

Structure of vorticity field created in HIC. Global polarization.

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Heavy-ion collisions

- ▶ Hot and dense created matter undergoes explosive expansion — **the Little Bang**
- ▶ Large initial orbital angular momentum is partially transferred to the medium, what leads to the non-vanishing averaged *vorticity*:

$$\mathbf{L} \longrightarrow \langle \boldsymbol{\omega} \rangle = \langle \text{rot } \mathbf{v} \rangle$$

- ▶ The vorticity leads to the *global particle polarization*

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

F. Becattini, M.A. Lisa, Annu. Rev. Nucl. Part. Sci. **70** (2020)

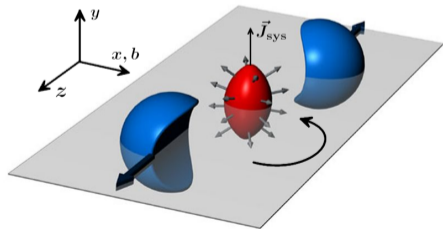
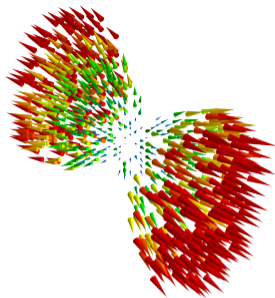
- ▶ The vorticity field may have *rich space-time structure*

- ▶ **Femto-vortex sheets:**

M.I. Baznat, K.K. Gudima, A.S. Sorin, and O.V. Teryaev,
Phys. Rev. C **93** (2016)

- ▶ **Vortex rings:**

Yu.B. Ivanov, A.A. Soldatov, Phys. Rev. C **97** (2018)



Global Λ and $\bar{\Lambda}$ polarization

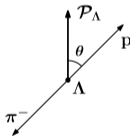
- ▶ The Λ and $\bar{\Lambda}$ are the *self-analyzing particles*: due to **P**-violation in weak decays, the angular distribution of final protons depends on the orientation of the Λ -hyperon spin

- ▶ In the hyperon *rest frame*, the decay product distribution is

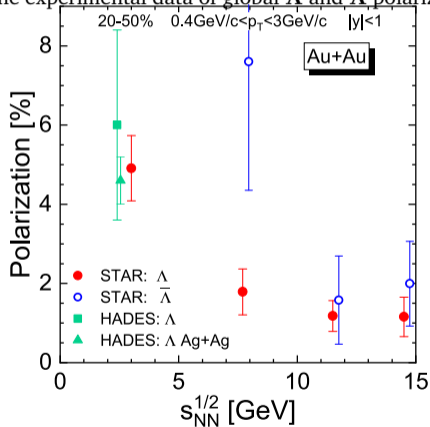
$$\frac{dN}{d \cos \theta} = \frac{1}{2} (1 + \alpha_H \cos \theta)$$

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$$

according to direction \mathcal{P}_H



- ▶ The experimental data of global Λ and $\bar{\Lambda}$ polarization



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

R.A.Yassine et al. (HADES Coll.) arXiv:2207.05160

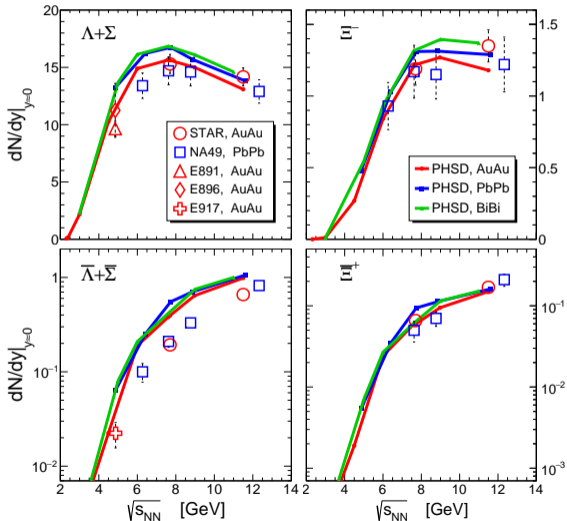
► The **PHSD** performance test

- The **PHSD transport model** as a heavy-ion collisions framework

W. Cassing, E.L. Bratkovskaya,
Phys. Rev. C **78** (2008)
Nucl. Phys. A **831** (2009)

- Good description of a large number of experimental observables

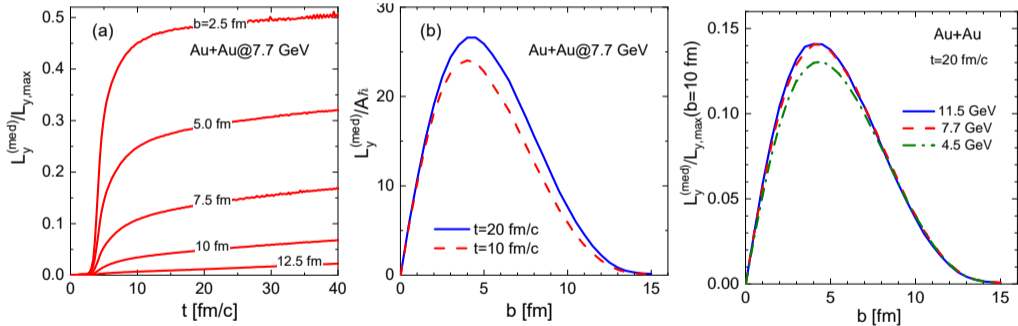
O. Linnyk, E.L. Bratkovskaya, W. Cassing,
Prog. Part. Nucl. Phys. **87** (2016)



Angular momentum transfer

Total angular momentum

$$\frac{\mathbf{L}}{A} = \mathbf{e}_y \frac{b}{2} \sqrt{s_{NN} - 4m_N^2} \quad (1)$$



The formation of polarization signal of hyperons has more complicated nature than a direct transformation of the initial angular momentum.

Polarization of particles with spin in vorticity field

► The thermodynamic approach

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

Relativistic thermal vorticity:

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

Spin vector:

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

s – spin, p_δ – 4 momentum of particle

We assume the Boltzmann limit $(1 \pm n(x, p)) \approx 1$

Polarization: $\mathbf{P} = \mathbf{S}^*/s$, where \mathbf{S}^* spin vector in rest frame

The fluidization procedure: Landau frame

- ▶ Transition from kinetic to hydrodynamic description via *fluidization* procedure:

$$T^{\mu\nu}(\mathbf{x}, t) = \frac{1}{\mathcal{N}} \sum_{a, i_a} \frac{p_{i_a}^\mu(t) p_{i_a}^\nu(t)}{p_{i_a}^0(t)} \Phi(\mathbf{x}, \mathbf{x}_{i_a}(t)), \quad \mathcal{N} = \int \Phi(\mathbf{x}, \mathbf{x}_i(t)) d^3x,$$

$$J_B^\mu(\mathbf{x}, t) = \frac{1}{\mathcal{N}} \sum_{a, i_a} B_{i_a} \frac{p_{i_a}^\mu(t)}{p_{i_a}^0(t)} \Phi(\mathbf{x}, \mathbf{x}_{i_a}(t)), \quad \Phi(\mathbf{x}, \mathbf{x}_i(t)) - \text{smearing function},$$

$$u_\mu T^{\mu\nu} = \varepsilon u^\nu, \quad n_B = u_\mu J_B^\mu, \quad \longrightarrow \quad \text{EoS} \quad \longrightarrow \quad \text{Temperature}(\varepsilon, n_B)$$

- ▶ Equation of State: **Hadron resonance gas**

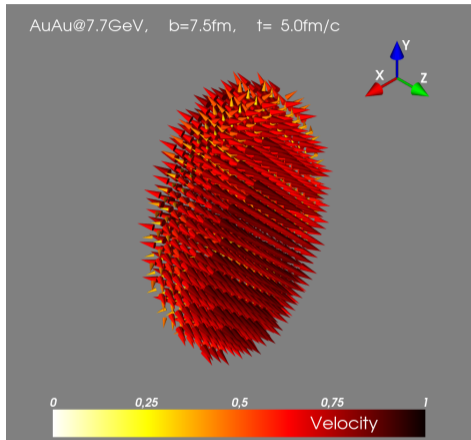
L.M. Satarov, M.N. Dmitriev, and I.N. Mishustin, Phys. Atom. Nucl. 72 (2009)

- ▶ *The fluidization criterion: **fluidize only cells with $\varepsilon > 0.05 \text{ GeV}/\text{fm}^3$!***
- ▶ *Spectators separation: spectators moves with approximately beam rapidity $|y - y_b| \leq 0.27$
Spectator nucleons do not form fluid!*
- ▶ *Propagation of hadrons in mean field is switched off.*

Velocity and vorticity fields

$$\omega_{\text{STAR}} \approx 10^{22} \text{ s}^{-1} \approx 6.6 \text{ MeV}/\hbar$$

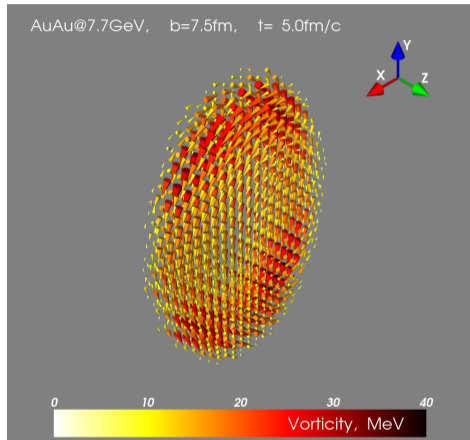
arXiv: 2211.09219



Hydrodynamic velocity field

$$\varepsilon > 0.05 \text{ GeV}/\text{fm}^3$$

$$\mathbf{v} \approx \mathbf{v}_{\text{Hubble}} = (\alpha_T x, \alpha_T y, \alpha_z z)$$



Hydrodynamic vorticity field

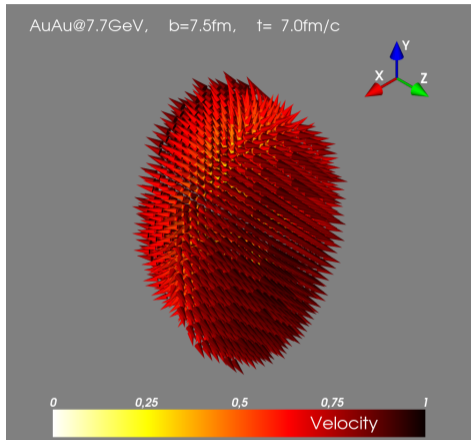
$$\boldsymbol{\omega} = \text{rot } \mathbf{v}$$

for clarity draw only $|\boldsymbol{\omega}| > 5 \text{ MeV}/\hbar$

Velocity and vorticity fields

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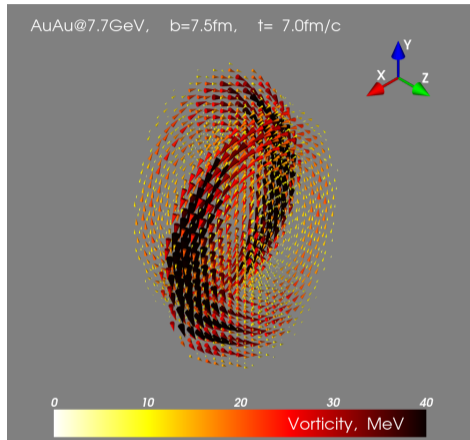
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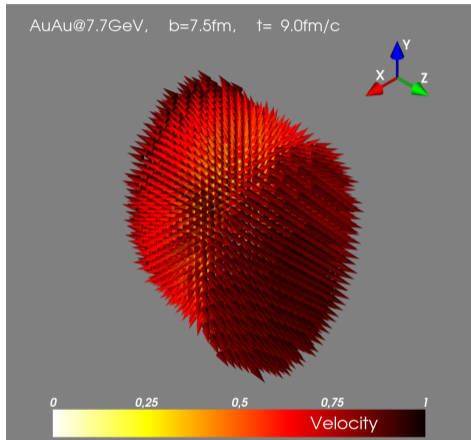
$$\boldsymbol{\omega} = \text{rot } \mathbf{v}$$

$$|\boldsymbol{\omega}|_{\text{max}} \approx 67.1 \text{ MeV}/\hbar!$$

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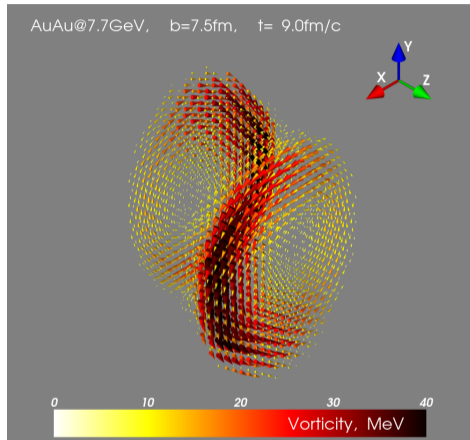
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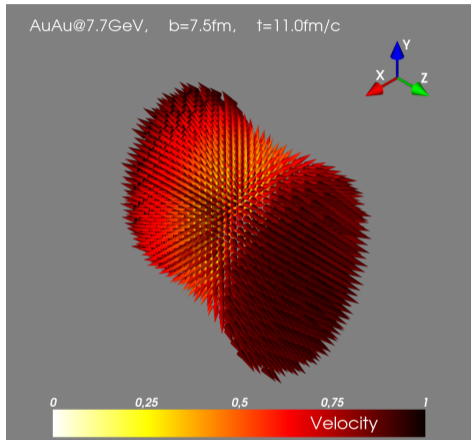
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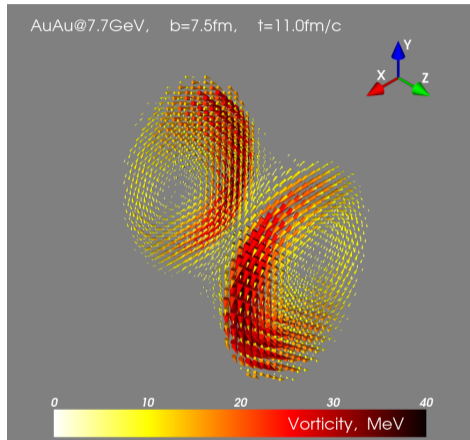
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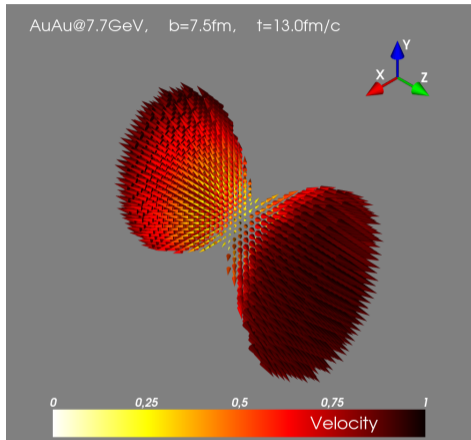
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for clarity draw only $|\boldsymbol{\omega}| > 5 \text{ MeV}/\hbar$

Velocity and vorticity fields

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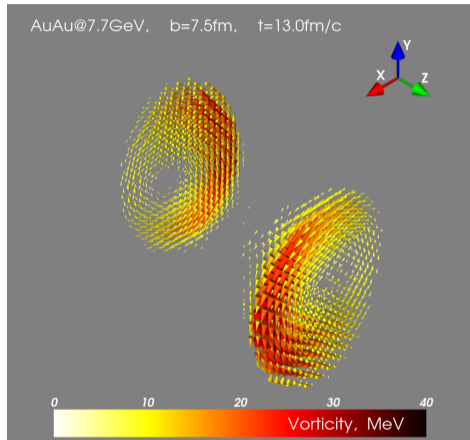
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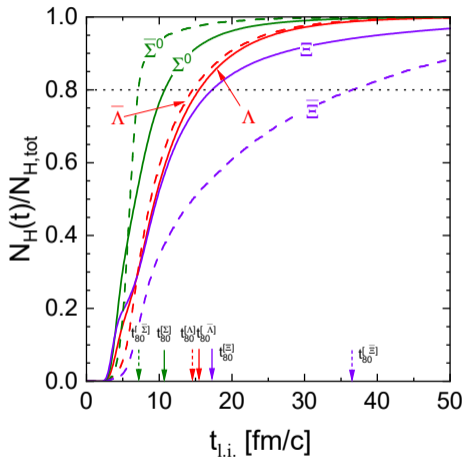
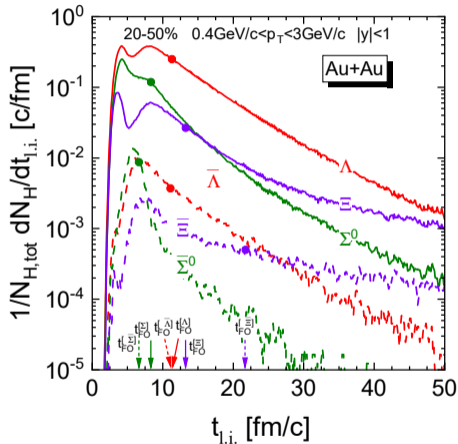
Hydrodynamic vorticity field

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Rates of final hyperon production

► Trace to time of the last interaction, AuAu@7.7GeV



Strong decays are already naturally included.

Different freeze-out can lead to different polarization.

Polarization of particles with spin in vorticity field

► The thermodynamic approach

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

Relativistic thermal vorticity:

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Spin vector:

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s – spin, p_δ – 4 momentum of particle

Polarization: $\mathbf{P} = \mathbf{S}^*/s$

\mathbf{S}^* spin vector in rest frame

► Our statements

☞ *Hydro velocity.* ☞ *No spectators.*

► Interaction/production point

☞ *No "Medium":* $\varepsilon < 0.05 \text{ GeV}/\text{fm}^3$
 \Rightarrow *No thermal vorticity* $\varpi_{\mu\nu} = 0$

Elastic or inelastic process:

"Medium": particle is polarized.

No "Medium": zero polarization.

Strong decays:

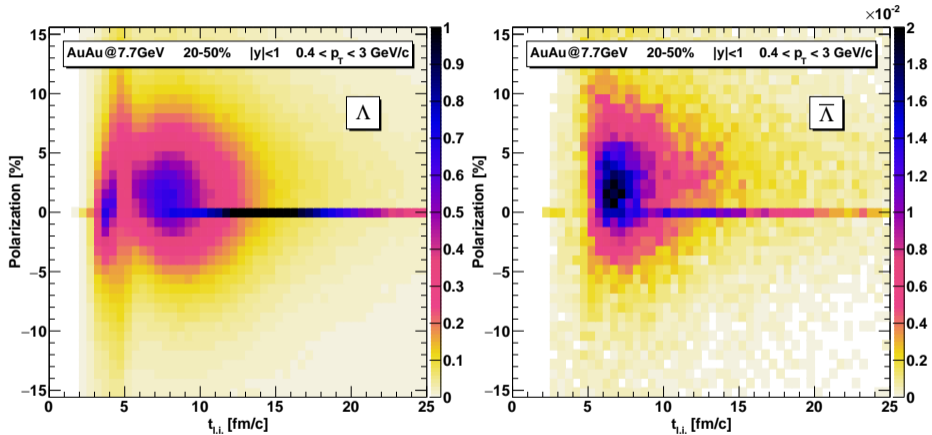
$\Sigma^* \rightarrow \Lambda + \pi, \quad \Xi^* \rightarrow \Xi + \pi$

spin transfer $C_{\Lambda\Sigma^*} = C_{\Xi\Xi^*} = 1/3$

$$S_{\text{Doughter}} = C_{DP} S_{\text{Parent}}$$

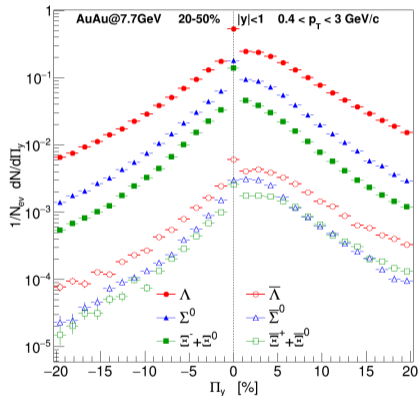
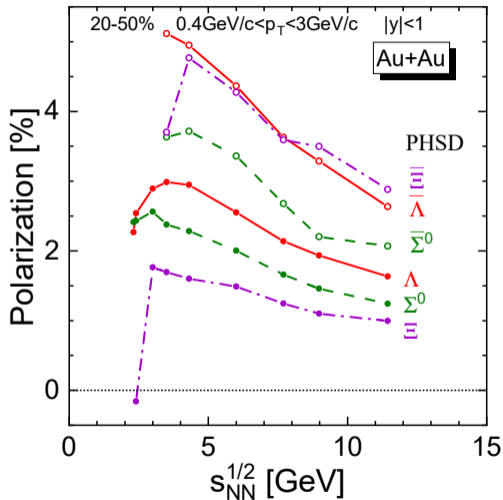
► Particles gone into infinity carry info about last interaction point.

Polarization at the last interaction point



“Line” corresponds to the interactions out of “Medium”.

Polarization of different species of hyperons



The Λ and $\bar{\Lambda}$ polarization

► The feed-down effects

strong: *is already included*

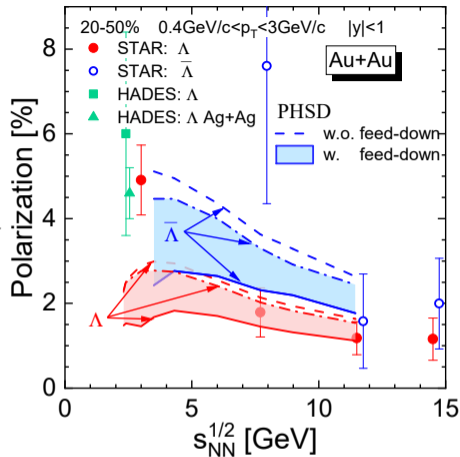
weak: $\Xi \rightarrow \Lambda + \pi$ $c\tau = 4.91 - 8.71$ cm

EM: $\Sigma^0 \rightarrow \Lambda + \gamma$ $c\tau = 2.2 \times 10^4$ fm

Spin transfer coefficients:

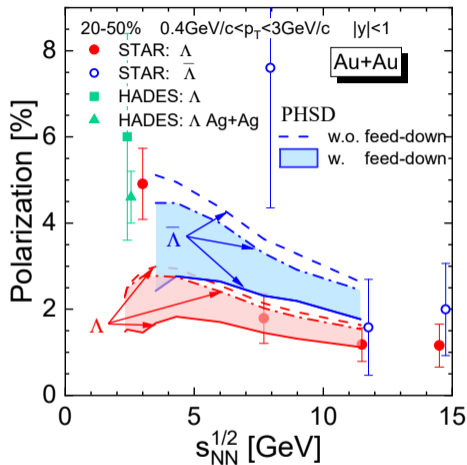
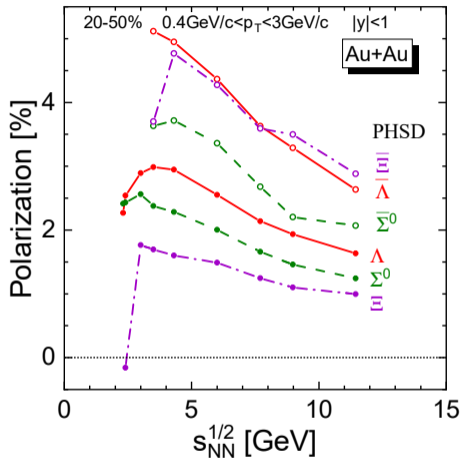
$C_{\Lambda \Xi^-} = 0.927$, $C_{\Lambda \Xi^0} = 0.900$,

$C_{\Lambda \Sigma^0} = -1/3$



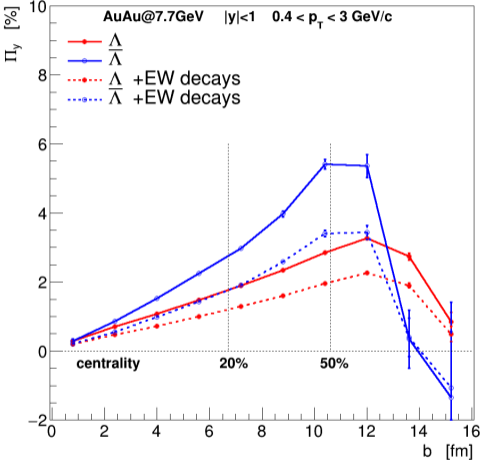
- The polarization of Λ hyperons *agrees* with experimental data, *except low energies* $\sqrt{s_{NN}} \leq 3$ GeV. The *maximum* of the Λ polarization at $\sqrt{s_{NN}} \approx 4$ GeV
- The polarization of $\bar{\Lambda}$ *larger in 1.5 – 2 times* than Λ .
At $\sqrt{s_{NN}} \geq 11.5$ GeV *agrees* with experimental data, but at $\sqrt{s_{NN}} \leq 7.7$ GeV *less*

The Ξ polarization (Λ from Ξ)?!



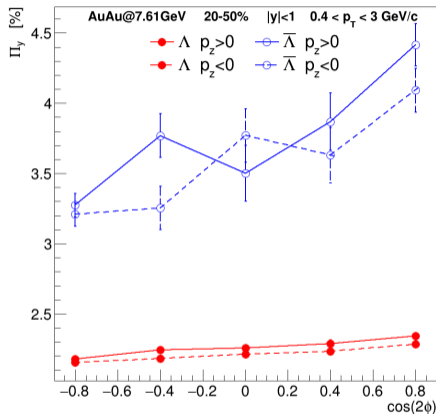
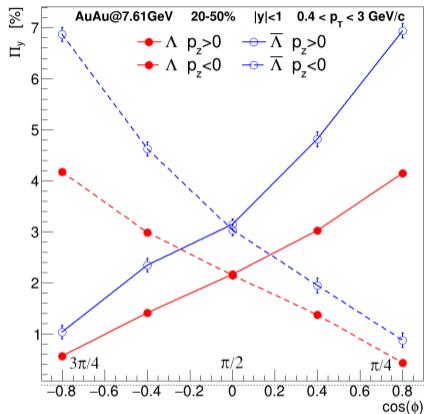
weak decay: $\Xi \rightarrow \Lambda + \pi$ $c\tau = 4.91 - 8.71$ cm
no contamination from Σ^0

Polarization vs Centrality



► Maximum at 50%

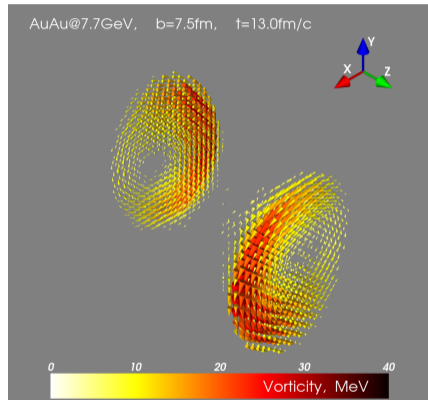
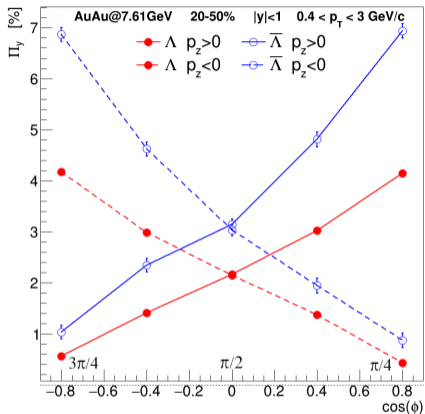
Polarization vs Forward-Backward flow



Reaction plane is $y = 0$.

- Correlation between polarization and directed flow – structure of vortex rings?

Polarization vs Forward-Backward flow



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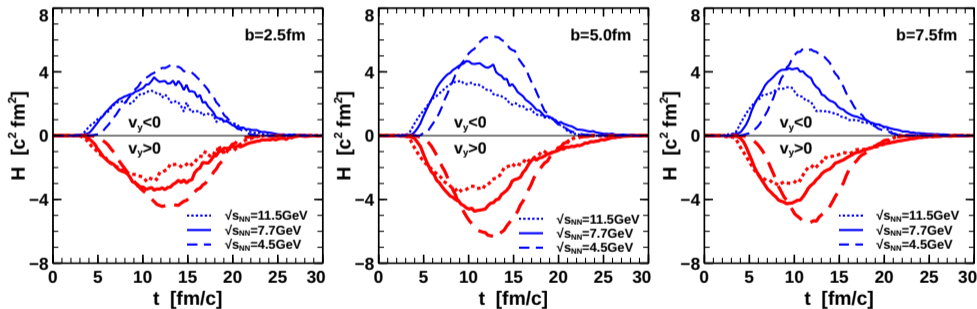
- Correlation between polarization and directed flow – structure of vortex rings?

Conclusions

- ▶ Angular momentum transfer (maximum at [5-10%]) is not enough to describe polarization.
- ▶ The polarization of the Λ hyperons *agrees* with experimental data, *except low energies* $\sqrt{s_{NN}} \leq 3$ GeV. The *maximum* of the Λ polarization at $\sqrt{s_{NN}} \approx 4$ GeV. The polarization of $\bar{\Lambda}$ *larger in 1.5 – 2 times* than Λ . It *agrees* with experimental data at $\sqrt{s_{NN}} = 11.5$ GeV, but is *less* at $\sqrt{s_{NN}} = 7.7$ GeV.
- ▶ Strong polarization suppression is caused by the *feed-down from Σ^0 and $\bar{\Sigma}^0$* hyperons.
- ▶ Uncertainty in ratio of Σ^0 to Λ production leads to big uncertainty in measured global polarization of Λ hyperons.
- ▶ The experimental study of global polarization of Ξ (maybe Ω) is suggested as the best probe for the Λ polarization.
- ▶ Centrality dependence is in agreement with experiment.
- ▶ Strong correlation between polarization and directed flow.

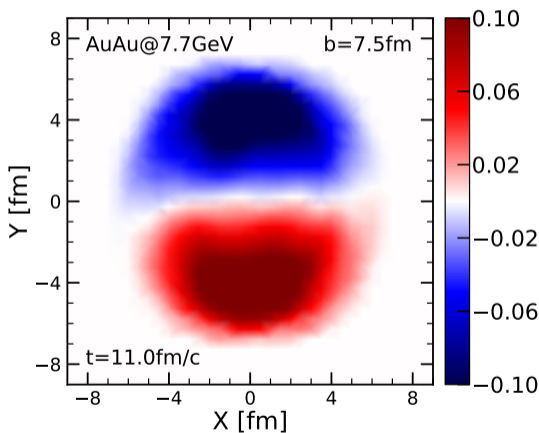
Helicity $h = (\boldsymbol{\omega} \cdot \mathbf{v})$

Axial vortical effect Phys. Rev. C 95, 011902 (2017): helicity is the source of polarization



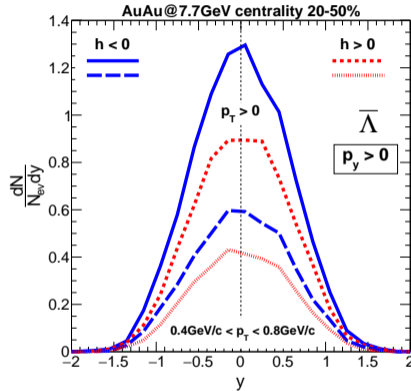
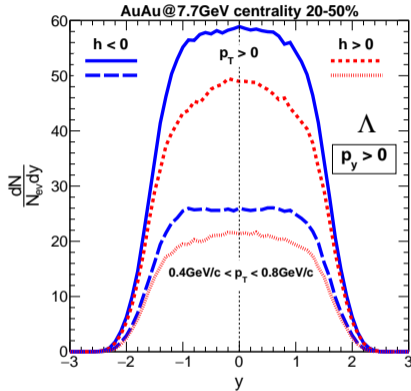
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Hydrodynamic helicity field integrated over z

Helicity $h = (\omega \cdot \mathbf{v})$ and Lambda



- Lambdas can be produced in different helicity regions.

