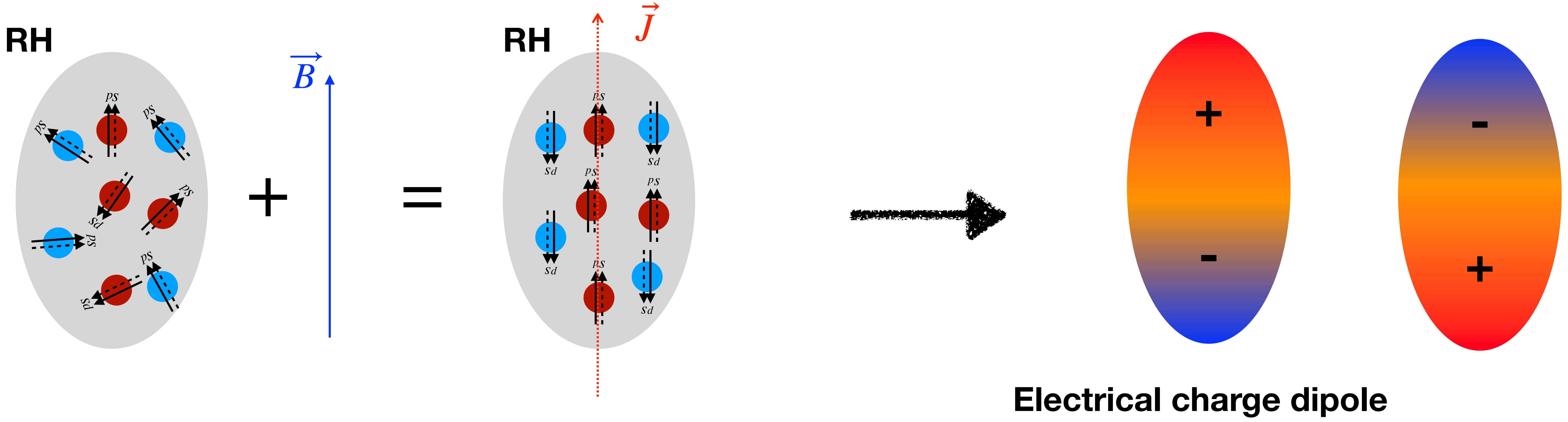
Impact of globally spin-aligned vector mesons on the search for the chiral magnetic effect in heavy-ion collisions

Diyu Shen(FDU), Jinhui Chen (FDU), Aihong Tang(BNL) and Gang Wang(UCLA)

Physics Letters B 839 (2023) 137777

The chiral magnetic effect (CME)

Chirality imbalance + Magnetic field = Electric current



- Event by event fluctuating chirality imbalance may exist in heavy-ion collisions.
- With spin being polarized by external magnetic field, quarks with opposite charges move in opposite directions.
- Charge separation along direction perpendicular to reaction plane.

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

The CME measurements

- The CME observable $\Delta\gamma_{112}$ was proposed.

  S.A. Voloshin, PRC, 70 057901 (2004)

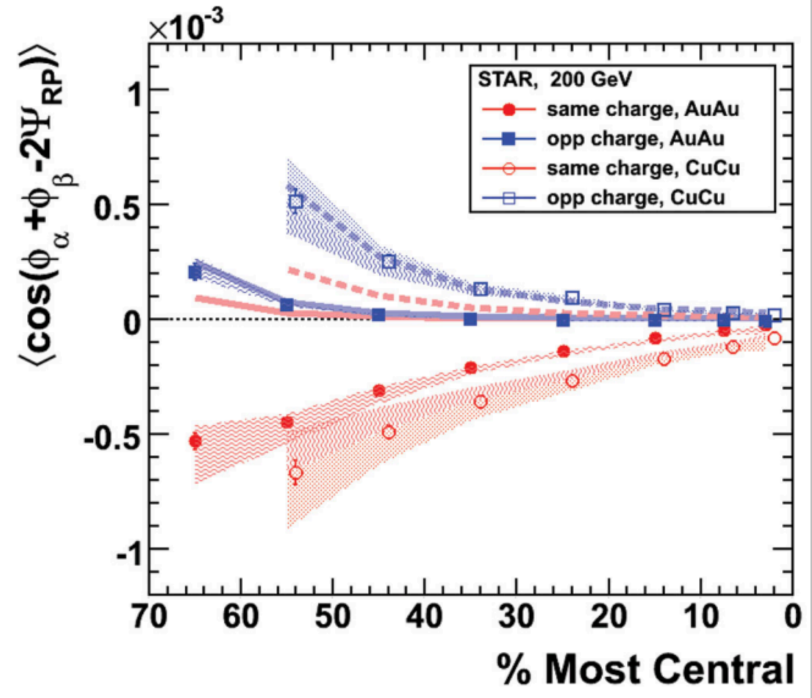
- Non-zero $\Delta\gamma_{112}$ in A+A collisions has been observed by STAR and ALICE.

- Non-zero $\Delta\gamma_{112}$ in p+A collisions has been observed by CMS.

- Painful fighting with CME backgrounds.
  - Background control.
  - New observables.

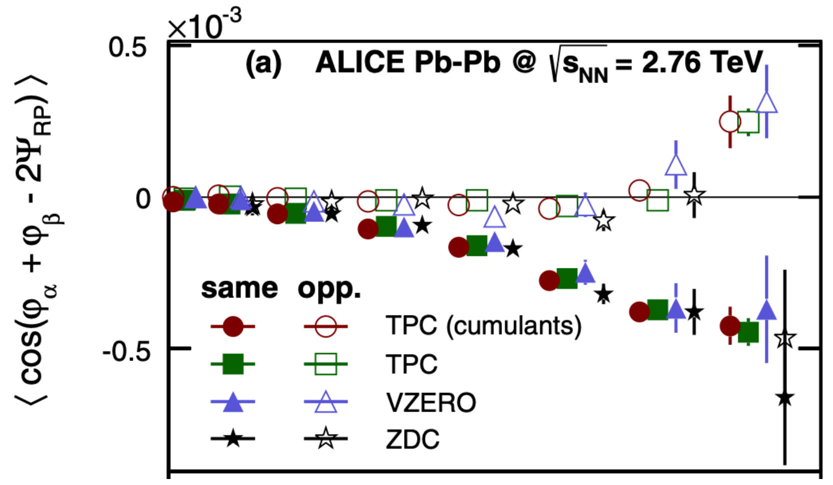
- No firm conclusion yet.

(2009) STAR, PRL 103 251601



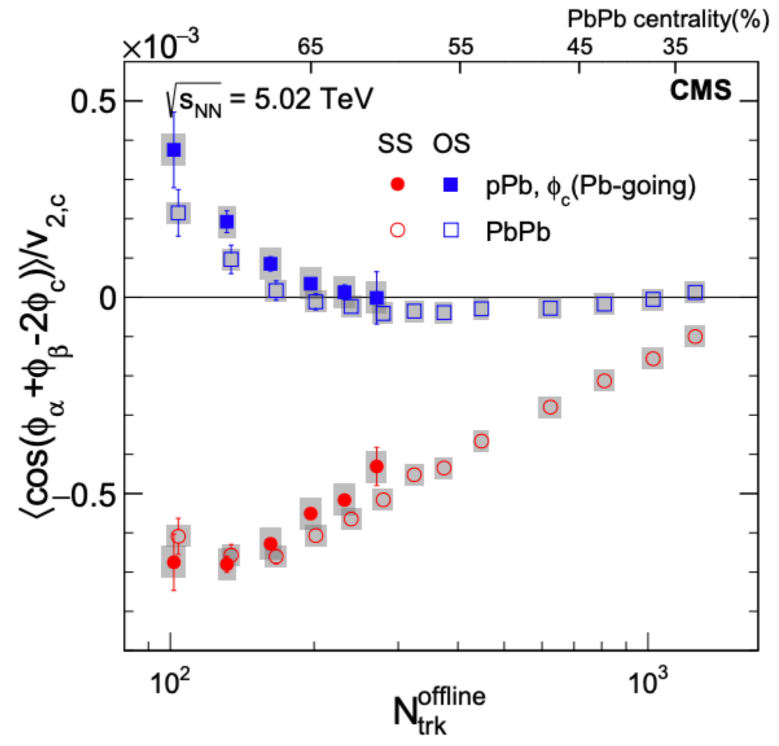
(2013) STAR, PRC 88, 064911

(2013) ALICE, PRL 110, 012301



(2014) STAR, PRC 89, 044908

(2017) CMS, PRL 118, 122301



(2018) CMS, PRC 97, 044912

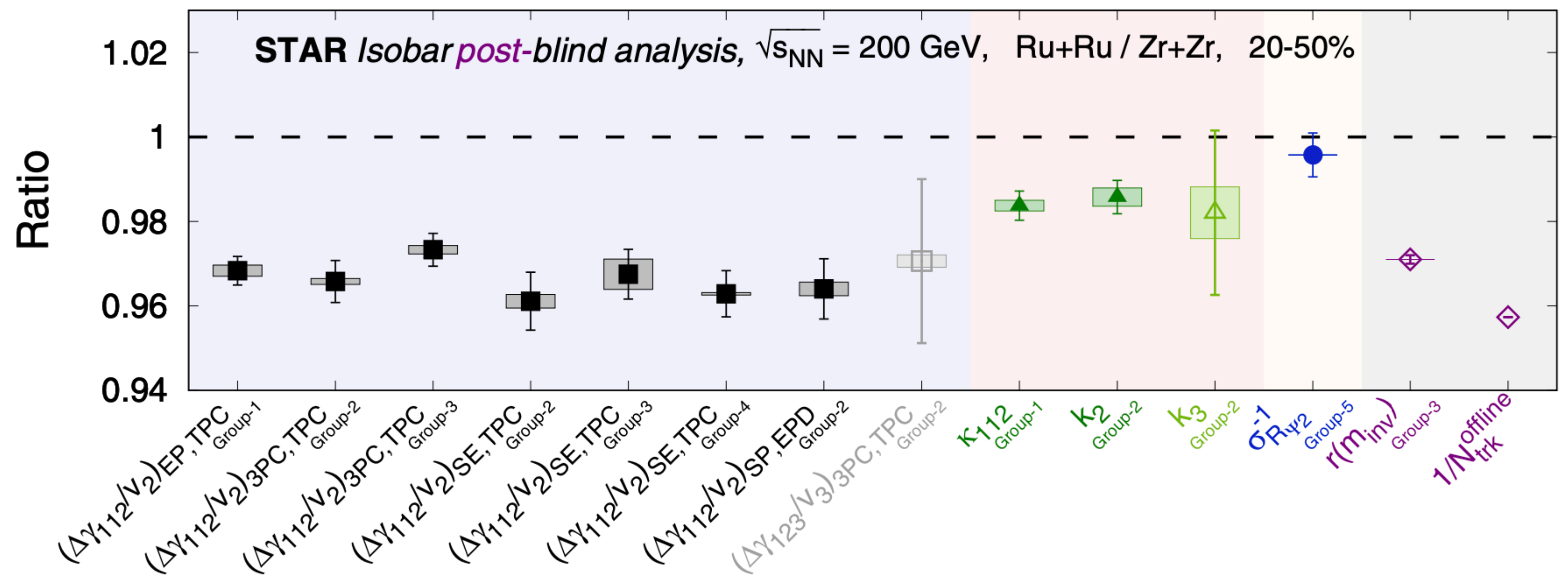
(2018) ALICE, PLB 777 151

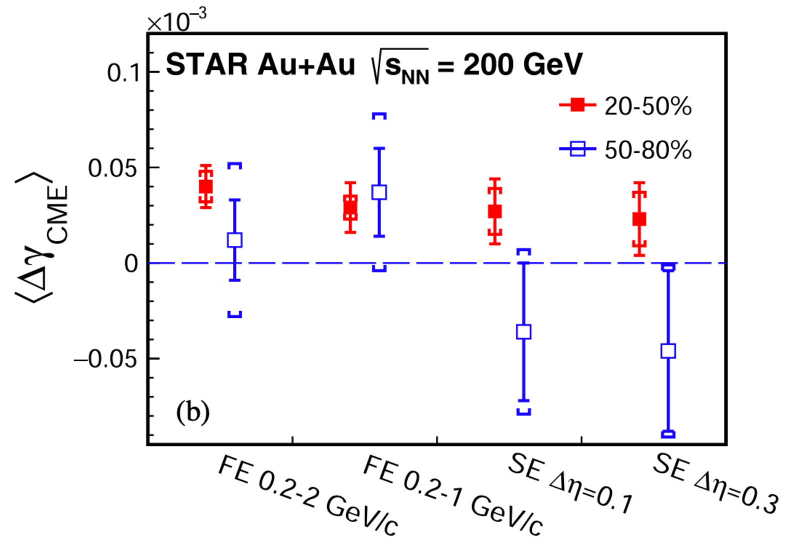
(2022) ALICE, arXiv:2210.15383

(2022) STAR, PRL 128, 0921301

(2022) STAR, PRC 106, 034908

(2022) STAR, PRC 105, 014901

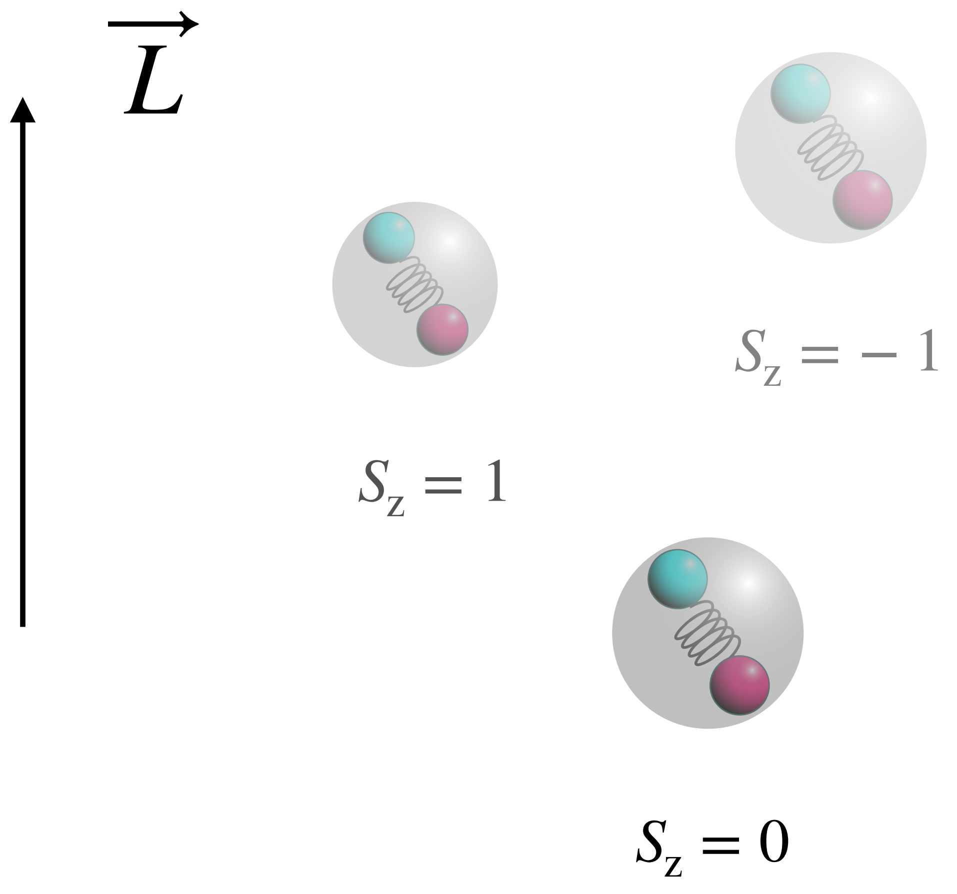


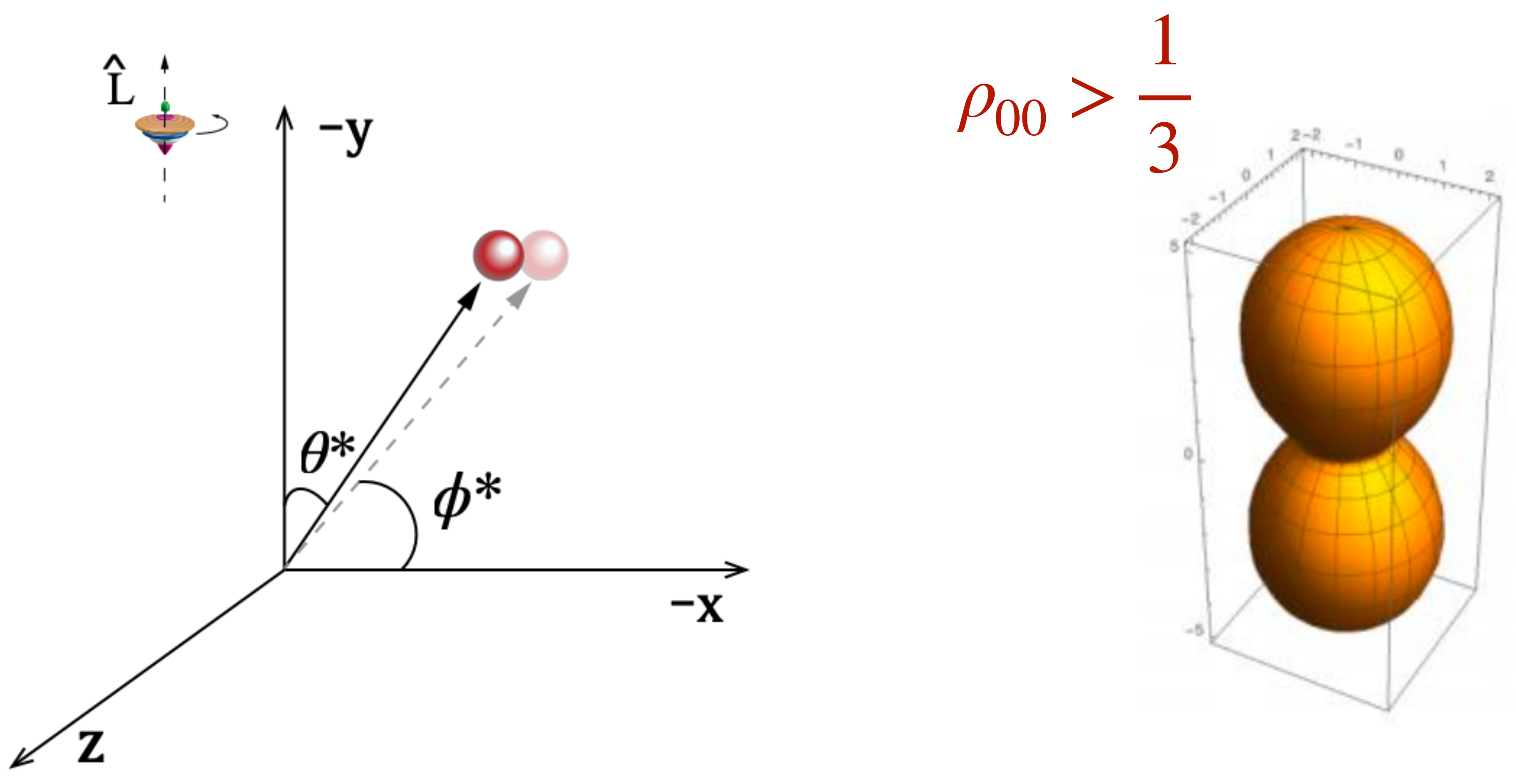


(2023) STAR, PLB 839 137779

The global spin alignment of vector mesons

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



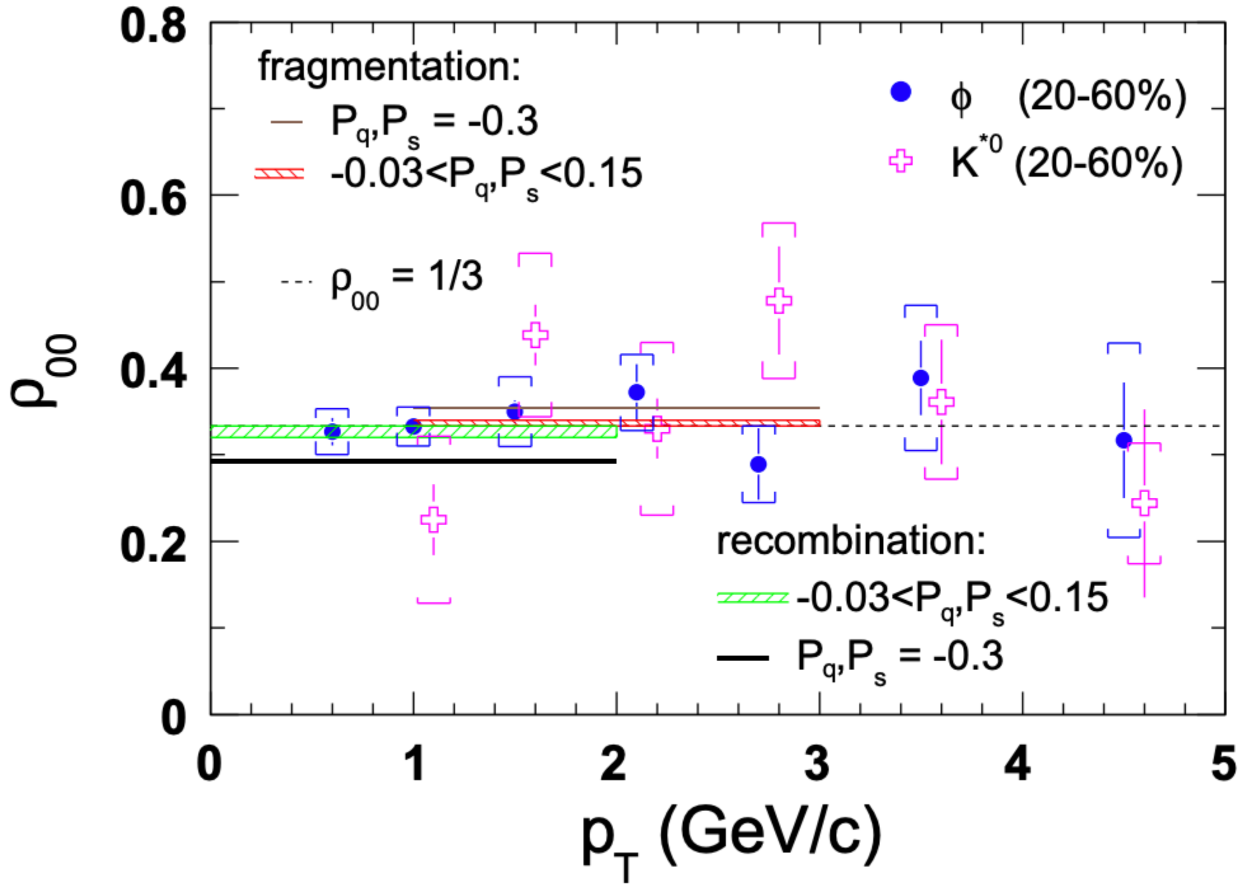


- Spin state along orbit angular momentum, characterized by ρ_{00} in spin density matrix.
- Distribution of decay products depend on the ρ_{00} (for vector mesons decay to two pseudo-scalers)

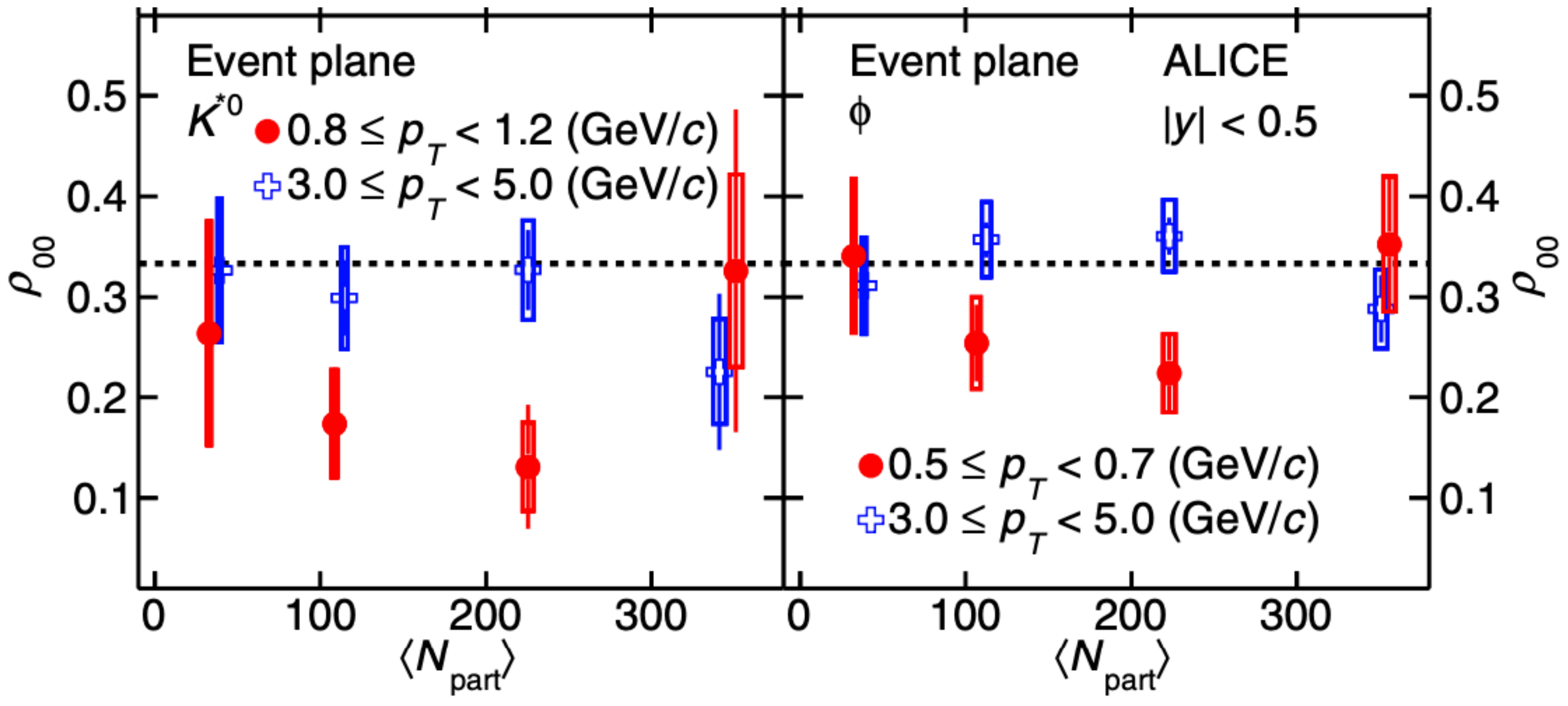
$$\frac{dN}{d\cos\theta^*} = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right] \qquad \frac{dN}{d\phi^*} = \frac{1}{2\pi}\left[1 - \frac{1}{2}(3\rho_{00}-1)\cos 2\phi^*\right]$$

The global spin alignment measurements

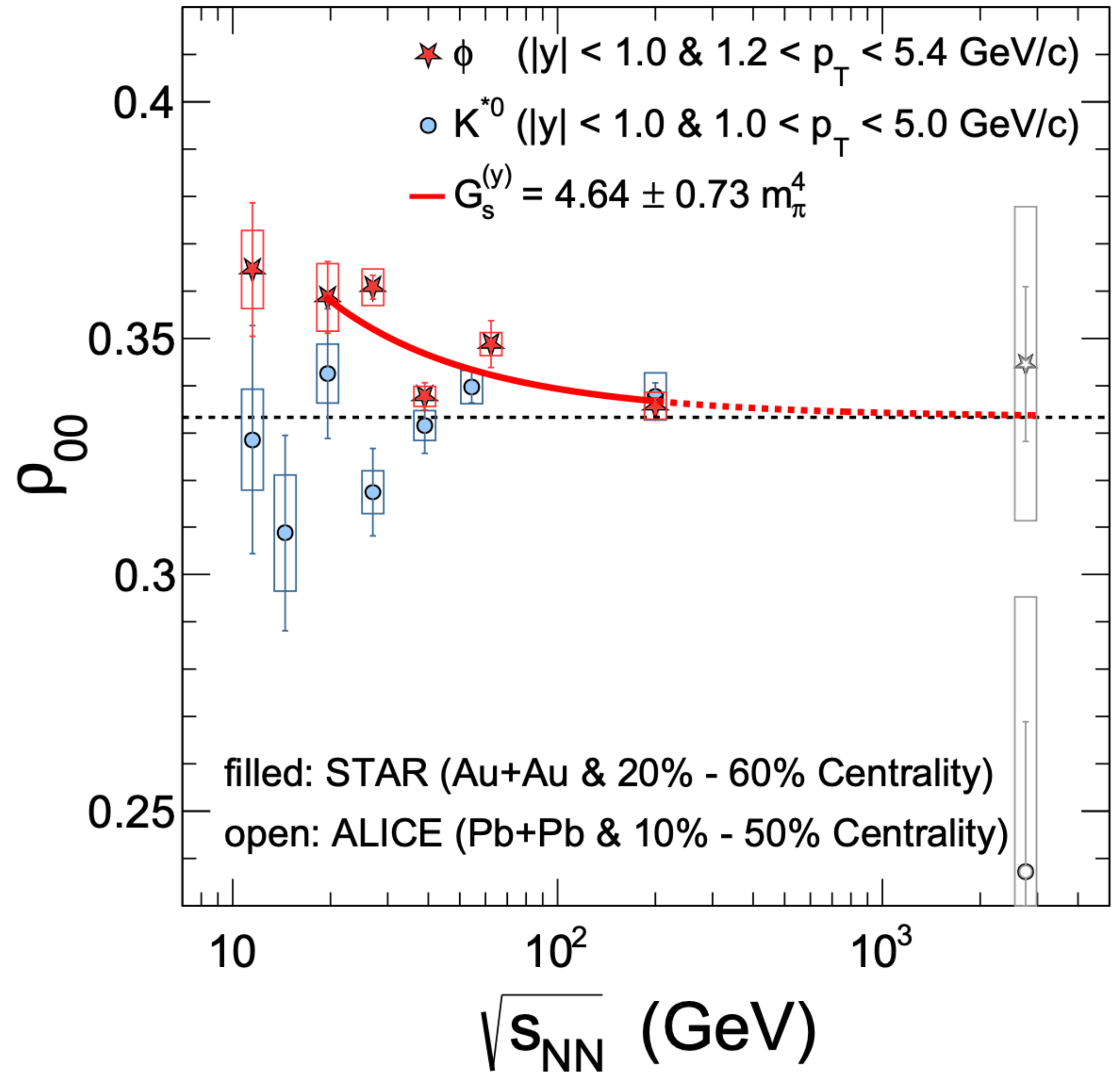
(2008) STAR, PRC 77 61902



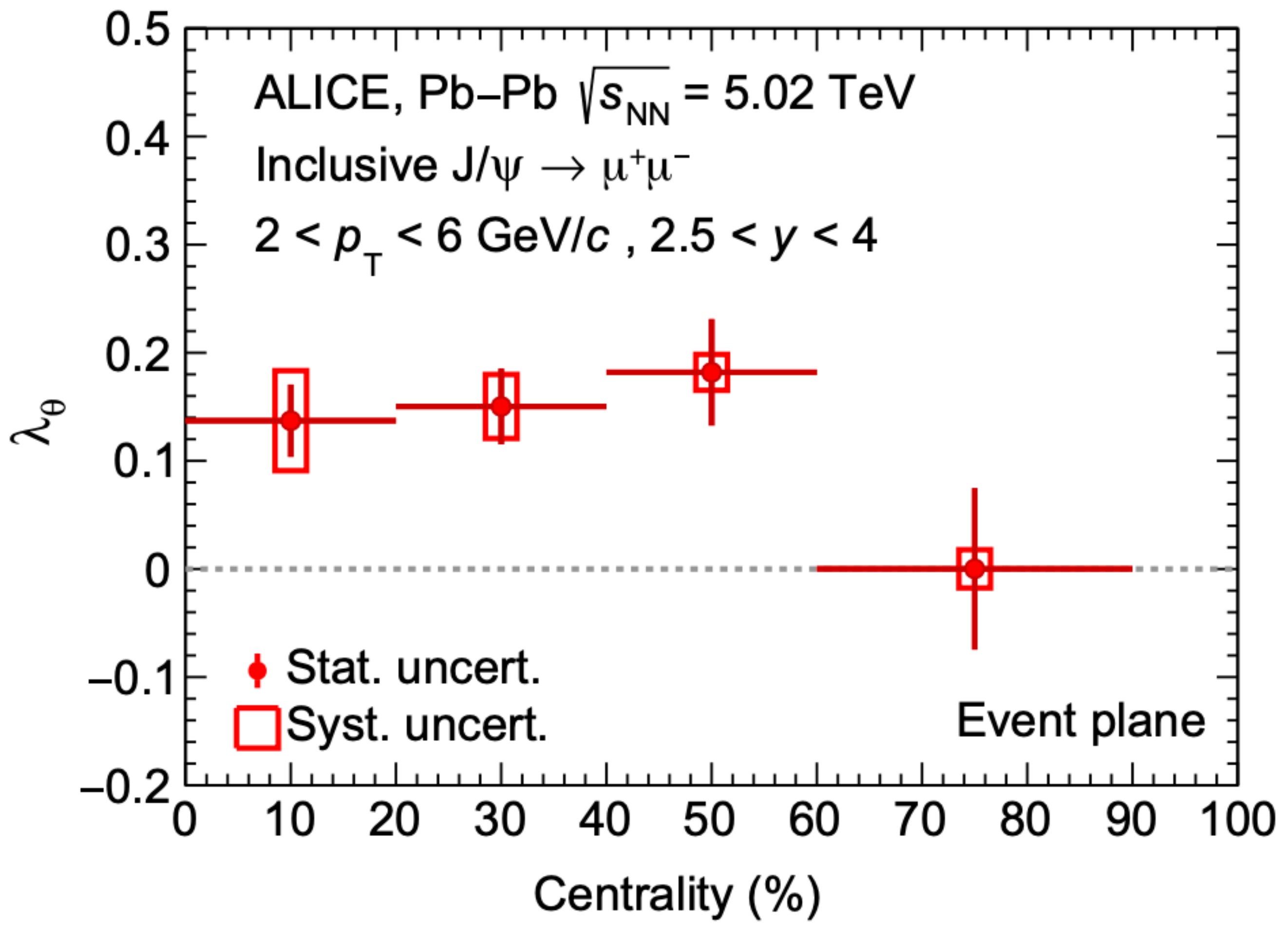
(2020) ALICE, PRL 125, 012301



(2023) STAR, Nature 614, 244–248



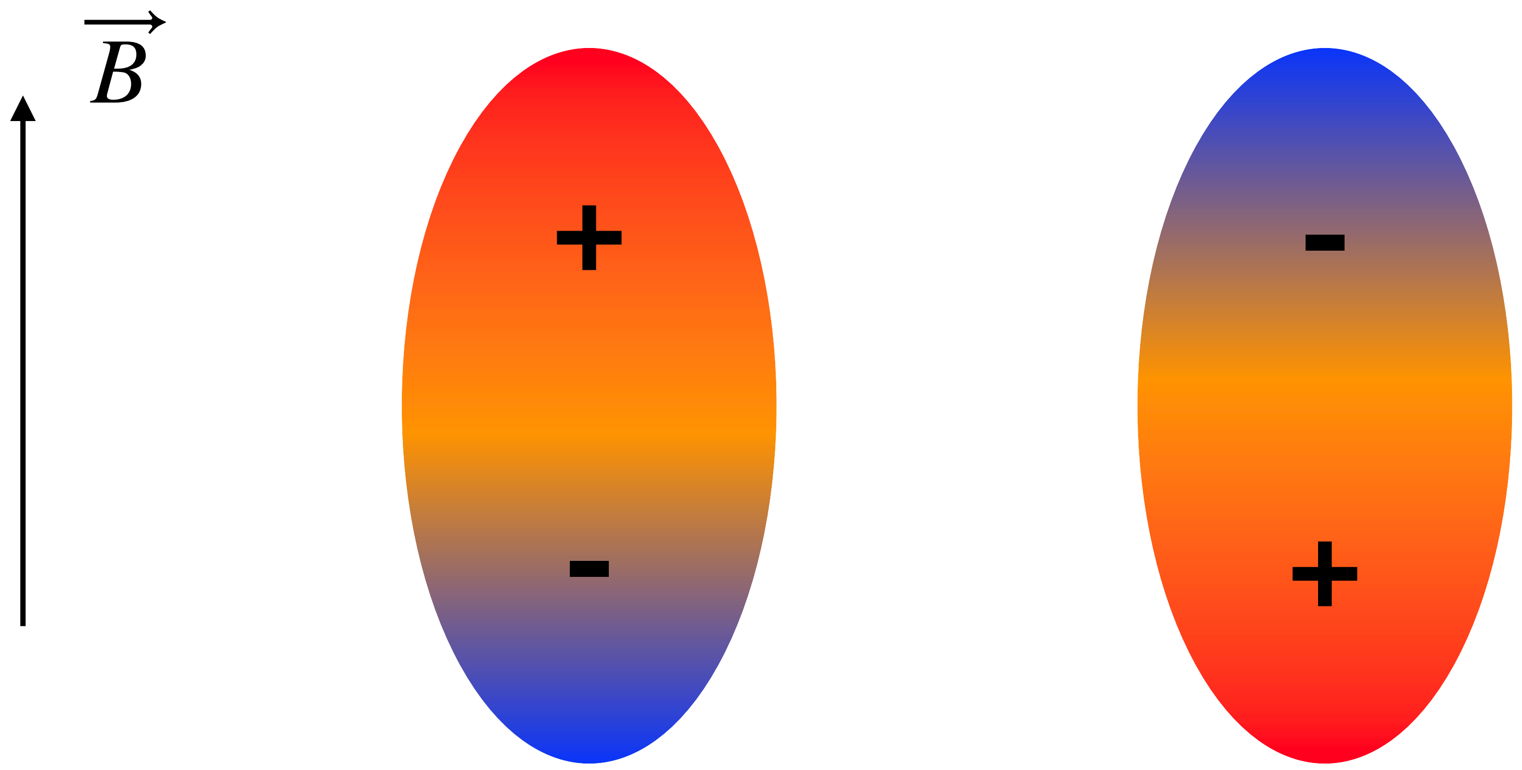
(2023) ALICE, RPL 131, 042303



- Spin alignment of vector mesons along direction perpendicular to reaction plane has been observed in experiment.

The global spin alignment as the CME backgrounds

CME

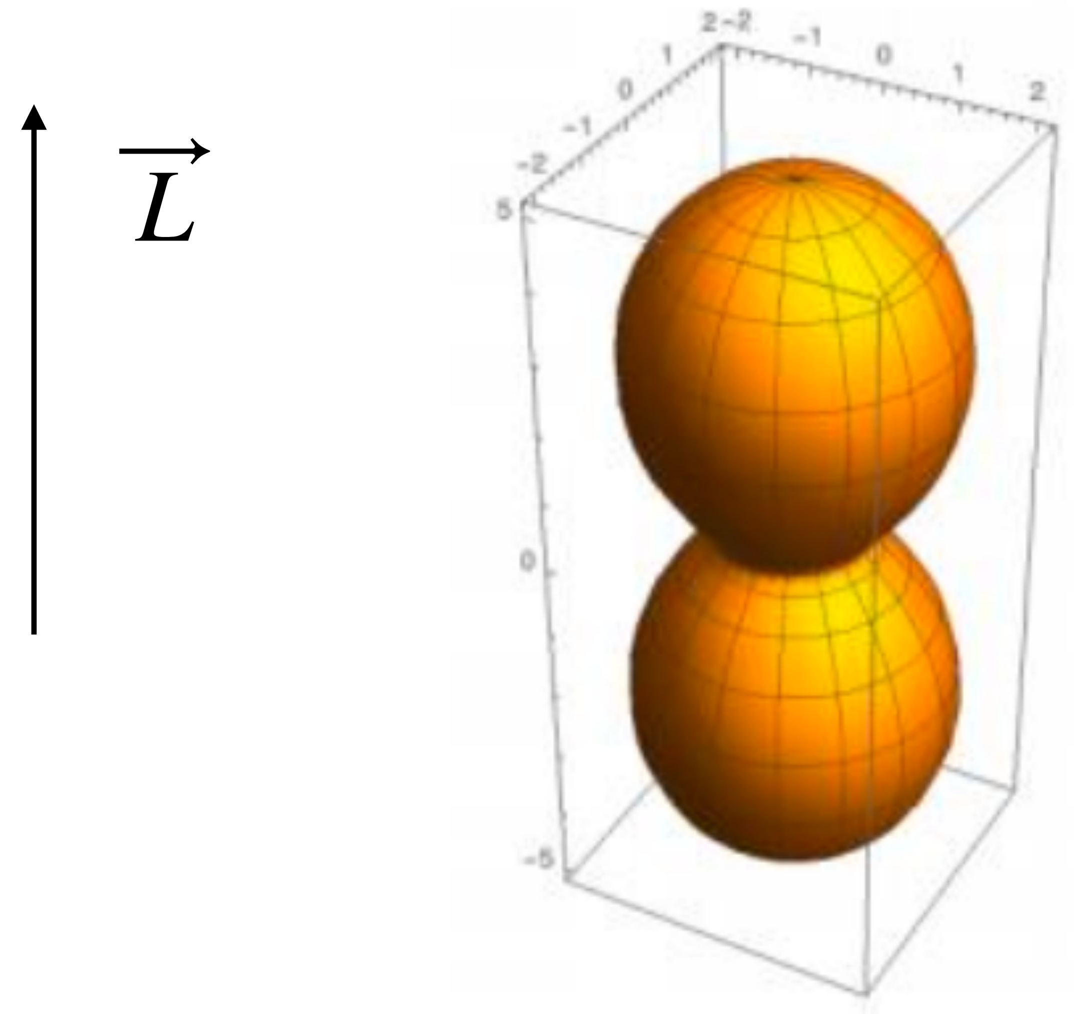


$a_1^+ > 0$ $a_1^+ < 0$

$a_1^- < 0$ $a_1^- > 0$

- Charge separation along B field

Global spin alignment of vector meson



- Unique distribution of decay products (oppositely charged).

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

The global spin alignment to the $\Delta\gamma$ observable

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

$$\gamma_{112}^{\mathrm{OS}} = \left\langle \cos(\phi_+ + \phi_- - 2\Psi_{\mathrm{RP}}) \right\rangle$$
$$= \left\langle \cos\Delta\phi_+ \right\rangle \langle \cos\Delta\phi_- \rangle + \frac{N_\rho}{N_+N_-}\mathrm{Cov}(\cos\Delta\phi_+, \cos\Delta\phi_-) - \left\langle \sin\Delta\phi_+ \right\rangle \langle \sin\Delta\phi_- \rangle - \frac{\mathrm{N}_\rho}{\mathrm{N}_+\mathrm{N}_-}\mathrm{Cov}(\sin\Delta\phi_+, \sin\Delta\phi_-)$$

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

e.g $\rho \rightarrow \pi^+\pi^-$, the decay products are correlated due to momentum conservation.

In ρ rest frame, the ϕ^* distribution of daughters is given by

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

The covariance between decay products is given by

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

The global spin alignment to the $\Delta\gamma$ observable

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

The $\Delta\gamma$ is proportional to $(\rho_{00} - \frac{1}{3})$ in ρ rest frame.

In lab frame, the Lorentz boost depends on the momentum of ρ,

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

$$\Delta\gamma_{112} = \frac{N_\rho}{N_+N_-}\left[\frac{1}{8}(f_c+f_s)(3\rho_{00}-1) - \frac{1}{2}(f_c - f_s)\right] \sim k_1(\rho_{00} - \frac{1}{3}) + k_2 v_2^\rho$$

Model simulations

Setups of toy model

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

- 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

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

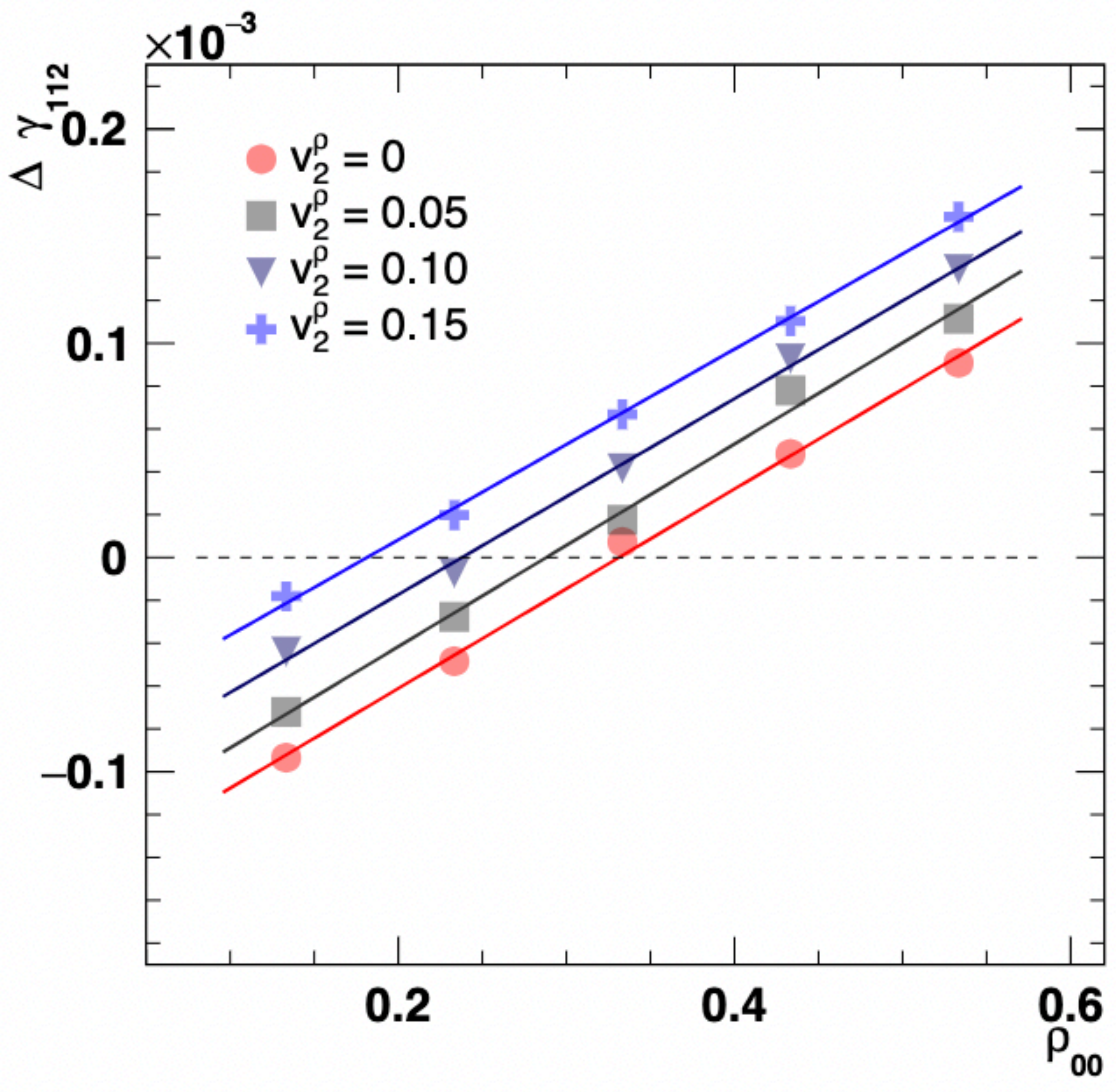
Setups of AMPT

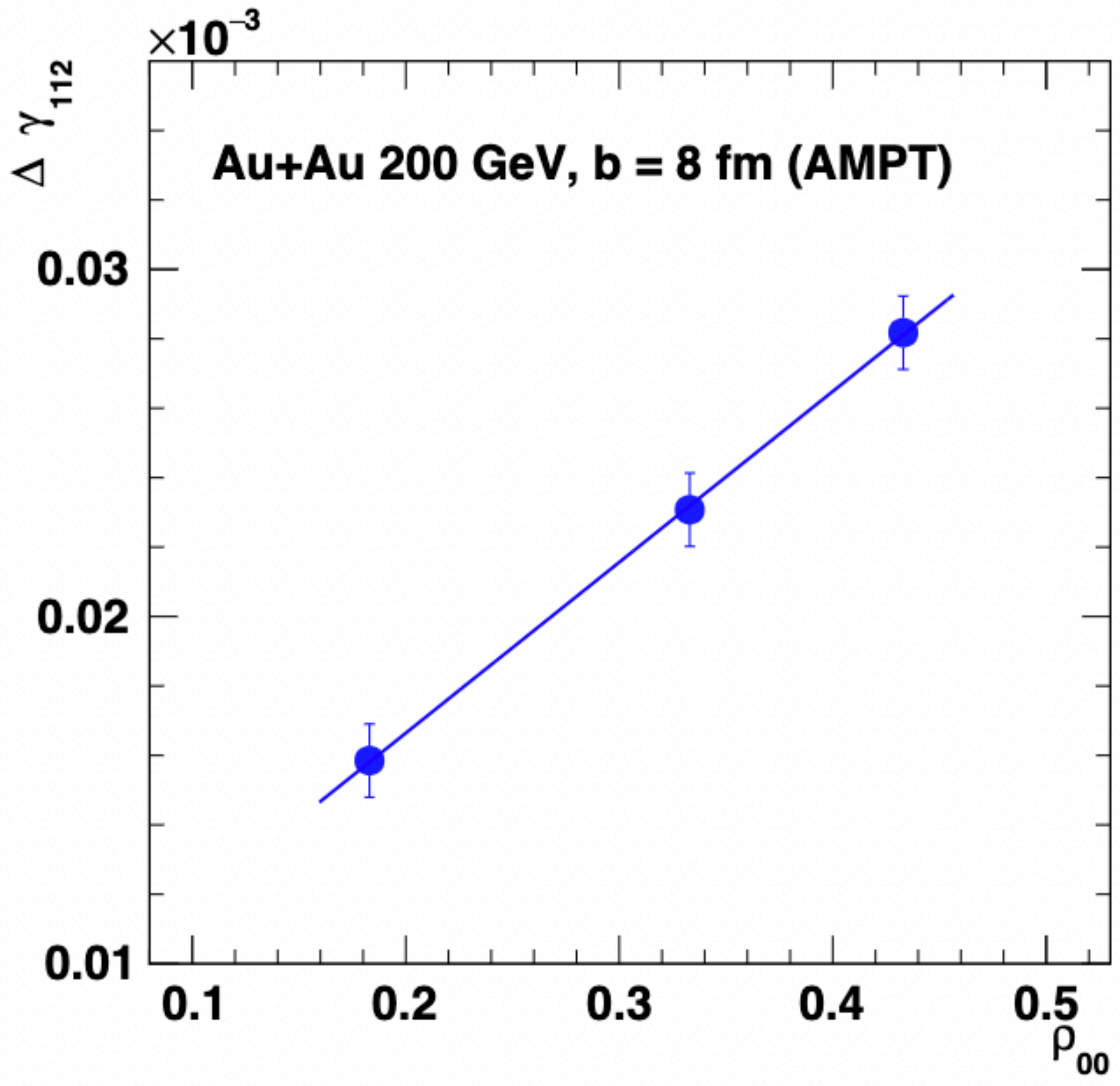
S. Lan, et al. Phys. Lett. B 780 319
D. Shen, et al. Chin. Phys. C 45 054002

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

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

The global spin alignment to the $\Delta\gamma$ observable





$$\Delta\gamma_{112} \sim k_1(\rho_{00} - \frac{1}{3}) + k_2 v_2^\rho$$

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

The global spin alignment to the $R_{\Psi_2}(\Delta S)$ observable

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

Definition:

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

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

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

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

$$\sigma^2(\Delta S_{\rm real}) = f_s\left[\sigma_s^2 + \frac{N_\rho}{N_+N_-}\left(1+\frac{3\rho_{00}-1}{4}\right)\right],$$

$$\sigma^2(\Delta S_{\rm shuffled}) = f_s\sigma_s^2,$$

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

$$\sigma^2(\Delta S^{\perp}_{\rm shuffled}) = f_c\sigma_c^2,$$

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

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

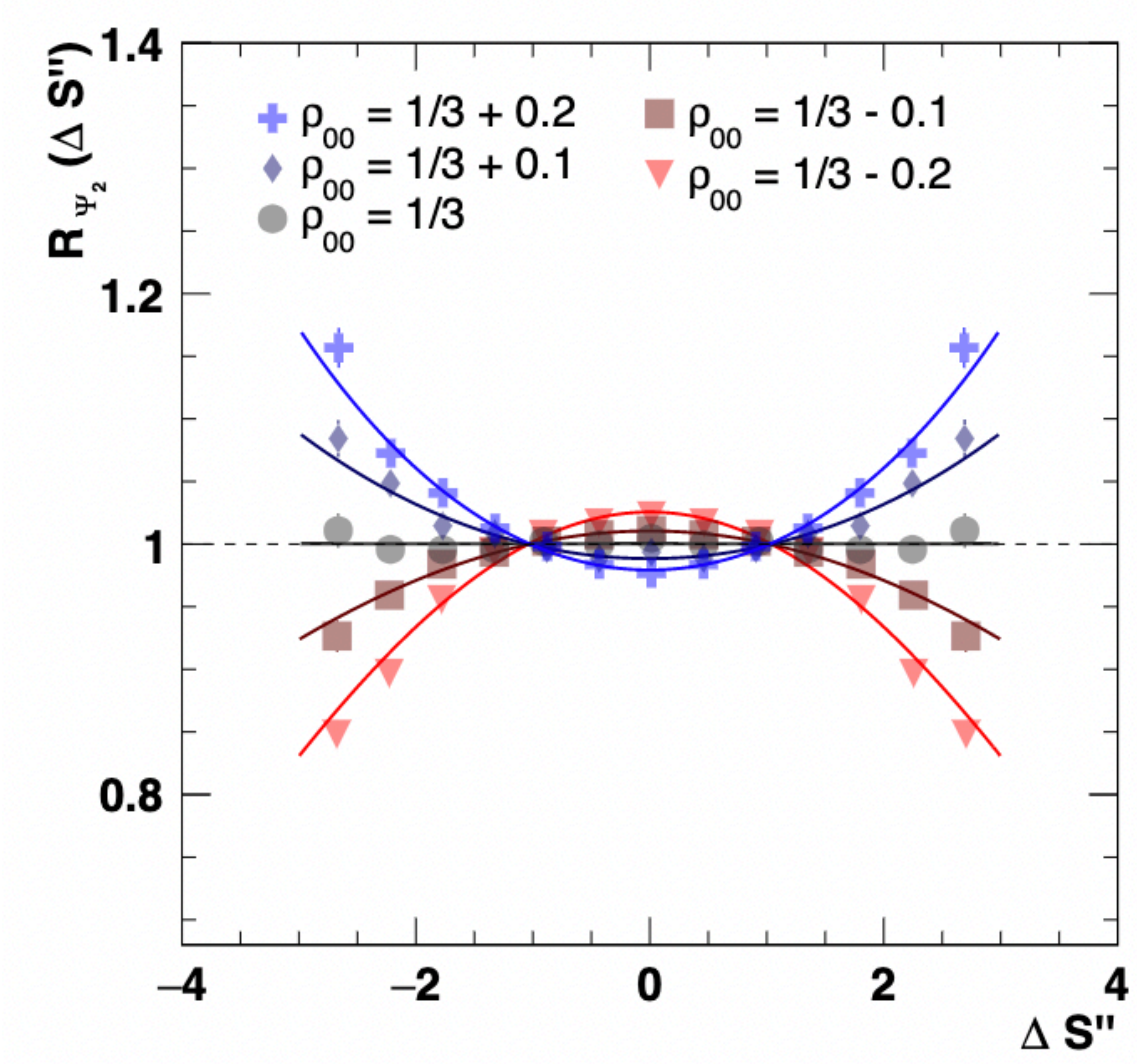
$$\Delta\sigma_R^2 = \sigma^2(\Delta S_{\rm real}) - \sigma^2(\Delta S_{\rm shuffled}) - \sigma^2(\Delta S^{\perp}_{\rm real}) + \sigma^2(\Delta S^{\perp}_{\rm shuffled}).$$

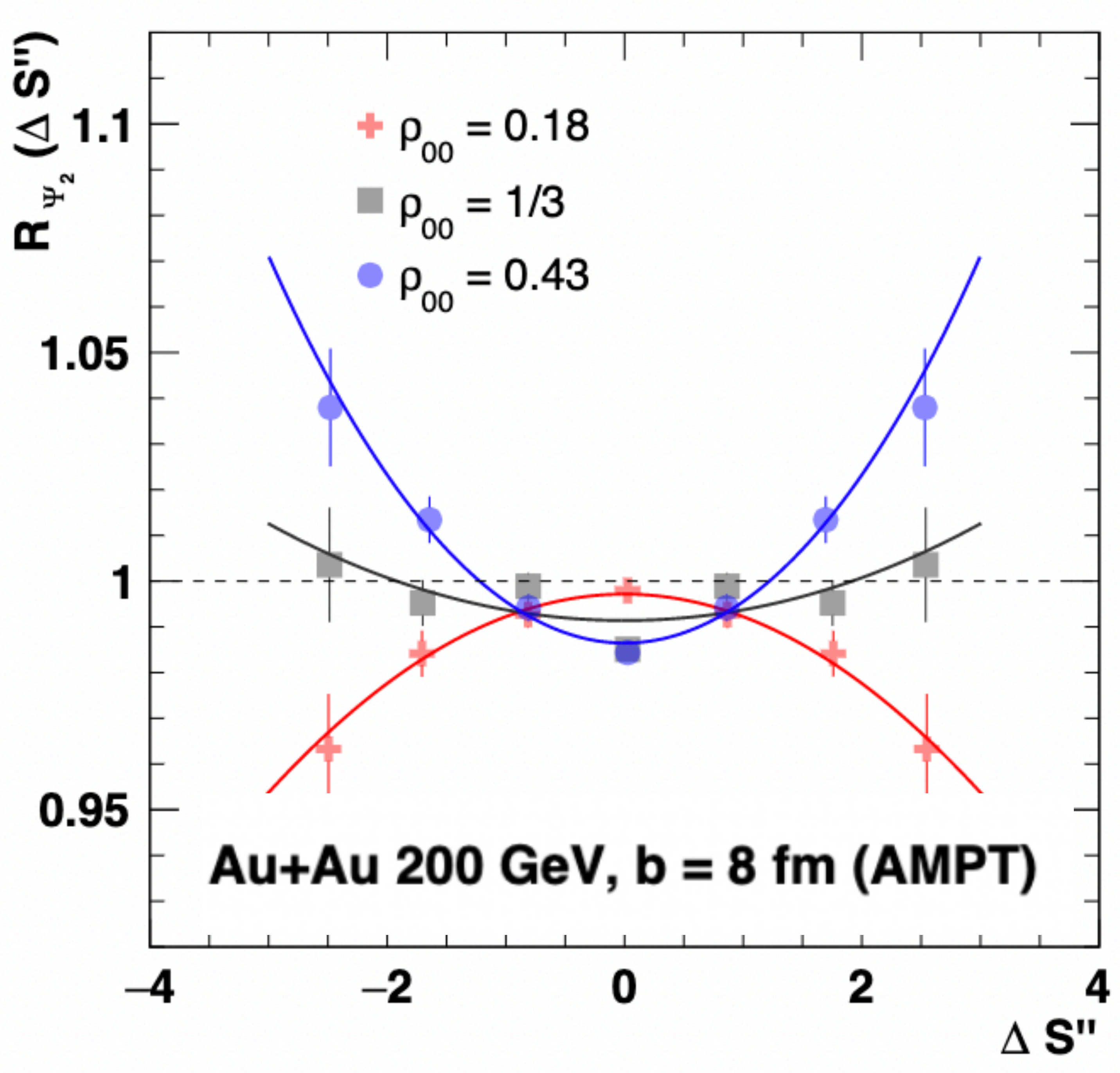
$$\Delta\sigma_R^2 = \frac{N_\rho}{N_+N_-}\left[\frac{1}{4}(f_c+f_s)(3\rho_{00}-1) + (f_c-f_s)\right].$$

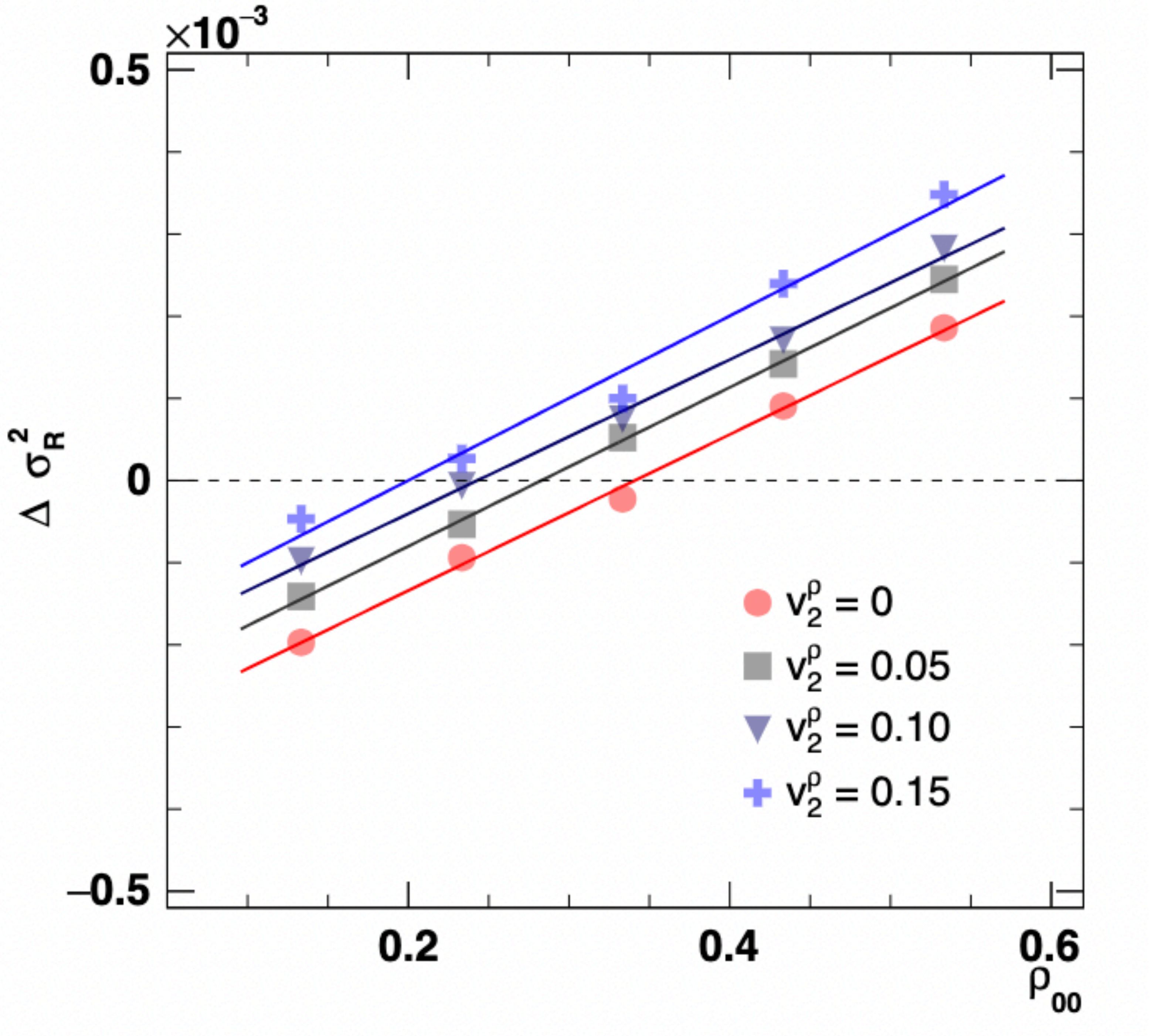
$$\Delta\sigma_R^2 \sim k'_1(\rho_{00}-\frac{1}{3}) + k'_2 v_2^{\rho}$$

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

The global spin alignment to the $R_{\Psi_2}(\Delta S)$ observable







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

$$\Delta\sigma_R^2 \sim k'_1(\rho_{00}-\frac{1}{3}) + k'_2 v_2^\rho$$

$R_{\Psi_2}(\Delta S)$ has similar ρ_{00} dependence as γ_{112}, $\Delta\sigma_R^2$ is also a linear function.

The global spin alignment to the signed balance function

Signed balance function

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

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

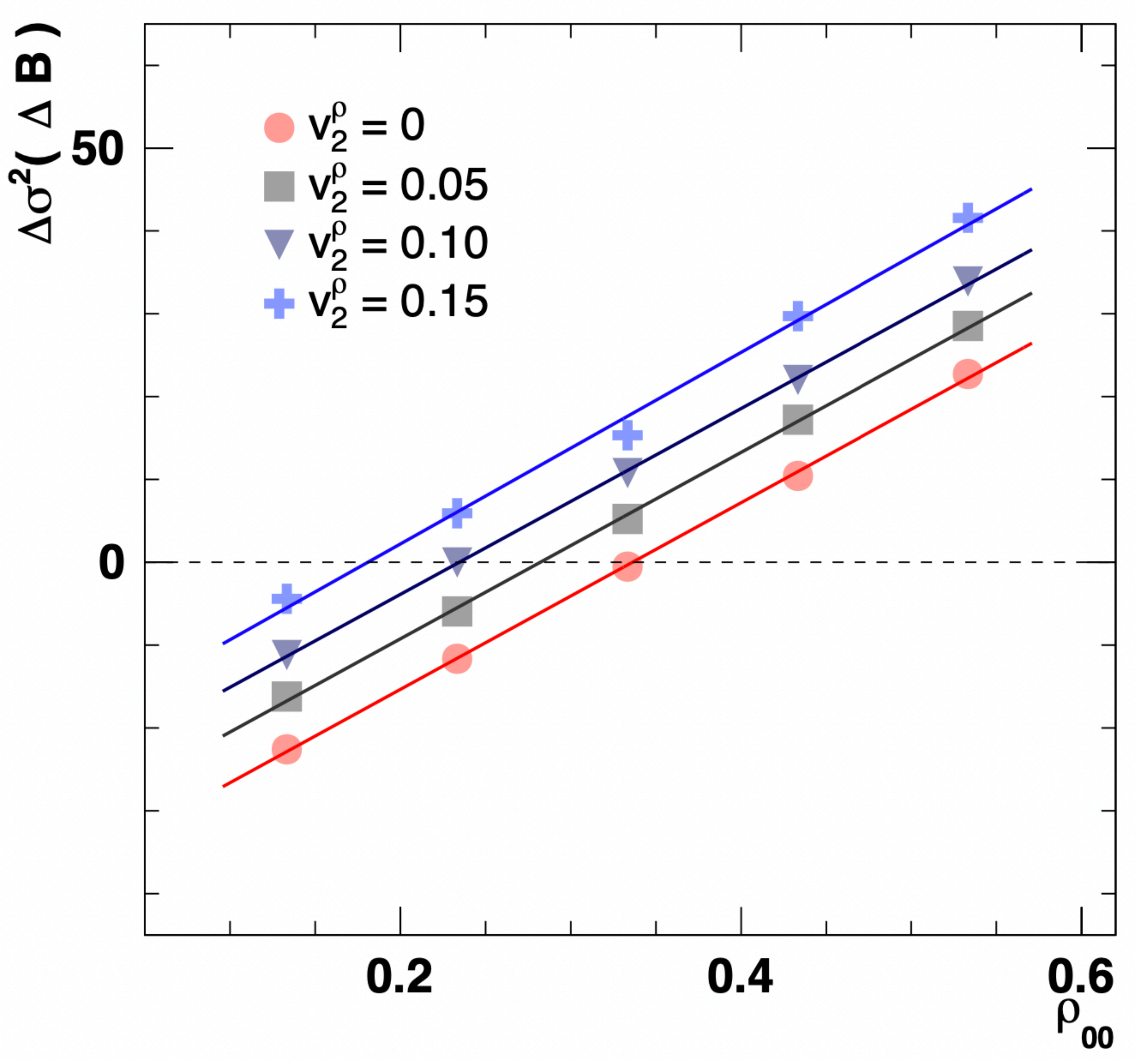
$$r \equiv \sigma(\Delta B_y)/\sigma(\Delta B_x).$$

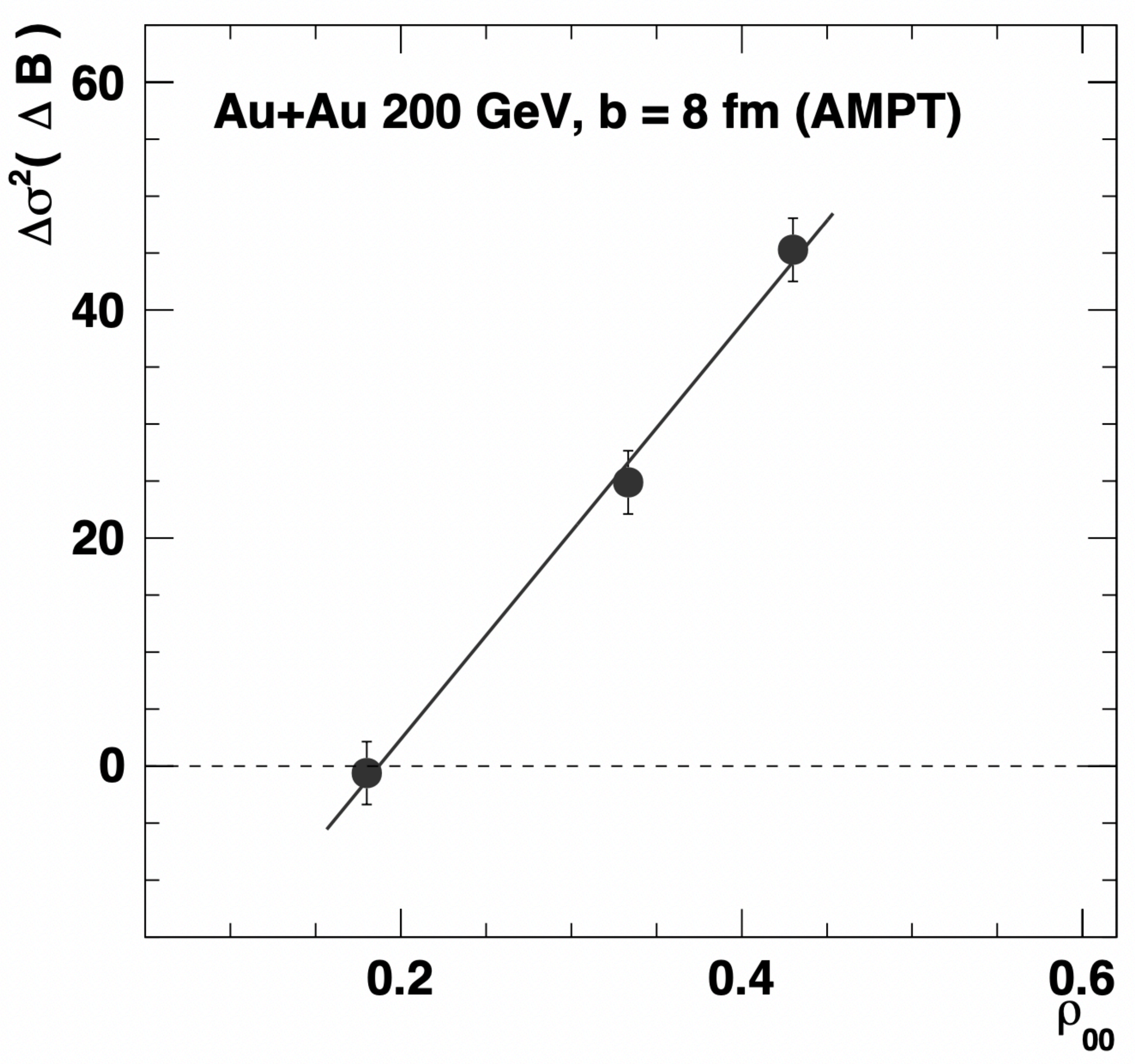
Assuming all particles have same p_T, we will have

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

$$\Delta\sigma^2(\Delta B) = \sigma^2(\Delta B_y) - \sigma^2(\Delta B_y) \sim k''_1(\rho_{00} - \frac{1}{3}) + k''_2 v_2^{\rho}$$

The global spin alignment to the signed balance function

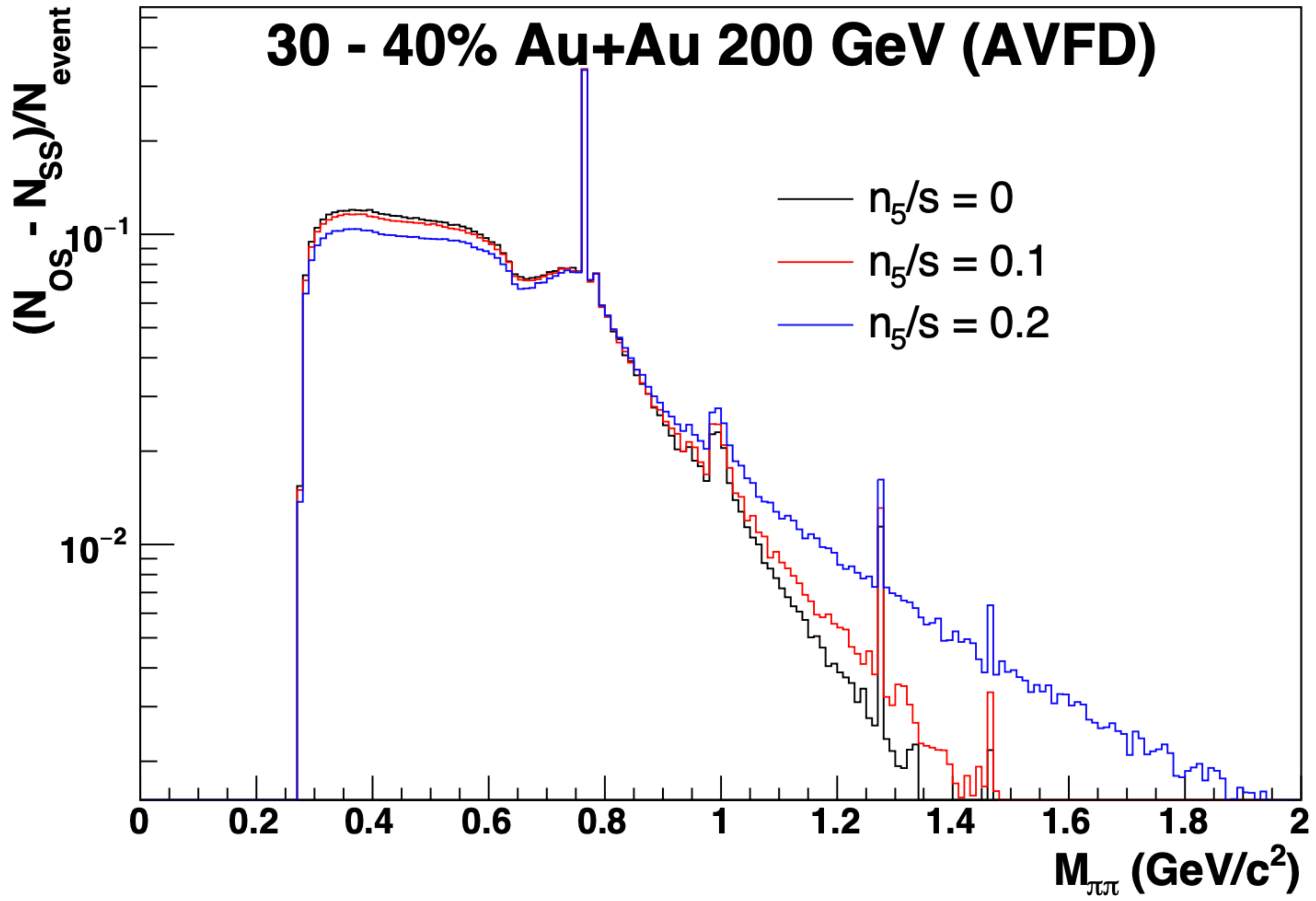




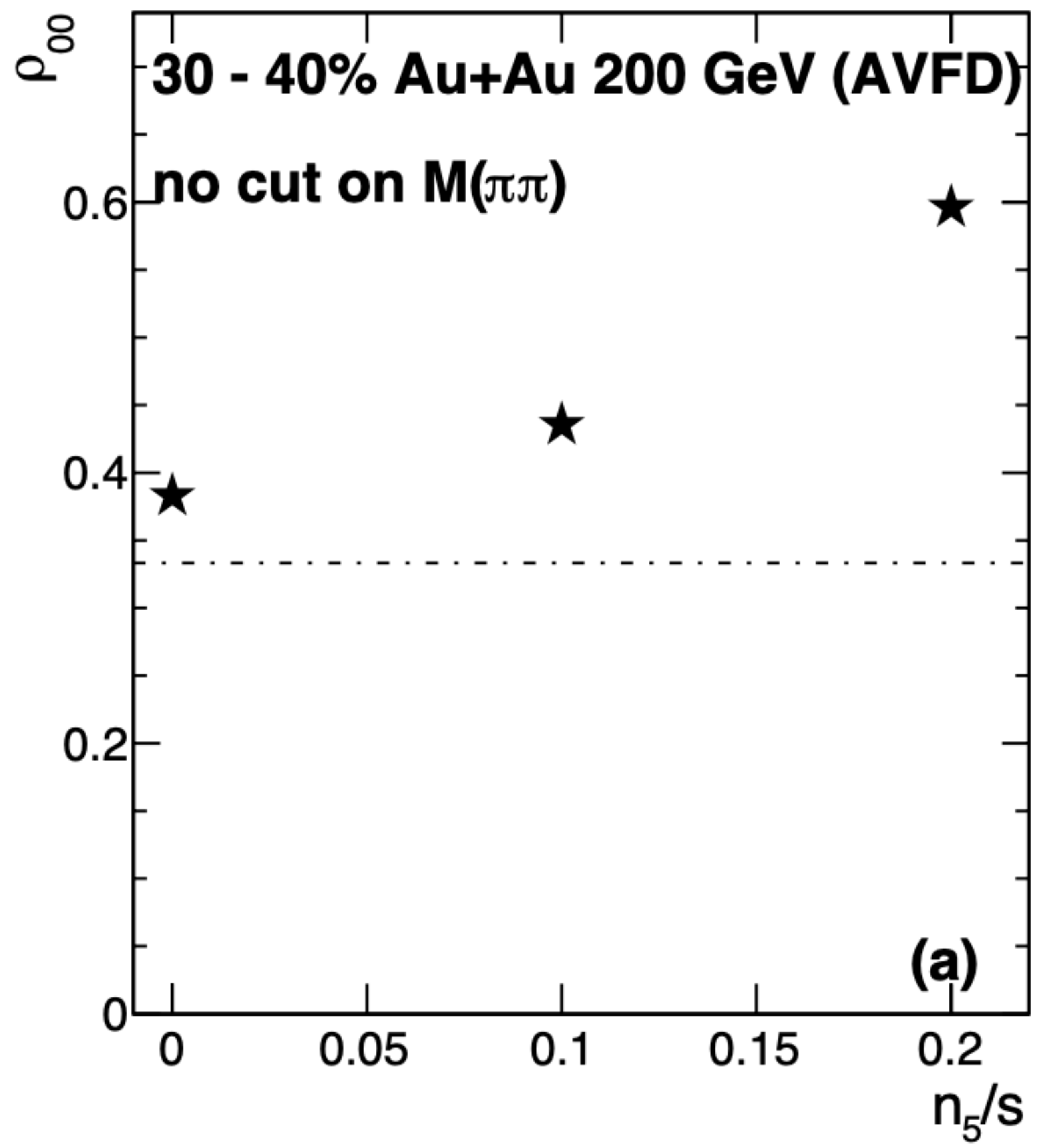
$$\Delta\sigma^2(\Delta B) \sim k''_1(\rho_{00} - \frac{1}{3}) + k''_2 v_2^\rho$$

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

The CME contribution to observed ρ_{00}



Zhiwan Xu, et.al., arXiv:2307.14997



- The charge separation makes the invariant mass distribution of OS pairs to be different from SS pairs, as well as mixed event pairs.
- The reconstructed resonances will be influenced by CME, the observed ρ_{00}, as well as v_2^{ρ}, is influenced consequently.

Summary

- The $\Delta\gamma_{112}$, $R_{\Psi_2}(\Delta S)$ and signed balance function $r_{\rm lab}$ are all 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 $r_{\rm lab}$.

- The spin alignment of vector meson can also be influenced by CME.