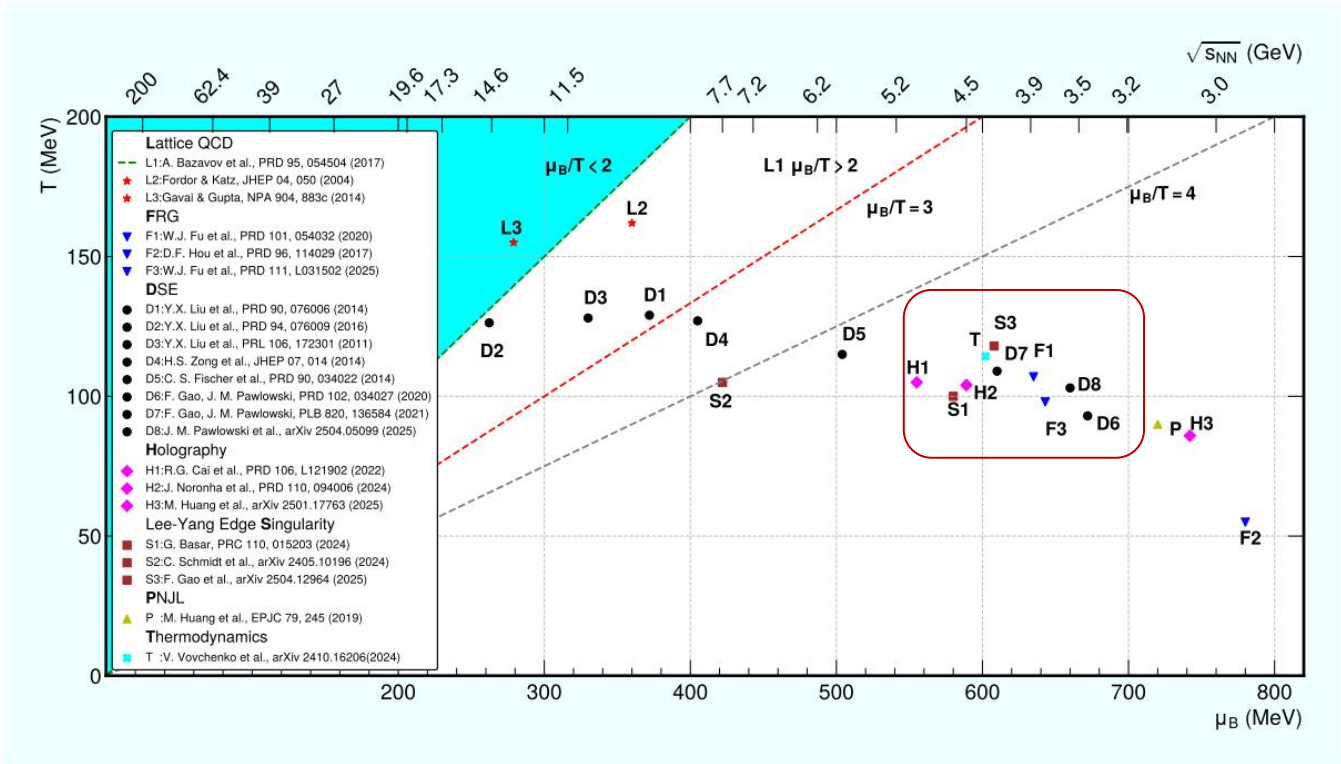
Nonmonotonicity of Transverse Momentum Correlations in Au+Au Collisions at RHIC

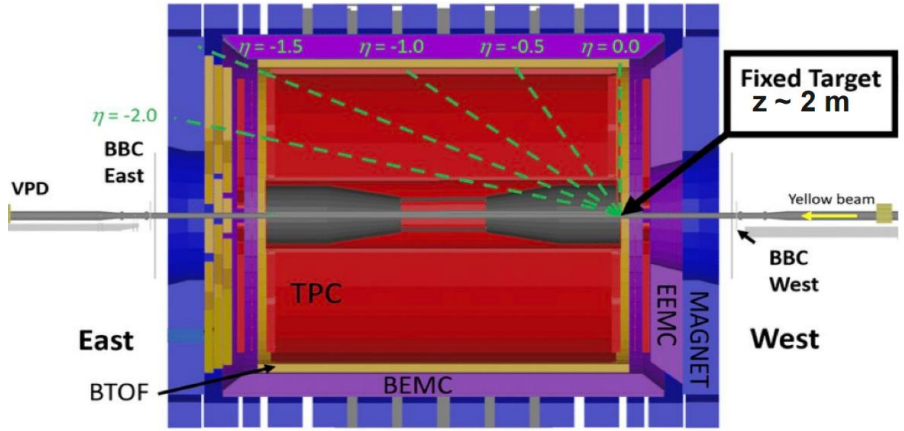
Zheng Liu
Fudan University

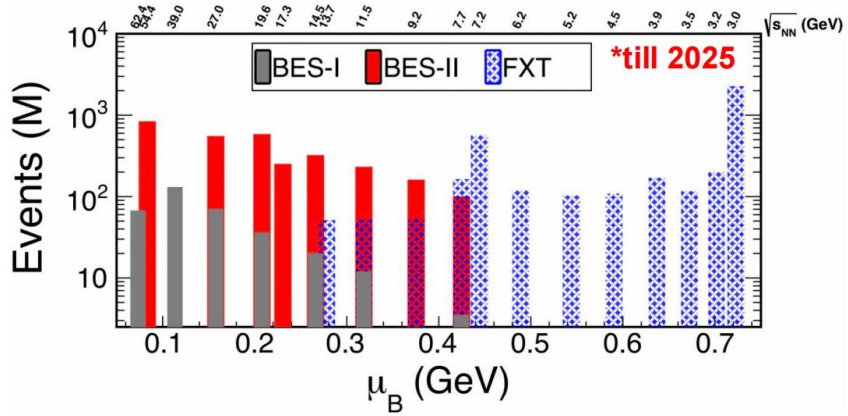
STAR Collaboration *Phys. Rev. Lett.* **137**, 132301 (2026)

Exploring QCD Matter at High Baryon Density

Y. Zhang et al., Eur. Phys. J. Spec. Top. (2026)







- The QCD phase structure at high baryon density remains poorly constrained by both theory and experiment
- STAR BES-II, particularly the FXT program, extends experimental access to this region with upgraded detectors and high-statistics data

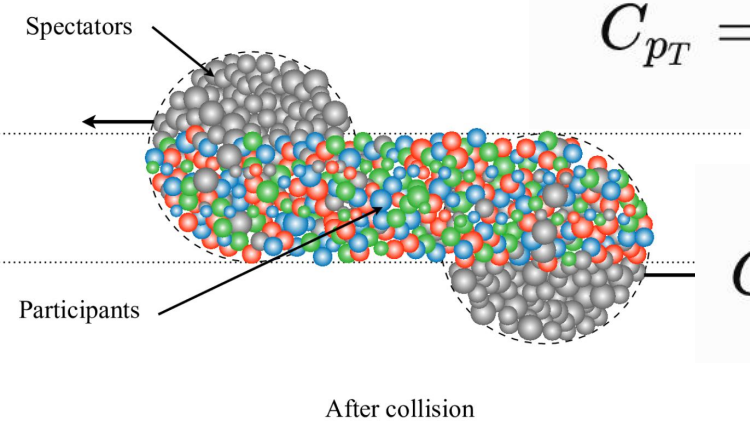
Isolating Dynamical Two-Particle Correlations

$$\langle \Delta p_{T,i} \Delta p_{T,j} \rangle = \left\langle \frac{\sum_{i \neq j}^{N} \left(p_{T,i} - \langle\langle p_T \rangle\rangle\right)\left(p_{T,j} - \langle\langle p_T \rangle\rangle\right)}{N(N-1)} \right\rangle$$

Only distinct-particle pairs (i ≠j) are included, excluding self-pair contributions.

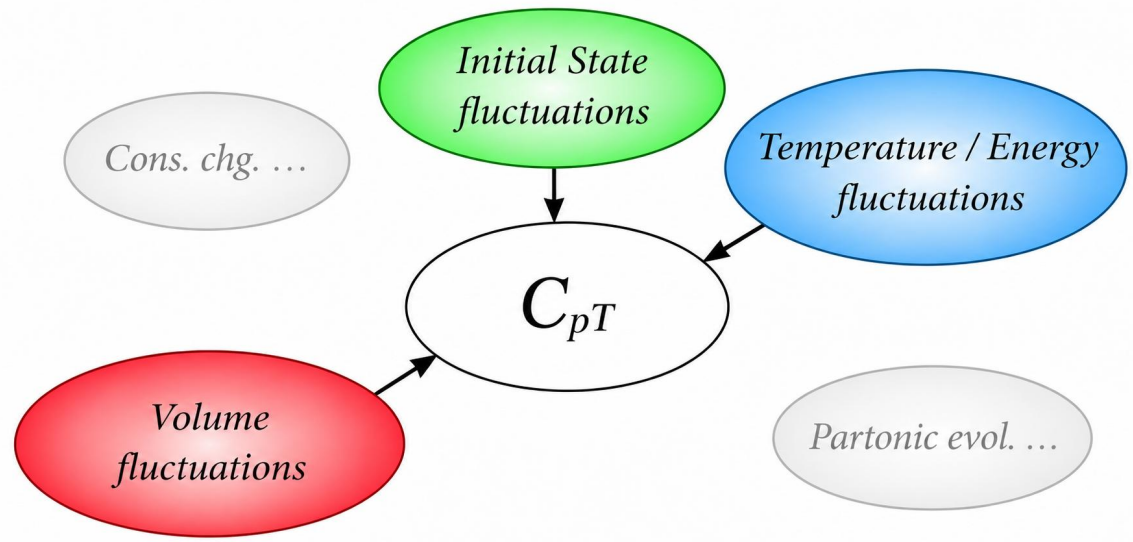
If particle-production sources contribute approximately independently, the relative correlation strength is expected to decrease with increasing system size:

$$C_{p_T} = \frac{\sqrt{\langle \Delta p_{T,i} \Delta p_{T,j} \rangle}}{\langle\langle p_T \rangle\rangle}$$

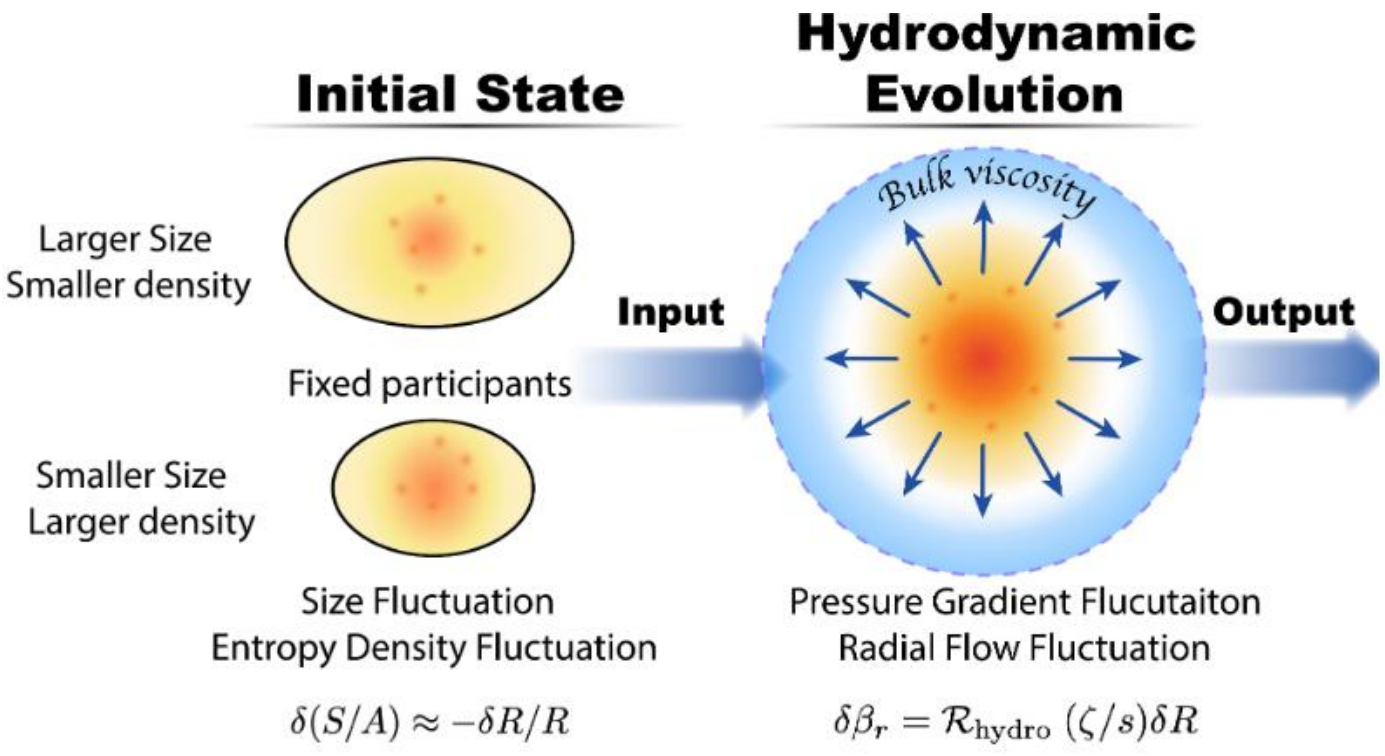


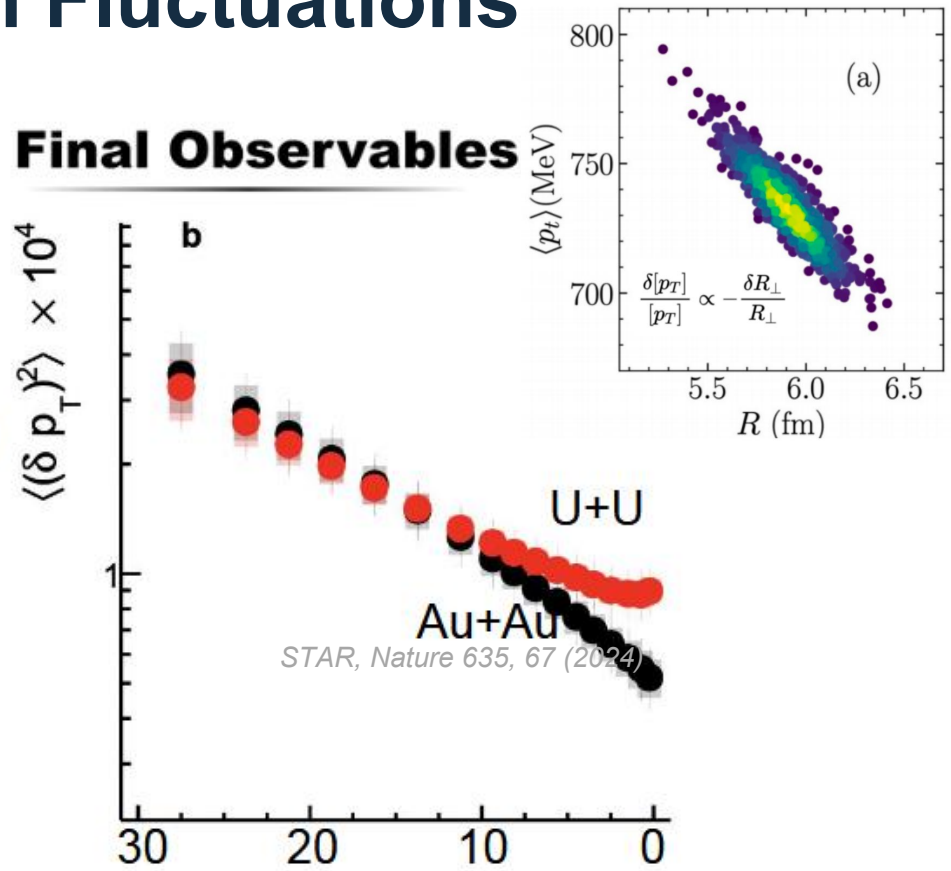
$$C_{p_T} \propto N_{\text{part}}^{-1/2}$$

$\sqrt{s_{NN}}$ (GeV)	No. of Events collected (10^6)	μ_B (MeV)
3.0 (FXT)	260+2000	760
3.2 (FXT)	200	699
3.5 (FXT)	120	670
3.9 (FXT)	120	633
4.5 (FXT)	110	590
5.2 (FXT)	100	540
7.7 (FXT)	260	420
7.7 (COL)	104	420



Nuclear Structure Seeds Momentum Fluctuations

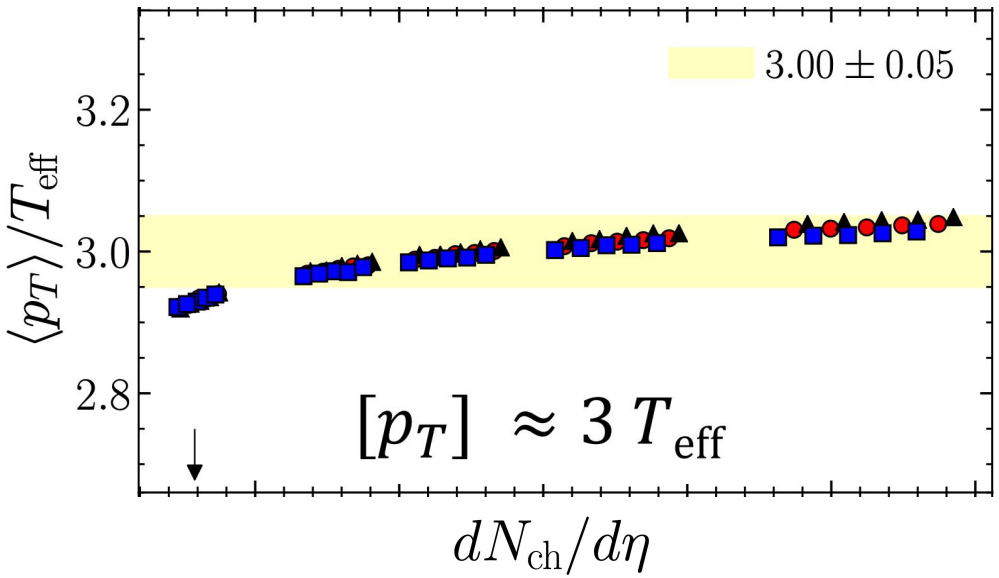




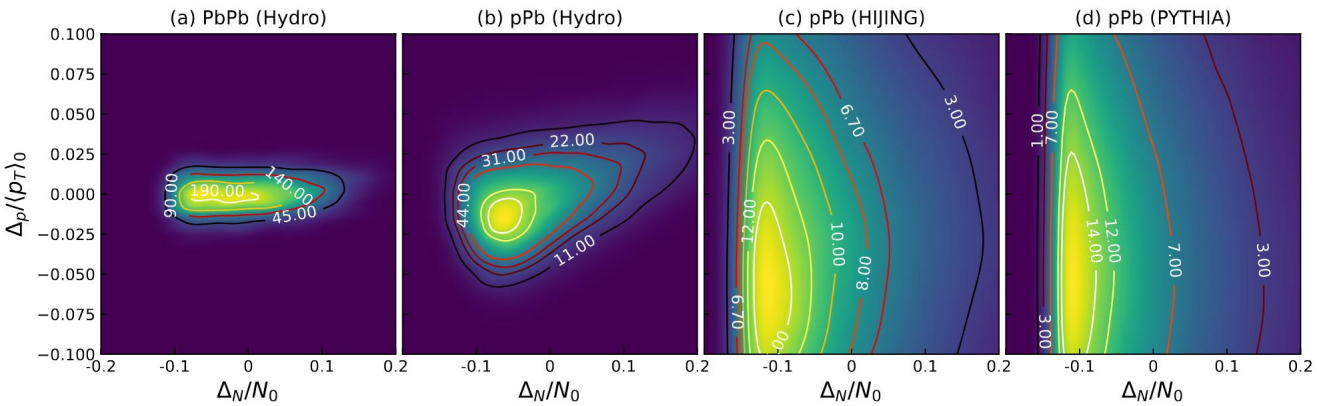
- **Linear response linking final fluctuation to the initial size fluctuation**
- **Mean-pT fluctuations carry information about initial-state geometry and nuclear structure**

Momentum Fluctuations and Medium Response

Gardim et al., Phys. Lett. B 856, 138937 (2024)



Y.-S. Mu et al., Phys. Rev. Lett. 135, 162301 (2025)

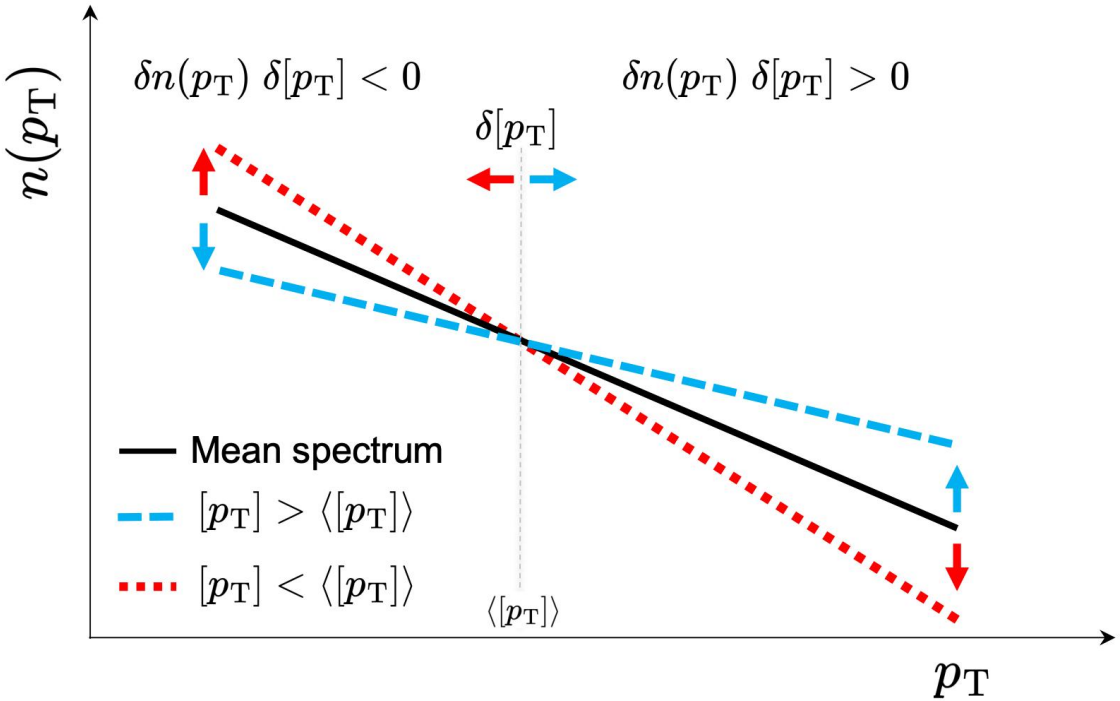


$$\frac{\Delta_p}{\langle p_T \rangle_0} = c_s^2 \frac{\Delta_N + \delta}{N_0} \qquad (c_s^2)^3 \frac{\{\Delta_N^3\}}{N_0^3} - 3(c_s^2)^2 \frac{\{\Delta_N^2 \Delta_p\}}{N_0^2 \langle p_T \rangle_0} + 3c_s^2 \frac{\{\Delta_N \Delta_p^2\}}{N_0 \langle p_T \rangle_0^2} - \frac{\{\Delta_p^3\}}{\langle p_T \rangle_0^3} = 0$$

- In ultra-central Pb–Pb collisions,$< p_T >$ provides an approximate measure of the effective temperature
- Event-by-event fluctuations in mean pT, combined with multiplicity fluctuations, can provide information about the thermodynamic response of the QCD medium
- May help constrain the QCD equation of state at high baryon density

Radial Flow Fluctuations

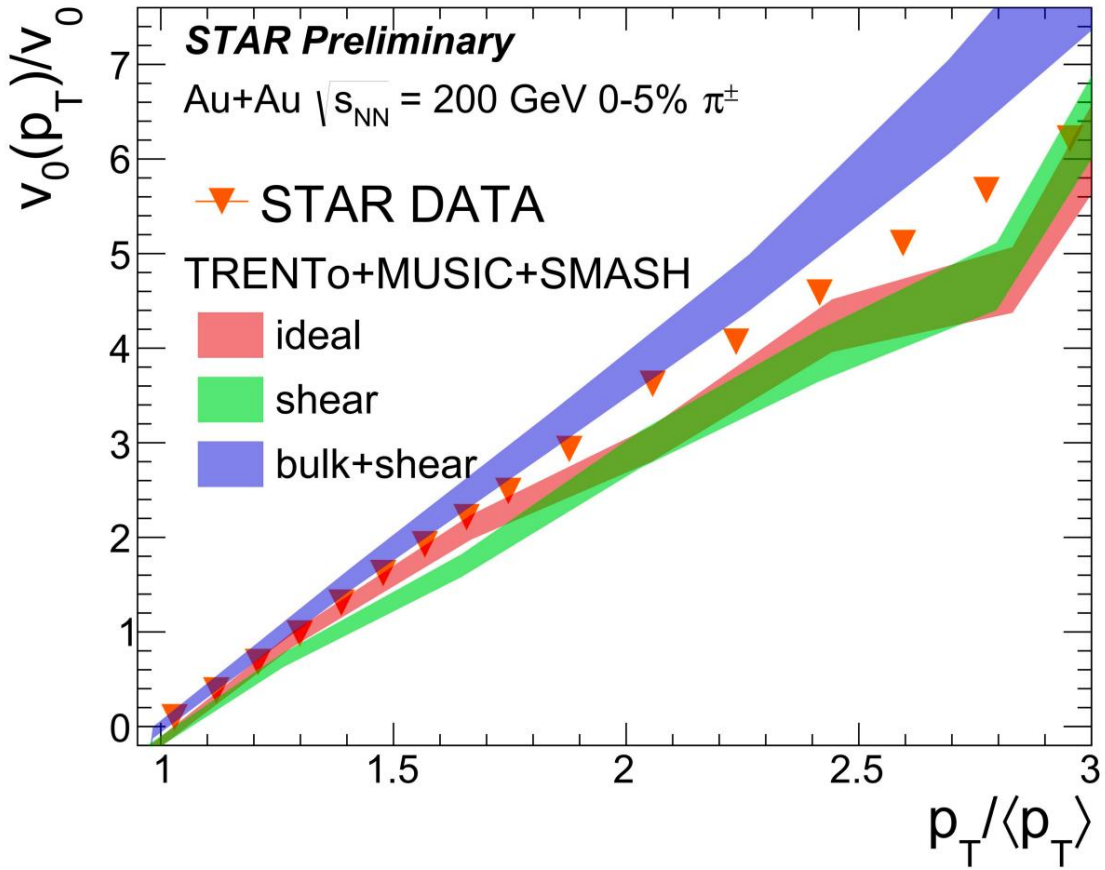
ATLAS Collaboration, Phys. Rev. Lett. 136, 032301 (2026)



$$v_0(p_T) = \frac{\langle \delta n(p_T)\delta[p_T]\rangle}{\langle n(p_T)\rangle \langle [p_T]\rangle} \times \frac{1}{v_{0,\mathrm{int}}}$$

$$v_{0,\mathrm{int}} \equiv \frac{\sqrt{\langle (\delta[p_T])^2\rangle}}{\langle [p_T]\rangle}$$

Model calculation: L. Du, Phys. Rev. C 113, 014901 (2026)

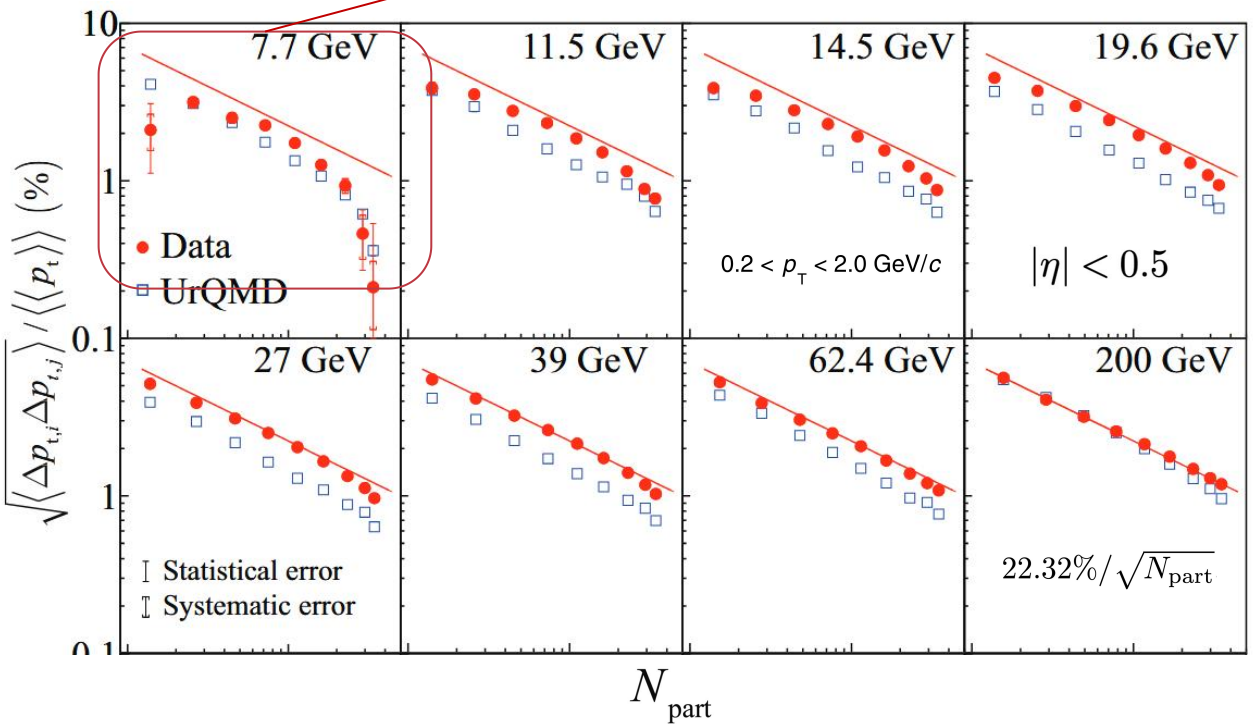


Mean-pT fluctuations and v0(pT) provide complementary constraints on radial flow dynamics and bulk viscosity

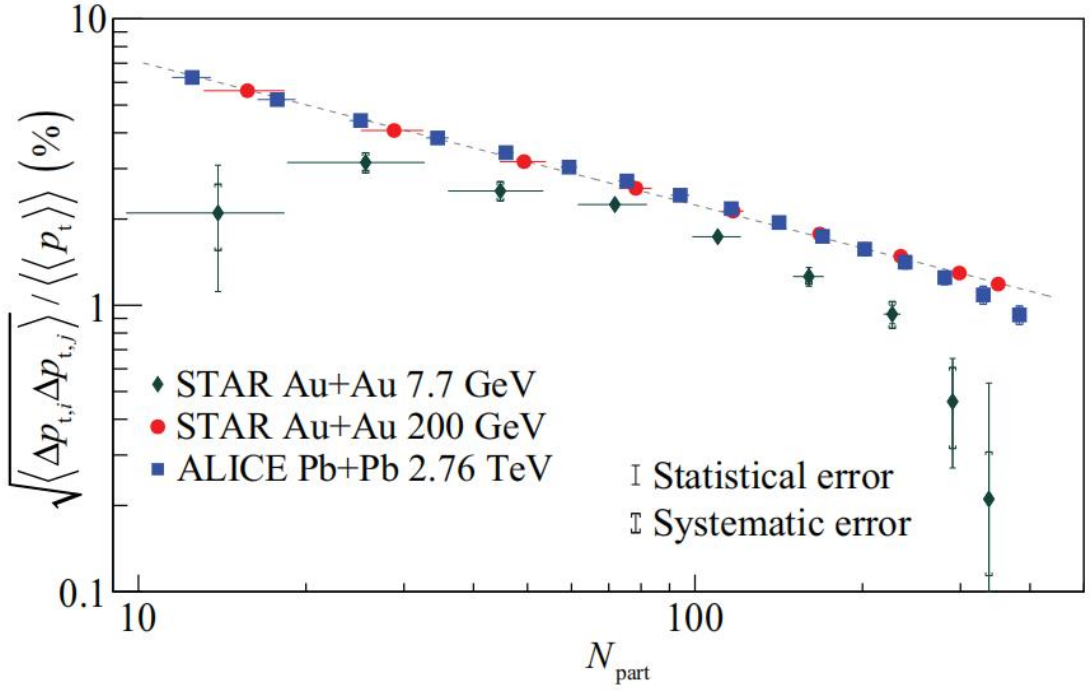
BES-I Results: Power Law

STAR, PRC 99, 044920 (2019)

deviation most clearly at 7.7 GeV



Comparison with ALICE result at 2.76 TeV

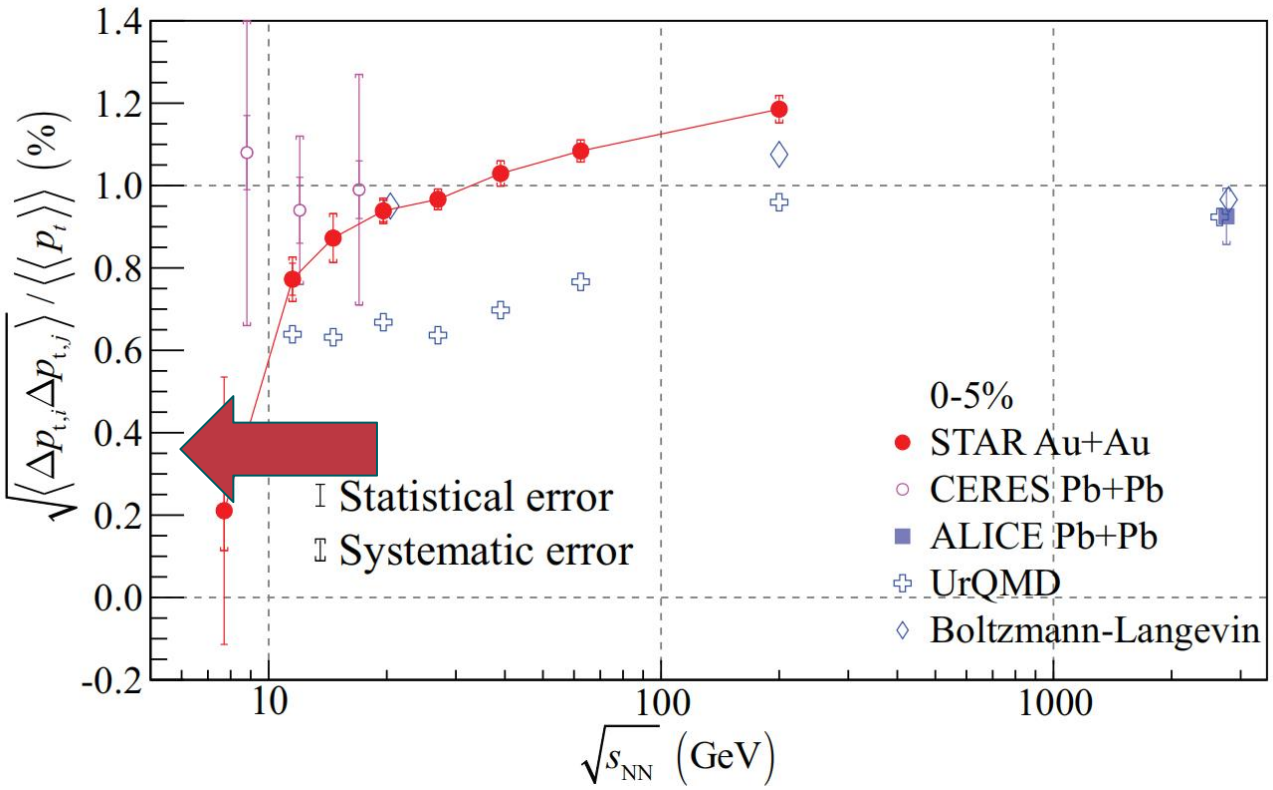


At higher energies, CpT approximately follows power-law scaling. Deviations become more pronounced toward lower BES-I energies, especially at 7.7 GeV, motivating measurements in the STAR FXT region.

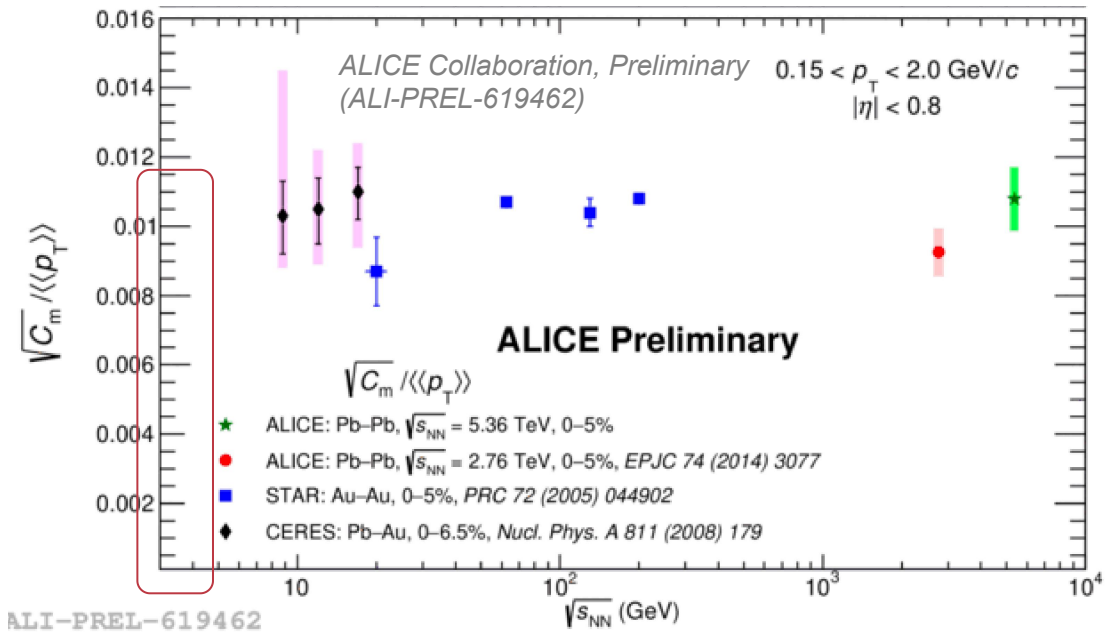
BES-I Results: Energy Dependence

STAR, PRC 99, 044920 (2019)

STAR BES-I: 0–5% Central Au+Au

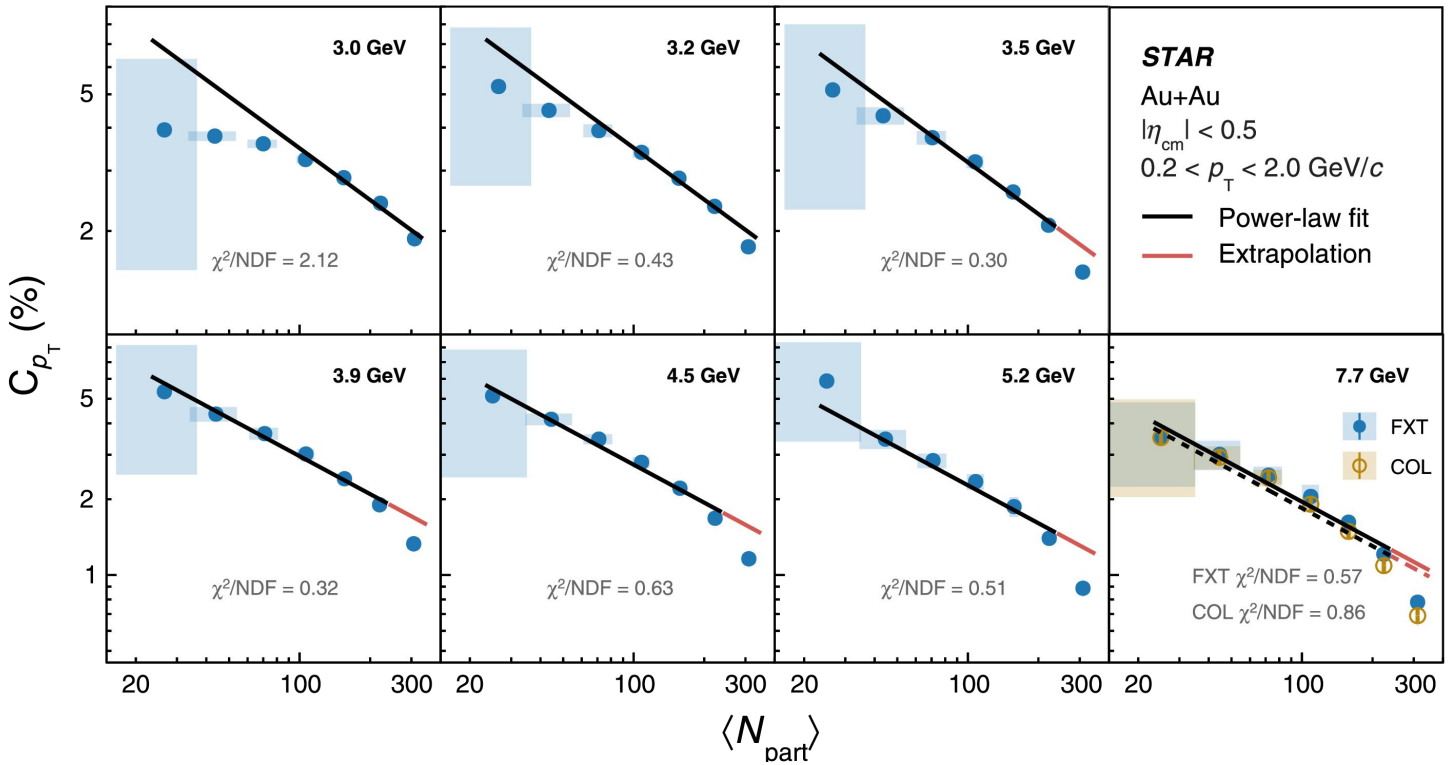


$$C_m = \left(\frac{Q_1^2 - Q_2}{N_{ch}(N_{ch}-1)}\right) - \left(\frac{Q_1}{N_{ch}}\right)^2$$



- The normalized correlation strength increases monotonically with collision energy across the STAR BES-I measurements.
- Previous measurements provide a reference for extending the energy scan into the high-baryon-density region

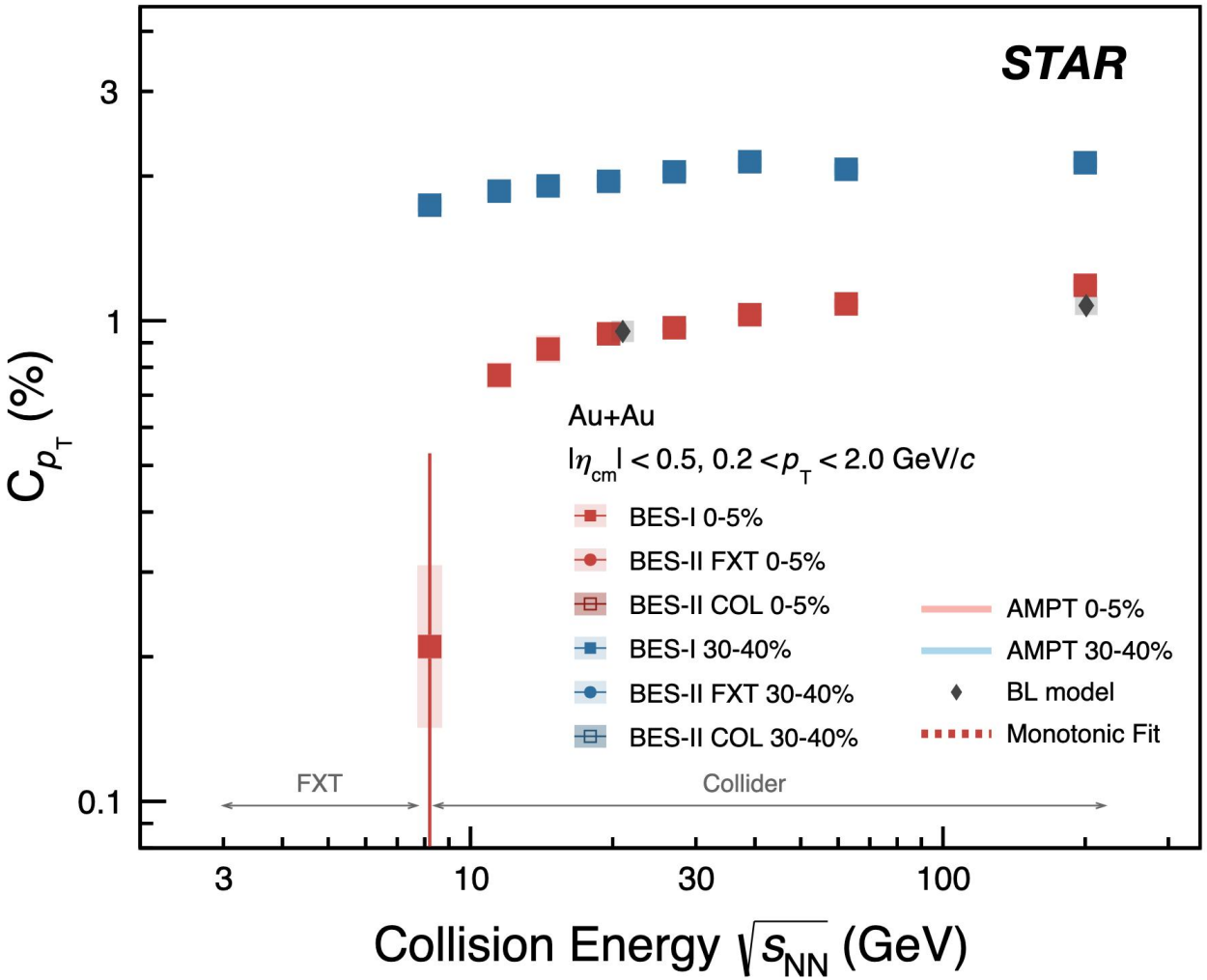
Central Collisions Deviate from Source Scaling



- The exponent is fixed to −1/2, as expected from independent-source scaling, given the limited centrality resolution at low collision energies

- Observes 3.0 GeV breakdown of this scaling, possibly due to dominance of hadronic interactions
- The deviations in 0-10% suggest the onset of additional dynamical effects beyond trivial statistical fluctuations

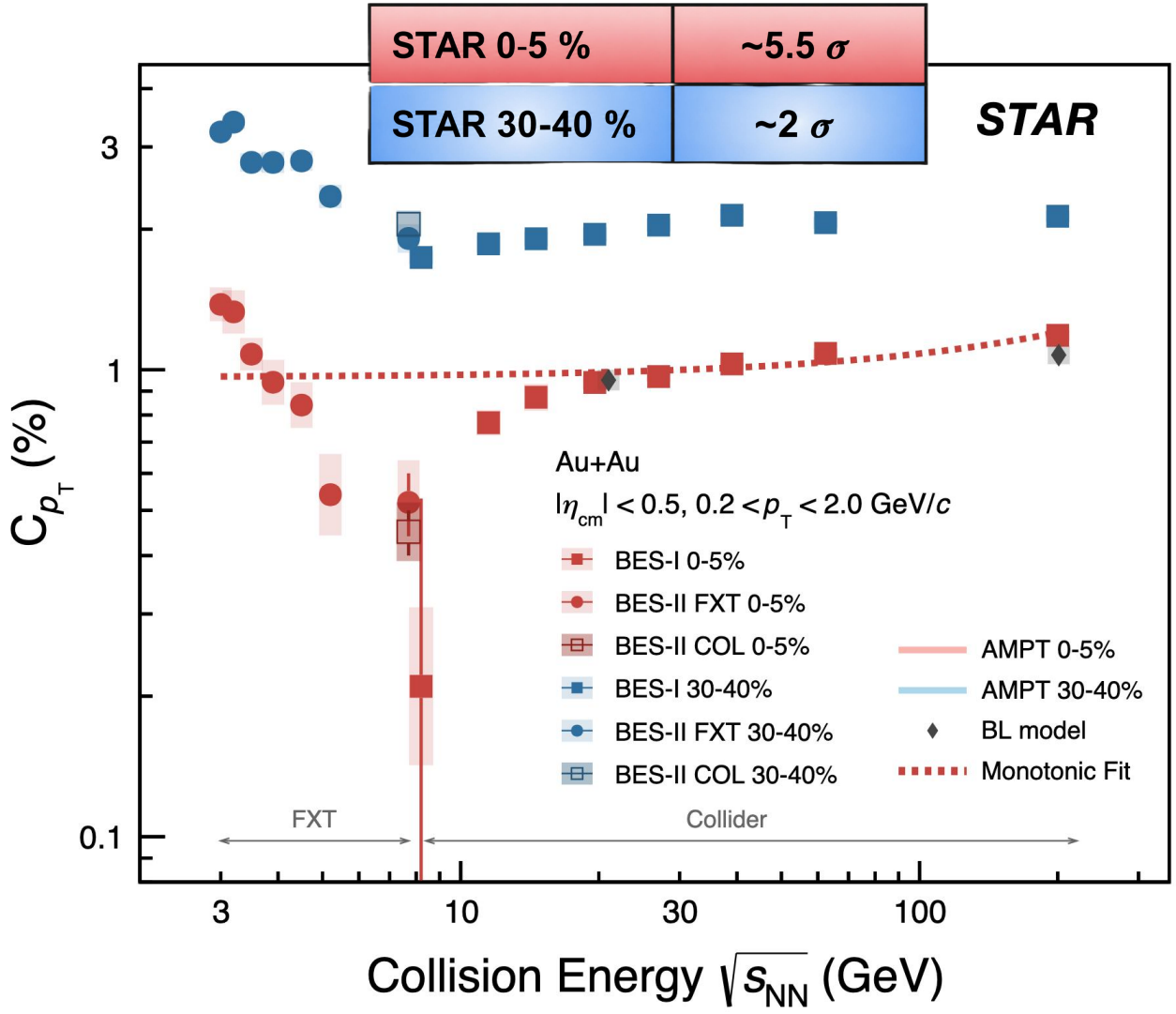
Nonmonotonic Energy Dependence in Central Collisions



- A monotonous collision energy dependence
- Central(0-5%) collisions shows stronger trend than mid-central(30-40%)
- The Boltzmann–Langevin model reproduces the observed behavior

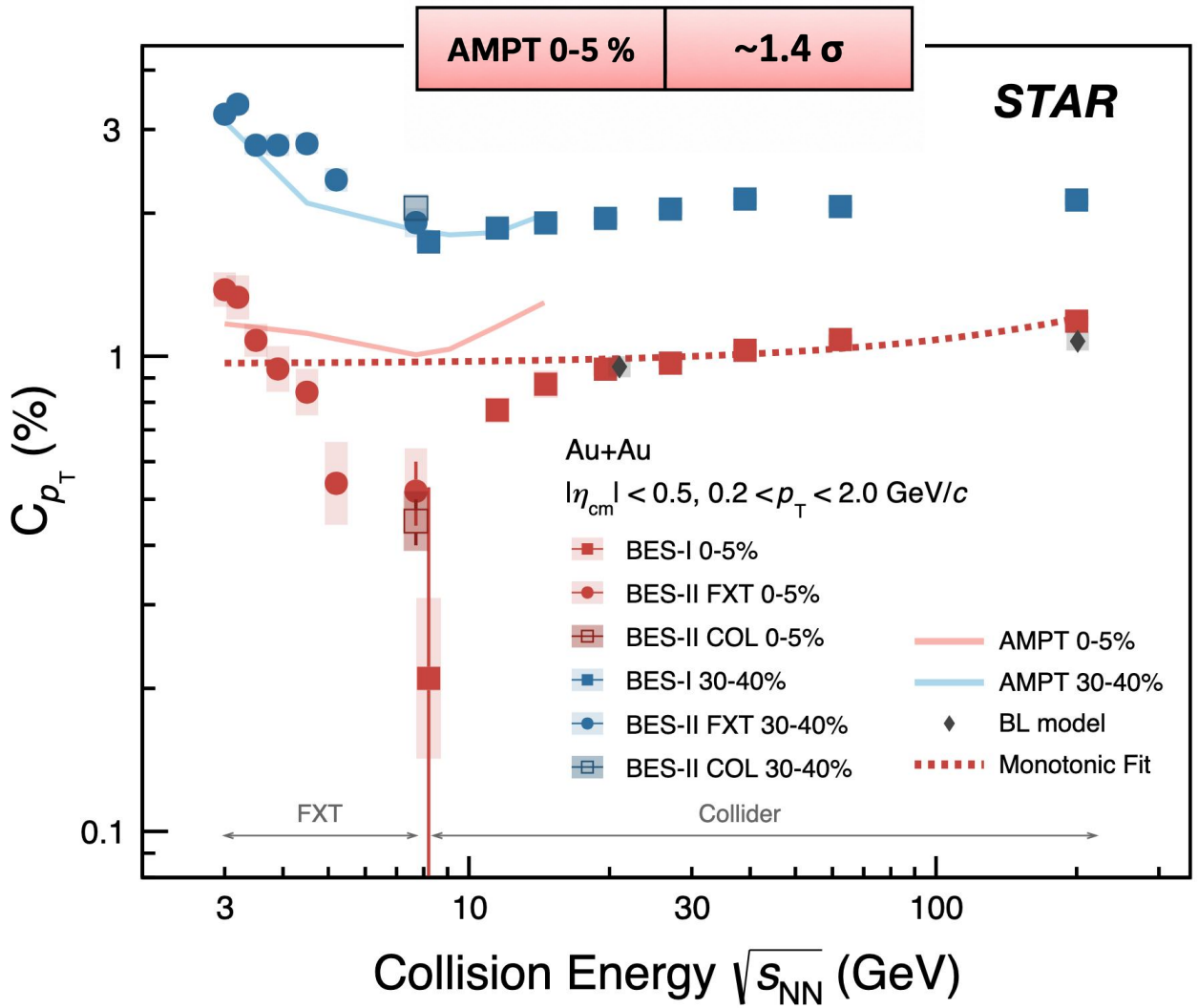
S. Gavin et. al., PRC 95, 064901 (2017)

Nonmonotonic Energy Dependence in Central Collisions



- A monotonous collision energy dependence
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- BES-II results show a significant non-monotonic behavior in 0–5% central collisions, but not in 30–40%
- At 7.7 GeV, BES-II is consistent with BES-I, with substantially reduced uncertainties

Nonmonotonic Energy Dependence in Central Collisions



- A monotonous collision energy dependence
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- BES-II results show a significant non-monotonic behavior in 0–5% central collisions, but not in 30–40%
- At 7.7 GeV, BES-II is consistent with BES-I, with substantially reduced uncertainties
- AMPT describes mid-central (30–40%) data, but cannot reproduce the central (0–5%) behavior.

AMPT: L. Zhang, J. Chen, C. Zhang, PRC 111, 024911 (2025); R.X. Cao, S. Zhang, Y.-G. Ma, PRC 106, 014910 (2022)

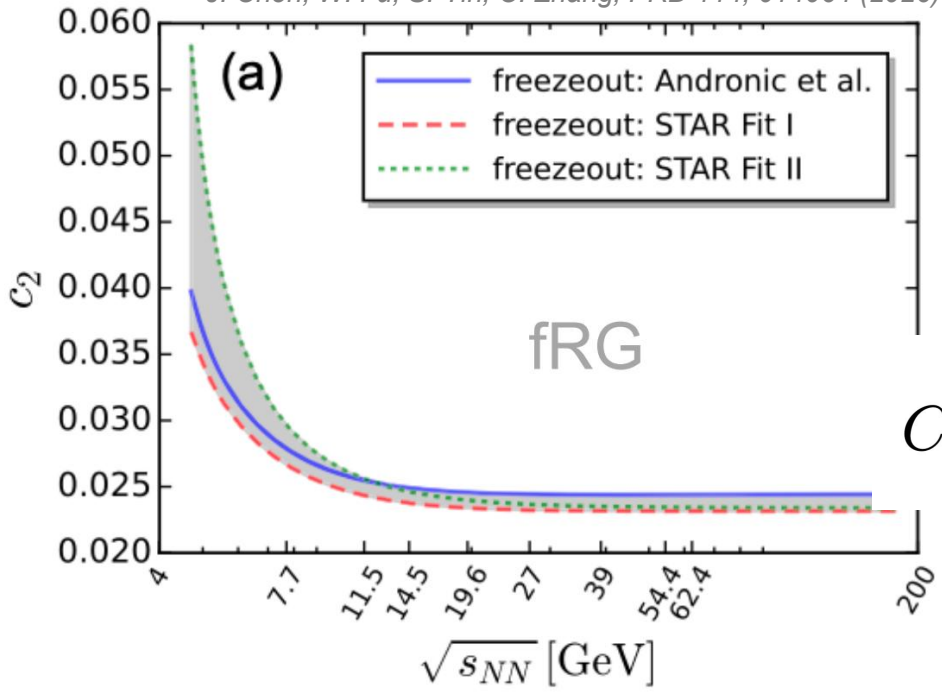
Unsettled interpretations: Temperature Fluctuations

H. Liu, P. Wu, H.M. Liu, P.C. Chu, 2607.19275

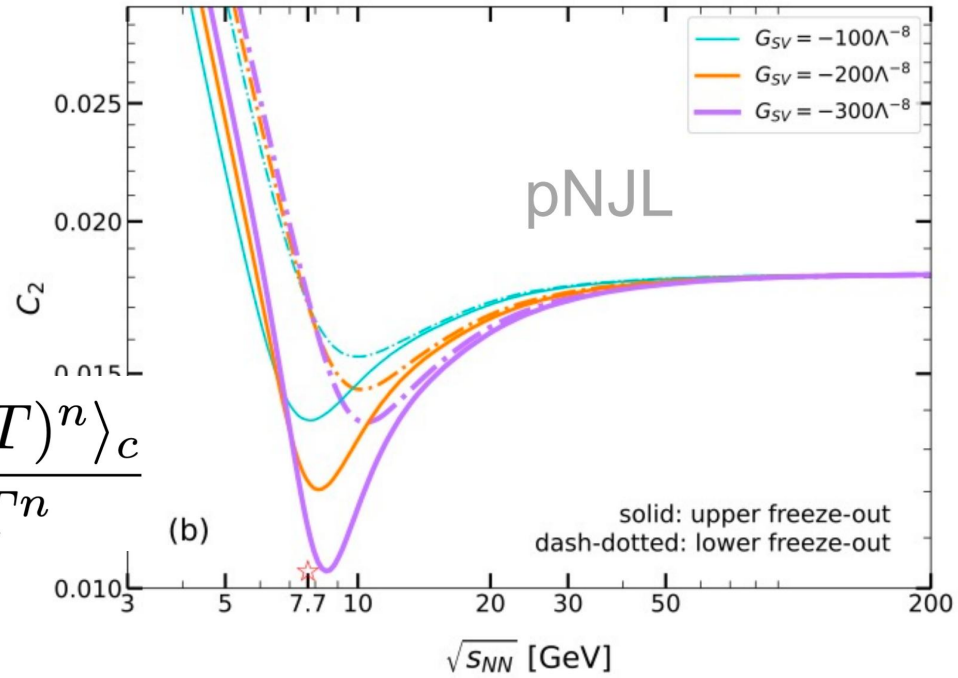
requires dynamical modeling

Temperature fluctuation interpretation

J. Chen, W. Fu, S. Yin, C. Zhang, PRD 114, 014064 (2026)



$$C_n = \frac{\langle (\Delta T)^n \rangle_c}{T^n}$$



- Model calculations predict different energy dependences of temperature fluctuations, reflecting their sensitivity to the QCD equation of state and freeze-out conditions

- If the event-wise mean transverse momentum tracks the effective temperature, temperature fluctuations may contribute to the observed dynamical pT correlations

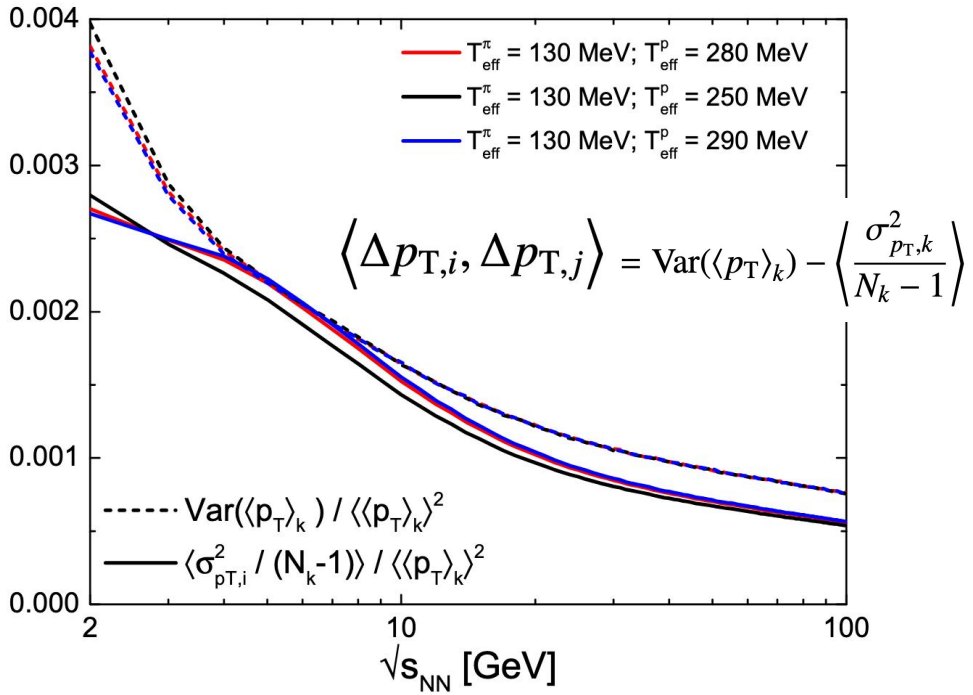
Unsettled interpretations: Baryon–Meson Composition

T. Reicherte, J. Steinheimera,b, M. Bleicher, 2606.03294

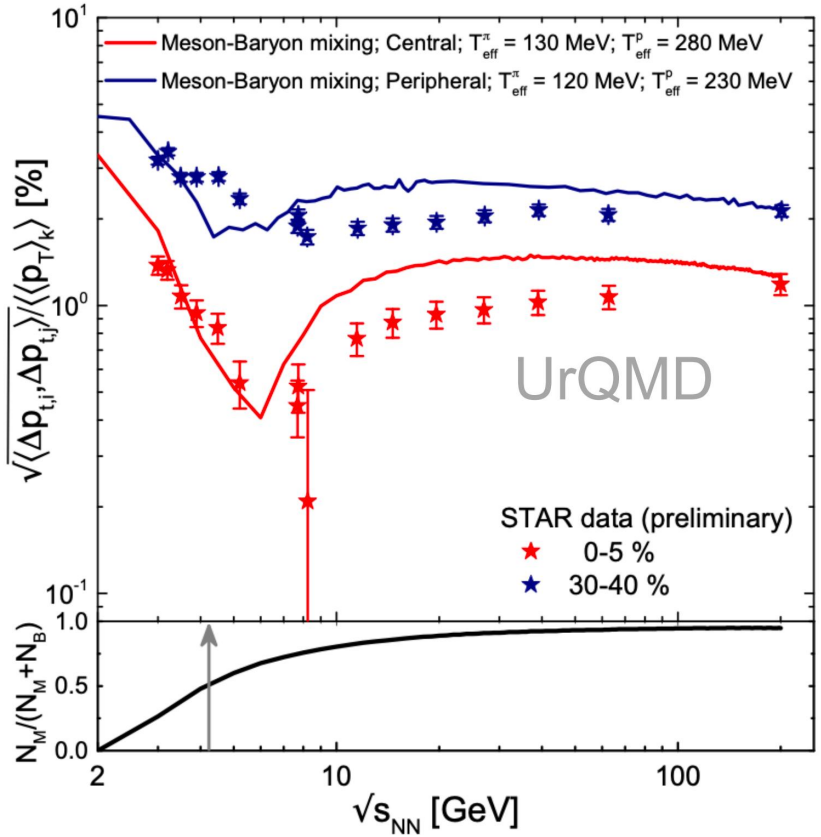
Baryon-meson mixing effect

Mixing term

$$\left\langle \Delta p_{\mathrm{T},i} \Delta p_{\mathrm{T},j} \right\rangle = -\frac{N_M N_B}{N_t^2 (N_k - 1)} (\mu_M - \mu_B)^2$$



The baryon-to-meson composition changes with collision energy

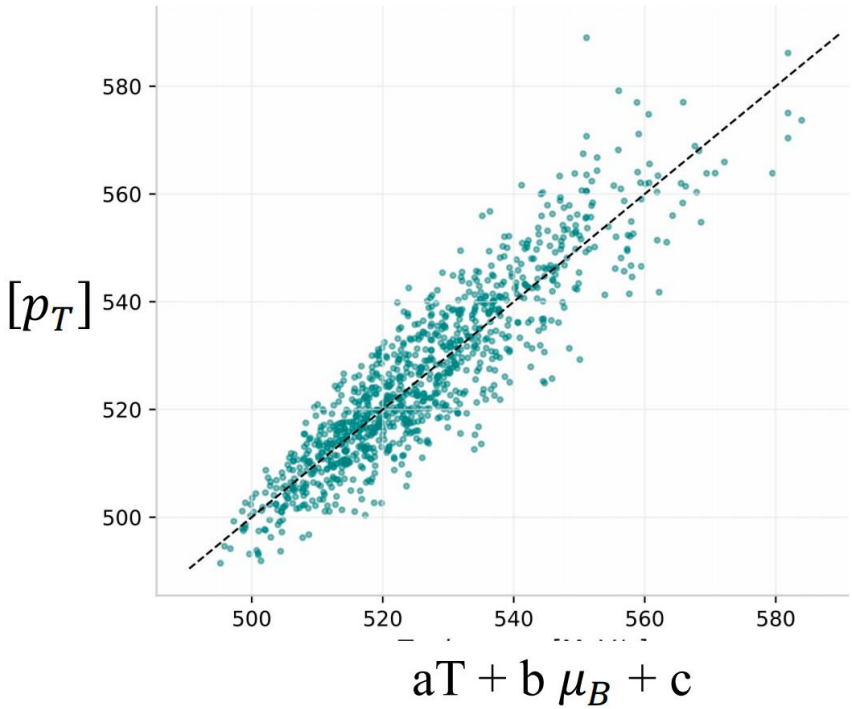


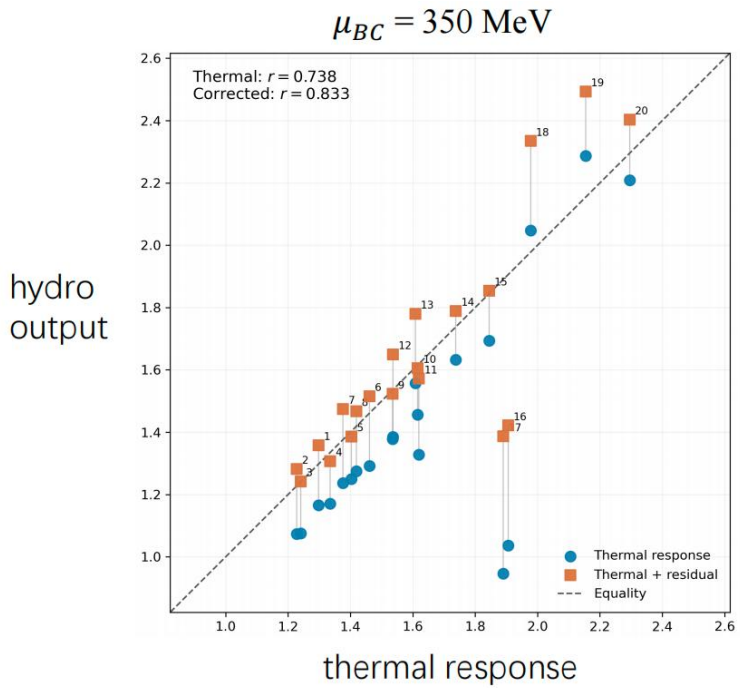
May contribute to the low-energy behavior of pT correlations, but further quantitative studies are needed to establish its role

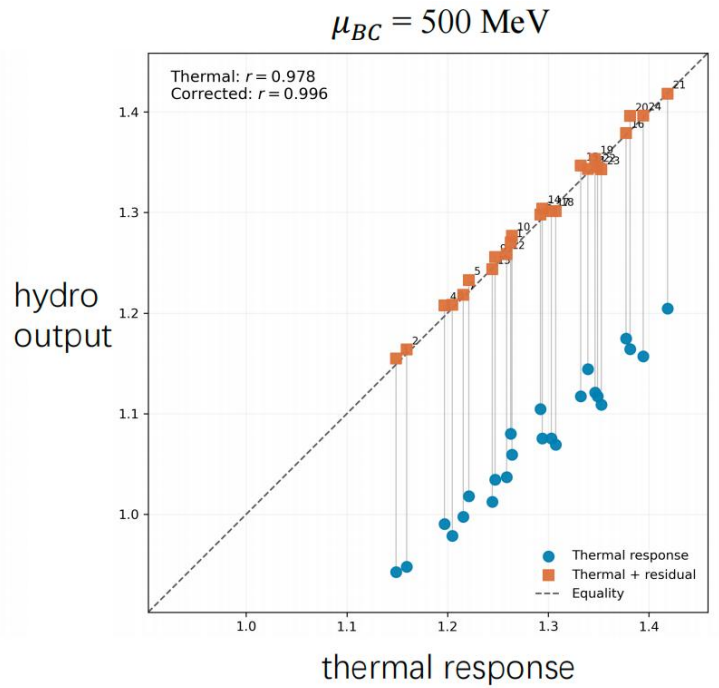
Unsettled interpretations: Recent Model Study

Hydrodynamic + EOS

Yesterday's Yushan and Prof Yan's talk







Validated by hydro: a sensitive probe of QCD EoS

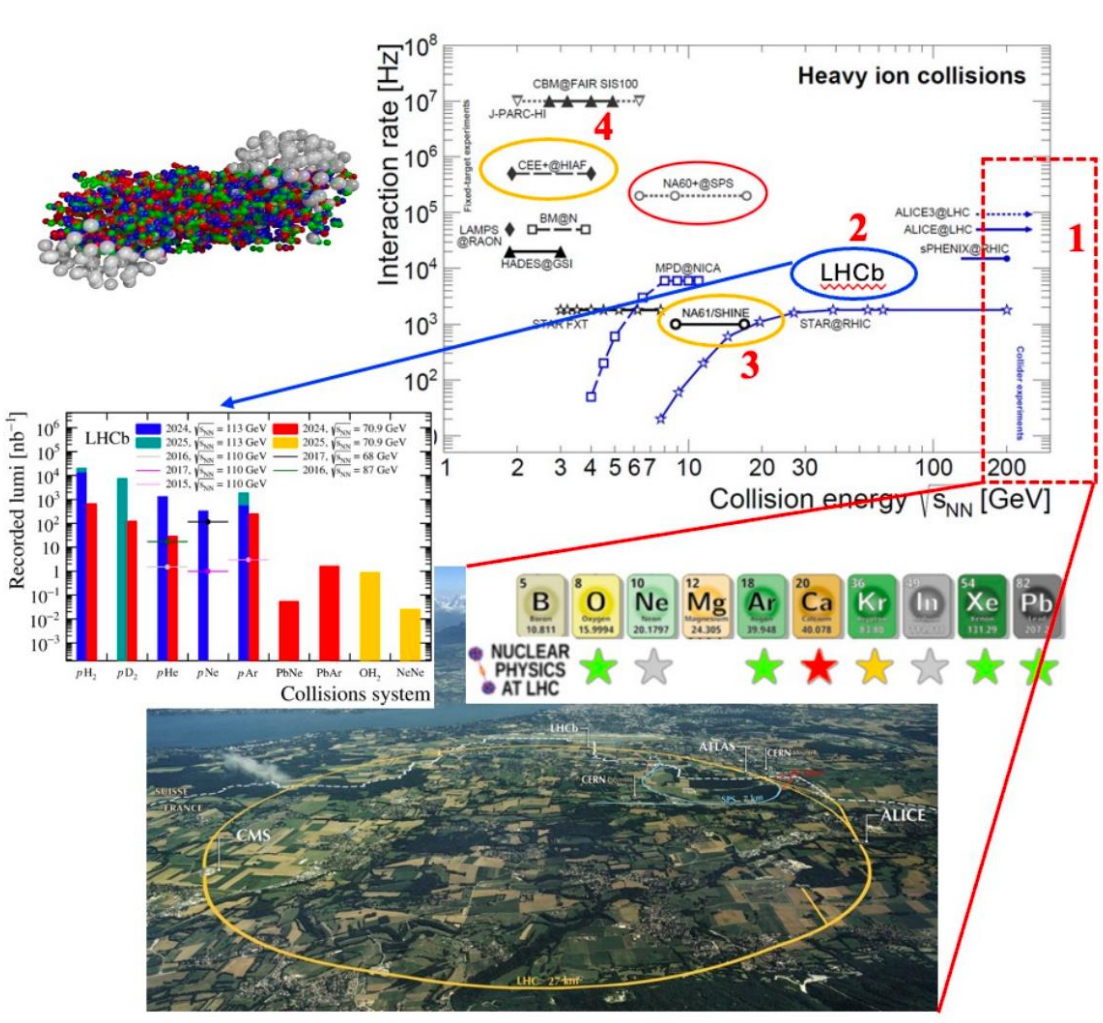
Unsettled interpretations: Conclusion

- Possible mechanisms, not definitive explanations. The discussed model studies illustrate possible contributions to the observed nonmonotonic behavior, but its underlying origin remains unresolved.

- A theoretical challenge at high baryon density. A quantitative understanding of dynamical pT fluctuations requires further investigation of the interplay between the QCD equation of state, non-equilibrium dynamics, and hadronic composition.

- An opportunity for collaboration. We hope these measurements will stimulate further theoretical calculations and collaborative efforts to understand the evolution of dynamical fluctuations in baryon-rich QCD matter

System scan and energy scan



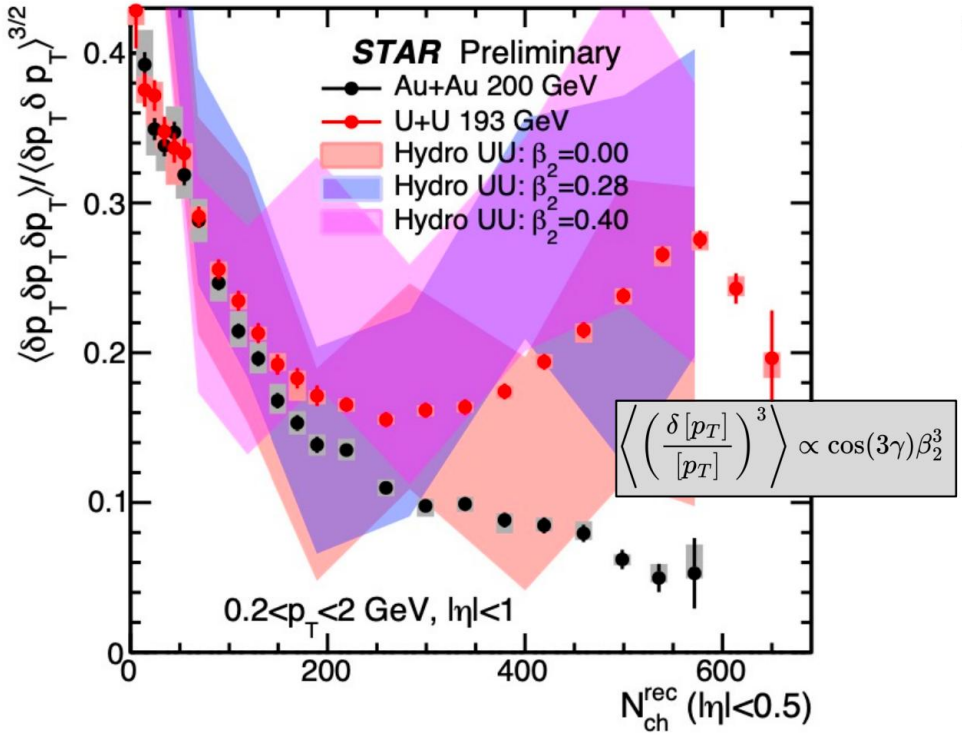
To disentangle these effects, we need a two-dimensional strategy combining energy dependence and collision system dependence

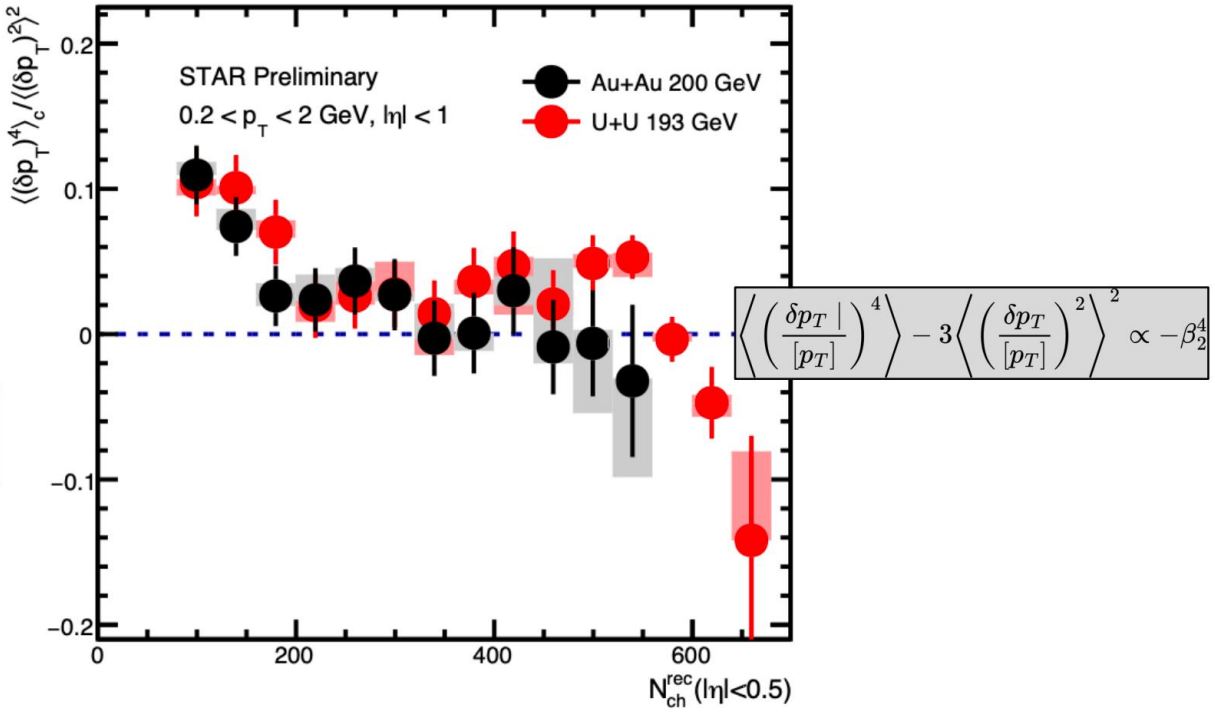
- Energy Scan : Bridge Collider (LHC/RHIC) -> Mid-energy (LHCb SMOG) -> High μ_B FXT (STAR, NA61, CEE+@HIAF, CBM)
- System Scan (A+A, p+A): Vary system size (O, Ne, Ar, Xe, Au, Pb at fixed collision energy to disentangle initial-state geometry & hadronic mixing from QGP thermodynamic response

Motivation for higher-order results

Initial state effect by higher-order

C. Zhang (STAR), IJMPE 32, 2341001 (2023)



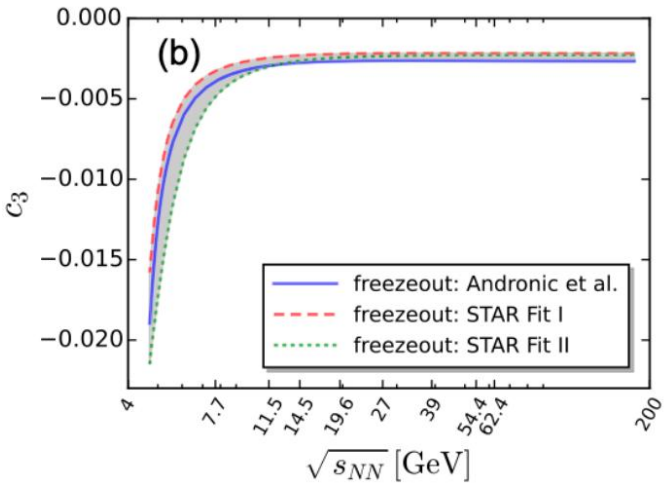


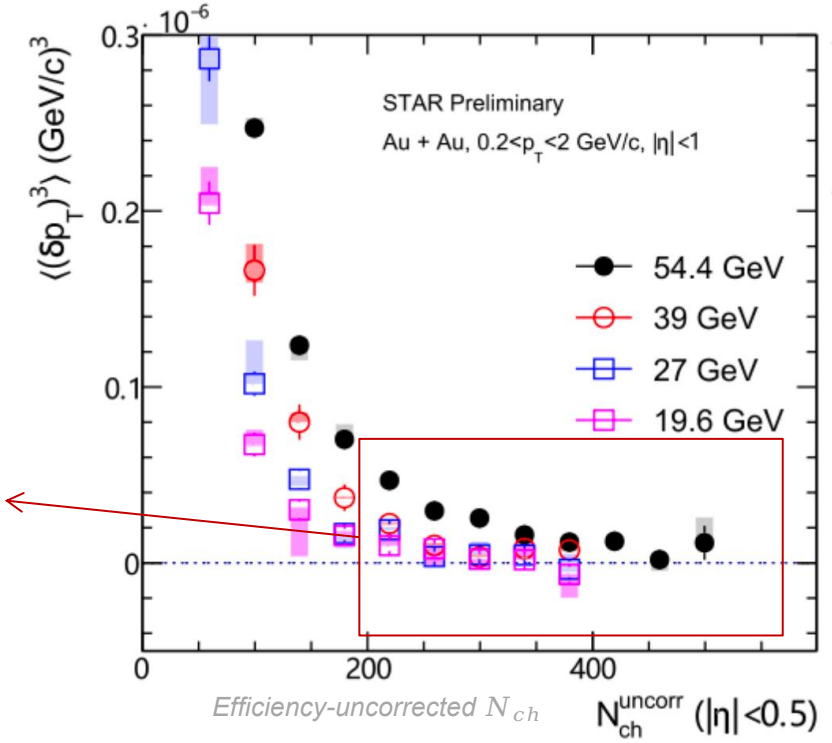
- Independence source model: following $1/N^{n-1}$ within power-law decrease in high-order
- UU AuAu, indicates possible size fluctuation from initial state

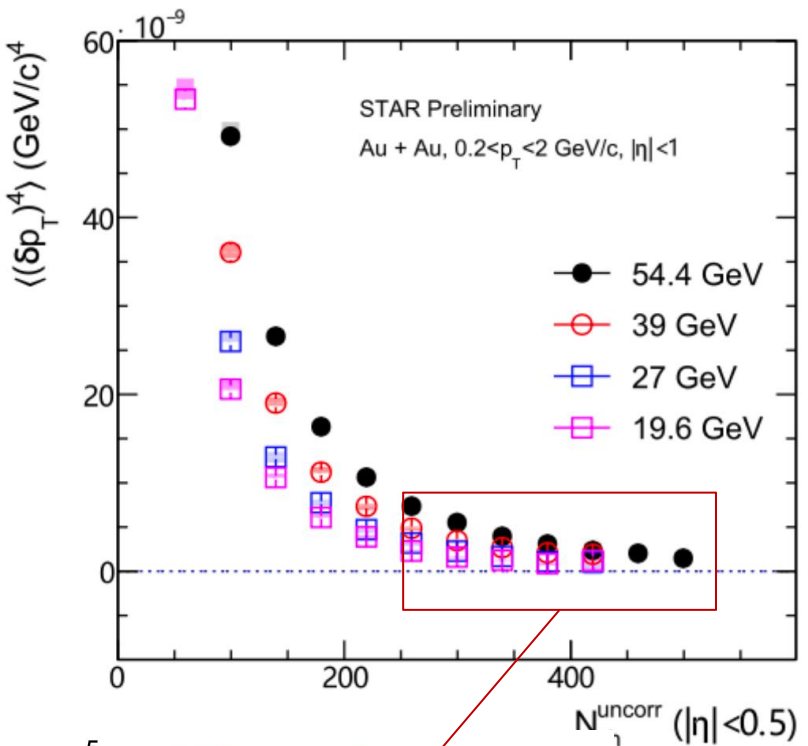
Motivation for higher-order results

Energy dependence of higher order

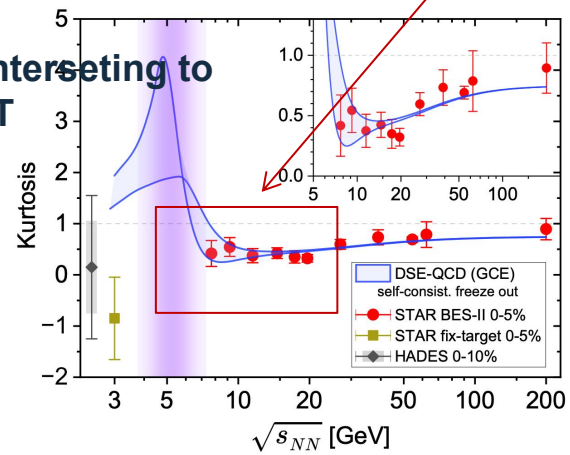
Negative skewness predicted by fRG







Analog: interseting to see in FXT



Slight energy dependence is observed

Summary

1. First measurement of dynamical (pT) correlations at high baryon density
    - STAR FXT extends measurements to ($\sqrt{s_{nn}} = 3.0 - 7.7$GeV, $\mu_B \approx 400 - 760$ MeV)
    - Breakdown of independent-source scaling
    - A significant nonmonotonic structure is observed in 0–5% central collisions ($\approx 5\delta$), unlike mid-central data ($\approx 2\sigma$) and AMPT calculations ($\approx 1.4\sigma$)
2. New constraints on baryon-rich QCD matter
    - The underlying mechanism remains unresolved.
    - Higher-order pT correlations and future low-energy measurements may help disentangle different physical contributions.

Efficient Pair Sums and Self-Pair Removal

1. Definition of Q_n

$$Q_n = \sum_{i=1}^{N_{\mathrm{ch}}} (p_{T,i})^n.$$

2. Expansion of Q_1^2

$$Q_1^2 = \sum_{i \neq j} p_{T,i} p_{T,j} + \sum_i p_{T,i}^2 \quad \Rightarrow \quad Q_1^2 - Q_2 = \sum_{i \neq j} p_{T,i} p_{T,j}$$

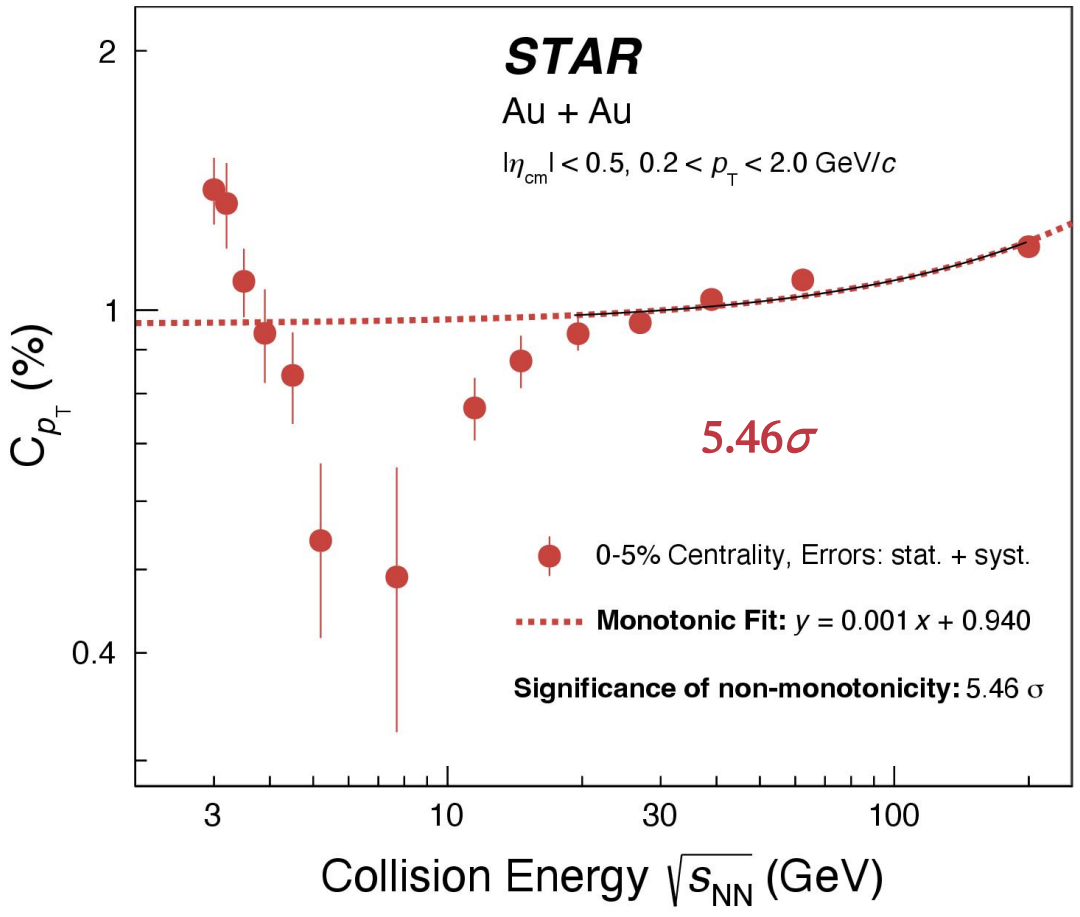
$$\langle \Delta p_{T,i} \Delta p_{T,j} \rangle = \left\langle \frac{Q_1^2 - Q_2}{N_{\mathrm{ch}}(N_{\mathrm{ch}} - 1)} \right\rangle_{\mathrm{ev}} - \left(\left\langle \frac{Q_1}{N_{\mathrm{ch}}} \right\rangle_{\mathrm{ev}} \right)^2 .$$

Subtract Q_2 to remove the diagonal self pairs.

Normalize distinct ordered pairs event by event, then take the ensemble average.

One pass through the particles replaces a nested pair loop.

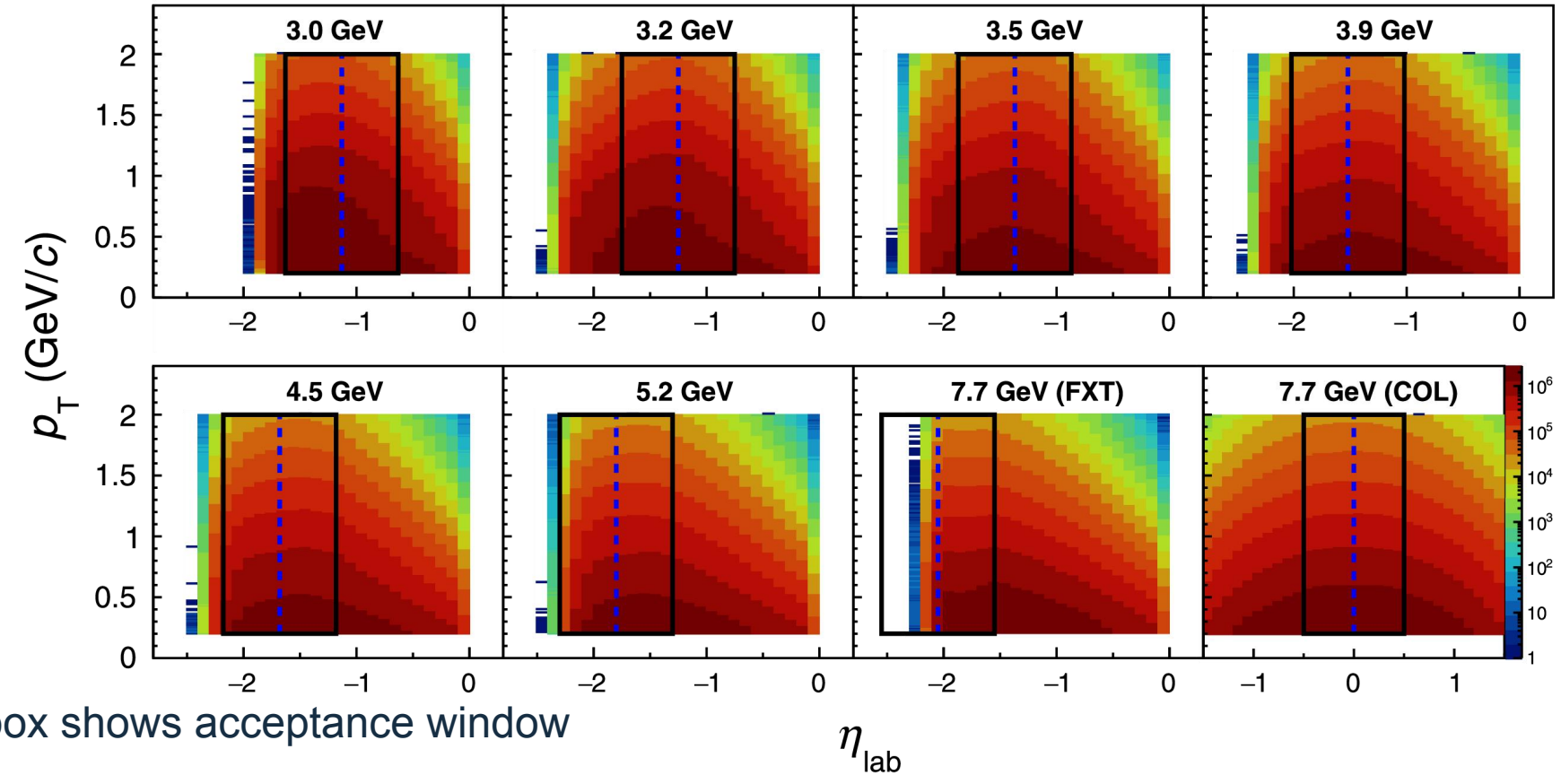
A Deviation from a Specified Monotonic Baseline



First-order polynomial anchored to high-energy points, roughly 20–200 GeV

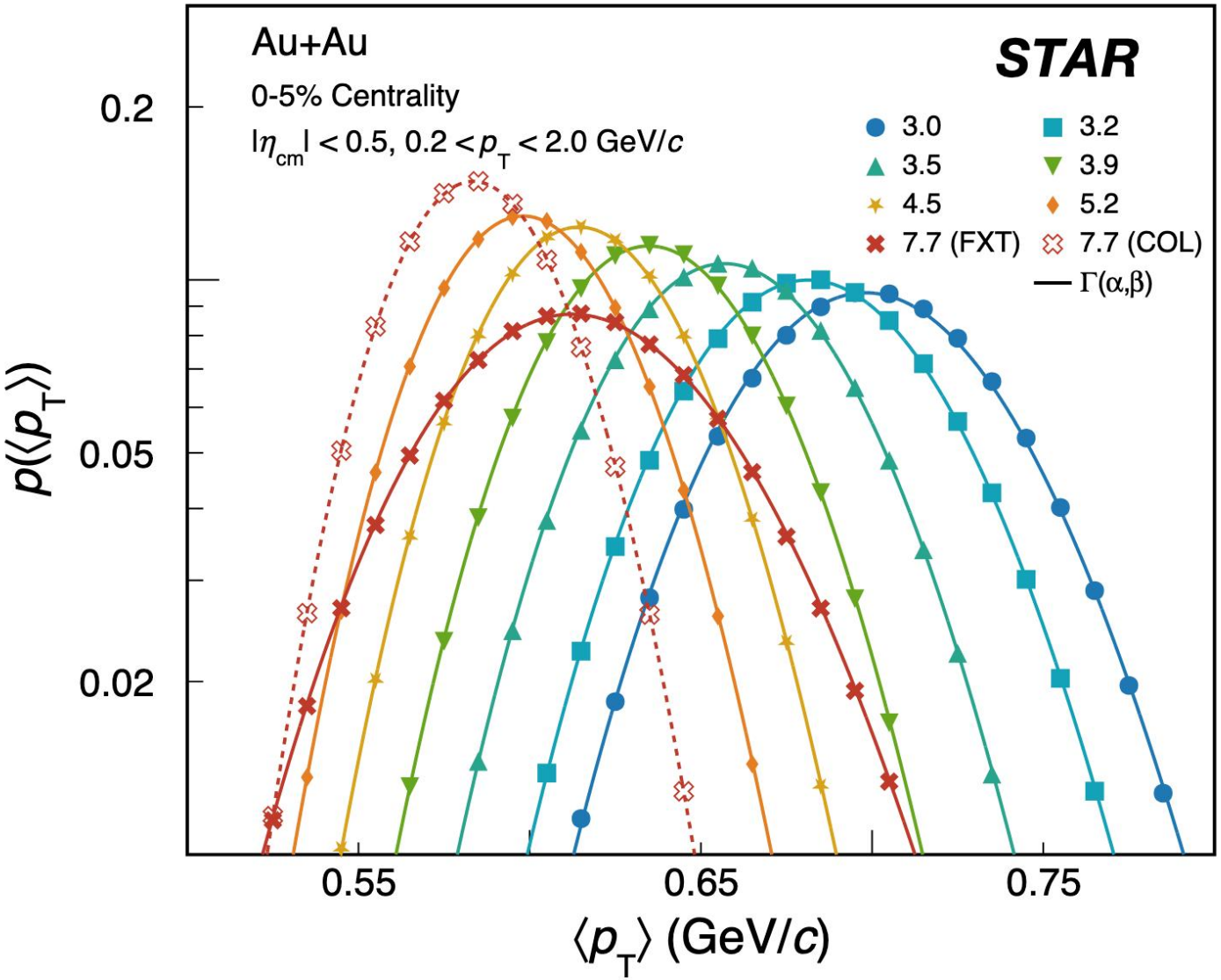
Statistical and systematic uncertainties added in quadrature

Kinematic Acceptances



- Solid black box shows acceptance window
- Only TPC used for analysis
- Slight loss at 7.7 GeV fixed-target, 7.7 GeV center-of-mass complements and verifies results

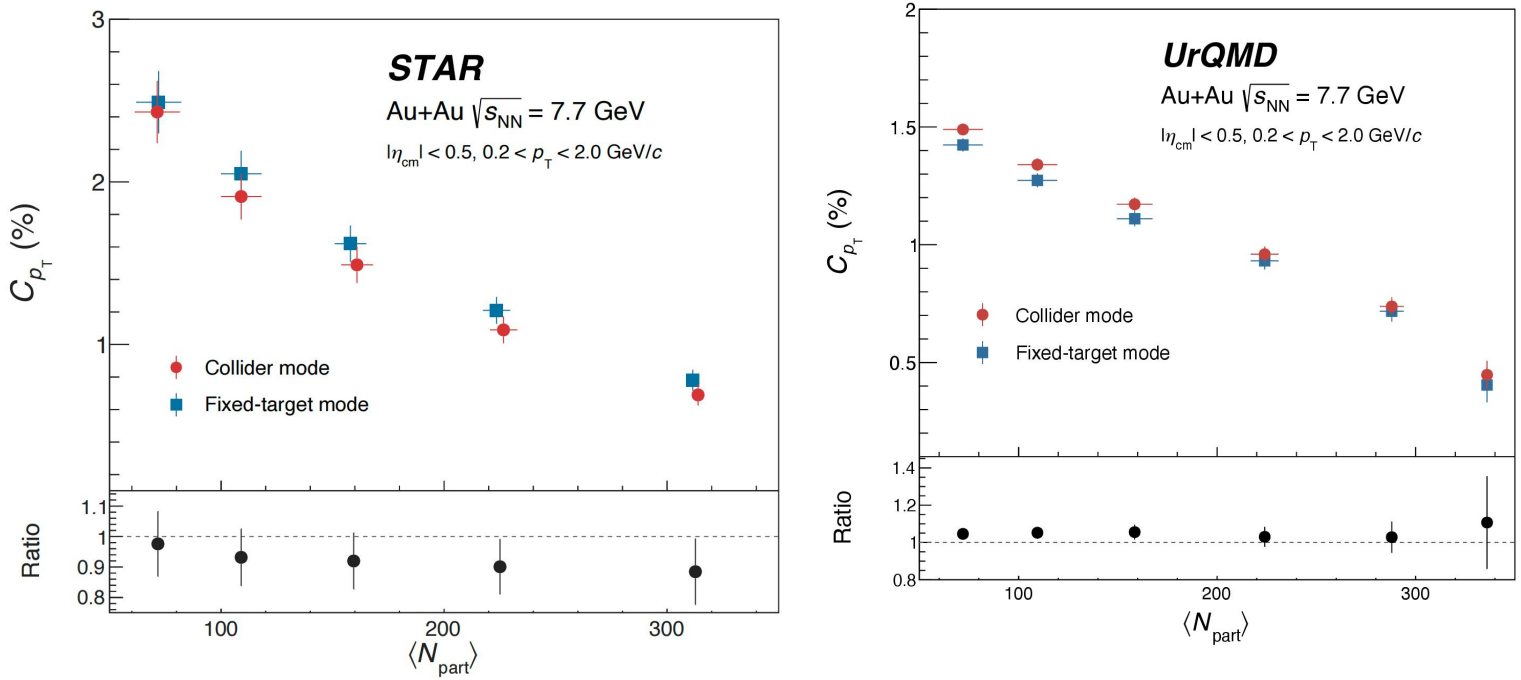
Event-by-Event Distributions of Mean pT



- Changes in the position and shape of these distributions across collision energies
- The curves are fitted with Gamma distributions to characterize their shapes
- Clear energy dependence on the mean and width

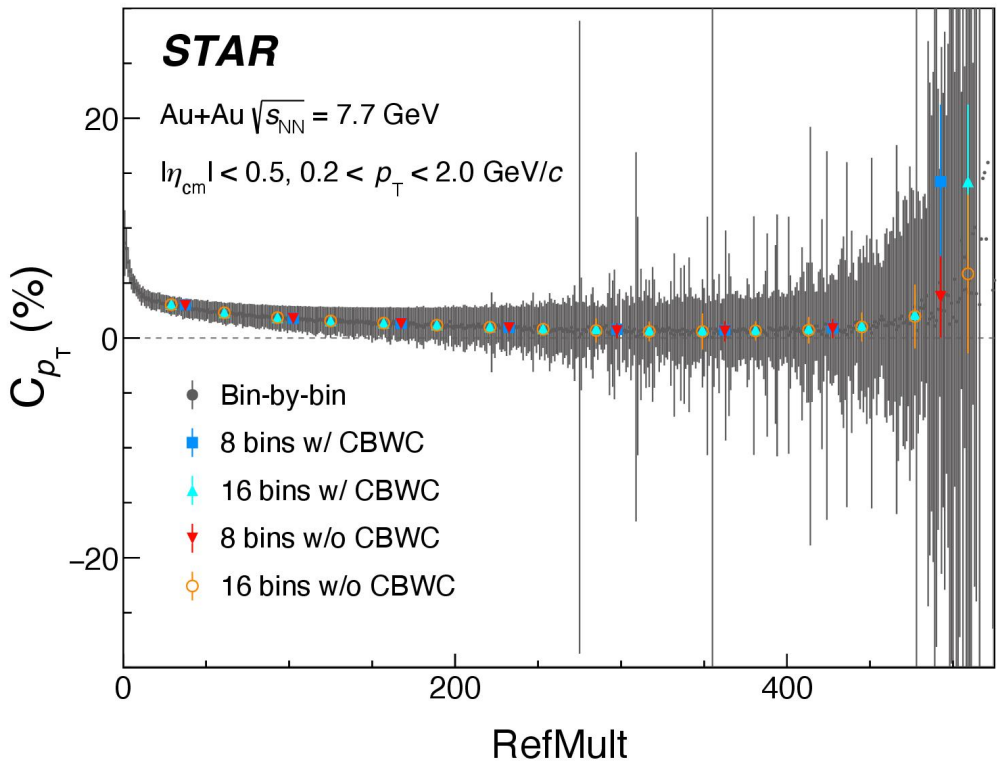
$$\mathrm{Var}(\bar{p}_T) = \frac{\sigma^2_{p_T}}{N} + \frac{N-1}{N} C_{\mathrm{pair}}$$

Frame Cross-Check



- This cross-check compares CpT vs Npart in 7.7 GeV Au+Au collisions: left panel for STAR data, right for UrQMD
- Within statistical uncertainties, both experiment and model yield compatible results for collider and fixed-target modes, confirming frame stability of CpT

Centrality Bin Width Cross-Check



7.7 GeV collider data

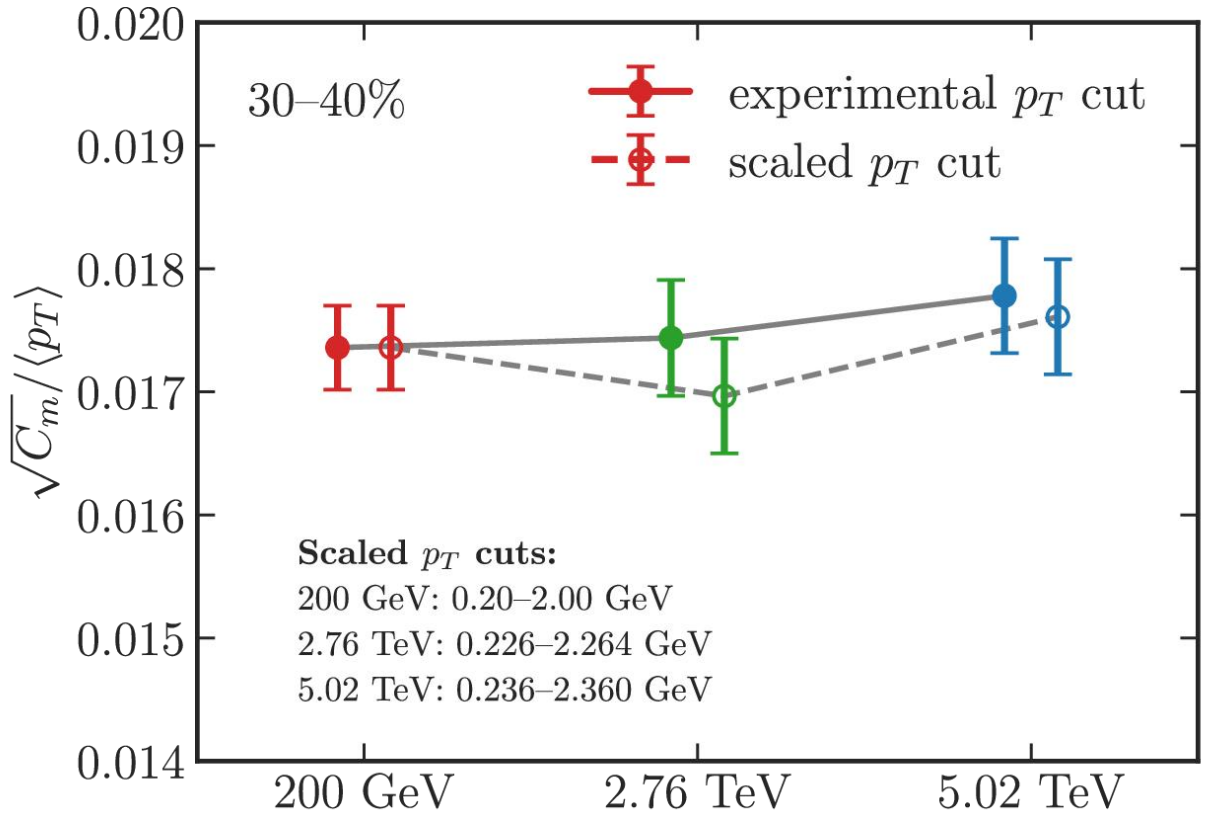
Unit RefMult bins compared with 8 or 16 centrality classes.

With and without the centrality-bin-width correction (CBWC).

Only statistical uncertainties appear in this figure.

The tested bin sizes and CBWC procedure give consistent C_{p_T} values.

Kinematic Cuts Shape an Integrated Observable



Lipei Du compares fixed experimental p_T windows with cuts scaled to the mean momentum.

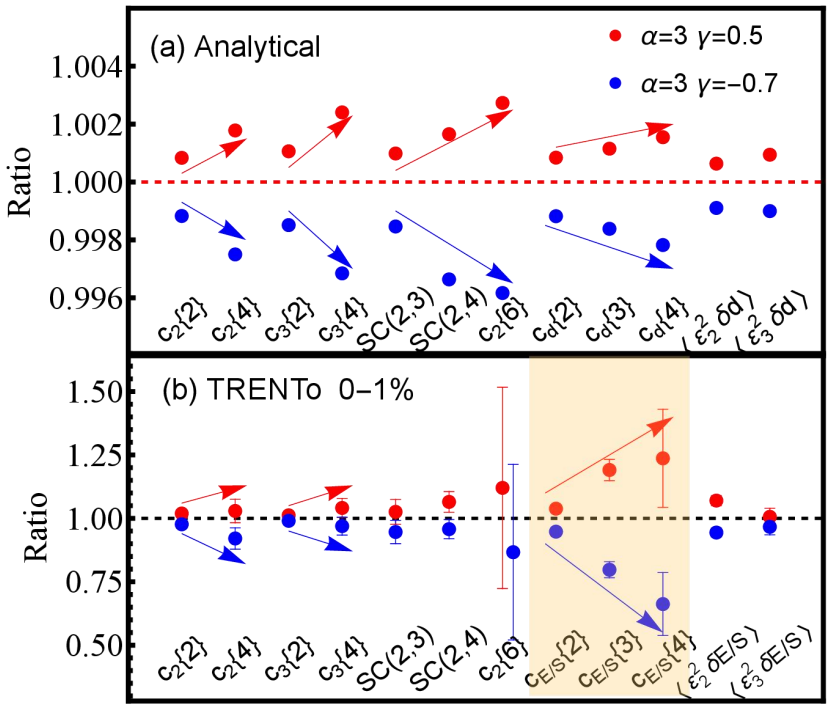
The comparison shows that kinematic projection can change an apparent energy dependence.

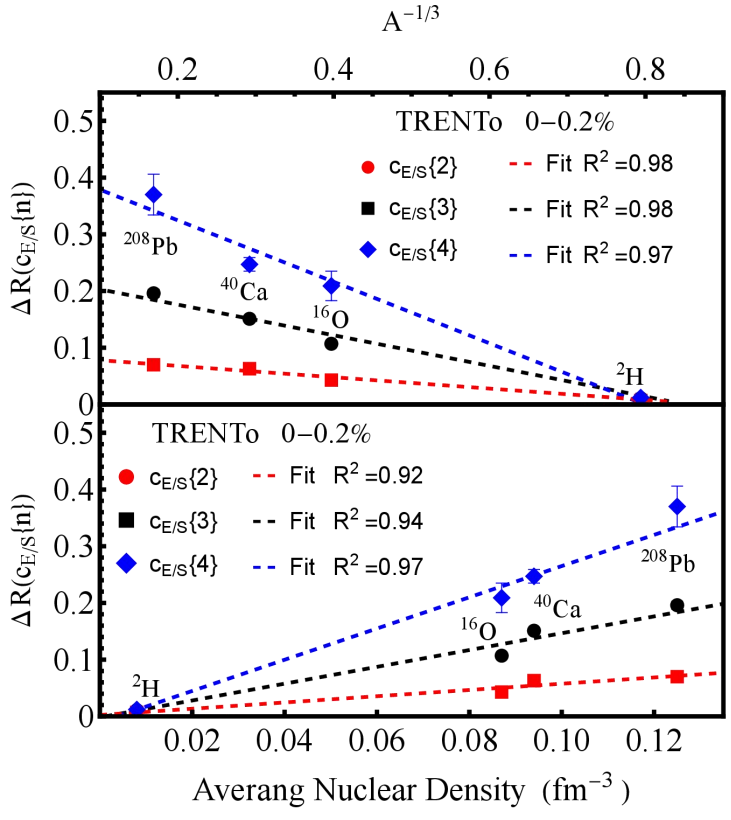
This is a high-energy model study, not a correction applied to the FXT data.

The 7.7 GeV cross-check does not imply invariance under every cut.

Lipei Du, Phys. Lett. B 874, 140225 (2026)

Higher Orders as a Future Nuclear-Structure Probe





Pei Li et al. study NN-SRC in initial-state fluctuations.

Predicted sensitivity is stronger at third and fourth order:

$c_{E/S}\{3\}$ and $c_{E/S}\{4\}$.

Higher-order mean-p_T measurements offer a complementary future direction.

Pei Li, K.-J. Sun, B. Zhou and G.-L. Ma, arXiv:2511.23293v1 (2025)