Probing early-time longitudinal dynamics with the $\Lambda$ hyperon's spin polarization in relativistic heavy-ion collisions

Sangwook Ryu

in collaboration with
Sahr Alzhrani, Vahidin Jupic and Chun Shen

S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)
S. Ryu, V. Jupic, and C. Shen (arXiv:2106.08125)
Model: spin polarization in E-by-E hydrodynamics

Initial energy-momentum conservation

\[
\frac{d^2}{d^2 \mathbf{x}_\perp} \begin{pmatrix} E \\ p^z \end{pmatrix} = m_N \begin{pmatrix} [T_A(\mathbf{x}_\perp) + T_B(\mathbf{x}_\perp)] \cosh y_{\text{beam}} \\ [T_A(\mathbf{x}_\perp) - T_B(\mathbf{x}_\perp)] \sinh y_{\text{beam}} \end{pmatrix} \equiv M(\mathbf{x}_\perp) \begin{pmatrix} \cosh y_{\text{CM}} \\ \sinh y_{\text{CM}} \end{pmatrix}
\]

Energy-momentum tensor:

\[
T^\tau_\eta(\tau_0, \mathbf{x}_\perp, \eta_s) = e(\mathbf{x}_\perp, \eta_s) \cosh (f y_{\text{CM}}) \\
T^\tau_\eta(\tau_0, \mathbf{x}_\perp, \eta_s) = \frac{e(\mathbf{x}_\perp, \eta_s)}{\tau_0} \sinh (f y_{\text{CM}})
\]

Spin polarization vector

\[
S^\mu(p) = \frac{1}{4m} \int p \cdot d^3 \Sigma n_0 (1 - n_0) A^\mu \frac{1}{S} S^\mu(p)
\]

Axial vector

\[
A^\mu_{\text{BBP}} = -\epsilon^{\mu \rho \sigma \tau} \left( \frac{1}{2} \omega_{\rho \sigma} p_\tau + \frac{1}{E} \hat{t}_\rho \xi_\sigma \lambda p^\lambda p_\tau \right) \\
\hat{t}^\mu = (1, 0, 0, 0)
\]

F. Becattini, M. Buzzegoli, and A. Palermo (2021)

\[
A^\mu_{\text{LY}} = -\epsilon^{\mu \rho \sigma \tau} \left[ \frac{1}{2} \omega_{\rho \sigma} p_\tau + \frac{1}{E} u_\rho \xi_\sigma \lambda p^\lambda p_\tau + \frac{b_i}{\beta E} u_\rho p^\perp_\sigma \partial_\tau (\beta \mu_B) \right] \\
p^\mu_\perp = p^\mu - (p \cdot u) u^\mu
\]

S. Y. F. Liu and Y. Yin (2021)

C. Yi, S. Pu, and D. Yang (2021)

Thermal vorticity

\[
\omega^{\mu \nu} = -\frac{1}{2} \left[ \partial^\mu \left( \frac{u^\nu}{T} \right) - \partial^\nu \left( \frac{u^\mu}{T} \right) \right]
\]

And shear

\[
\xi^{\mu \nu} = \frac{1}{2} \left[ \partial^\mu \left( \frac{u^\nu}{T} \right) + \partial^\nu \left( \frac{u^\mu}{T} \right) \right]
\]
**Result :** charged hadron yield and anisotropic flow

S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)

- Our framework provides reasonable descriptions of hadron yield and anisotropic (elliptic and triangular) flow coefficients.

- Experimental data favor $\frac{\eta T}{\epsilon + P} \sim 0.08 - 0.16$ and hot spot width $w = 0.4 - 0.8 \text{ fm}$.

(see backup slide for $w$-dependence.)
Result: A hyperon polarization the global polarization

S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)

• Global polarization is strongly sensitive to the shear viscosity, because the vortical movement is smeared faster in the presence of viscosity.
• Global polarization is dominated by system’s thermal vorticity.

\[
S^y_{\text{global}} = \frac{1}{4m} \int dy \int d^2p_\perp \int p \cdot d^3n_0 (1 - n_0) A^y
\]

\[\eta T / (e + P) = 0.01 \]
\[w = 0.4 \text{ fm} \]
\[e_{sw} = 0.5 \text{ GeV/fm}^3 \]
\[\text{Au+Au@200 GeV} \]
\[0.5 < p_T < 3 \text{ GeV} \]
\[|\eta| < 1 \]
Result: \( \Lambda \) hyperon polarization

longitudinal polarization

centrality and azimuthal dependence

- The shear-induced polarization is substantial for azimuthal dependence of the longitudinal polarization.

\[
A_{\text{SIP-BBP}}^{\mu} = -\varepsilon^{\mu \rho \sigma \tau} \frac{1}{E} \hat{t}_\rho \xi_\sigma \lambda p^\lambda p^\tau \quad \text{and} \quad A_{\text{SIP-LY}}^{\mu} = -\varepsilon^{\mu \rho \sigma \tau} \frac{1}{E} u_\rho \xi_\sigma \lambda p^\lambda p^\tau
\]

\[
\langle \cos \theta^*_p \rangle(\phi_p) = \langle \cos^2 \theta^*_p \rangle \alpha_\Lambda P^z(\phi_p) = \frac{\alpha_\Lambda}{3} P^z(\phi_p)
\]

\[
P^z_n \equiv \int_0^{2\pi} \frac{d\phi}{2\pi} P^z(\phi) e^{i\epsilon_\phi} \quad p^z_n \{\text{SP}\} \equiv \frac{\langle \text{Im} \left[ P^z_n Q^*_n, A \right] \rangle_{\text{ev}}}{\sqrt{\langle \text{Re} \left[ Q^*_n, A Q^*_n, B \right] \rangle_{\text{ev}}}}
\]

\[
\eta T/(e + P) = 0.08 \\
w = 0.8 \text{ fm} \\
e_{sw} = 0.5 \text{ GeV/fm}^3
\]

\[
\left| \eta \right| < 1 \\
0.5 < p_T < 3 \text{ GeV}
\]

20-60\% Au+Au @ 200 GeV

\[
w = 0.8 \text{ fm} \\
\eta T/(e + P) = 0.08 \\
e_{sw} = 0.5 \text{ GeV/fm}^3
\]

Au+Au@200 GeV
Result: \( A \) hyperon polarization

Longitudinal polarization correlation with anisotropic flow coefficient \( v_n \)

- Longitudinal polarization is positively correlated with the anisotropic flow.
- Predictions for the \( n \)-th Fourier coefficients of \( P^z(\phi_p) \): \( p^z_3\{\text{SP}\} \) and \( p^z_4\{\text{SP}\} \) are comparable to \( p^z_2\{\text{SP}\} \).

\[
p^z_n\{\text{SP}\} = \frac{\langle \text{Im} P^z_n Q_{n,A}^* \rangle_{ev}}{\sqrt{\langle \text{Re} Q_{n,A} Q_{n,B}^* \rangle_{ev}}}
\]

\[
\rho(v_n^2, (P^z_n)^2) = \frac{\langle \delta v_n^2 \delta(P^z_n)^2 \rangle_{ev}}{\sqrt{\langle [\delta v_n^2]^2 \rangle_{ev} \langle [\delta(P^z_n)^2] \rangle_{ev}}}
\]

\[
(\delta O = \delta O - \frac{\langle \delta O \delta N_{\text{ch}} \rangle_{ev}}{\langle (\delta N_{\text{ch}})^2 \rangle_{ev}} \delta N_{\text{ch}})
\]
Backup
Result: sensitivity to width of energy deposit

charged hadron production and anisotropic flow

S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)
Result: sensitivity to width of energy deposit

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global and longitudinal polarization

\[ \eta T/(e + P) = 0.08, \ e_{sw} = 0.5 \ \text{GeV/fm}^3 \]

Thermal vorticity

Au+Au@200 GeV

\[ 0.5 < p_T < 3 \ \text{GeV} \]

\[ |\eta| < 1 \]