Spin polarization of Λ hyperons from dissipative spin hydrodynamics

David Wagner

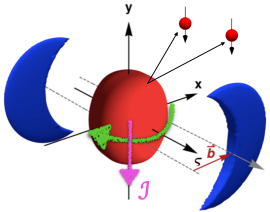
Chirality 2026
Zhuhai, China

18 November 2026

Sapna, S. K. Singh, D. Wagner, Phys. Rev. C **112**, 054902 (2025)

D. Wagner, Phys. Rev. D **111**, 016008 (2025)

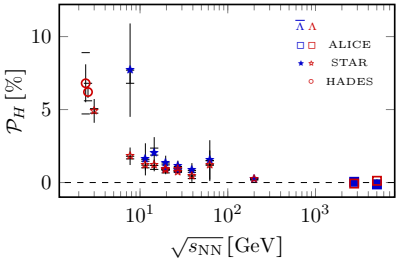
Global Λ-Polarization

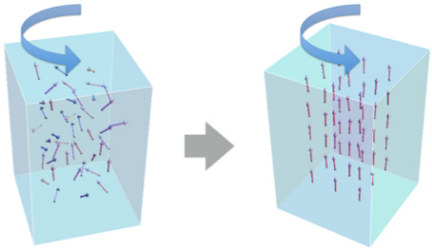


- "Global": Integrated polarization along the direction of orbital angular momentum
- Can be explained by assuming spins in equilibrium

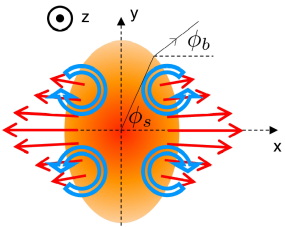
$\rightarrow$ "Polarization through rotation"

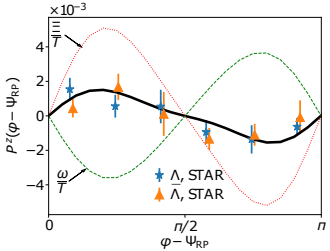
  - Analogous to Barnett effect





Local Λ-Polarization



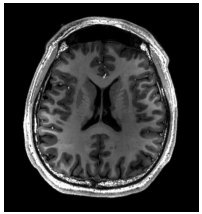


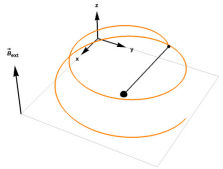
- "Local": Angle-dependent polarization along beam-direction
- Can be explained by incorporating shear effects
  - $\rightarrow$ Simple picture of polarization through rotation not complete
- Possible answer: develop a theory of **spin hydrodynamics** to describe polarization dynamics

F. Becattini, M. Buzzegoli, G. Inghirami, I. Karpenko, A. Palermo, Phys. Rev. Lett. **127**, 272302 (2021).

Analogy: Magnetic resonance imaging (MRI)

- MRI: Large constant B-field in z-direction and short-lived alternating field in x, y-plane
- Identify materials by relaxation times T_1, T_2





Bloch equations

$$T_2 \dot{M}_{x,y} + M_{x,y} = \mu_2 (\mathbf{M} \times \mathbf{B})_{x,y},$$
$$T_1 \dot{M}_z + M_z = \mu_1 (\mathbf{M} \times \mathbf{B})_z + M_0.$$

How long do spins take to equilibrate in high-energy collisions?

$\mu_1 = T_1 gq/(2m)$, $\mu_2 = T_2 gq/(2m)$. Animation: https://en.wikipedia.org/wiki/Bloch_equations.

Conservation equations

$$\partial_\mu T^{\mu\nu} = 0,$$
$$\hbar \partial_\lambda S^{\lambda\mu\nu} + T^{[\mu\nu]} = 0.$$

- Theory is based on conservation laws
- **10** equations for **16**+**24** quantities
  - Underdetermined system
  - Additional information about dissipative quantities has to be provided
- Use *quantum kinetic theory* as the microscopic basis

$A^{[\mu} B^{\nu]} = A^\mu B^\nu - A^\nu B^\mu.$

QFT

$$(i\partial\!\!\!/ - m)\widehat{\psi} = \widehat{\rho}$$

$\Downarrow$

QKT

$$k \cdot \partial f = C[f]$$

$\Downarrow$

Hydro

$$\partial_\mu T^{\mu\nu} = 0$$

$$\lambda_{\mathrm{C}} \ll \lambda_{\mathrm{mfp}} \ll L_{\mathrm{hydro}}$$

Power counting

- Basic idea: Count small quantities to organise the fluid equations
- Slowly varying flow:

$$\mathrm{Kn} = \frac{\lambda_{\mathrm{mfp}}}{L_{\mathrm{hydro}}}\,, \qquad \mathrm{Kn}_Q = \frac{\lambda_{\mathrm{C}}}{L_{\mathrm{hydro}}}\,, \qquad \mathrm{Ro}_Q^{-1} \sim \lambda_{\mathrm{C}} \frac{|S_0^{\mu\nu\lambda}|}{P_0 \beta_0^2}$$

- Small dissipative corrections:

$$\mathrm{Re}^{-1} \sim \frac{|\delta T^{\mu\nu}|}{P_0}\,, \qquad \mathrm{Re}_Q^{-1} \sim \frac{|\delta S^{\mu\nu\lambda}|}{P_0 \beta_0}$$

- Assume $\mathrm{Kn} \sim \mathrm{Re}^{-1}$, $\mathrm{Kn}_Q \sim \mathrm{Ro}_Q^{-1} \sim \mathrm{Re}_Q^{-1}$

Closure of the equations

Truncate the spin equations at second order $\mathrm{Kn} \times \mathrm{Re}_Q^{-1}$
Keep only quantities with nonvanishing first-order asymptotic values

$\lambda_C = \hbar/m$; $\beta_0 \coloneqq 1/T$.

Result for small polarization: spin dynamics can be described through **11** quantities:

- the **spin potential** $\Omega_0^{\mu\nu} = u^{[\mu}\kappa_0^{\nu]} + \epsilon^{\mu\nu\alpha\beta}u_\alpha\omega_{0,\beta}$
- the **spin-shear-stress tensor** $\mathfrak{t}^{\mu\nu}$

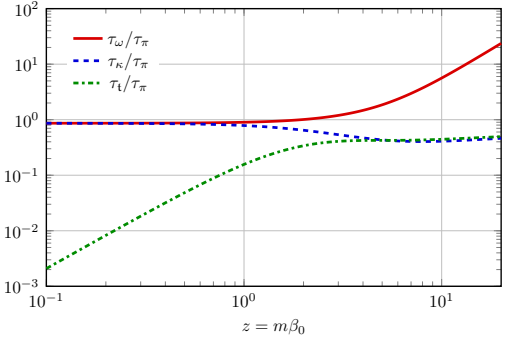
Equations of motion

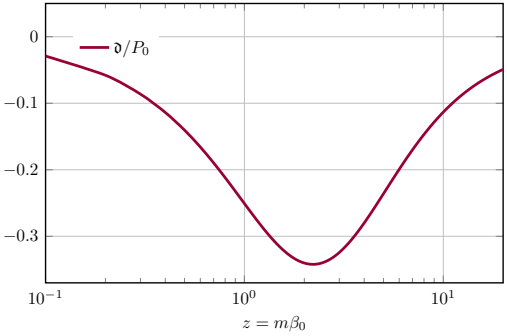
$$\tau_\omega\dot{\omega}_0^{\langle\mu\rangle} + \omega_0^\mu = -\beta_0\omega_K^\mu + \ell_{\omega\kappa}\epsilon^{\mu\nu\alpha\beta}u_\nu\nabla_\alpha\kappa_{0,\beta} + \cdots,$$
$$\tau_\kappa\dot{\kappa}_0^{\langle\mu\rangle} + \kappa_0^\mu = -\beta_0\dot{u}^\mu + \frac{\tau_\kappa}{2}\epsilon^{\mu\nu\alpha\beta}u_\nu\nabla_\alpha\omega_{0,\beta} + \ell_{\kappa\mathfrak{t}}\Delta^\mu_\lambda\nabla_\nu\mathfrak{t}^{\nu\lambda} + \cdots,$$
$$\tau_\mathfrak{t}\dot{\mathfrak{t}}^{\langle\mu\nu\rangle} + \mathfrak{t}^{\mu\nu} = \mathfrak{d}\beta_0\sigma^{\mu\nu} + \ell_{\mathfrak{t}\kappa}\nabla^{\langle\mu}\kappa_0^{\nu\rangle} + \cdots.$$

- System of *coupled relaxation-type equations*
  - Coupling leads to the emergence of spin waves
  - Relaxation controlled by times τ_ω, τ_κ, $\tau_\mathfrak{t}$
  - Asymptotics determined by ω_K^μ, $\dot{u}^\mu$, $\sigma^{\mu\nu}$

$\dot{u}^\mu$: acceleration; ω_K^μ: kinematic vorticity; $\sigma^{\mu\nu}$: shear tensor. D. Wagner, Phys. Rev. D **111**, 016008 (2025).

Relaxation times and first-order coefficients





- τ_ω grows with $(m\beta_0)^2$ compared to τ_κ and $\tau_{\mathfrak{t}}$ for large $m\beta_0$
- $\tau_{\mathfrak{t}}$ vanishes for $m\beta_0 \to 0$

Curves for scalar–pseudoscalar (SPS) interaction. Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

Setup

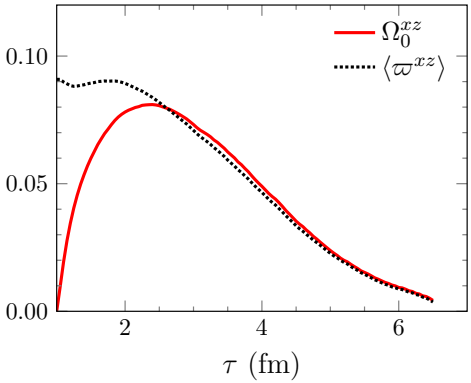
- Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- Initially vanishing spin fields
- Choose NJL-type interaction

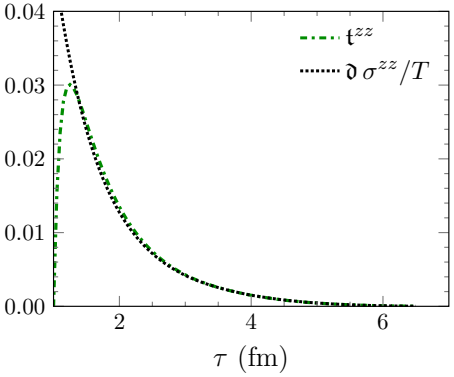
$$\mathcal{L}_{\text{int}} \sim G\left[(\bar{\psi}\psi)^2 - (\bar{\psi}\gamma_5\psi)^2\right]$$

for computing the transport coefficients

Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

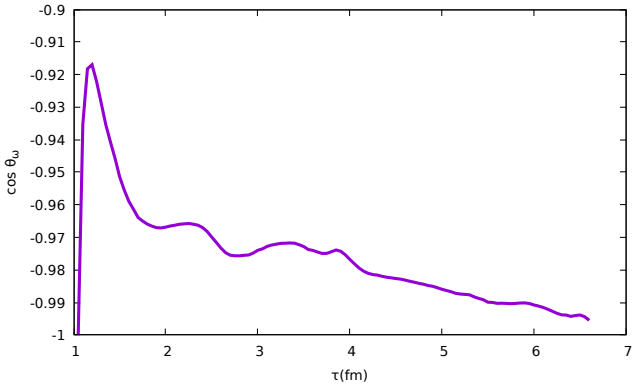
Simulation: Evolution





Energy-weighted averages, $\varepsilon > 0.5$ GeV/fm^3. Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

Simulation: Evolution

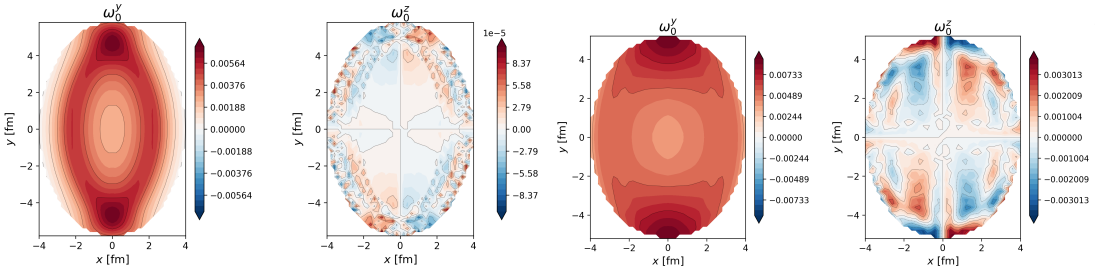


- Magnetic part of spin potential ω_0^μ and kinematic vorticity ω_K^μ (anti)align over time
  $\rightarrow$ Barnett effect at work

$\arccos(0.92) \approx 23^\circ$

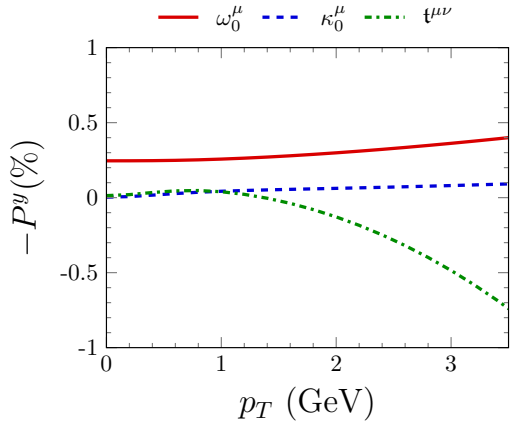
Simulation: Evolution

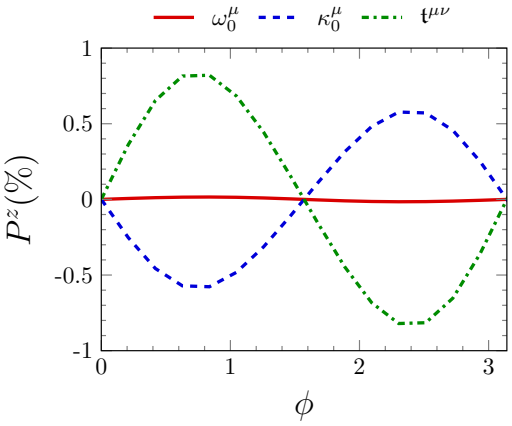
$\tau = 1.150\,\mathrm{fm}$ $\tau = 4.750\,\mathrm{fm}$



- y-component of ω_0^μ present at early times
- z-component of ω_0^μ develops later

Simulation: Polarization contributions

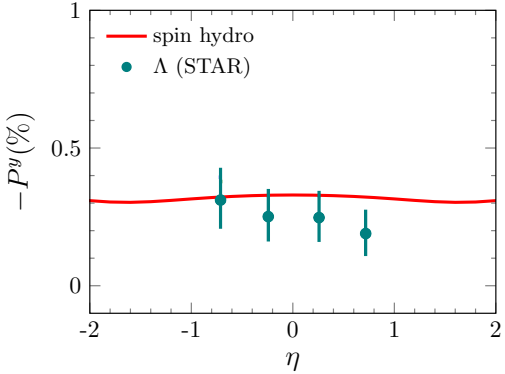


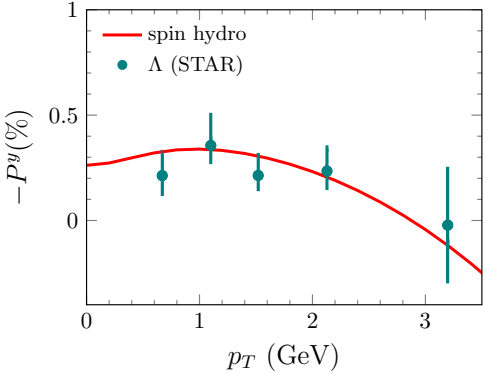


- Magnetic part ω_0^μ dominates at low p_T
- $\mathfrak{t}^{\mu\nu}$ compensates κ_0^μ

Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

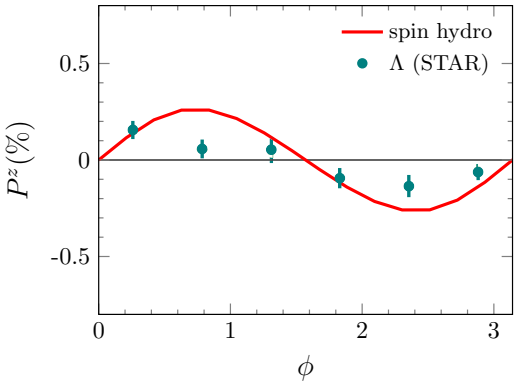
Simulation: Global polarization

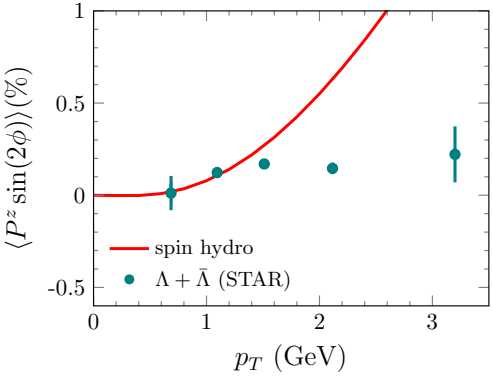




Au+Au, 200 GeV, 20–50%. Sapna, S. K. Singh, D. Wagner, Phys. Rev. C **112**, 054902 (2025)
STAR data: Phys. Rev. C **98**, 014910 (2018).

Simulation: Local polarization





Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025); STAR: Phys. Rev. Lett. **123**, 132301 (2019)

Summary and outlook

- Derived dissipative spin hydrodynamics from QFT via QKT
  - Main result: Only the quantities ω_0^μ, κ_0^μ, $\mathfrak{t}^{\mu\nu}$ need dynamical treatment
  - All transport coefficients of the chosen truncation can be (and have been) computed
- Numerical implementation shows promising results
- Interesting future avenue: Numerical study of dissipative spin hydro in different setups
  - Differences to local-equilibrium results expected to become especially relevant at lower collision energies

$$S_0^\mu = \frac{\hbar}{2N(k)m}\int \mathrm{d}\Sigma_\lambda k^\lambda \left(u^\mu \omega_0^\nu k_\nu - E_{\mathbf{k}}\omega_0^\mu + \epsilon^{\mu\nu\alpha\beta}u_\nu k_\alpha \kappa_{0,\beta}\right) f_0 \widetilde{f}_0,$$

$$\delta S^\mu \simeq -\frac{1}{N(k)}\int \mathrm{d}\Sigma_\lambda k^\lambda \mathfrak{r}_\mathfrak{t}\mathfrak{t}_\rho{}^{\langle\beta}\epsilon^{\gamma\rangle\mu\sigma\rho}u_\sigma k_{\langle\beta}k_{\gamma\rangle} f_0\widetilde{f}_0\,.$$

$$\overline{S}_0^\mu = -\frac{\hbar}{4\overline{N}m}\int \mathrm{d}\Sigma_\lambda \left(J_{21}u^\mu\omega_0^\lambda + J_{20}\omega_0^\mu u^\lambda + J_{21}\epsilon^{\mu\nu\lambda\beta}u_\nu\kappa_{0,\beta}\right),$$

$$\delta\overline{S}^\mu \simeq 0\,.$$

Lowest-order approximation: $\mathfrak{r}_\mathfrak{t} = 1/(3J_{42})$; DW, Phys. Rev. D **111**, 016008 (2025)

NJL-type interactions

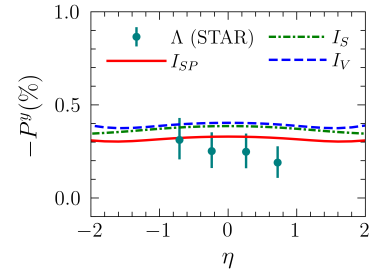
$$\text{SPS } (I_{SP}): \quad \mathcal{L}_{\text{int}} \sim G\left[(\bar{\psi}\psi)^2 - (\bar{\psi}\gamma_5\psi)^2\right],$$

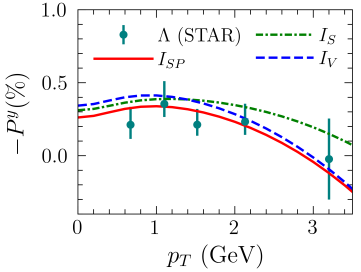
$$\text{S } (I_S): \quad \mathcal{L}_{\text{int}} \sim G(\bar{\psi}\psi)^2,$$

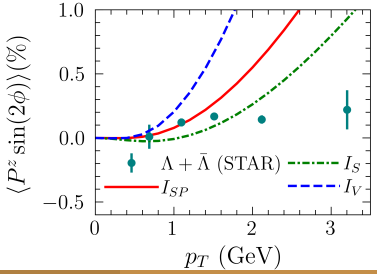
$$\text{V } (I_V): \quad \mathcal{L}_{\text{int}} \sim G(\bar{\psi}\gamma^\mu\psi)(\bar{\psi}\gamma_\mu\psi).$$

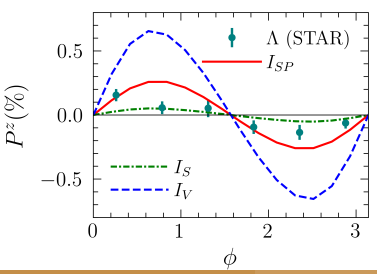
Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

Appendix: Interaction dependence of polarization

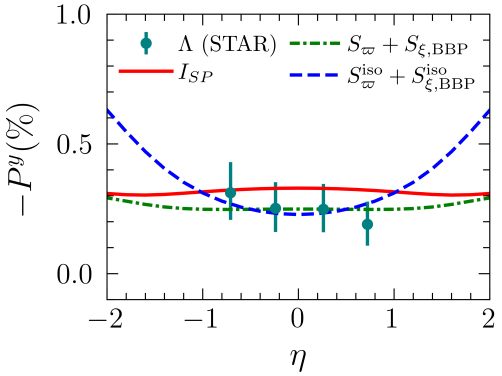


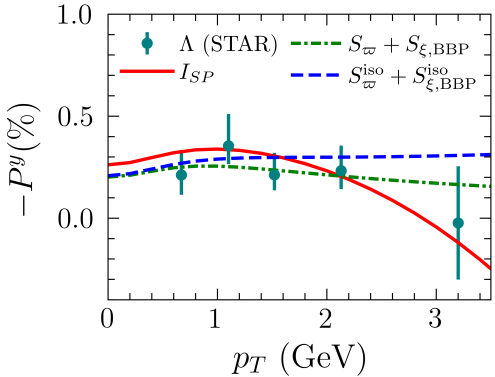






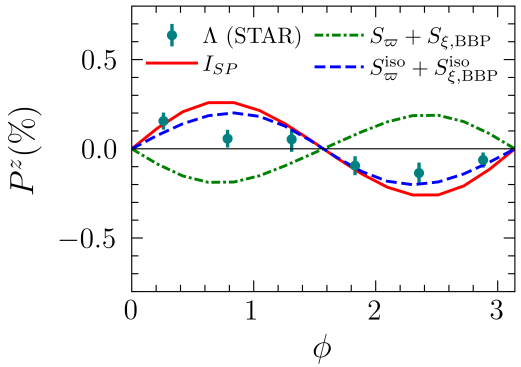
Appendix: Comparison to BBP — global polarization

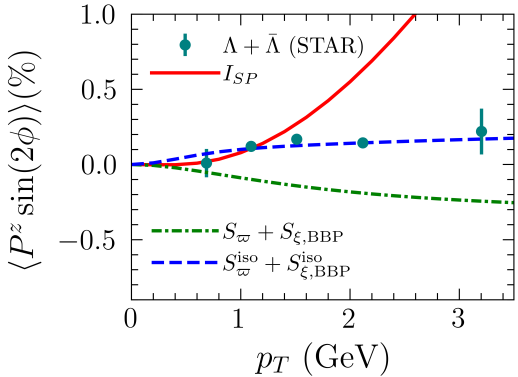




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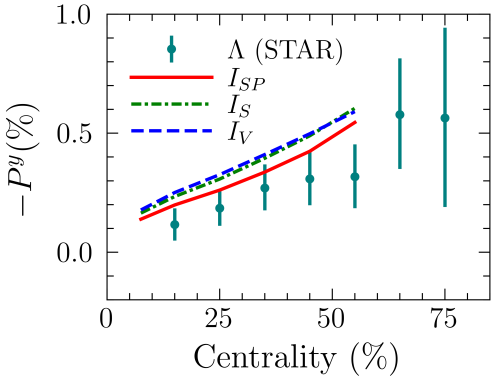
Appendix: Comparison to BBP — local polarization

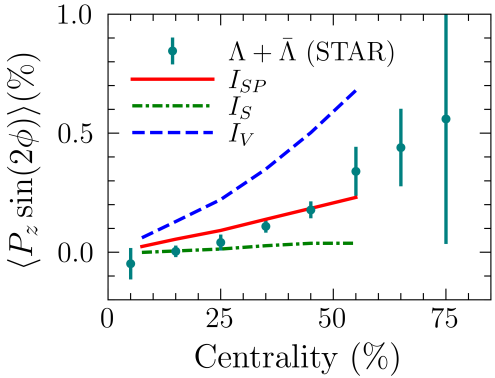




Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

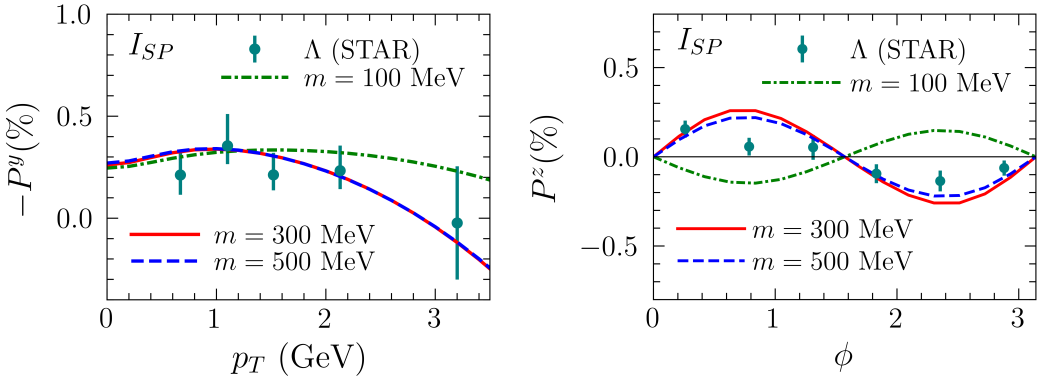
Appendix: Centrality dependence





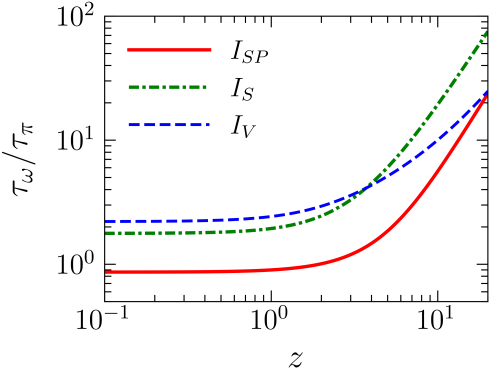
Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

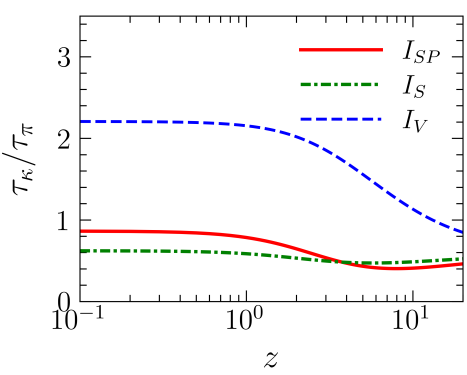
Appendix: Mass dependence



Mass of the fluid quasiparticles; emitted Λ mass fixed. Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

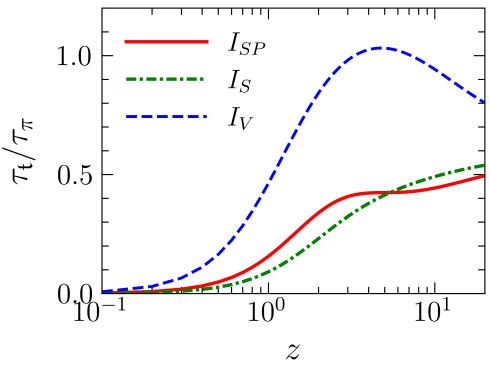
Appendix: Relaxation times

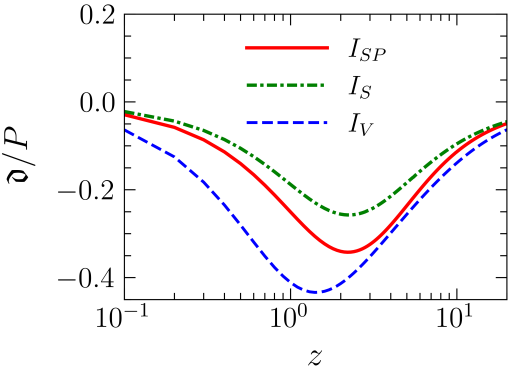




$z = m/T$. Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

Appendix: Spin-shear coefficients





$z = m/T$. Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

Common background for the three interactions

$$\eta = C_\eta \frac{\varepsilon + P}{T}, \qquad C_\eta = 0.12, \qquad \tau_\pi = \frac{5\eta}{\varepsilon + P} = \frac{0.6}{T} \quad (\hbar = c = k_B = 1).$$

- Spin relaxation: $\tau_X = (\tau_X/\tau_\pi)\, 0.6/T$, $X = \omega, \kappa, \mathfrak{t}$
- Spin fields initially zero at $\tau_0 = 1$ fm/c
- Fluid quasiparticles: $m = 300$ MeV; emitted hyperons: $m_\Lambda = 1.115$ GeV
- Particlisation at $\varepsilon = 0.5$ GeV/fm^3
  - Democratic Grad approximation: use the same Grad coefficient for all hadron species

Sapna, S. K. Singh, DW, Phys. Rev. C **112**, 054902 (2025)

Boltzmann equation with collisions

$$k \cdot \partial f = \frac{1}{2} \int \mathrm{d}\Gamma_1 \mathrm{d}\Gamma_2 \mathrm{d}\Gamma' \, \delta^{(4)}(k_1 + k_2 - k - k') \, \mathcal{W} \times \left[f_1^\Delta f_2^\Delta \, \widetilde{f} \, \widetilde{f}'^\Delta - \widetilde{f}_1^\Delta \widetilde{f}_2^\Delta \, f \, f'^\Delta \right],$$

$$f_i^\Delta := f(x + \Delta_i - \Delta, k_i, \mathfrak{s}_i), \qquad \widetilde{f} := 1 - f.$$

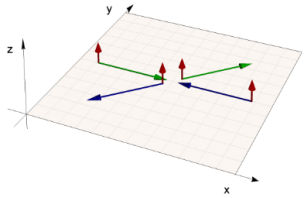
- Equivalence up to first order in quantum corrections:

$$f(x + \Delta, k, \mathfrak{s}) = f(x, k, \mathfrak{s}) + \Delta^\mu \partial_\mu f(x, k, \mathfrak{s}) + \mathcal{O}(\hbar^2).$$

- A (momentum- and spin-dependent) **spacetime shift** Δ^μ enters
  $\rightarrow$ Particles do not scatter at the same spacetime point!

$\mathrm{d}\Gamma = 2\mathrm{d}^4k \, \delta(k^2 - m^2) \, \mathrm{d}S(k).$

DW, N. Weickgenannt, D. H. Rischke, Phys. Rev. D **106**, 116021 (2022)



- Assume that collisions take place in a point x

$$\Delta L^{\mu\nu} = x^{[\mu}(k_1 + k_2 - k - k')^{\nu]} = 0.$$

  - $\rightarrow$ Total orbital angular momentum cannot change
  - $\rightarrow$ Spin is conserved on its own
  - $\rightarrow$ No exchange of spin and orbital angular momenta
- Collisions must be **nonlocal** for spin equilibration!
- Becomes manifest through a spacetime shift Δ^μ that is fixed by the microscopic interaction

W. Florkowski, A. Kumar, R. Ryblewski, Prog. Part. Nucl. Phys. **108**, 103709 (2019)

Local-equilibrium distribution function

$$f_{\mathrm{eq}}(x,k,\mathfrak{s}) = \exp\left[\alpha_0 - \beta_0 E_{\mathbf{k}} + \frac{\hbar}{4}\Omega_{0,\mu\nu}\Sigma^{\mu\nu}_{\mathfrak{s}}\right], \qquad \Sigma^{\mu\nu}_{\mathfrak{s}} = -\frac{1}{m}\epsilon^{\mu\nu\alpha\beta}k_\alpha \mathfrak{s}_\beta.$$

- Local-equilibrium distribution function makes local collision term vanish (without spacetime shifts Δ^μ)
- Has to depend on the **collisional invariants**: charge, four-momentum and total angular momentum
- Necessary conditions on Lagrange multipliers for a vanishing **nonlocal** collision term:

$$\partial^\mu \alpha_0 = 0, \qquad \partial^{(\mu}(\beta_0 u^{\nu)}) = 0, \qquad \Omega_0^{\mu\nu} = -\frac{1}{2}\partial^{[\mu}(\beta_0 u^{\nu]}).$$

- Same conditions as for **global** equilibrium, where $k \cdot \partial f_{\mathrm{eq}} = 0$

DW, Phys. Rev. D **111**, 016008 (2025); $E_{\mathbf{k}} = u \cdot k$; Boltzmann limit

Local equilibrium and dissipative corrections

$$f = f_{\mathrm{eq}} + \delta f,$$

$$f_{\mathrm{eq}} = \left[\exp\left(\beta_0 u\cdot k + \frac{\hbar}{4m}\epsilon^{\mu\nu\alpha\beta}\Omega_{0,\mu\nu}k_\alpha \mathfrak{s}_\beta\right) + 1\right]^{-1},$$

$$\delta f = f_0(1-f_0)\sum_{\ell,n}\mathcal{H}^{(\ell)}_{\mathbf{k}n}k_{\mu_1}\cdots k_{\mu_\ell}\left(\rho_n^{\mu_1\cdots\mu_\ell} - \mathfrak{s}_\mu \tau_n^{\mu,\mu_1\cdots\mu_\ell}\right).$$

- We want to describe a *dissipative spin fluid*
- Express δf in terms of irreducible moments
- Equations of motion can be derived from Boltzmann equation
  - Not closed, equation for e.g. $\rho_r^{\mu\nu}$ depends on $\rho_{r-1}^{\mu\nu}$, $\rho_{r-2}^{\mu\nu}$

DW, Phys. Rev. D **111**, 016008 (2025); $f_0 = (e^{\beta_0 u\cdot k}+1)^{-1}$, $\alpha_0 = 0$

Standard dissipation

$$\rho_r^{\mu_1\cdots\mu_\ell}(x) \coloneqq \int \mathrm{d}\Gamma\, E_{\mathbf{k}}^r k^{\langle\mu_1}\cdots k^{\mu_\ell\rangle}\, \delta f(x,k,\mathfrak{s}).$$

Spin dissipation

$$\tau_r^{\mu,\mu_1\cdots\mu_\ell}(x) \coloneqq \int \mathrm{d}\Gamma\, \mathfrak{s}^\mu E_{\mathbf{k}}^r k^{\langle\mu_1}\cdots k^{\mu_\ell\rangle}\, \delta f(x,k,\mathfrak{s}).$$

- Perform moment expansion including spin degrees of freedom
- Equations of motion can be derived from Boltzmann equation
- Knowing the evolution of all moments is equivalent to solving the Boltzmann equation

DW, Phys. Rev. D **111**, 016008 (2025)

Quantum inverse Reynolds numbers

$$\frac{|\tau_r^\mu|}{\beta_0^{2-r}P_0} \sim \frac{|\tau_r^{\mu,\nu}|}{\beta_0^{1-r}P_0} \sim \frac{|\tau_r^{\mu,\nu\lambda}|}{\beta_0^{-r}P_0} \sim \mathrm{Re}_Q^{-1}.$$

- Leading spin quantities: $\mathcal{O}(\mathrm{Kn}_Q) \sim \mathcal{O}(\mathrm{Re}_Q^{-1}) \sim \mathcal{O}(\mathrm{Ro}_Q^{-1})$
- Next order couples spin to fluid gradients or dissipation:

$$\mathcal{O}(\mathrm{Kn}_Q\mathrm{Re}^{-1}) \sim \mathcal{O}(\mathrm{Kn}\,\mathrm{Re}_Q^{-1}) \sim \mathcal{O}(\mathrm{Re}_Q^{-1}\mathrm{Re}^{-1}).$$

- First-order sources: vorticity (axial vector), acceleration and $\nabla^\mu\alpha_0$ (vectors), shear (rank-two tensor)
- No first-order source for the remaining irreducible spin moments:

$$\tau_{r,\alpha}{}^{\alpha} \simeq 0, \qquad \tau_r^{\langle\mu,\nu\lambda\rangle} \simeq 0, \qquad \tau_r^{\mu,\mu_1\cdots\mu_\ell} \simeq 0 \quad (\ell > 2).$$

DW, Phys. Rev. D **111**, 016008 (2025)

- Derive asymptotic (Navier-Stokes) relations to close the system

Asymptotic matching (example)

$$\rho_r^{\mu\nu} = 2\eta_r \sigma^{\mu\nu} + \mathcal{O}(\mathrm{Kn}\,\mathrm{Re}^{-1}) = \frac{\eta_r}{\eta_0}\pi^{\mu\nu} + \mathcal{O}(\mathrm{Kn}\,\mathrm{Re}^{-1})$$

- Use these first-order relations *inside second-order terms*
- Errors from this substitution are third order
- Keep the evolution equation for $\pi^{\mu\nu}$, including its relaxation time
- Apply the same procedure to spin

DW, A. Palermo, V. E. Ambruș, Phys. Rev. D **106**, 016013 (2022); DW, Phys. Rev. D **111**, 016008 (2025)

Conserved currents

$$\frac{1}{2}T^{(\mu\nu)} = \int \mathrm{d}\Gamma\, k^\mu k^\nu f,$$
$$S^{\lambda\mu\nu} = -\frac{1}{2m}\int \mathrm{d}\Gamma\, k^\lambda \epsilon^{\mu\nu\alpha\beta} k_\alpha \mathfrak{s}_\beta f,$$
$$T^{[\mu\nu]} = \frac{1}{2}\int [\mathrm{d}\Gamma]\, \widetilde{\mathcal{W}}\, \Delta^{[\mu} k^{\nu]} (f_1 f_2 - f f').$$

$$\int \mathrm{d}\Gamma\, k^\mu C[f] = 0, \qquad \partial_\lambda T^{\lambda\mu} = 0, \qquad \hbar\partial_\lambda S^{\lambda\mu\nu} = T^{[\nu\mu]}.$$

DW, Phys. Rev. D **111**, 016008 (2025); $[\mathrm{d}\Gamma] = \mathrm{d}\Gamma_1 \mathrm{d}\Gamma_2 \mathrm{d}\Gamma \mathrm{d}\Gamma'$

Spin potential and spin-shear-stress tensor

$$\Omega_0^{\mu\nu} = u^{[\mu}\kappa_0^{\nu]} + \epsilon^{\mu\nu\alpha\beta}u_\alpha\omega_{0,\beta},$$

$$S^{\lambda\mu\nu} = A\,u^\lambda u^{[\mu}\kappa_0^{\nu]} + B\,u^\lambda\epsilon^{\mu\nu\alpha\beta}u_\alpha\omega_{0,\beta} + C\,u^{[\mu}\epsilon^{\nu]\lambda\alpha\beta}u_\alpha\omega_{0,\beta} + D\,\Delta^{\lambda[\mu}\kappa_0^{\nu]} + E\,\mathfrak{t}^{\lambda[\mu}u^{\nu]}.$$

- $u\cdot\omega_0 = u\cdot\kappa_0 = 0$.
- $\mathfrak{t}^{\mu\nu}$ is symmetric, traceless and orthogonal to u^μ.

$\omega_K^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}u_\nu\nabla_\alpha u_\beta$, $\sigma^{\mu\nu} = \nabla^{\langle\mu}u^{\nu\rangle}$. DW, Phys. Rev. D **111**, 016008 (2025)

Spacetime shifts

$$\Delta^\mu = -\frac{i\hbar}{8m}\frac{m^4}{\mathcal{W}} M^{\gamma_1\gamma_2\delta_1\delta_2} M^{\zeta_1\zeta_2\eta_1\eta_2} \times h_{1,\gamma_1\eta_1} h_{2,\gamma_2\eta_2} h'_{\zeta_2\delta_2} [h, \gamma^\mu]_{\zeta_1\delta_1},$$

$$h = \frac{1}{4m}(\mathbb{1} + \gamma_5 \not{s})(\not{k} + m).$$

- Depend on the transfer-matrix elements

$$\langle 11' | \widehat{t} | 22' \rangle = \bar{u}_{1,\alpha} \bar{u}_{1',\beta} u_{2,\gamma} u_{2',\delta} M^{\alpha\beta\gamma\delta}.$$

- Manifestly covariant

→ no "no-jump" frame

DW, N. Weickgenannt, D. H. Rischke, Phys. Rev. D **106**, 116021 (2022); DW, Phys. Rev. D **111**, 016008 (2025)

NJL-type interaction

$$M_{\alpha\alpha'\alpha_1\alpha_2} = \frac{2G}{\hbar}\left(\Gamma^{(c)}_{\alpha\alpha_1}\Gamma^{(c)}_{\alpha'\alpha_2} - \Gamma^{(c)}_{\alpha\alpha_2}\Gamma^{(c)}_{\alpha'\alpha_1}\right).$$

DW, M. Shokri, D. H. Rischke, Phys. Rev. Research **6**, 043103 (2024)

Thermal gluon exchange

$$M_{\alpha\alpha'\alpha_1\alpha_2} = \frac{2g}{\hbar}\left[\gamma^\mu_{\alpha\alpha_1}\frac{g_{\mu\nu}}{(k-k_1)^2 - m_{\text{th}}^2}\gamma^\nu_{\alpha'\alpha_2} - \gamma^\mu_{\alpha\alpha_2}\frac{g_{\mu\nu}}{(k-k_2)^2 - m_{\text{th}}^2}\gamma^\nu_{\alpha'\alpha_1}\right],$$

$$m_{\text{th}} = \frac{\sqrt{2N_C + N_f}}{3\sqrt{2}}\, gT.$$

DW, M. Shokri, D. H. Rischke, Phys. Rev. Research **6**, 043103 (2024)