Institute of Physics, Academia Sinica

BARYONS 2025

Local Spin Polarization by color-field correlators and momentum anisotropy

Haesom Sung

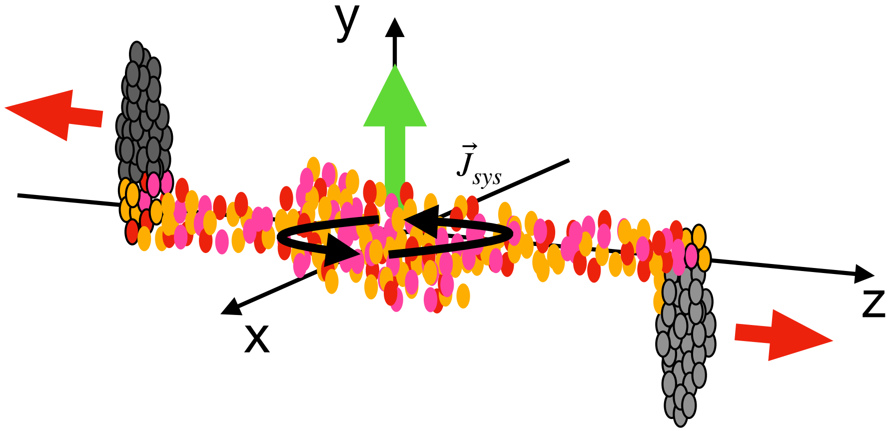
Berndt Müller, and Di-Lun Yang

Haesom Sung, Berndt Müller, Di-Lun Yang, arXiv:2507.23210v2

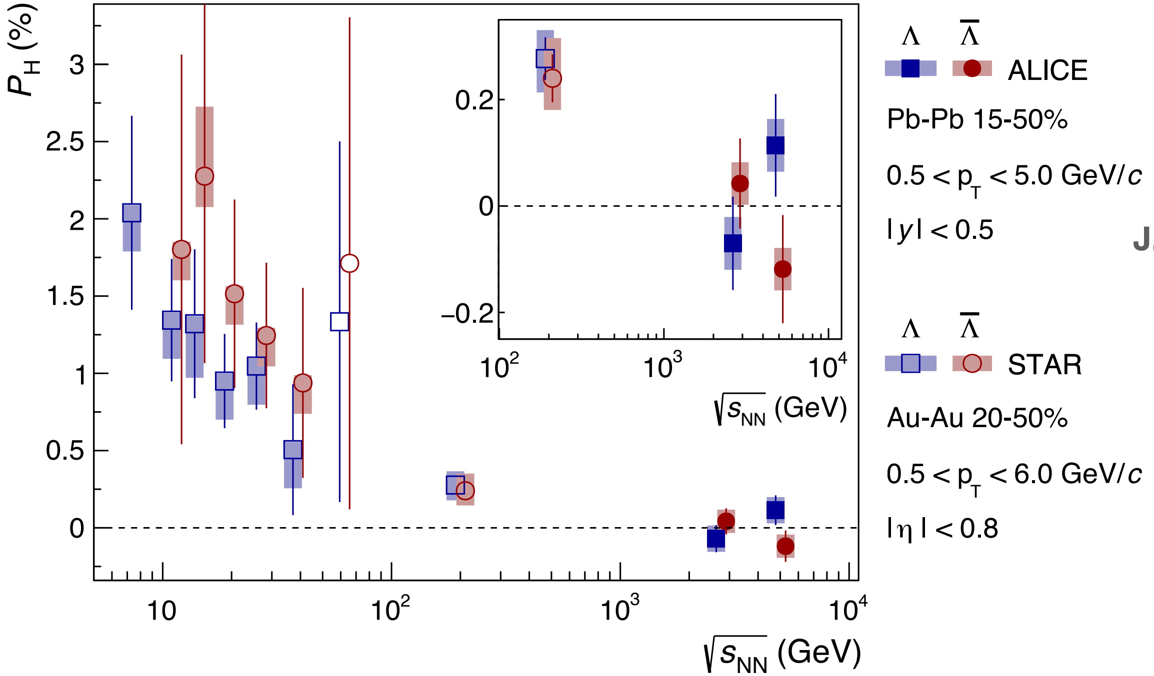
2025.11.11

Motivation

Positive Λ Spin Polarization

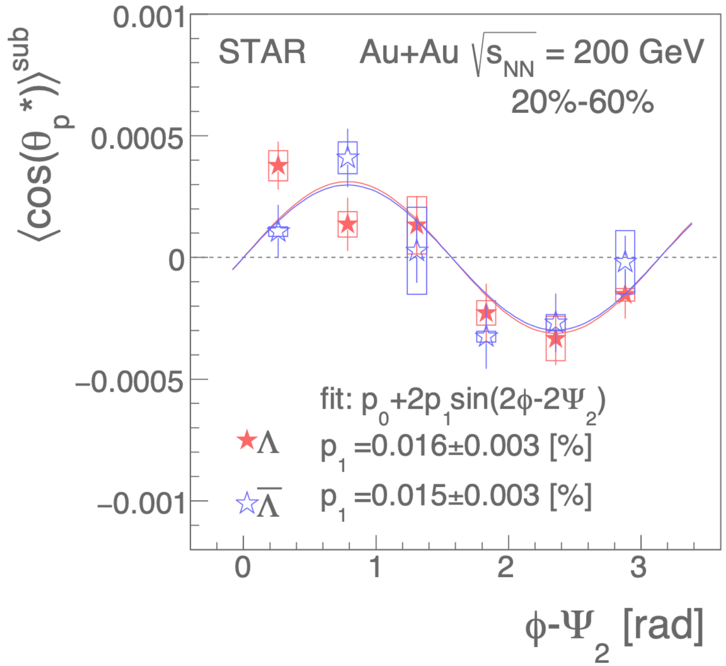


L. Adamczyk et al. (STAR), Nature 548, 62 (2017)
S. Acharya et al. (ALICE), Phys. Rev. C 101, 044611 (2020)



Non-zero global Λ polarization in small collision systems

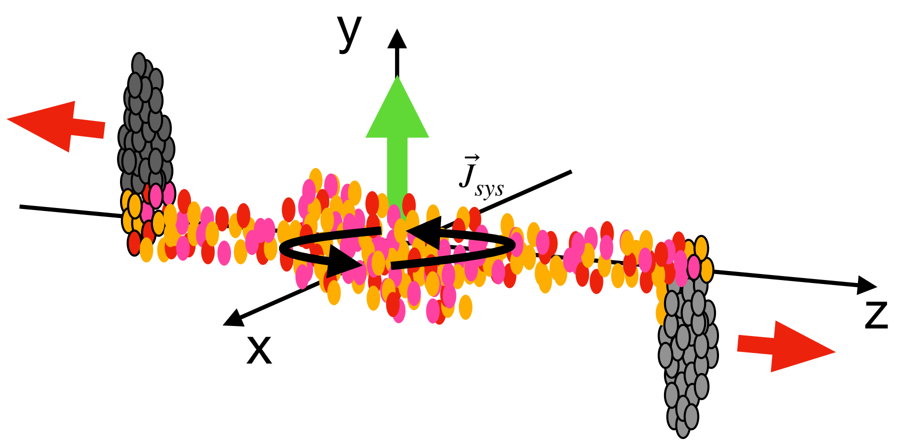
J. Adam et al. (STAR), *Phys.Rev.Lett.* 123 (2019) 13, 132301



$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle \cos^2\theta_p^* \rangle}$$

Motivation

Positive Λ Spin Polarization



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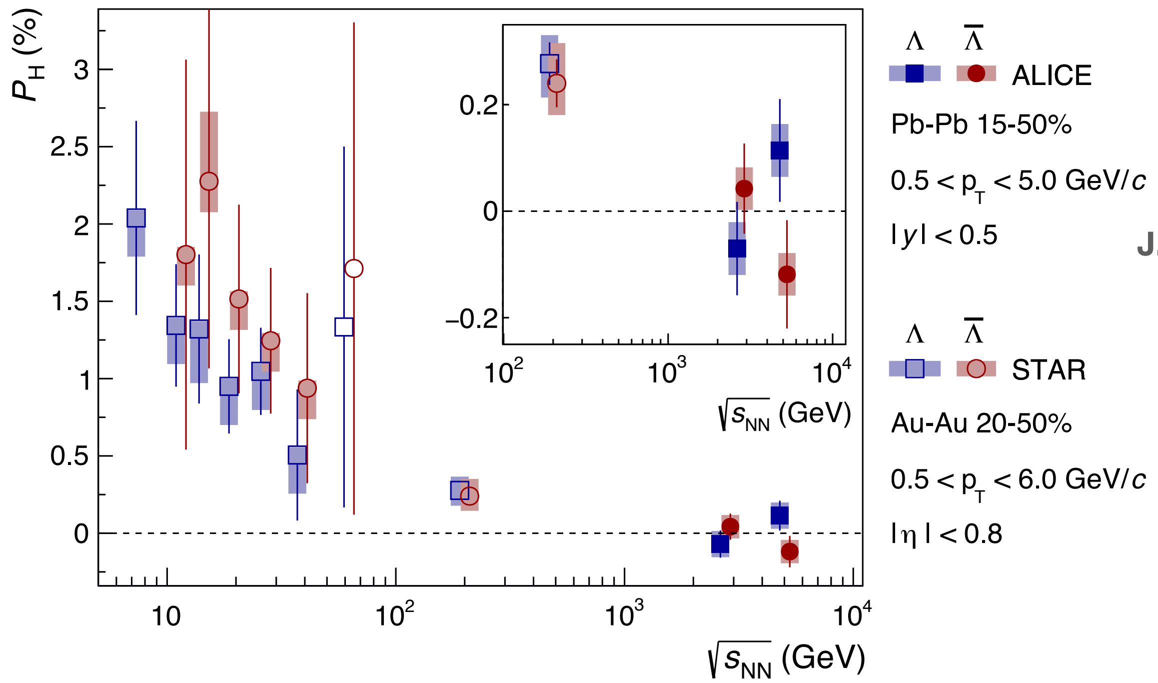
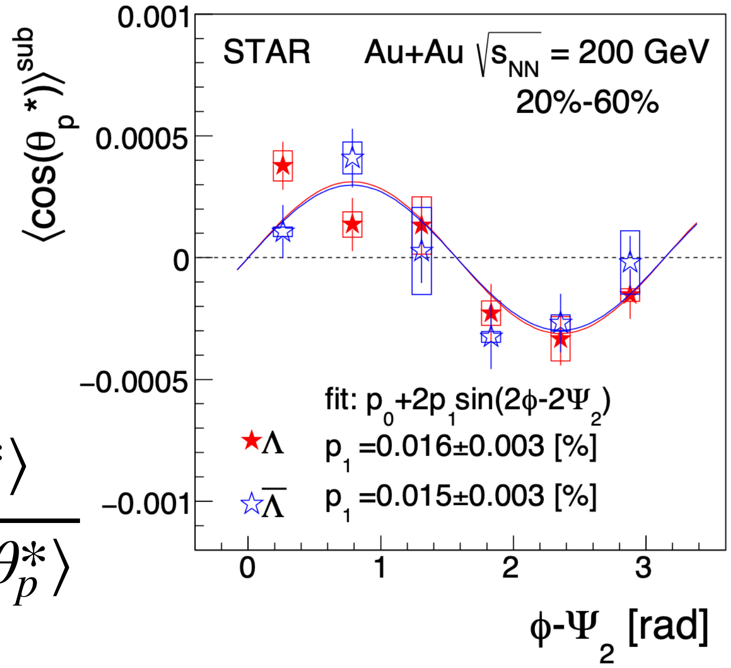


J. Adam et al. (STAR), *Phys.Rev.Lett.* 123 (2019) 13, 132301



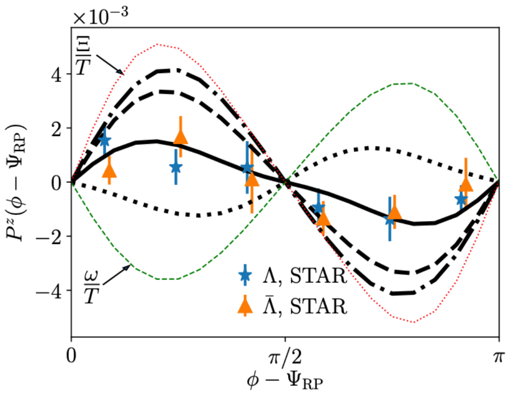
A **sinusoidal** structure of longitudinal Λ polarization with azimuthal angle

$$P_z = \frac{\langle \cos \theta_p^* \rangle}{\alpha_H \langle \cos^2 \theta_p^* \rangle}$$

Longitudinal Local Polarization

Hydrodynamic with Thermal Vorticity & Shear effect

* **Au+Au collisions** $\sqrt{s_{NN}} = 200$ **GeV** (iso-thermal)
  F. Becattini, I. Karpenko, PRL 120, 012302 (2018)
  F. Becattini et al., PRL. 127,272302 (2021)



$$S^\mu = S^\mu_\varpi + S^\mu_\xi$$

Opposite sign from vorticity contribution

Thermal vorticity

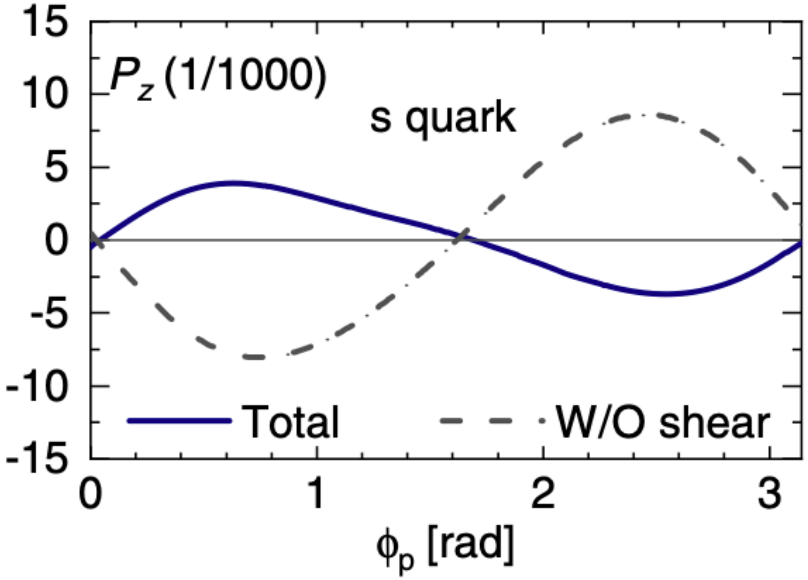
$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$$

Thermal shear

$(\xi_{\mu\nu} = 0$ at global equilibrium)

$$\xi_{\mu\nu} = \frac{1}{2}(\partial_\mu \beta_\nu + \partial_\nu \beta_\mu)$$

Baochi Fu et al., *Phys.Rev.Lett.* 127 (2021) 14, 142301 (s-quark equilibrium)



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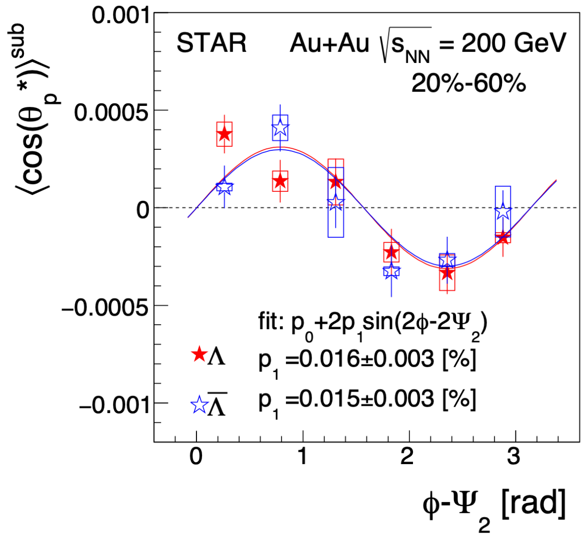
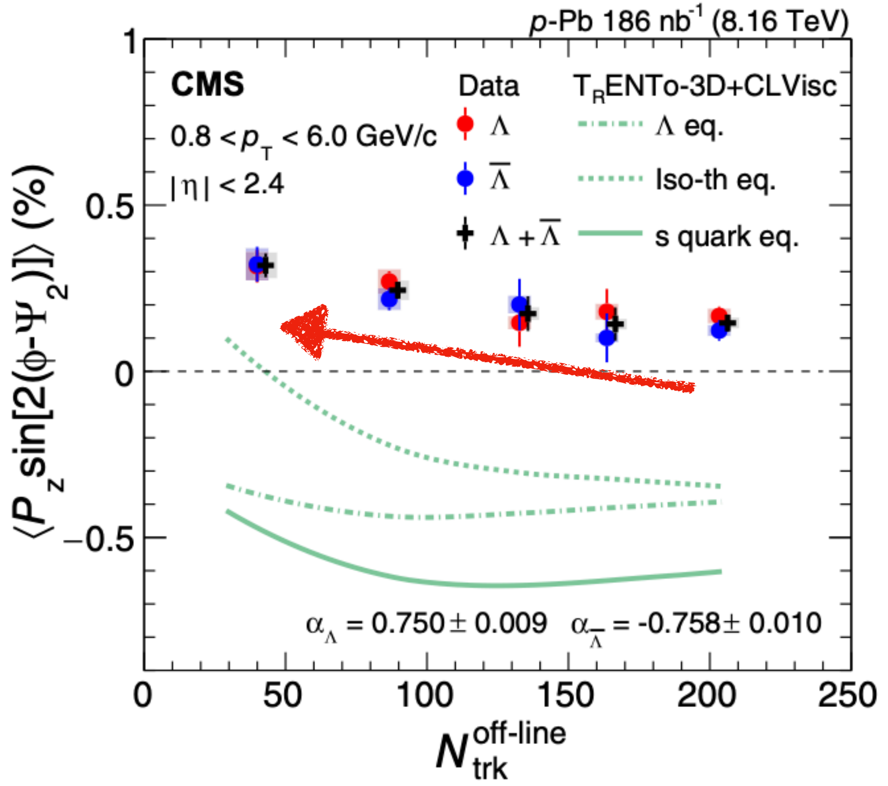
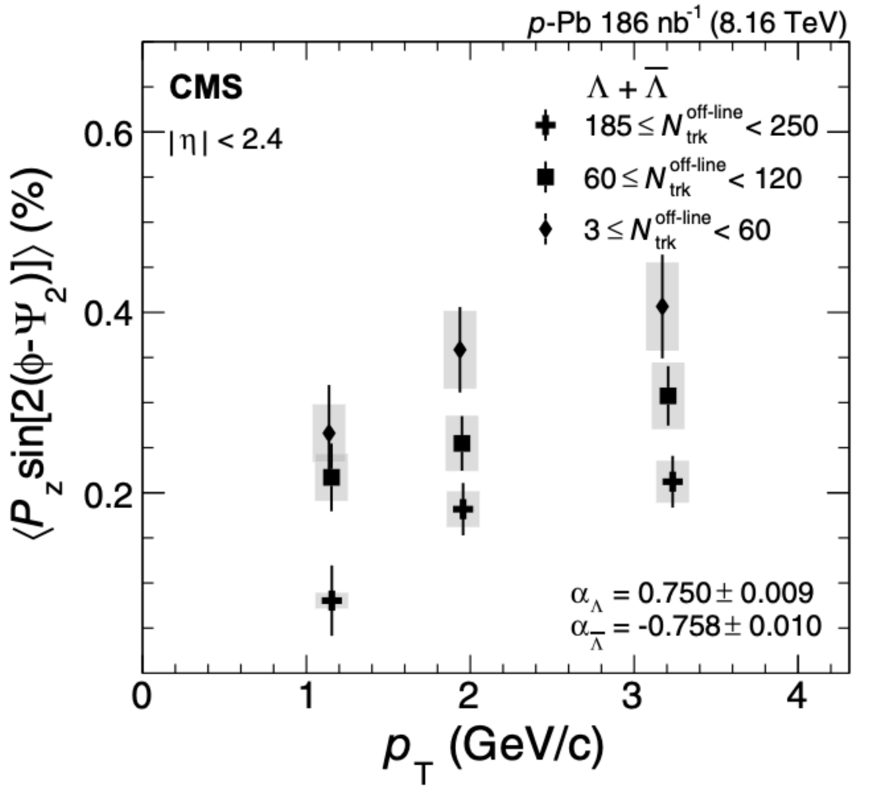


LSP with centrality and p_T

A. Hayrapetyan et al. (CMS), Phys.Rev.Lett. 135 (2025) 13, 132301
Cong Yi et al., *Phys.Rev.C* 111 (2025) 4, 044901

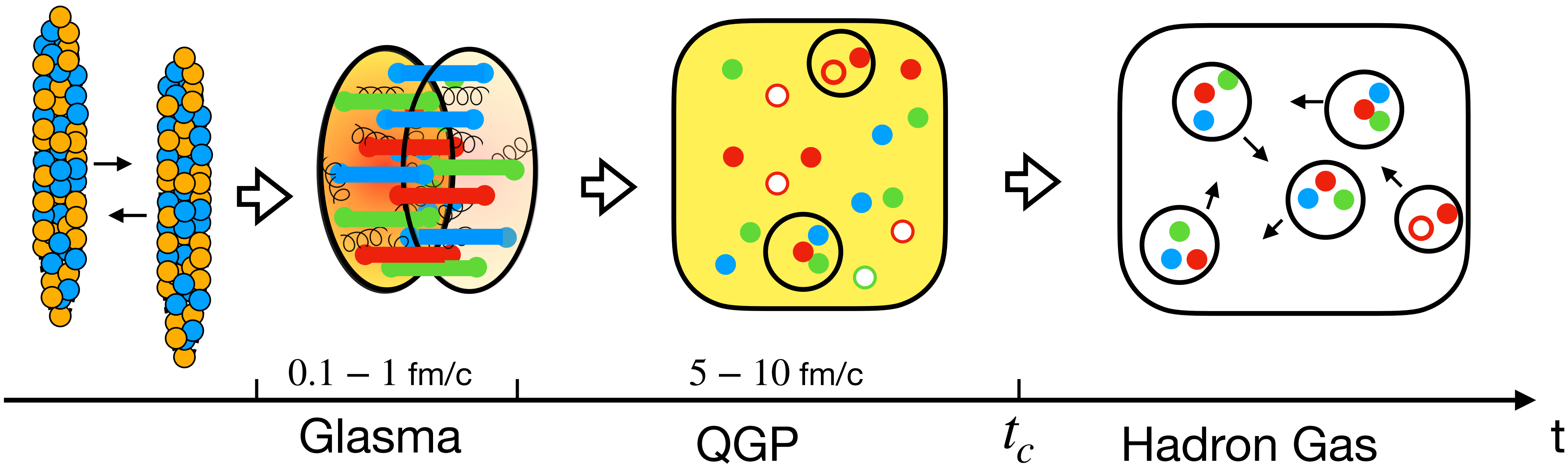
p+Pb collisions at 8.16 TeV



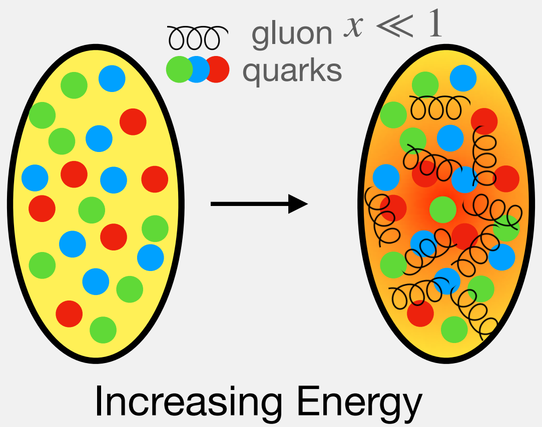


Thermal vorticity and thermal shear effect can not describe this experimental result with centrality and p_T dependence

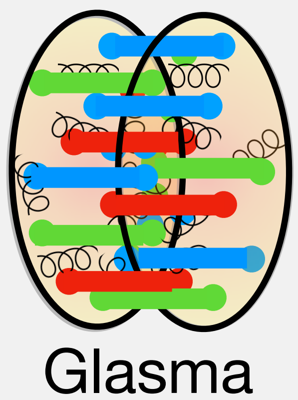
Initial stages of heavy ion collisions



Color Glass Condensate (CGC) :



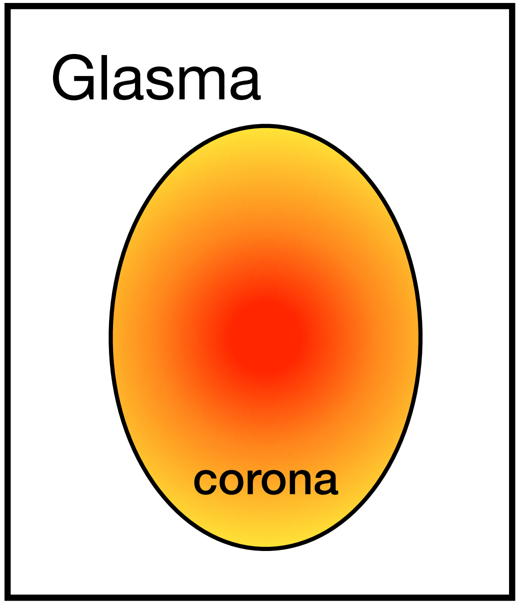
High density gluon described by chromo-electric and -magnetic fields with saturation scale (Q_s)

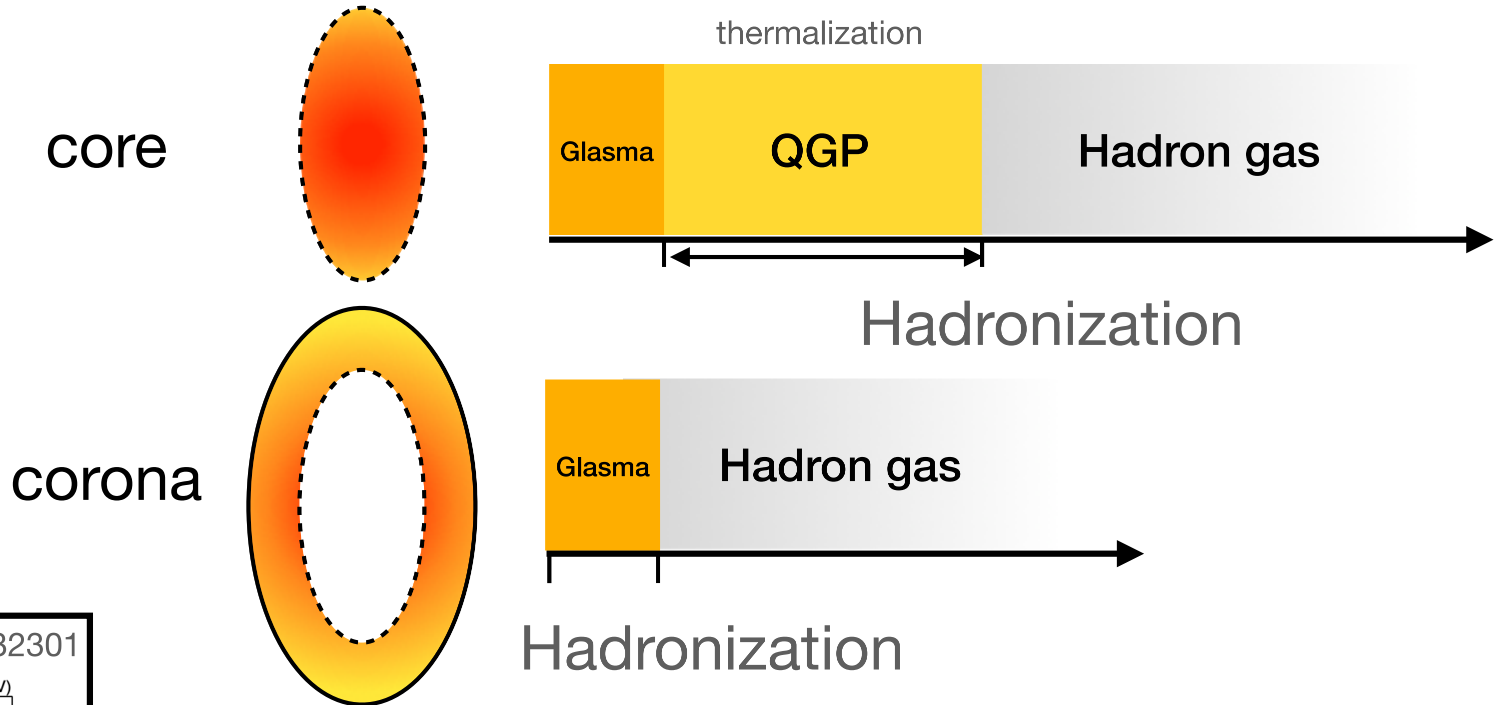


-> Longitudinal chromo-electric and chromo-magnetic fields between the color source of two colliding nuclei

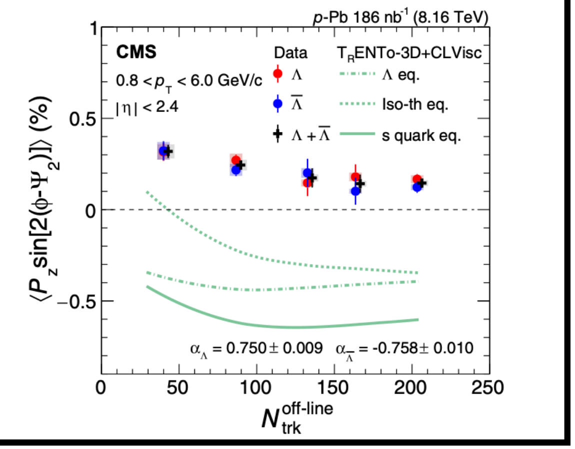
non-equilibrium

Corona effect





Phys.Rev.Lett. 135 (2025) 13, 132301



-> **Glasma in corona** is more important in small collision system

-> How the Glasma from corona can influence the initial local polarization of strange quarks

Polarization from QKT

$$V^\mu(p,x) = V^{s\mu}(p,x)I$$
$$A^\mu(p,x) = A^{s\mu}(p,x)I$$

$$P^\mu(\mathbf{p}) = \frac{\mathrm{tr}_c[\int d\Sigma \cdot pA^\mu(\mathbf{p},x)]}{2M_\Lambda \mathrm{tr}_c[\int d\Sigma \cdot V(\mathbf{p},x)]} \propto A^{s\mu}$$

Assuming the perfect transition of the polarization from quarks to hadrons, (s-equilibrium scenario)

$$V^{s\mu}(\mathbf{p},x) = \left(\frac{p^\mu}{2p_0} f_V^{\mathrm{s}}(p,x)\right)_{p_0=\epsilon_{\mathbf{p}}}$$

$$A^{s\mu}(\mathbf{p},\mathbf{x}) = \frac{1}{2\epsilon_{\mathbf{p}}}\left[-\frac{\hbar g}{4N_c}\tilde{F}^{a\mu\nu}(x)\partial_{p\nu} f_V^a(p,x)\right]_{p_0=\epsilon_{\mathbf{p}}}$$
$$+\frac{\hbar g}{8N_c}\tilde{F}^{a\mu\nu}(x)\partial_{p_\perp \nu}\left(f_V^a(p,x)/\epsilon_{\mathbf{p}}\right)_{p_0=\epsilon_{\mathbf{p}}},$$

$$f_V = f_V^s I + f_V^a t^a$$

f_V^s and f_V^a are color-singlet and color-octet quark distributions

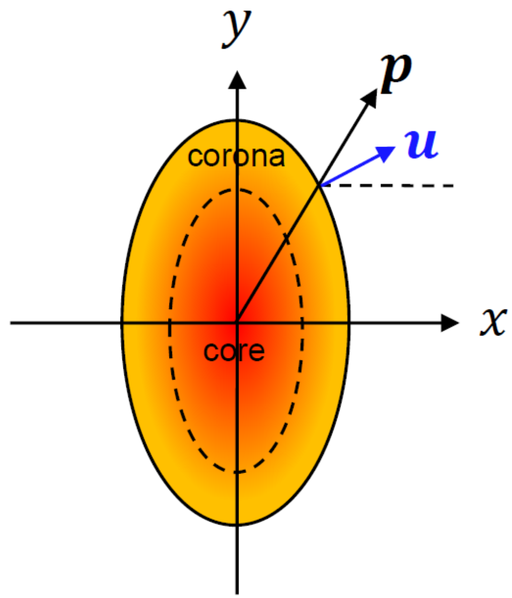
For weak coupling, $f_V^a(p,x)$ can be solved from the collisionless color-octet Vlasov equation perturbatively.

$$f_V^a(p,x) = -\frac{g}{p_0}\int_{t_i}^{x_0} dx_0' p^\mu F^a_{\nu\mu}(x')\partial_p^\nu f_V^{\mathrm{s}}(p,x')\Big|_{\mathrm{c}},$$

$$\boxed{\Lambda_c \to Q_s\,(Glasma), \quad \Lambda_c \to T\,(QGP)}$$

$$\boxed{\Rightarrow A^{s\mu}(\mathbf{p},\mathbf{x}) \approx \frac{\hbar g^2 \Delta t}{8\epsilon_{\mathbf{p}} N_c}\langle \tilde{F}^{a\mu\nu}(x) F^{a\alpha\beta}(x)\rangle u_\alpha\left(\frac{u_0 p_\nu p_\beta}{\epsilon_{\mathbf{p}}^2}\partial^2_{p\cdot u} + \frac{1}{\epsilon_{\mathbf{p}}}\left(\frac{p_{(\nu}\bar{n}_{\beta)}}{\epsilon_{\mathbf{p}}} - 2\frac{p_\nu p_\beta}{\epsilon_{\mathbf{p}}^2}\right)\partial_{p\cdot u}\right) f_V^{\mathrm{s}}\left(\frac{p\cdot u}{\Lambda_c}\right)_{p_0=\epsilon_{\mathbf{p}}}}$$

Polarization from QKT



$$P^{\mu}(\mathbf{p}) = \frac{\epsilon_{\mathbf{p}} \mathrm{tr}_c[\int d\Sigma \cdot p A^{s\mu}(\mathbf{p}, x)]}{M_{\Lambda} \mathrm{tr}_c[\int d\Sigma \cdot p f_V^s(\mathbf{p}, x)} \propto A^{s\mu}$$

Only parity-even correlators:
$\langle E^i(x) E^j(x) \rangle = \delta^{ij} \langle E^i(x) E^i(x) \rangle, \quad \langle B^i(x) B^j(x) \rangle = \delta^{ij} \langle B^i(x) B^i(x) \rangle, \quad \langle E^i(x) B^j(x) \rangle = 0.$

$$A^{sz}(\mathbf{p}, \mathbf{x}) \approx \frac{\hbar g^2 \Delta t}{8 \epsilon_{\mathbf{p}}^2 N_c} \left(\langle B_z^a(x) B_z^a(x) \rangle + \langle E_{\mathrm{T}}^a(x) E_{\mathrm{T}}^a(x) \rangle \right) \epsilon^{zjk} p^j u^k$$

$$\boxed{\sim (\mathbf{p} \times \mathbf{u})^z}$$

$$\times \left(u^0 \partial_{p \cdot u} - \epsilon_{\mathbf{p}}^{-1} \right) \partial_{p \cdot u} f_V^s \left(\frac{p \cdot u}{\Lambda_c} \right) \Bigg|_{p_0 = \epsilon_{\mathbf{p}}}$$

Chromo-Lorentz force:

$$\mathbf{F}^a = g(\mathbf{E}^a + \mathbf{u} \times \mathbf{B}^a)$$

Color-octet polarization pseodu-vector:

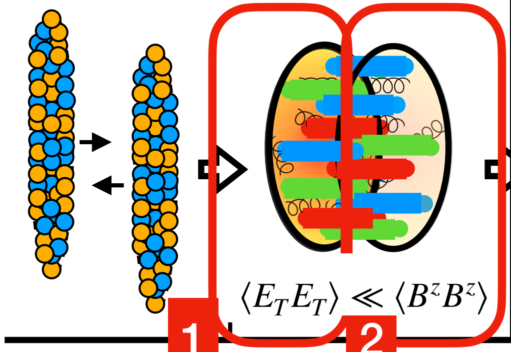
$$\mathbf{P}^a = g(\mathbf{B}^a - \mathbf{u} \times \mathbf{E}^a)$$

Color singlet spin observable

$$\boxed{\mathbf{A}^s \propto \langle (\mathbf{p} \cdot \mathbf{F}^a) \mathbf{P}^a \rangle \sim (\mathbf{p} \times \mathbf{u}) (\langle \mathbf{B}^a \mathbf{B}^a \rangle + \langle \mathbf{E}^a \mathbf{E}^a \rangle)}$$

parity-even

LSP in Glasma



GBW dipole distribution:

$$\langle B^z B^z \rangle \simeq \frac{1}{g^2}\frac{(N_c^2-1)}{2N_c}Q_s^4$$

K. J. Golec-Biernat, M. Wusthoff, Phys. Rev. D 59, 014017 (1998), **Pablo Guerrero-Rodr´ıguez et al.**, Phys. Rev. D 104, 014011 (2021)

1. Non-equilibrium: Schwinger Pair production $\Gamma \sim e^{-\pi m^2/|eE|}$

Julian S, et al., Phys. Rev. 82, 664 (1951).

$$f_V^s(p\cdot u/Q_s) = e^{-\pi (p\cdot u)^2/|gE^a|}$$

where $|gE^a| = \sqrt{(N_c^2-1)(2N_c)}Q_s^2$

2. Quasi-equilibrium:

$$f_V^s(p\cdot u/Q_s) = \frac{1}{e^{p\cdot u/Q_s}+c}$$

polarization vanish for isotropic flow $\delta = 0$

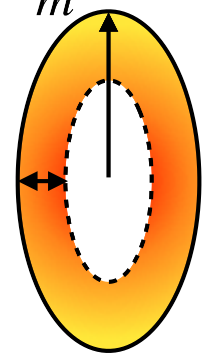
$$x = r\sqrt{1-\epsilon}\cos\Phi, \qquad y = r\sqrt{1+\epsilon}\sin\Phi$$

$$p^\mu = (\epsilon_T \cosh y_p, p_T\cos\phi, p_T\sin\phi, \epsilon_T\sinh y_p)$$

$$u^\mu = \frac{1}{N_v}\left(1, u_T(1+\delta)\frac{x\tau}{r_m^2}, u_T(1-\delta)\frac{y\tau}{r_m^2}, 0\right)$$

r_m corona

$$\tilde{\tau}_f = \sqrt{\tau^2 - x^2 - y^2} = \sqrt{t^2 - r^2}$$

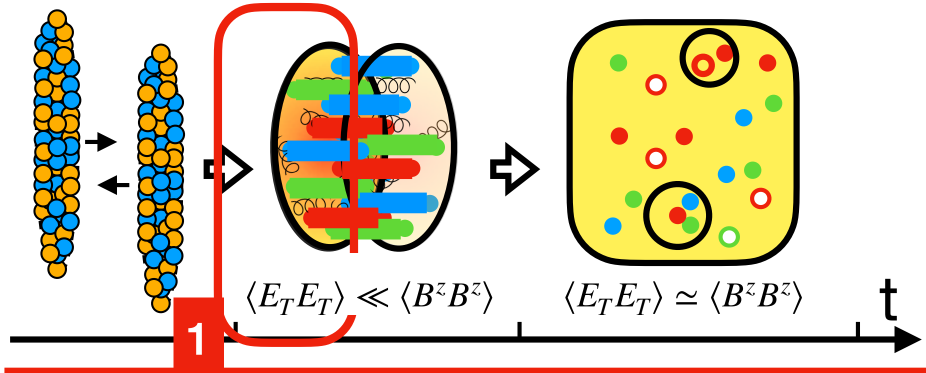


$$r_m - \Delta t \le r \le r_m$$

	Glasma (Non-eq)	Glasma (Quasi-eq)
ϵ	0	
δ	0.3	
$\tilde{\tau}_f$	0	
r_m	0.5 fm	
Λ_c	$Q_s = 1.5$ or 2 GeV	
u_T	0.01	0.2

- anisotropy of transverse plane (ϵ)
- anisotropy of flow (δ)
- proper time $(\tilde{\tau}_f)$
- maximum radius (r_m)

LSP in Glasma



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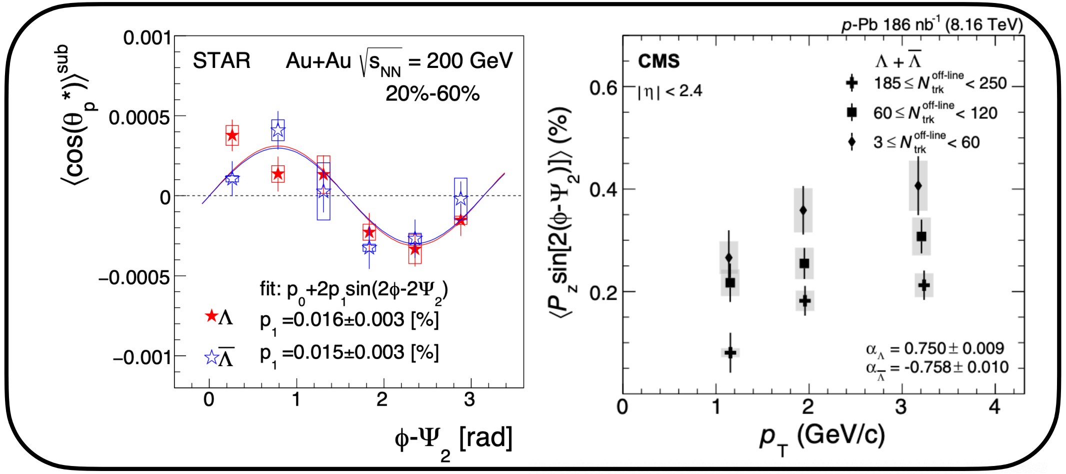
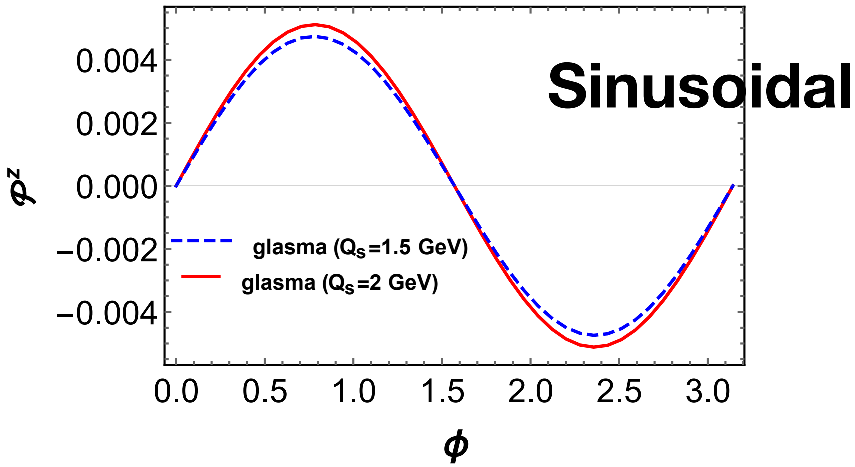
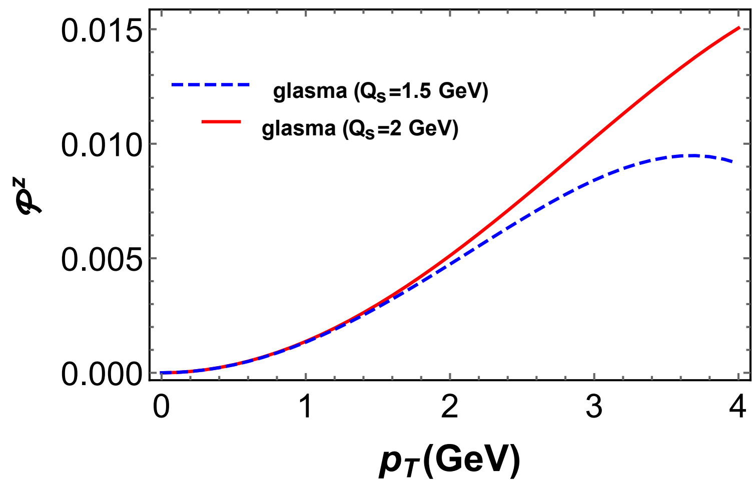
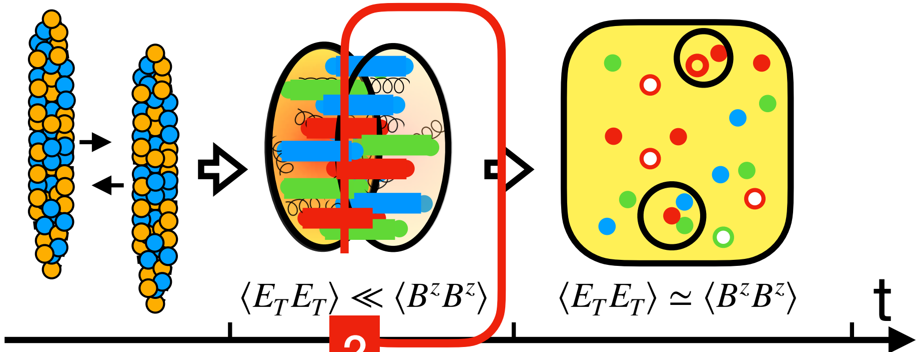






LSP in Glasma



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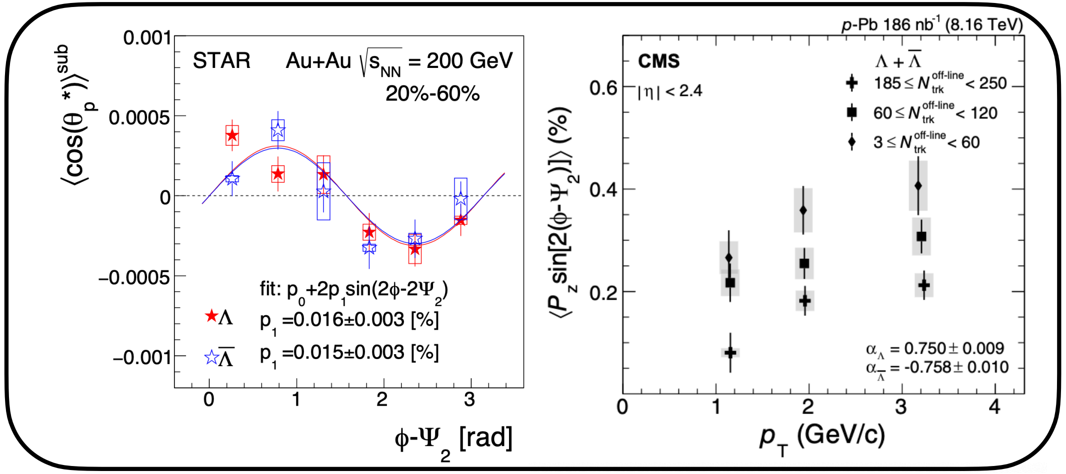
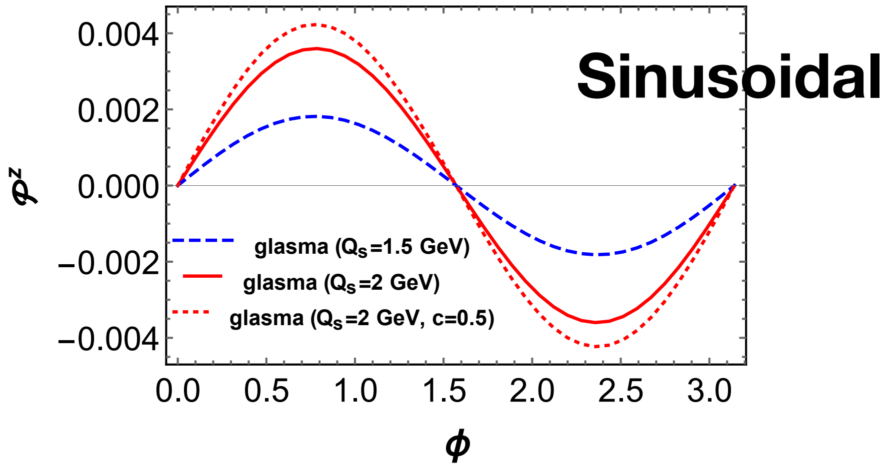
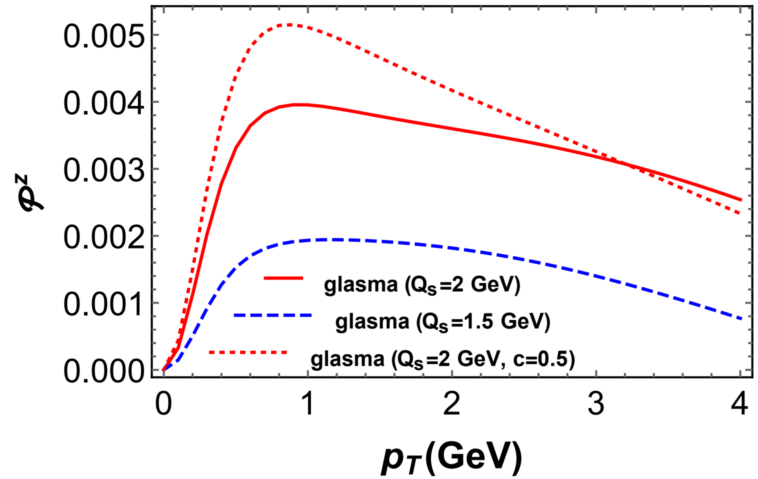
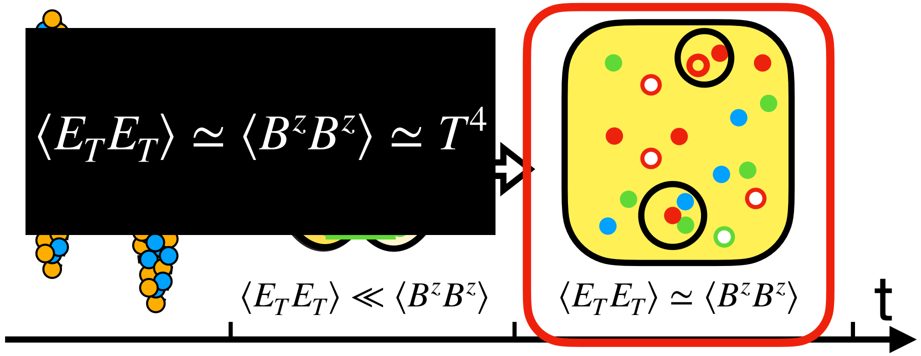
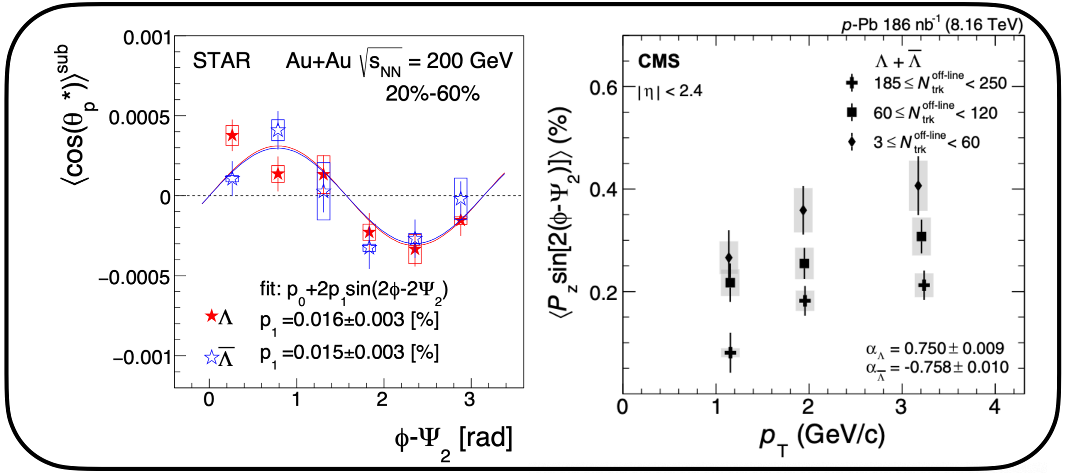




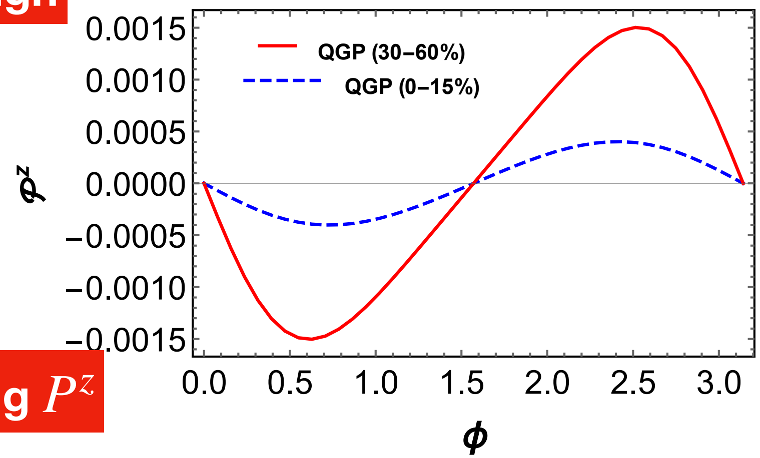


LSP in QGP





Opposite sign



3. QGP: $\quad {}^*Q_s \to T$

$$f_V^s(p\cdot u/T) = \frac{1}{e^{p\cdot u/T}+1}$$

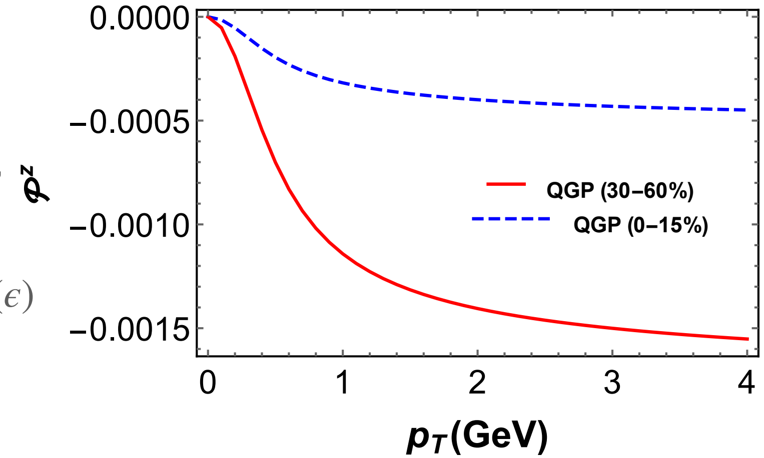
Decreasing P^z

Au+Au at $\sqrt{s_{NN}} = 130$ GeV

	QGP (30-60%)	QGP (0-15%)
ϵ	0.14	0.06
δ	0.37	0.12
$\tilde{\tau}_f$	4.3 fm	7.7 fm
r_m	3.8 fm	6.5 fm
Λ_c	$T = T_f = 165$ MeV	

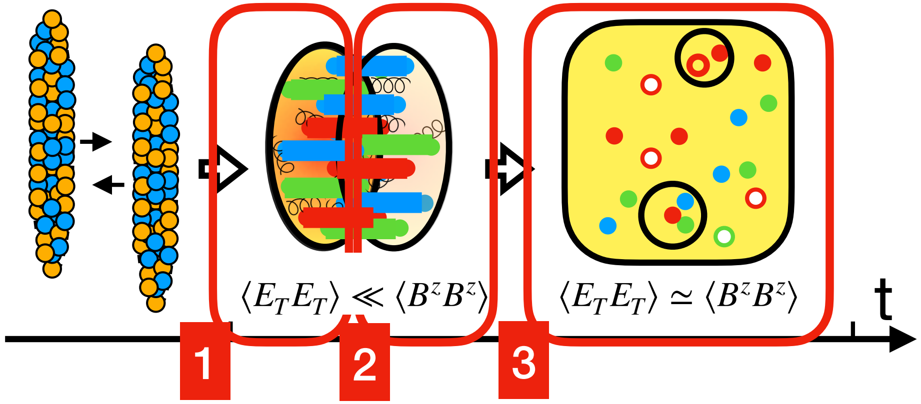
***Thermal model**
Avdhesh Kumar et al., Phys. Rev. D 109, 054038 (2024), **Wojciech F, et al.**, Phys. Rev. C100, 054907 (2019)

- anisotropy of transverse plane (ϵ)
- anisotropy of flow (δ)
- proper time $(\tilde{\tau}_f)$
- maximum radius (r_m)



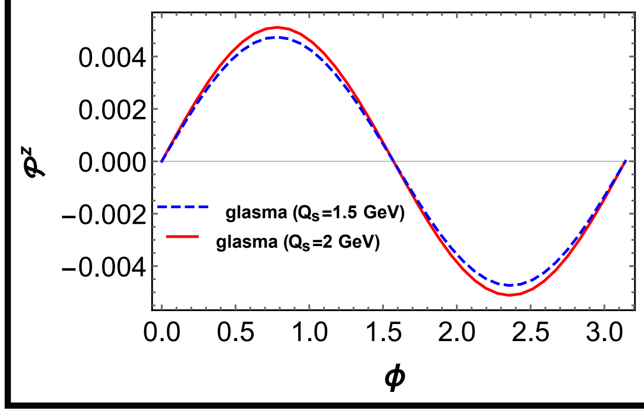
LSP in Glasma and QGP

Haesom Sung, Berndt Müller, Di-Lun Yang, r arXiv:2507.23210v2

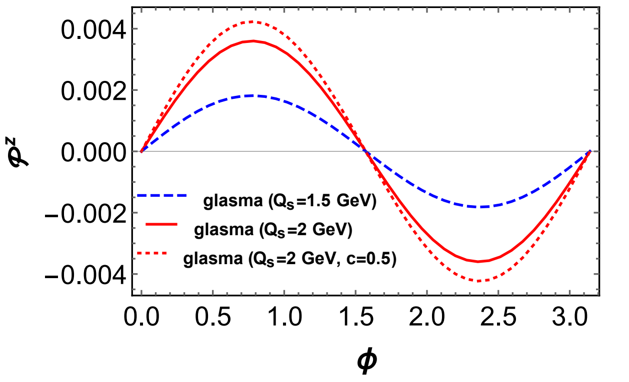


$$P^z = \frac{N_{GL} P^z_{GL} + N_{QGP} P^z_{QGP}}{N_{GL} + N_{QGP}}$$

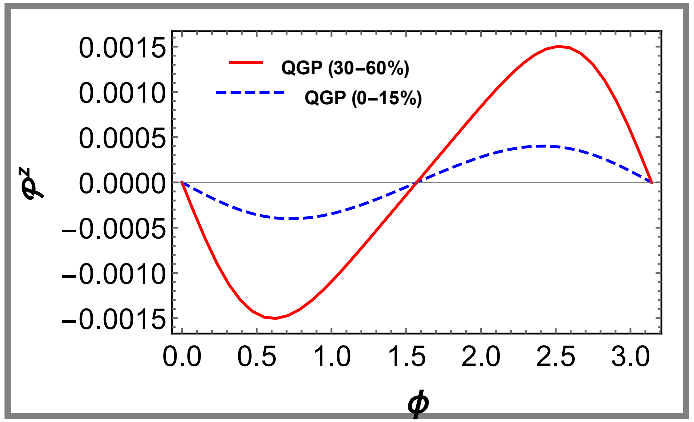
1. Glasma(non-eq)



2. Glasma(quasi-eq)



3. QGP



In **small system**, $N_{GL} \gg N_{QGP}$, so we can expect the **Sinusoidal** Polarization in azimuthal angle

+Hydrodynamic contribution (vorticity+shear)

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

Baochi Fu et al., *Phys.Rev.Lett.* 127 (2021) 14, 142301

Summary

- **In small collision systems**, initial non-equilibrium glasma (corona) generates the observed longitudinal Λ polarization with $\sin 2\phi$ pattern and an increasing tendency with p_T, which indicate that **the coherent gluons may play a significant role for local polarization.**

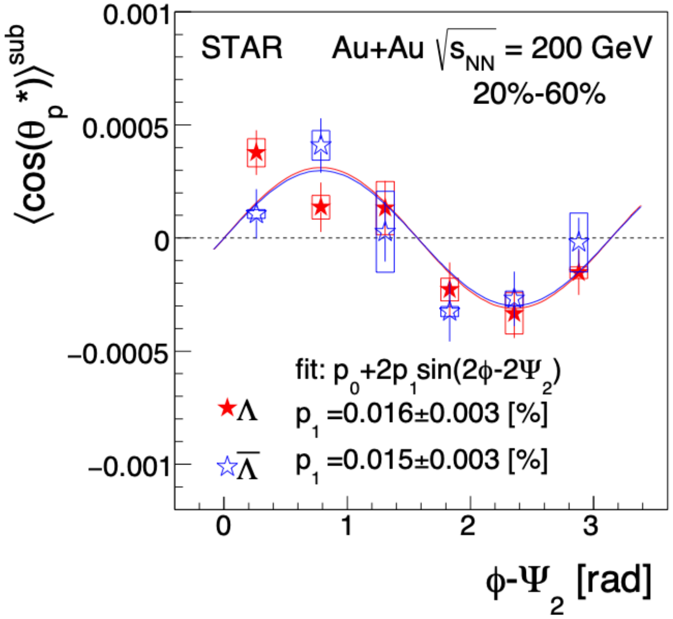
- To reproduce experimental data, it is essential to develop sophisticated simulations of the core and corona from the glasma to QGP.

Y. Kanakubo, Y. Tachibana, and T. Hirano, Interplay between core and corona components in high-energy nuclear collisions, Phys. Rev. C 105, 024905 (2022), arXiv:2108.07943 [nucl-th].

Reference

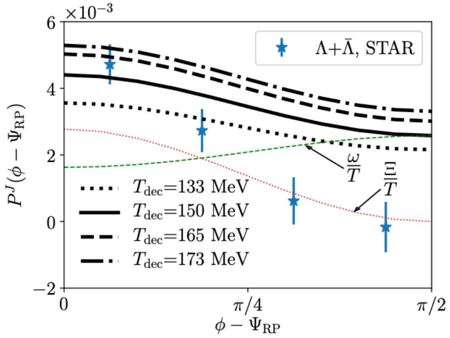
Vorticity and Shear

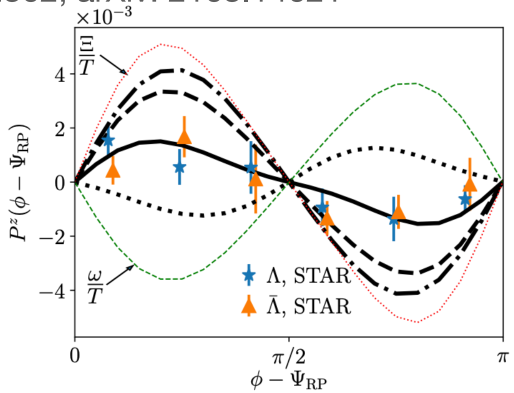
STAR:2019erd: Experimental result



Phys.Rev.Lett. 127 (2021) 27, 272302, arXiv: 2103.14621

Becattini:2021iol





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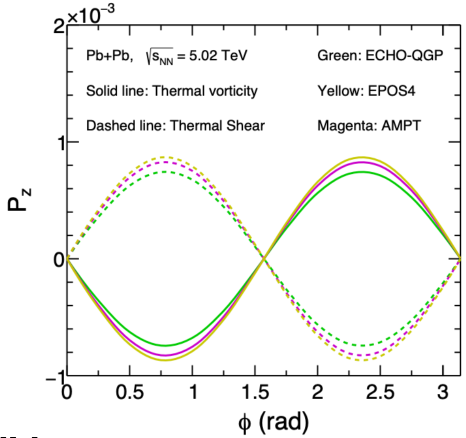
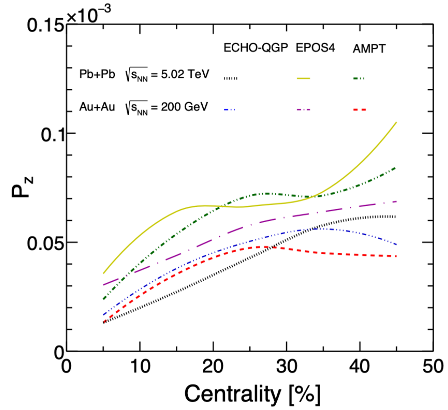
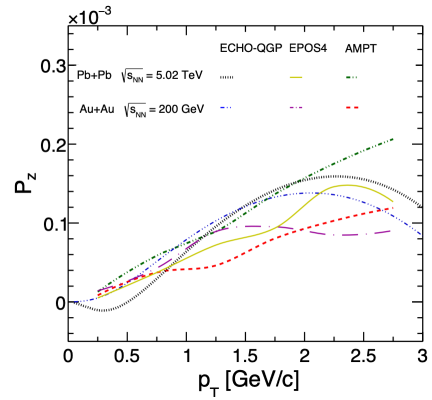
Phys.Scripta 100 (2025) 6, 065310, *Phys.Scripta* 100 (2025) 065310 • e-Print: 2404.15138 [hep-ph]







Florkowski:2021xvy

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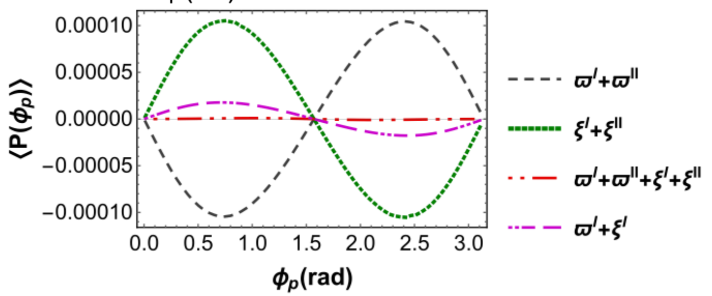
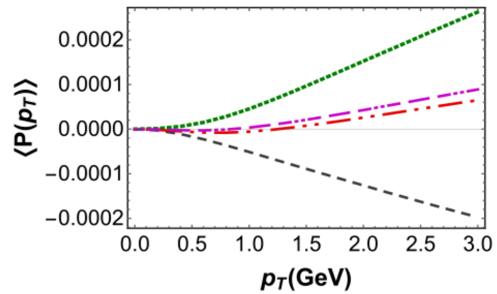
$$\xi_{\mu\nu} = \underbrace{\frac{1}{2T}\left(\partial_\mu u_\nu + \partial_\nu u_\mu\right)}_{\xi^I_{\mu\nu}} \underbrace{-\frac{1}{2T^2}\left(u_\nu \partial_\mu T + u_\mu \partial_\nu T\right)}_{\xi^{II}_{\mu\nu}}.$$



(a)



(b)

Vorticity and Shear

STAR:2019erd: Experimental result

Cong Yi, et al., *Phys.Rev.C* 111 (2025) 4, 044901, arXiv 2408.04296 [hep-ph]

- Spin polarization of Λ hyperons along beam direction in p+Pb collisions at $\sqrt{s_{NN}}$ =8.16 TeV using hydrodynamic approaches (Theoretical prediction) (a) Λ equilibrium, (b) s quark equilibrium, and (c) iso-thermal equilibrium: