Institute of Physics, Academia Sinica

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

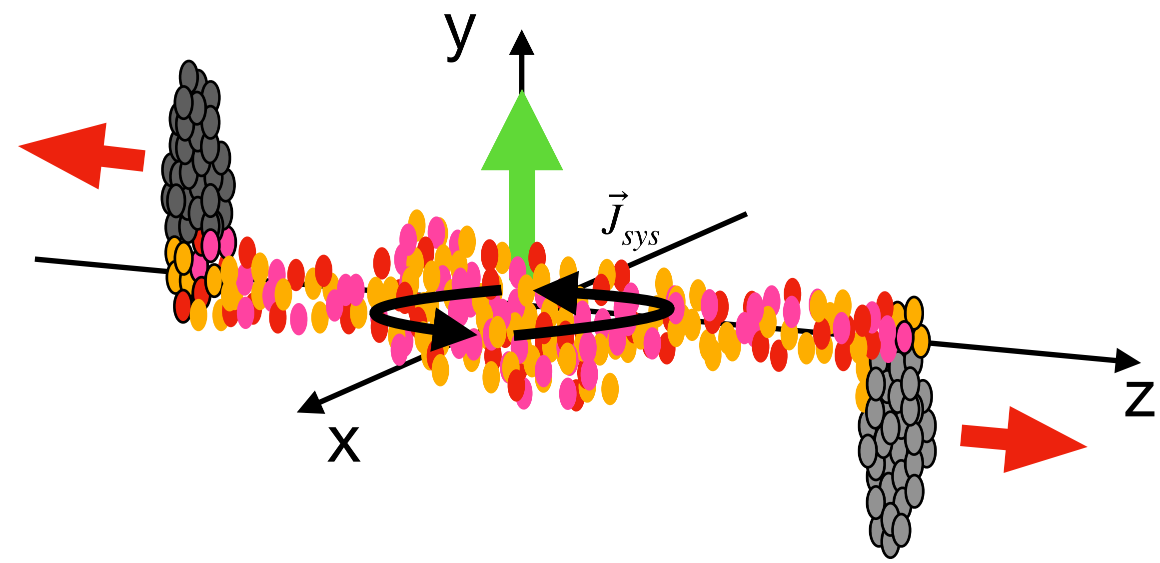
Workshop on recent developments from QCD to nuclear matter

Dec. 17-20, 2025, Taipei

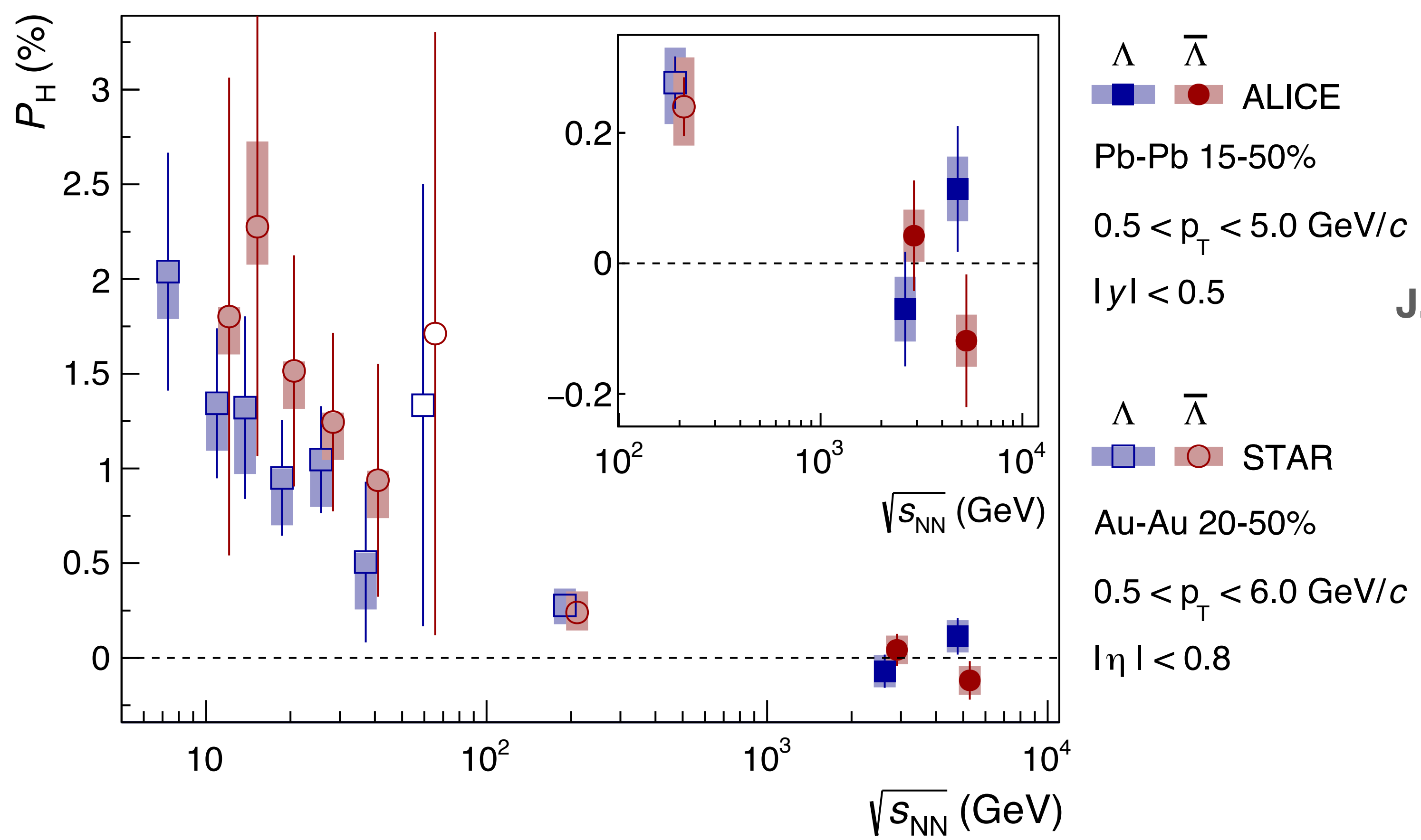
2025.12.20

Motivation

Positive Global Polarization

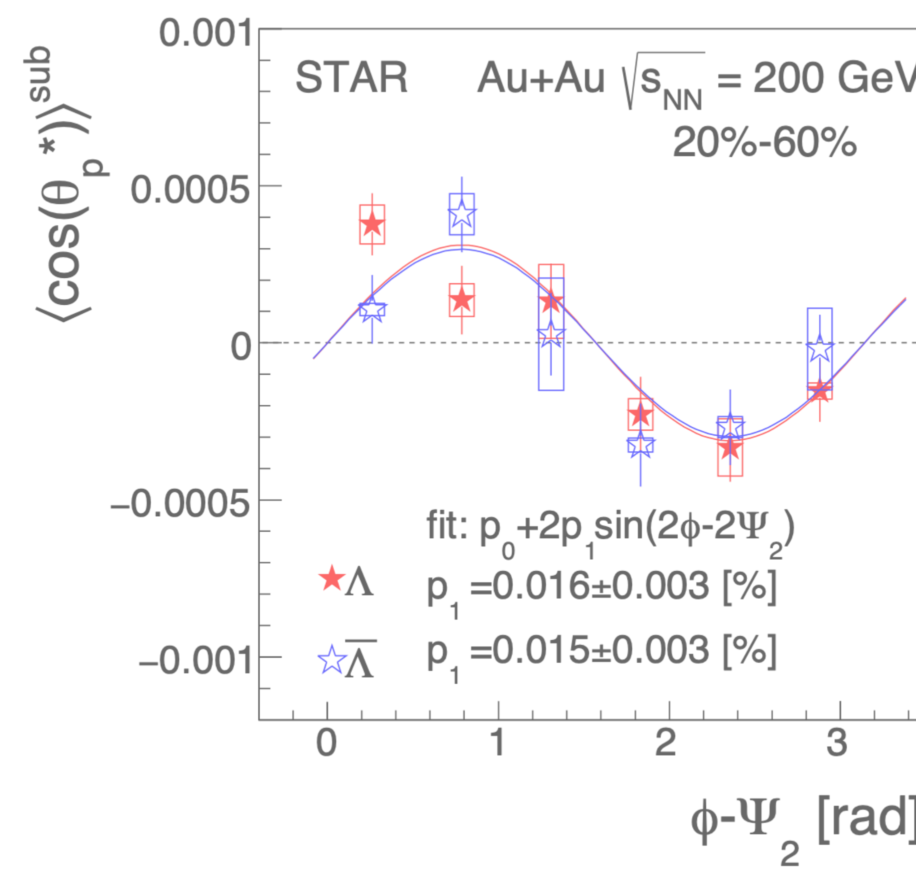


L. Adamczyk et al. (STAR), Nature 548, 62 (2017)
S. Acharya et al. (ALICE), Phys. Rev. C 101, 044611 (2020)



Non-zero global Λ polarization in small collision systems

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

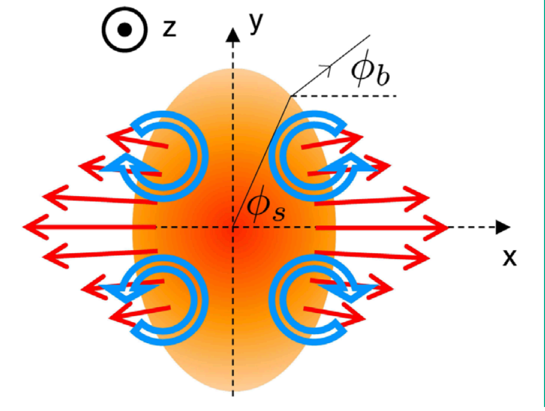


Global polarization (P_H) can be measured by averaging a corresponding projection of proton direction (n_p), $n_{p\perp RP} = \sin\theta_p \sin(\psi_p - \Psi_{RP})$

$$P_H = \frac{8}{\pi\alpha_H}\langle\sin(\phi_p - \Psi_{RP})\rangle$$

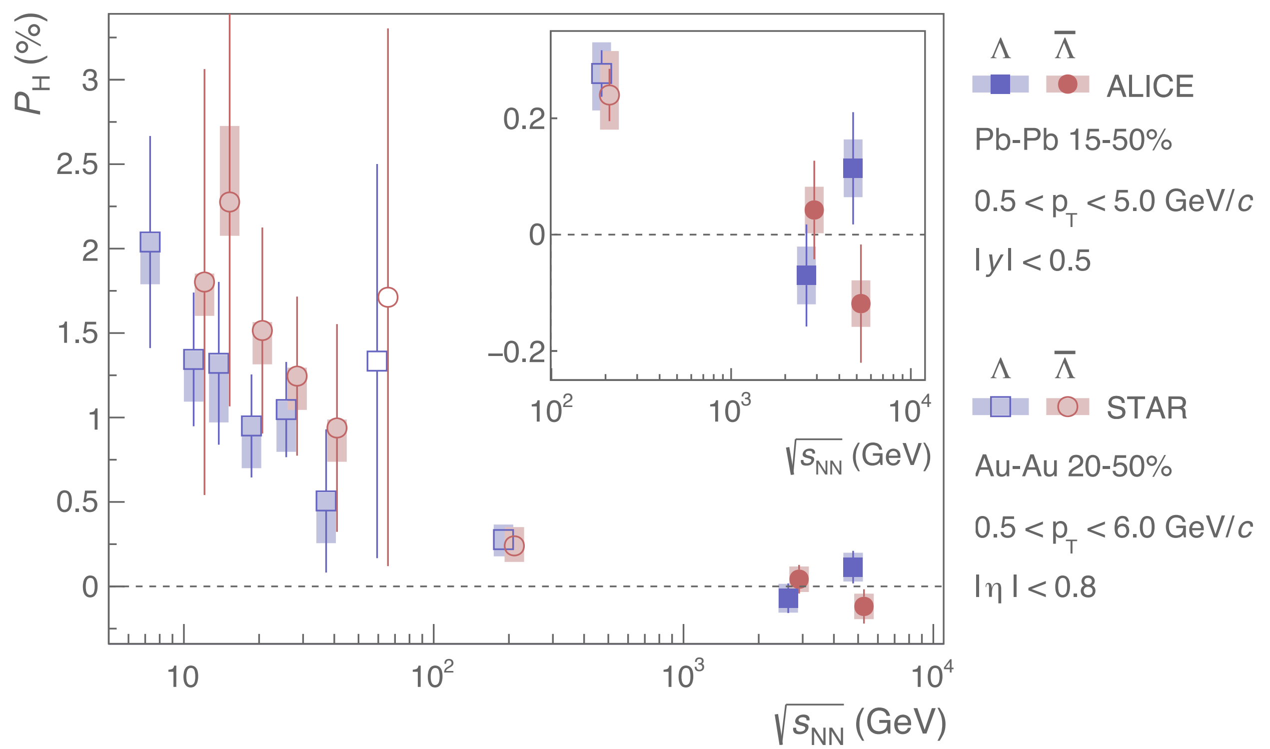
Motivation

Longitudinal Local Polarization

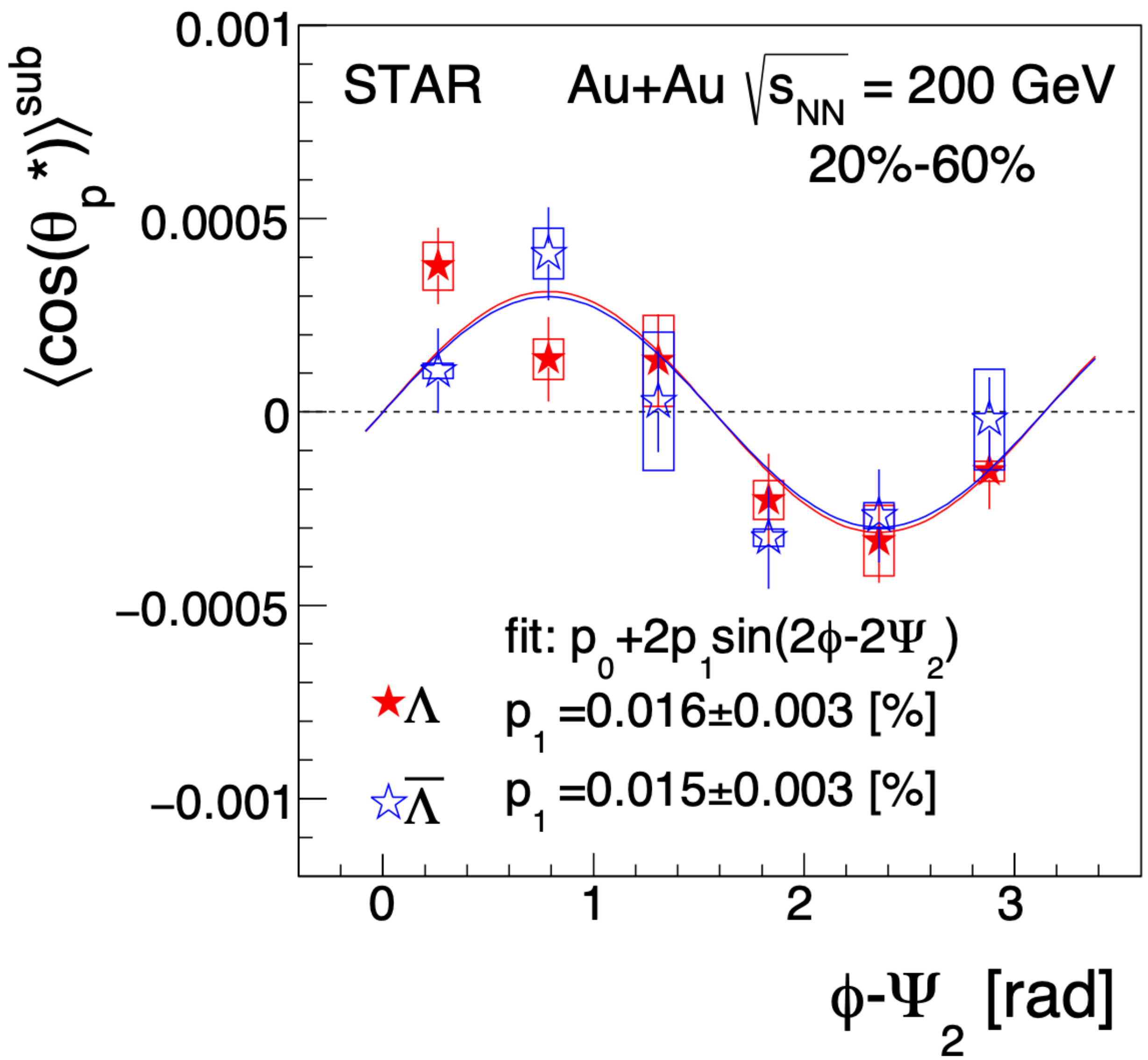


$$P_z = \frac{\langle \cos \theta_p^* \rangle}{\alpha_H \langle \cos^2 \theta_p^* \rangle}$$

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



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

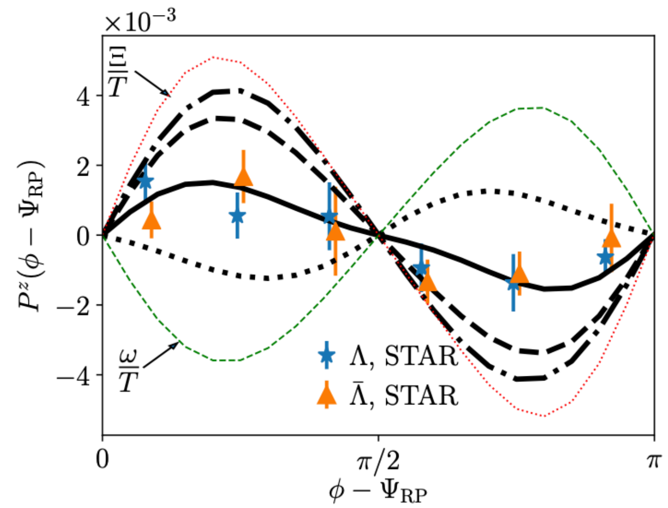


A **sinusoidal** structure of longitudinal Λ polarization with azimuthal angle

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

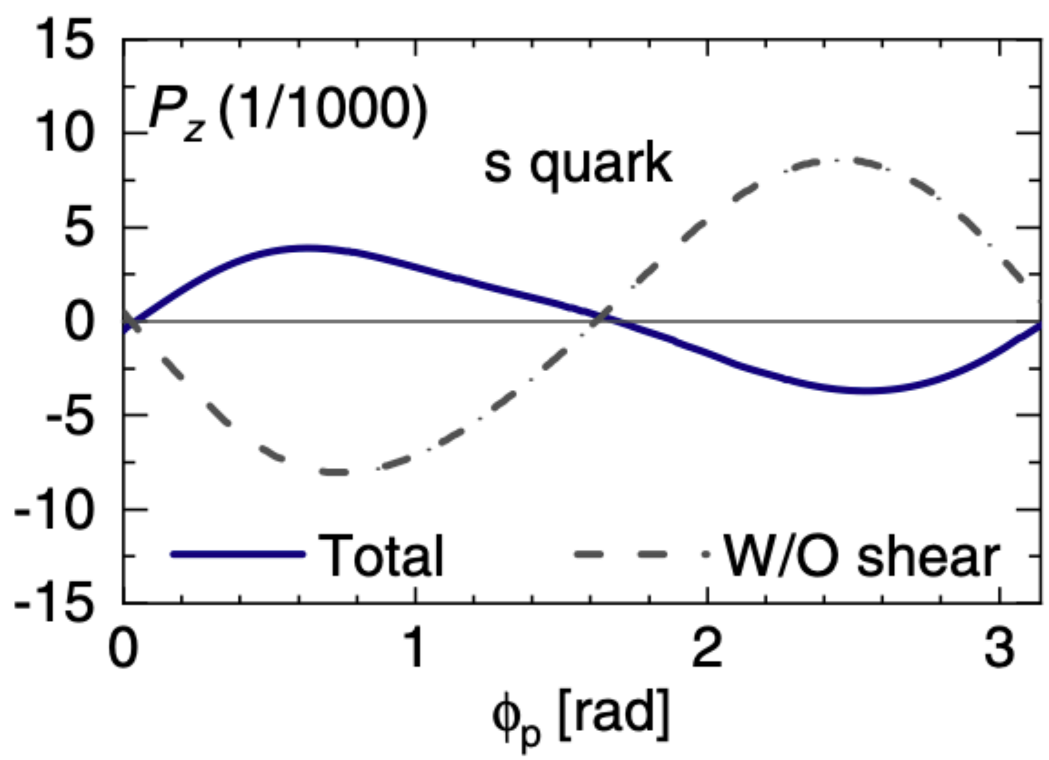
$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_{\mu}\beta_{\nu} - \partial_{\nu}\beta_{\mu})$$

Thermal shear

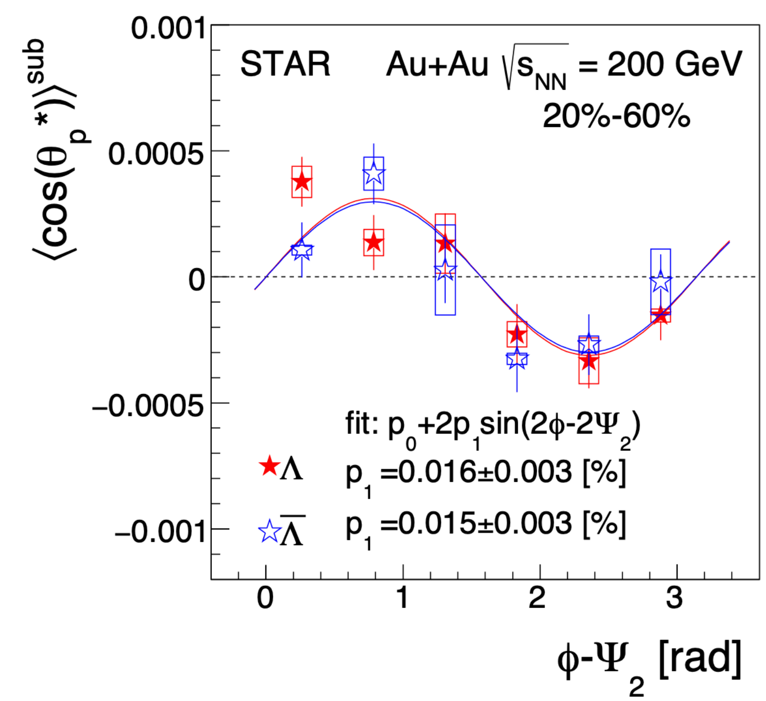
$(\xi_{\mu\nu} = 0$ at global equilibrium)

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

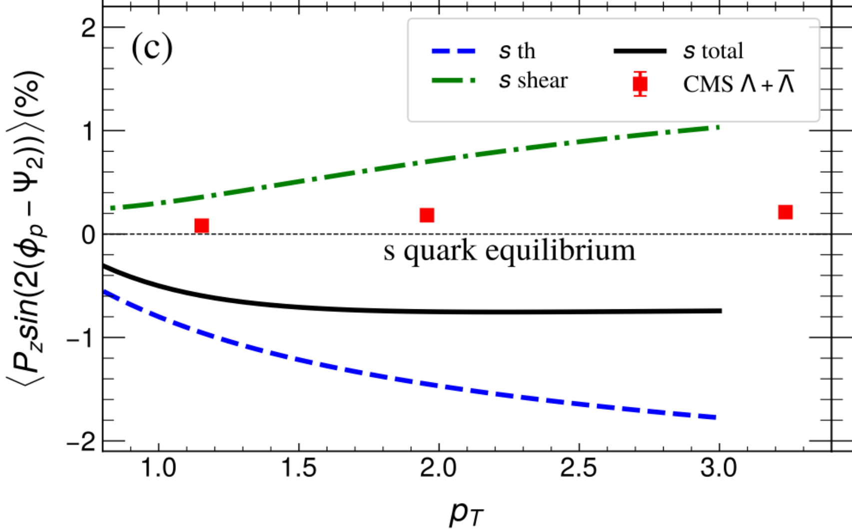
Baochi Fu et al., *Phys.Rev.Lett.* 127 (2021) 14, 142301 (s-quark equilibrium)



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

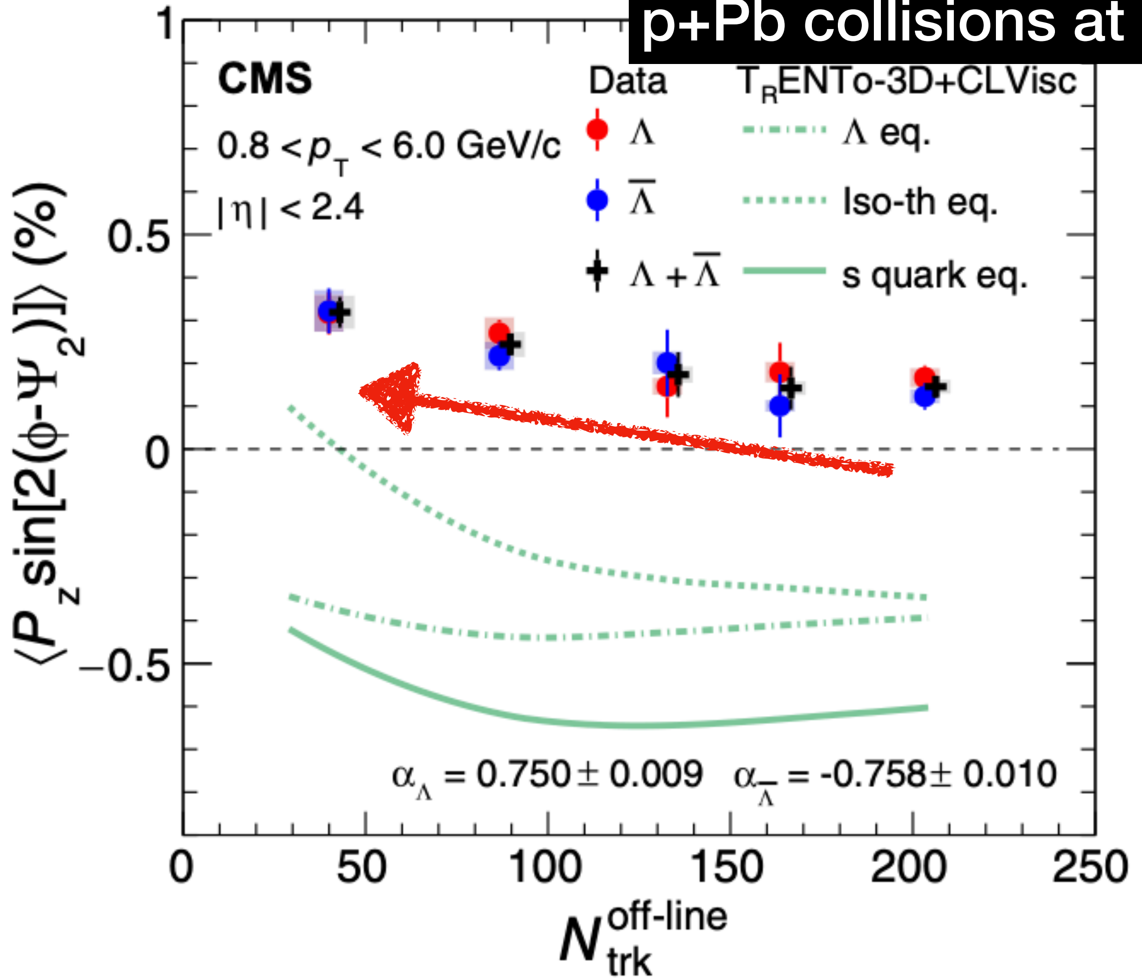


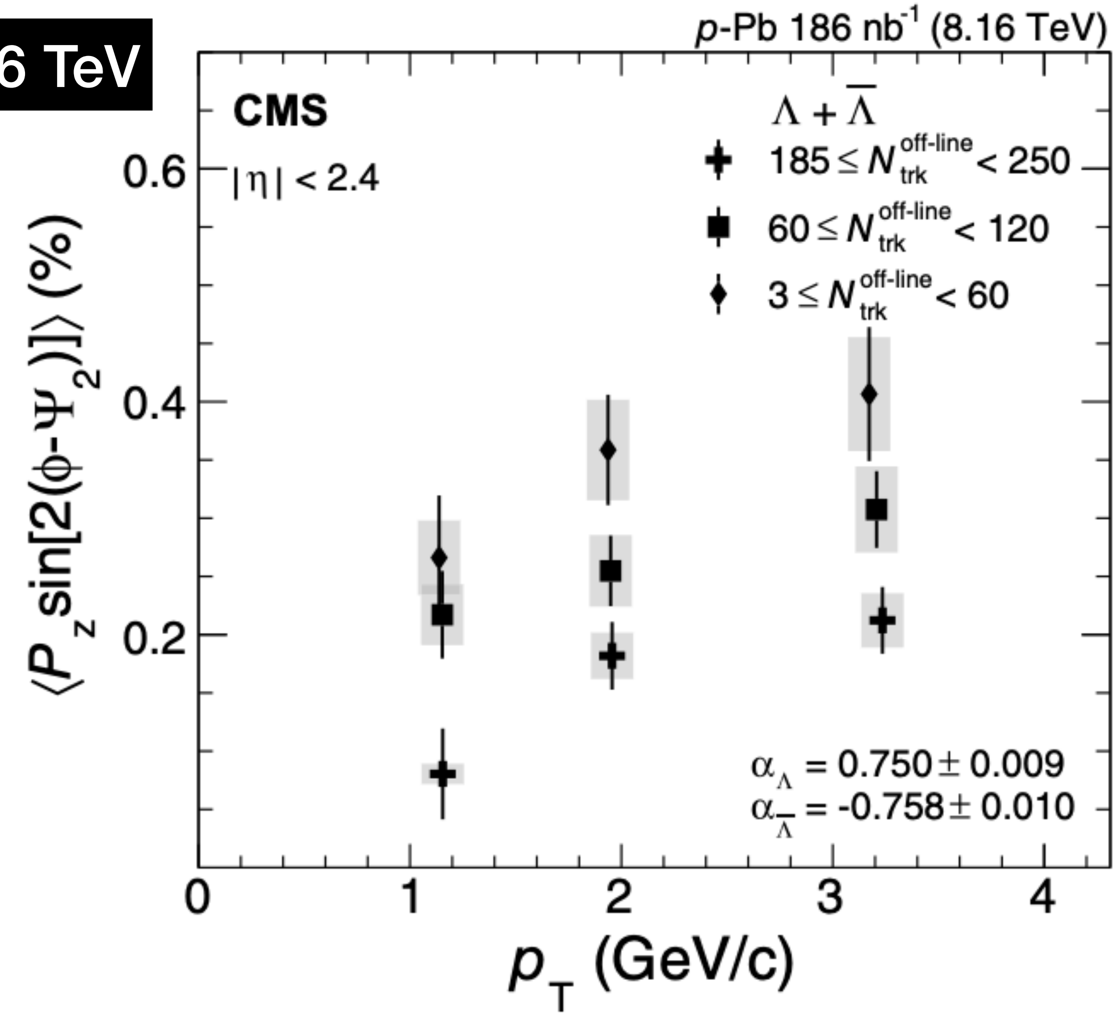
LSP with centrality and p_T



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

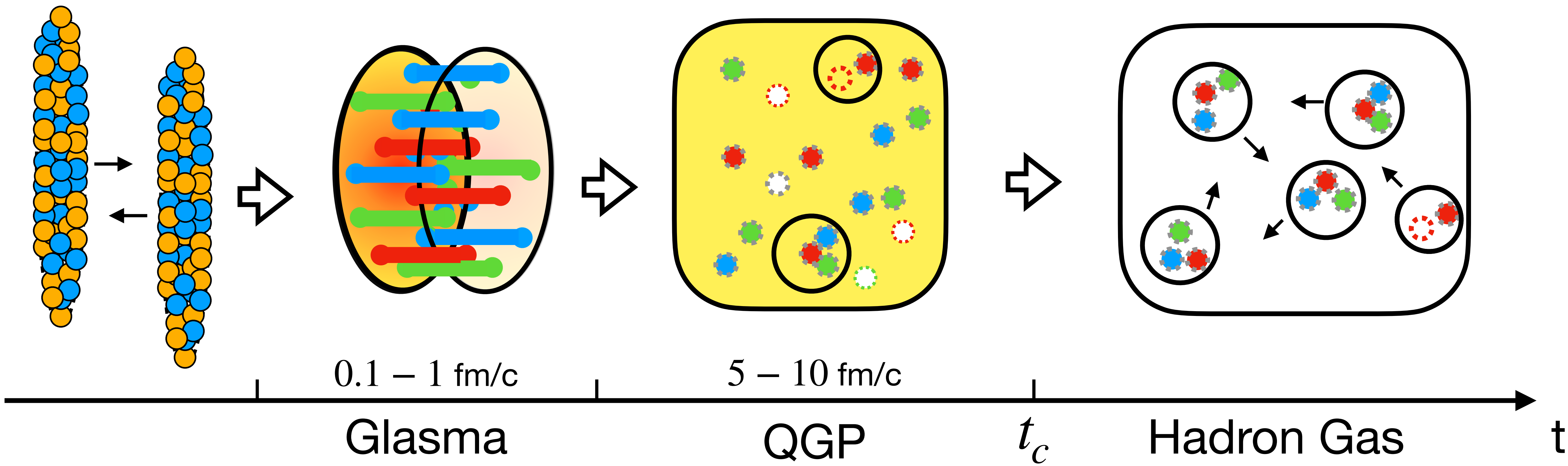
p+Pb collisions at 8.16 TeV



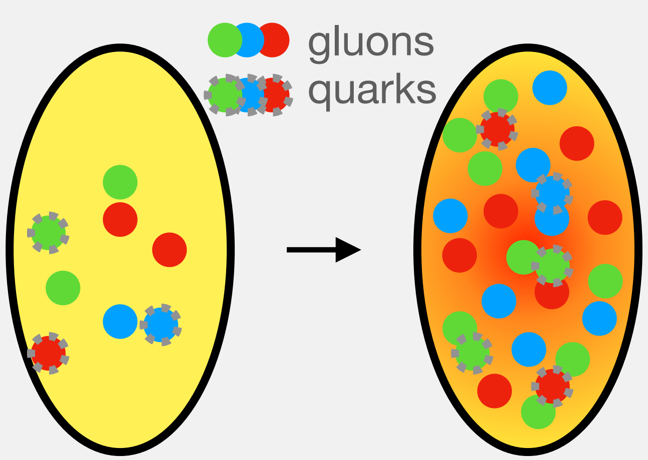


Thermal vorticity and thermal shear effect can not describe this experimental result with multiplicity and p_T dependence

Initial stages of heavy ion collisions

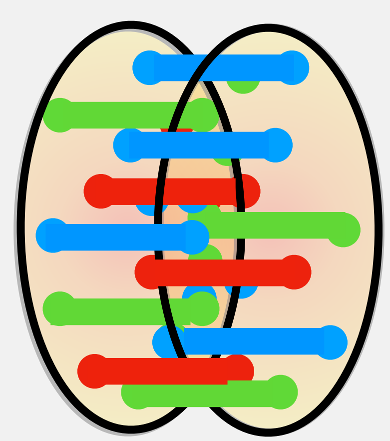


Color Glass Condensate (CGC) :



Increasing Energy

Small-x gluon density is very high below the saturation scale (Q_s) behaving as classical color fields

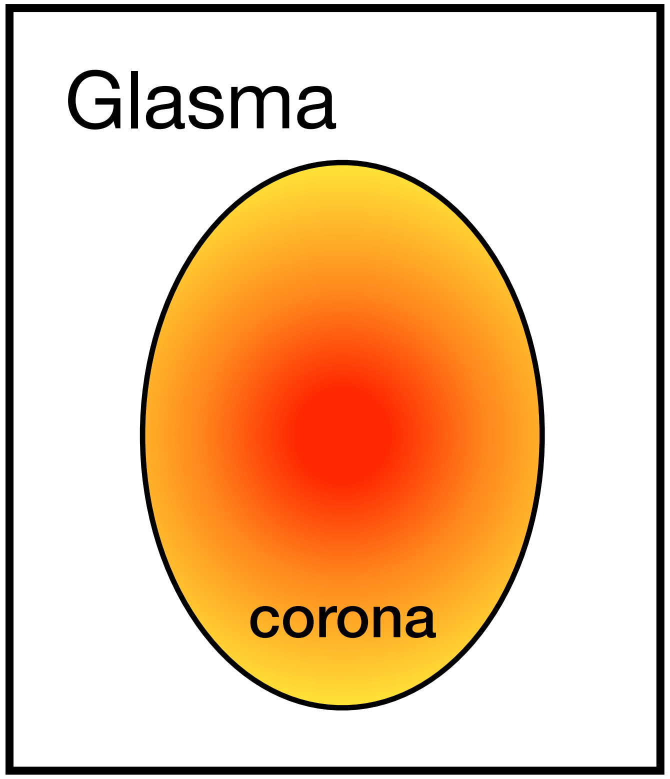


Glasma

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

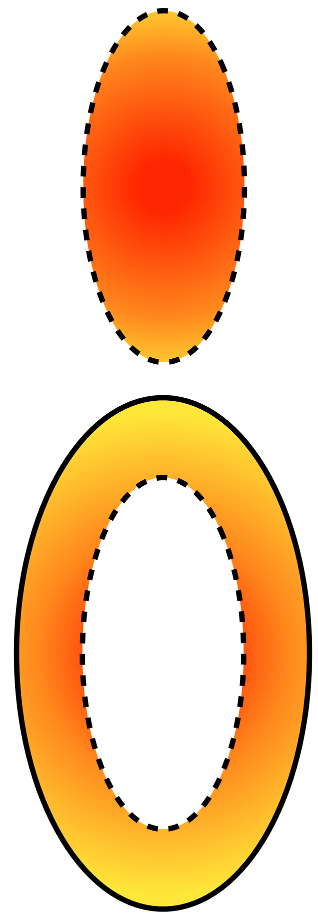
non-equilibrium

Corona effect

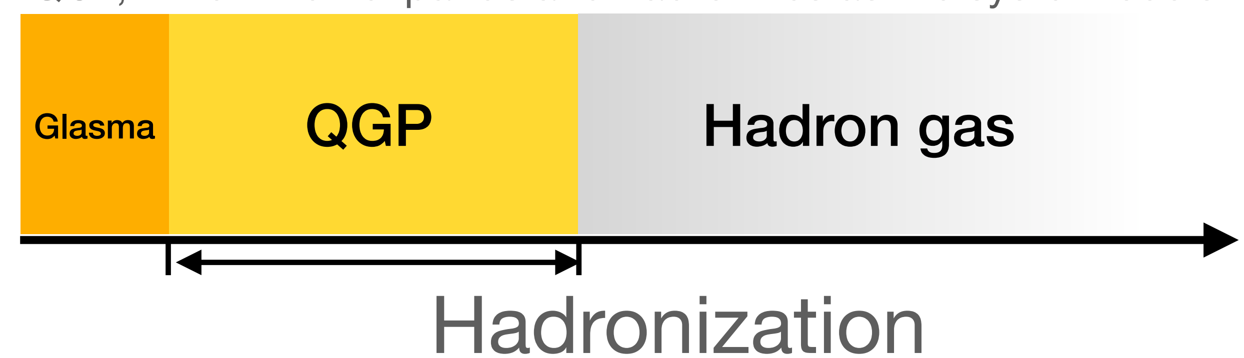


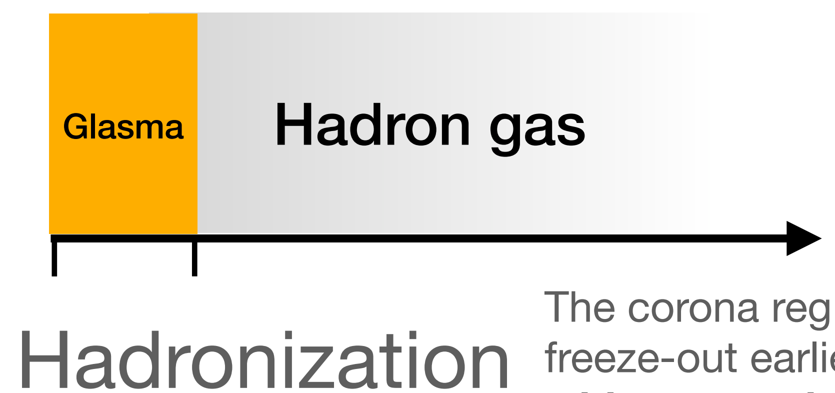
core

corona



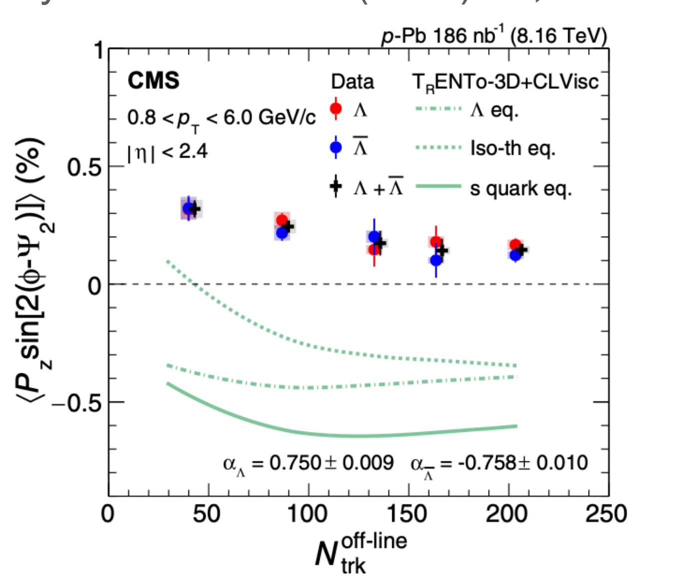
The core region undergoes full **thermalization**, forming the QGP, which then expands and hadronizes as the system cools





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

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

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

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

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

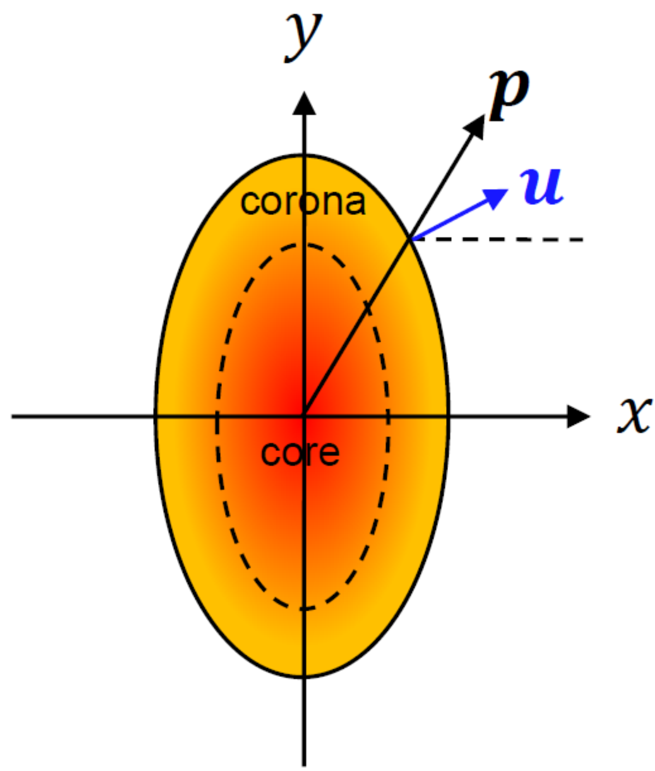
For weak coupling, $f_V^a(p,x)$ can be expressed perturbatively in terms of the singlet distribution.

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

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

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

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

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

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

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

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

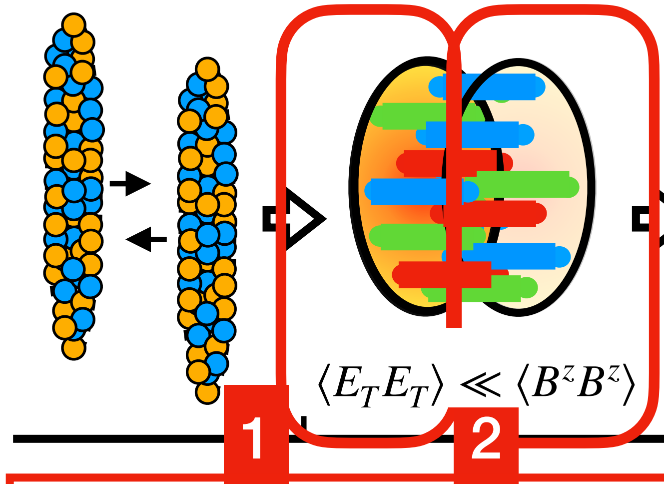
Chromo-Lorentz force:

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

Color-octet polarization pseodu-vector:

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

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-Rodŕıguez 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:

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

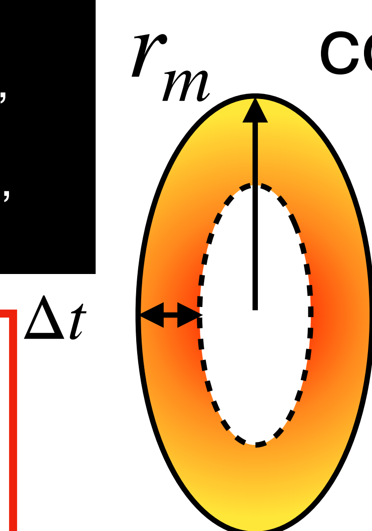
polarization vanish for isotropic flow $(\delta = 0)$

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

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

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

corona



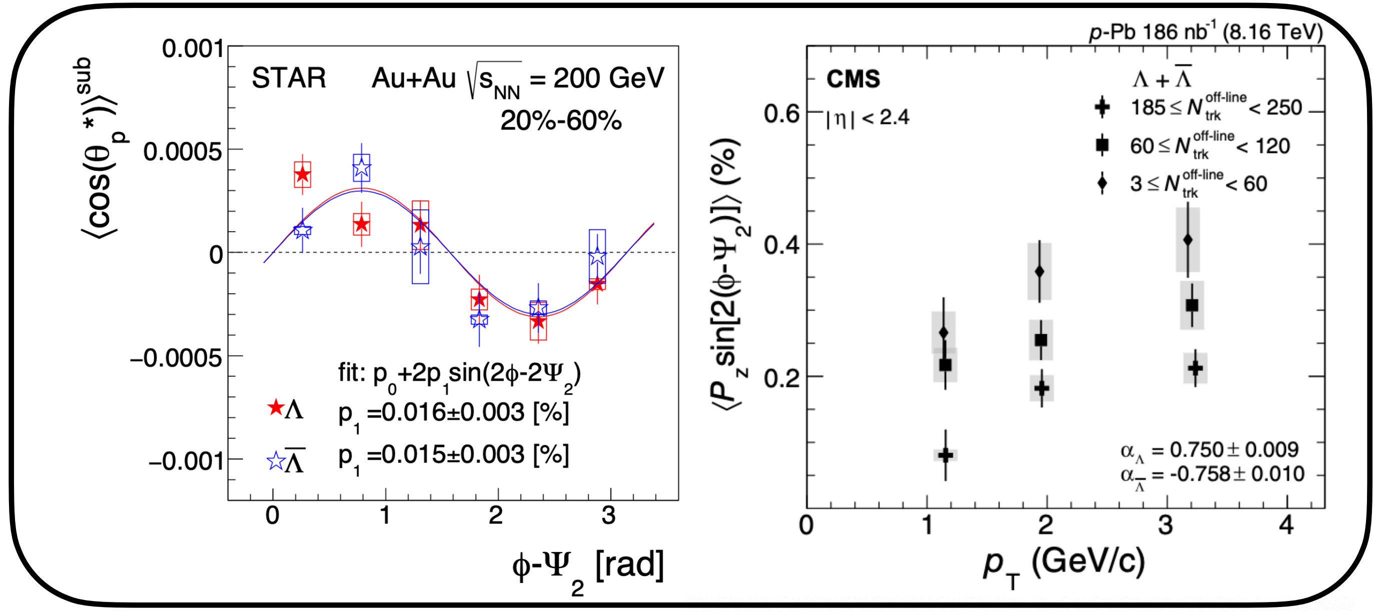
$$\tilde{\tau}_f = \sqrt{\tau^2 - x^2 - y^2} = \sqrt{t^2 - r^2}$$

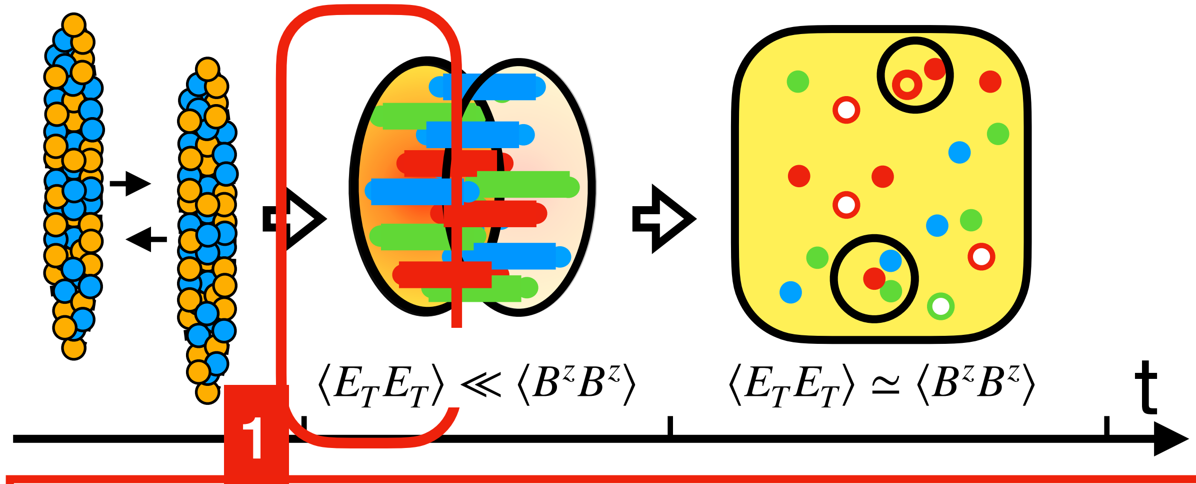
$$r_m - \Delta t \le r \le r_m$$

	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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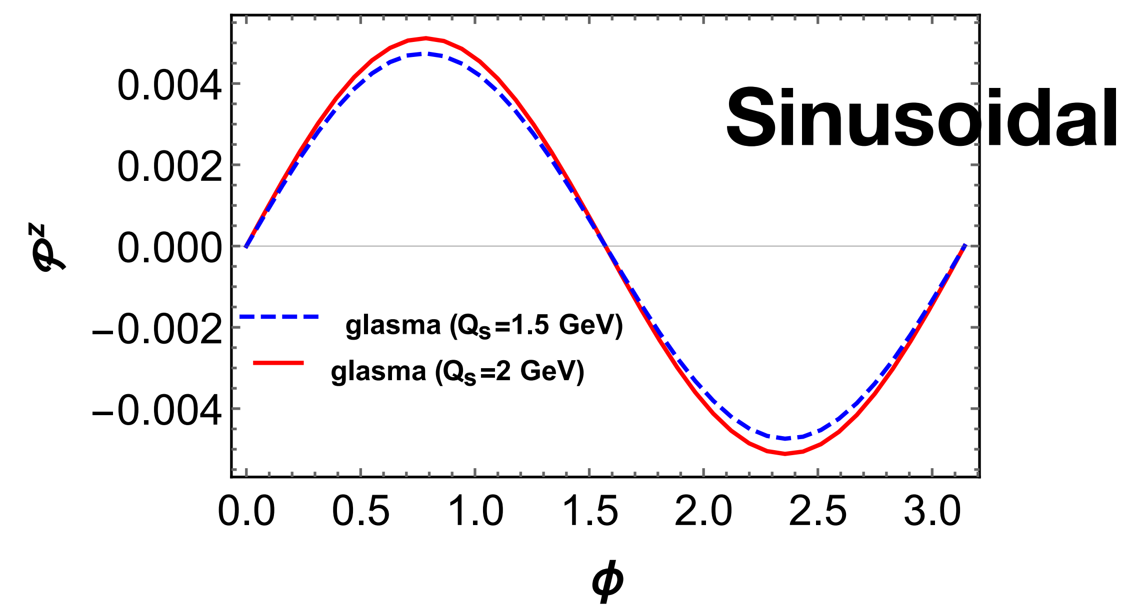
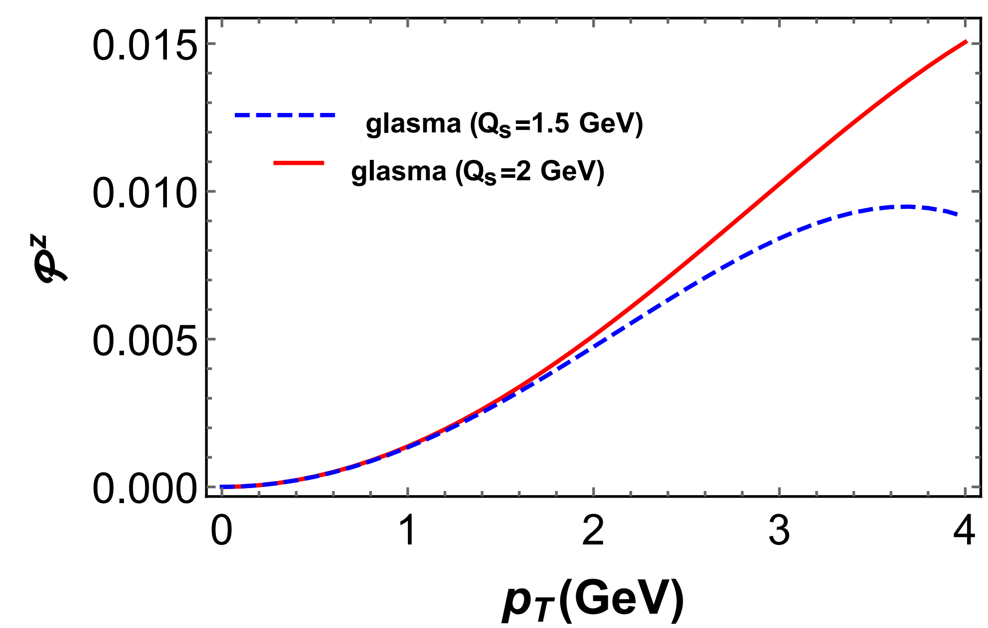
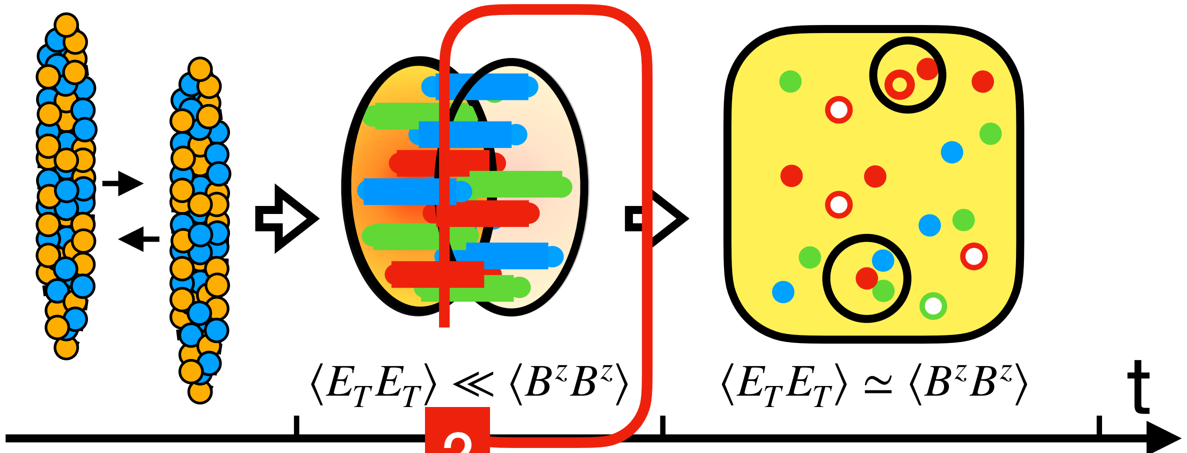
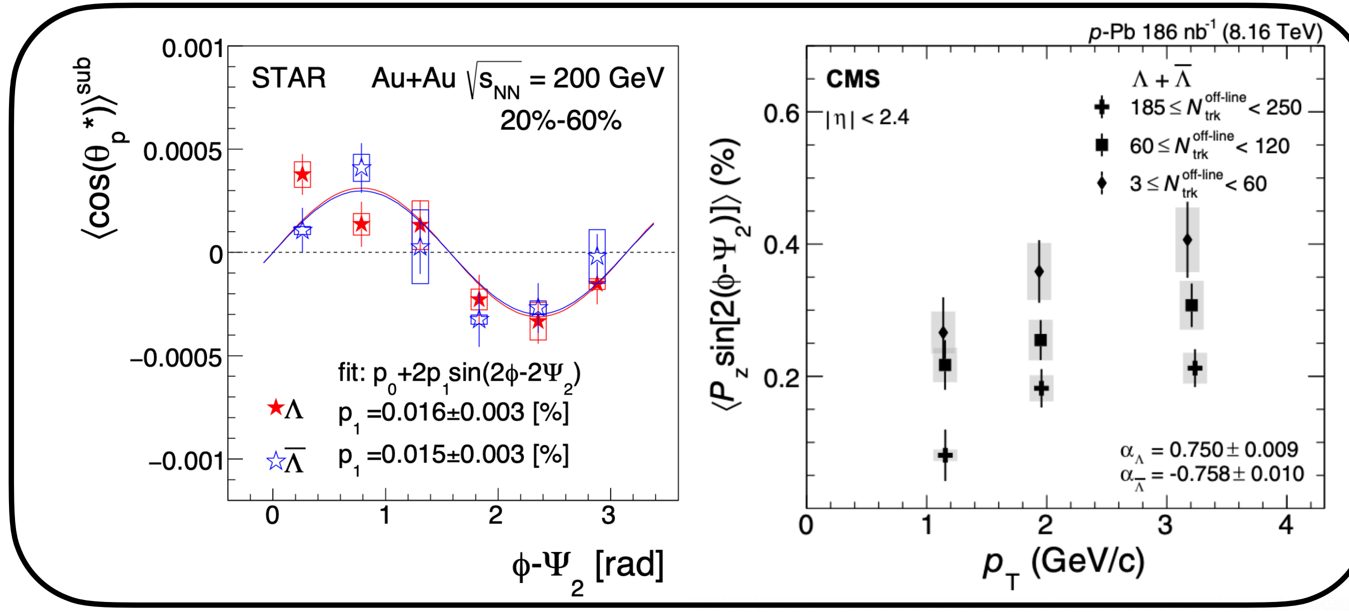
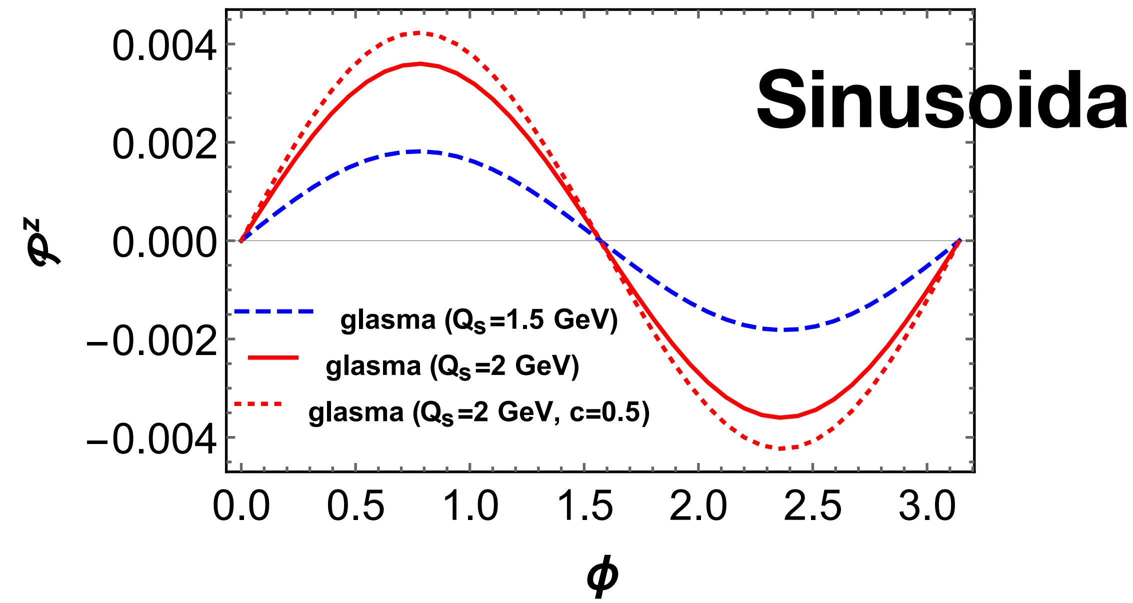




LSP in Glasma







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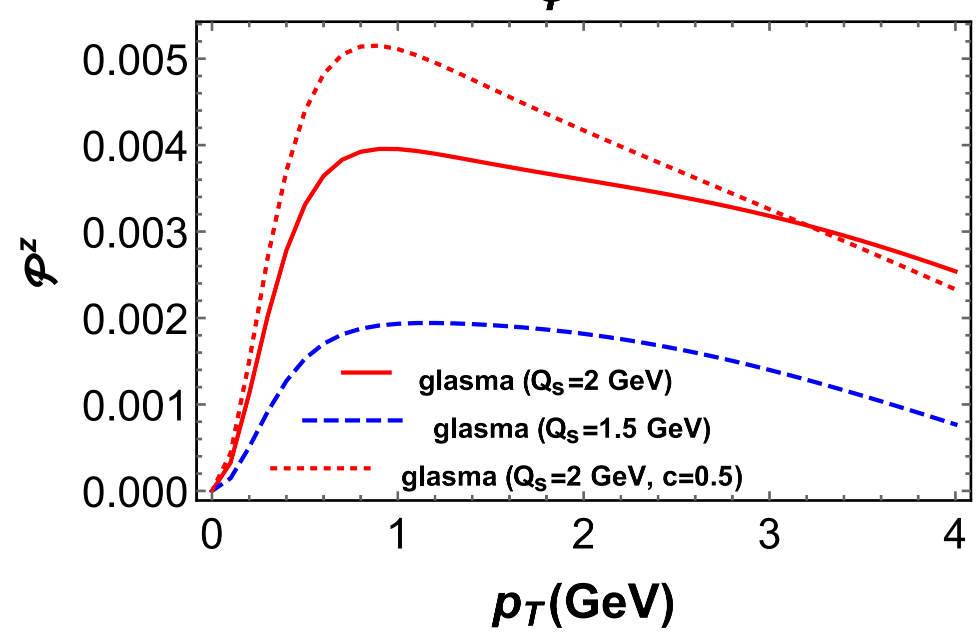
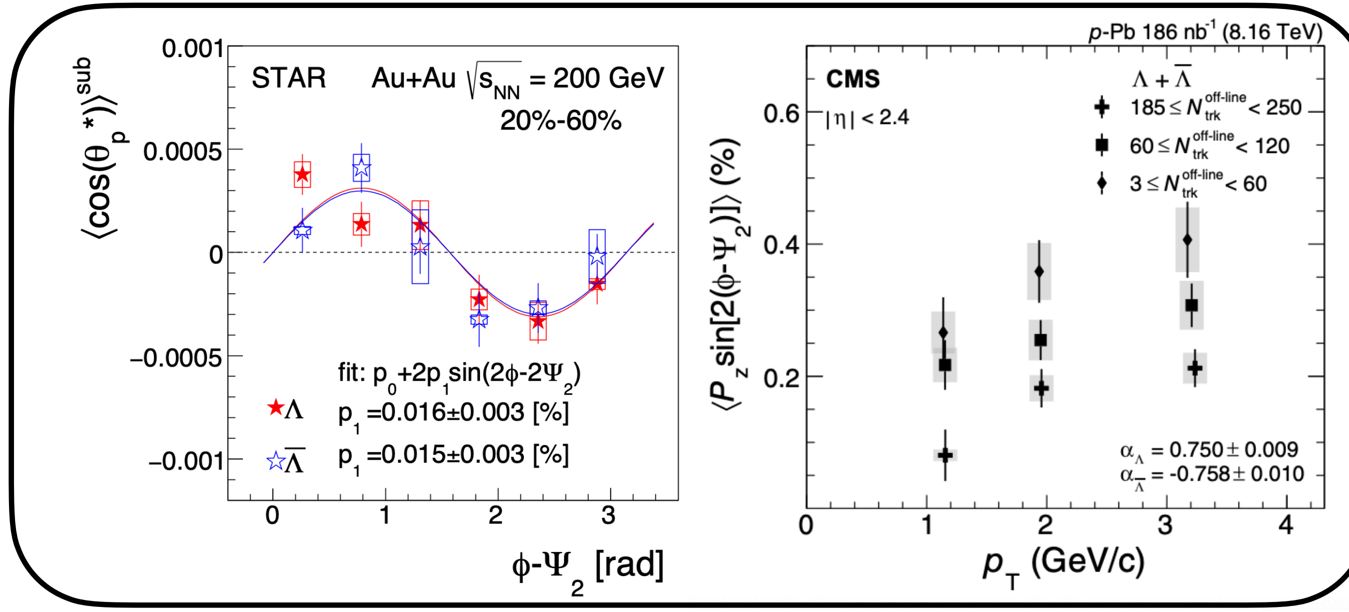
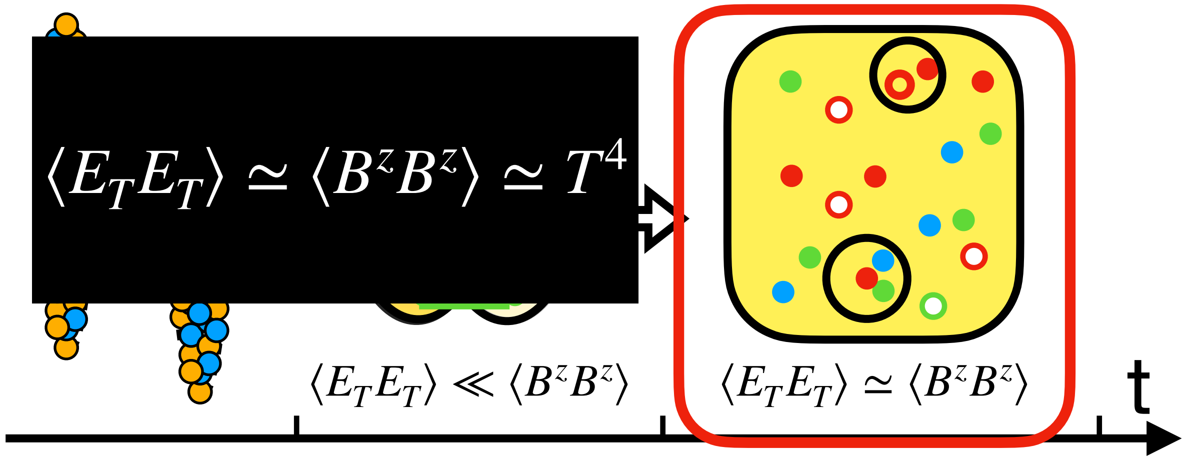


LSP in QGP





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

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

Opposite sign

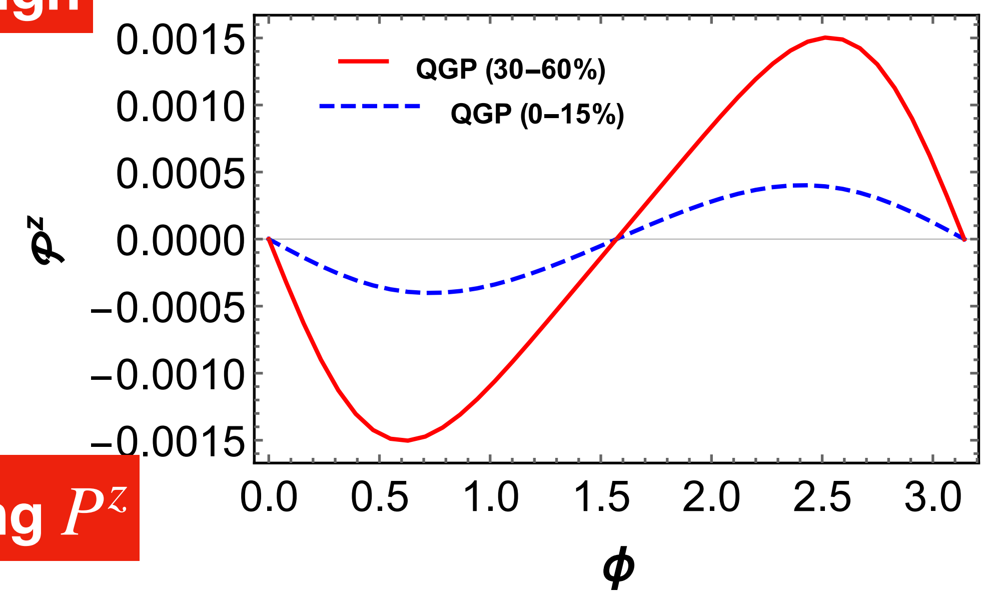
Decreasing P^z

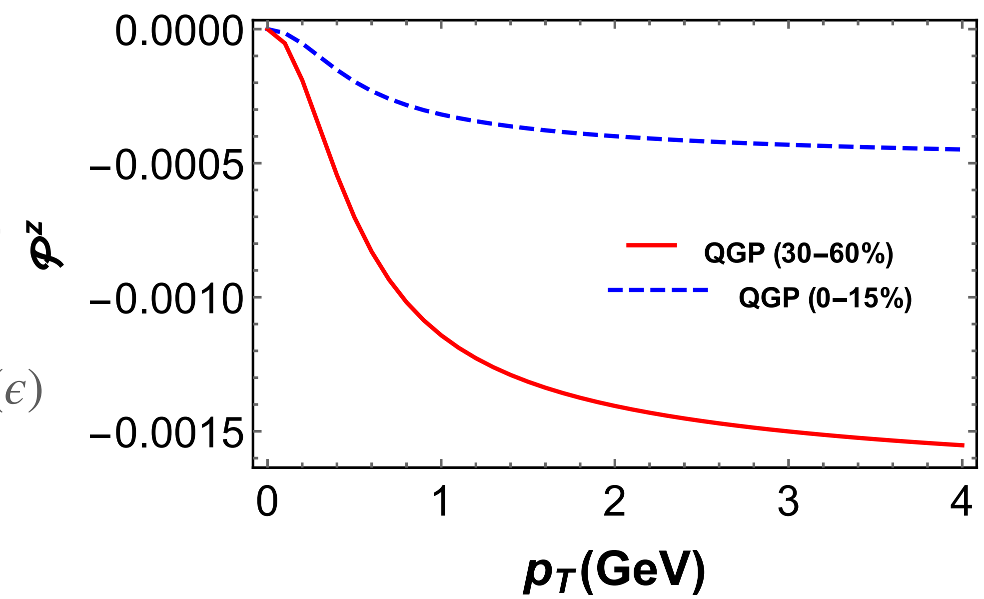
Au+Au at $\sqrt{s_{NN}} = 130$ GeV

	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)

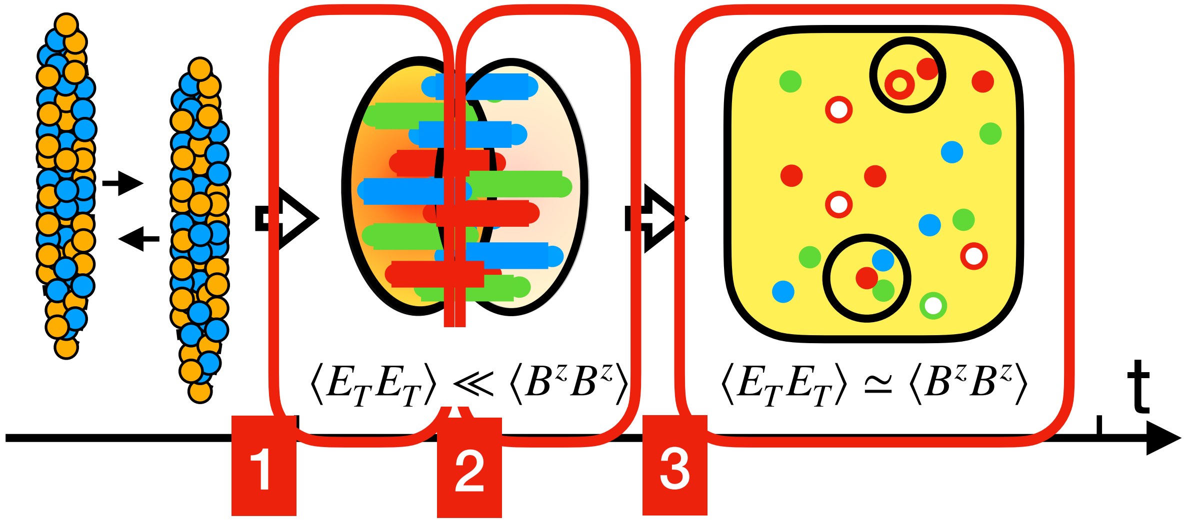
- anisotropy of transverse plane (ϵ)
- anisotropy of flow (δ)
- proper time ($\tilde{\tau}_f$)
- maximum radius (r_m)



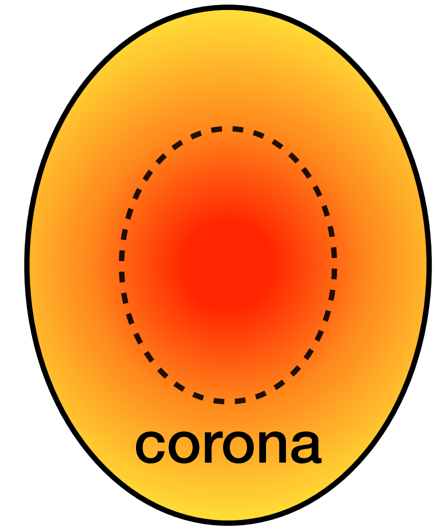


LSP in Glasma and QGP

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

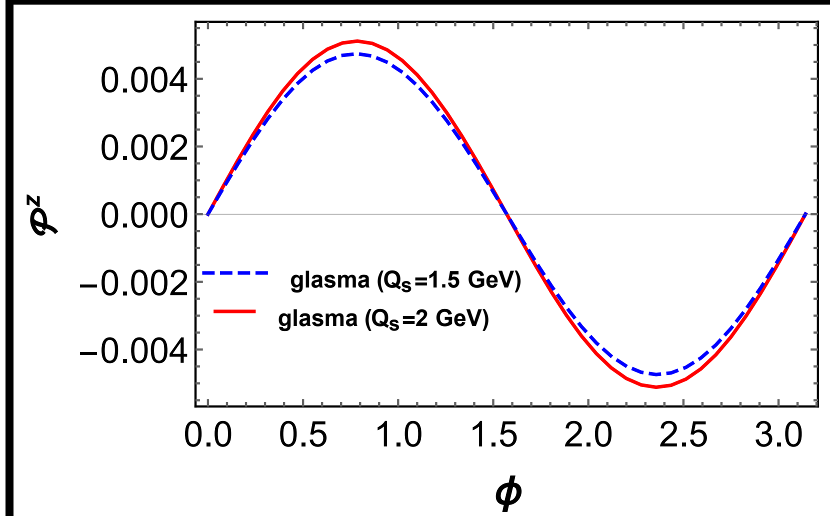


$$P^z = \frac{N_{GL} P^z_{GL} + N_{QGP} P^z_{QGP}}{N_{GL} + N_{QGP}}$$

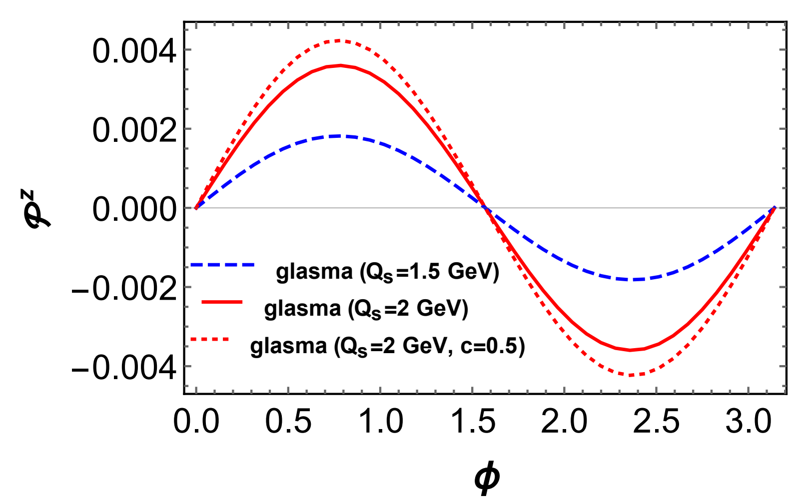


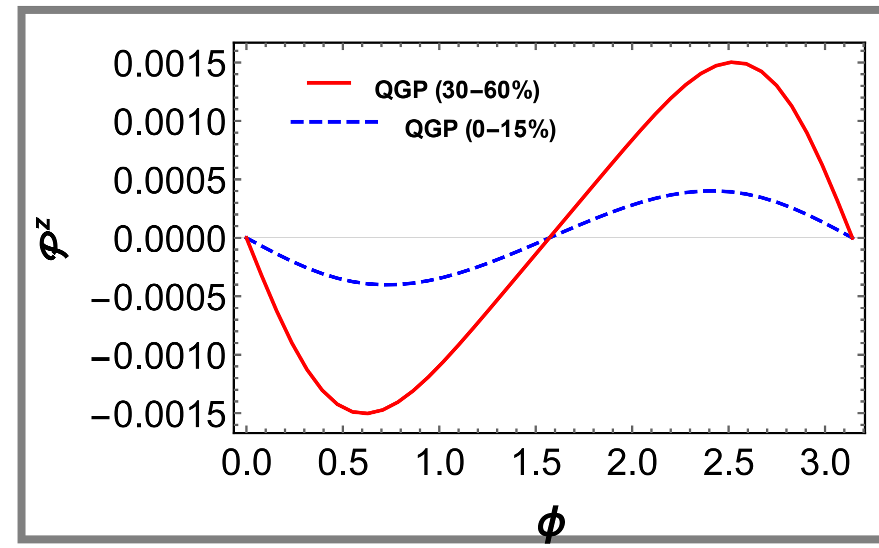
3. QGP

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

+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.

*Currently, we are discussing about deriving initial conditions for hydrodynamics and evolve spin polarization from Glasma to QGP and Hadron gas.

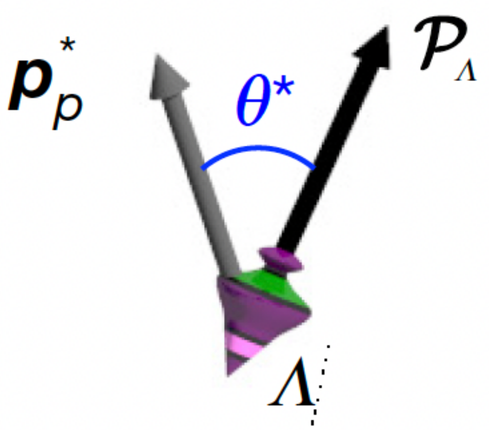
Y. Kanakubo, Y. Tachibana, and T. Hirano, Interplay between core and corona components in high-energy nuclear collisions, Phys. Rev. C 105, 024905 (2022), arXiv:2108.07943 [nucl-th].

Reference

Experiment

Positive Λ Global Polarization

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



Λ polarization vector

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \mathbf{P}_\Lambda \cdot \hat{\mathbf{p}}_p^*) = \frac{1}{4\pi}(1 + \alpha_\Lambda \mathbf{P}_\Lambda \cos\theta^*)$$

proton momentum unit vector

The proton tends to be emitted along the spin direction of the Λ with probability (opposite for antiparticle)

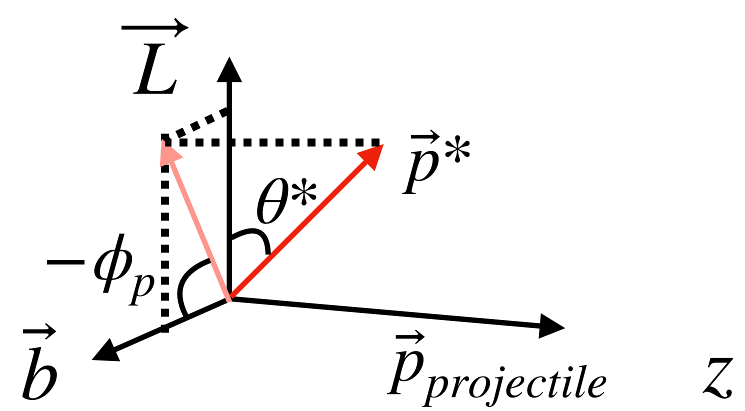
$$\boxed{\Rightarrow \mathbf{P}_\Lambda = \frac{\langle \cos\theta_p^* \rangle}{\alpha_\Lambda \langle \cos^2\theta_p^* \rangle}}$$

$\mathbf{P}_\Lambda$ = hyperon polarization vector

α_Λ = hyperson decay parameter

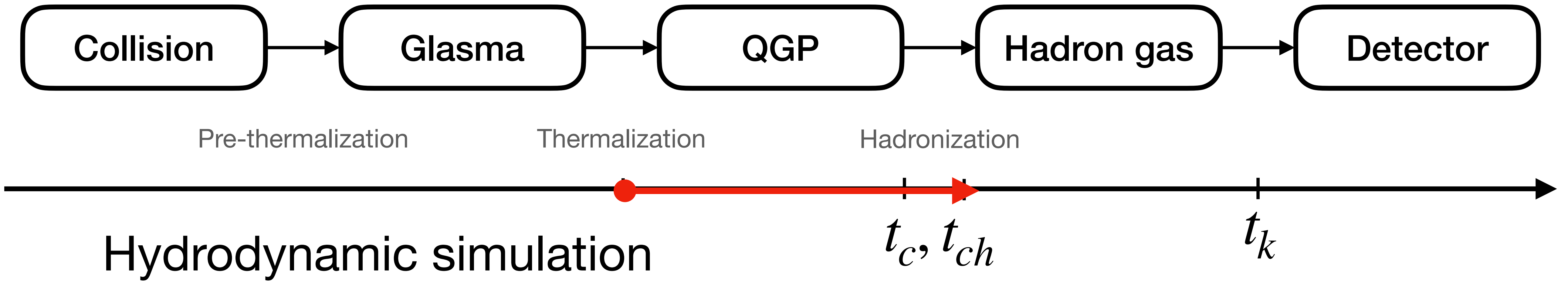
$(\alpha_\Lambda = 0.750, \alpha_{\bar{\Lambda}} = -0.758)$ **BESIII Collaboration**, Nature Phys, 15(2019) 631-634

$\hat{p}_p^*$ = unit vector along proton(dauther baryon) momentum

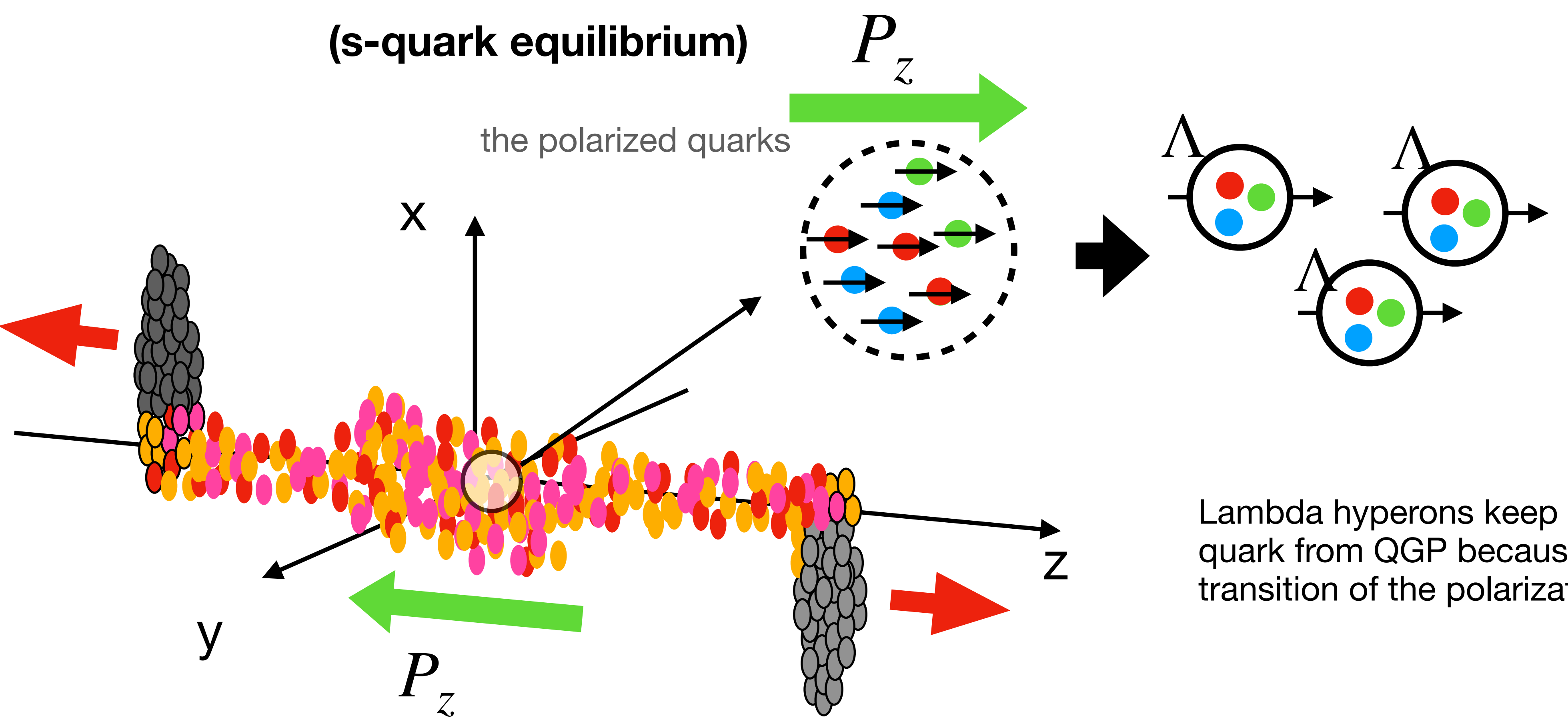


Longitudinal Polarization

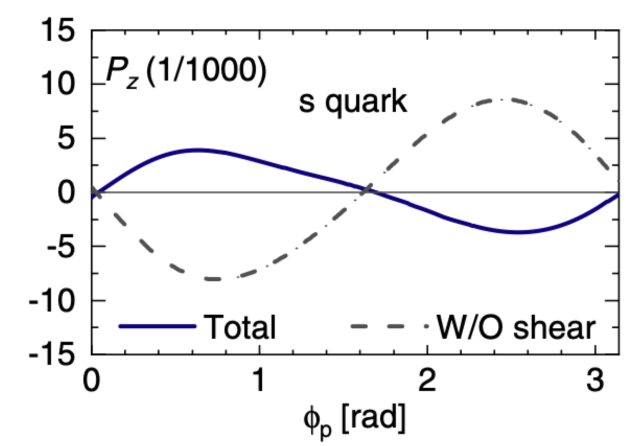
s-quark equilibrium



(s-quark equilibrium)



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

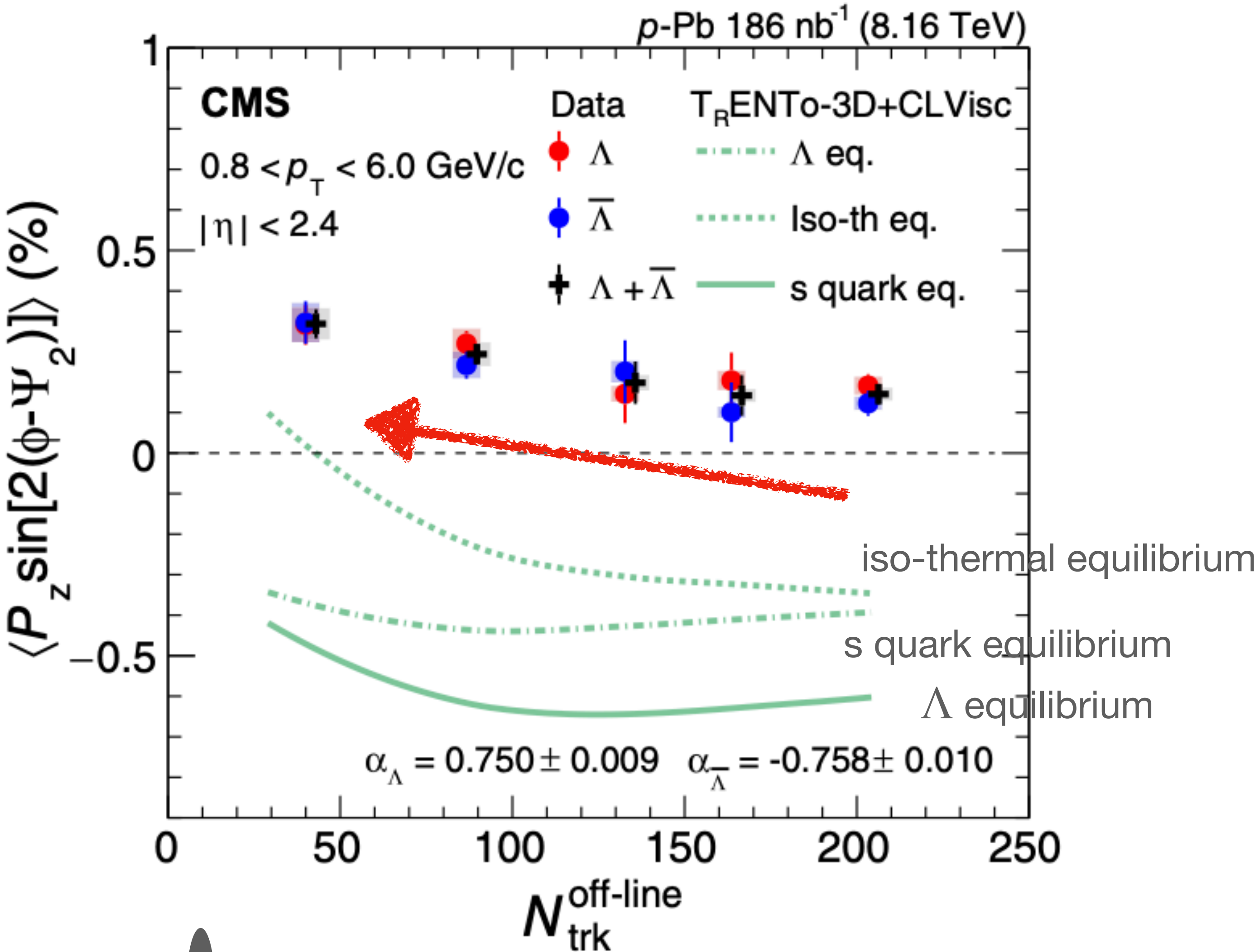


Lambda hyperons keep the spin direction of the strange quark from QGP because we assume the perfect transition of the polarization from quarks to hadrons.

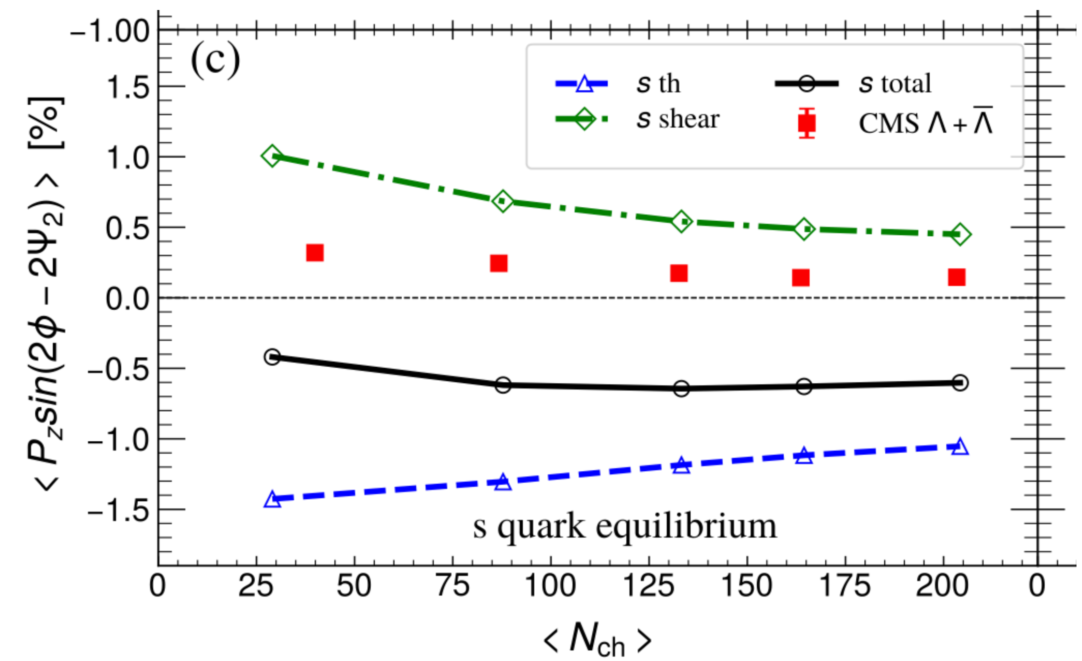
LSP with multiplicity and p_T in p+ Pb collision

Hydrodynamic simulation (vorticity+shear)

A. Hayrapetyan et al. (CMS), Phys.Rev.Lett. 135 (2025) 13, 132301



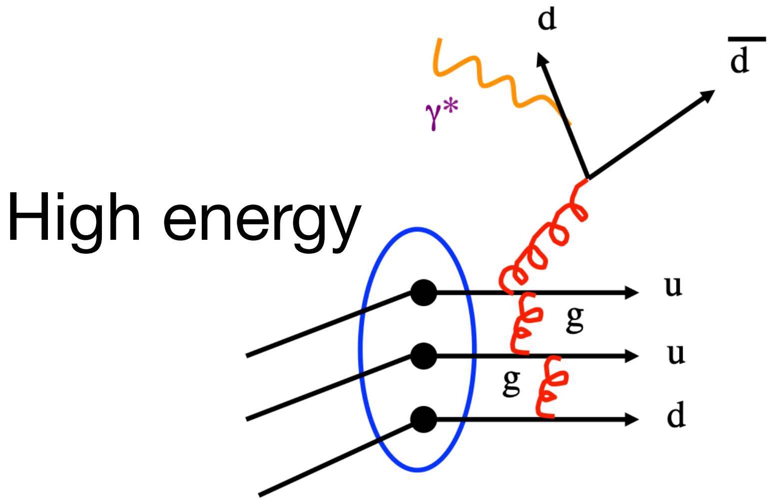
Cong Yi et al., *Phys.Rev.C* 111 (2025) 4, 044901

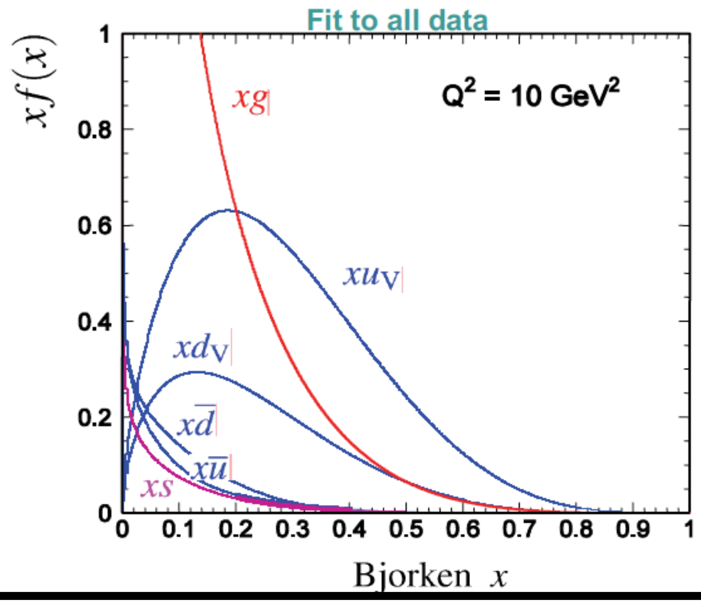


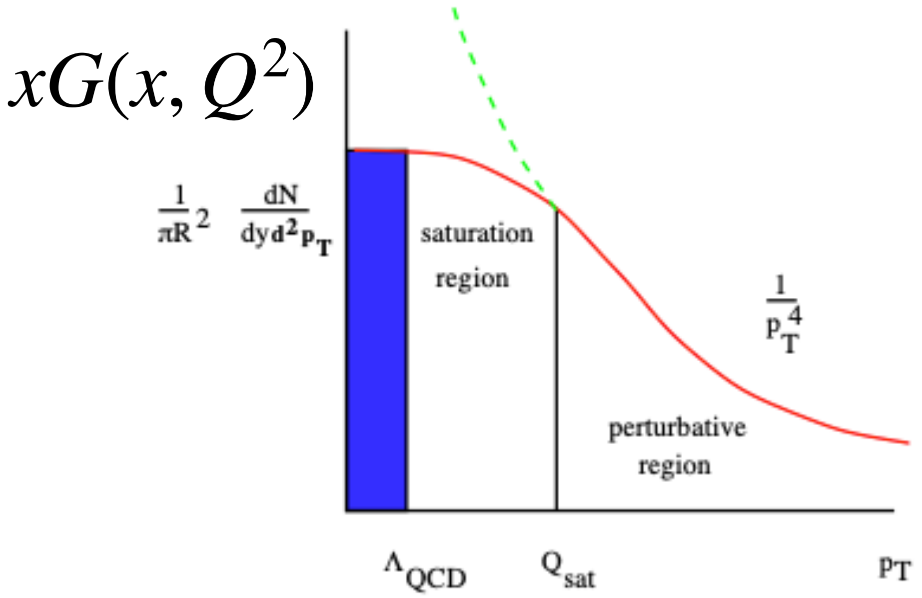
Color Glass Condensate (CGC)

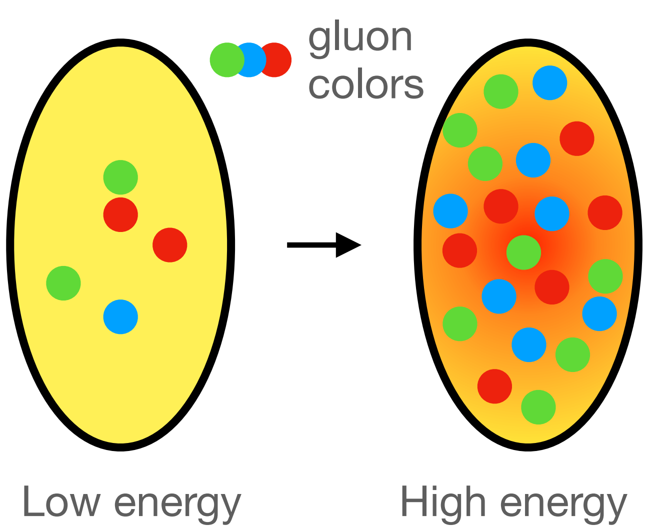
M.A. Thomson, Michaelmas 2011

Raju Venugopalan, Orsay Summer School (2014)









- Color: gluons have color
- Glass: gluons with small longitudinal momentum fraction $(x \ll 1)$ are created by long-lived partons that are distributed randomly on the transverse disk
- Condensate: small-x gluon density is very high, and saturated