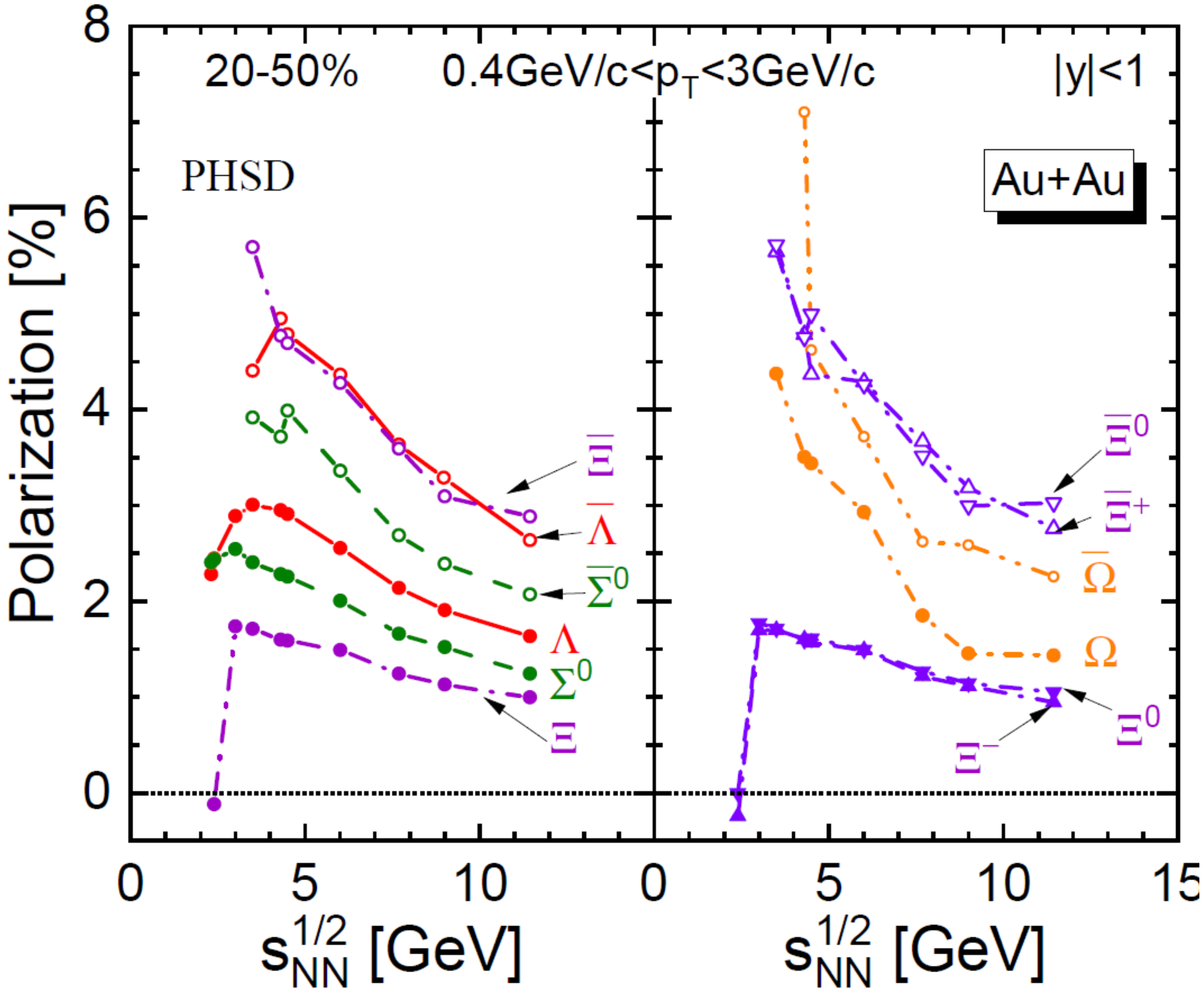
Two main sources for Λ and only one for $\overline{\Lambda}$

The relation $P_y(\overline{\Lambda}) > P_y(\Lambda)$ holds for both instantaneous and accumulated polarizations for $t_{\mathrm{l.i.}} \gtrsim 3\,\mathrm{fm}/c$

For $t \gtrsim 10\,\mathrm{fm}/c$ the accumulated polarization stays $\approx$ constant

Change in the polarization sign at the moment of full overlap.

Hyperon Polarization



Different polarization of particles and antiparticles for all kinds of hyperons

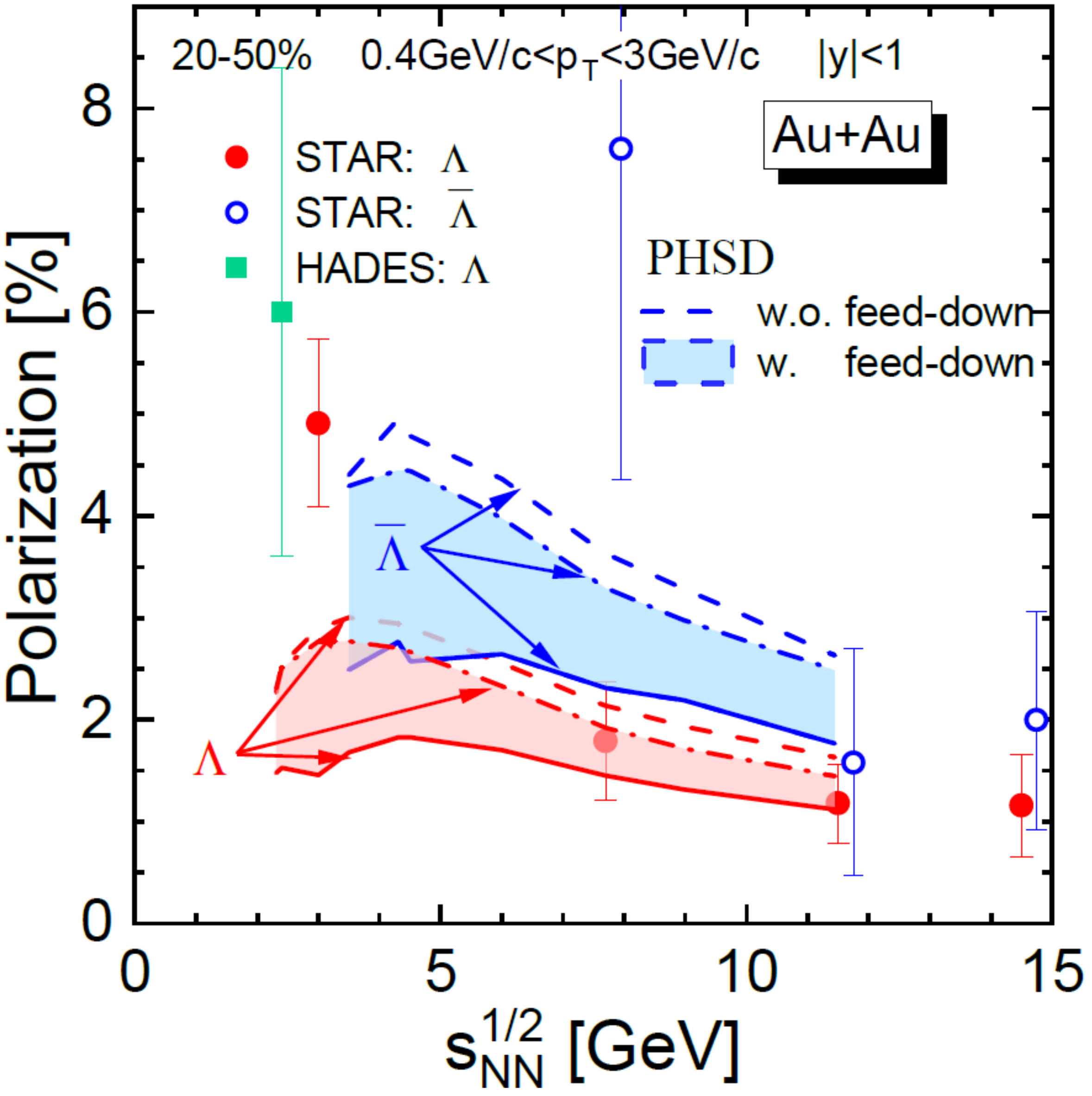
Polarization of all hyperon species decrease with an energy increase for $\sqrt{s_{NN}} \gtrsim 5\,\mathrm{GeV}$

The strongest decrease and smallest difference is for Ω and $\overline{\Omega}$. The energy trend is also different.

The polarization hierarchy holds for the energy range $\sqrt{s_{NN}} = 3.5 - 11.5\,\mathrm{GeV}$:
$P_{\overline{\Xi}} \approx P_{\overline{\Lambda}} > P_{\overline{\Sigma}^0} > P_{\Lambda} > P_{\Sigma^0} > P_{\Xi}$

The maximum of Λ and $\overline{\Lambda}$ polarization occurs at $\sqrt{s_{NN}} \approx 4\,\mathrm{GeV}$.

Feed-down effects



The feed-down contributions:

- **strong** decays are already included in PHSD
- **weak** decays: $\Xi \to \Lambda + \pi$,

contribution from Ω is negligible

- **electromagnetic** decays: $\Sigma \to \Lambda + \gamma$

The relationship between the multiplicities of Λ and Σ hyperons is unknown, so the filled area in the figure corresponds to their different proportions

Strong polarization suppression is caused by the *feed-down from Σ^0 and $\overline{\Sigma}^0$* hyperons.

Conclusion

- ✔ The (2+1)D Hubble-like expansion + vorticity at the system edges $\leftrightarrow$ two deformed elliptical vortex rings.
- ✔ Different polarization of particles and antiparticles for all hyperons.
- ✔ The difference in polarizations arises naturally and can be related to the difference in the thermodynamic conditions and vorticity field.
- ✔ Strong polarization suppression due to the feed-down from $\Sigma^0(\overline{\Sigma}^0)$.
- ✔ The helicity separation effect in the reaction plane.