

University of Chinese Academy of Sciences

Probing Chiral-Imbalance Fluctuations with Hyperon Spin Correlations

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In collaboration with Zilin Yuan, Mei Huang and Guannan Xie

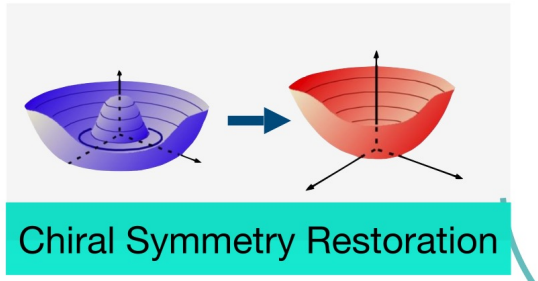
Based on arXiv: 2611.04970

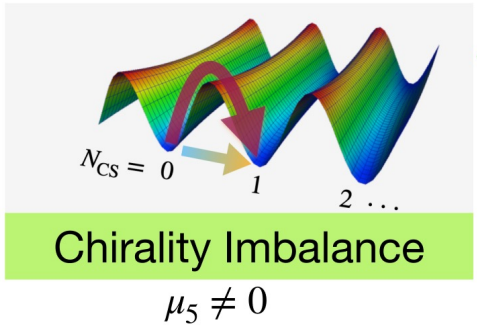
The 10th International Conference on Chirality, Vorticity and Magnetic Fields in Quantum Matter,
November 16 - 20, 2026, Zhuhai, China

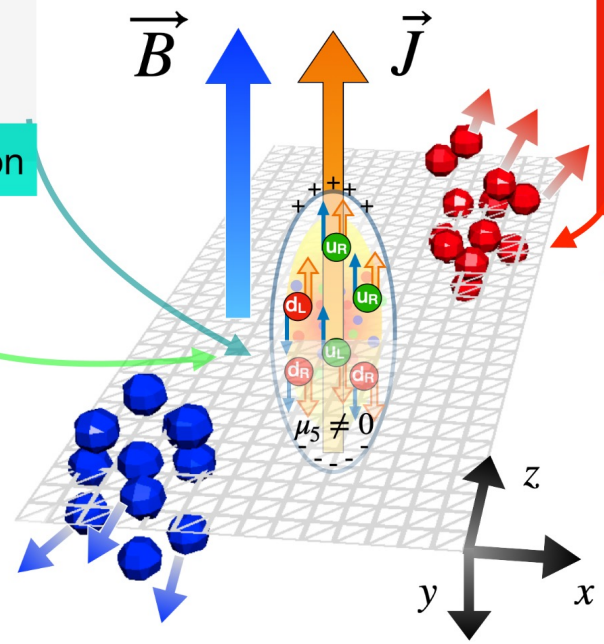
Outline

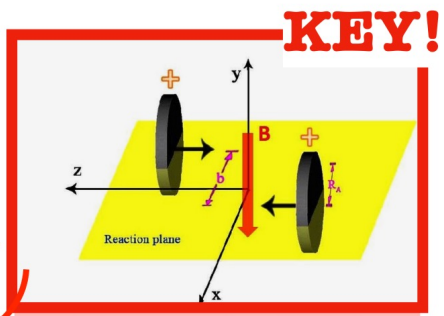
- Introduction to chiral imbalance and hyperon spin correlations
- Numerical framework: AMPT with chiral anomaly transport
- Sensitivity of hyperon spin correlations to chiral imbalance strength and spatial coherence
- Summary

Chiral Magnetic Effect and limitations









D. Kharzeev, J. Liao, P. Tribedy
Int. Joul of Mod Phys E, Vol. 33, No. 09, 2430007 (2024)

$$\vec{J} = \frac{e^2}{2\pi^2}\mu_5 \vec{B}$$

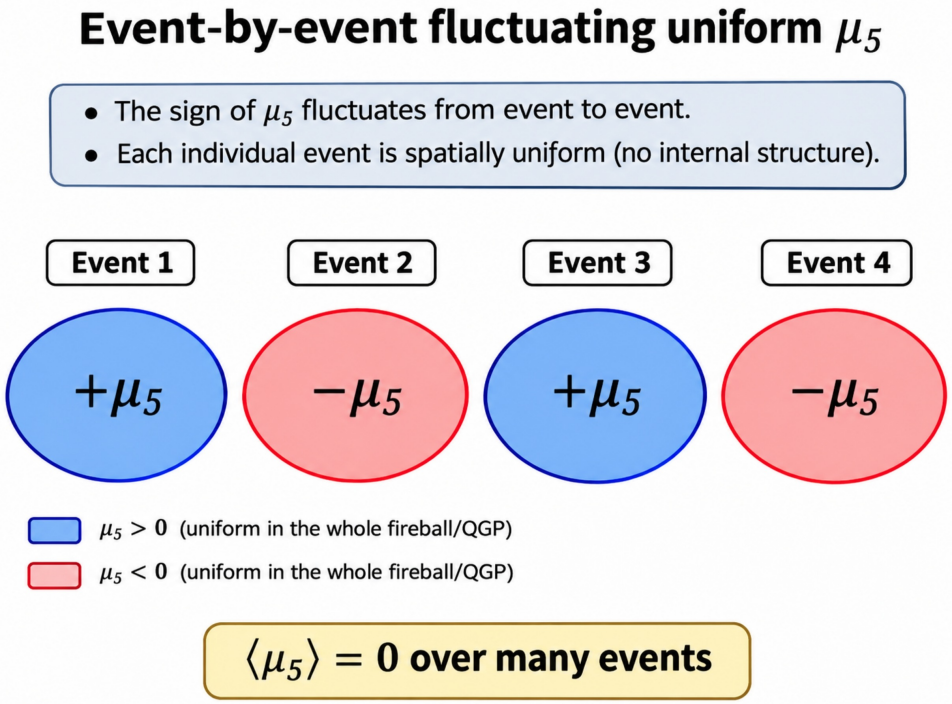
$$\gamma^{112} = \langle \cos(\varphi_1 + \varphi_2 - 2\Psi_{RP}) \rangle$$

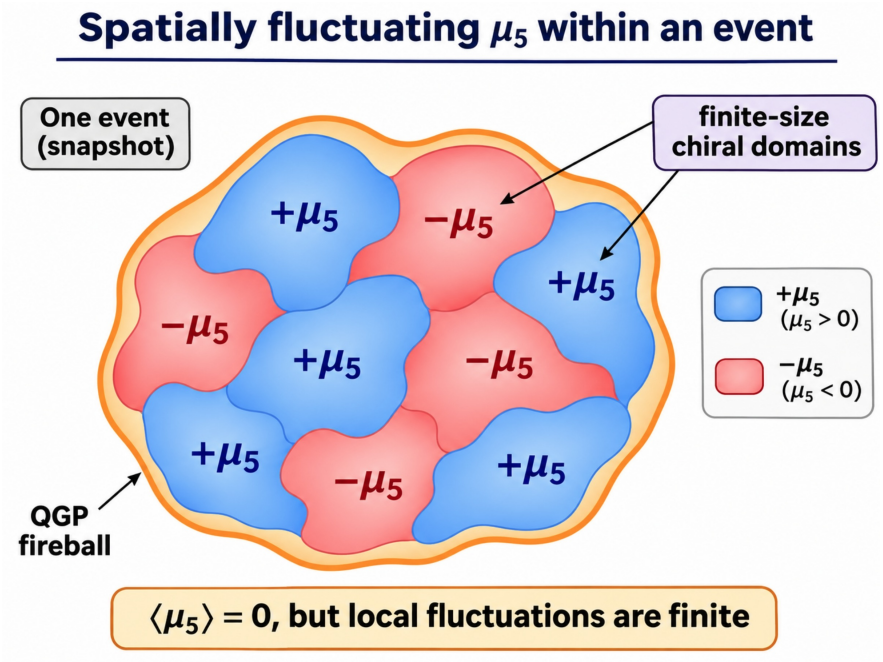
$$\Delta\gamma^{112} = \gamma^{112}_{OS} - \gamma^{112}_{SS}$$

- Local chiral-imbalance fluctuations, together with a strong magnetic field, can induce charge separation via the Chiral Magnetic Effect.
- Limitations of conventional CME observables: Background contamination, Magnetic-field dependence.

Spatial Structure of Chiral imbalance

How are chiral-imbalance fluctuations correlated in space ?





Event-by-event uniform μ_5
- Sign fluctuates between events.
- Spatially uniform within each event.

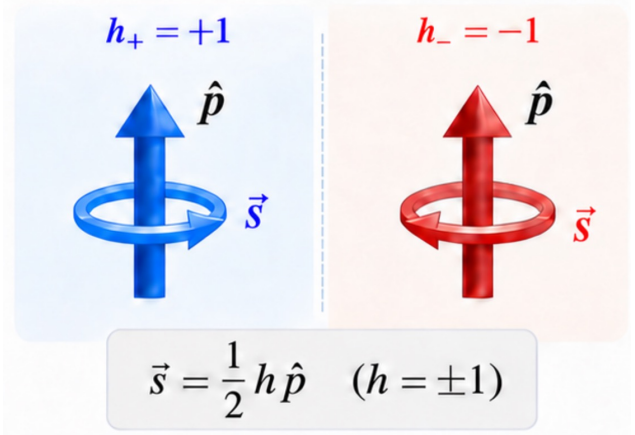
Spatially fluctuating μ_5
- Different signs coexist.
- Finite-size domains within one event.

Conventional CME-sensitive observables do not directly resolve the spatial correlation structure of axial-charge fluctuations.

Local Helicity Response

1. Spin–momentum locking

In the massless-quark limit, chirality coincides with helicity and helicity determines the orientation of spin relative to momentum.



2. Local helicity asymmetry

A local chiral imbalance biases the populations of positive- and negative-helicity quarks.

$$H_a(\boldsymbol{x}, \boldsymbol{p}) = \frac{f_{a,+}(\boldsymbol{x}, \boldsymbol{p}) - f_{a,-}(\boldsymbol{x}, \boldsymbol{p})}{f_{a,+}(\boldsymbol{x}, \boldsymbol{p}) + f_{a,-}(\boldsymbol{x}, \boldsymbol{p})}$$

For a given phase-space cell, this corresponds to the local helicity polarization:

$$P_{h,a}(\vec{x}, \vec{p}) \equiv \langle h_a \rangle_{\vec{x},\vec{p}} = H_a(\vec{x}, \vec{p})$$

3. Local response versus event average

A local chiral imbalance induces a local helicity polarization:

$$\mu_5(\vec{x}) \neq 0 \quad \Longrightarrow \quad H_a(\vec{x}, \vec{p}) \neq 0$$

For sign-symmetric chiral-imbalance fluctuations, however, the event-averaged polarization vanishes:

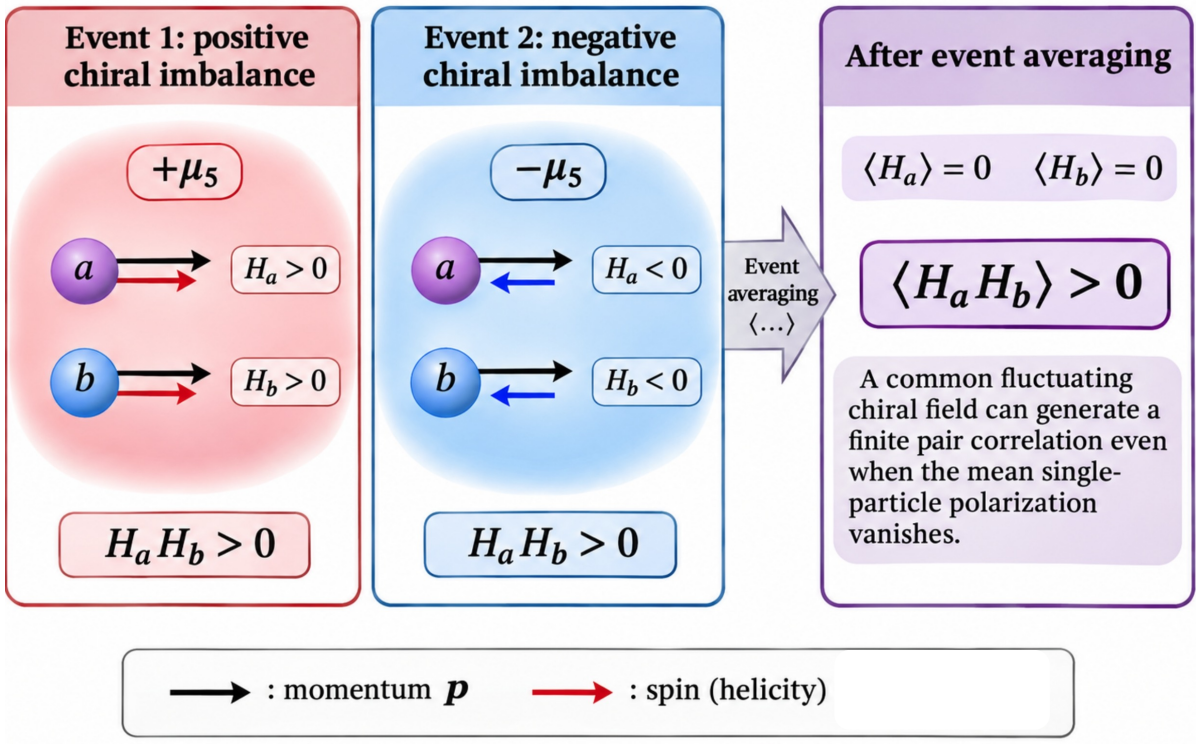
$$\langle P_{h,a} \rangle_{\text{events}} \simeq 0$$

From Chiral imbalance to Spin Correlations

1. From single-particle to two-particle spin correlation

The two-particle spin correlation depends on both the helicity product and the relative momentum direction.

$$\vec{s}_a \cdot \vec{s}_b = \frac{1}{4} h_a h_b \cos\theta_{ab}$$



2. Fluctuating chiral field generates pair correlations

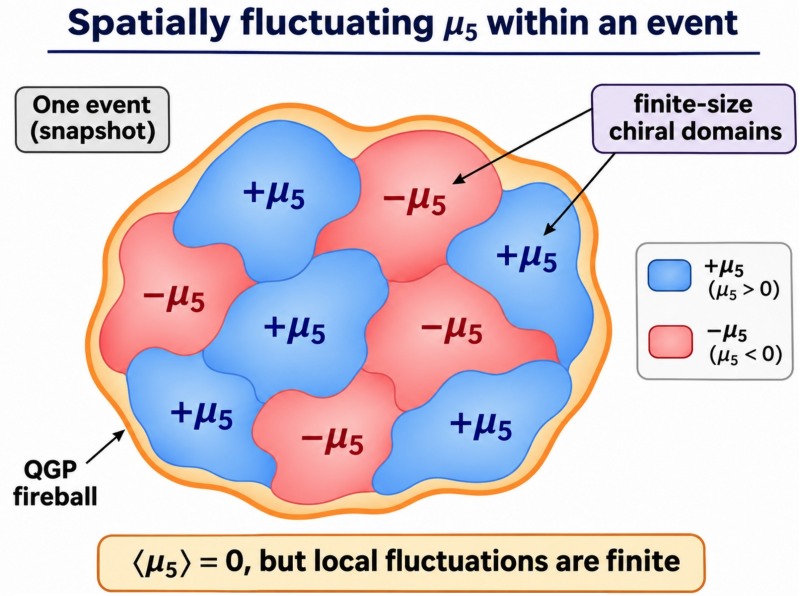
Although the event-averaged helicity polarization vanishes, the two-particle helicity correlation can remain finite.

3. The resulting pair spin correlation

$$P_{ab} = \frac{4}{3} \langle \boldsymbol{s}_a \cdot \boldsymbol{s}_b \rangle = \frac{1}{3} \sum_{i=x,y,z} C_{ii}^{ab}$$

$$P_{ab}^{(\chi)}(\theta_{ab}) \simeq \frac{1}{3} \langle h_a h_b \cos\theta_{ab} \rangle_{\theta_{ab}} \simeq \frac{1}{3} \langle H_a H_b \rangle_{\theta_{ab}} \cos\theta_{ab},$$

How Spatial Coherence Modifies Spin Correlations



$$P_{ab}^{(\chi)}(\theta_{ab}) \simeq \frac{1}{3}\langle H_a H_b \rangle_{\theta_{ab}} \cos\theta_{ab}$$

Quark pair in the same domain:

$$H_a H_b = s_i^2 |H_a H_b| > 0$$

Quark pair in the different domain:

$$H_a H_b = s_i s_j |H_a H_b| \begin{cases} > 0 & \text{same sign} \\ < 0 & \text{opposite sign} \end{cases}$$

Define an average over all quark pairs in a small θ range within a single event:

Uniform μ_5 in one event:

$$\overline{H_a H_b}^{\text{uniform}}(\theta) = \frac{\sum_{\text{all pairs}} h_a h_b}{N_{\text{pair}}(\theta)} > 0.$$

Spatially fluctuating μ_5 in one event:

$$\overline{H_a H_b}^{\text{fluctuating}}(\theta) = \frac{1}{N_{\text{pair}}(\theta)}\left(N_{\text{same}} H_a H_b{}^{\text{same}} + N_{\text{diff}} H_a H_b{}^{\text{diff}}\right) < \overline{H_a H_b}^{\text{uniform}}(\theta)$$

Transport and collective expansion induce a statistical correlation between emission positions and final-state momenta.

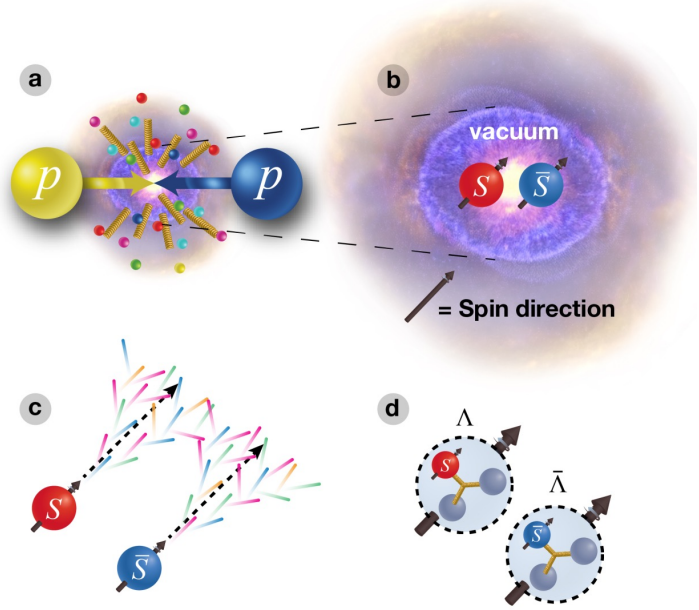
$$f(\theta) = \frac{\overline{H_a H_b}^{\text{fluctuating}}(\theta)}{\overline{H_a H_b}^{\text{uniform}}(\theta)} \approx \frac{N_{\text{same}}(\theta)}{N_{\text{all pair}}(\theta)}$$

Hyperon Spin Correlations in Experiment

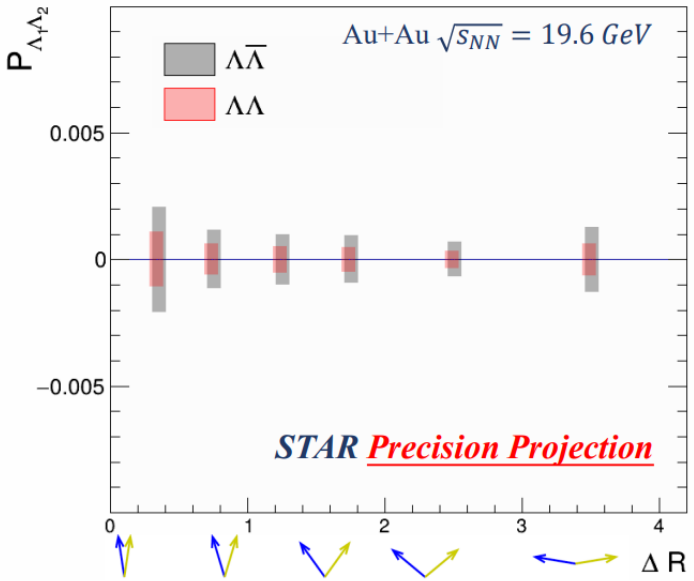
- Positive spin correlation between Λ anti-Λ observed by previous STAR measurement.

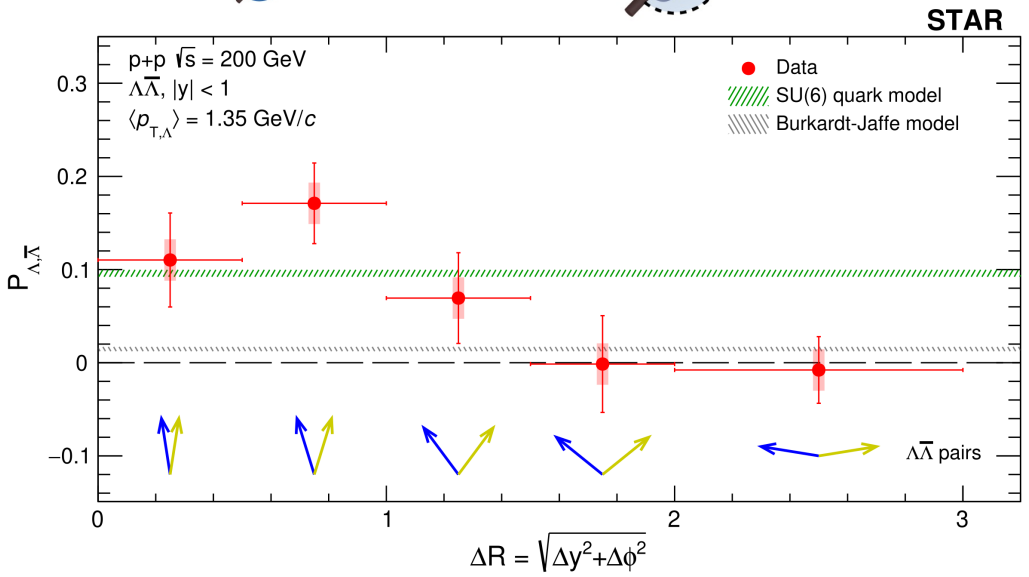
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^{\star}} = \frac{1}{2}[1+\alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos\theta^{\star}],$$

- Such measurement in AA collisions may provide a complementary experimentally testable strategy for constraining the spatial structure of chiral-imbalance fluctuations.



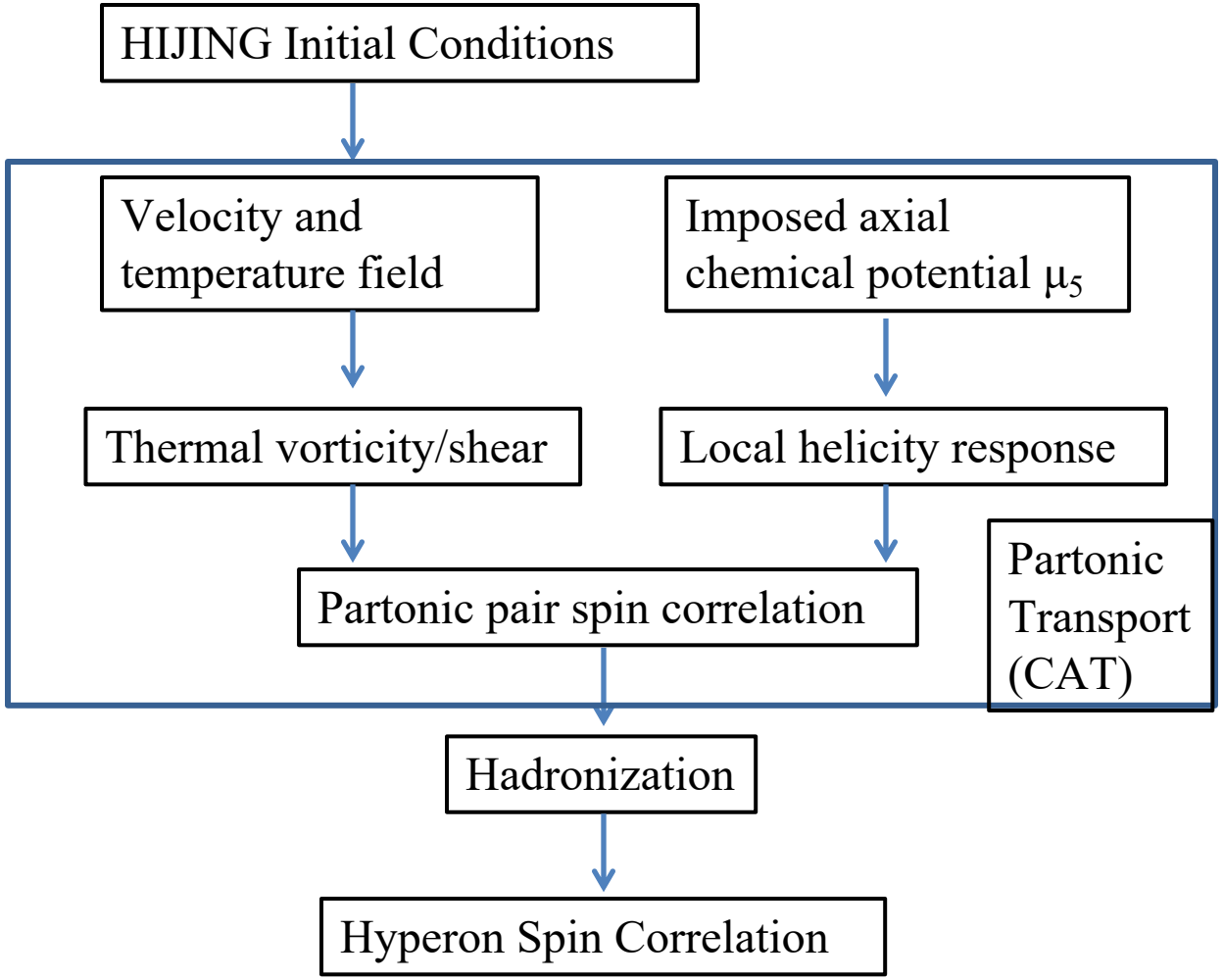
Tong Fu
SQM 2026





STAR Collaboration, Nature 650, 65–71 (2026).

Numerical Framework



Two contributions to partonic spin correlations

1. Chiral imbalance Contribution
Imposed μ_5 provides local helicity response

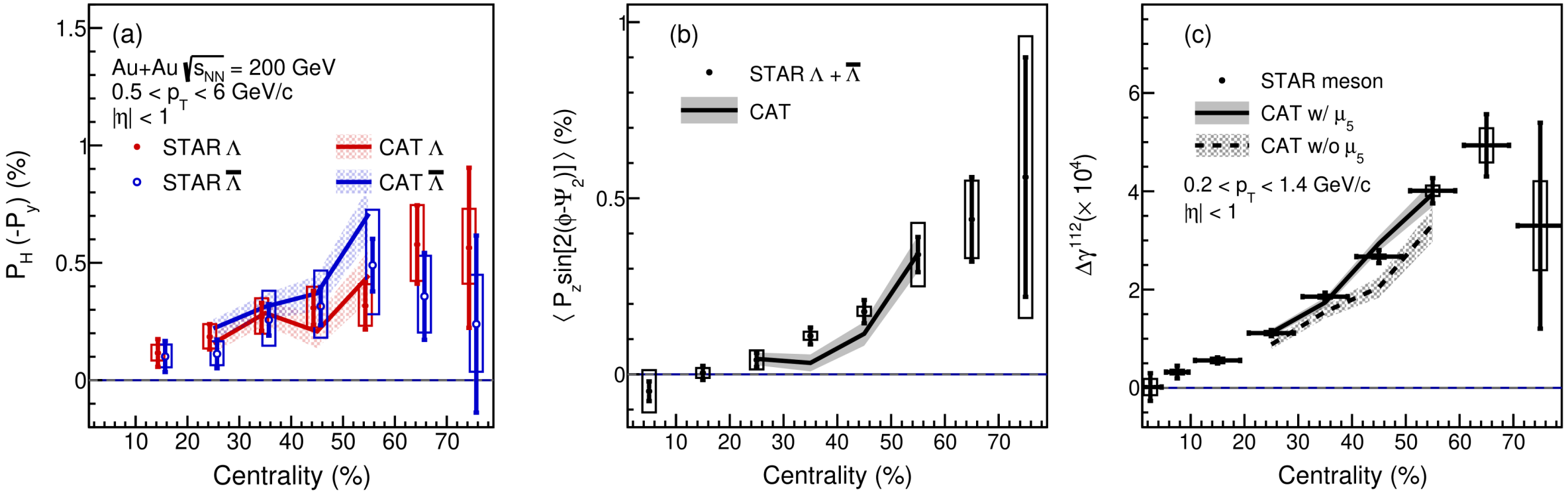
2. Conventional spin baseline
HIJING/AMPT provides the local velocity and temperature fields.
Thermal-vorticity and shear contributions are calculated independently.

Spin from partons to hyperons

Partonic transport and quark coalescence with SU(6) constituent-quark spin transfer.

Yuan, Zilin and Huang, Anping and Zhou, Wen-Hao and Ma, Guo-Liang and Huang, Mei, Phys.Rev.C 109 (2024) 3, L031903

Experimental Benchmarks



- The global and longitudinal polarization observables constrain the conventional spin response, including contributions from thermal vorticity and shear.
- CME-sensitive $\Delta\gamma^{112}$ observable, including finite μ_5 improves the description of the measured correlation in the present calculation.

Common-mode Spin Correlation

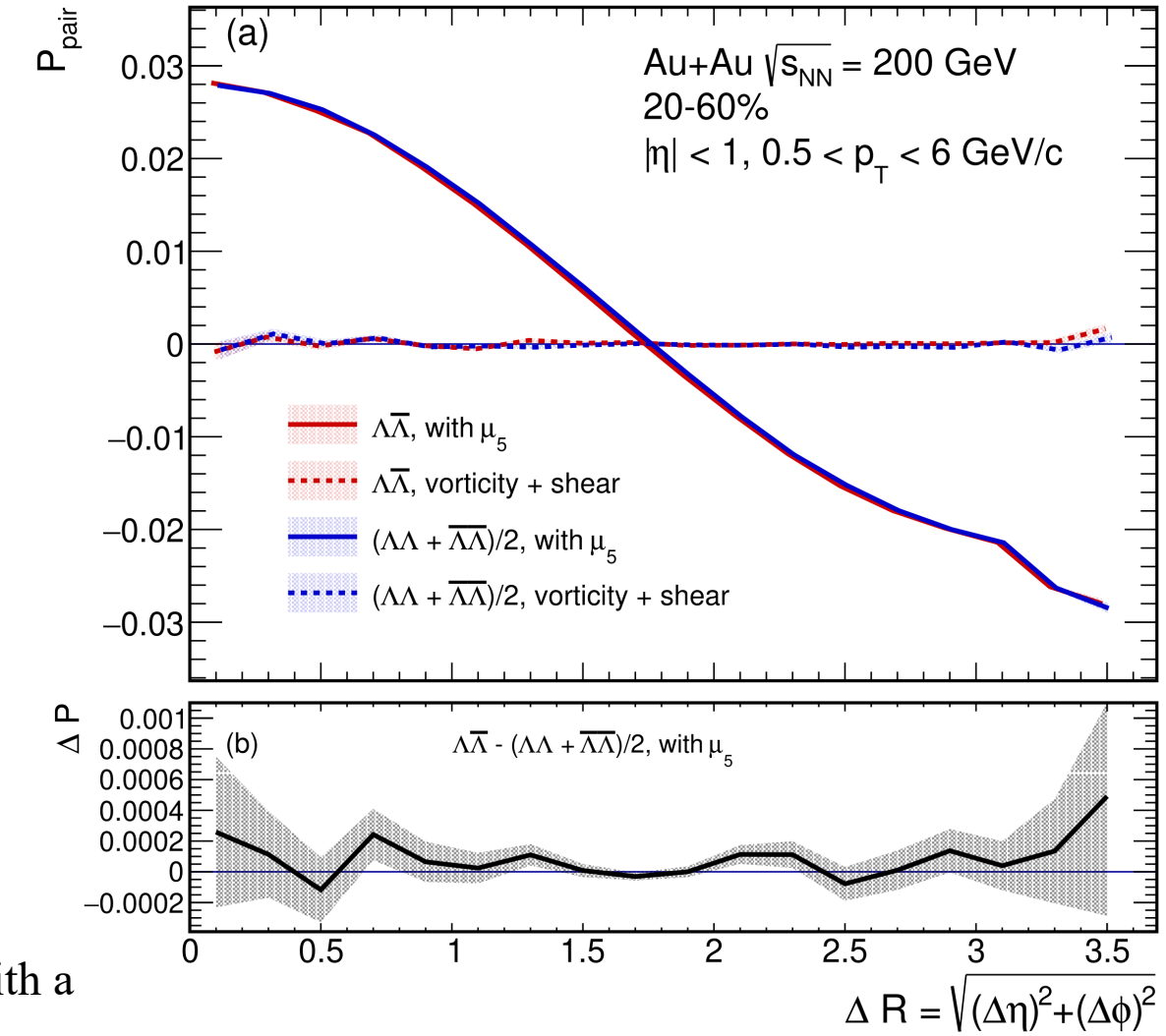
- Spin correlations generated by thermal vorticity and shear are substantially smaller than the finite μ_5 results over most of the investigated range.
- Strong sensitivity of the pair spin Correlation to chiral imbalance.
- Similar μ_5 induced spin correlations for like-sign and unlike-sign pairs.

$$\Delta P(\Delta R) = P_{\Lambda\bar{\Lambda}}(\Delta R) - \frac{P_{\Lambda\Lambda}(\Delta R) + P_{\bar{\Lambda}\bar{\Lambda}}(\Delta R)}{2}$$

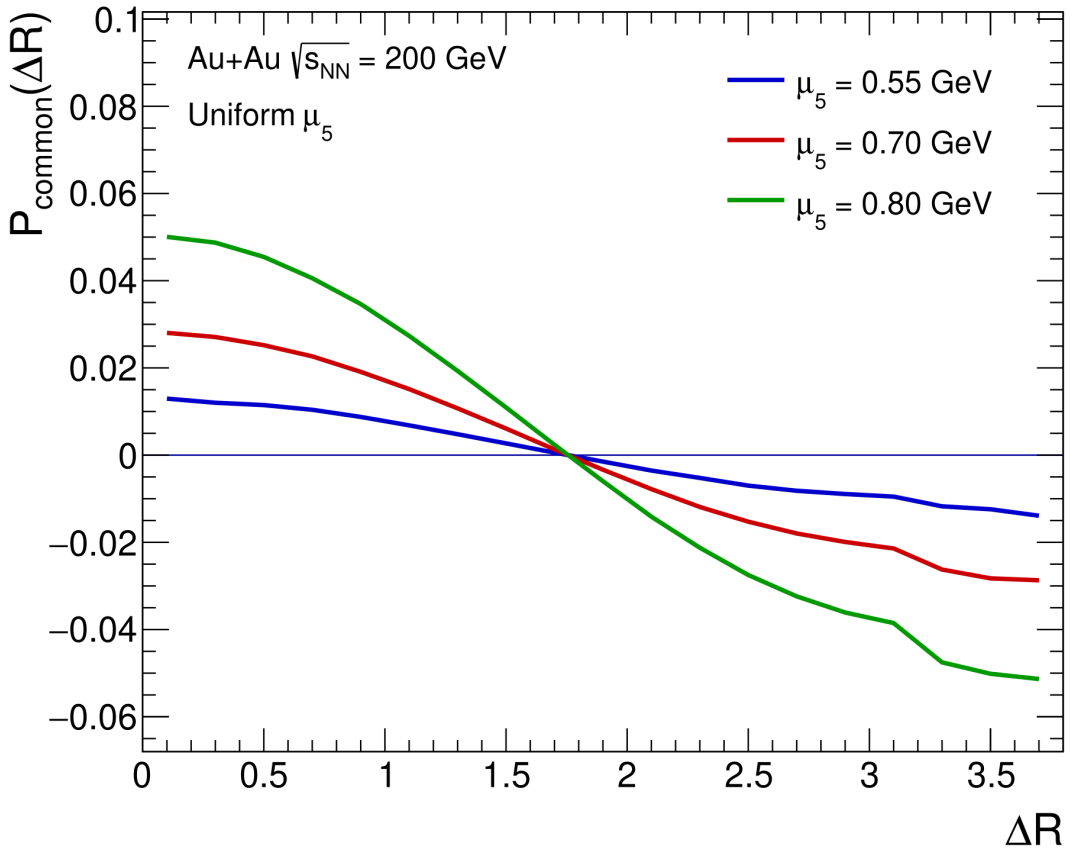
- Define the common-mode spin correlation

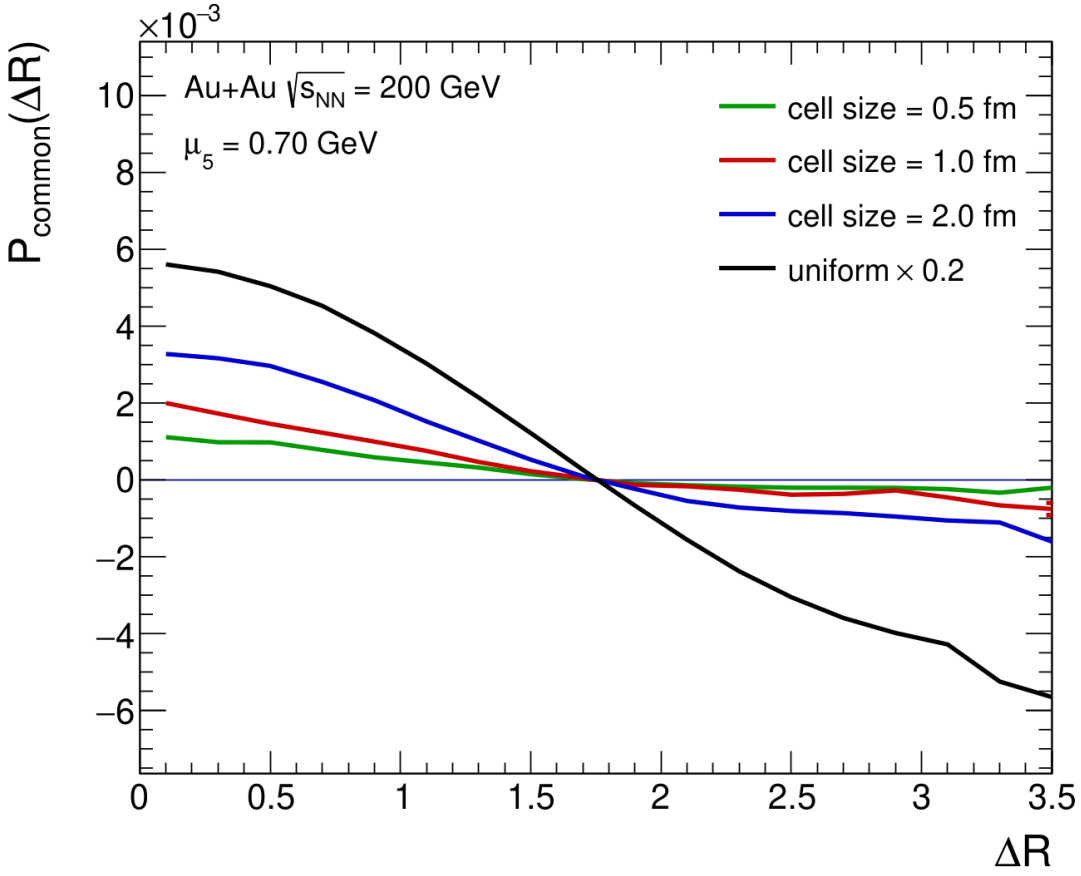
$$P_{\mathrm{common}}(\Delta R) = \frac{1}{4}\left[P_{\Lambda\Lambda}(\Delta R) + 2P_{\Lambda\bar{\Lambda}}(\Delta R) + P_{\bar{\Lambda}\bar{\Lambda}}(\Delta R)\right].$$

Preserves the common response and cancels backgrounds with a specific particle–antiparticle sign structure.



Dependence on μ_5 and Domain Size





- Increasing μ_5 enhances the magnitude of both short- and long-range correlations, while preserving a similar ΔR dependence.
- Increasing domain size enhances the magnitude of both short- and long-range correlations, while also change the ΔR dependence.

Sensitivity to Spatial Coherence.

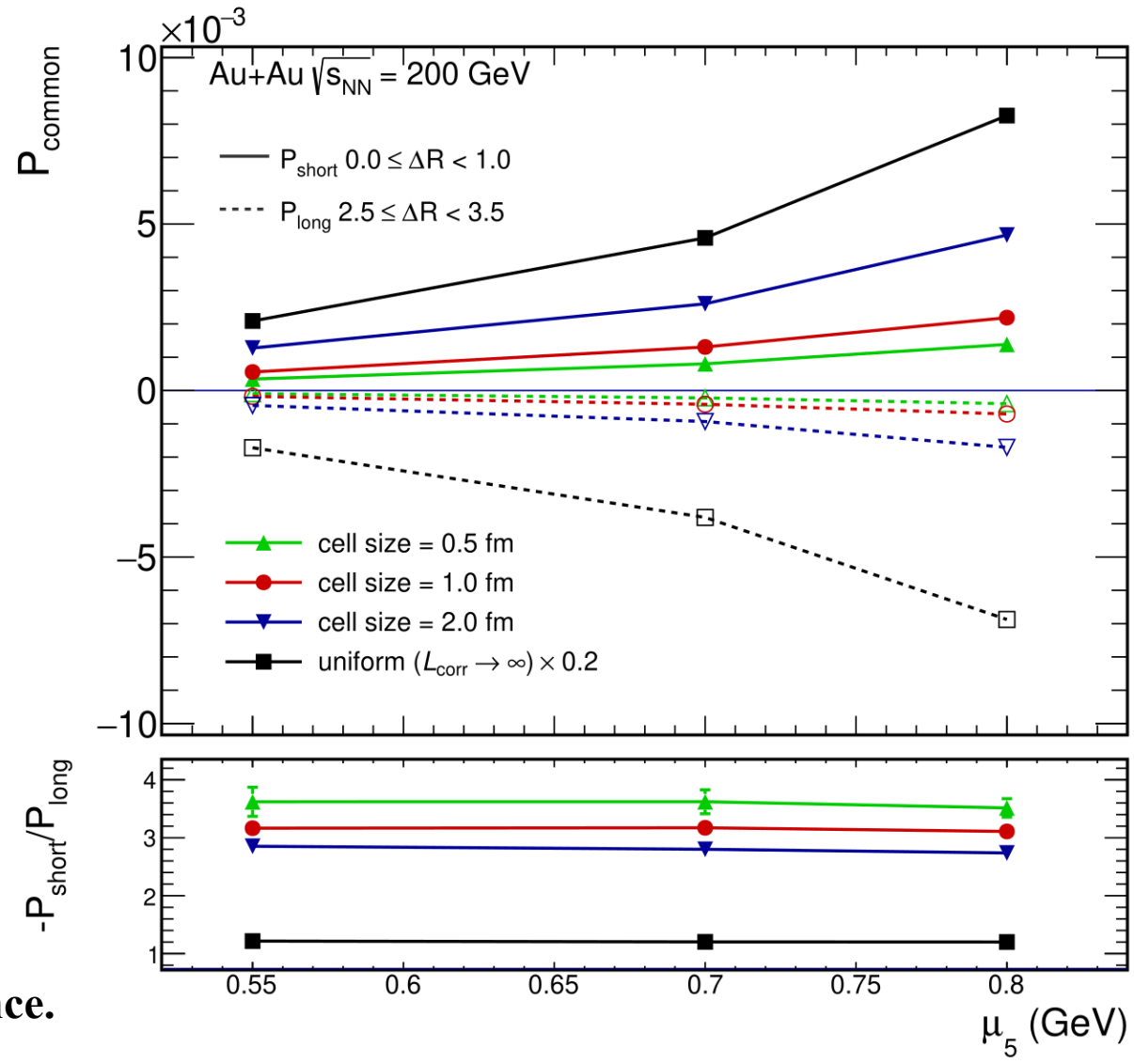
$$P_{\text{short}} = \langle P_{\text{common}} \rangle_{0 \le \Delta R < 1.0} \qquad P_{\text{long}} = \langle P_{\text{common}} \rangle_{2.5 \le \Delta R < 3.5}$$

- Both P_{short} and P_{long} increase in magnitude with increasing μ_5.
- The absolute correlation strength also depends on the spatial domain size.

$$\mathcal{R}_{SL} = -\frac{P_{\text{short}}}{P_{\text{long}}}$$

- The ratio exhibits only a weak dependence on μ_5 over the investigated range.
- A clear ordering with the domain size is observed.

The Short-to-Long Ratio Is Sensitive to Spatial Coherence.



Summary

- Chiral-imbalance fluctuations generate finite pair-spin correlations even when the mean helicity polarization vanishes.
- AMPT+CAT predicts an approximately common response across hyperon-pair channels, larger than the thermal-vorticity + shear baseline.
- Correlation magnitudes probe both fluctuation strength and spatial coherence; the short-to-long ratio is primarily sensitive to coherence within the explored range.

