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Modeling Λ polarization in Au+Au collisions at $\sqrt{s_{NN}} = 200\ GeV$ using relativistic spin hydrodynamics (based on arxiv:2605.08219)

66. Cracow School of Theoretical Physics

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Introduction

- Non-central heavy-ion collisions generate large orbital angular momentum $\rightarrow$ formation of a rotating quark–gluon plasma (QGP)
- Orbital angular momentum $\rightarrow$ fluid vorticity $\rightarrow$ thermal vorticity couples to spin
- Thermal vorticity induces spin polarization in local equilibrium
- First measurement of Λ hyperon global polarization by the STAR Collaboration (2017) at RHIC [L. Adamczyk et al. (STAR), Nature 548 (2017)]
- The QGP behaves as an almost perfect fluid $\rightarrow$ relativistic hydrodynamics $\rightarrow$ EFT of conserved quantities

Flow

- We are interested in spin polarization induced in asymmetric and symmetric heavy ion collisions
- New family of analytic 1+1 D flows was recently proposed in [S. Shi, S. Jeon, C. Gale, Phys. Rev. C 105 (2022)]

$$u^\tau = \frac{1}{2}\left(\sqrt{\frac{t_0 e^{\eta-\eta_0} + \tau a}{t_0 e^{\eta-\eta_0} + \tau/a}} + \sqrt{\frac{t_0 e^{\eta-\eta_0} + \tau/a}{t_0 e^{\eta-\eta_0} + \tau a}}\right) \tag{1}$$

$$u^\eta = \frac{1}{2\tau}\left(\sqrt{\frac{t_0 e^{\eta-\eta_0} + \tau a}{t_0 e^{\eta-\eta_0} + \tau/a}} - \sqrt{\frac{t_0 e^{\eta-\eta_0} + \tau/a}{t_0 e^{\eta-\eta_0} + \tau a}}\right) \tag{2}$$

- Parameters: a — asymmetry parameter ($a = 1$ symmetric), t_0 — initial time, η_0 — rapidity shift τ_0 - scaling parameter

Spin hydrodynamics

- Density operator in local thermal equilibrium follows as

$$\widehat{\rho}_{\rm LTE} = \frac{1}{Z_{\rm LTE}} \exp\left[-\int_\Sigma d\Sigma_\mu(x) \left(\beta_\nu(x)\, \widehat{T}^{\mu\nu}(x) - \xi(x)\, \hat{j}^\mu(x) - \frac{1}{2}\, \omega_{\alpha\beta}(x)\, \widehat{S}^{\mu,\alpha\beta}(x) \right) \right] \tag{3}$$

- Pseudogauge freedom in the definition of energy-momentum tensor and spin tensor

$$\widehat{T}^{\mu\nu} \to \widehat{T}^{\mu\nu} + \frac{1}{2}\partial_\lambda(\widehat{\Phi}^{\lambda,\mu\nu} + \widehat{\Phi}^{\nu,\lambda\mu} + \widehat{\Phi}^{\mu,\nu\lambda}),$$
$$\widehat{S}^{\lambda,\mu\nu} \to \widehat{S}^{\lambda,\mu\nu} + \widehat{\Phi}^{\lambda,\mu\nu},\ \widehat{\Phi}^{\mu,\nu\lambda} = -\widehat{\Phi^{\mu,\lambda\nu}} \tag{4}$$

- Main idea: Total angular momentum is conserved. Spin is not instantaneously equilibrated, its dynamics must be included [R. Singh, Int. J. Mod. Phys. A 38 (2023) no.20, 2330011], [W. Florkowski, A. Kumar, R. Ryblewski, Prog. Part. Nucl. Phys. **108** (2019) 103709]
- Symmetric energy-momentum tensor

$$\partial_\lambda \widehat{S}^{\lambda,\mu\nu} = \widehat{T}^{\mu\nu} - \widehat{T}^{\nu\mu} = 0 \tag{5}$$

- New Lagrange multiplier - spin potential $\omega^{\mu\nu}$

$$\widehat{T}^{\mu\nu}_{\rm GLW} = \frac{i}{4}\left[\widehat{\bar{\psi}}\gamma^\mu \overleftrightarrow{\partial}^\nu \widehat{\psi} + \widehat{\bar{\psi}}\gamma^\nu \overleftrightarrow{\partial}^\mu \widehat{\psi} \right],\ \widehat{S}^{\lambda,\mu\nu}_{\rm GLW} = \frac{1}{4}\,\widehat{\bar{\psi}}\left\{ \gamma^\lambda, \Sigma^{\mu\nu} \right\} \widehat{\psi} \tag{6}$$

Spin polarization

- The polarization vector is obtained as the thermal expectation value of the Pauli–Lubanski operator [F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Annals Phys. **338** (2013)]

$$P^{\mu}(p) = \langle \widehat{\rho}\,\widehat{\Pi} \rangle = -\frac{1}{8m}\,\epsilon^{\mu\nu\rho\sigma}\,p_{\sigma}\,\frac{\int_{\Sigma_{FO}} d\Sigma_{\lambda}(x)\,p^{\lambda}\,n_F(x,p)\big(1-n_F(x,p)\big)\,\omega_{\nu\rho}(x)}{\int_{\Sigma_{FO}} d\Sigma_{\lambda}(x)\,p^{\lambda}\,n_F(x,p)} \tag{7}$$

- Unknown component is spin potential → found from the conservation equation of spin tensor

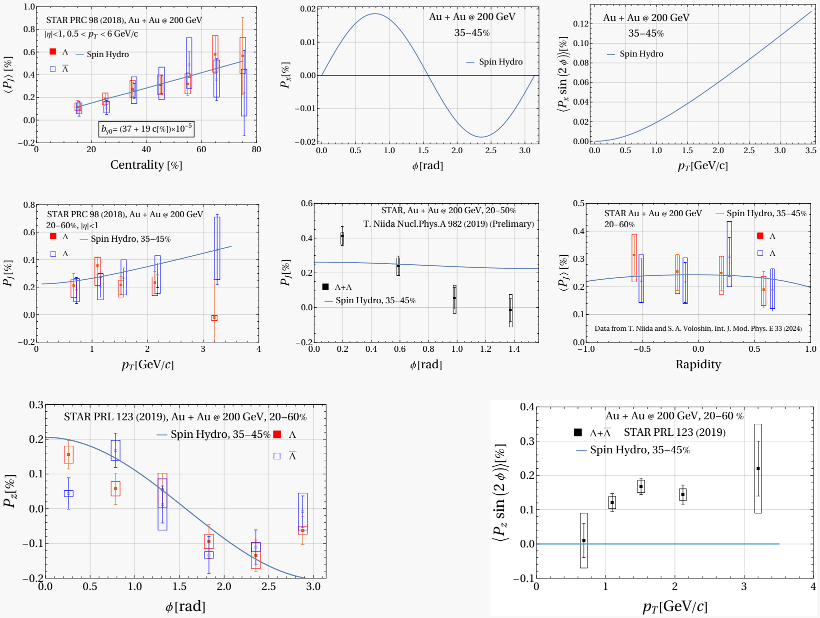
$$\partial_{\lambda} S^{\lambda,\mu\nu} = 0 \tag{8}$$

- We initialize spin components as

$$\omega_x(\tau_s,\eta_s) = \frac{b_{x0}\,u^3(\tau_s,\eta_s)}{u^0(\tau_s,\eta_s)^2}, \qquad [\eta_s - \text{odd}], \tag{9}$$

$$\omega_y(\tau_s,\eta_s) = -\frac{b_{y0}}{u^0(\tau_s,\eta_s)}, \qquad [\eta_s - \text{even}]. \tag{10}$$

Spin polarization in 1+1 D model



1-1-2 model

- In order to obtain better agreement with the data, we introduce transversal flow as

$$u^\mu = \left(\gamma_\perp\, u^0, \boldsymbol{u}_\perp, \gamma_\perp\, u^3\right), \; \gamma_\perp = \sqrt{1 + |\boldsymbol{u}_\perp|^2} \tag{11}$$

- Strength of transversal is described as

$$\boldsymbol{u}_\perp = u_\perp \frac{\left(R_y^2 \cos\varphi,\; R_x^2 \sin\varphi\right)}{\sqrt{R_y^4 \cos^2\varphi + R_x^4 \sin^2\varphi}}\,,$$
$$\delta = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}, \qquad R_x = \frac{R_{\mathrm{FO}}}{\sqrt{1+\delta}}, \qquad R_y = \frac{R_{\mathrm{FO}}}{\sqrt{1-\delta}}. \tag{12}$$

- Additionally, temperature dependence obtains modified profile as

$$T(\tau,\, x,\, y,\, \eta_s) = T(\tau,\, \eta_s) \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right), \sigma_x^2 = \frac{\sigma^2}{1+\delta}, \sigma_y^2 = \frac{\sigma^2}{1-\delta}. \tag{13}$$

- New parameters controlling the size and deformation of freeze-out elipsoid: R_{FO} and δ, variation of temperature: σ

1-1-2 Hadron spectra fit

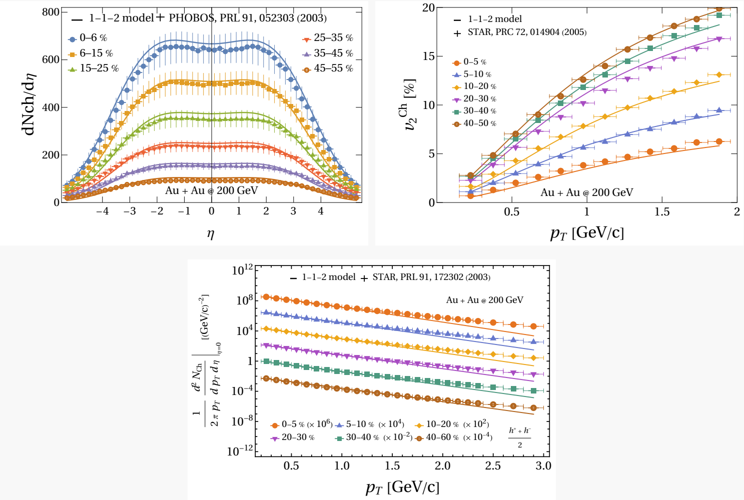


Figure 2: The hadron spectra distribution obtained using the $1-1-2$ model for Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV for various centrality classes.

Spin initialization in 1-1-2 model

- Introduction of transversal flow components, u_x and u_y allows for a_z to contribute to the polarization component P_z
- In order to keep minimal set of parameters, we intialize spin components as

$$a_z(\tau_s, \eta_s) = \frac{a_{z0}\, u^3(\tau_s, \eta_s)}{u^0(\tau_s, \eta_s)^2}, \quad [\eta_s - \mathrm{odd}] \tag{14}$$

$$\omega_y(\tau_s, \eta_s) = \frac{b_{y0}}{u^0(\tau_s, \eta_s)}. \quad [\eta_s - \mathrm{even}] \tag{15}$$

- The parameter b_{y0} is chosen to reproduce the experimental global spin polarization, while a_{z0} is fixed from the local longitudinal polarization, using $\langle P_z \sin(2\phi)\rangle(p_T = 1.09\ \mathrm{GeV}/c) = 0.121\%$ for the 20–60% centrality class [STAR PRL 123 (2019)]

Spin polarization components - transversal plane

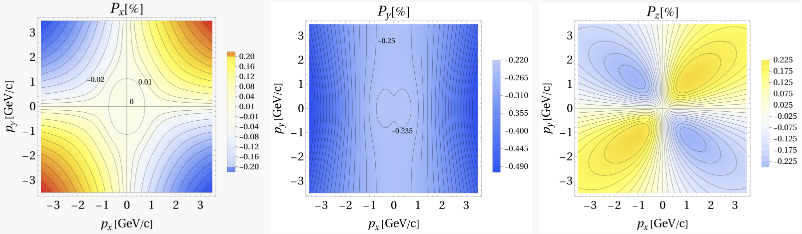


Figure 3: The local spin polarization vector components at mid-rapidity as a functions of transverse momentum components for Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV within centrality class $35 - 45\%$ for $1 + 1 + 2$D freeze-out.

- longitudinal component P_z and P_x display quadrupole structure
- Component P_y has negative values - in the direction of initial angular momentum

Spin polarization P_x- azimuthal angle and transversal momentum

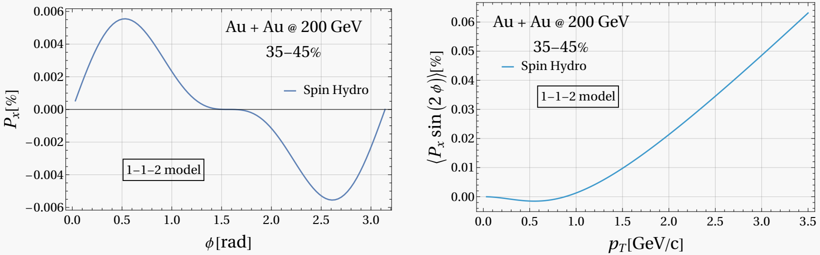


Figure 4: The in-plane transverse spin polarization P_x as a function of momentum azimuthal angle ϕ (left), and its second Fourier coefficient as a function of transverse momentum p_T (right) for Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV within the centrality class 35–45% for $1+1+2$D freeze-out.

- P_x component in respect to azimuthal angle is in agreement with [A. Arslan, W.-B. Dong, C. Gale, S. Jeon, Q. Wang, X.-Y. Wu, arXiv:2509.00796 (2025)]
- Second Fourier coefficient of P_x displays a minimum due to the inclusion of transverse momentum

Spin polarization P_z

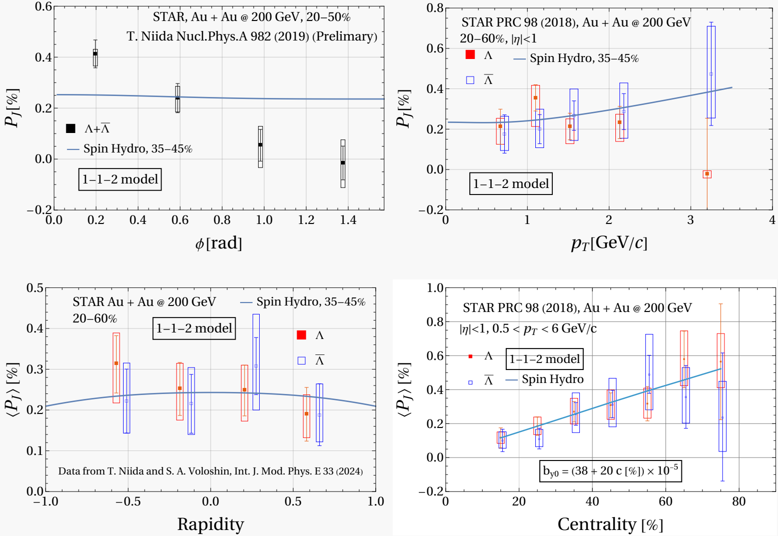


Figure 5: The P_J component as a function of the azimuthal angle ϕ and transverse momentum p_T (top), and the global spin polarization $\langle P_J \rangle$ as a function of centrality and rapidity (bottom).

Longitudinal spin polarization P_z

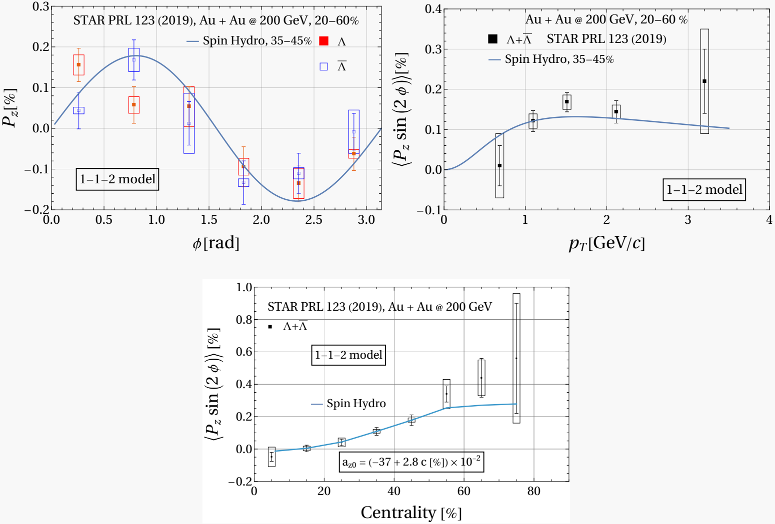


Figure 6: The local longitudinal spin polarization P_z as a function of the azimuthal angle ϕ and the second Fourier coefficient as a function of transverse momentum p_T (top), together with the centrality dependence of the second Fourier coefficient of P_z (bottom).

Conclusion and Outlook

- We have performed a fit to hadronic spectra in order to obtain the parameters of the hydrodynamic evolution
- We have obtained qualitative and quantitative agreement with the most spin polarization observables using the 1-1-2 model
- This model has significant potential and can be applied to smaller or asymmetric systems as well (O+O, Pb+p, . . .)
- Additional inclusion of dissipation or stochastic fluctuations may provide further insight and improvement