Spin alignment from anisotropic momentum distribution

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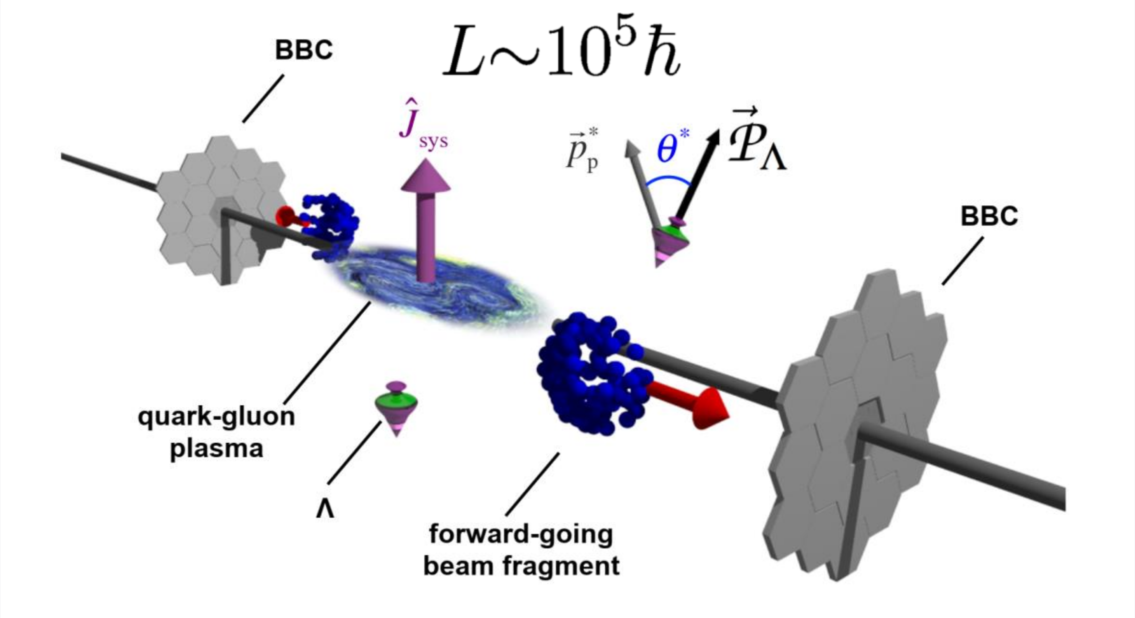
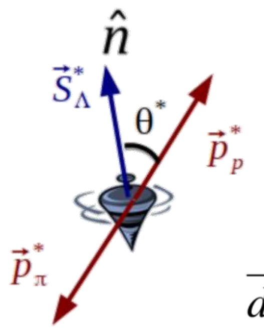
Outline

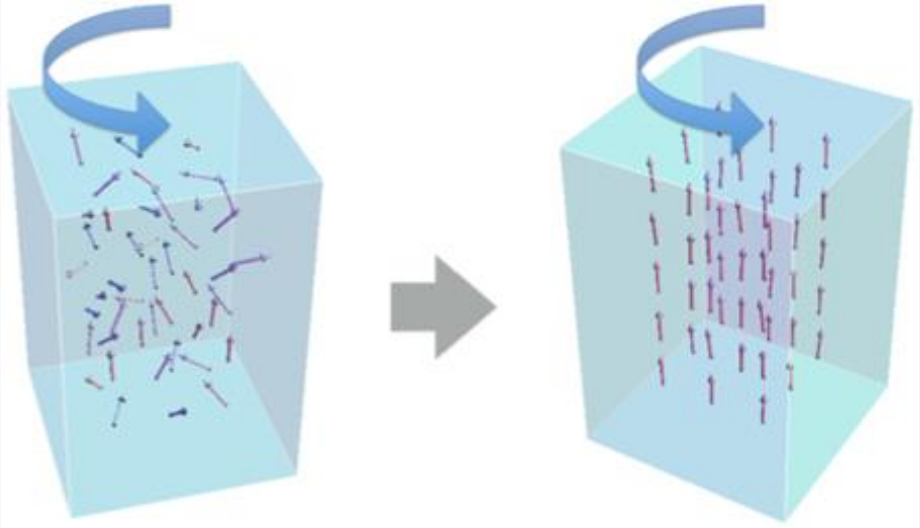
Introduction





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

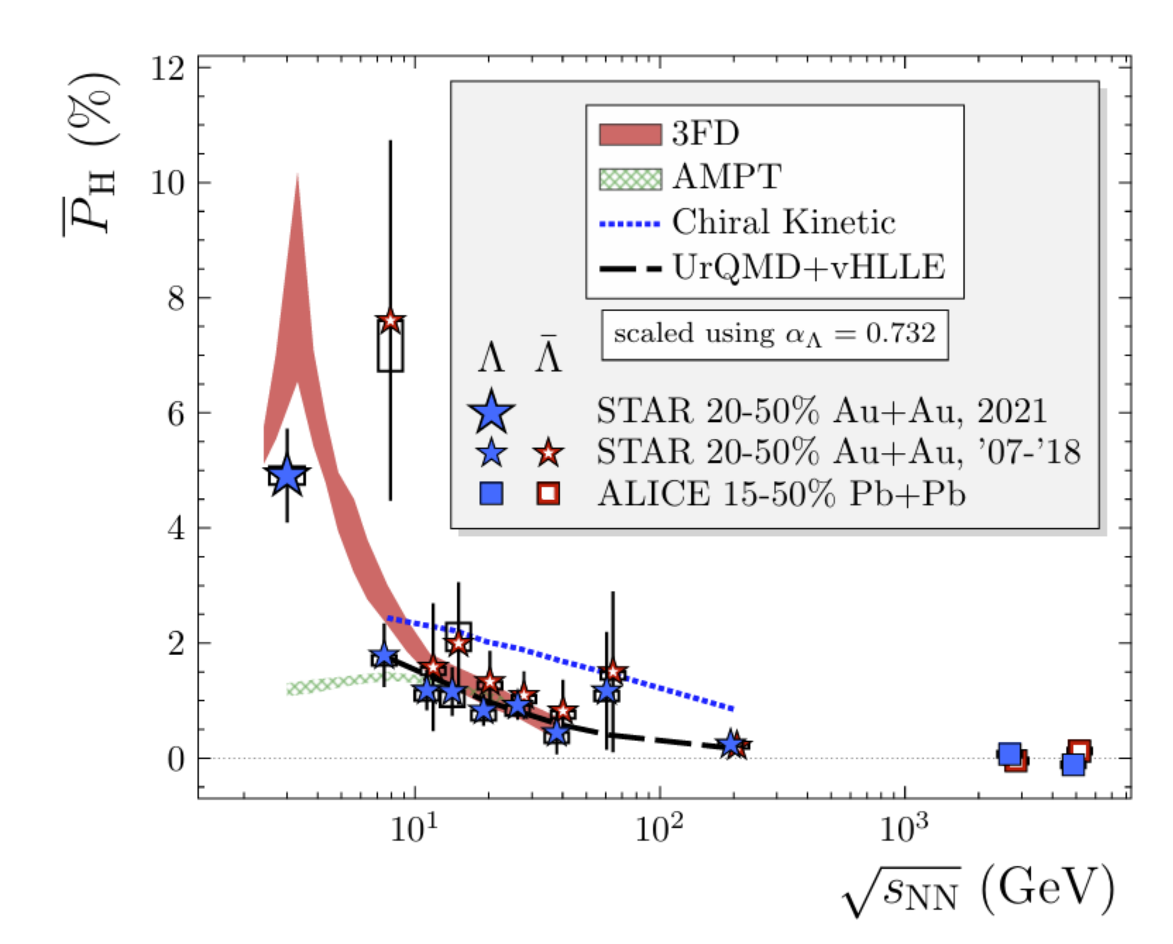
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right).$$



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)*

Global polarization



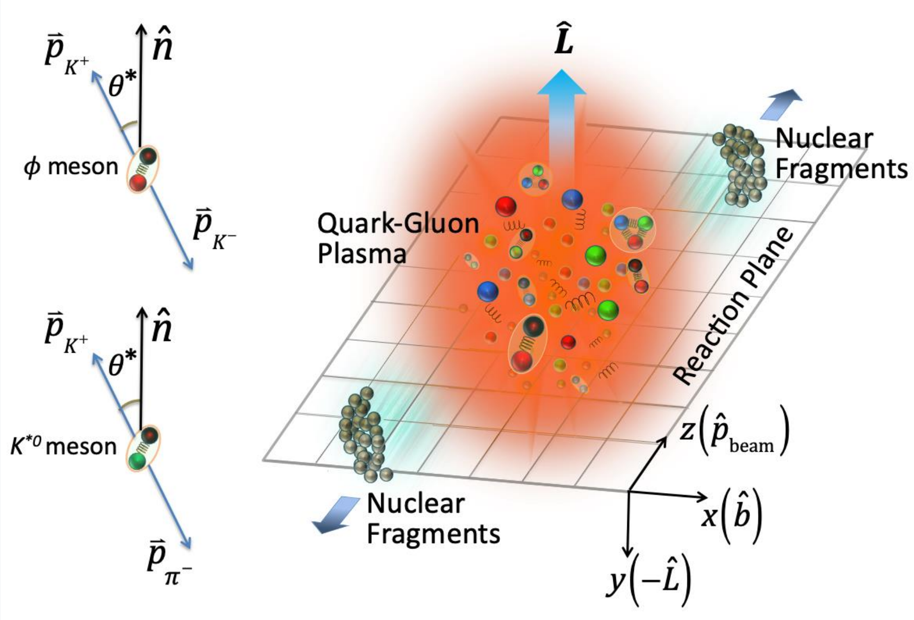
Spin polarization vector:

$$S^\mu_\varpi(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F},$$

$$S^\mu_\xi(p) = -\frac{1}{4m}\epsilon^{\mu\rho\sigma\tau}\frac{p_\tau p^\lambda}{\varepsilon} \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\hat{t}_\rho \xi_{\sigma\lambda}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}$$

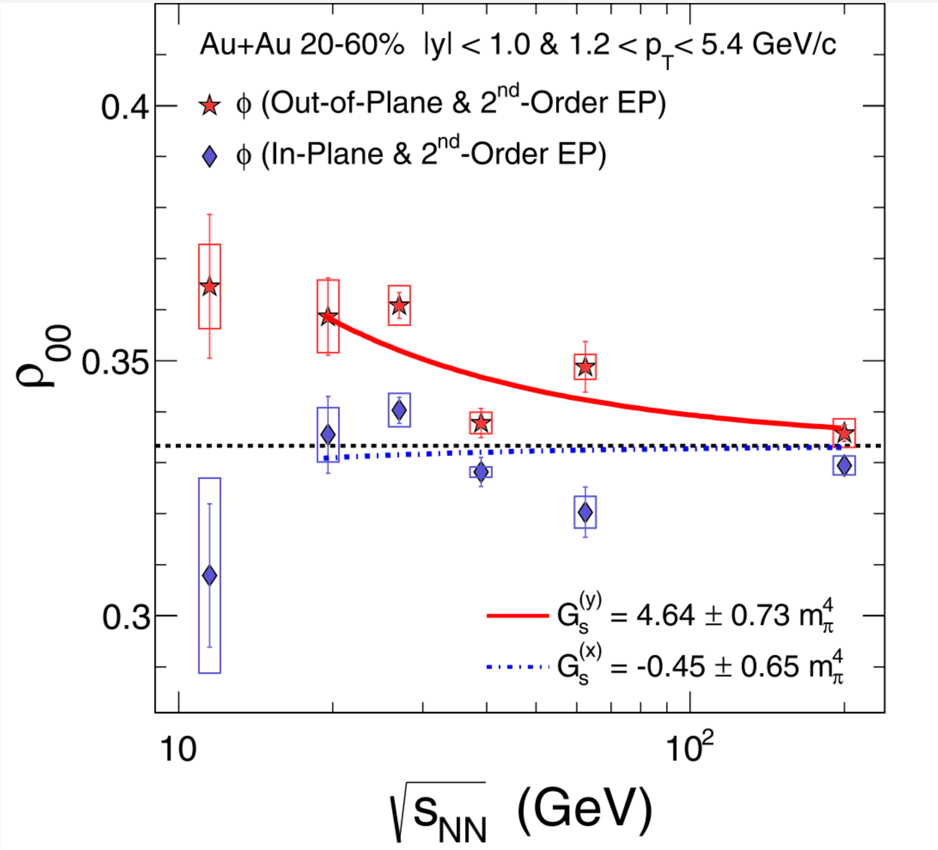
- *Phys.Rev.Lett. 94 (2005) 102301*
- *Phys.Rev.C 95 (2017) 5, 054902*
- *STAR Nature 548 (2017) 62-65*
- *STAR Phys.Rev.C 104 (2021) 6, L061901*

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

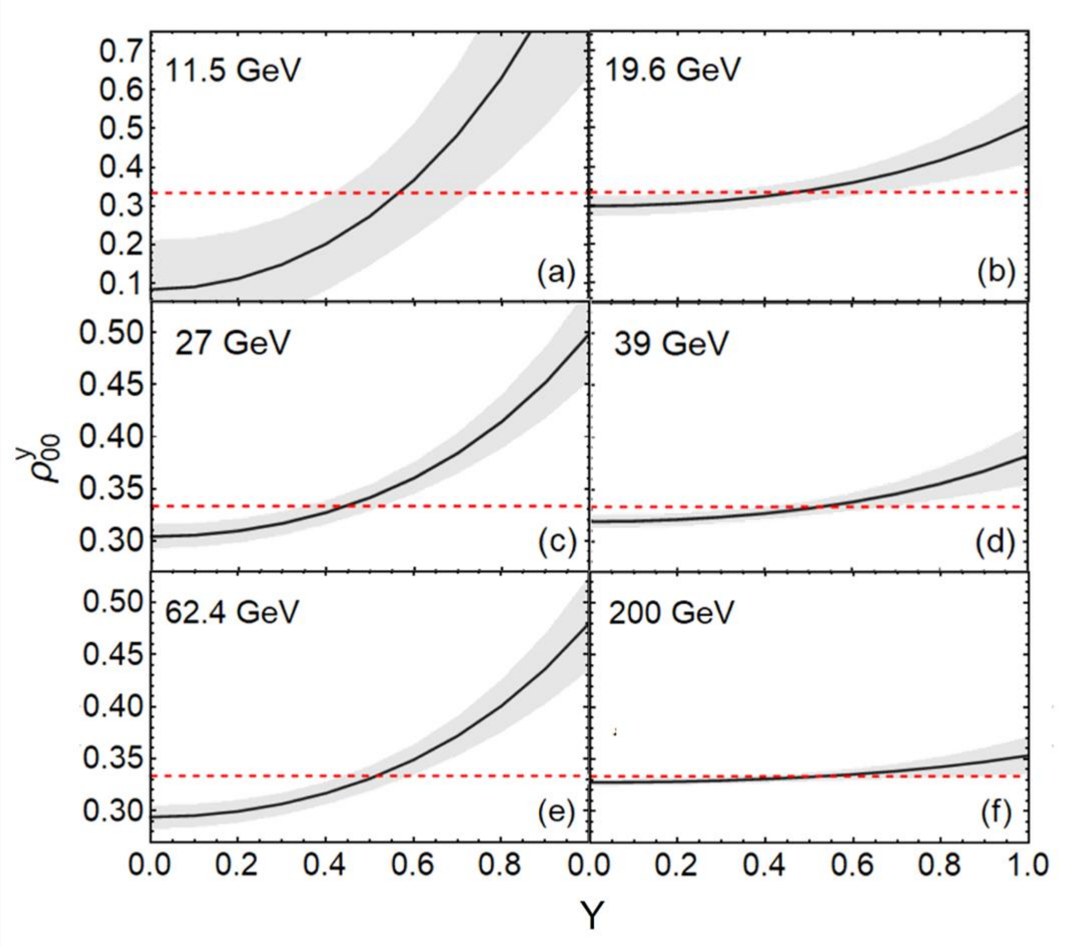
Orbit→ Spin: $\rho_{00} - \frac{1}{3} \sim -\omega^2 \sim -10^{-4}$ ❌

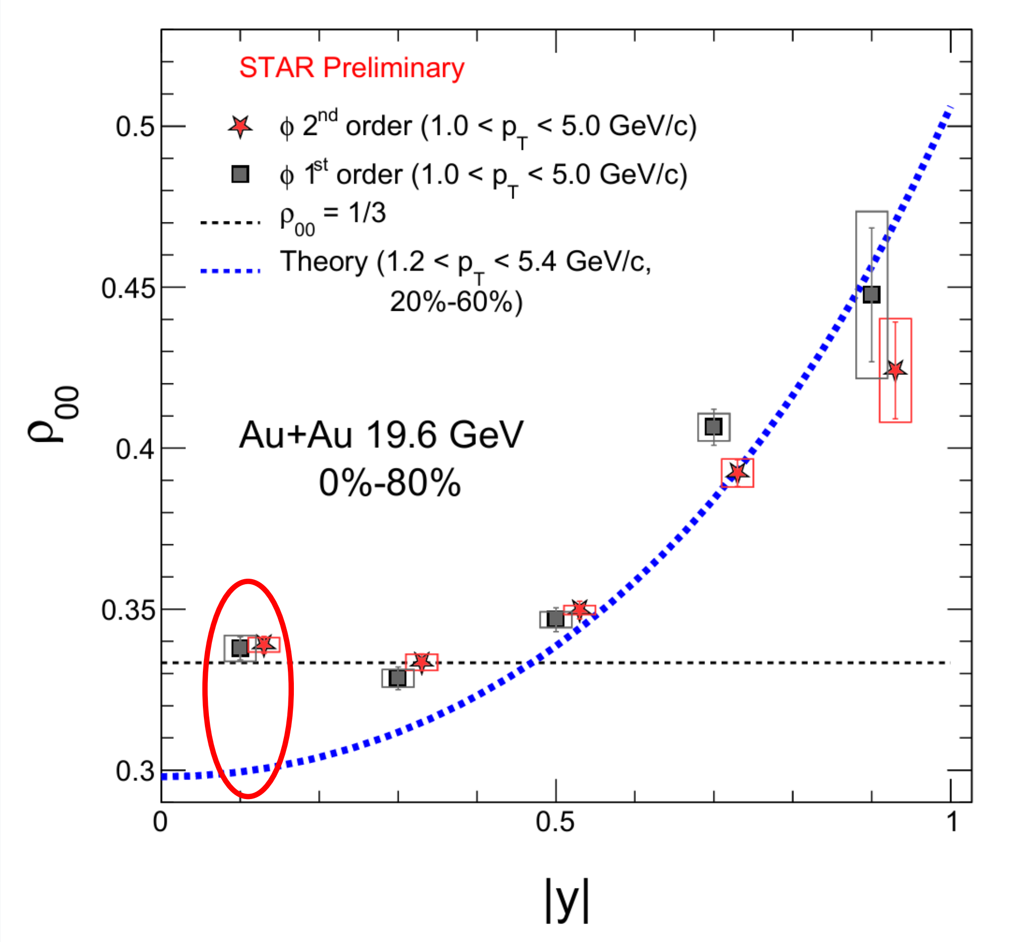
Other sources: spin correlation, color field, **strong force field**, thermal shear, anisotropy……

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

Rapidity spectra

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



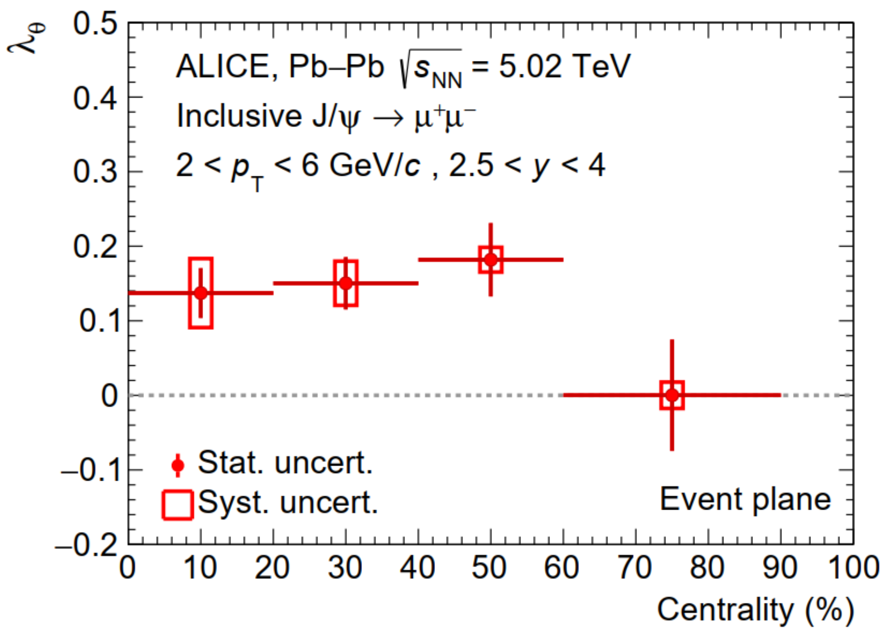


$$\langle \delta\rho_{00}^{y} \rangle (\mathbf{p}) = \frac{8}{3m_\phi^4}(C_1 + C_2)F^2\left(\frac{p_x^2 + p_z^2}{2} - p_y^2\right), \xrightarrow{Y=0} < \delta\rho_{00}^{y} > \propto 3v_2 - 1 < 0$$

J/Ψ spin alignment

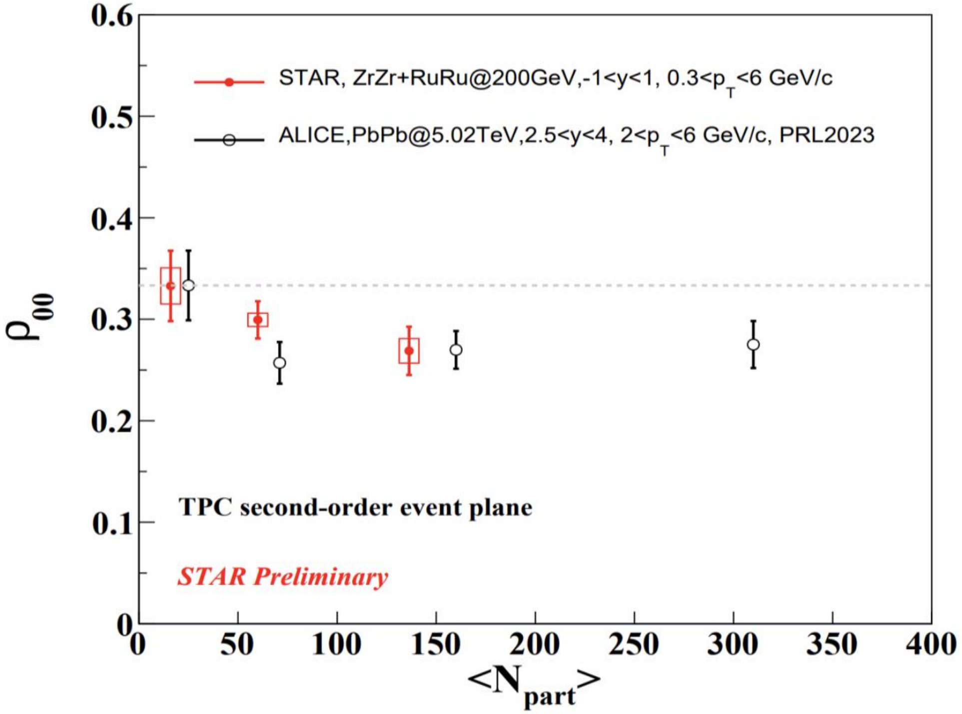
ALICE:

Phys.Rev.Lett. 131 (2023) 4, 042303



STAR:

PoS SPIN2023 (2024) 236



Experiments:

$$\rho_{00}^{J/\Psi} - \frac{1}{3} < 0$$

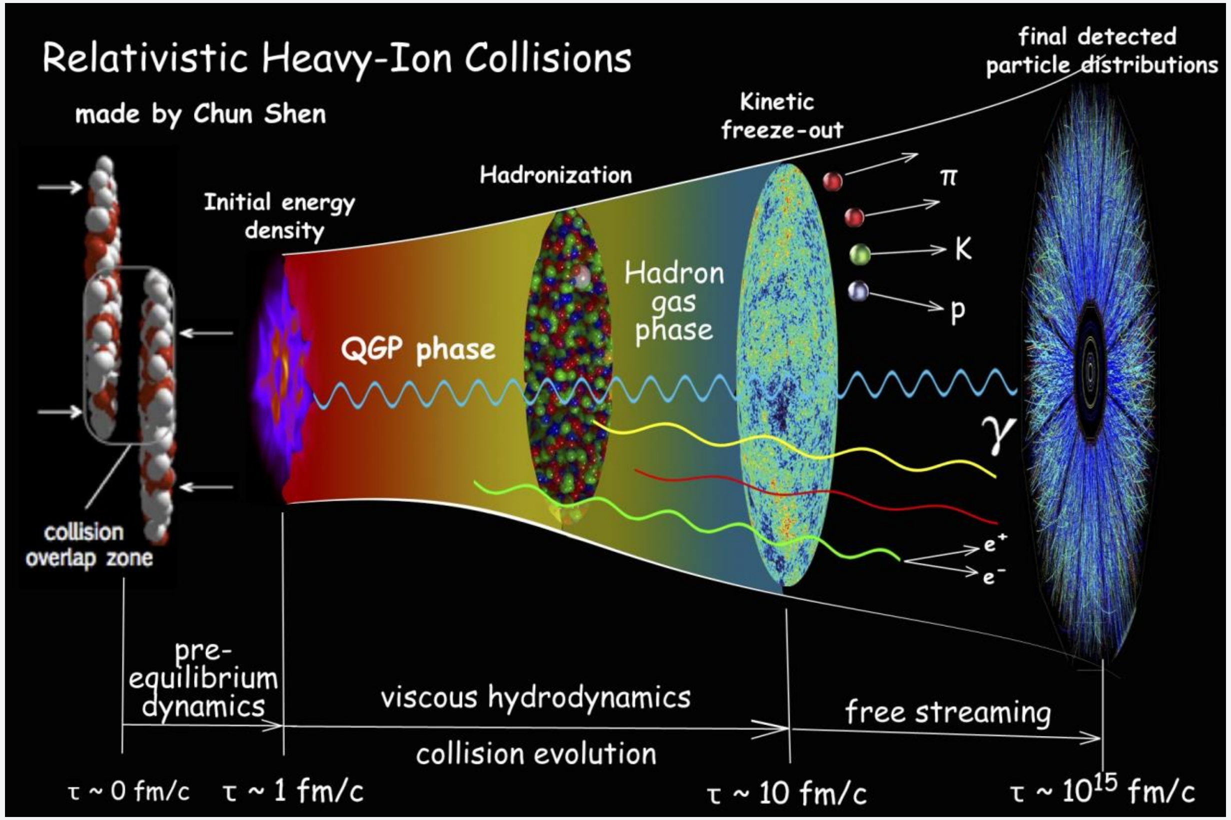
Phys.Rev.D 108 (2023) 1, 016020 A. Kumar et al.
Phys.Rev.D 109 (2024) 3, 034034 S. Fang et al.
Phys.Rev.D 111 (2025) 5, 056005 D.-L. Yang
Phys.Rev.D 111 (2025) 7, 074002 Z.-S. Chen, S. Lin

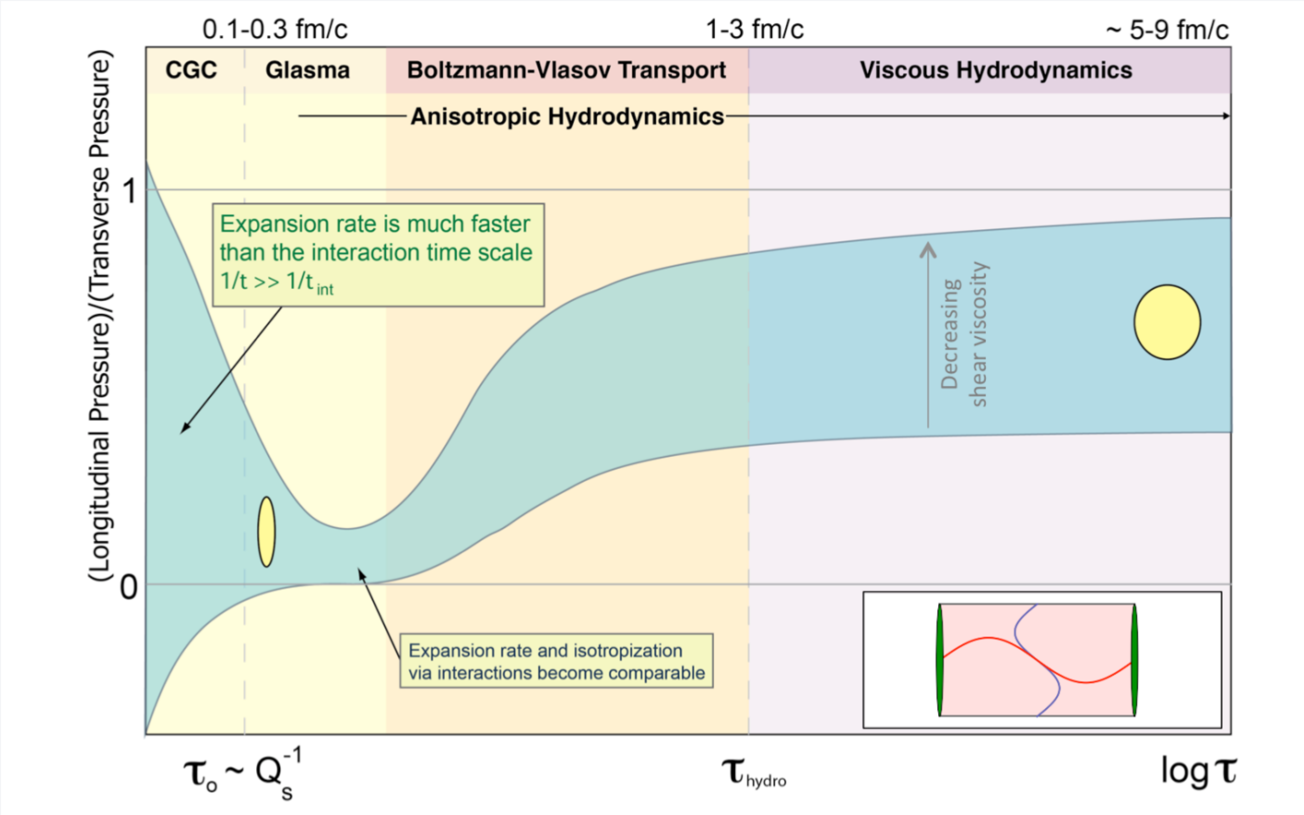
New sources are required

Outline

Anisotropy of QGP

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





Geometry difference ⟹ Anisotropy in initial ⟹ Anisotropy at freeze out

Anisotropy at freeze out state: determined by transport coefficients κ, ζ, η ...

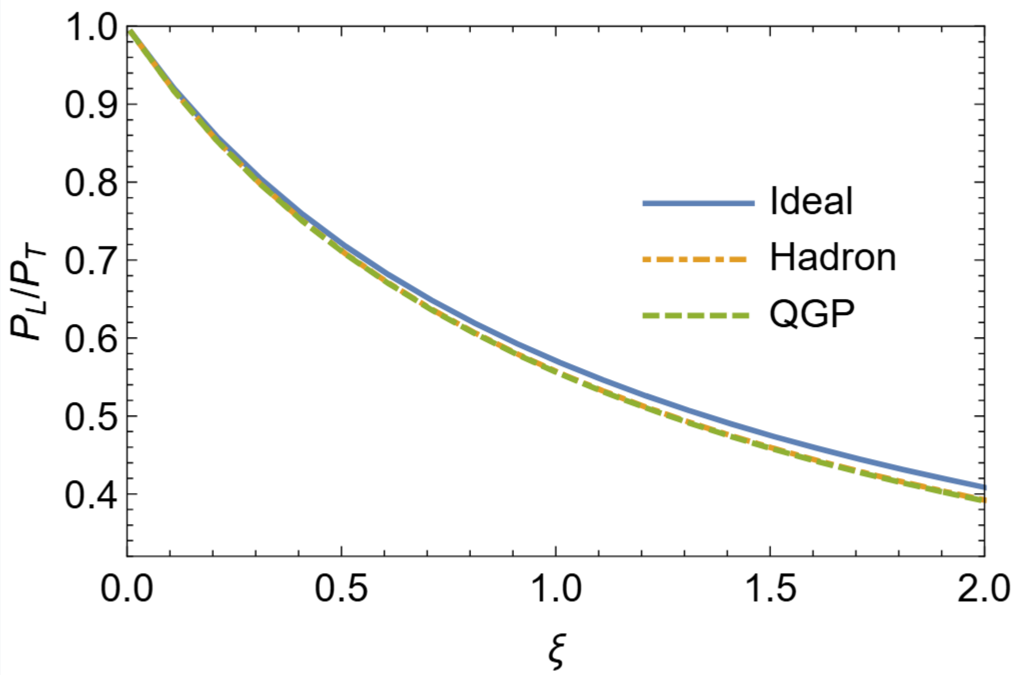
Anisotropy of QGP

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

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



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

Navier-Stockes theory

$$\left(\frac{P_L}{P_T}\right)_{\mathrm{NS}} = \frac{3T\tau - \frac{16\eta}{s}}{3T\tau + \frac{8\eta}{s}}.$$

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

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

General analysis

2→1 coalescence process:

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

General form:

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

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

Weighted by RS distribution

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

$$\boxed{\begin{aligned} &c_2 > 0, \delta\rho_{00} > 0 \\ &c_2 < 0, \delta\rho_{00} < 0 \\ &c_2 = 0, \delta\rho_{00} = 0 \end{aligned}}$$

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

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:

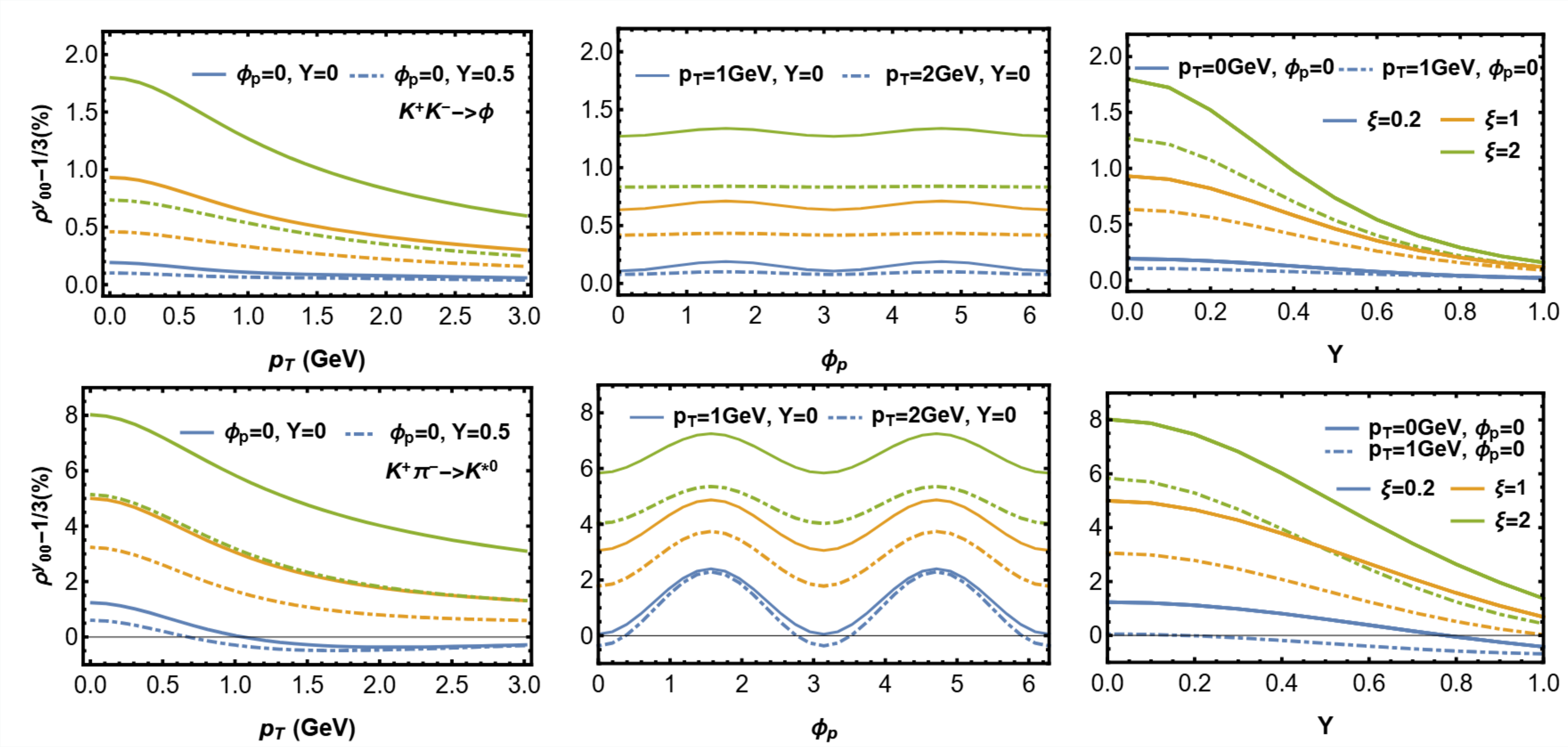
$$\mathcal{L}_{\phi KK} = i g_{\phi KK} \phi^{\mu} \left(K^{+} \partial_{\mu} K^{-} - K^{-} \partial_{\mu} K^{+} + K^{0} \partial_{\mu} \overline{K}^{0} - \overline{K}^{0} \partial_{\mu} K^{0} \right) ,$$

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

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

$$c_1^{K^{*0}} = 0, \qquad c_2^{K^{*0}} = 2 g_{K^{*0} K\pi}^2 .$$

$$\Longrightarrow \quad \delta\rho_{00} > 0$$



1.Decrease with rapidity (opposite to data).
2.Magnitude ~ several percents.

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.

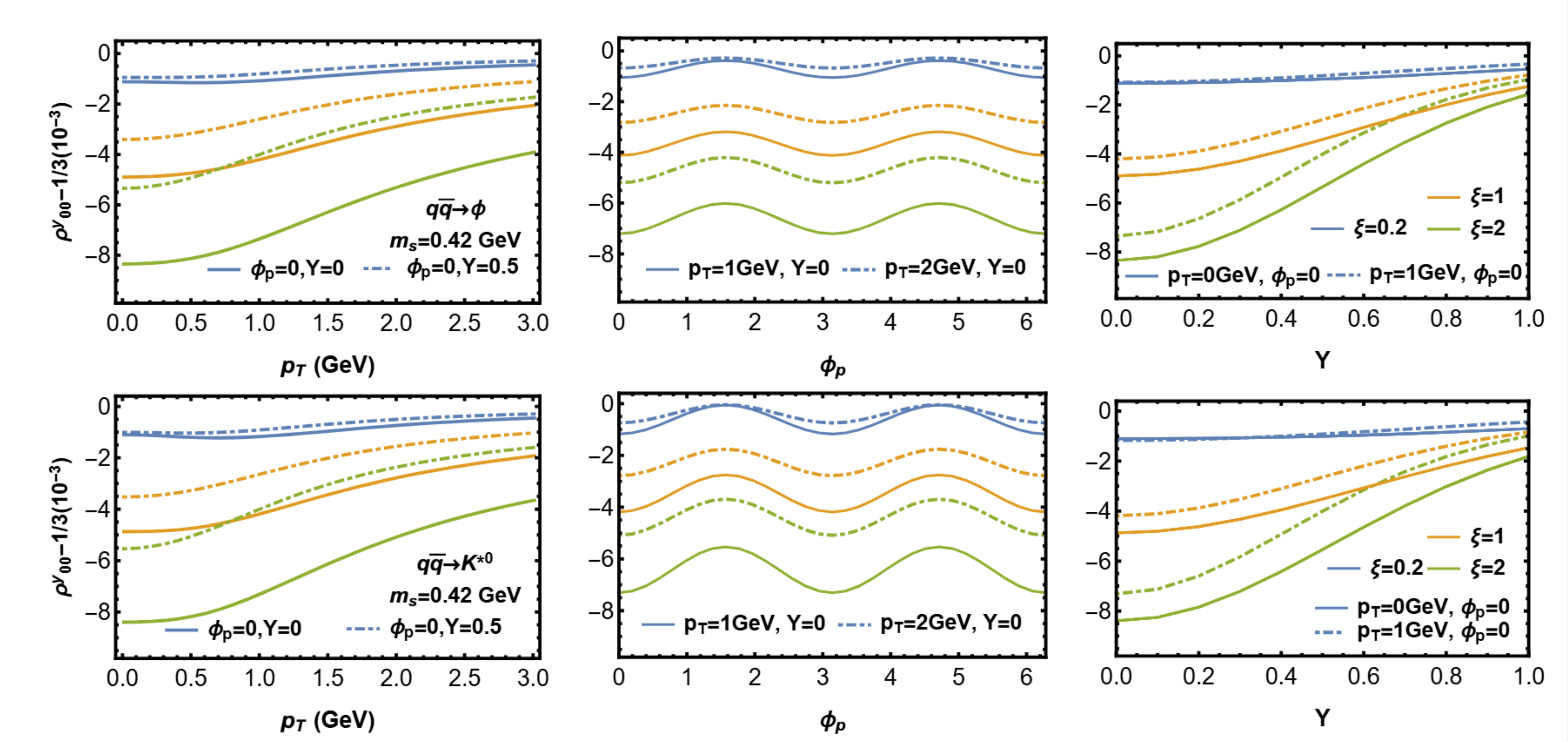
$$c_1^\phi = -2g_{\phi s\bar{s}}^2 \ , \qquad c_1^{K^{*0}} = -2g_{K^{*0}d\bar{s}}^2\left[1-\frac{(m_s-m_d)^2}{m_{K^{*0}}^2}\right] \ ,$$

$$\boxed{c_2^\phi = -2g_{\phi s\bar{s}}^2 \ , \quad c_2^{K^{*0}} = -2g_{K^{*0}d\bar{s}}^2 \ .} < 0$$

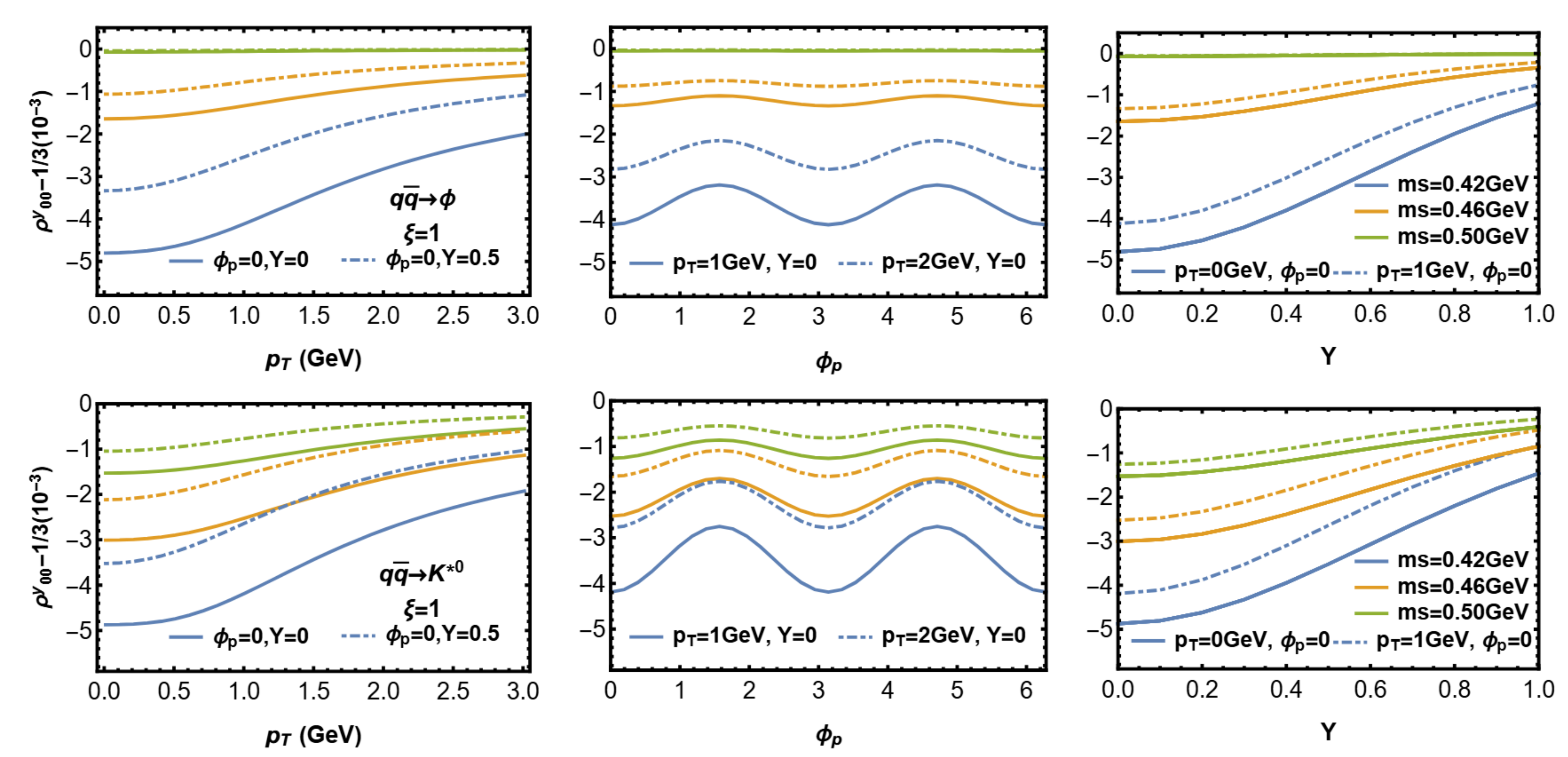
$$\delta\rho_{00} < 0$$

Parameters: quark mass m_s, anisotropy parameter ξ

Spin alignment with varying ξ



Spin alignment with varying m_s



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 vertexs

$\zeta = 0$: pure vector coupling, $\delta\rho_{00} < 0$
$\zeta = -\frac{2M}{m_1+m_2}$: P wave dominate (L->S)
identical to hadronic case, $\delta\rho_{00} > 0$

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

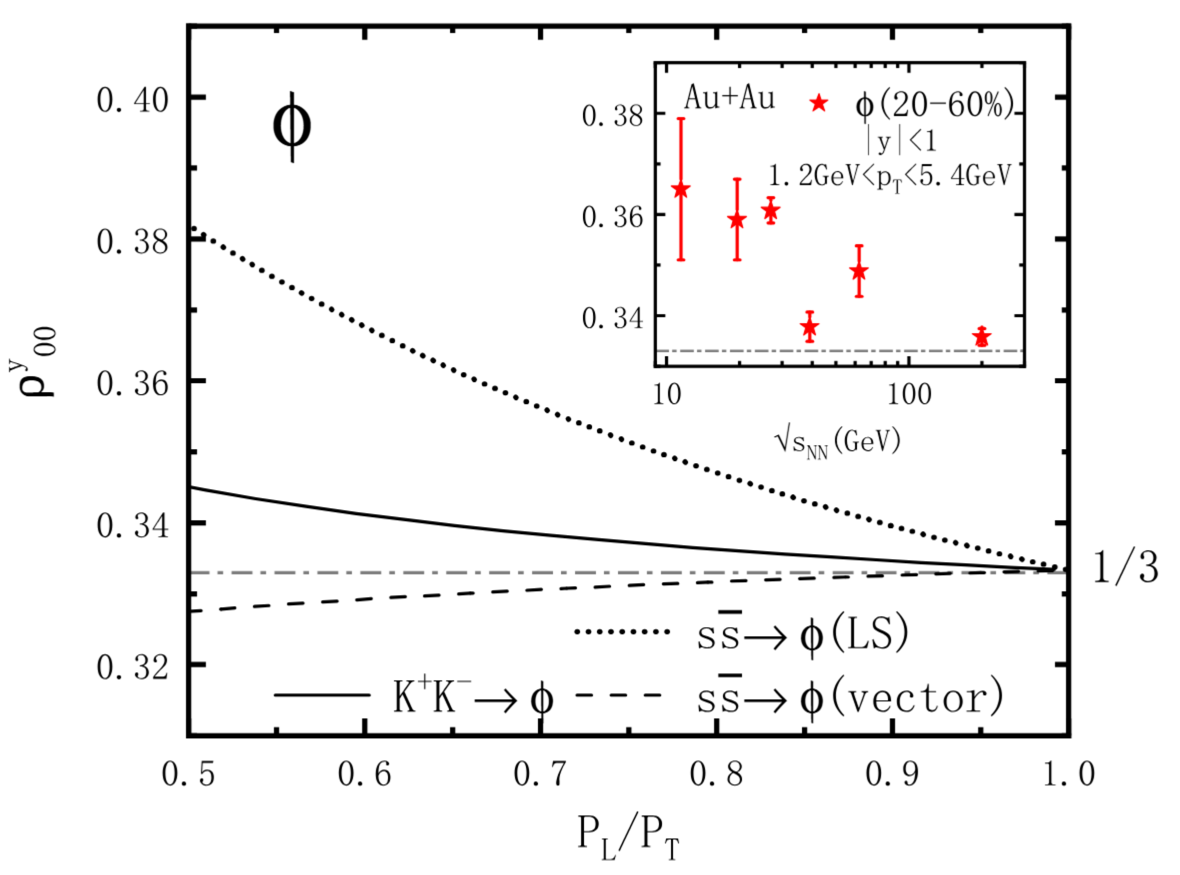
$$c_2^\phi = -2g^2_{\phi s\bar{s}}\left(1-\zeta_\phi^2\frac{m_s^2}{M^2}-\zeta_\phi^2\frac{m_\phi^2-4m_s^2}{4M^2}\right)\ ,$$

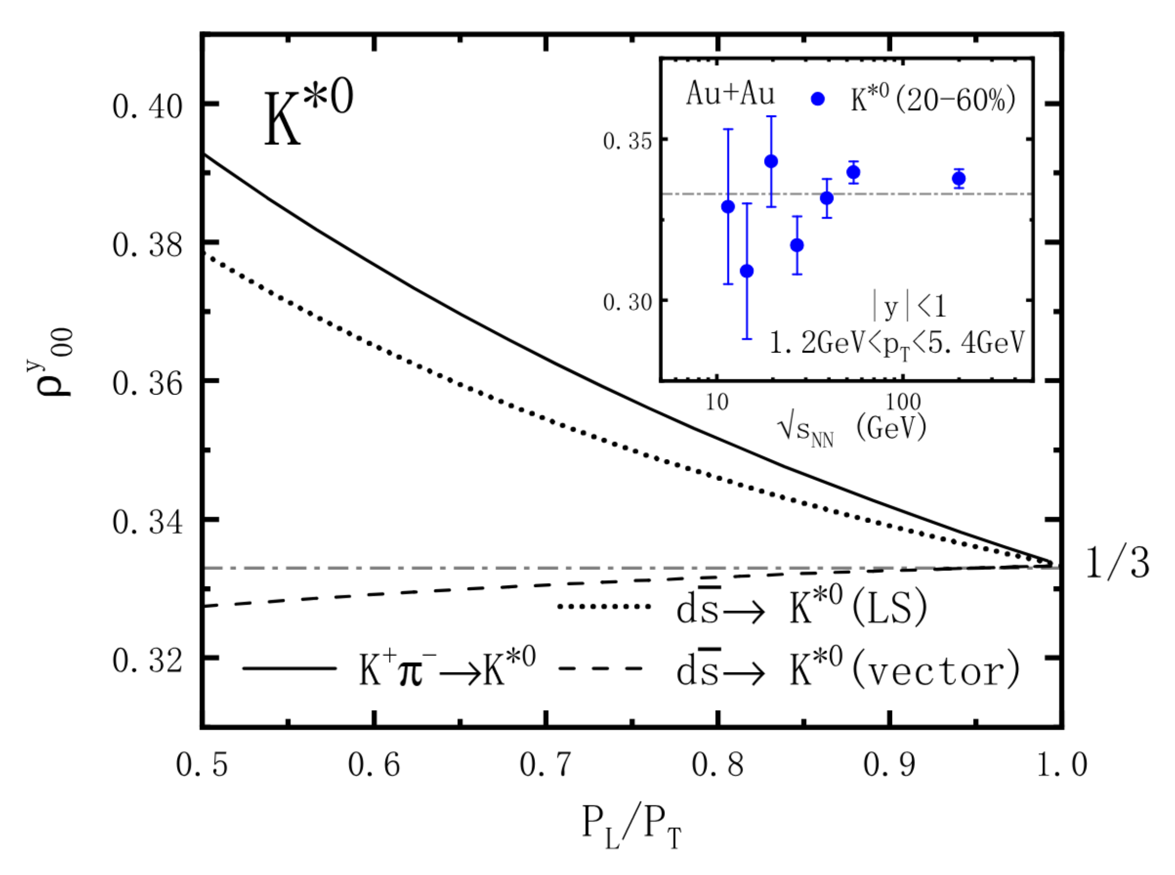
$$c_1^{K^{*0}} = -2g^2_{K^{*0}d\bar{s}}\left(1+\zeta_K\frac{m_d+m_s}{2M}\right)^2\left[1-\frac{(m_d-m_s)^2}{m^2_{K^{*0}}}\right],$$

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

Predictions

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





ϕ: long life-time -> anisotropy significant when produced

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

Outline

pNRQCD Lagrangian

$$\mathcal{L} = \mathcal{L}_{gluon} + \mathcal{L}_{light-quark} + \int d^3\mathbf{r} Tr \left\{ \mathrm{S}^\dagger \left(i\partial_0 - h_s\right) \mathrm{S} + \mathrm{O}^\dagger \left(i\partial_0 - h_o\right) \mathrm{O} + \mathrm{O}^\dagger g_s \mathbf{r}\cdot\mathbf{E}\mathrm{S} + \mathrm{S}^\dagger g_s \mathbf{r}\cdot\mathbf{E}\mathrm{O} + \frac{1}{2}\mathrm{O}^\dagger \{g_s \mathbf{r}\cdot\mathbf{E}, \mathrm{O}\} + \mathrm{O}^\dagger \mu\cdot B\mathrm{S} + \mathrm{S}^\dagger \mu\cdot B\mathrm{O} + \frac{1}{2}\mathrm{O}^\dagger \{\mu\cdot B, \mathrm{O}\} + \cdots \right\},$$

$$\mathrm{S} = \frac{1}{\sqrt{N_C}} S$$
$$\mathrm{O} = \frac{O^a T^a}{\sqrt{T_F}}$$
$$\mu = \frac{g_s}{2m_Q}\left(\sigma_Q - \sigma_{\overline{Q}}\right)$$
$$h_{0/s} = -\frac{\nabla^2_{cm}}{4M} - \frac{\nabla^2_{rel}}{M} + V_{o/s}(r)$$
$$V_s = -C_F \frac{\alpha_s}{r}$$
$$V_o = \frac{1}{2N_c}\frac{\alpha_s}{r}.$$

J/Ψ production: $c + \bar{c} \rightarrow [c\bar{c}]_8 \rightarrow J/\Psi + g$

Chromo-electric decay: ${}^3P_J^{(8)} \rightarrow {}^3S_1^{(0)}$ (spin independent)

Chromo-magnetic decay: ${}^1S_0^{(8)} \rightarrow {}^3S_1^{(0)}$ (spin related)

Phys.Rev.D 111 (2025) 5, 056005 D.-L. Yang
Phys.Rev.D 111 (2025) 7, 074002 Z.-S. Chen, S. Lin

Production rate

Anisotropic distributed

$$\Gamma_\lambda(\mathbf{p}_1, R) = \int \frac{d\mathbf{p}_2 d\mathbf{k} d\mathbf{p}_{rel}}{(2\pi)^9 2E_k} d\sigma^\lambda \boxed{f_{c\bar{c}}(p_2, p_{rel}, R)} \left[1 + \boxed{f_g(k, R)}\right].$$

$$d\sigma^\lambda_{E1}(p_1, p_2, k, p_{rel}) = \delta(E_{p_1} + E_k - E_{p_2}) \delta^{(3)}(p_1 + k - p_2) |M_e^\lambda(|p_{rel}|)|^2,$$

$$d\sigma^\lambda_{M1}(p_1, p_2, k, p_{rel}) = \delta(E_{p_1} + E_k - E_{p_2}) \delta^{(3)}(p_1 + k - p_2) |M_b^\lambda(|p_{rel}|)|^2,$$

$$|M_e^\lambda|^2 = g_s^2 \frac{T_F(N_C^2 - 1)}{N_C} \Sigma_{\lambda_1=\pm} \varepsilon^{*,i}_{\lambda_1}(k) \varepsilon^{*,j}_{\lambda_1}(k) E_k^2 \int dr \left[\psi^{*,\lambda}_{100}(r) \mathbf{r}^i \Psi^\lambda_{rel}(r)\right] \times \int dr \left[\psi^{*,\lambda}_{100}(r) \mathbf{r}^j \Psi^\lambda_{rel}(r)\right]^*,$$

$$|M_b^\lambda|^2 = \frac{g_s^2}{m_Q^2} \frac{T_F(N_C^2 - 1)}{N_C} \Sigma_{\lambda_1=\pm} \epsilon^{*,i}_\lambda \epsilon^j_\lambda \left[\int d^3\mathbf{r} \psi^{*,\lambda}_{100}(r) \left(k \times \varepsilon^*_{\lambda_1}\right)^i \Psi^1_{rel}(r)\right] \times \left[\int d^3\mathbf{r} \psi^{*,\lambda}_{100}(r) \left(k \times \varepsilon^*_{\lambda_1}\right)^j \Psi^1_{rel}(r)\right]^*.$$

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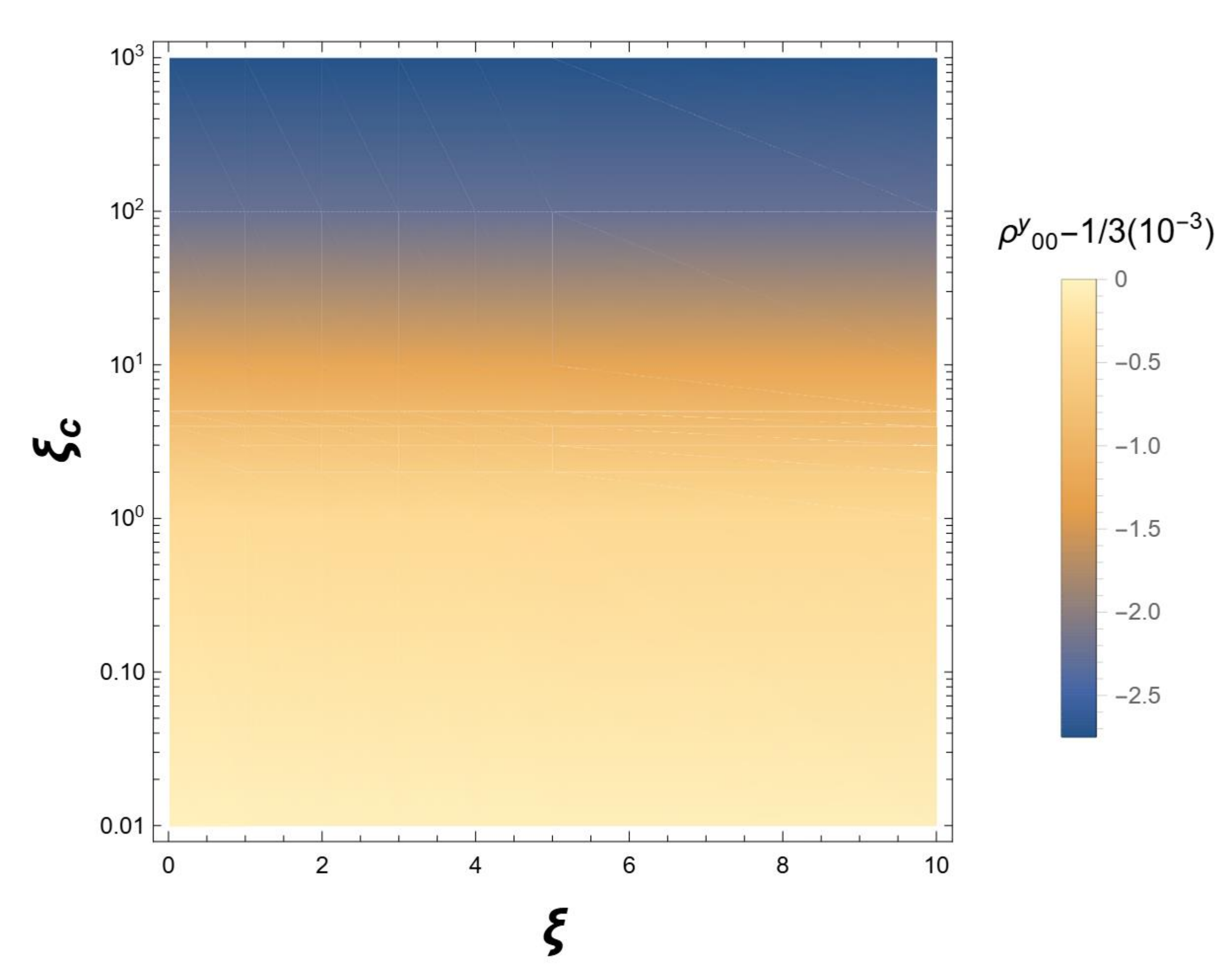
JHEP 01 (2021) 046 X.J. Yao et.al

Spin alignment



$$f_g = \frac{1}{\exp\left[\beta_0\sqrt{p_T^2+(1+\xi)\,p_z^2+m_T^2}\right]-1},$$

$$\boxed{\begin{aligned} f_{c\bar{c}} &= f_c\left(\frac{p_{cm}-p_{rel}}{2}\right) f_{\bar{c}}\left(\frac{p_{cm}+p_{rel}}{2}\right) \\ &\approx \exp\left[-\beta_0\sqrt{p_{cm,T}^2+(1+\xi_c)\,p_{cm,z}^2+4M^2}\right] \end{aligned}},$$

Imprecise assumption

Conclusion:

1. Anisotropy of gluon field can induce negative spin alignment
2. Magnitude is 10^-5 without quark distribution anisotropy due to the thermal mass.
3. Precise prediction relies on exact charm quark distribution

Outline

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 zero rapidity.
2. For light mesons, tensor coupling vertex is important in study the spin-related phenomena, the sign of spin alignment is determined by the ratio between tensor coupling and vector coupling vertex. It helps to study the hadronization process of light mesons.
3. For heavy quarks, it might be a potential source of J/Psi's spin alignment.

Thank you