Spin polarization in heavy-ion collisions

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Rotation and Polarization : Barnett effect

An initially unmagnetized body becomes magnetized under rotation, due to spin alignment induced by conservation of total angular momentum.

$$M = \chi \Omega / \gamma$$

where χ is the magnetic susceptibility, Ω is the angular velocity and γ is the gyromagnetic ratio.

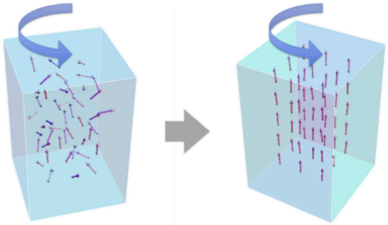


Image source : Front. Phys. 3:54 (2015)

Polarization in lab. QGP?

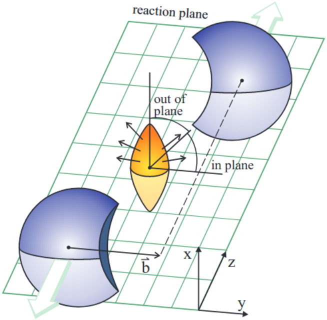
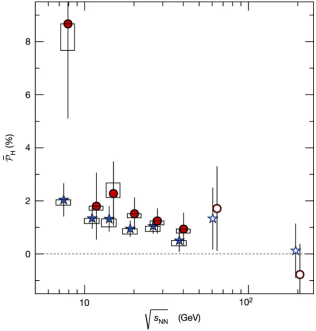


Image source - arXiv:0910.4114

- Nuclei carry a large orbital angular momentum (OAM), $L_0 = pb \simeq A\sqrt{s_{NN}}b/2$.
- e.g. for $\sqrt{s_{NN}} = 200$ GeV and $b = 5$ fm, $L_0 \sim 5 \times 10^5$.
- A fraction of L_0 if transferred to QGP fireball will result in polarization of quarks.
- A signature of an OAM would be the polarization of the emitted hadrons

Experimental observation of Λ-polarization



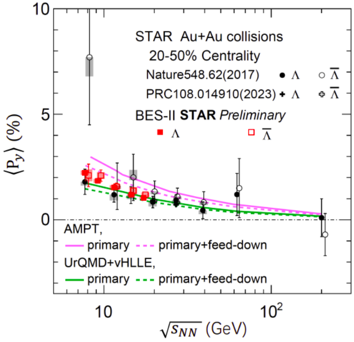
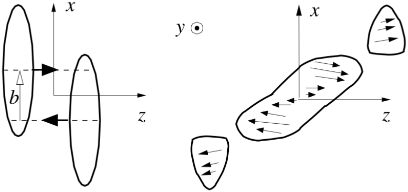


Image source: STAR Collaboration (left) Nature 548, 62-65 (2017) and (right) arXiv:2412.09897

Perturbative QCD approach to spin polarization

- *Given the nature of partonic interaction at high energy, the global angular momentum would never lead to a collective rotation of the system.* PRL 94, 102301 (2005)
- Global rotation leads to gradient of p_z in transverse plane leading to relative momentum $\Delta p_z = \frac{dp_z}{dx}\Delta x$ and hence relative OAM $(\Delta x \Delta p_z)$ between two quarks. This leads to quark polarization due to spin-orbit coupling.
- In coalescence model, $P_\Lambda = P_s \approx P_q$.
- This calculation gives large polarization value compared to data.



Hydrodynamic approaches to spin Polarization

1. Without Spin Current Evolution
   a. Quantum Statistical Approach
      - Based on local equilibrium density matrix (Zubarev formalism)
      - Spin polarization from thermal vorticity and thermal shear [Becattini-Buzzegoli-Palermo (BBP)]
   b. Equilibrium Chiral Kinetic Theory
      - First-order gradient expansion of axial Wigner function
      - Spin polarization from thermal vorticity and thermal shear [Liu and Yin (LY)]
2. With Spin Current Evolution
   a. (Ideal) Spin Hydrodynamics
      - Derived from kinetic theory with local collisions
      - Spin treated as classical $\mathcal{O}(\hbar^0)$ field
   b. (Dissipative) Spin Hydrodynamics
      - Derived from kinetic theory with non-local collisions
      - Spin treated as quantum $\mathcal{O}(\hbar)$ effect

Quantum statistical approach

- Consider a non-relativistic system of spin-$\frac{1}{2}$ particles in thermodynamic equilibrium and rotating with angular velocity ω. The density operator is given by

$$\hat{\rho} = \frac{1}{Z} \exp\left[-\frac{1}{T}(\hat{H} - \vec{\omega}.\hat{\mathbf{J}})\right]$$

where $\hat{H}$ is the Hamiltonian operator and $\hat{\mathbf{J}}$ is the total angular momentum operator.

- Mean spin is given by

$$\langle \hat{\mathbf{S}} \rangle = \mathrm{tr}[\hat{\rho}\hat{\mathbf{S}}]$$

- Assume the rotation to be along the z-axis and no spin-orbit coupling. A convenient basis is the eigenbasis of J_z and S_z denoted by $|n, m_l, m_s\rangle$. We have

$$\langle \hat{\mathbf{S}} \rangle = \frac{\hat{k}}{2} \tanh\left(\frac{\omega}{2T}\right) \approx \frac{\omega}{4T}\hat{k} \qquad \text{for } \frac{\omega}{T} \ll 1$$

Quantum statistical approach

AOP 338, 32 (2013); PLB 820, 136519 (2021) and PRL 127, 272302 (2021)

- Compute local equilibrium density operator ($\hat{\rho}_{\text{LE}}$) by maximizing entropy ($S = -\text{tr}[\hat{\rho}\ \log\hat{\rho}]$) subject to constraints

$$n_\mu\ \text{tr}[\hat{\rho}\hat{T}^{\mu\nu}] = n_\mu T^{\mu\nu} \quad , \quad n_\mu\ \text{tr}[\hat{\rho}\hat{N}^{\mu}] = n_\mu N^{\mu}$$

  In the Belinfante pseudogauge (spin tensor is 0), the procedure gives:

$$\hat{\rho}_{\text{LE}} = \frac{1}{Z_{\text{LE}}} \exp\left[-\int_\Sigma d\Sigma_\mu \left(\beta_\nu \hat{T}^{\mu\nu} - \zeta \hat{N}^\mu\right)\right] \text{ with } \beta_\nu = \frac{u_\nu}{T}\ , \zeta = \frac{\mu}{T}$$

- Evaluate the mean value of a quantum operator as

$$O(x) = \text{tr}[\hat{\rho}_{\text{LE}}\hat{O}(x)]$$

.

Polarization of spin-1/2 particles in a fluid cell is

$$S_\mu(x,p) = -\frac{1}{8m}\epsilon_{\mu\rho\sigma\tau}(1-n_F)\varpi^{\rho\sigma}p^\tau + \mathcal{O}(\varpi^2)$$

where n_F is the Fermi-Dirac distribution and $\varpi_{\rho\sigma}$ is thermal vorticity defined as

$$\varpi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma\beta_\rho - \partial_\rho\beta_\sigma) \qquad \text{with} \qquad \beta_\rho = \frac{u_\rho}{T}$$

Mean polarization vector is given by

$$S^\mu(p) = \frac{\int_\Sigma (d\Sigma.p)\, S^\mu(x,p) n_F(x,p)}{\int_\Sigma (d\Sigma.p)\, n_F(x,p)}$$

Input T, u^μ and their gradients from the numerical solution of relativistic hydrodynamics to compute the above expression.

Hydrodynamic simulation for global polarization

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Nuclear Physics A 967 (2017) 764–767

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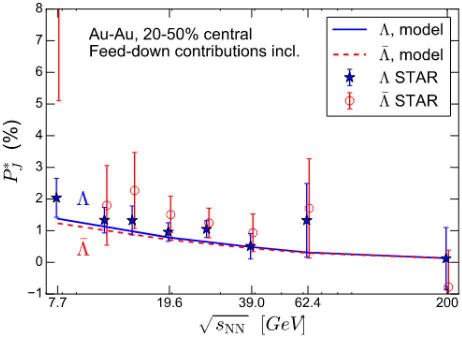
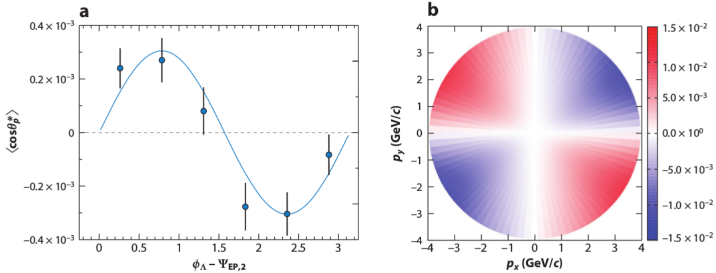
Vorticity in the QGP liquid and Λ polarization at the RHIC Beam Energy Scan

Iurii Karpenko[a,b], Francesco Becattini[a,c]



Spin sign puzzle

"Hydrodynamics predict a negative sign of the longitudinal component of the polarization vector."



Ann. Rev. Nucl. Part. Sci. 70 (2020) 395

Additional contribution from thermal shear, $\xi_{\mu\nu} = \frac{1}{2}(\partial_\sigma\beta_\rho + \partial_\rho\beta_\sigma)$, was derived such that

$$S^\mu(p) = S^\mu_\varpi(p) + S^\mu_\xi(p)$$

The sign of longitudinal polarization is still negative.

Isothermal approximation

At high energies $\mu_B \approx 0$. Hence, constant energy density implies constant T on Σ, so that

$$\hat{\rho}_{\rm LE} \sim \exp\left[-\frac{1}{T}\int_\Sigma d\Sigma_\mu \ \hat{T}^{\mu\nu} u_\nu\right]$$

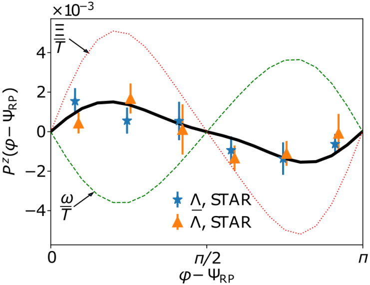
This gives Prescription I (PRL 127, 272302 (2021))

$$S^\mu(p) = -\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int d\Sigma\cdot p\ n_F(1-n_F)\left[\omega_{\nu\rho} + 2\hat{t}_\nu \frac{p^\lambda}{p\cdot\hat{t}}\Xi_{\lambda\rho}\right]}{8 m_\Lambda T \int d\Sigma \cdot p\ n_F}$$

where $\hat{t} = (1,0,0,0)$ and

$$\omega_{\nu\rho} = \frac{1}{2}(\partial_\rho u_\nu - \partial_\nu u_\rho)$$

$$\Xi_{\nu\rho} = \frac{1}{2}(\partial_\rho u_\nu + \partial_\nu u_\rho)$$



Chiral kinetic theory approach

JHEP07(2021)188 and PRL 127, 142301 (2021)

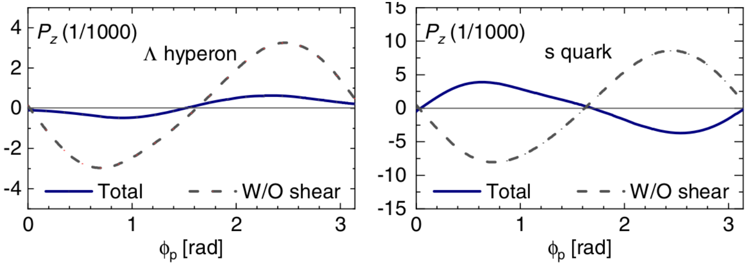
- The expression of axial Wigner function $\mathcal{A}^\mu$ from chiral kinetic theory is

$$\mathcal{A}^\mu = \sum_{\lambda=\pm}\left(\lambda p^\mu f_\lambda + \frac{1}{2}\frac{\epsilon^{\mu\nu\alpha\rho} p_\nu u_\alpha \partial_\rho f_\lambda}{p\cdot u}\right)$$

Replace f_λ with local equilibrium distribution $n_F(\beta(\varepsilon_0 - \Delta\varepsilon_\lambda))$ with $\varepsilon_0 = p\cdot u$, $\Delta\varepsilon_\lambda = -\lambda\omega\cdot p/(2\varepsilon_0)$ and expand to first order in gradients. Finally, averaging over Σ gives Prescription II

$$\begin{aligned} S^\mu(p) &= S^\mu_\varpi(p) + S^\mu_{\xi,\mathrm{LY}}(p) \\ S^\mu_{\xi,\mathrm{LY}}(p) &= -\frac{\epsilon^{\mu\nu\rho\sigma}}{4m} p_\sigma \frac{\int d\Sigma\cdot p\ n_F(1-n_F)\frac{p_\perp^\lambda u_\nu}{p\cdot u}\xi_{\rho\lambda}}{\int d\Sigma\cdot p\ n_F} \end{aligned}$$

- For $m = m_\Lambda$, $S_z(\phi)$ has wrong sign. However, for $m \approx 300$ MeV, the sign is correct. *"The memory of strange quark polarization is preserved in the measured Λ polarization"*.



Results from Prescription II. Image source: PRL 127, 142301 (2021)

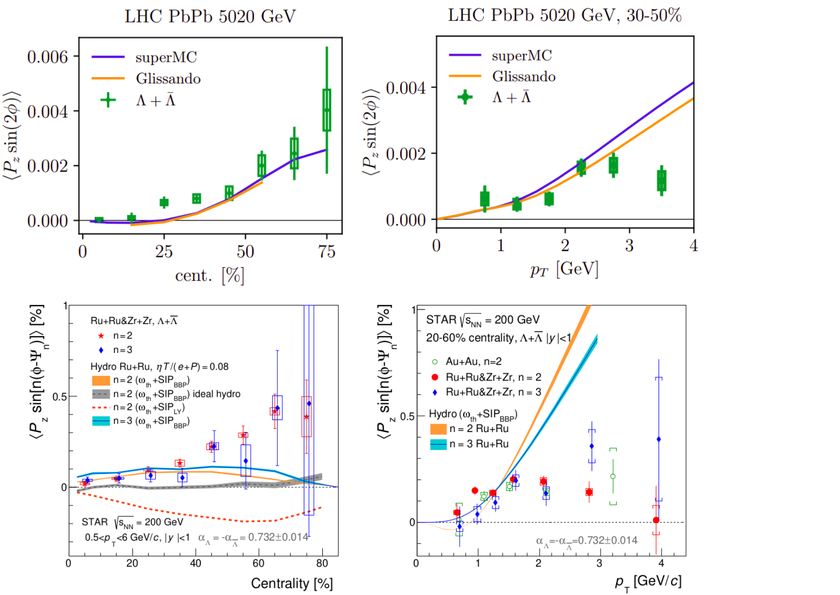
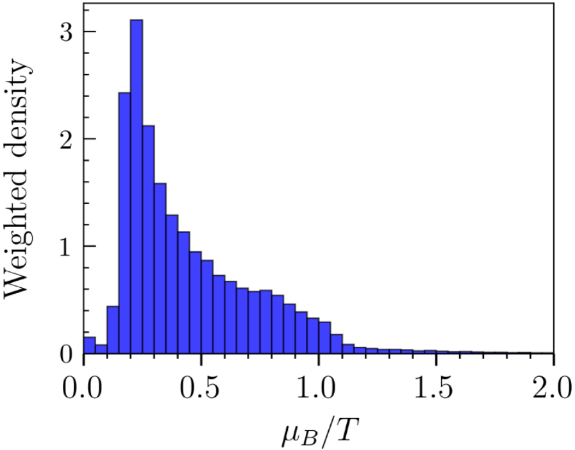


Image source: (top) Eur.Phys.J.Plus 138 (2023) 6, 547, and (bottom) PRL 131, 202301 (2023)

μ_B distribution on the particlization surface



SKS, R. Ryblewski, W. Florkowski, PRC 111, 024907 (2025)

Spin polarization in small systems

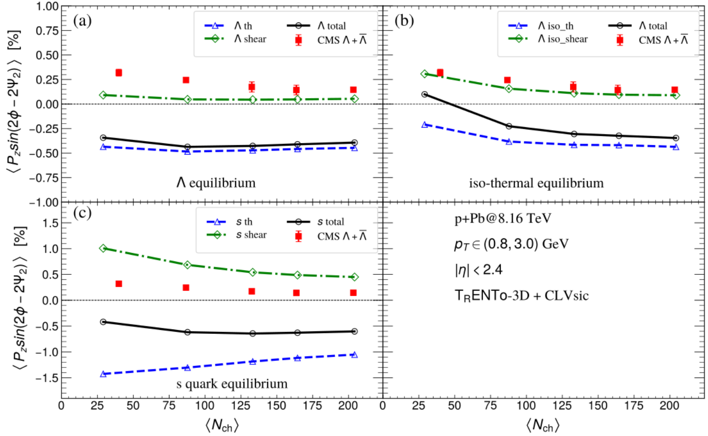
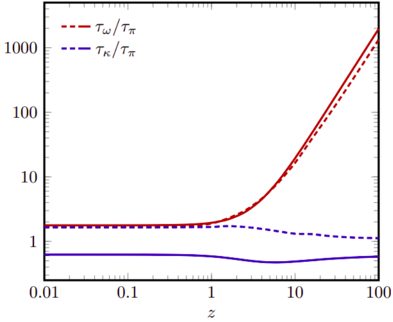


Image source: PRC 111, 044901 (2025)

Spin relaxation times



Spin relaxation times in units of the relaxation time of the shear-stress tensor (τ_π) for a scalar four-fermion interaction, $\mathcal{L}_{\text{int}} = G(\bar{\psi}\psi)^2$ plotted as a function of $z = m/T$. Image source: Phys.Rev.Res. 6 (2024) 4, 043103

Relativistic spin hydrodynamics

- Prescriptions I & II assume instantaneous equilibration of spin degrees of freedom.

- Spin relaxation time can become comparable to the lifetime of the fireball. In that case spin dynamics cannot be neglected.

- Spin dynamics is introduced by demanding conservation of total angular momentum

$$D_\mu J^{\mu,\alpha\beta} = 0$$

in addition to conservation of energy-momentum and charge

$$D_\mu T^{\mu\nu}(x) = 0 \quad , \quad D_\mu N^\mu(x) = 0.$$

- We have $J^{\mu,\alpha\beta} = L^{\mu,\alpha\beta} + S^{\mu,\alpha\beta}$, where $L^{\mu,\alpha\beta} = T^{\mu[\beta}x^{\alpha]}$. This gives

$$D_\mu S^{\mu,\alpha\beta} = T^{[\beta\alpha]} = T^{\beta\alpha} - T^{\alpha\beta}$$

where $T^{[\beta\alpha]}$ is the antisymmetric part of energy-momentum tensor.

Kinetic description of currents

- In kinetic theory, macroscopic quantities are obtained from moments of the single-particle distribution function

$$N^\mu = \int \frac{d^3p}{(2\pi)^3 p^0}\; p^\mu \; f(x,p)$$

$$T^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3 p^0}\; p^\mu \; p^\nu \; f(x,p)$$

- Can we define an analogous expression for the spin current, $S^{\mu,\alpha\beta}$?

- This requires extending $f(x,p)$ to include spin degrees of freedom $\rightarrow$ spin-dependent distribution $f(x,p,\mathfrak{s})$.

$$S^{\mu,\alpha\beta} = \sigma \int d\Gamma \; k^\mu \; \Sigma_{\mathfrak{s}}^{\alpha\beta} \; f(x,p,\mathfrak{s})$$

where $\Sigma_{\mathfrak{s}}^{\mu\nu} = -\frac{1}{m}\epsilon^{\mu\nu\alpha\beta} k_\alpha \mathfrak{s}_\beta$ and $d\Gamma$ is the measure for extended phase space.

- The goal is to derive a kinetic equation for $f(x, p, \mathfrak{s})$ that relaxes to equilibrium. In the spin sector, this requires that collisions allow conversion between orbital and spin angular momentum to conserve total angular momentum.

- The time evolution of the single-particle distribution function, $f(x, p, \mathfrak{s})$, is determined by the Boltzmann equation

$$k.\partial f(x, p, \mathfrak{s}) = C[f] = C_{\text{local}}[f] + C_{\text{nonlocal}}[f]$$

- Non-local collisions provide an exchange mechanism between spin and orbital angular momentum, facilitating spin equilibration.

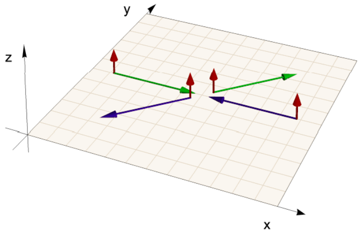


Image source:Prog. Part. Nucl. Phys. 108 (2019) 103709

- Equilibrium distribution is defined as

$$C_{\text{local}}[f_{\text{eq}}] = 0$$

- Local-equilibrium distribution function is

$$f_{\text{eq}}(x, p, \mathfrak{s}) = \left[\exp\left(\frac{p.u}{T} - \frac{\mu}{T} - \frac{\sigma\hbar}{2}\ \Omega_{0,\mu\nu}\Sigma_{\mathfrak{s}}^{\mu\nu}\right) \pm 1\right]^{-1}$$

where $\Omega_{0,\mu\nu}$ (or $\omega_{\mu\nu}$) is known as spin potential.

- Spin potential is a rank-2 antisymmetric tensor and can be decomposed as

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

- The anti-symmetric part of energy-momentum tensor is

$$T^{[\mu\nu]} = \frac{\hbar\sigma}{2} \int d\Gamma\ \Sigma_{\mathfrak{s}}^{\mu\nu}\ C[f] \qquad \Rightarrow \qquad T_0^{[\mu\nu]} \neq 0$$

- The equations of ideal spin hydrodynamics are

$$D_\mu T_0^{(\mu\nu)} = 0 + \mathcal{O}(\hbar^2) \qquad , \qquad D_\lambda S_0^{\lambda,\mu\nu} = \frac{1}{\hbar} T_0^{[\nu\mu]} + \mathcal{O}(\hbar^2)$$

- In small polarization limit, spin evolution decouples from the background. Numerical solution of spin hydrodynamics requires μ_B, T and u^μ from the background.

Image source: https://pixabay.com/

Relativistic dissipative spin hydrodynamics

Derived in D. Wagner, PRD 111, 016008 (2025) using the moment expansion method. Numerically solved in Sapna, **SKS** and D. Wagner, arXiv:2503.22552

$$\tau_\omega \dot{\omega}_0^{\langle\mu\rangle} + \omega_0^\mu = -\frac{\omega_K^\mu}{T} + \delta_{\omega\omega}\omega_0^\mu\theta + \epsilon^{\mu\nu\alpha\beta}u_\nu\left(\ell_{\omega\kappa}\nabla_\alpha\kappa_{0,\beta} - \tau_\omega\dot{u}_\alpha\kappa_{0,\beta}\right) + \lambda_{\omega\omega}\sigma^{\mu\nu}\omega_{0,\nu} + \lambda_{\omega\mathfrak{t}}\mathfrak{t}^\mu{}_\nu\omega_K^\nu\ ,$$

$$\tau_\kappa\dot{\kappa}_0^{\langle\mu\rangle} + \kappa_0^\mu = -\frac{\dot{u}^\mu}{T} + \delta_{\kappa\kappa}\kappa_0^\mu\theta + \epsilon^{\mu\nu\alpha\beta}u_\nu\left(\frac{\tau_\kappa}{2}\nabla_\alpha\omega_{0,\beta} + \tau_\kappa\dot{u}_\alpha\omega_{0,\beta}\right) + \ell_{\kappa\mathfrak{t}}\Delta^\mu_\lambda\nabla_\nu\mathfrak{t}^{\nu\lambda} + \tau_{\kappa\mathfrak{t}}\mathfrak{t}^{\mu\nu}\dot{u}_\nu + \left(\lambda_{\kappa\kappa}\sigma^{\mu\nu} + \frac{\tau_\kappa}{2}\omega_K^{\mu\nu}\right)\kappa_{0,\nu},$$

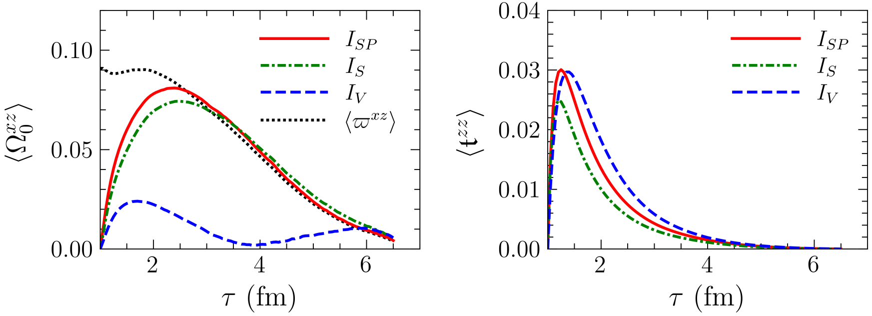
$$\tau_\mathfrak{t}\dot{\mathfrak{t}}^{\langle\mu\nu\rangle} + \mathfrak{t}^{\mu\nu} = \frac{\mathfrak{d}}{T}\sigma^{\mu\nu} + \delta_{\mathfrak{t}\mathfrak{t}}\mathfrak{t}^{\mu\nu}\theta + \lambda_{\mathfrak{t}\mathfrak{t}}\mathfrak{t}_\lambda{}^{\langle\mu}\sigma^{\nu\rangle\lambda} + \frac{5}{3}\tau_\mathfrak{t}\mathfrak{t}_\lambda{}^{\langle\mu}\omega_K^{\nu\rangle\lambda} + \ell_{\mathfrak{t}\kappa}\nabla^{\langle\mu}\kappa_0^{\nu\rangle} + \tau_{\mathfrak{t}\omega}\omega_K^{\langle\mu}\omega_0^{\nu\rangle} + \lambda_{\mathfrak{t}\omega}\sigma_\lambda{}^{\langle\mu}\epsilon^{\nu\rangle\lambda\alpha\beta}u_\alpha\omega_{0,\beta}.$$

In above equations, the symbols are as follows:

$$A^{\langle\mu\rangle} = \Delta^{\mu\nu}A_\nu, \quad \dot{A} = u\cdot\partial A, \quad \nabla^\mu = \Delta^{\mu\nu}\partial_\nu, \quad \sigma^{\mu\nu} = D^{\langle\mu}u^{\nu\rangle}$$

$$\omega_K^{\mu\nu} = \frac{1}{2}\Delta^\mu_\alpha\Delta^\nu_\beta D^{[\alpha}u^{\beta]} = \epsilon^{\mu\nu\alpha\beta}u_\alpha\omega_{K,\beta}$$

Results: Time evolution of spin potential and spin-shear stress



Sapna, **SKS**, D. Wagner, arXiv:2503.22552

Results are for three interactions (i) Scalar (I_S): $\mathcal{L}_{\text{int,S}} = G(\bar{\psi}\psi)^2$, (ii) Scalar+Pseudoscalar (I_{SP}): $\mathcal{L}_{\text{int,SP}} = G[(\bar{\psi}\psi)^2 - (\bar{\psi}\gamma_5\psi)^2]$, and (iii) Vector ($I_V$): $\mathcal{L}_{\text{int,V}} = -G(\bar{\psi}\gamma^\mu\psi)^2$

- The spin polarization is given by Prescription III

$$\boxed{S^\mu(p) = S^\mu_\omega(p) + S^\mu_\kappa(p) + S^\mu_{\mathfrak{t}}(p)}$$

where

$$S^\mu_\omega(p) = \frac{1}{N(p)} \int \mathrm{d}\Sigma \cdot p \frac{u^\mu(\omega_0 \cdot p) - \omega_0^\mu(p \cdot u)}{2m_\Lambda} f_0 \widetilde{f_0},$$

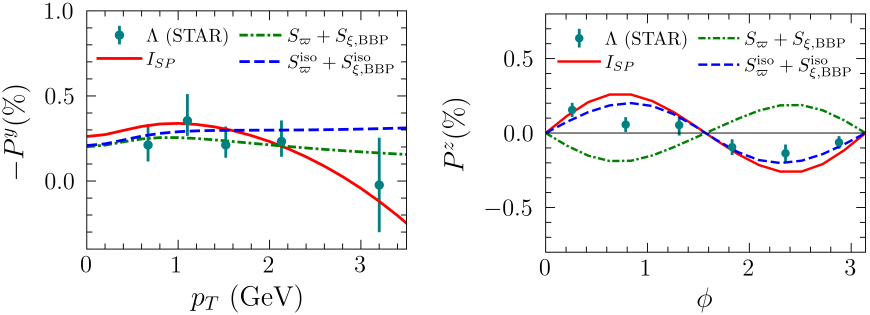
$$S^\mu_\kappa(p) = -\frac{1}{N(p)} \int \mathrm{d}\Sigma \cdot p \frac{\epsilon^{\mu\nu\rho\sigma} u_\nu p_\sigma}{2m_\Lambda} \kappa_{0,\rho} f_0 \widetilde{f_0} \ ,$$

$$S^\mu_{\mathfrak{t}}(p) = \frac{1}{N(p)} \int \mathrm{d}\Sigma \cdot p \frac{\epsilon^{\mu\nu\rho\sigma} u_\nu p^\lambda p_\sigma}{3T^2(\varepsilon + P)} \mathfrak{t}_{\rho\lambda} f_0 \widetilde{f_0} \ ,$$

and f_0 denotes the Fermi-Dirac distribution, $\widetilde{f_0} = 1 - f_0$, and $N(p) = 2\int \mathrm{d}\Sigma \cdot p\, f_0$.

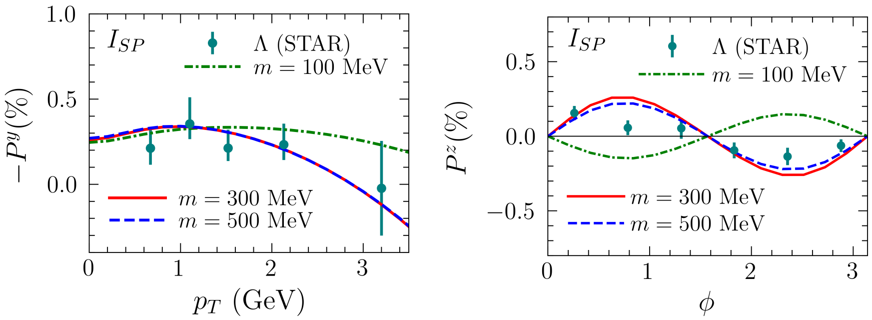
- Note that $S^\mu_{\mathfrak{t}}(p)$ is a dissipative correction to spin polarization.

Results: Spin Polarization



Comparison with Prescription I. Sapna, **SKS**, D. Wagner, arXiv:2503.22552

Results: Sensitivity to mass parameter



Spin polarization for different values of *m*. Sapna, **SKS**, D. Wagner, arXiv:2503.22552

- Dissipative effects are necessary to describe the polarization measurements.

Kinetic theory approach with local collisions only

- The energy-momentum tensor is symmetric, so that total spin is conserved (PRC 97 (2018) 4, 041901)

$$D_\mu S^{\mu,\alpha\beta} = 0$$

- Equilibrium spin tensor is given by (PRC 98, 044906 (2018))

$$S^{\alpha,\beta\gamma} = A_1 u^\alpha \omega^{\beta\gamma} + A_2 u^\alpha u^{[\beta} \kappa_0^{\gamma]} + A_3 \left(u^{[\beta} \omega^{\gamma]\alpha} + g^{\alpha[\beta} \kappa_0^{\gamma]} \right)$$

where $\kappa_{0,\mu} = \omega_{\mu\alpha} u^\alpha$ and

$$A_1 = \mathcal{C} \frac{T^3}{\pi^2} \left[\left(4 + \frac{m^2}{2T^2} \right) K_2\left(\frac{m}{T}\right) + \frac{m}{T} K_1\left(\frac{m}{T}\right) \right]$$

$$A_2 = 2\mathcal{C} \frac{T^3}{\pi^2} \left[\left(12 + \frac{m^2}{2T^2} \right) K_2\left(\frac{m}{T}\right) + 3\frac{m}{T} K_1\left(\frac{m}{T}\right) \right]$$

$$A_3 = -\mathcal{C} \frac{T^3}{\pi^2} \left[4K_2\left(\frac{m}{T}\right) + \frac{m}{T} K_1\left(\frac{m}{T}\right) \right]$$

- Numerical solution of spin hydrodynamics require initial spin potential, $T(x)$, $\mu_B(x)$, and $u^\mu(x)$.

Numerical solution of spin conservation equations

- The spin conservation equations are numerically solved in **SKS**, R. Ryblewski and W. Florkowski, PRC 111, 024907 (2025).

- Similar to traditional hydrodynamics, we need an initial condition and information about the spin thermalization time (τ_0^s). We treat the initial time as a parameter, with two parameters in total: m and τ_0^s.

- We use the following initial condition for the spin polarization tensor

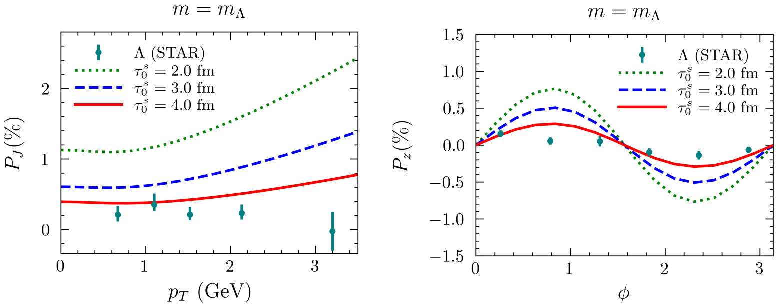
$$\omega_{\mu\nu}(\tau_0^s) = \varpi_{\mu\nu}^{\text{iso}} + 4\hat{\tau}_{[\mu}\xi_{\nu]\rho}^{\text{iso}} u^\rho,$$

  $\hat{\tau} = (1,0,0,0)$ being the unit normal to constant τ hypersurface.

- The spin polarization is obatined using Prescription IV (see also PRC 105 (2022), 044907)

$$\boxed{S^\mu(p) = -\frac{1}{8m_\Lambda}\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int d\Sigma \cdot p \; n_F(1-n_F)\omega_{\nu\rho}}{\int d\Sigma \cdot p \; n_F}}$$

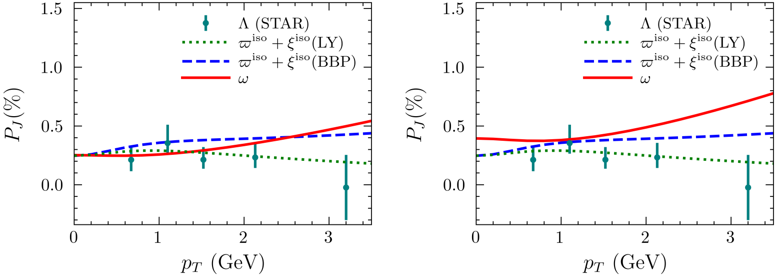
- Note that the initial time for background hydrodynamics is 1 fm. We take $m_\Lambda = 1.115$ GeV.



Simulation results for a fixed m but different τ_0^s PRC 111, 024907 (2025)

- “Good” fit is obtained if the initial spin time is 4 fm. What happens between 1 and 4 fm? *Dissipative processes are important at early times, while spin-conserving processes dominate at later stages.*

- We fix $\tau_0^s = 4$ fm,



Simulation results for a fixed τ_0^s but different mass (left) $m = 300$ MeV, (right) $m = 1.115$ GeV PRC 111, 024907 (2025)

- "Good" fit is obtained for small m. Relaxation seems to be faster for less massive particles.

Summary

- Discussed four prescriptions for analyzing spin polarization.
- Equilibrium based approaches rely on assumptions that are not universally valid.
- Discussed two schemes for spin dynamics in the fireball produced in heavy-ion collisions.
- Results suggest that at high temperatures and with long fireball lifetimes, the four prescriptions yield "equivalent" descriptions at the switching hypersurface
- The results also highlight that a consistent treatment of dissipative effects is crucial in microscopic approaches for matching experimental data.
- The real test of the approaches will be at lower collision energies or in small systems.