PacificSPIN 2026
The 13th Circum-Pan-Pacific Symposium on High Energy Spin Physics

Local Spin Polarization by color-field correlators and momentum anisotropy

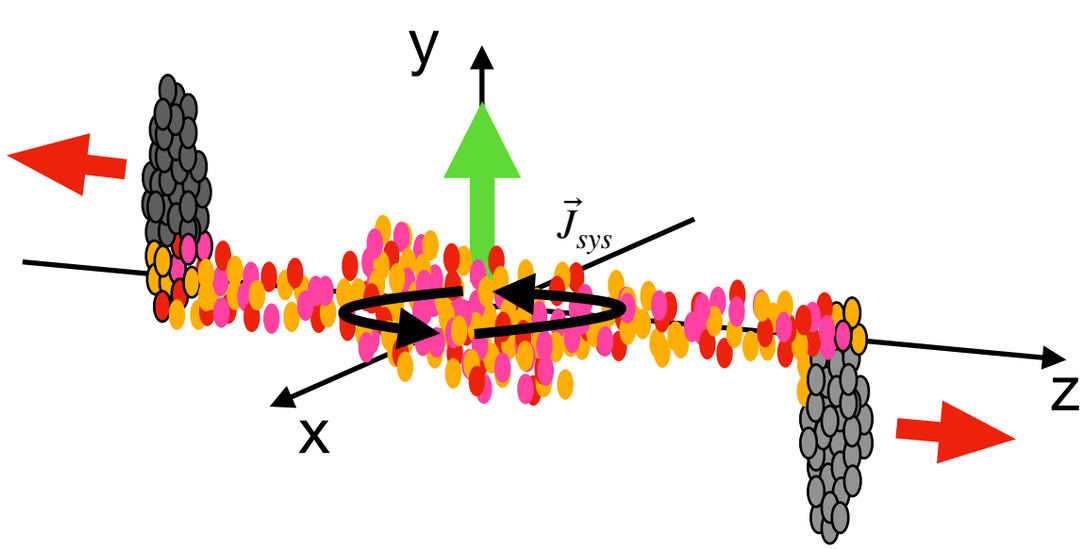
Haesom Sung
Berndt Müller, and Di-Lun Yang

Haesom Sung, Berndt Müller, Di-Lun Yang, arXiv:2507.23210v3

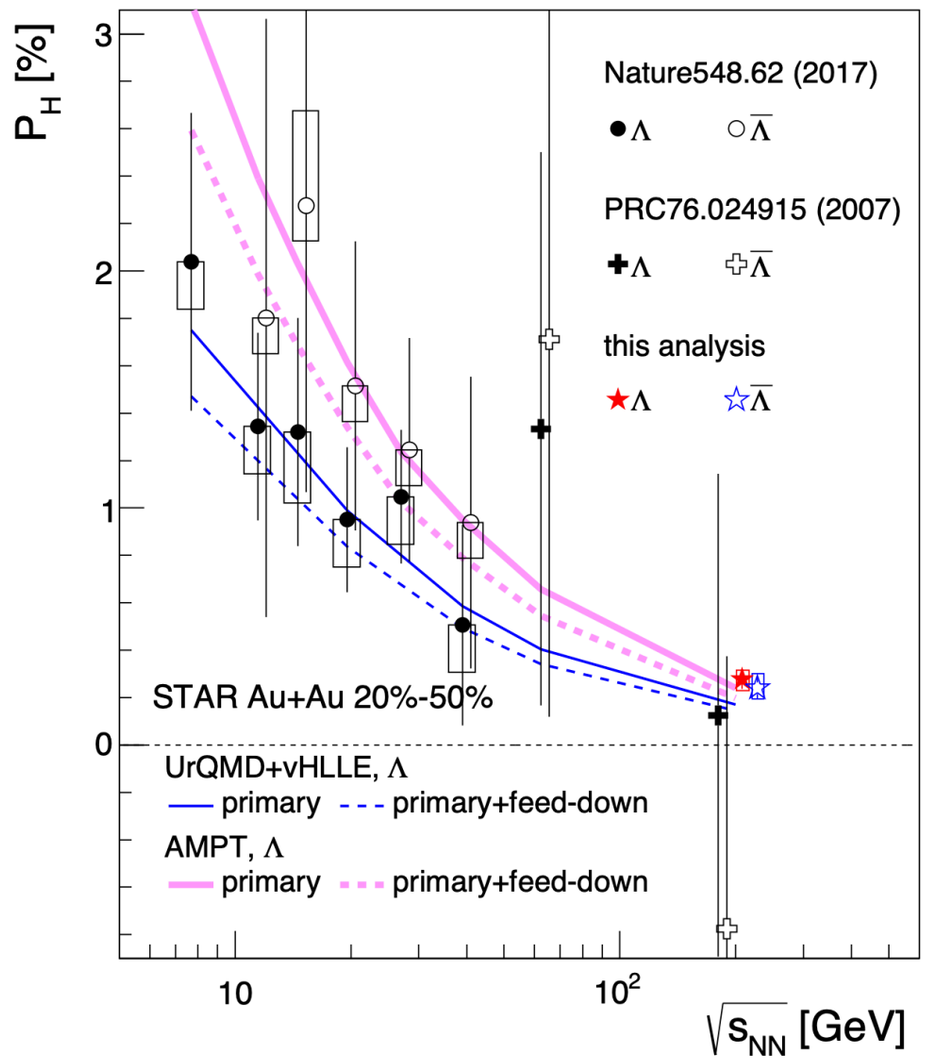
2026.10.29

Motivation

Λ Global Polarization



L. Adamczyk et al. (STAR), Nature 548, 62 (2017)
J. Adam et al. (STAR), Phys. Rev. C 98, 014910(2018)]
S. Acharya et al. (ALICE), Phys. Rev. C 101, 044611 (2020)



UrQMD+vHLLE: **I. Karpenko, et al,** Eur. Phys. J. C 77, 213 (2017)
AMPT: **H. Li, et al,** Phys. Rev. C 96, 054908 (2017)

Cooper-Frye formula

F. Becattini, et al., Ann. Phys. 338, 32 (2013)
R. Fang, et al., PRC 94, 024904 (2016)

$$P^{\mu}_{\varpi} = \epsilon^{\mu\rho\sigma\tau} p_{\tau} \frac{\int_{\Sigma} d\Sigma \cdot p n_F (1 - n_F) \varpi_{\rho\sigma}}{\int_{\Sigma} d\Sigma \cdot p n_F}$$

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

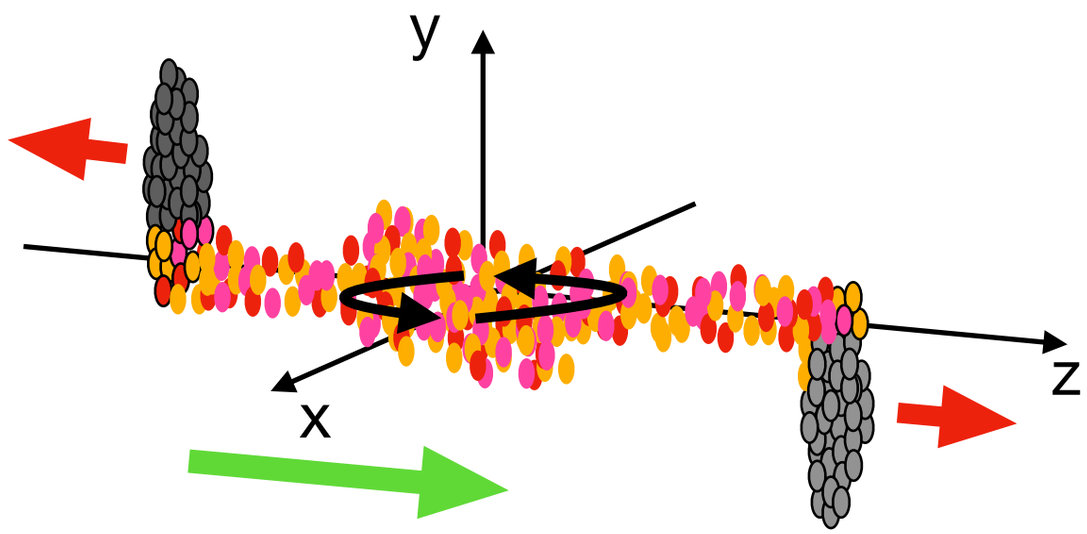
Global polarization from vorticity

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

$$P_{\Lambda} = \int_{p} P^{-y}(p) \simeq \frac{\omega}{2T} \sim 2\,\%$$

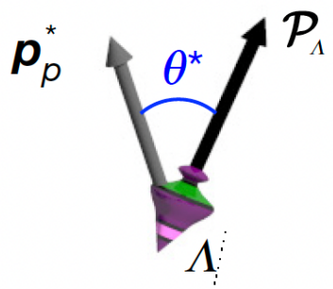
$$\omega \simeq 0.02\,\text{fm}^{-1},$$
$$T \simeq 100\ \text{MeV}$$

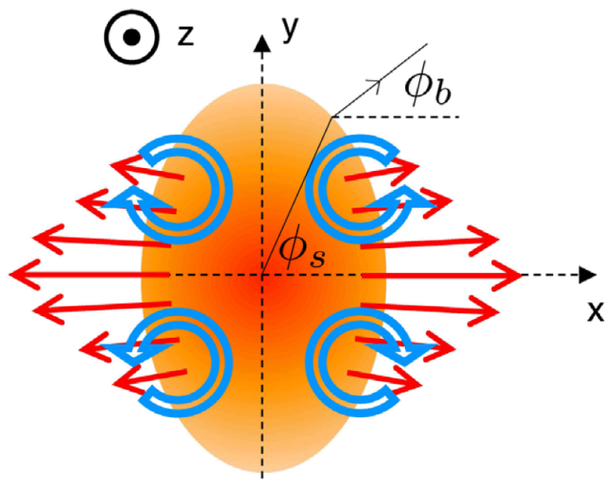
Motivation
Longitudinal Polarization



$$P^z$$

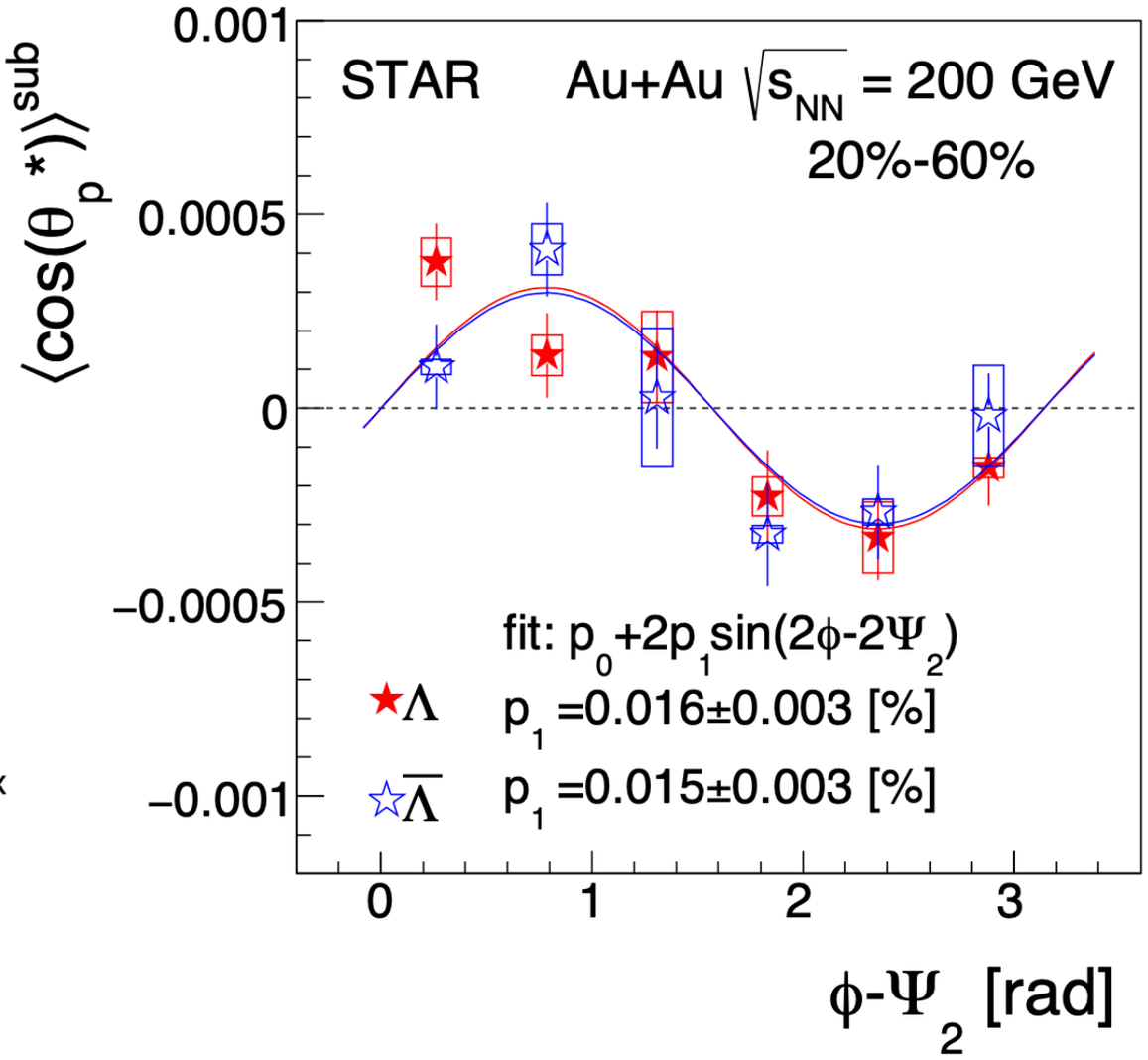
$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle \cos^2\theta_p^* \rangle}$$





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

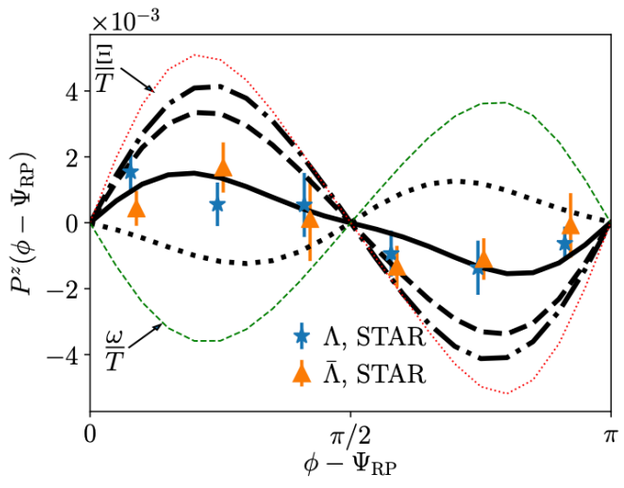
J. Adam et al. (STAR), PRL. 123 (2019) 13, 132301



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)



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

Vorticity and shear effect have **opposite signs**

Thermal vorticity

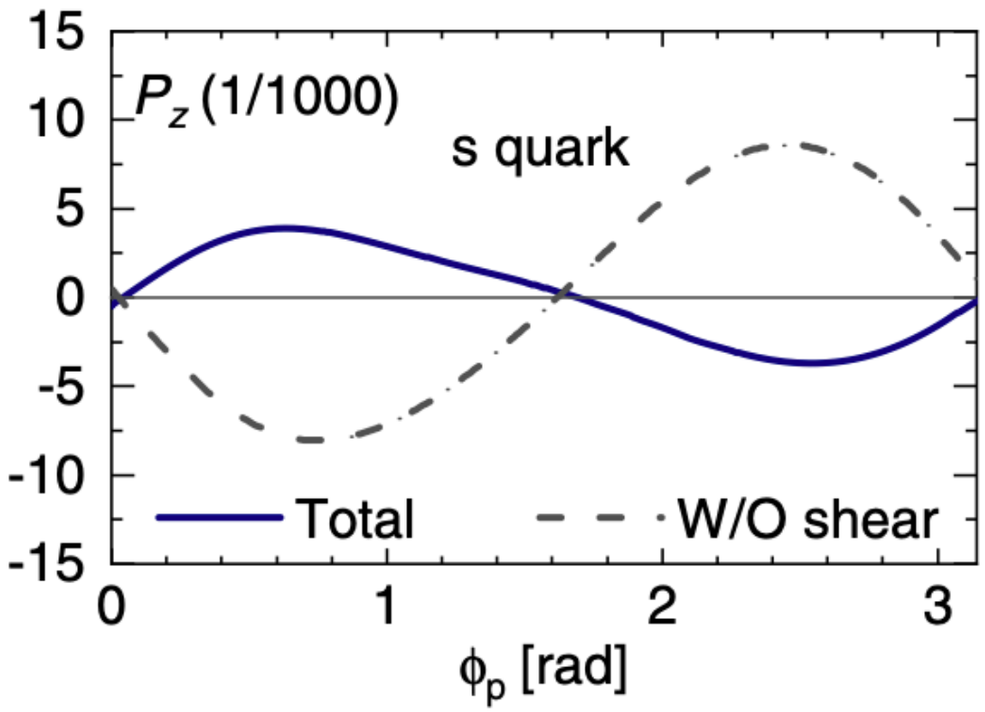
$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$$

Thermal shear

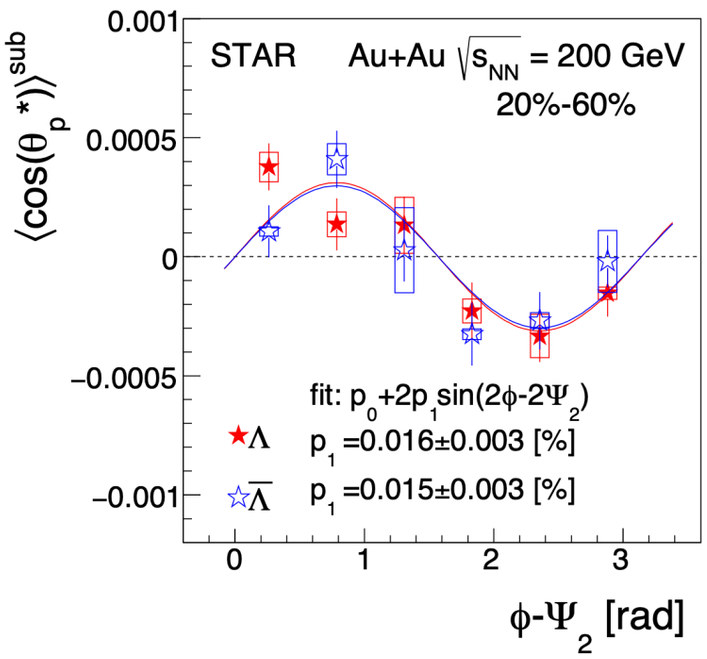
$$(\xi_{\mu\nu} = 0 \quad \text{at global equilibrium})$$

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

Baochi Fu et al., PRL. 127 (2021) 14, 142301
(s-quark equilibrium)



J. Adam et al. (STAR), PRL. 123 (2019) 13, 132301

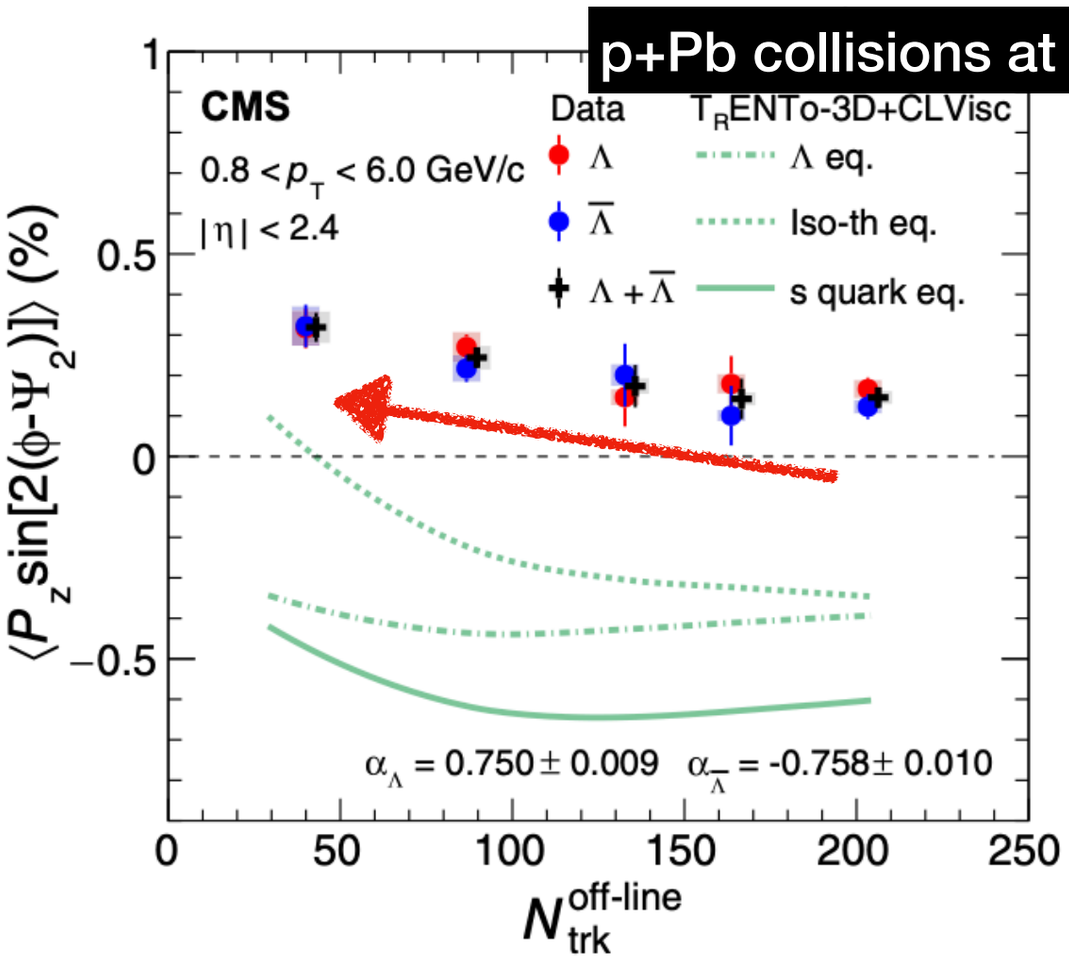


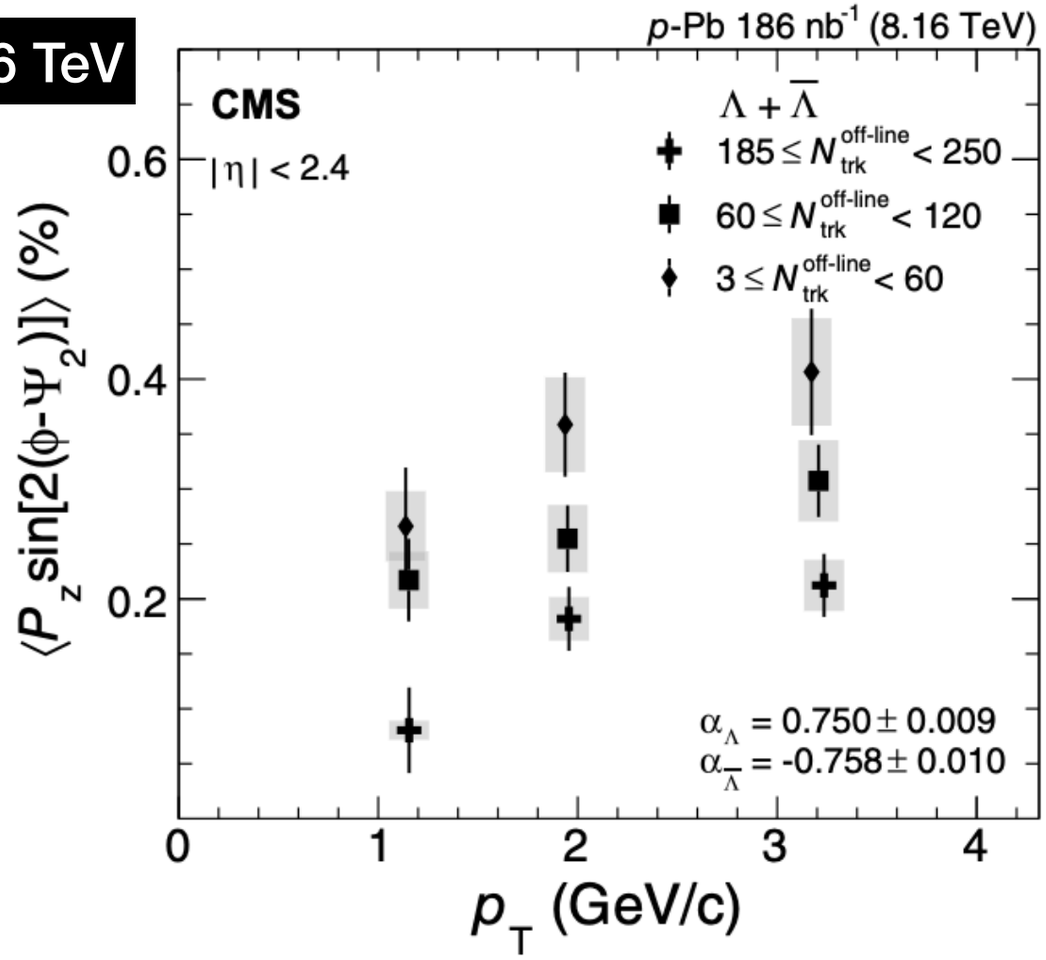
Longitudinal Local Polarization

Multiplicity and p_T dependence

A. Hayrapetyan et al. (CMS), PRL. 135 (2025) 13, 132301
Cong Yi et al., *Phys.Rev.C* 111 (2025) 4, 044901 [Hydro (Vorticity+Shear)]

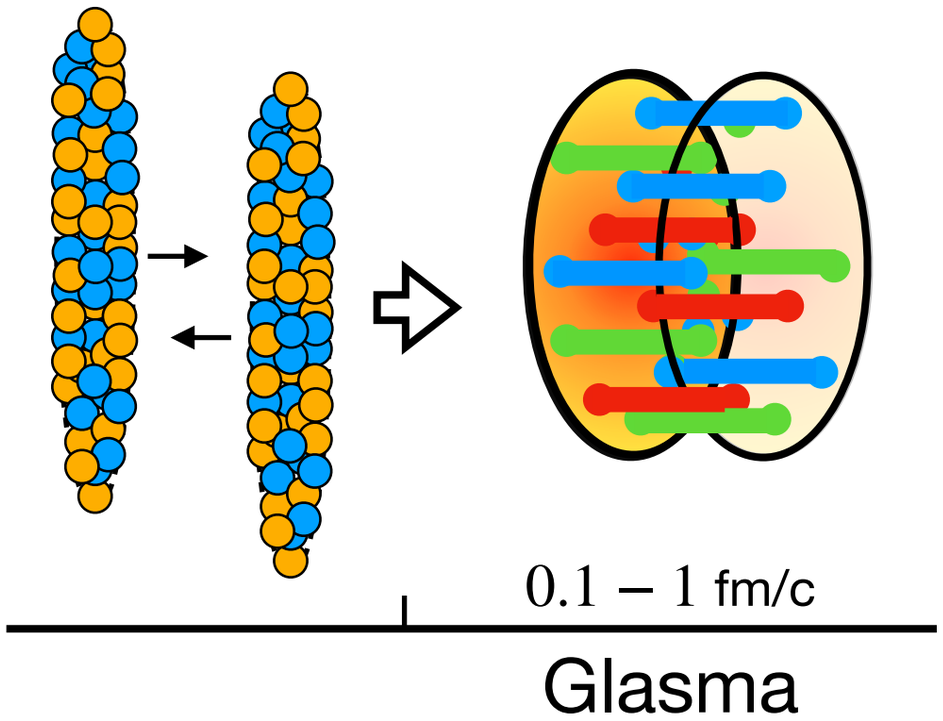
p+Pb collisions at 8.16 TeV



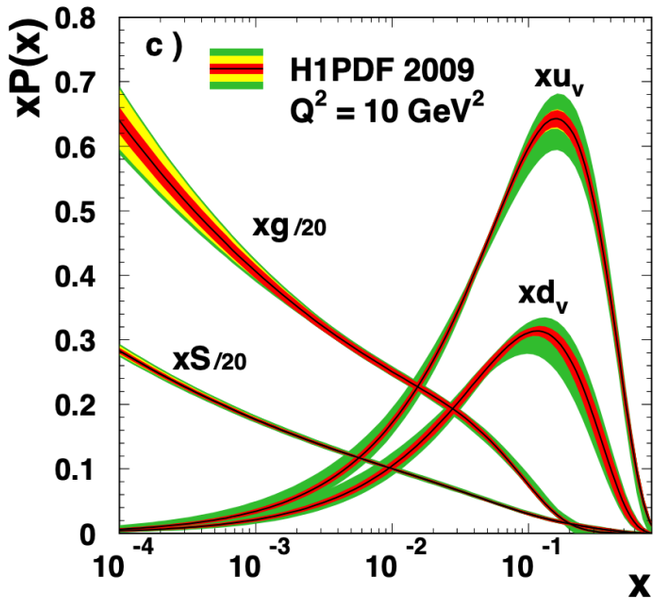


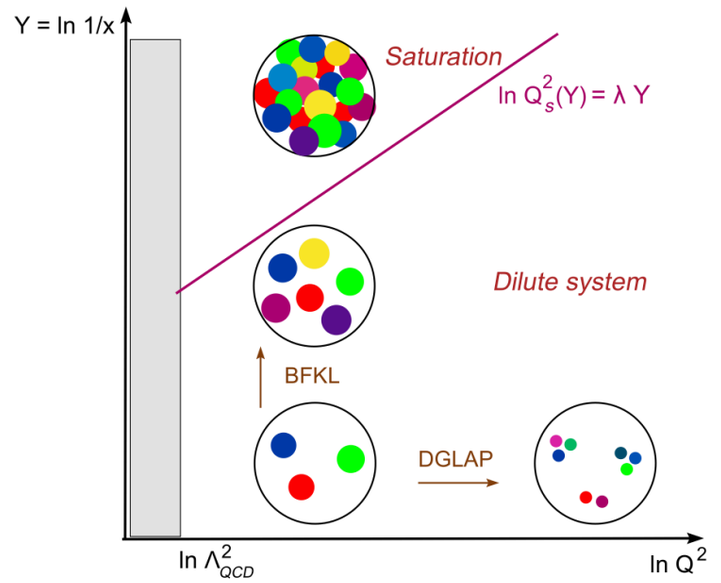
Thermal vorticity and thermal shear effect can not describe this experimental result with multiplicity and p_T dependence

Initial stages of heavy ion collisions

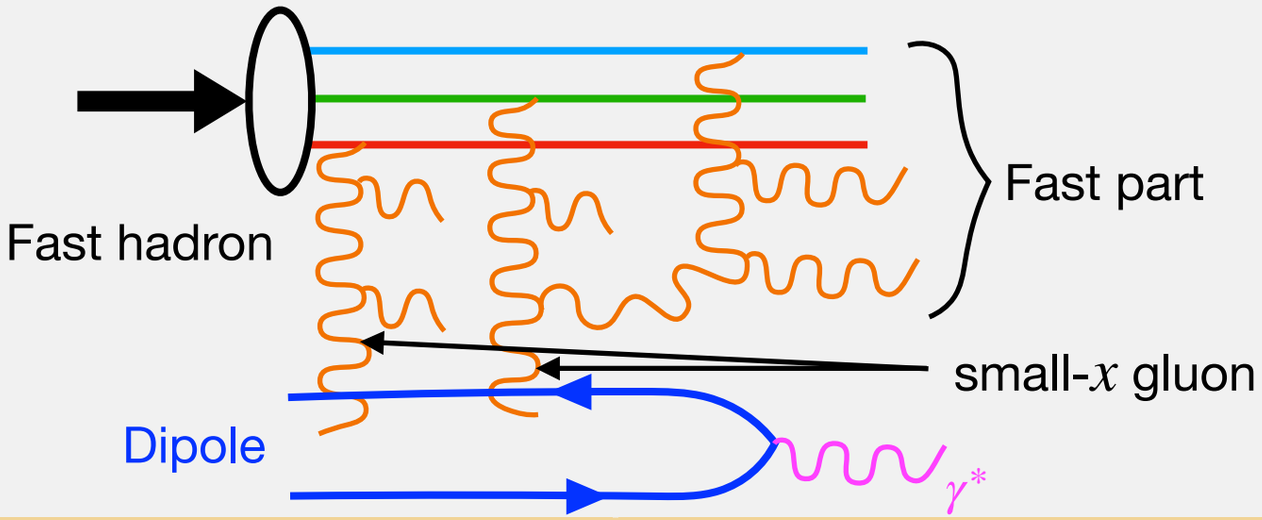


F. Gelis et al., Ann.Rev.Nucl.Part.Sci.60:463-489,2010





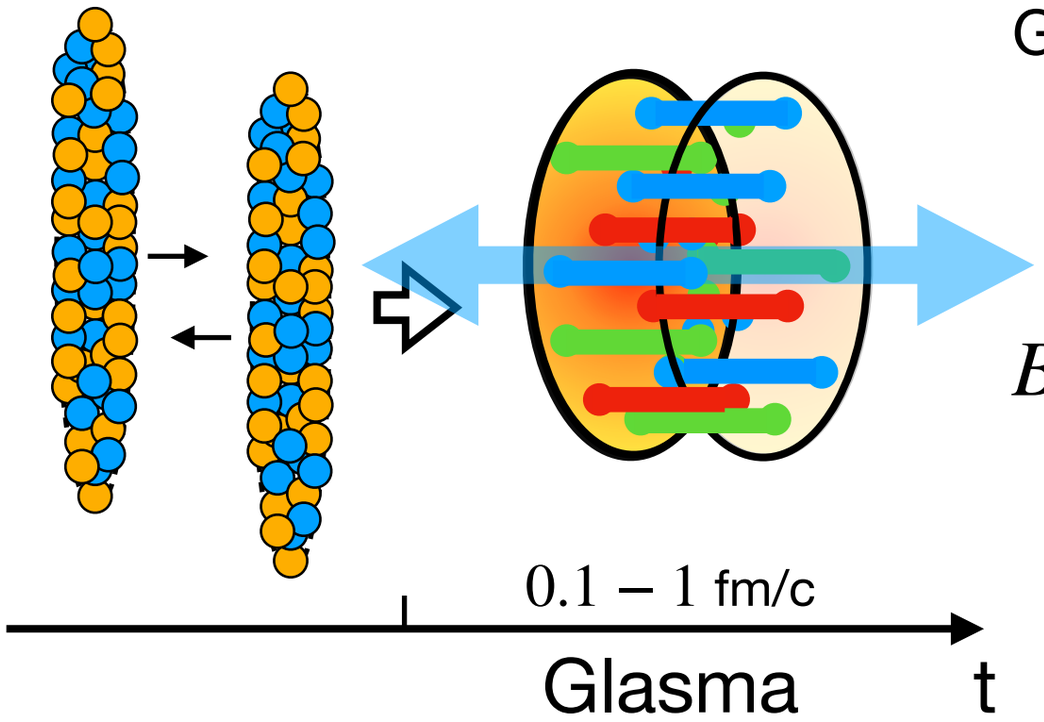
Color Glass Condensate (CGC) : Highly populated soft gluons ($E < Q_S$) sourced by hard hadrons



$$D^\mu F^{(a)}_{\mu\nu} = \delta^{\nu+}\delta(x^-)\rho^a(x_\perp)$$

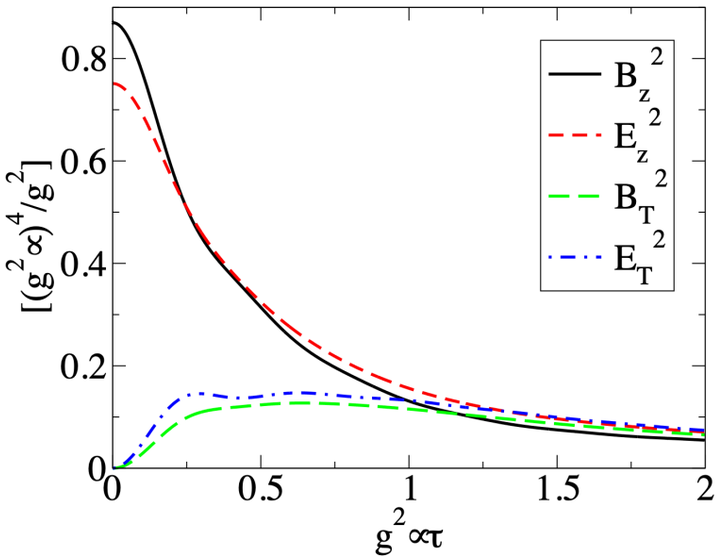
soft gluons — hard partons

Initial stages of heavy ion collisions

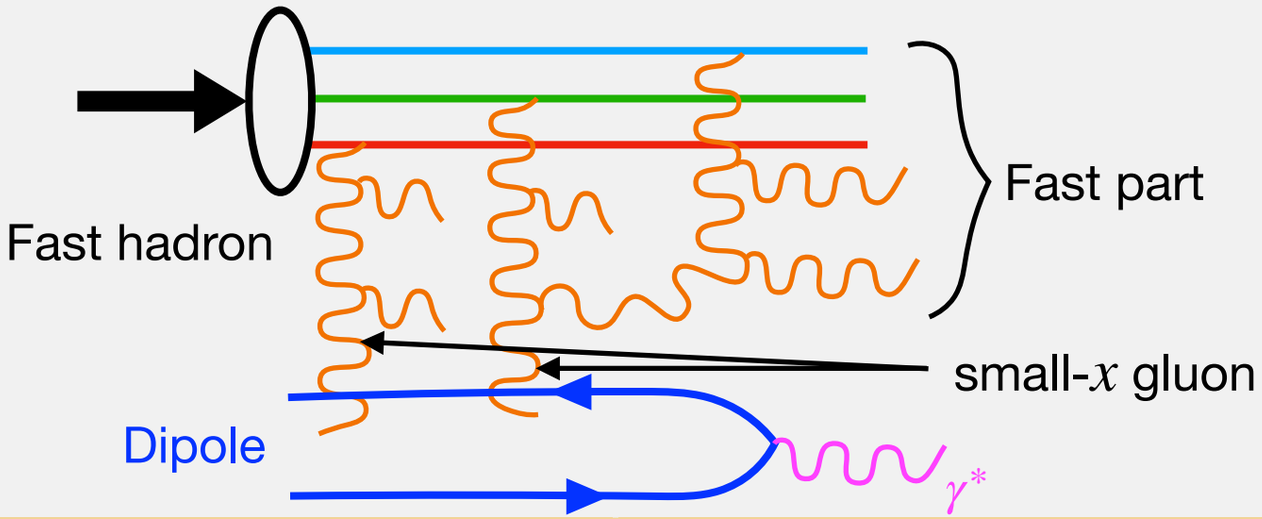


Glasma : color flux tubes

T. Lappi, PLB643(2006)11-16



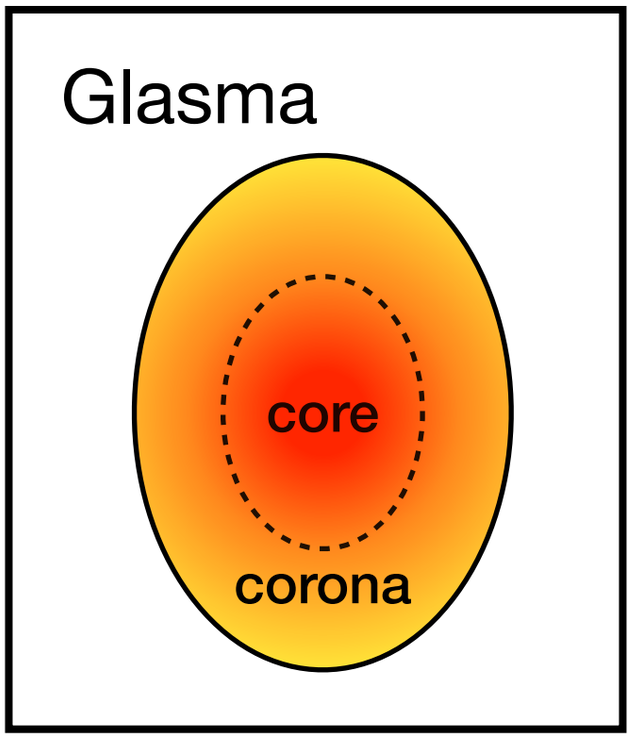
Color Glass Condensate (CGC) : Highly populated soft gluons ($E < Q_S$) sourced by hard hadrons

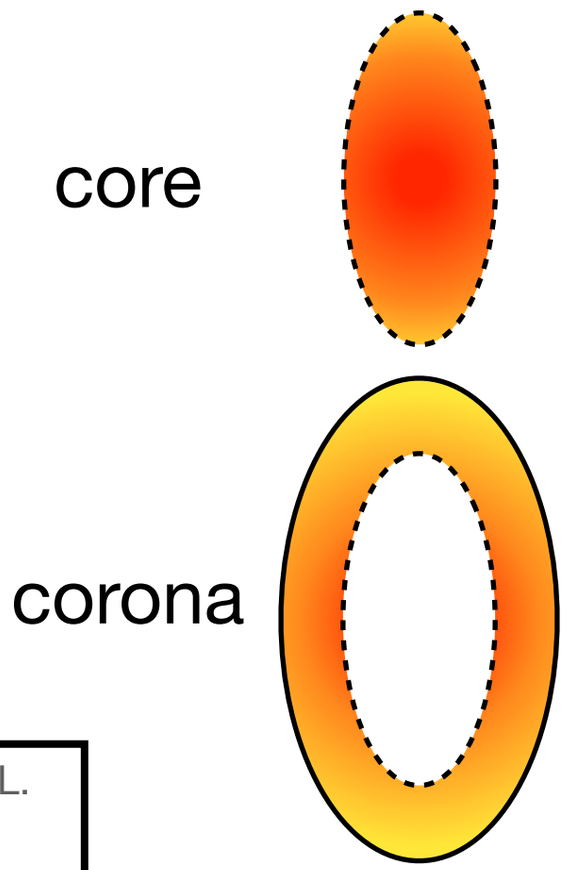


$$D^\mu F^{(a)}_{\mu\nu} = \delta^{\nu+}\delta(x^-)\rho^a(x_\perp)$$

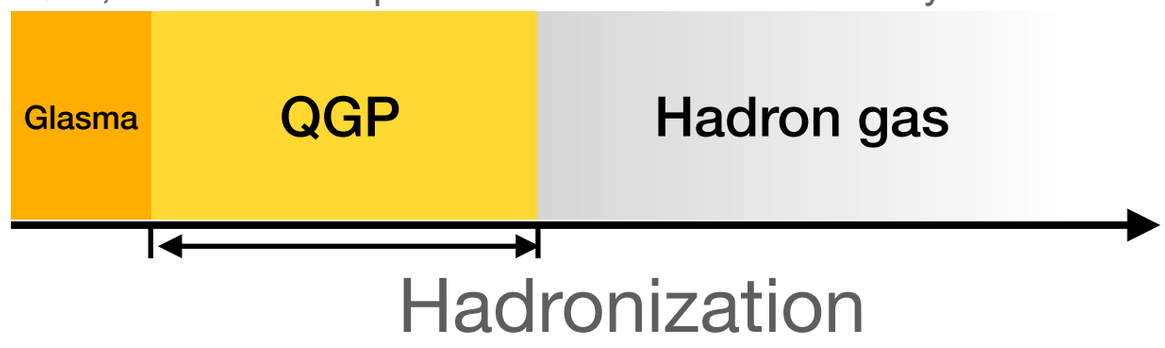
soft gluons — hard partons

Corona effect





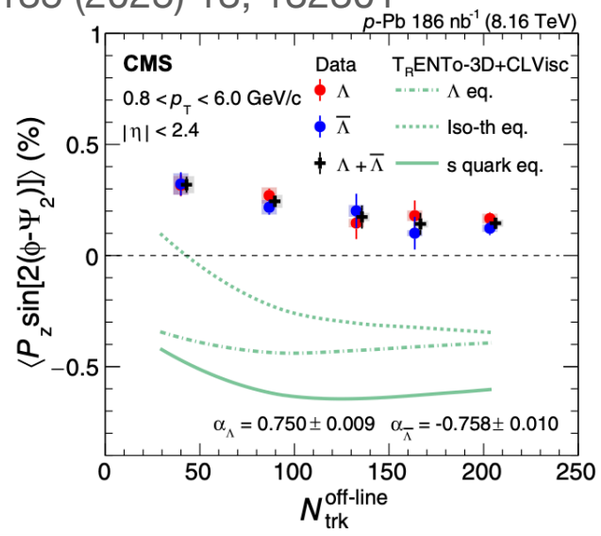
The core region undergoes full **thermalization**, forming the QGP, which then expands and hadronizes as the system cools





The corona region has a lower density and freeze-out earlier. It can hadronize directly **without passing through the QGP phase**

A. Hayrapetyan et al. (CMS) PRL. 135 (2025) 13, 132301



-> In small collisions system, **corona region(Glasma)** is more important

-> How the Glasma from corona can influence the 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)**

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

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

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

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

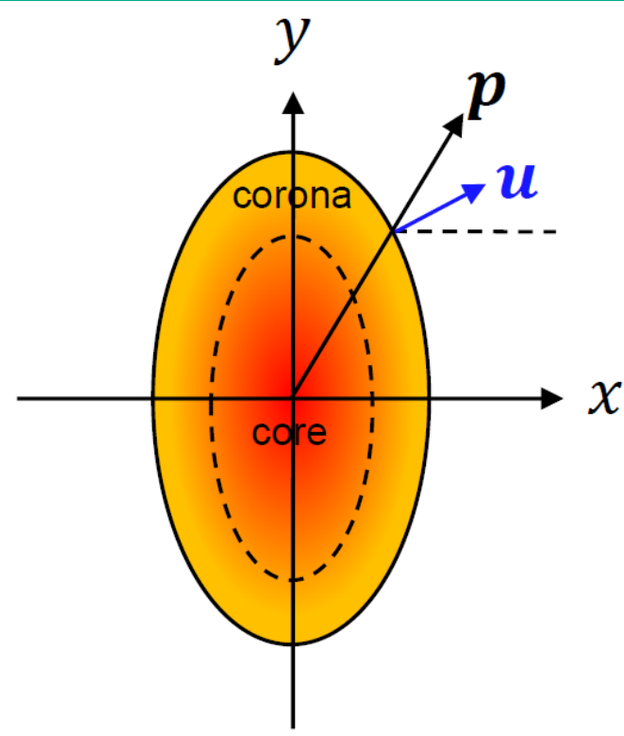
For weak coupling, $f_V^{a}(p,x)$ can be expressed perturbatively in terms of the singlet distribution.

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

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

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

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:

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

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

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

Color-singlet polarization pseudo-vector

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

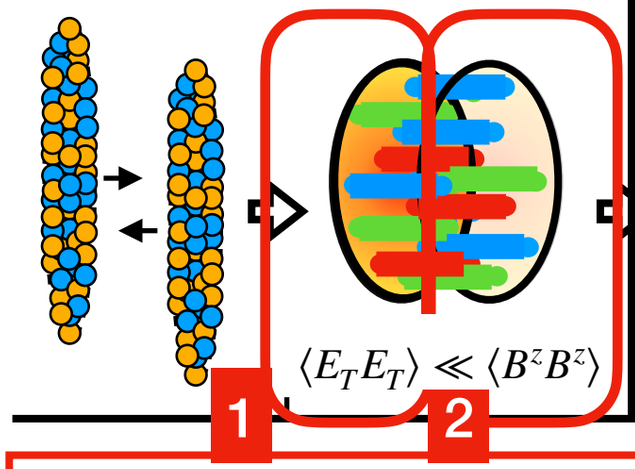
Chromo-Lorentz force:

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

Color-octet polarization pseudo-vector:

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

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-Rodríguez 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 ($\delta = 0$)

corona

r_m

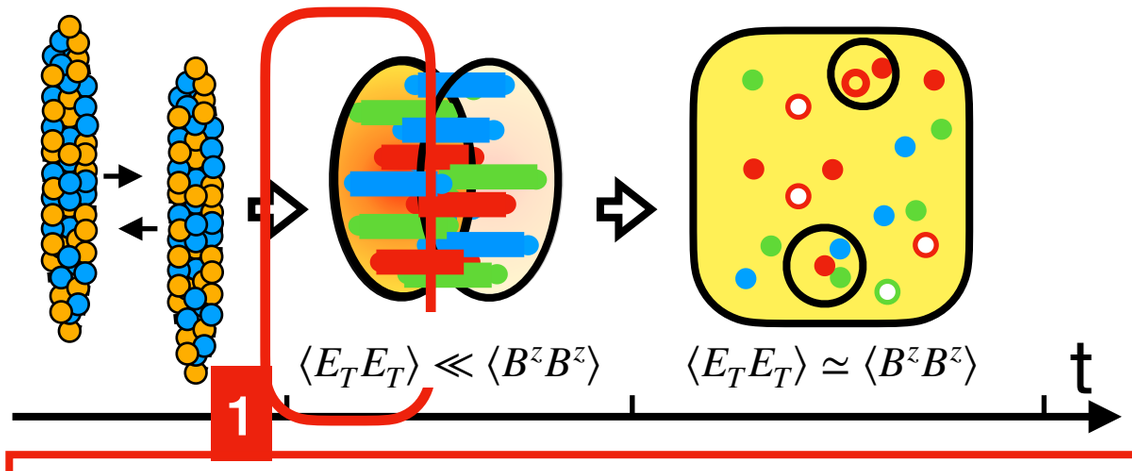
Δt

$$r_m - \Delta t \leq r \leq r_m$$

	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

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

LSP in Glasma



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

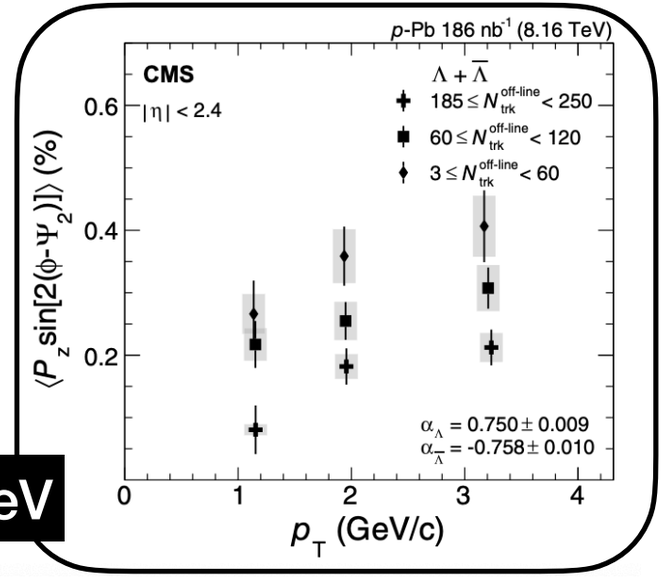
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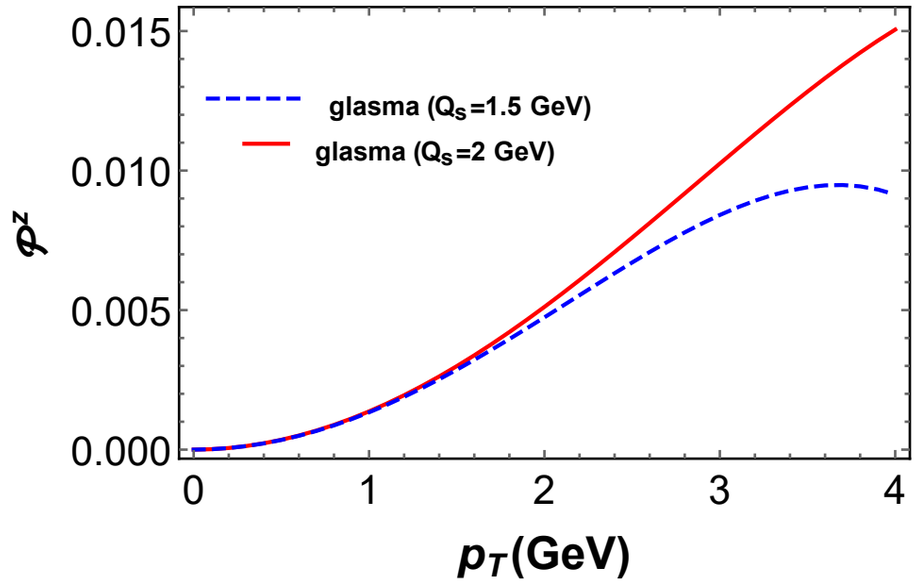
where $|gE^a| = \sqrt{(N_c^2-1)(2N_c)Q_s^2}$

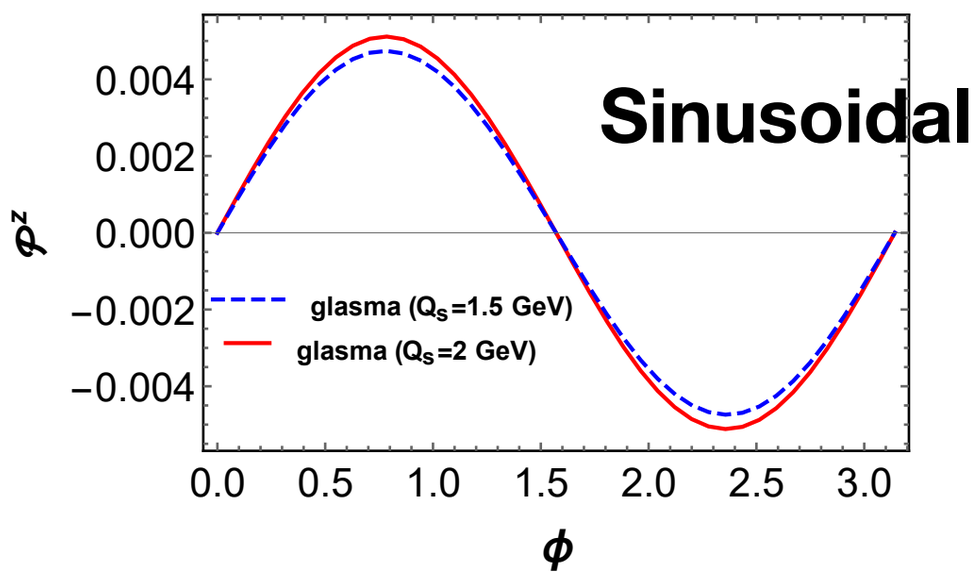
2. Quasi-equilibrium:

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

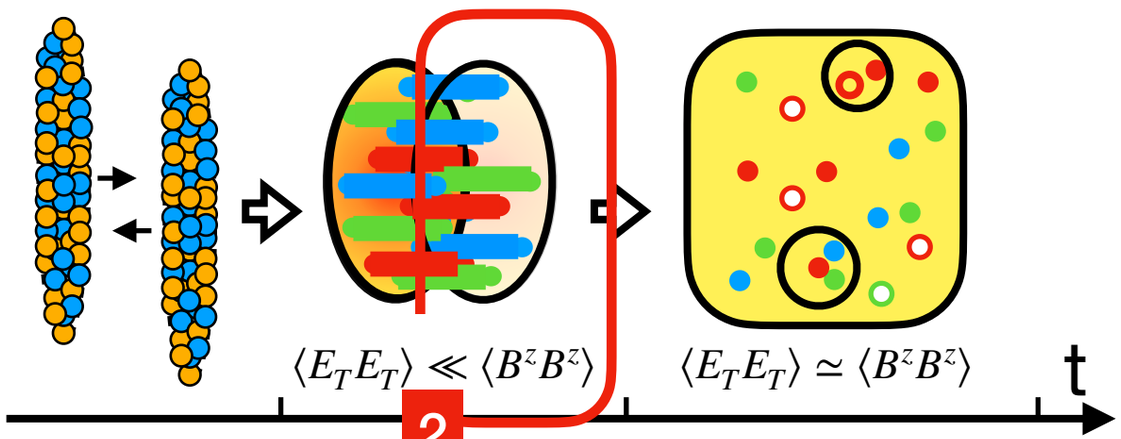


p+Pb collisions at 8.16 TeV





LSP in Glasma



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

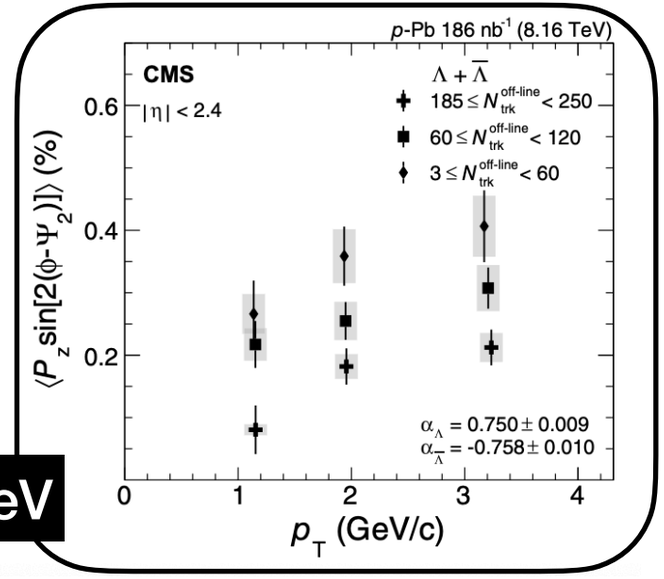
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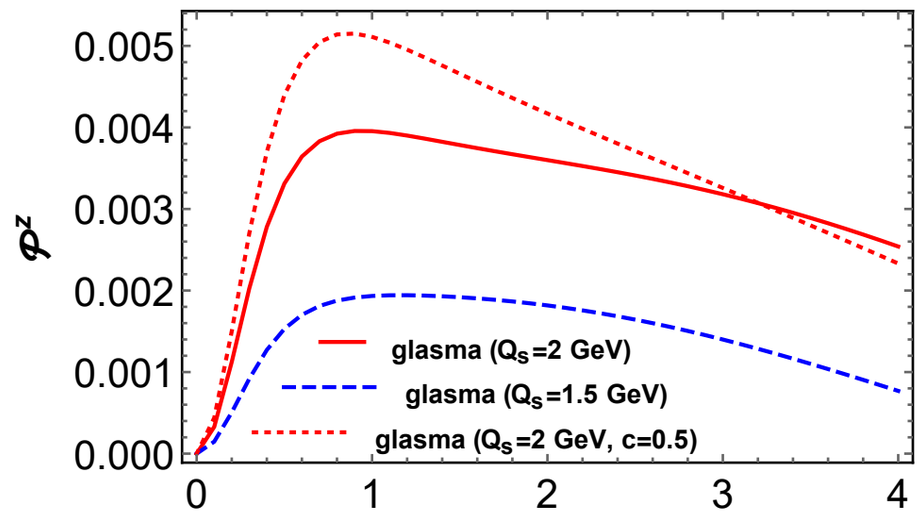
where $|gE^a| = \sqrt{(N_c^2-1)(2N_c)Q_s^2}$

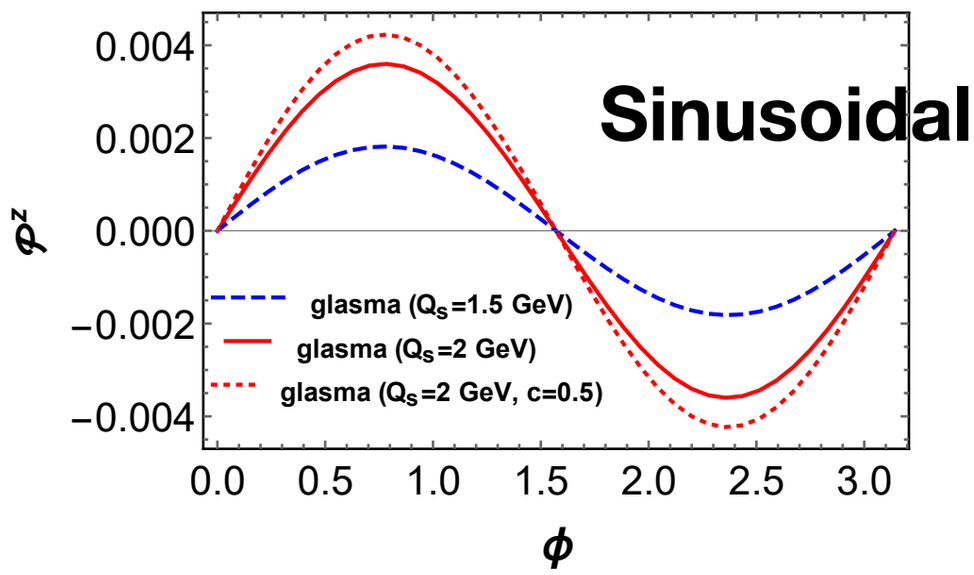
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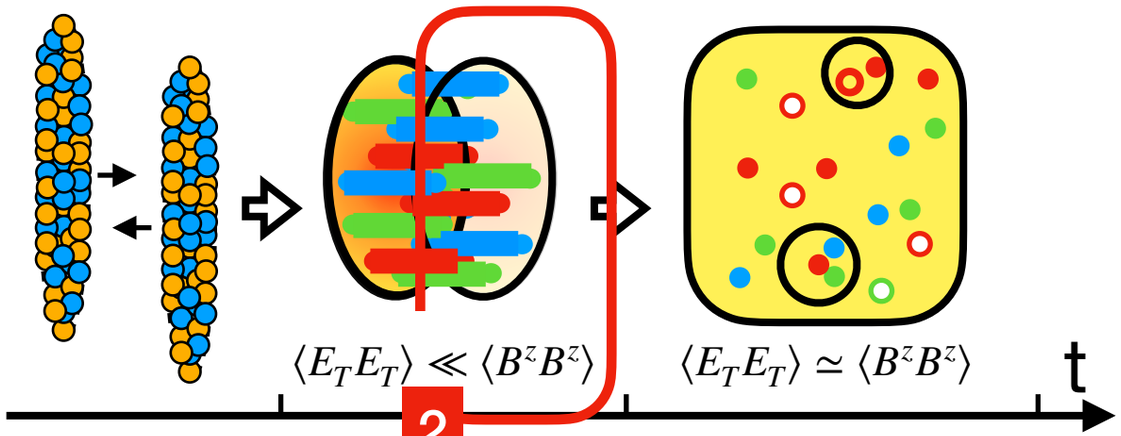


p+Pb collisions at 8.16 TeV





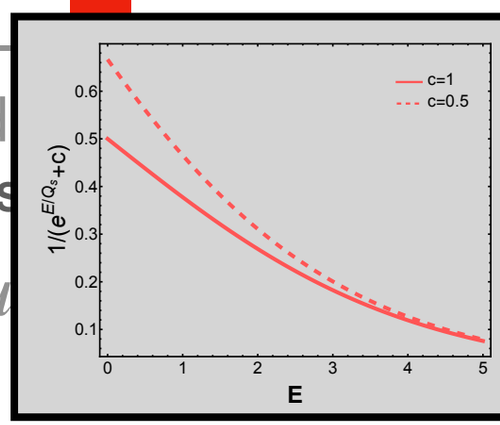
LSP in Glasma



2

1. Non-
prod
Julian S

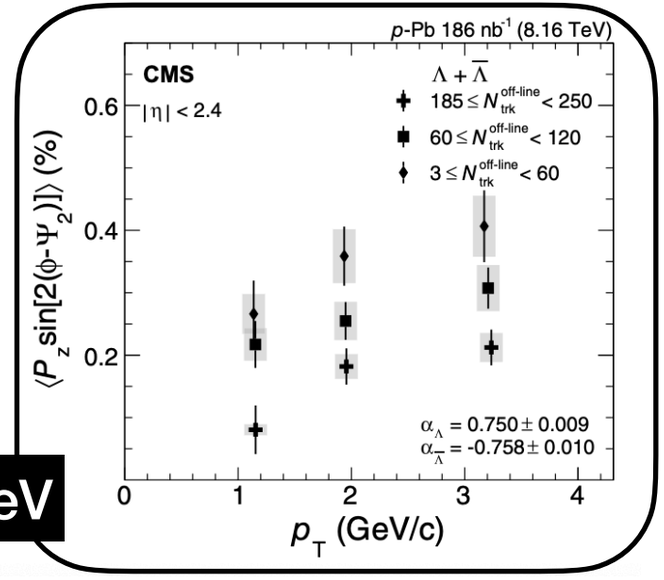
$f_V^s(p \cdot u$



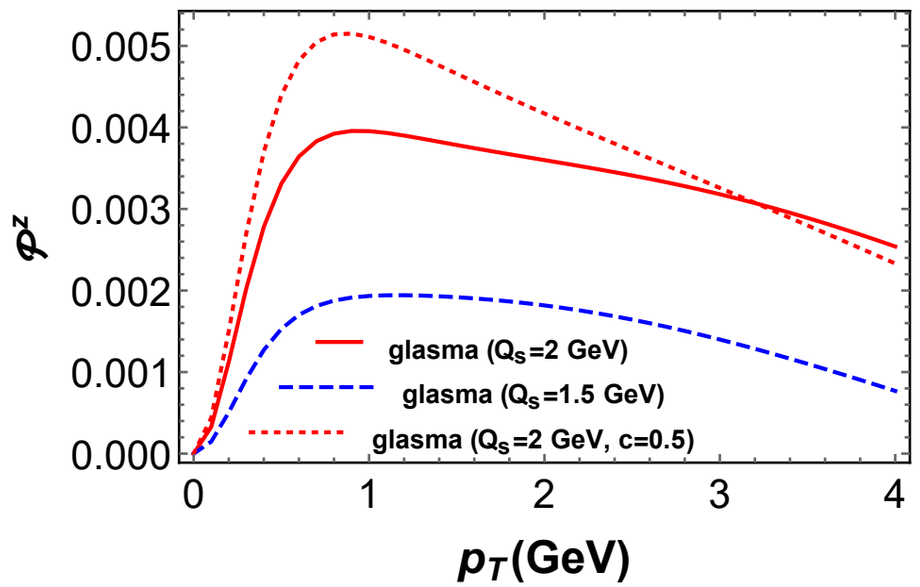
c<1:
Overpopulation of quarks at low energy

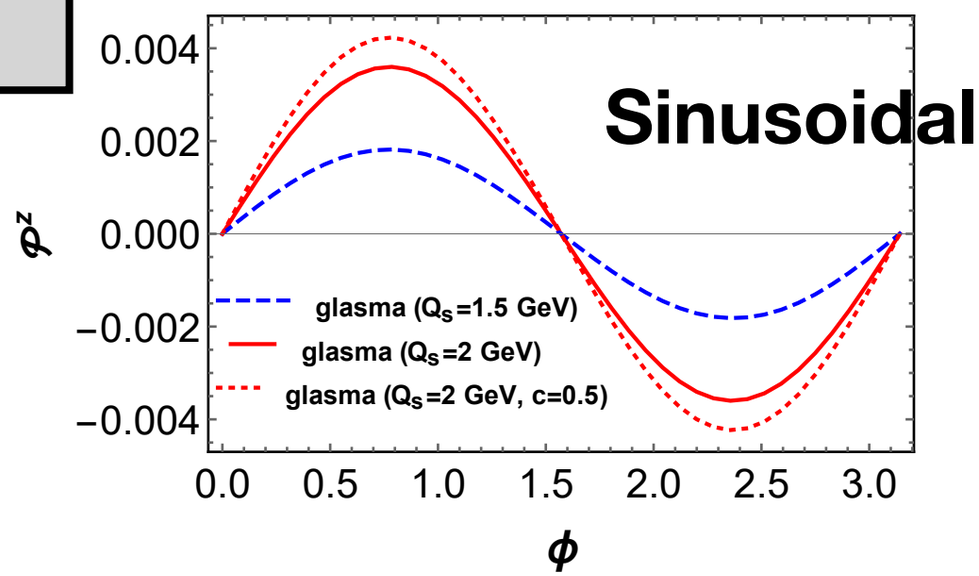
2. Quasi-equilibrium:

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

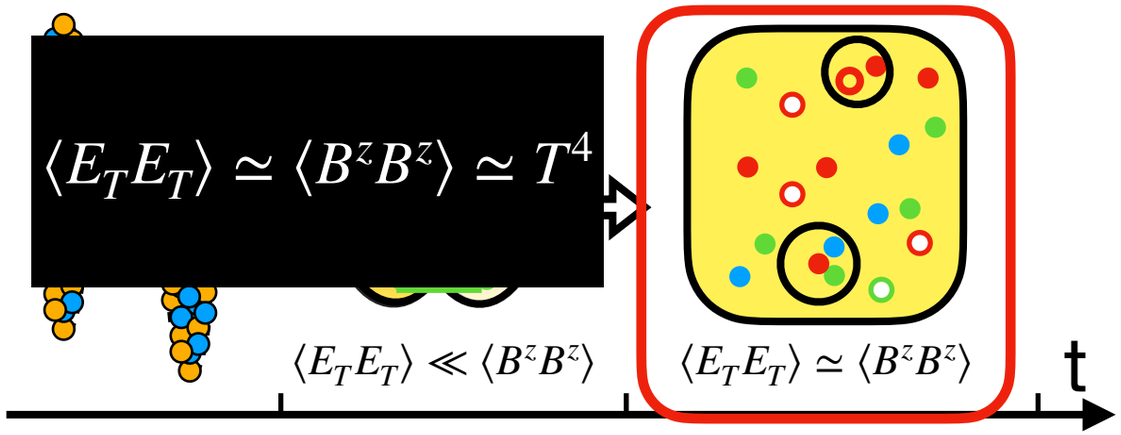


p+Pb collisions at 8.16 TeV





LSP in QGP



3. QGP: $^*Q_s \rightarrow T$

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

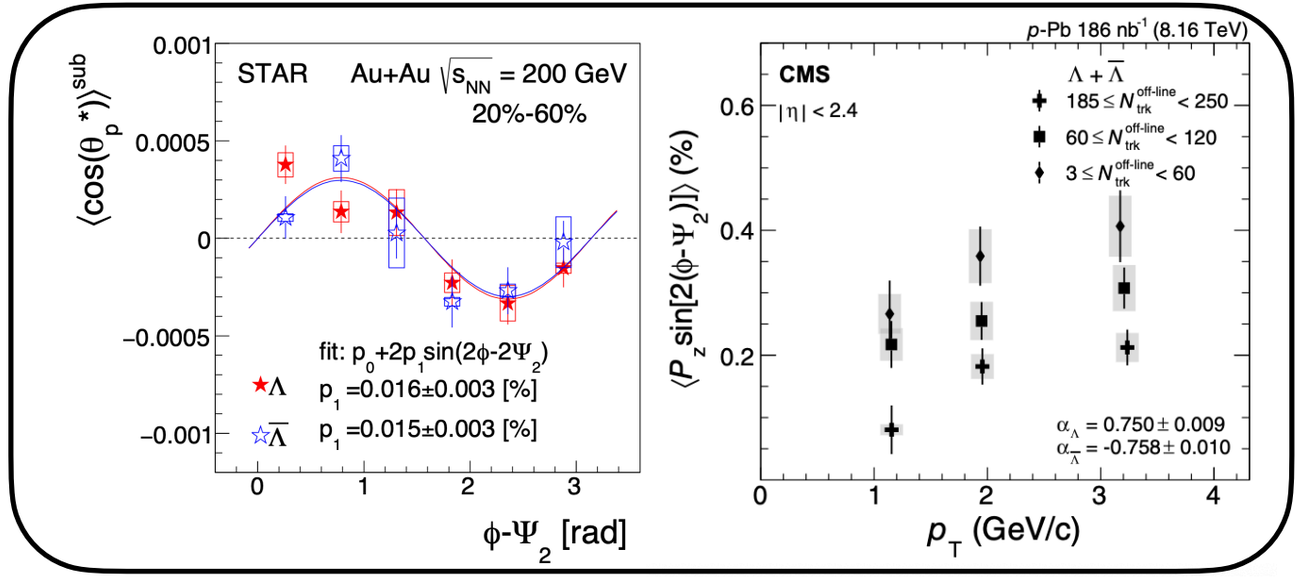
	QGP (30-60%)	QGP (0-15%)
ϵ	0.14	0.06
δ	0.37	0.12
$\tilde{\tau}_f$	4.3 fm	7.7 fm
r_m	3.8 fm	6.5 fm
Λ_c	$T = T_f = 165$ MeV	

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

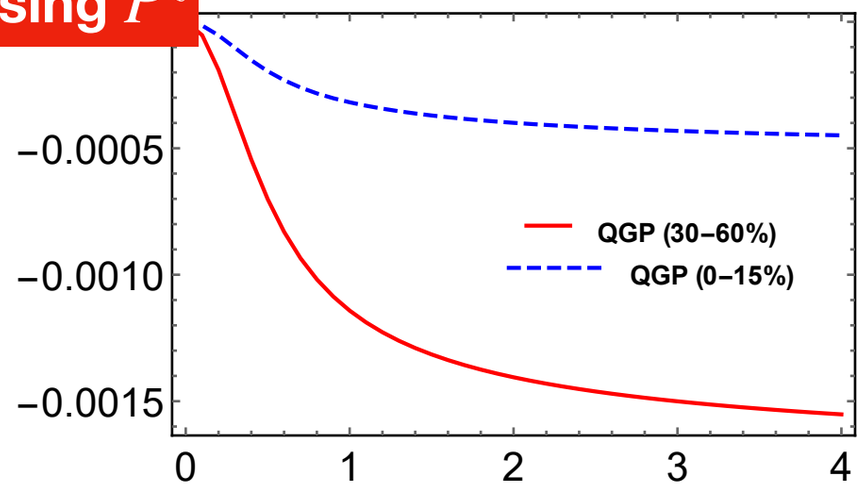
***Thermal model**

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

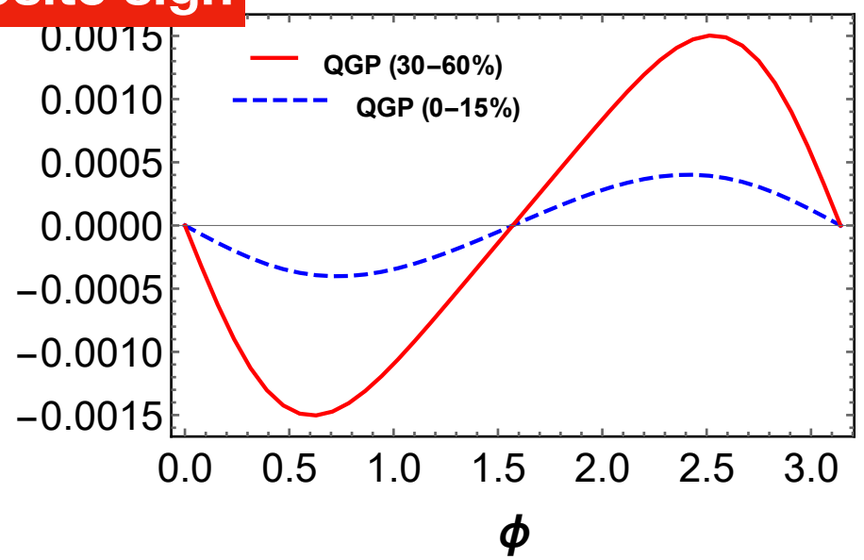
- anisotropy of transverse plane (ϵ)
- anisotropy of flow (δ)
- proper time ($\tilde{\tau}_f$)
- maximum radius (r_m)



Decreasing P^z



Opposite sign



Negative Polarization in QGP

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

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

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

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

For a small flow velocity, $G(p\cdot u/\Lambda_c) \approx G(p^0u^0/\Lambda_c) - \frac{\mathbf{p}\cdot\mathbf{u}}{\Lambda_c}G(p^0u^0/\Lambda_c) + \mathcal{O}\left(\left(\frac{\mathbf{p}\cdot\mathbf{u}}{\Lambda_c}\right)^2\right)$

$$d\Sigma\cdot p = drd\Phi d\eta\sqrt{1-\epsilon^2}\left(G_1\cosh(y_p-\eta)\right) + G_2$$

where $G_1 = \sqrt{m^2+p_T^2}\tau_f$, $\quad G_2 = -(xp^x + yp^y)$ => + P_z

	QGP	Glasma
Λ_c	$165 MeV$	$2\,GeV$

$$\int d\Sigma\cdot pA^{sz} \approx -\int d\Sigma\cdot p\left(u^xp^y - u^yp^x\right)u^0G(\Phi)$$

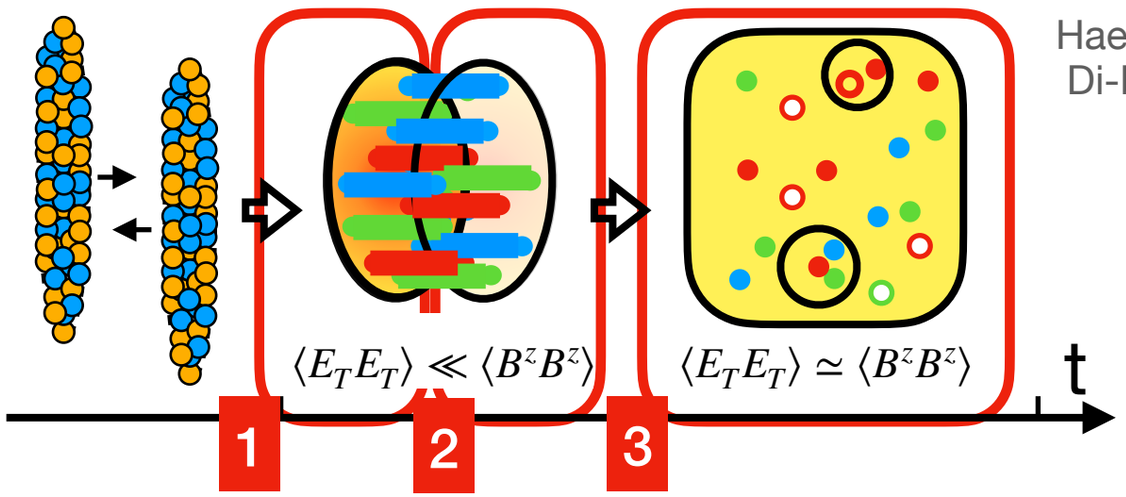
$$\approx \int dr\,d\Phi\,d\eta\, r\sqrt{1-\epsilon^2}\Big[\Big(+\,G_2\left(u^xp^y - u^yp^x\right)G(p^0u^0/\Lambda_c)$$

$$+G_1\cosh(y_p-\eta)\left(u^xp^y - u^yp^x\right)\frac{\boldsymbol{p\cdot u}}{\Lambda_c}G'(p^0u^0/\Lambda_c)\Big]u^0$$

(+ / -)

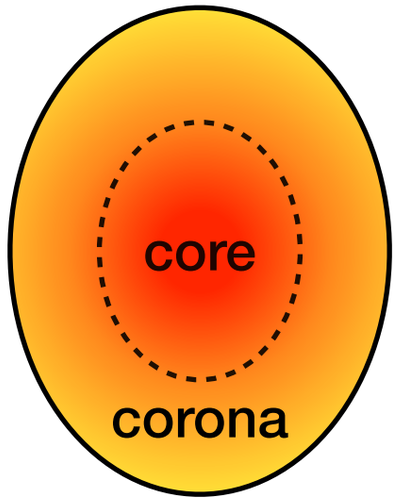
For QGP, $|\mathbf{p}\cdot\mathbf{u}| > \Lambda_c$
=> Flip the polarization sign

LSP in Glasma and QGP

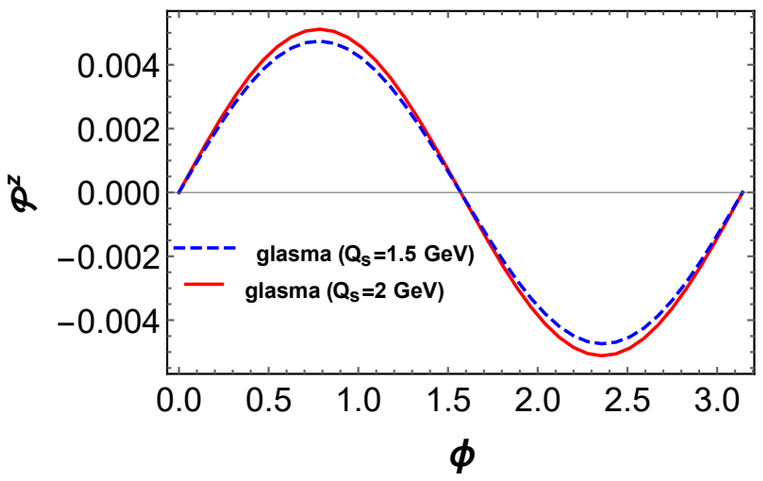


Haesom Sung, Berndt Müller,
Di-Lun Yang, arXiv:2507.23210v3

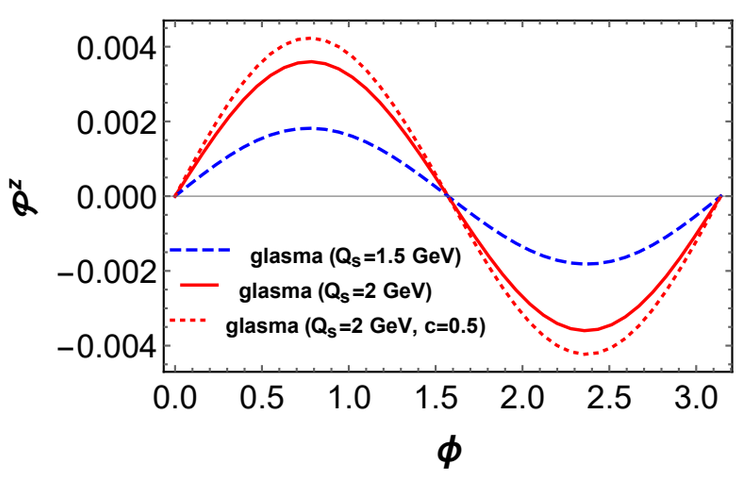
$$P^z = \frac{N_{GL}P^z_{GL} + N_{QGP}P^z_{QGP}}{N_{GL} + N_{QGP}}$$



1. Glasma(non-eq)

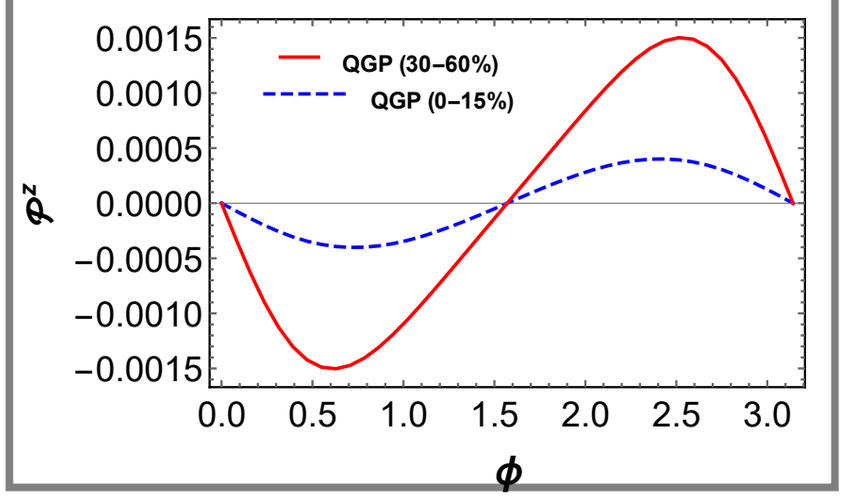


2. Glasma(quasi-eq)



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

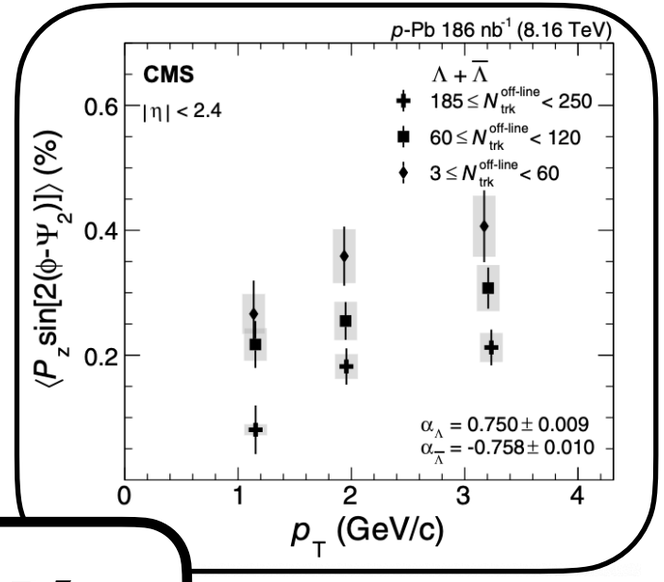
3. QGP

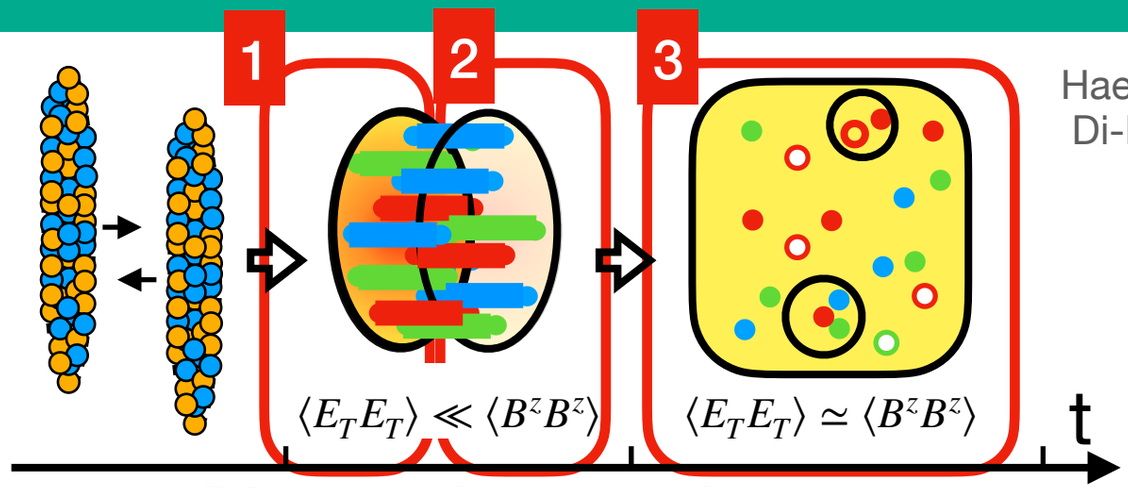


+Hydrodynamic contribution (vorticity+shear)

F. Becattini et al., PRL. 127,272302 (2021)
Baochi Fu et al., PRL. 127 (2021) 14, 142301

LSP in Glasma and QGP

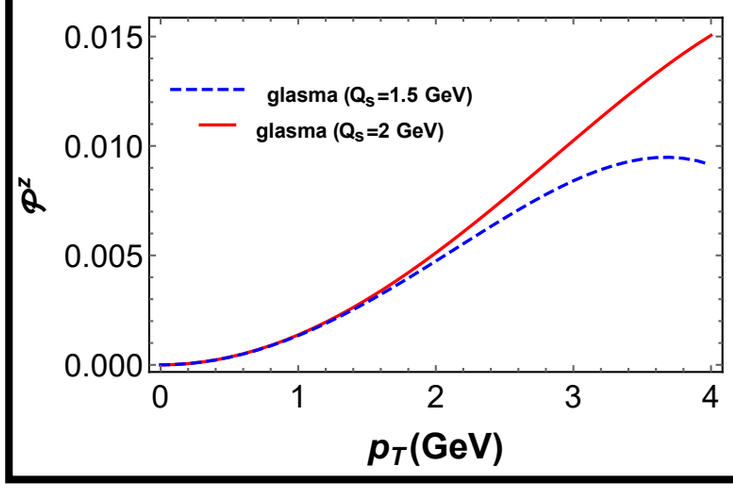




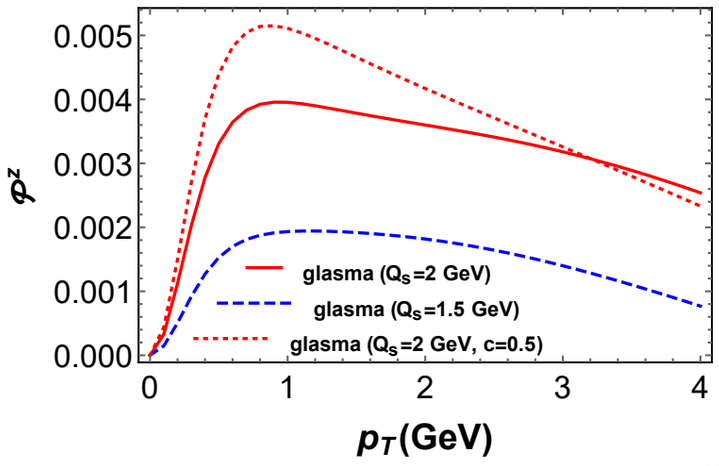
Haesom Sung, Berndt Müller, Di-Lun Yang, arXiv:2507.23210v3

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

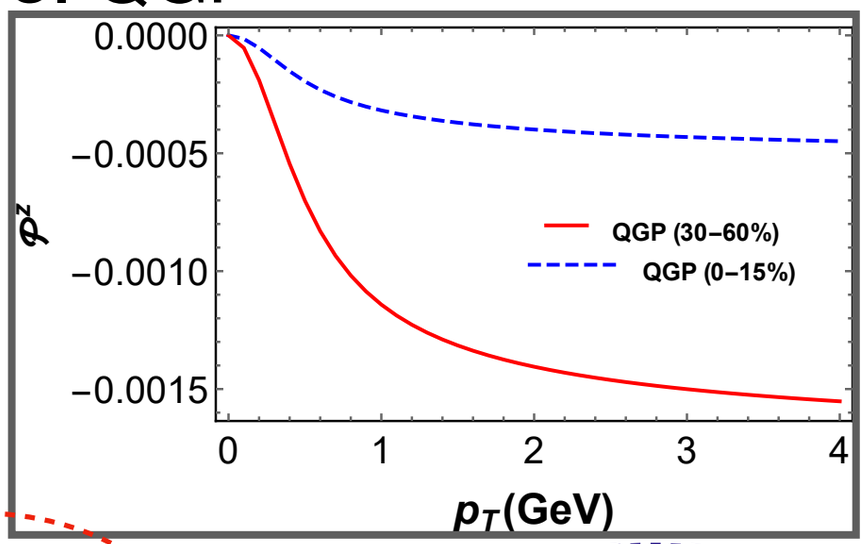
1. Glasma(non-eq)



2. Glasma(quasi-eq)



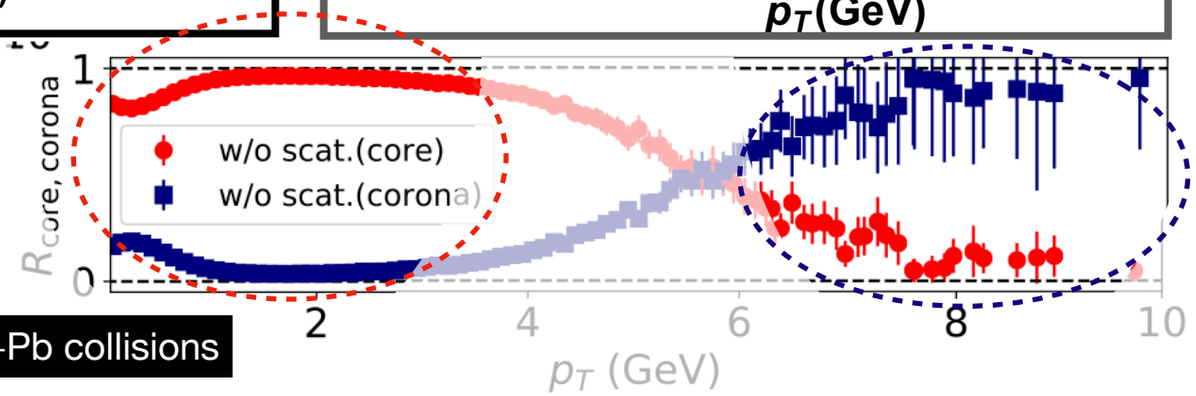
3. QGP



N_{GL} for smaller system and high p_T

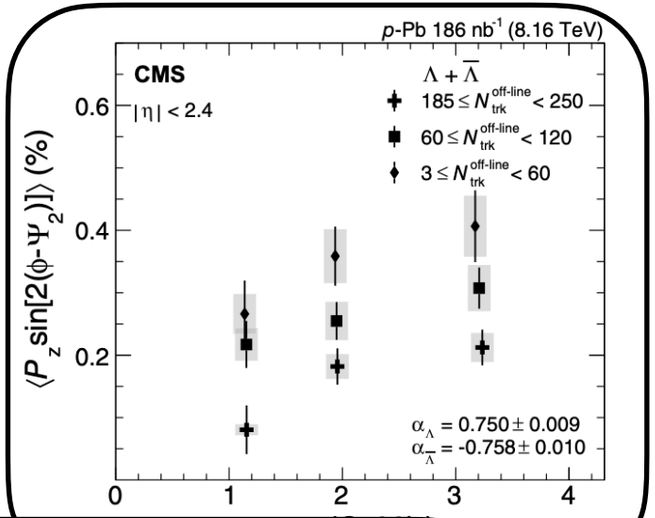
N_{QGP} for larger system and low p_T

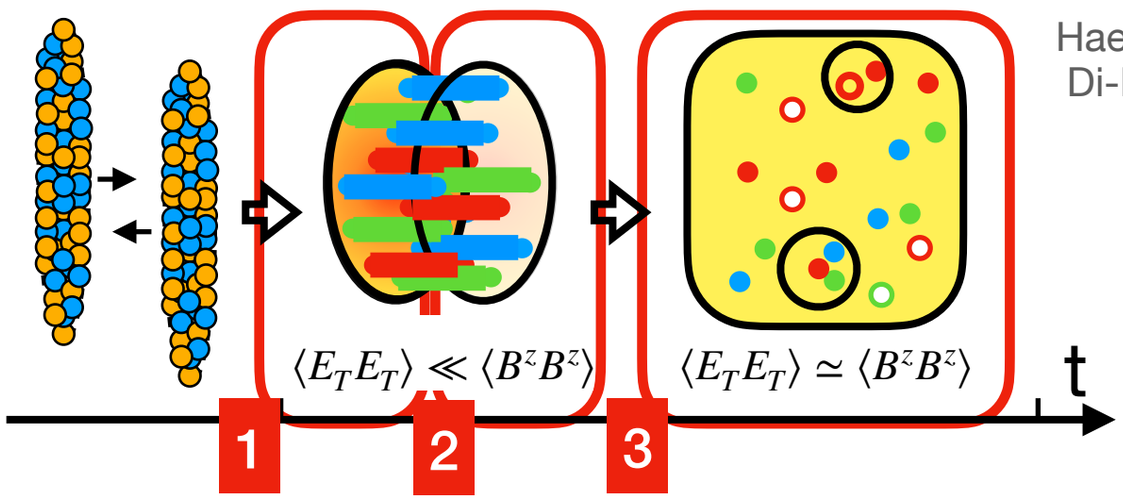
Y. Kanakubo, Y. Tachibana, and T. Hirano, Phys. Rev. C 105, 024905 (2022)



Pb+Pb collisions

LSP in Glasma and QGP

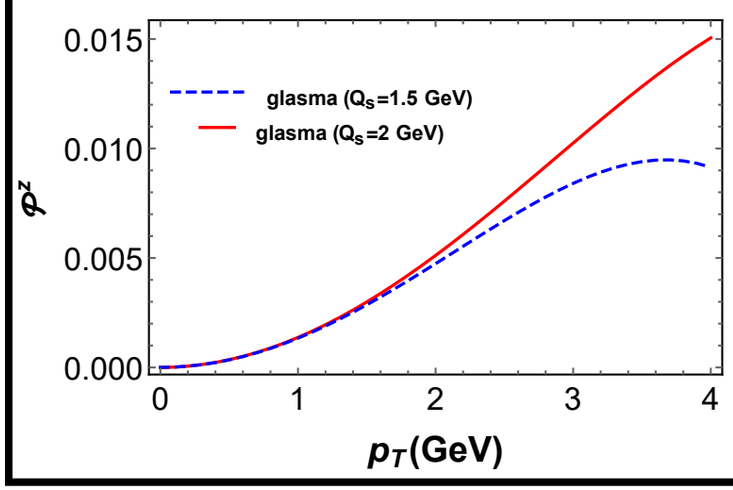




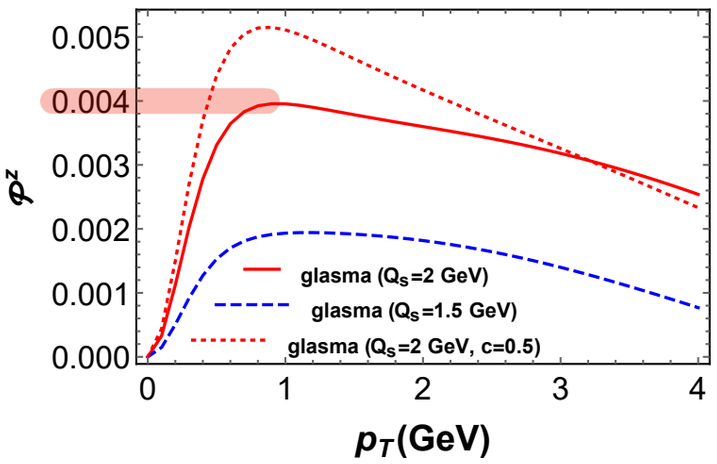
Haesom Sung, Berndt Müller, Di-Lun Yang, arXiv:2507.23210v3

$$P^z = \frac{N_{GL}P^z_{GL} + N_{QGP}P^z_{QGP}}{N_{GL} + N_{QGP}} \sim 0.1\,\%$$

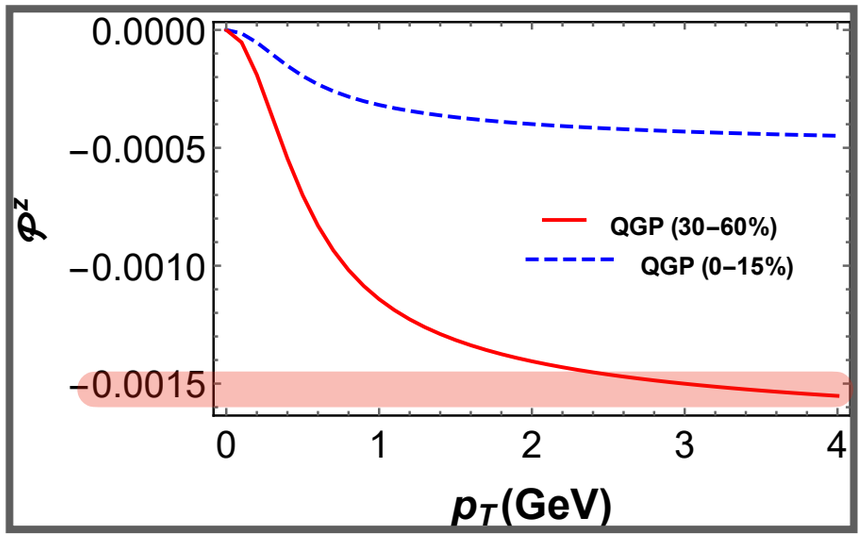
1. Glasma(non-eq)



2. Glasma(quasi-eq)



3. QGP



N_{GL} for smaller system and high p_T

N_{QGP} for larger system and low p_T

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

$N_{GL} \approx N_{QGP}$ where rapidity $\sim \mathcal{O}(10)$

$P^z_{GL} = 4 \times 10^{-3}$ and $P^z_{QGP} = -1.5 \times 10^{-3}$

Summary

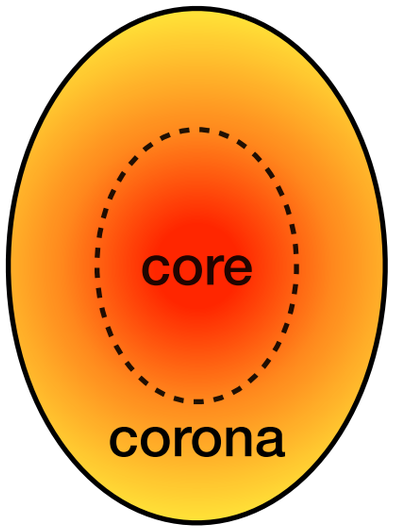
- **In small collision systems**, initial non-equilibrium glasma (corona) generates the observed longitudinal Λ polarization with $\sin 2\phi$ pattern and an increasing tendency with p_T, which indicate that **the coherent gluons may play a significant role for local polarization.**

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

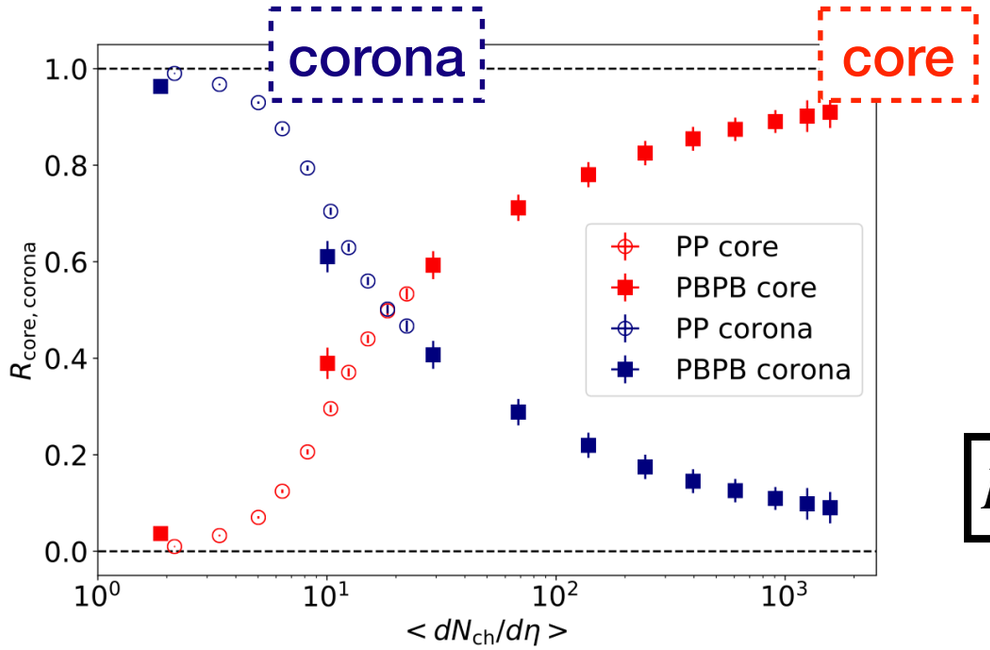
Appendix

Corona effect

Glasma



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

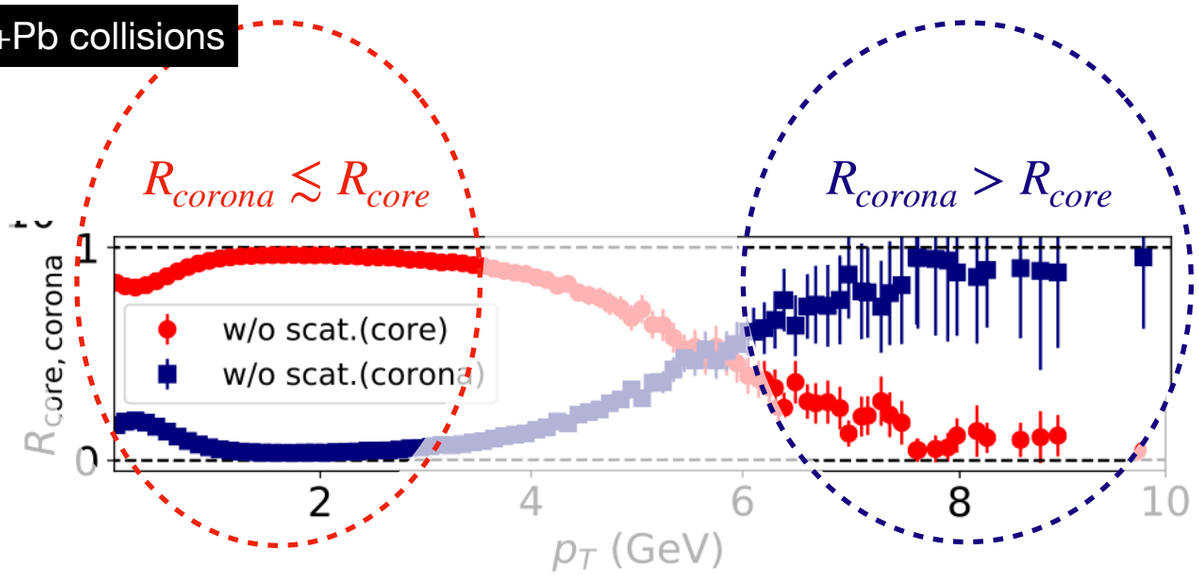


p+p collisions at $\sqrt{s} = 7\,TeV$

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: $R_{corona} < R_{core}$