Vector-Meson Spin Alignment from Anisotropic Momentum Distribution

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Based on: arXiv: 2607.06138, 26xx.xxxxx in preparation

Collaborators: Xin-Li Sheng, Yi-Liang Yin, Prof. Qun Wang, Prof. Dirk H. Rischke

Outline

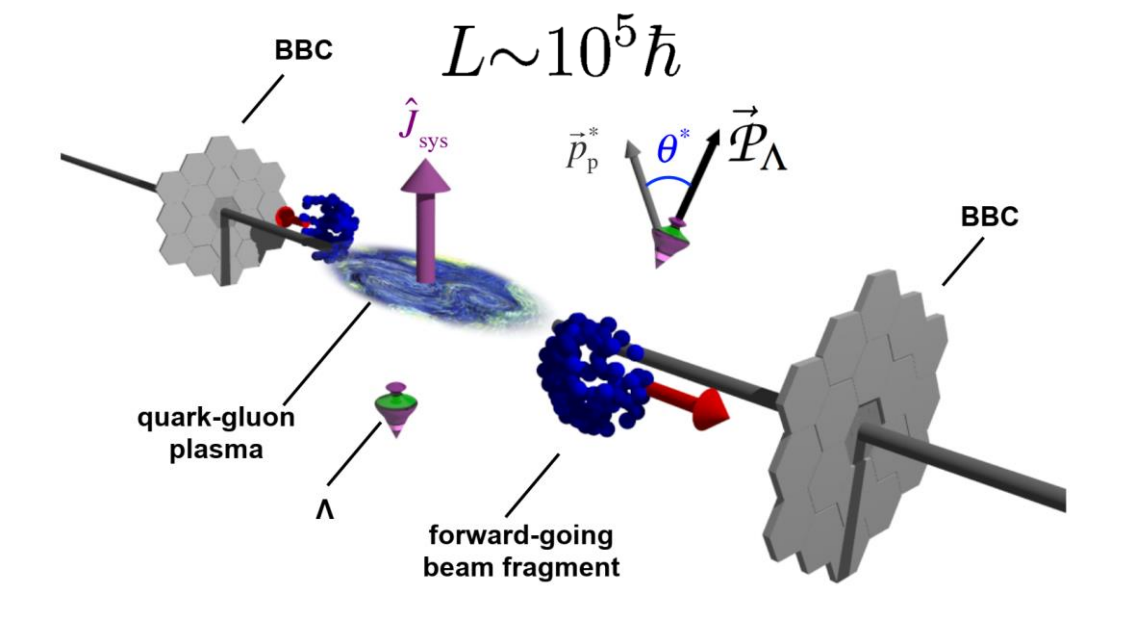
01 **Introduction**

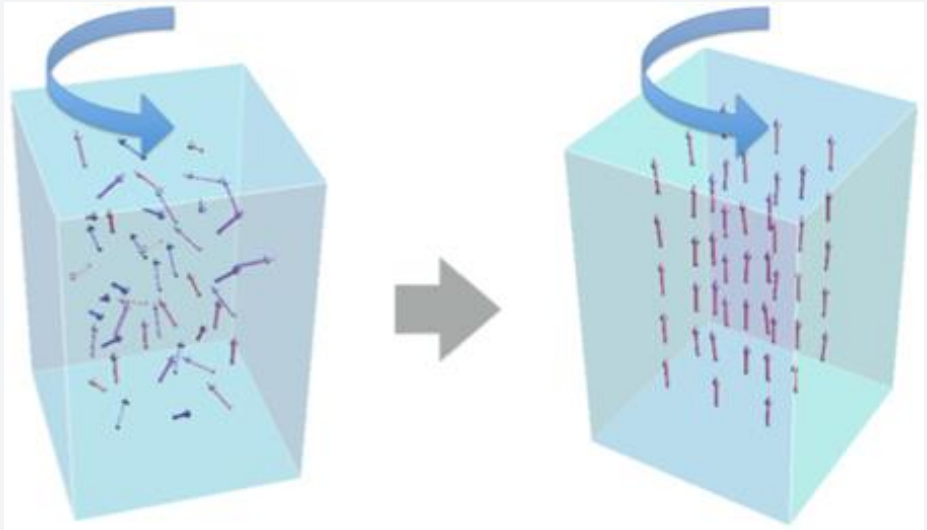
02 Spin alignment of ϕ and $K^{*,0}$ with anisotropy

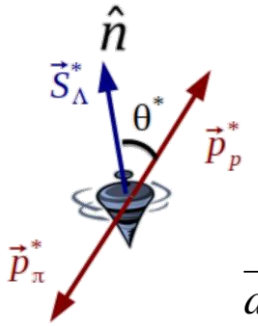
03 Spin alignment of ρ^0 meson at threshold

04 Summary

Introduction







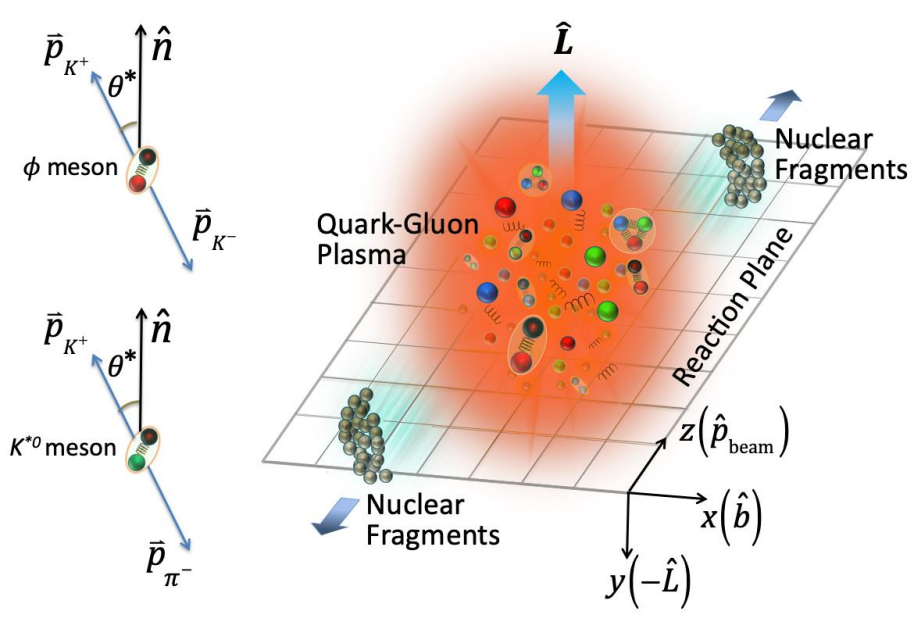
$$\Lambda \rightarrow p + \pi^-$$

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right).$$

Orbit angular momentum ➡ Spin polarization

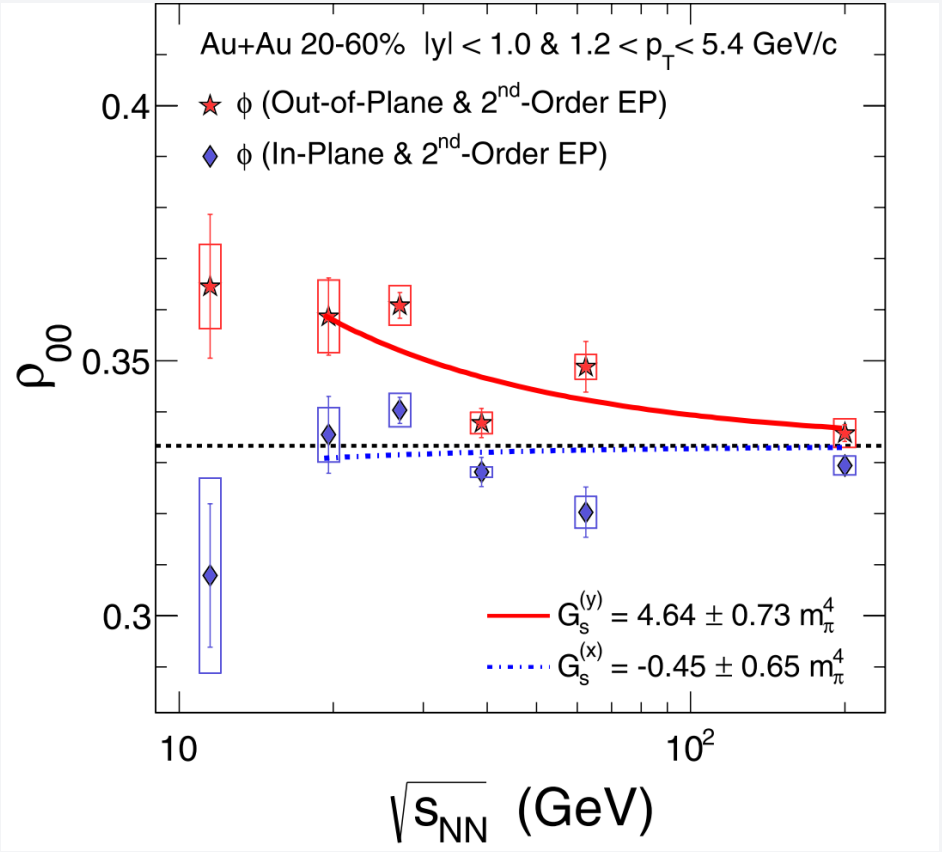
Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. ***94****, 102301 (2005)*
Z.-T. Liang and X.-N. Wang, Phys. Lett. B ***629****, 20 (2005)*
J.-H. Gao et al., Phys. Rev. C ***77****, 044902 (2008)*

Spin alignment



$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

Z.-T. Liang, X.-N. Wang, Phys.Lett.B 629 (2005) 20-26



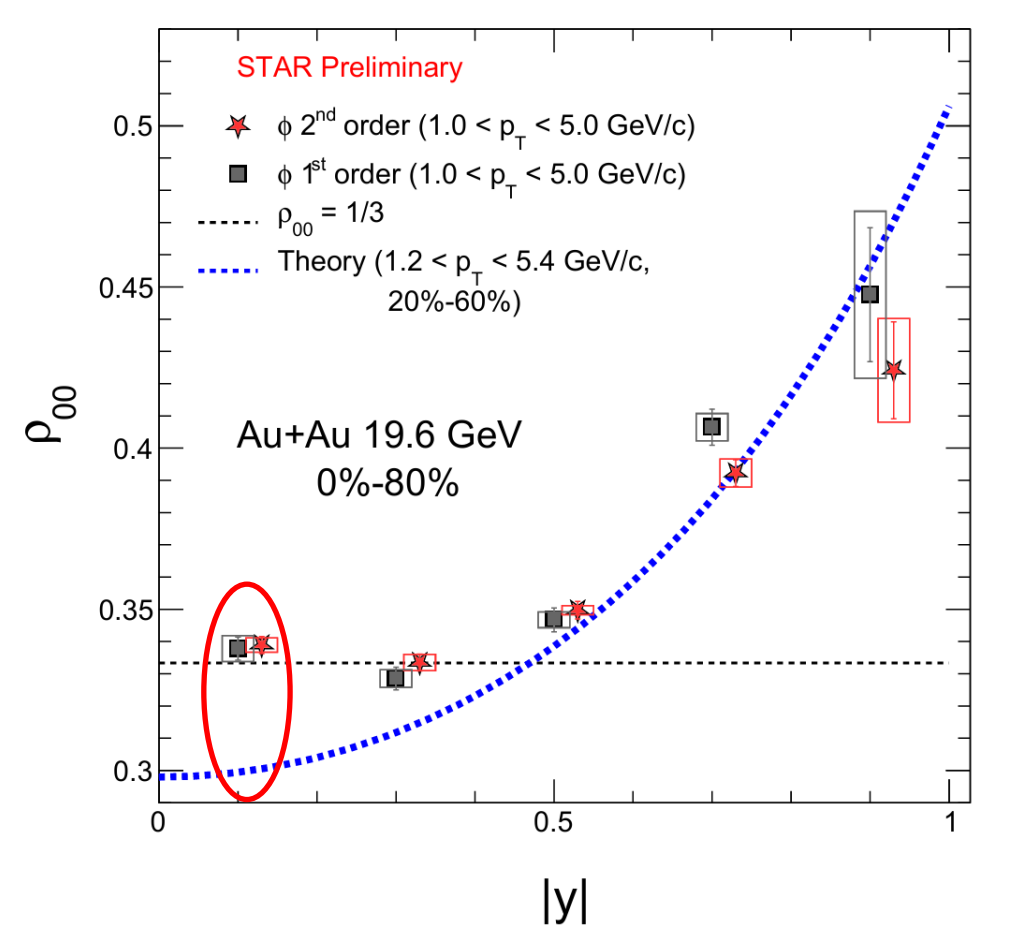
STAR Nature 614 (2023) 7947, 244-248
X.-L. Sheng et al. PRL. 131 (2023) 4, 042304

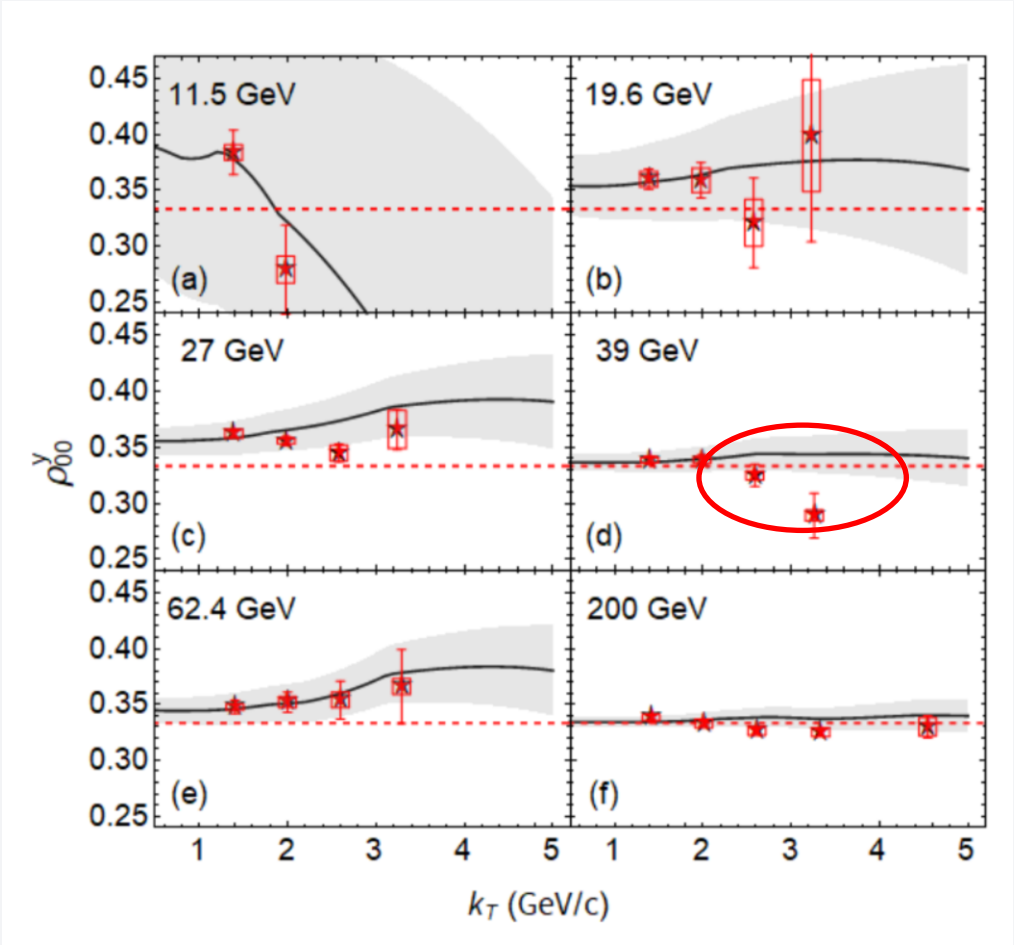
Orbit→ Spin: $\rho_{00} - \frac{1}{3} \sim -\omega^2 \sim -10^{-4}$ ✖

Other sources: spin correlation, color field, **strong force field**, thermal shear, anisotropy……

$$\rho_{00}^{\phi} - \frac{1}{3} \sim < B_{\phi}^2 > \sim 0.01$$

Rapidity/PT spectra





New sources required

Phys.Rev.C 108 (2023) 5, 054902, X.-L. Sheng et al.
Phys.Rev.Lett. 131 (2023) 4, 042304, X.-L. Sheng et al.

Outline

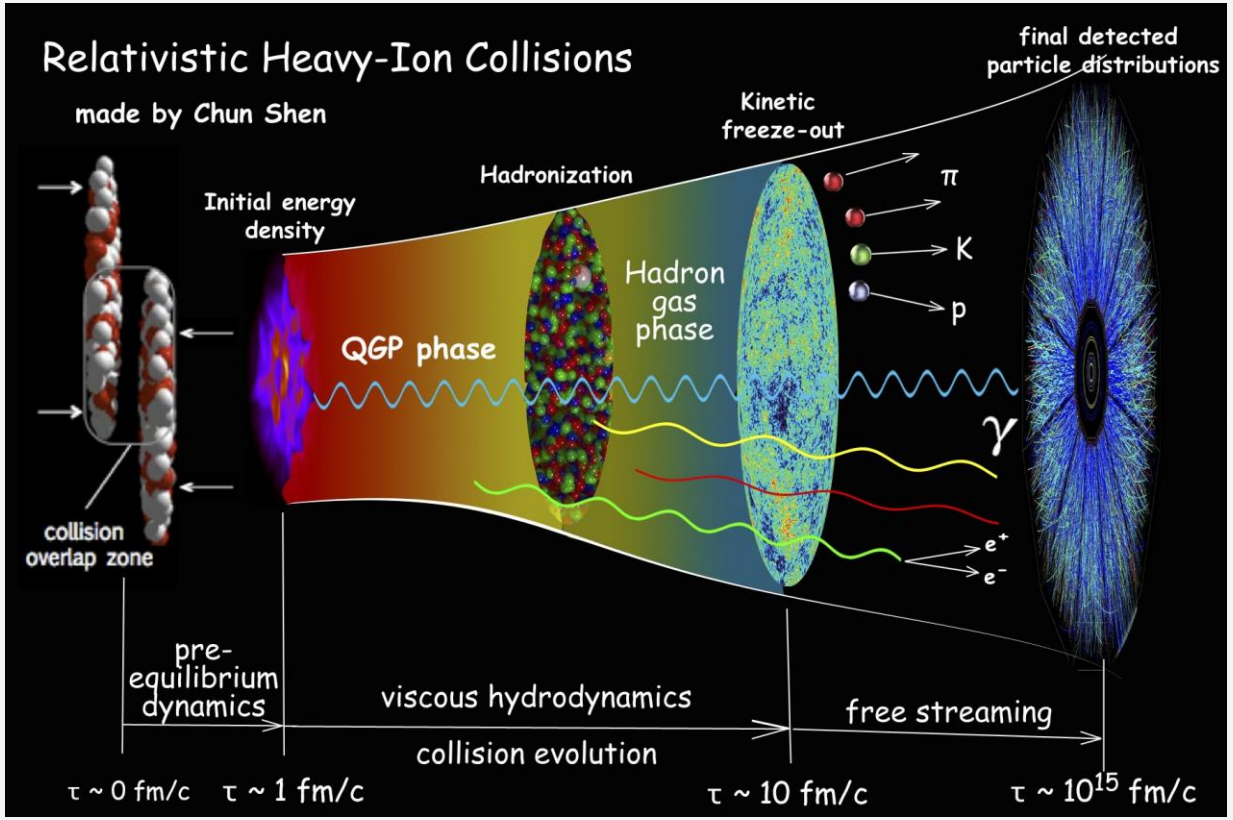
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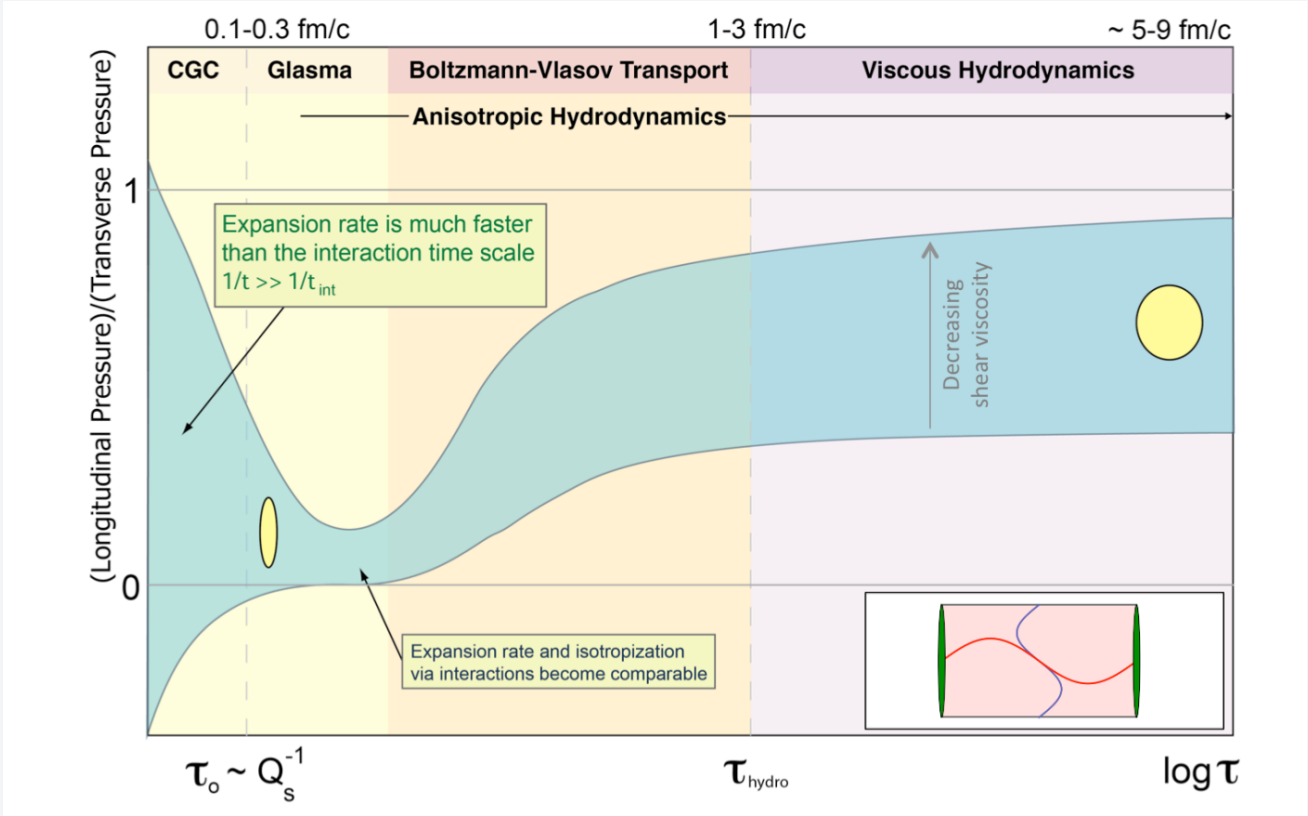
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Anisotropy of QGP



Acta Phys.Polon.B 45 (2014) 12, 2355-2394



Geometry difference ⟹ Anisotropy in initial ⟹ Anisotropy at freeze out

Anisotropy related with transport coefficients κ, ζ, η ...

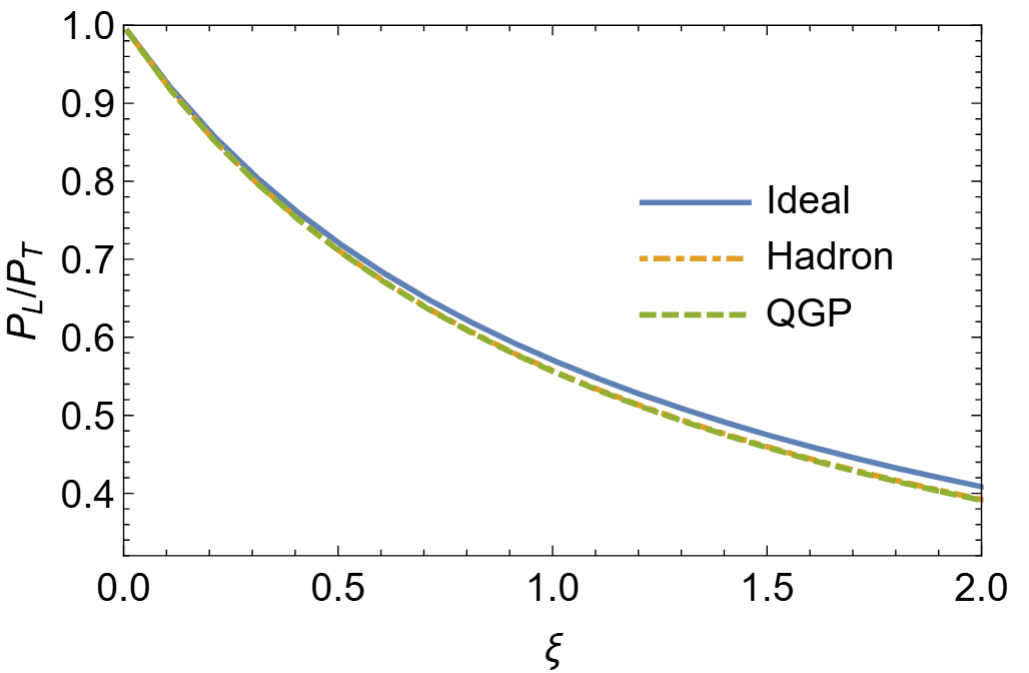
Anisotropy of QGP

Romatschke-Strickland Distribution

Simplest case: $l^\mu = (0,0,0,1)$

Phys.Rev.D 68 (2003) 036004
Phys.Rev.C 90 (2014) 5, 054910
Nucl.Phys.A 848 (2010) 183-197

$$f^{\mathrm{RS}}(p,\xi) = \frac{d_s}{\exp\left(\beta\sqrt{p^\mu p^\nu(u_\mu u_\nu + \xi l_\mu l_\nu)}\right) \pm 1},$$



Ideal: $m = 0$
Hadron: π, K, p
QGP: $q, \bar{q}, g, m_s = 420MeV$,
$m_{u,d} = \frac{gT}{\sqrt{6}}$, $m_g = \frac{\sqrt{3}}{2} gT$

Almost identical in three models

Anisotropy vs. Energy

Navier-Stokes theory + Bjorken flow

$$u^{\mu} = \left(\frac{t}{\tau}, 0, 0, \frac{z}{\tau}\right)$$

$$T^{\mu\nu} = \varepsilon u^{\mu} u^{\nu} - P\Delta^{\mu\nu} + 2\eta\sigma^{\mu\nu}$$

$$P_L = P - \frac{4\eta}{3\tau}$$

$$P_T = P + \frac{2\eta}{3\tau}$$

Conformal theory: $\varepsilon = 3P = \frac{3}{4}Ts$

$$\frac{P_L}{P_T} = \frac{3T\tau - \frac{16\eta}{s}}{3T\tau + \frac{8\eta}{s}}$$

Anisotropy from thermal shear

High energy: τ=10fm/c, η/S=1/(4π) → PL/PT=0.92
Low energy: τ=8fm/c, η/S=0.2 → PL/PT=0.77

$$\sqrt{s_{NN}}\downarrow \Rightarrow \frac{P_L}{P_T}\downarrow \Rightarrow \xi\uparrow$$

Nucl.Phys.A 967 (2017) 784-787

General analysis

2→1 coalescence process:

$$d\sigma_\lambda(p,q) = \epsilon_\mu^*(p,\lambda)\,\epsilon_\nu(p,\lambda)\,\mathcal{M}^{\mu\nu}(p,q)\ ,$$

General form:

$$\mathcal{M}^{\mu\nu}(p,q) = c_1\, m_V^2\, g^{\mu\nu} + c_2\, q^\mu q^\nu + c_3\, p^\mu p^\nu + c_4\,(p^\mu q^\nu + q^\mu p^\nu) + ic_5(p^\mu q^\nu - q^\mu p^\nu) + ic_6\,\epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta\ ,$$

$$\Gamma_\lambda \propto \int \frac{d^3\mathbf{p}\, d^3\mathbf{q}}{4E_{p_1}E_{p_2}} \delta(E_p - E_{p_1} - E_{p_2})\,\sigma_\lambda(p,q) f_1(p_1) f_2(p_2),$$

$q_x^2 = q_y^2 > q_z^2$

$c_2 > 0, \delta\rho_{00} > 0$
$c_2 < 0, \delta\rho_{00} < 0$
$c_2 = 0, \delta\rho_{00} = 0$

Weighted by RS distribution

$$\delta\rho_{00}(p) \approx \frac{c_2\left[\langle q_y^2\rangle - \frac{1}{3}\langle \mathbf{q}^2\rangle\right]}{c_2\langle \mathbf{q}^2\rangle - 3m_V^2 c_1}\ ,$$

ϕ and K^{*0} with hadronic interaction

Vector meson production: quark level (QGP) + hadron interaction (hadron gas)

Long life-time meson(ϕ ...): quark interaction dominant
Short life-time meson(K^{*0}, ρ ...): hadron interaction dominant

Vertex from Chiral perturbation theory:

$$\mathcal{L}_{\phi KK} = ig_{\phi KK}\phi^{\mu}\left(K^{+}\partial_{\mu}K^{-} - K^{-}\partial_{\mu}K^{+} + K^{0}\partial_{\mu}\overline{K}^{0} - \overline{K}^{0}\partial_{\mu}K^{0}\right) ,$$

$$\mathcal{L}_{K^{*0}K\pi} = ig_{K^{*0}K\pi}K^{*0}_{\mu}\left(K^{-}\partial^{\mu}\pi^{+} - \pi^{+}\partial^{\mu}K^{-} + K^{0}\partial^{\mu}\pi^{0} - \pi^{0}\partial^{\mu}K^{0}\right) .$$

$$c_1^{\phi} = 0 , \qquad c_2^{\phi} = 2g^2_{\phi KK} ,$$

$$c_1^{K^{*0}} = 0 , \qquad c_2^{K^{*0}} = 2g^2_{K^{*0}K\pi} \quad \Longrightarrow \quad \delta\rho_{00} > 0$$

ϕ and K^{*0} with vector coupling

Vertex *Phys.Rev.D 109 (2024) 3, 036004, X.-L.Sheng et al.*

$$\mathcal{L}_{\phi} = g_{\phi s\bar{s}}\overline{\psi}_s\gamma^{\mu}\psi_s\phi_{\mu} \ ,$$

$$\mathcal{L}_{K^{*0}} = g_{K^{*0}d\bar{s}}\overline{\psi}_d\gamma^{\mu}\psi_s K^{*0}_{\mu} \ ,$$

Phys. Rev. D 100, 114038 (2019) Y.-Z. Xu et al.
Eur. Phys. J. C 81, 895 (2021) Y.-Z. Xu et al.

$$c_1^{\phi} = -2g^2_{\phi s\bar{s}} \ ,$$

$$c_1^{K^{*0}} = -2g^2_{K^{*0}d\bar{s}}\left[1 - \frac{(m_s - m_d)^2}{m^2_{K^{*0}}}\right] \ ,$$

$$c_2^{\phi} = -2g^2_{\phi s\bar{s}} \ ,$$

$$c_2^{K^{*0}} = -2g^2_{K^{*0}d\bar{s}} \ .$$

< 0

$\delta\rho_{00} < 0$

Parameters: quark mass m_s, anisotropy parameter ξ

ϕ and K^{*0} with tensor coupling vertex

General effective vertex:

Phys.Rev.C 58 (1998) 2393-2413

$$\mathcal{L}_{\phi} = g_{\phi s\bar{s}}\overline{\psi}_s \left[\gamma^{\mu} + \frac{\zeta_{\phi}}{2M}\sigma^{\mu\nu}(\overrightarrow{\partial_{\nu}} + \overleftarrow{\partial_{\nu}})\right]\psi_s\phi_{\mu} \ ,$$

$$\mathcal{L}_{K^{*0}} = g_{K^{*0}d\bar{s}}\overline{\psi}_d \left[\gamma^{\mu} + \frac{\zeta_{K}}{2M}\sigma^{\mu\nu}(\overrightarrow{\partial_{\nu}} + \overleftarrow{\partial_{\nu}})\right]\psi_s K^{*0}_{\mu} \ ,$$

γ^{μ}: vector coupling

$\sigma^{\mu\nu}$: tensor coupling

ζ: ratio between two vertices

$\zeta = 0$: pure vector coupling, $\delta\rho_{00} < 0$

$\zeta = -\frac{2M}{m_1+m_2}$: P wave dominate

identical to hadronic case, $\delta\rho_{00} > 0$

$$c_1^{\phi} = -2g_{\phi s\bar{s}}^2\left(1+\zeta_{\phi}\frac{m_s}{M}\right)^2 \ ,$$

$$c_2^{\phi} = -2g_{\phi s\bar{s}}^2\left(1-\zeta_{\phi}^2\frac{m_s^2}{M^2}-\zeta_{\phi}^2\frac{m_{\phi}^2-4m_s^2}{4M^2}\right) \ ,$$

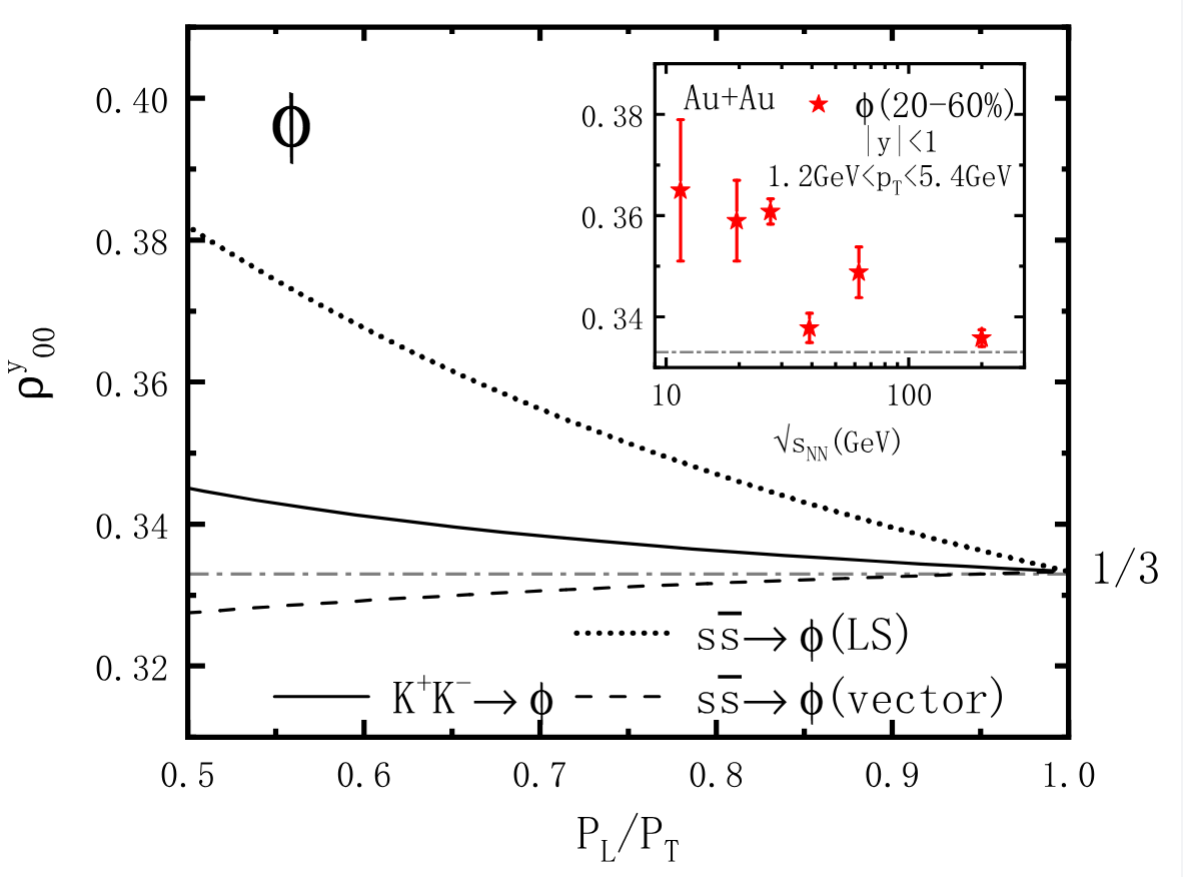
$$c_1^{K^{*0}} = -2g_{K^{*0}d\bar{s}}^2\left(1+\zeta_K\frac{m_d+m_s}{2M}\right)^2\left[1-\frac{(m_d-m_s)^2}{m_{K^{*0}}^2}\right] \ ,$$

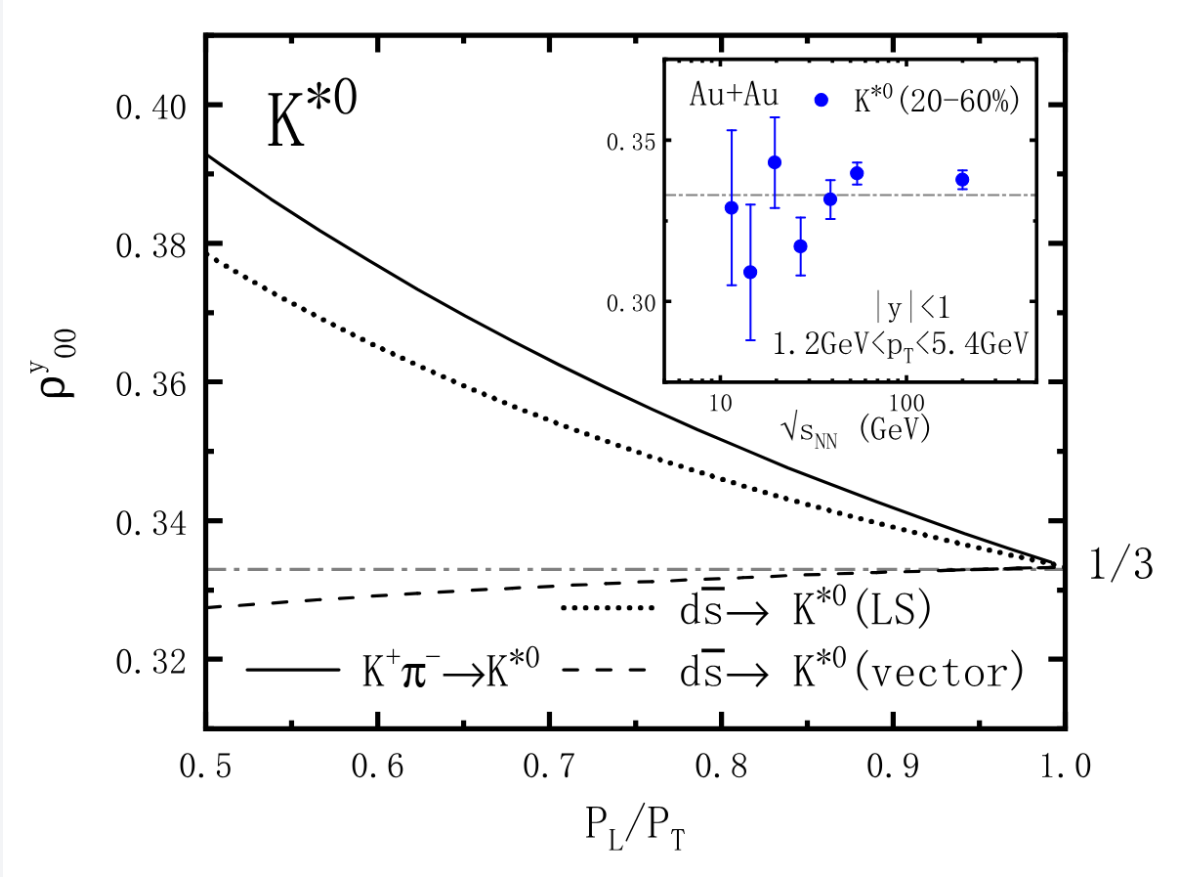
$$c_2^{K^{*0}} = -2g_{K^{*0}d\bar{s}}^2\left[1-\zeta_K^2\frac{(m_d+m_s)^2}{4M^2}-\zeta_K^2\frac{m_{K^{*0}}^2-(m_d+m_s)^2}{4M^2}\right] \ .$$

Spin alignment with anisotropy

arXiv: 2607.06138 Wen-Bo Dong et.cl

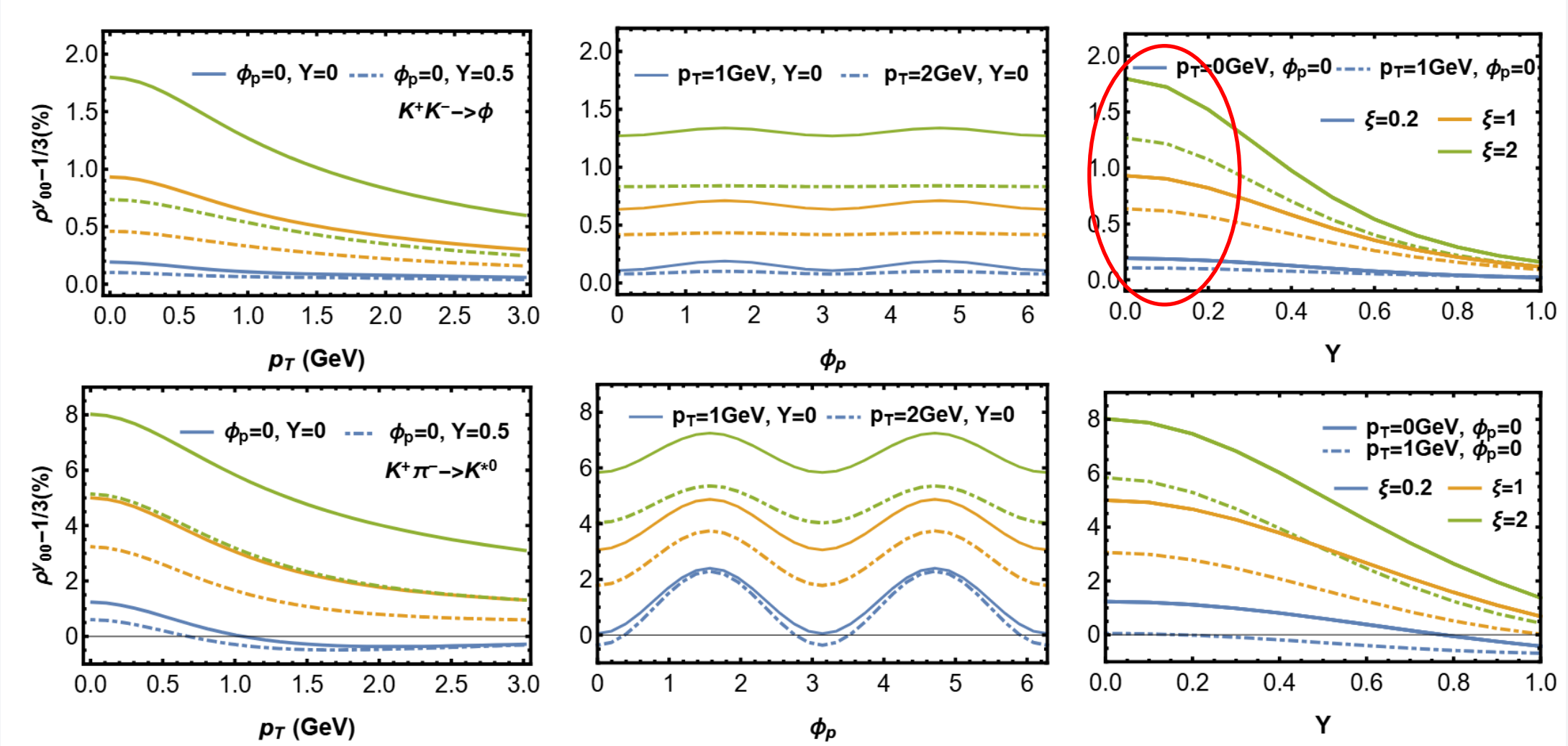
$$\zeta = -\frac{2M}{m_1+m_2},\ m_s = 0.42GeV,\ p^\mu \parallel u^\mu$$





ϕ: long life-time -> anisotropy significant when produced
K^{*0}: short life-time -> system closer to isotropy when produced

Hadronic interaction with varying ξ



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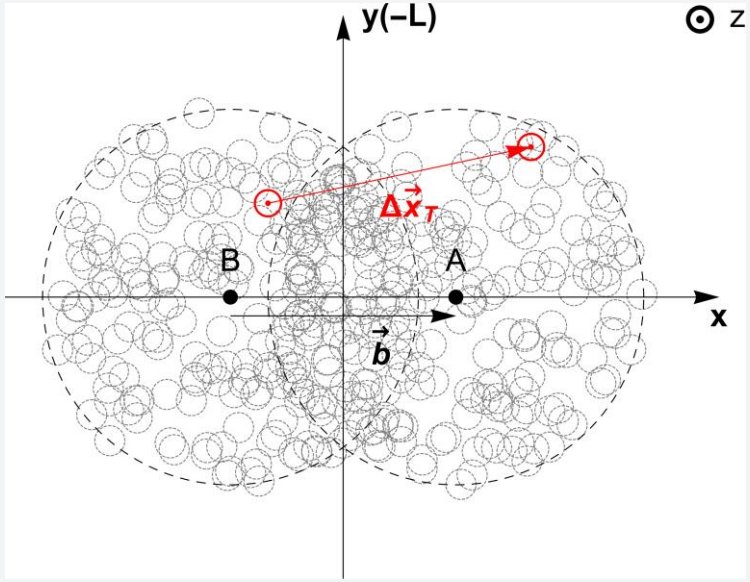
04 Summary

Threshold collision (2.65GeV)

$$NN \to NN\rho^0$$

Two incoming nucleons: $(m_N + m_\rho/2, 0, 0, \pm p)$,
highly anisotropic, identical to $P_L/P_T \to \infty$ $(\xi = -1)$

$$\rho^{\mathrm{AuAu}}_{\lambda_1\lambda_2} \approx \frac{\left\langle\left\langle \sigma^{NN}_{\lambda_1\lambda_2}(x_a, x_b)\right\rangle f_N(x_a)\, f_N(x_b)\right\rangle}{\left\langle\left\langle \sigma^{NN}_{\mathrm{tot}}\right\rangle f_N(x_a)\, f_N(x_b)\right\rangle},$$



Chiral perturbation theory

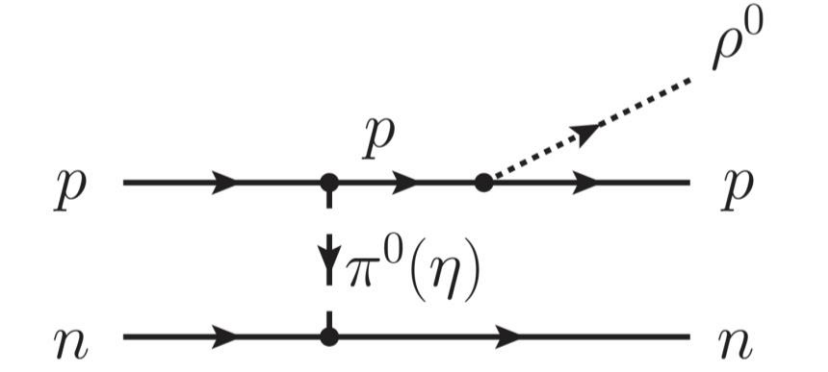
$$\begin{aligned}
\mathcal{L}_{V\Phi\Phi} &= -2g f^{abc}\phi^a v^b_\mu \partial^\mu \phi^c\,, \\
\mathcal{L}_{BBV} &= 2i f^{abc} g \overline{B}^c \gamma^\mu v^a_\mu B^b + g v^{(s)}_\mu \overline{B}^b \gamma^\mu B^b\,, \\
\mathcal{L}_{BBV\Phi} &= \frac{2g}{F_0} f^{abc}\left(D d^{cef} + iF f^{cef}\right)\overline{B}^f \gamma^\mu\gamma_5 B^e v^a_\mu \phi^b\,, \\
\mathcal{L}_{BB\Phi} &= \frac{1}{F_0}\left(d_{bca} D + i f_{bca} F\right)\partial_\mu \phi_b \overline{B}_a \gamma^\mu\gamma_5 B_c\,.
\end{aligned}$$

B: Baryon field
v_μ: vector meson field
ϕ: pseudo-scalar meson field
f^{abc}: anti-symmetric structure constant
d^{abc}: symmetric structure constant

Based on W.-B. Dong, Y.-L. Yin et.cl in preparation

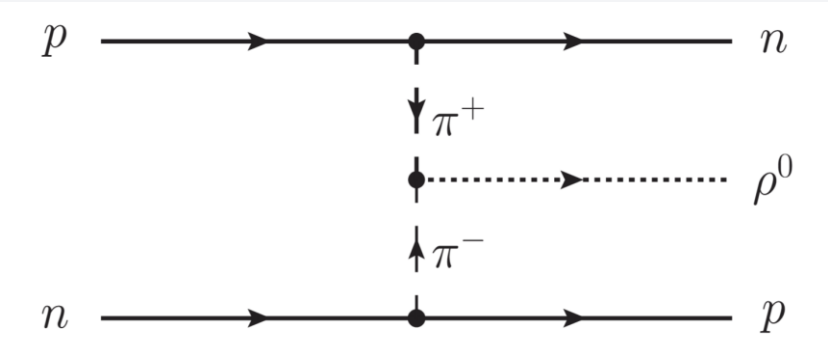
Spin alignment of ρ^0 meson

Direct emission: $NN \to NN\rho^0$
(resonance, vector meson exchange excluded)



$$\rho_{00}^{dir} \sim 0.45 + \cdots$$

Coalescence: $NN \to NN(\pi^+\pi^-) \to NN\rho^0$



$$\rho_{00}^{coal} = 0$$

$$c_1 = 0, c_2 > 0,$$
$$q_y^2 = 0 \ll q_z^2$$

- Independent with spin polarization of incoming particles, $O(\partial^0)$ effect.
- Strongly related with production channel.

$$\rho_{00}^{tot} \sim 0.314$$

remarks:
- Anisotropy induced spin alignment might be nonmonotonic with energy.
- Combine with UrQMD, counting the production channel and momentum distribution.

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summary

1. Anisotropy in momentum space can induce a non-vanishing spin alignment and determines the magnitude. It may help us to explain the inconsistent between data and theoretical prediction at pT/rapidity spectral.

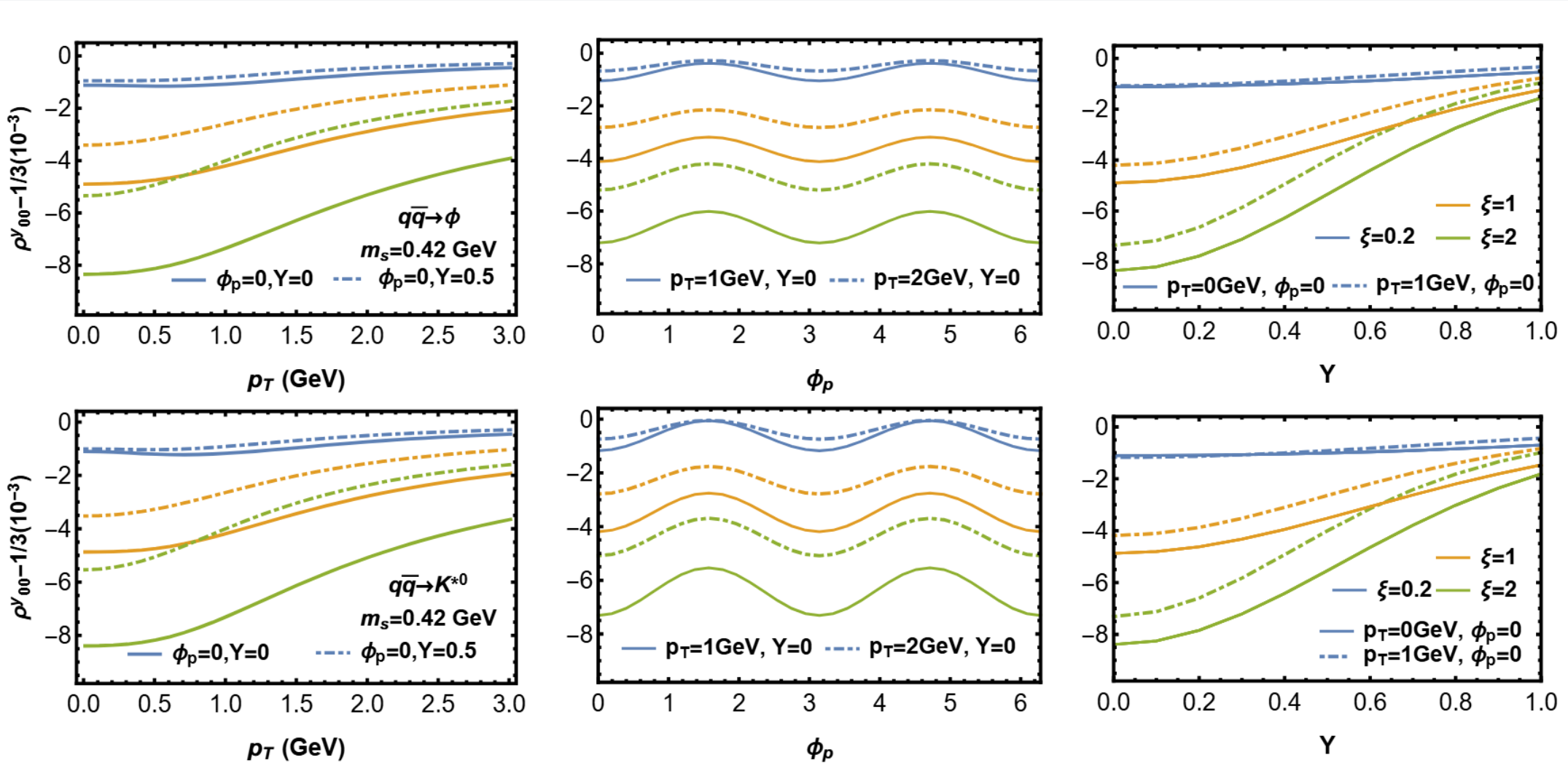
2. The spin alignment is strongly dependent with production channel. It helps to study the hadronization process of light mesons.

3. Anisotropy in extremely low collision energy is different, might leading to nonmonotonic energy dependence.

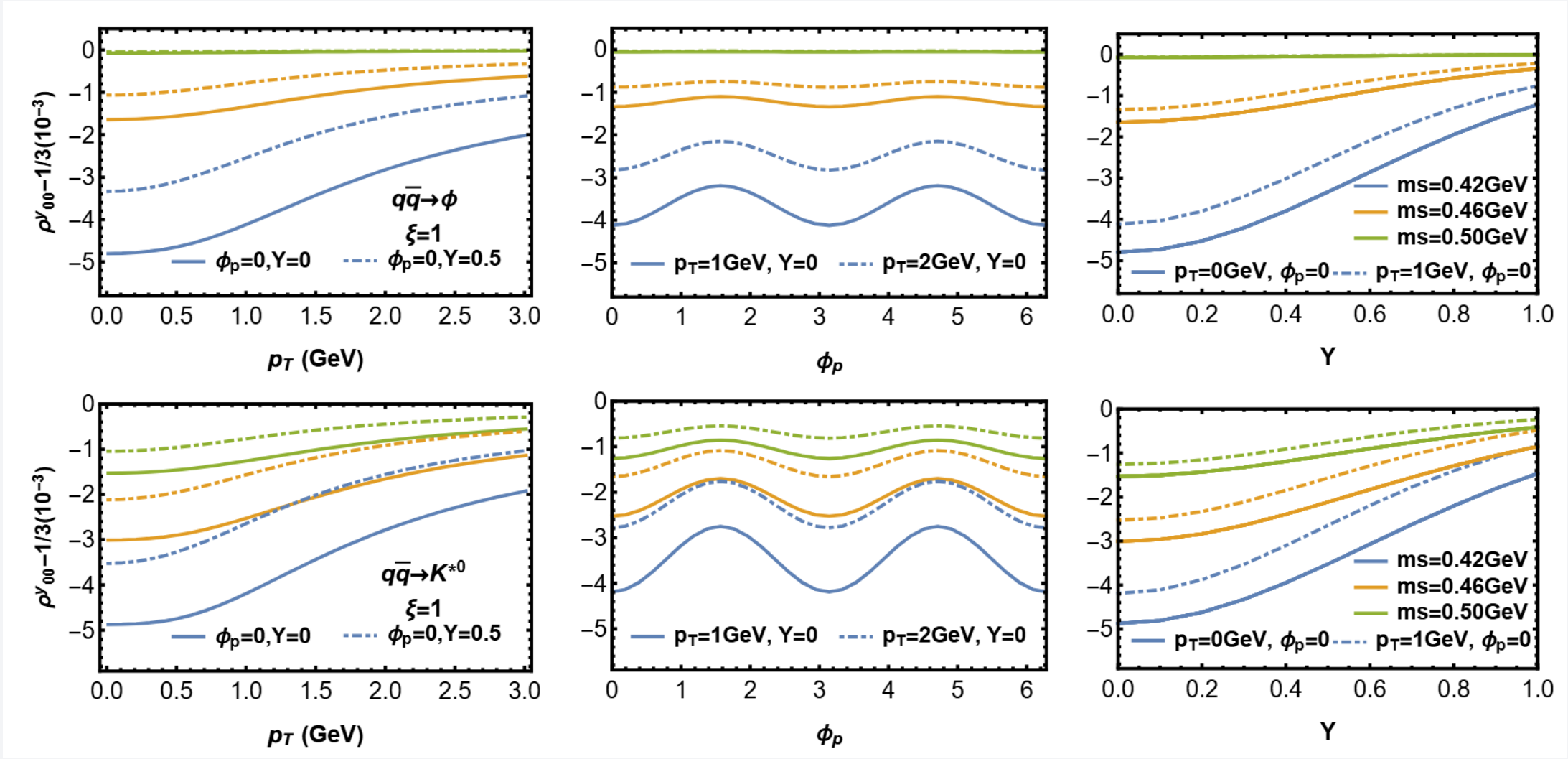
Thank you



Vector coupling with varying ξ



Vector coupling with varying m_s



Chiral perturbation theory

$$\mathcal{L}^{(2)} = Tr\left[\overline{B}\left(iD_\mu\gamma^\mu - M_0\right)B\right] - \frac{D}{2}Tr\left(\overline{B}\gamma^\mu\gamma_5\left\{u_\mu, B\right\}\right)$$
$$- \frac{F}{2}Tr\left(\overline{B}\gamma^\mu\gamma_5\left[u_\mu, B\right]\right) + \frac{F_0^2}{4}Tr\left(\left(D'_\mu U\right)^\dagger D'^{,\mu}U\right),$$

$$D_\mu B = \partial_\mu B + \left[\Gamma_\mu, B\right] - igv_\mu^{(s)}B\ ,$$
$$D'_\mu U = \partial_\mu U + \left[\Gamma_\mu, U\right]\ .$$

$$\Gamma_\mu = \frac{1}{2}\left[u^\dagger\left(\partial_\mu - ir_\mu\right)u + u\left(\partial_\mu - il_\mu\right)u^\dagger\right],$$
$$u_\mu = i\left[u^\dagger\left(\partial_\mu - ir_\mu\right)u - u\left(\partial_\mu - il_\mu\right)u^\dagger\right],$$

$$B = \frac{1}{\sqrt{2}}B^a\lambda^a = \frac{1}{\sqrt{2}}\begin{pmatrix} \Sigma^0 + \frac{1}{\sqrt{3}}\Lambda & \sqrt{2}\Sigma^+ & \sqrt{2}p \\ \sqrt{2}\Sigma^- & -\Sigma^0 + \frac{1}{\sqrt{3}}\Lambda & \sqrt{2}n \\ \sqrt{2}\Xi^- & \sqrt{2}\Xi^0 & -\frac{2}{\sqrt{3}}\Lambda \end{pmatrix},$$

$$v^\mu = v_a^\mu\lambda^a + \frac{1}{3}v_{(s)}^\mu I = \begin{pmatrix} \rho^0 + \omega & \sqrt{2}\rho^+ & \sqrt{2}K^{*,+} \\ \sqrt{2}\rho^- & -\rho^0 + \omega & \sqrt{2}K^{*,0} \\ \sqrt{2}K^{*,-} & \sqrt{2}\overline{K}^{*,0} & \sqrt{2}\phi \end{pmatrix}^\mu,$$

$$\Phi = \lambda_a\phi_a = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\overline{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix}.$$