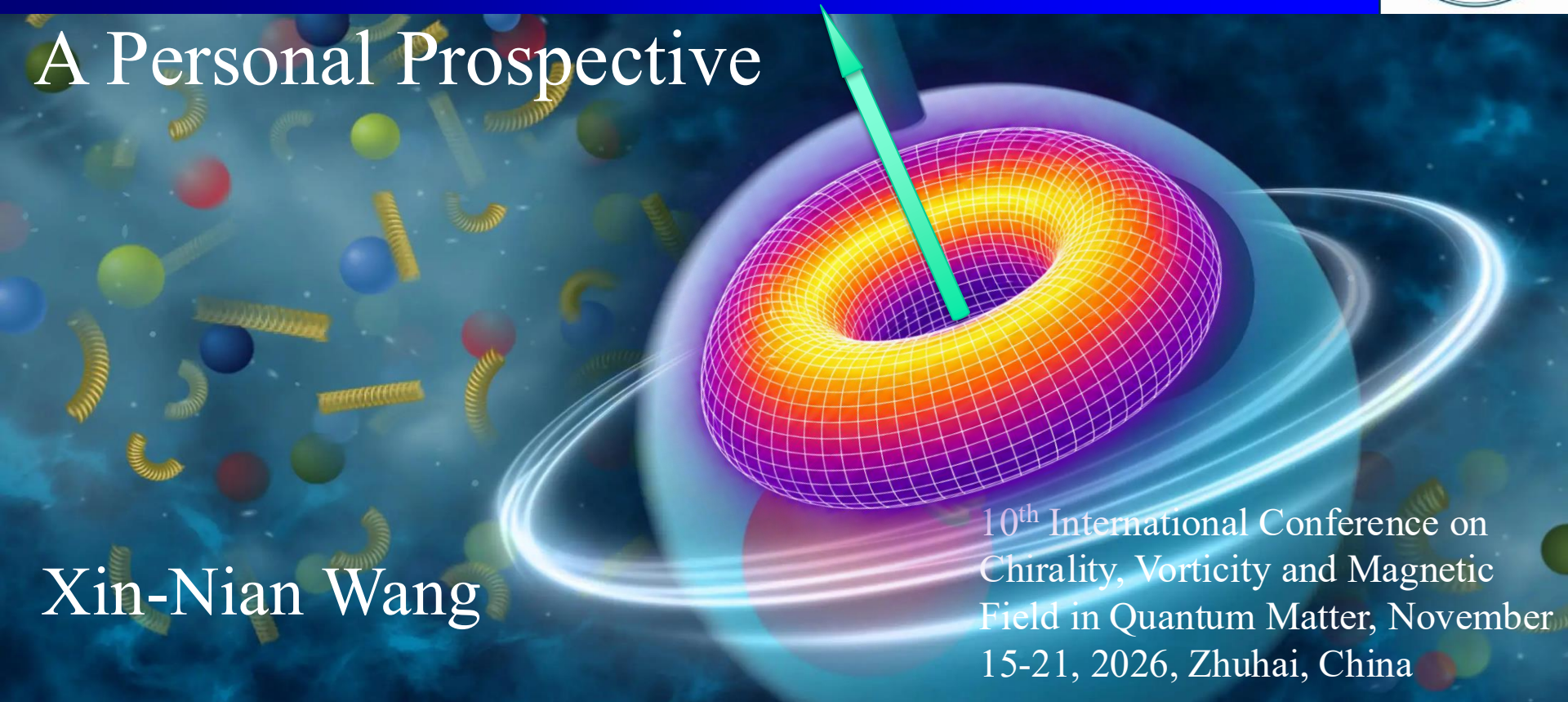
Spin polarization in unpolarized nuclear collisions: from RHIC to EIC

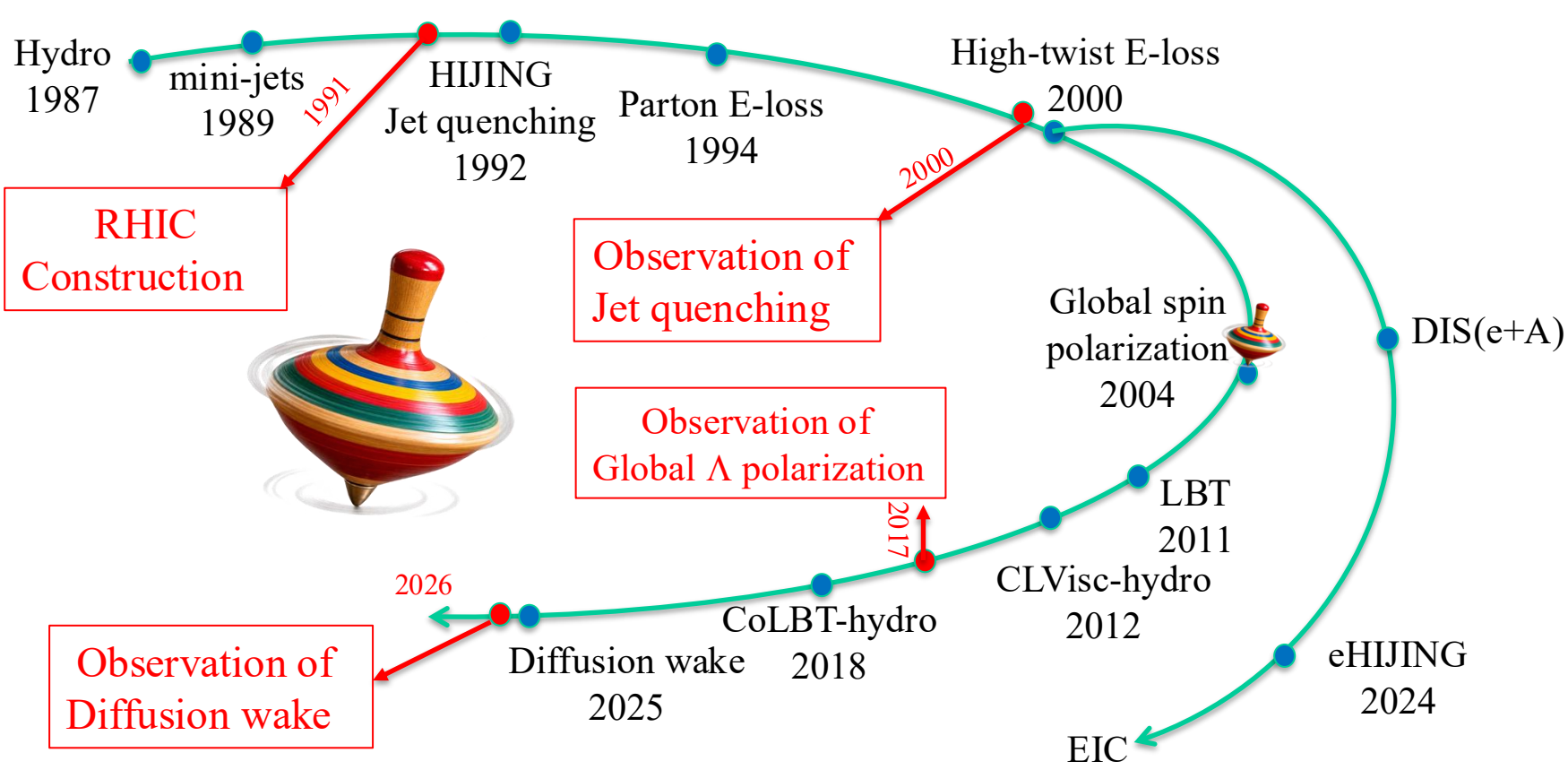
A Personal Prospective



Xin-Nian Wang

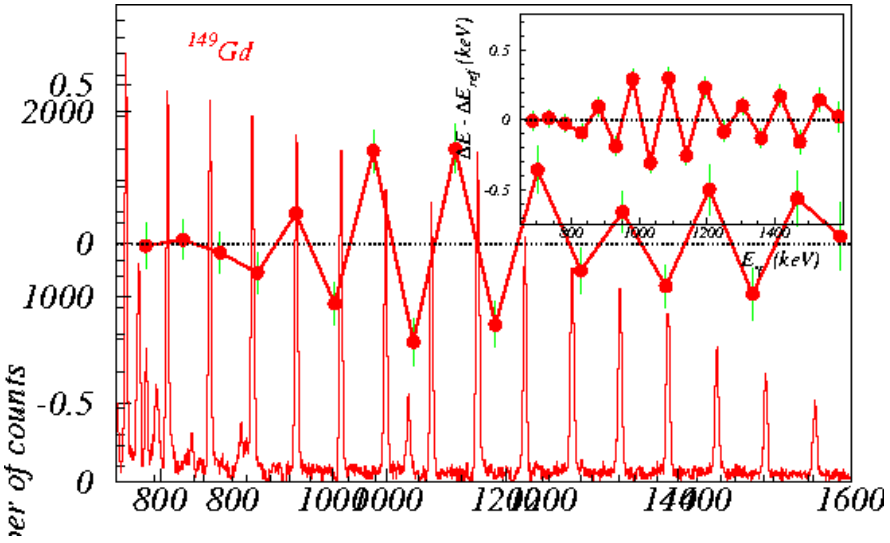
10th International Conference on Chirality, Vorticity and Magnetic Field in Quantum Matter, November 15-21, 2026, Zhuhai, China

My spin orbital coupling in nuclear collisions



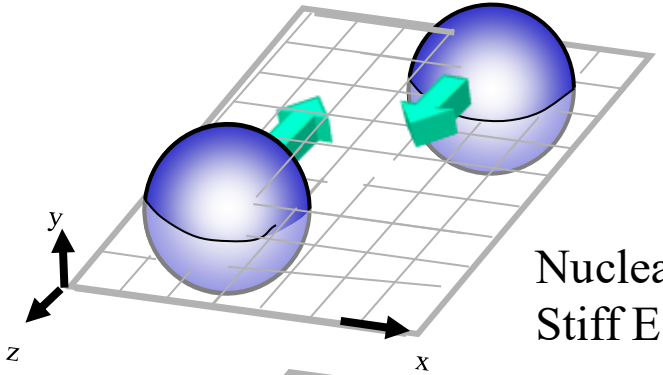
Orbital Angular Momentum in nuclear collisions

Spins of super-deformed nuclei in low-energy nuclear collisions:

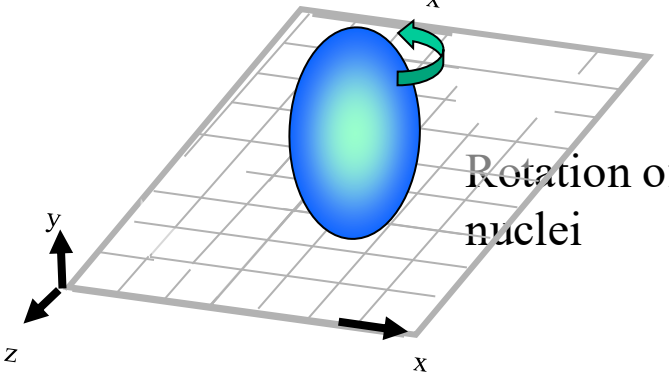


Janssens and Khoo, Ann. Rev. Nucl. Part. Sci. 41, 321 (1991).

moments of inertial

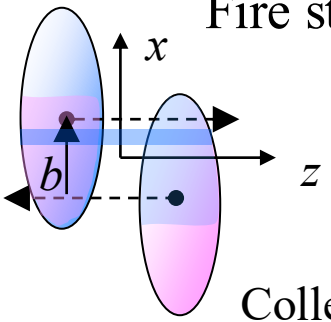


Nuclear fusion
Stiff EOS



Rotation of deformed nuclei

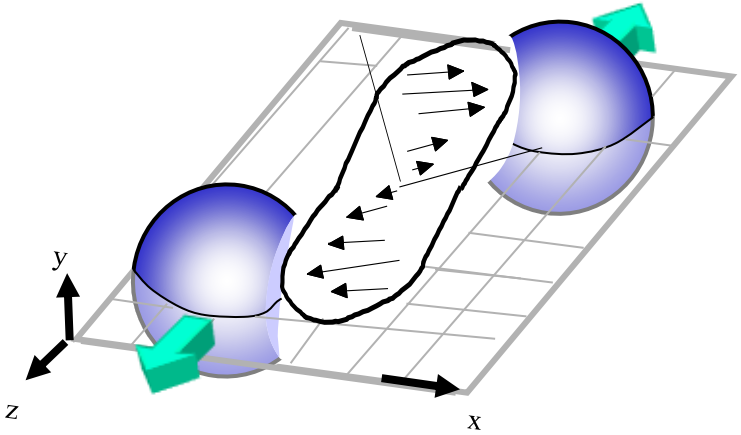
Transverse gradient of fluid velocity & vorticity

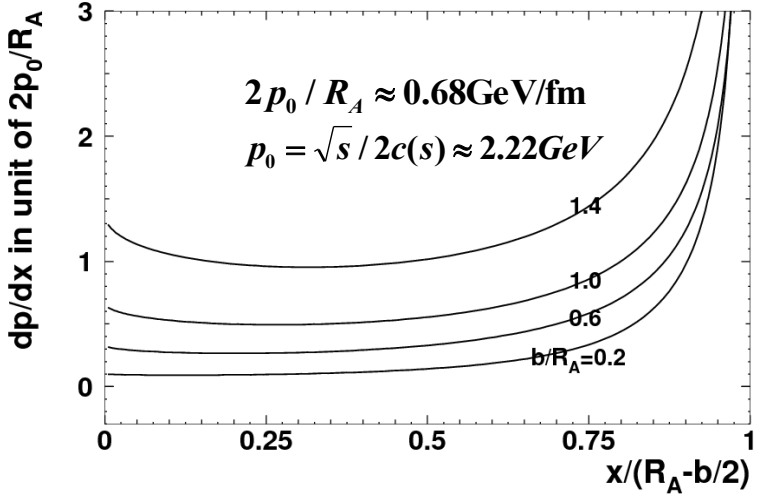


Fire streak model

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

Collective longitudinal momentum per produced parton





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

No rotating QGP!

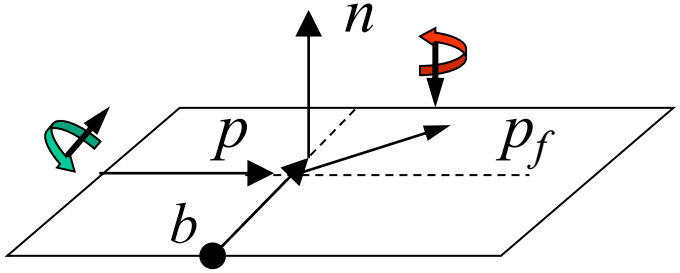
Spin polarization via spin-orbital coupling in collisions

Liang & XNW, PRL 94 (2005) 102301

Gyulassy-Wang static potential model $A^0(q_T) = \dfrac{1}{q_T^2 + \mu^2}$

$$\frac{d\sigma^+}{d^2b} + \frac{d\sigma^-}{d^2b} = 4C_T\alpha_s^2 K_0^2(\mu b)$$

$$\frac{d\sigma^+}{d^2b} - \frac{d\sigma^-}{d^2b} = -\mu\frac{\vec{p}\cdot(\hat{\vec{b}}\times\vec{n})}{E(E+m_q)}4C_T\alpha_s^2 K_0(\mu b)K_1(\mu b),$$



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

Fixed direction of the impact-parameter or orbital angular momentum

spin-vorticity (local orbital) coupling

$$P_q = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = -\frac{\pi}{2}\frac{\mu p}{E(E+m_q)}$$

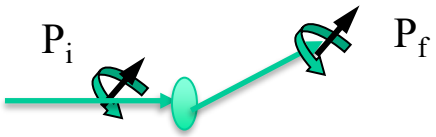
nonrelativistic limit: ($m_q \gg p, \mu$)

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

Polarization rate and approach to equilibrium

Huang, Huovinen & XNW, PRC84 (2011) 054910

$$P_f - P_i = -\frac{(1-P_i^2)\pi\mu p}{2E(E+m) - P_i\pi\mu p}$$



In non-relativistic limit

$$\pi\mu p/E \approx \pi\mu p/m \approx \omega \qquad \frac{dP}{dt} = -\frac{1}{\tau_q}\frac{(1-P^2)\omega/2m}{1-P\omega/2m}$$

For $\omega P/m << 1$ $\quad \frac{dP}{dt} = -\frac{1}{\tau_q}(1-P^2)\frac{\omega}{2m}$ $\quad P = -tanh(\frac{\omega}{2m}\frac{t}{\tau_q})$

Include back-reaction (de-polarization) ⟶ Equilibrium ?

Spin polarization in equilibrium & CME, CVE

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

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

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

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

Spin: vorticity coupling

Magnetic coupling

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

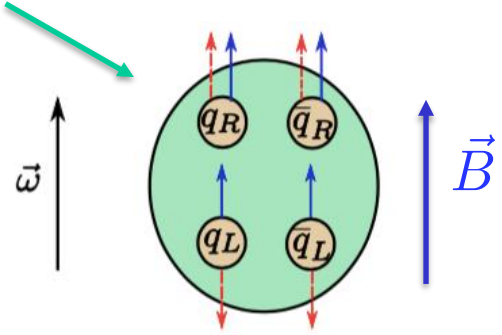
Pu, Gao, Liang, Wang & XNW, PRL 109 (2012) 232301

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

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

Quantum kinetic equation

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



Local spin polarization

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

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

Effects of spin polarization

Liang & XNW, PRL 94 (2005) 102301

- Hyperon polarization
- Polarization of thermal photons and dileptons (vector mesons, ϕ, J/ψ)
- Spin polarization through hadronic interaction (pA, eA)

Jet-induced Mach-cones

Linear response of jet-induced medium response:

$$T^{\mu\nu} = (e+p)u^\mu u^\nu - pg^{\mu\nu} + \pi^{\mu\nu}$$

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

$$e = e_0 + \delta e, \qquad p = p_0 + \delta p, \qquad u^\mu \simeq (1, \delta\mathbf{v})$$

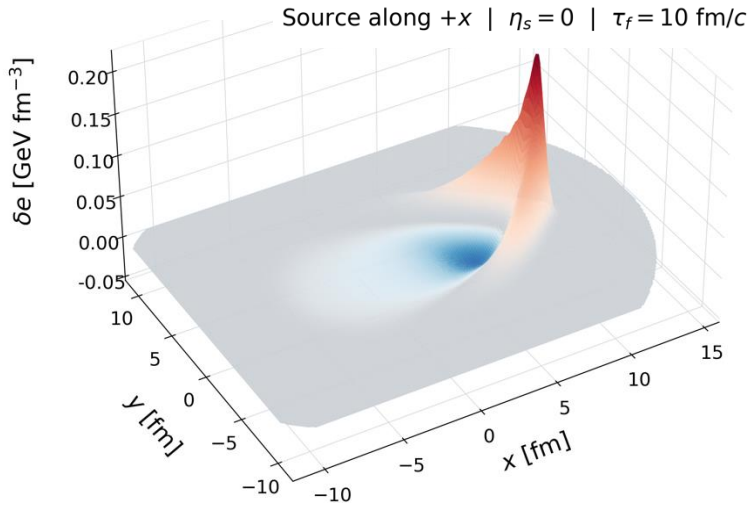
$$\delta\mathbf{g} = (e_0 + p_0)\delta\mathbf{v} = \hat{\mathbf{k}}\,\delta g_L + \delta\mathbf{g}_T, \qquad \delta p = c_s^2 \delta e$$

$$\partial_t \delta e + ik\delta g_L = J^0,$$

$$\partial_t \delta g_L + ikc_s^2 \delta e + \Gamma_s k^2 \delta g_L = J_L,$$

$$\partial_t \delta\mathbf{g}_T + D_\eta k^2 \delta\mathbf{g}_T = \mathbf{J}_T,$$

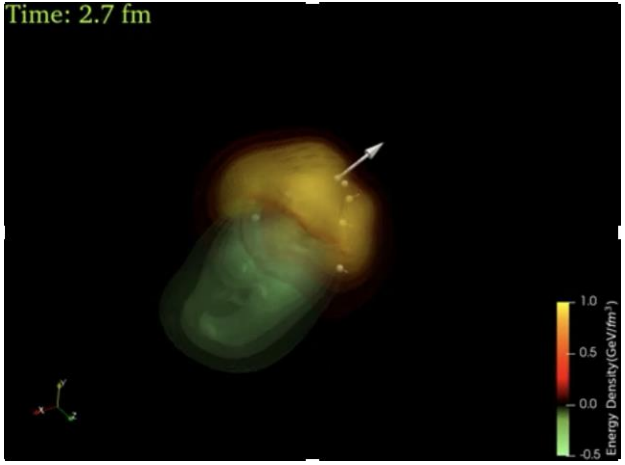
$$D_\eta = \eta/(e_0 + p_0) \qquad \Gamma_s = (4/3)D_\eta$$



Wu, Ke, Yang and XNW (preliminary)

Diffusion wake from Z-jet and dijet

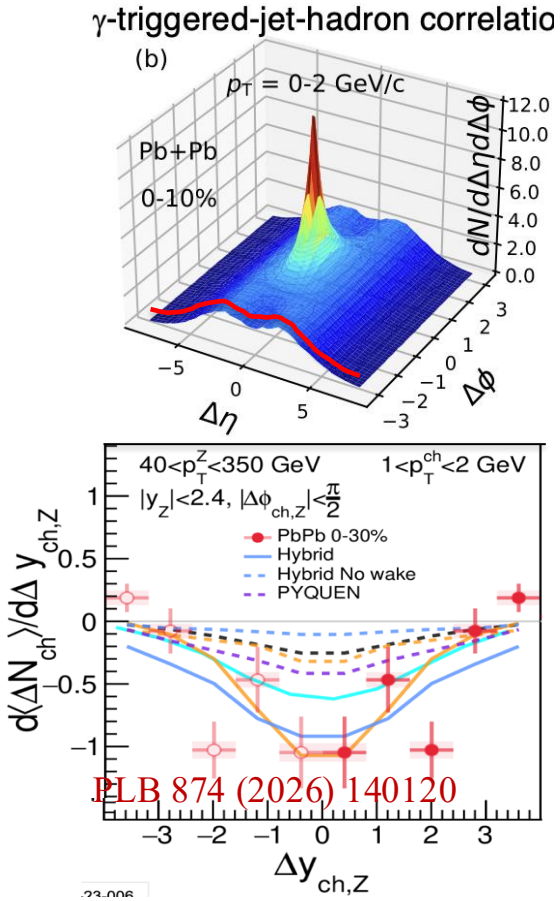
Mach-cone from CoLBT simulation



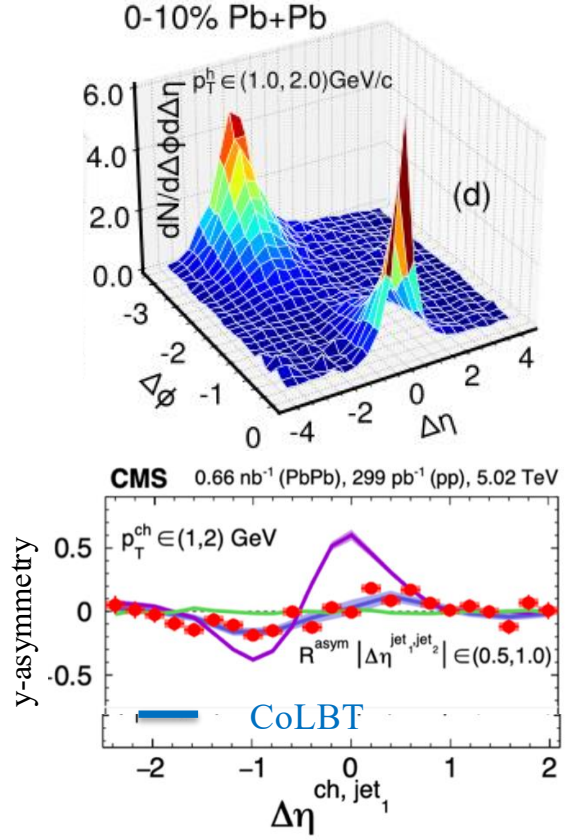
Diffusion wake leads to depletion of soft hadron yield in the back of jet direction

Yang, XNW, et al, *PRL,* 130 (2023) , 052301

Yang, XNW, PRL 135 (2025) 7, 072302



PLB 874 (2026) 140120



CMS: PRL 137 (2026) 7, 071902

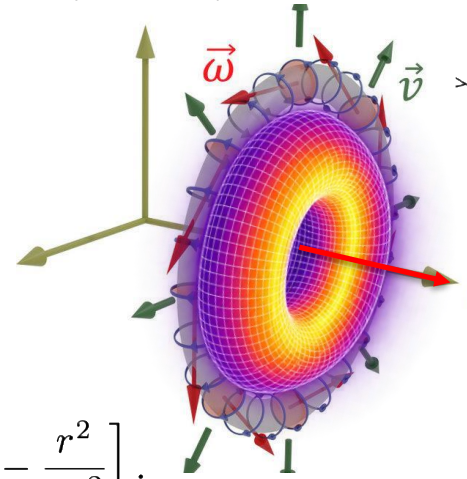
Vortex ring

vorticity

$$\partial_t \delta \mathbf{g}_T + D_\eta k^2 \delta \mathbf{g}_T = \mathbf{J}_T,$$

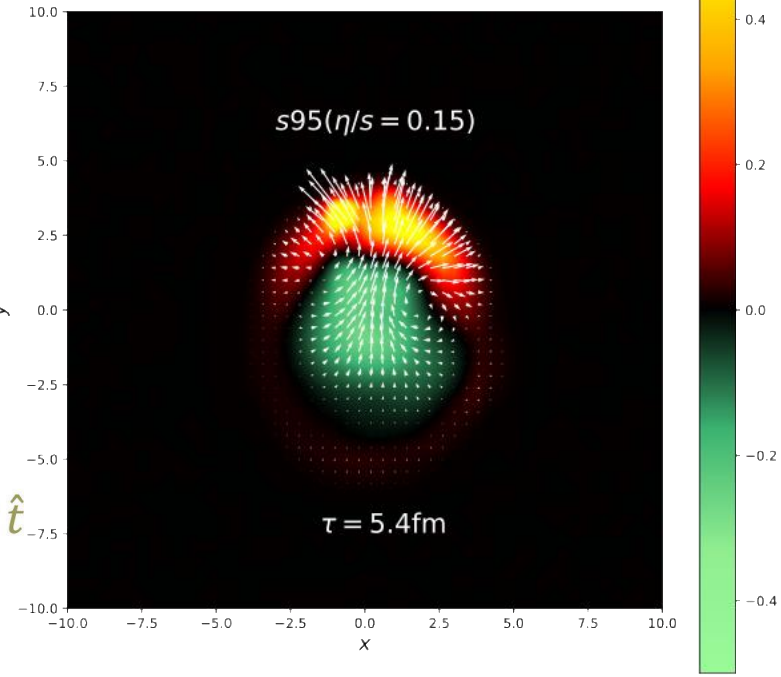
$$\boldsymbol{\omega} = \nabla \times \delta \mathbf{v} = \frac{1}{(e_0 + p_0)} \nabla \times \delta \mathbf{g} = \frac{1}{(e_0 + p_0)} \nabla \times \delta \mathbf{g}_T$$

$$\left(\partial_t - D_\eta \nabla^2\right) \boldsymbol{\omega} = \frac{1}{(e_0 + p_0)} \nabla \times \mathbf{J}$$



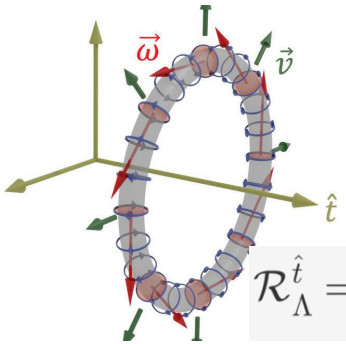
A Gaussian source term:

$$\partial_t \omega_\phi = \frac{J_0(t)\, r}{w_0 \sigma^2} \exp\left[-\frac{(x - x_j(t))^2}{2L^2} - \frac{r^2}{2\sigma^2}\right].$$



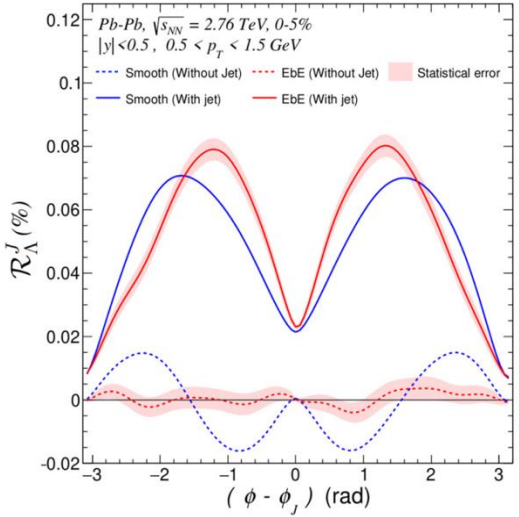
Jet-induced medium response from CoLBT

Jet induced spin polarization via vortex ring

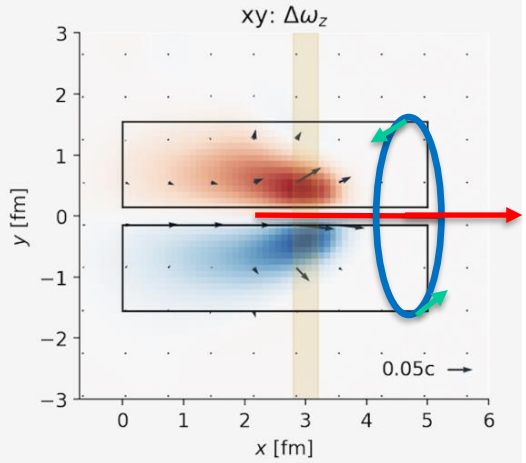


Ribeiro, et al, Phys Rev C. 109.014905

$$\mathcal{R}^{\hat{t}}_{\Lambda} = \left\langle \frac{\mathbf{P}_{\Lambda} \cdot (\hat{t} \times \mathbf{p}_{\Lambda})}{|\hat{t} \times \mathbf{p}_{\Lambda}|} \right\rangle$$

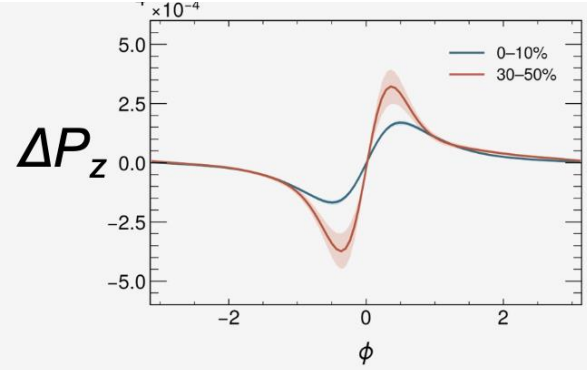


CoLBT-hydro



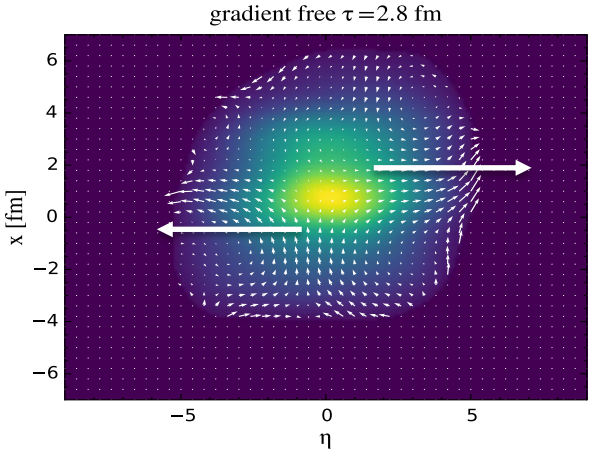
$\Delta\omega_z$, transverse plane (0–10%)

Cong Yi, Pang,Qin & XNW (preliminary)

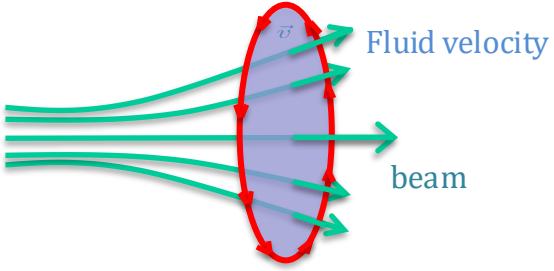


thermal-vorticity contribution only

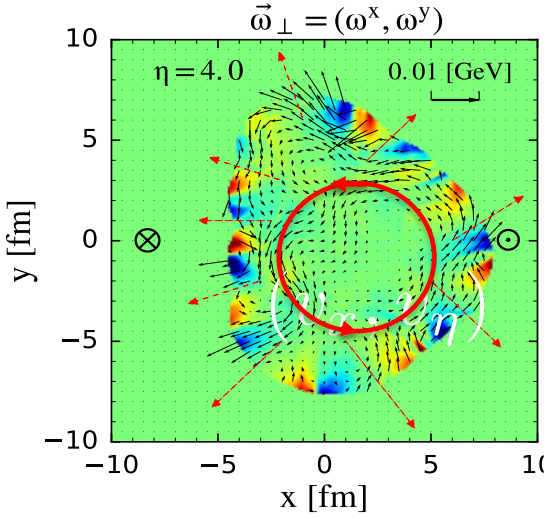
Longitudinal flow induced vorticity ring



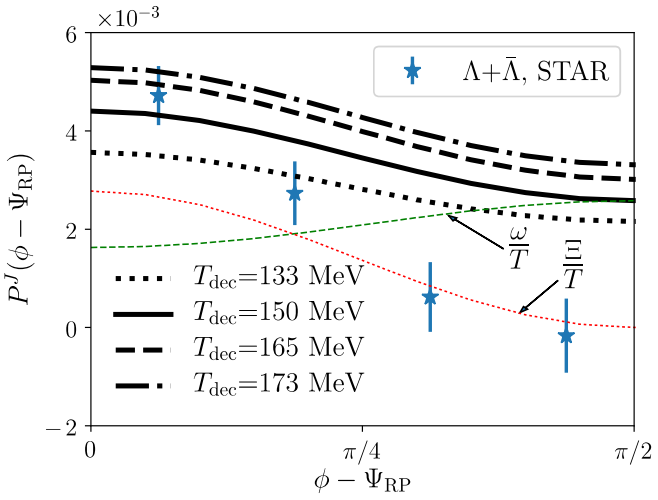
$\vec{\omega} = \vec{\nabla} \times \vec{v}$



Transverse vorticity ring,
in addition to the global net vorticity

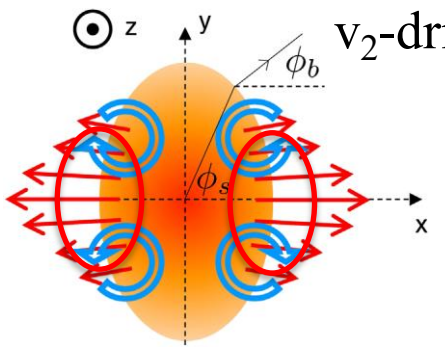


ϕ-dependence of P_T

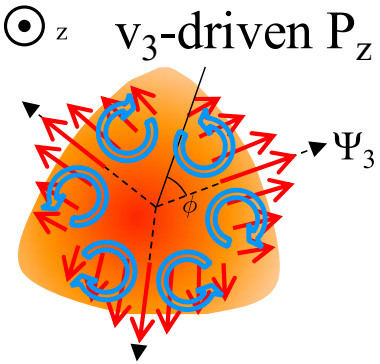


Pang, Petersen, Wang & XNW, PRL 117(2016) 192301

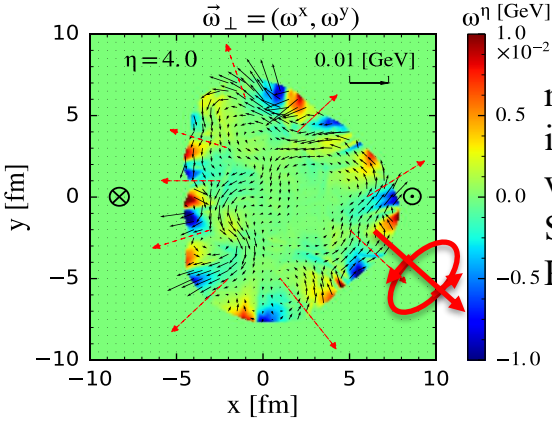
Vorticity ring and local longitudinal spin polarization



v_2-driven P_z

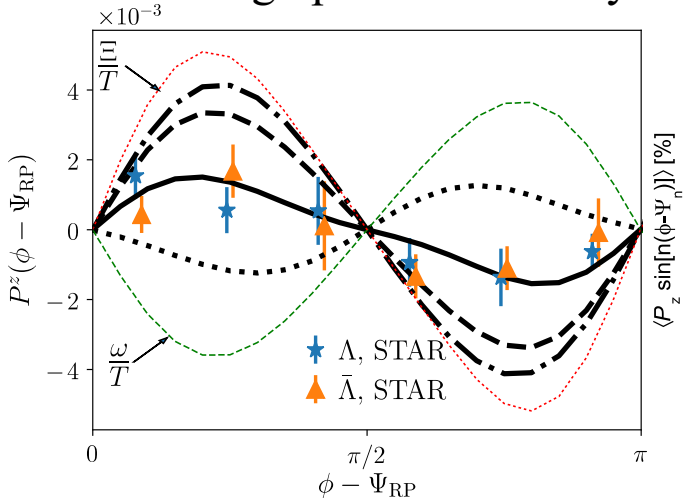


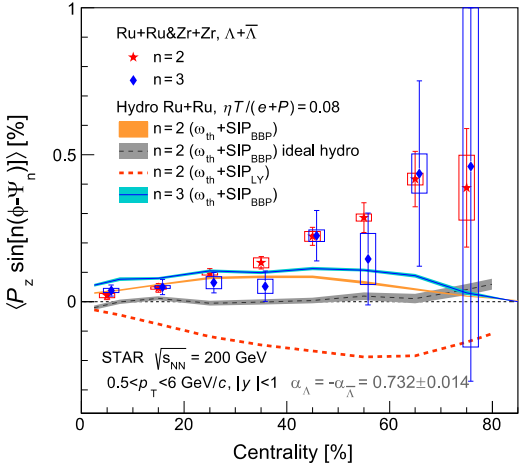
v_3-driven P_z

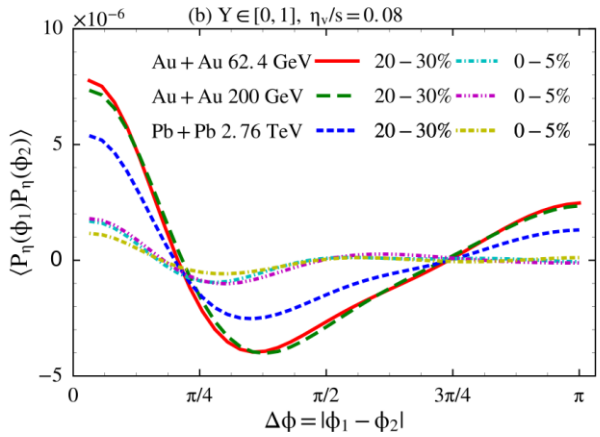


mini-jet induced vorticity ring: Short range P_z correlation

Sign puzzle: Vorticity or shear induced?







Vector meson spin alignment

Z. Liang and XNW, PLB 629 (2005) 20

Simple recombination model

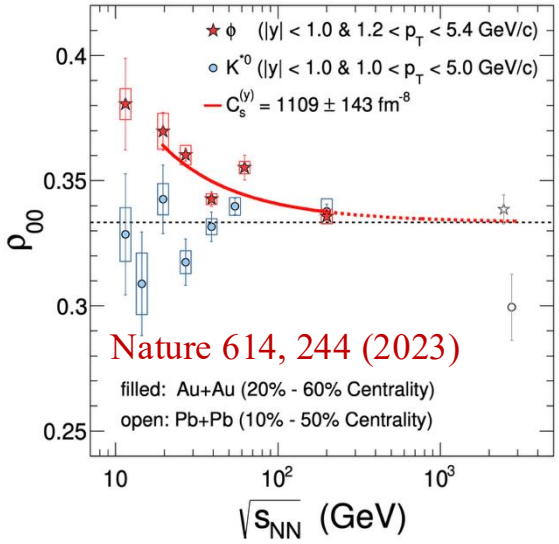
$$\rho_{00} = \frac{1 - P_q P_{\bar{q}}}{3 + P_q P_{\bar{q}}} \leq \frac{1}{3}$$

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)

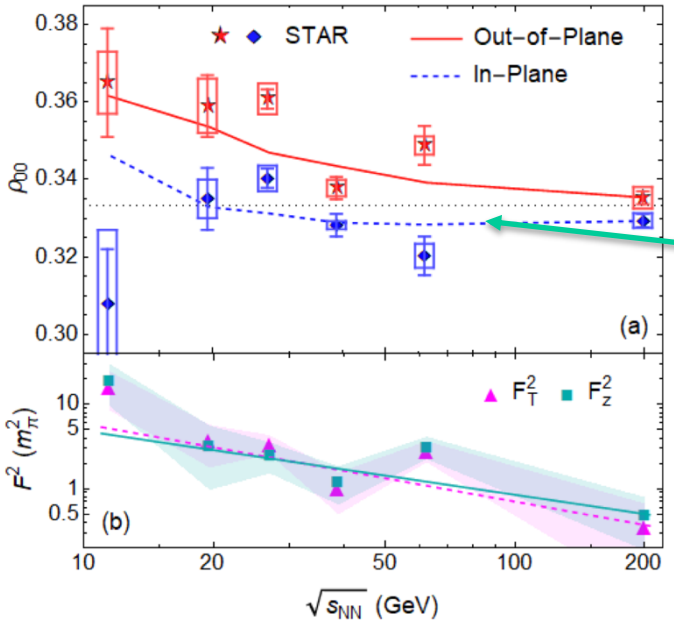
STAR: Large ϕ meson spin alignment



Too big to be explained by vorticity, EM, etc

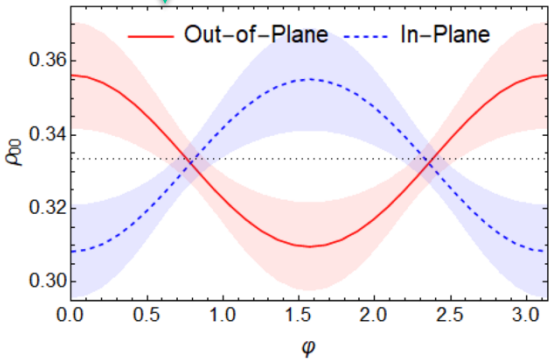
$$P_{q(\bar{q})} \approx \frac{1}{4m_q}\epsilon^{\mu\nu\rho\sigma}\left[\omega \pm \frac{e_q}{(u\cdot p)T}F_{\rho\sigma}\right]p_\nu$$

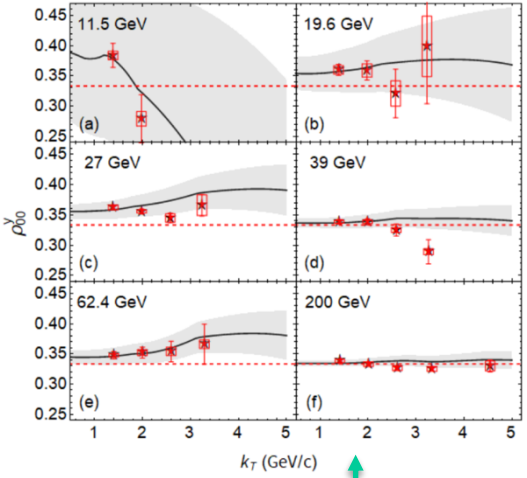
Barometer of strong force field fluctuations



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

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





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

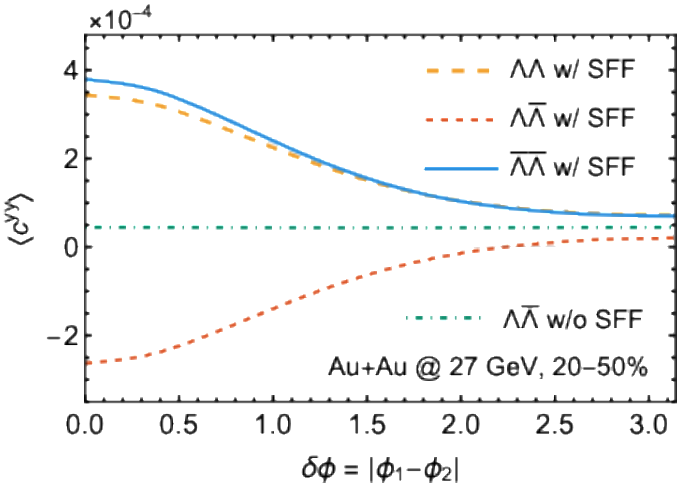
$$\left\langle (g_\phi \mathbf{B}^\phi_{z}/T_\mathrm{h})^2 \right\rangle = \left\langle (g_\phi \mathbf{E}^\phi_{z}/T_\mathrm{h})^2 \right\rangle \equiv F_z^2$$

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

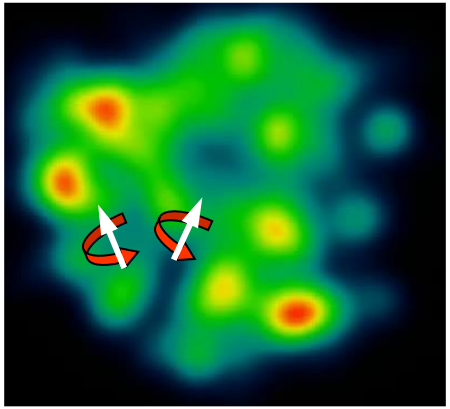
Sheng, Oliva, Liang, Wang and XNW, PRL 131, 042304 (2023)

Hyperon spin correlations

Sheng, Wu, Rischke, XNW, *PRL* 136 (2026) 8, 082301



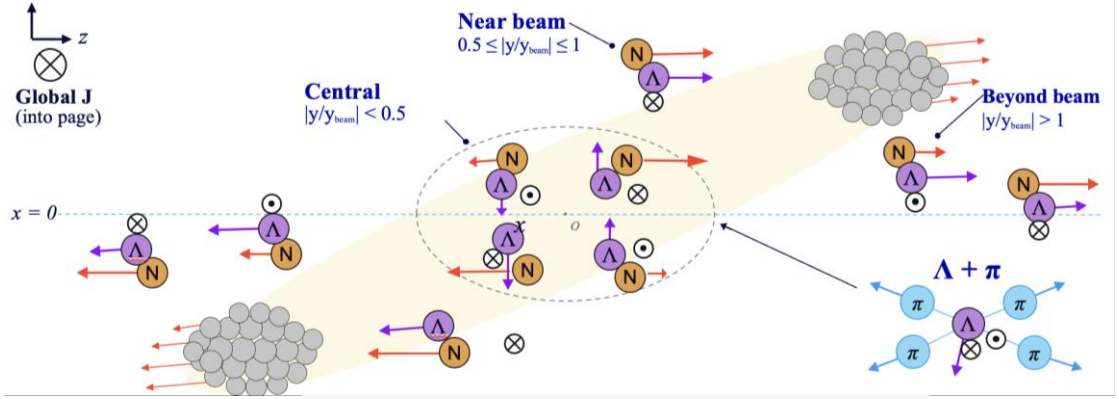
strong-field induced hyperon spin correlation



1. Different from shear-induced spin correlation
2. Only same flavor correlation, no K* spin alignment
3. Background from spin correlation in initial production
4. Spin correlation from gluon-fluctuation

→ J/ψ , D* early freeze-out, no effect on hadron with late freeze-out

Λ polarization due to hadronic interaction

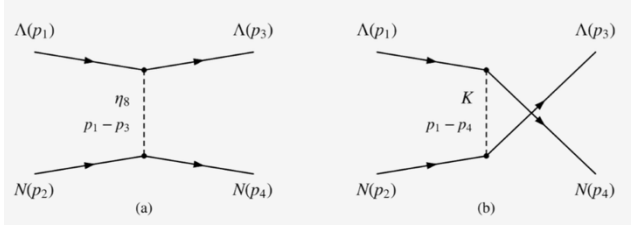


(1) Hyperon production through hadronic interaction at low energy

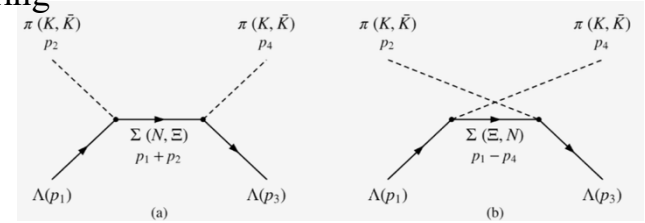
(2) Hyperon spin polarization through hadronic rescattering in the hadronic stage at both low and high energy

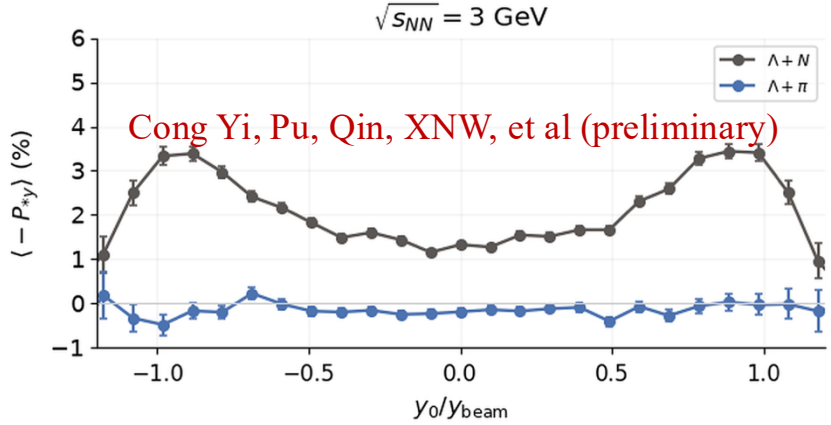
$\Lambda+N$

derivative coupling

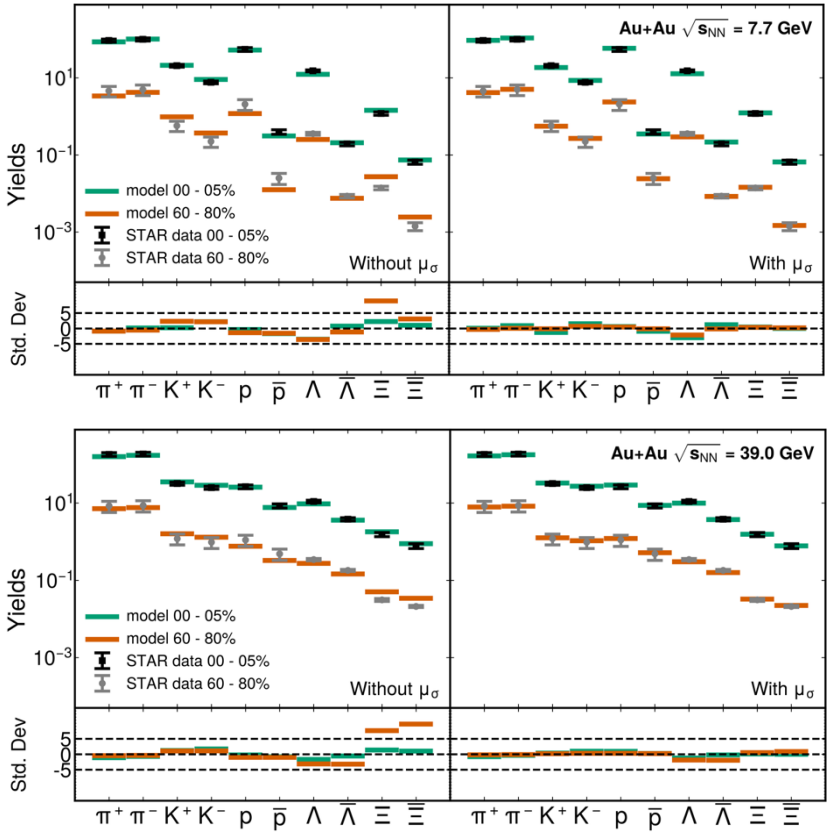


$\Lambda+\pi/K$

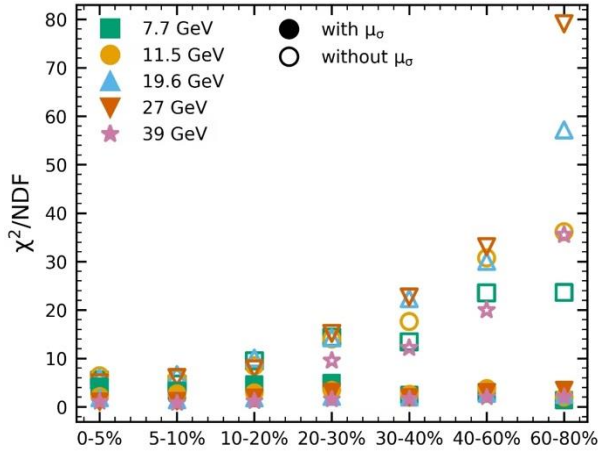




Spin polarization and hadron chemistry



$$N = \frac{V}{2\pi^2} \sum_{s_z=-s}^{+s} \int p^2 \frac{dp}{e^{E^*/T} \pm 1} \qquad E^* = E - \mu - \mu_\sigma s_z$$

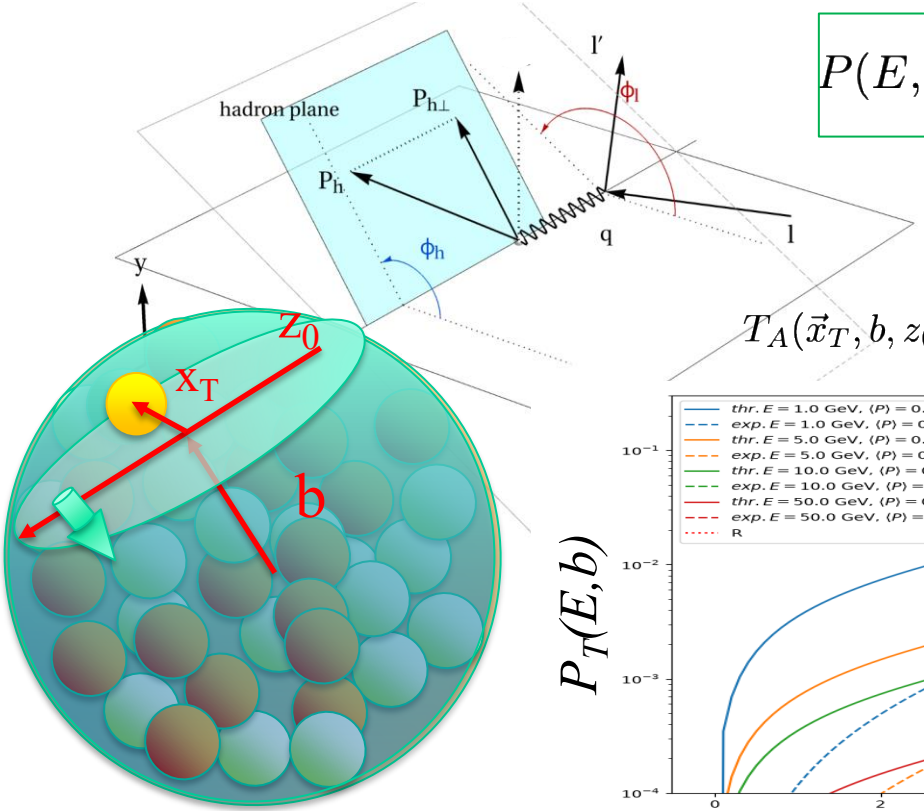


μ_σ significantly improves the agreement between model and experiment

Wu, Liang, Pang, XNW & Huang (preliminary)

Spin polarization in unpolarized e+A collisions

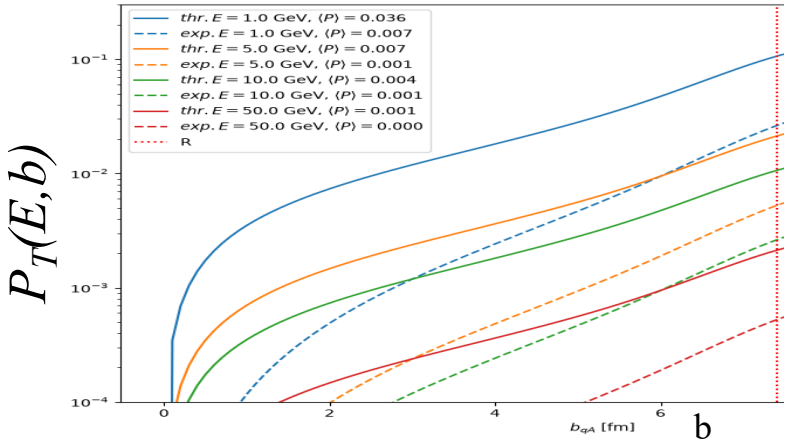
Transverse polarization from q-N scattering at fixed b



$$P(E,b,z_0) = \frac{\int d^2x_\perp\, T_A(\vec{x}_\perp,b,z_0)\,(d\sigma_+ - d\sigma_-)}{\int d^2x_\perp\, T_A(\vec{x}_\perp,b,z_0)(d\sigma_+ + d\sigma_-)}$$

$$\frac{d\sigma^+}{d^2x_T} - \frac{d\sigma^-}{d^2x_T} = -\mu\frac{\vec{p}\cdot(\hat{\vec{x}}_T\times\vec{n})}{E(E+m_q)}4C_T\alpha_s^2K_0(\mu x_T)K_1(\mu x_T),$$

$$T_A(\vec{x}_T,b,z_0) = \int_{z_0}^{\infty} dz\,\rho_A\left(\sqrt{(x_T\cos\phi+b)^2+(x_T\sin\phi)^2+z^2}\right)$$

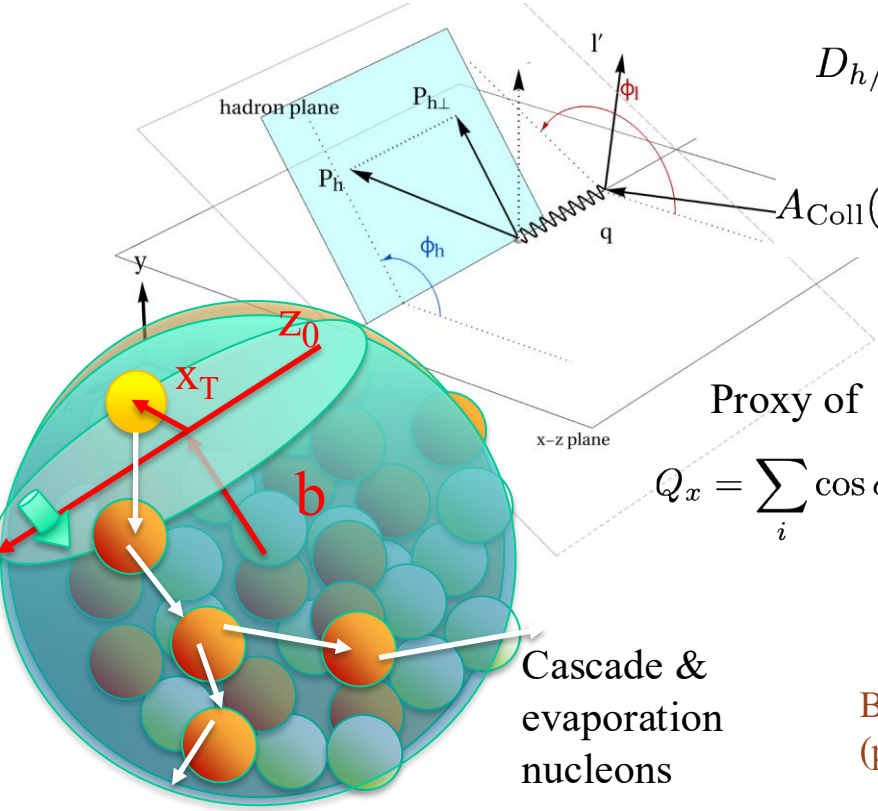


Overlap function at
$\mathbf{x_T}$+**b** for γ*+A at z_0

Bahder, Zheng & XNW
(preliminary)

Single spin asymmetry in unpolarized e+A collisions

Asymmetry using Collins fragmentation function



$$D_{h/q} = D_1(p_T, z) + s_T \frac{p_\perp}{zM_h} H_1^\perp(p_T, z)\cos(\phi_s - \phi_h)$$

$$A_{\mathrm{Coll}}(x, Q^2, z) \equiv 2\langle \cos\Delta\phi \rangle = -\langle P_q \rangle (x, Q^2) \frac{\langle p_T H_1^\perp(z) \rangle}{M_h \langle D_1(z) \rangle}$$

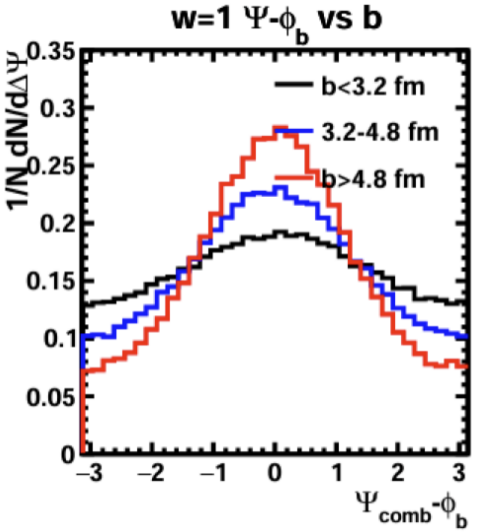
Proxy of impact-parameter

$$Q_x = \sum_i \cos\phi_i, \quad Q_y = \sum_i \sin\phi_i,$$

$$\Psi_1 = \mathrm{atan2}(Q_y, Q_x)$$

Cascade & evaporation nucleons

Bahder, Zheng & XNW (preliminary)



Summary and Future perspective

Spin dynamics opens up a new window for the study of nuclear collisions with many unexpected phenomena. Jet-induced vortex ring drives local vorticity. Effects of fluctuating strong force field.

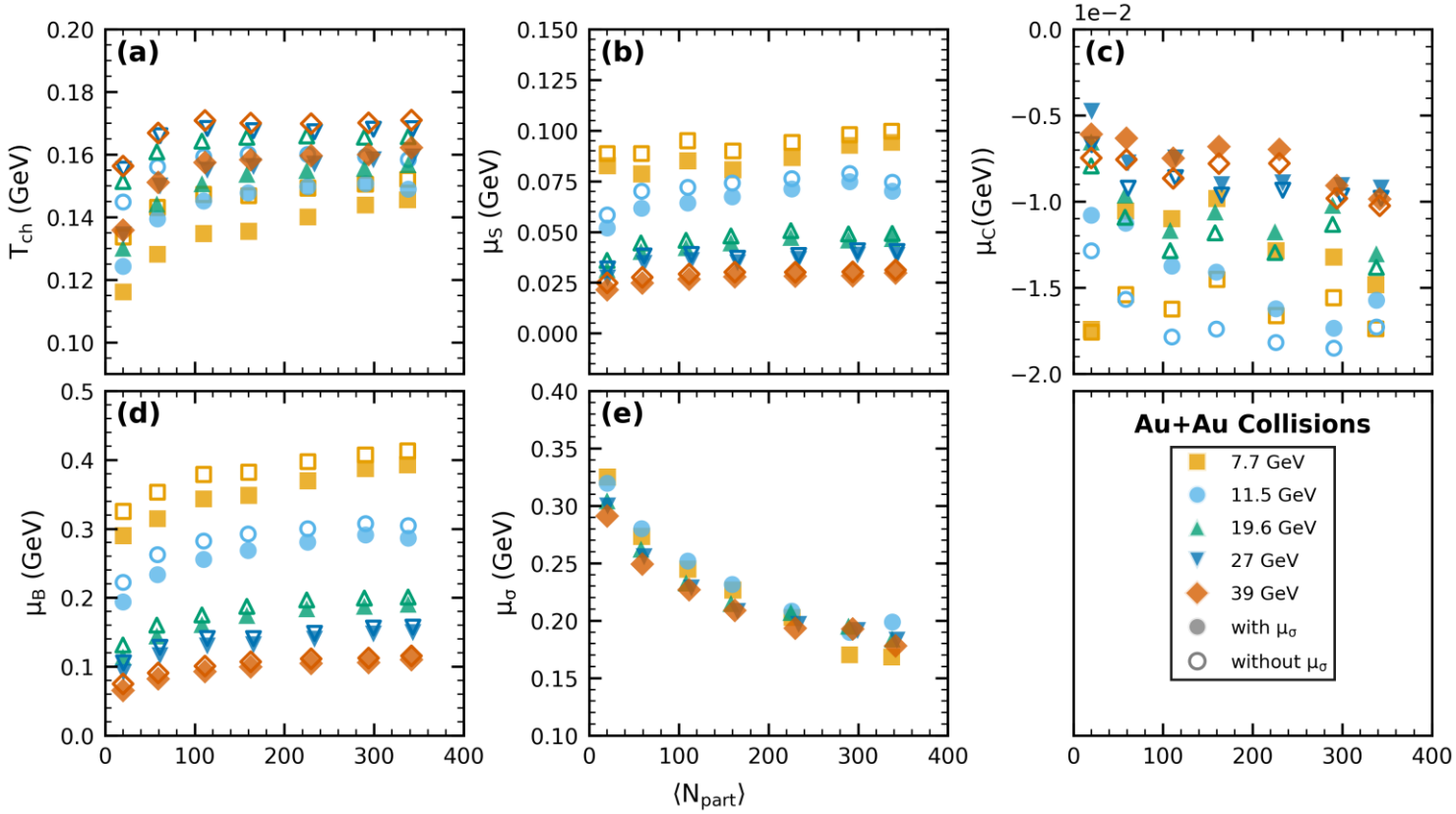
- Spin alignment of K^*: correlation of strong force field of different flavor?

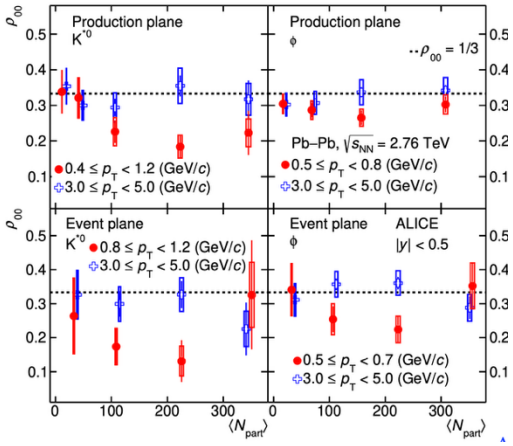
- Correlation of Λ spin polarization

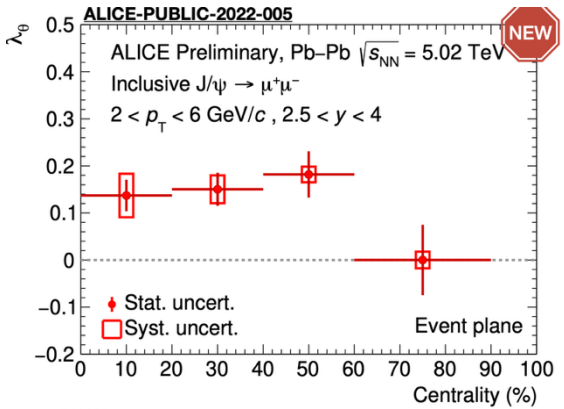
- Spin alignment of J/Ψ: fluctuation of gluonic field at shorter distance?

- Effect of hadronic interaction?
- Spin polarization from jet-induced vortex ring

- Spin polarization in unpolarized eA collisions at EIC


(a)
(b)
(c)
(d)
(e)
T_{ch} (GeV)
μ_S (GeV)
μ_C(GeV))
1e−2
μ_B (GeV)
μ_σ (GeV)
⟨N_{part}⟩
Au+Au Collisions
7.7 GeV
11.5 GeV
19.6 GeV
27 GeV
39 GeV
with μ_σ
without μ_σ


Production plane
K*0
Production plane
ϕ
ρ00 = 1/3
Pb–Pb, √sNN = 2.76 TeV
0.4 ≤ pT < 1.2 (GeV/c)
3.0 ≤ pT < 5.0 (GeV/c)
0.5 ≤ pT < 0.8 (GeV/c)
3.0 ≤ pT < 5.0 (GeV/c)
Event plane
K*0
0.8 ≤ pT < 1.2 (GeV/c)
3.0 ≤ pT < 5.0 (GeV/c)
Event plane
ϕ
ALICE
|y| < 0.5
0.5 ≤ pT < 0.7 (GeV/c)
3.0 ≤ pT < 5.0 (GeV/c)
ρ00
⟨Npart⟩


ALICE-PUBLIC-2022-005
NEW
ALICE Preliminary, Pb–Pb √sNN = 5.02 TeV
Inclusive J/ψ → μ+μ−
2 < pT < 6 GeV/c , 2.5 < y < 4
λθ
Stat. uncert.
Syst. uncert.
Event plane
Centrality (%)

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)

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

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

Spin alignment on the hadronization hyper surface

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

Momentum-dependence

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

Hyperon spin correlations

Simple quark model of hyperon spin $P_H^\mu(x,p) \approx P_s^\mu(x,R_s p), \;\; p_s = R_s p$

Hyperon spin correlation (H: Λ, Λbar)

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

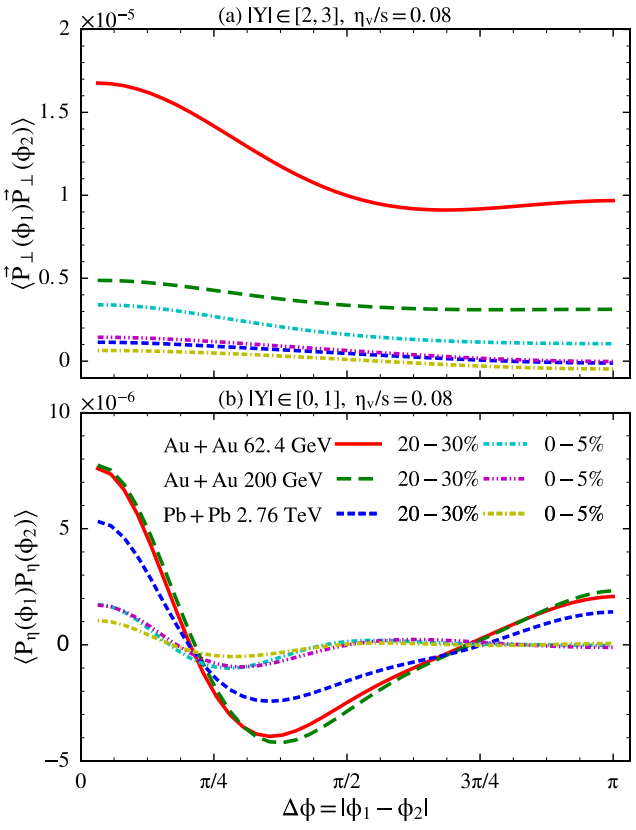
$\left\langle \cdots \right\rangle$ average over freeze-out hypersurface

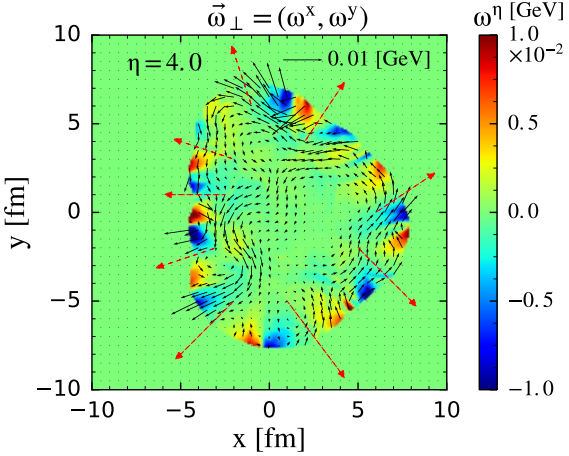
Short-distance correlation of the ϕ field

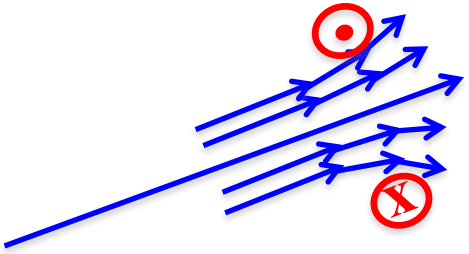
$$\left\langle g_\phi^2 F^\phi(x)F^\phi(y)/[T(x)T(y)]\right\rangle = F^2 G(x-y)$$

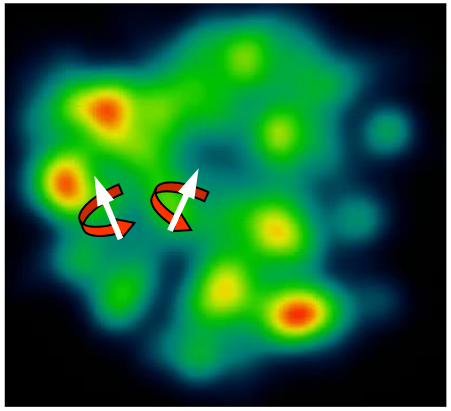
$$G(x-y) \equiv \exp\left[-\frac{(x^0-y^0)^2}{\sigma_t^2} - \frac{(\mathbf{x}-\mathbf{y})^2}{\sigma_x^2}\right]$$

Hyperon spin correlations









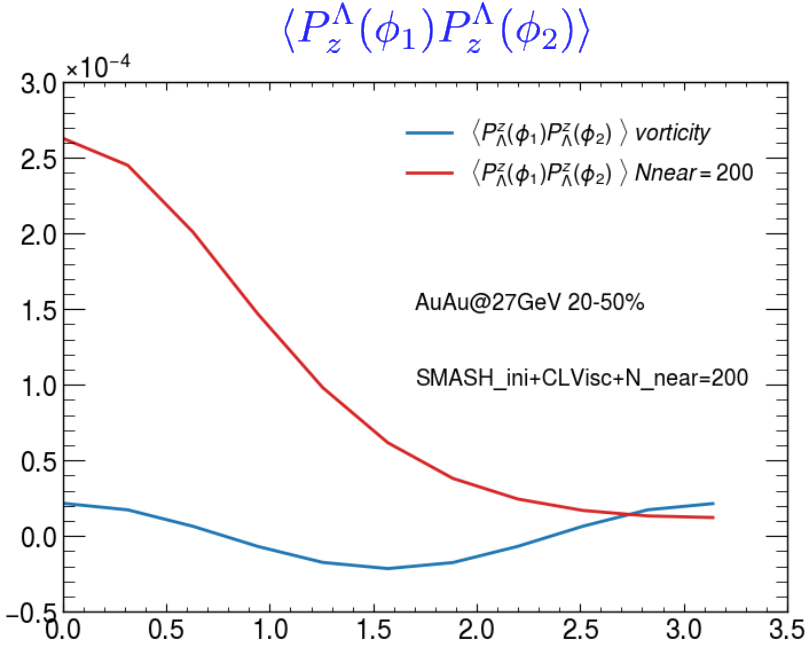
Pang, Petersen, Wang & XNW,
PRL 117(2016) 192301

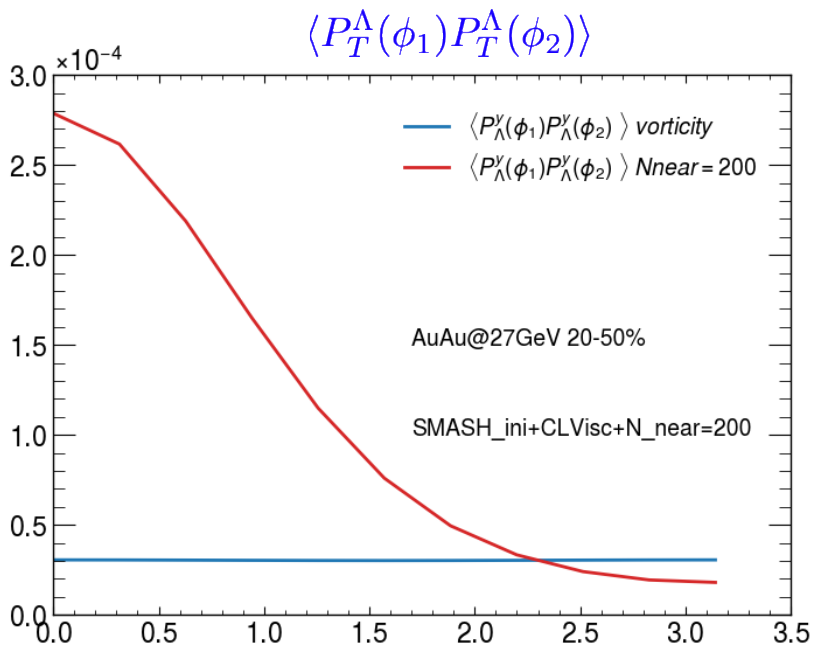
Vorticity ring:

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 correlation





Dominated by the correlation due to strong force field!

Sensitive to the correlation length σ