Hyperon vs. anti-hyperon polarization. What is the difference?

Evgeni Kolomeitsev

Joint Institute for Nuclear Research, Dubna, Russia
Matej Bel University, Banska Bystrica, Slovakia

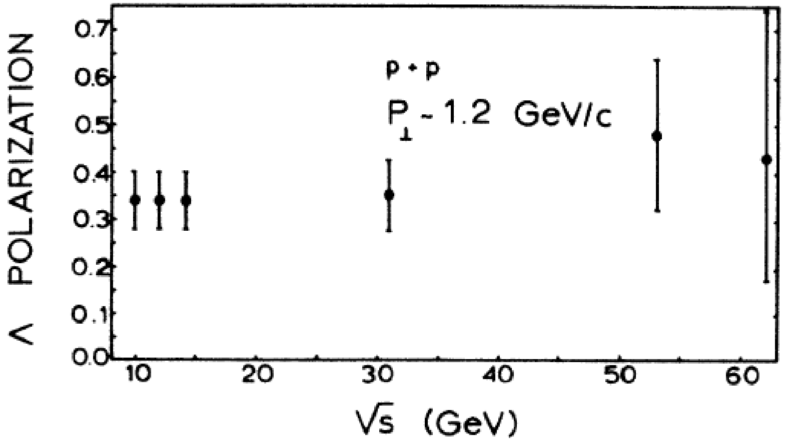
work done with Nikita Tsegelnik and Vadim Voronyuk

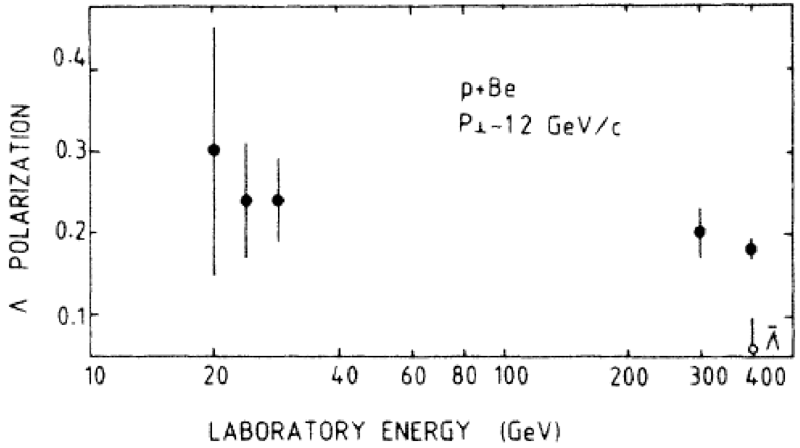
Phys. Rev. C **107** (2023) 034906
Particles **2023** (2023) 373
arXiv:2305.10792 [nucl-th]
Particles **2024**, 7 (2024) 984

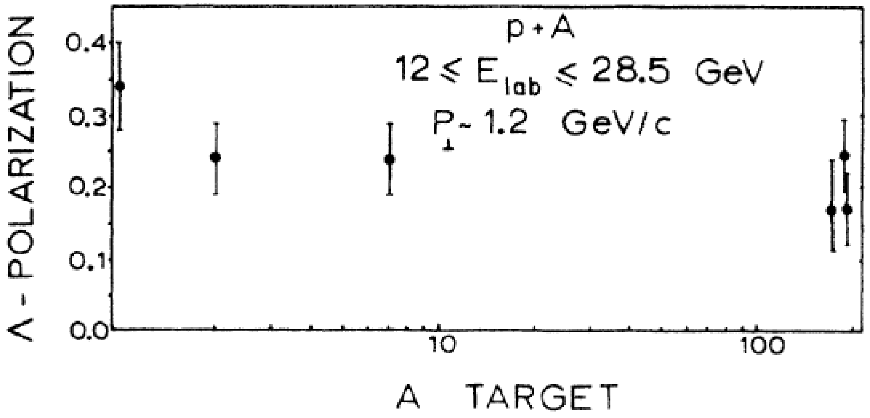
High energy inclusive Λ production in pp and pA scattering

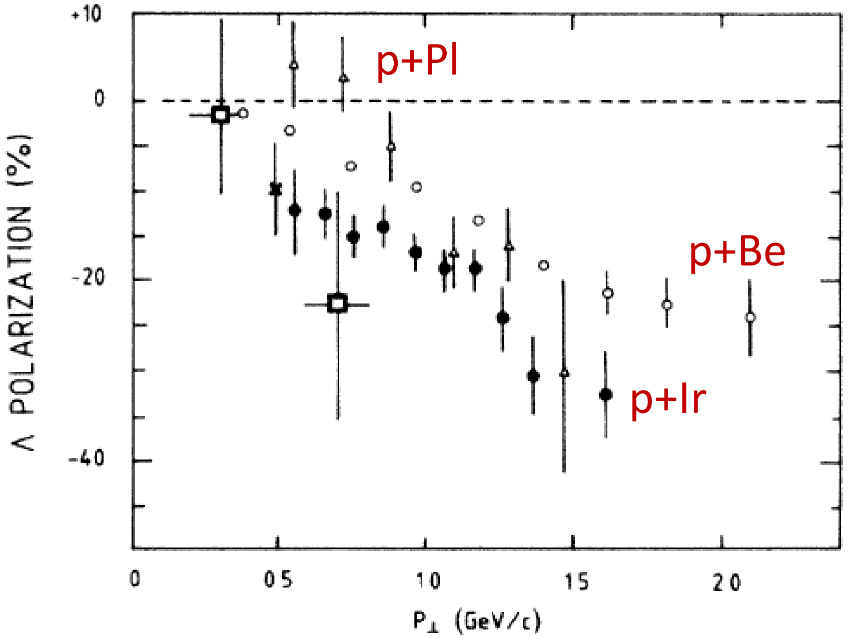
$$p(p_{\rm beam}) + A \to \Lambda(p_\Lambda) + X$$

quantization axis $\boldsymbol{n} \propto [\boldsymbol{p}_{\rm beam} \times \boldsymbol{p}_\Lambda]$ creation plane









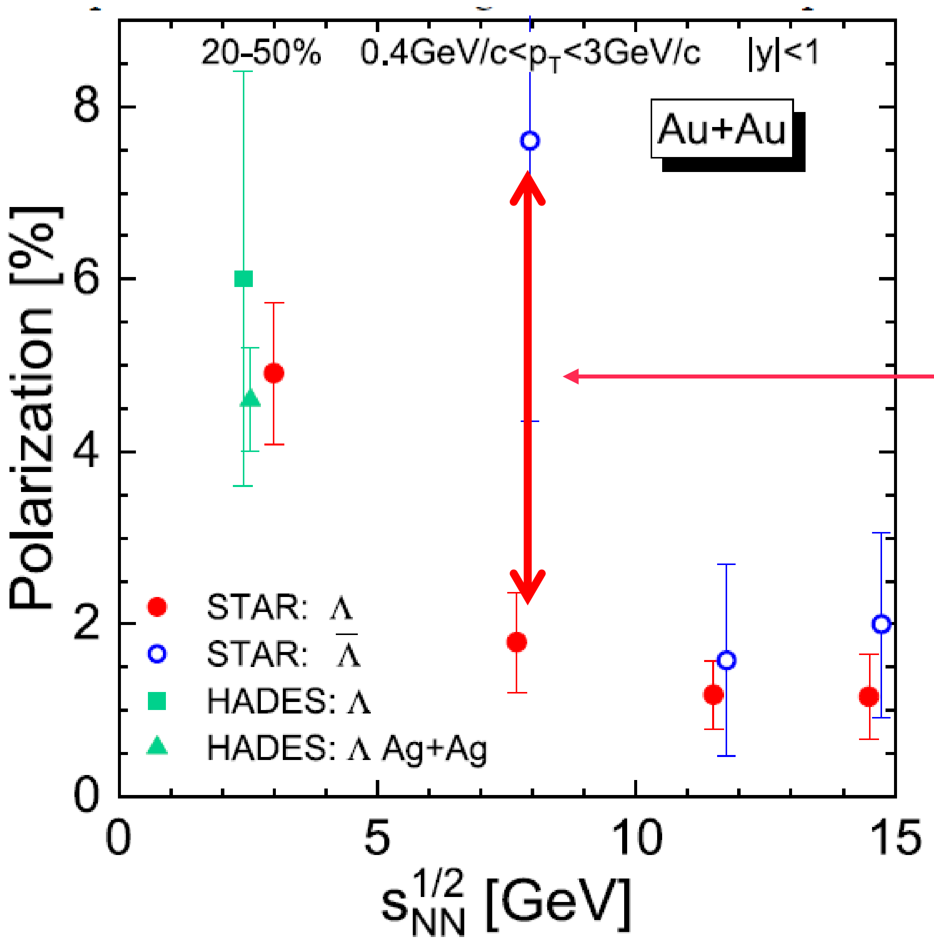
- Λ polarization is negative with respect to the creation plane
- at fixed x_F, Λ polarization decreases linearly with p_T
- at fixed p_T, Λ polarization decreases linearly with x_F
- Λ polarization does not depend on the beam energy, nor on target nature
- anti-Λs are not polarized! [Felix, Mod. Phys. Lett. A 14, 827 (1999)]

- **Polarization in HICs**

BEVALAC. Ar+KCl @ 1.8 GeV/u, BNL [Harris et al., PRL **47**, 229 (1981)] 70 Λ registered, (P_Λ=-0.10+-0.05)

JINR. C-C,Ne,Cu,Zr,Pb @ 4.5 GeV/u, Dubna [Anikina et al., ZPC **25**, 1 (1984)] no polarization P_Λ~0

- **STAR data**



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)

- **the thermodynamical approach** F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Annals Phys. **338** (2013)

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

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

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

Relativistic thermal vorticity:

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

$$\omega^{\mu\nu} = -\epsilon^{\mu\nu\rho\sigma}u_\rho\bar{\omega}_\sigma$$

$$\bar{\omega}^\mu = \gamma^2\big((\boldsymbol{v}\boldsymbol{\omega}), \boldsymbol{\omega} + [\boldsymbol{v}\times\partial_t\boldsymbol{v}]\big) \approx \big((\boldsymbol{v}\boldsymbol{\omega}), \boldsymbol{\omega}\big)$$

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

vorticity $\boldsymbol{\omega} = \mathrm{rot}\boldsymbol{v}$

helicity $h = (\boldsymbol{v}\boldsymbol{\omega})$

Spin vector:

$$S^\mu(x,p) = -\tfrac{1}{6}s\,(s+1)\varepsilon^{\mu\nu\lambda\delta}\varpi_{\nu\lambda}p_\delta/m$$

$$S^\mu \approx \frac{s(s+1)}{6mT}\big(\bar{\omega}^\mu(u\cdot p) - u^\mu(\bar{\omega}\cdot p)\big)$$
$$\approx \frac{s(s+1)}{6mT}\big((\boldsymbol{\omega}\boldsymbol{p}), E\boldsymbol{\omega} - [\boldsymbol{p}\times\boldsymbol{\lambda}_\omega]\big) + O(v^2) \qquad \boldsymbol{\lambda}_\omega = [\boldsymbol{\omega}\times\boldsymbol{v}]$$

s – spin, *p* – 4 momentum of particle

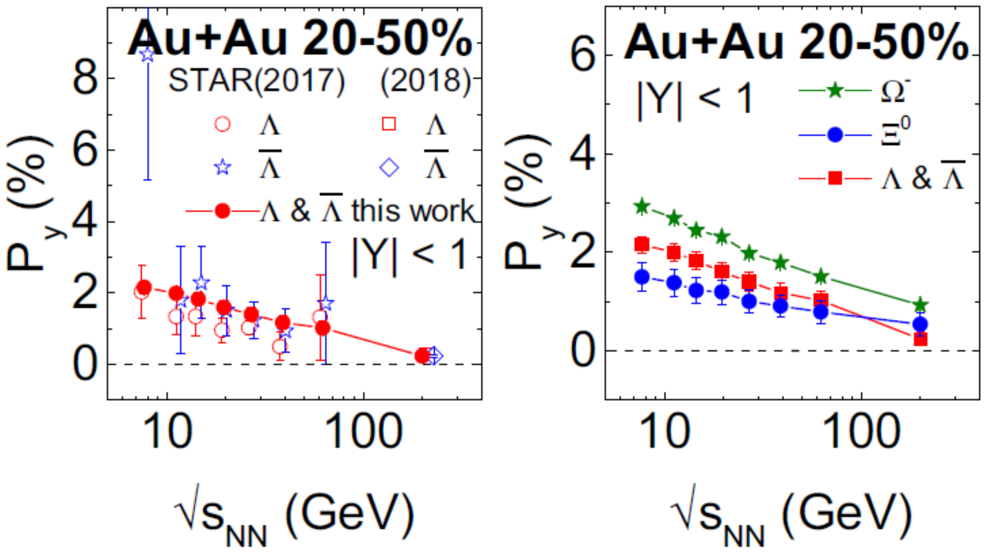
is the Lamb vector also known as the vortex force transverse to the fluid motion. It is a measure of the Coriolis acceleration of a velocity field under the effect of its own rotation.

In the rest frame of the particle, which is used for experimental identification of the fermion polarization $S^{*\mu} = (0, \boldsymbol{S}^*)$

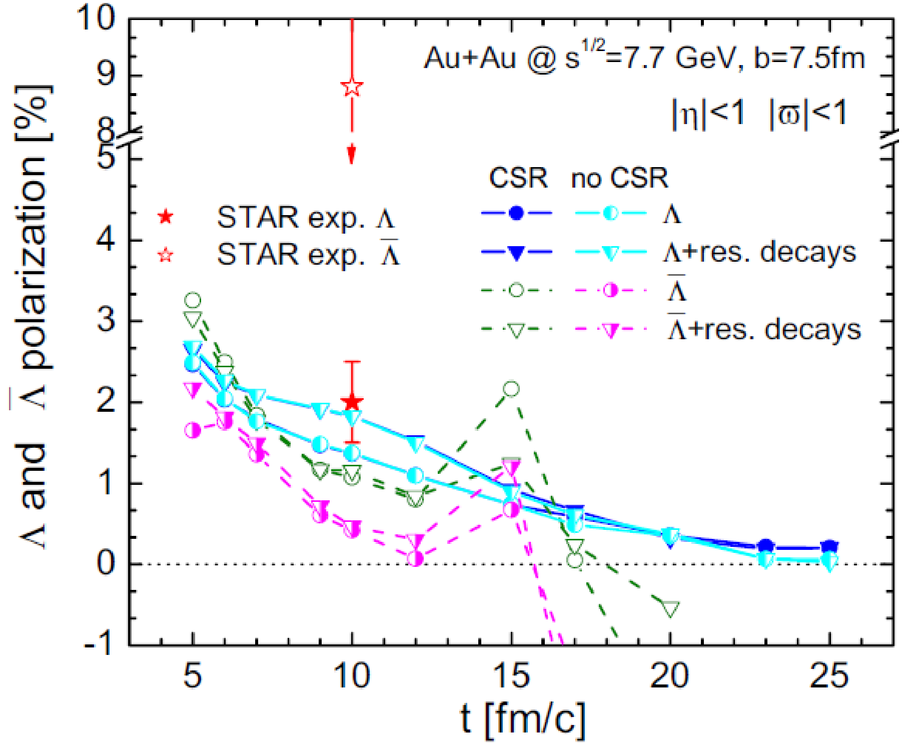
$$\boldsymbol{S}^* \approx \boldsymbol{S} - \frac{\boldsymbol{p}}{2m}S^0 \approx \frac{s(s+1)}{6}\left(\frac{\boldsymbol{\omega}}{T} - \left[\frac{\boldsymbol{p}}{m}\times\frac{\boldsymbol{\lambda}_\omega}{T}\right]\right) + O(\boldsymbol{v}^2, \boldsymbol{p}^2/m^2)$$

- **realizations of the thermodynamical approach** *in transport codes*

AMPT Wei, Deng, Huang PRC 99, 014905 (2019)

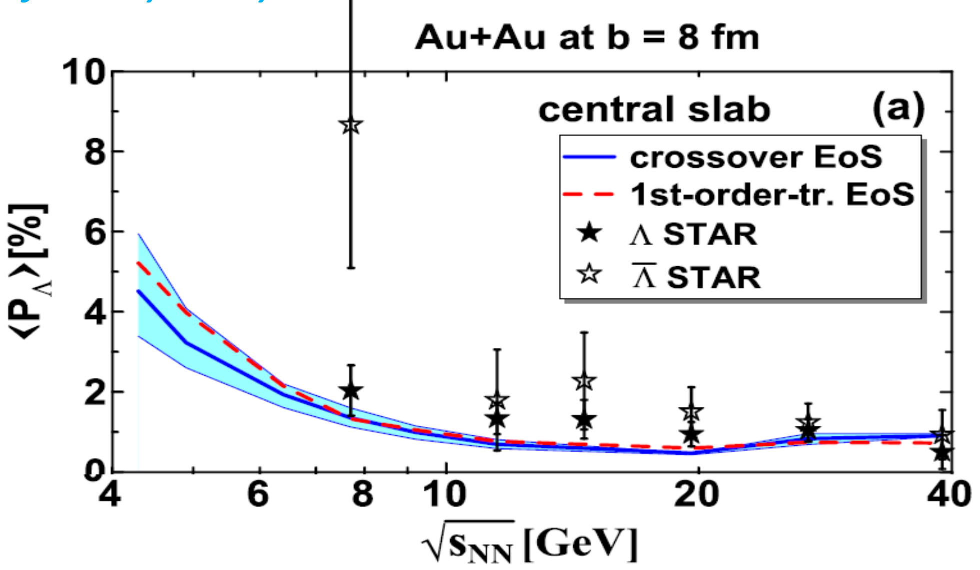


PHSD Kolomeitsev, Toneev, Voronyuk, PRC97 (2018) 064902



polarization of hyperons in medium at the certain moment of time

in 3 fluid hydrodynamics Ivanov, Toneev, Soldatov PRC 100 (2019) 014908



Most of the approaches give the same polarization signa for Lambda and anti-Lambda

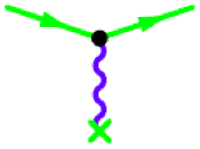
except URQMD Vitiuk, Bravina, Zabrodin, PLB 803 (2020) 135298

- **vector meson field interaction**

Csernai, Kapusta, Welle, PRC 99 (2019) 021901(R)

The interaction of the spin with the vector ω meson is

$$H^V_{\rm spin} = -\frac{g_{V\Lambda}}{m_\Lambda}\beta \boldsymbol{S}\cdot\boldsymbol{B}_V - i\frac{g_{V\Lambda}}{m_\Lambda^2}\boldsymbol{S}\cdot[\boldsymbol{\nabla}\times\boldsymbol{E}_V] - \frac{g_{V\Lambda}}{2m_\Lambda^2}\boldsymbol{S}\cdot[\boldsymbol{E}_V\times\boldsymbol{p}]$$



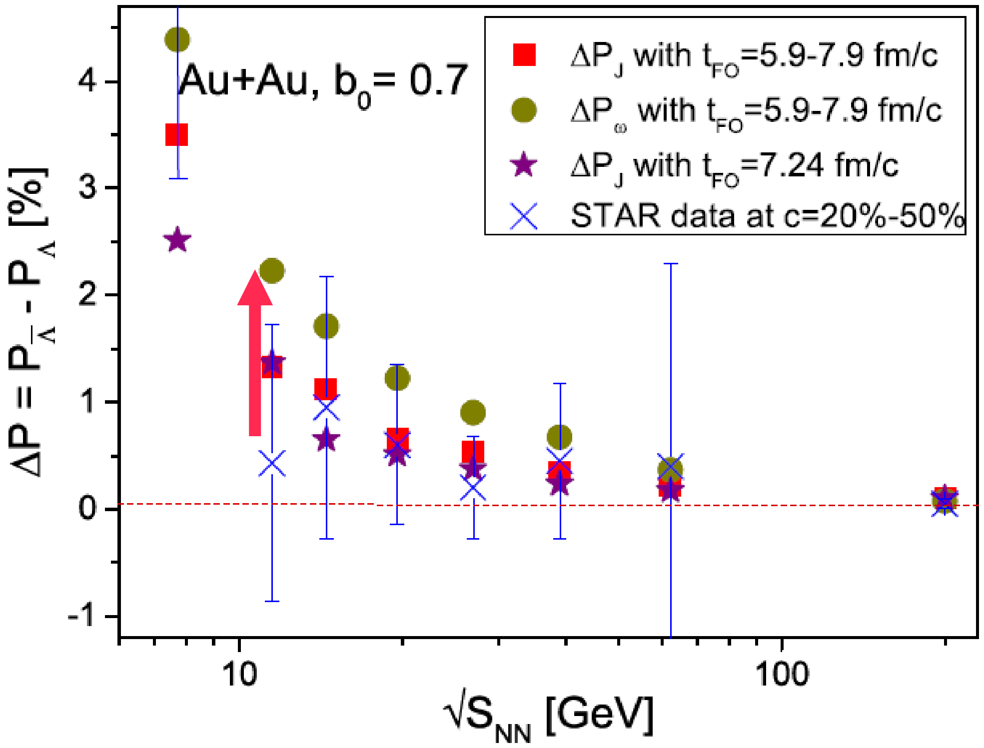
V

$$V^\mu = \frac{g_{VB}}{m_V^2}J^\mu_B \qquad \boldsymbol{B}_V = [\boldsymbol{\nabla}\times\boldsymbol{V}] \qquad \boldsymbol{E}_V = -\nabla V_0 - \frac{\partial \boldsymbol{V}}{\partial t} \qquad \beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

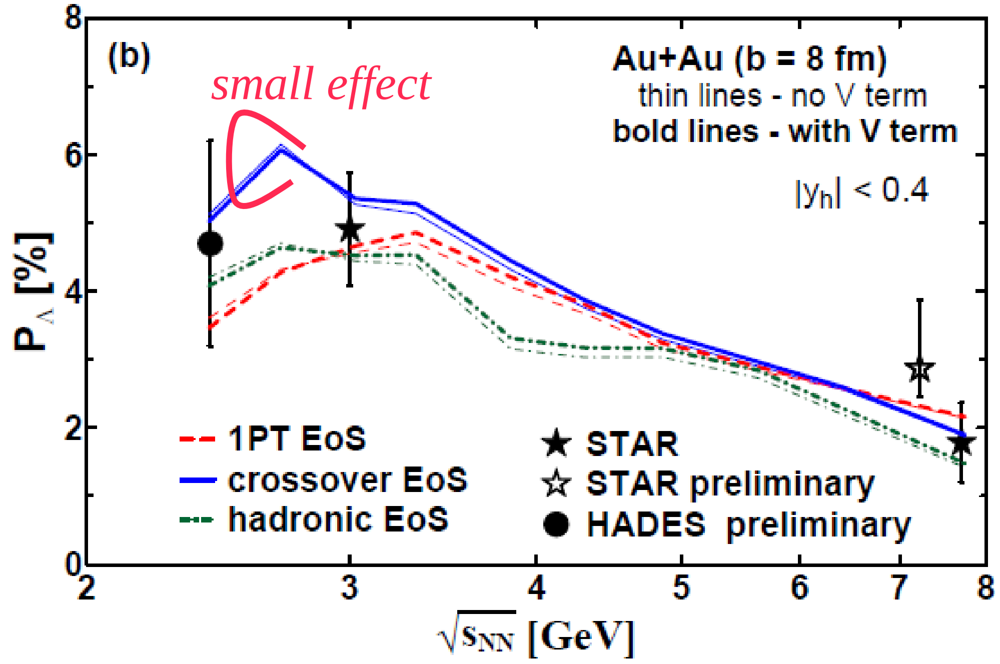
distinguishes baryons and anti-baryons

induced by vorticity

PICR hydro Xie, Chen, Csernai, EPJC81(2021)12



3-Fluid hydro Ivanov, Soldatov, PRC105 (2022)



The meson-field induced polarization does not explain the splitting at the energy of 7.7 GeV

- **axial vortical effect** Sorin and Teryaev, PRC 95 (2017) 011902

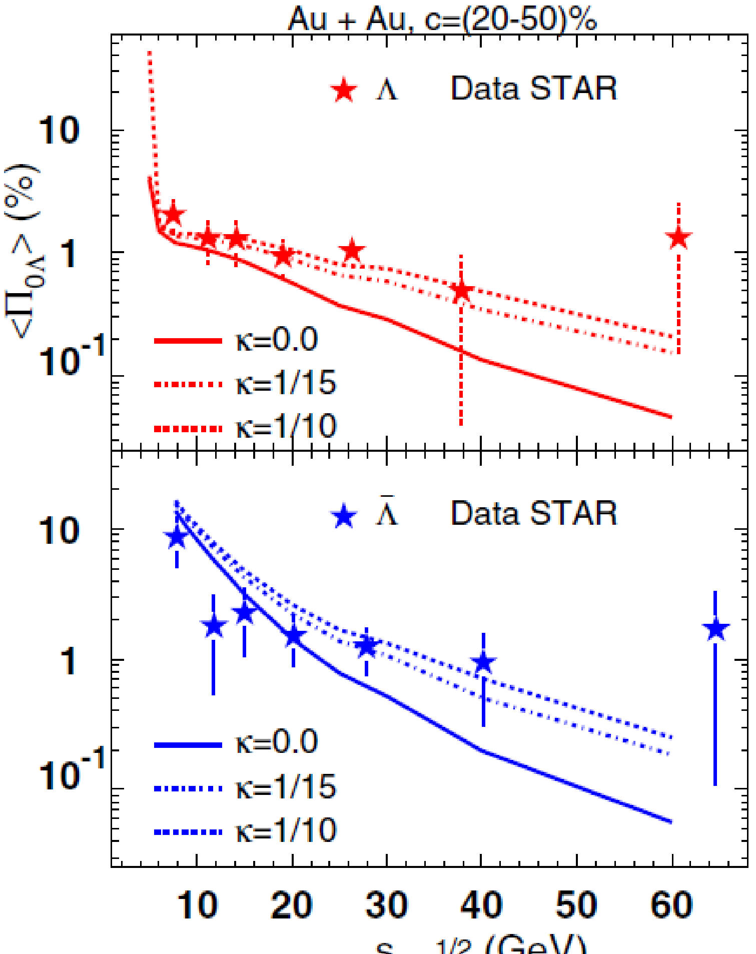
the axial current of strange chiral particles $J^{\mu}_{5,s}(x) = N_c\left(\frac{\mu^2}{2\pi^2} + \kappa\frac{T^2}{6}\right)\epsilon^{\mu\nu\alpha\beta}u_{\nu}\partial_{\alpha}u_{\beta}$

N_c - number of colors

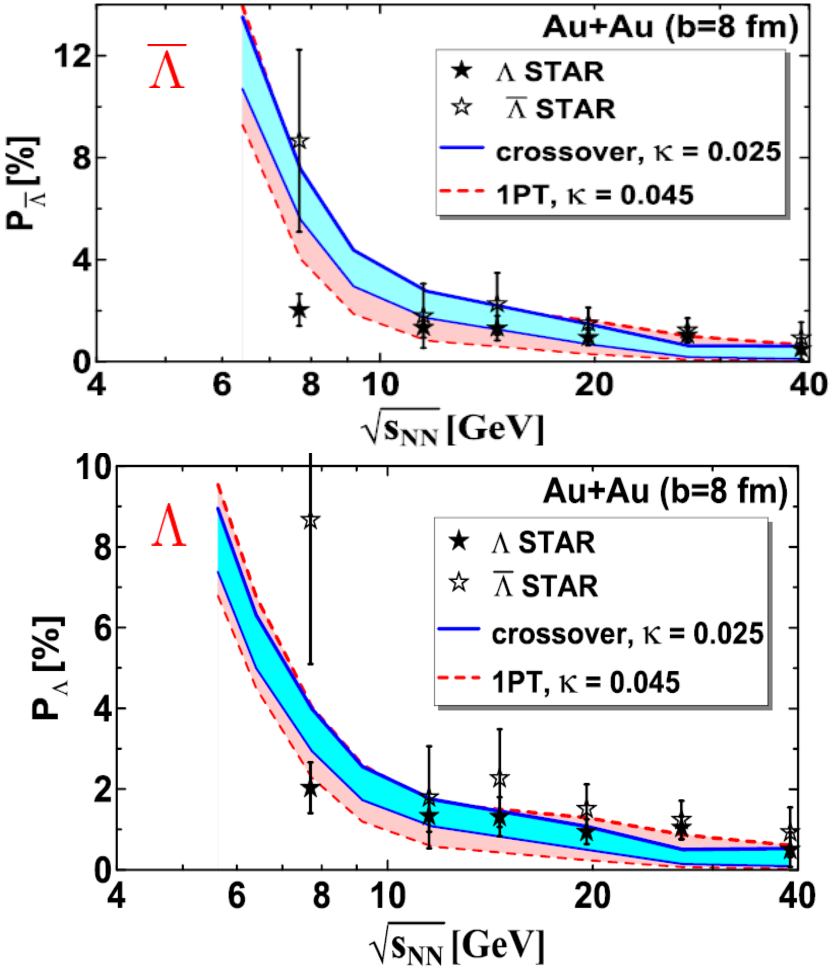
μ_s – strangenss chemical potential

$\mu_s = -\mu_{\bar{s}} = \mu_B/3 - \mu_S$

QGSM Baznat, Gudima, Sorin, Teryaev, PRC 97 (2018) 041902(R)



3 Fluid hydro Ivanov PRC102 (2020) 044904



Λ

$$P_{\Lambda} = \frac{N_c}{\langle n_{\Lambda} + n_{\overline{K^*}}\rangle}\left\langle \frac{\mu_s^2}{2\pi^2} + \kappa\frac{T^2}{6}\right\rangle\langle\omega_{xz}\rangle$$

$\overline{\Lambda}$

$$P_{\overline{\Lambda}} = \frac{N_c}{\langle n_{\overline{\Lambda}} + n_{K^*}\rangle}\left\langle \frac{\mu_{\bar{s}}^2}{2\pi^2} + \kappa\frac{T^2}{6}\right\rangle\langle\omega_{xz}\rangle$$

$$\langle n_{\overline{\Lambda}} + n_{K^*}\rangle \ll \langle n_{\Lambda} + n_{\overline{K^*}}\rangle$$

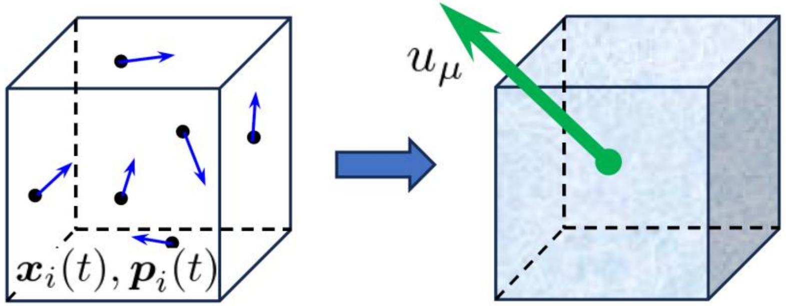
⇓

$$P_{\overline{\Lambda}} >> P_{\Lambda}$$

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

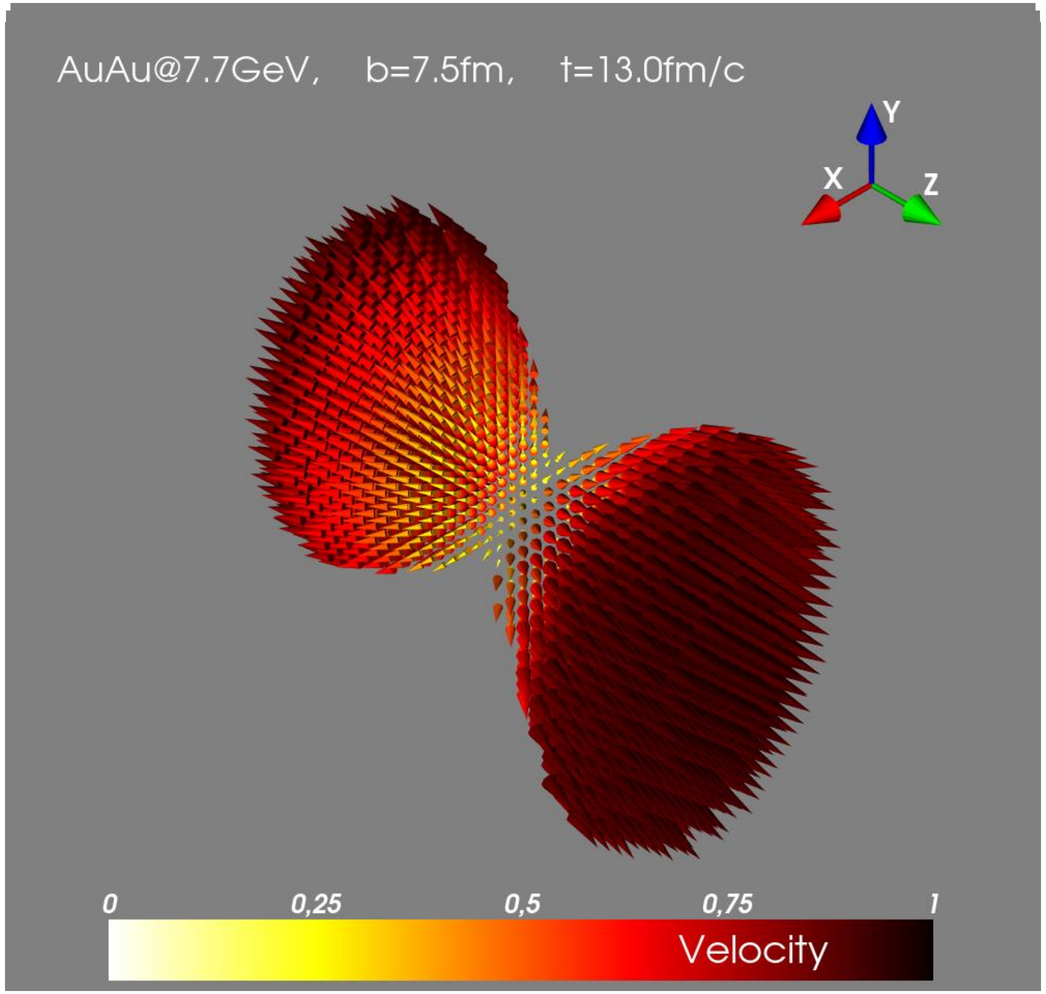
$$J^\mu_B = \sum_{a,i_a} B_{i_a} \frac{p^\mu_{i_a}(t)}{p^0_{i_a}(t)} \Phi\left(\boldsymbol{x}, \boldsymbol{x}_{i_a}(t)\right)$$

$$n_B = u_\mu J^\mu_B$$

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

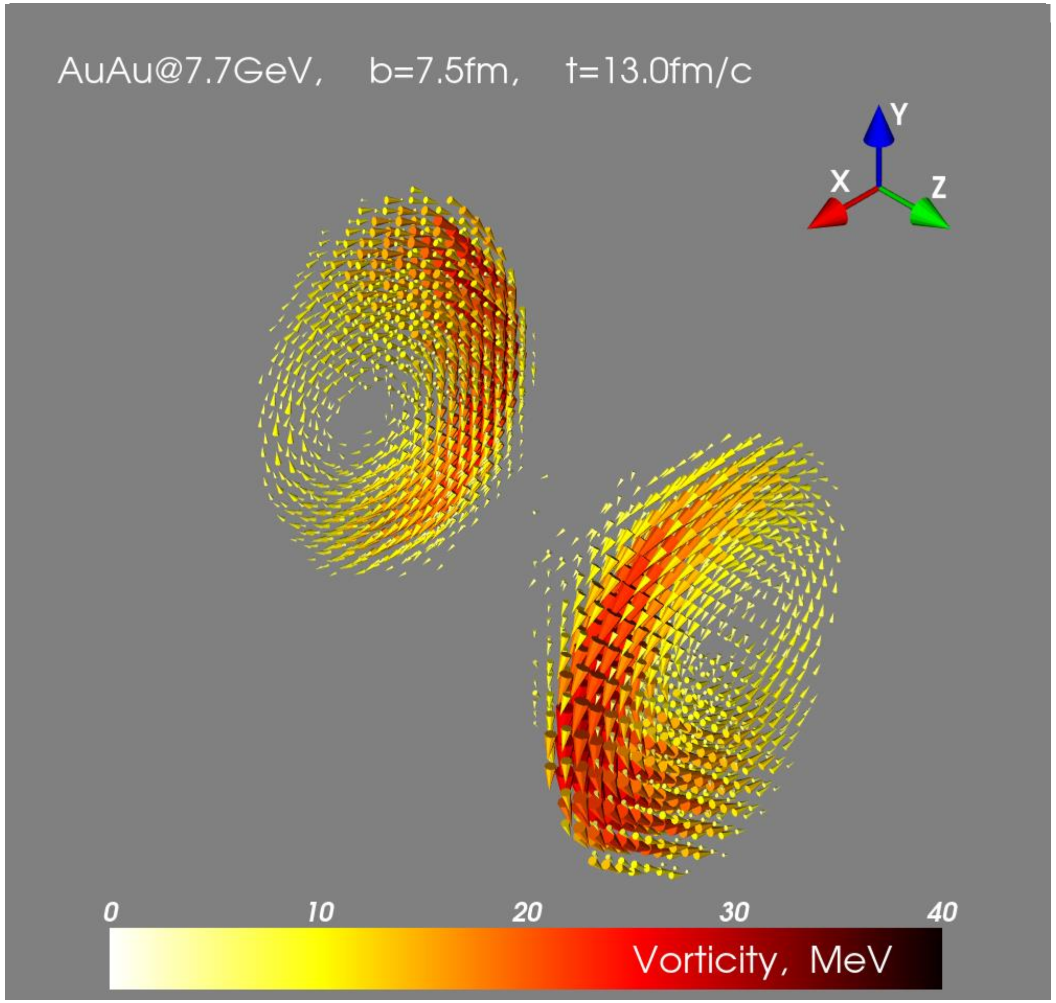
No mean field effects are included in particle propagation an in $T^{\mu\nu}$

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

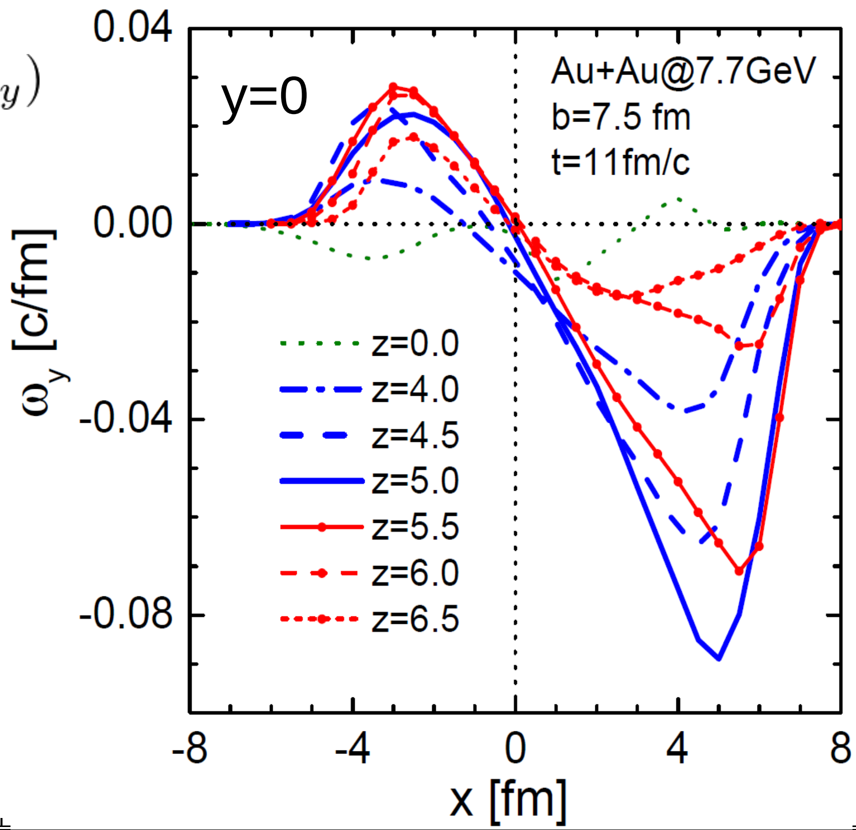
Two bubliks are formed

Vorticity field (ω_x, ω_y)

Au+Au @ 7.7 GeV

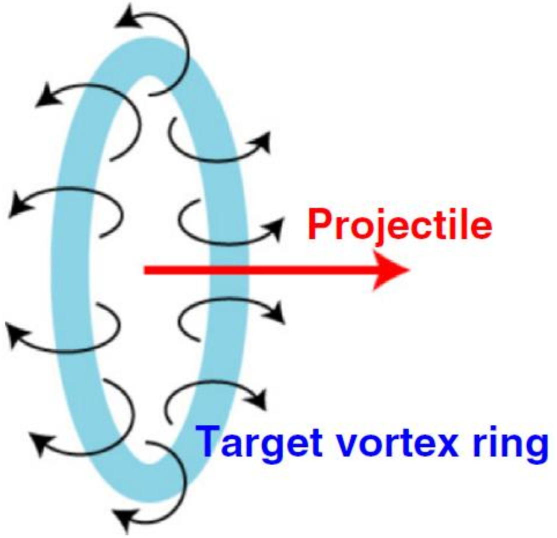
b=7.5 fm

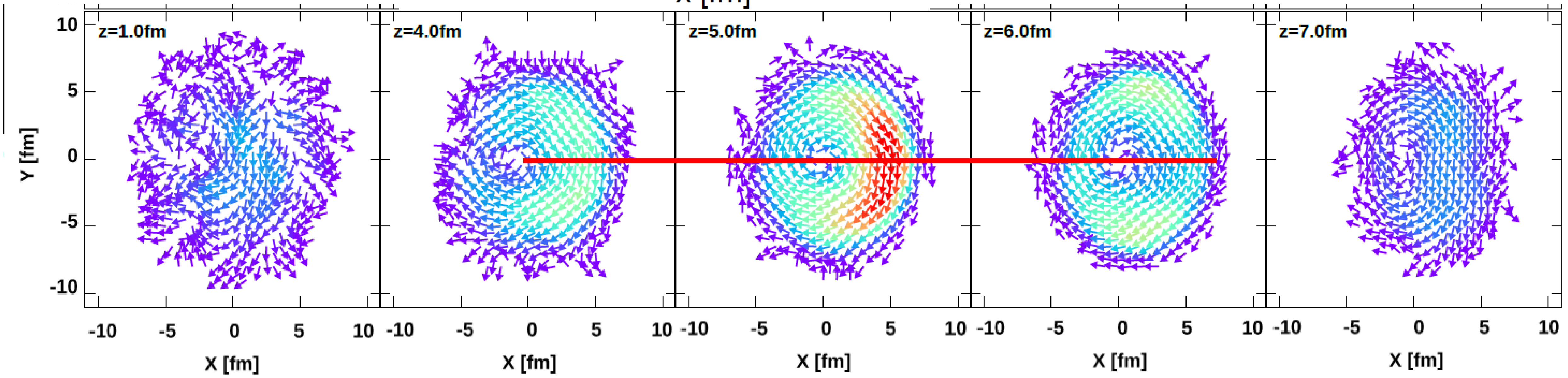
t=11 fm/c



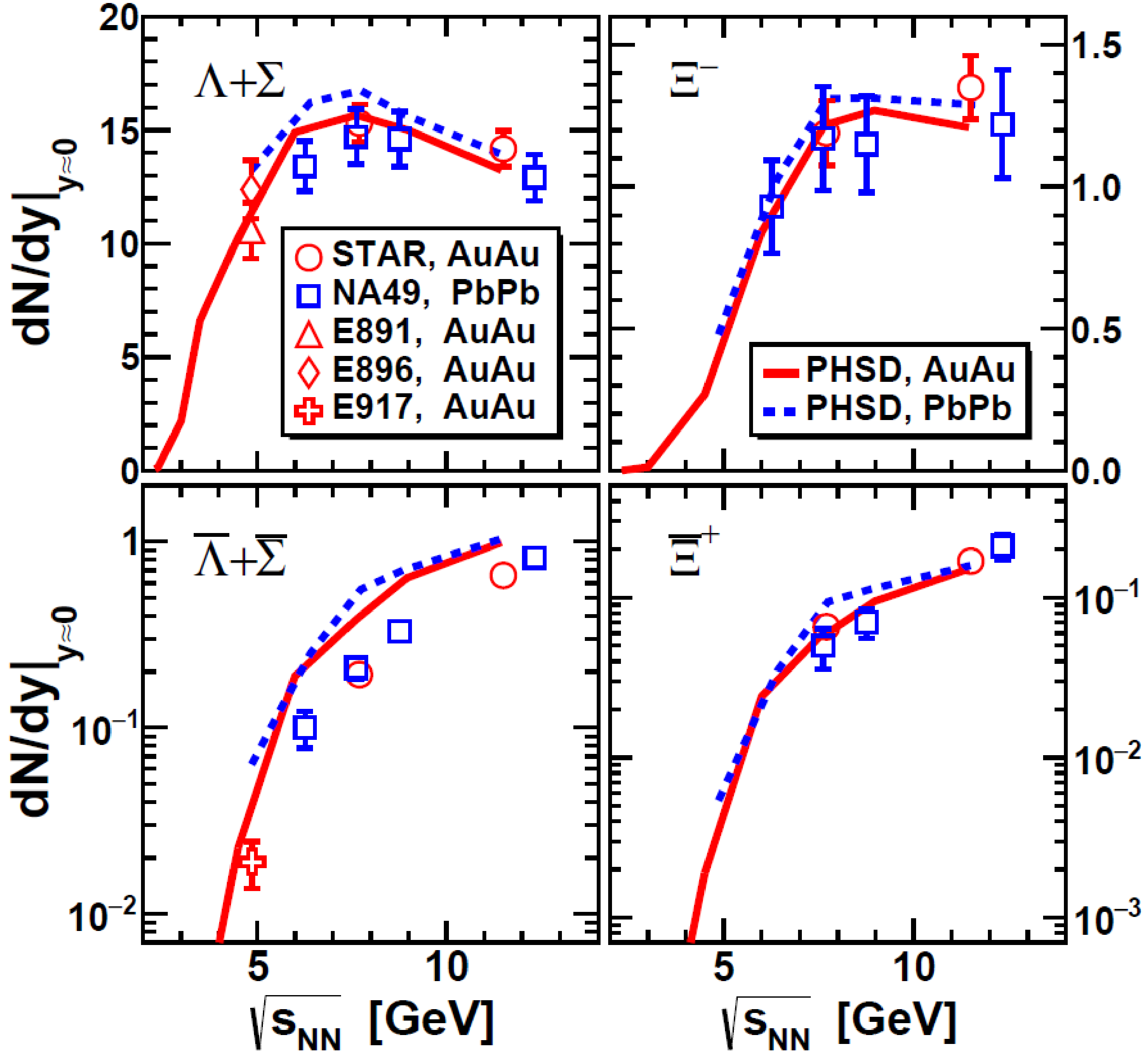
Yu.B. Ivanov, A.A. Soldatov predicted in [PRC97 (2018)] within the 3-fluid hydro model the formation of vortex rings

Vortex ring





Hyperon and anti-hyperon production



Ω ant $\overline{\Omega}$ multiplicities

Exp: NA49 PRL 94 (2005) 192301

central Pb+Pb collisions at energy 40AGeV

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

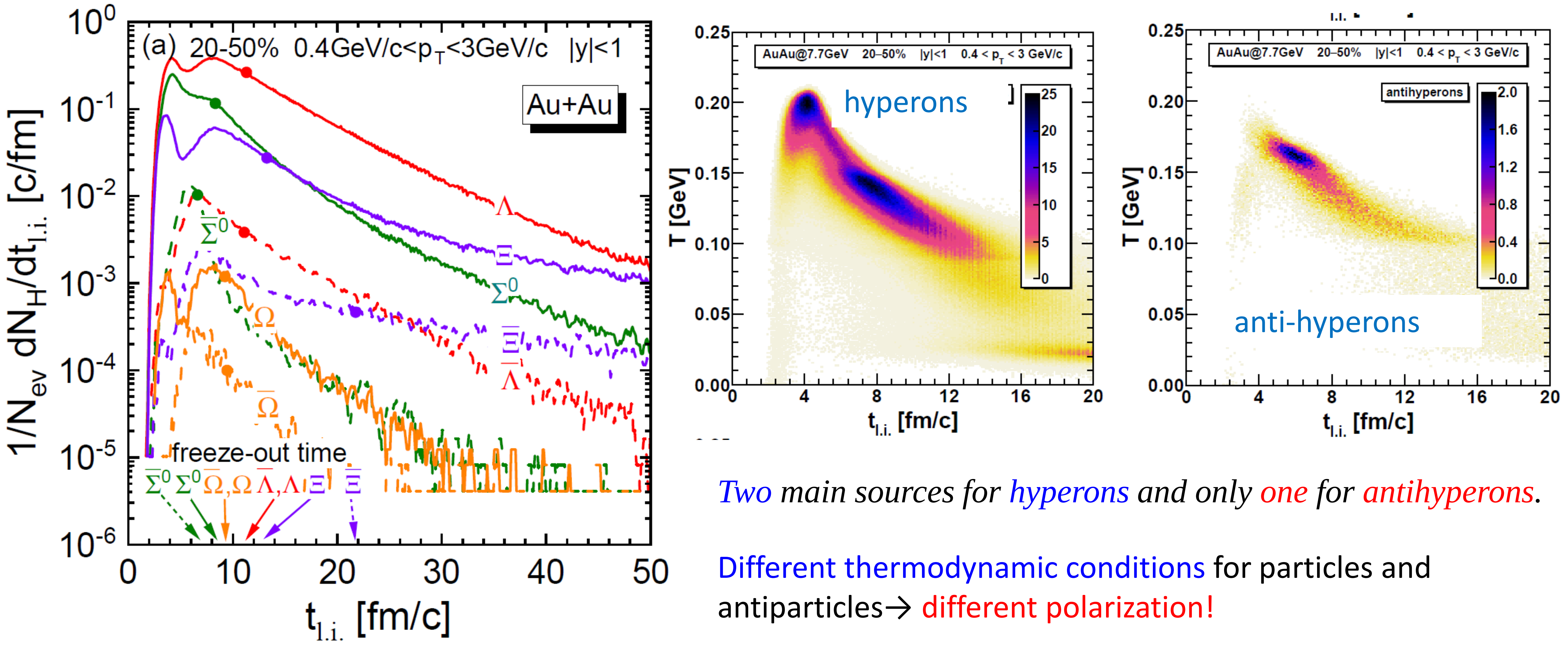
$$M^{(\mathrm{exp})}_{\Omega+\overline{\Omega}} = 0.14 \pm 0.05$$

PHSD:

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

Dynamics of hyperon production

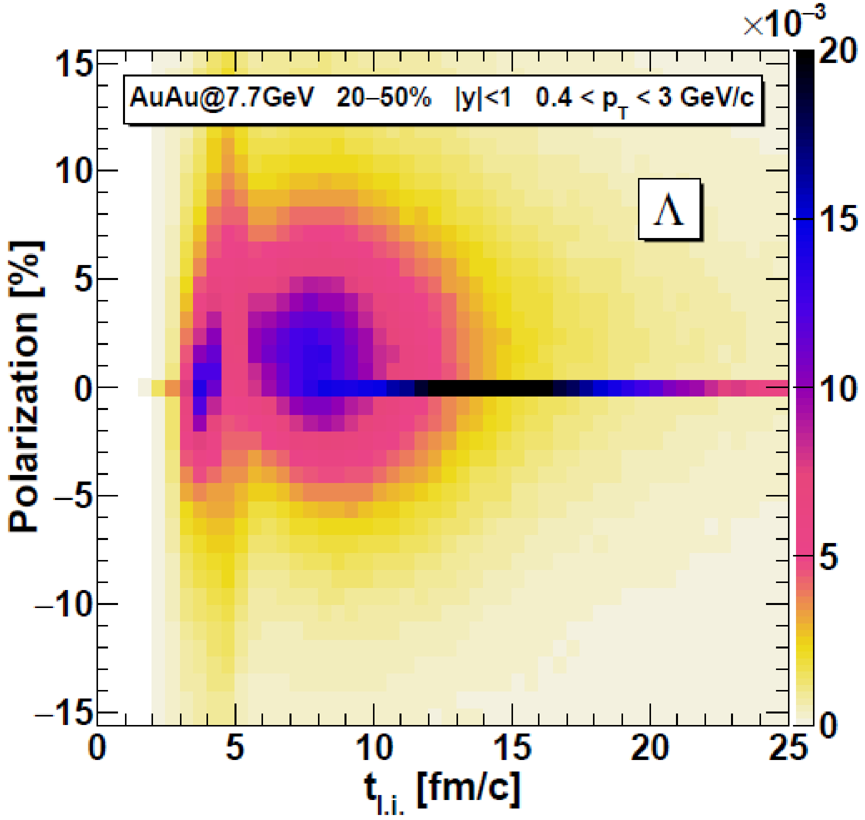
We store the time marker for each 'newly-created' particle. After the completion of a code run, we can look at survived hyperons and obtain the distribution of the time of the last interaction, $t_{\mathrm{l.i.}}$ (TLI).

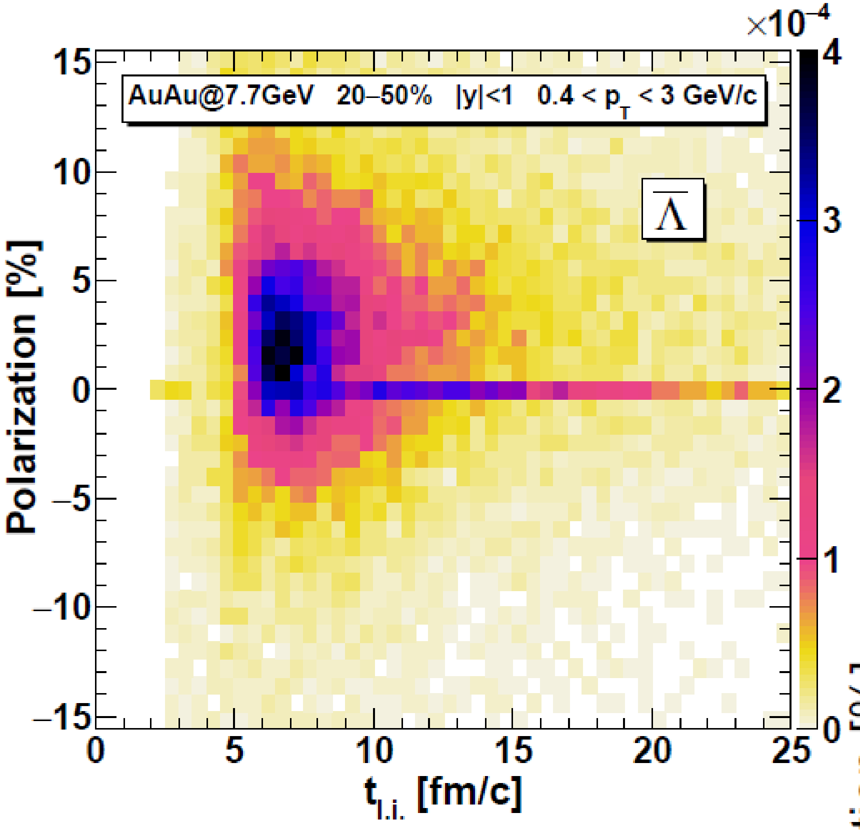


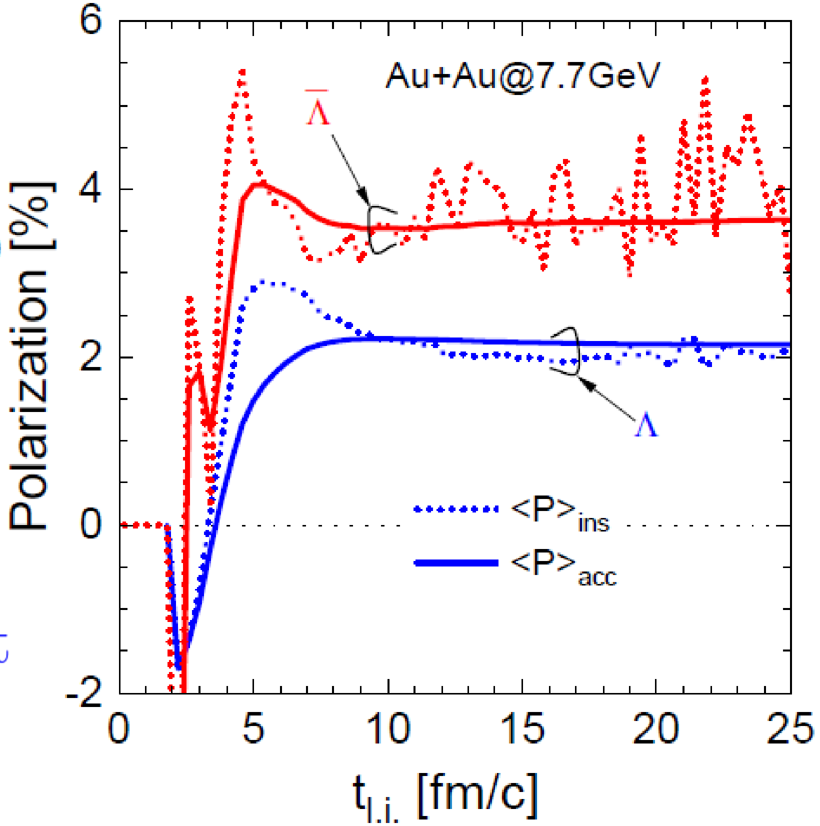
Two main sources for hyperons and only one for antihyperons.

Different thermodynamic conditions for particles and antiparticles→ different polarization!

Polarization source







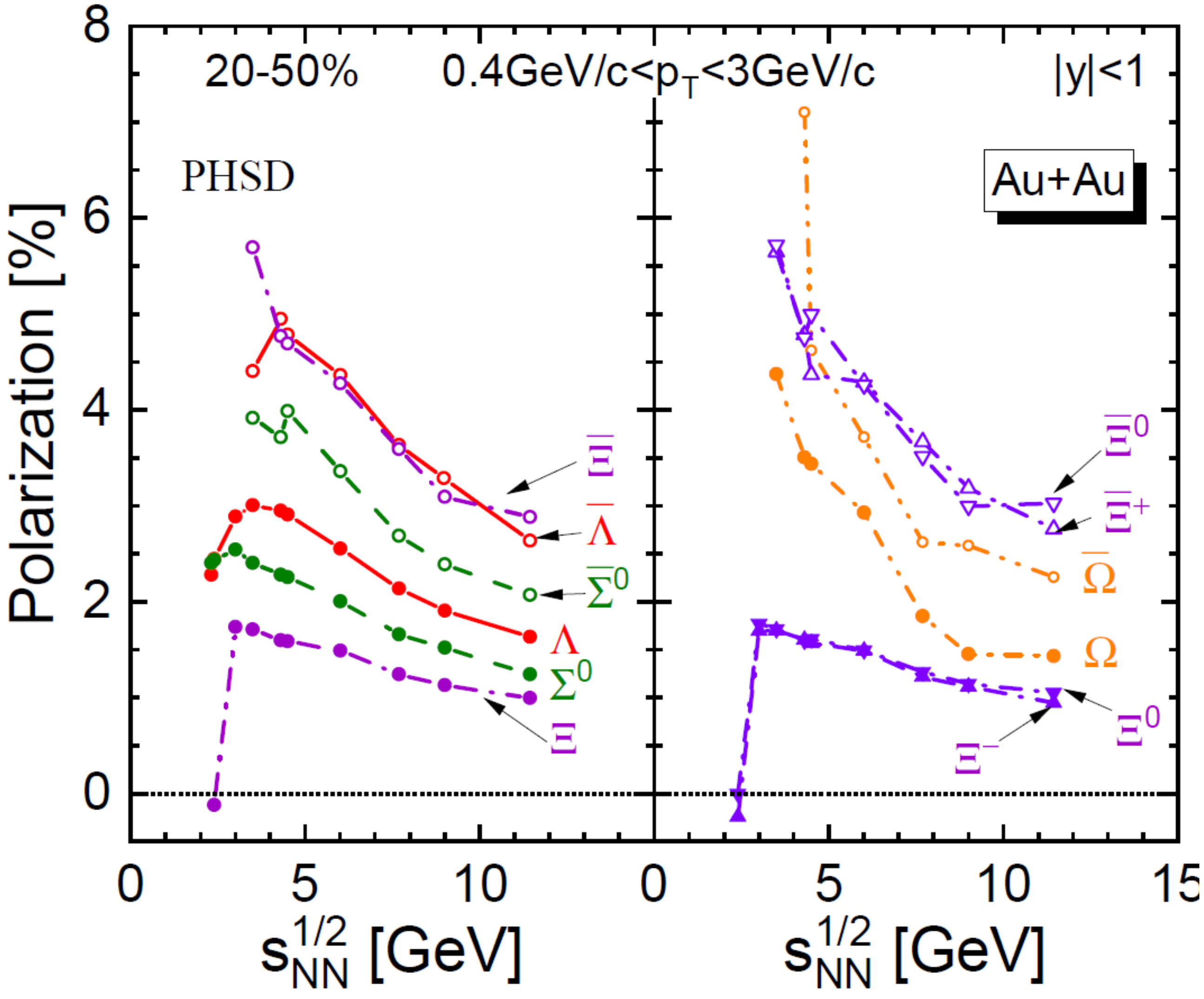
Two main sources for Λ and only one for $\bar{\Lambda}$

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

For $t \gtrsim 10\,\text{fm}/c$ 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

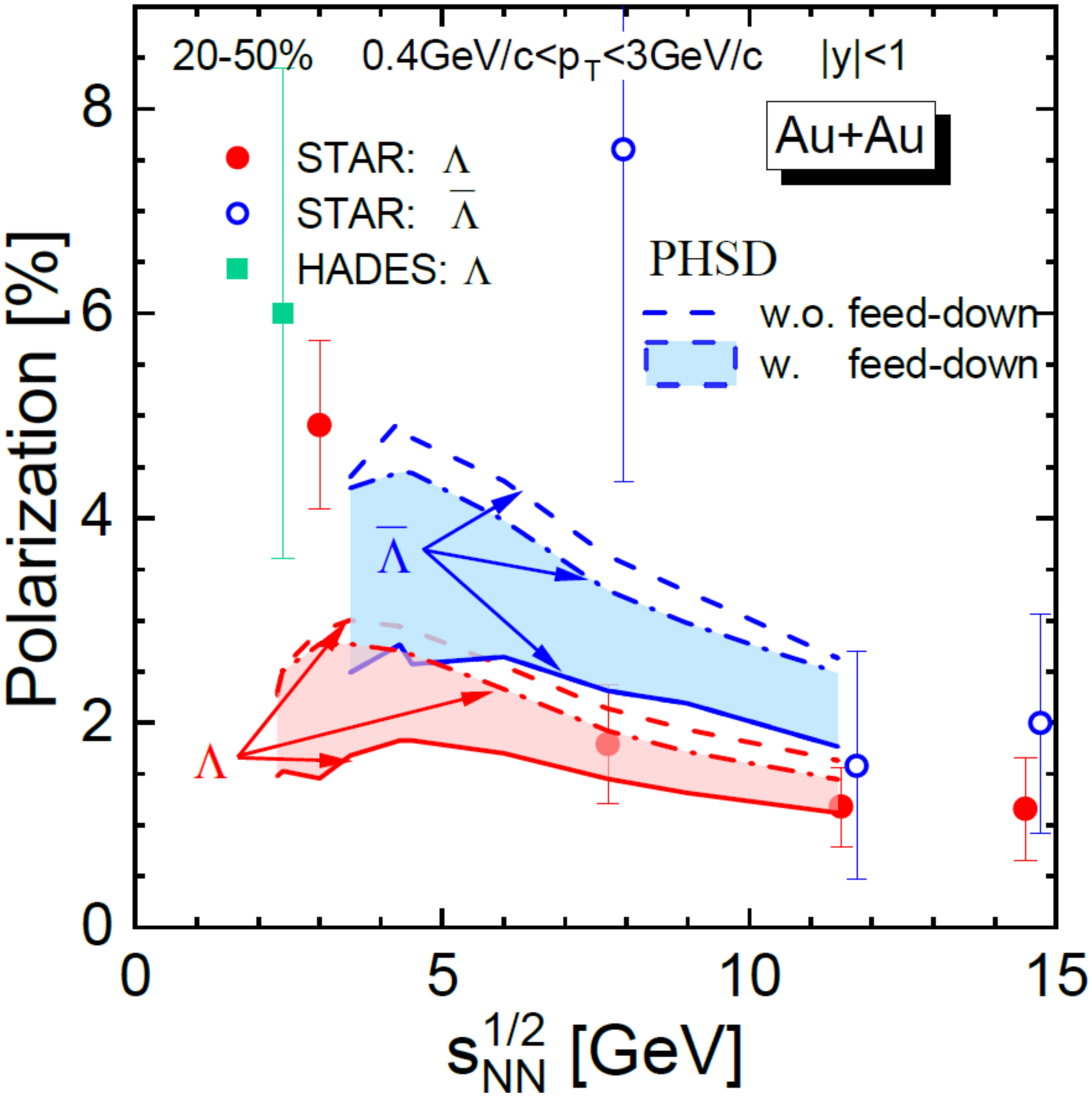
Polarization of all hyperon species decrease with an energy increase for $\sqrt{s_{NN}} \gtrsim 5\,\mathrm{GeV}$

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.

Bi+Bi collisions at 9.0 GeV

- **hyperon multiplicities**

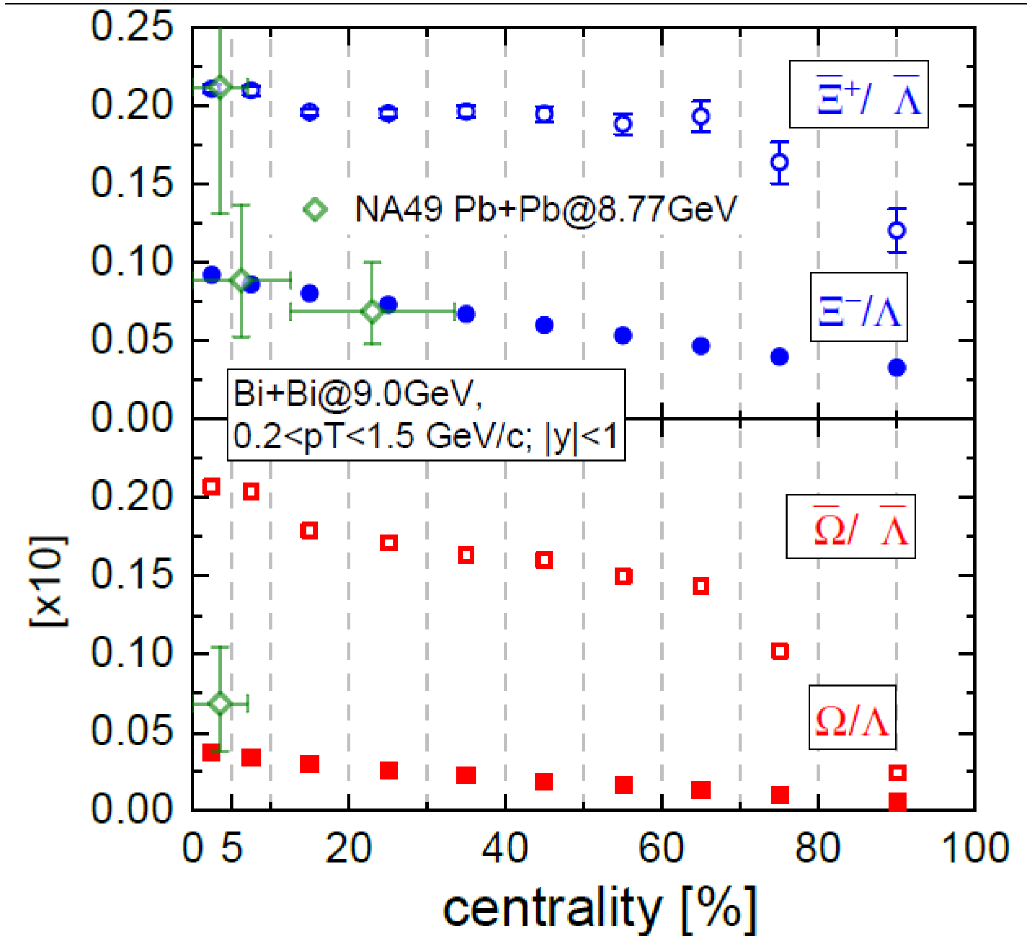
0-5% centrality class

$$M_\Lambda : M_\Xi : M_\Omega = 1 : (9.10 \pm 0.02) \times 10^{-2} : (3.71 \pm 0.04) \times 10^{-3}\,,$$
$$M_{\overline{\Lambda}} : M_{\overline{\Xi}} : M_{\overline{\Omega}} = 1 : (2.09 \pm 0.02) \times 10^{-1} : (2.16 \pm 0.06) \times 10^{-2}\,.$$

NA49 Pb+Pb @ 8.77 GeV [40AGeV] 0-7% centrality class

$$M_\Lambda : M_\Xi : M_\Omega = 1 : (7 \pm 1) \times 10^{-2} : (3 \pm 2) \times 10^{-3}\,,$$
$$M_{\overline{\Lambda}} : M_{\overline{\Xi}} = 1 : (2 \pm 0.5) \times 10^{-1}$$

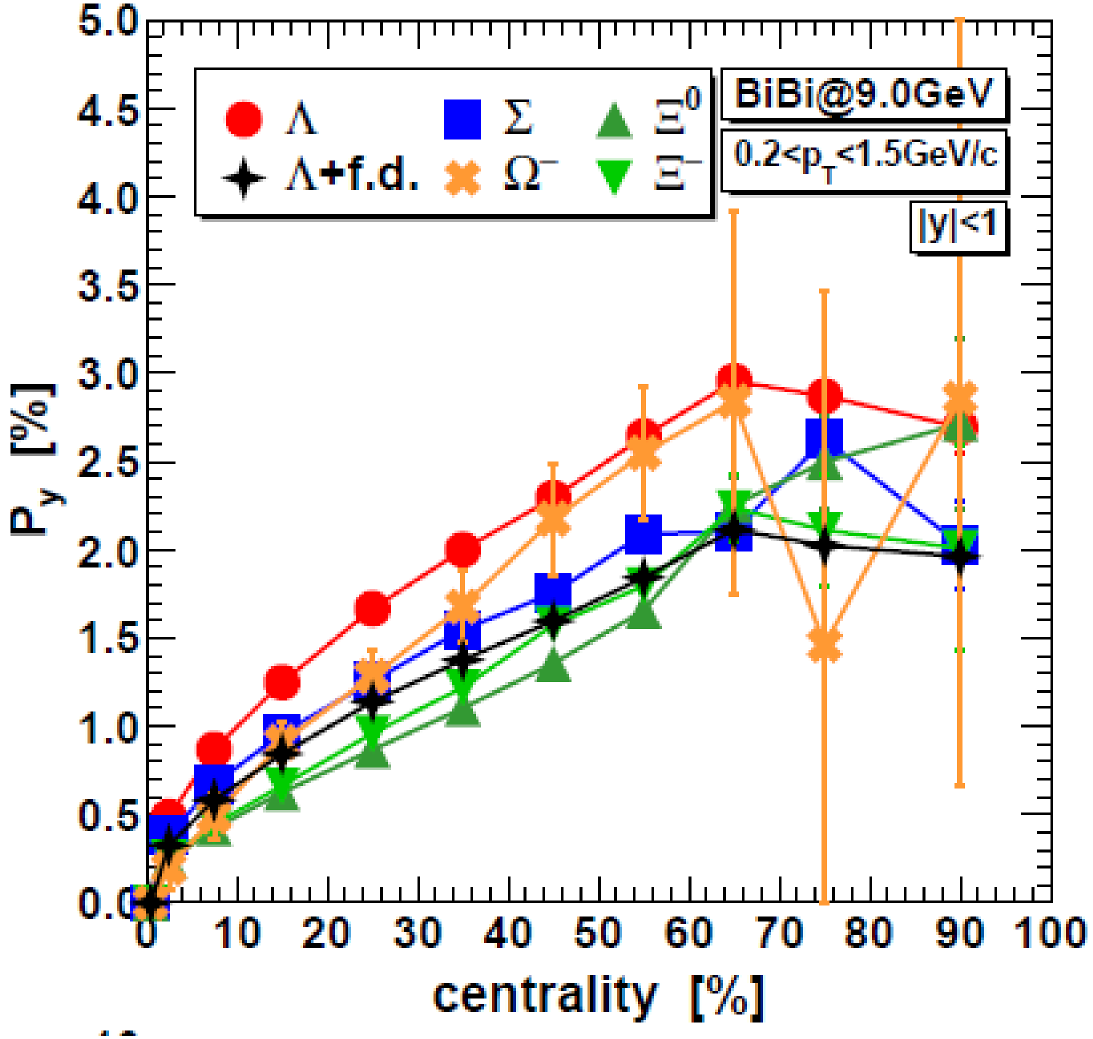
- **the relative enhancement** of multi-strange particle production in central heavy-ion collisions with respect to peripheral ones

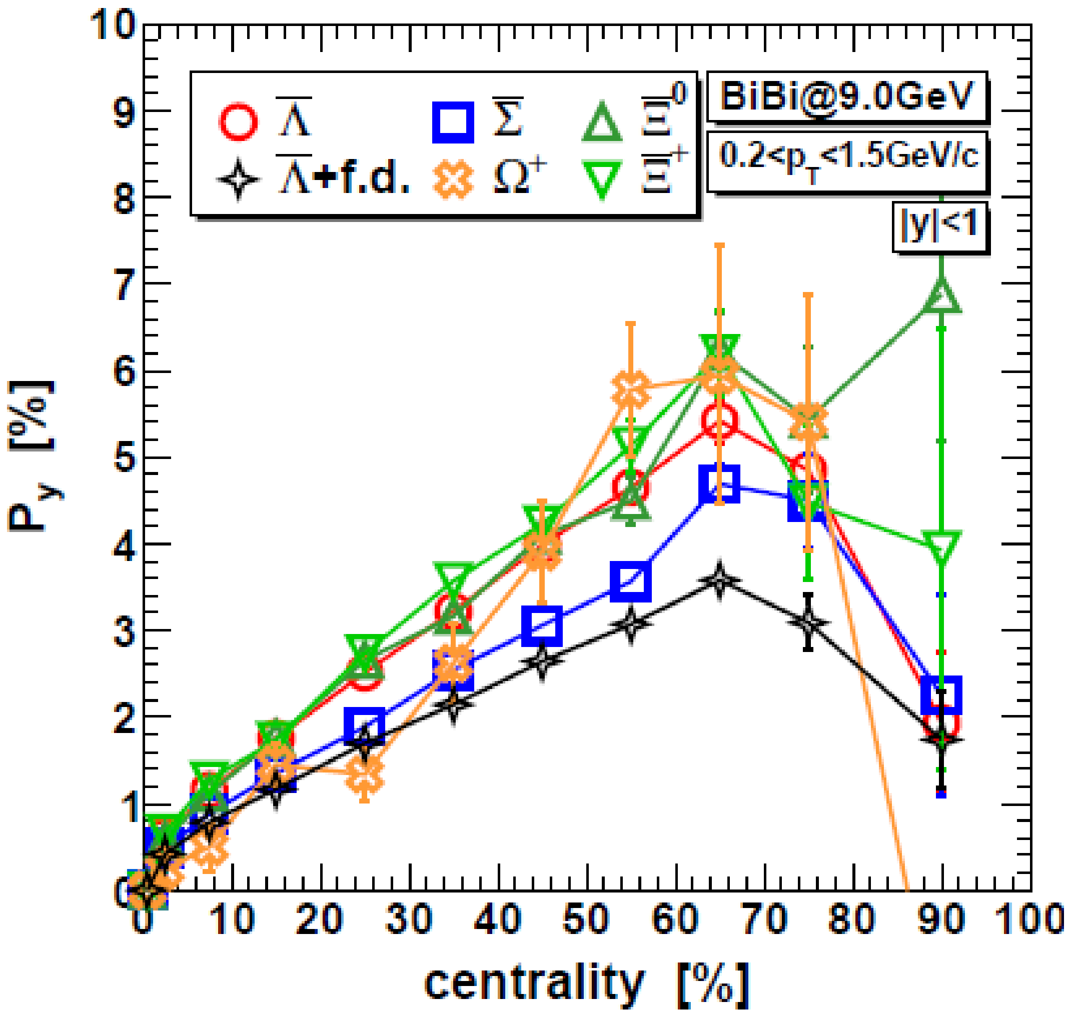


Ratios of experimental mid-rapidity multiplicities measured by the NA49 collaboration in Pb + Pb @ 8.77 GeV.

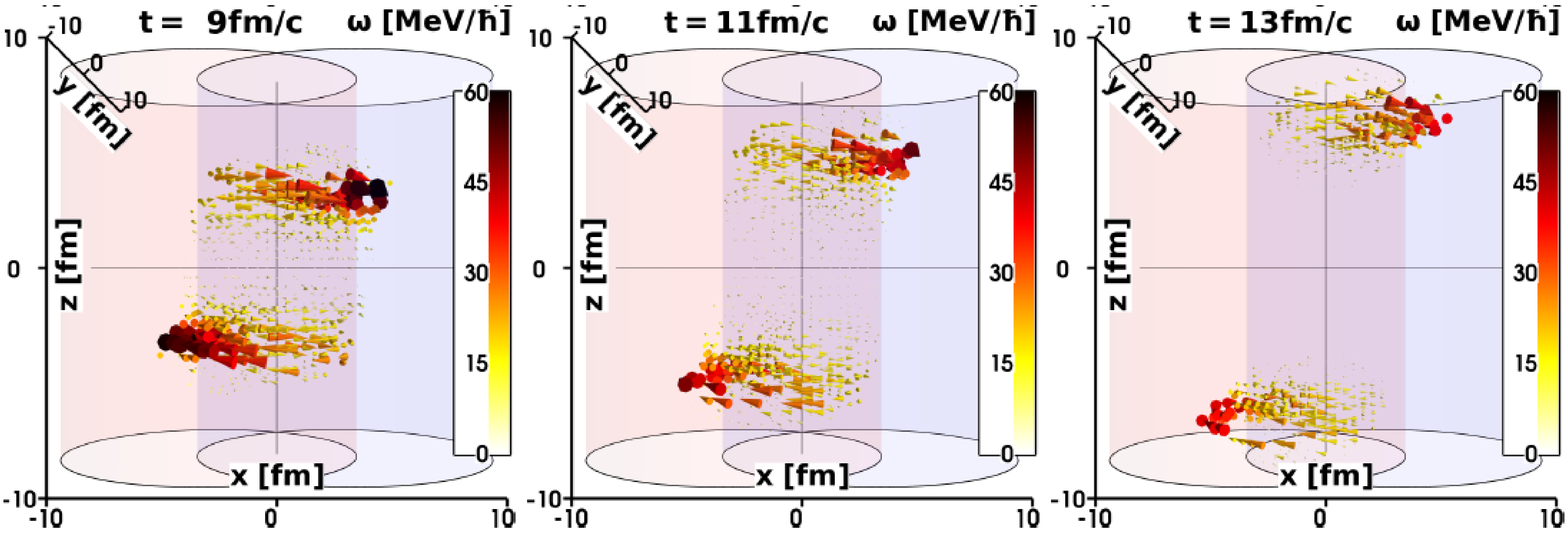
$$\frac{\overline{\Xi}^+}{\overline{\Lambda}} > \frac{\Xi^-}{\Lambda} \quad \text{and} \quad \frac{\overline{\Omega}}{\overline{\Lambda}} > \frac{\Omega}{\Lambda}$$

- centrality dependence of the polarization





- **velocity and vorticity field**

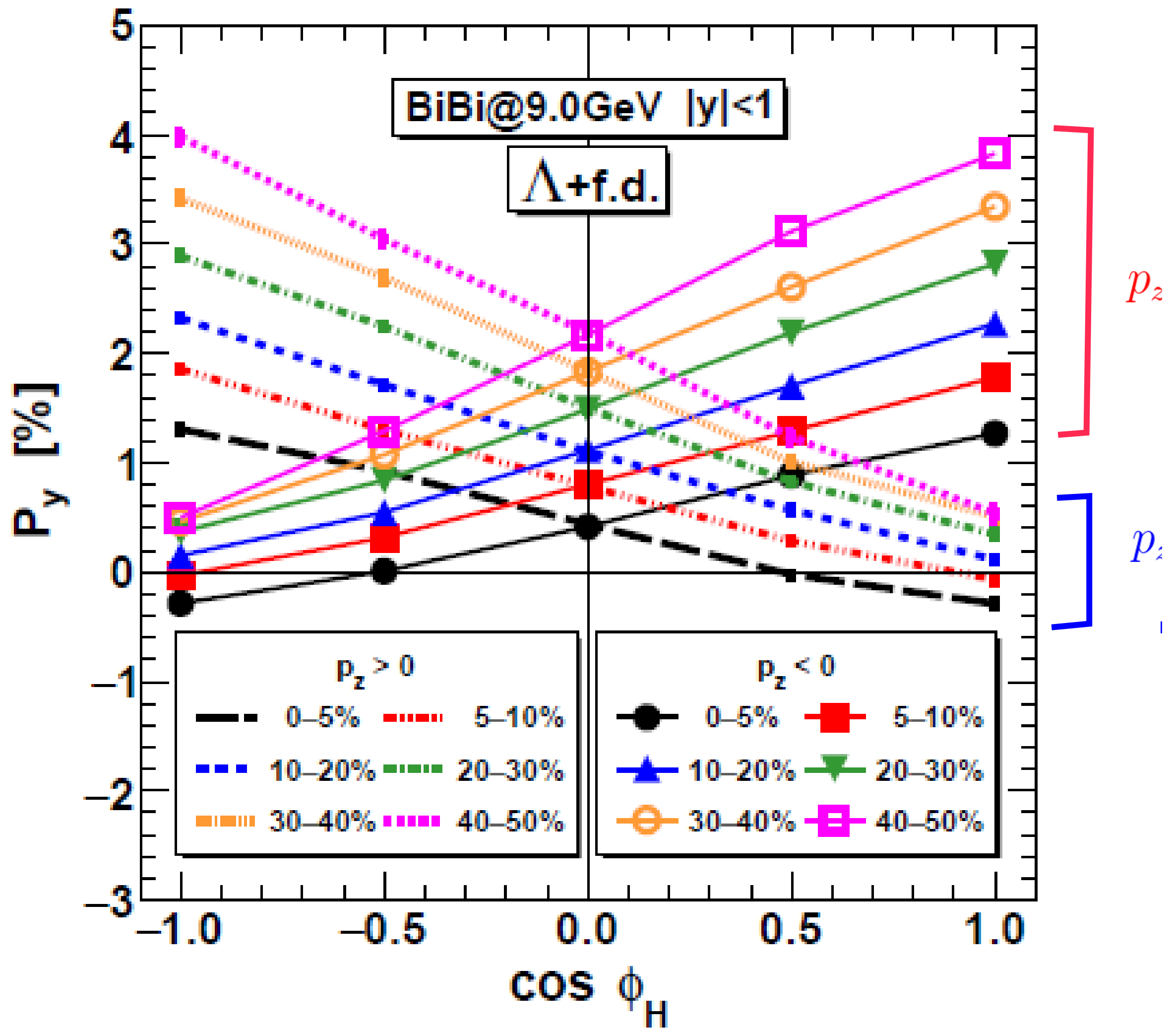


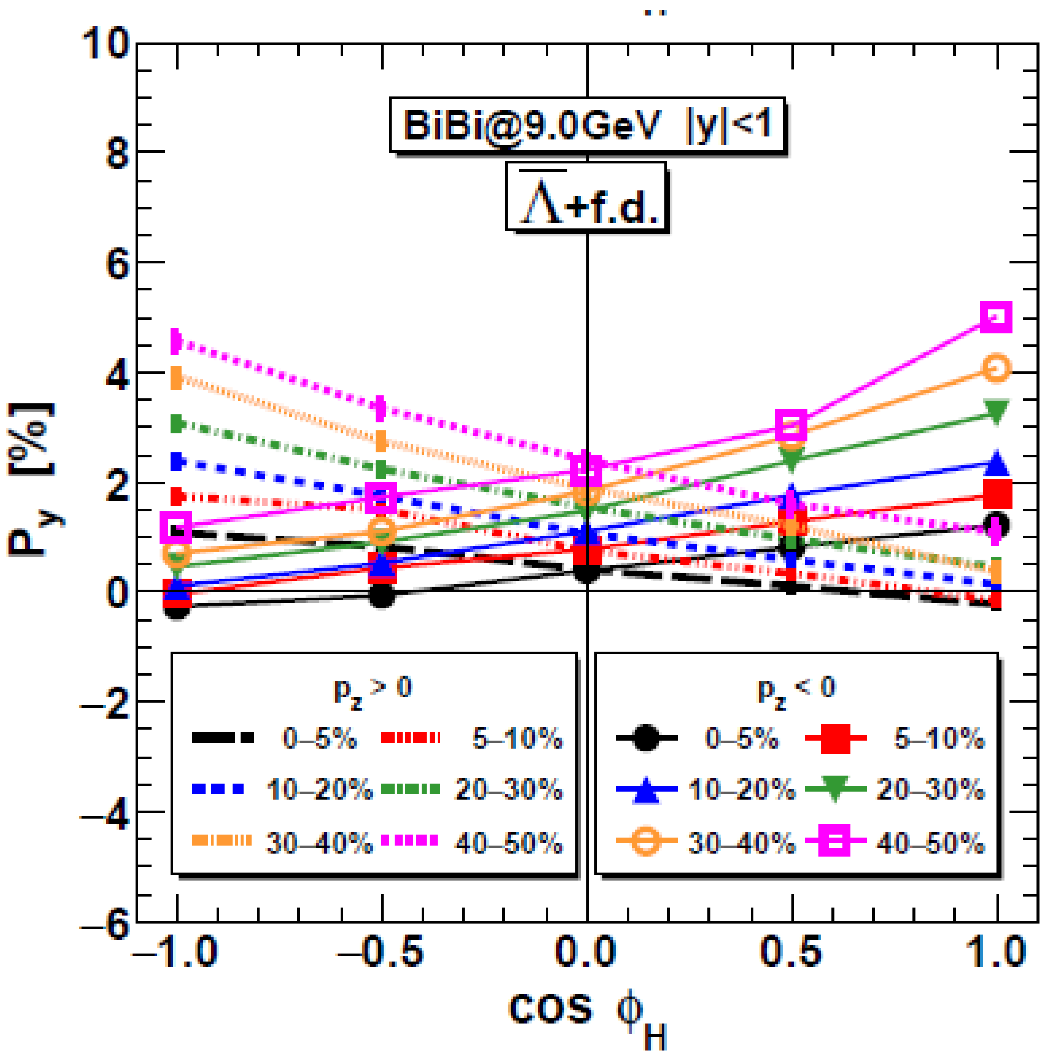
It is interesting whether experimental data could reveal information about an operative polarizing mechanism.

One can try to separate the hyperons stemming from the most vortical parts of the bubliks.
They would have opposite polarization directions, P_y. For this, we select positive or negative projections of the momenta along the collision axis, $p_z \gtrless 0$, and look at the dependence of the hyperon polarization on the azimuthal angle

$$\cos\phi_H = \frac{p_x}{p_x^2 + p_y^2}$$

- **angular dependence of the polarization**





Conclusion

- ✔ The (2+1)D Hubble-like expansion + vorticity at the system edges $\leftrightarrow$ two deformed elliptical vortex rings bubliks.
- ✔ 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, and different mean free paths of hyperons and anti-hyperons
- ✔ Strong polarization suppression due to the feed-down from $\Sigma^0(\overline{\Sigma}^0)$.
- ✔ We show that, for the considered hyperon polarization mechanism, the structure of the vorticity field makes an imprint on the polarization signal as a function of the azimuthal angle in the transverse momentum plane.