Initial-state and non-equilibrium effects on spin transport in nuclear collisions

Di-Lun Yang

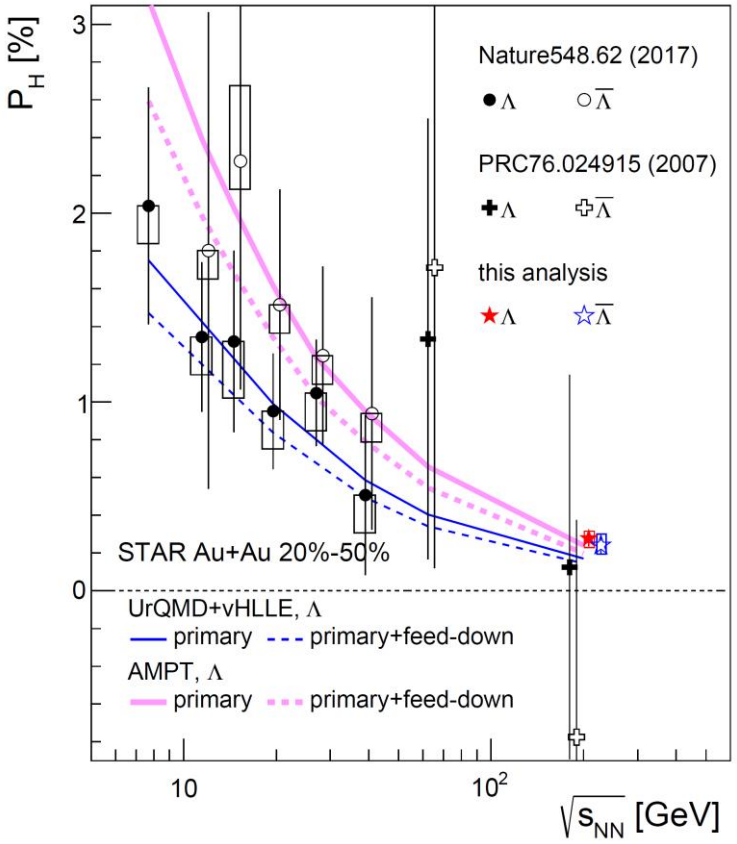
Institute of Physics, Academia Sinica

(Pacific Spin 2026, Taipei, Oct 27)

Global Λ polarization in HIC

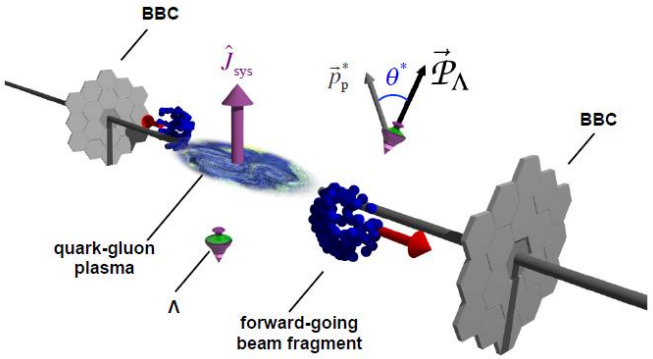
- The measurement of global polarization of Λ hyperons revealed the spin-orbit interaction & strong vorticity in heavy ion collisions. Z.-T. Liang & X.-N. Wang, PRL. 94, 102301 (2005)

  (relativistic Barnett effect)



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

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



❖ 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)

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

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

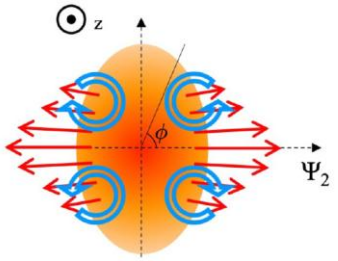
❖ Global pol. from (average) kinetic vorticity :

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

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

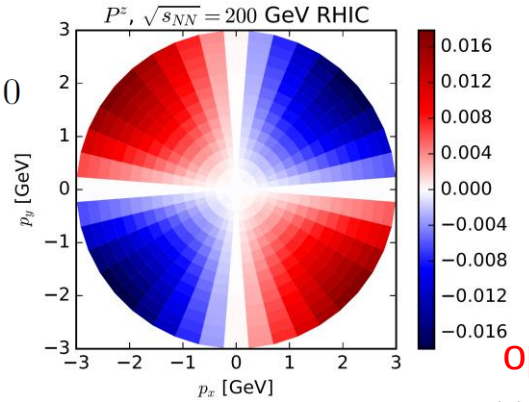
Longitudinal (local) polarization

- Longitudinal polarization along the beam direction in HIC :



$$P_{2,z} < 0$$

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

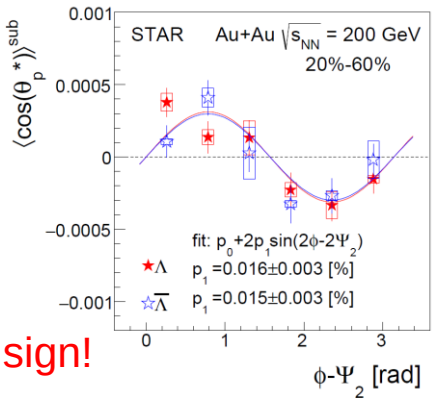


$$P_{2,z} = \langle P_z \sin 2(\phi - \Psi_2) \rangle$$

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

v.s.

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

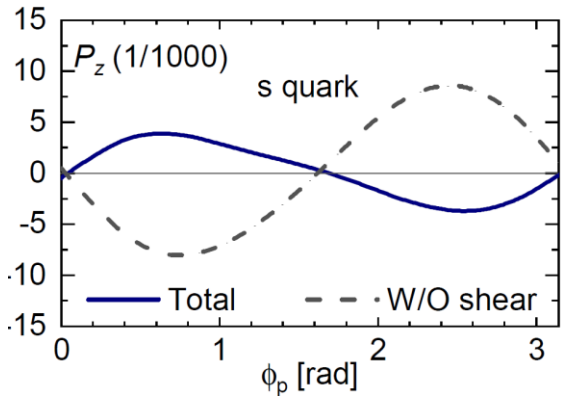


$$P_{2,z} > 0$$

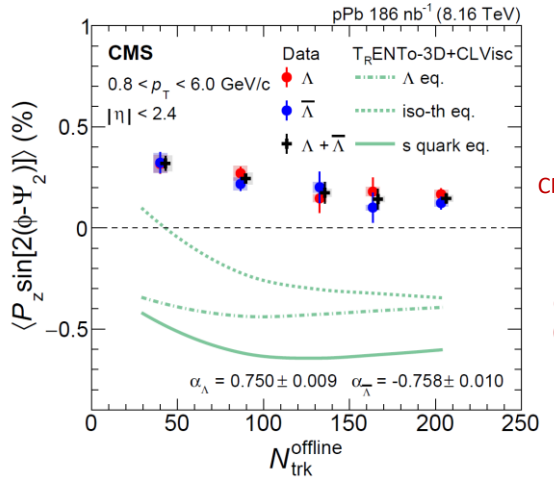
opposite sign!

❖ Thermal-shear corrections : $\mathcal{P}^\mu(p) = \dfrac{\int d\Sigma_x \cdot p f_p^{(0)}(1 - f_p^{(0)}) \epsilon^{\mu\nu\rho\sigma} q_\nu \left[\omega_{\rho\sigma} - u_\rho \pi_{\sigma\lambda} p^\lambda / (Tp \cdot u)\right]}{8 M_\Lambda \int d\Sigma_x \cdot p f_p^{(0)}}$

(local equilibrium, indep. of int.)



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



CMS, PRL 135 (2025) 132301

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

open question!

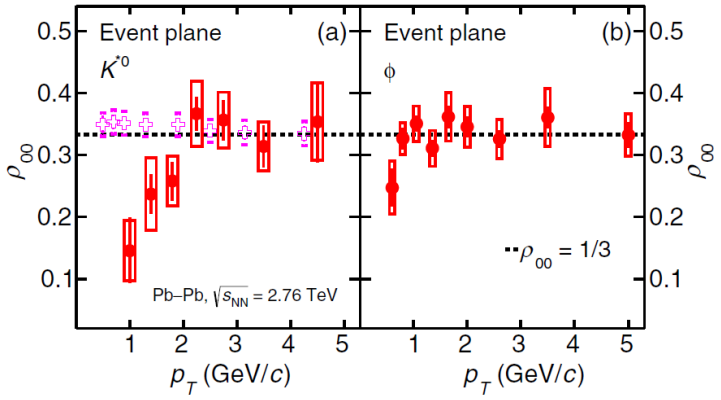
new effects needed

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 :

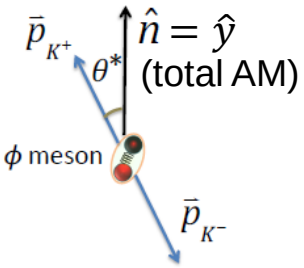
$$\frac{dN}{d\cos\theta^*} \propto [1 - \rho_{00} + \cos^2\theta^*(3\rho_{00} - 1)]$$



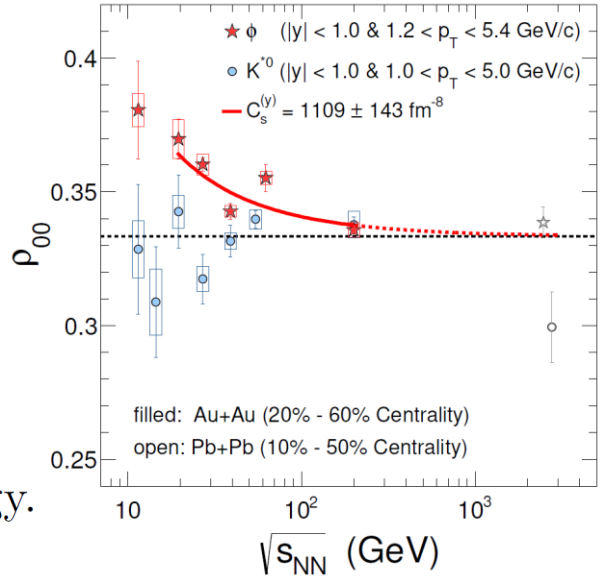
S. Acharya et al. (ALICE), PRL.125, 012301 (2020)

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

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



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



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

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

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

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

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

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

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

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

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

($\hbar$: gradient corrections in phase space)

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

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

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

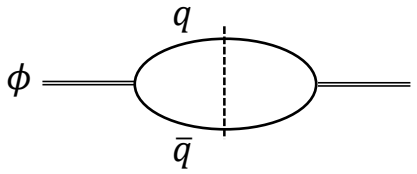
(dynamical) (non-dynamical)

❑ Spin alignment from quark coalescence :

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

$(\rho_{\lambda\lambda}\propto f_\lambda^\phi,\ \lambda=0,\pm1)$

quark-meson int. : $\mathcal{L}_{\rm int} = g_\phi\bar{\psi}\gamma^\mu V_\mu\psi$



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

An intuitive picture

- An intuitive construction of color-singlet spin observables :

❖ Building blocks for quark transport :

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

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) : $\delta\rho_{00} = \rho_{00} - \frac{1}{3} \sim \langle \boldsymbol{\mathcal{P}}^a\cdot\boldsymbol{\mathcal{P}}^a\rangle \sim \langle \boldsymbol{B}^a\cdot\boldsymbol{B}^a\rangle$

➢ spin polarization of Λ (strange-equilibrium scenario) : p – even scalar

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

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

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

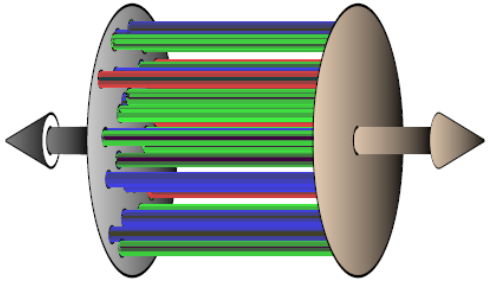
$$\mathcal{A}^\mu(p,x) = \int d^4y e^{\frac{ip\cdot y}{\hbar}}\left\langle \bar\psi\left(x-\frac{y}{2}\right)\gamma^\mu\gamma^5\psi\left(x+\frac{y}{2}\right)\right\rangle = \mathcal{A}^{s\mu}(p,x) + t^a\mathcal{A}^{a\mu}(p,x)$$

color singlet $\boldsymbol{\mathcal{P}}$ color octet $\boldsymbol{\mathcal{P}}^a$

DY, JHEP 06, 140 (2022)
B. Müller, DY, PRD 105, L011901 (2022)

Color-field induced spin alignment

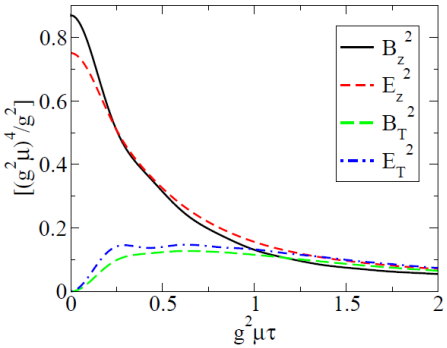
- Initial-state gluons may form the glasma phase characterized by predominantly longitudinal chromo-electromagnetic fields from **color glass condensate (CGC).**



(at top RHIC & LHC energies)

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

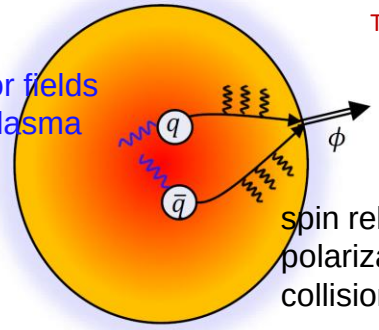
J. Berges et al., Rev. Mod. Phys. 93 (2021) 3, 035003



T. Lappi, PLB 643 (2006) 11-16

- Assuming the early quark production in glasma

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



spin relaxation or polarization from collisions

❖ 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 :

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

glasma effect :

$$\mathrm{Tr_c}\langle \hat{\mathcal{P}}_q^z(\boldsymbol{q}/2)\hat{\mathcal{P}}_{\bar{q}}^z(\boldsymbol{q}/2)\rangle_{\boldsymbol{q}=0} < 0$$

$$\Longrightarrow \delta\rho_{00} = \rho_{00} - \frac{1}{3} \propto -\langle B^{az}(x)B^{az}(x')\rangle e^{-2\Delta t/\tau_R} < 0$$

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

(mesons at rest)

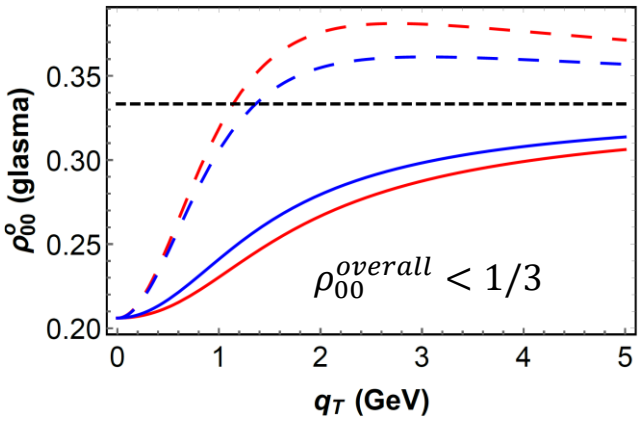
glasma effect

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



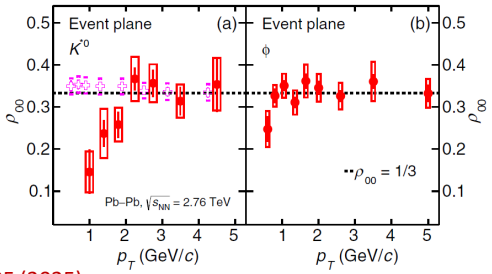
$v^y = 0$ ◯◯

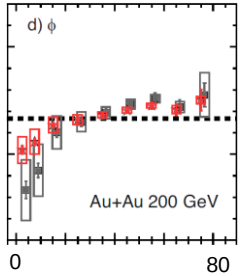
$v^x = v^y$ ◎

$y_q = 1$

$y_q = 0$

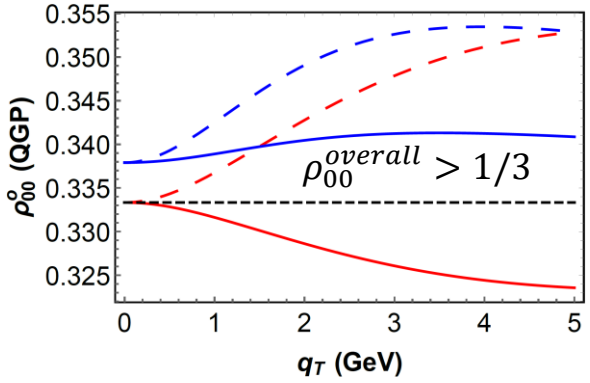
weighting needed : $\langle \rho_{00}(q_T) \rangle = \dfrac{\int d\phi_q dy_q [\rho_{00}(\boldsymbol{q})\mathcal{N}]}{\int \phi_q dy_q \mathcal{N}}$



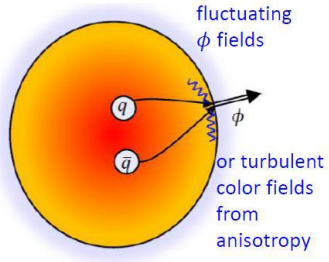


DY, PRD 110, 056005 (2025)

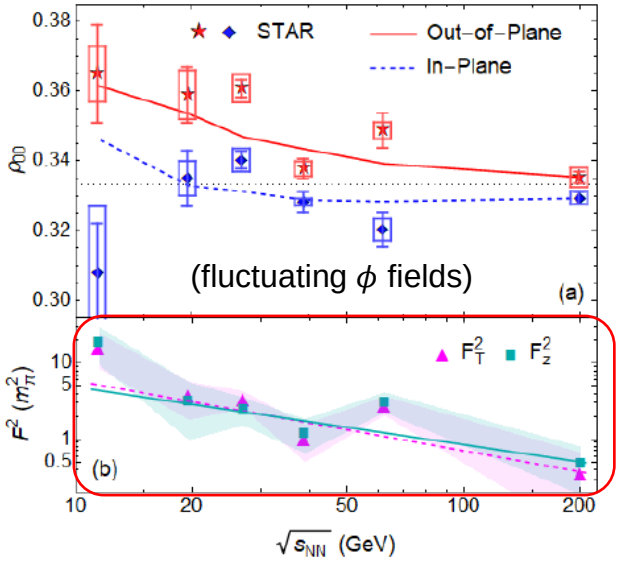
❖ Final-state effect (strong-force fields in QGP) : low-energy



(isotropic color fields from QGP : qualitative)



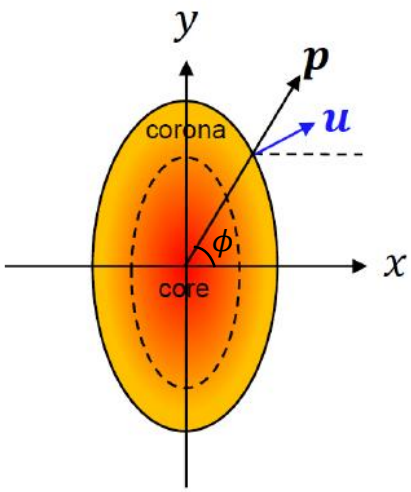
X.-L. Sheng et al., PRD 109, 036004, (2024)
PRL 131, 042304 (2023)
B. Müller, DY, PRD 105, L011901 (2022)
DY, JHEP 06, 140 (2022)



isotropic, competition with glasma effect at high energies?

Longitudinal Λ polarization (focused on pA)

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

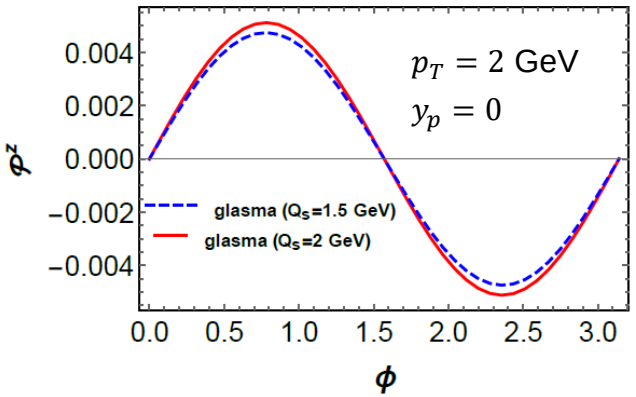


weak initial anisotropic flow from pressure gradient

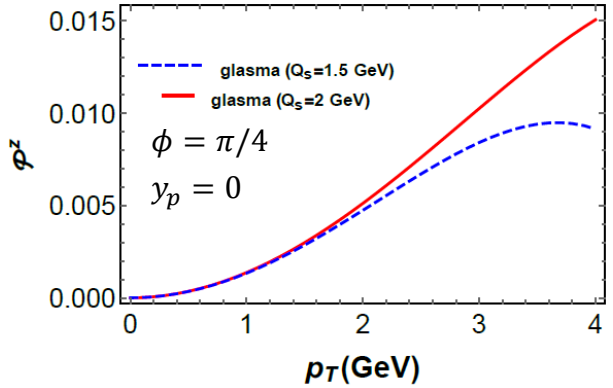
$$\mathcal{P}^z \approx \frac{\hbar(N_c^2-1)Q_s^2\Delta t}{16M_\Lambda N_c^2\epsilon_{\boldsymbol{p}}\int d\Sigma\cdot p f_V^{\rm s}}\int d\Sigma\cdot p(p^x u^y - p^y u^x)$$

$\boldsymbol{p}\times\boldsymbol{u}$ structure

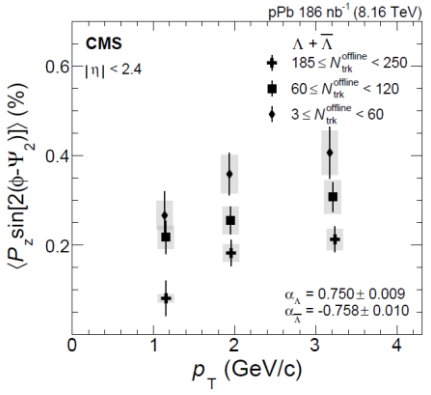
$$\times\left(u^0\partial_{p\cdot u/Q_s} - Q_s/\epsilon_{\boldsymbol{p}}\right)\partial_{p\cdot u/Q_s} f_V^{\rm s},\quad f_V^{\rm s}(p\cdot u/Q_s) = e^{-\pi(p\cdot u)^2/|gE^a|}.$$



$\propto sin2\phi$



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



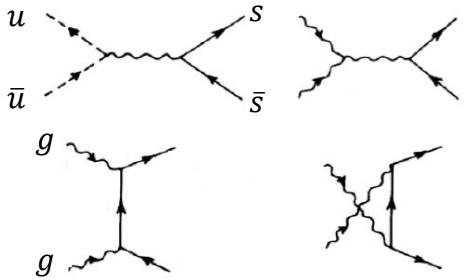
✓ consistent sign & comparable order of magnitude with observations

! caveat : sensitive to $\int d\Sigma\cdot p$ & $|\boldsymbol{p}\cdot\boldsymbol{u}|$

See the talk by Haesom Sung

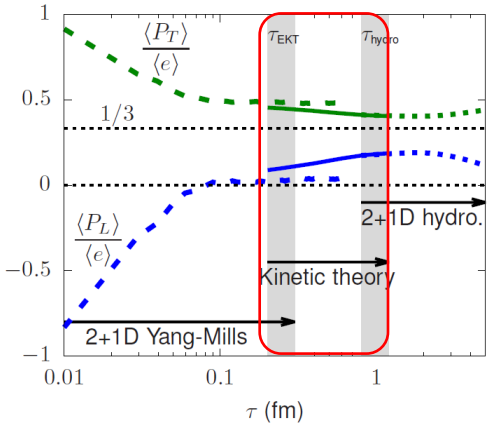
Local spin polarization from gluon fusion

- Strangeness enhancement :



J. Rafelski, Phys. Rept. 88, 331 (1982)
J. Rafelski & B. Müller, PRL 48, 1066 (1982)

(+ QKT for s polarization from gluon fusion?)



A. Kurkela, et al. PRL 122 (2019) 12, 122302

- Non-equilibrium phase in early times ($f_V \ll 1$) :

$$p\cdot\partial f_V \approx p_\mu \Sigma_V^{<\mu} + m\Sigma_S^{<} = \Gamma^{<},$$ (gain term dominates)

$$p\cdot\partial \tilde{a}_\mu \approx -\frac{\hbar}{2}\tilde{F}^{<\mu\nu}p_\nu, \quad \tilde{F}^{\lessgtr\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F^{\lessgtr}_{\alpha\beta}, \quad F^{\lessgtr}_{\alpha\beta} = \partial_{[\alpha}\Sigma^{\lessgtr}_{V\beta]}.$$

N. Benoit, DY, preliminary

- Initial anisotropic flow of gluons ($n_g(q,x) = n_g(q\cdot u)$) :

$$p_\nu \tilde{F}^{<\mu\nu} = \frac{2g^4}{(2\pi)^4}\epsilon^{\mu\nu\alpha\beta}p_\nu\left[\rho_t u_\beta \hat{p}^\rho_\perp \partial_\alpha u_\rho + \rho_s \partial_\alpha u_\beta\right]$$

(sym or antisym) (antisym)

$$\Rightarrow \quad \tilde{a}^i(\boldsymbol{p},x) \approx \frac{\hbar\alpha_s^2}{\pi^2\epsilon_{\boldsymbol{p}}}\rho_s(\boldsymbol{p})\epsilon^{ijk}p^k\Delta u^j, \quad \Rightarrow \quad (x_0 - t_{\rm i} \to 0) \quad \mathcal{P}^i(\boldsymbol{p},x) \approx \frac{\rho_s(\boldsymbol{p})\epsilon^{ijk}p^k(\partial_0 u^j)}{16\pi^4 M_\Lambda \epsilon_{\boldsymbol{p}}\rho_V(\boldsymbol{p})}$$

(time-dep & weak flow) $\Delta u^j = u^j(x_0) - u^j(t_{\rm i}).$

$\mathcal{P}(\boldsymbol{p}) \propto \boldsymbol{u}\times\boldsymbol{p}$

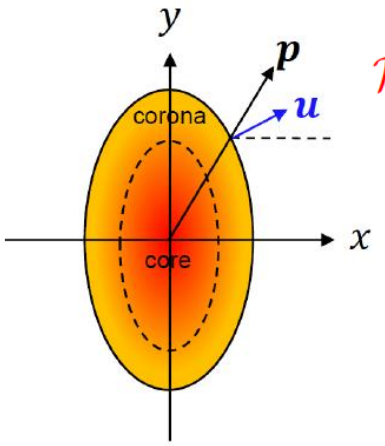
for small systems?

Numerical estimate

- Longitudinal polarization:

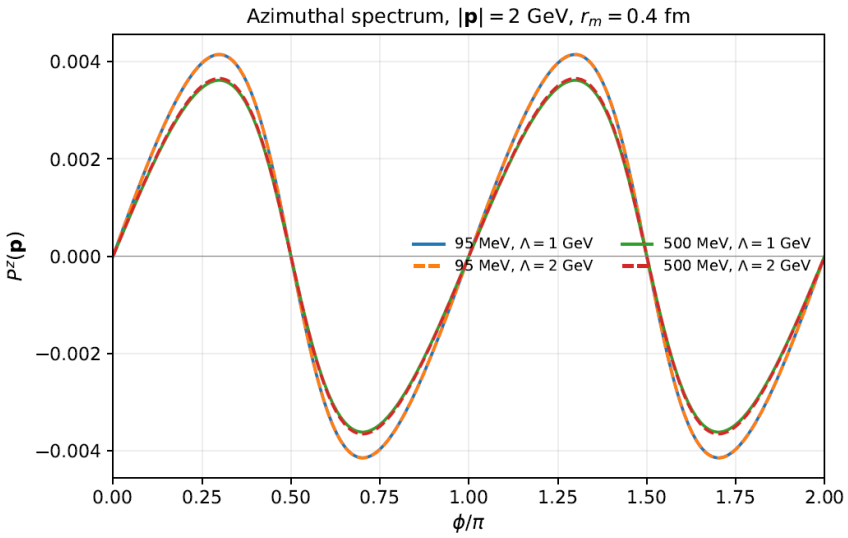
$$\mathcal{P}^z(\boldsymbol{p},x) \approx \frac{\rho_s(|\boldsymbol{p}|)}{16\pi^4 M_\Lambda \rho_V(|\boldsymbol{p}|)\epsilon_{\boldsymbol{p}}}\left(p^y(\partial_0 u^x) - p^x(\partial_0 u^y)\right)$$

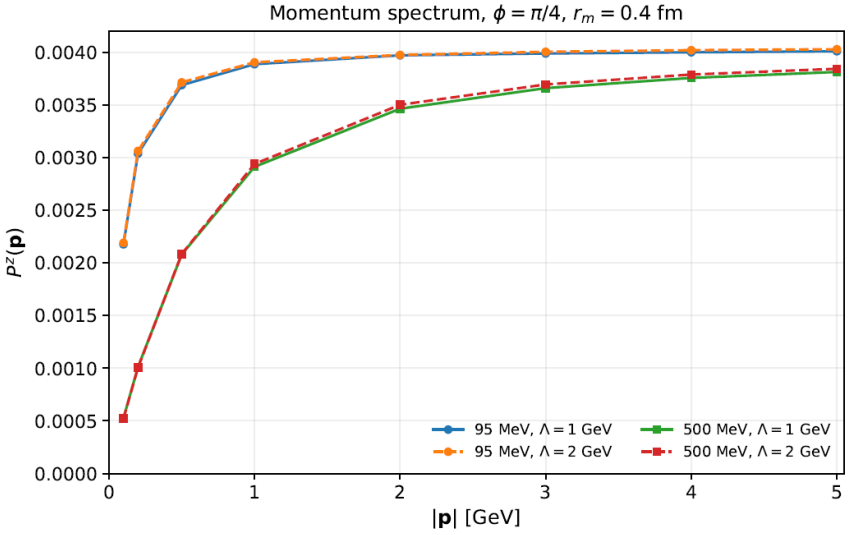
$$\mathcal{P}^z(\boldsymbol{p},t) = \frac{1}{2\pi}\int_0^{2\pi} d\Phi \mathcal{P}^z(\boldsymbol{p},x)\Theta(\boldsymbol{p}\cdot\boldsymbol{u})|_{r=r_m,\tau=t}$$



$$\mathcal{P}(p) \propto \dot{\boldsymbol{u}} \times \boldsymbol{p}$$

N. Benoit, DY, preliminary





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.
- ✓ **QKT** is a useful tool to study **non-equilibrium** spin transport.
- ✓ **Overpopulated initial-state gluons** 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.
- ➢ (Collective) spin transport for heavy quarks : more sensitive to the early-state (e.g., 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., $\mathcal{A}^\mu(\boldsymbol{p},x) = \mathcal{A}^{s\mu}(\boldsymbol{p},x) I + \mathcal{A}^{a\mu}(\boldsymbol{p},x)\, t^a$, $f_V(\boldsymbol{p},x) = f_V^{\rm s}(\boldsymbol{p},x) I + f_V^a(\boldsymbol{p},x)\, t^a$,

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

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

SKEs : $$p^\rho\left(\partial_\rho f_V^{\rm s} + \frac{g}{2N_c} F^a_{\nu\rho}\partial_p^\nu f_V^a\right) = \mathcal{C}_{\rm s},\quad p^\rho\left(\partial_\rho f_V^a + g F^a_{\nu\rho}\partial_p^\nu f_V^{\rm s} + \frac{d^{bca}}{2} g F^b_{\nu\rho}\partial_p^\nu f_V^c\right) = \mathcal{C}^a_{\rm o},$$

diffusion — dynamical spin polarization

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

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

Axial Wigner functions :

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

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

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

Spin polarization: $$\mathcal{P}^\mu(\boldsymbol{p}) = \frac{\int d\Sigma\cdot p\,{\rm Tr}_{\rm c}\mathcal{A}^\mu(\boldsymbol{p},x)}{2m\int d\Sigma\cdot p\,(2\epsilon_{\boldsymbol{p}})^{-1} f_V^{\rm s}(\boldsymbol{p},x)} = \frac{\int d\Sigma\cdot p\,\mathcal{A}^{s\mu}(\boldsymbol{p},x)}{2m\int d\Sigma\cdot p\,(2\epsilon_{\boldsymbol{p}})^{-1} f_V^{\rm s}(\boldsymbol{p},x)}.$$

Axial kinetic theory

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

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

standard Vlasov eq.

EM fields

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 : $p\cdot\Delta\tilde{a}^\mu+eF^{\nu\mu}\tilde{a}_\nu-\frac{e}{2}\hbar\epsilon^{\mu\nu\rho\sigma}p_\rho(\partial_\sigma F_{\beta\nu})\partial_p^\beta f_V=\hat{L}^{\mu\nu}\tilde{a}_\nu+\hbar\hat{H}^{\mu\nu}\partial_\nu f_V.$

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

(entangled f_V & $\tilde{a}^\mu$) spin relaxation dynamical spin pol. from spin-orbit int.

➢ 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)

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

- Relaxation-time approx. & weak coupling :

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

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

Spin alignment from glasma

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

  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)

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

suppressed

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

  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 : $f_{\mathrm{V}}^{\mathrm{s}}(\epsilon_{\boldsymbol{p}},t_{\mathrm{i}})=1/\left(e^{\epsilon_{\boldsymbol{p}}/Q_s}+1\right)$

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

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

$Q_s\approx 1\sim 2$ GeV

glasma effect relaxation effect

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

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

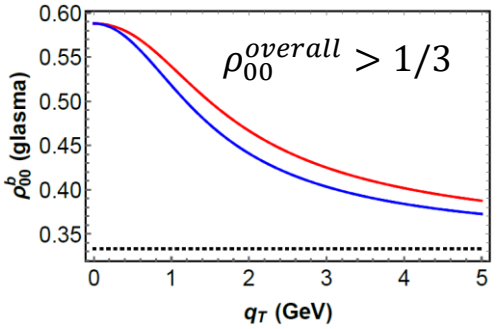
(model dependent)

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?

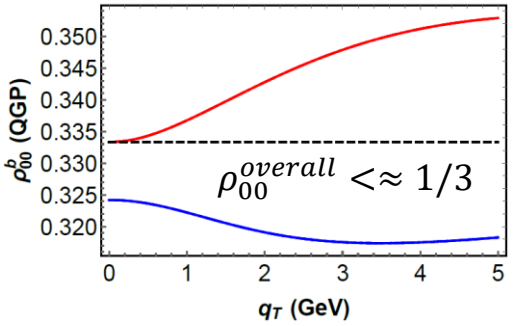
initial-state



v.s.

$y_q = 1$

$y_q = 0$

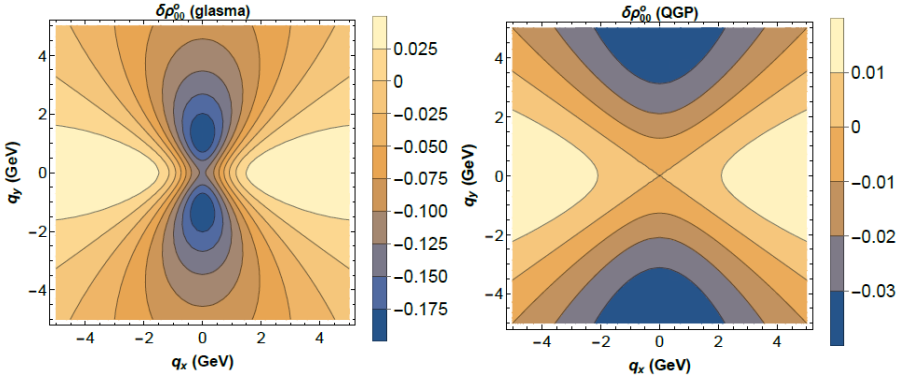


final state

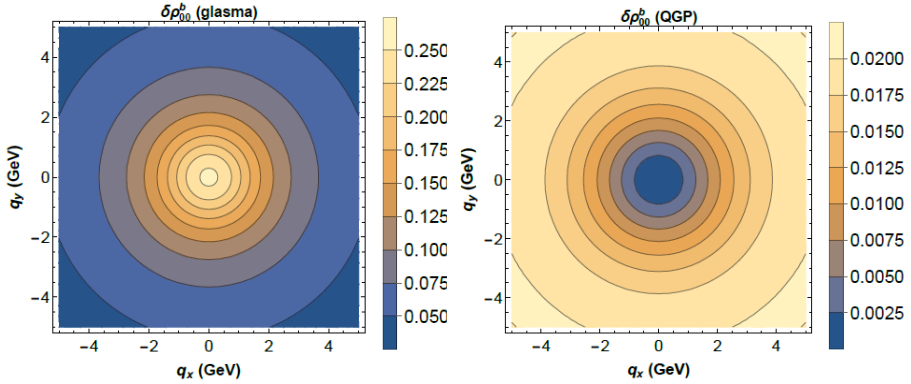
(qualitative)

- Detailed transverse-momentum dependence :

❖ Transverse (out-of-plane) :



❖ Longitudinal :



More on spin polarization from color fields

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

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

- Manifestation of $sin2\phi$: when $|\boldsymbol{p}\cdot\boldsymbol{u}| \ll Q_s$

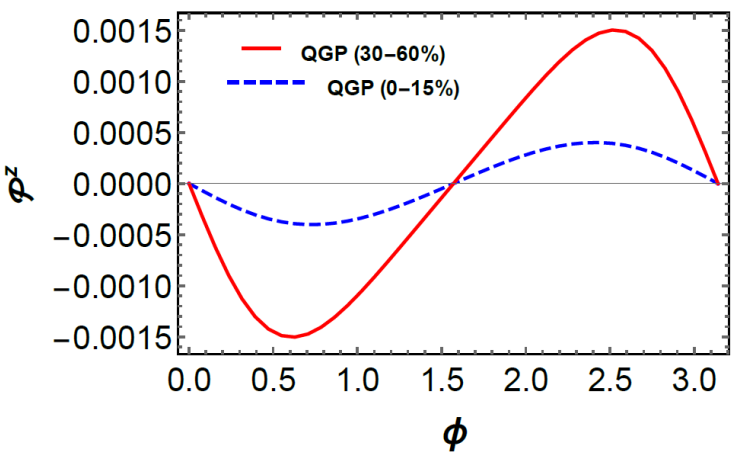
$$\int d\Sigma \cdot p(p^x u^y - p^y u^x) \xrightarrow{G_2 \text{ dominates}} \int d\Sigma \cdot p u^{[y} p^{x]} u^0 \approx u_T p_T^2 \pi \sin 2\phi \int \frac{dr d\eta r^3 \tau \delta}{r_m^2}$$

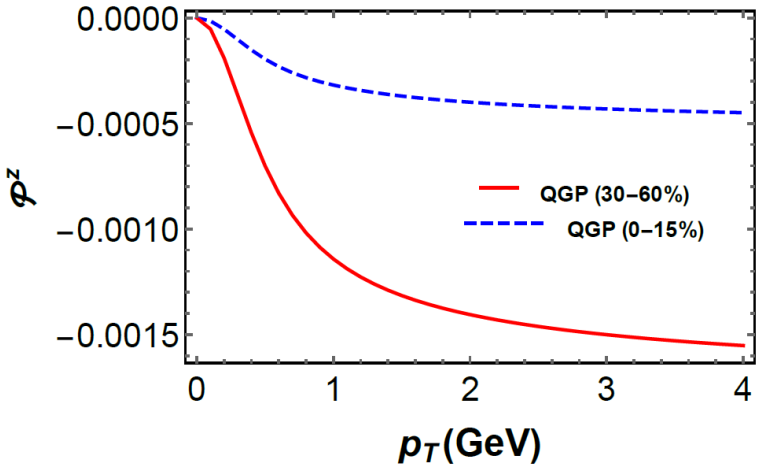
$$u^\mu = \frac{1}{N_u}(t, x\sqrt{1+\delta}, y\sqrt{1-\delta}, z)$$

- QGP case : when $|\boldsymbol{p}\cdot\boldsymbol{u}| \gtrsim T$ ⟹ G_1 dominates

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

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

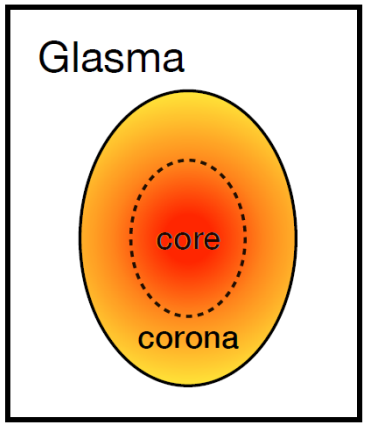




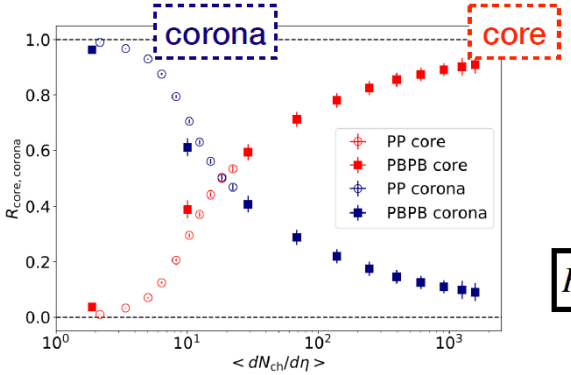
Core-corona scanario

Corona effect

Haesom Sung, ISMD 2026



Y. Kanakubo, Y. Tachibana, and T. Hirano, Phys. Rev. C 105, 024905 (2022), arXiv:2108.07943

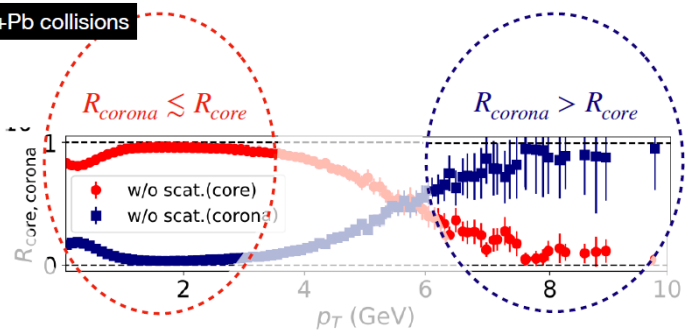


p+p collisions at $\sqrt{s} = 7\,TeV$

Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76\,TeV$

$R_{corona} \sim 0.5$ at $\langle dN_{ch}/d\eta \rangle \sim 11$

Pb+Pb collisions



In high p_T: $R_{corona} > R_{core}$

In small p_T: $R_{corona} < R_{core}$