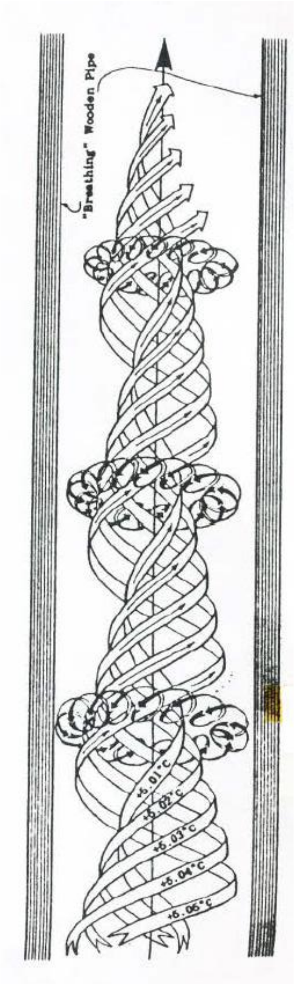
Hyperon polarization in heavy-ion collisions and in hadronic reactions



Evgeni Kolomeitsev

Joint Institute for Nuclear Research, Dubna, Russia

work with Nikita Tsegelnik and Vadim Voronyuk

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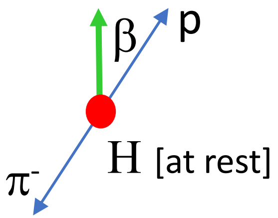
Particles **2023** (2023) 373
arXiv:2305.10792 [nucl-th]

Standard measurements in HIC: PID, momenta distributions → *multiplicities, p_T- and y-spectra, flows*

“New” measurements: averaged spin orientation

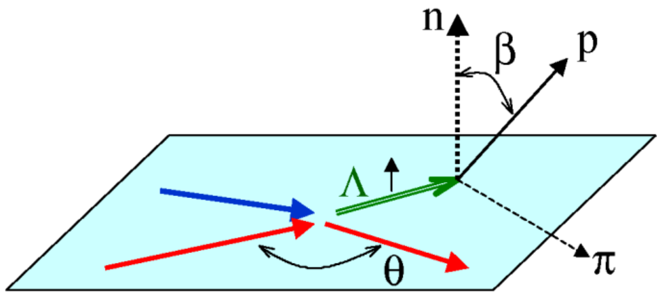
Can be done for hyperons which are “self-analyzing particles”.



$$4\pi \frac{d\Gamma}{d\Omega_p} = \Gamma\,[1+\alpha_H\,\cos\beta]$$

elementary processes

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



$$\mathcal{M}(\bar p,\bar q;p,q)=\langle\Lambda(\bar p)\pi(\bar q)|N(p)\,\overline{K}(q)\rangle=(2\pi)^4\,i\,\delta^{(4)}(i-f)\frac{T(\bar p,\bar q;p,q)}{2\sqrt{\omega\bar\omega}}$$

$$T(\bar p,\bar q;p,q)=\bar u_N(\bar p)\left(\mathcal{T}_+(\sqrt{s},\theta)\hat P_+ + \mathcal{T}_-(\sqrt{s},\theta)\hat P_-\right)u_N(p)$$

$$\hat P^\pm=\frac{1}{2}\left(1\pm\frac{\not w}{\sqrt{w^2}}\right)\qquad w=p+q \qquad s=w^2$$

partial-wave decomposition M_{J^P}

$$\mathcal{T}_+(\sqrt{s},\theta)=M_{\frac12^-}(\sqrt{s})+3\,\cos\theta\,p\,\bar p\,M_{\frac32^+}(\sqrt{s})+\dots$$

$$\mathcal{T}_-(\sqrt{s},\theta)=-M_{\frac12^+}(\sqrt{s})-(E+m)\,(\bar E+\bar m)\,M_{\frac32^+}(\sqrt{s})+\dots$$

$$J^P\to L_J:\ \tfrac12^-\to S_0\,,\ \tfrac12^+\to P_1\,,\ \tfrac32^+\to P_3$$

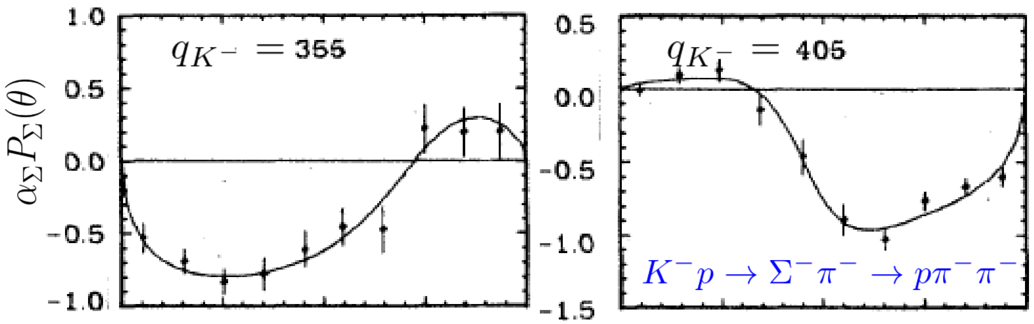
$$\frac{d\sigma(\boldsymbol\zeta)}{d\Omega_{\boldsymbol p_H}}=\frac12\frac{d\sigma}{d\Omega_{\boldsymbol p_H}}-\frac{1}{64\,\pi^2\,s}\frac{\bar p}{p}\,\Im(\mathcal{T}_+\mathcal{T}_-^*)\,[\boldsymbol p\times\bar{\boldsymbol p}_H]\cdot\boldsymbol\zeta$$

spin vector

spin-summed cross section

$$S_H^\mu=\left(\frac{\boldsymbol p_H\boldsymbol\zeta}{m_H},\boldsymbol\zeta+\frac{(\boldsymbol p_H\cdot\boldsymbol\zeta)\,\boldsymbol p_H}{m_H\,(E_H+m_H)}\right)$$

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



[Barngerter et al PRD23]

interference of s- and p-waves

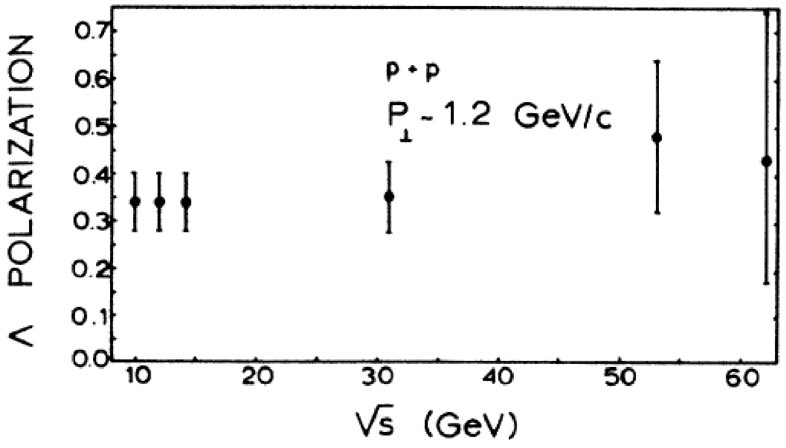
$$\Im(S_0P_1^*)\,,\ \Im(S_0P_3^*)\,,\ \Im(P_1P_3^*)\,,\dots$$

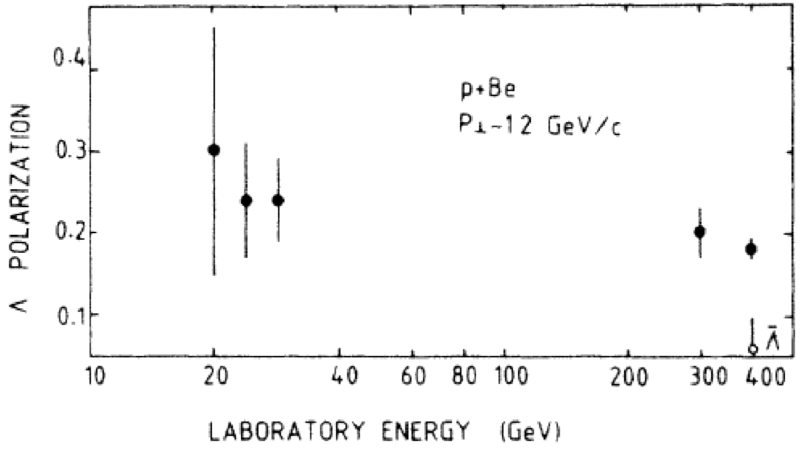
Colliding ideal spheres do not spin up!

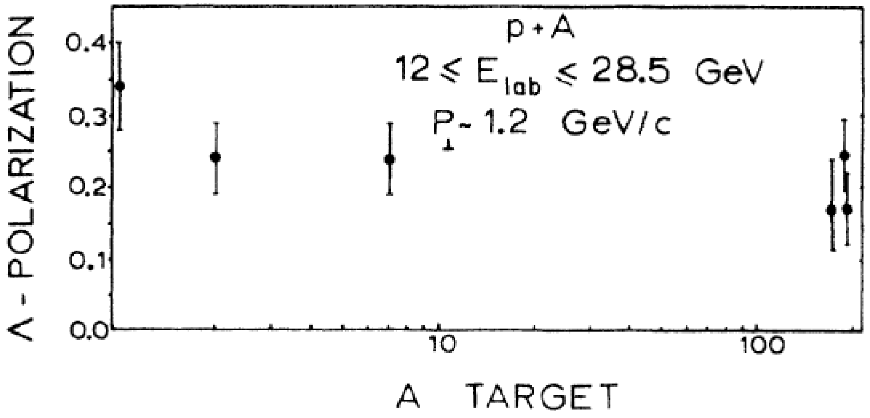
elementary processes

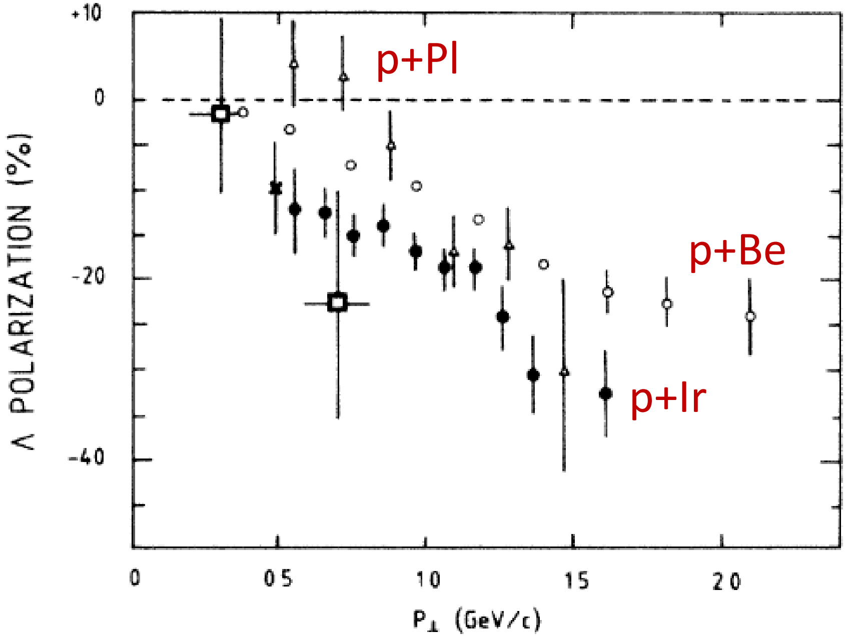
- High energy inclusive Λ production in pp and pA scattering $p(p_{\rm beam}) + A \rightarrow \Lambda(p_\Lambda) + X$

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







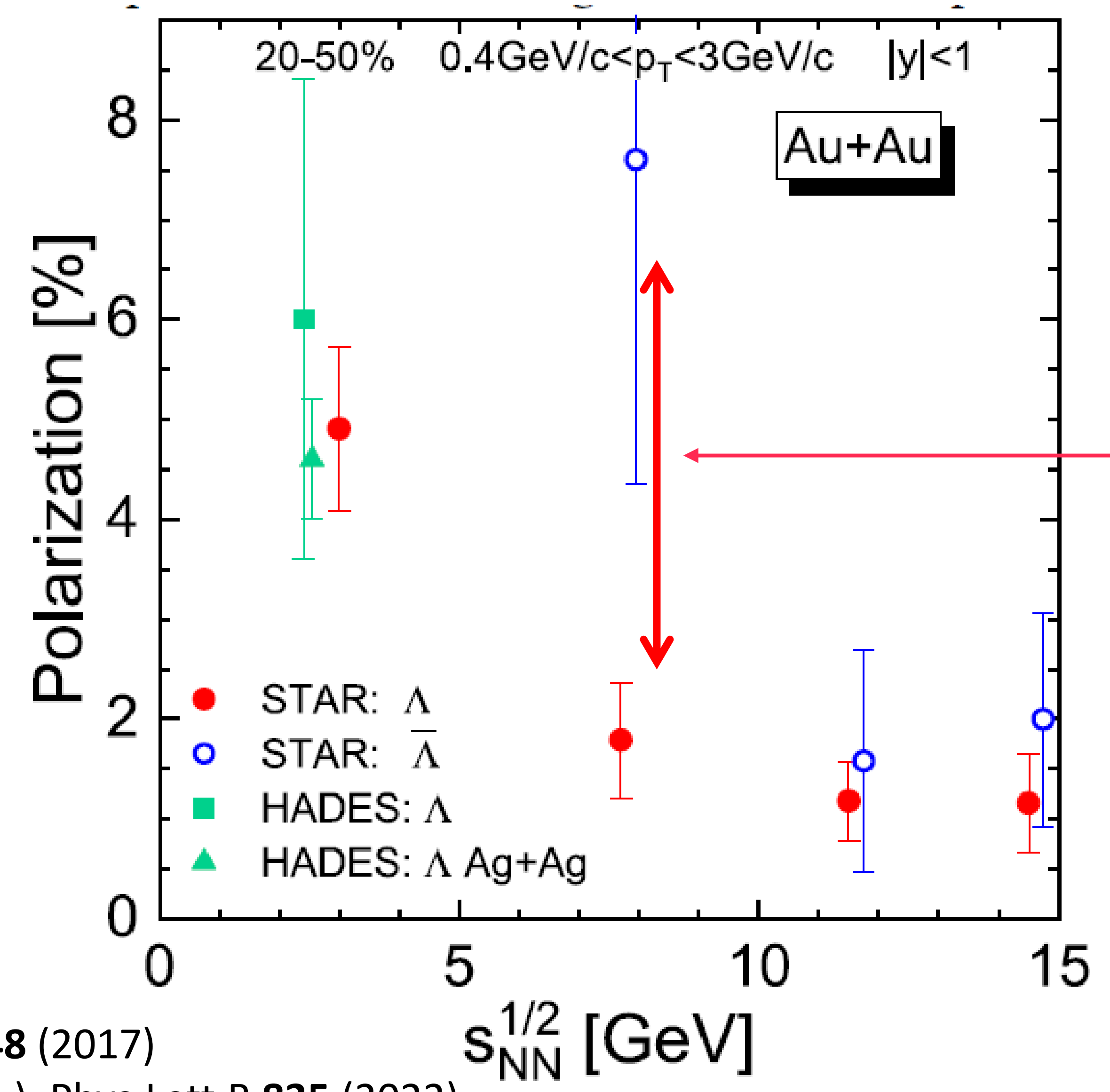


- Λ polarization is negative with respect to the creation plane
- at fixed x_F, Λ polarization decreases linearly with p_T
- at fixed p_T, Λ polarization decreases linearly with x_F
- Λ polarization does not depend on the beam energy, nor on target nature
- anti-Λs are not polarized! [Felix, Mod. Phys.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

collective processes

- Ar+KCl @ 1.8 GeV/u, BNL [Harris et al., PRL **47**, 229 (1981)] 70 Λ registered, (P_Λ=-0.10+-0.05)
- C-C,Ne,Cu,Zr,Pb @ 4.5 GeV/u, Dubna [Anikina et al., ZPC **25**, 1 (1984)] no polarization P_Λ~0

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

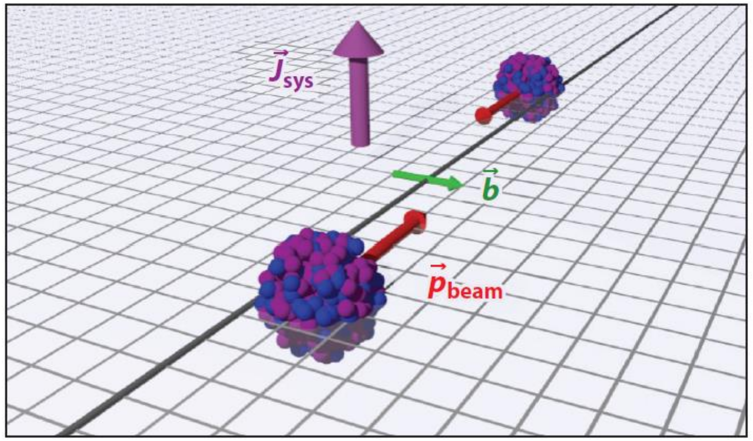


Λ – anti-Λ splitting in global polarization

L. Adamczyk et al., Nature **548** (2017)

R.A.Yassine et al. (HADES Coll.), Phys.Lett.B **835** (2022)

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

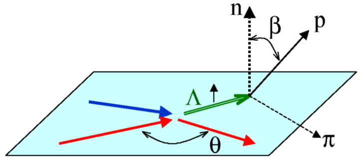
In equilibrium! density matrix

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

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

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

How fast the equilibrium can be approached?



Polarization generation rate $\propto \left\langle \left(\frac{d\sigma(\boldsymbol{\zeta})}{d\Omega_{\boldsymbol{p}_H}} = \frac{1}{2}\frac{d\sigma}{d\Omega_{\boldsymbol{p}_H}} - \frac{1}{64\,\pi^2\, s}\frac{\bar{p}}{p}\Im(\mathcal{T}_+\,\mathcal{T}_-^*)\,[\boldsymbol{p}\times\bar{\boldsymbol{p}}_H]\cdot\boldsymbol{\zeta}\right) f_N(\boldsymbol{p}, \boldsymbol{v}(\boldsymbol{r}))\, f_{\overline{K}}(\boldsymbol{q}, \boldsymbol{v}(\boldsymbol{r})) \right\rangle_{\boldsymbol{p},\boldsymbol{q},\boldsymbol{r}}$

if $\quad \boldsymbol{v} = [\boldsymbol{r}\times\boldsymbol{\omega}] + \dots$ $\qquad f_N(p, \boldsymbol{v}(\boldsymbol{r})) \propto e^{-\frac{1}{T}(E_p - [\boldsymbol{r}\times\boldsymbol{\omega}]\boldsymbol{p} + \dots)}$

momentum distributions of initial particles

The thermodynamic approach

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

Relativistic thermal vorticity:

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu), \quad \beta_\nu = \frac{u_\nu}{T} \qquad \omega^{\mu\nu} = -\epsilon^{\mu\nu\rho\sigma} u_\rho \bar{\omega}_\sigma \qquad \bar{\omega}^\mu = \gamma^2\big((\boldsymbol{v\omega}), \boldsymbol{\omega} + [\boldsymbol{v} \times \partial_t \boldsymbol{v}]\big) \approx \big((\boldsymbol{v\omega}), \boldsymbol{\omega}\big)$$

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

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

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

Spin vector:

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

s – spin, *p*– 4 momentum of particle

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

$\boldsymbol{\lambda}_\omega = [\boldsymbol{\omega} \times \boldsymbol{v}]$ 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.

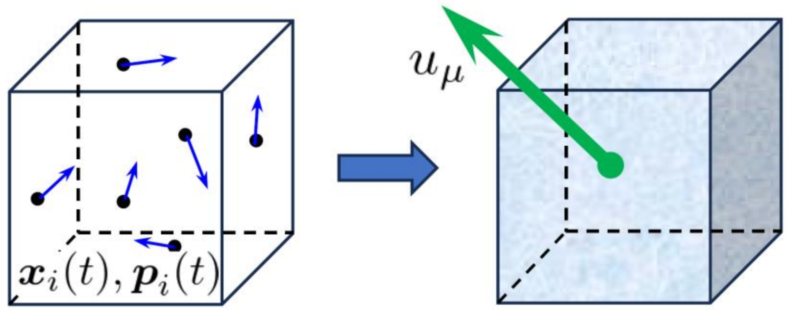
In the rest frame of the particle, which is used for experimental identification of the fermion polarization $S^{*\mu} = (0, \boldsymbol{S}^*)$

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

What velocity, vorticity, and helicity field can be created in HICs?

● **Setup** The **P**arton-**H**adron-**S**tring **D**ynamic model: *the generalized off-shell transport equations*, ***D**ynamical **Q**uasi-**P**article **M**odel* (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/fm³.
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

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

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

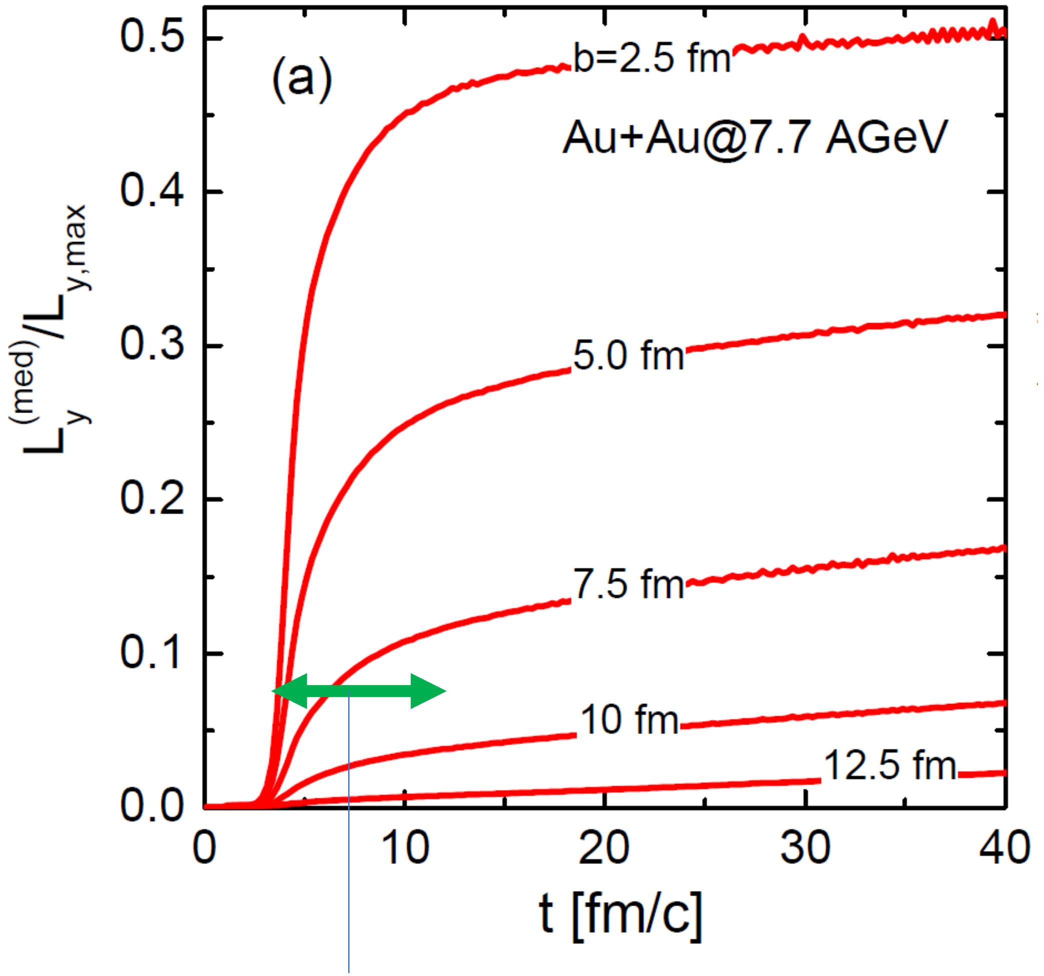
$$\varepsilon, n_B \longrightarrow \textbf{EoS} \longrightarrow T(\varepsilon, n_B)$$

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

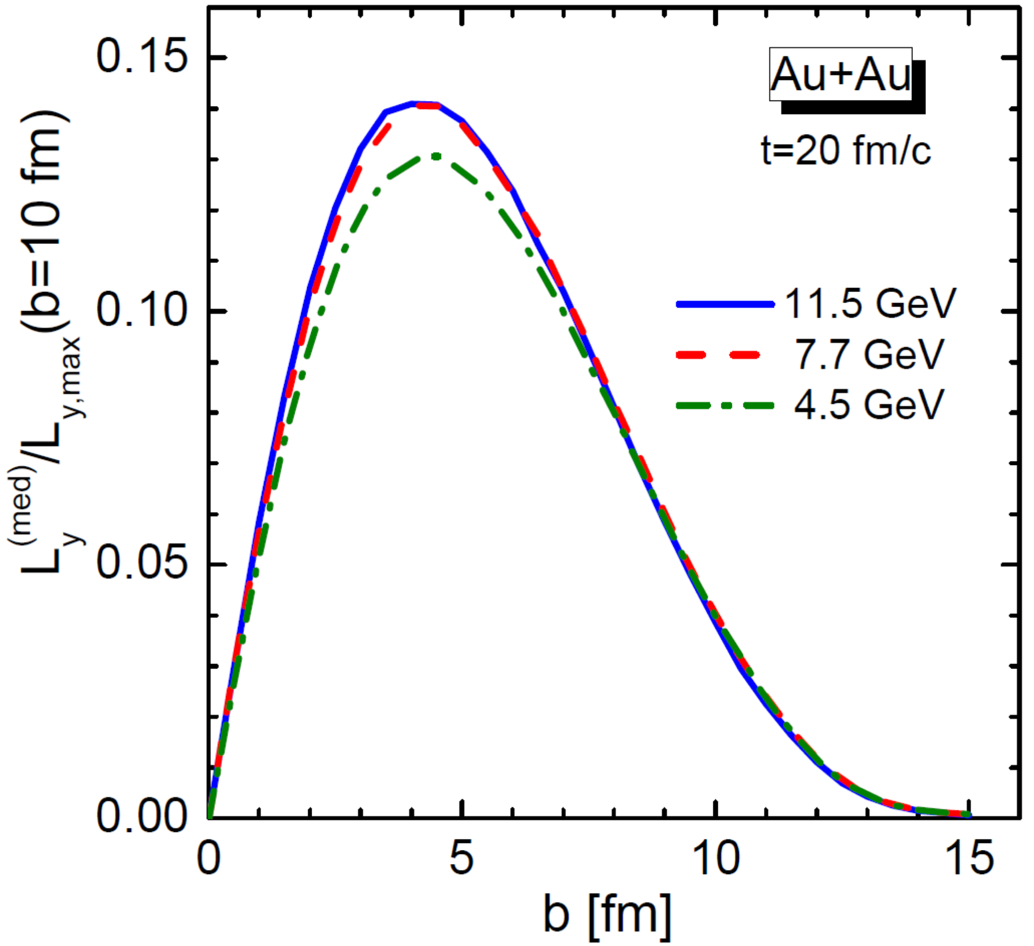
Angular momentum transfer

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

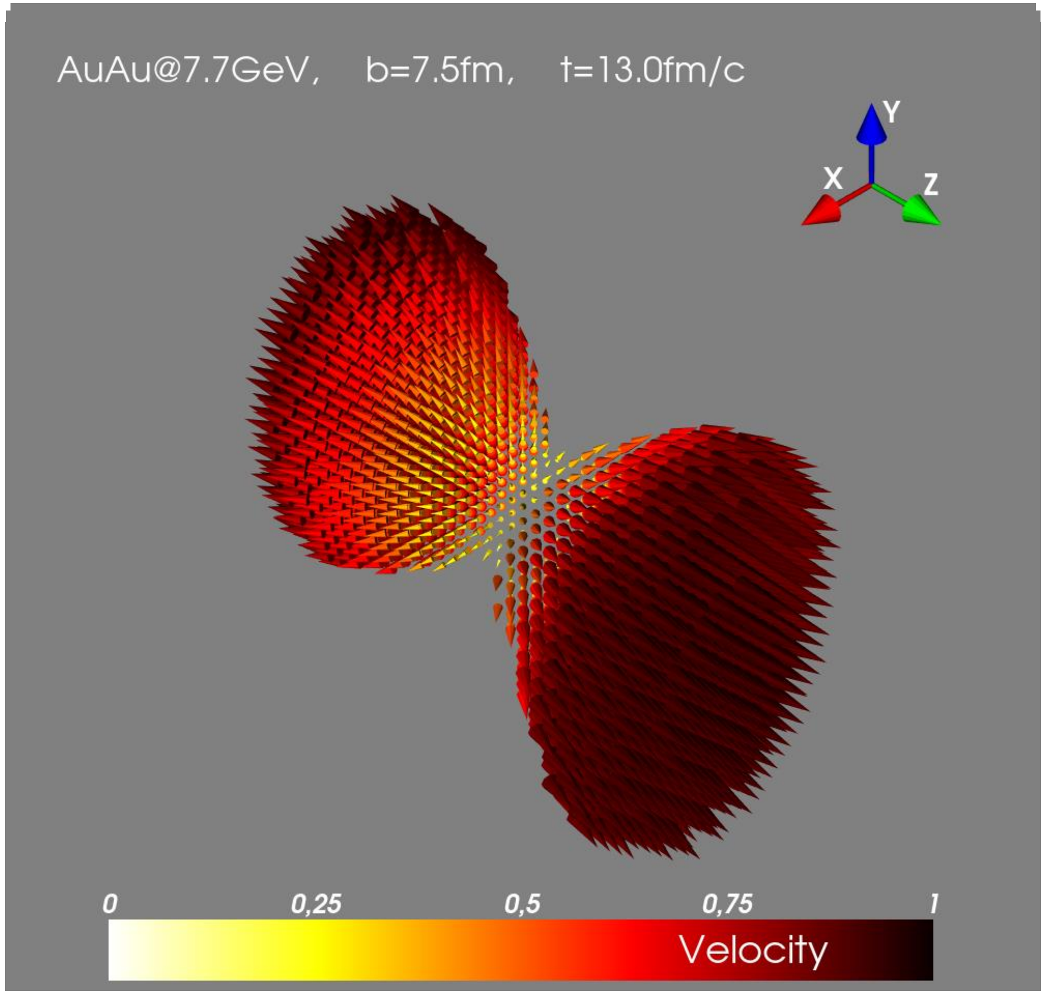


transition time scale ~10fm/c



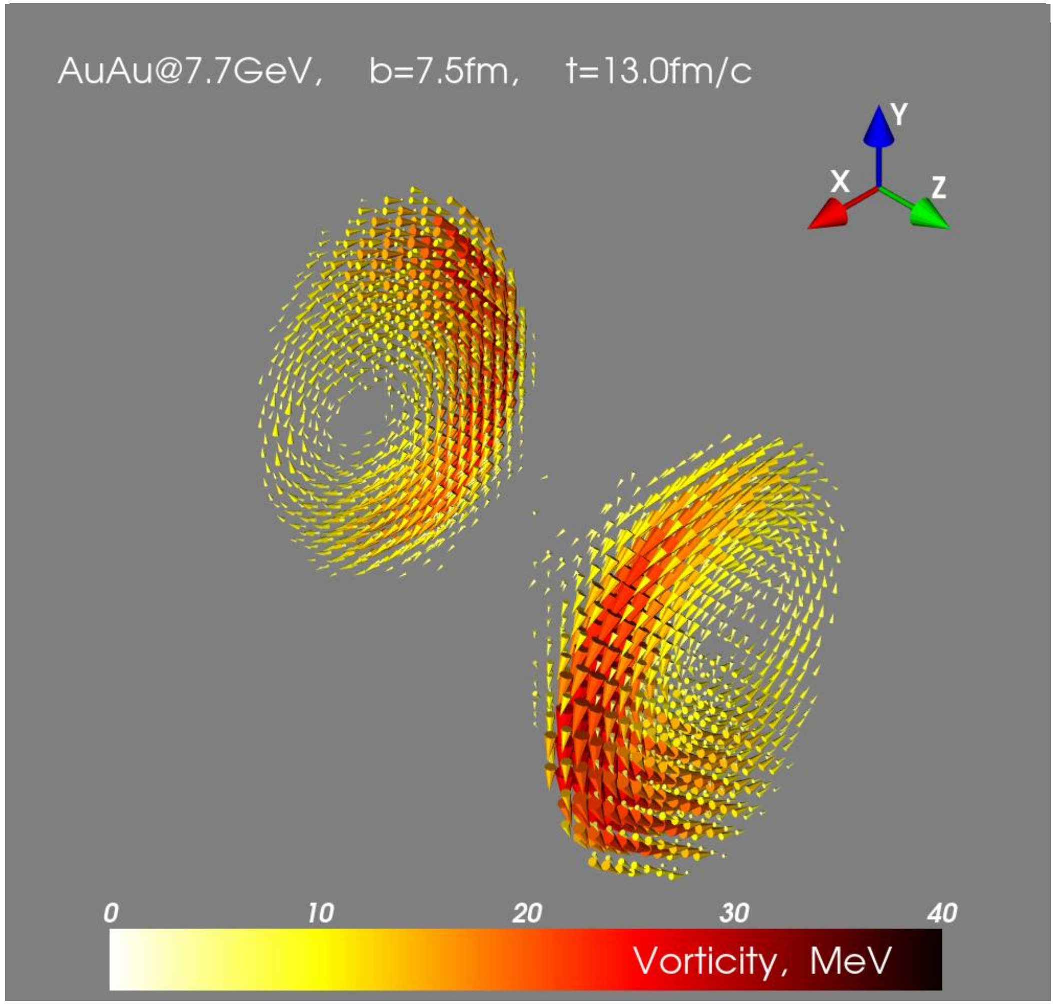
similar dependence was derived in [Becattini, Piccinini, Rizzo, PRC77 (2008)]

Velocity and vorticity fields



Hydrodynamic velocity field

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



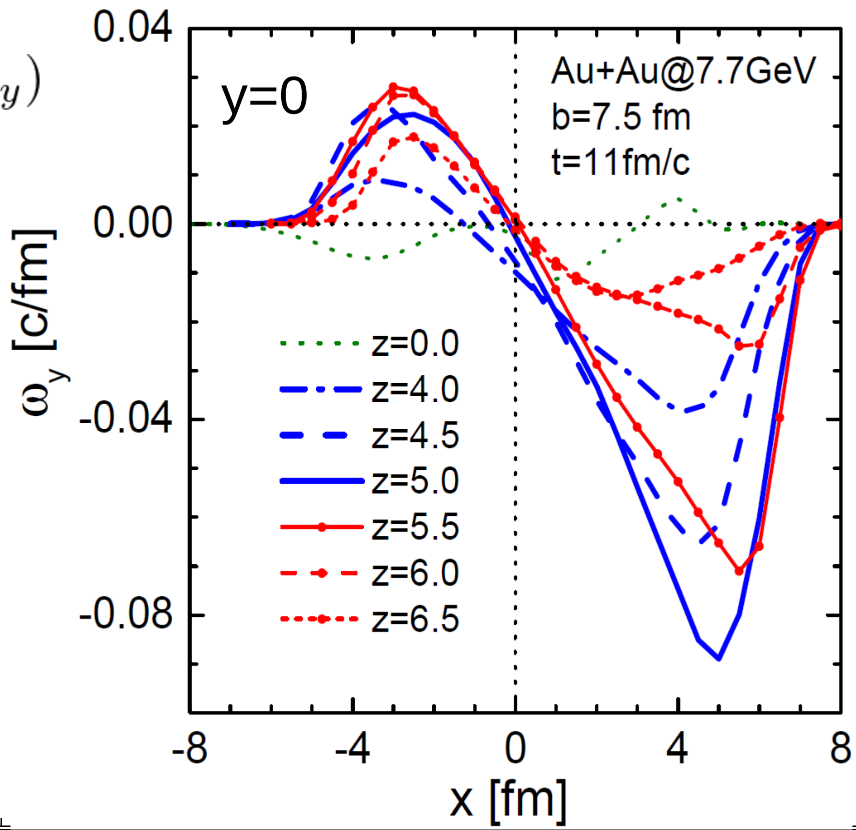
Hydrodynamic vorticity field

Vorticity field (ω_x, ω_y)

Au+Au @ 7.7 GeV

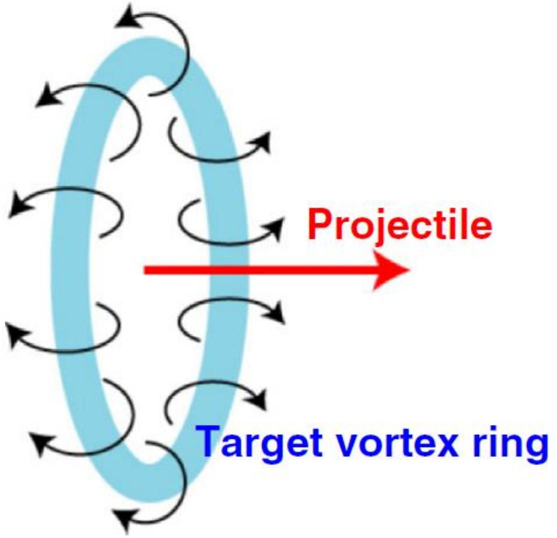
b=7.5 fm

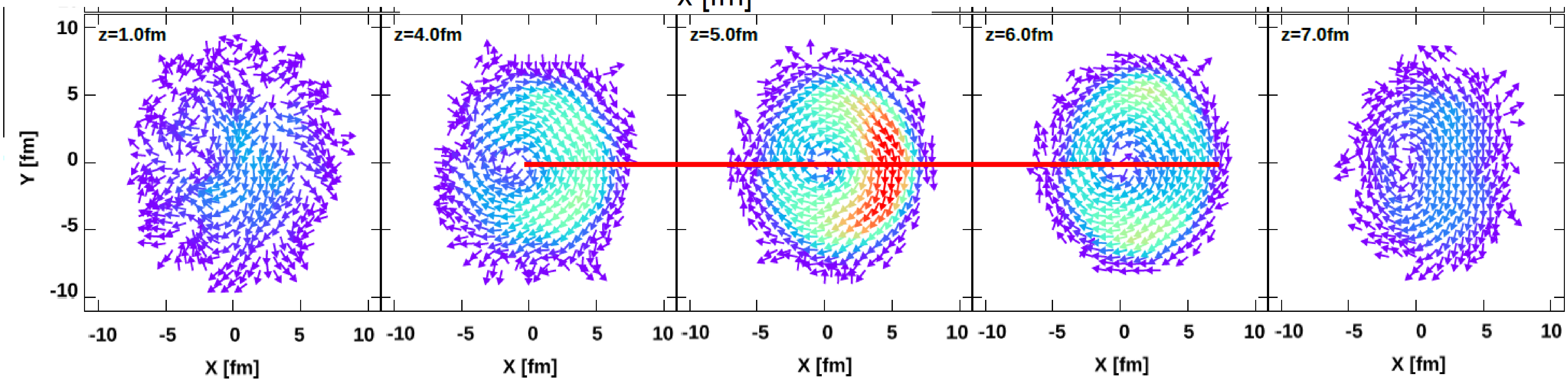
t=11 fm/c



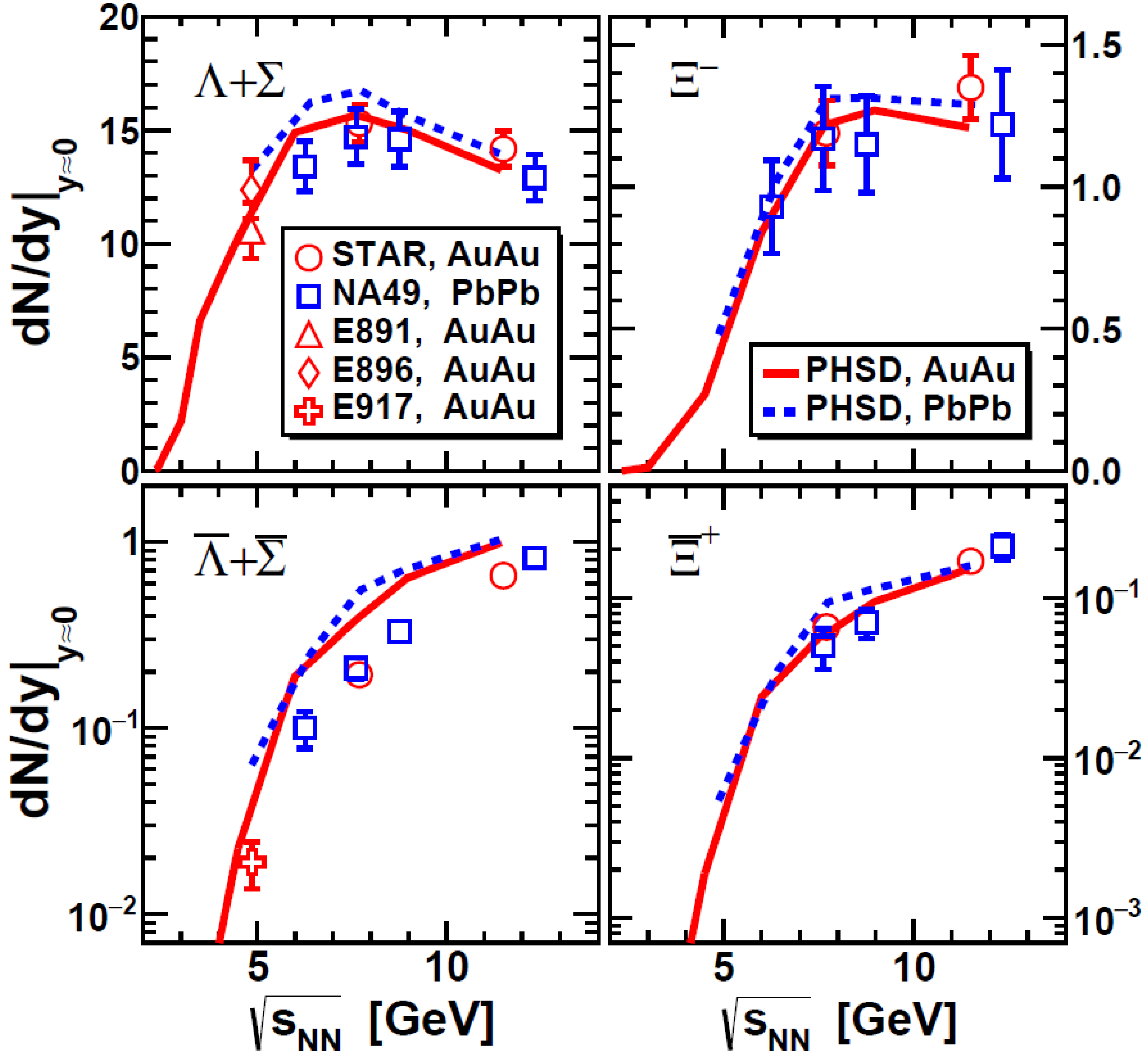
Yu.B. Ivanov, A.A. Soldatov predicted in [PRC97 (2018)] within the 3-fluid hydro model the formation of vortex rings

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

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

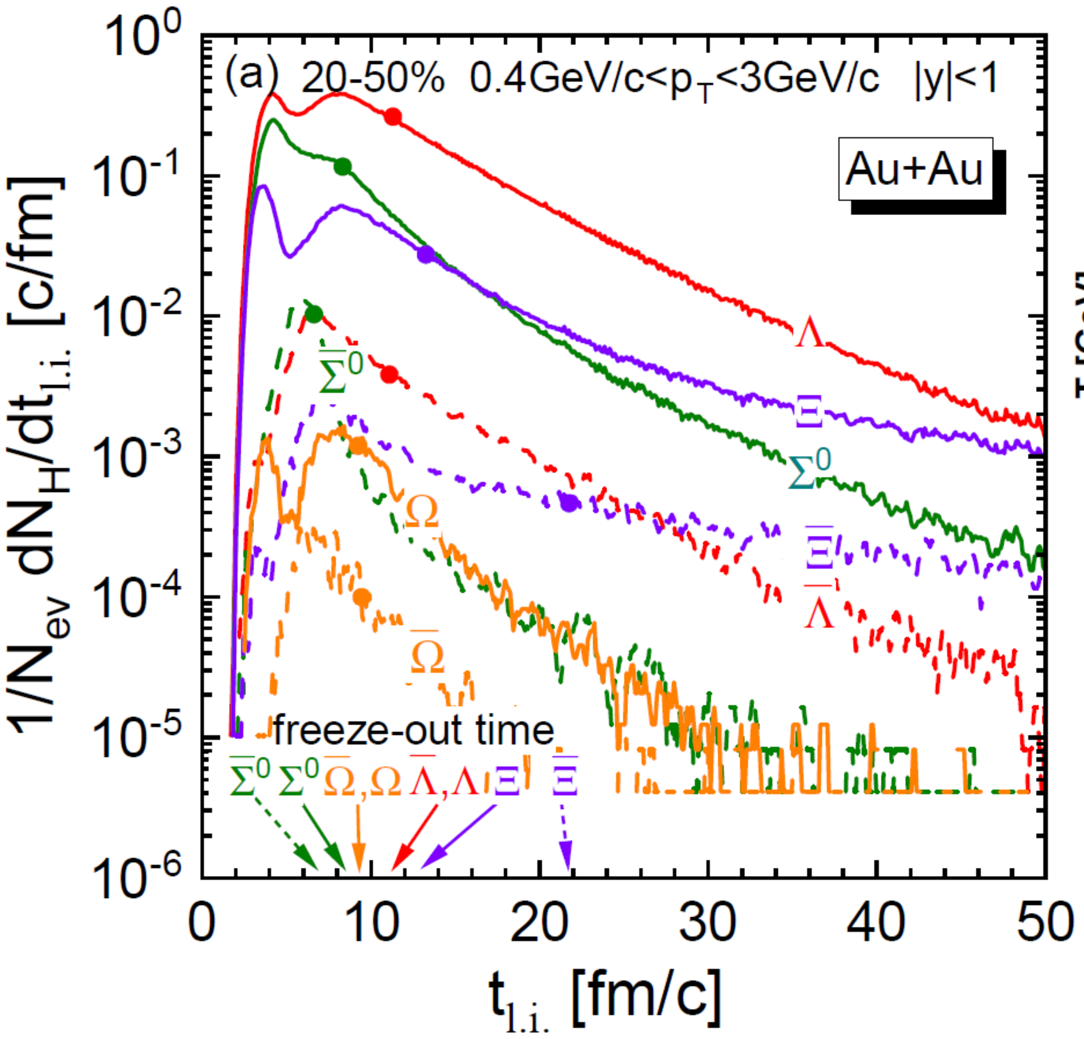
$$M^{(\mathrm{exp})}_{\Omega+\overline{\Omega}} = 0.14 \pm 0.05$$

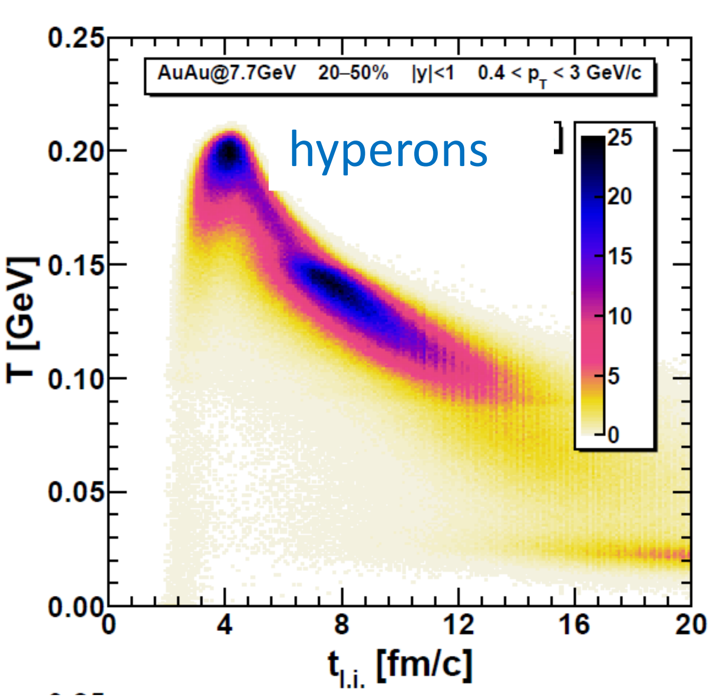
Theory:

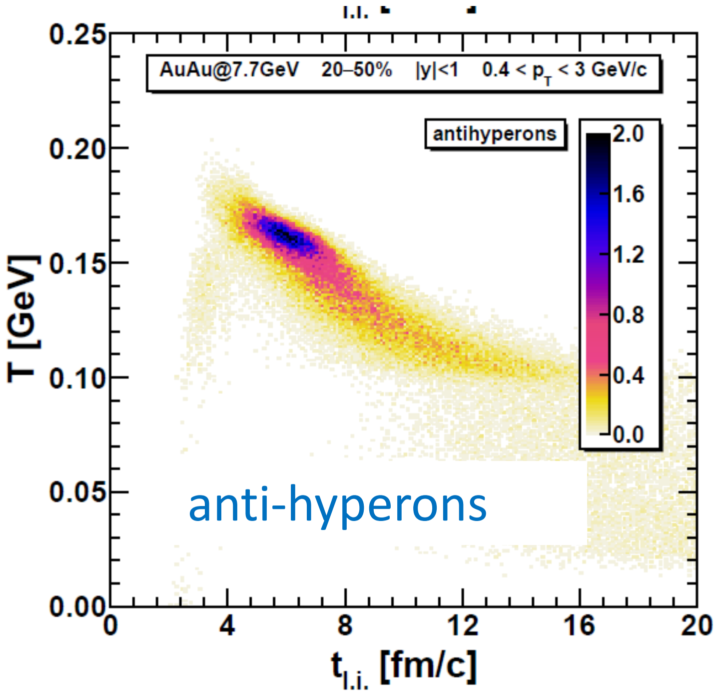
$$M_{\Omega} = 0.123\,, \quad M_{\overline{\Omega}} = 0.018$$

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, $t_{\mathrm{l.i.}}$ (TLI).



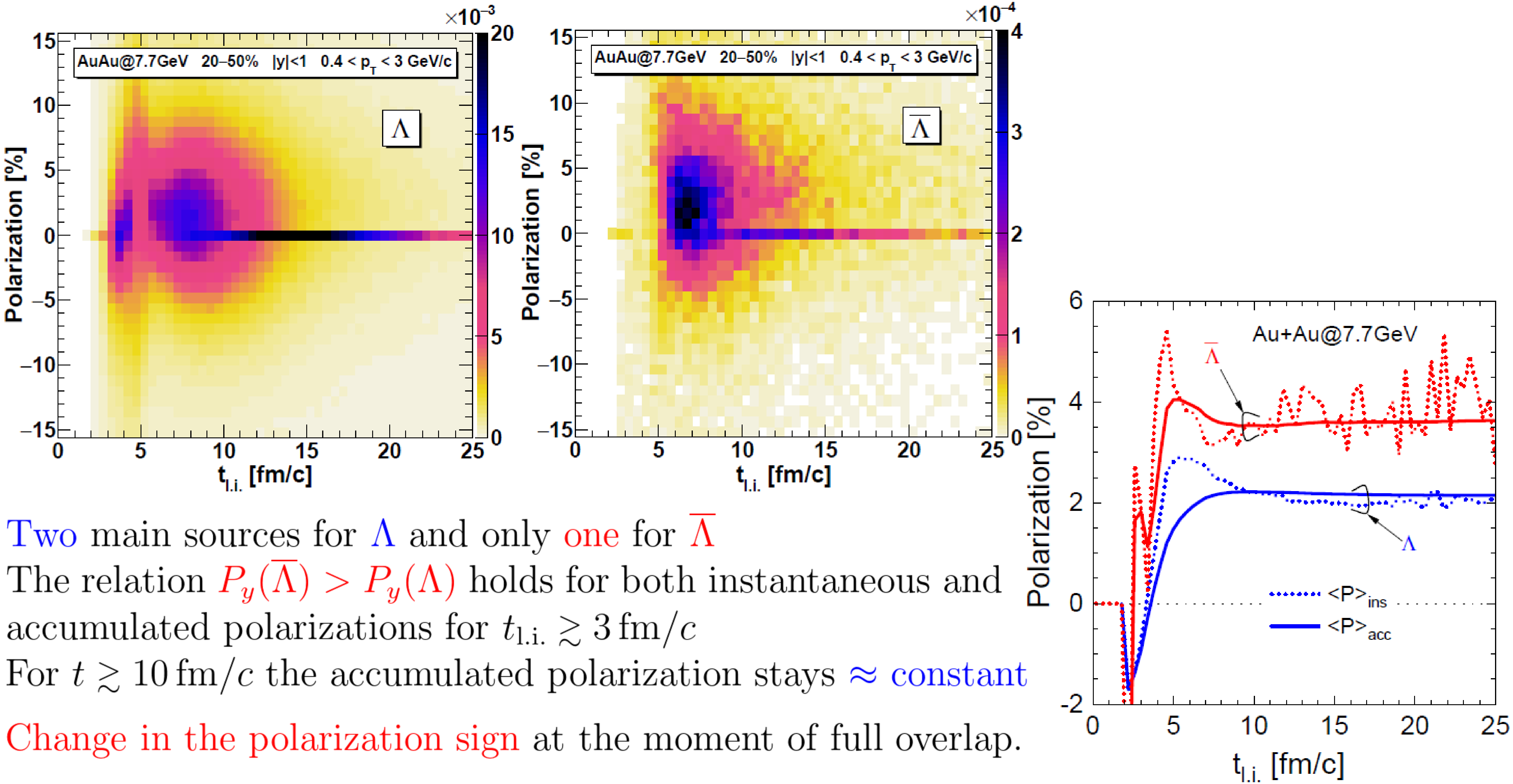




Two main sources for hyperons and only one for antihyperons.

Different thermodynamic conditions for particles and antiparticles→ *different polarization!*

Polarization source



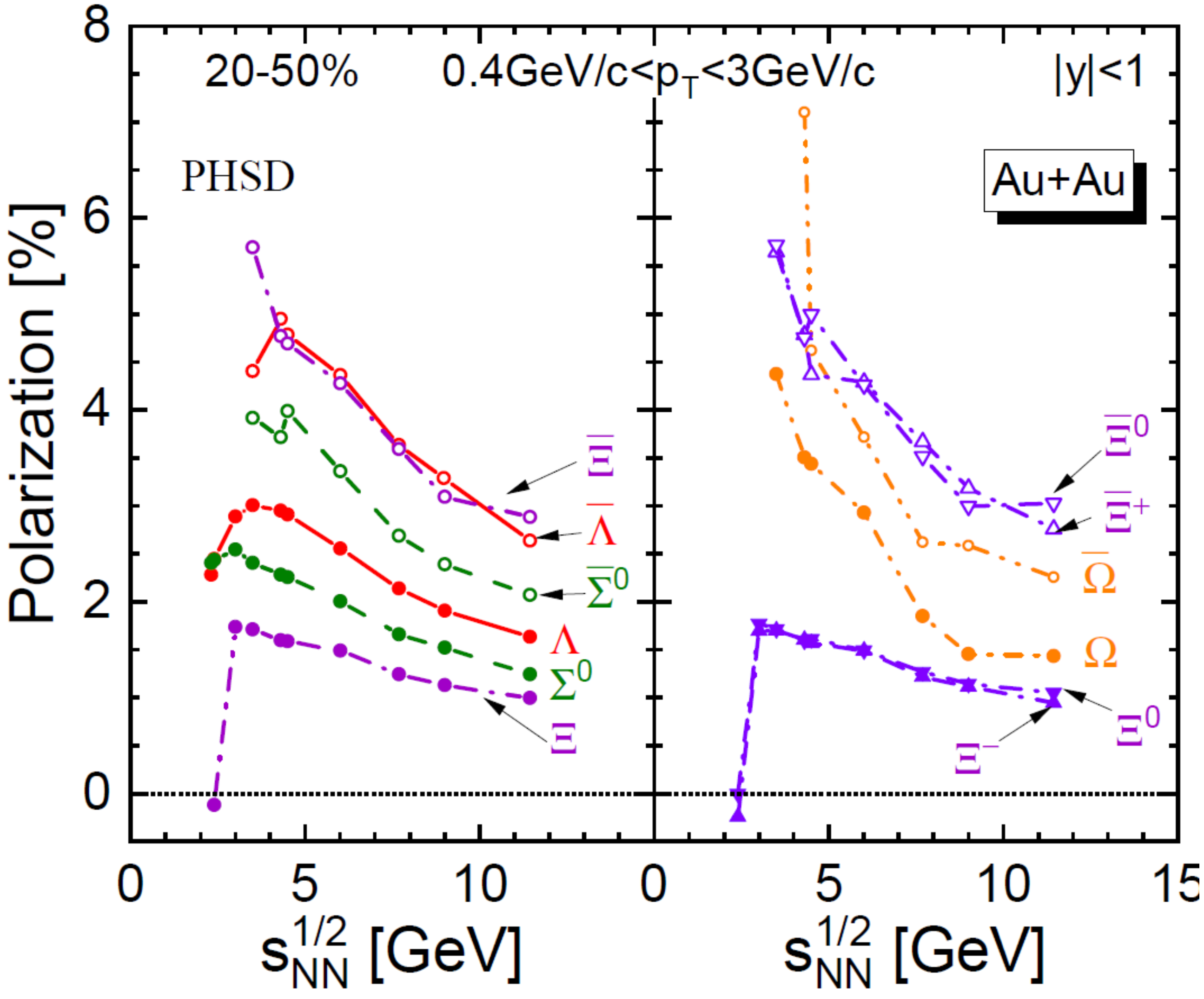
Two main sources for Λ and only one for $\overline{\Lambda}$

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

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

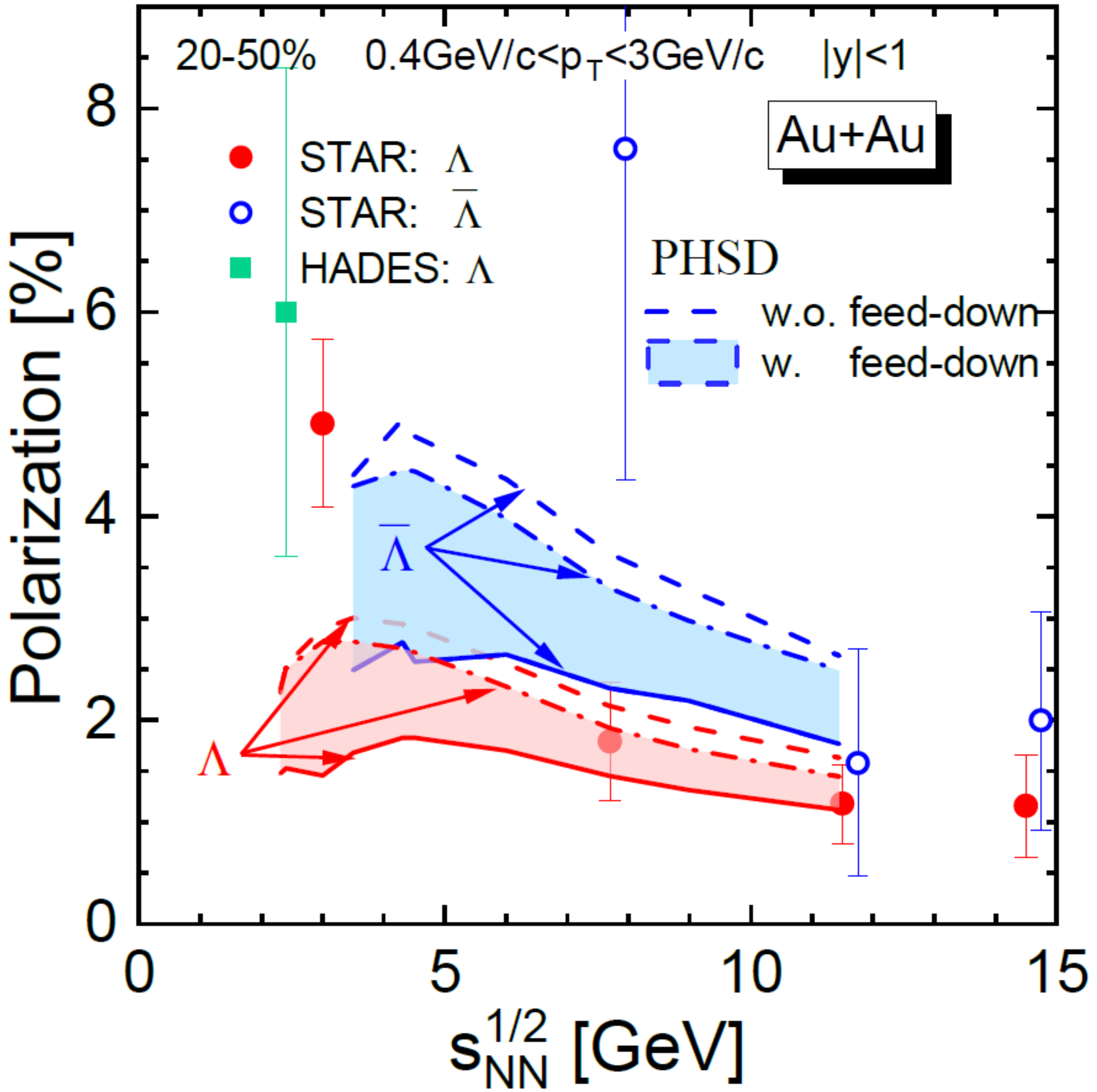
Polarization of all hyperon species decrease with an energy increase for $\sqrt{s_{NN}} \gtrsim 5\,\mathrm{GeV}$

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 $\Sigma^0(\overline{\Sigma}^0)$.