Spin alignment of vector mesons by glasma fields

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(SQM2024, June 5th, 2024)

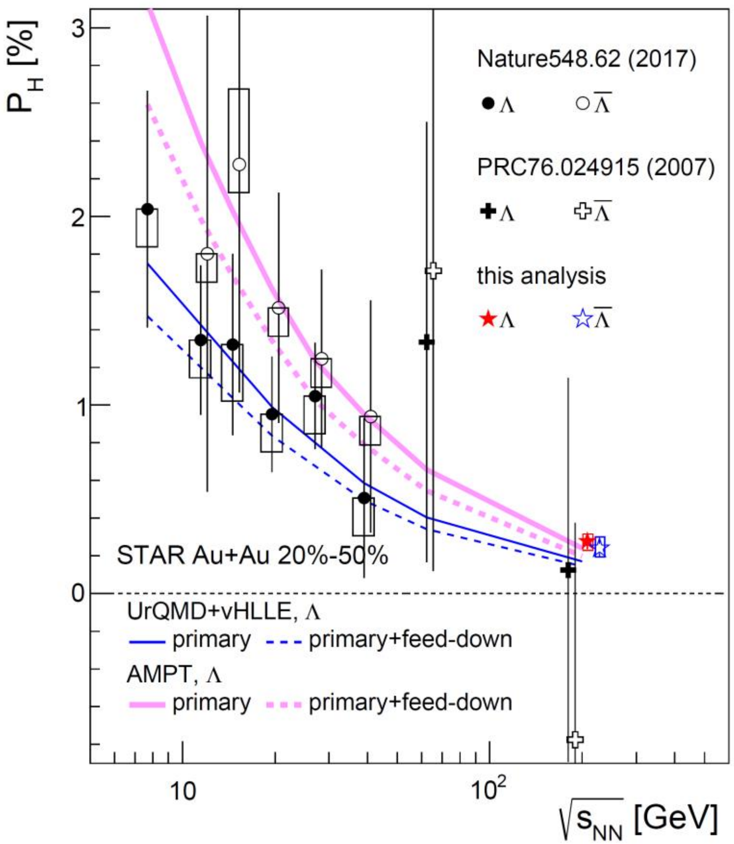
primary references :

A. Kumar, B. Müller, DY, PRD 108, 016020 (2023), arXiv:2304.04181

A. Kumar, B. Müller, DY, PRD 107, 076025 (2023), arXiv:2212.13354

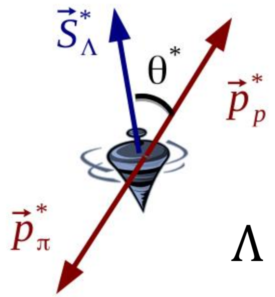
Global Λ polarization in HIC

- The large AM generated in HIC could induce spin polarization of the QGP via spin-orbit interaction. (relativistic Barnett effect) Z.-T. Liang and X.-N. Wang, PRL. 94, 102301 (2005)
- Global polarization of Λ hyperons :



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

❖ Self-analyzing via the weak decay :



$$\Lambda \to p + \pi^-$$

T. Niida, QM18

❖ In global equilibrium : F. Becattini, et al., Ann. Phys. 338, 32 (2013); R. Fang, et al., PRC 94, 024904 (2016)

$$\mathcal{P}^\mu(\boldsymbol{p}) = \frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_\nu \frac{\int d\Sigma \cdot p\,\omega_{\rho\sigma} f_p^{(0)}(1-f_p^{(0)})}{\int d\Sigma \cdot p f_p^{(0)}},$$

$$\omega_{\mu\nu} = \frac{1}{2}(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu).$$

thermal vorticity $(\beta^\mu \equiv u^\mu/T)$

❖ Indication of strong (kinetic) vorticity :

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \Longrightarrow \omega \sim 10^{22}\,\mathrm{s}^{-1}$$

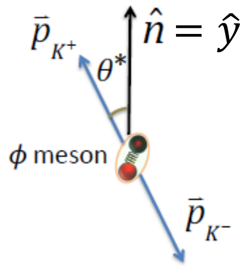
F. Becattini et al., PRC95, 054902 (2017)

Spin alignment of vector mesons

- Production of the decay daughter w.r.t the quantization axis :

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

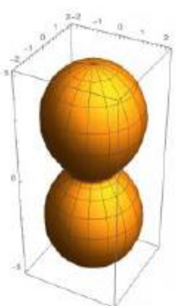
$$\rho_{00} = \frac{1 - \langle \mathcal{P}_q^y \mathcal{P}_{\bar{q}}^y \rangle}{3 + \langle \mathcal{P}_q^y \mathcal{P}_{\bar{q}}^y \rangle}$$



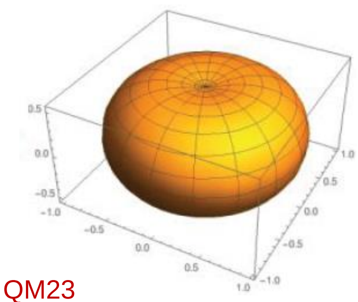
Z.-T. Liang and X.-N. Wang, PLB 629, 20 (2005)

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

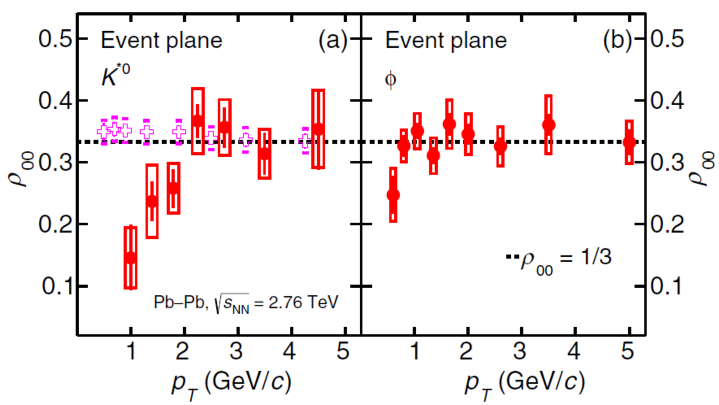
$\rho_{00} > 1/3$:



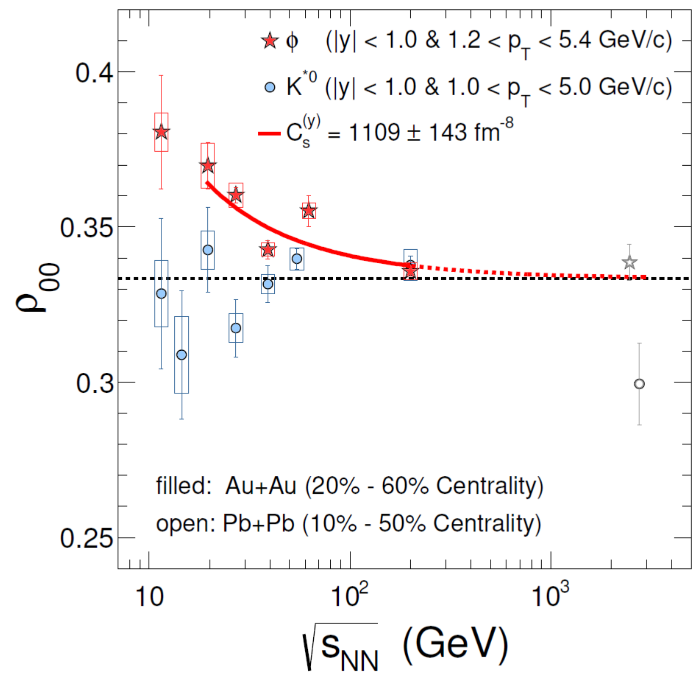
$\rho_{00} < 1/3$:



B. Xi, QM23



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



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

Spin polarization beyond subatomic swirls?

- Spin alignment puzzle : the deviation of ρ_{00} 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. (from Λ polarization)

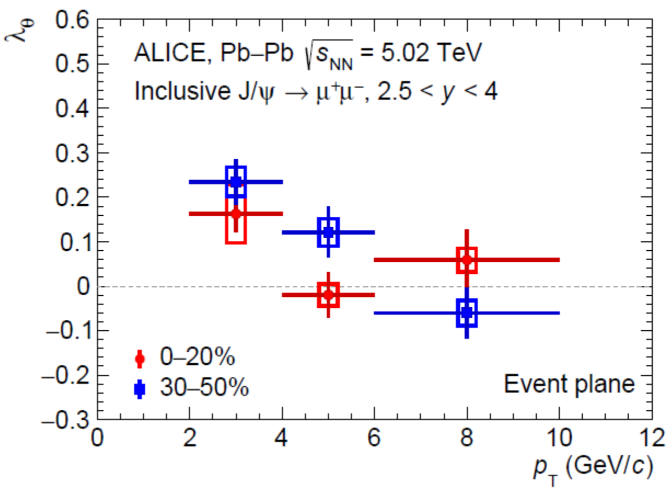
- Flavor & collision energy dep. :

	ϕ	K^{*0}
ALICE	$\rho_{00} < 1/3$ ($p_T \leq 1$ GeV)	$\rho_{00} < 1/3$
STAR	$\rho_{00} > 1/3$	$\rho_{00} \approx 1/3$

- Spin alignment for J/ψ :

  S. Acharya et al. , PRL 131,042303 (2023)

$$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}} > 0 \Rightarrow \rho_{00} < \frac{1}{3}$$



- Other sources for spin correlation (alignment) besides vorticity?

From spin correlations to spin alignment

- Spin alignment is led by spin correlations : $\langle \mathcal{P}_q^i \mathcal{P}_{\bar{q}}^i \rangle \neq \langle \mathcal{P}_q^i \rangle \langle \mathcal{P}_{\bar{q}}^i \rangle$

  ⇨ $\rho_{00} \neq 1/3$ with $\langle \mathcal{P}_{q/\bar{q}}^i \rangle = 0$ is possible

  spin polarization of Λ could be unaffected

  (the sources for spin alignment may be fluctuating)

- Spin quantization axis needs not be parallel to the spin polarization (or correlation)
- Anisotropic spin correlation is needed :

X.-L. Sheng et al., PRD 109, 036004, (2024)
A. Kumar, B. Müller, DY, PRD 108, 016020 (2023)

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

(quark model & kinetic equation of vector mesons in the non-relativistic limit)

$$\xrightarrow[|\langle \mathcal{P}_q^i \mathcal{P}_{\bar{q}}^i \rangle| \ll 1]{} \quad \rho_{00} \approx \frac{1}{3} + \frac{1}{9} \mathrm{Tr}_c \left(\langle \hat{\mathcal{P}}_q^x \hat{\mathcal{P}}_{\bar{q}}^x \rangle + \langle \hat{\mathcal{P}}_q^z \hat{\mathcal{P}}_{\bar{q}}^z \rangle - 2 \langle \hat{\mathcal{P}}_q^y \hat{\mathcal{P}}_{\bar{q}}^y \rangle \right)$$

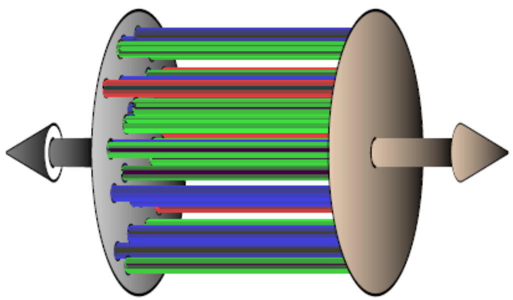
$$\rho_{00} = 1/3 \ \text{ when } \langle \mathcal{P}_q^j \mathcal{P}_{\bar{q}}^j \rangle \neq 0 \text{ is isotropic.}$$

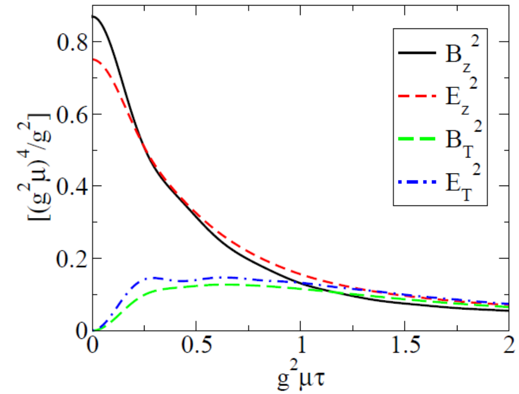
- ❑ Electromagnetic fields can polarize the spin. How about gluonic fields in QCD matter?

$$\mathcal{P}^i(\boldsymbol{p}) \propto c_1 B^i + c_2 \epsilon^{ijk} p_j E_k$$

Color-field induced spin alignment

- Small-x gluons may form a glasma state characterized by mostly longitudinal chromo-electromagnetic fields in early times of HIC from CGC.



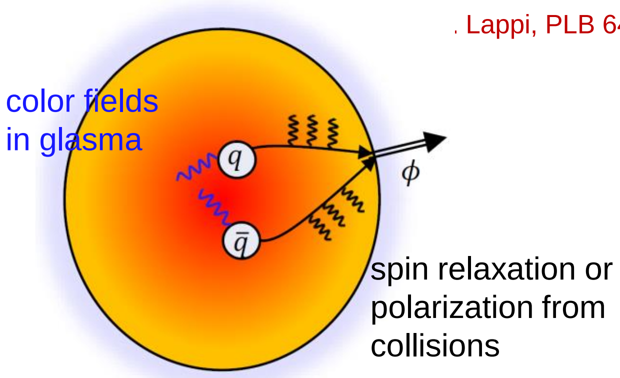


Reviews : F. Gelis et al., Ann.Rev.Nucl.Part.Sci.60:463-489,2010

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

. Lappi, PLB 643 (2006) 11-16

❖ Why glasma fields :
(1) intrinsic saturation scale $Q_s \gg \omega$
(2) fluctuating
(3) intrinsic anisotropy



- An order of magnitude estimate for the glasma effect ?
- How to track the spin evolution of massive quarks in phase space?
  quantum kinetic theory from Wigner functions

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

Axial kinetic theory

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

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)

➢ SKE : $p\cdot\Delta f_V = \mathcal{C}[f_V], \quad \Delta_\mu = \partial_\mu + \underbrace{eF_{\nu\mu}}_{\text{EM fields}}\partial_p^\nu.$

standard Vlasov eq.

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

($\tilde{a}^\mu(p,x)$: effective spin four vector)
($\hbar$: gradient correction in phase space)

(entangled f_V & $\tilde{a}^\mu$)

➢ Axial Wigner functions :

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

dynamical (w/ memory effect) non-dynamical (w/o memory effect)

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

- Relaxation-time approx. & weak coupling :

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

$$\Rightarrow \quad \delta\tilde{a}^\mu(\boldsymbol{p},x) = \frac{\hbar e}{2}\int_{t_{\rm i}}^{t_{\rm f}} dx_0' e^{-(x_0-x_0')/\tau_{\rm R}}\epsilon^{\mu\nu\rho\sigma}\hat{p}_\rho\left(\partial_{x'\sigma}F_{\beta\nu}(x')\right)\partial_{\boldsymbol{p}}^\beta f_V(p,x')$$

Spin alignment from glasma

- Generalized AKT with color fields : $\tilde{a}^{\mu}(\boldsymbol{p},x)=\tilde{a}^{s\mu}(\boldsymbol{p},x)I+\boxed{\tilde{a}^{a\mu}(\boldsymbol{p},x)}\,t^{a}.$

  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)

$$\tilde{a}^{a\mu}(\boldsymbol{p},x)\approx-\frac{\hbar g}{2}e^{-(t_{\rm f}-t_{\rm i})/\tau_{\rm R}^{\rm o}}\left(B^{a\mu}(t_{\rm i})\partial_{\epsilon_{\boldsymbol{p}}}f_{\rm V}^{\rm s}(\epsilon_{\boldsymbol{p}},t_{\rm i})-B^{a\mu}(t_{\rm f})\partial_{\epsilon_{\boldsymbol{p}}}f_{\rm V}^{\rm s}(\epsilon_{\boldsymbol{p}},t_{\rm f})\right)$$

suppressed

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

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

- Initial quark distribution function : $f_{\rm V}^{\rm s}(\epsilon_{\boldsymbol{p}},t_{\rm i})=1/\left(e^{\epsilon_{\boldsymbol{p}}/Q_s}+1\right)$

❖ spin correlation : $\langle\mathcal{P}_q^z\mathcal{P}_{\bar{q}}^z\rangle\sim\frac{Q_s^2}{m_q m_{\bar{q}}}e^{-2(t_{\rm f}-t_{\rm i})/\tau_{\rm R}^{\rm o}}$

❖ Order-of-magnitude estimation (for ϕ) : $\rho_{00}\sim\frac{1}{3+10\,e^{-2(t_{\rm f}-t_{\rm i})/\tau_{\rm R}^{\rm o}}}<\frac{1}{3}$

$Q_s\approx 1\sim 2\ {\rm GeV}$

glasma effect relaxation effect

❖ Heavy-quark approx. : $\tau_{\rm R}^{\rm o}\approx\left(\frac{g^2C_2(F)m_D^2T}{6\pi m^2}\ln g\right)^{-1}\approx 5\,{\rm fm/c}\Longrightarrow\rho_{00}\approx 0.24$

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

(model dependent)

Spin alignment with momentum dependent

- How to retrieve the momentum dep.? boosting the color fields to the lab frame

$$B^{ai}_{\rm r} = \gamma(B^{ai} + \epsilon^{ijk} v_j E^a_k) - (\gamma - 1)\boldsymbol{B}^a \cdot \hat{\boldsymbol{v}} \hat{v}^i, \quad v^i = q^i/\sqrt{|\boldsymbol{q}|^2 + M^2} \text{ and } \hat{v}^i = v^i/|\boldsymbol{v}|.$$

- Momentum-dep. analysis (qualitative) : mid-rapidity, small-momentum region

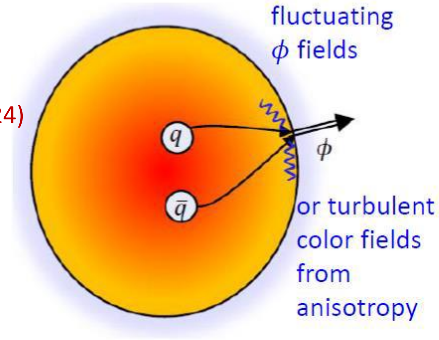
glasma : $$\rho_{00} - \frac{1}{3} \propto (v_x^2 - 2v_y^2 - 1) \int d\Sigma_X \cdot q \langle B^{az}(0, \boldsymbol{x}) B^{az}(0, \boldsymbol{x}) \rangle$$

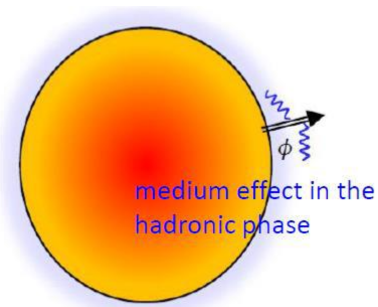
isotropic BFs : $$\rho_{00} - \frac{1}{3} \propto (v_x^2 - 2v_y^2) \int d\Sigma_X \cdot q \langle F^a(x) F^a(x) \rangle, \quad B^{ai} = E^{ai} = F^a.$$

	small-P_T	large-P_T	central	non-central
glasma	$\rho_{00}^{\phi,J/\psi} < 1/3$	$\rho_{00}^{\phi,J/\psi} \lesssim 1/3$	$\rho_{00}^{\phi,J/\psi} < 1/3$	$\rho_{00}^{\phi,J/\psi} \lesssim 1/3$
effective potential	$\lvert\rho_{00}^{\phi,J/\psi} - 1/3\rvert \gtrsim 0$	$\lvert\rho_{00}^{\phi,J/\psi} - 1/3\rvert > 0$	$\rho_{00}^{\phi,J/\psi} < 1/3$	$\rho_{00}^{\phi,J/\psi} > 1/3$

- Other proposals :

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)





D. Wagner, N. Weickgenannt, E. Speranza,PRR 5, 013187 (2023)
F. Li, S. Liu, arXiv:2206.11890
A. Kumar, Philipp Gubler, DY, PRD 109, 054038 (2024)

Summary

❑ Take-home messages :

- ✓ In general, spin alignment may be a useful probe for strong interaction forces led by gluons in QCD matter.
- ✓ Fluctuating glasma fields provide intrinsic anisotropy, especially for $\rho_{00} < 1/3$, and the required energy scale much larger than vorticity (or hydrodynamic gradients).
- ✓ However, the order-of-magnitude estimate (qualitatively consistent with LHC data) is sensitive to the initial distribution function of quarks, subject to the perturbative color fields, and the spin relaxation in the QGP.

❑ Outlook :

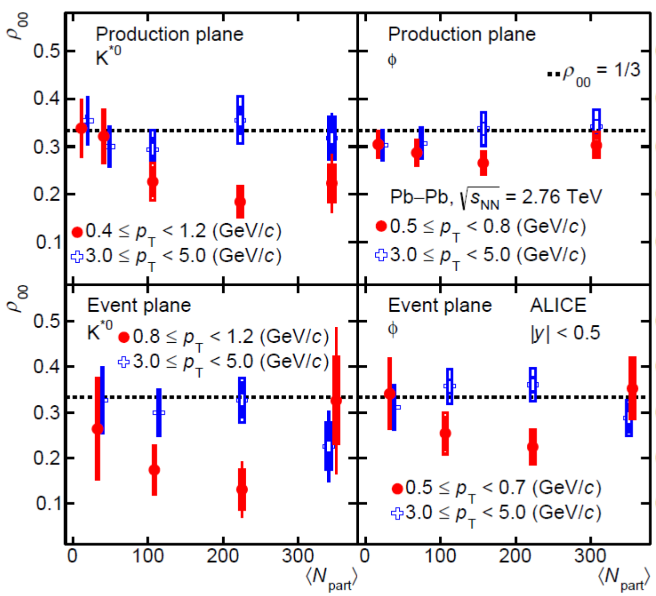
- ✓ Spin alignment of the quarkonium like J/ψ may be a better probe for glamsa or other color-field effects.
- ✓ Heavy quarkonium or heavy quarks are more applicable for the kinetic theory and more reliably described by effective field theories with systematic power counting.

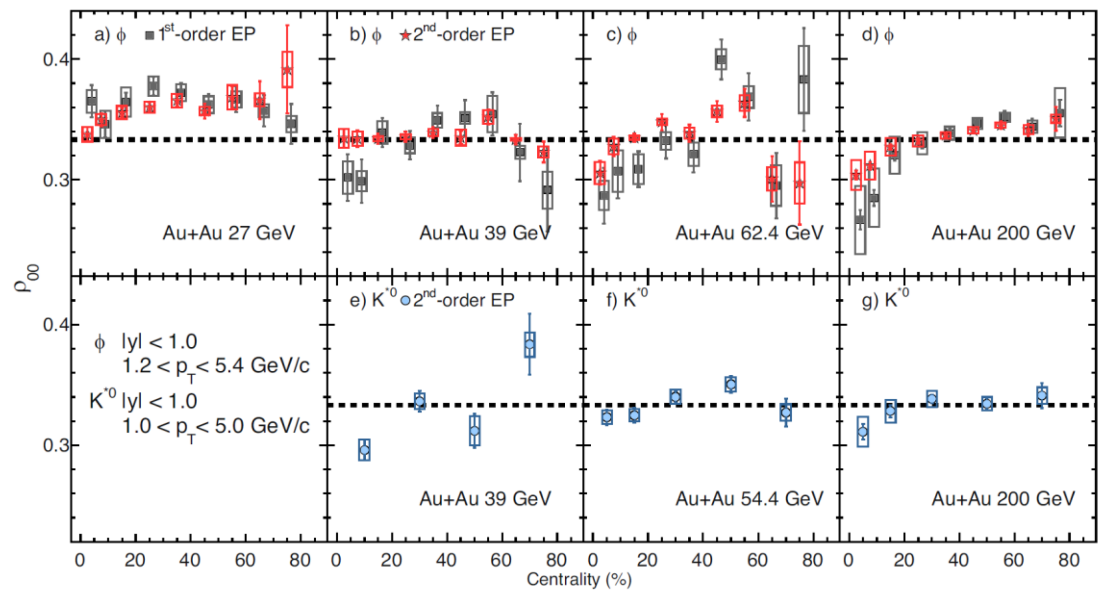
E.g., DL & X. Yao, “Quarkonium Polarization in Medium from Open Quantum Systems and Chromomagnetic Correlators”, arXiv: 2405.20280

Thank you!

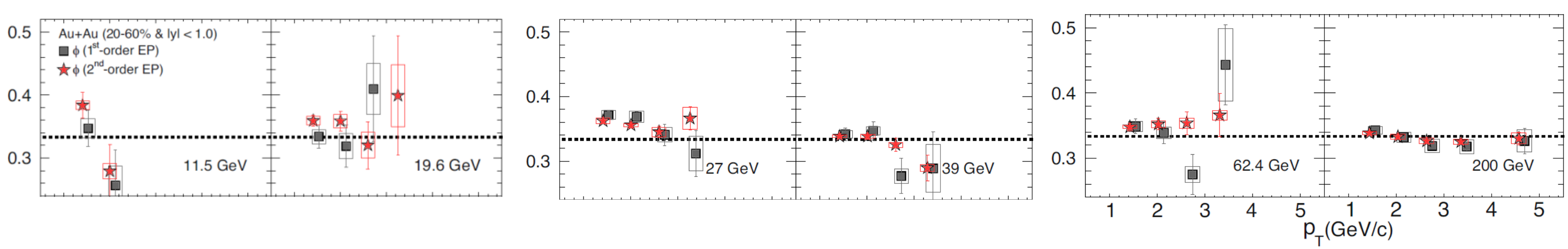
More experimental data

❖ Centrality dependence :





❖ pT dependence in RHIC :



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., $\mathcal{A}^\mu(\boldsymbol{p},x) = \mathcal{A}^{s\mu}(\boldsymbol{p},x)I + \mathcal{A}^{a\mu}(\boldsymbol{p},x)\,t^a,\ f_V(\boldsymbol{p},x) = f^{\rm s}_{\rm V}(\boldsymbol{p},x)I + f^a_{\rm V}(\boldsymbol{p},x)\,t^a,$

$\tilde{a}^\mu(\boldsymbol{p},x) = \tilde{a}^{s\mu}(\boldsymbol{p},x)I + \tilde{a}^{a\mu}(\boldsymbol{p},x)\,t^a.$

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

SKEs : $p^\rho\left(\partial_\rho f^{\rm s}_{\rm V} + \frac{g}{2N_c}F^a_{\nu\rho}\partial^\nu_p f^a_V\right) = \mathcal{C}_{\rm s},\ p^\rho\left(\partial_\rho f^a_{\rm V} + gF^a_{\nu\rho}\partial^\nu_p f^{\rm s}_V + \frac{d^{bca}}{2}gF^b_{\nu\rho}\partial^\nu_p f^c_V\right) = \mathcal{C}^a_{\rm o},$

diffusion — dynamical spin polarization

AKEs : $p^\rho\partial_\rho\tilde{a}^{s\mu} + \frac{g}{2N_c}\left(p^\rho F^a_{\nu\rho}\partial^\nu_p\tilde{a}^{a\mu} + F^{a\nu\mu}\tilde{a}^a_\nu\right) - \frac{\hbar}{4N_c}\epsilon^{\mu\nu\rho\sigma}p_\rho(\partial_\sigma gF^a_{\beta\nu})\partial^\beta_p f^a_V = \mathcal{C}^\mu_{\rm s},$

$$p^\rho\partial_\rho\tilde{a}^{a\mu} + g\left(p^\rho F^a_{\nu\rho}\partial^\nu_p\tilde{a}^{s\mu} + F^{a\nu\mu}\tilde{a}^{\rm s}_\nu\right) + \frac{d^{bca}}{2}g\left(p^\rho F^b_{\nu\rho}\partial^\nu_p\tilde{a}^{c\mu} + F^{b\nu\mu}\tilde{a}^c_\nu\right) - \frac{\hbar}{2}\epsilon^{\mu\nu\rho\sigma}p_\rho(\partial_\sigma gF^a_{\beta\nu})\partial^\beta_p f^{\rm s}_V = \mathcal{C}^{a\mu}_{\rm o}.$$

Axial Wigner functions :

$$\mathcal{A}^{s\mu}(\boldsymbol{p},x) = \frac{1}{2\epsilon_{\boldsymbol{p}}}\left[\tilde{a}^{s\mu} - \frac{\hbar}{4N_c}\tilde{F}^{a\mu\nu}\left(\partial_{p\nu}f^a_{\rm V} - \frac{\epsilon_{\boldsymbol{p}}}{2}\partial_{p_\perp\nu}(f^a_{\rm V}/\epsilon_{\boldsymbol{p}})\right)\right]_{p_0=\epsilon_{\boldsymbol{p}}},$$

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

dynamical (w/ memory effect) — non-dynamical (w/o memory effect)

Spin polarization:

$$\mathcal{P}^\mu(\boldsymbol{p}) = \frac{\int d\Sigma\cdot p\,{\rm Tr}_c\mathcal{A}^\mu(\boldsymbol{p},x)}{2m\int d\Sigma\cdot p\,(2\epsilon_{\boldsymbol{p}})^{-1}f^{\rm s}_{\rm V}(\boldsymbol{p},x)} = \frac{\int d\Sigma\cdot p\,\mathcal{A}^{s\mu}(\boldsymbol{p},x)}{2m\int d\Sigma\cdot p\,(2\epsilon_{\boldsymbol{p}})^{-1}f^{\rm s}_{\rm V}(\boldsymbol{p},x)}.$$

Spin correlations from color fields

- Spin density matrix can be directly related to Wigner functions of the coalesced quark and antiquark through the quark-meson interaction.

❖ Kinetic theory of vector mesons :

$$q\cdot\partial f^{\phi}_{\lambda} = \epsilon^*_\mu(\lambda,\boldsymbol{q})\epsilon_\nu(\lambda,\boldsymbol{q})\left[\mathcal{C}^{\mu\nu}_{\rm coal}(q,x)(1+f^\phi_\lambda) - \mathcal{C}^{\mu\nu}_{\rm diss}(q,x)f^\phi_\lambda\right] \approx \boxed{\epsilon^*_\mu(\lambda,\boldsymbol{q})\epsilon_\nu(\lambda,\boldsymbol{q})\mathcal{C}^{\mu\nu}_{\rm coal}(q,x)}$$

quark-meson int. :

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

➡

$$\rho_{00}(q) = \frac{\int d\Sigma_X\cdot q f^\phi_0(q,X)}{\int d\Sigma_X\cdot q\big(f^\phi_0(q,X)+f^\phi_{+1}(q,X)+f^\phi_{-1}(q,X)\big)}$$

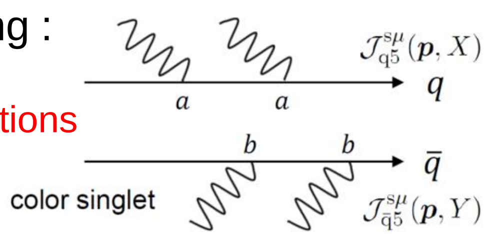
$$= \frac{1-\mathrm{Tr_c}\langle\hat{\mathcal{P}}^y_q(\boldsymbol{q}/2)\hat{\mathcal{P}}^y_{\bar q}(\boldsymbol{q}/2)\rangle_{\boldsymbol{q}=0}}{3-\sum_{i=x,y,z}\mathrm{Tr_c}\langle\hat{\mathcal{P}}^i_q(\boldsymbol{q}/2)\hat{\mathcal{P}}^i_{\bar q}(\boldsymbol{q}/2)\rangle_{\boldsymbol{q}=0}}$$

❖ Spin correlations in the non-relativistic limit :

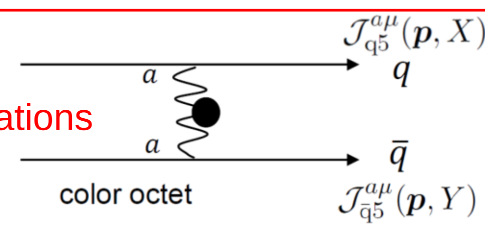
$$\mathrm{Tr_c}\langle\hat{\mathcal{P}}^i_q(\boldsymbol{p})\hat{\mathcal{P}}^i_{\bar q}(\boldsymbol{p})\rangle \approx \frac{4\int d\Sigma_X\cdot p\big(\langle\mathcal{A}^{si}_q(\boldsymbol{p},X)\mathcal{A}^{si}_{\bar q}(\boldsymbol{p},X)\rangle + \langle\mathcal{A}^{ai}_q(\boldsymbol{p},X)\mathcal{A}^{ai}_{\bar q}(\boldsymbol{p},X)\rangle/(2N_c)\big)}{\int d\Sigma_X\cdot p f^{\rm s}_{{\rm V}q}(\boldsymbol{p},X) f^{\rm s}_{{\rm V}\bar q}(\boldsymbol{p},X)}$$

➢ Weak coupling :

4-field correlations $\propto g^4$



2-field correlations $\propto g^2$



A. Kumar, B. Müller, DY, PRD 107, 076025 (2023)   A. Kumar, B. Müller, DY, PRD 108, 016020 (2023)

Color fields from the glasma

- Solving linearized Yang-Mills eqs. : $[D_\mu, F^{\mu\nu}] = J^\nu$

P. Guerrero-Rodrguez, T. Lappi, PRD 104, 014011 (2021)

- Color-field correlators in the glasma :

evolution in time

e.g. $$\langle E_T^{ai}(X')E_T^{aj}(X'')\rangle = -\bar{N}_c \epsilon^{in}\epsilon^{jm}\int_{\perp;q,u}^{X'}\int_{\perp;l,v}^{X''}\Omega_-(u_\perp,v_\perp)\frac{q^n l^m}{ql}\times J_1(qX'_0)J_1(lX''_0),$$

$$\langle B_T^{ai}(X')B_T^{aj}(X'')\rangle = -\bar{N}_c \epsilon^{in}\epsilon^{jm}\int_{\perp;q,u}^{X'}\int_{\perp;l,v}^{X''}\Omega_+(u_\perp,v_\perp)\frac{q^n l^m}{ql}\times J_1(qX'_0)J_1(lX''_0),$$

$$\bar{N}_c \equiv \frac{1}{2}g^2 N_c(N_c^2-1),$$

$$\Omega_\mp(u_\perp,v_\perp) = [G_1(u_\perp,v_\perp)G_2(u_\perp,v_\perp) \mp h_1(u_\perp,v_\perp)h_2(u_\perp,v_\perp)],$$

$$\int_{\perp;q,u}^{X'} \equiv \int \frac{d^2q_\perp}{(2\pi)^2}\int d^2u_\perp e^{iq_\perp(X'-u)_\perp}.$$

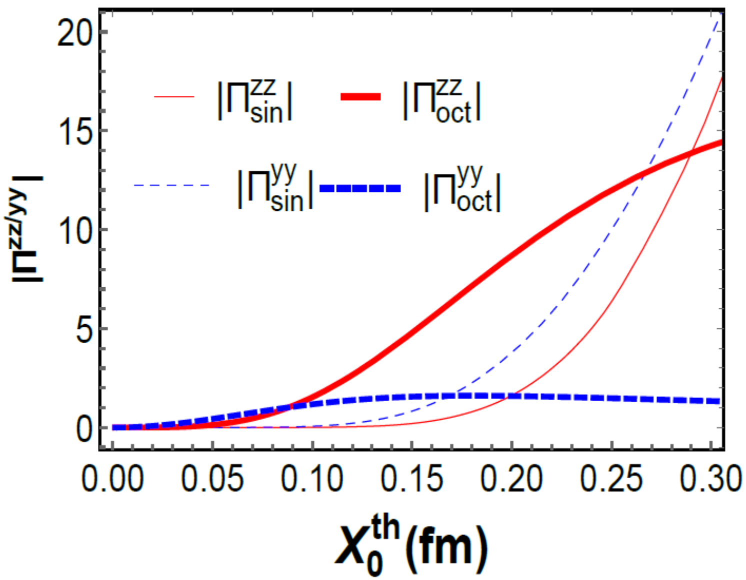
unpolarized & linearly polarized
Gluon distribution functions

- Golec-Biernat Wusthoff (GBW) distribution : K. J. Golec-Biernat and M. Wustho, PRD 59, 014017 (1998)

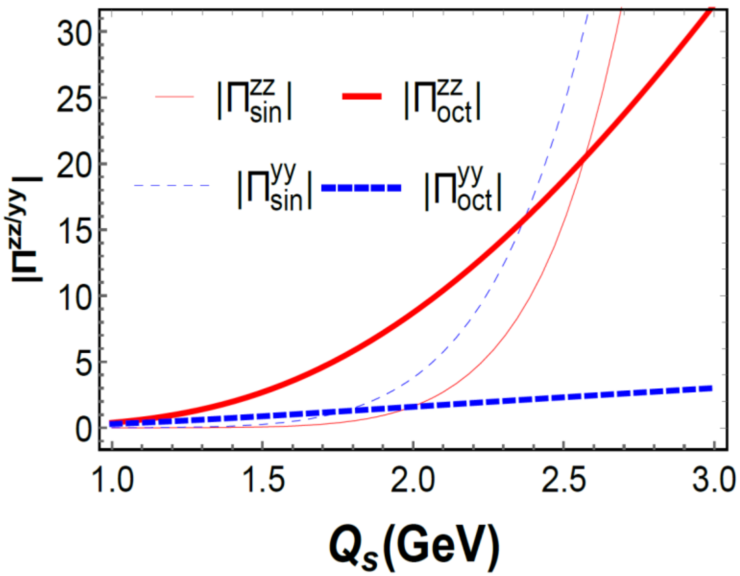
$$\Omega_\pm(u_\perp,v_\perp) = \Omega(u_\perp,v_\perp) = \frac{Q_s^4}{g^4N_c^2}\left(\frac{1-e^{-Q_s^2|u_\perp-v_\perp|^2/4}}{Q_s^2|u_\perp-v_\perp|^2/4}\right)^2$$

Singlet v.s. octet

- More sophisticated analysis : $\mathrm{Tr_c}\langle\hat{\mathcal{P}}^i_q(\boldsymbol{q}/2)\hat{\mathcal{P}}^i_{\bar{q}}(\boldsymbol{q}/2)\rangle = \Pi^{ii}_{\mathrm{oct}} + \Pi^{ii}_{\mathrm{sin}} + \Pi^{ii}_{\mathrm{EM}}$ (suppressed)



$Q_s = 2$ GeV



$X_0^{\mathrm{th}} = 0.2$ fm

⇨ $Q_s = 2$ GeV & $X_0^{\mathrm{th}} = 0.2$ fm for $|\Pi^{zz}_{\mathrm{oct}}| > |\Pi^{ii}_{\mathrm{sin}}|$