Disentangling the nature of the momentum fluctuations and radial flow at the RHIC-STAR experiment

Chunjian Zhang

Fudan University

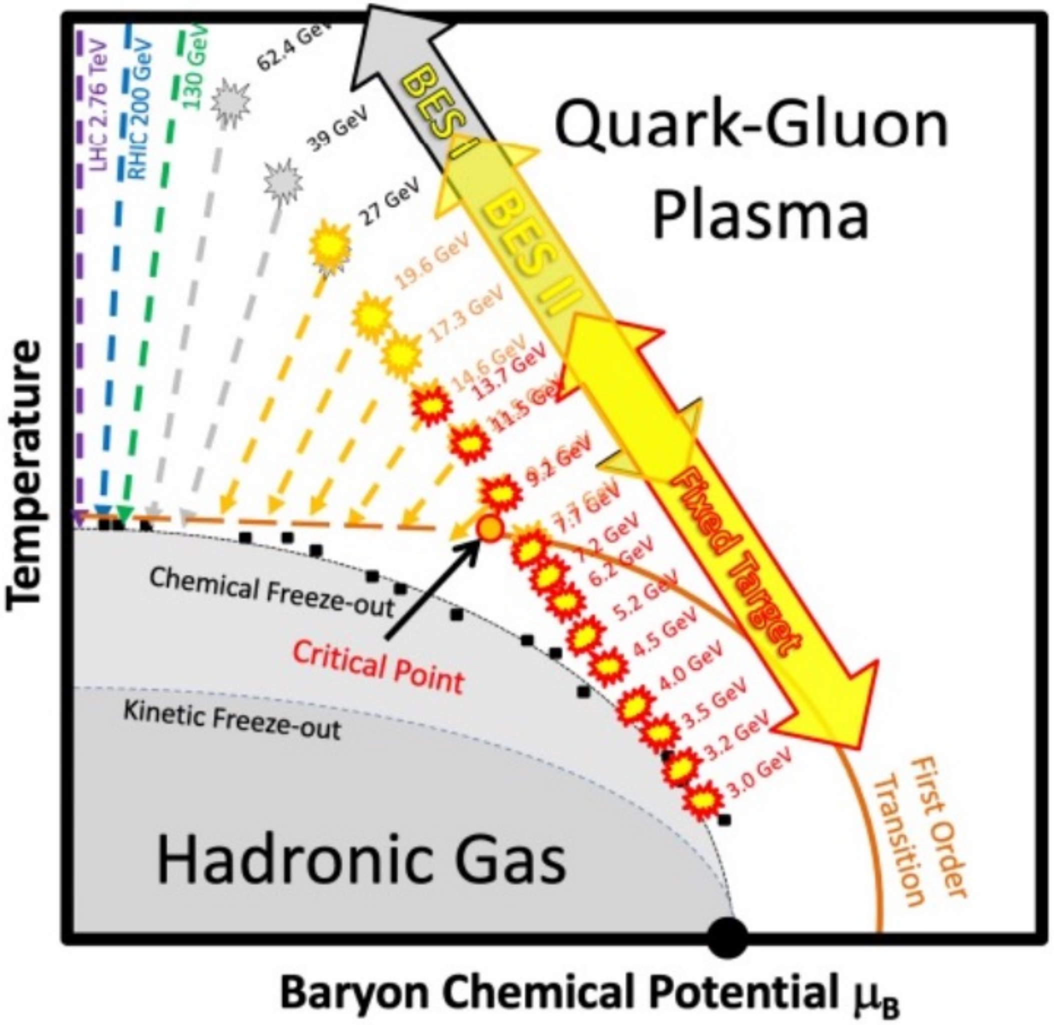
October 8-11, 2025, Dalian

The QCD Phase Diagram: From Theory to Experimental Signatures

STAR

Supported by the U.S. DEPARTMENT OF ENERGY | Office of Science

QCD Phase Diagram and RHIC Beam Energy Scan



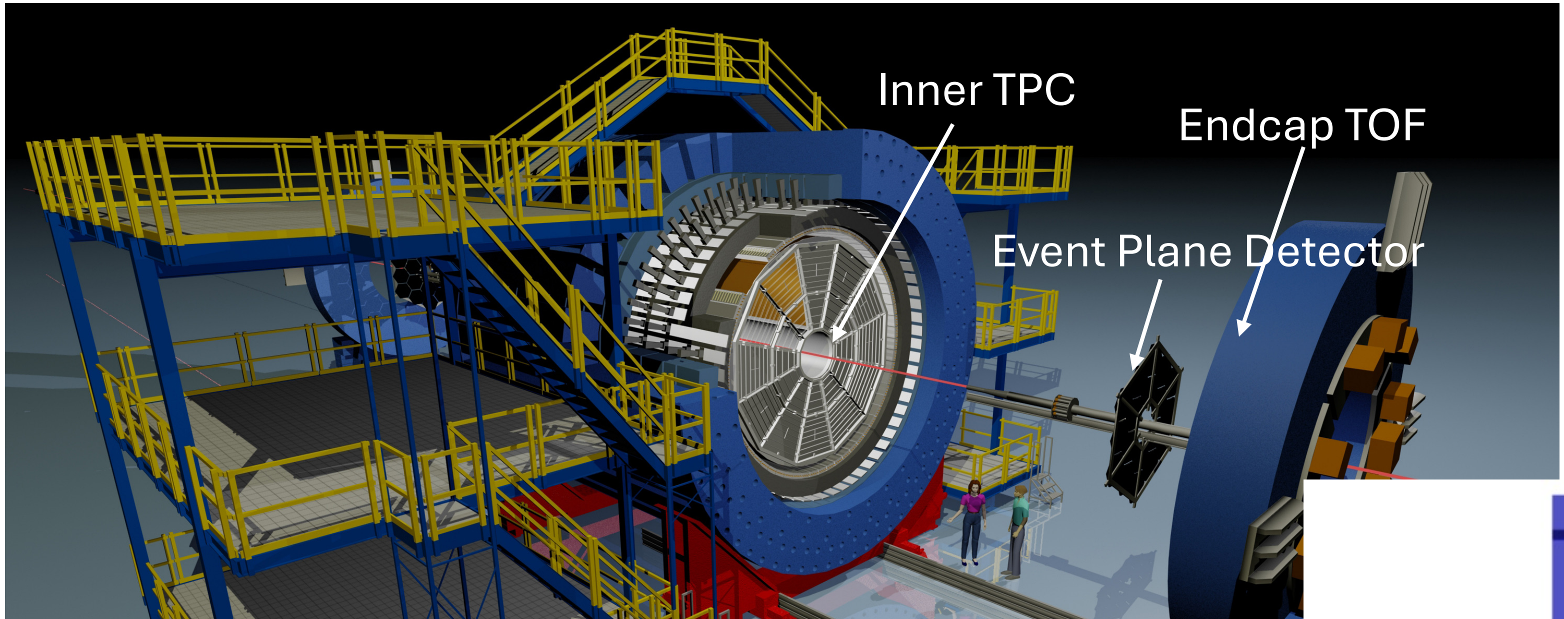
Determine QCD phase diagram via high energy heavy-ion collisions: seeking to map onset of deconfinement, and the predicted QCD critical point

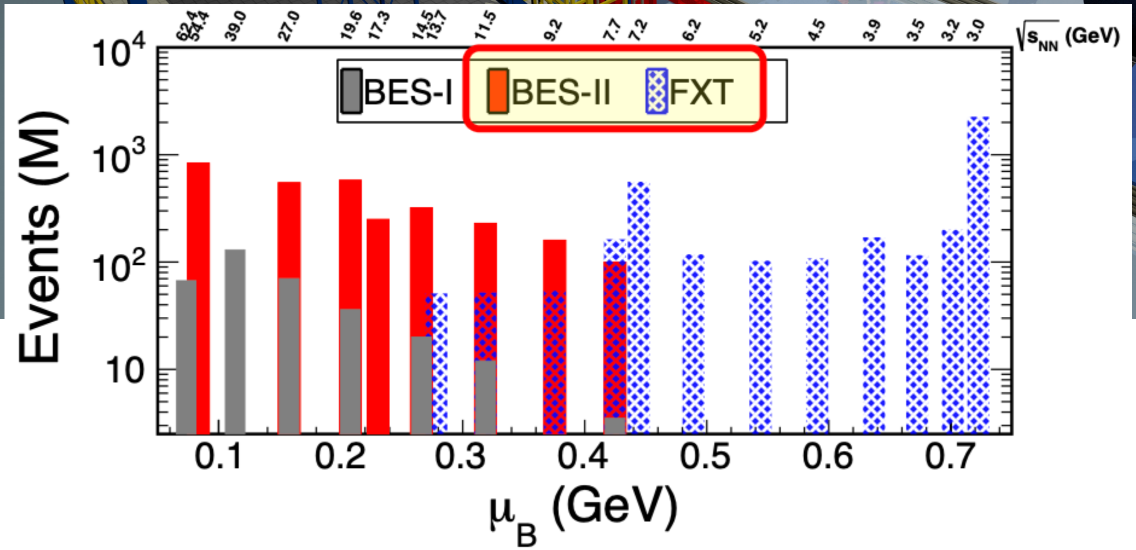
Crossover at μ_B close to 0 and predicted 1st-order phase transition at high μ_B

Beam Energy Scan program at RHIC:

- Vary initial T and μ_B
- Explore different trajectories across the phase boundary

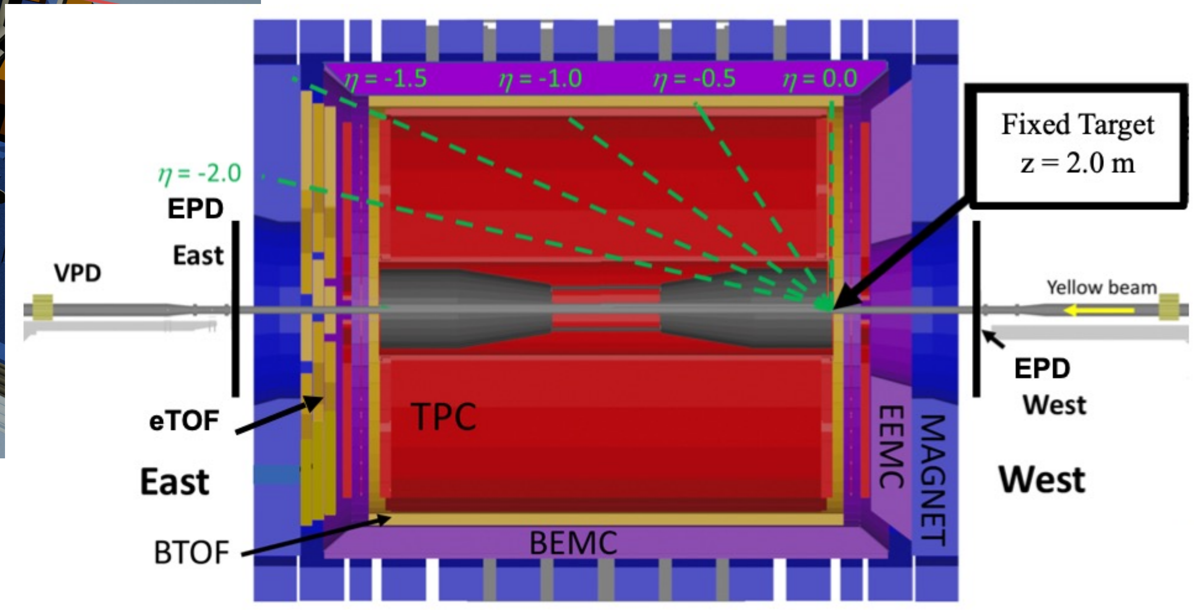
The BES-II Upgrades and fixed-target (FXT) setup at STAR





Large datasets with iTPC upgrade ~10 X BES-I

- Enhanced Acceptance (p_T and y)
- Enhanced PID mid and forward
- Enhanced Event Plane Resolution
- Enhanced Centrality Definition
- Enhanced $\sqrt{s}$ range

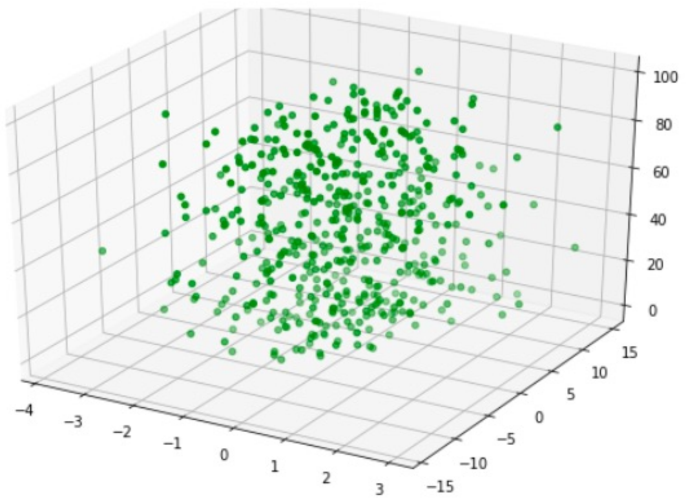


Mid-rapidity for 3.0 GeV is y = 1.049

Measurement: mean transverse momentum fluctuations

J. Jia, S. Huang, C. Zhang, PRC 105 , 014906 (2022)
S. Bhatta, C. Zhang, J. Jia, PRC106, L031901 (2022)
C. Zhang, A. Behera, S. Bhatta, J.Jia, PLB 822, 136702 (2021)

$$f\left(p_{x1}, p_{y1}, p_{z1}, p_{x2}, p_{y2}, p_{z2}\ldots\right)$$



Event-by-event temperature fluctuations

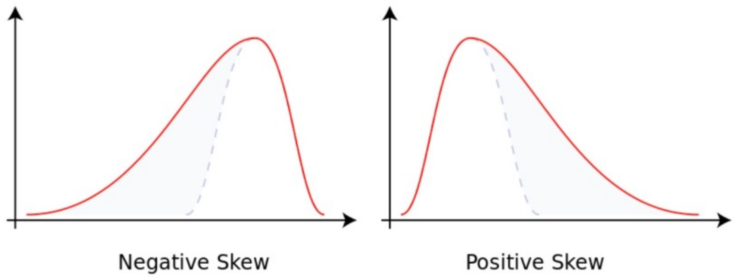
Mean: $$\langle\langle p_{\mathrm{t}}\rangle\rangle = \frac{\sum_{k=1}^{N_{\text{events}}} \langle p_{\mathrm{t}}\rangle_k}{N_{\text{events}}} \quad \text{where} \quad \langle p_{\mathrm{t}}\rangle_k = \frac{\sum_{i=1}^{N_k} p_{\mathrm{t},i}}{N_k}$$

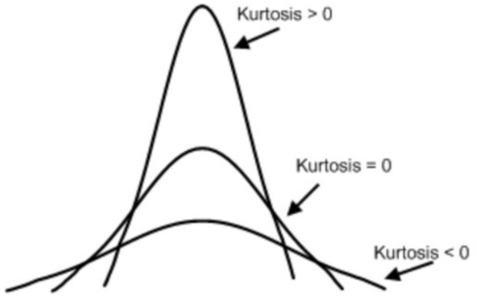
Variance: $$\left\langle (\delta p_T)^2 \right\rangle = \frac{\sum_i \sum_{j\neq i} \omega_i\omega_j \left(p_{T,i} - \langle [p_T] \rangle\right)\left(p_{T,j} - \langle [p_T] \rangle\right)}{\sum_i \sum_{j\neq i} \omega_i\omega_j},$$

Skewness: $$\left\langle (\delta p_T)^3 \right\rangle = \frac{\sum_{i,j\neq i,k\neq j\neq i} \omega_i\omega_j\omega_k \left(p_{T,i} - \langle [p_T] \rangle\right)\left(p_{T,j} - \langle [p_T] \rangle\right)\left(\left(p_{T,k} - \langle [p_T] \rangle\right)\right.}{\sum_{i,j\neq i,k\neq j\neq i} \omega_i\omega_j\omega_k},$$

Kurtosis: $$\left\langle (\delta p_T)^4 \right\rangle = \frac{\sum_{i,j\neq i,k\neq j\neq i,l\neq k\neq j\neq i} \omega_i\omega_j\omega_k\omega_l \left(p_{T,i} - \langle [p_T] \rangle\right)\left(p_{T,j} - \langle [p_T] \rangle\right)\left(\left(p_{T,k} - \langle [p_T] \rangle\right)\right)\left(p_{T,l} - \langle [p_T] \rangle\right)}{\sum_{i,j\neq i,k\neq j\neq i,l\neq k\neq j\neq i} \omega_i\omega_j\omega_k\omega_l}$$

Related to the entropy of the initial source presumably deposited early
in the collision before thermalization and interactions with QGP



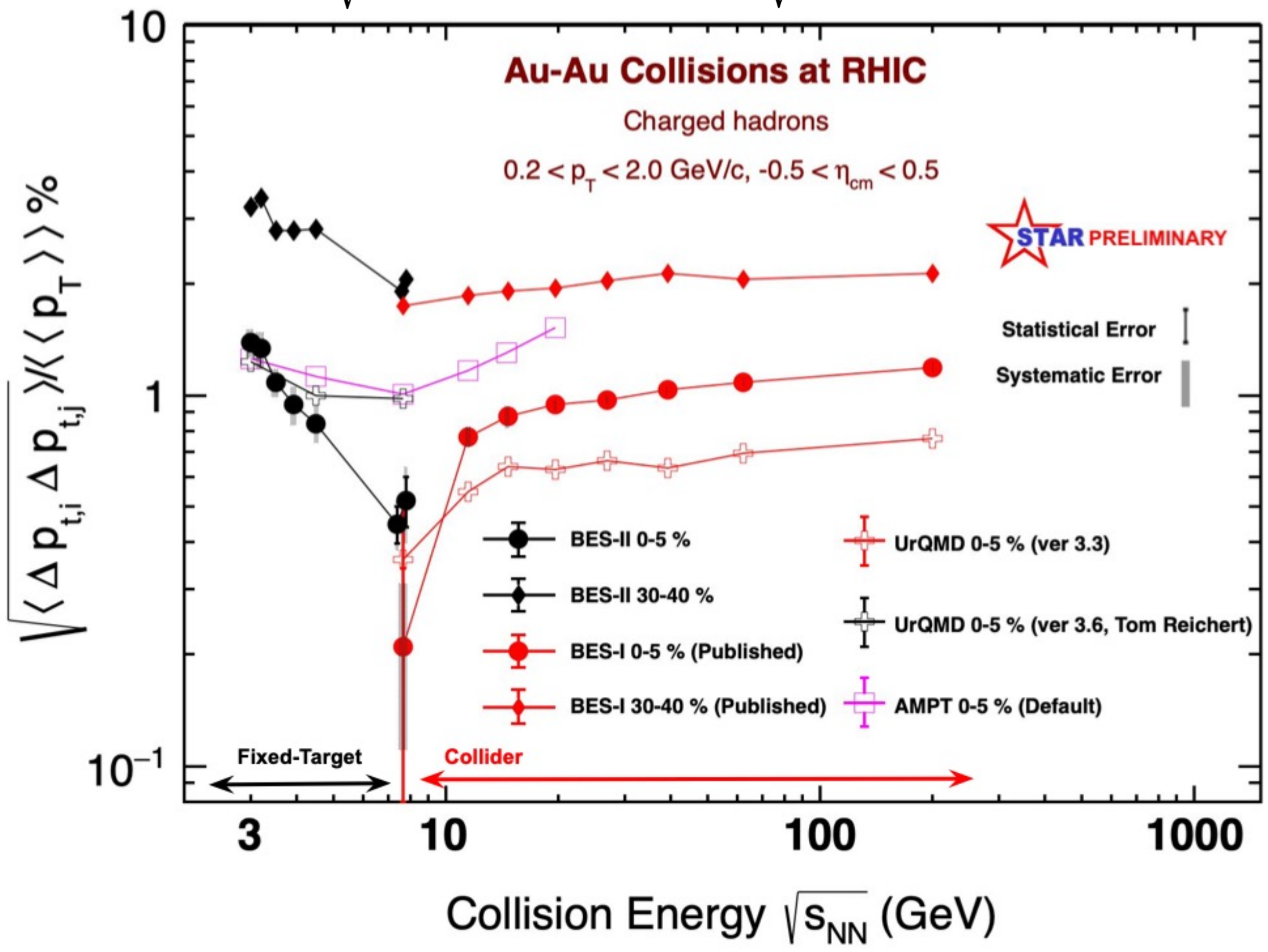


S. Gavin, Phys. Rev. Lett. 92, 162301

Correlator $\sqrt{\Delta p_{T,i}\Delta p_{T,j}}/\langle\langle p_T\rangle\rangle$ vs collision energy in FXT mode

Rutik Manikandhan (UH) Quark Matter 2025

$$\sqrt{\langle\Delta p_{t,i}\Delta p_{t,j}\rangle}/\langle\langle p_T\rangle\rangle = \sqrt{\langle(\delta p_T)^2\rangle}/\langle\langle p_T\rangle\rangle$$



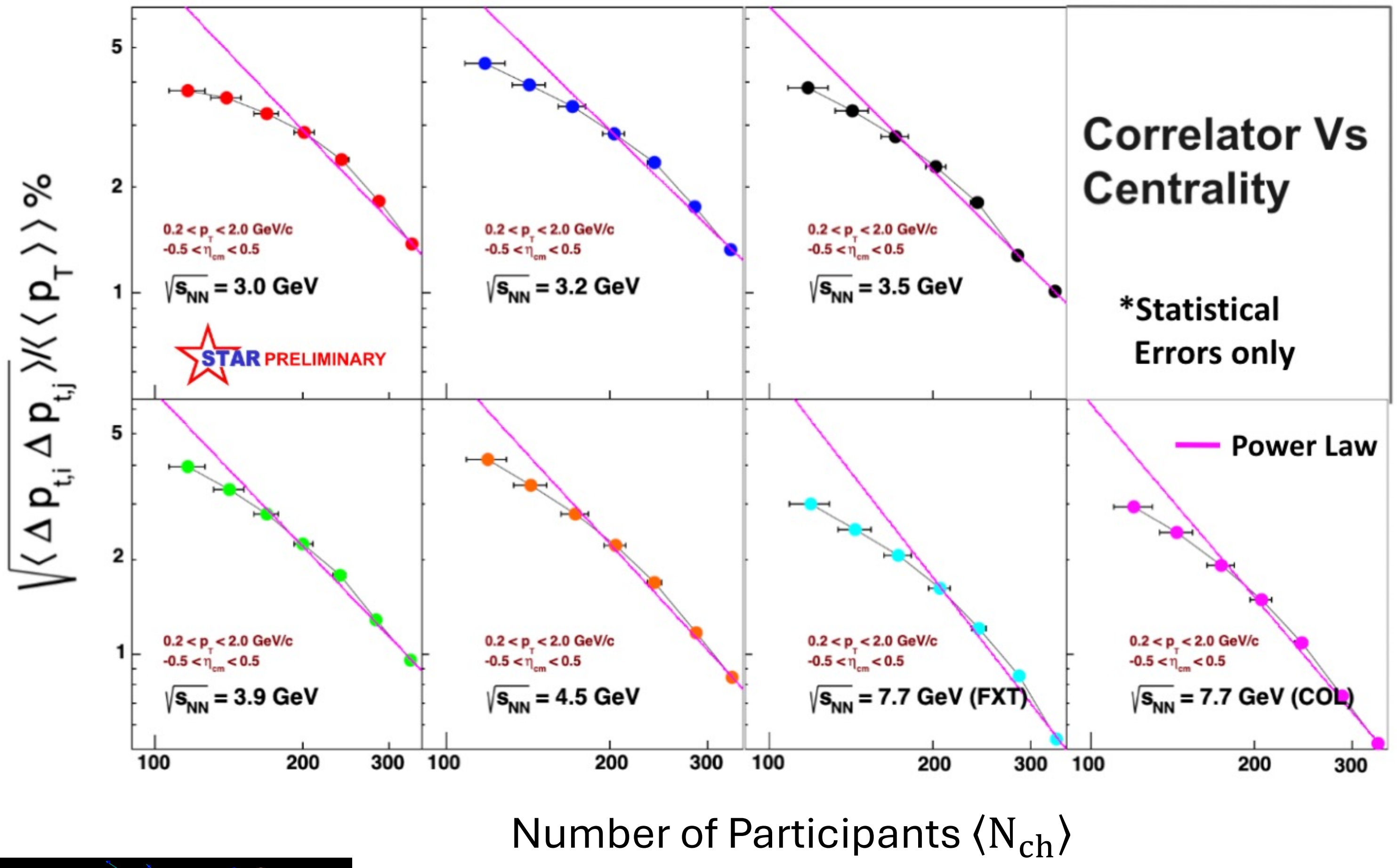
- ❑ The correlator is scaled by the mean to remove trivial energy dependence
- ❑ Efficiency independent
- ❑ Significant non-monotonic dependence in most central collisions.
- ❑ Transport codes provide a **qualitative** description of measurements [4],

Our measurements show non-monotonicity in the region predicted by various theoretical estimates for the location of the critical point.

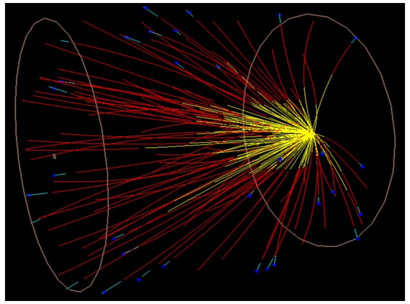
AMPT: L. Zhang, J. Chen, C. Zhang, PRC 111, 024911 (2025)

Correlator $\sqrt{\Delta p_{T,i}\Delta p_{T,j}}/\langle\langle p_T\rangle\rangle$ vs centrality in FXT mode

Rutik Manikandhan (UH) Quark Matter 2025



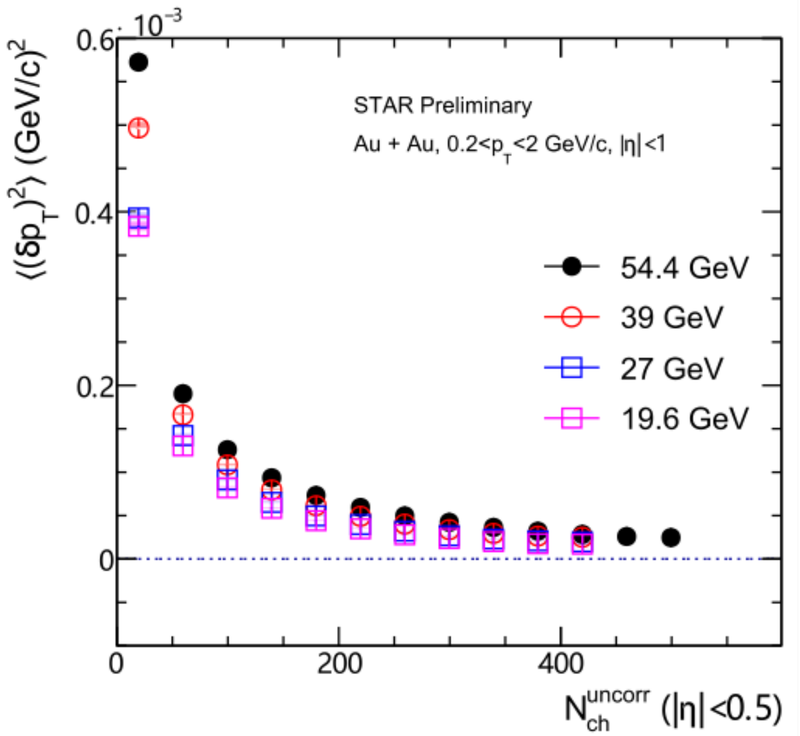
- ❑ correlations larger in the peripheral collisions and decrease with centrality
- ❑ Measurements deviate from power law behavior, implying the centrality dependence does not follow a simple superposition scenario

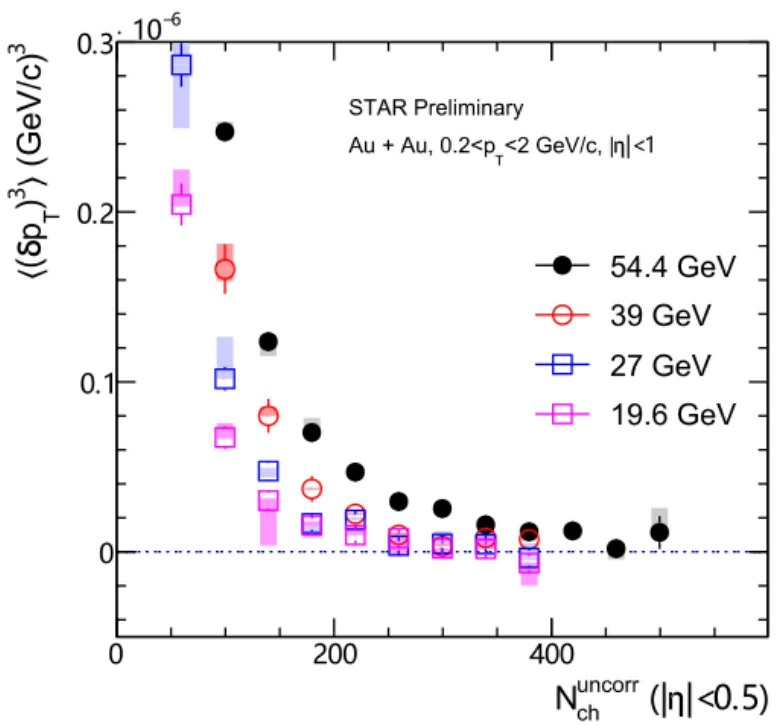


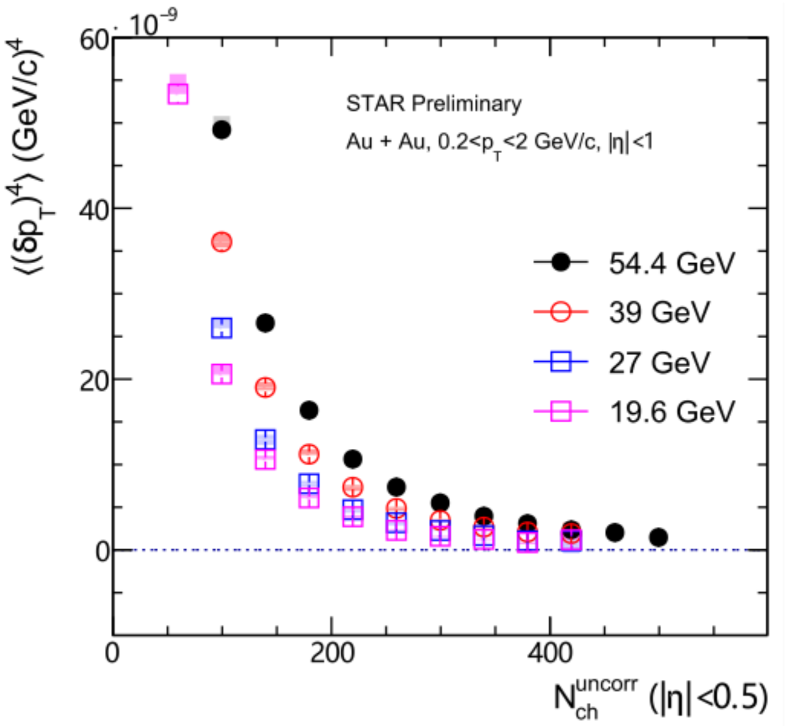
- ❑ **Independent of the collision mode**: good agreement between measurements made at 7.7 GeV in FXT and collider modes.

Correlator $\langle(\delta p_T)^n\rangle$ vs centrality in collider mode

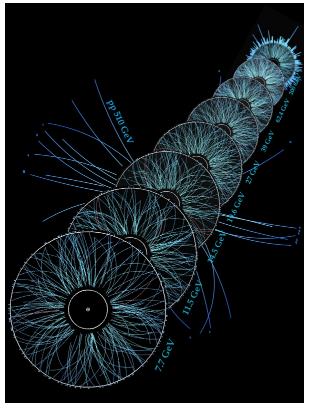
Yining Gao (Fudan) Quark Matter 2025







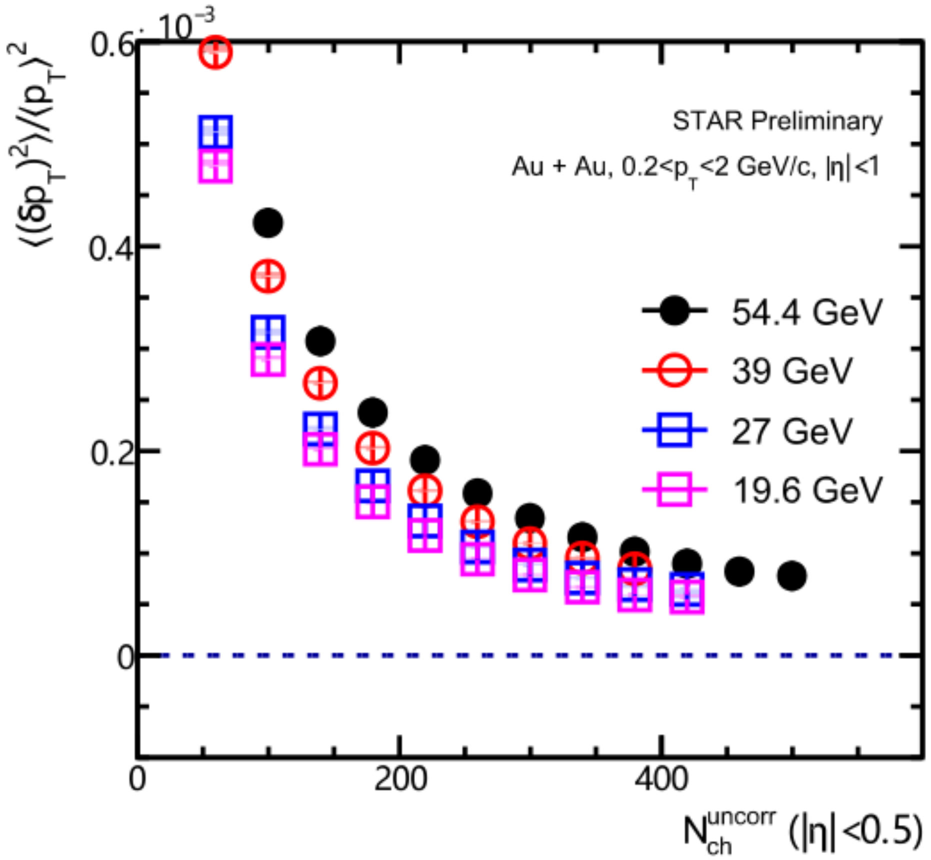
Efficiency-uncorrected N_{ch}

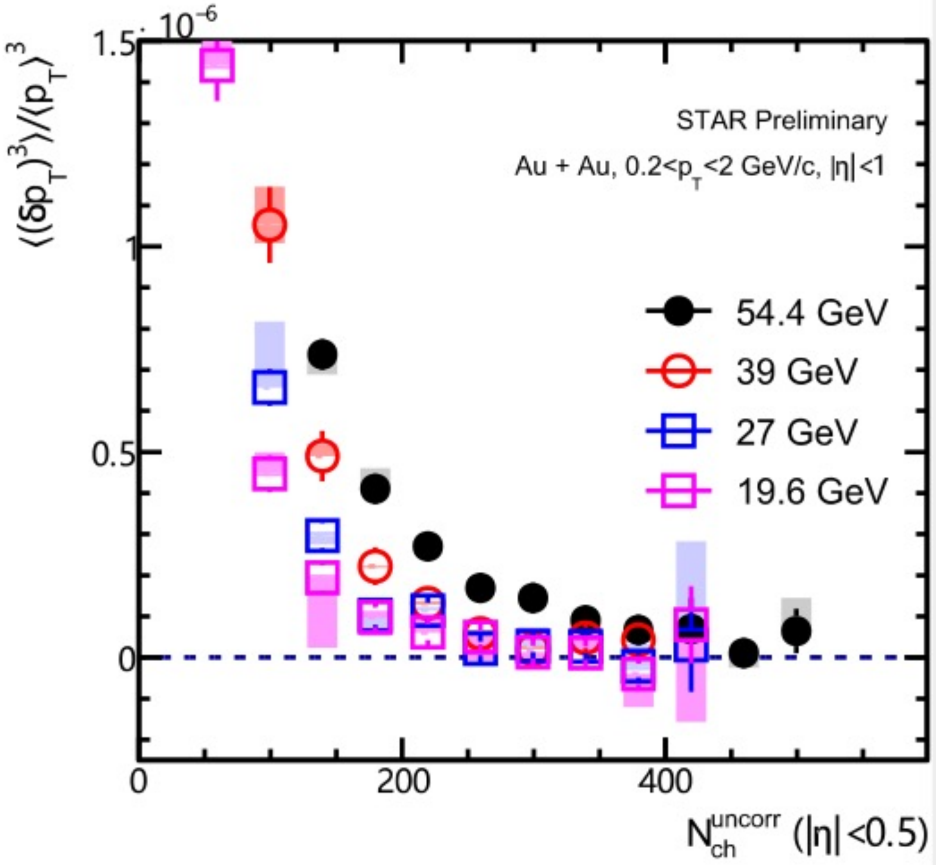


- ❑ **Values of correlators of variance, skewness and kurtosis increase towards peripheral collisions.**
- ❑ **Slight energy dependence is observed.**

Correlator $\langle(\delta p_T)^n\rangle$ vs centrality in collider mode

Yining Gao (Fudan) Quark Matter 2025





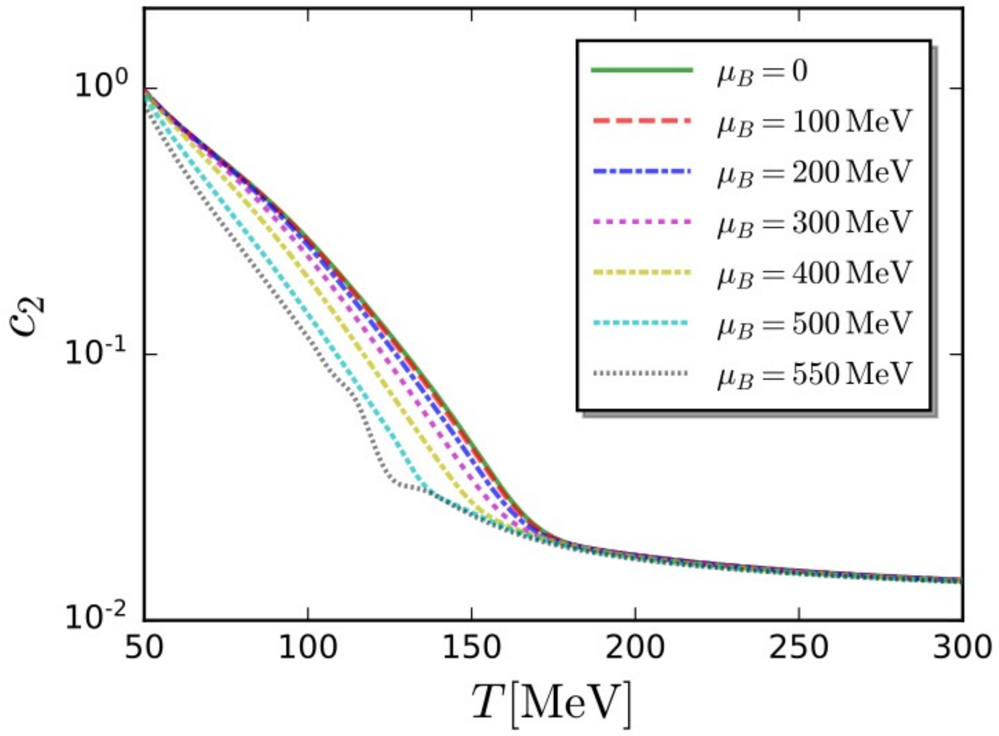
- **With increasing charge-multiplicity, the normalized correlators of variance and skewness decrease in magnitudes.**
- **Energy dependence that increase towards peripheral collisions are observed.**

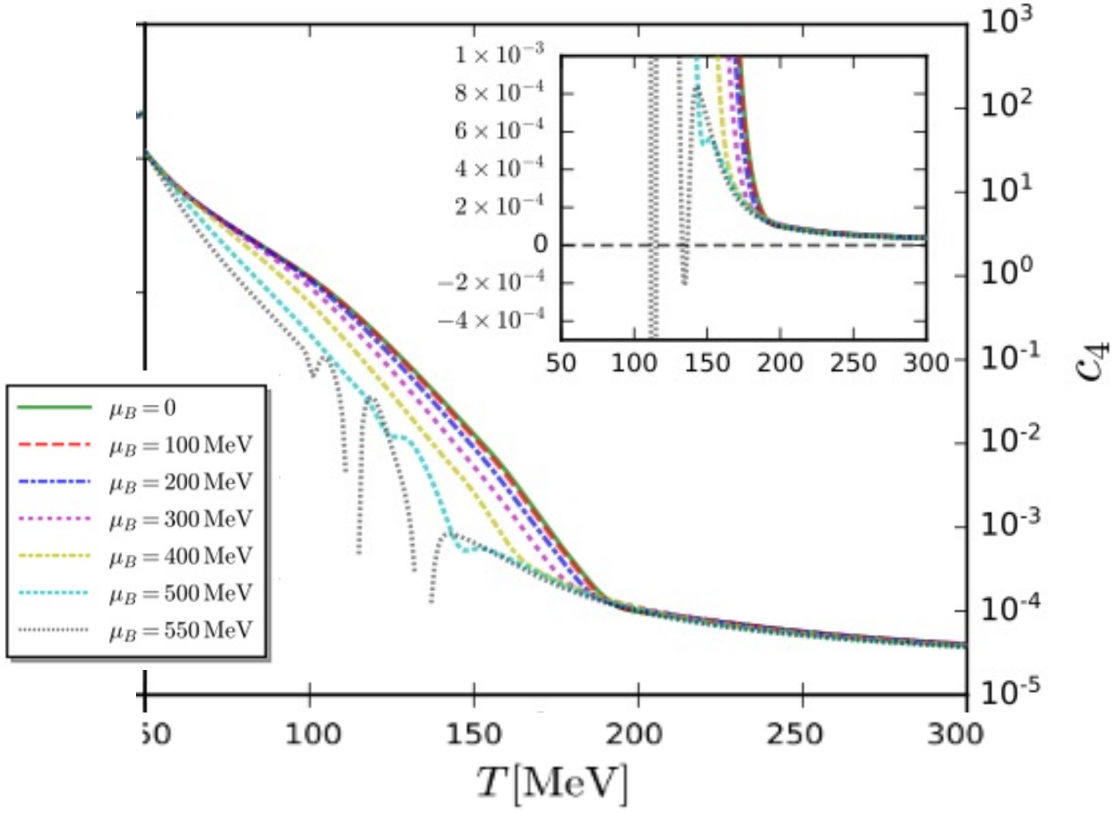
Our measurement are useful to further understand initial conditions and EbE fluctuations across different collision energies.

High-order fluctuations of temperature in fRG approach

$$c_2 = \frac{1}{\chi_2}, \qquad c_3 = -\frac{\chi_3}{{\chi_2}^3}, \qquad c_4 = 3\frac{{\chi_3}^2}{{\chi_2}^5} - \frac{\chi_4}{{\chi_2}^4}$$

2+1 flavor LEFT within the fRG approach





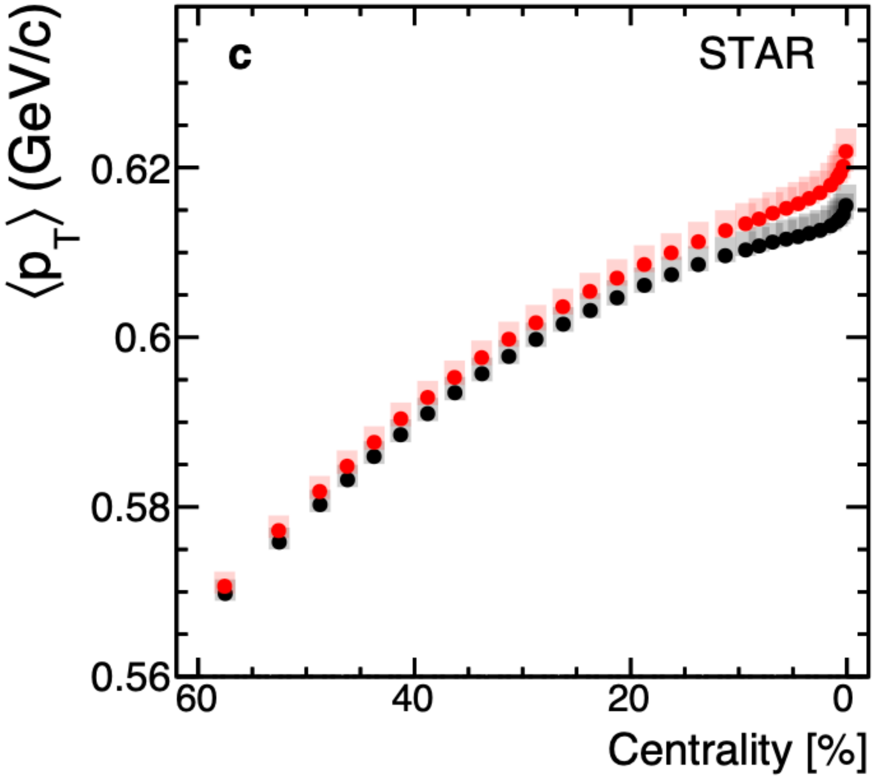
- ❑ **Indicating a significant suppression of temperature fluctuations in QGP phase compared to those in HRG phase.**

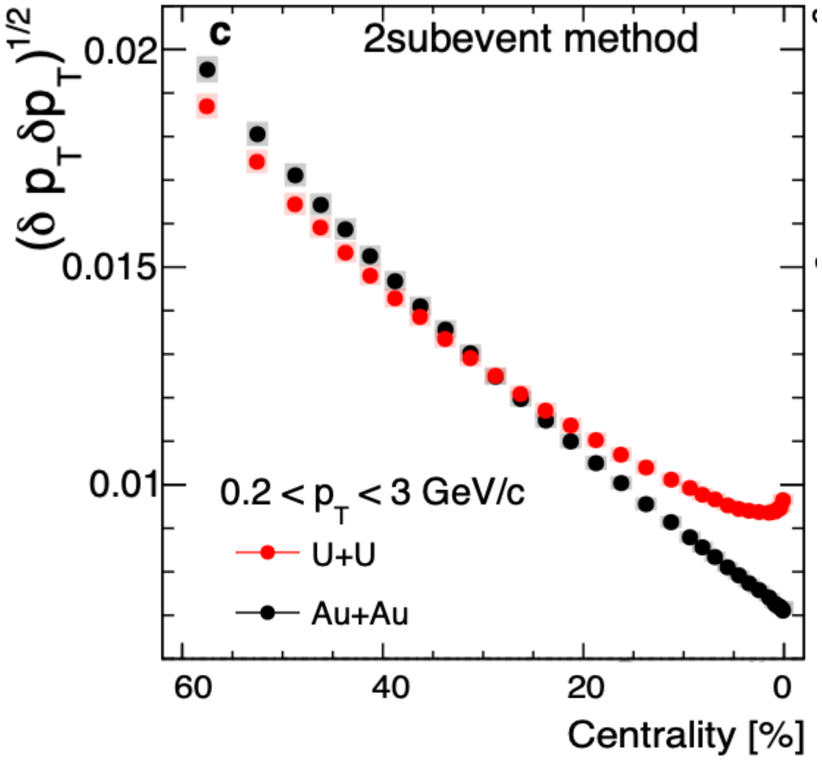
- ❑ **The suppression is more remarkable for high-order temperature fluctuations**

J. Chen, W. Fu, S. Yin, C. Zhang, arXiv:2504.06886

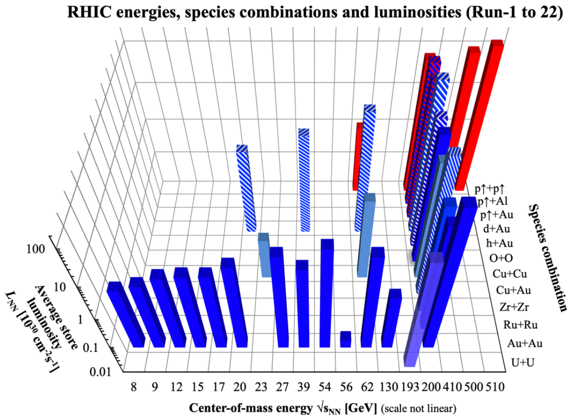
[p_T] fluctuations as another novel tool to image nuclear structure

STAR, Reports on Progress in Physics: Original Research (accepted)





large enhancement in mean and variance ⟶ size fluctuations enhanced

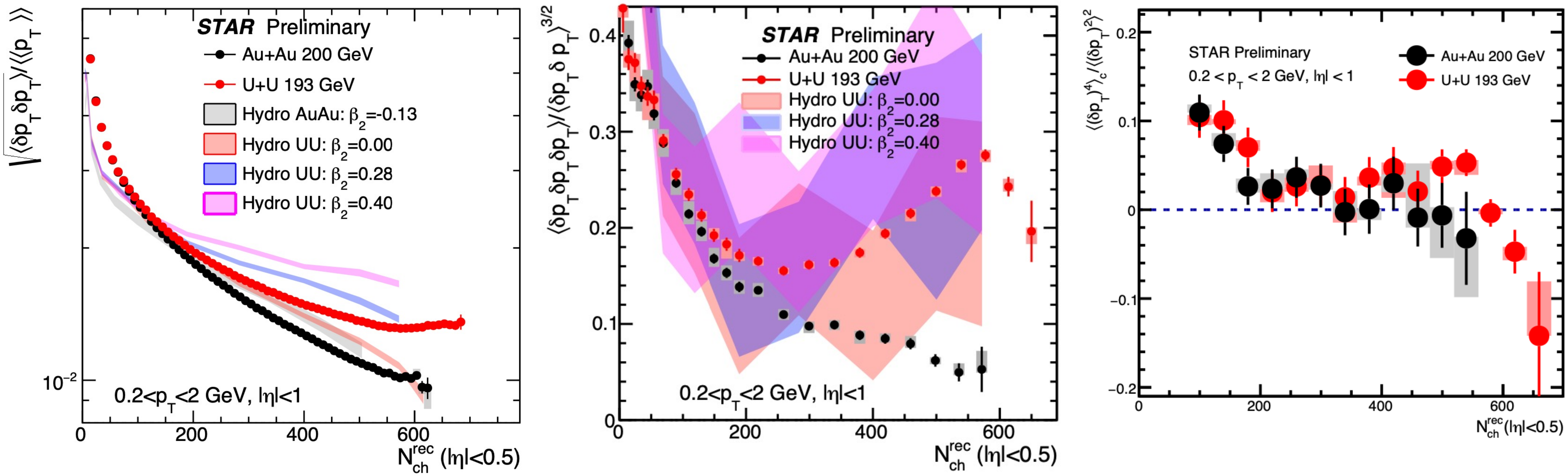


[p_T] fluctuations also serve as a good observable to image nuclear deformation.

ALICE, PLB 850, 138541 (2024); ATLAS, PRL 133, 252301 (2024)

$[p_T]$ fluctuations as another novel tool to image nuclear structure

C. Zhang, IJMPE 32, 2341001 (2023)



Au+Au: variance and skewness follow independent source scaling $1/N_s^{n-1}$ within power-law decrease

U+U: large enhancement in normalized variance and skewness and sign-change in normalized kurtosis
⟶ size fluctuations enhanced

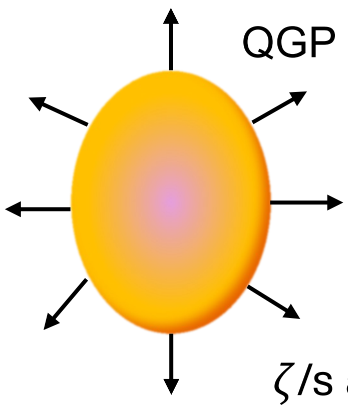
The nuclear deformation role is further confirmed by hydro calculations.

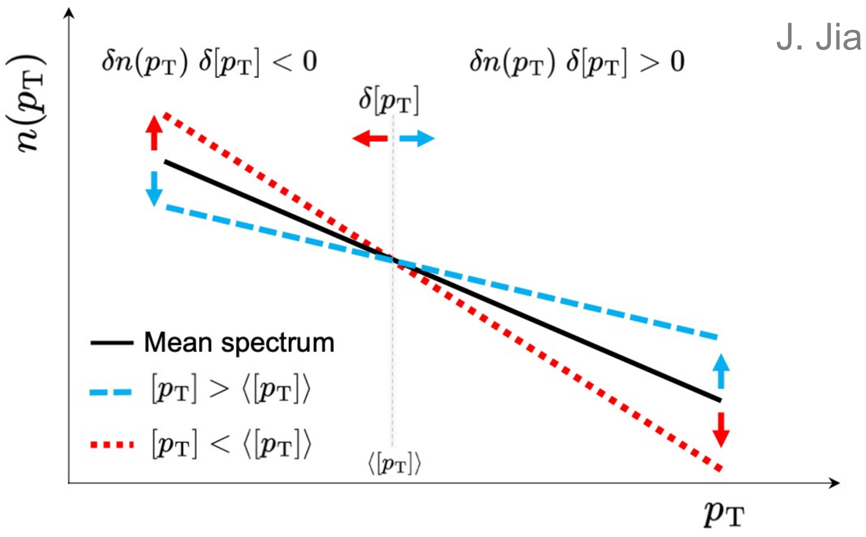
$[p_T]$ fluctuations also serve as a good observable to image nuclear deformation.

ALICE, PLB 850, 138541 (2024); ATLAS, PRL 133, 252301 (2024)

Radial flow $v_0(p_T)$ measurement in 200 GeV

Radial expansion: the n=0 modulation





Spectra slope quantified by $[p_T]$ in each event:
Fluctuation in $[p_T]$ →Fluctuation in spectra.

Quantify the correlation induced by radial flow using
covariance between $n(p_T)$ and $[p_T]$: $\langle \delta n(p_T) \delta[p_T] \rangle$

B. Schenke, C. Shen, D. Teaney, PRC 102, 034905 (2020)
T. Parida, R. Samanta, J.Y. Ollitrault, PLB 857, 138985 (2024)
S. A. Jahan, H. Roch, C. Shen. arXiv: 2507.11394
L. Du, 2508.07184

Calculated within a reference range, p_T-independent.

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

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

Pearson Correlations between local possiblity of particle yield and reference mean p_T from spectra

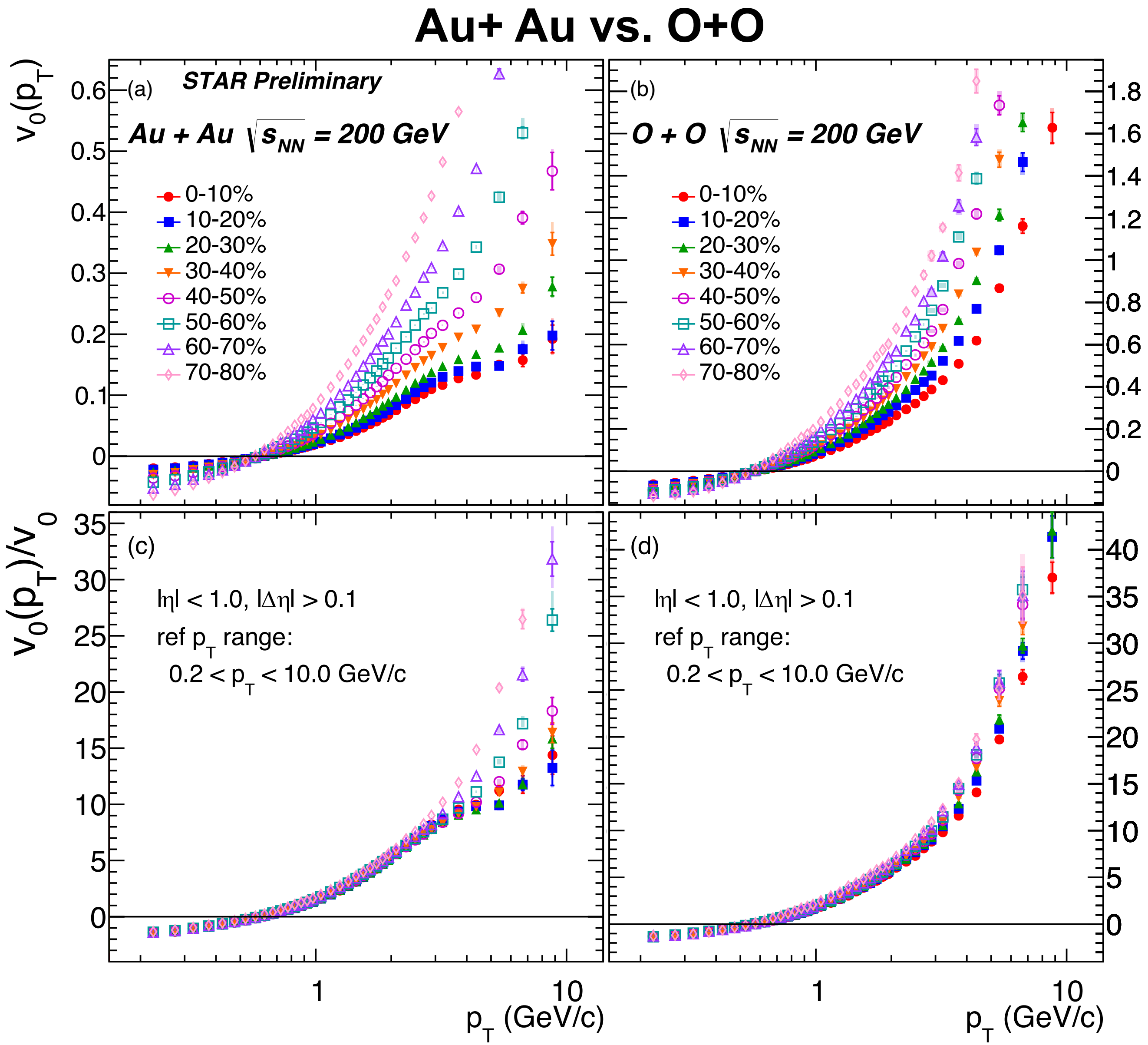
Remove influence from global fluctuations

This allows us to verify the signatures of radial flow, like for anisotropic flow (n≥1)

$v_0(p_T)$ in system-size comparison

New

Zaining Wang (Fudan & Stony Brook), Initial Stages 2025



First measurement at RHIC energy

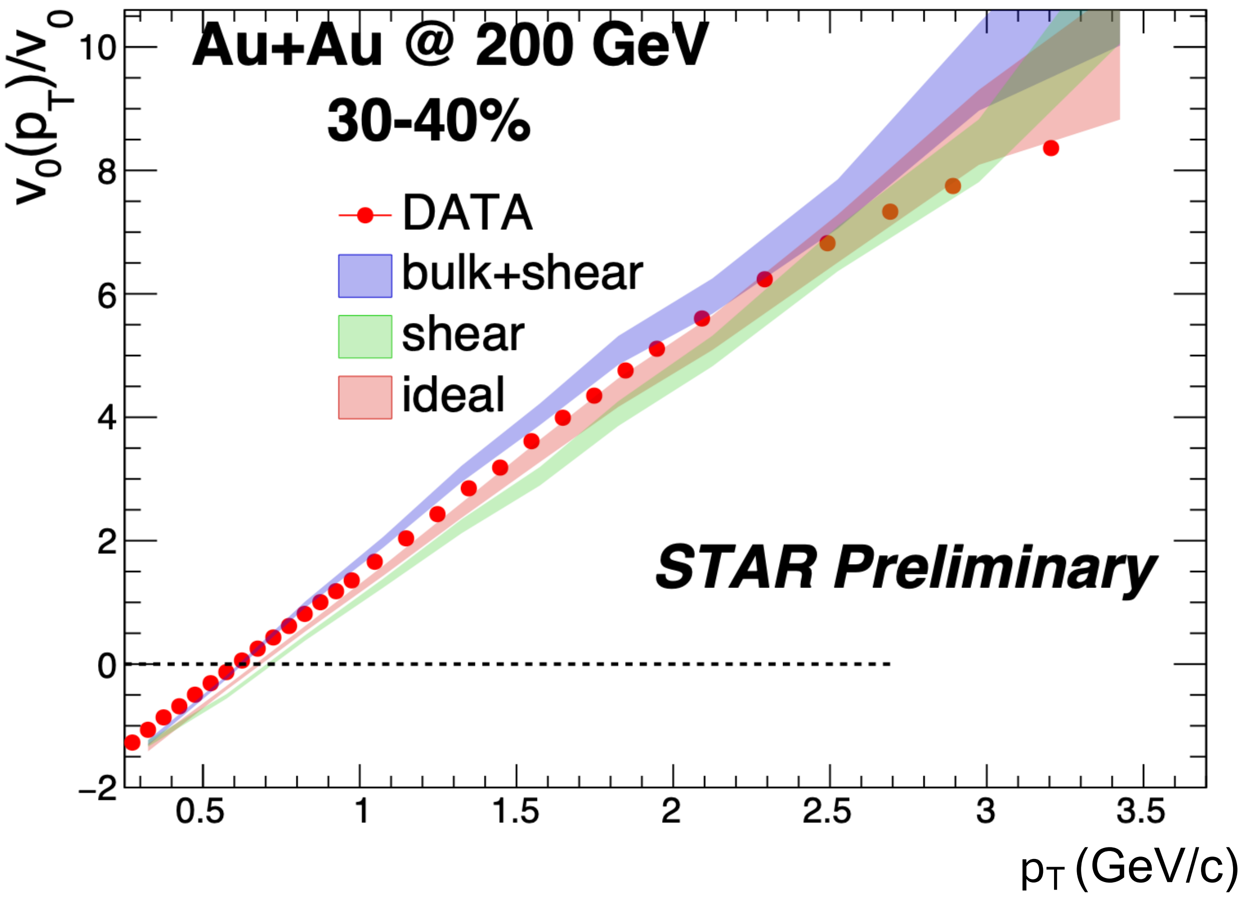
Increase with p_T
Exhibiting a strong centrality dependence.
The zero-crossing point coincides with $\langle[p_T]\rangle$, where fluctuations vanish

After normalization, all centralities collapse onto a single trend, indicating a hydrodynamic collective response to global fluctuations

$$v_0(p_T) = \frac{\langle \delta n(p_T)\, \delta [p_T]_{p_T^{ref}} \rangle}{\langle \delta n(p_T) \rangle \, (\langle \delta [p_T] \rangle v_0)_{p_T^{ref}}}$$

Bulk viscosity sensitivity

New

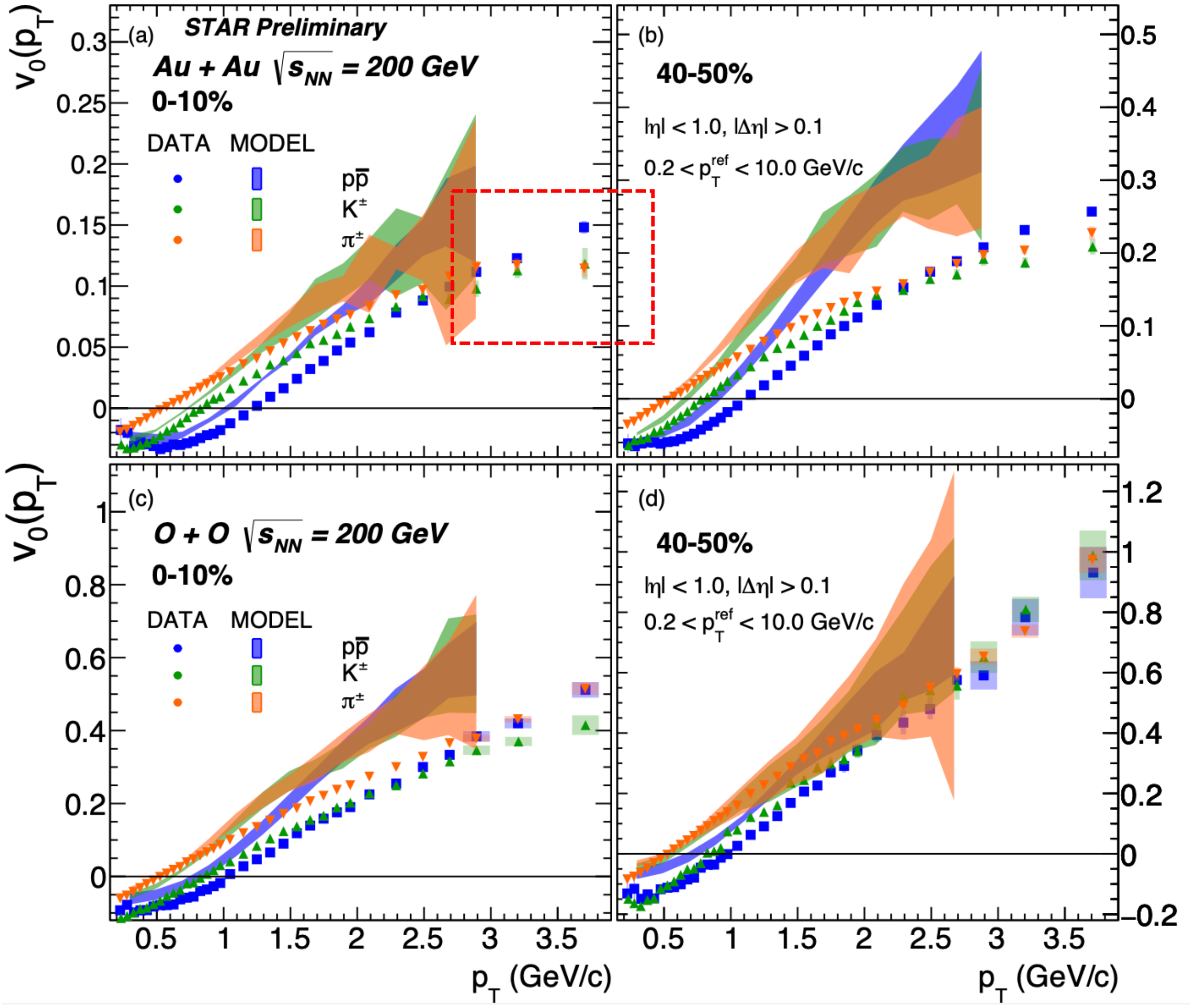


The observable shows sensitivities to bulk viscosity

Model calculations from Lipei Du

PID measurement and data-model comparisons

New



$$v_0(p_T) = \frac{\langle \delta n(p_T)\, \delta[p_T]_{p_T^{ref}} \rangle}{\langle \delta n(p_T) \rangle \left(\langle \delta[p_T] \rangle v_0 \right)_{p_T^{ref}}}$$

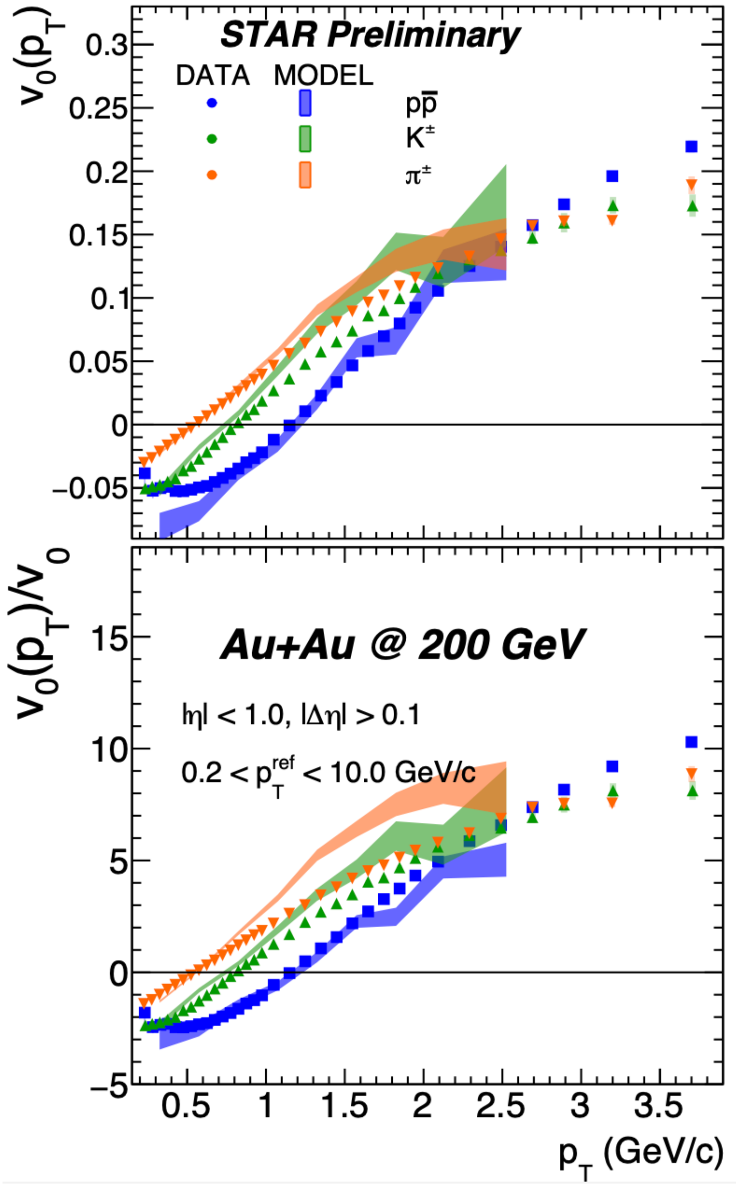
The stronger boost experienced by heavier particles gives rise to a clear mass ordering

3D-Glauber+MUSIC+UrQMD model also show clear mass ordering, but quantitative differences compared to data

Model calculations from Chun Shen

PID measurement and data-model comparisons

New



$$v_0(p_T) = \frac{\langle \delta n(p_T)\, \delta[p_T]_{p_T^{ref}} \rangle}{\langle \delta n(p_T) \rangle \left(\langle \delta [p_T] \rangle v_0 \right)_{p_T^{ref}}}$$

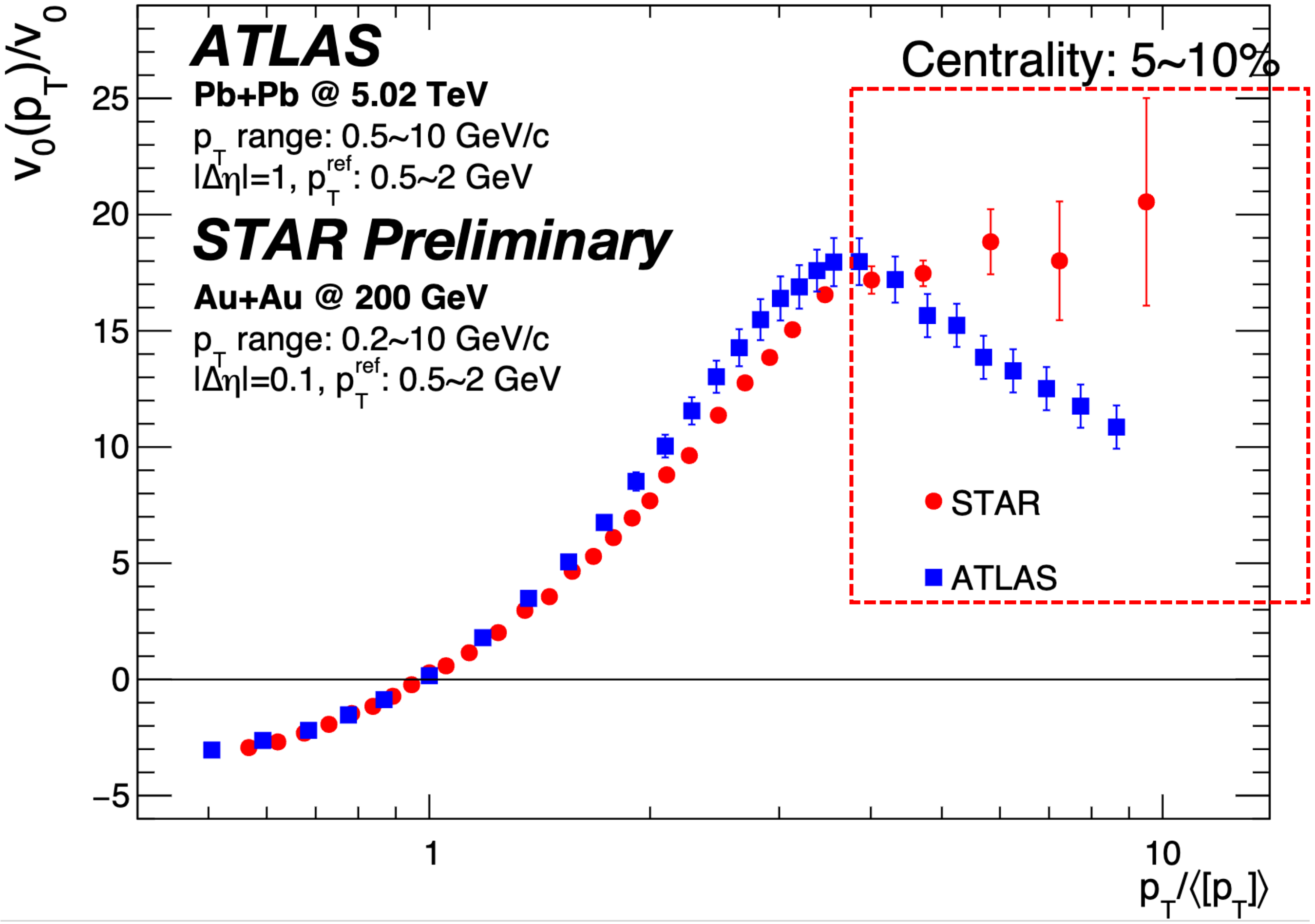
TRENTo+free-streaming+MUSIC+iSS+SMASH seems more comparable with data.

More model calculations are needed to tune for fitting this new observables at RHIC energies.

Model calculations from Lipei Du

Energy evolution from LHC to RHIC energies

New



Close radial flow fluctuations between the LHC and RHIC measurements with similar slope at low p_T

$p_T > 4$ GeV/c region is different.

Future system- and energy-scans are interesting and useful for understanding radial flow

Conclusions and Outlooks

1. **Observation of non-monotonic dependence** of mean p_T fluctuations at high baryon density**,** **negative kurtosis** in highly-deformed U^{238}.

2. **Negative kurtosis** in highly deformed U^{238} indicates the nuclear structure effect.

3. New measurements to help narrow down the nature of radial flow and temperature fluctuation, including the **QGP collectivity behavior, initial conditions, and nuclear structure imaging.**