NSTC 國家科學及技術委員會
National Science and Technology Council

Intense field and vorticity (Theory)

Di-Lun Yang
Institute of Physics,
Academia Sinica

(ATHIC, April 25th, 2023)

Outline

- Intense vortical and electromagnetic fields in HIC
  - Global & local spin polarization of Lambda hyperons
  - Quantum transport theories and resulting corrections beyond global equilibrium
  - Chiral magnetic effect and other effects led by magnetic fields

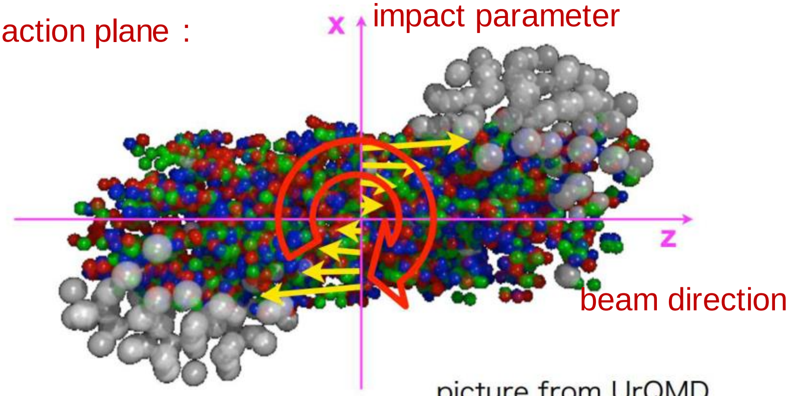
- Exotic fields in QCD from strong int. : chromo-electromagnetic fields or vector-meson fields
  - Spin alignment of vector mesons
  - Possible sources beyond vorticity (& EM fields)

- Many interesting developments and results, limited samples presented here due to the time constraint.

Subatomic swirls

- Strong vortical fields in HIC :

reaction plane :

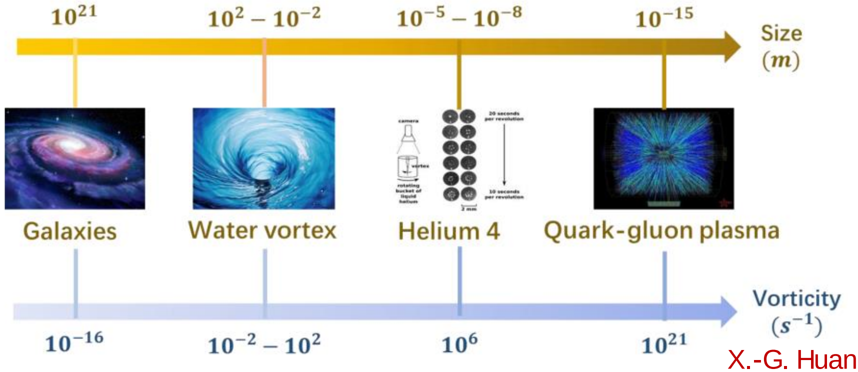


picture from UrQMD

- Angular momentum (AM) to (kinetic) vorticity :

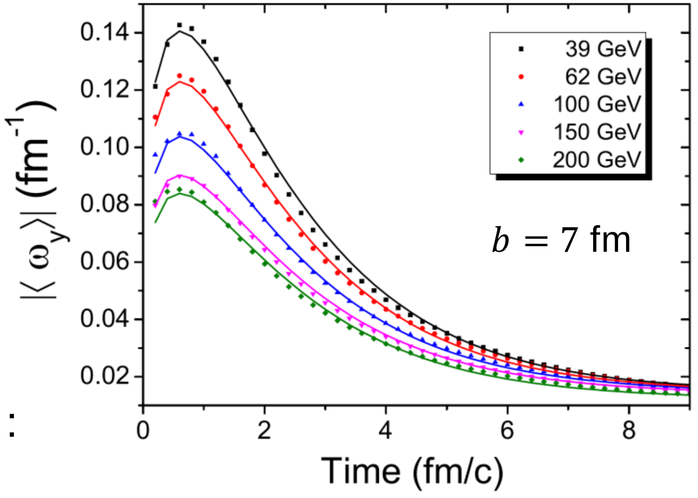
$$\mathbf{L} = \frac{1}{2}\int d^3\mathbf{r}\epsilon|\mathbf{r}|^2(1-\hat{\boldsymbol{\omega}}\cdot\hat{\mathbf{r}})\boldsymbol{\omega},$$

$\boldsymbol{\omega} = \nabla\times\mathbf{v} = \text{const.}$ ϵ : energy density

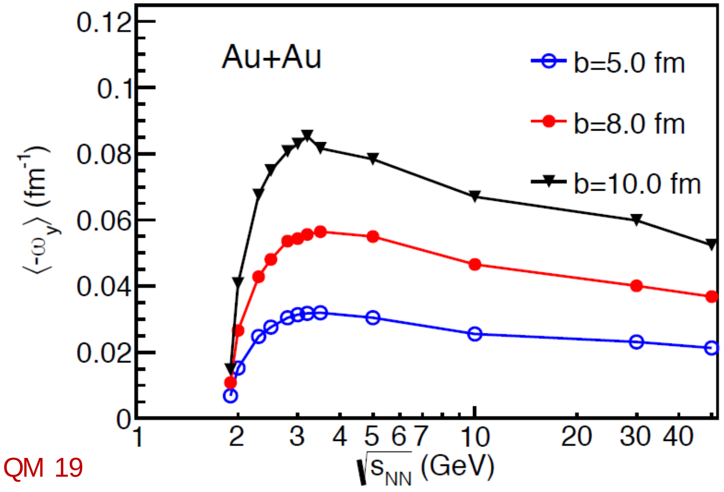


X.-G. Huang, QM 19

Y. Jiang, Z.-W. Lin, J. Liao, PRC 94, 044910 (2016)
see also W.-T. Deng and X.-G. Huang, PRC 93, 064907 (2016)

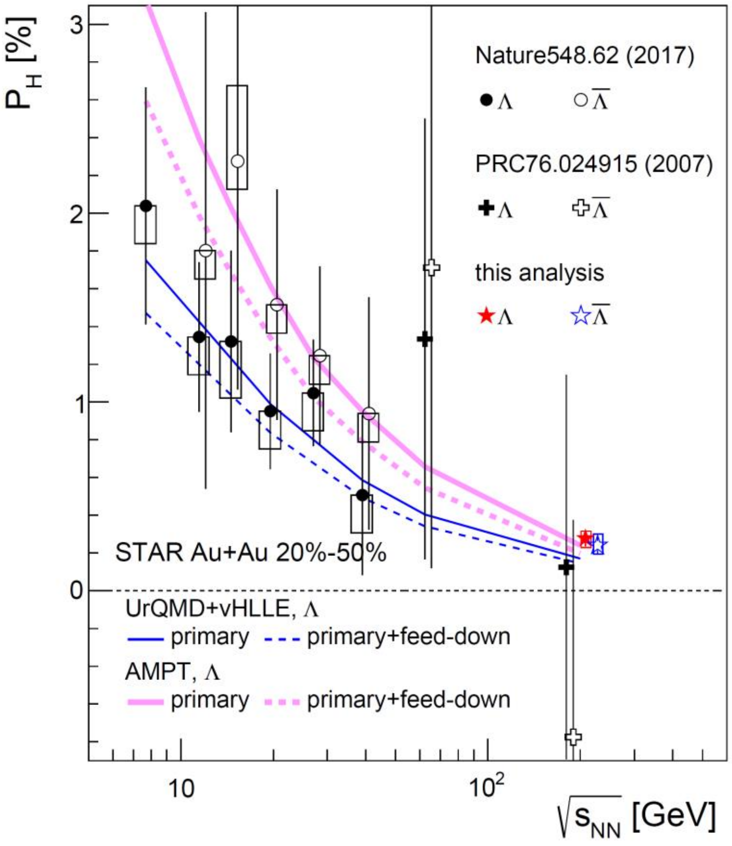


X.-G. Deng et al., PRC101.064908 (2020)



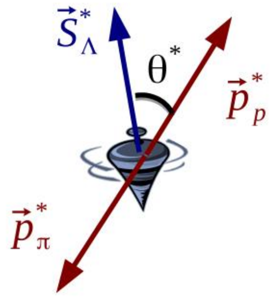
Global Λ polarization in HIC

- The large AM generated in HIC could induce spin polarization of the QGP via spin-orbit interaction. (relativistic Barnett effect) Z.-T. Liang, 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 :



T. Niida, QM18

❖ The daughter particle is emitted preferably parallel to the spin of Λ

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

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}^*_\mathbf{p})$$

(experiment talk by J. Chen)

Theoretical description for global polarization

- Spin polarization spectrum (canonical) :

$$\mathcal{P}^\mu(\mathbf{p}) = \frac{\int d\Sigma \cdot p\boxed{\mathcal{J}_5^\mu(p,X)}}{2m\int d\Sigma\cdot \mathcal{N}(p,X)}\Bigg|_{p_0=\epsilon_{\mathbf{p}}}$$

axial-charge current density in phase space

(modified Cooper-Frye formula)

❖ pseudo-gauge dep. : canonical spin fulfills SO(3) algebra S. Dey et al., arXiv:2303.05271

- Global equilibrium (global rotation):

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

Killing cond. :

$$"\partial_\mu\beta_\nu + \partial_\nu\beta_\mu = 0"$$

$$\beta^\mu \equiv u^\mu/T$$

$$\boxed{\omega_{\mu\nu} = \frac{1}{2}(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu)}. \xrightarrow[T=\text{const.}]{} \omega_{\mu\nu} = -\epsilon_{\mu\nu\alpha\beta}\boxed{\omega^\alpha}u^\beta$$

thermal vorticity

kinetic vorticity

F. Becattini et al., Ann. Phys. 338, 32 (2013)

R. Fang et al., PRC 94, 024904 (2016)

→ Agrees with global Λ polarization

(+hydro)

- Indication of kinetic vorticity : $P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \longrightarrow \omega \sim 10^{22}\,\mathrm{s}^{-1}$

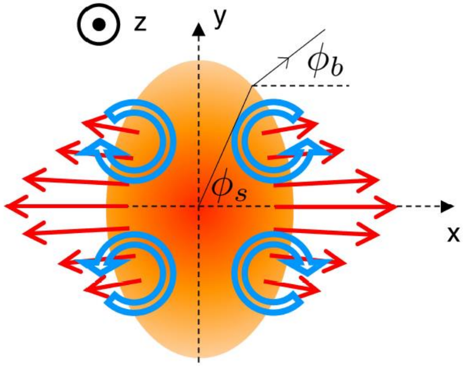
F. Becattini et al., PRC95, 054902 (2017)

Local (longitudinal) polarization : a sign problem

- Local vorticity from transverse expansion : longitudinal vorticity & polarization

- Disagreement btw theory & experiment :

  A “spin sign problem” for longitudinal polarization



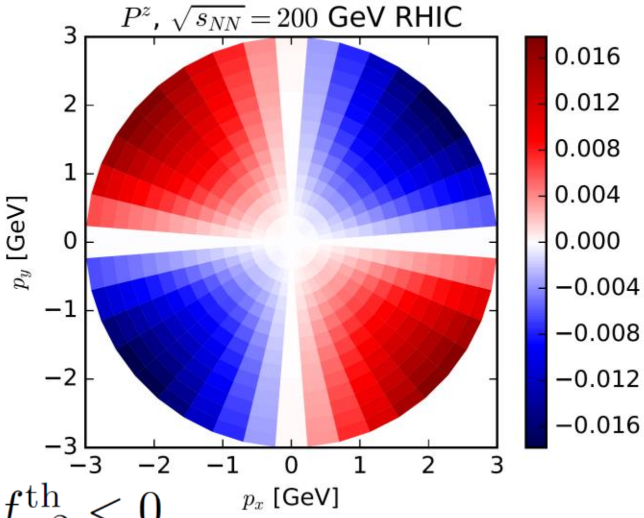
F. Becattini, I. Karpenko, PRL 120, 012302 (2018).

See also X.-L. Xia et al., PRC98.024905 (2018)

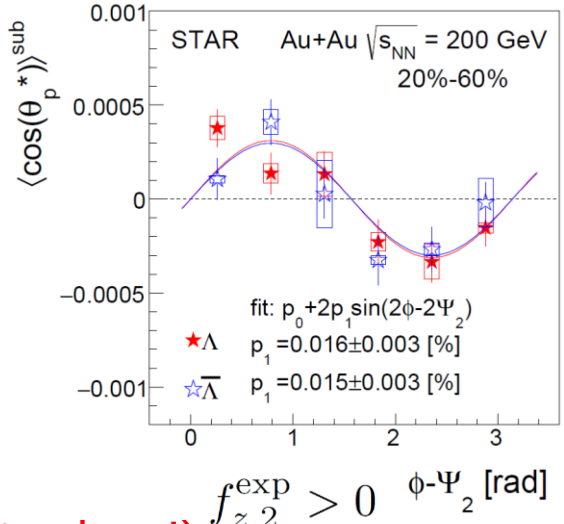
J. Adam et al. (STAR), PRL. 123, 132301 (2019)

spin harmonics :

$$\frac{dP^z}{2\pi d\phi} = f_{z,0} + 2f_{z,2}\sin(2\phi)$$



v.s.



$f_{z,2}^{\mathrm{th}} < 0$

$f_{z,2}^{\mathrm{exp}} > 0$

(same structure, opposite signs!)

- Corrections beyond global equilibrium? How to delineate the dynamical spin evolution of quarks traversing QGP? quantum transport theory is needed

Spin hydrodynamics

- Introduce a spin tensor, $S^{\lambda\mu\nu}$, as an additional dynamical quantity.

  W. Florkowski, B. Friman, A. Jaiswal, E. Speranza, PRC 97, no. 4, 041901 (2018)
  W. Florkowski et al., PRD 97, no. 11, 116017 (2018)
  spin hydro review: W. Florkowski, A. Kumar, R. Ryblewski, PPNP 108 (2019) 103709

- Energy-momentum + angular-momentum cons (10 hydro eqs):

$$\partial_\mu T^{\mu\nu} = 0, \qquad \partial_\lambda S^{\lambda\mu\nu} = \boxed{T^{\nu\mu} - T^{\mu\nu}}.$$

(AM transfer from the spin-orbit int.)

- 10 hydrodynamic variables : $T,\ u^\mu,\ \boxed{\Omega^{\mu\nu}}.$ $\xrightarrow{}$ $\Omega^{\mu\nu} = \omega^{\mu\nu}$

  spin chemical potential

  global equilibrium

  K. Hattori et al., PLB 795 (2019) 100-106

- Constitutive relations depend on pseudo-gauges : hydro variables & transport coefficients are related in different pseudo-gauges.
  (bridging the spin hydro & traditional hydro)

  K. Fukushima, S. Pu, PLB 817 (2021) 136346
  S. Li, M. Stephanov, H.-U. Yee, PRL 127, 082302 (2021)

- To spin polarization : $\mathcal{P}^\mu(\boldsymbol{p}) = \frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_\nu \frac{\int d\Sigma \cdot p \Omega_{\rho\sigma} f_p^{(0)} (1 - f_p^{(0)})}{\int d\Sigma \cdot p f_p^{(0)}}$
  (assumption)

- Phase-space info is needed for describing the spin polarization spectra

➢ Spin hydro. from kinetic theory : relaxation-time approx., methods of moment, etc.

S. Bhadury et al., PRL 129, 192301 (2022)   N. Weickgenannt et al., PRD 106, 096014 (2022)

➢ Formulating spin hydro directly from QFT

M. Hongo et al., JHEP 11 (2021) 150
J. Hu, PRD 103, 116015 (2021)

QKT for relativistic fermions

- To capture the intertwined dynamics of charge and spin transport in phase space.
- Massless fermions : chiral kinetic theory (CKT) QKT Review : Y. Hidaka S. Pu, Q, Wang, DY, PPNP 127 (2022) 103989
- Axial kinetic theory : scalar/axial-vector kinetic eqs. (SKE/AKE)

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

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

standard Boltzmann (Vlasov) eq.

➢ AKE : $p\cdot\Delta\tilde{a}^\mu+F^{\nu\mu}\tilde{a}_\nu+\hbar Q^\mu[f_V]=\hat{L}^{\mu\nu}\tilde{a}_\nu+\hbar\hat{H}^{\mu\nu}\partial_\nu f_V$ (entangled f_V & $\tilde{a}^\mu$)

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

- Matrix valued spin dependent distributions (MVSD) :

N. Weickgenannt et al., PRL127, 052301 (2021)
N. Weickgenannt et al., PRD 104 (1) (2021) 016022
X.-L. Sheng et al., PRD 104 (1) (2021) 016029

$$\delta(p^2-m^2)\,p\cdot\partial f(x,p,\mathfrak{s})=\delta(p^2-m^2)\,\mathfrak{C}_{\text{on-shell}}[f]$$

➢ Non-local collisions from the spacetime shift : $f(x+\hbar\Delta,p,\mathfrak{s})$

(valid up to $\hbar$: physically equivalent to the quantum corrections in AKT)

❑ To spin pol. spectra :

$$\mathcal{J}_5^\mu(\boldsymbol{p},x)\propto\int dp_0\mathcal{A}^\mu(p,x)\begin{cases}\mathcal{A}^\mu=2\pi\left(\delta(p^2-m^2)\tilde{a}^\mu+\hbar\tilde{F}^{\mu\nu}p_\nu\delta'(p^2-m^2)f_V\right)\\ \text{or}\\ \mathcal{A}^\mu=4\pi\delta(p^2-m^2)m\int dS(p)\mathfrak{s}^\mu f(x,p,\mathfrak{s})\end{cases}$$

❖ quark-potential scattering approach X. Li, S. Cao, Eur.Phys.J.C 83 (2023) 1, 96 (X. Li, poster)

Spin polarization beyond global equilibrium

- Local-equilibrium corrections (independent of int.) :

Y. Hidaka, S. Pu, DY, PRD 97, 016004 (2018)
S. Liu and Y. Yin, PRD 104, 054043 (2021)
S. Liu, Y. Yin, JHEP 07, 188 (2021)
F. Becattini, M. Buzzegoli, A. Palermo, PLB 820,136519 (2021)

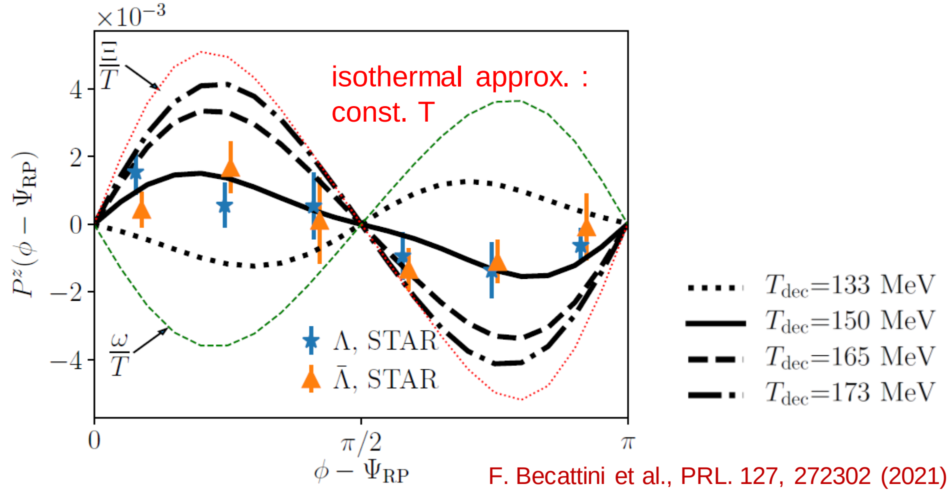
(thermal) shear :

$$\mathcal{J}^{\mu}_{\text{shear}} = -\frac{f_p^{(0)}(1-f_p^{(0)})}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta p^\sigma \underbrace{\partial_{<\sigma}u_{\nu>}}_{\text{shear strength}}$$

spin-Hall effect :

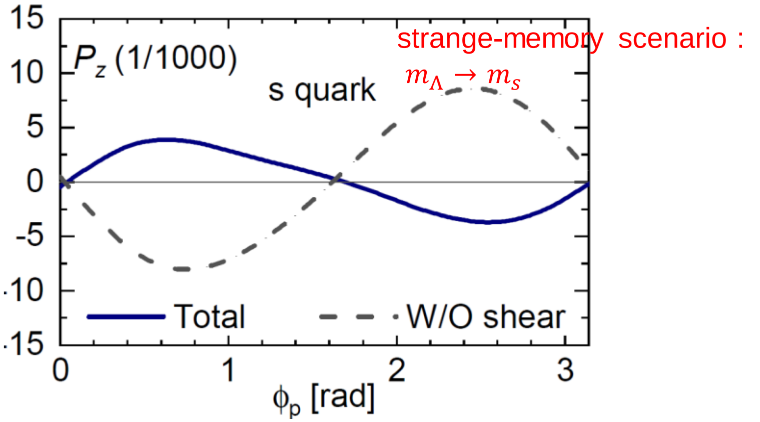
$$\mathcal{J}^{\mu}_{\text{chemical}} = \frac{f_p^{(0)}(1-f_p^{(0)})}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta \underbrace{\partial_\nu \frac{\mu}{T}}_{\text{chemical-potential/temperature gradient}}$$

- Shear corrections on longitudinal polarization :



isothermal approx. : const. T

F. Becattini et al., PRL. 127, 272302 (2021)



strange-memory scenario : $m_\Lambda \to m_s$

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

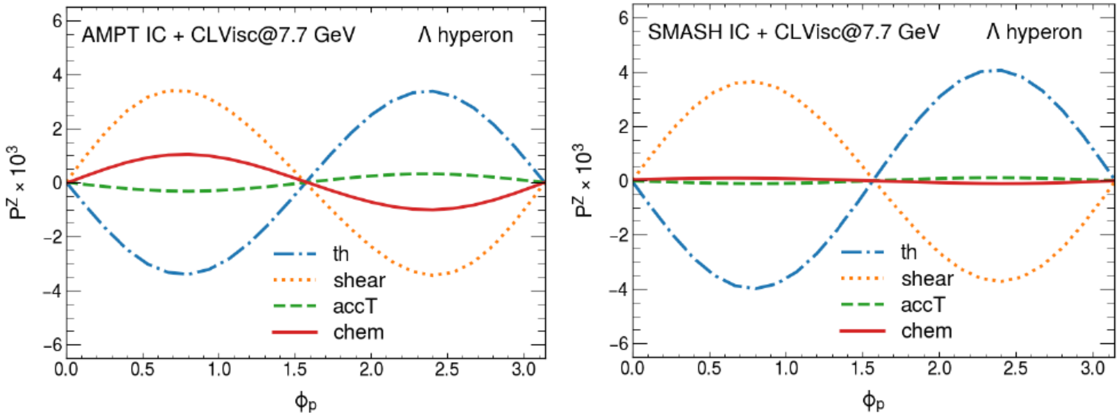
- Sensitive to the adopted approximations and numerical parameters

C. Yi, S. Pu, DY, PRC 104, 064901 (2021)
W. Florkowski et al., PRC 105, 064901 (2022)
Y. Sun, Z. Zhang, C. M. Ko, W. Zhao, PRC 105, 034911 (2022)
S. Alzharani, S. Ryu, C. Shen, PRC 106, 014905 (2022)

spin polarization review : F. Becattini, Rept. Prog. Phys. 85, 122301 (2022)

Spin Hall effect & helicity polarization

- Spin Hall effect on local polarization : prominent at low energy but sensitive to ICs.



X.-Y. Wu, C. Yi, G.-Y. Qin, S. Pu,
PRC 105, 064909 (2022)

(X.-Y. Wu, talk Mon)

see also

S. Ryu, V. Jupic, C. Shen, PRC 104, 054908 (2021)

B. Fu et al., arXiv:2201.12970

❖ spin-shear coupling & other non-equilibrium corrections from collisions by QKT

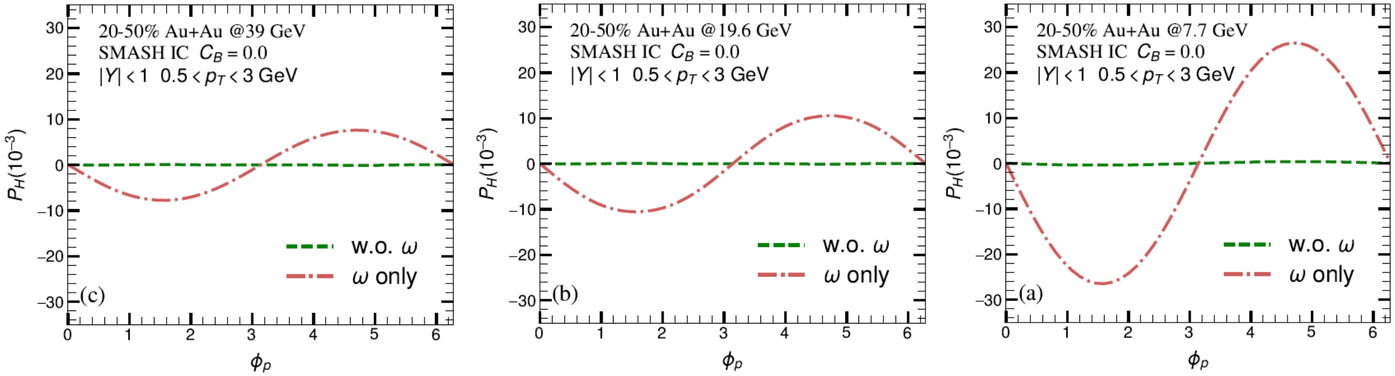
(S. Lin, talk Wed)

S. Lin, Z. Wang, JHEP 12 (2022) 030

S. Fang, S. Pu, DY, PRD 106, 016002 (2022)

Z. Wang, PRD 106, 076011 (2022)

- Helicity polarization : $\mathcal{P}_{\rm H}(\boldsymbol{p}) = \hat{\boldsymbol{p}}\cdot\mathcal{P}(\boldsymbol{p})$ probes the detailed structure of local (kinetic) vorticity



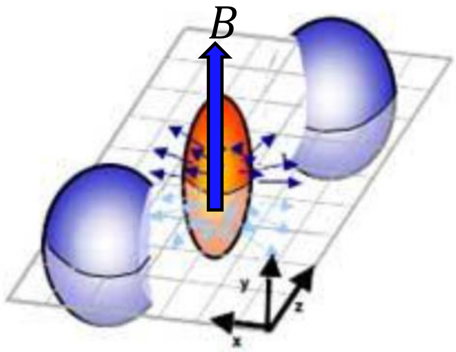
C. Yi, S. Pu, J.-H. Gao, DY,
PRC 105, 044911 (2022)

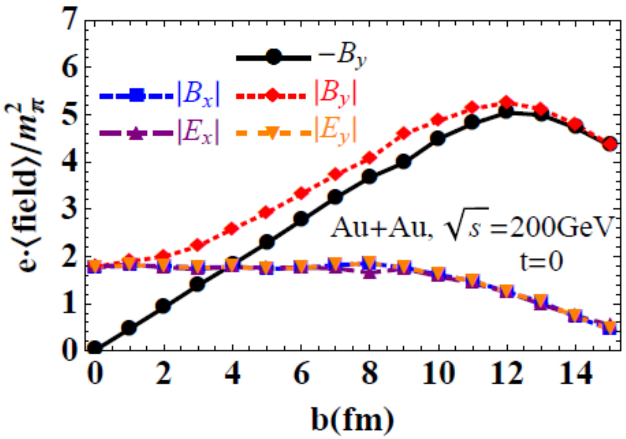
C. Yi et al., arXiv:2304.08777

➢ Mismatch with experimental data (if found) will imply the non-equilibrium corrections.

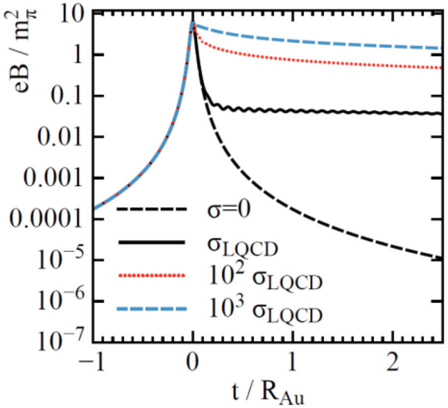
Strong electric/magnetic fields in HIC

- Initial strong B fields generated by colliding nuclei : $eB \sim m_\pi^2 \sim 10^{18}$ Gauss



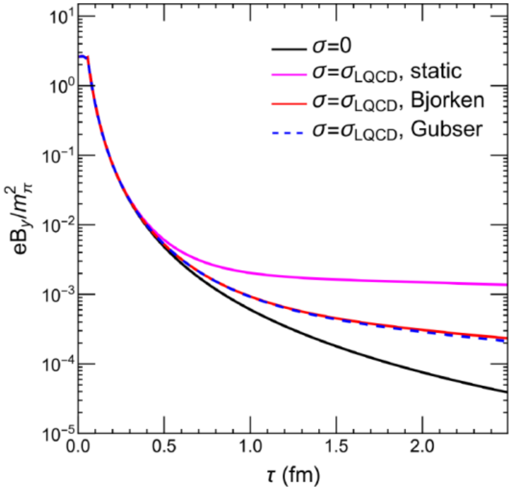


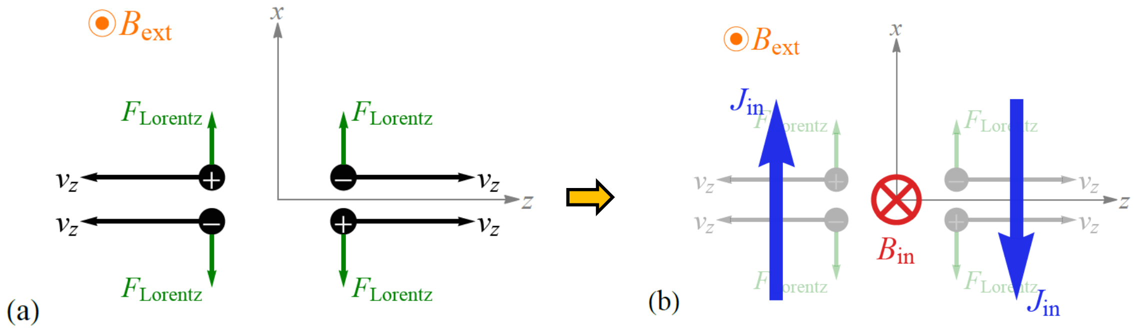
D.-W. Deng, X.-G. Huang, PRC 85, 044907 (2012)



L. Mclerran, V. Skokov, NPA 929 (2014) 184-190

❖ Lifetime of B fields could be extended by nonzero σ but reduced by longitudinal expansion





A. Huang et al., PRC 107, 034901 (2023)

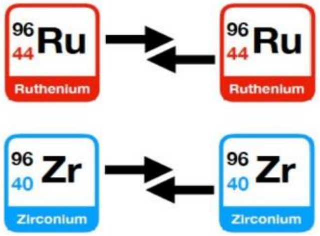
Status of the chiral magnetic effect

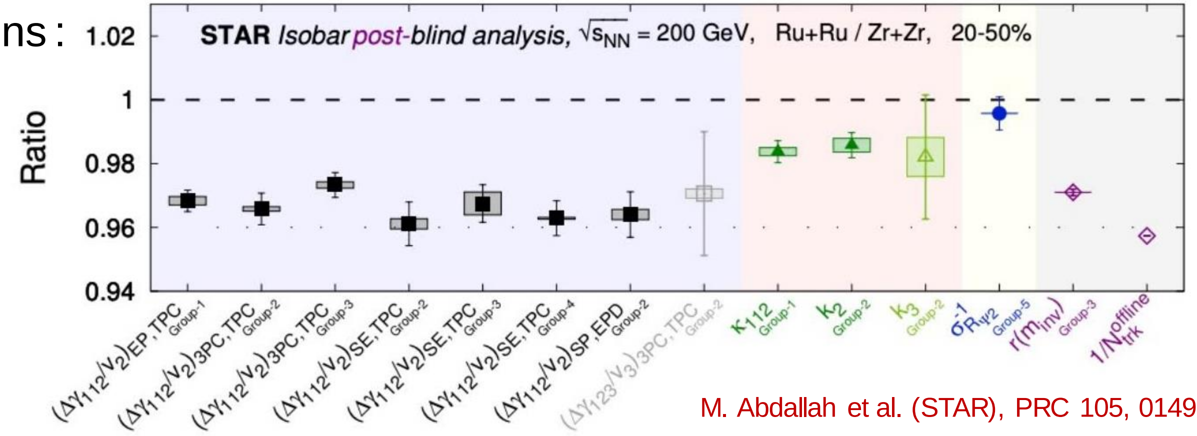
- Strong B fields could be applied to probe local parity violation of QCD : $J^{\mu} = \frac{e^2\mu_5}{2\pi^2}B^{\mu}$

Review : D. Kharzeev et al., PPNP. 88, 1 (2016)

❖ Opposite & same charge correlators : $\Delta\gamma = \gamma_{\mathrm{OS}} - \gamma_{\mathrm{SS}}, \quad \gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}})\rangle$

❖ Isobar collisions :

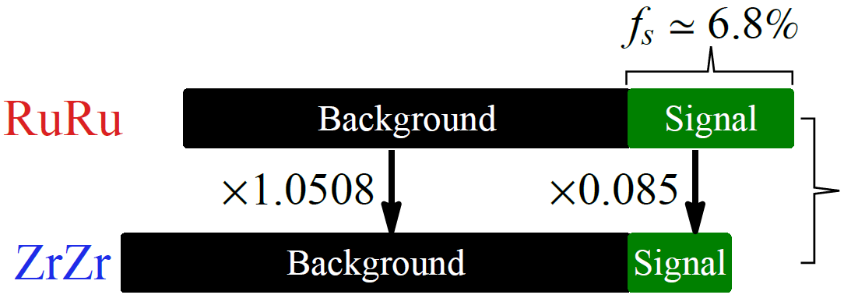




<1 (predefined baseline)
no CME?

M. Abdallah et al. (STAR), PRC 105, 014901 (2022)

❖ A new theoretical baseline? Difference of multiplicity & flow considered


$f_s \simeq 6.8\%$

RuRu Background Signal

×1.0508 ×0.085

ZrZr Background Signal

overall ratio

$R \simeq 0.9641$

(but not all. E.g. non-flow)

D. Kharzeev, J. Liao, S. Shi, PRC.106.L051903 (2022)

Y. Feng et al., PRC 105, 024913 (2022)

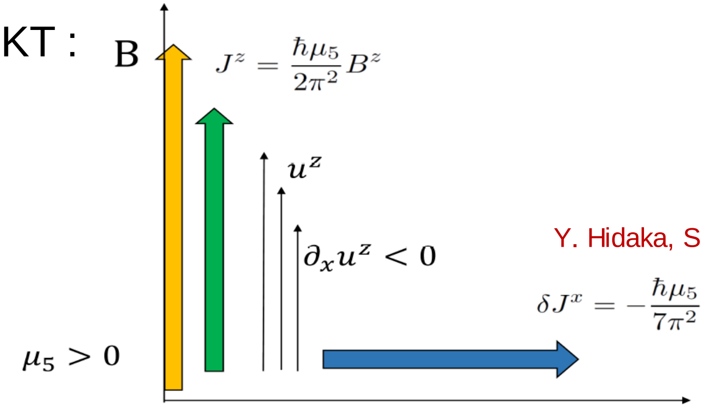
Non-equilibrium corrections on CME

- Viscous (shear) corrections on CVE/CME : $\delta J^\mu = \xi_1 \partial^{<\mu} u^{\nu>} \omega_\nu + \xi_2 Q \partial^{<\mu} u^{\nu>} B_\nu$

D. Kharzeev, H.-U. Yee, PRD 84, 045025 (2011)

- Relaxation-time approx. in CKT :

Y. Hidaka, DY, PRD 98, 016012 (2018)



Y. Hidaka, S. Pu, DY, NPA 982 (2019) 547-550

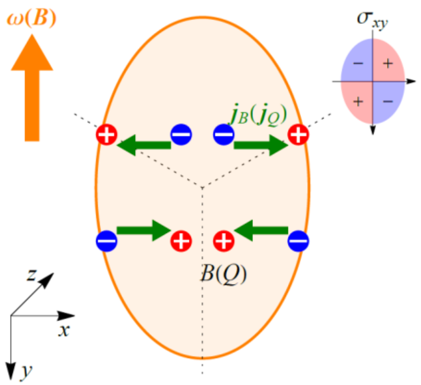
$$\delta J^x = -\frac{\hbar\mu_5}{7\pi^2}\tau_R B^z \partial_x u^z$$

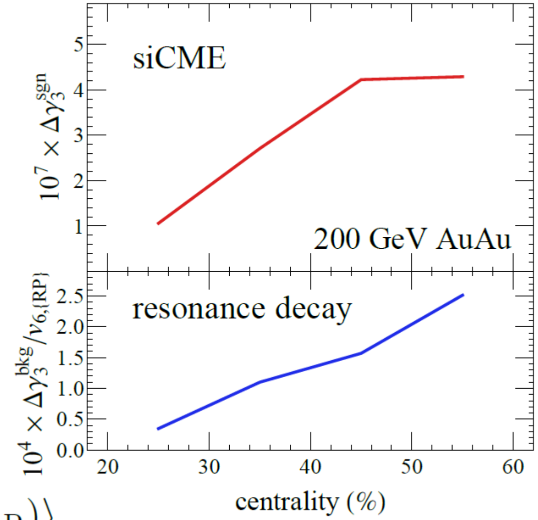
- Moment expansion method :

$$\xi_1 \approx -0.62\frac{\eta}{s}\frac{\mu_5\mu}{T} = -0.05\frac{\mu_5\mu}{T}$$

$$\xi_2 \approx -6.70\frac{\eta}{s}\frac{\mu_5}{T} = -0.53\frac{\mu_5}{T}$$

S. Shi, C. Gale, S. Jeon, PRC 103, 044906 (2021)
M. Buzzegoli et al., PRC 106, L051902 (2022)





$$\gamma_3^{\alpha\beta} \equiv \langle \cos(3\phi_\alpha + 3\phi_\beta - 6\Psi_{\rm RP}) \rangle$$

Other effects related to magnetic fields

❑ magnetic-field effects on HIC phenomenology & QCD properties :

- The direct photon elliptic flow from a weak magnetic field in QGP (J.-A. Sun, talk Mon)
  J.-A. Sun, L. Yan, arXiv:2302.07696
- Two-point functions from CKT in magnetized plasma (L. Yang, talk Mon)
  L. Yang, PRD 105, 074039 (2022)
- Anisotropic heavy-quark potential by magnetic fields (H.-X. Zhang, poster)
  H.-X. Zhang, arXiv:2301.09110
- QCD Kondo effect under magnetic catalysis (S. Yasui, talk Wed)
  K. Hattori et al., arXiv:2211.16150
- Influence of quark anomalous magnetic moment on QCD phase diagram (M. Kawaguchi, talk Wed)
  M. Kawaguchi, M. Huang, arXiv:2205.08169
- Unphysical topological charge of nonabelian gauge theory and implications to hadron physics (N. Yamanaka, poster)

Spin alignment of vector mesons

- Normalized spin density matrix :

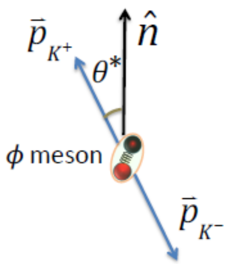
$$\frac{dN}{d\cos\theta^*} \propto [1-\rho_{00}+\cos^2\theta^*(3\rho_{00}-1)]$$

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

(assume spin pol along $\hat{n}$)

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

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

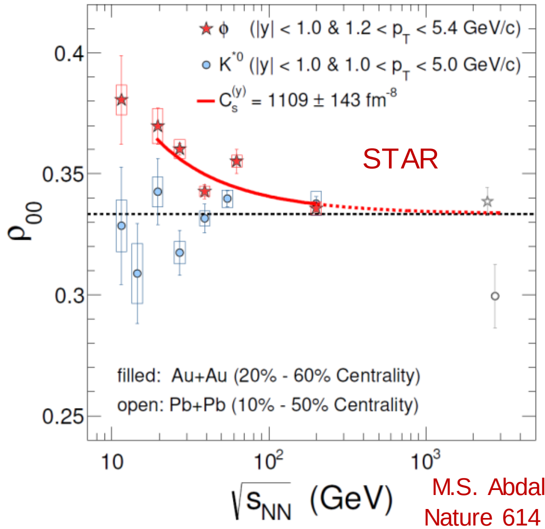


- Spin alignment puzzle : negligible deviation of ρ_{00} from 1/3 from vorticity

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)

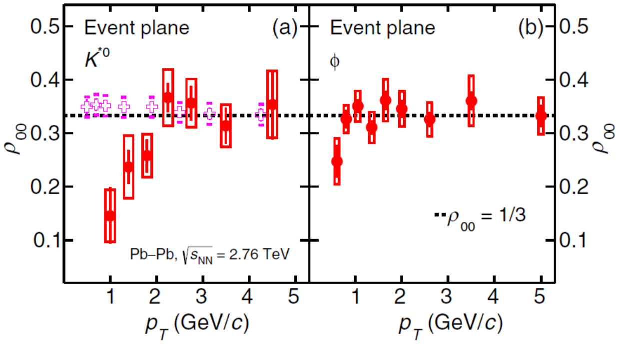
- Large deviations from experiments :

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



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

ALICE:



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

- Other sources for spin polarization (alignment) beyond hydrodynamic gradients? (electromagnetic fields decay too fast)

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)

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

- Anisotropic spin correlation is needed :

  X.-L. Sheng et al., arXiv:2206.05868

  A. Kumar, B. Müller, DY, arXiv:2212.13354

  see also A. Kumar, B. Müller, DY, arXiv:2304.04181 for a slightly different expression

  $$\rho_{00} \approx \frac{1 + \sum_{j=x,y,z} \langle \mathcal{P}_q^j \mathcal{P}_{\bar{q}}^j \rangle - 2\langle \mathcal{P}_q^y \mathcal{P}_{\bar{q}}^y \rangle}{3 + \sum_{j=x,y,z} \langle \mathcal{P}_q^j \mathcal{P}_{\bar{q}}^j \rangle}$$

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

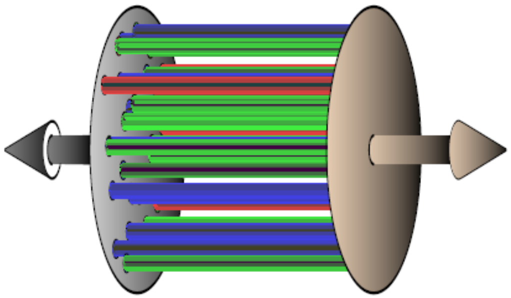
  $$\xrightarrow[|\langle \mathcal{P}_q^i \mathcal{P}_{\bar{q}}^i \rangle| \ll 1]{} \quad \rho_{00} \approx \frac{1}{3} + \frac{2}{9}\left(\langle \mathcal{P}_q^x \mathcal{P}_{\bar{q}}^x \rangle + \langle \mathcal{P}_q^z \mathcal{P}_{\bar{q}}^z \rangle - 2\langle \mathcal{P}_q^y \mathcal{P}_{\bar{q}}^y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

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

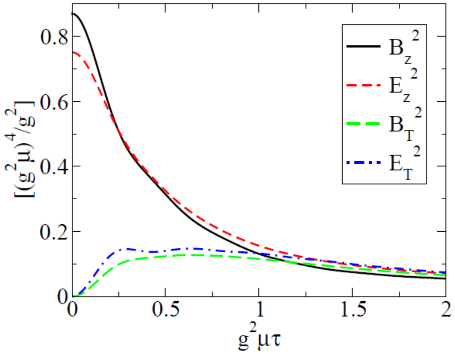
- Early-time or late-time effects?

Color-field induced spin alignment

- Scenario I : early-time effect from color fields in the glasma

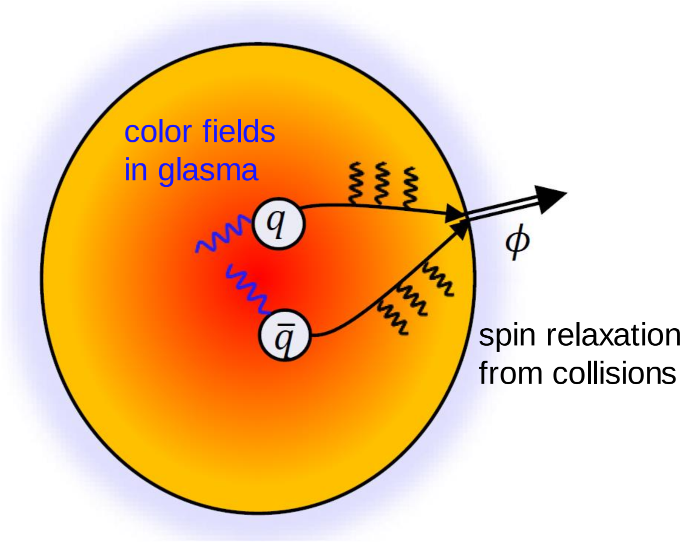


review: F. Gelis et al., Ann.Rev.Nucl.Part.Sci.60:463-489,2010



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

(H. Taya, plenary talk Mon & H. Matsuda, talk Mon)



- QKT is generalized to incorporate color dof.

X.-L. Luo, J.-H. Gao, JHEP 11, 115 (2021) (X. Luo, poster)
B. Müller, DY, PRD 105, L011901 (2022)
DY, JHEP 06, 140 (2022)

- Relate the spin density matrix to the Wigner functions of the coalesced quark and antiquark through the quark-meson interaction.

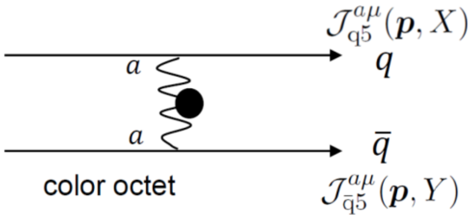
quark-meson int. : $\mathcal{L}_{\rm int} = g_\phi \Gamma\cdot V\bar{\psi}\psi$

$$\rho_{\lambda_1\lambda_1}(\boldsymbol{q}) = \frac{\int d\Sigma\cdot q f^{\phi}_{\lambda_1}(\boldsymbol{q},x)}{\sum_{\lambda=0,\pm1} f^{\phi}_{\lambda}(\boldsymbol{q},x)} = \frac{\int d\Sigma\cdot q\epsilon^*_\mu(\lambda_1,\boldsymbol{q})\epsilon_\nu(\lambda_1,\boldsymbol{q})\boxed{\mathcal{C}^{\mu\nu}_{\rm coal}(\boldsymbol{q},x)}}{\int d\Sigma\cdot q\sum_{\lambda=0,\pm1}\epsilon^*_\mu(\lambda,\boldsymbol{q})\epsilon_\nu(\lambda,\boldsymbol{q})\mathcal{C}^{\mu\nu}_{\rm coal}(\boldsymbol{q},x)}$$

X.-L. Sheng et al., arXiv:2206.05868
A. Kumar, B. Müller, DY, arXiv:2304.04181

Spin alignment from glasma

- Vanishing spin polarization but nonzero correlations :



primary contribution : 2-field correlations $\propto \langle B^{az}(X)B^{az}(X)\rangle_{X_0=0}$

A. Kumar, B. Müller, DY, arXiv:2304.04181, arXiv:2212.13354

- Numerical estimation : $\rho_{00} \sim \dfrac{1}{3+10e^{-2X_0^{\mathrm{eq}}/\tau_{\mathrm{R}}^{\mathrm{o}}}} < \dfrac{1}{3}$ (zero momentum)

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

  glasma effect relaxation effect (hard to estimate)

- Momentum-dep. analysis (qualitative) : boosting the color fields to the lab frame

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

isotropic BFs : $\rho_{00}-\dfrac{1}{3} \propto (v_x^2-v_y^2)\displaystyle\int d\Sigma\cdot q\langle B^{az}(0,\boldsymbol{X})B^{az}(0,\boldsymbol{X})\rangle$

	small-$\mathrm{P_T}$	large-$\mathrm{P_T}$	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	$\rho_{00}^{\phi,J/\psi} \gtrsim 1/3$	$\rho_{00}^{\phi,J/\psi} > 1/3$	$\rho_{00}^{\phi,J/\psi} \gtrsim 1/3$	$\rho_{00}^{\phi,J/\psi} > 1/3$

(high energy)

(low & high)

Spin alignment from vector-meson fields

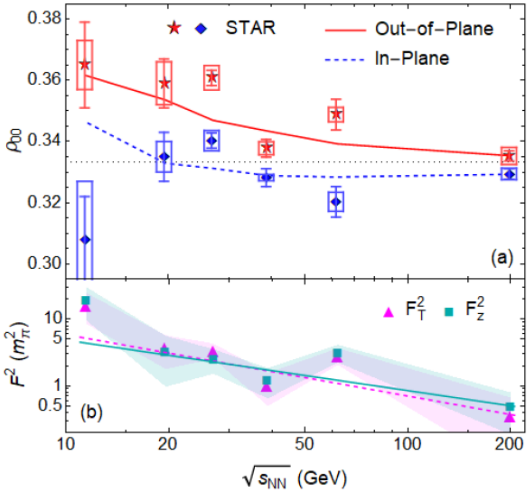
- Scenario II : late-time effect from vector-meson fields

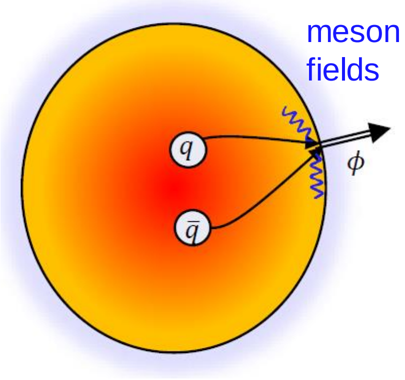
❖ From fluctuating vector-meson fields :

$$\rho_{00}(x,\mathbf{k}) \approx \frac{1}{3} - \frac{4g_\phi^2}{m_\phi^2 T_{\rm h}^2} C_1 \left[\frac{1}{3}\mathbf{B}'_\phi\cdot\mathbf{B}'_\phi - (\boldsymbol{\epsilon}_0\cdot\mathbf{B}'_\phi)^2\right] - \frac{4g_\phi^2}{m_\phi^2 T_{\rm h}^2} C_2 \left[\frac{1}{3}\mathbf{E}'_\phi\cdot\mathbf{E}'_\phi - (\boldsymbol{\epsilon}_0\cdot\mathbf{E}'_\phi)^2\right]$$

X.-L. Sheng et al., arXiv:2206.05868, arXiv:2205.15689

(Q. Wang, talk Mon)





meson fields

(coexistence of quark & hadron dof)

❖ Other effects in early or late times : turbulent color fields in anisotropic QGP

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

- Scenario III : hadronic interactions

❖ Shear corrections on vector-meson Wigner functions from spin-1 QKT or linear response theory

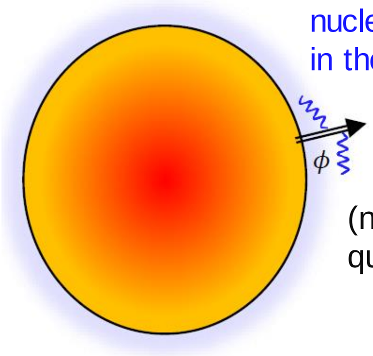
D. Wagner, N. Weickgenannt, E. Speranza, PRR 5, 013187 (2023)
F. Li, S. Liu, arXiv:2206.11890

❖ Mass splitting by rotations (M. Wei, poster)

M. Wei, M. Huang, arXiv:2303.01897

❖ Extracting phi meson properties in pA might help

(P. Gubler, talk Mon)



nuclear-matter effect in the hadronic phase

(no explicit quark dof)

Summary & outlook

- HIC provide an ideal test ground to study various mechanisms under intense fields ranging from vortical and electromagnetic fields to exotic fields stemming from strong interaction in QCD.

❖ vorticity & spin polarization :

✓ Corrections beyond global equilibrium play an important role for local spin polarization

✓ Many developments on spin hydro & QKT for ultimately understanding dynamical spin evolution of quarks traversing QGP

➢ Quantitative estimation for non-equilibrium corrections on local spin polarization?

➢ Simplified spin transport models are needed for practical simulations

➢ From spin polarization of quarks to of hadrons : more rigorous approaches?

❖ Magnetic fields & CME : a baseline with all background effects included?

❖ Color fields or vector-meson fields from strong int.:

✓ Spin alignment provides a great opportunity to explore these strong fields in QCD.

➢ Early-time effects : quantitative estimate for spin relaxation?

➢ Meson fields or effective potential : first-principle estimation?

➢ More precise estimation and reliable comparisons with the growing data

Thank you!