Anisotropy induced spin alignment

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Outline

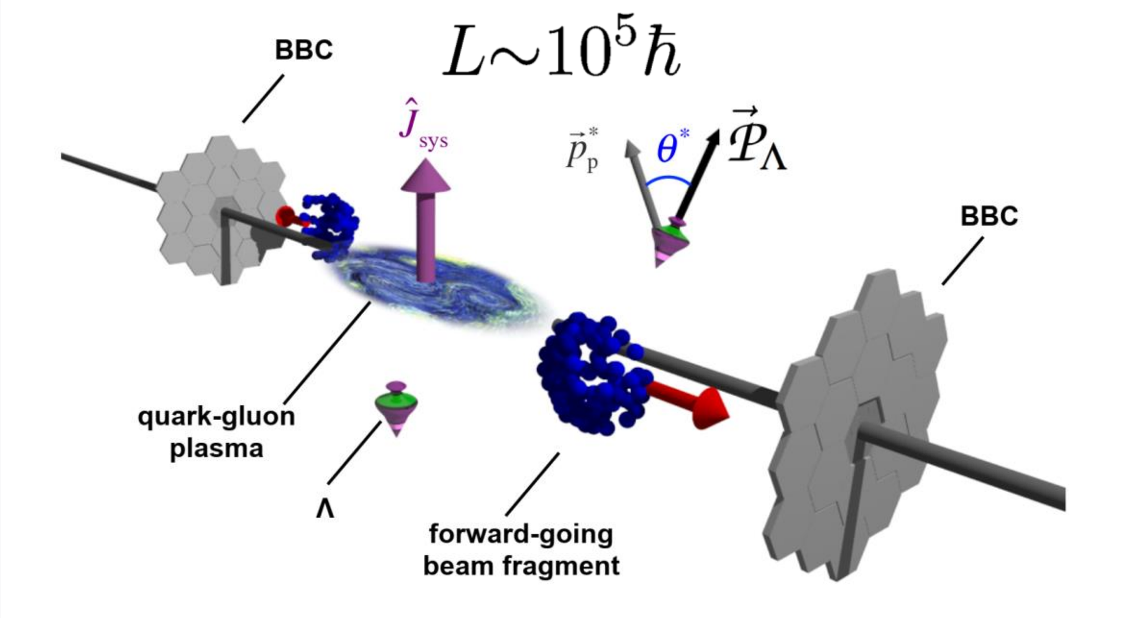
01 **Introduction**

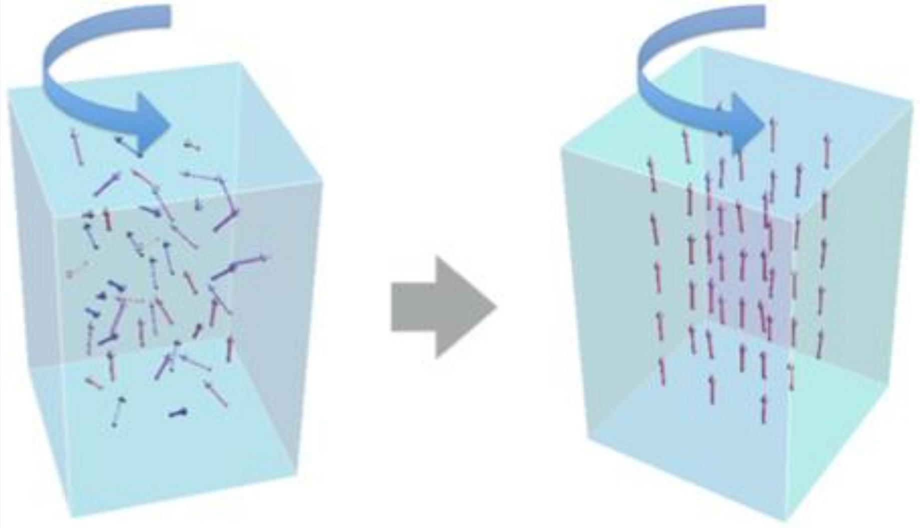
02 Spin alignment of ϕ and $K^{*,0}$ with anisotropy

03 Spin alignment of J/Ψ with anisotropic gluon field

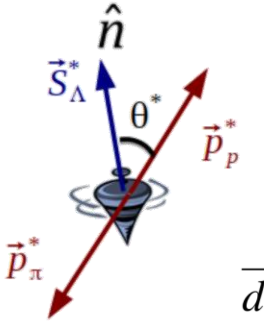
04 Summary

Introduction





Orbit angular momentum → Spin polarization

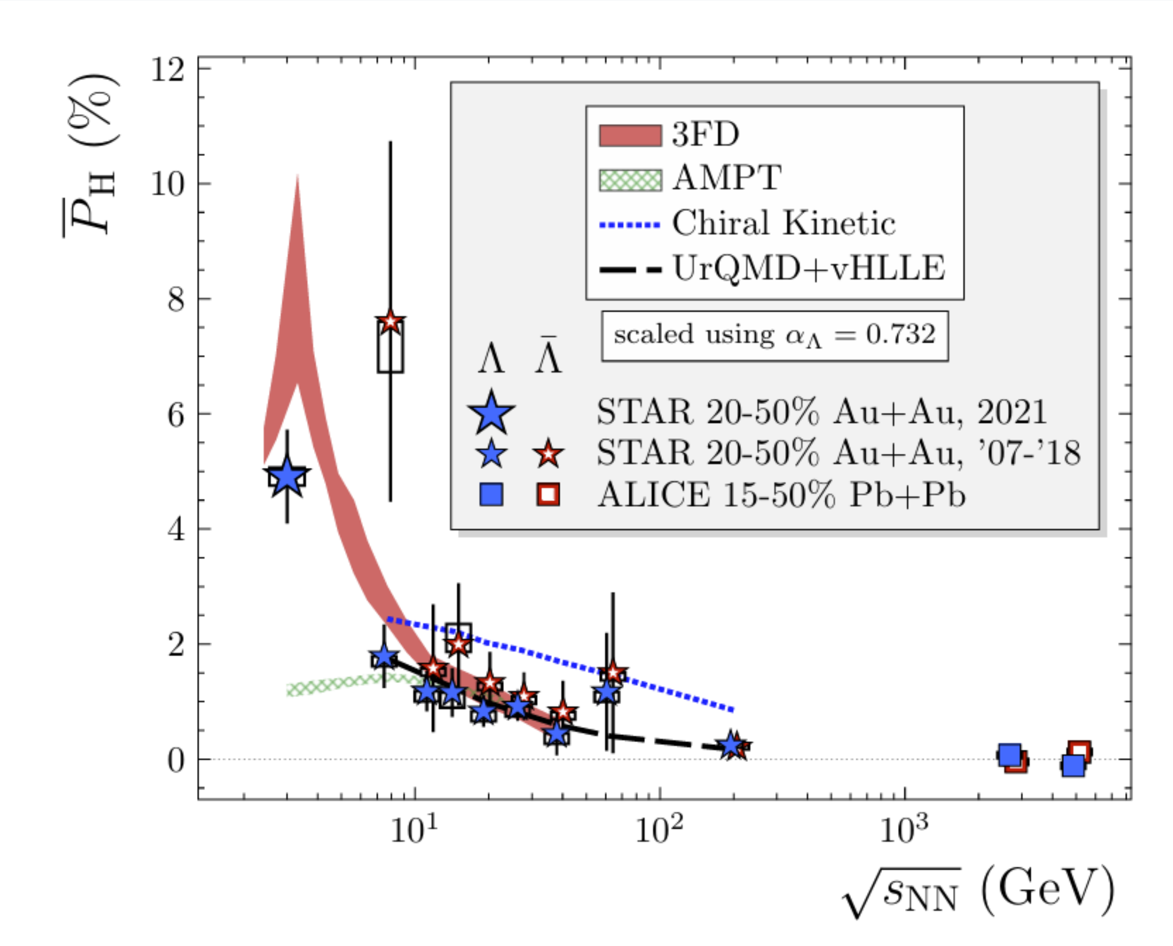


$$\Lambda \to p + \pi^-$$

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

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



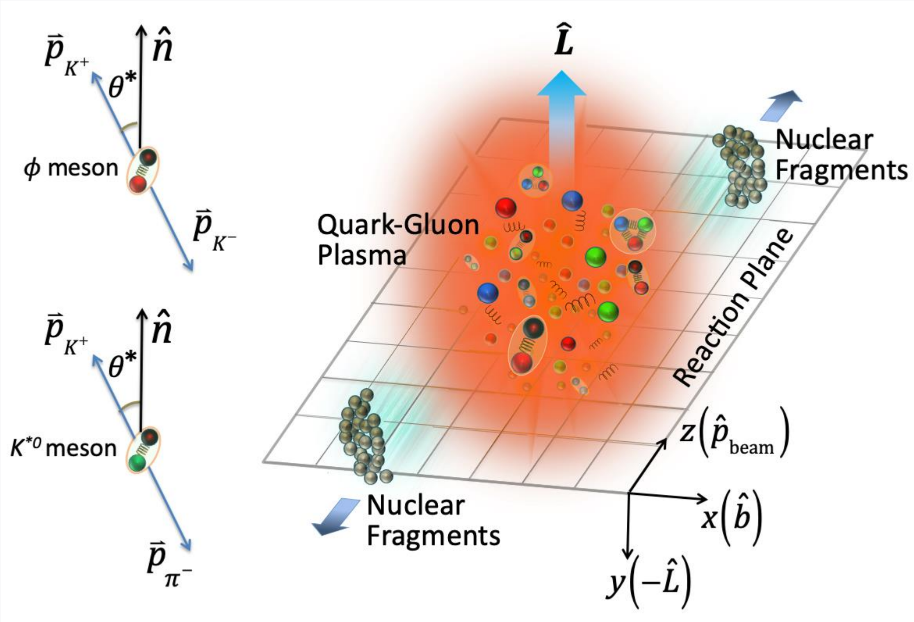
Spin polarization vector:

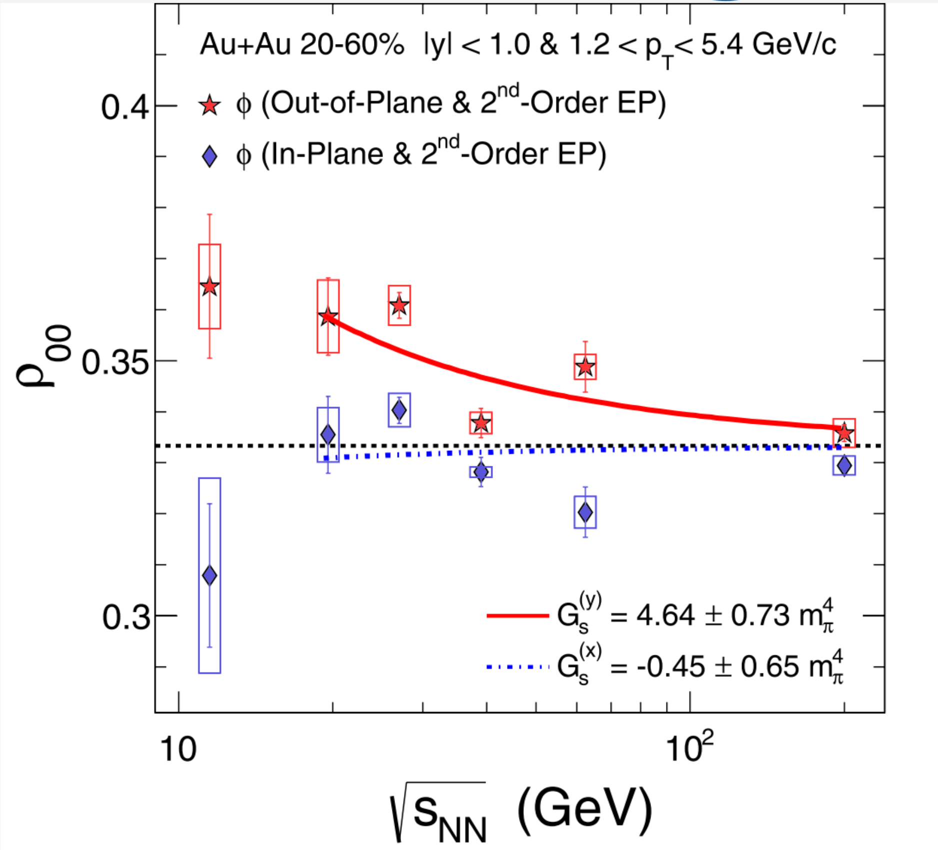
$$S^\mu_\varpi(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F},$$

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

- *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

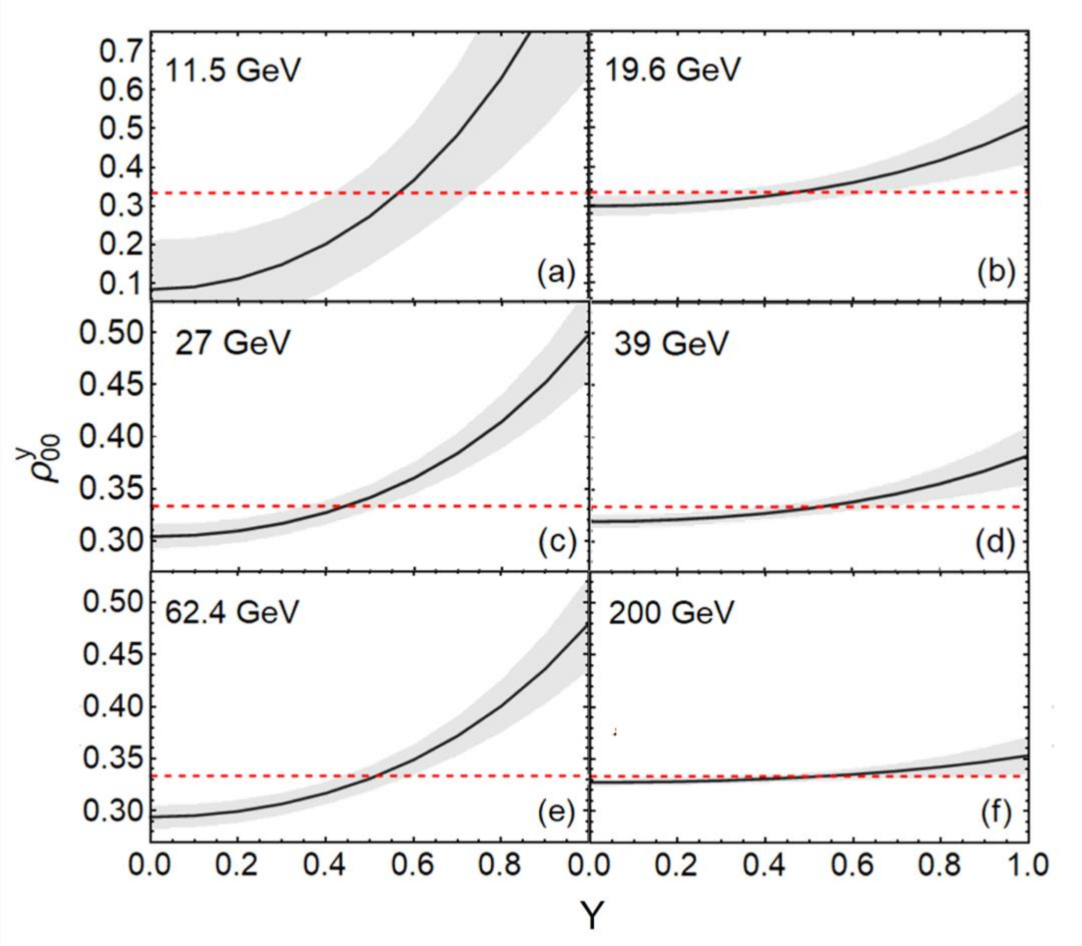
Orbit→ Spin: $\rho_{00} - \frac{1}{3} \sim -\omega^2 \sim -10^{-4}$ ✗

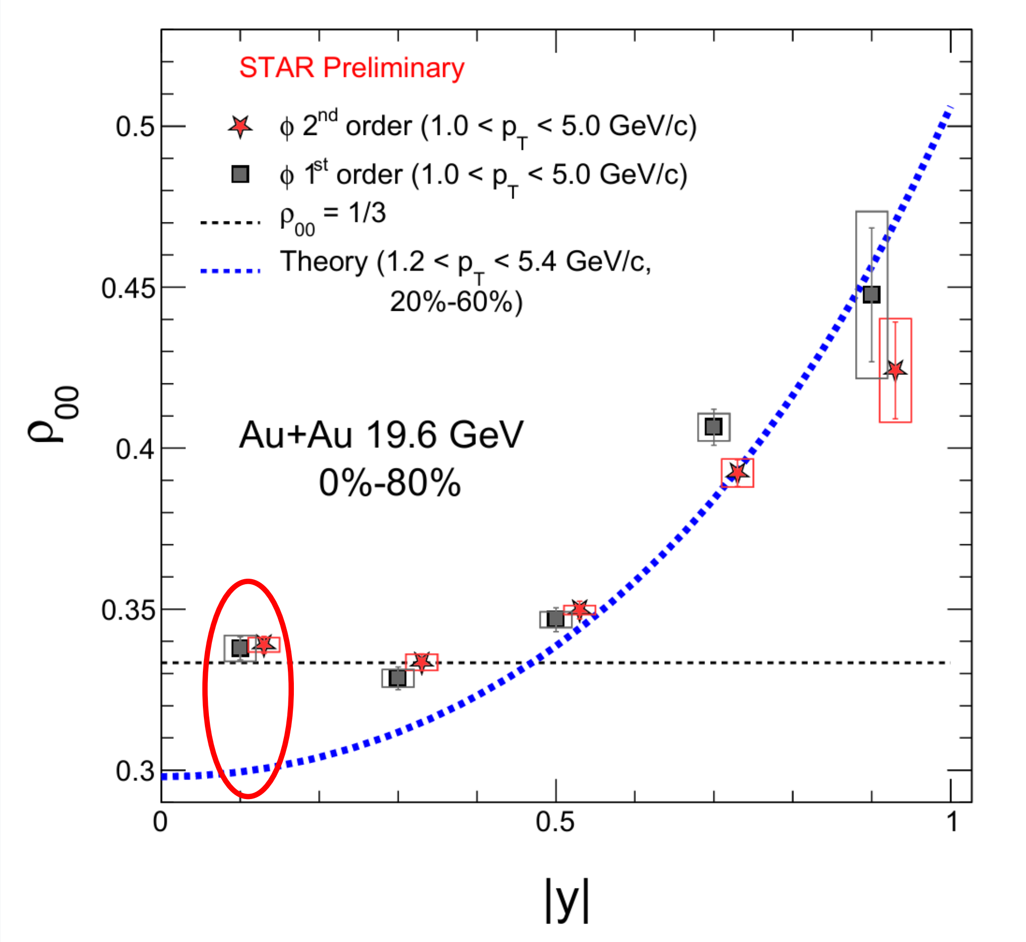
Other sources: electromagnetic field, color field, **strong force field**, thermal shear, anisotropy……

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

Rapidity spectra

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





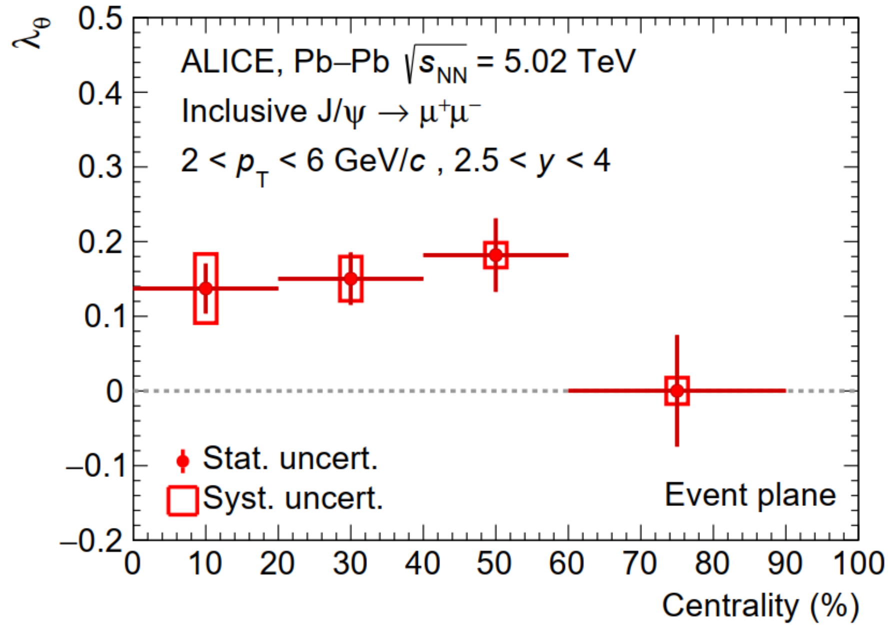
$$\langle \delta\rho_{00}^{y} \rangle (\mathbf{p}) = \frac{8}{3m_\phi^4}(C_1 + C_2)F^2 \left(\frac{p_x^2 + p_z^2}{2} - p_y^2 \right),$$

Y=0 ⟹ $< \delta\rho_{00}^{y} > \propto 3v_2 - 1 < 0$

J/Ψ spin alignment

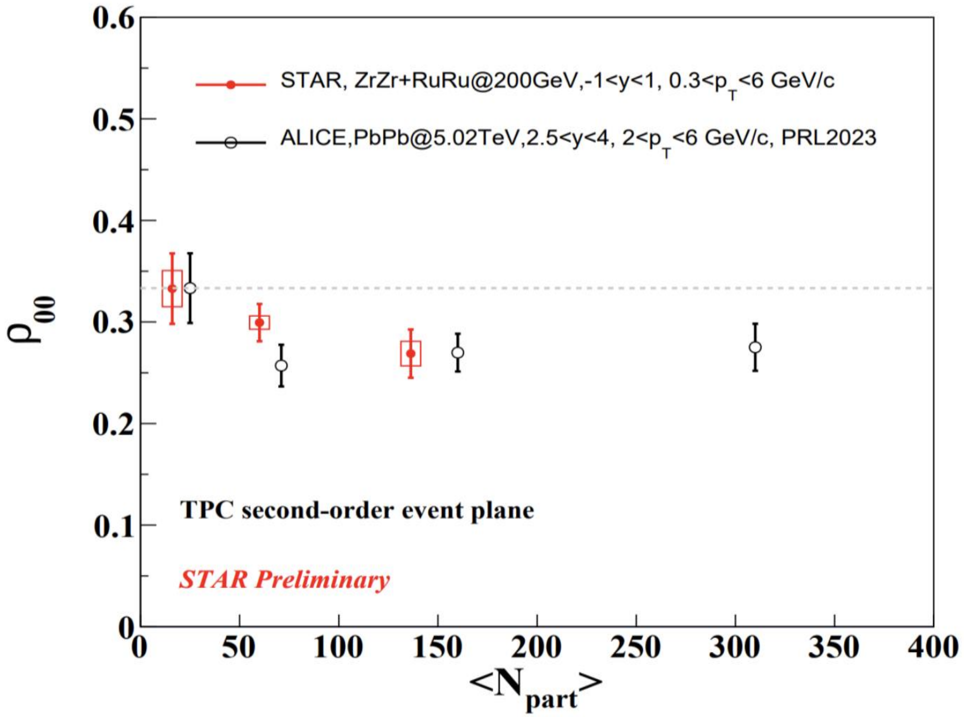
ALICE:

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



STAR:

PoS SPIN2023 (2024) 236



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

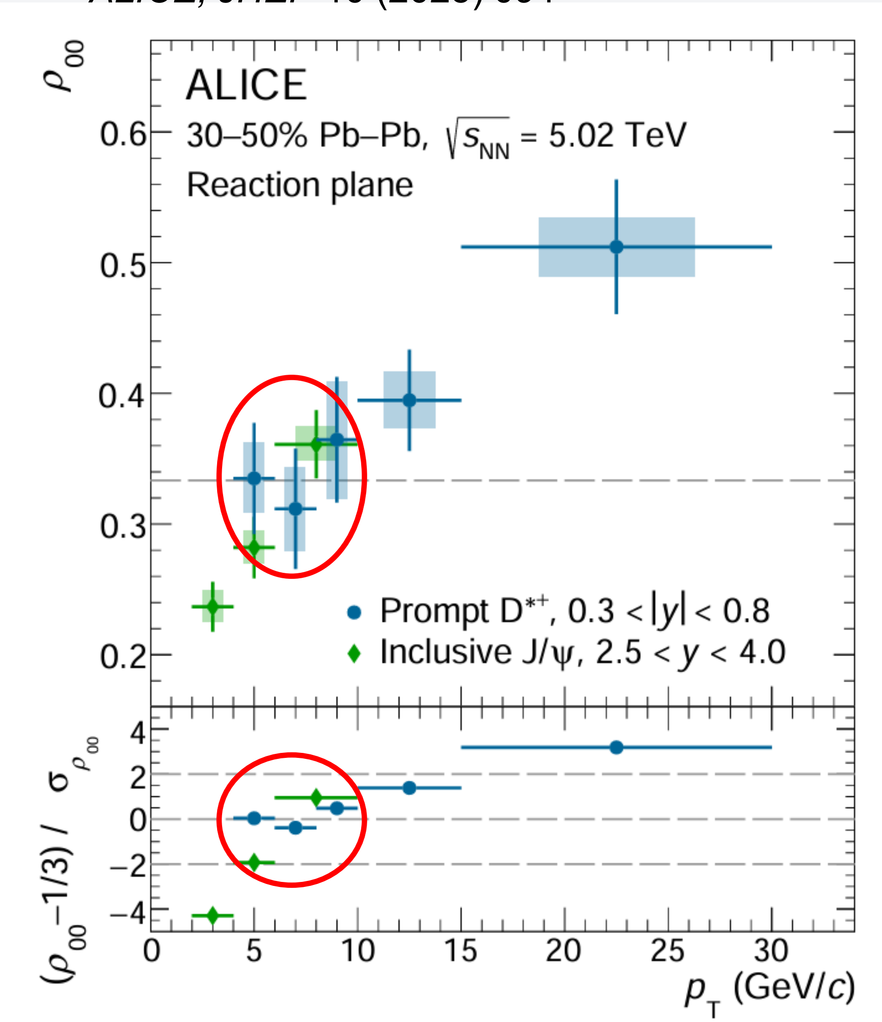
Strong force field contribution: $\rho_{00}^{J/\Psi} - \frac{1}{3} > 0$

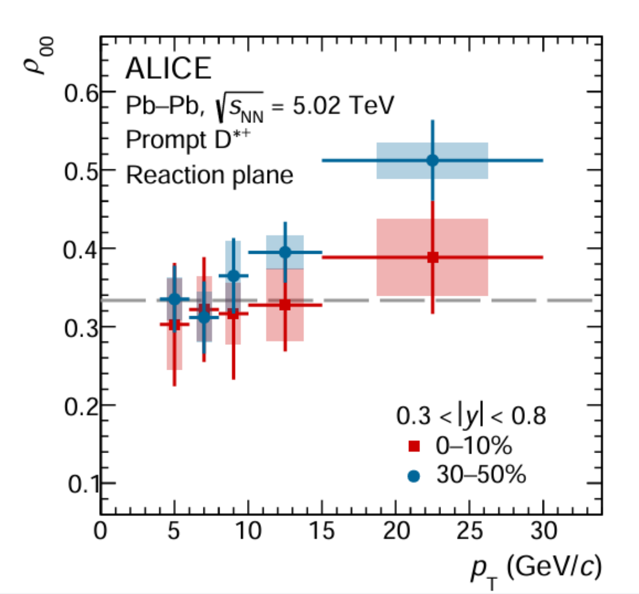
New sources are required

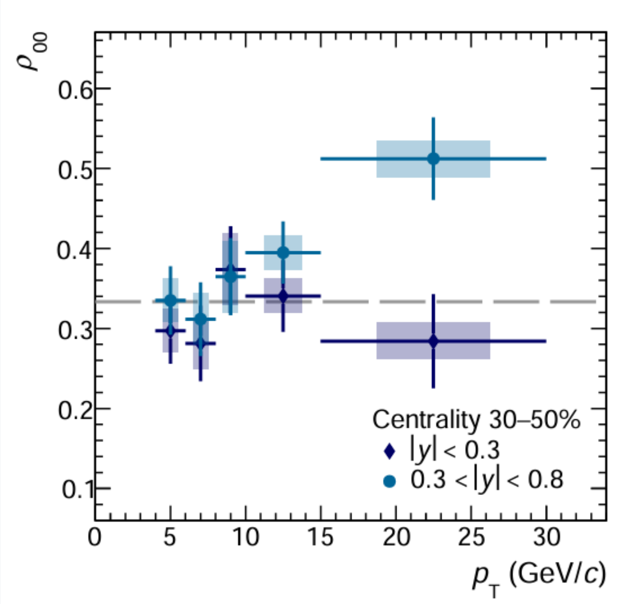
Phys.Rev.D 108 (2023) 1, 016020 A. Kumar et al.
Phys.Rev.D 109 (2024) 3, 034034 S. Fang et al.
Phys.Rev.D 111 (2025) 5, 056005 D.-L. Yang
Phys.Rev.D 111 (2025) 7, 074002 Z.-S. Chen, S. Lin

Heavy flavor spin alignment

ALICE, JHEP 10 (2025) 094







Low pT: regeneration
Large pT: initial state production

$$gg \to g^* \to J/\Psi, gg \to g + J/\Psi$$

cross in the region [5,10]GeV,
production mechanism reason?

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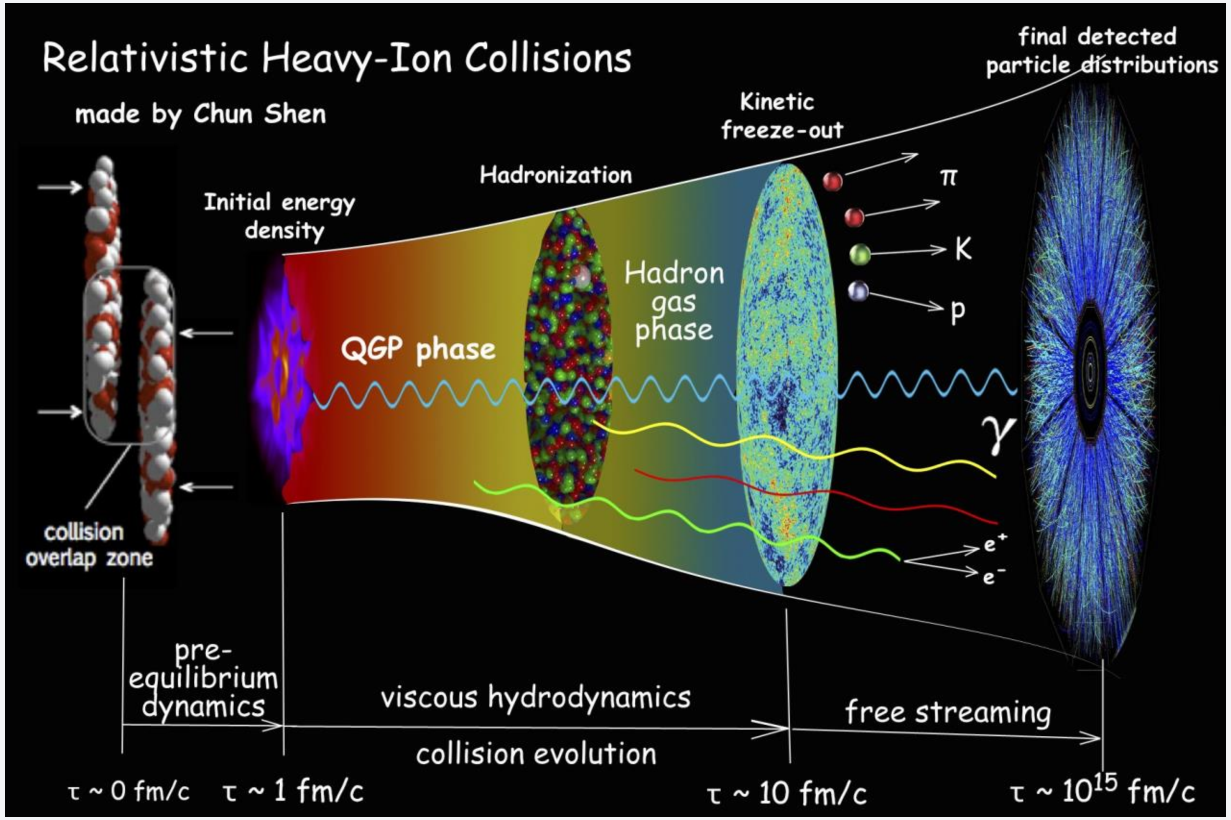
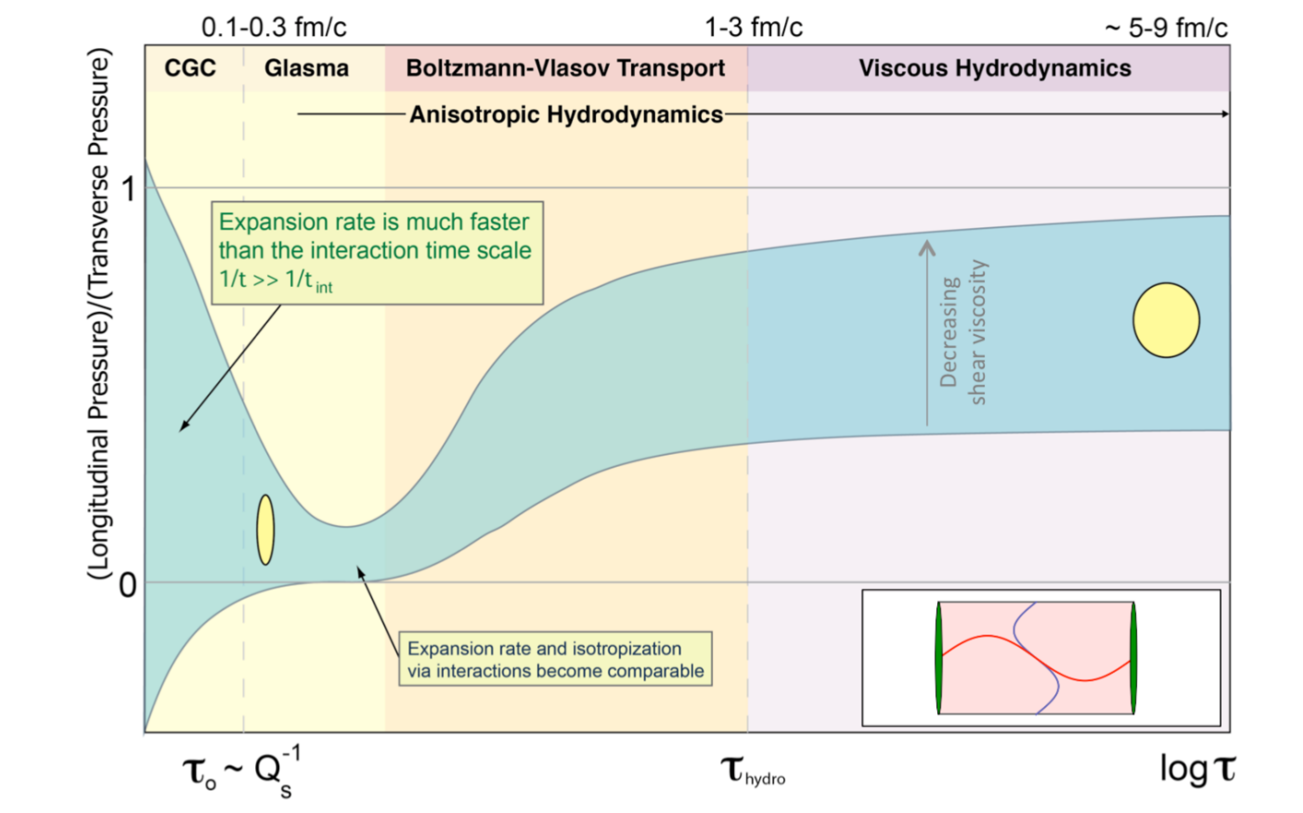
Anisotropy of QGP



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



Geometry difference ⟶ Anisotropy of QGP ⟶ aHydro revolution τ_{iso}

τ_{iso}: isotropization time (determined by transport coefficients κ, ζ, η ...)

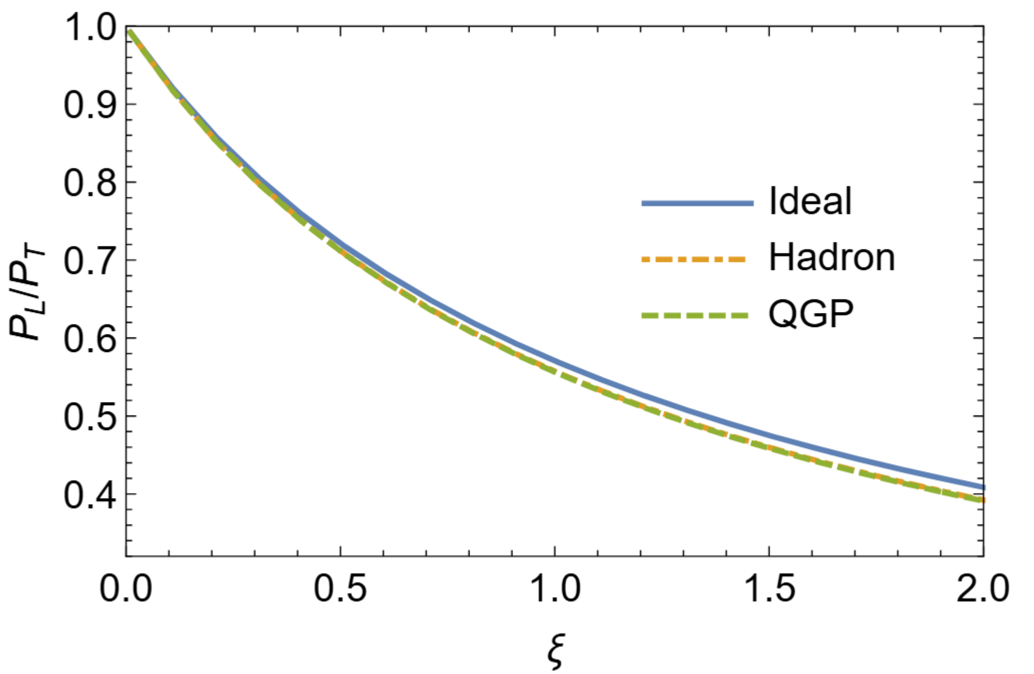
Anisotropy of QGP

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

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



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 → PL/PT=0.92
Low energy: τ=8fm/c, η/S=0.3 → PL/PT=0.65

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

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:

$$\mathcal{M}^{\mu\nu}(p,q) = c_1\, m_V^2\, g^{\mu\nu} + c_2\, q^\mu q^\nu + c_3\, p^\mu p^\nu + c_4\left(p^\mu q^\nu + q^\mu p^\nu\right),$$

$$\Gamma_\lambda \propto \int \frac{d^3\mathbf{p}\, d^3\mathbf{q}}{4E_{p_1}E_{p_2}}\delta(E_p - E_{p_1} - E_{p_2})\left[-c_1\, m_V^2 + c_2\left|q\cdot\epsilon(p,\lambda)\right|^2\right] f_1(p_1) f_2(p_2)\,,$$

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

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

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 Rainbow approximation

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

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

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

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

Bethe-Salpeter wave function

$$B(\mathbf{p}-\mathbf{p}',\mathbf{p}') = \frac{1-\exp\left\{-\left[(E^s_{\mathbf{p}-\mathbf{p}'} - E^{\bar{s}}_{\mathbf{p}'})^2 - (\mathbf{p}-2\mathbf{p}')^2\right]/\sigma^2\right\}}{\left[(E^s_{\mathbf{p}-\mathbf{p}'} - E^{\bar{s}}_{\mathbf{p}'})^2 - (\mathbf{p}-2\mathbf{p}')^2\right]/\sigma^2},$$

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

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

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

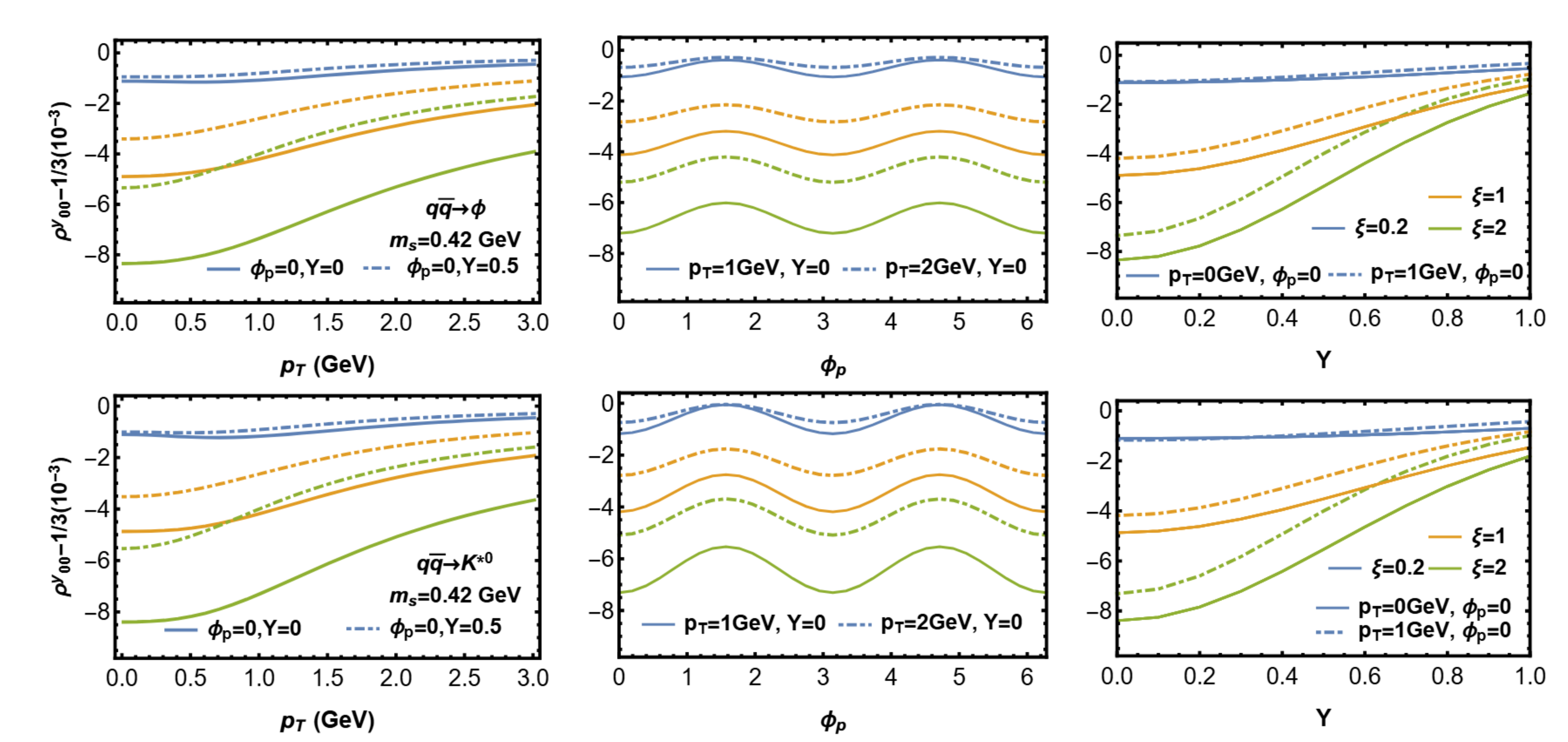
$$c_2^{K^{*0}} = -2g^2_{K^{*0} d\bar{s}} \,.$$

< 0

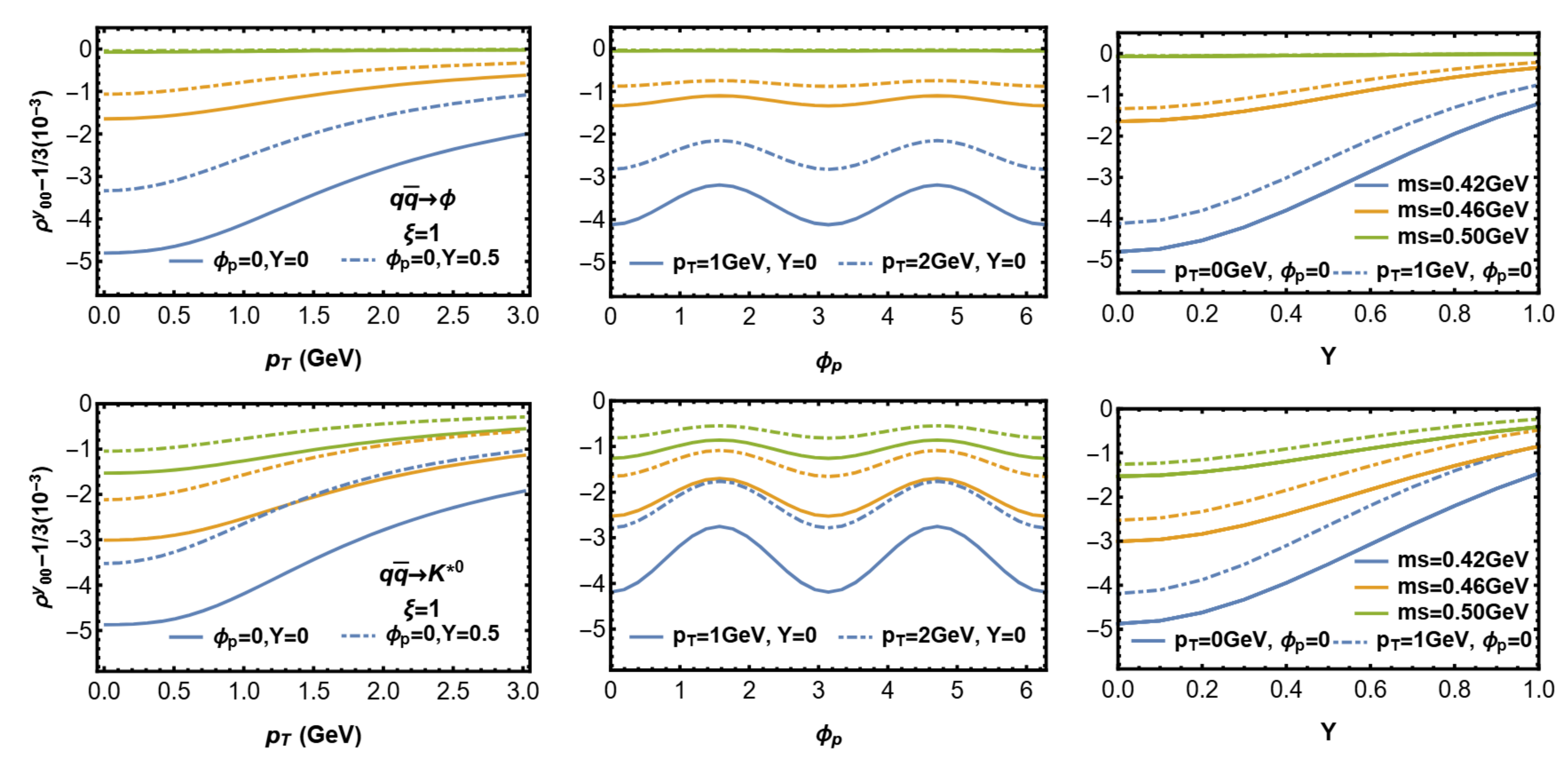
$\delta\rho_{00} < 0$

Parameters: quark mass m_s, anisotropy parameter ξ

Spin alignment with varying ξ



Spin alignment with varying m_s



ϕ and K^{*0} with hadronic interaction

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

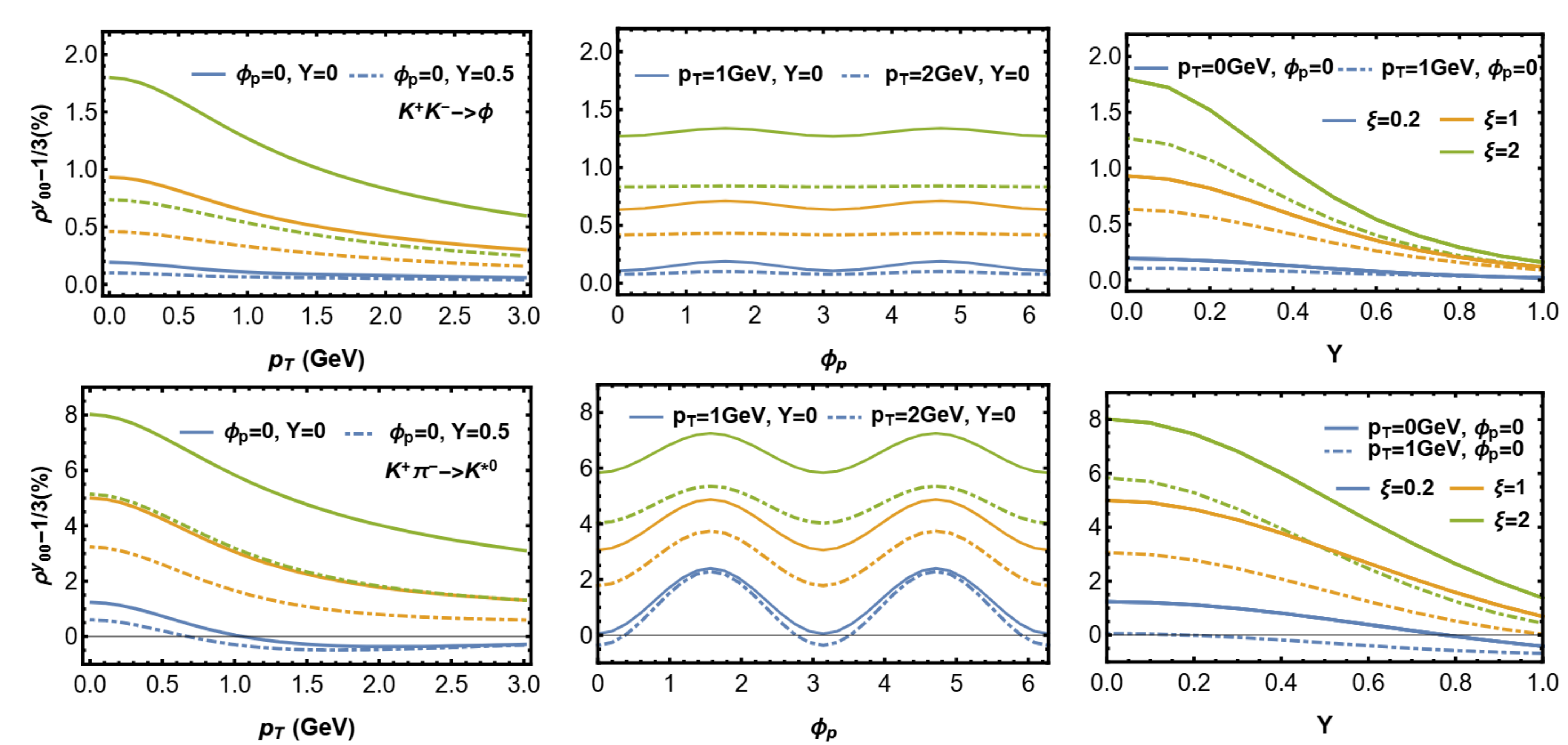
Long life-time meson(ϕ ...): quark interaction dominant
Short life-time meson(K^{*0}, ρ ...): hadron interaction dominant

Vertex from Chiral perturbation theory

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

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

$\longrightarrow$ $\delta\rho_{00} > 0$



1.Decrease with rapidity (opposite to data).

2.Magnitude ~ several percents.

ϕ and K^{*0} with LS coupling vertex

General effective vertex:

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

$$\mathcal{L}_I^{\phi} = g_{\phi s\bar{s}}\overline{\psi}_s \left[i\gamma^\mu \left(1+\zeta_\phi \frac{m_s}{M}\right) + \frac{\zeta_\phi}{2M}\overleftrightarrow{\partial}^\mu \right] \psi_s \phi_\mu \,,$$

$$\mathcal{L}_I^{K^{*0}} = g_{K^{*0}d\bar{s}}\overline{\psi}_d \left[i\gamma^\mu \left(1+\zeta_K \frac{m_d+m_s}{2M}\right) + \frac{\zeta_K}{2M}\overleftrightarrow{\partial}^\mu \right] \psi_s K^{*0}_\mu \,,$$

γ^μ: S wave coalescence

$\overleftrightarrow{\partial}$: LS coupling

ζ: ratio between two vertex

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

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

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

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

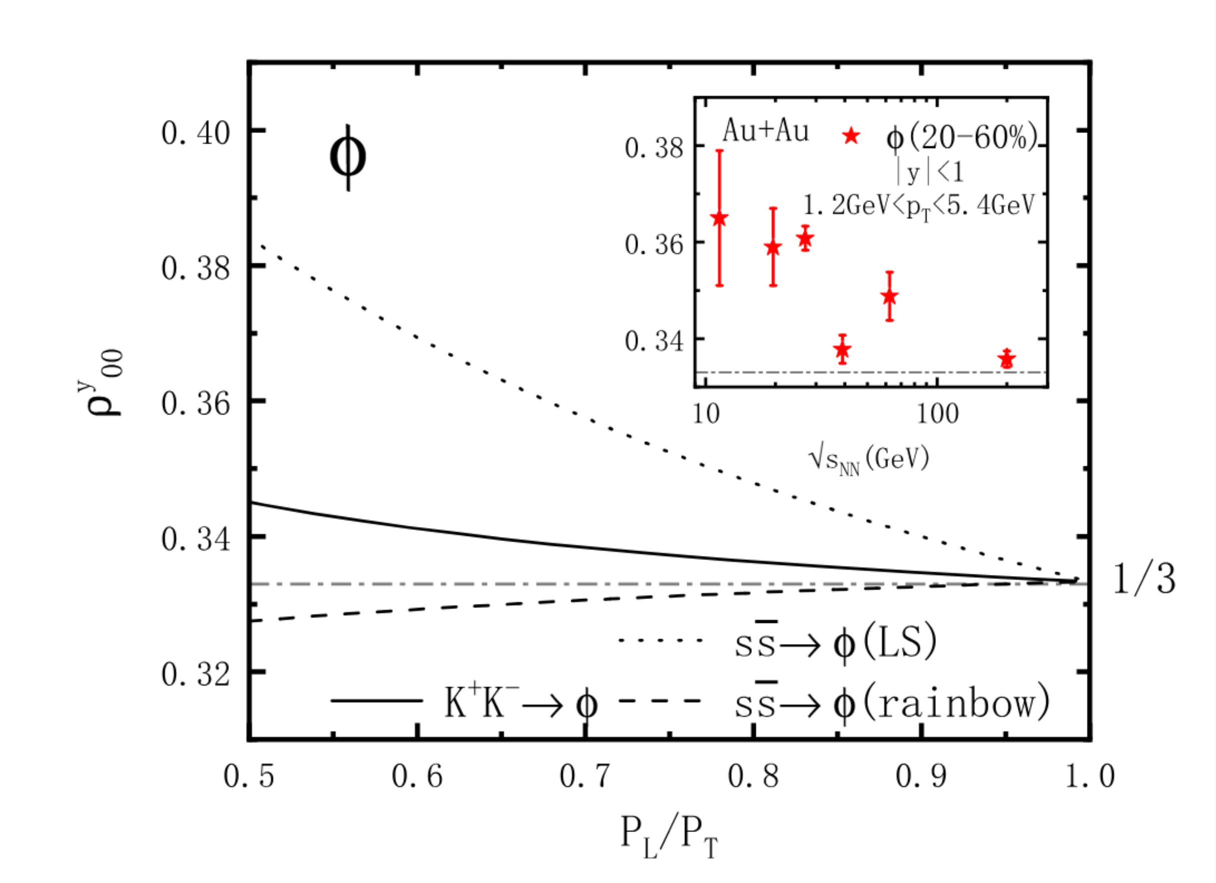
$\zeta = 0$: S wave (rainbow approximation)

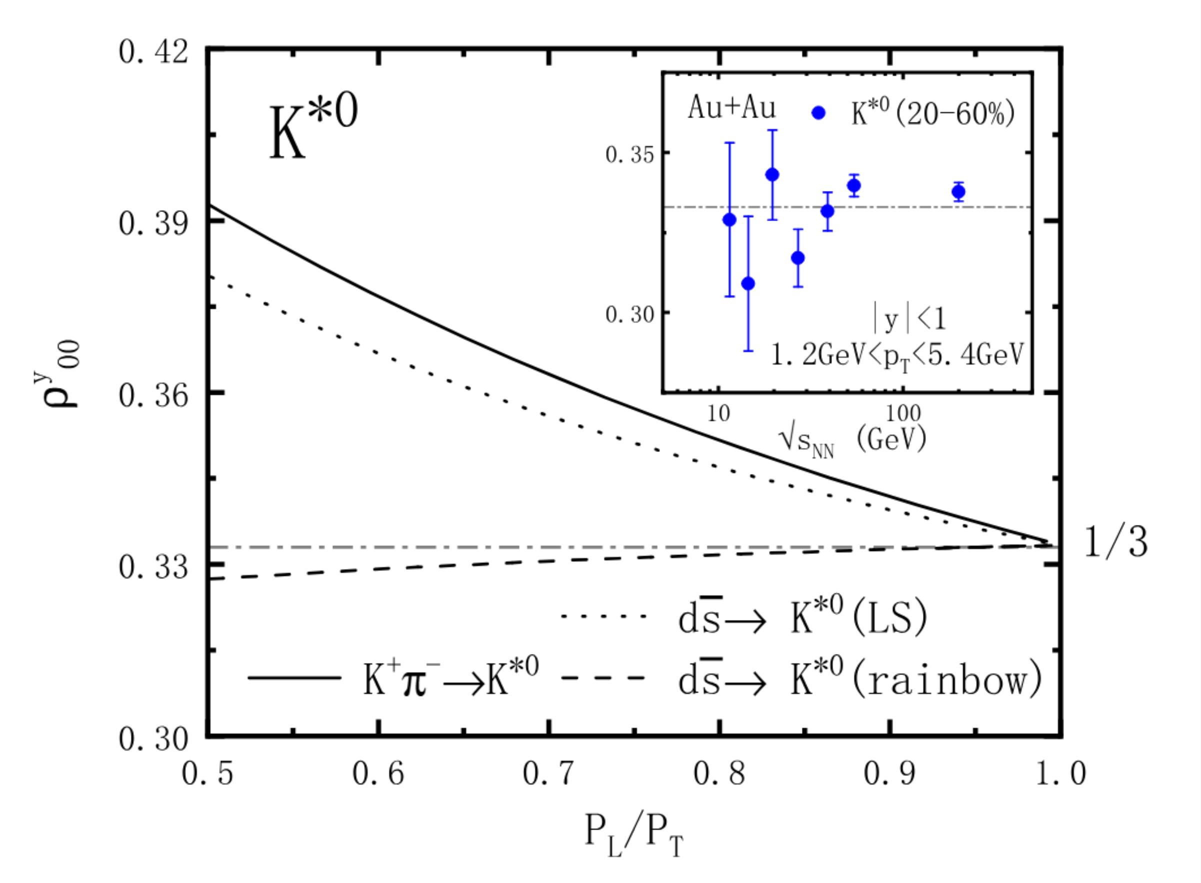
$\zeta = -\frac{2M}{m_1+m_2}$: related to P wave

(orbit-> spin) identical to hadronic case

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

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pNRQCD Lagrangian

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

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

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)

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Cross section

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

$$d\sigma^\lambda_{E1}(p_1, p_2, k, p_{rel}) = \delta(E_{p_1} + E_k - E_{p_2})\,\delta^{(3)}(p_1 + k - p_2)\,|M_e^\lambda(|p_{rel}|)|^2,$$
$$d\sigma^\lambda_{M1}(p_1, p_2, k, p_{rel}) = \delta(E_{p_1} + E_k - E_{p_2})\,\delta^{(3)}(p_1 + k - p_2)\,|M_e^\lambda(|p_{rel}|)|^2,$$

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

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

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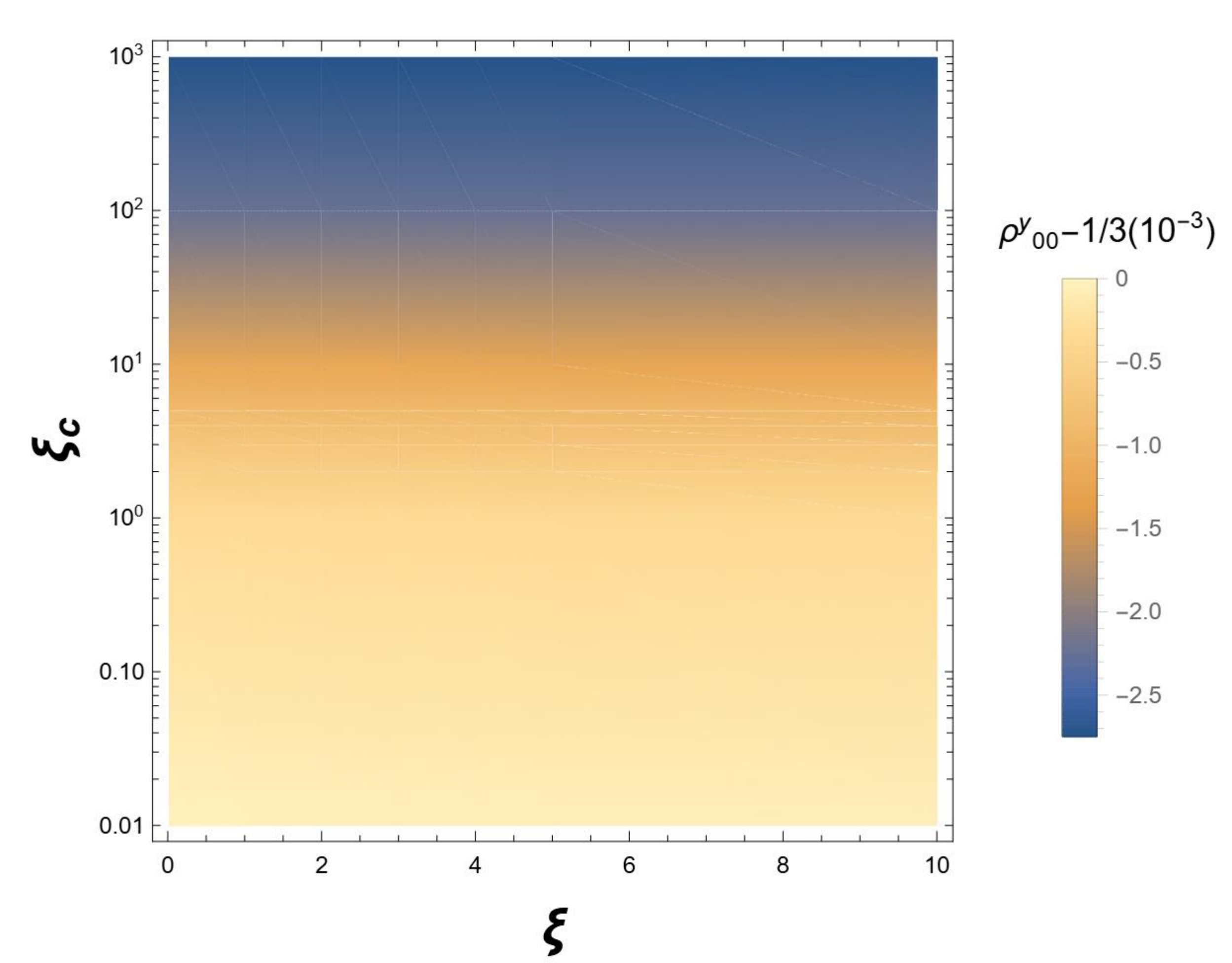
JHEP 01 (2021) 046 X.J. Yao et.al

Spin alignment



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

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

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

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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 zero rapidity.
2. For light mesons, LS coupling vertex is important in study the spin-related phenomena, the sign of spin alignment is determined by the ratio between LS coupling and γ^{μ} 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