

BARYONS 2025

INTERNATIONAL
CONFERENCE ON THE
STRUCTURE OF BARYONS

10-14 NOV 2025
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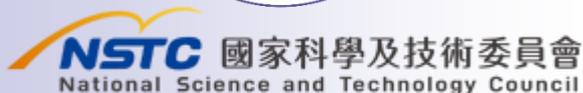


Probing QCD matter from spin “polarization and alignment” of hadrons in nuclear collisions



Di-Lun Yang

Institute of Physics, Academia Sinica
(Baryons 2025, Jeju Island, Nov. 13)

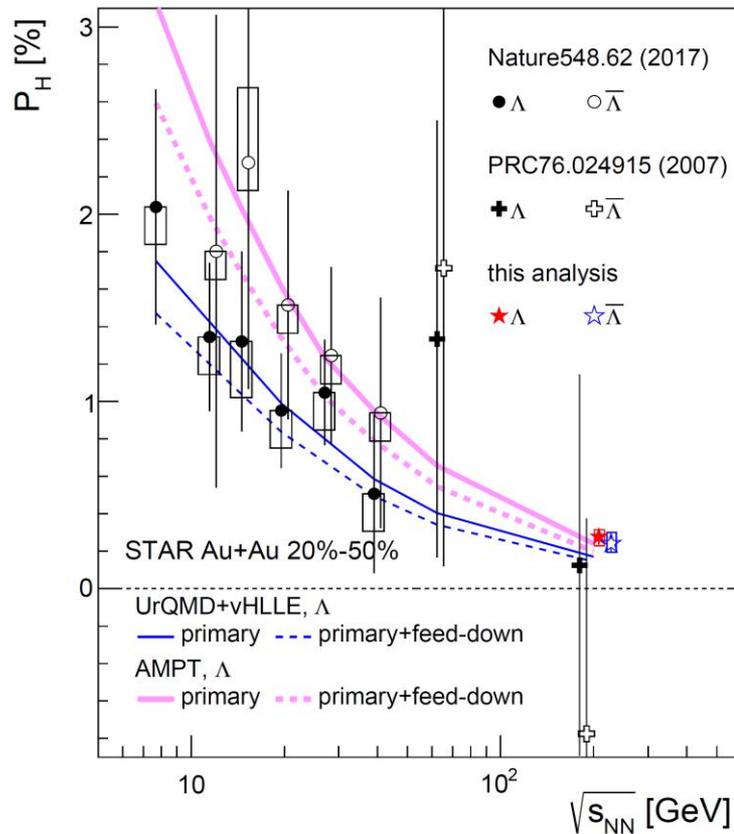


Global Λ polarization in HIC

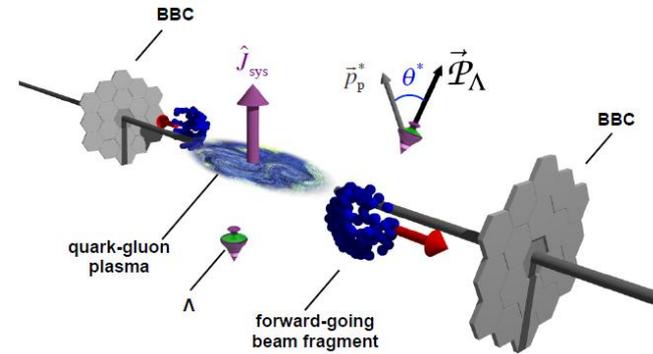
- The measurement of global polarization of Λ hyperons revealed the spin-orbit interaction & strong vorticity in heavy ion collisions. Z.-T. Liang & X.-N. Wang, PRL. 94, 102301 (2005)

(relativistic Barnett effect)

- Self-analyzing via the weak decay : $\Lambda \rightarrow p + \pi^-$



L. Adamczyk et al. (STAR), Nature 548, 62 (2017)



- Successfully described by the modified Cooper–Frye formula in **global equilibrium** : F. Becattini, et al., Ann. Phys. 338, 32 (2013)
R. Fang, et al., PRC 94, 024904 (2016)

$$\mathcal{P}^\mu = \frac{\int d\Sigma \cdot p f_p^{(0)} (1 - f_p^{(0)}) \epsilon^{\mu\nu\rho\sigma} q_\nu \omega_{\rho\sigma}}{8M_\Lambda \int d\Sigma \cdot p f_p^{(0)}}$$

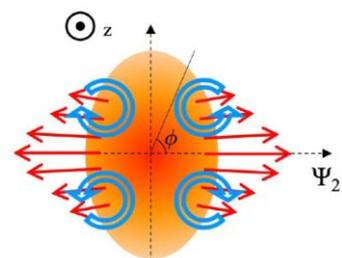
$$\omega_{\rho\sigma} = \frac{1}{2} \left(\partial_\rho \left(\frac{u_\sigma}{T} \right) - \partial_\sigma \left(\frac{u_\rho}{T} \right) \right) \cdot \text{thermal vorticity}$$

- Global pol. from (average) kinetic vorticity :

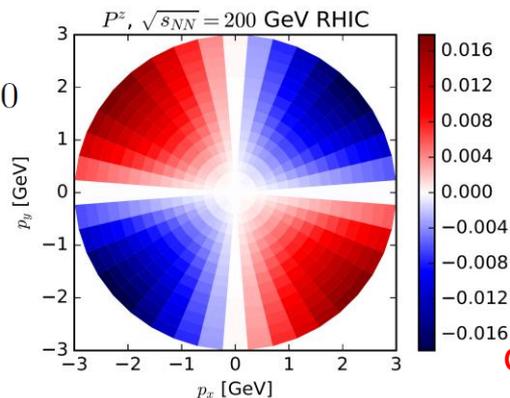
$$P_{\Lambda(\bar{\Lambda})} \approx \int_p \mathcal{P}^{-y}(p) \simeq \frac{\omega}{2T} \longrightarrow \omega = \frac{1}{2} |\nabla \times u| \sim 10^{22} s^{-1}$$

Longitudinal (local) polarization

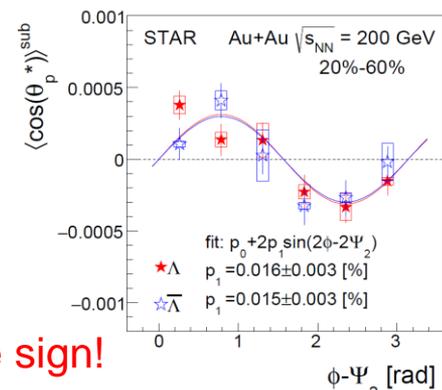
Longitudinal polarization along the beam direction in HIC :



F. Becattini, I. Karpenko, PRL 120, 012302 (2018).



J. Adam et al. (STAR), PRL. 123, 132301 (2019)



$P_{2,z} > 0$

$$P_{2,z} = \langle P_z \sin 2(\phi - \Psi_2) \rangle$$

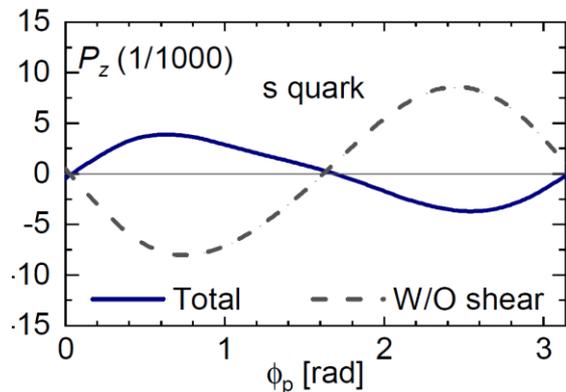
$$\approx \int_0^{2\pi} d(\phi - \Psi_2) \frac{P_z \sin 2(\phi - \Psi_2)}{2\pi}$$

V.S.

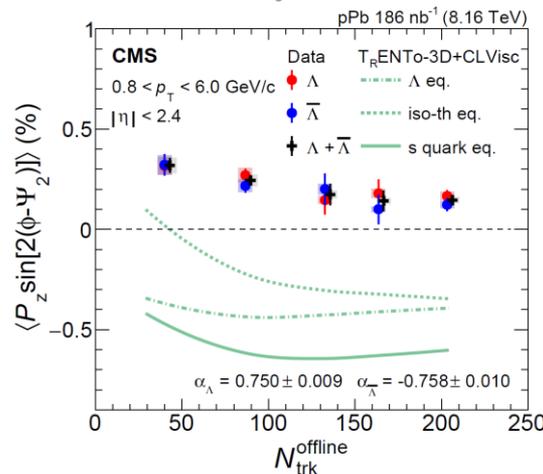
opposite sign!

❖ Thermal-shear corrections : (local equilibrium, indep. of int.)

$$\mathcal{P}^\mu(p) = \frac{\int d\Sigma_x \cdot p f_p^{(0)} (1 - f_p^{(0)}) \epsilon^{\mu\nu\rho\sigma} q_\nu [\omega_{\rho\sigma} - u_\rho \pi_{\sigma\lambda} p^\lambda / (T p \cdot u)]}{8M_\Lambda \int d\Sigma_x \cdot p f_p^{(0)}}$$



open question!



CMS, PRL 135 (2025) 132301

C. Yi et al., PRC 111 (2025) 044901

new effects needed

B. Fu et al., PRL 127, 142301 (2021)

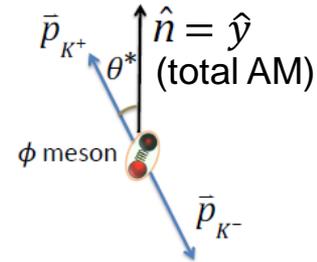
See also F. Becattini et al., PRL. 127, 272302 (2021), C. Yi et al., PRC 104. 064901 (2021)

Spin alignment of vector mesons

- Angular dep. of the decay particle w.r.t the spin quantization axis :

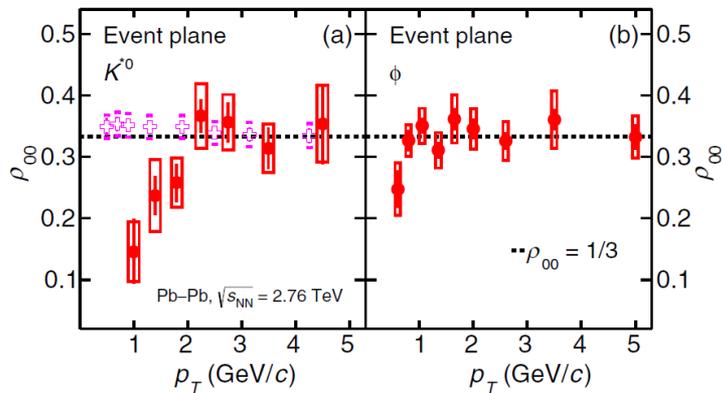
$$\frac{dN}{d \cos \theta^*} \propto [1 - \rho_{00} + \cos^2 \theta^* (3\rho_{00} - 1)]$$

$$\rho_{00} = \frac{1 - \langle \mathcal{P}_q^y \mathcal{P}_{\bar{q}}^y \rangle}{3 + \langle \mathcal{P}_q^y \mathcal{P}_{\bar{q}}^y \rangle}$$

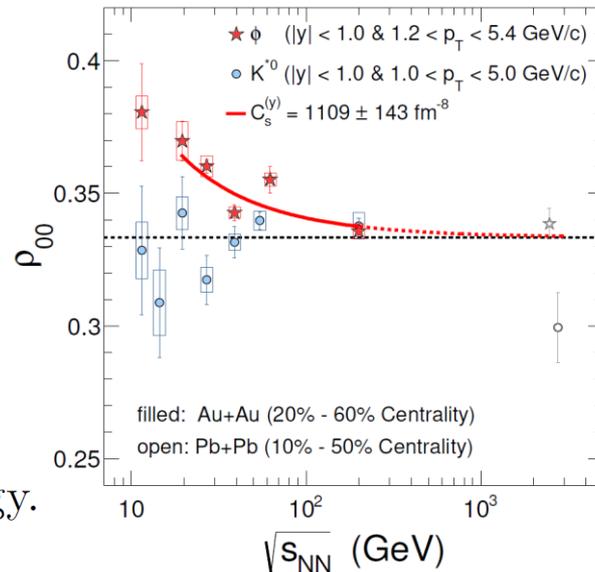


Z.-T. Liang and X.-N. Wang, PLB 629, 20 (2005)

$\rho_{00} \neq 1/3$: spin correlation



S. Acharya et al. (ALICE), PRL.125, 012301 (2020)



M.S. Abdallah et al. (STAR), Nature 614 (2023) 7947, 244-248,

- Spin alignment puzzle : the deviation from 1/3 is unexpectedly large.

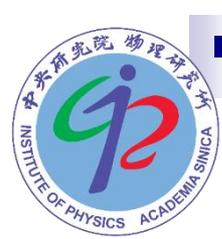
e.g. $\rho_{00} \approx \frac{1}{3} - \left(\frac{\omega}{T}\right)^2$, $\frac{\omega}{T} \sim 0.1\%$ at LHC energy.

➔ **Beyond hydro**: opportunities to probe microscopic int. in QCD matter

- Electromagnetic fields can polarize the spin. How about gluon fields?

$$\mathcal{P} \propto \mathbf{B} - \mathbf{u} \times \mathbf{E}$$

magnetic pol. spin Hall effect with momentum anisotropy



QKT for relativistic massive fermions

- **Quantum kinetic theory (QKT)** : tracking the spin evolution in phase space

Review : Y. Hidaka S. Pu, Q, Wang, DY, PPNP 127, 103989 (2022)

- **Axial kinetic theory (AKT)** : scalar/axial-vector kinetic eqs. (SKE/AKE)

➤ SKE : $p \cdot \Delta f_V = \mathcal{C}[f_V], \quad \Delta_\mu = \partial_\mu + eF_{\nu\mu} \partial_p^\nu.$

K. Hattori, Y. Hidaka, DY, PRD 100 (2019), 096011
DY, K. Hattori, Y. Hidaka, JHEP 20, 070 (2020)

standard Boltzmann (Vlasov) eq.

➤ AKE : $p \cdot \Delta \tilde{a}^\mu + eF^{\nu\mu} \tilde{a}_\nu - \frac{\hbar}{2} \epsilon^{\mu\nu\rho\sigma} p_\rho (\partial_\sigma eF_{\beta\nu}) \partial_p^\beta f_V = q_\nu \widehat{\Sigma_V^\nu} \tilde{a}^\mu + \dots + \frac{\hbar}{2} \epsilon^{\mu\nu\rho\sigma} q_\nu (\Delta_\sigma \widehat{\Sigma_V^\rho}) f_V,$

($\tilde{a}^\mu(p, x)$: effective spin four vector)

entangled f_V & \tilde{a}^μ

$$\widehat{AB} = A^<B^> - A^>B^<.$$

(\hbar : gradient corrections in phase space)

□ Spin pol. spectra : $\mathcal{P}^\mu(\mathbf{p}) = \frac{\int d\Sigma \cdot p \mathcal{J}_5^\mu(\mathbf{p}, x)}{2m \int d\Sigma \cdot \mathcal{N}(\mathbf{p}, x)}, \quad \mathcal{J}_5^\mu(\mathbf{p}, x) \propto \int dp_0 \mathcal{A}^\mu(p, x)$

$$\mathcal{A}^\mu = 2\pi \left(\delta(p^2 - m^2) \tilde{a}^\mu + \hbar \delta'(p^2 - m^2) e \tilde{F}^{\mu\nu} p_\nu f_V \right)$$

(dynamical)

(non-dynamical)

- Spin alignment from quark coalescence :

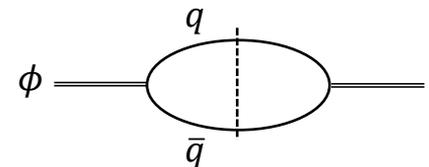
KE for vector mesons : $q \cdot \partial f_\lambda^\phi \approx \epsilon_\mu^*(\lambda, \mathbf{q}) \epsilon_\nu(\lambda, \mathbf{q}) \mathcal{C}_{\text{coal}}^{\mu\nu}(q, x)$

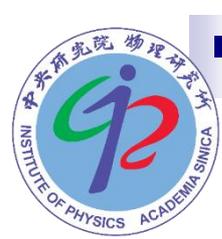
quark-meson int. :

$$\mathcal{L}_{\text{int}} = g_\phi \bar{\psi} \gamma^\mu V_\mu \psi$$

($\rho_{\lambda\lambda} \propto f_\lambda^\phi, \lambda = 0, \pm 1$)

➔ $\rho_{00}(q) = \frac{\int d\Sigma_X \cdot q f_0^\phi(q, X)}{\int d\Sigma_X \cdot q (f_0^\phi(q, X) + f_{+1}^\phi(q, X) + f_{-1}^\phi(q, X))}$





An intuitive picture

- An intuitive construction of color-singlet spin observables :

- ❖ Building blocks for quark transport :

$$\mathbf{F}^a = g(\mathbf{E}^a + \mathbf{u} \times \mathbf{B}^a), \quad \mathcal{P}^a = g(\mathbf{B}^a - \mathbf{u} \times \mathbf{E}^a).$$

chromo-Lorentz force

chromo-magnetic polarization & spin Hall effect

- ❖ Parity-even correlators only :

$$\langle E^i(x)E^j(x) \rangle = \delta^{ij} \langle E^i(x)E^i(x) \rangle, \quad \langle B^i(x)B^j(x) \rangle = \delta^{ij} \langle B^i(x)B^i(x) \rangle, \quad \langle E^i(x)B^j(x) \rangle = 0.$$

- spin alignment (without flow) : $\delta\rho_{00} = \rho_{00} - \frac{1}{3} \sim \langle \mathcal{P}^a \cdot \mathcal{P}^a \rangle \sim \langle \mathbf{B}^a \cdot \mathbf{B}^a \rangle$
- spin polarization of Λ (strange-equilibrium scenario) : p – even scalar

$$\mathcal{P} \sim \langle (\mathbf{p} \cdot \mathbf{F}^a) \mathcal{P}^a \rangle \quad \text{flow-induced polarization}$$

$$\sim \langle (\mathbf{p} \times \mathbf{u}) (\langle \mathbf{B}^a \cdot \mathbf{B}^a \rangle + \langle \mathbf{E}^a \cdot \mathbf{E}^a \rangle) \rangle \quad p \text{ – even axial-vector}$$

- Such effects as **non-equilibrium** spin transport can be systematically derived from the **QKT with color dof**.

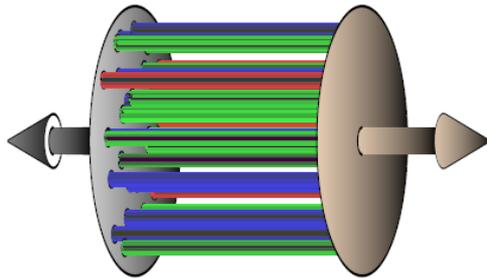
$$\mathcal{A}^\mu(p, x) = \int d^4y e^{\frac{i\mathbf{p}\cdot\mathbf{y}}{\hbar}} \left\langle \bar{\psi} \left(x - \frac{\mathbf{y}}{2} \right) \gamma^\mu \gamma^5 \psi \left(x + \frac{\mathbf{y}}{2} \right) \right\rangle = \mathcal{A}^{\text{S}\mu}(p, x) + t^a \mathcal{A}^{\text{O}\mu}(p, x)$$

color singlet

color octet

Color-field induced spin alignment

- **Initial-state** gluons may form the **glasma** phase characterized by predominantly longitudinal chromo-electromagnetic fields from **color glass condensate (CGC)**.



(at top RHIC & LHC energies)

Reviews : F. Gelis et al., Ann.Rev.Nucl.Part.Sci.60:463-489,2010

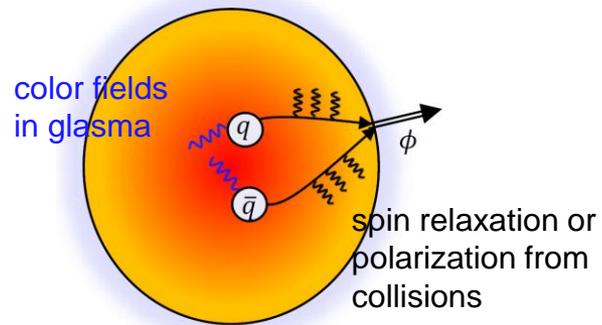
J. Berges et al., Rev. Mod. Phys. 93 (2021) 3, 035003

- Assuming the early quark production in glasma

N. Tanji, J. Berges, PRD, 97, 034013 (2018)

❖ Why glasma fields for spin alignment?

- (1) intrinsic saturation scale $Q_s \gg \omega$
- (2) fluctuating (no effect on global Λ pol.)
- (3) intrinsic anisotropy (need not be along \hat{n})



Updated coalescence model :

$$\rho_{00}(q) \approx \frac{1 - \text{Tr}_c \langle \hat{\mathcal{P}}_q^y(\mathbf{q}/2) \hat{\mathcal{P}}_{\bar{q}}^y(\mathbf{q}/2) \rangle_{\mathbf{q}=0}}{3 - \sum_{i=x,y,z} \text{Tr}_c \langle \hat{\mathcal{P}}_q^i(\mathbf{q}/2) \hat{\mathcal{P}}_{\bar{q}}^i(\mathbf{q}/2) \rangle_{\mathbf{q}=0}}$$

glasma effect :

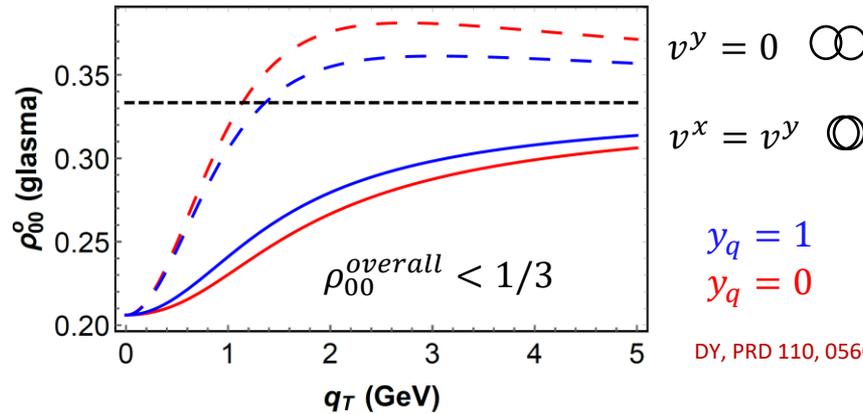
$$\text{Tr}_c \langle \hat{\mathcal{P}}_q^z(\mathbf{q}/2) \hat{\mathcal{P}}_{\bar{q}}^z(\mathbf{q}/2) \rangle_{\mathbf{q}=0} < 0$$

\longrightarrow $\delta\rho_{00} = \rho_{00} - \frac{1}{3} \propto -\langle B^{az}(x) B^{az}(x') \rangle e^{-2\Delta t/\tau_R} < 0$
A. Kumar, B. Müller, DY, PRD 107, 076025 (2023)

glasma effect
relaxation in QGP

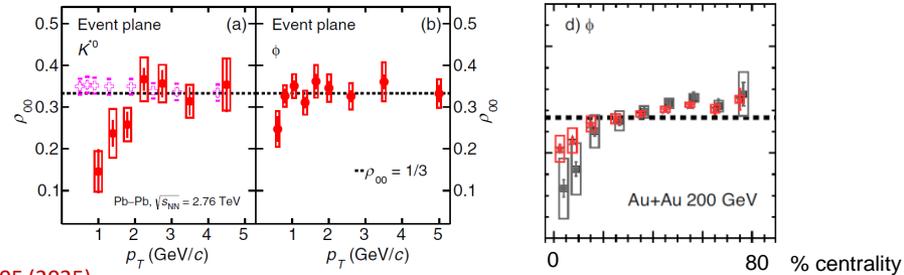
Transverse spin alignment spectra

- Out-of-plane spin alignment (ϕ mesons) : boost color fields for momentum dep.
- ❖ Initial-state effect (glasma) : high-energy

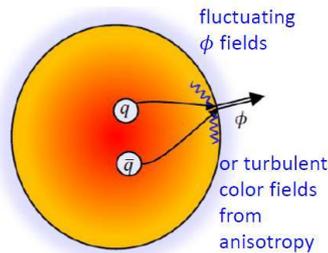
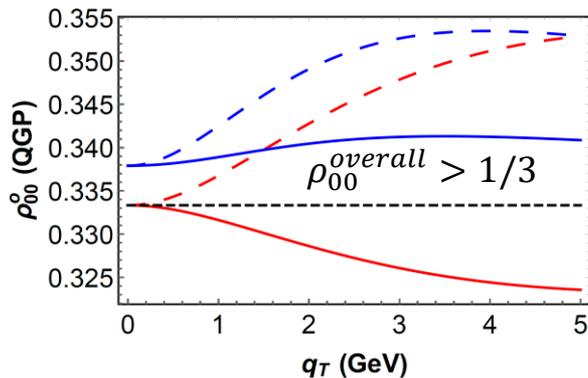


DY, PRD 110, 056005 (2025)

weighting needed : $\langle \rho_{00}^0(q_T) \rangle = \frac{\int d\phi_q dy_q [\rho_{00}^0(\mathbf{q}) \mathcal{N}]}{\int \phi_q dy_q \mathcal{N}}$

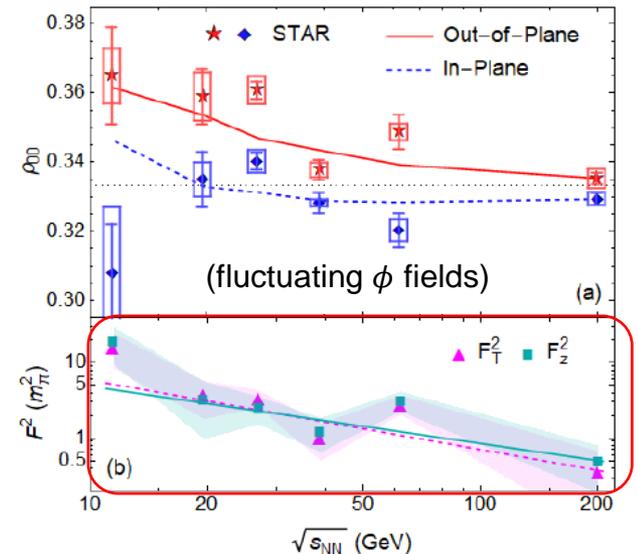


- ❖ Final-state effect (strong-force fields in QGP) : low-energy



X.-L. Sheng et al., PRD 109, 036004, (2024)
 PRL 131, 042304 (2023)
 B. Müller, DY, PRD 105, L011901 (2022)
 DY, JHEP 06, 140 (2022)

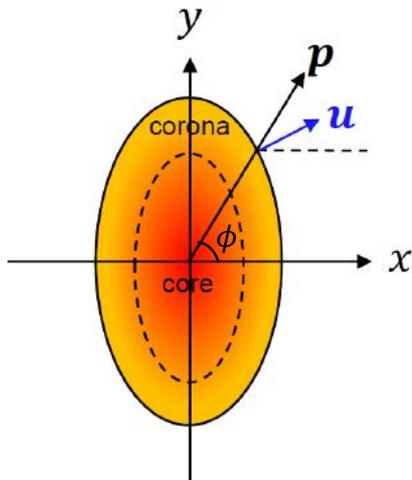
(isotropic color fields from QGP : qualitative)



isotropic, competition with glasma effect at high energies?

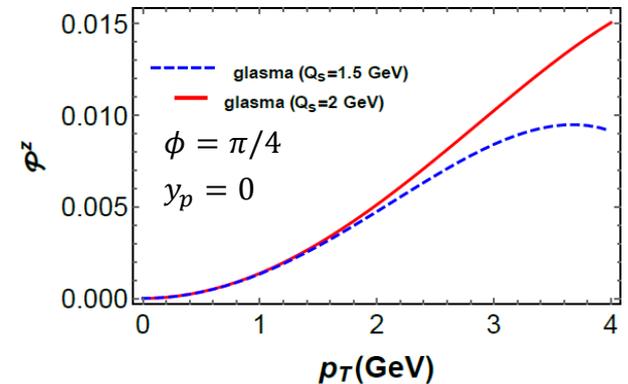
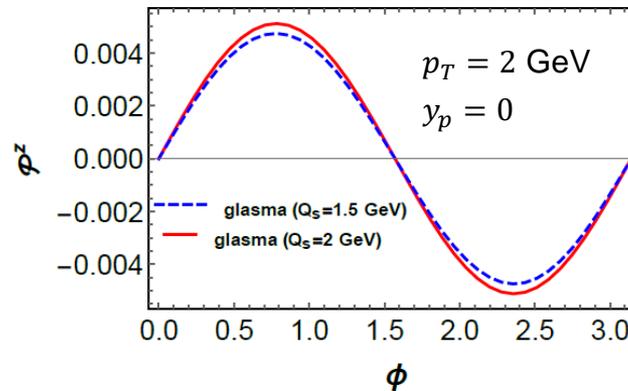
Longitudinal Λ polarization (focused on pA)

- Longitudinal polarization from the **corona of glasma** (early hadronization) :



weak initial anisotropic flow from pressure gradient

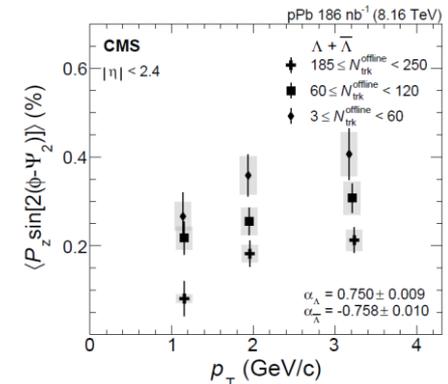
$$\mathcal{P}^z \approx \frac{\hbar(N_c^2 - 1)Q_s^2 \Delta t}{16M_\Lambda N_c^2 \epsilon_p} \int d\Sigma \cdot p (p^x u^y - p^y u^x) \mathbf{p} \times \mathbf{u} \text{ structure} \\ \times (u^0 \partial_{p \cdot u / Q_s} - Q_s / \epsilon_p) \partial_{p \cdot u / Q_s} f_V^S, \quad f_V^S(p \cdot u / Q_s) = e^{-\pi(p \cdot u)^2 / |gE^\alpha|}$$

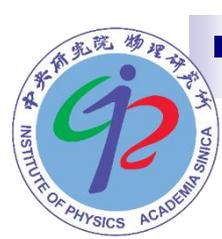


H. Sung, B. Müller, DY, arXiv: 2507.23210

- ✓ consistent sign & comparable order of magnitude with observations

See the talk by Haesom Sung (14;35, Nov. 11, Parallel Session A)





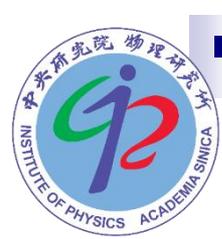
Conclusions & outlook

□ Conclusions :

- ✓ Spin polarization phenomena for hadrons (Λ polarization & vector-meson spin alignment) provide a new opportunity to study QCD matter (glasma & QGP) in nuclear collisions.
- ✓ Coherent gluons characterized by color fields could play a significant role on local spin polarization and spin alignment on top of the “hydro” contributions.
- ✓ The size and energy dependence of collision systems may be helpful to disentangle the competing effects.

□ Outlook :

- More sophisticated modeling & simulations are needed.
e.g., more accurate estimation on spin relaxation in QGP
- (Collective) spin transport for heavy quarks : more sensitive to the glasma effects.
- Local spin polarization in low-energy collisions : non-equilibrium spin transport of hadrons?



Axial kinetic theory with color fields

- Incorporation of background color fields into Wigner functions and kinetic equations.

- Color decomposition : $O = O^s I + O^a t^a$

U. W. Heinz, Phys. Rev. Lett. 51, 351 (1983)

H. T. Elze, M. Gyulassy, D. Vasak, Nucl. Phys. B276, 706 (1986).

e.g., $\mathcal{A}^\mu(\mathbf{p}, x) = \mathcal{A}^{s\mu}(\mathbf{p}, x)I + \mathcal{A}^{a\mu}(\mathbf{p}, x)t^a$, $f_V(\mathbf{p}, x) = f_V^s(\mathbf{p}, x)I + f_V^a(\mathbf{p}, x)t^a$,
 $\tilde{a}^\mu(\mathbf{p}, x) = \tilde{a}^{s\mu}(\mathbf{p}, x)I + \tilde{a}^{a\mu}(\mathbf{p}, x)t^a$.

- Kinetic equations : DY, JHEP 06, 140 (2022)

SKEs : $p^\rho \left(\partial_\rho f_V^s + \frac{g}{2N_c} F_{\nu\rho}^a \partial_p^\nu f_V^a \right) = \mathcal{C}_s$, $p^\rho \left(\partial_\rho f_V^a + g F_{\nu\rho}^a \partial_p^\nu f_V^s + \frac{d^{bca}}{2} g F_{\nu\rho}^b \partial_p^\nu f_V^c \right) = \mathcal{C}_o^a$,

diffusion

dynamical spin polarization

AKEs : $p^\rho \partial_\rho \tilde{a}^{s\mu} + \frac{g}{2N_c} \left(p^\rho F_{\nu\rho}^a \partial_p^\nu \tilde{a}^{a\mu} + F^{a\nu\mu} \tilde{a}_\nu^a \right) - \frac{\hbar}{4N_c} \epsilon^{\mu\nu\rho\sigma} p_\rho (\partial_\sigma g F_{\beta\nu}^a) \partial_p^\beta f_V^a = \mathcal{C}_s^\mu$,

$p^\rho \partial_\rho \tilde{a}^{a\mu} + g \left(p^\rho F_{\nu\rho}^a \partial_p^\nu \tilde{a}^{s\mu} + F^{a\nu\mu} \tilde{a}_\nu^s \right) + \frac{d^{bca}}{2} g \left(p^\rho F_{\nu\rho}^b \partial_p^\nu \tilde{a}^{c\mu} + F^{b\nu\mu} \tilde{a}_\nu^c \right) - \frac{\hbar}{2} \epsilon^{\mu\nu\rho\sigma} p_\rho (\partial_\sigma g F_{\beta\nu}^a) \partial_p^\beta f_V^s = \mathcal{C}_o^{a\mu}$.

Axial Wigner functions : $\mathcal{A}^{s\mu}(\mathbf{p}, x) = \frac{1}{2\epsilon_{\mathbf{p}}} \left[\tilde{a}^{s\mu} - \frac{\hbar}{4N_c} \tilde{F}^{a\mu\nu} \left(\partial_{p\nu} f_V^a - \frac{\epsilon_{\mathbf{p}}}{2} \partial_{p_\perp\nu} (f_V^a / \epsilon_{\mathbf{p}}) \right) \right]_{p_0=\epsilon_{\mathbf{p}}}$,

$\mathcal{A}^{a\mu}(\mathbf{p}, x) = \frac{1}{2\epsilon_{\mathbf{p}}} \left[\tilde{a}^{a\mu} - \frac{\hbar}{2} \tilde{F}^{a\mu\nu} \left(\partial_{p\nu} f_V^s - \frac{\epsilon_{\mathbf{p}}}{2} \partial_{p_\perp\nu} (f_V^s / \epsilon_{\mathbf{p}}) \right) \right]_{p_0=\epsilon_{\mathbf{p}}}$.

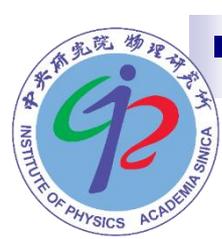
dynamical (w/ memory effect)

non-dynamical (w/o memory effect)

Spin

polarization:

$\mathcal{P}^\mu(\mathbf{p}) = \frac{\int d\Sigma \cdot p \text{Tr}_c \mathcal{A}^\mu(\mathbf{p}, x)}{2m \int d\Sigma \cdot p (2\epsilon_{\mathbf{p}})^{-1} f_V^s(\mathbf{p}, x)} = \frac{\int d\Sigma \cdot p \mathcal{A}^{s\mu}(\mathbf{p}, x)}{2m \int d\Sigma \cdot p (2\epsilon_{\mathbf{p}})^{-1} f_V^s(\mathbf{p}, x)}$.



Axial kinetic theory

- Axial kinetic theory : scalar/axial-vector kinetic eqs. (SKE/AKE)

- SKE : $p \cdot \Delta f_V = \mathcal{C}[f_V]$, $\Delta_\mu = \partial_\mu + e \underbrace{F_{\nu\mu}}_{\text{EM fields}} \partial_p^\nu$.
standard Vlasov eq.

K. Hattori, Y. Hidaka, DY, PRD 100, 096011 (2019)
DY, K. Hattori, Y. Hidaka, JHEP 20, 070 (2020)
Z. Wang, X. Guo, P. Zhuang, Eur. Phys. J. C 81, 799 (2021)

- AKE : $p \cdot \Delta \tilde{a}^\mu + e F^{\nu\mu} \tilde{a}_\nu - \frac{e}{2} \hbar \epsilon^{\mu\nu\rho\sigma} p_\rho (\partial_\sigma F_{\beta\nu}) \partial_p^\beta f_V = \underbrace{\hat{L}^{\mu\nu} \tilde{a}_\nu}_{\text{spin relaxation}} + \underbrace{\hbar \hat{H}^{\mu\nu} \partial_\nu f_V}_{\text{dynamical spin pol. from spin-orbit int.}}$.

($\tilde{a}^\mu(p, x)$: effective spin four vector)

(\hbar : gradient correction in phase space)

(entangled f_V & \tilde{a}^μ)

spin relaxation

dynamical spin pol.
from spin-orbit int.

- Axial Wigner functions :

$$\mathcal{A}^\mu(\mathbf{p}, x) = \frac{1}{2\epsilon_{\mathbf{p}}} \left[\tilde{a}^\mu - \frac{\hbar}{2} \tilde{F}^{\mu\nu} \left(\partial_{p\nu} f_V - \frac{\epsilon_{\mathbf{p}}}{2} \partial_{p\perp\nu} (f_V / \epsilon_{\mathbf{p}}) \right) \right]_{p_0 = \epsilon_{\mathbf{p}} = \sqrt{|\mathbf{p}|^2 + m^2}}$$

dynamical (w/ memory effect)

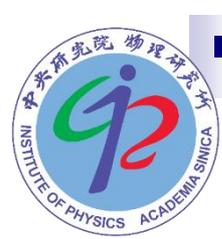
non-dynamical (w/o memory effect)

$$\Rightarrow \mathcal{P}^\mu(\mathbf{p}) = \frac{\int d\Sigma \cdot p \mathcal{A}^\mu(\mathbf{p}, x)}{2m \int d\Sigma \cdot p (2\epsilon_{\mathbf{p}})^{-1} f_V(\mathbf{p}, x)}$$

- Relaxation-time approx. & weak coupling :

$$p \cdot \partial \tilde{a}^\mu - \frac{e}{2} \hbar \epsilon^{\mu\nu\rho\sigma} p_\rho (\partial_\sigma F_{\beta\nu}) \partial_p^\beta f_V = -\frac{p_0 \delta \tilde{a}^\mu}{\tau_R}, \quad \delta \tilde{a}^\mu = \tilde{a}^\mu - \tilde{a}_{\text{eq}}^\mu.$$

$$\Rightarrow \delta \tilde{a}^\mu(\mathbf{p}, x) = \frac{\hbar e}{2} \int_{t_i}^{t_f} dx'_0 e^{-(x_0 - x'_0)/\tau_R} \epsilon^{\mu\nu\rho\sigma} \hat{p}_\rho (\partial_{x'_\sigma} F_{\beta\nu}(x')) \partial_p^\beta f_V(p, x')$$



Spin alignment from glasma

- Generalized AKT with color fields : $\tilde{a}^\mu(\mathbf{p}, x) = \tilde{a}^{s\mu}(\mathbf{p}, x)I + \boxed{\tilde{a}^{a\mu}(\mathbf{p}, x)} t^a$.
DY, JHEP 06, 140 (2022)
 B. Müller, DY, PRD 105, L011901 (2022) (more dominant in the perturbative approach)

- Dynamical spin polarization from glasma fields : A. Kumar, B. Müller, DY, PRD 108, 016020 (2023)

$$\tilde{a}^{a\mu}(\mathbf{p}, x) \approx -\frac{\hbar g}{2} e^{-(t_f - t_i)/\tau_R^0} (B^{a\mu}(t_i) \partial_{\epsilon_{\mathbf{p}}} f_V^s(\epsilon_{\mathbf{p}}, t_i) - B^{a\mu}(t_f) \partial_{\epsilon_{\mathbf{p}}} f_V^s(\epsilon_{\mathbf{p}}, t_f))$$

suppressed

- Correlation of initial color magnetic fields : $g^2 \langle B^{az}(x) B^{az}(x) \rangle_{x_0=t_i} \sim \frac{Q_s^4 (N_c^2 - 1)}{2N_c}$

K. J. Golec-Biernat and M. Wusthoff, Phys. Rev. D 59, 014017 (1998)
 P. Guerrero-Rodríguez and T. Lappi, Phys. Rev. D 104, 014011 (2021)

- Initial quark distribution function : $f_V^s(\epsilon_{\mathbf{p}}, t_i) = 1 / (e^{\epsilon_{\mathbf{p}}/Q_s} + 1)$

- ❖ spin correlation : $\langle \mathcal{P}_q^z \mathcal{P}_{\bar{q}}^z \rangle \sim \frac{Q_s^2}{m_q m_{\bar{q}}} e^{-2(t_f - t_i)/\tau_R^0}$

- ❖ Order-of-magnitude estimation (for ϕ) : $\rho_{00} \sim \frac{1}{3 + 10 e^{-2(t_f - t_i)/\tau_R^0}} < \frac{1}{3}$

glasma effect relaxation effect

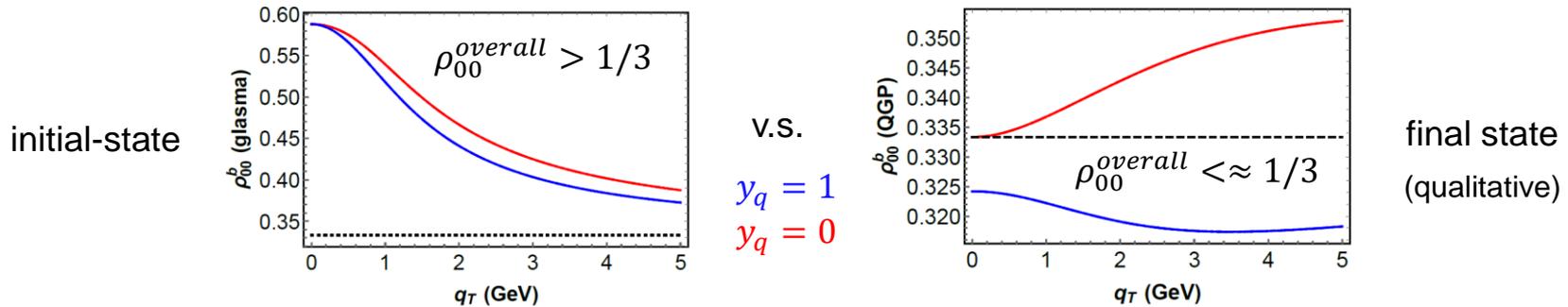
- ❖ Heavy-quark approx. : $\tau_R^0 \approx \left(\frac{g^2 C_2(F) m_D^2 T}{6\pi m^2} \ln g \right)^{-1} \approx 5 \text{ fm}/c \Rightarrow \rho_{00} \approx 0.24$

M. Hongo et al., JHEP 08, 263 (2022)

(model dependent)

Observables for future measurements

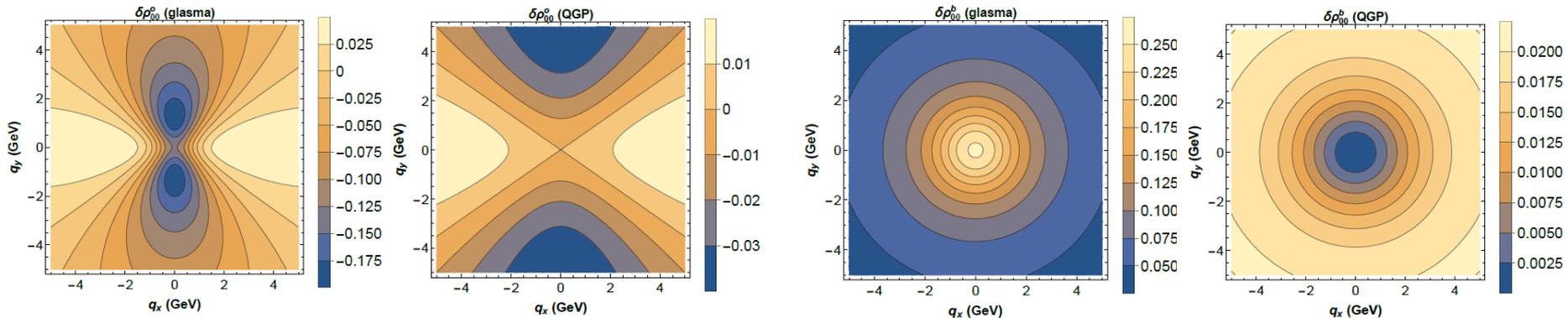
- Longitudinal spin alignment along the beam direction : DY, PRD 110, 056005 (2025)
- \hat{n} is uncorrelated to the reaction plane : weak centrality dependence?

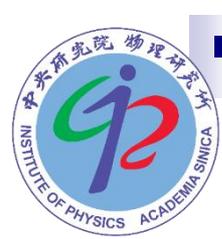


- Detailed transverse-momentum dependence :

❖ Transverse (out-of-plane) :

❖ Longitudinal :





More on spin polarization from color fields

- Isochronous freeze-out in 3+1 D : $\tilde{\tau} \equiv \sqrt{\tau^2 - x^2 - y^2}$

$$d\Sigma \cdot p = dr d\Phi d\eta r \sqrt{1 - \epsilon^2} (G_1 \cosh(y_p - \eta) + G_2), \quad G_1 = \sqrt{(m^2 + p_T^2)} \tau_f,$$

$$G_2 = -(xp^x + yp^y)$$

- Manifestation of $\sin 2\phi$: when $|\mathbf{p} \cdot \mathbf{u}| \ll Q_s$

$$\int d\Sigma \cdot p (p^x u^y - p^y u^x) \xrightarrow{G_2 \text{ dominates}} \int d\Sigma \cdot p u^{[y} p^{x]} u^0 \approx u_T p_T^2 \pi \sin 2\phi \int \frac{dr d\eta r^3 \tau \delta}{r_m^2}$$

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

- QGP case : when $|\mathbf{p} \cdot \mathbf{u}| \gtrsim T \xrightarrow{\text{yellow arrow}} G_1 \text{ dominates}$

H. Sung, B. Müller, DY, arXiv: 2507.23210

single freeze-out thermal model at $\sqrt{s_{NN}} = 130$ GeV

