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

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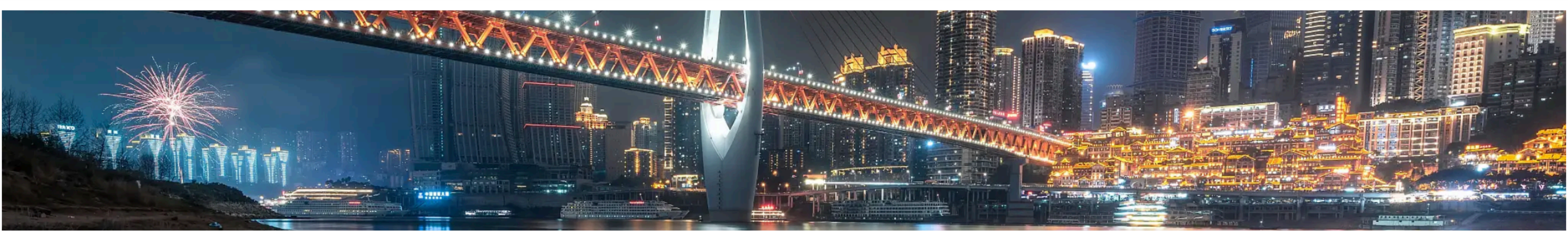
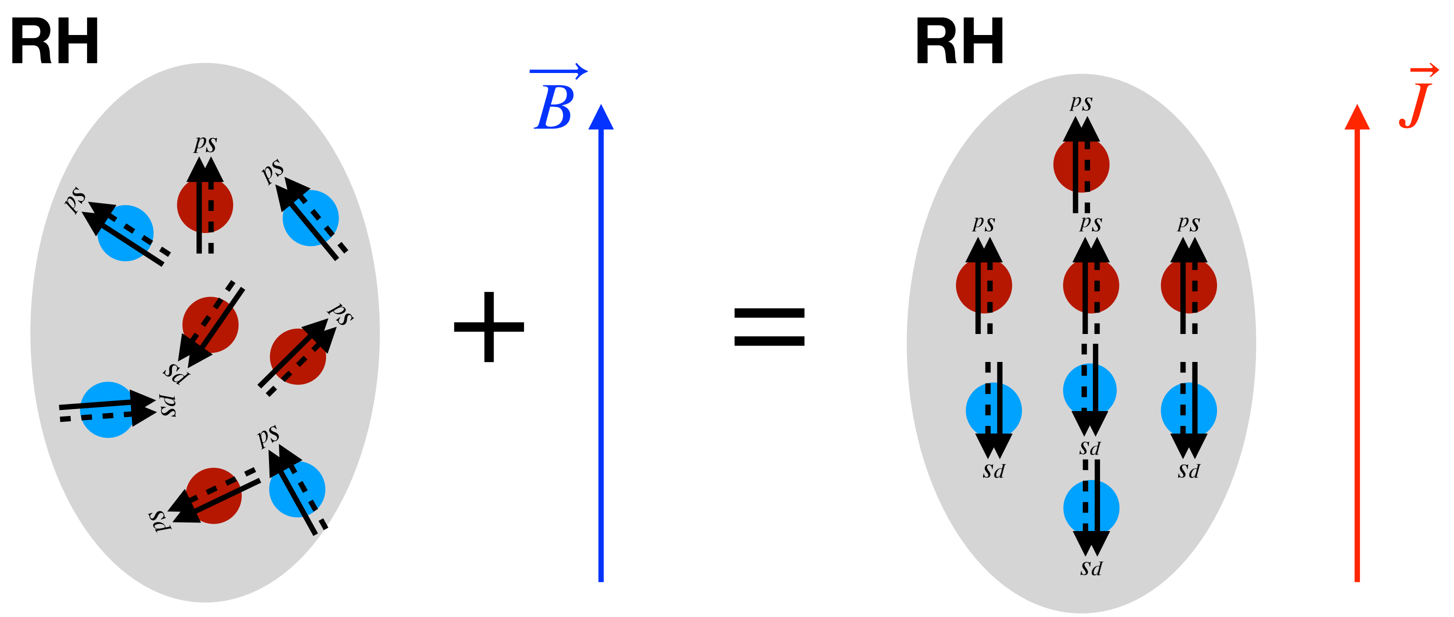
STAR regional conference, Chongqing, Oct. 10-15, 2024

Zhiyi Wang, Jinhui Chen, Diyu Shen, Aihong Tang, Gang Wang, arXiv:2409.04675 (2024)
Diyu Shen, Jinhui Chen, Aihong Tang and Gang Wang, Phys. Lett. B 839 (2023) 137777



Introduction of chiral magnetic effect

Chirality imbalance + Magnetic field = Electrical current

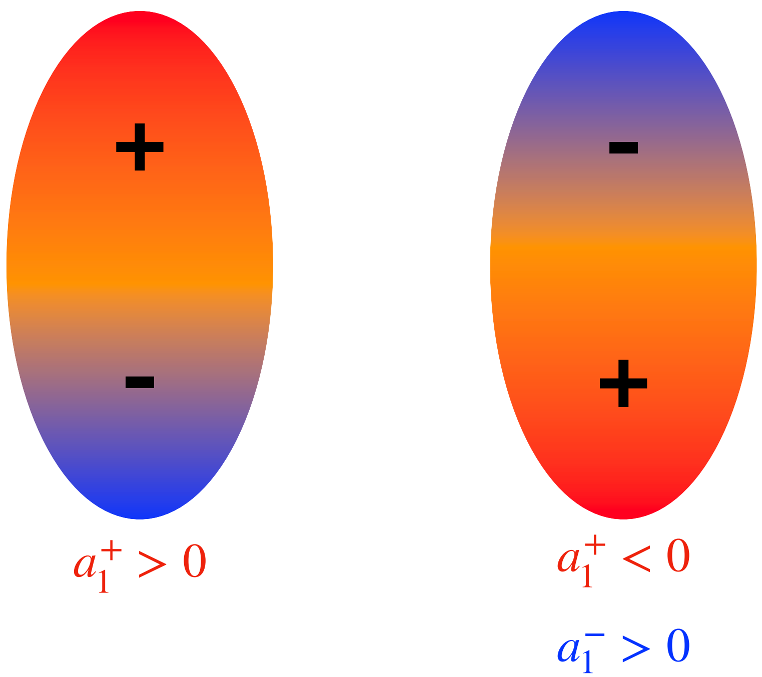


- Local CP violation in QCD results in chirality imbalance in quark gluon plasma.
- With spin being polarized by external magnetic field, quarks with opposite charge move in opposite direction.
- Charge separation along the magnetic field.

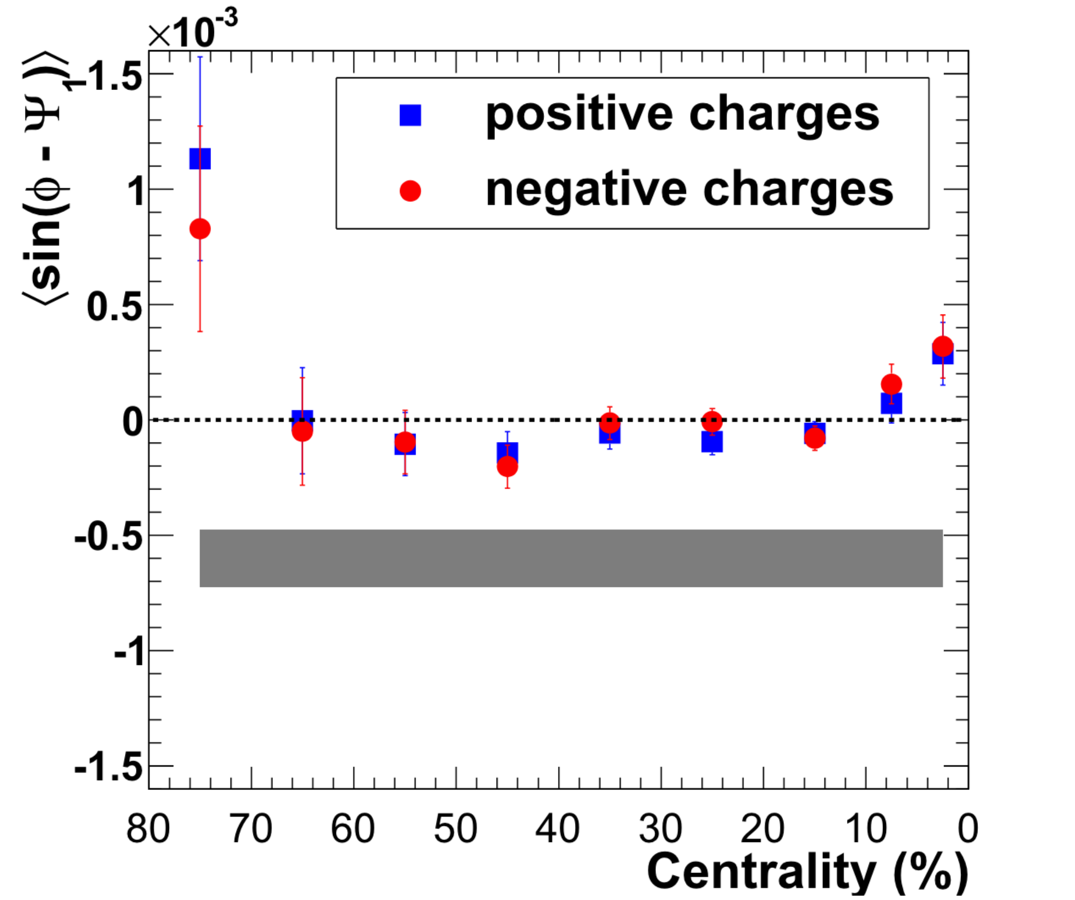
D.E. Kharzeev, J. Liao, Nat. Rev. Phys. 3 (2021) 55–63

How to measure the CME?

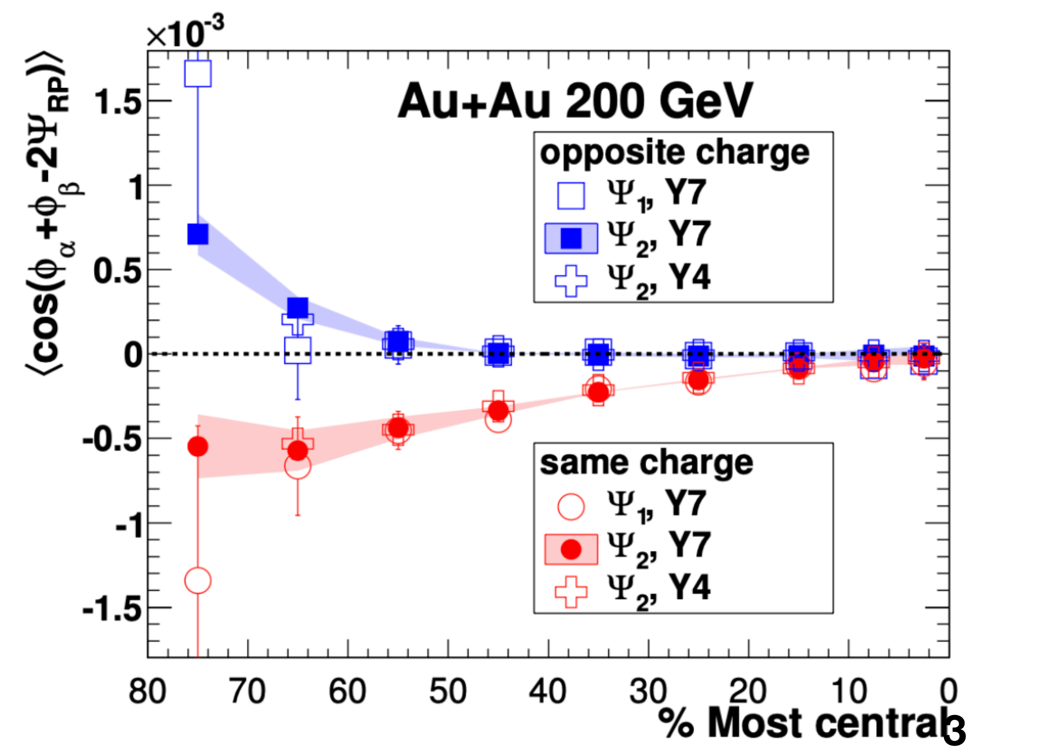
$$f(\Delta\phi^+) = 2a_1^+ \sin(\Delta\phi^+) + \sum 2v_n \cos(n\Delta\phi^+)$$



STAR, Phys. Rev. C, 88 064911



- Charge separation is averaged out over many collisions.
- Multi-particle correlations measure fluctuations.



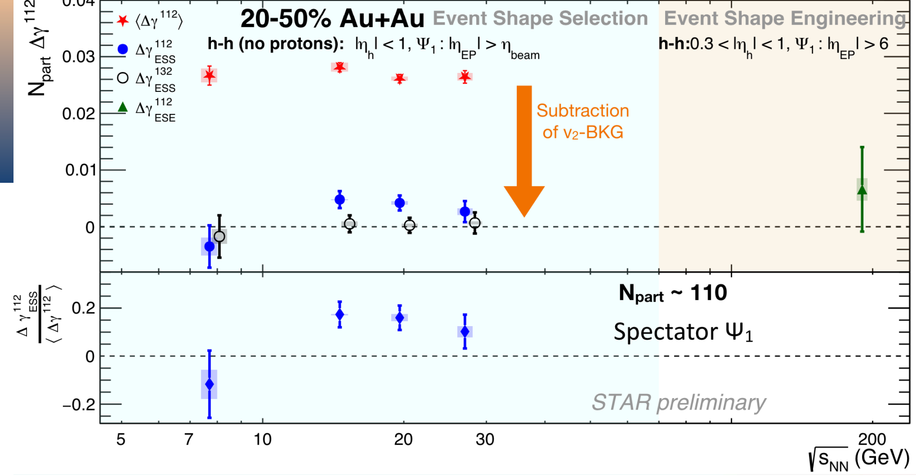
$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = v_1^\alpha v_1^\beta - a_1^\alpha a_1^\beta$$

$$\gamma_{112}^{OS} = a_1^2$$

$$\gamma_{112}^{SS} = -a_1^2$$

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

The CME measurements



(2022) STAR, PRC 105, 014901

(2022) ALICE, arXiv:2210.15383

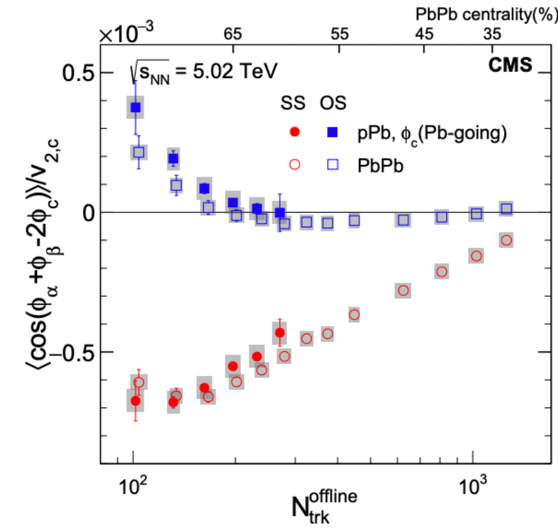
- The CME observable $\Delta\gamma_{112}$ was proposed.

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

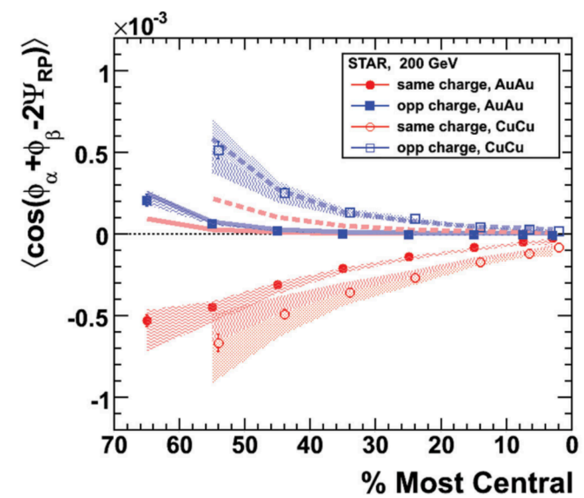
- Non-zero $\Delta\gamma_{112}$ in A+A collisions has been observed by STAR and ALICE.

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

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

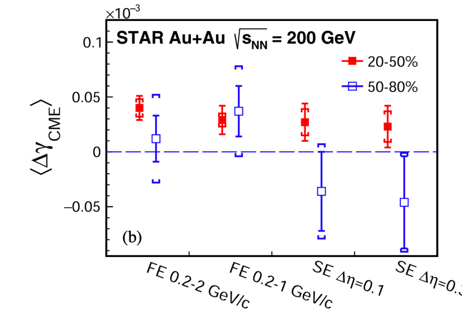


(2017) CMS, PRL 118, 122301



(2009) STAR, PRL 103 251601

(2023) STAR, PLB 839 137779



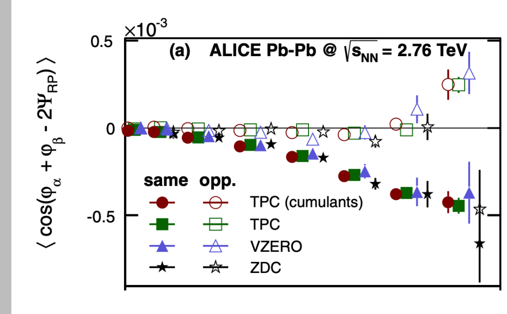
(2022) STAR, PRL 128, 0921301

(2022) STAR, PRC 106, 034908

(2018) CMS, PRC 97, 044912

(2018) ALICE, PLB 777 151

(2014) STAR, PRC 89, 044908

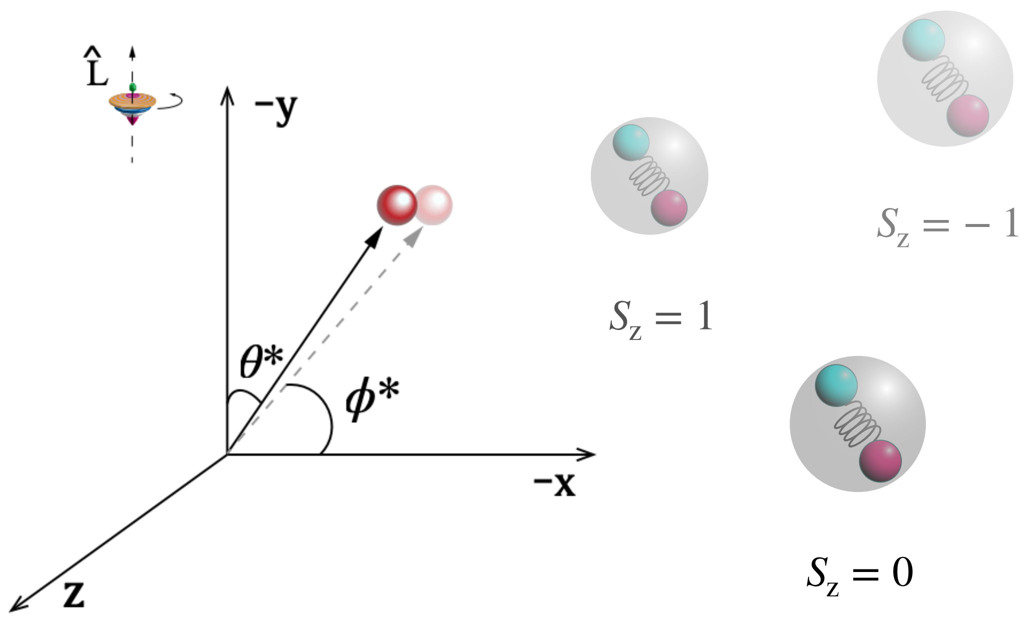


(2013) ALICE, PRL 110, 012301

(2013) STAR, PRC 88, 064911

The global spin alignment of vector mesons

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



$$\frac{d^2N}{d\cos\theta^* d\beta} = \frac{3}{8\pi}[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* \\ -\sqrt{2}(\mathrm{Re}\rho_{10} - \mathrm{Re}\rho_{0-1})\sin(2\theta^*)\cos\beta \\ +\sqrt{2}(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1})\sin(2\theta^*)\sin\beta \\ -2\mathrm{Re}\rho_{1-1}\sin^2\theta^*\cos(2\beta) \\ +2\mathrm{Im}\rho_{1-1}\sin^2\theta^*\sin(2\beta)]$$

$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

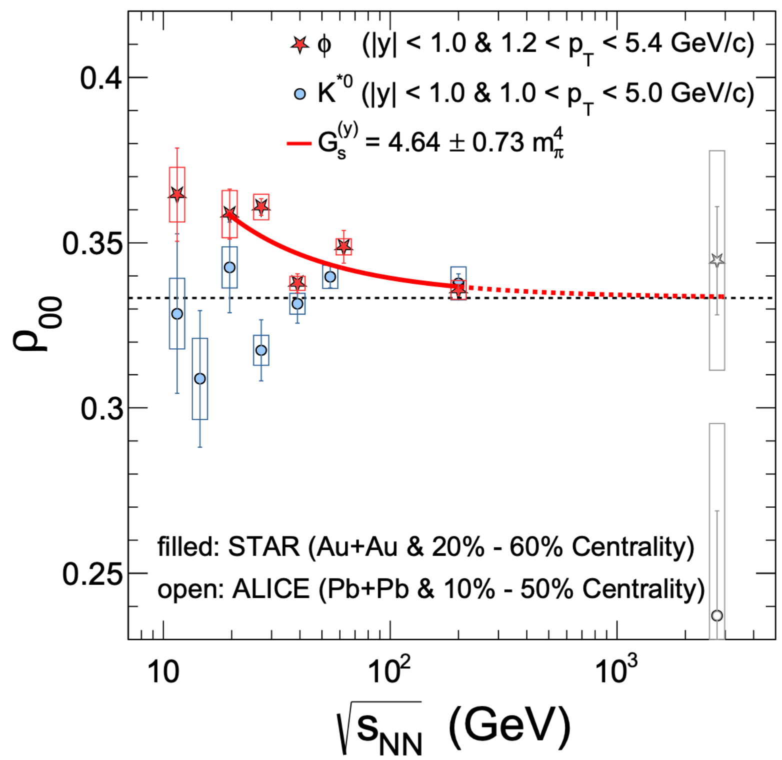
- Spin state along orbit angular momentum, characterized by spin density matrix.
- Distribution of decay products depend on vector meson spin, in the transverse plane:

$$\frac{dN}{d\phi^*} = \frac{1}{2\pi}\left[1 - \frac{1}{2}(3\rho_{00}-1)\cos 2\phi^* + \sqrt{2}\mathrm{Im}(\rho_{10}-\rho_{0-1})\sin 2\phi^* + \mathrm{Re}\,\rho_{1-1}\cos 2\phi^*\right]$$

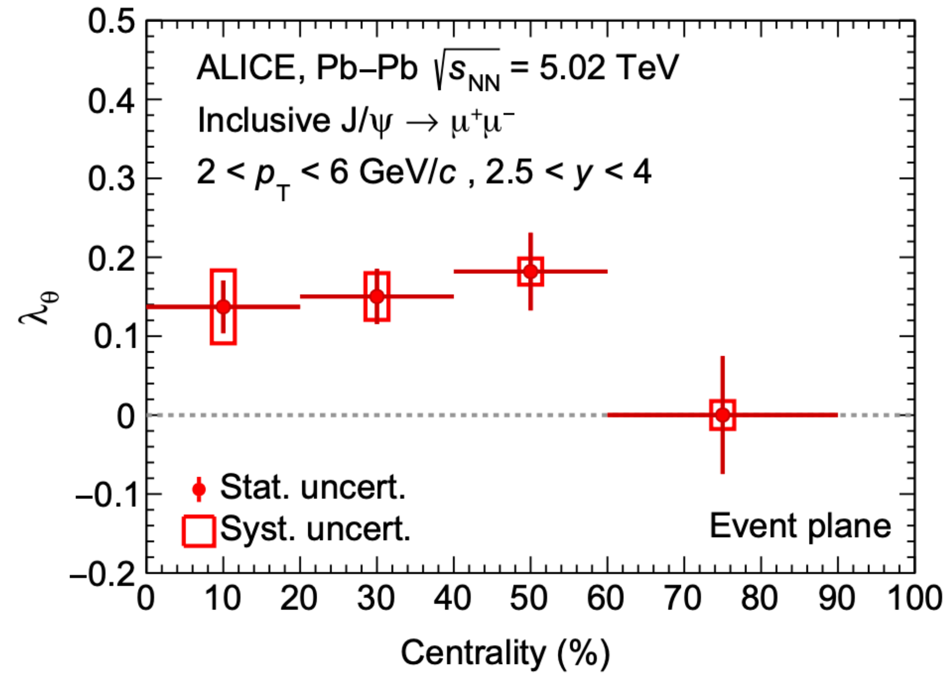
Zhiyi Wang et al., arXiv:2409.04675 (2024)

The global spin alignment measurements

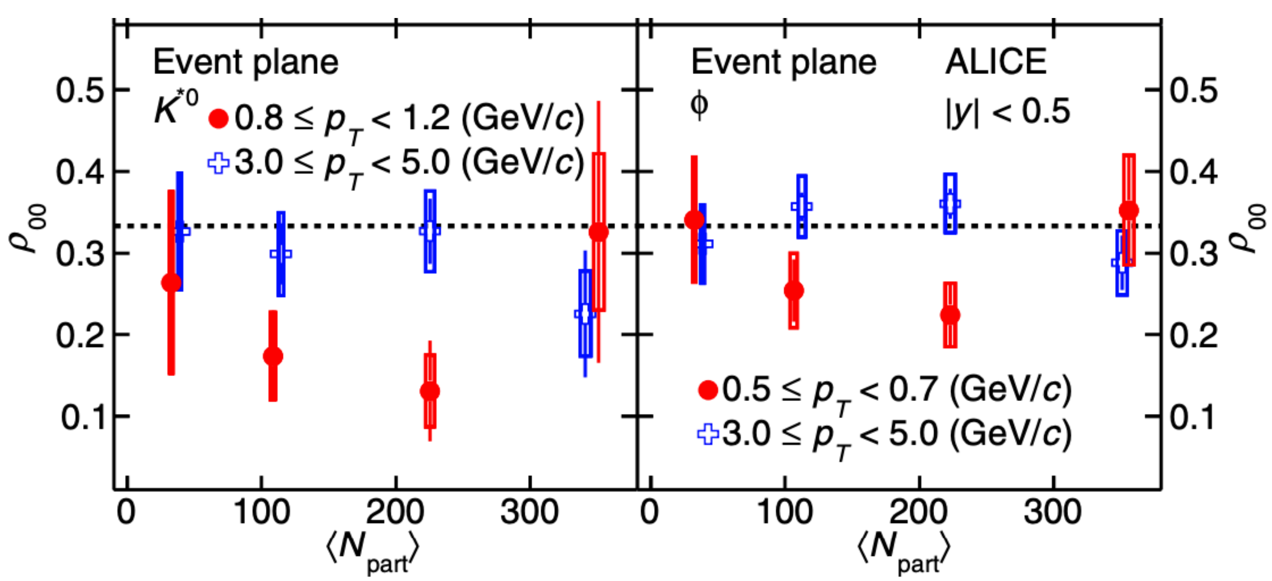
(2023) STAR, Nature 614, 244–248



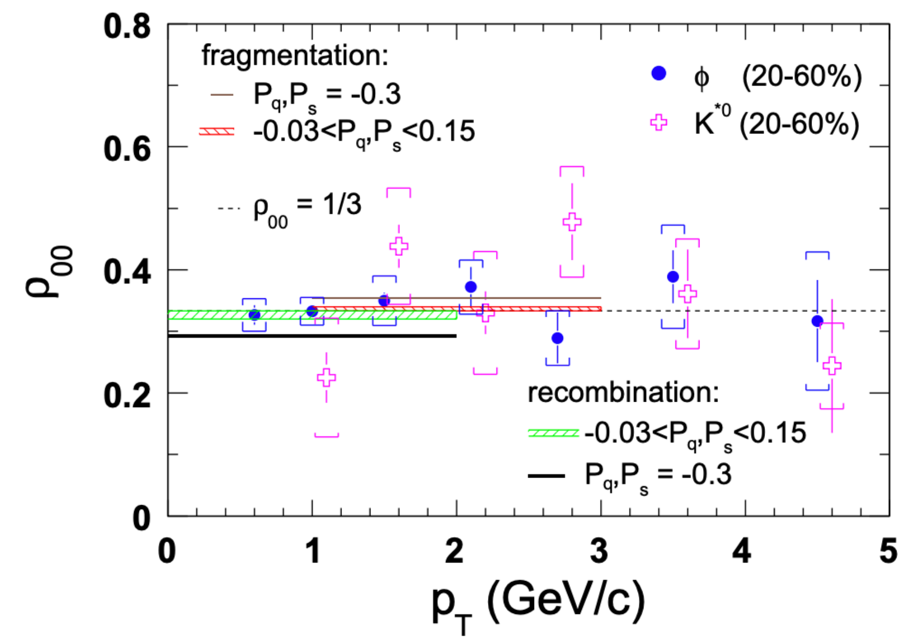
(2023) ALICE, RPL 131, 042303



(2020) ALICE, PRL 125, 012301



(2008) STAR, PRC 77 61902

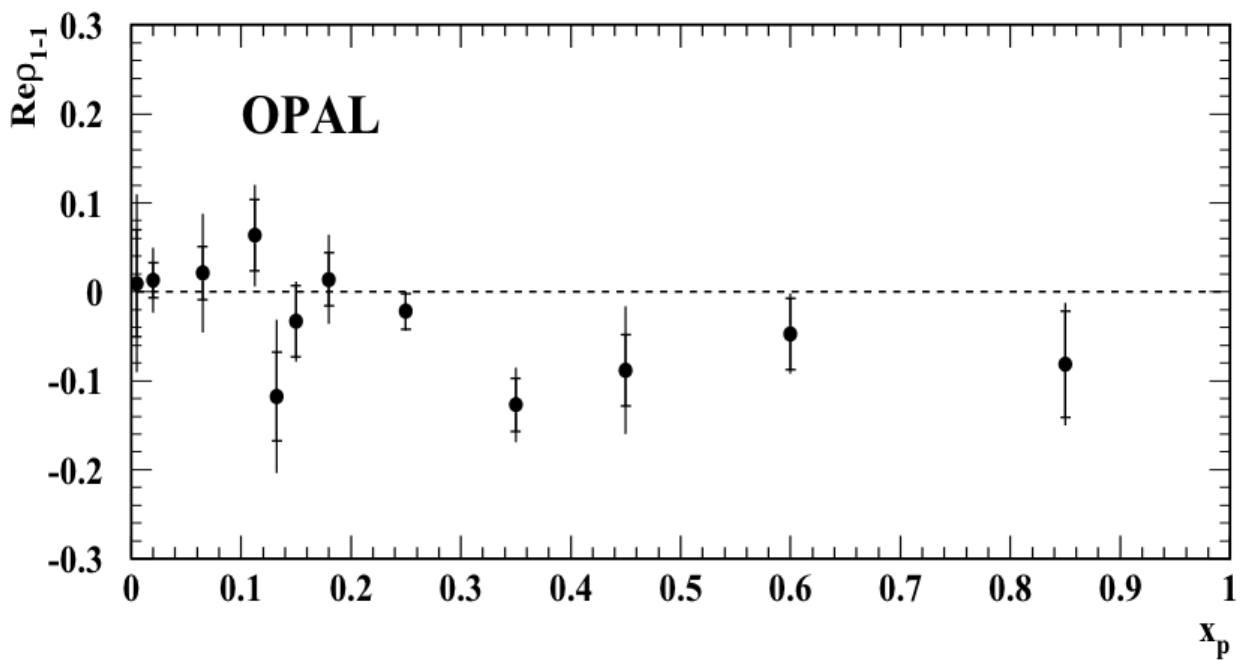


- Spin alignment of vector mesons along direction perpendicular to reaction plane has been observed in experiment.

The off-diagonal terms

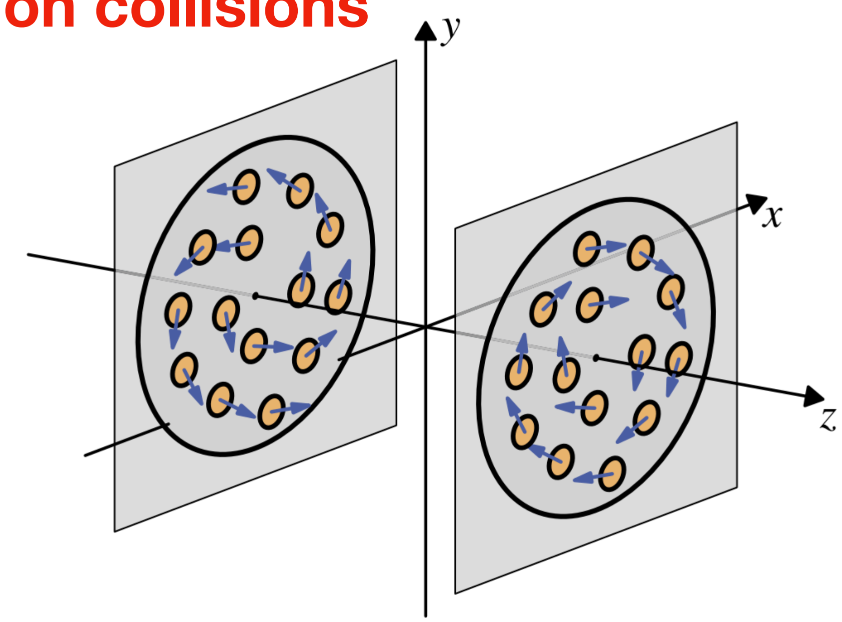
OPAL Collab., Phys. Lett. B 412 (1997) 210–224.

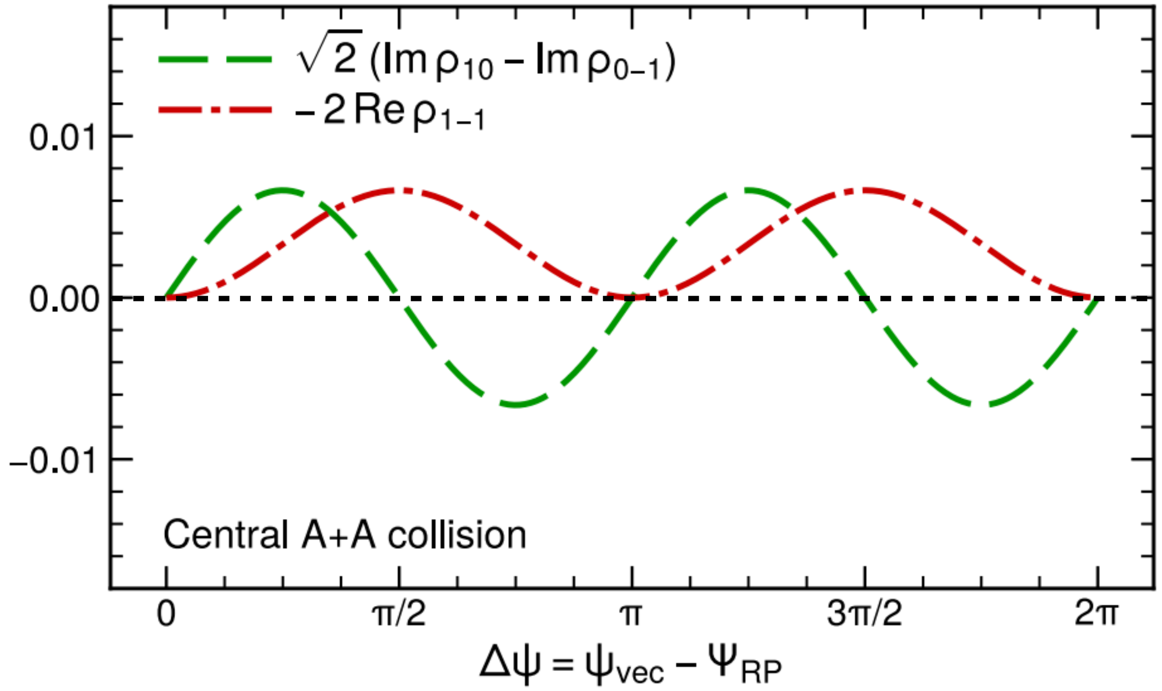
Z^0 **decayed** K^{*0}



Xia et., al., Phys. Lett. B 817, 136325 (2021);

Heavy-ion collisions





- Spin coherence gives finite $\mathrm{Re}\rho_{1-1}$.
- Experimental measurements (quark matter 2025)?

Vector meson spin 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

$$\frac{dN}{d\phi^*} = \frac{1}{2\pi}\left[1 - \frac{1}{2}(3\rho_{00} - 1)\cos 2\phi^* + \sqrt{2}\mathrm{Im}(\rho_{10} - \rho_{0-1})\sin 2\phi^* + \mathrm{Re}\,\rho_{1-1}\cos 2\phi^*\right]$$

The covariance between decay products is given by

$$\mathrm{Cov}(\cos\phi_+^*, \cos\phi_-^*) = -\left\langle \cos^2\phi_+^* \right\rangle + \left\langle \cos\phi_+^* \right\rangle^2 = -\frac{1}{2} + \frac{1}{8}(3\rho_{00} - 1) - \frac{\mathrm{Re}\rho_{1-1}}{4},$$

$$\mathrm{Cov}(\sin\phi_+^*, \sin\phi_-^*) = -\left\langle \sin^2\phi_+^* \right\rangle + \left\langle \sin\phi_+^* \right\rangle^2 = -\frac{1}{2} - \frac{1}{8}(3\rho_{00} - 1) + \frac{\mathrm{Re}\rho_{1-1}}{4}.$$

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

Therefore, $\Delta\gamma^* = \gamma^{*OS} - \gamma^{*SS} = \frac{N_\rho}{N_+N_-}[\frac{3}{4}(\rho_{00} - \frac{1}{3}) - \frac{1}{2}\mathrm{Re}\rho_{1-1}]$

The $\Delta\gamma$ is proportional to $(\rho_{00} - \frac{1}{3}) - \frac{2}{3}\mathrm{Re}\rho_{1-1}$ in decay rest frame.

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

Boost factor in plane

$$\mathrm{Cov}(\cos\phi_+, \cos\phi_-) = f_c \mathrm{Cov}(\cos\phi_+^*, \cos\phi_-^*) = f_c\left[-\frac{1}{2} + \frac{1}{8}(3\rho_{00} - 1) - \frac{\mathrm{Re}\rho_{1-1}}{4}\right]$$

$$\mathrm{Cov}(\sin\phi_+, \sin\phi_-) = f_s \mathrm{Cov}(\sin\phi_+^*, \sin\phi_-^*) = f_s\left[-\frac{1}{2} - \frac{1}{8}(3\rho_{00} - 1) + \frac{\mathrm{Re}\rho_{1-1}}{4}\right]$$

Boost factor out of plane

$$f_c = f_0 + \sum a_n (v_2^\rho)^n$$

$$f_s = f_0 + \sum b_n (v_2^\rho)^n$$

$$\Delta\gamma_{112} = \frac{N_\rho}{N_+N_-}\left[(f_c + f_s)[(\frac{3}{8}(\rho_{00} - 1) - \frac{1}{4}\mathrm{Re}\rho_{1-1}] - \frac{1}{2}(f_c - f_s)\right] \sim \mathrm{spin} + v_2^\rho$$

Model simulations

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

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

Setups of toy model

- Spectrum of primordial pion

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

- 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

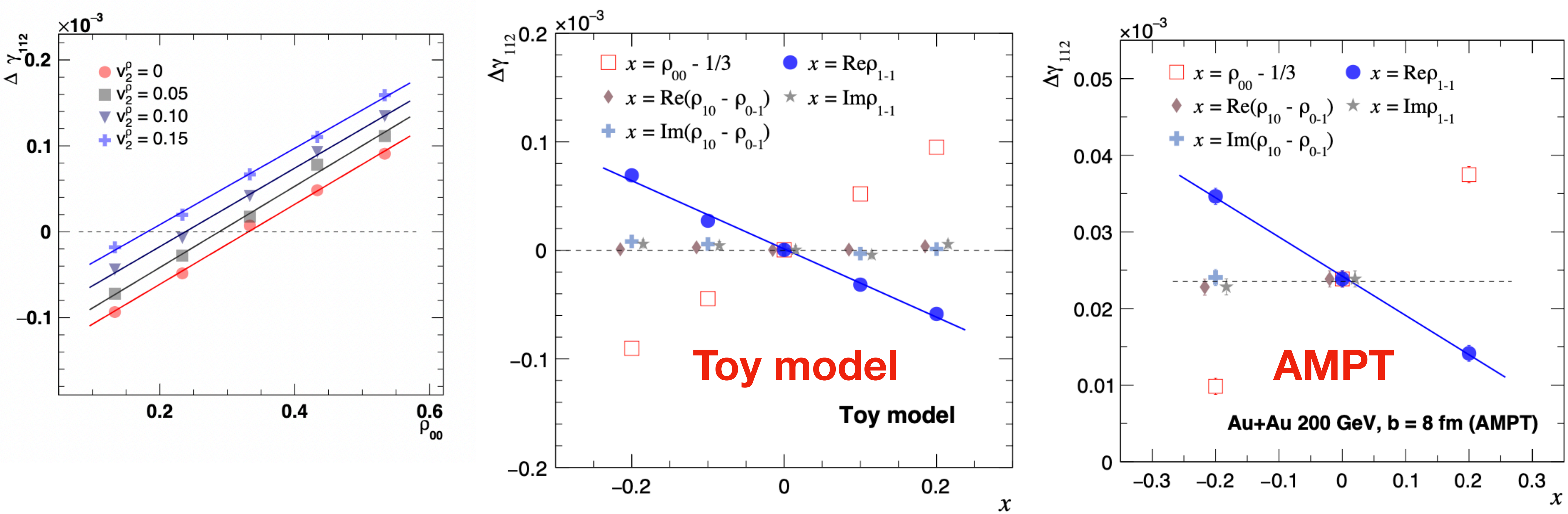
- String melting version
- AuAu 200 GeV with impact parameter b ~ 8 fm
- Spin alignment effect is introduced by sampling decay products according to

$$\begin{aligned}\frac{d^2N}{d\cos\theta^* d\beta} = \frac{3}{8\pi}[&(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* \\ &-\sqrt{2}(\mathrm{Re}\rho_{10} - \mathrm{Re}\rho_{0-1})\sin(2\theta^*)\cos\beta \\ &+\sqrt{2}(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1})\sin(2\theta^*)\sin\beta \\ &-2\mathrm{Re}\rho_{1-1}\sin^2\theta^*\cos(2\beta) \\ &+2\mathrm{Im}\rho_{1-1}\sin^2\theta^*\sin(2\beta)]\end{aligned}$$

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

D. Shen et al., Phys. Lett. B 839 (2023) 137777

Z. Wang et al, arXiv:2409.04675 (2024)



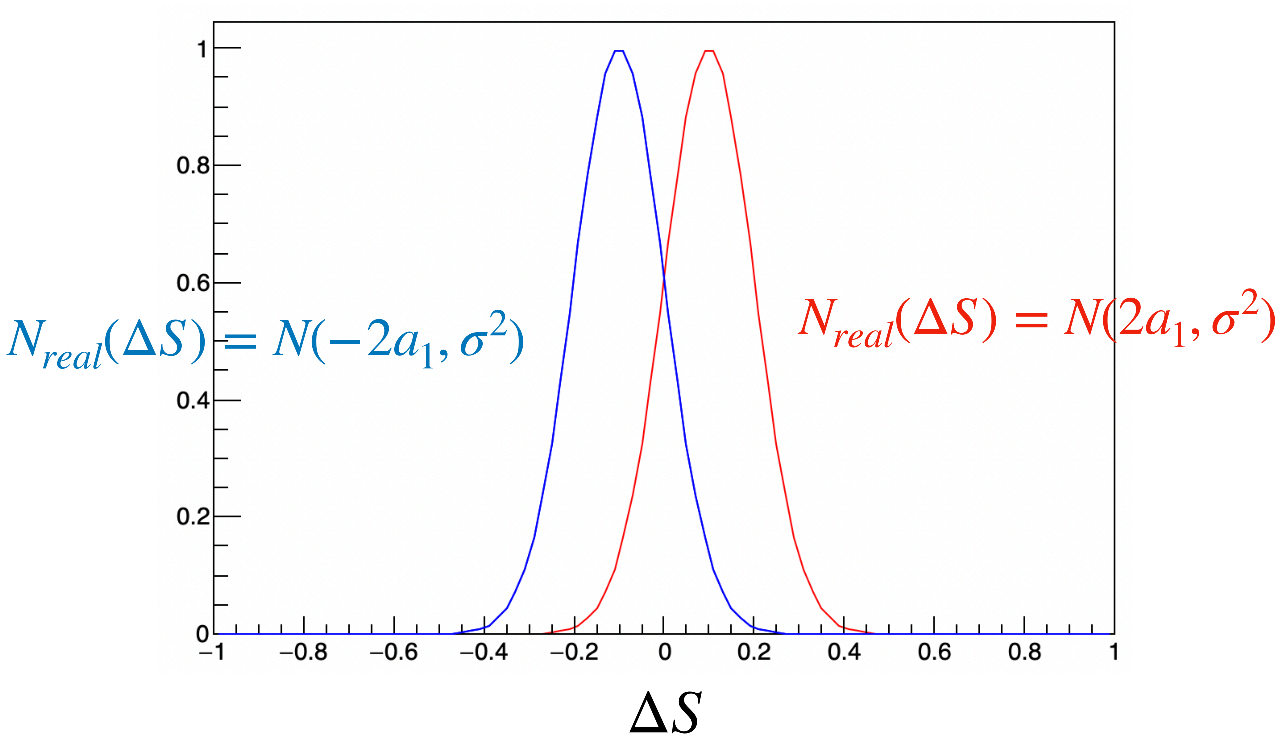
- A linear dependence of $\Delta\gamma$ as a function of ρ_{00} and $\mathrm{Re}\rho_{1-1}$ has been observed, slope and intercept depend on spectra and flow of ρ mesons.

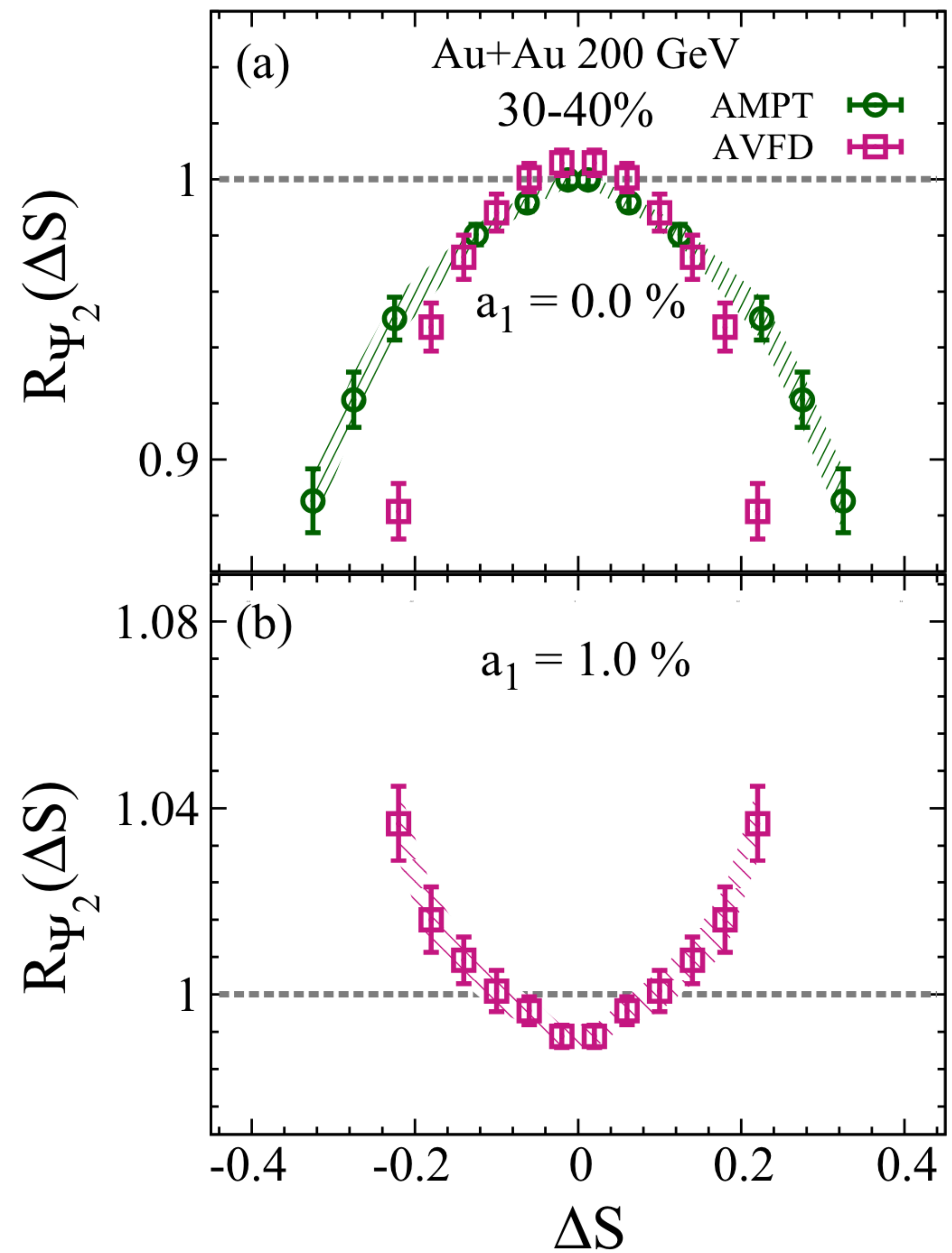
Global spin alignment to the R correlator

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

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

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





Global spin alignment to the R correlator

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

Definition:

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

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

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

$$\sigma^2(\Delta S_{\rm real}) = f_0 \left[\sigma_s^2 - \frac{2N_\rho}{N_+N_-}{\rm Cov}(\sin\phi^*_+, \sin\phi^*_-)\right]$$

$$\sigma^2(\Delta S^{\perp}_{\rm real}) = f_0 \left[\sigma_c^2 - \frac{2N_\rho}{N_+N_-}{\rm Cov}(\cos\phi^*_+, \cos\phi^*_-)\right]$$

$$\sigma^2(\Delta S_{\rm shuffled}) = f_0\sigma_s^2,$$
$$\sigma^2(\Delta S^{\perp}_{\rm shuffled}) = f_0\sigma_c^2,$$

$$S_{\rm concavity} = {\rm Sign}\left[{\rm Re}\,\rho_{1-1} - \frac{3}{2}(\rho_{00} - \frac{1}{3})\right]$$

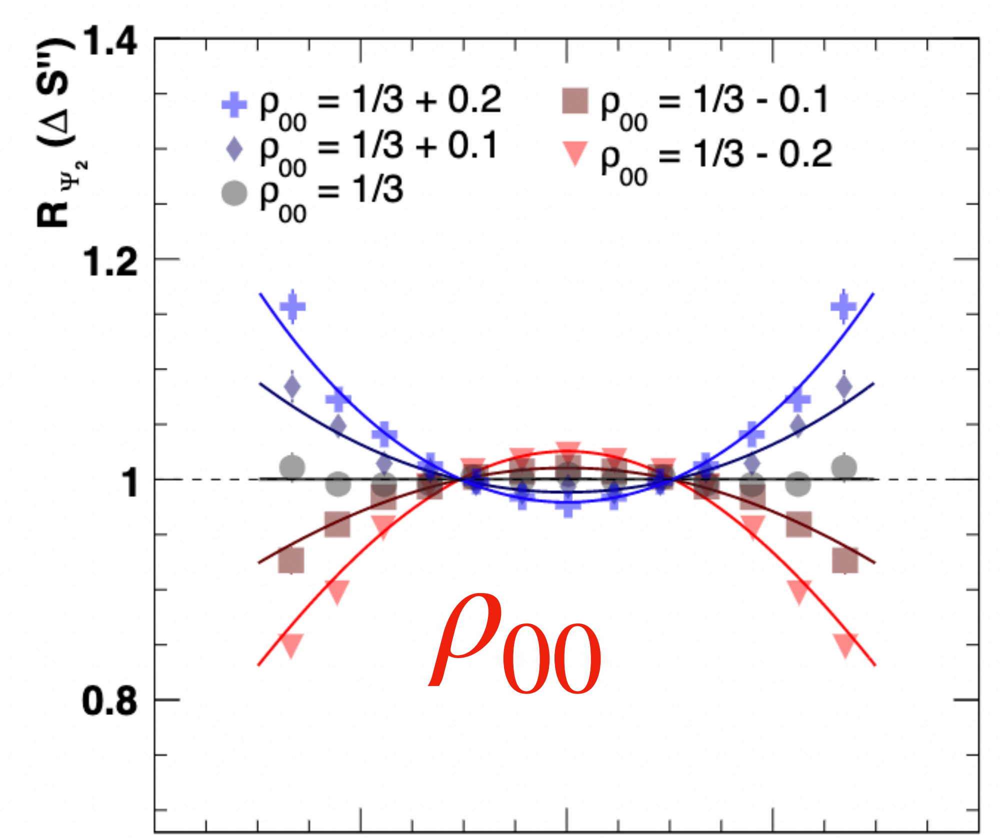
Constructing direct subtraction:

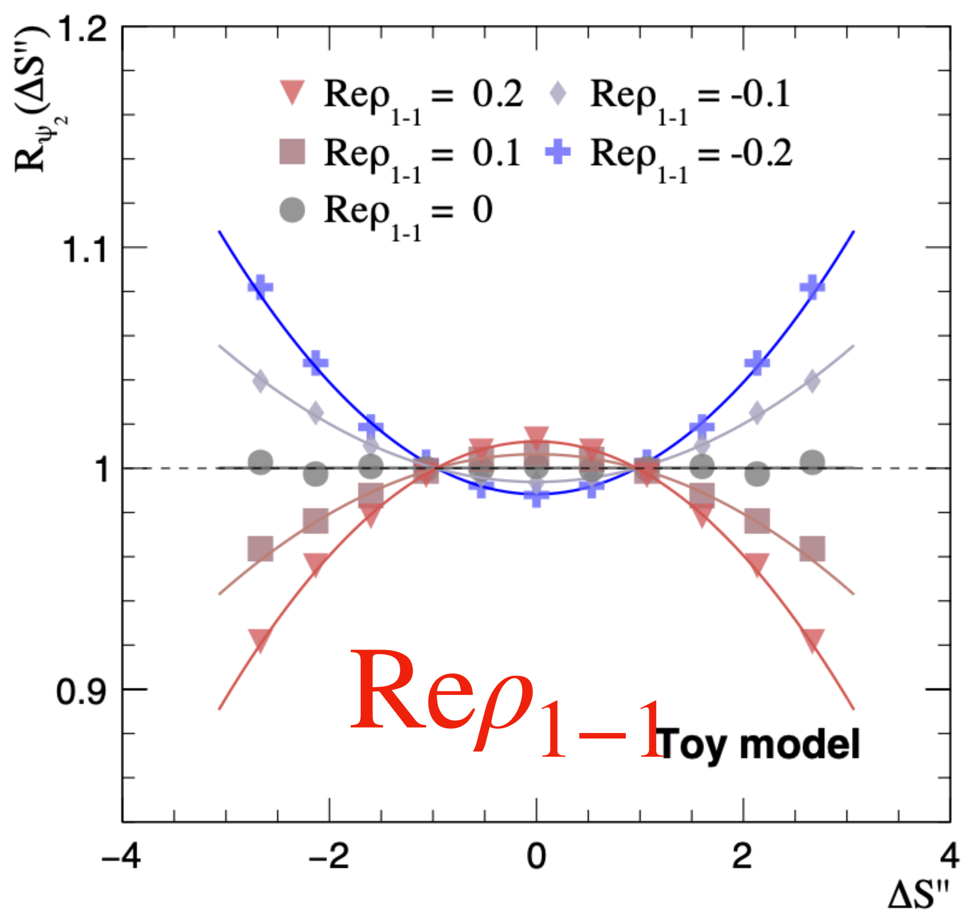
$$\Delta\sigma^2_R = \sigma^2(\Delta S_{\rm real}) - \sigma^2(\Delta S_{\rm shuffled}) - \sigma^2(\Delta S^{\perp}_{\rm real}) + \sigma^2(\Delta S^{\perp}_{\rm shuffled})$$

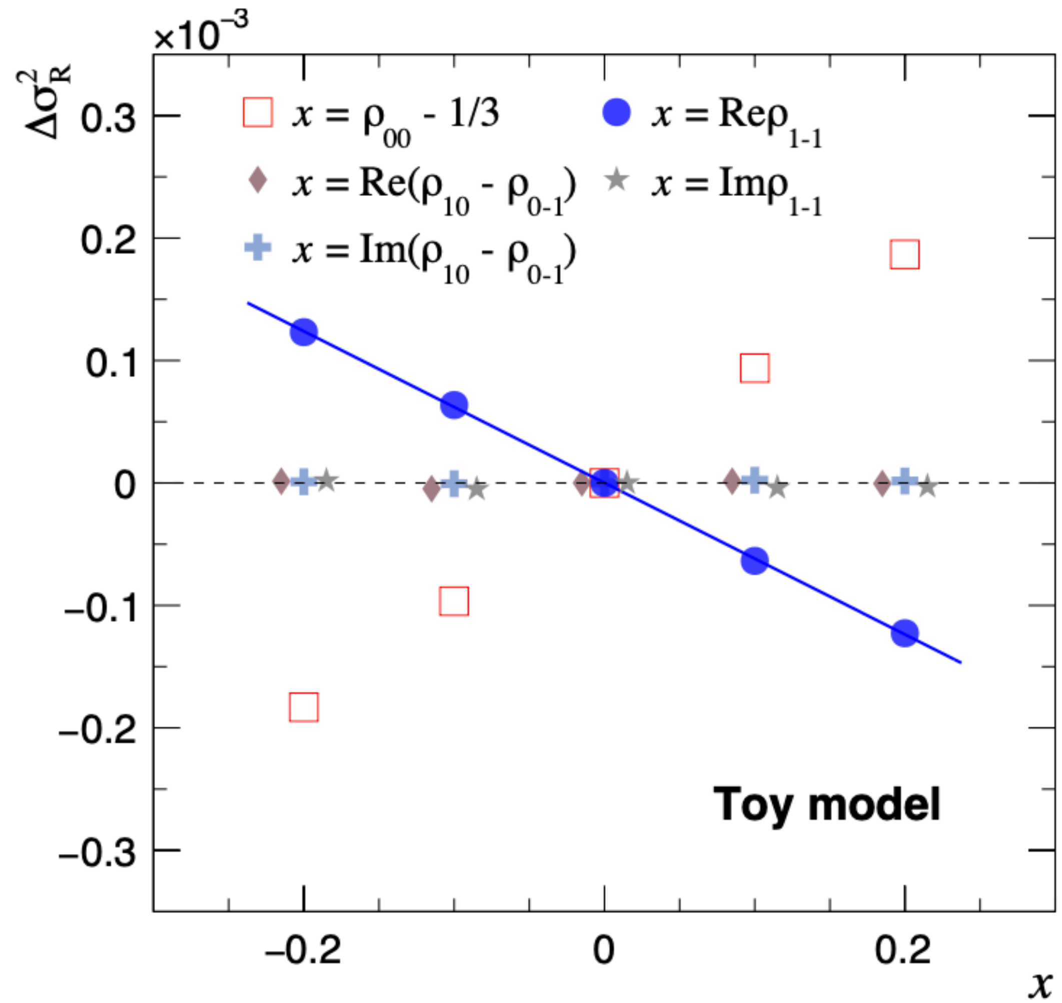
$$\Delta\sigma^2_R = f_0 \frac{N_\rho}{N_+N_-}\left[\frac{3}{2}(\rho_{00} - \frac{1}{3}) - {\rm Re}\,\rho_{1-1}\right]$$

$$\Delta\sigma^2_R = 2\Delta\gamma$$

Global spin alignment to the R correlator

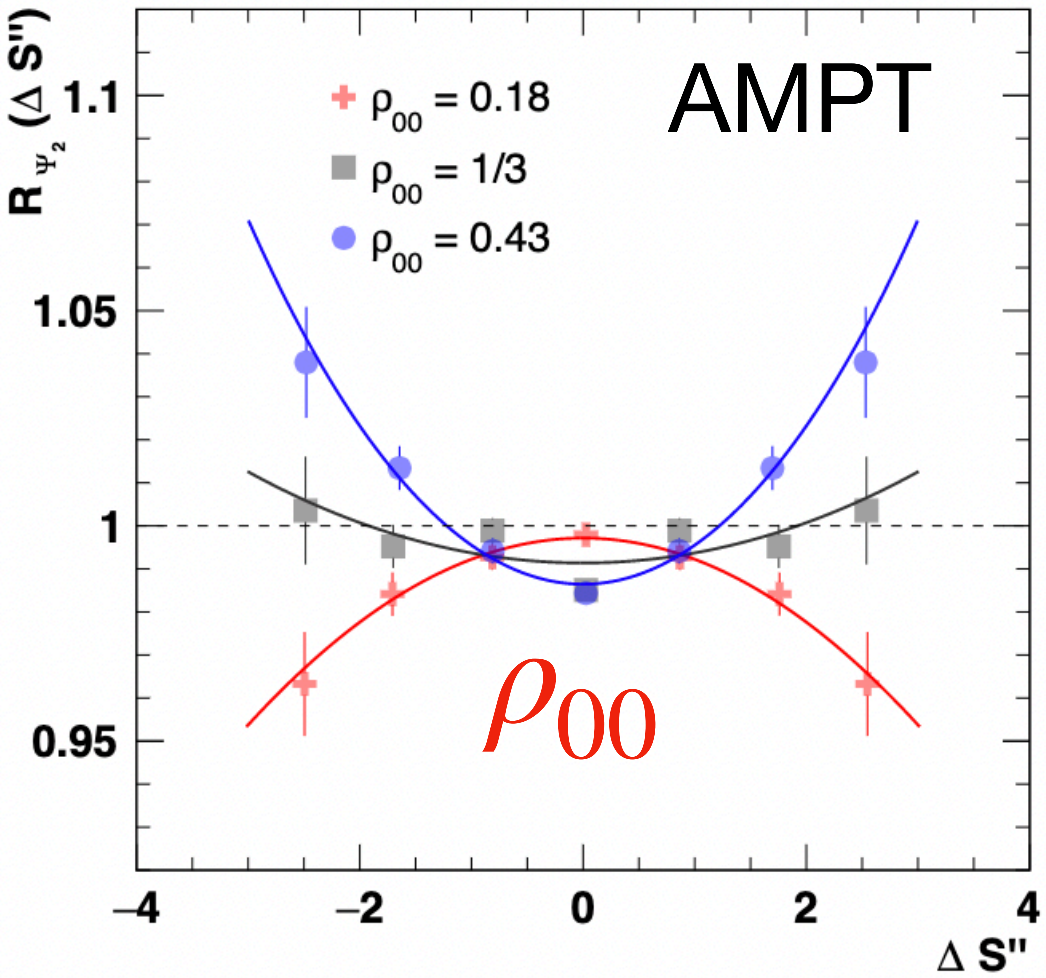


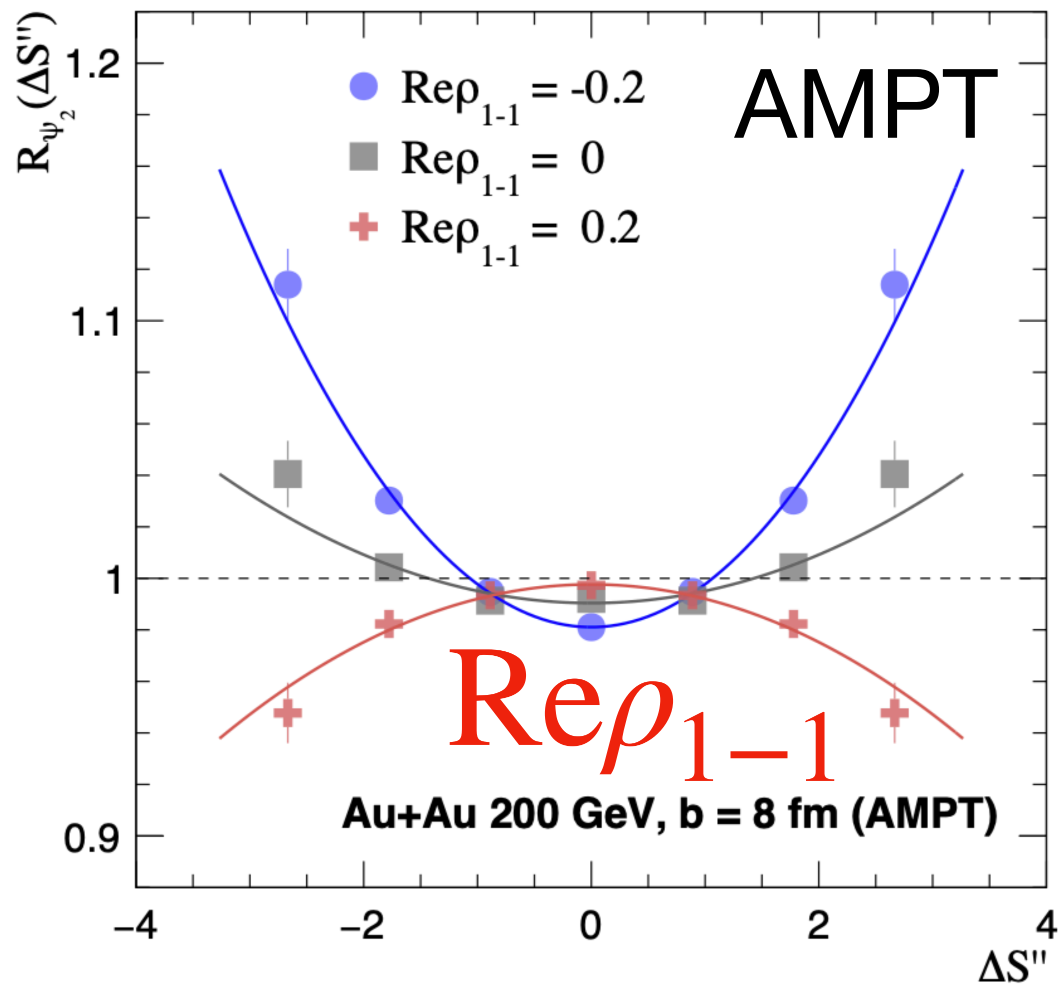




- $R_{\Psi_2}(\Delta S)$ could be concave and convex depending on ρ_{00} and $\mathrm{Re}\rho_{1-1}$.
- $\Delta\sigma_R^2$ is sensitive to ρ_{00} and $\mathrm{Re}\rho_{1-1}$.

Global spin alignment to the R correlator





Simulations in AMPT model are consistent with toy model qualitatively.

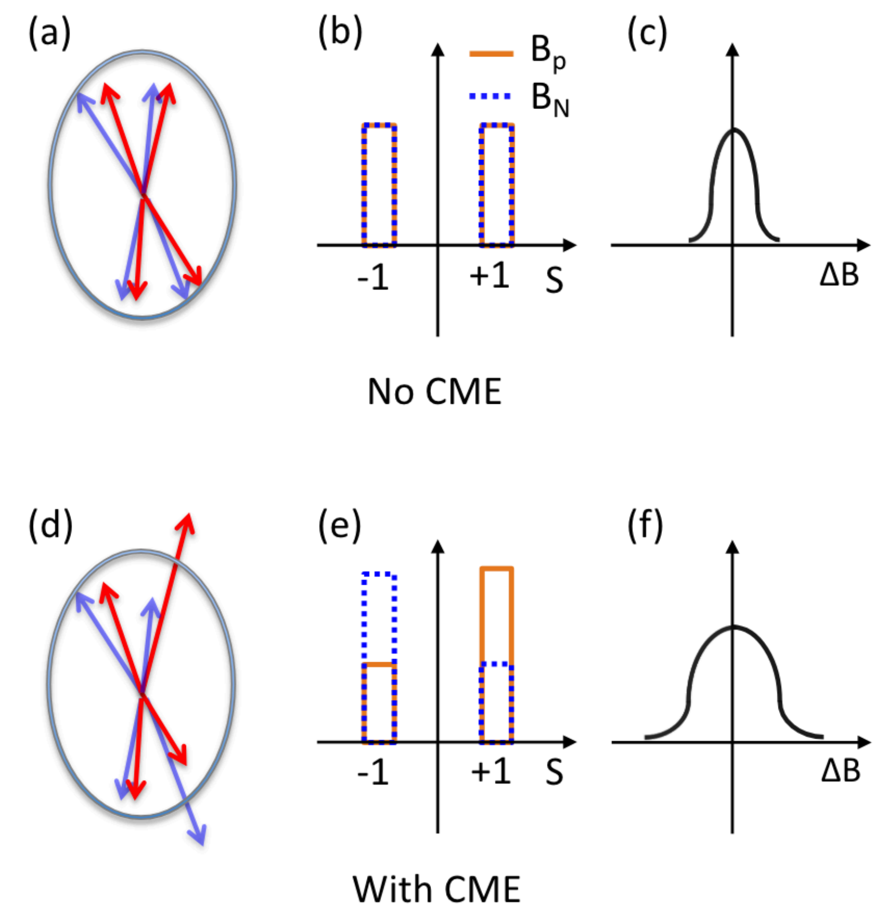
Global spin alignment to the signed balance function

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

Signed balance function

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

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



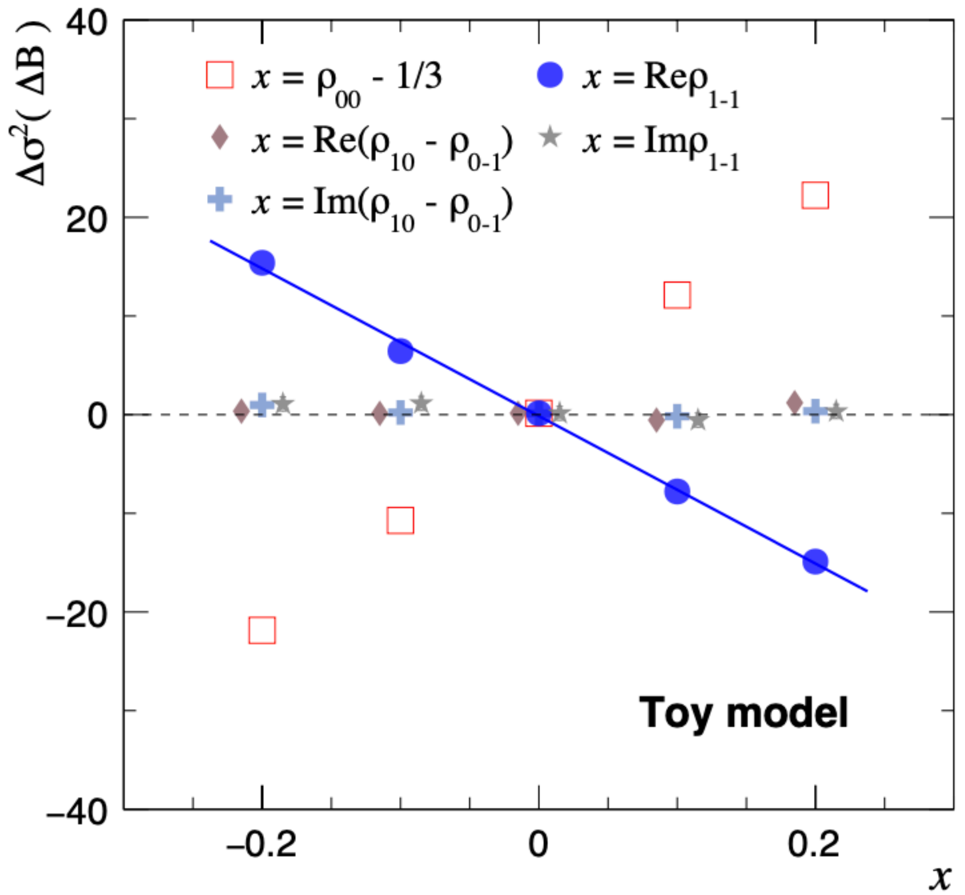
Assuming all particles have same pT, we will have

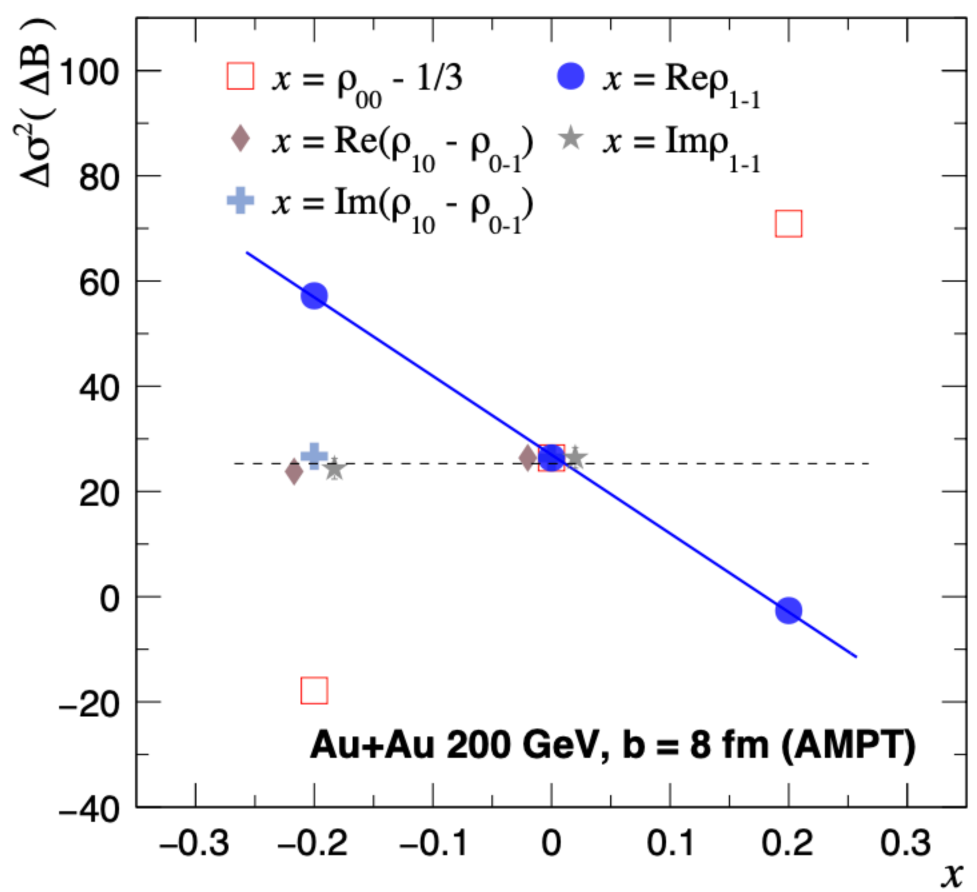
$$\sigma^2(\Delta B_y) \approx \frac{64M^2}{\pi^4}\left(\frac{4}{9M} + 1 + \frac{4}{3}v_2\right)\sigma^2(\Delta S_{\rm real}),$$
$$\sigma^2(\Delta B_x) \approx \frac{64M^2}{\pi^4}\left(\frac{4}{9M} + 1 - \frac{4}{3}v_2\right)\sigma^2(\Delta S_{\rm real}^{\perp}).$$

$$\Delta\sigma^2(\Delta B) = \sigma^2(\Delta B_y) - \sigma^2(\Delta B_y) \sim c_1 + c_2\left[\frac{3}{2}(\rho_{00} - \frac{1}{3}) - \mathrm{Re}\,\rho_{1-1}\right]$$

Z. Wang et al, arXiv:2409.04675 (2024)

Global spin alignment to the signed balance function

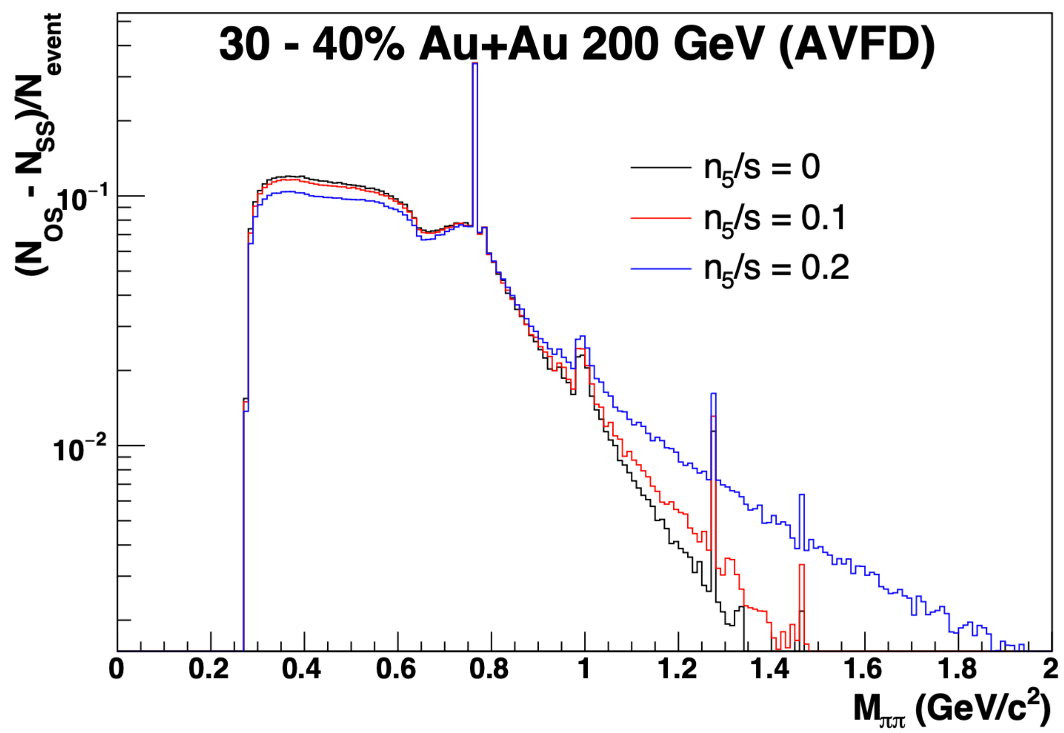


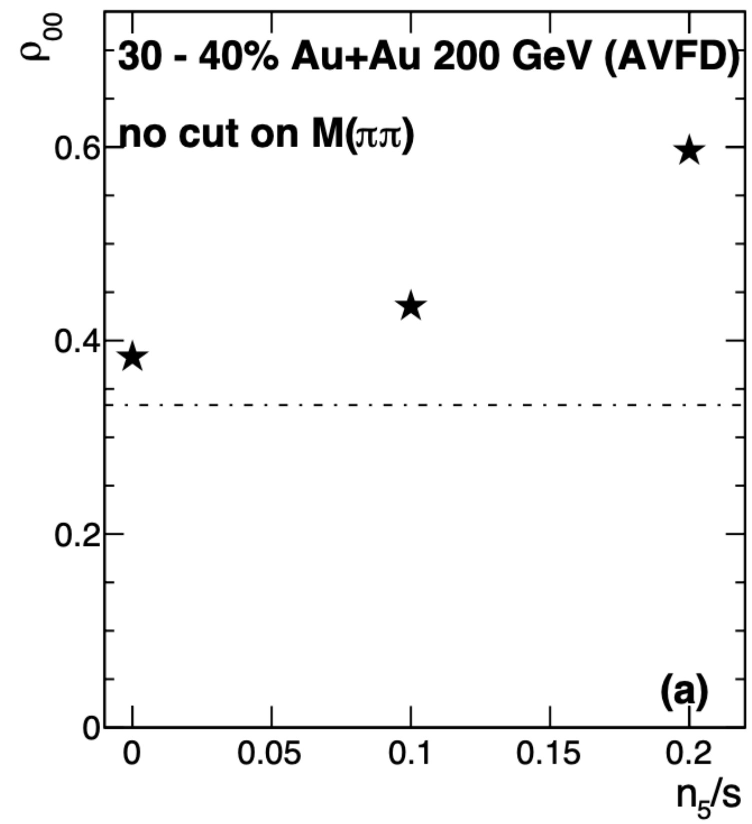


$$c_1 + c_2 \left[\frac{3}{2}(\rho_{00} - \frac{1}{3}) - \mathrm{Re}\,\rho_{1-1} \right]$$

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

The global spin alignment from CME

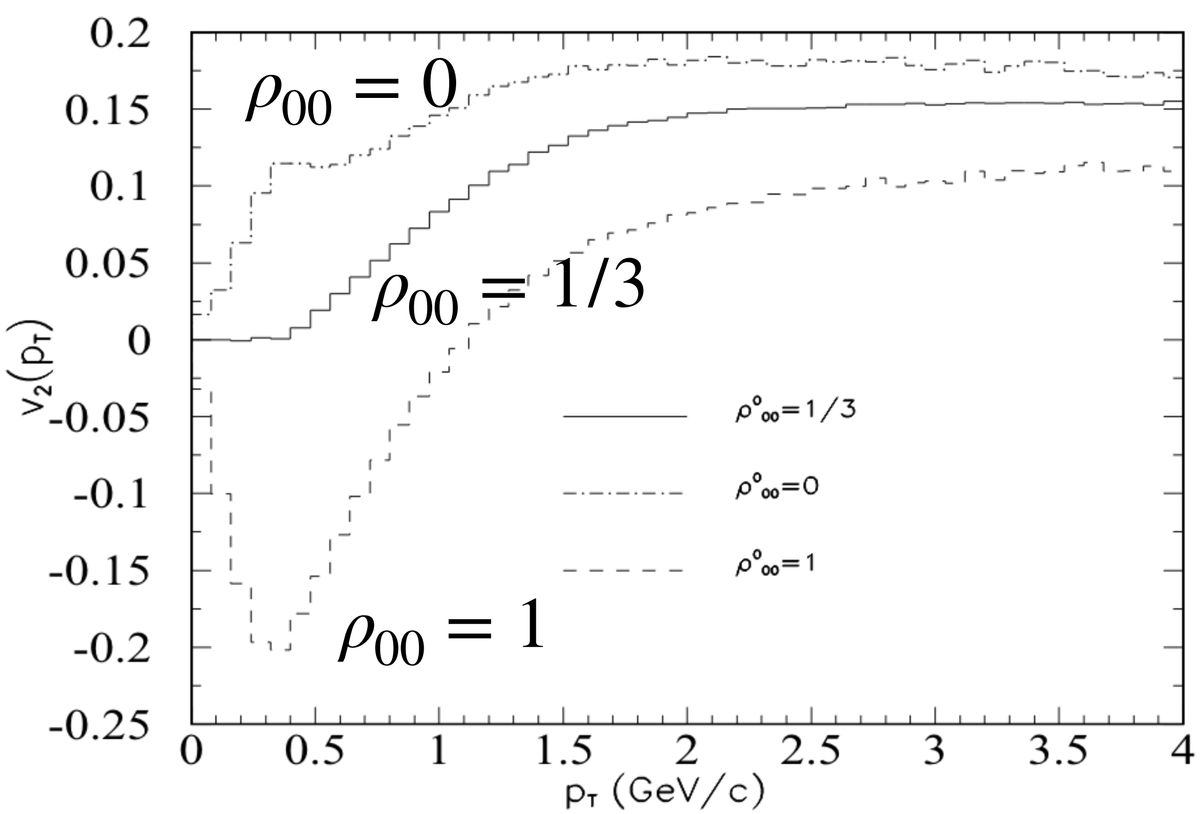




- The CME needs quark to be polarized by magnetic filed, the quark polarization means spin alignment of vector mesons.
- A fraction of ρ meson is from $\pi\pi$ regeneration, the CME will make the distribution of relative angular momentum of the $\pi\pi$ pair to be anisotropic. Due to the angular momentum conservation, the regenerated ρ has anisotropic spin distribution.

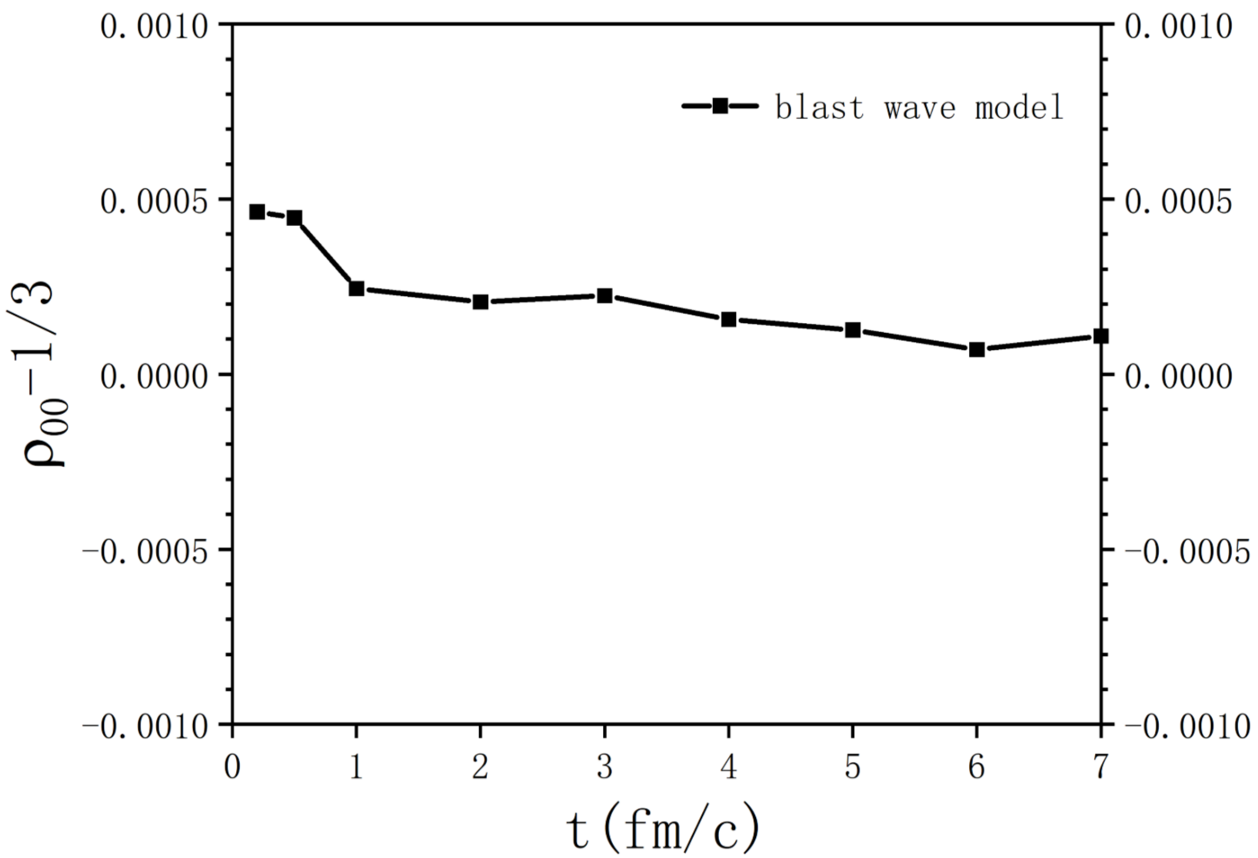
The global spin alignment from CME

Z.T. Liang and X.N. Wang, Phys. Lett. B



Influence of spin alignment on v2

Yi-Liang Yin et al., Phys. Rev. C 110 024905 (2024)



Influence v2 on spin alignment

Summary

- The $\Delta\gamma_{112}$, $R_{\Psi_2}(\Delta S)$ and signed balance function r_{lab} are both influenced by the spin effect of vector mesons.
- It can be a dilution effect to the CME observables, depending on the $\rho_{00} - \frac{1}{3}$ and $\text{Re}\rho_{1-1}$.
- Motivating us to measure the $\text{Re}\rho_{1-1}$ in experiment (hopefully to be shown at QM 2025).

Future work:

- Influence on the CME background control methods in experiment (spectator plane/ participant plane, event shape engineering)?