Institute of Physics, Academia Sinica

Taiwan Nuclear Physics Retreat 2026

(TNP 2026)

Local Spin Polarization by color-field correlators and momentum anisotropy

Haesom Sung

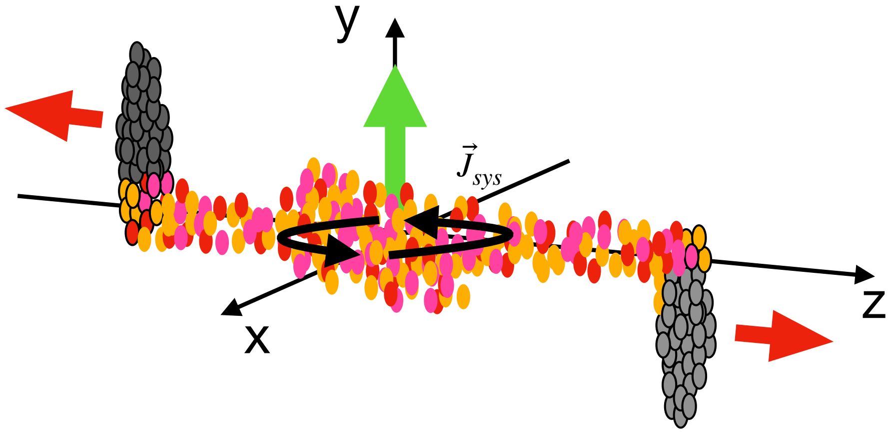
Berndt Müller, and Di-Lun Yang

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

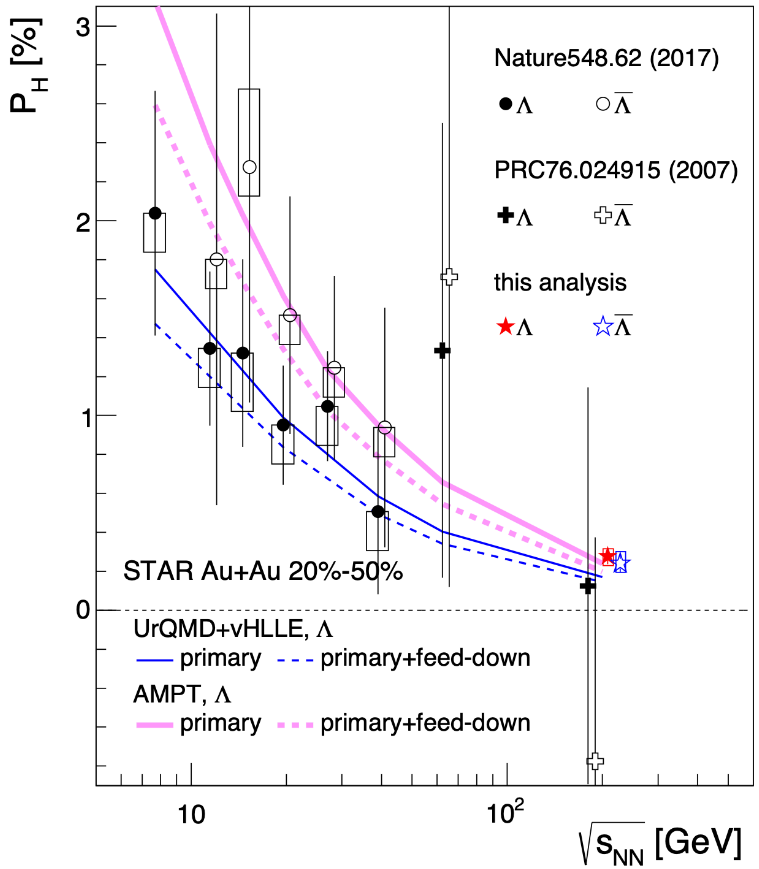
2026.04.22

Motivation

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)

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

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

Global polarization from vorticity

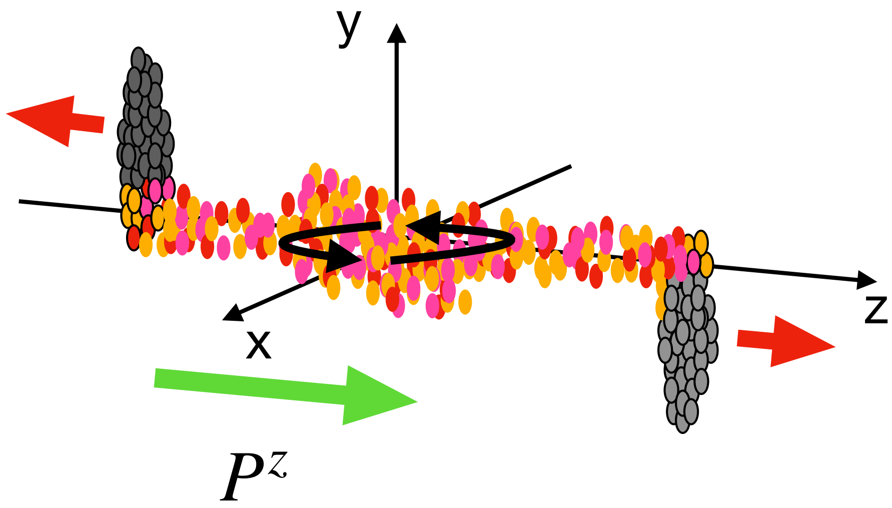
F. Becattini et al., PRC95, 054902 (2017)

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

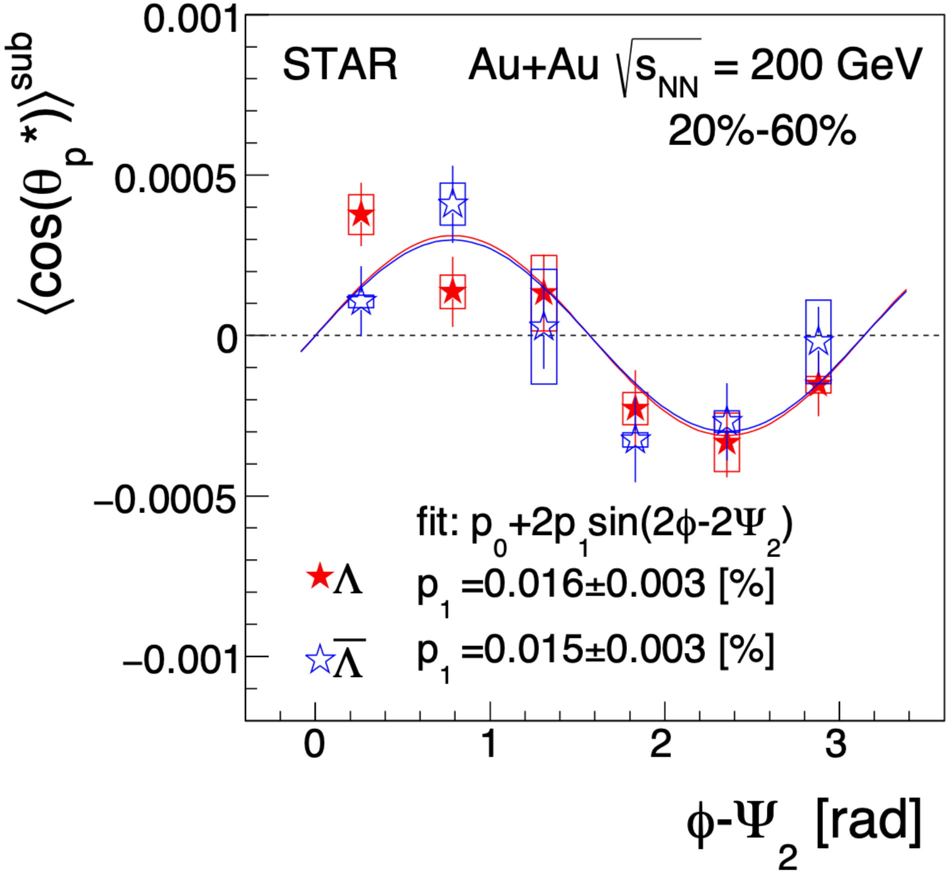
$$\omega \simeq 0.02\,\mathrm{fm}^{-1}$$

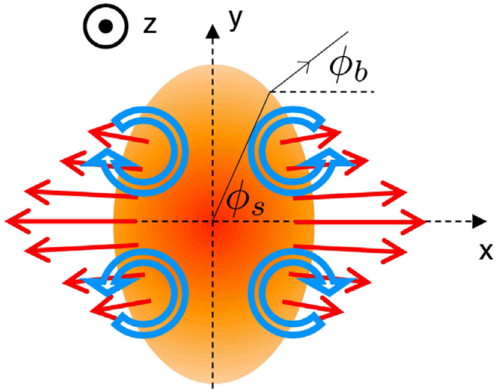
Motivation
Longitudinal Polarization

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



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



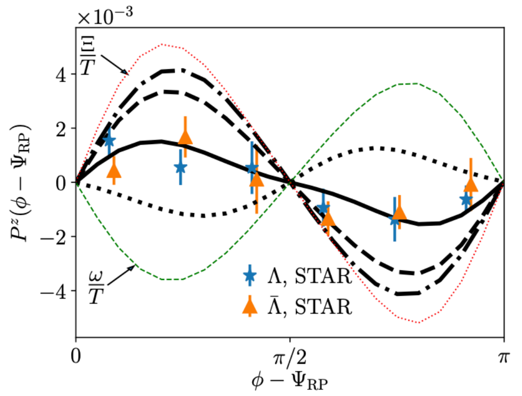


$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle \cos^2\theta_p^* \rangle}$$

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)



$$S^{\mu} = S^{\mu}_{\varpi} + S^{\mu}_{\xi}$$

Vorticity and shear effect have **opposite signs**

Thermal vorticity

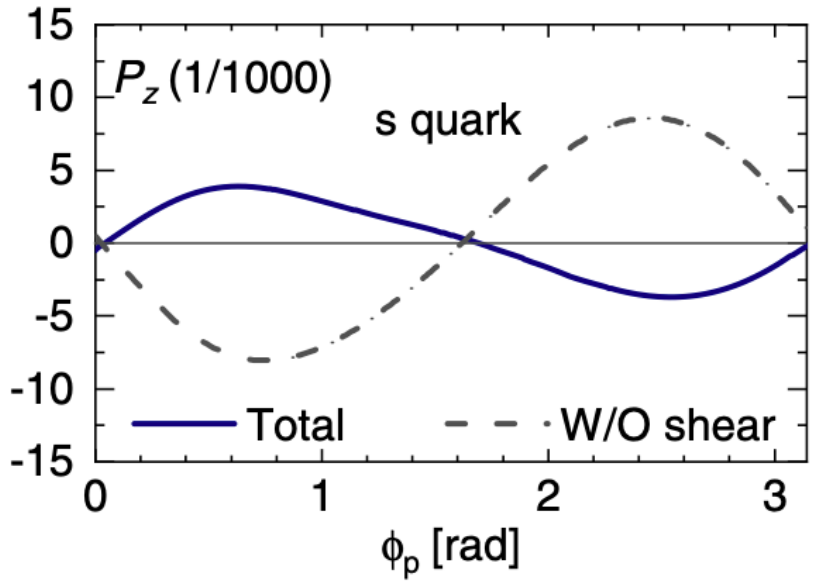
$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_{\mu}\beta_{\nu} - \partial_{\nu}\beta_{\mu})$$

Thermal shear

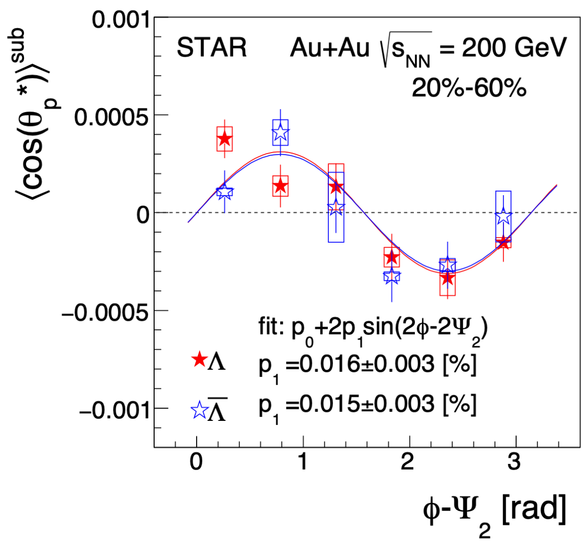
$$(\xi_{\mu\nu} = 0 \quad \text{at global equilibrium})$$

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

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



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

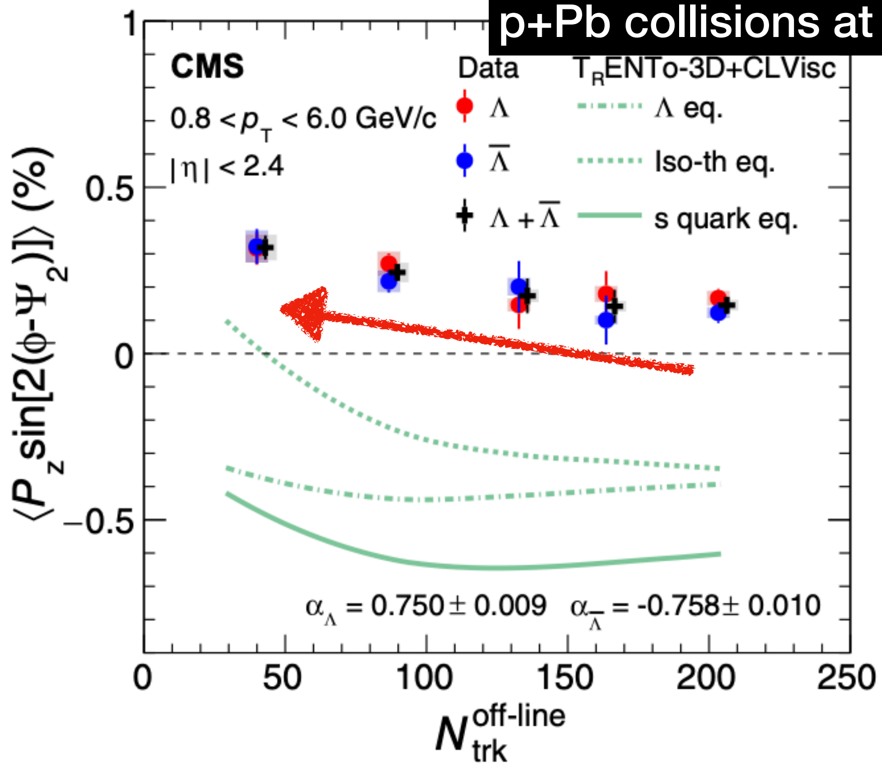


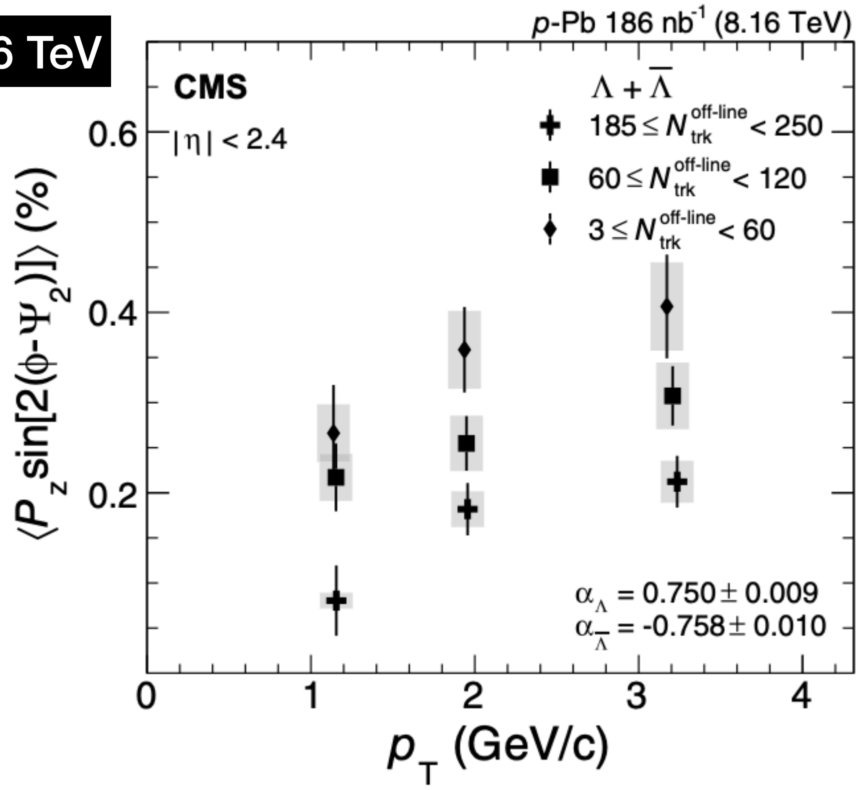
Longitudinal Local Polarization

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)]

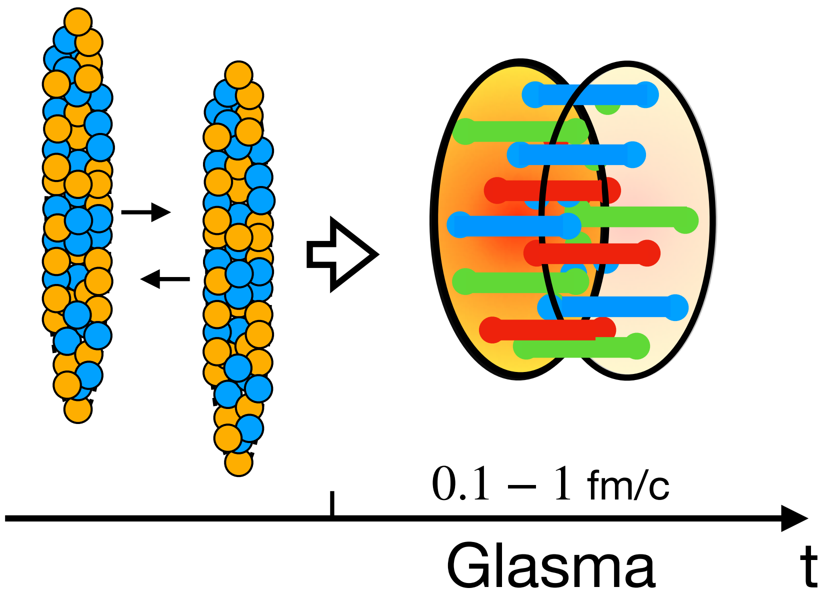
p+Pb collisions at 8.16 TeV



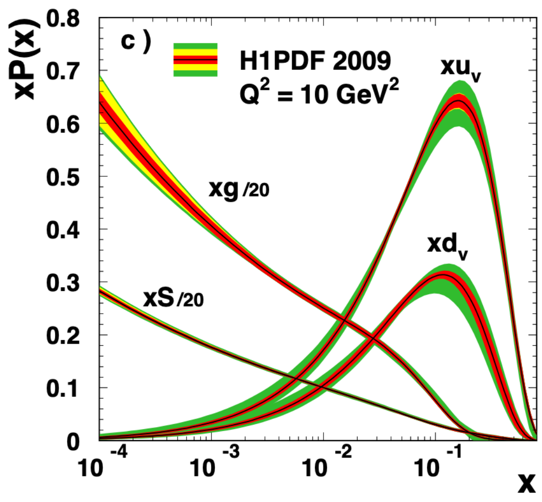


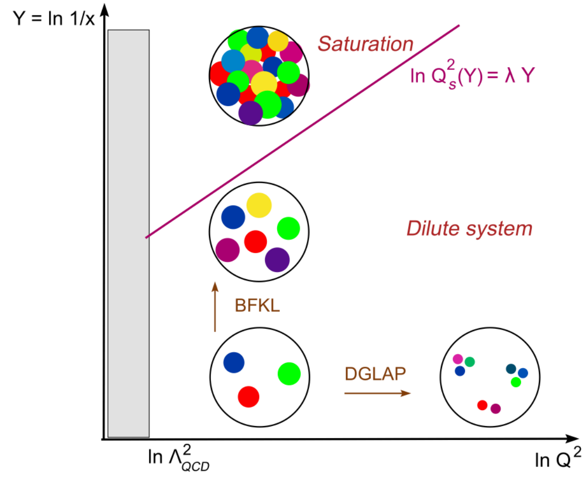
Thermal vorticity and thermal shear effect can not describe this experimental result with multiplicity and p_T dependence

Initial stages of heavy ion collisions

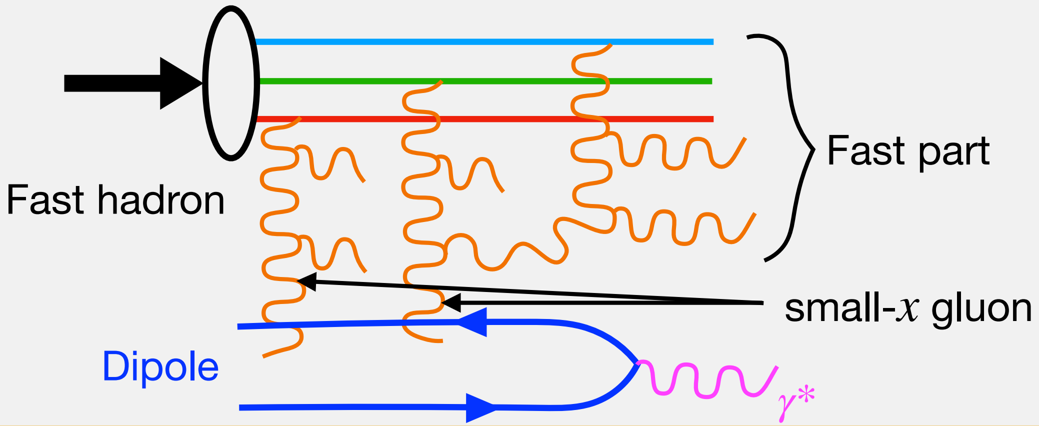


F. Gelis et al., Ann.Rev.Nucl.Part.Sci.60:463-489,2010





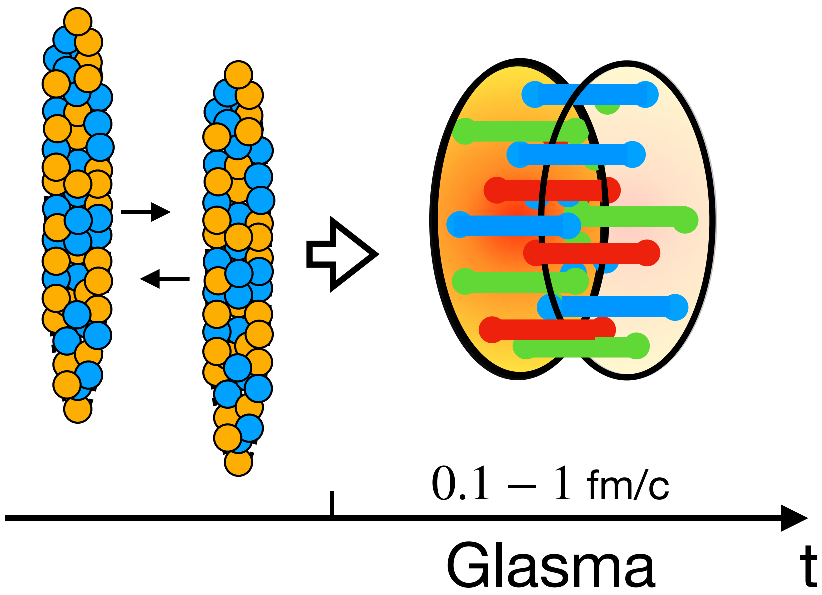
Color Glass Condensate (CGC) : Highly populated soft gluons ($E < Q_S$) sourced by hard hadrons



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

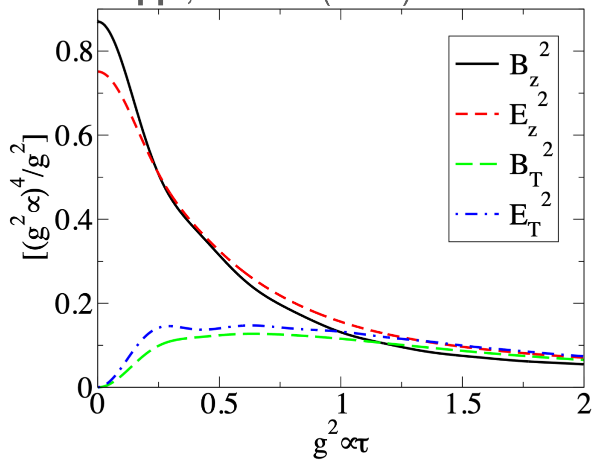
soft gluons — hard partons

Initial stages of heavy ion collisions

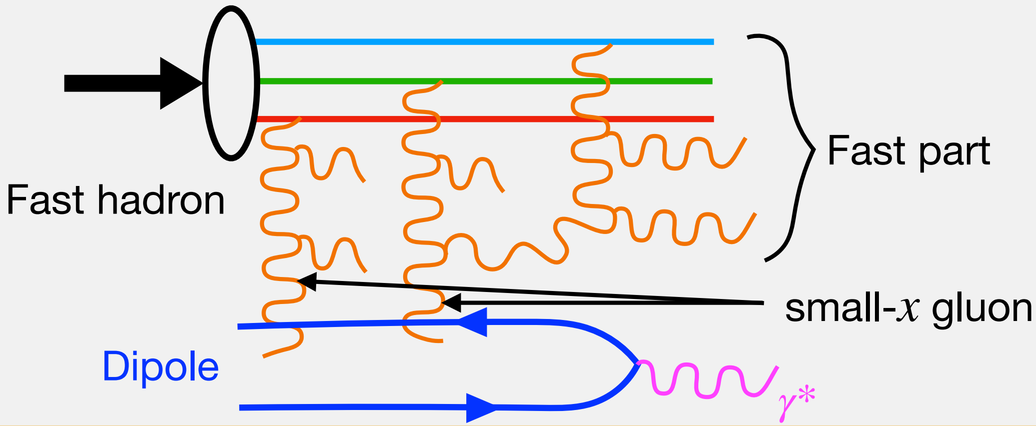


Glasma : color flux tubes

T. Lappi, PLB643(2006)11-16



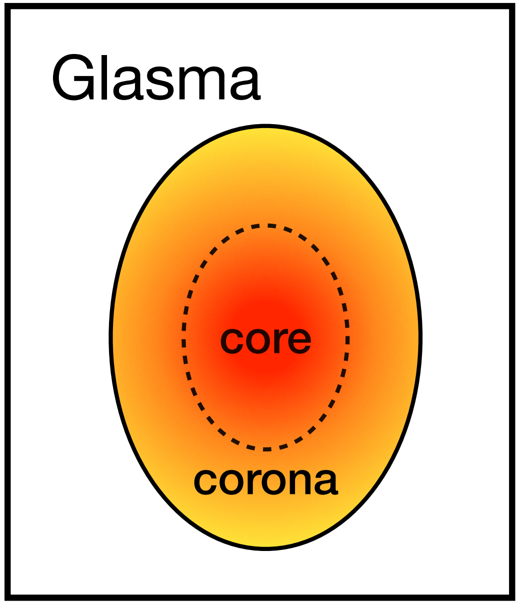
Color Glass Condensate (CGC) : Highly populated soft gluons ($E < Q_S$) sourced by hard hadrons

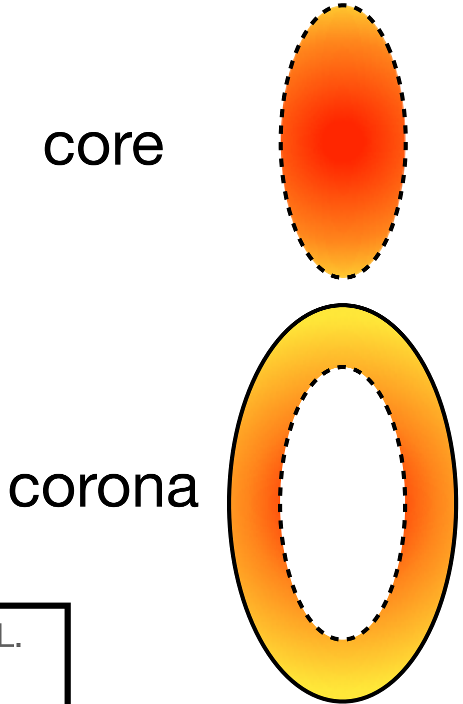


$$D^\mu F^{(a)}_{\mu\nu} = \delta^{\nu+}\delta(x^-)\rho^a(x_\perp)$$

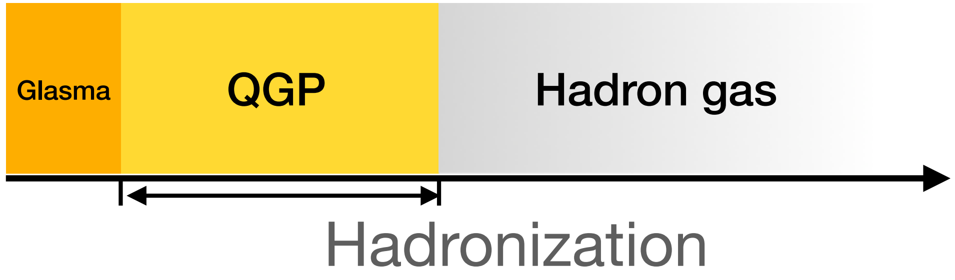
soft gluons — hard partons

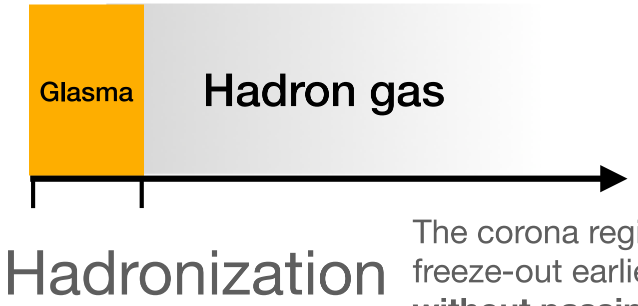
Corona effect





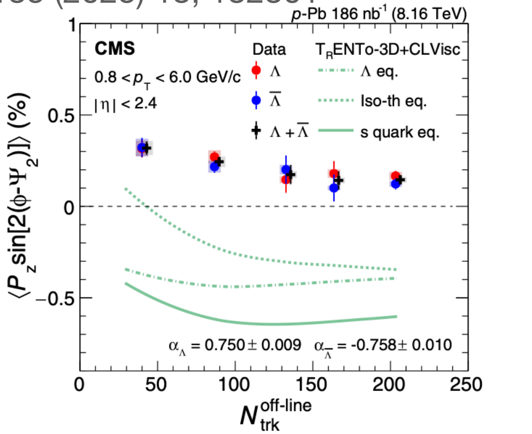
The core region undergoes full **thermalization**, forming the QGP, which then expands and hadronizes as the system cools





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)**

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

$$m = m_s$$

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

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

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

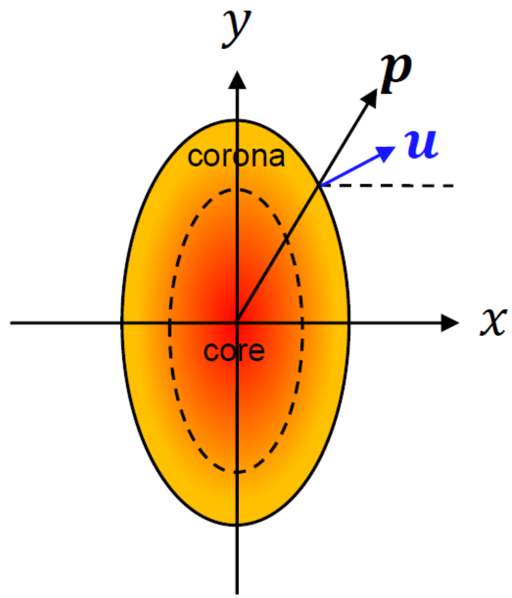
For weak coupling, $f_V^a(p,x)$ can be expressed perturbatively in terms of the singlet distribution.

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

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

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

Polarization from QKT



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

Only parity-even correlators:

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

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

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

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

Color-singlet polarization pseudo-vector

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

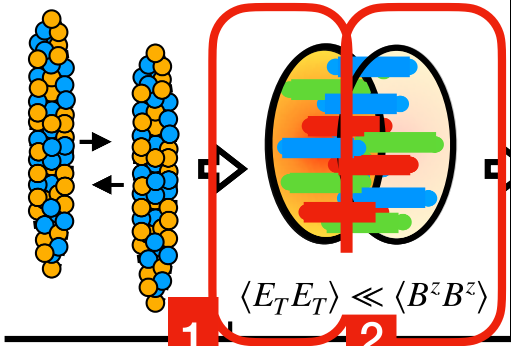
Chromo-Lorentz force:

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

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-Rodŕıguez et al.**, Phys. Rev. D 104, 014011 (2021)

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

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

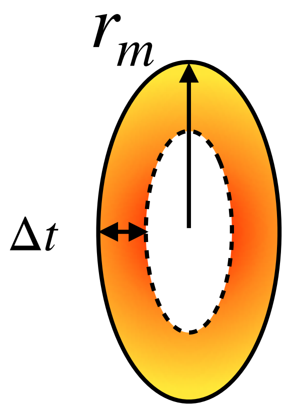
2. Quasi-equilibrium:

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

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

corona

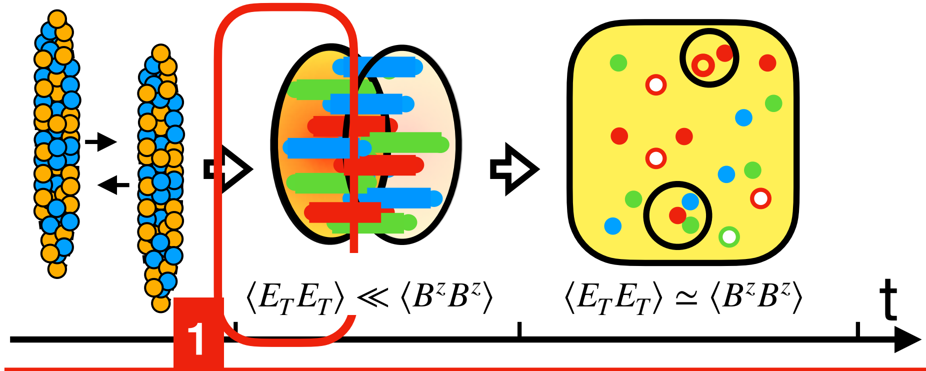
$$r_m - \Delta t \le r \le r_m$$

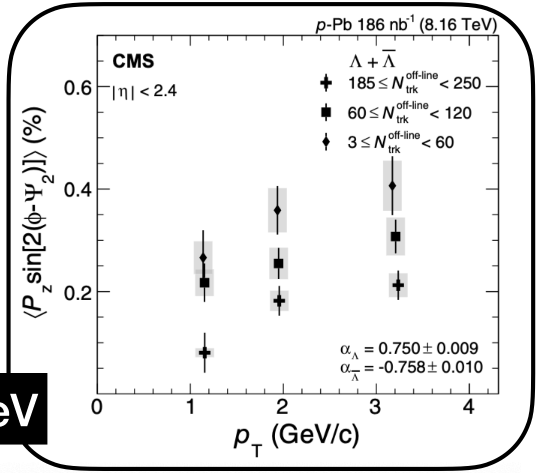


	Glasma (Non-eq)	Glasma (Quasi-eq)
ϵ	0	
δ	0.3	
$\tilde{\tau}_f$	0	
r_m	0.5 fm	
Λ_c	$Q_s = 1.5$ or 2 GeV	
u_T	0.01	0.2

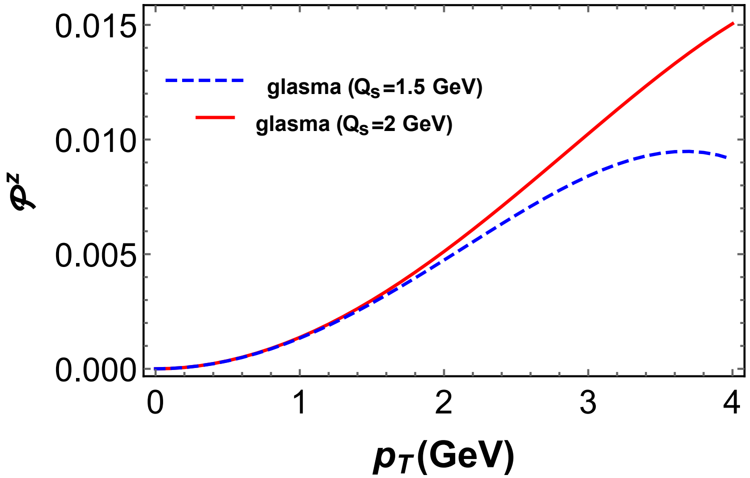
$$u^\mu = \frac{1}{N_v}\left(1, u_T(1+\delta)\frac{x\tau}{r_m^2}, u_T(1-\delta)\frac{y\tau}{r_m^2}, 0\right)$$

LSP in Glasma





p+Pb collisions at 8.16 TeV



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

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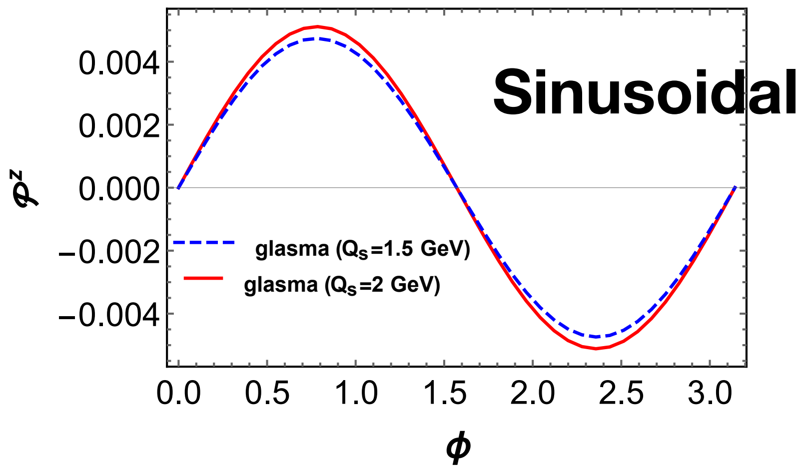
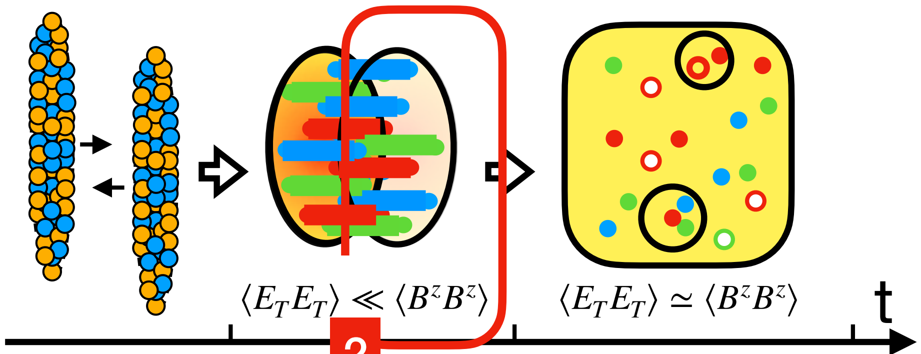


LSP in Glasma



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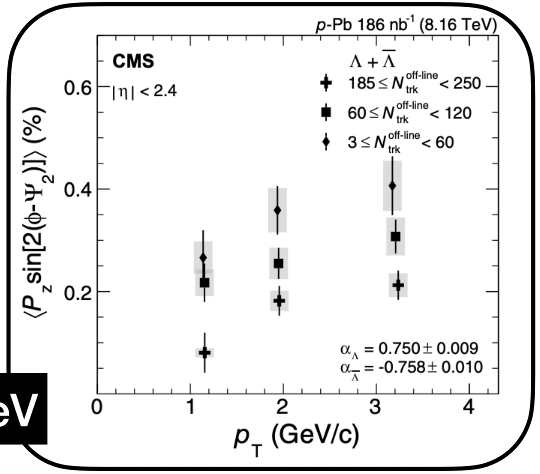

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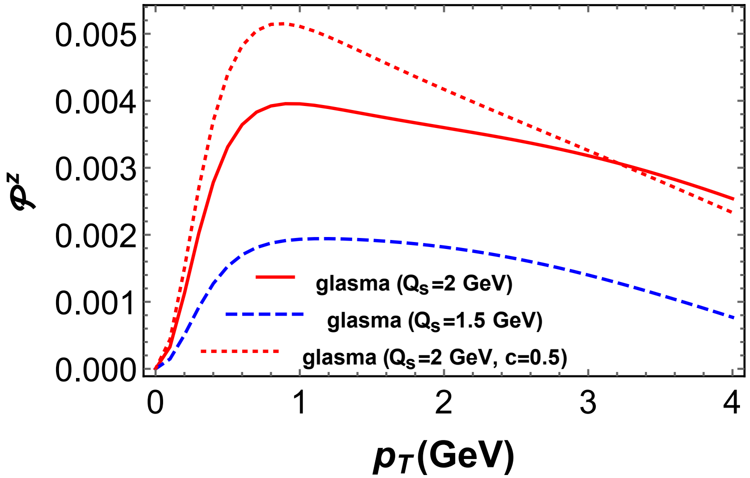
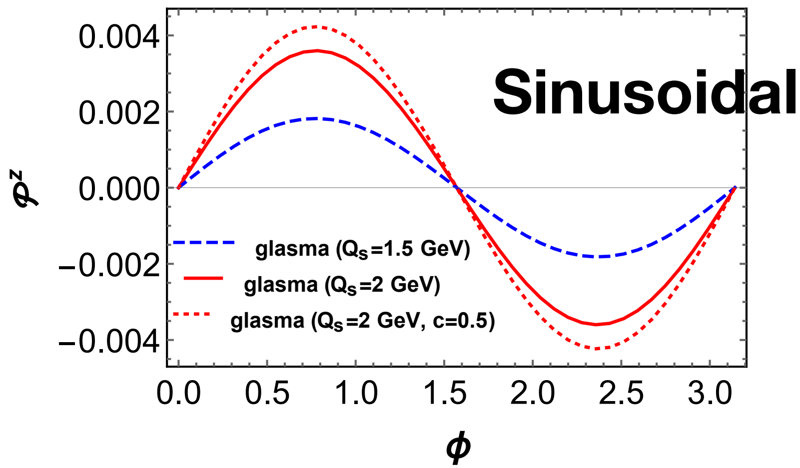
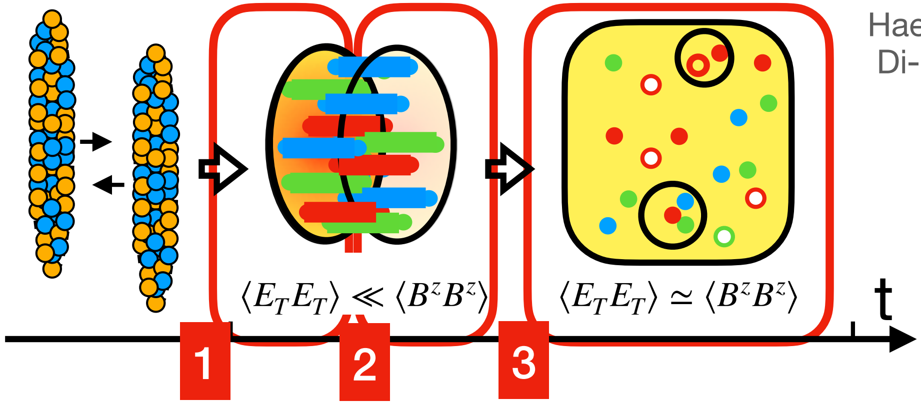


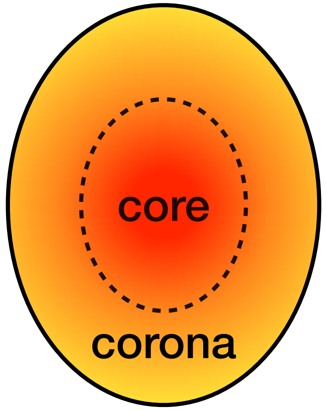


LSP in Glasma and QGP

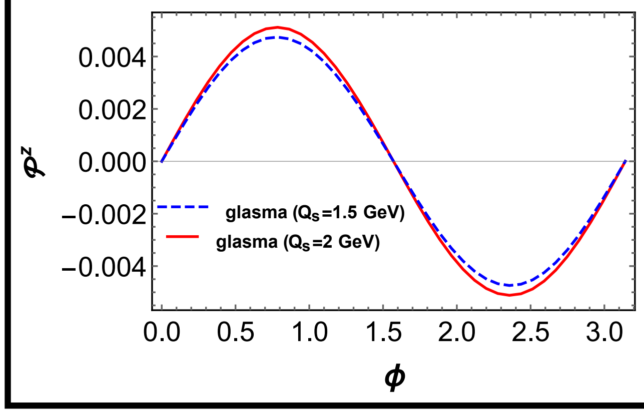


Haesom Sung, Berndt Müller,
Di-Lun Yang, arXiv:2507.23210v3

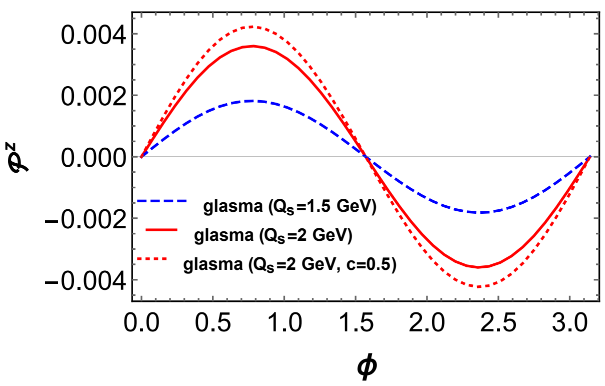
$$P^z = \frac{N_{GL} P^z_{GL} + N_{QGP} P^z_{QGP}}{N_{GL} + N_{QGP}}$$



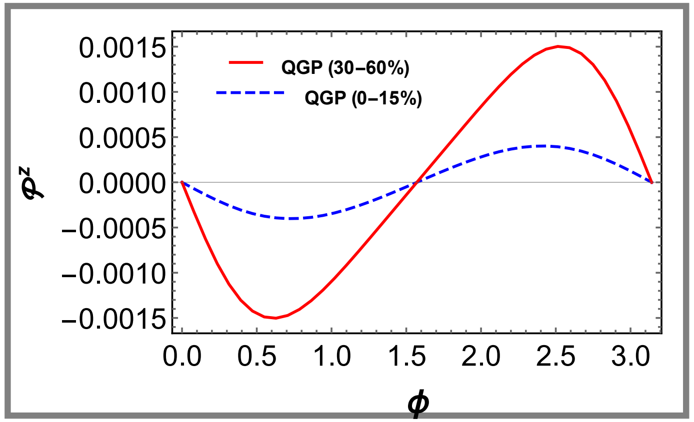
1. Glasma(non-eq)



2. Glasma(quasi-eq)



3. QGP

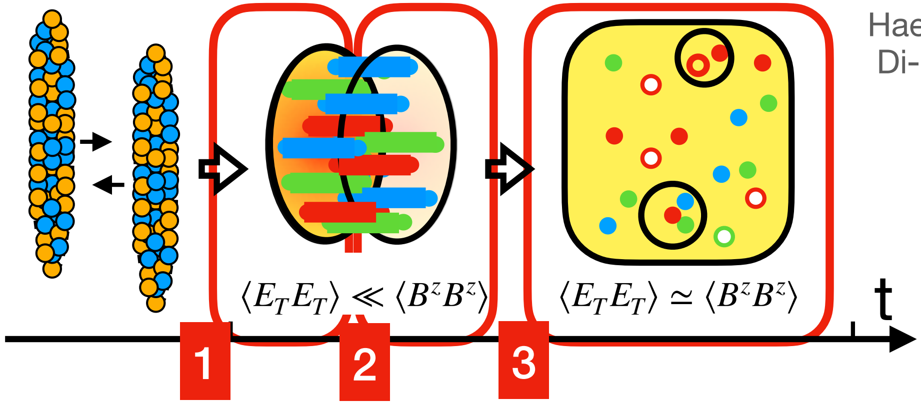


In **small system**, $N_{GL} \gg N_{QGP}$, so we can expect the **Sinusoidal** structure in azimuthal angle

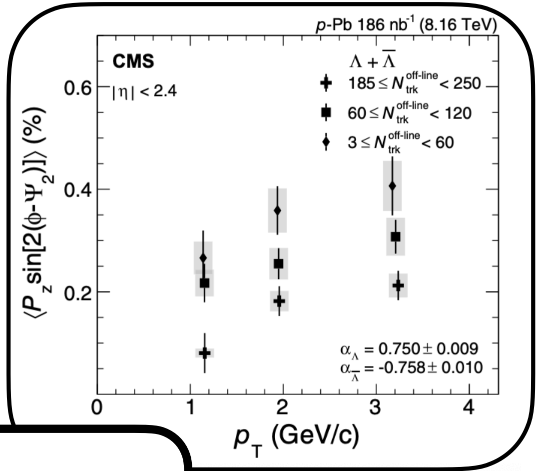
+Hydrodynamic contribution (vorticity+shear)

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

LSP in Glasma and QGP

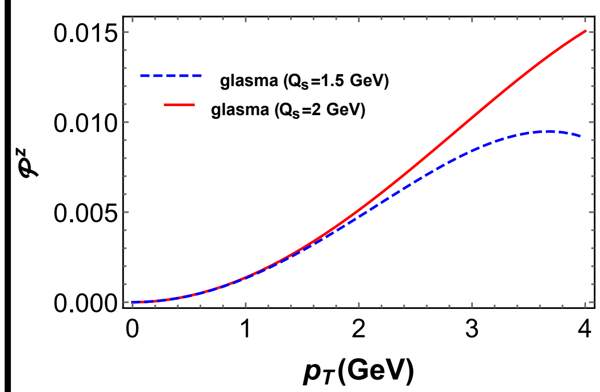


Haesom Sung, Berndt Müller,
Di-Lun Yang, arXiv:2507.23210v3

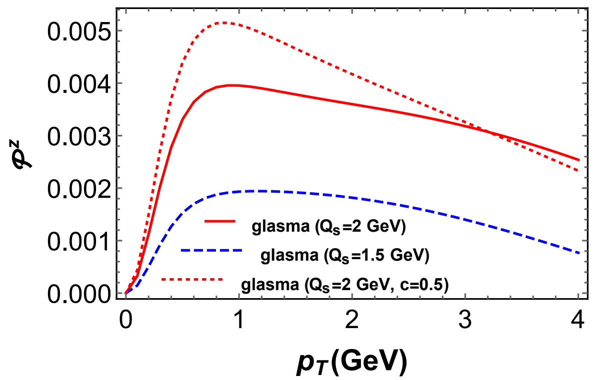


$$P^z = \frac{N_{GL} P^z_{GL} + N_{QGP} P^z_{QGP}}{N_{GL} + N_{QGP}}$$

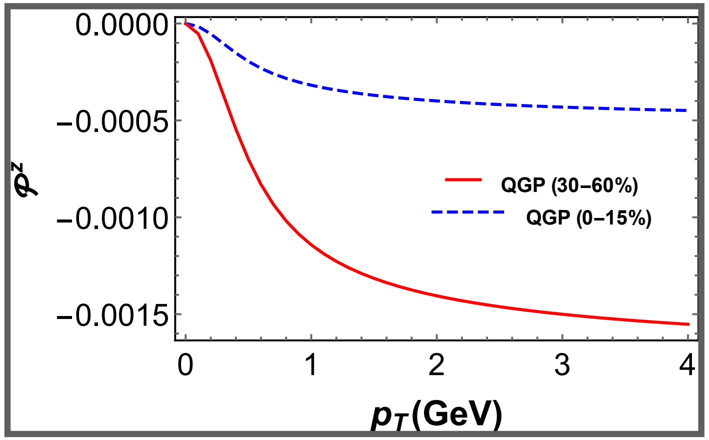
1. Glasma(non-eq)



2. Glasma(quasi-eq)



3. QGP



N_{GL} for smaller system and high p_T

N_{QGP} for larger system and low p_T

+Hydrodynamic contribution (vorticity+shear)

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

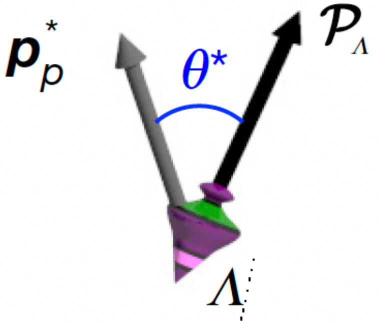
- To reproduce experimental data, it is essential to develop sophisticated simulations of the core and corona from the glasma to QGP.

Appendix

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)

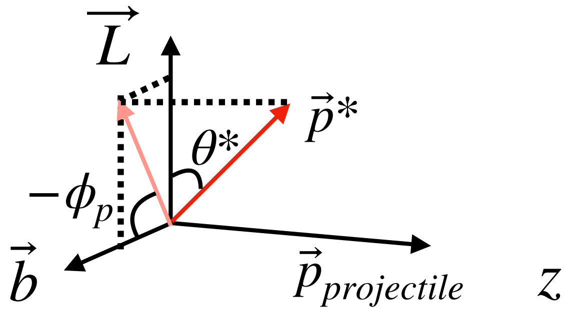
$$\Rightarrow \mathbf{P}_\Lambda = \frac{\langle \cos\theta_p^* \rangle}{\alpha_\Lambda \langle \cos^2\theta_p^* \rangle}$$

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

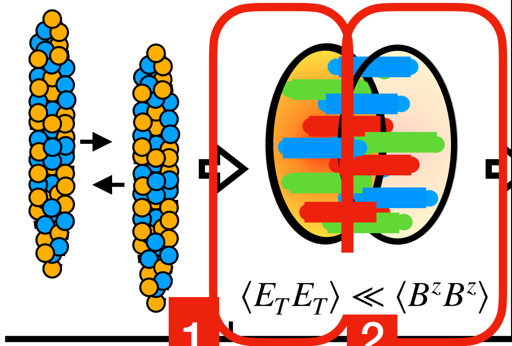
α_Λ = hyperson decay parameter

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

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



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:

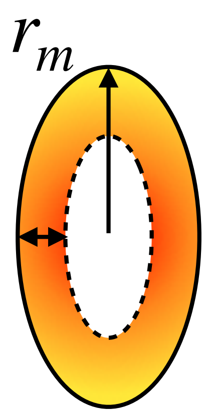
$$f_V^s(p\cdot u/Q_s) = \frac{1}{e^{p\cdot u/Q_s}+c}$$

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

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

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

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



corona

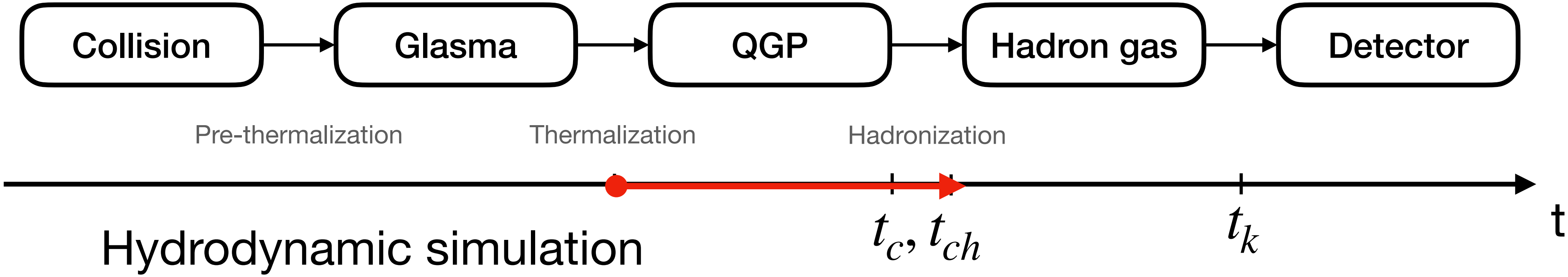
$$\tilde{\tau}_f = \sqrt{\tau^2 - x^2 - y^2} = \sqrt{t^2 - r^2}$$

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

	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

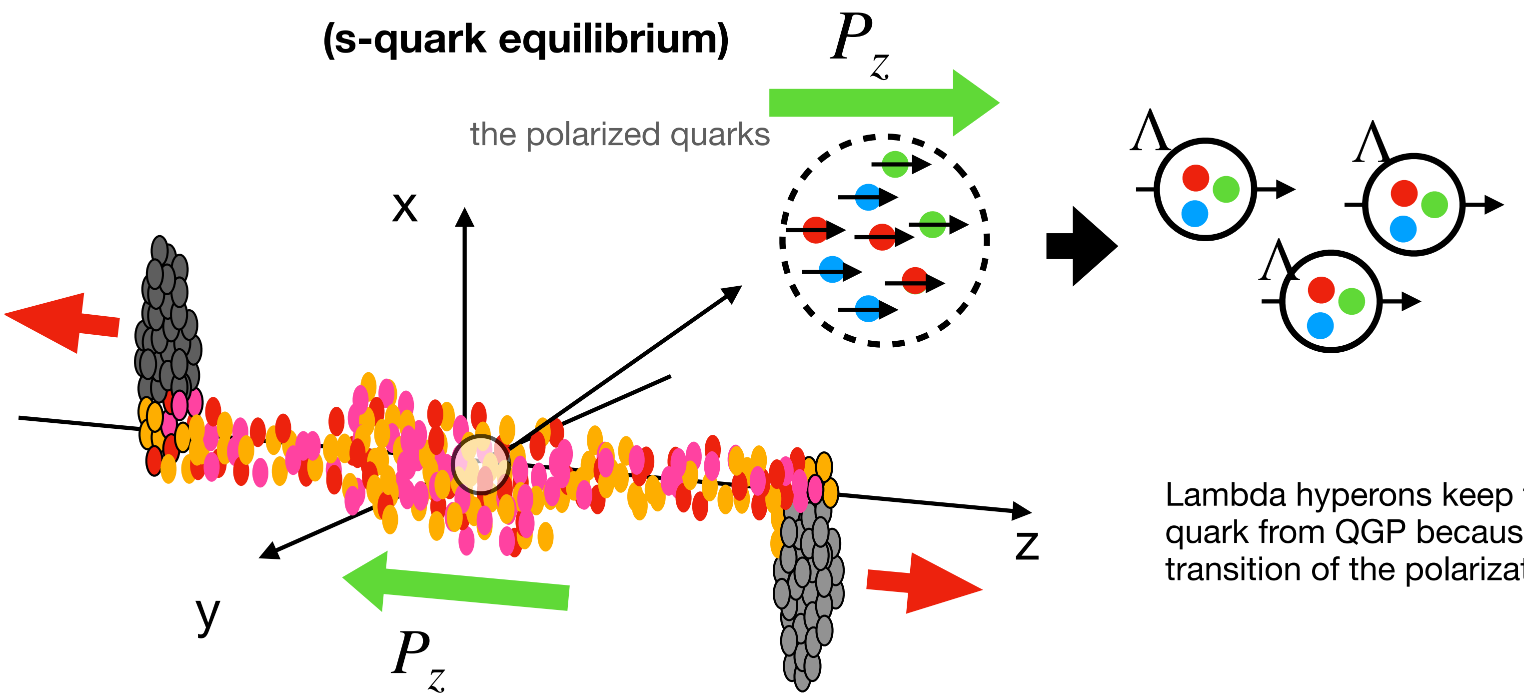
- anisotropy of transverse plane (ϵ)
- anisotropy of flow (δ)
- proper time $(\tilde{\tau}_f)$
- maximum radius (r_m)

Longitudinal Polarization
s-quark equilibrium

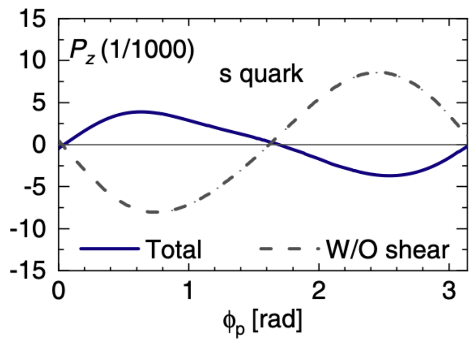


Hydrodynamic simulation

(s-quark equilibrium)



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

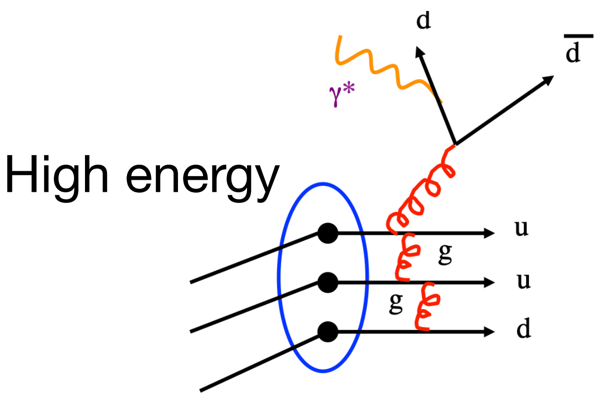


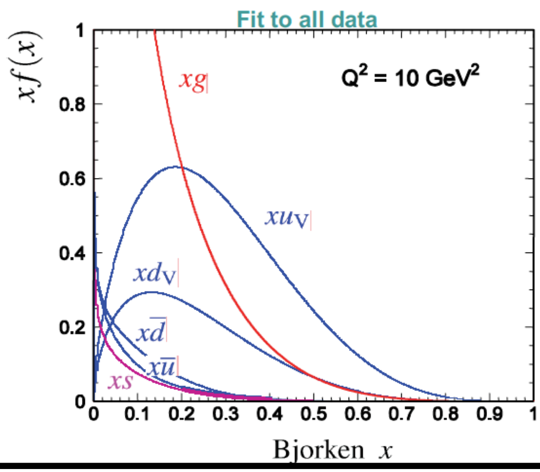
Lambda hyperons keep the spin direction of the strange quark from QGP because we assume the perfect transition of the polarization from quarks to hadrons.

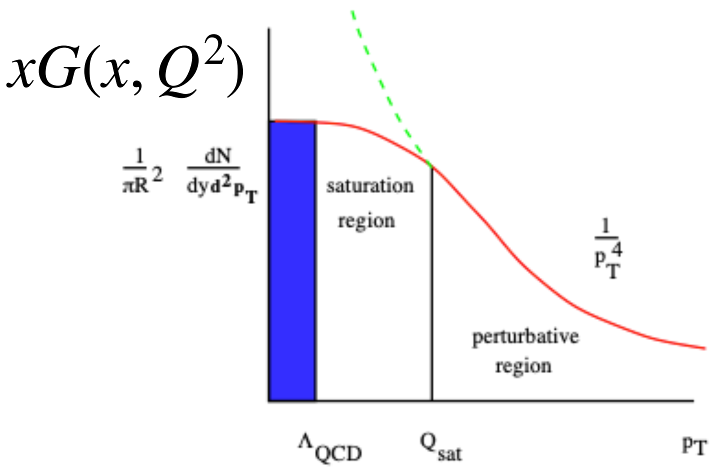
Color Glass Condensate (CGC)

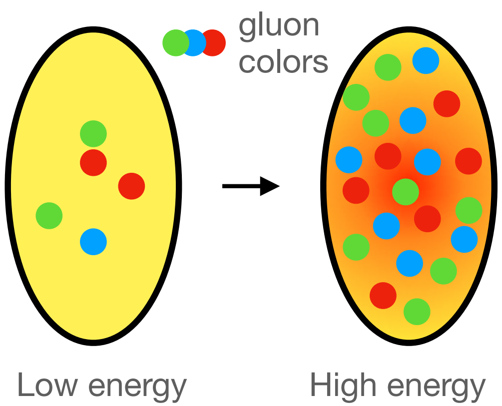
M.A. Thomson, Michaelmas 2011

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

Overpopulation of quarks in low energy

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

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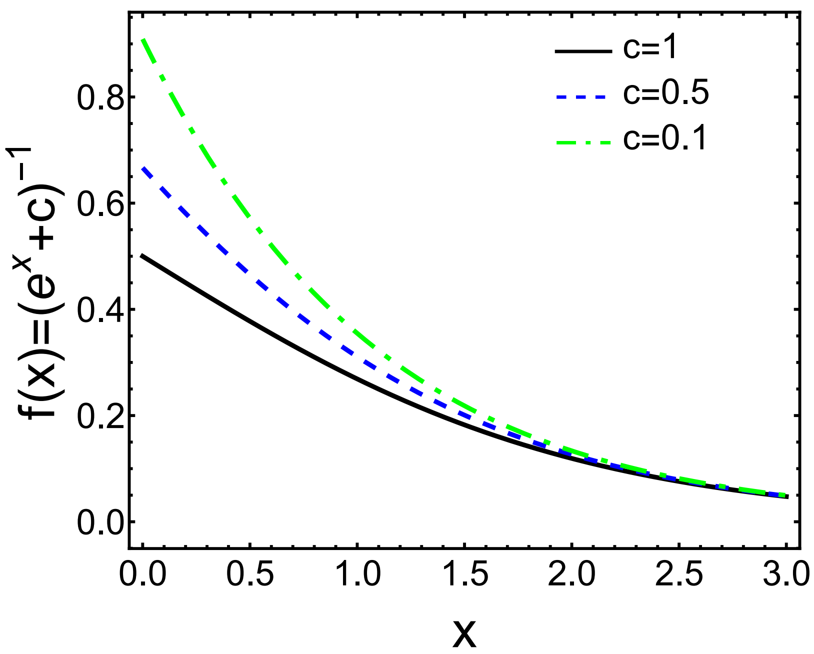
$$f_V^s(p \cdot u/Q_s) = \frac{1}{e^{p \cdot u/Q_s} + c}$$



c<1: Overpopulation of quarks at low energy

Describing the overpopulation of quarks driven by the high density of gluons at low energy while satisfying the Pauli exclusions principle