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Impact of globally spin-aligned vector mesons on the search for the chiral magnetic effect in heavy-ion collisions

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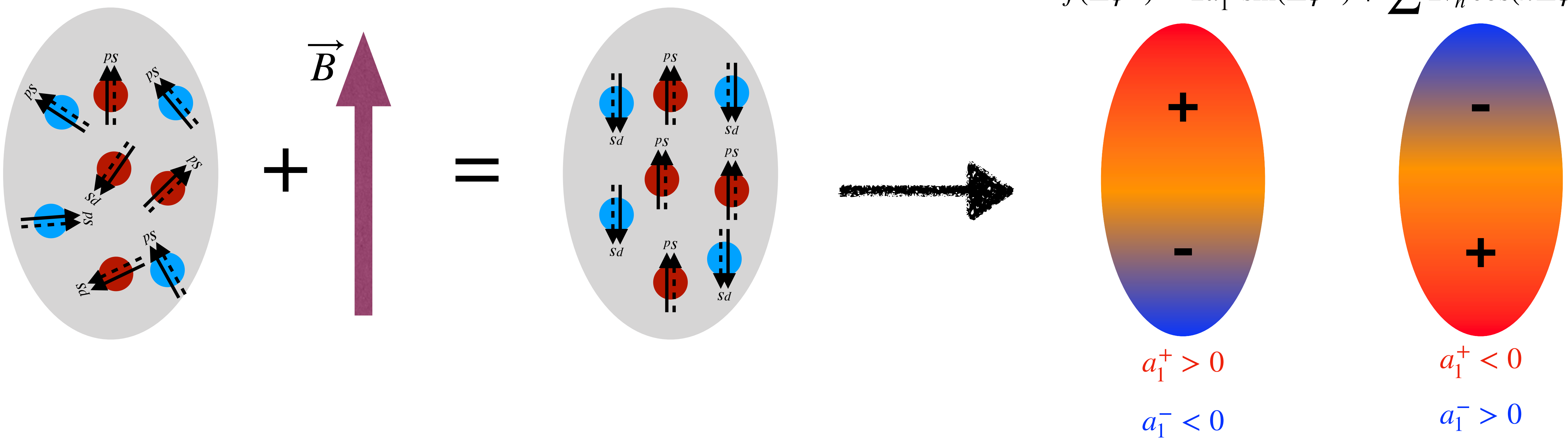
The chiral magnetic effect

Chirality imbalance + external magnetic field = electrical current

$$f(\Delta\phi^+) = 2a_1^+ \sin(\Delta\phi^+) + \sum 2v_n \cos(n\Delta\phi^+)$$



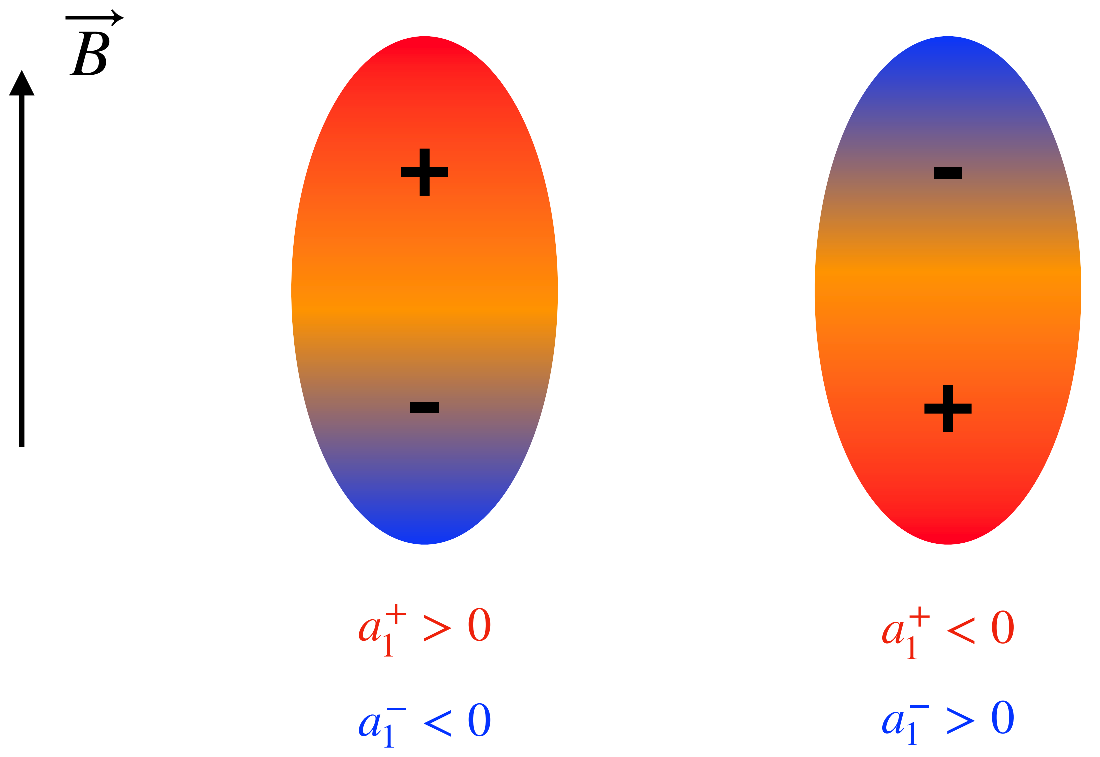
- **Electrical current along the $\vec{B}$ field generates charge separation.**
- **Charge dipole gives non-zero a_1 ($-a_1$) to positively (negatively) charged particles, while the a_1 fluctuates event by event so on average $\langle a_1 \rangle = 0$.**
- **Observables are developed in experiment to measure the a_1 and/or charge separation.**

D.E. Kharzeev, J. Liao, Nat. Rev. Phys. 3 (2021) 55–63

The chiral magnetic effect

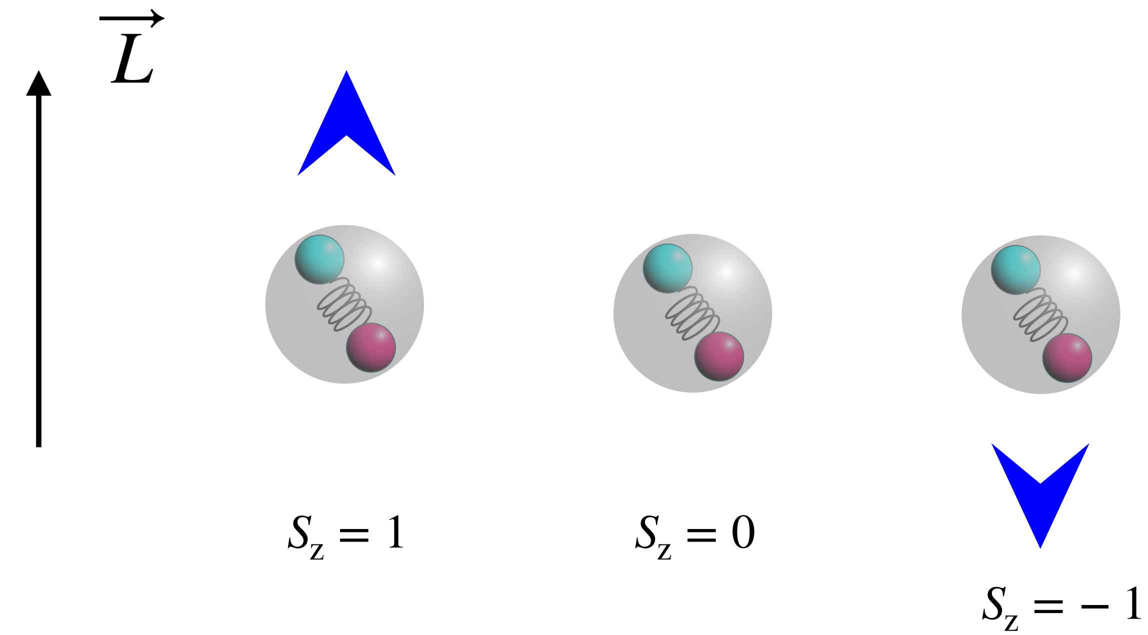
Z.T. Liang et al., Physics Letters B 629 (2005) 20–26

CME



- **Charge separation along B field, characterized by non-zero a_1.**

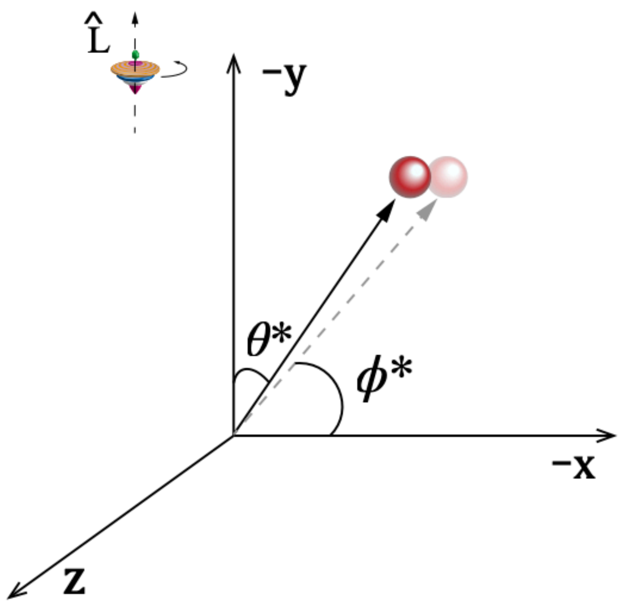
Global spin alignment of vector meson



- **Spin state along orbital angular momentum, characterized by ρ_{00} in spin density matrix.**

Directions of $\vec{B}$ and $\vec{L}$ are correlated, both are perpendicular to reaction plane

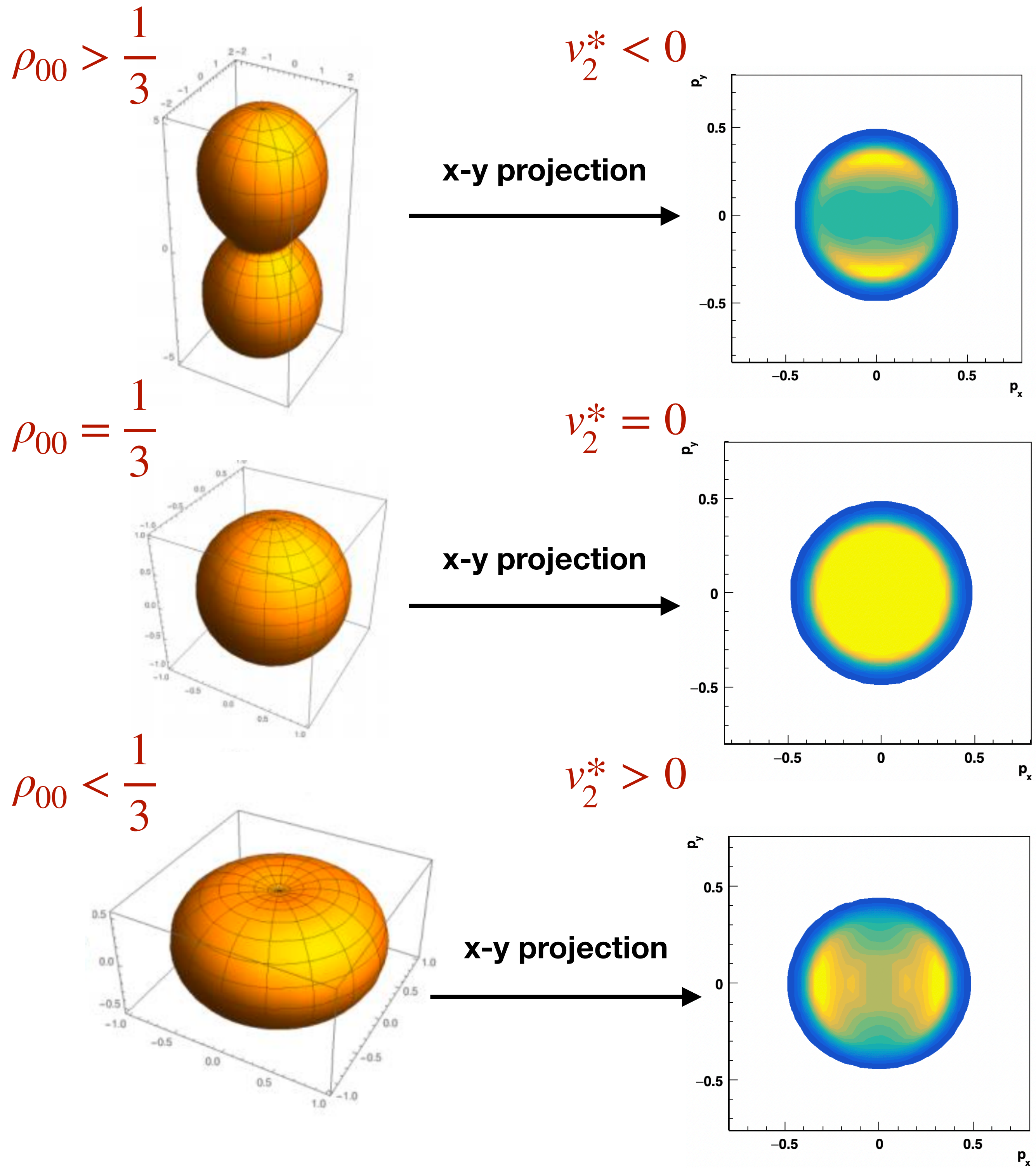
Global spin alignment



$$\frac{dN}{d\cos\theta^*} = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

$$\frac{dN}{d\phi^*} = \frac{1}{2\pi}\left[1 - \frac{1}{2}(3\rho_{00}-1)\cos 2\phi^*\right]$$

$$\therefore\ v_2^* = -\frac{3\rho_{00}-1}{4}$$



$\rho_{00} \neq 1/3$ **means non-zero "elliptic flow" of decay products in CMS.**

Global spin alignment to the $\Delta\gamma$ observable

$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

S.A. Voloshin, Phys. Rev. C 70 (2004) 057901

$$\gamma_{112}^{\mathrm{OS}} = \left\langle \cos(\phi_+ + \phi_- - 2\Psi_{\mathrm{RP}}) \right\rangle$$

$$= \left\langle \cos\Delta\phi_+ \right\rangle \langle \cos\Delta\phi_- \rangle + \frac{N_\rho}{N_+N_-}\mathrm{Cov}(\cos\Delta\phi_+, \cos\Delta\phi_-) - \left\langle \sin\Delta\phi_+ \right\rangle \langle \sin\Delta\phi_- \rangle - \frac{\mathrm{N}_\rho}{\mathrm{N}_+\mathrm{N}_-}\mathrm{Cov}(\sin\Delta\phi_+, \sin\Delta\phi_-)$$

$$\langle ab \rangle = \langle a \rangle \langle b \rangle + \mathrm{Cov}(a, b)$$

In center-of-mass system, the covariance between π^+ and π^- from ρ decays is

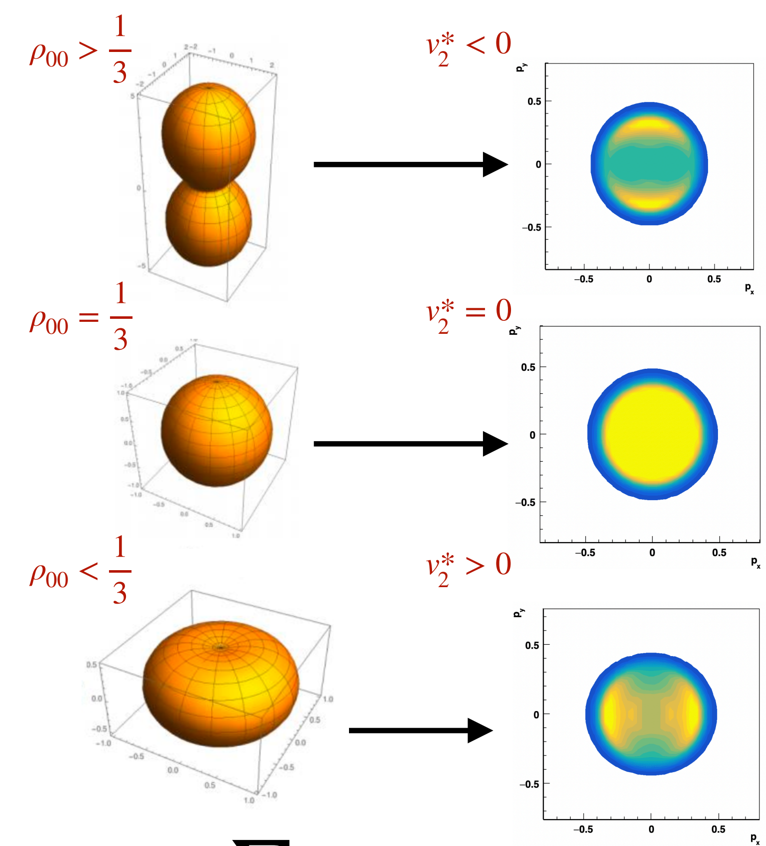
$$\mathrm{Cov}(\cos\phi_+^*, \cos\phi_-^*) = -\left\langle \cos^2\phi_+^* \right\rangle + \left\langle \cos\phi_+^* \right\rangle^2 = -\frac{1}{2} + \frac{1}{8}(3\rho_{00} - 1),$$

$$\mathrm{Cov}(\sin\phi_+^*, \sin\phi_-^*) = -\left\langle \sin^2\phi_+^* \right\rangle + \left\langle \sin\phi_+^* \right\rangle^2 = -\frac{1}{2} - \frac{1}{8}(3\rho_{00} - 1)\,.$$

Where we used $\phi_+^* = \phi_-^* + \pi$ and $\frac{dN}{d\phi^*} = \frac{1}{2\pi}\left[1 - \frac{1}{2}(3\rho_{00} - 1)\cos 2\phi^*\right]$

Global spin alignment to the $\Delta\gamma$ observable

Therefore, $\Delta\gamma^* = \gamma^{*OS} - \gamma^{*SS} = \dfrac{N_\rho}{N_+N_-}\dfrac{3\rho_{00}-1}{4} = -\dfrac{N_\rho}{N_+N_-}v_2^*$



The $\Delta\gamma$ is proportional to the "elliptic flow" of decay products in ρ rest frame.

In lab frame,

Boost factor in plane

$$\mathrm{Cov}(\cos\phi_+, \cos\phi_-) = f_c \mathrm{Cov}(\cos\phi_+^*, \cos\phi_-^*) = f_c\left[-\frac{1}{2} + \frac{1}{8}(3\rho_{00}-1)\right] \qquad f_c = f_0 + \sum a_n (v_2^\rho)^n$$

$$\mathrm{Cov}(\sin\phi_+, \sin\phi_-) = f_s \mathrm{Cov}(\sin\phi_+^*, \sin\phi_-^*) = f_s\left[-\frac{1}{2} - \frac{1}{8}(3\rho_{00}-1)\right] \qquad f_s = f_0 + \sum b_n (v_2^\rho)^n$$

Boost factor out of plane

$$\Delta\gamma_{112} = \frac{N_\rho}{N_+N_-}\left[\frac{1}{8}(f_c+f_s)(3\rho_{00}-1) - \frac{1}{2}(f_c - f_s)\right] \sim \frac{N_\rho}{N_+N_-}\left[A_1(3\rho_{00}-1) + A_2 v_2^\rho\right]$$

A linear dependence of $\Delta\gamma_{112}$ on ρ_{00}.

Global spin alignment to the R correlator

Definition: N. Magdy, Phys. Rev. C 97 (2018) 061901

$$R_{\Psi_2}(\Delta S) \equiv \frac{N(\Delta S_{\text{real}})}{N(\Delta S_{\text{shuffled}})} \Big/ \frac{N(\Delta S^{\perp}_{\text{real}})}{N(\Delta S^{\perp}_{\text{shuffled}})},$$

$$\Delta S = \langle \sin \Delta\phi_+ \rangle - \langle \sin \Delta\phi_- \rangle,$$
$$\Delta S^{\perp} = \langle \cos \Delta\phi_+ \rangle - \langle \cos \Delta\phi_- \rangle,$$

$\text{Cov}(\ \langle \sin \Delta\phi_+ \rangle, \langle \sin \Delta\phi_- \rangle\ )$

$$\sigma^2(\Delta S_{\text{real}}) = f_s\left[\sigma_s^2 + \frac{N_\rho}{N_+N_-}\left(1 + \frac{3\rho_{00}-1}{4}\right)\right],$$
$$\sigma^2(\Delta S_{\text{shuffled}}) = f_s\sigma_s^2,$$
$$\sigma^2(\Delta S^{\perp}_{\text{real}}) = f_c\left[\sigma_c^2 + \frac{N_\rho}{N_+N_-}\left(1 - \frac{3\rho_{00}-1}{4}\right)\right],$$
$$\sigma^2(\Delta S^{\perp}_{\text{shuffled}}) = f_c\sigma_c^2,$$

$$\frac{S_{\text{concavity}}}{\sigma_R^2} = \frac{1}{\sigma^2(\Delta S_{\text{real}})} - \frac{1}{\sigma^2(\Delta S_{\text{shuffled}})} - \frac{1}{\sigma^2(\Delta S^{\perp}_{\text{real}})} + \frac{1}{\sigma^2(\Delta S^{\perp}_{\text{shuffled}})}.$$

$$\text{Sign}(S_{\text{concavity}}) = \text{Sign}\left[-\frac{N_\rho}{2N_+N_-}(3\rho_{00}-1)\right]$$

$$\Delta\sigma_R^2 = \sigma^2(\Delta S_{\text{real}}) - \sigma^2(\Delta S_{\text{shuffled}}) - \sigma^2(\Delta S^{\perp}_{\text{real}}) + \sigma^2(\Delta S^{\perp}_{\text{shuffled}}).$$

$$\Delta\sigma_R^2 = \frac{N_\rho}{N_+N_-}\left[\frac{1}{4}(f_c+f_s)(3\rho_{00}-1) + (f_c - f_s)\right].$$

A linear dependence of $\Delta\sigma_R^2$ on ρ_{00}.

Global spin alignment to the signed balance function

Signed balance function

A. H. Tang, Chin. Phys. C 44 054101

$$\Delta B_y \equiv \left[\frac{N_{y(+-)} - N_{y(++)}}{N_+} - \frac{N_{y(-+)} - N_{y(--)}}{N_-}\right] - \left[\frac{N_{y(-+)} - N_{y(++)}}{N_+} - \frac{N_{y(+-)} - N_{y(--)}}{N_-}\right] = \frac{N_+ + N_-}{N_+ N_-}[N_{y(+-)} - N_{y(-+)}],$$

$$r \equiv \sigma(\Delta B_y)/\sigma(\Delta B_x).$$

Assuming all particles have same pT, we will have

$$\sigma^2(\Delta B_y) \approx \frac{64M^2}{\pi^4}\left(\frac{4}{9M} + 1 + \frac{4}{3}v_2\right)\sigma^2(\Delta S_{\mathrm{real}}),$$

$$\sigma^2(\Delta B_x) \approx \frac{64M^2}{\pi^4}\left(\frac{4}{9M} + 1 - \frac{4}{3}v_2\right)\sigma^2(\Delta S^{\perp}_{\mathrm{real}}).$$

$$\Delta\sigma^2(\Delta B) \equiv \sigma^2(\Delta B_y) - \sigma^2(\Delta B_x) \approx c_1 + c_2(3\rho_{00} - 1),$$

A linear dependence of $\Delta\sigma^2(\Delta B)$ on ρ_{00}.

Model simulations

A. H. Tang, Chin. Phys. C 44 054101

Setups of toy model

- Spectrum of primordial pion

$$\frac{dN_{\pi^\pm}}{dm_T^2} \propto \frac{1}{e^{m_T/T_{\mathrm{BE}}} - 1},$$

- Spectrum of ρ

$$\frac{dN_\rho}{dm_T^2} \propto \frac{e^{-(m_T - m_\rho)/T}}{T(m_\rho + T)},$$

- 195 pairs of $\pi^+\pi^-$ with 33 from ρ decays
- v_2 and v_3 of primordial pions are set to zero.
- Spin alignment effect is introduced by sampling decay products according to

$$\frac{dN}{d\cos\theta^*} = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

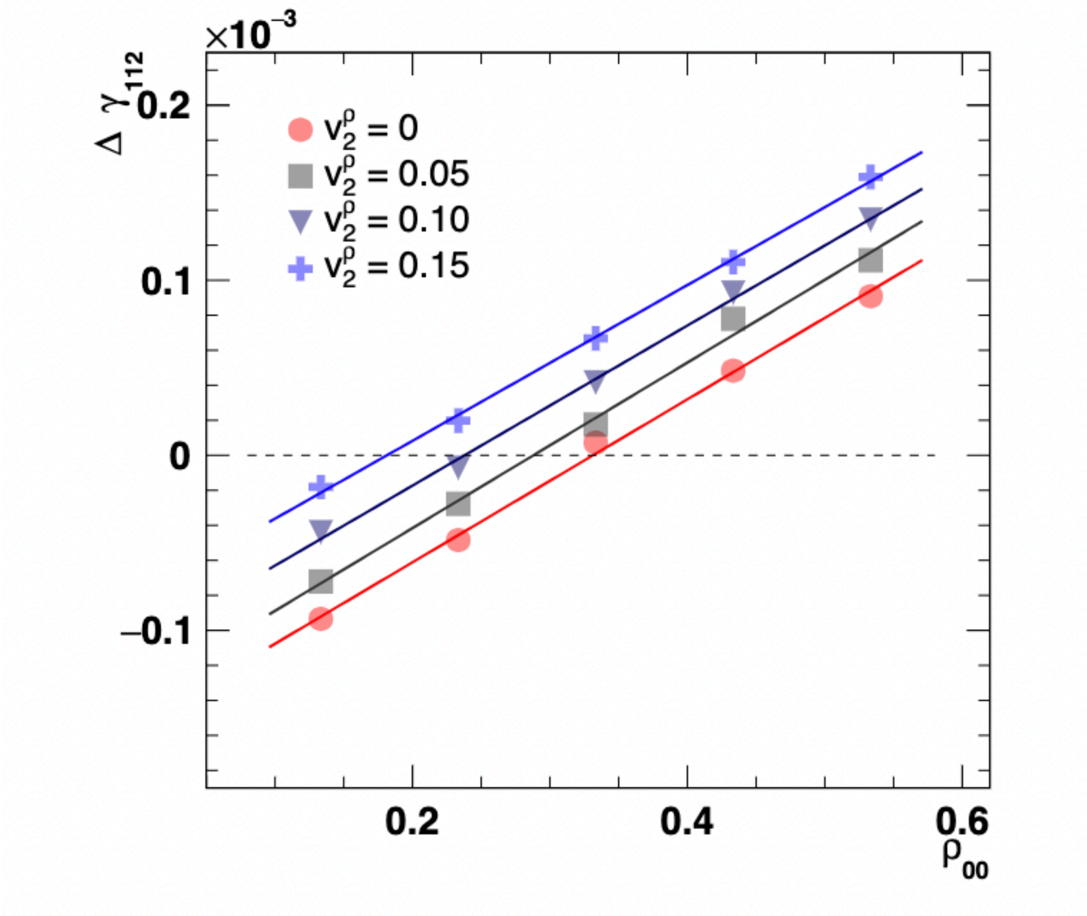
S. Lan, et al. Phys. Lett. B 780 319
D. Shen, et al. Chin. Phys. C 45 054002

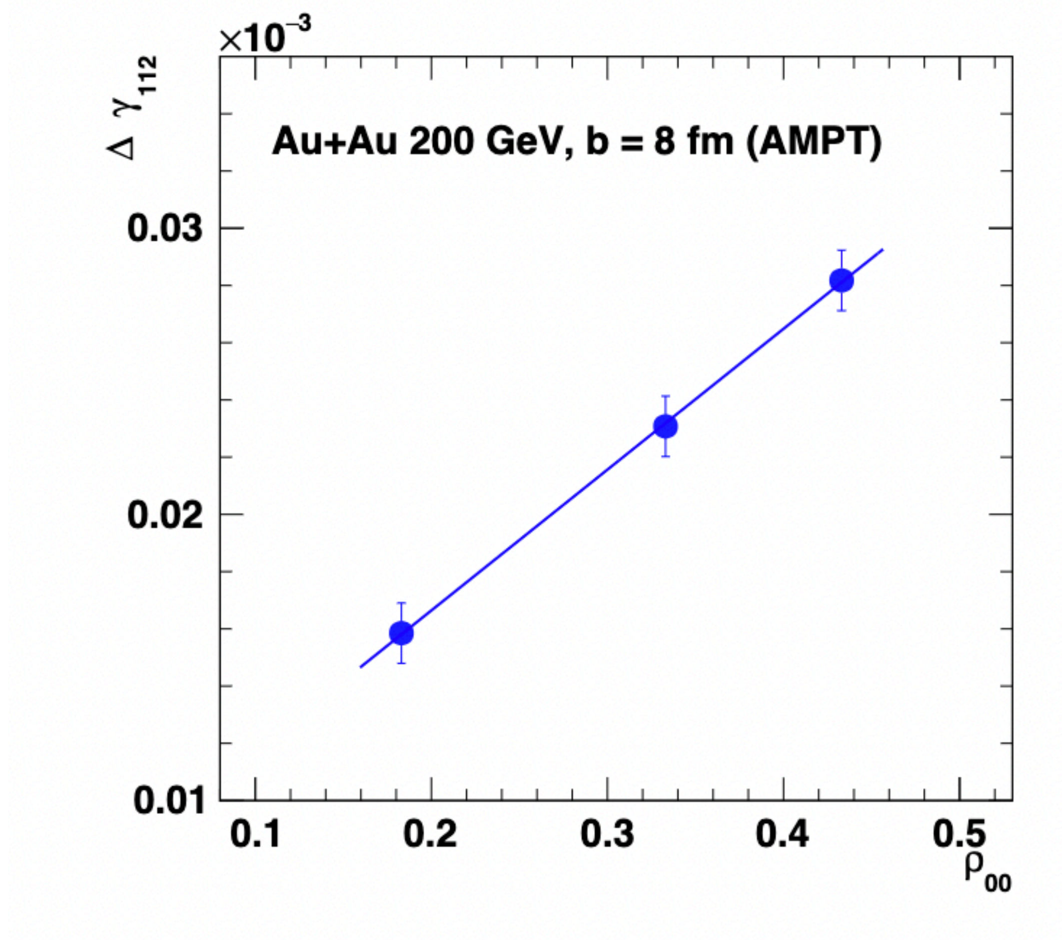
Setups of AMPT

- String melting version
- AuAu 200 GeV with impact parameter b ~ 8 fm
- Spin alignment effect is introduced by sampling decay products according to

$$\frac{dN}{d\cos\theta^*} = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

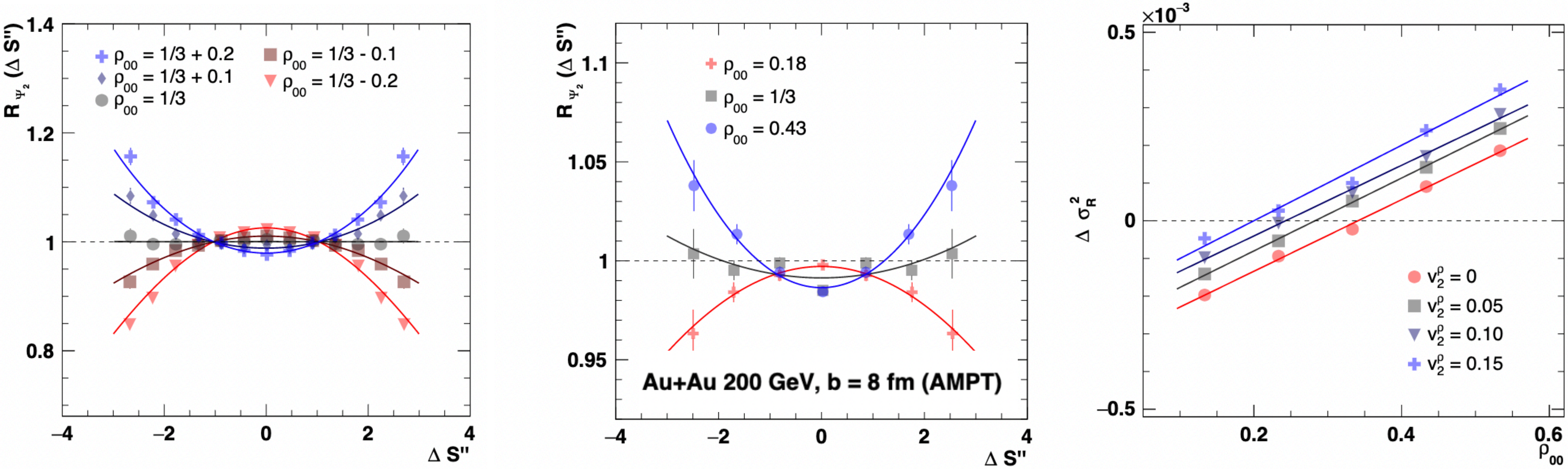
Model simulations





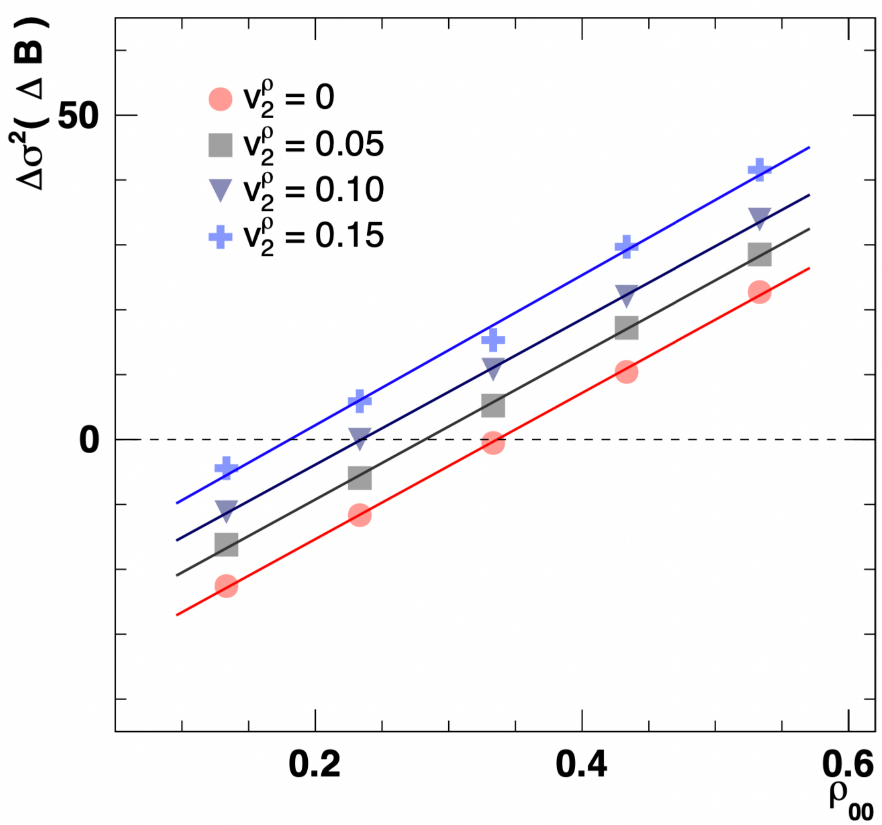
A linear dependence of $\Delta\gamma$ as a function of ρ_{00} has been observed, slope and intercept depend on spectra and flow of ρ mesons in models.

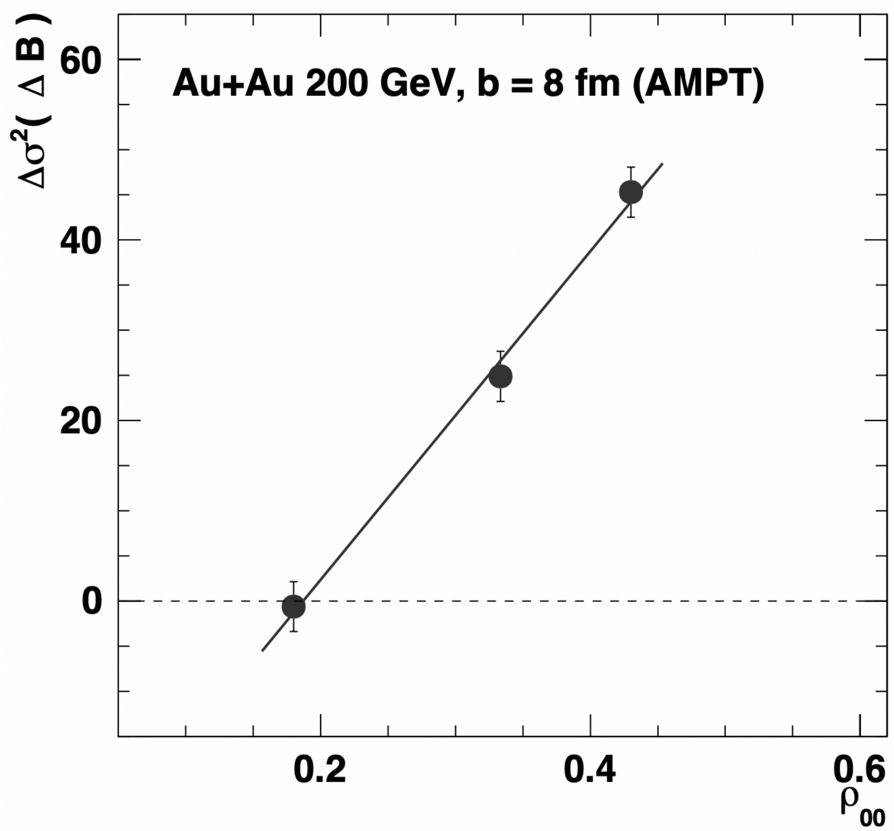
Model simulations



$R_{\Psi_2}(\Delta S)$ **has similar** ρ_{00} **dependence as gamma,** $\Delta\sigma_R^2$ **is also a linear function.**

Model simulations





Signed balance function is also sensitive to ρ_{00}, the $\Delta\sigma^2(\Delta B)$ is also a linear function.

Summary

- The $\Delta\gamma_{112}$, $R_{\Psi_2}(\Delta S)$ and signed balance function r_{lab} are both influenced by the spin alignment ρ_{00} of vector mesons.
- If the ρ_{00} is smaller (larger) than 1/3, it gives negative (positive) signal to the $\Delta\gamma_{112}$, $R_{\Psi_2}(\Delta S)$ and r_{lab}.
- The spin alignment of ρ_0 meson is critical for the CME measurements.