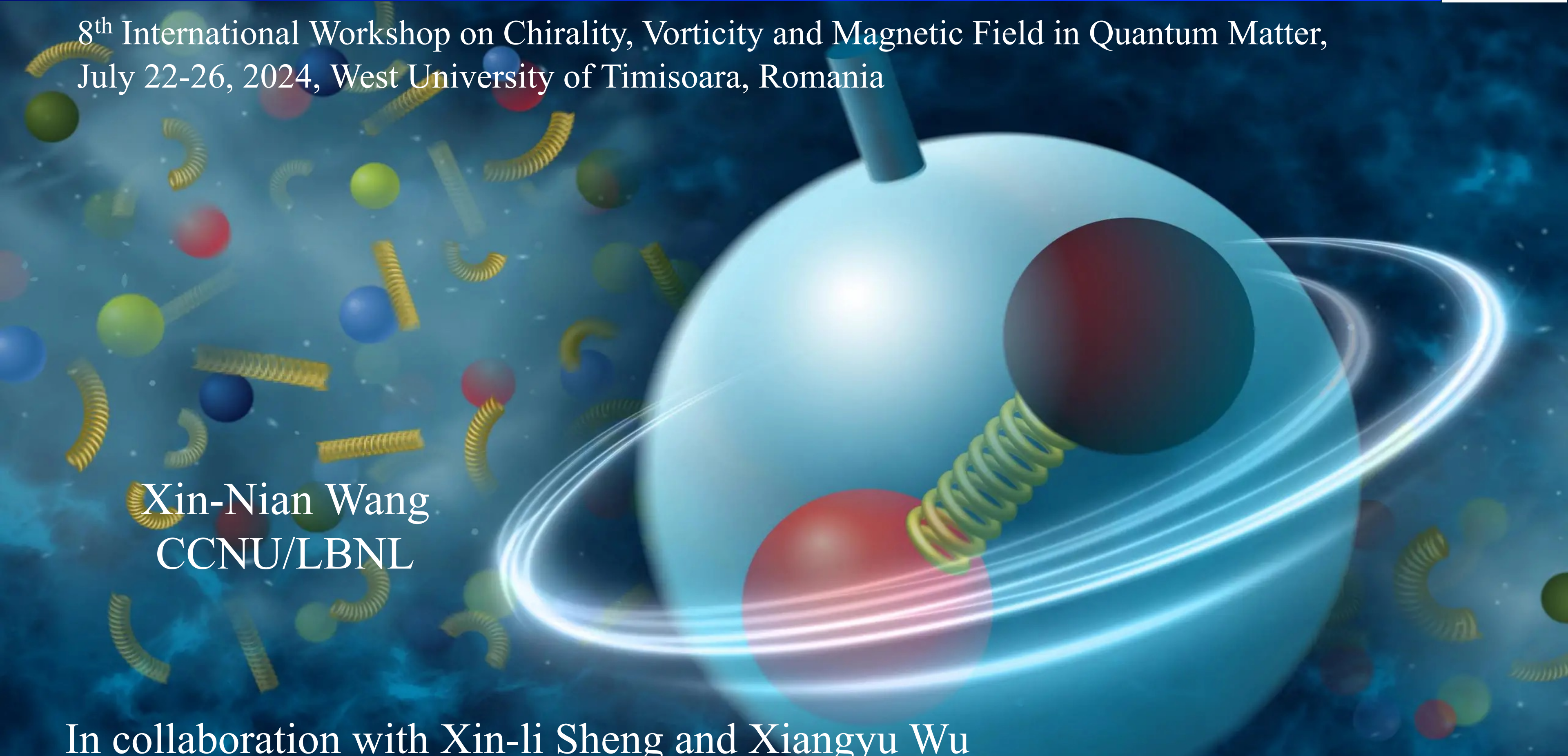
Λ-Λ(bar) Spin Correlation in Heavy-ion Collisions

8th International Workshop on Chirality, Vorticity and Magnetic Field in Quantum Matter,
July 22-26, 2024, West University of Timisoara, Romania

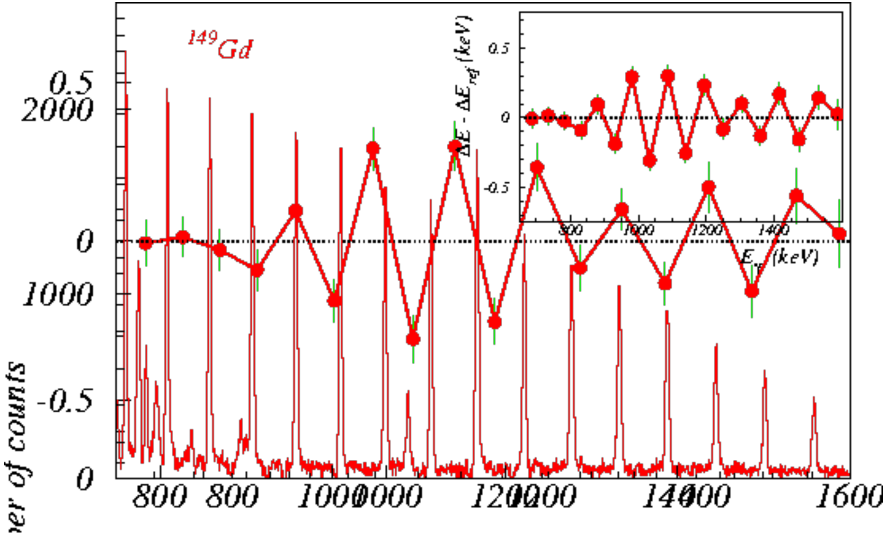


Xin-Nian Wang
CCNU/LBNL

In collaboration with Xin-li Sheng and Xiangyu Wu

Global Orbital Angular Momentum

Spins of superdeformed nuclei in low-energy nuclear collisions:



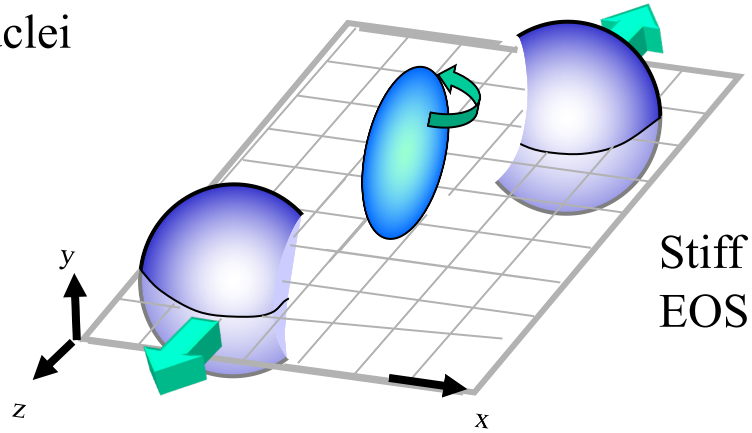
Janssens and Khoo, Ann. Rev. Nucl. Part. Sci. 41, 321 (1991).

moments of inertial

I was a Changjiang visiting professor in Shandong University 2000-2005

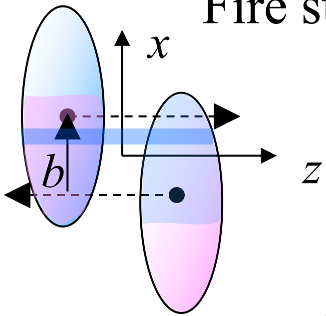
Zuo-tang Liang

Rotation of deformed nuclei



Stiff EOS

Transverse gradient of fluid velocity & vorticity



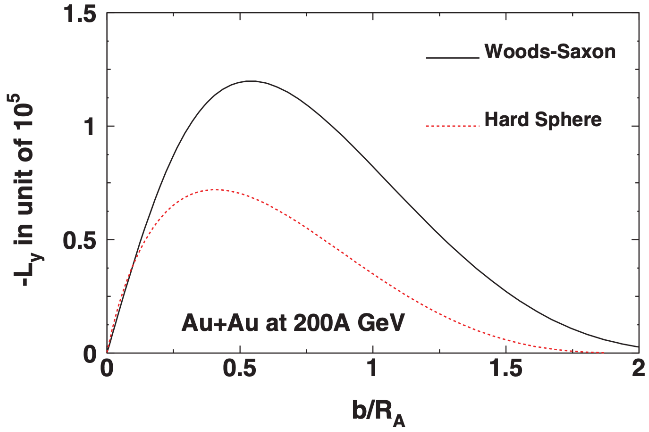
Fire streak model

$$p_z(x,b) = \frac{\sqrt{s}}{2}\,\frac{\dfrac{dN^P_{part}}{dx} - \dfrac{dN^T_{part}}{dx}}{c(s)\left(\dfrac{dN^P_{part}}{dx} + \dfrac{dN^T_{part}}{dx}\right)}$$

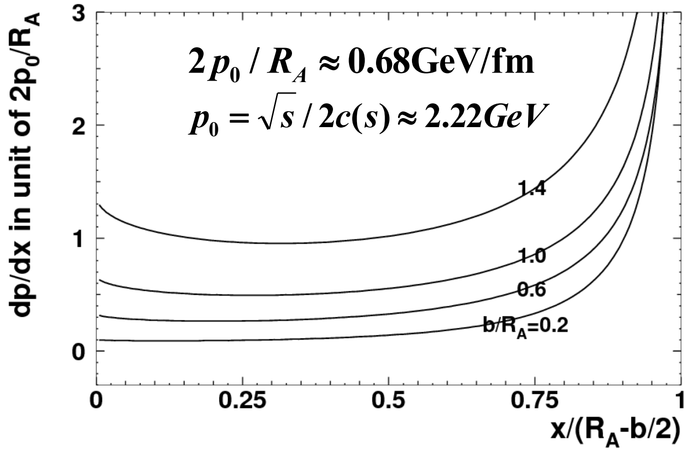
$$\vec{\omega} = \vec{\nabla} \times \vec{v} \sim -\hat{y}\langle \frac{1}{E}\frac{dp_z}{dx} \rangle$$

Collective longitudinal momentum per produced parton

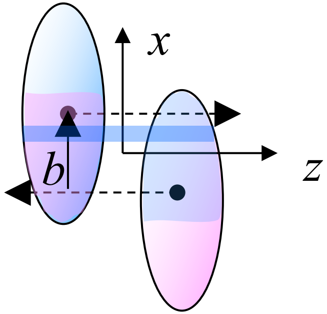
Liang & XNW, PRL 94 (2005) 102301



Total angular momentum carried by QGP



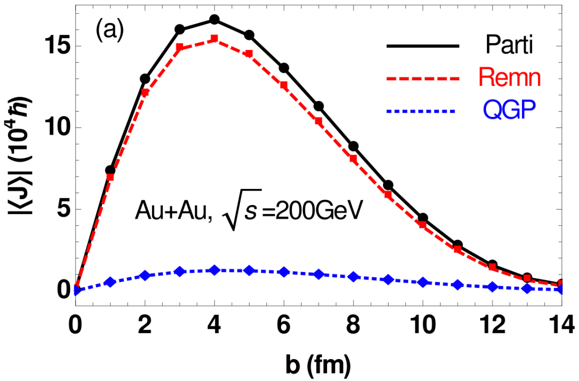
Fluid velocity & vorticity in HIJING

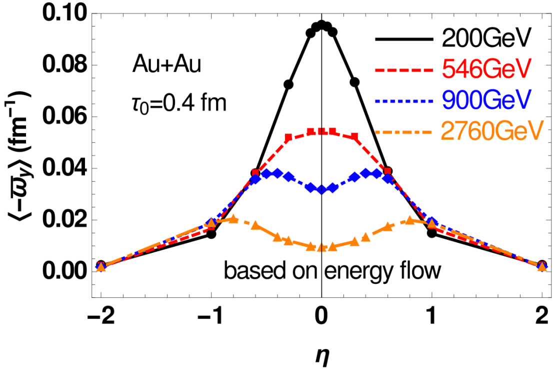


No complete stopping but approximate Bjorken scaling.

Small violation of BJ scaling at large y → local angular momentum or vorticity

BJ scaling violation and vorticity increase at lower colliding energies





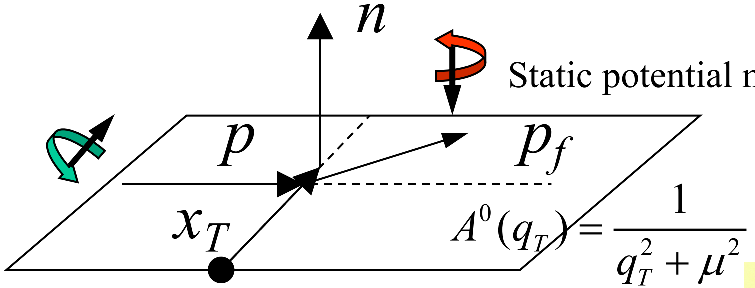
Gao, Chen, Deng, Liang, Q. Wang, XNW, PRC 77 (2008)044902

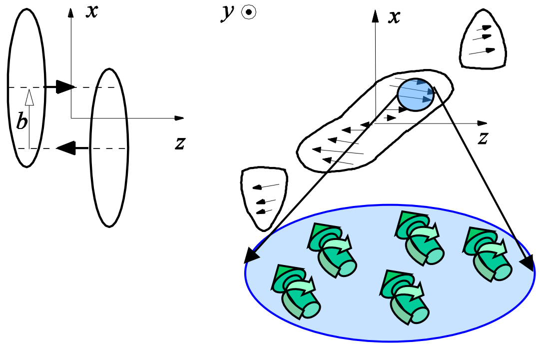
Deng, Huang, *PRC* 93 (2016) 6, 064907

Pang, Petersen, Q. Wang and XNW, *PRL 117* (2016) 19, 192301

Global spin polarization in A+A

Liang & XNW, PRL 94 (2005) 102301





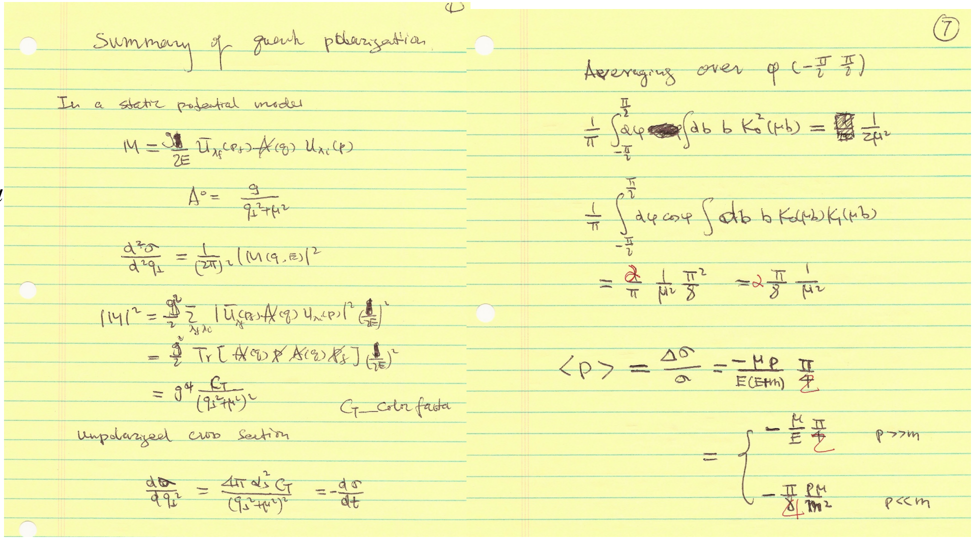
$$P_q \equiv \frac{\Delta\sigma}{\sigma} = -\pi \frac{\mu p}{4E(E+m_q)}$$

p: relative momentum of parton scattering with impact parameter b ~ $1/\mu$

spin-vorticity (orbital) coupling

nonrelativistic limit: $(m_q \gg p, \mu)$

$$P_q \approx -\pi \frac{\mu p}{4m_q^2} \sim -\omega/m \quad \text{or} - \omega/T$$



Spin polarization in equilibrium & CME, CVE

Dirac Eq. $$[\gamma^\mu(i\partial_\mu + e_q A_\mu) - m]\psi(x) = 0$$

Pu, Gao, Liang, Wang & XNW, PRL 109 (2012) 232301

Spin: vorticity coupling   Magnetic coupling

$$\delta E_s = \frac{\hbar}{2}\mathbf{n}\cdot\omega + e_q\hbar\frac{\mathbf{n}\cdot\mathbf{B}}{E_p}$$

$$\Pi = \frac{1}{2}\int\frac{d^3p}{(2\pi)^3}[f(E_p - \delta E_s) - f(E_p + \delta E_s)] \approx \int\frac{d^3p}{(2\pi)^3}\delta E_s\frac{\partial f(E_p)}{\partial E_p}$$

Polarization on the freeze-out surface:

$$\frac{d\Pi^\alpha(p)/d^3p}{d\rho(p)/d^3p} = \frac{\hbar}{4m}\frac{\int d\Sigma_\lambda p^\lambda\tilde{\Omega}^{\alpha\sigma}p_\sigma f_{\rm FD}(x,p)[1-f_{\rm FD}(x,p)]}{\int d\Sigma_\lambda p^\lambda f_{\rm FD}(x,p)}.$$

Becattini & Ferroni, EJPC 52 (2007) 597, Betz, Gyulassy & Torrieri, PRC 76 (2007) 044901, Becattini, Piccinini & Rizzo, PRC 77 (2008) 024906, Beccatini, Csernai & Wang, PRC 87 (2013) 034905, Xie, Glastad & Csernai, PRC 92 (2015) 064901, Deng & Huang, arXiv 1603.06117

Spin polarization and CME, CVE

$$[\gamma^\mu (i\partial_\mu + e_q A_\mu) - m]\,\psi(x) = 0$$

$$\gamma_\mu \left(p^\mu + \frac{1}{2} i \nabla^\mu\right) W(x,p) = 0,$$

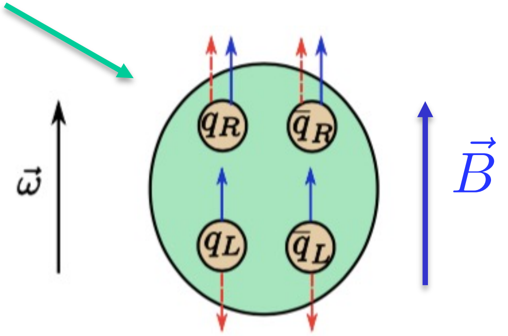
Pu, Gao, Liang, Wang & XNW,
PRL 109 (2012) 232301

Quantum kinetic equation

$$j^\mu = \int d^4p\, \mathcal{V}^\mu = n u^\mu + \xi \omega^\mu + \xi_B B^\mu,$$

$$j_5^\mu = \int d^4p\, \mathcal{A}^\mu = n_5 u^\mu + \xi_5 \omega^\mu + \xi_{B5} B^\mu.$$

$$\partial_\mu j^\mu = 0, \quad \partial_\mu j_5^\mu = -\frac{Q^2}{2\pi^2} E \cdot B,$$



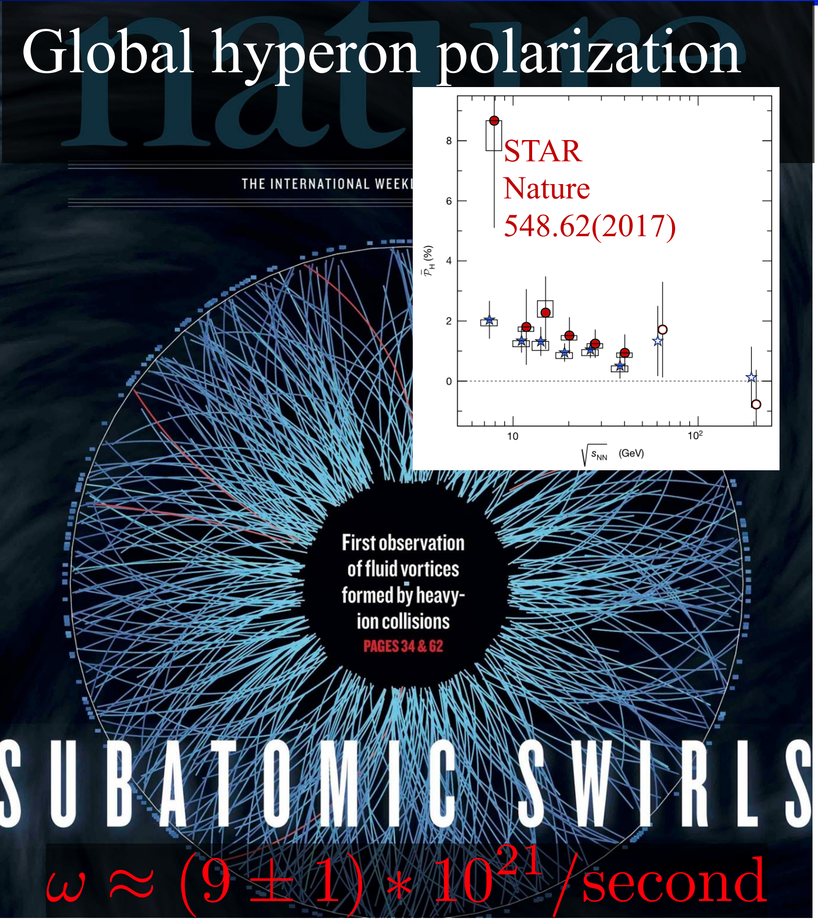
Local spin polarization

Chiral Magnetic Effect — Kharzeev, McLerran, Warringa (2008), Fukushima, Kharzeev, Warringa (2008)

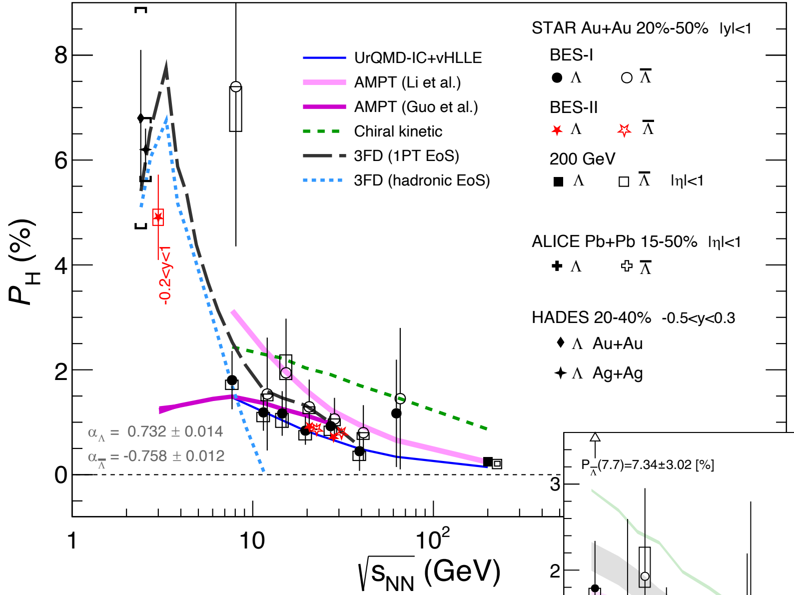
Chiral Vorticity Effect — Son, Surowka (2009), Kharzeev, Son (2011)

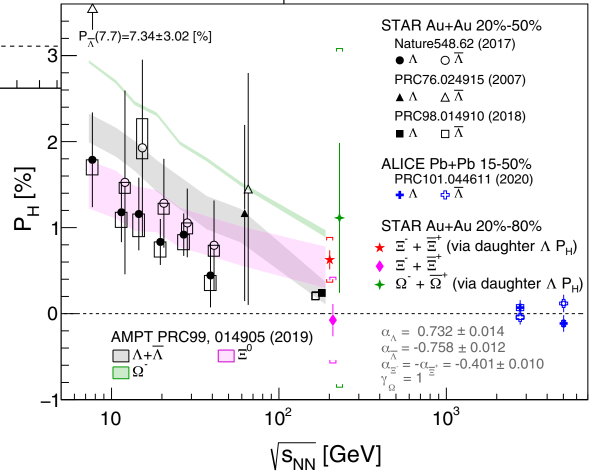
The most vortical fluid in nature

Global hyperon polarization



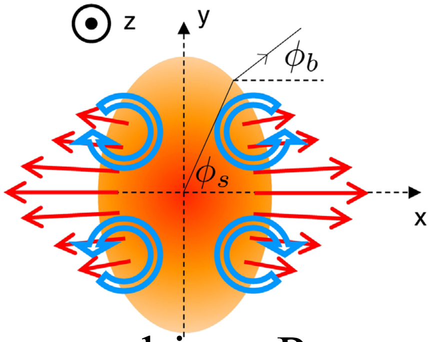
$\omega \approx (9 \pm 1) * 10^{21}/\text{second}$



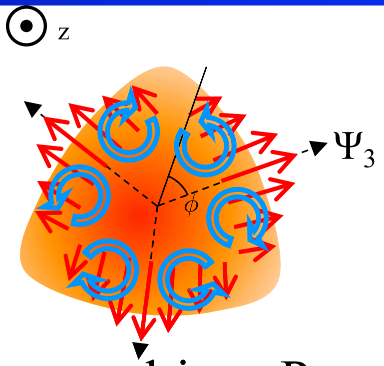


Becattini, Buzzegoli, Niida, Pu, Tang and Wang, arXiv:2402.04540

Local spin polarization

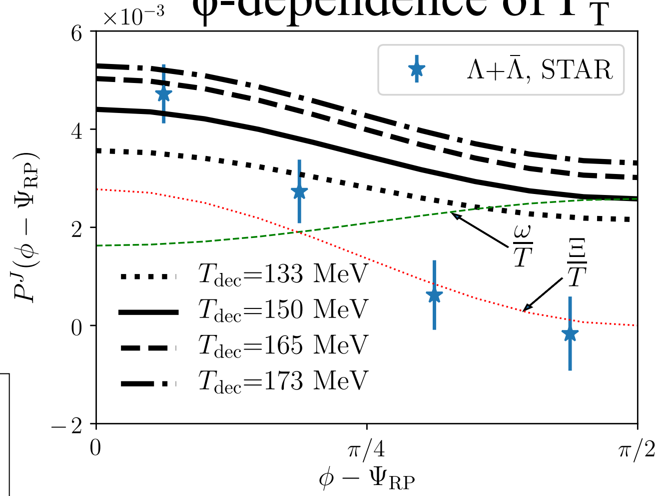


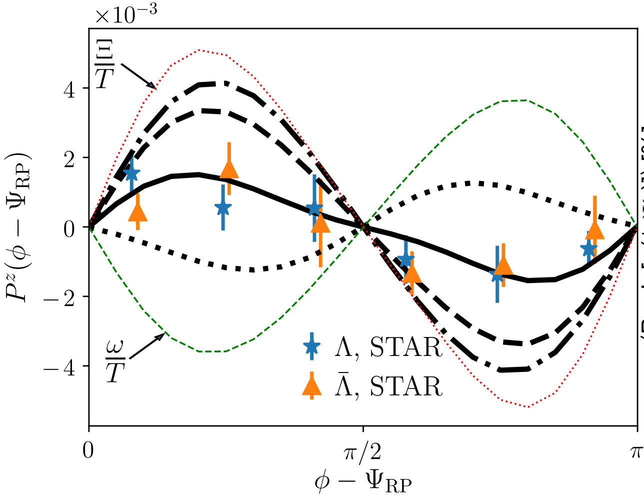
v_2-driven P_z

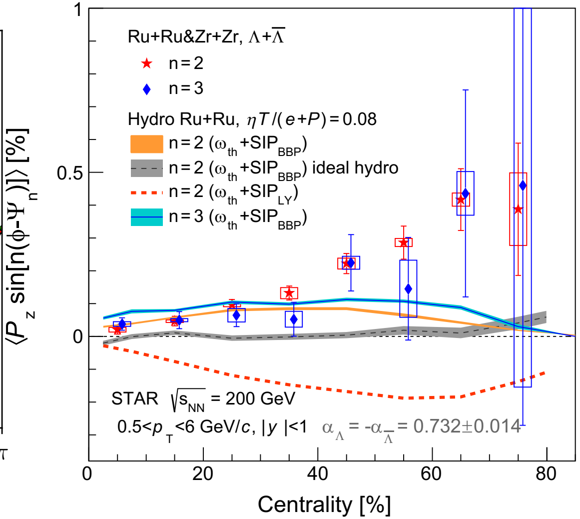


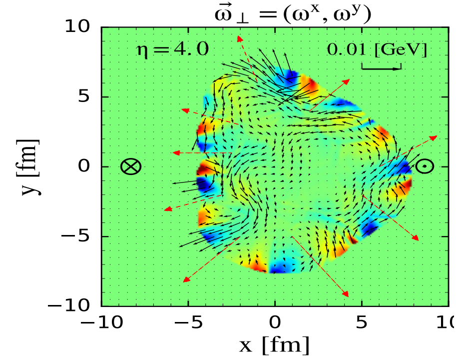
v_3-driven P_z

ϕ-dependence of P_T









Vector meson spin alignment

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Spin alignment of vector mesons in non-central $A + A$ collisions

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Available online 3 October 2005

Simple recombination model

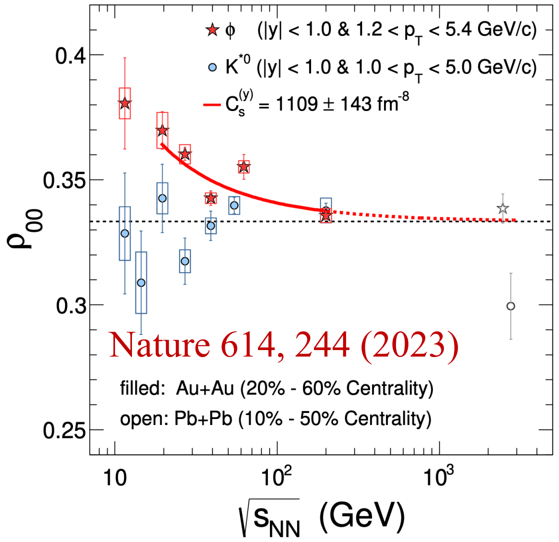
$$\rho_{00} = \frac{1 - P_q P_{\bar{q}}}{3 + P_q P_{\bar{q}}} \leq \frac{1}{3}$$

More sophisticated recombination model

$$\rho^{00} \approx \frac{1}{3} - \frac{4}{9} \langle P_q(\mathbf{x_q}, \mathbf{p}_q) P_{\bar{q}}(\mathbf{x}_{\bar{q}}, \mathbf{p}_{\bar{q}}) \rangle$$

Sheng, Wang and XNW, Phys. Rev. D 102, 056013 (2020)

STAR: Large ϕ meson spin alignment



Too big to be explained by vorticity, EM, etc

$$P_{q(\bar{q})} \approx \frac{1}{4m_q} \epsilon^{\mu\nu\rho\sigma} \left[\omega \pm \frac{e_q}{(u \cdot p)T} F_{\rho\sigma} \right] p_\nu$$

Polarization via strong interaction force

Chiral quark model: Manohar and Georgi (1984)

Effective interaction between quarks, gluon and Goldstone boson between Λ_χ and Λ_{QCD}

$$\mathcal{L} = \bar{\psi}\gamma^\mu(iD_\mu + V_\mu + g_A A_\mu \gamma_5)\psi - m\bar{\psi}\psi + \frac{1}{4}f^2 \mathrm{tr}\partial_\mu \Sigma^\dagger \partial^\mu \Sigma - \frac{1}{2}\mathrm{tr} F_{\mu\nu}F^{\mu\nu} + \cdots$$

$$V_\mu = \frac{1}{2}(\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger) \qquad A_\mu = \frac{i}{2}(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)$$

$$\xi = e^{iM/f} \qquad M = \frac{1}{\sqrt{2}}\begin{bmatrix} \sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{bmatrix}$$

$$P^\mu_{q(\bar{q})} \approx \frac{1}{4m_q}\epsilon^{\mu\nu\rho\sigma}\left[\omega_{\rho\sigma} \pm \frac{e_q}{(u\cdot p)T}F_{\rho\sigma} \pm \frac{g_V}{(u\cdot p)T}F^V_{\rho\sigma}\right]p_\nu$$

Strong interaction

Polarization via strong interaction force

Spin Boltzmann transport equation with quark coalescence

Sheng, Oliva, Liang, Wang and XNW, PRL 131, 042304 (2023)

$$k \cdot \partial_x f^V_{\lambda_1 \lambda_2}(x, \mathbf{k}) = \frac{1}{8} \left[\epsilon^*_\mu(\lambda_1, \mathbf{k}) \epsilon_\nu(\lambda_2, \mathbf{k}) \mathcal{C}^{\mu\nu}_{\text{coal}}(x, \mathbf{k}) - \mathcal{C}_{\text{diss}}(\mathbf{k}) f^V_{\lambda_1 \lambda_2}(x, \mathbf{k}) \right],$$

$$f^V_{\lambda_1 \lambda_2}(x, \mathbf{k}) \sim \frac{1}{\mathcal{C}_{\text{diss}}(\mathbf{k})} \left[1 - e^{-\mathcal{C}_{\text{diss}}(\mathbf{k}) \Delta t} \right] \epsilon^*_\mu(\lambda_1, \mathbf{k}) \epsilon_\nu(\lambda_2, \mathbf{k}) \mathcal{C}^{\mu\nu}_{\text{coal}}(x, \mathbf{k})$$

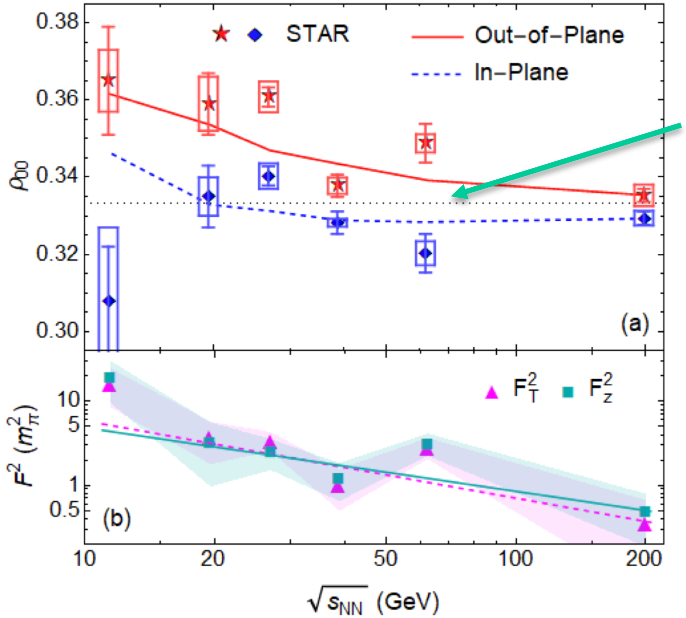
Spin alignment on the hadronization hyper surface

$$\rho_{00} \approx \frac{1}{3} + \frac{g_\phi^2}{m_\phi^2 T_{\text{eff}}^2} (C_1 B_\phi^2 + C_2 E_\phi^2) + \cdots$$

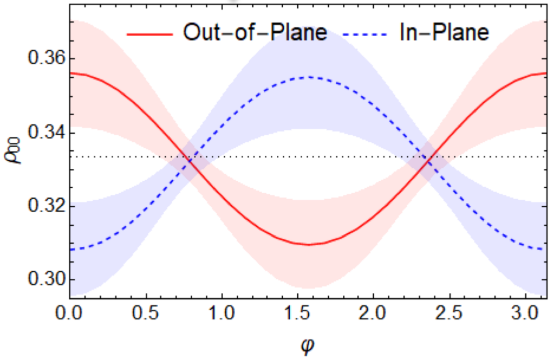
Momentum-dependence

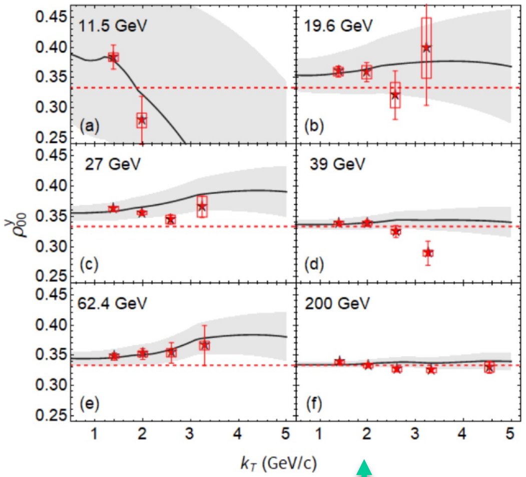
${B^2}_\phi$, ${E^2}_\phi$ rest frame → collisions frame

Barometer of strong force field fluctuations



In and out-plane splitting caused by v2 of the vector meson





$$\left\langle (g_\phi \mathbf{B}^\phi_{x,y}/T_\mathrm{h})^2 \right\rangle = \left\langle (g_\phi \mathbf{E}^\phi_{x,y}/T_\mathrm{h})^2 \right\rangle \equiv F_T^2$$

$$\left\langle (g_\phi \mathbf{B}^\phi_{z}/T_\mathrm{h})^2 \right\rangle = \left\langle (g_\phi \mathbf{E}^\phi_{z}/T_\mathrm{h})^2 \right\rangle \equiv F_z^2$$

k_T dependence of ρ_{00} dictated by vector meson's spectra

Sheng, Oliva, Liang, Wang and XNW, PRL 131, 042304 (2023)

Hyperon spin correlations

Simple quark model of hyperon spin $\quad P^\mu_H(x,p) \approx P^\mu_s(x, R_s p), \quad p_s = R_s p$

Hyperon spin correlation (H: Λ, Λbar)

$$C^{\mu\nu}_{H_1 H_2}(p_1, p_2) \equiv \langle \mathcal{P}^\mu_{H_1}(p_1) \mathcal{P}^\nu_{H_2}(p_2) \rangle$$

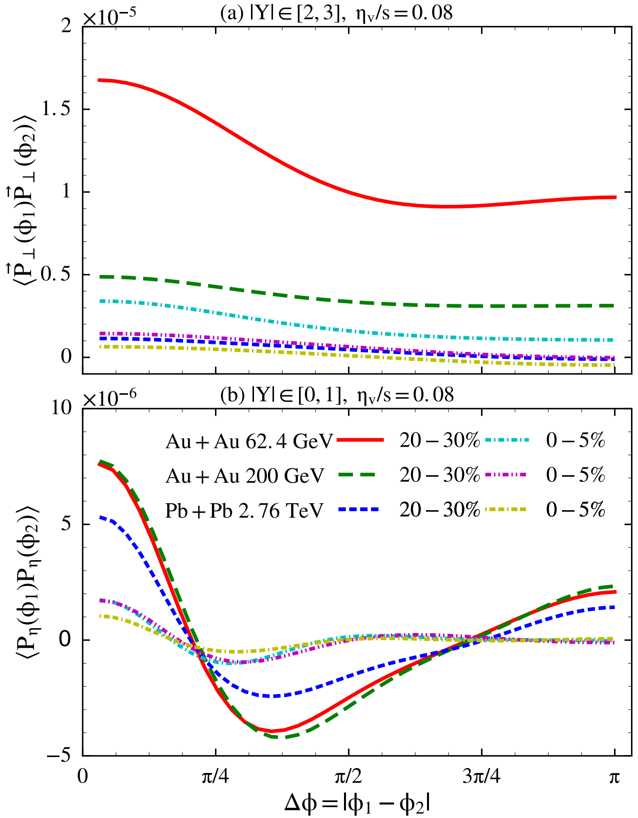
$\langle \cdots \rangle$ average over freeze-out hypersurface

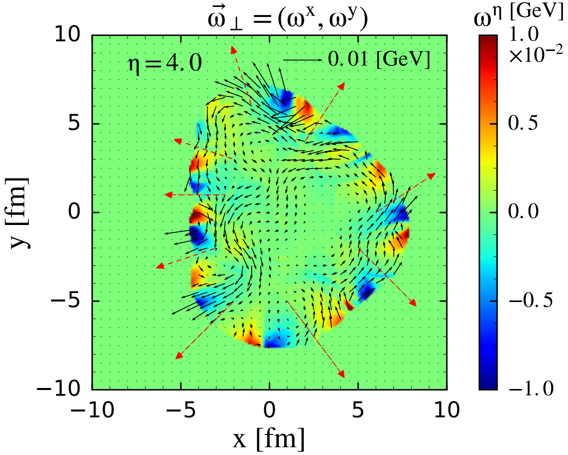
Short-distance correlation of the ϕ field

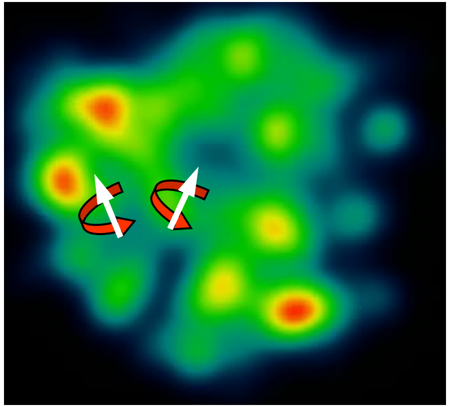
$$\langle g_\phi^2 F^\phi(x) F^\phi(y) / [T(x)T(y)] \rangle = F^2 G(x-y)$$

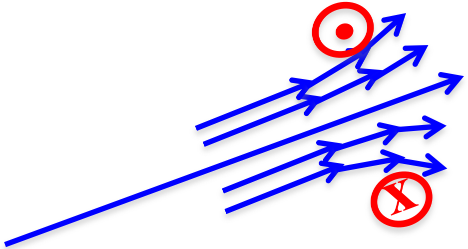
$$G(x-y) \equiv \exp\left[-\frac{(x^0-y^0)^2}{\sigma_t^2} - \frac{(\mathbf{x}-\mathbf{y})^2}{\sigma_x^2} \right]$$

Hyperon spin correlations









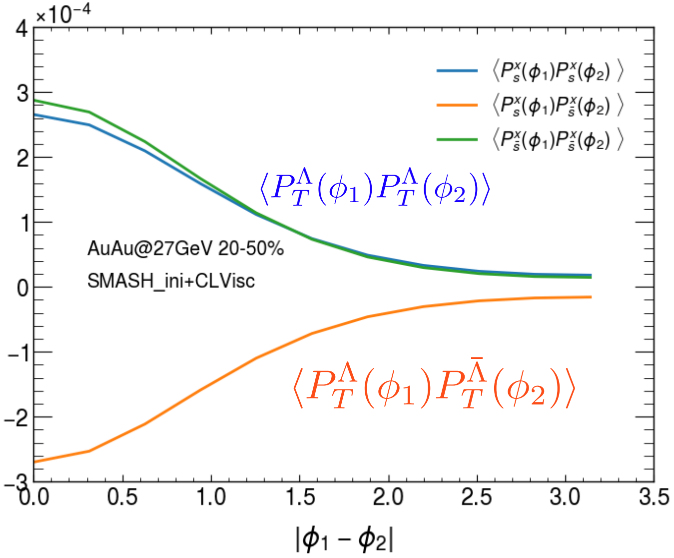
Pang, Petersen, Wang & XNW,
PRL 117(2016) 192301

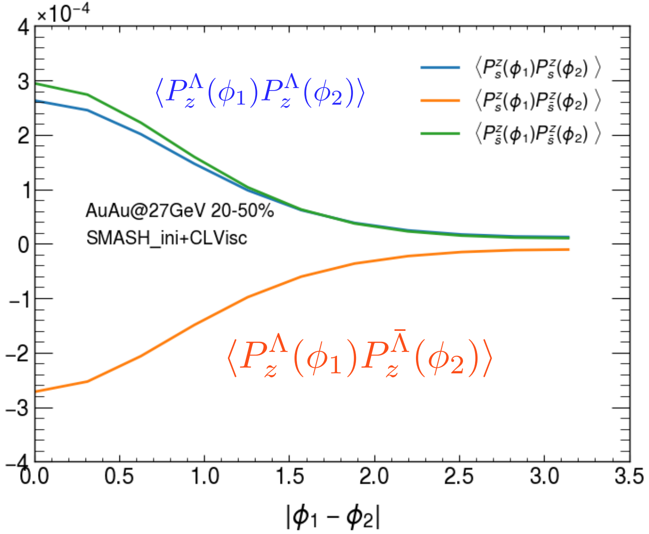
Vorticity ring:

Lisa, et al, *PRC* 104 (2021) 1, 011901

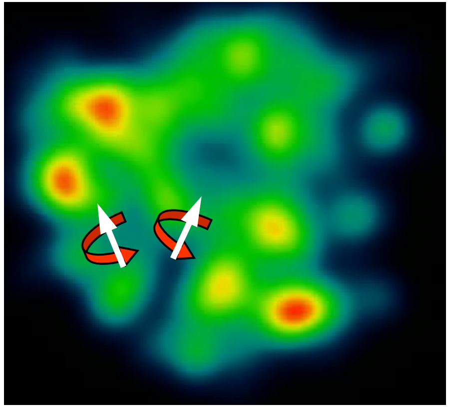
$$\mathcal{R} = \langle \frac{\vec{\omega} \cdot (\hat{t} \times \vec{v})}{|\hat{t} \times v|} \rangle$$

Hyperon spin correlations





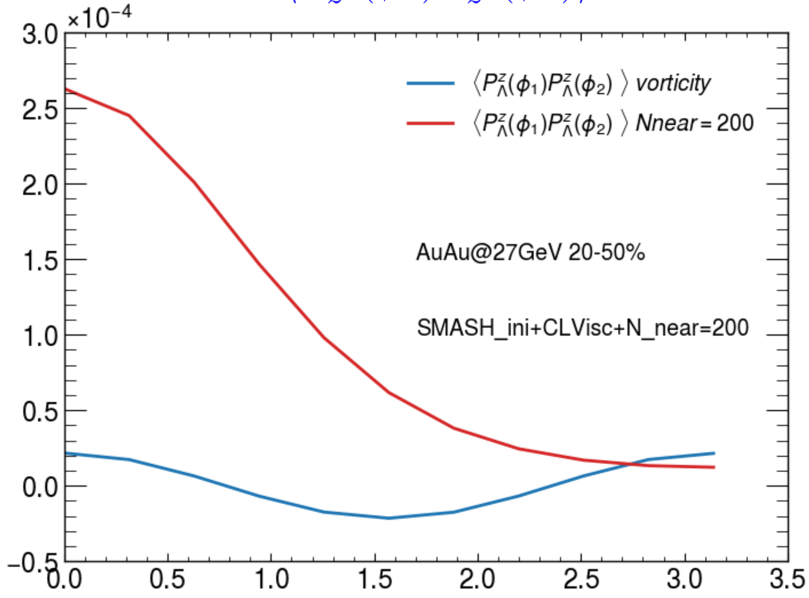
strong-field induced hyperon spin correlation



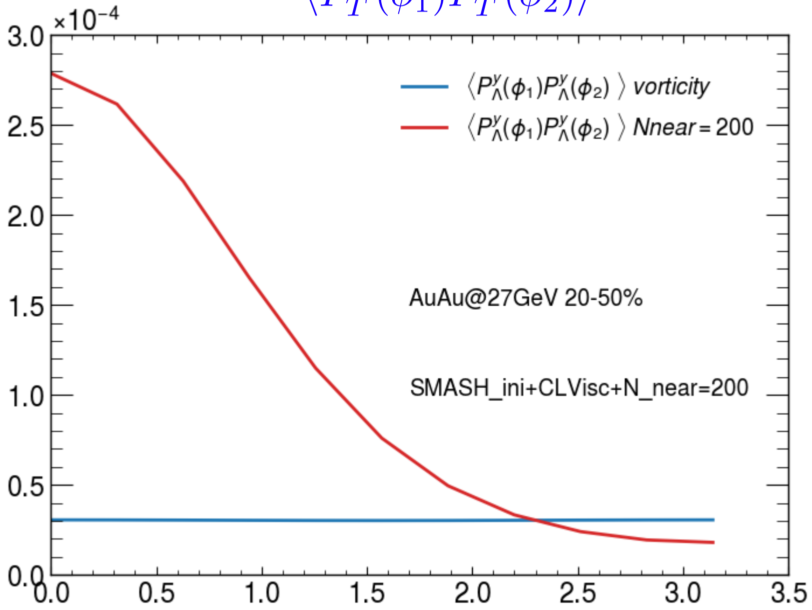
$$P^\mu_{q(\bar{q})} \approx \frac{1}{4m_q}\epsilon^{\mu\nu\rho\sigma}\left[\omega_{\rho\sigma} \pm \frac{e_q}{(u\cdot p)T}F_{\rho\sigma} \pm \frac{g_V}{(u\cdot p)T}F^V_{\rho\sigma}\right]p_\nu$$

Hyperon spin correlation

$\langle P_z^\Lambda(\phi_1) P_z^\Lambda(\phi_2) \rangle$



$\langle P_T^\Lambda(\phi_1) P_T^\Lambda(\phi_2) \rangle$



Dominated by the correlation due to strong force field!

Sensitive to the correlation length σ

Summary and Future perspective

Spin dynamics opens up a new window for the study of QGP matter with many unexpected phenomena

- Spin alignment of *K**: correlation of strong force field of different flavor?

- Correlation of Λ spin polarization

- Spin alignment of J/Ψ: fluctuation of gluonic field at shorter distance?

- Effect of hadronic interaction?