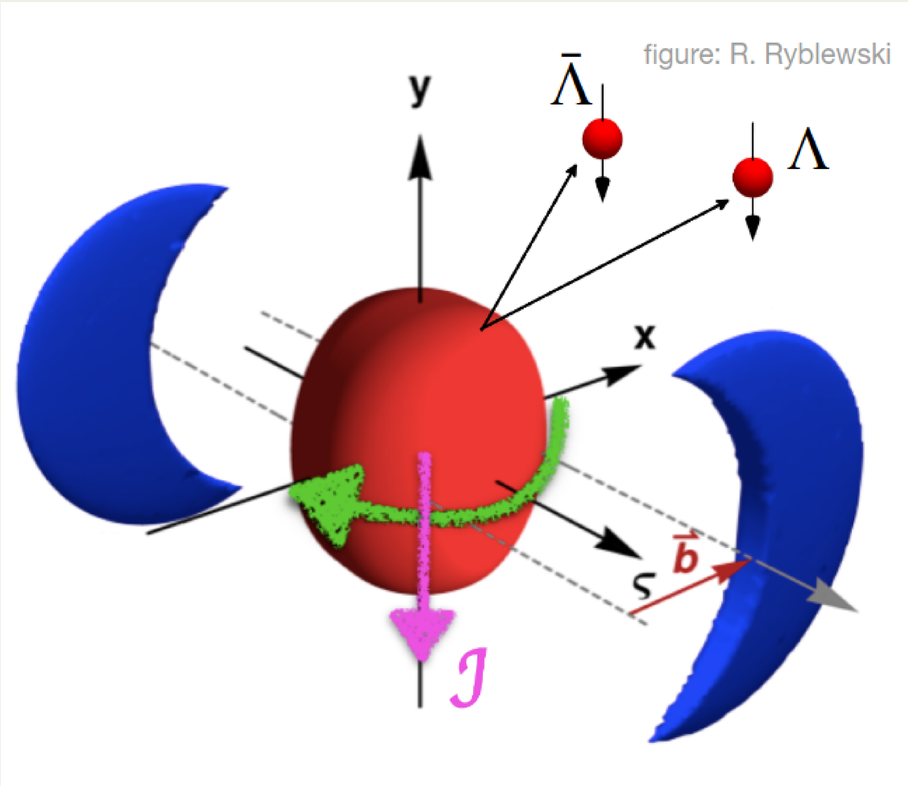
Longitudinal spin polarization in a thermal model with dissipative corrections

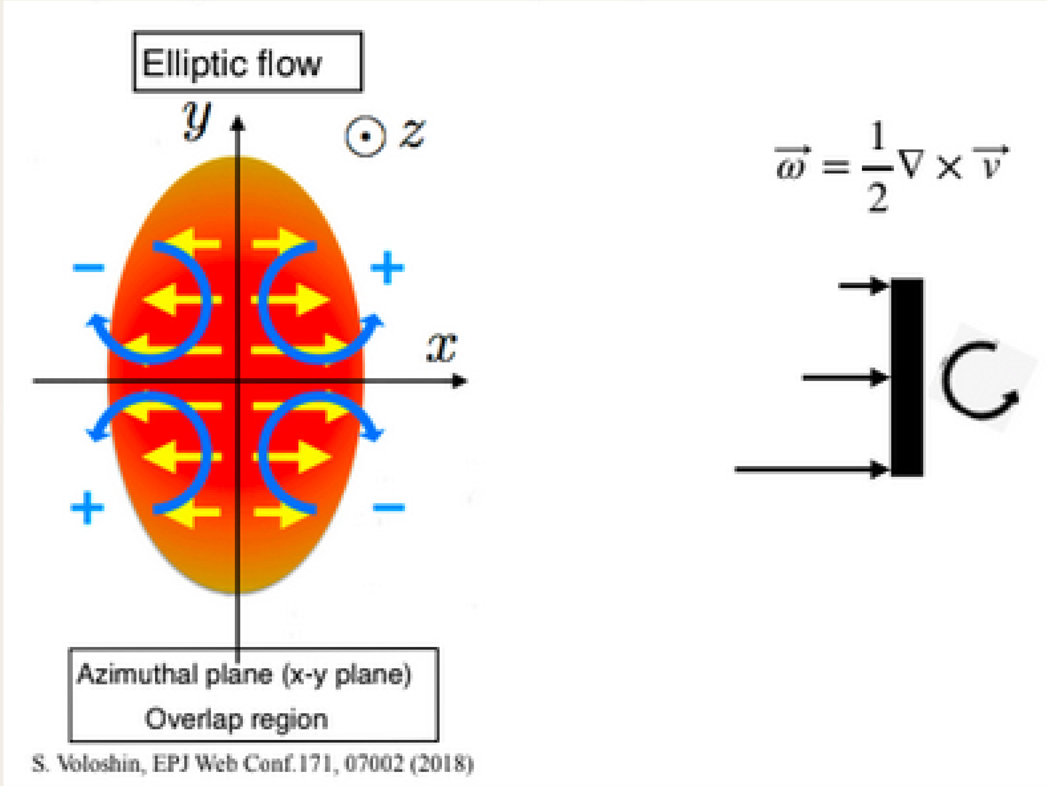
Soham Banerjee [1] Samapan Bhadury [2] Wojciech Florkowski [2] Amaresh Jaiswal [1 2] Radoslaw Ryblewski [3]

[1]SPS NISER,India [2]ITP Jagiellonian University,Poland [3]INP, Polish Academy of Sciences, Poland

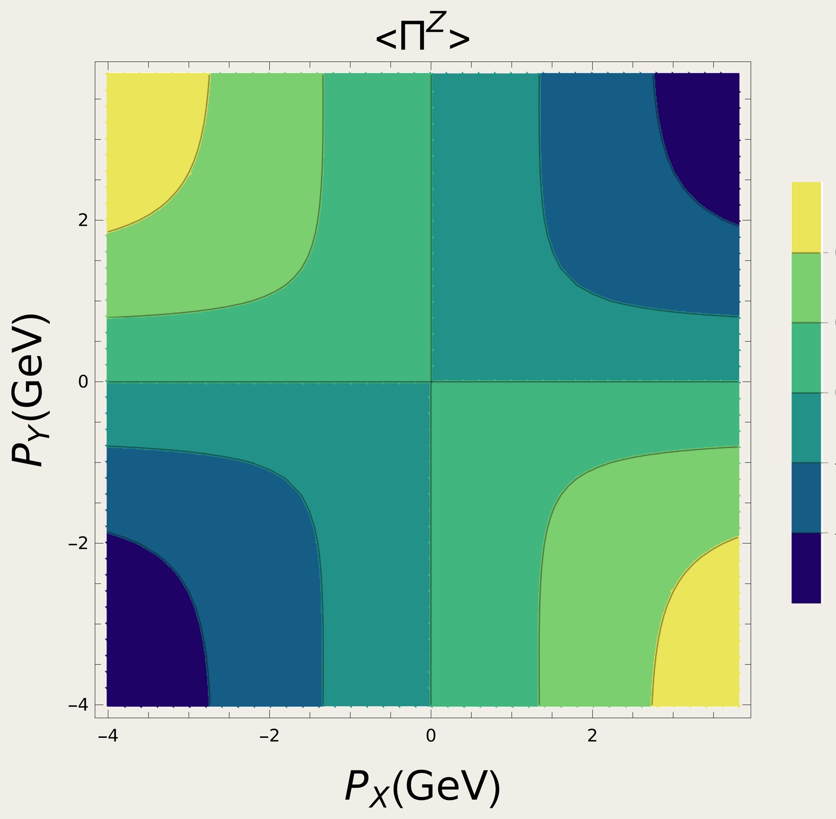
$\Lambda/\bar{\Lambda}$ hyperon polarization in non-central heavy ion collision



(a) Global angular momentum deposition



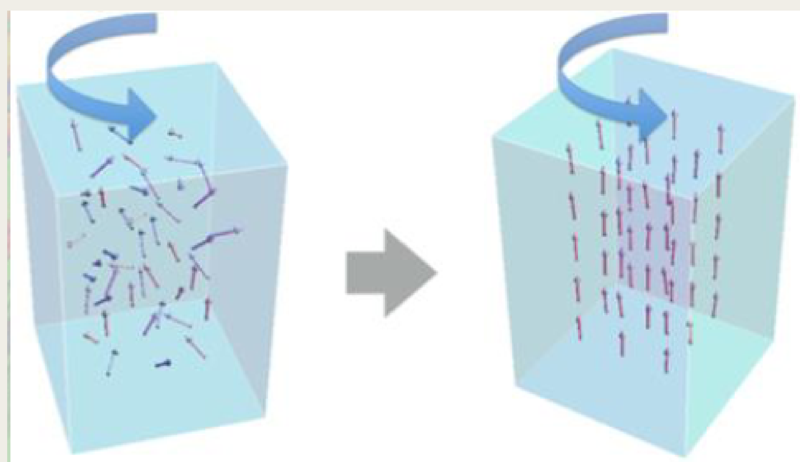
(b) Local polarization



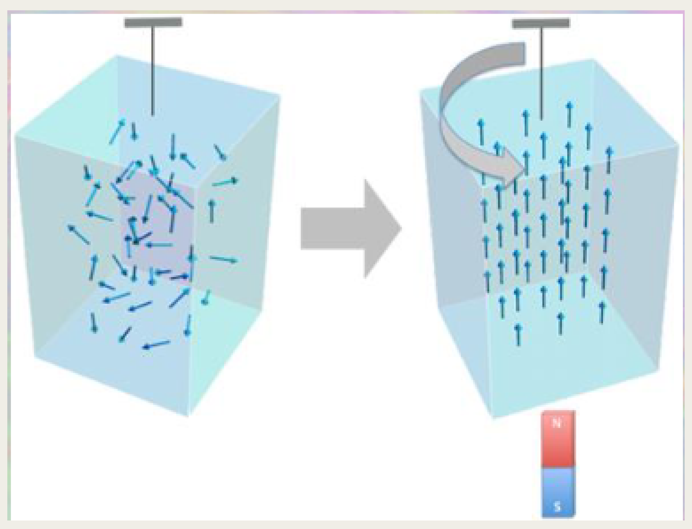
(c) Theoretical prediction with thermal vorticity

Angular momentum deposition

- Deposition of angular momentum in non-central heavy ion collison.
- Orbital angular momentum $\longleftrightarrow$ spin angular momentum through Barnett effect and Einstein–de Haas effect.



(a) Barnett Effect[Credit :Mike Lisa, OSU]



(b) Einstein–de Haas effect [Credit :Mike Lisa, OSU]

- Global polarization explained by theoretic models but fails for the local polarization. [F. Becattini et al. 2021]
- The local polarization is dependant on thermal vorticity $\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu)$
- Recent theoretical developments on spin relaxation time.

Spin Hydrodynamics

- From energy conservation: $\partial_\mu T^{\mu\nu} = 0$
- From number density conservation: $\partial_\mu N^\mu = 0$
- Total angular momentum

  $J^{\mu,\lambda\nu} = x^\lambda T^{\mu\nu} - x^\nu T^{\mu\lambda} + S^{\mu,\lambda\nu}$

$$\partial_\mu J^{\mu,\lambda\nu} = T^{\mu\nu} - T^{\nu\mu} + \partial_\mu S^{\mu,\lambda\nu} = 0;$$

- From spin conservation: $\partial_\mu S^{\mu,\nu\lambda} = 0$
- Promote spin tensor to an additional dynamical variable.
- $T^{\mu\nu}(\beta,\xi,\omega)$, $j^\mu(\beta,\xi,\omega)$, $S^{\mu,\nu\lambda}(\beta,\xi,\omega)$

Kinetic theory with spin

- Boltzmann equation: $p^\mu\partial_\mu f(x,p,s) = C[(x,p,s)]$
- RTA collision kernel: $C[f(x,p,s)] = \dfrac{u\cdot p}{\tau_s}[f_{eq}(x,p,s) - f(x,p,s)]$
- Chapman–Enskog expansion: $f(x,p,s) = f_{eq}(x,p,s) + \delta f(x,p,s)$

The spin tensor

- $f^\pm_{eq} = e^{\pm\xi - p.\beta + \frac{1}{2}\omega_{\mu\nu}s^{\mu\nu}}$
- $S^{\lambda,\mu\nu}_{eq} = \int dPdSp^\lambda s^{\mu\nu}[f_{s,eq}]$

  $= \frac{1}{m^2}\int dPp^\lambda e^{-p.\beta}(m^2\omega^{\mu\nu} + 2p_\rho p^{[\mu}\omega^{\nu]\rho})$
- $\delta f^\pm_s = -\frac{\tau_s}{u\cdot p}e^{\pm\xi-\beta\cdot p}\left[-p^\lambda p^\mu(\partial_\mu\beta_\lambda)\left(1+\frac{1}{2}s^{\alpha\beta}\omega_{\alpha\beta}\right) + \frac{1}{2}p^\mu s^{\alpha\beta}(\partial_\mu\omega_{\alpha\beta})\right]$ [Bhadury et al. 2020]
- $\delta S^{\lambda,\mu\nu} = \int dPdSp^\lambda s^{\mu\nu}(\delta f^+_s + \delta f^-_s)$

  $= \frac{\tau_s\cosh\xi}{m^2}\int\frac{dP}{(u\cdot p)}p^\lambda e^{-\beta\cdot p}$

  $\times\left[p^\rho p^\sigma(\partial_\sigma\beta_\rho)\left(m^2\omega^{\mu\nu} + 2p_\alpha p^{[\mu}\omega^{\nu]\alpha}\right) - m^2p^\rho(\partial_\rho\omega^{\mu\nu}) - 2p^\rho p_\alpha p^{[\mu}\left(\partial_\rho\omega^{\nu]\alpha}\right)\right]$
- $dP \equiv \frac{d^3p}{(2\pi)^3p^0}$

  $dS \equiv \frac{4m}{3\pi}d^4s\,\delta\left(s\cdot s + \frac{3}{4}\right)\delta(p\cdot s)$

Pauli-Lubanski vector

- $\langle P(\phi_p)\rangle = \dfrac{\int p_T dp_T E_p\frac{d\Pi^z(p)}{d^3p}}{\int d\phi_p p_T dp_T E_p\frac{dN(p)}{d^3p}}$
- $E_p\dfrac{dN(p)}{d^3p} = \dfrac{4\cosh\xi}{(2\pi)^3}\displaystyle\int\Delta\Sigma_\lambda p^\lambda e^{-\beta.p}, \quad \xi = \mu/T,\ \beta^\mu = u^\mu/T$
- $E_p\dfrac{d\Delta\Pi_\tau(x,p)}{d^3p} = -\dfrac{1}{2}\epsilon_{\tau\mu\nu\beta}\Delta\Sigma_\lambda E_p\dfrac{dS^{\lambda,\mu\nu}(\omega)}{d^3p}\dfrac{p^\beta}{m}$
- $E_p\frac{d\Pi_\alpha(p)}{d^3p} = -\frac{\cosh(\xi)}{2m(2\pi)^3}\int\Delta\Sigma\cdot p\,\epsilon_{\alpha\mu\nu\beta}p^\beta e^{-\beta\cdot p}\times\left[(1+\chi)\omega^{\mu\nu} - \frac{\tau_s}{(u\cdot p)}p^\rho(\partial_\rho\omega^{\mu\nu})\right]$

  $\chi = \frac{\tau_s}{(u\cdot p)}p^\rho p^\sigma(\partial_\sigma\beta_\rho) = \frac{\tau_s p^\rho p^\sigma\xi_{\sigma\rho}}{(u\cdot p)}$
- $\omega \longrightarrow \varpi$ and $\varpi_{0i} = 0$

Thermal Model

- Single freeze-out model.
- $\tau^2_f = t^2 - x^2 - y^2 - z^2$

  with $x^2 + y^2 \leq r^2_{max}$.
- Asymmetry of the fireball boundary $x = r_{\max}\sqrt{1-\epsilon}\,\cos\phi$

  $y = r_{\max}\sqrt{1+\epsilon}\,\sin\phi$
- Asymmetry of the hydrodynamic flow.

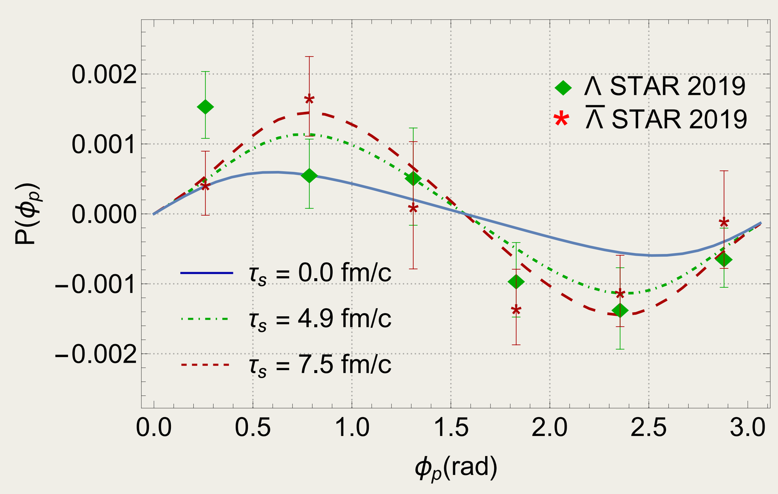
  $u^\mu = \dfrac{1}{N}(t,\,x\sqrt{1+\delta},\,y\sqrt{1-\delta},\,z)$

  $N = \sqrt{\tau^2 - (x^2-y^2)\delta}$

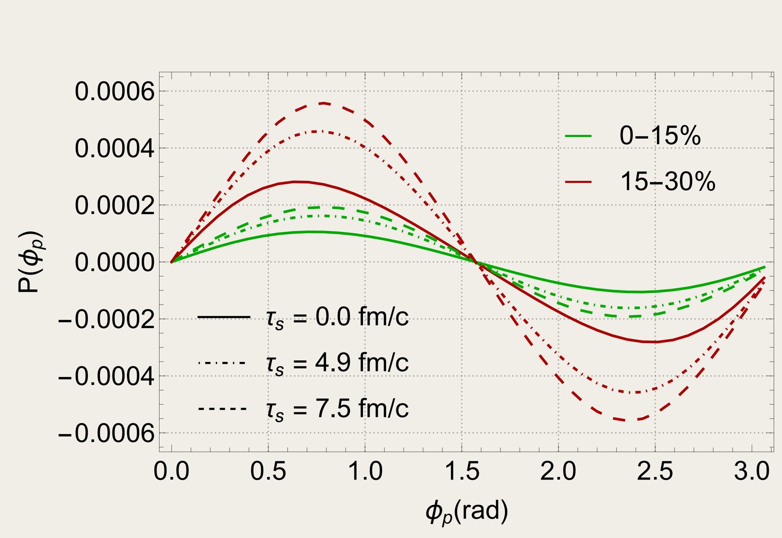
c %	ϵ	δ	τ_f [fm]	r_{max} [fm]
0-15	0.055	0.12	7.666	6.540
15-30	0.097	0.26	6.258	5.417
30-60	0.137	0.37	4.266	3.779

Freeze-out Temperature is $T_f = 165$ MeV. [Baran 2004], [Florkowski et al. 2019].

Results



(a) The longitudinal polarization shown as a function of the azimuthal angle ϕ_p for 30–60% Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [Banerjee et al. 2024] compared with the experimental data by STAR. [STAR 2019]



(b) Our predictions for the Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV for centralities $0-15\%$ and $15-30\%$

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