Vortex rings and global hyperon polarization at the NICA energies

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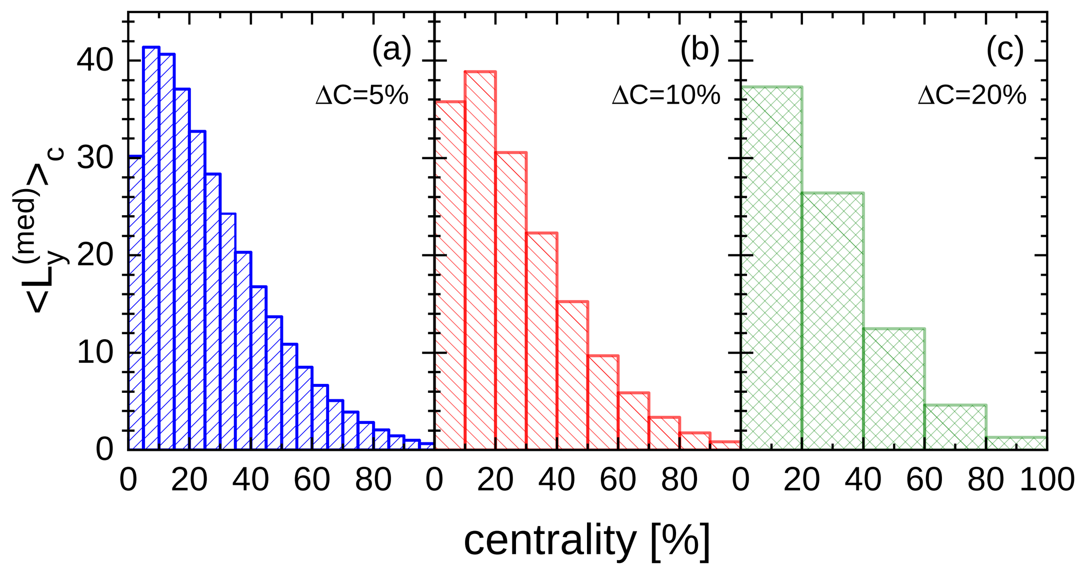
1. Introduction

- Hot and dense created matter undergoes explosive expansion.
- Angular momentum of ions $\longrightarrow$ medium $\longrightarrow$ **vorticity**

$$\boldsymbol{L}_{\rm ions} \longrightarrow \boldsymbol{L}_{\rm medium} \longrightarrow \boldsymbol{\omega} = {\rm rot}\,\boldsymbol{v} \neq 0$$



- Vorticity $\longrightarrow$ **spin polarization** [1] $\longleftrightarrow$ $\langle \boldsymbol{P}_\Lambda \rangle \approx {\rm rot}\left(\frac{\boldsymbol{v}}{4T}\right) \approx \frac{\boldsymbol{\omega}}{4T}$

$$S^\mu(x,p) = -\frac{s\,(s+1)}{12\,mT}\varepsilon^{\mu\nu\lambda\delta}\left[\partial_\lambda\left(\frac{u_\nu}{T}\right) - \partial_\nu\left(\frac{u_\lambda}{T}\right)\right]p_\delta$$

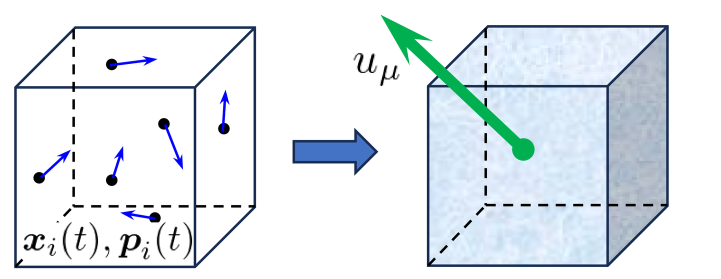
- The **P**-violation in weak decays $\longrightarrow$ the angular distribution of final protons depends on the orientation of the **Λ**-hyperons spin.
- Nonzero global polarization measured by **STAR** [2], **HADES** [3].

2. Setup

- The **P**arton-**H**adron-**S**tring **D**ynamic model [4]: *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 $\longrightarrow$ **fluidization** [5] $\longrightarrow$ hydrodynamics

$$u_\mu T^{\mu\nu} = \varepsilon\, u^\nu, \quad u^\mu = \gamma(1,\boldsymbol{v}), \quad T^{\mu\nu} = \sum_{a,i_a} \frac{p^\mu_{i_a}(t)\,p^\nu_{i_a(t)}}{p^0_{i_a}(t)}\Phi\left(\boldsymbol{x},\boldsymbol{x}_{i_a}(t)\right)$$

- **Fluidization criterion**: cells with $\varepsilon > 0.05\,{\rm GeV/fm^3}$. *Spectators do not form fluid!*
- **Spectator separation**: $||y_{\rm spectator}| - y_{\rm beam}| \le 0.27$

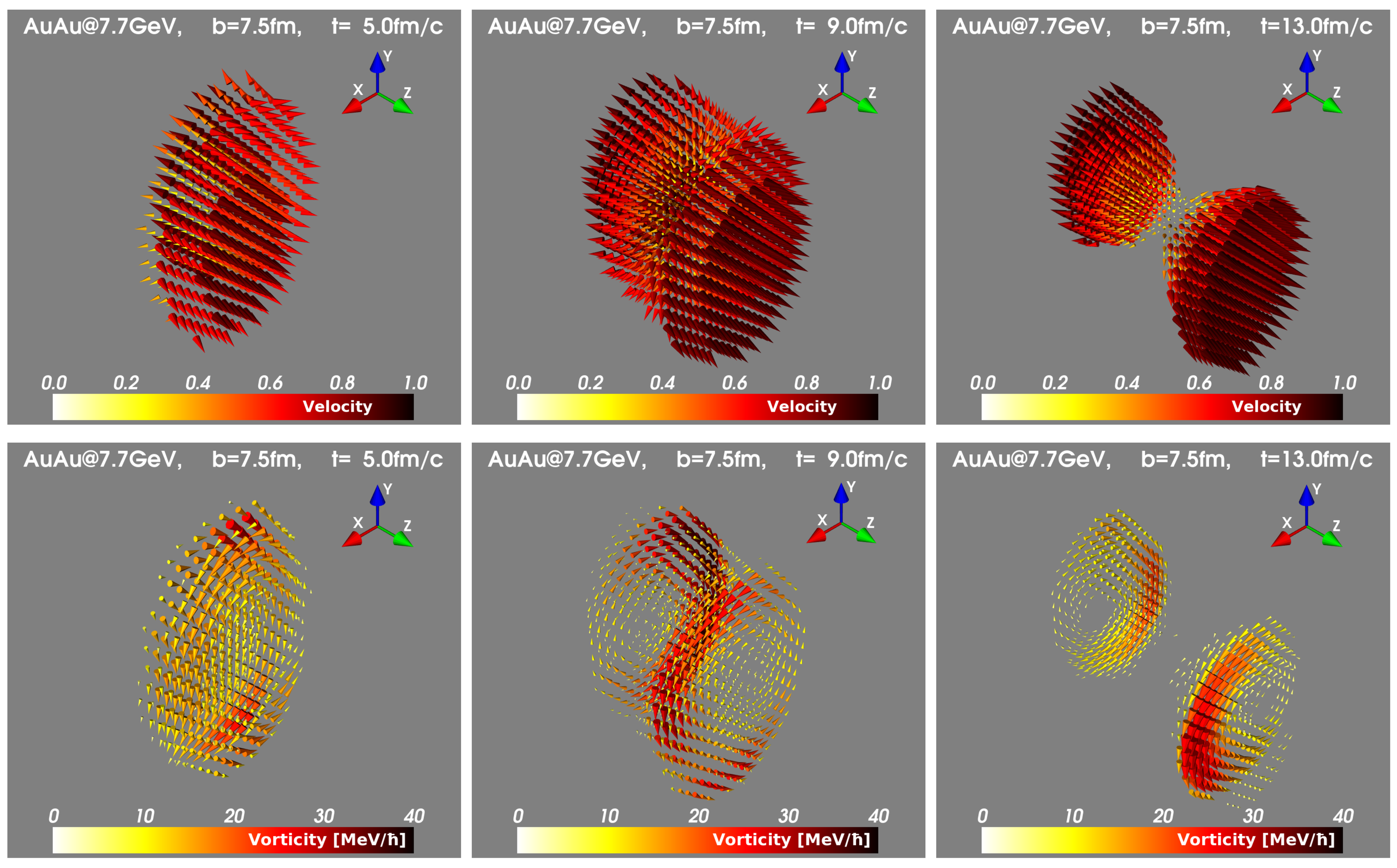


$$J^\mu_B = \sum_{a,i_a} B_{i_a}\frac{p^\mu_{i_a}(t)}{p^0_{i_a}(t)}\Phi\left(\boldsymbol{x},\boldsymbol{x}_{i_a}(t)\right), \qquad n_B = u_\mu J^\mu_B$$

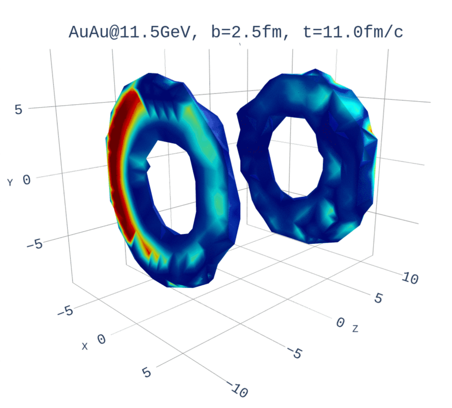
$$\int \Phi\left(\boldsymbol{x},\boldsymbol{x}_{i_a}(t)\right)\,d^3x = 1, \qquad \Phi \;-\; \text{smearing function}$$

$$\varepsilon, n_B \longrightarrow \textbf{EoS}\ [6] \longrightarrow T(\varepsilon, n_B)$$

3. Velocity and vorticity fields [5, 9]

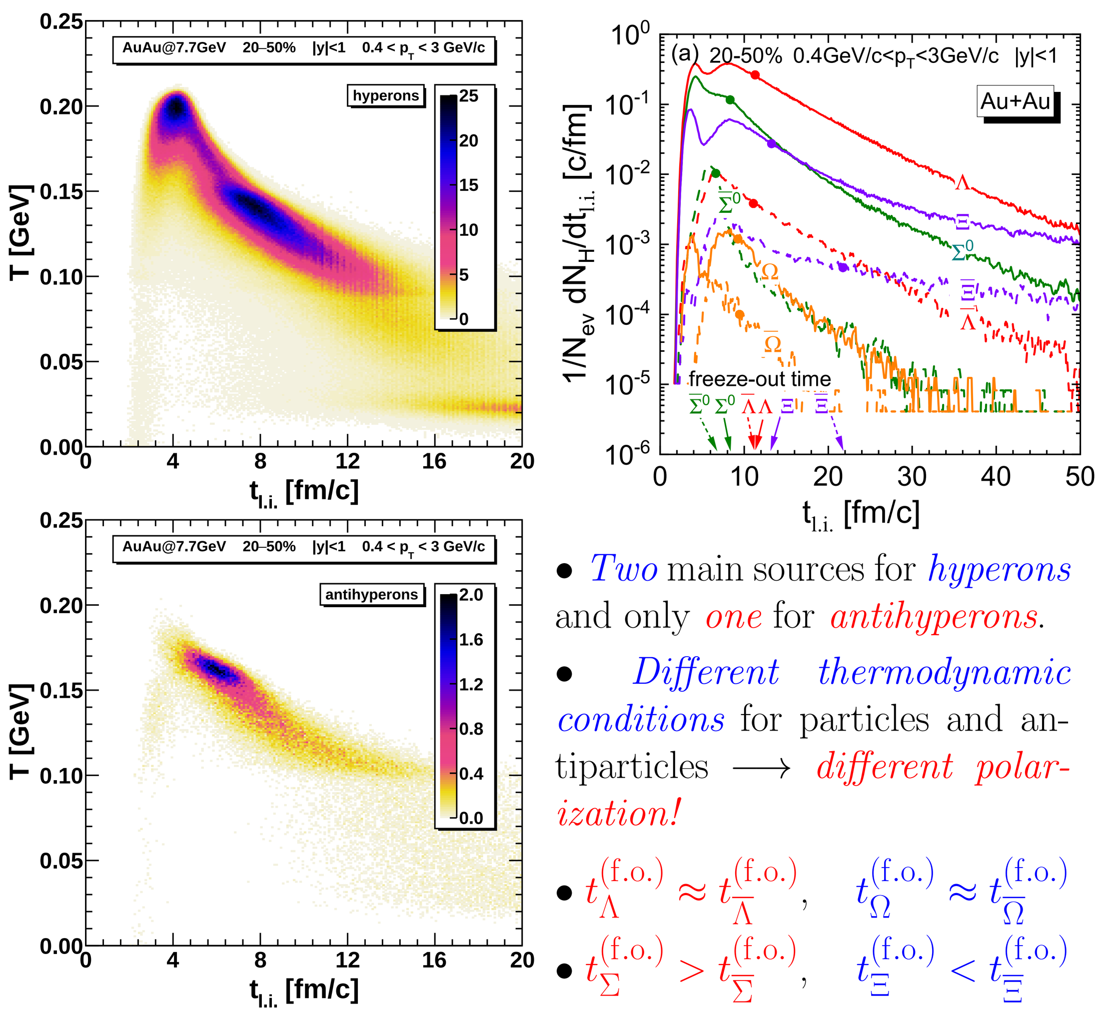


- The fireball velocity consist of the *irrotational* **(2+1)D Hubble-like** and *rotational* terms.
- Maximum of the vorticity is located *at the edges of the system*.
- Two deformed **elliptical vortex rings** move and rotate in opposite directions along the collision axis.



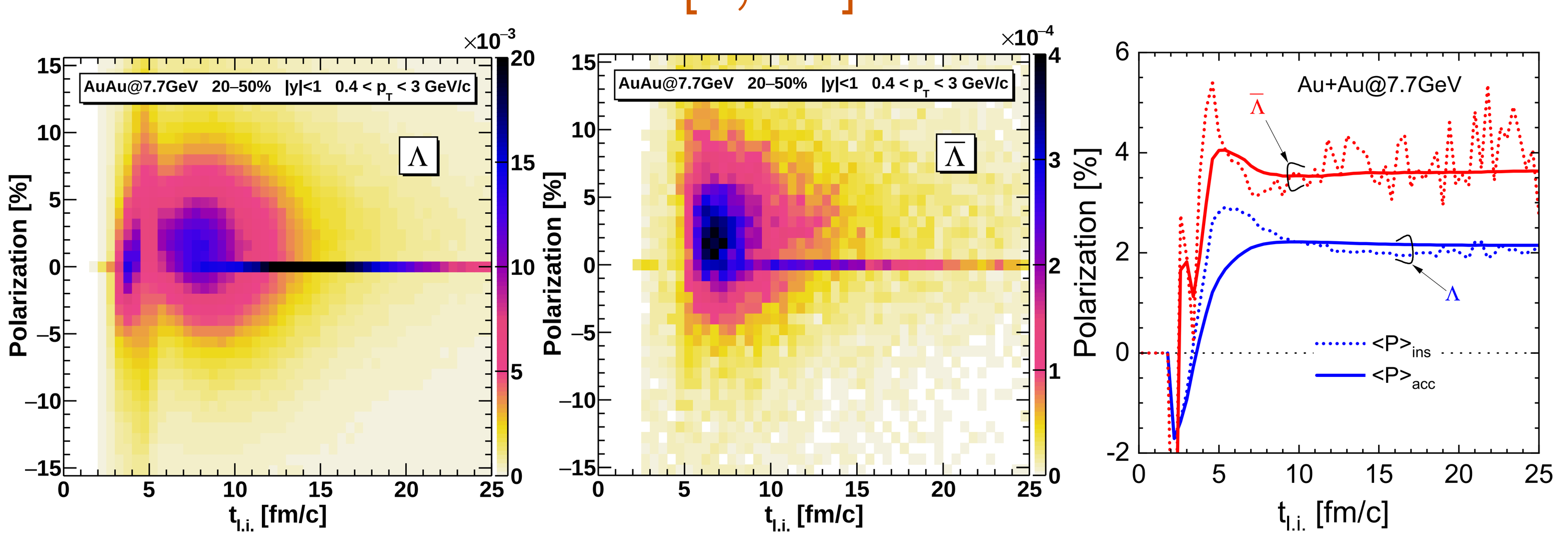
- The ring deformation depends on the impact parameter.
- In other works the **vortex sheets** [7], **vortex rings** [8] were predicted.

4. Freeze-out conditions [9, 10]



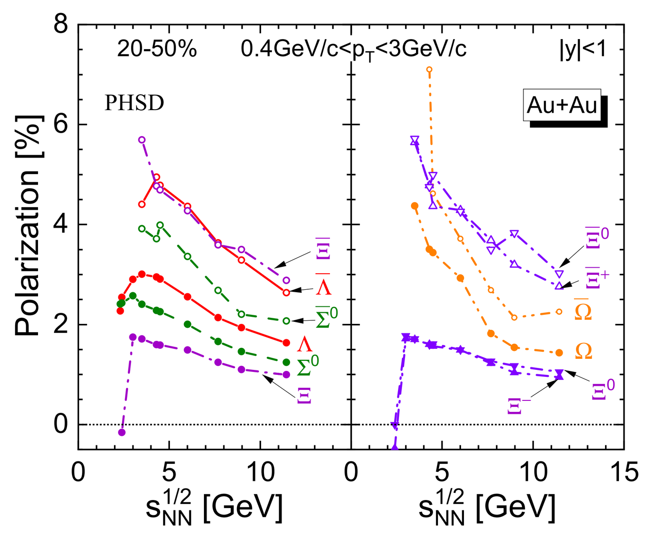
- *Two* main sources for *hyperons* and only *one* for *antihyperons*.
- *Different thermodynamic conditions* for particles and antiparticles $\longrightarrow$ *different polarization!*
- $t^{(\rm f.o.)}_\Lambda \approx t^{(\rm f.o.)}_{\bar\Lambda}$, $\quad t^{(\rm f.o.)}_\Omega \approx t^{(\rm f.o.)}_{\bar\Omega}$
- $t^{(\rm f.o.)}_\Sigma > t^{(\rm f.o.)}_{\bar\Sigma}$, $\quad t^{(\rm f.o.)}_\Xi < t^{(\rm f.o.)}_{\bar\Xi}$

5. Polarization source [9, 10]



- *Two* main sources for **Λ** and only *one* for $\bar{\boldsymbol{\Lambda}}$.
- The following relation holds for both instantaneous and accumulated polarizations for $t_{\rm l.i.} \gtrsim 3\,{\rm fm}/c$: $\quad P_y(\bar\Lambda) > P_y(\Lambda)$
- For $t \gtrsim 10\,{\rm fm}/c$ the accumulated polarization stays *approximately constant*.
- *Change in the polarization sign* at the moment of full overlap.

6. Hyperon species polarization [10]



- *Different polarization* of particles and antiparticles for all kinds of hyperons.
- Polarization of all hyperon species *decrease with an energy increase* for $\sqrt{s_{NN}} \gtrsim 5\,{\rm GeV}$.
- The *strongest decrease* and *smallest difference* is for **Ω** and $\bar{\boldsymbol{\Omega}}$. The energy trend is also different.
- The following polarization hierarchy holds for the energy range $\sqrt{s_{NN}} = 3.5 - 11.5\,{\rm GeV}$: $\quad P_{\bar\Xi} \approx P_{\bar\Lambda} > P_{\bar\Sigma^0} > P_\Lambda > P_{\Sigma^0} > P_\Xi$.
- The maximum of **Λ** and $\bar{\boldsymbol{\Lambda}}$ polarization occurs at $\sqrt{s_{NN}} \approx 4\,{\rm GeV}$.

7. Feed-down effects [10]

The feed-down contributions:
- **strong** decays are already included
- **weak** decays: $\boldsymbol{\Xi} \to \boldsymbol{\Lambda} + \boldsymbol{\pi}$, contribution from **Ω** is negligible
- **electromagnetic** decays: $\boldsymbol{\Sigma} \to \boldsymbol{\Lambda} + \boldsymbol{\gamma}$

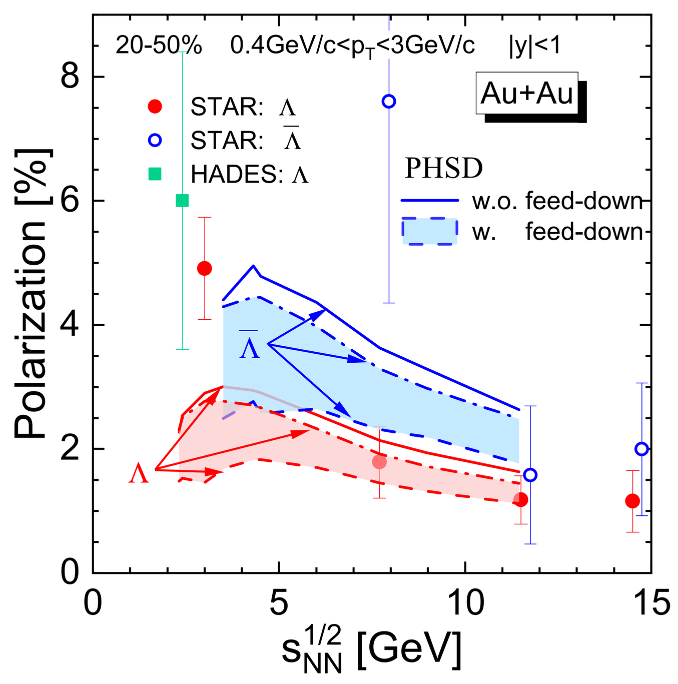
- The total measured spin vector for $\boldsymbol{\Lambda}(\bar{\boldsymbol{\Lambda}})$:

$$\boldsymbol{S}^{*(\rm meas)}_\Lambda = \boldsymbol{S}^{*(\rm prim)}_\Lambda + \boldsymbol{S}^{*(\Sigma^0)}_\Lambda + \boldsymbol{S}^{*(\Xi)}_\Lambda$$

$$\boldsymbol{S}^{*(\Sigma^0)}_\Lambda = f_{\Lambda\Sigma^0}C_{\Lambda\Sigma^0}\boldsymbol{S}^*_{\Sigma^0}, \qquad \boldsymbol{S}^{*(\Xi)}_\Lambda = f_{\Lambda\Xi}C_{\Lambda\Xi}B_{\Lambda\Xi}\boldsymbol{S}^*_\Xi$$

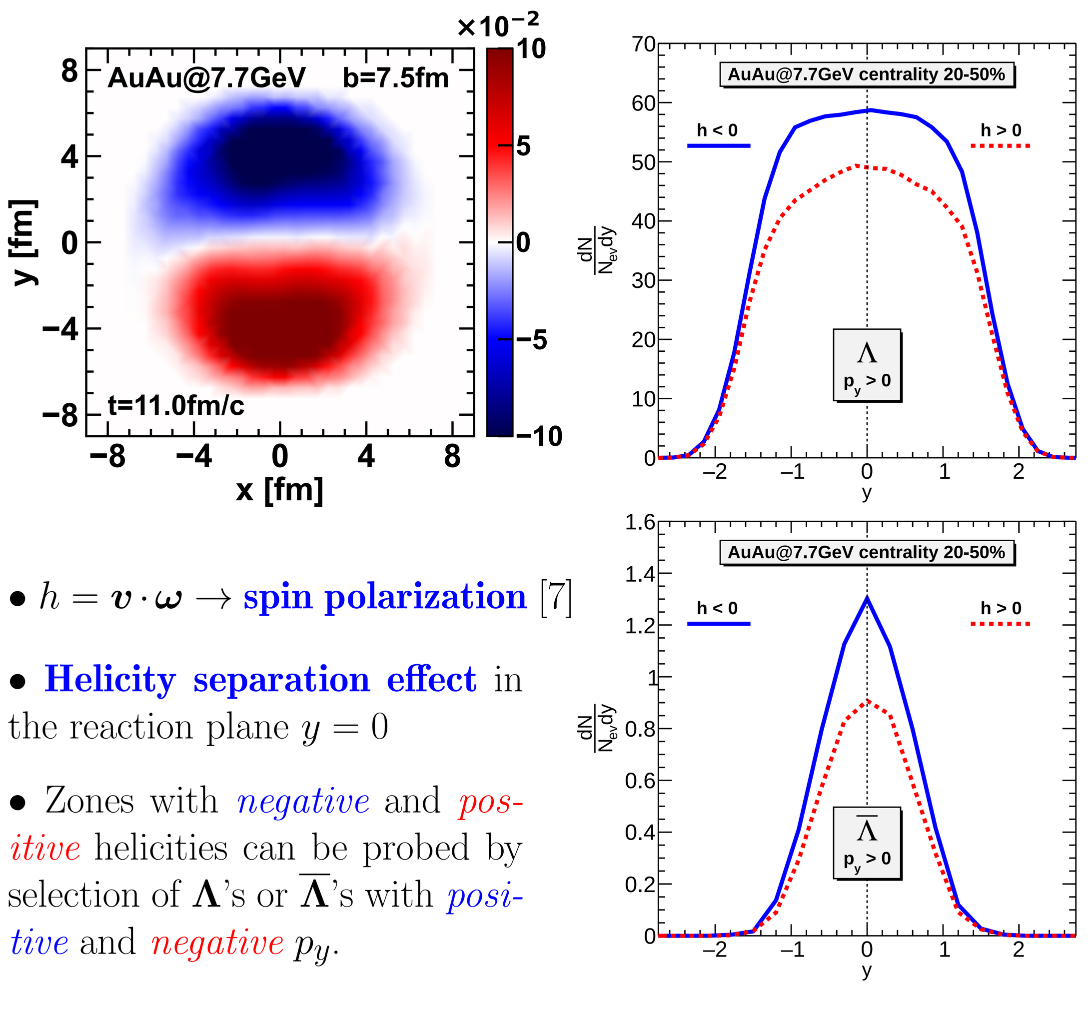
$$f_{HH'} = N_{H'}/(N_H + N_{H'}), \qquad B_{\Lambda\Xi} = 0.995$$

$$C_{\Lambda\Sigma^0} = -1/3, \quad C_{\Lambda\Xi^0} = 0.914, \quad C_{\Lambda\Xi^-} = 0.943$$



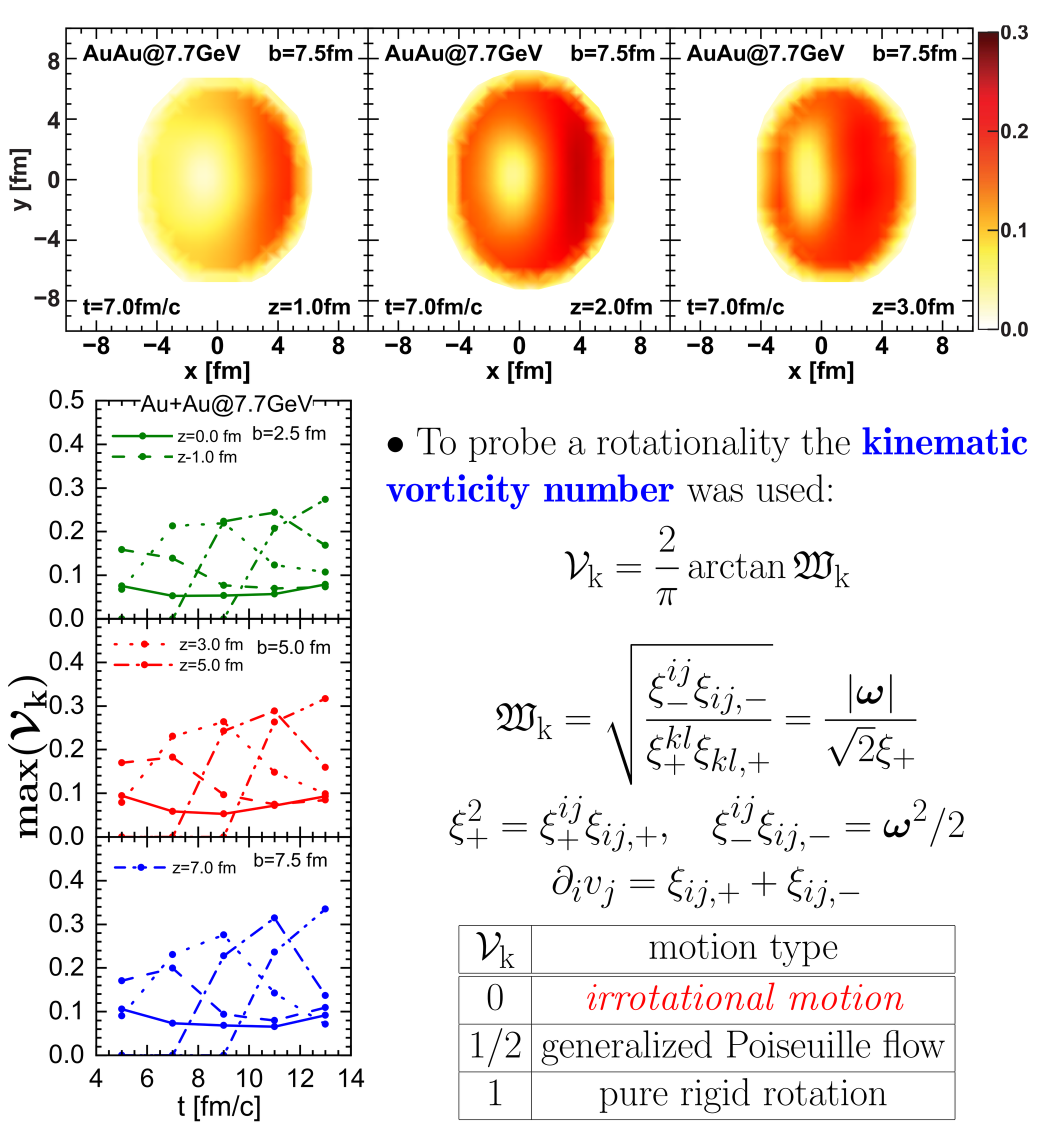
- Polarization of the **Λ** hyperons *agrees* with experimental data, except low energies $\sqrt{s_{NN}} \le 3\,{\rm GeV}$. The *maximum* of the **Λ** polarization at $\sqrt{s_{NN}} \approx 4\,{\rm GeV}$.
- Polarization of $\bar{\boldsymbol{\Lambda}}$ *larger* in 1.5 – 2 times than **Λ**. It *agrees* with experimental data at $\sqrt{s_{NN}} = 11.5\,{\rm GeV}$, but is *less* at $\sqrt{s_{NN}} = 7.7\,{\rm GeV}$.
- 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* $\boldsymbol{\Sigma}^0$ *and* $\bar{\boldsymbol{\Sigma}}^0$ hyperons.

8. Hydrodynamic helicity [5]



- $h = \boldsymbol{v}\cdot\boldsymbol{\omega} \to$ **spin polarization** [7]
- **Helicity separation effect** in the reaction plane $y = 0$
- Zones with *negative* and *positive* helicities can be probed by selection of **Λ**'s or $\bar{\boldsymbol{\Lambda}}$'s with *positive* and *negative* p_y.

9. Measure of rotationality [5]



- To probe a rotationality the **kinematic vorticity number** was used:

$$\mathcal{V}_{\rm k} = \frac{2}{\pi}\arctan\mathfrak{W}_{\rm k}$$

$$\mathfrak{W}_{\rm k} = \sqrt{\frac{\xi^{ij}_-\xi_{ij,-}}{\xi^{kl}_+\xi_{kl,+}}} = \frac{|\boldsymbol{\omega}|}{\sqrt{2}\xi_+}$$

$$\xi^2_+ = \xi^{ij}_+\xi_{ij,+}, \quad \xi^{ij}_-\xi_{ij,-} = \boldsymbol{\omega}^2/2$$

$$\partial_i v_j = \xi_{ij,+} + \xi_{ij,-}$$

$\mathcal{V}_{\rm k}$	motion type
0	*irrotational motion*
1/2	generalized Poiseuille flow
1	pure rigid rotation

10. Summary

- 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 $\boldsymbol{\Sigma}^0(\bar{\boldsymbol{\Sigma}}^0)$.
- The helicity separation effect in the reaction plane.
- The motion does not reach the Poiseuille flow and is close to the pure shear deformation.

References

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