中国高能核物理网络论坛
HIGH ENERGY NUCLEAR PHYSICS IN CHINA

Mean transverse momentum fluctuations as probes of nuclear structure and QCD matter

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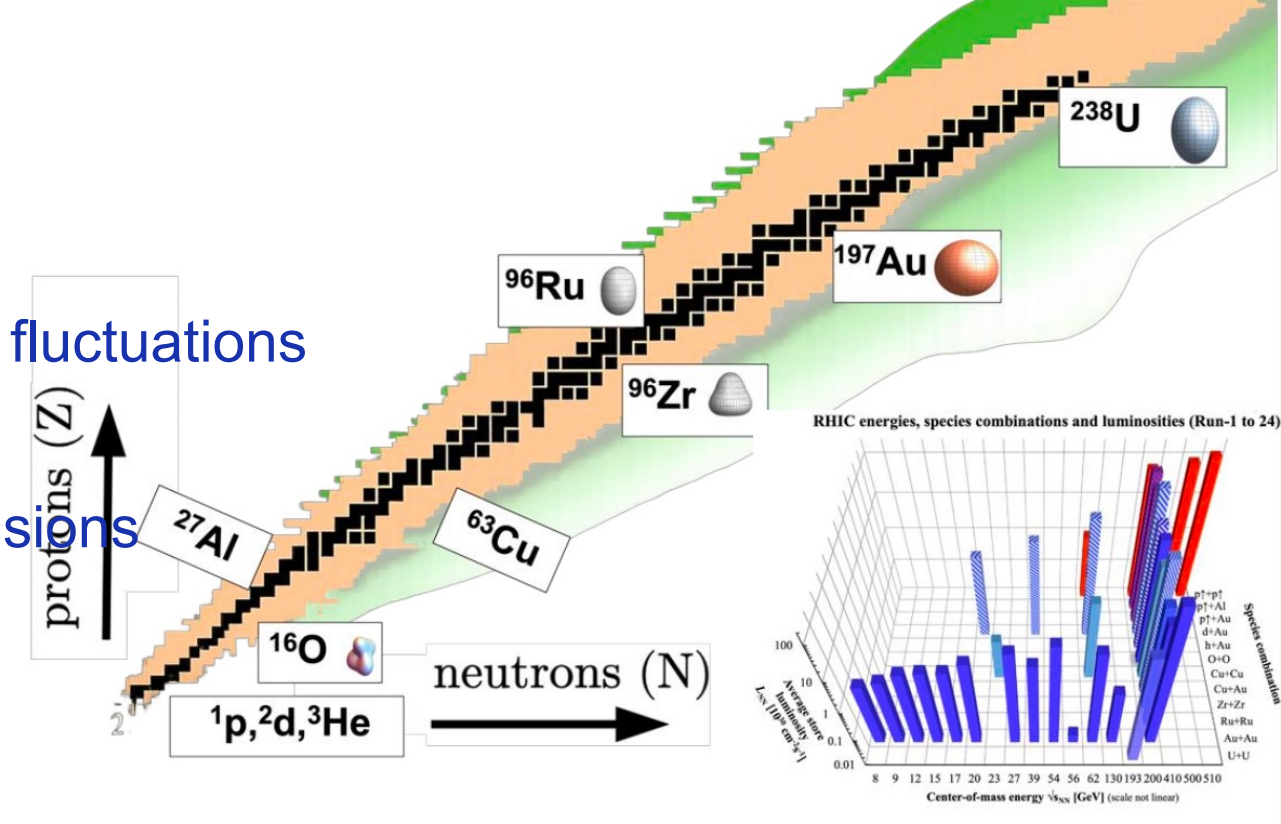
Outline

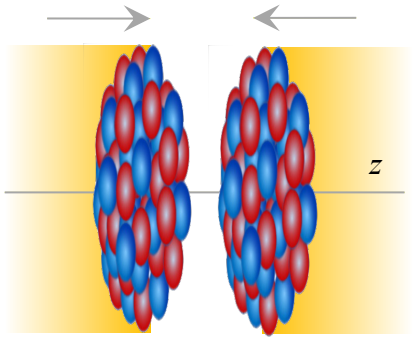
- **Introductions:** mean transverse momentum fluctuations
- Imaging nuclear structure in high-energy collisions
  - I. Nuclear structure in ^{238}U, ^{96}Ru/^{96}Zr
  - II. Geometry effect and subnucleon fluctuations in ^{16}O
- Probing QCD matter properties
  - I. Energy dependence of second-order p_T fluctuation in ^{197}Au + ^{197}Au collisions
  - II. Energy dependence of high-order p_T fluctuations in ^{197}Au + ^{197}Au collisions



❑ **Introductions:** mean transverse momentum fluctuations

Imaging by smashing method and event-by-event fluctuations

Nuclear configurations



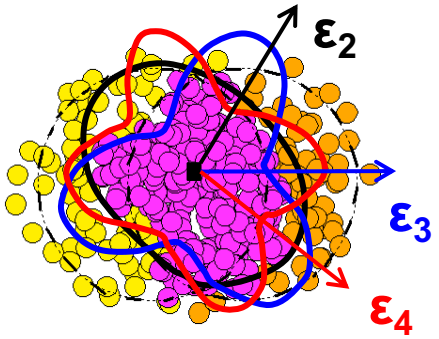
Nuclear density & correlations

Fast snapshot

$\tau \sim 2R_0/\Gamma \sim 0.1\mathrm{fm}/c$

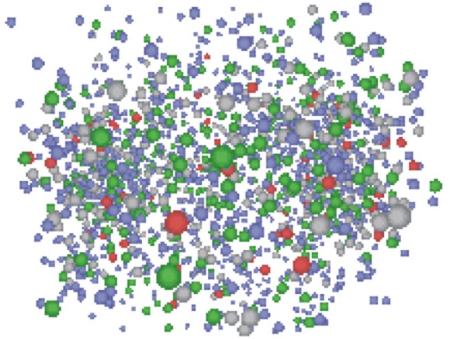
exposure

Initial geometry



Size & eccentricities

Final-state correlations



Momentum correlations

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

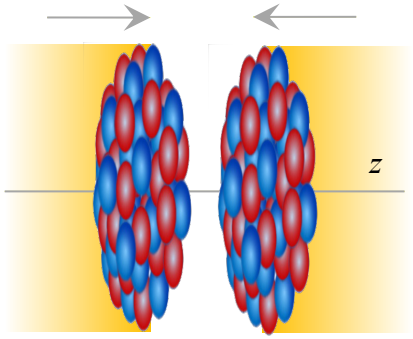
- β_2 → quadrupole deformation
- β_3 → octupole deformation
- γ → triaxiality
- a_0 → surface diffuseness
- R_0 → nuclear size

ab initio theory/shell model/DFT

J. Jia et al., *Nucl. Sci. Tech. 35, 220 (2024)*

Imaging by smashing method and event-by-event fluctuations

Nuclear configurations



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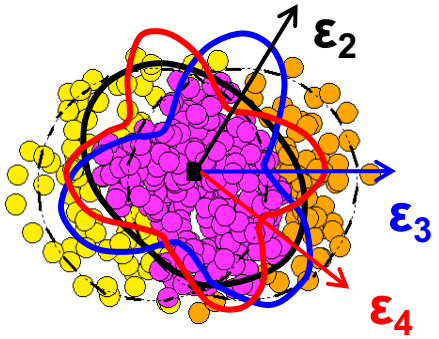

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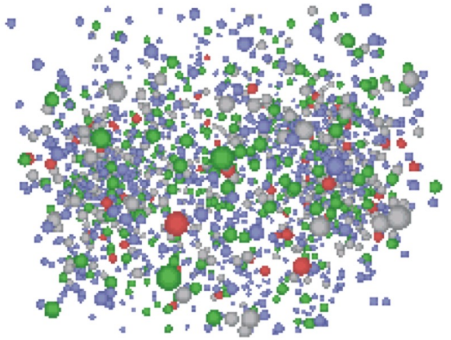

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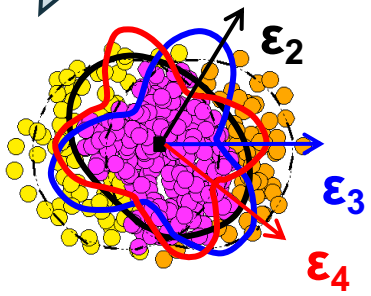


size & shape

J. Jia et al., *Nucl. Sci. Tech. 35, 220 (2024)*

$R_\perp^2 \propto \langle r_\perp^2 \rangle$

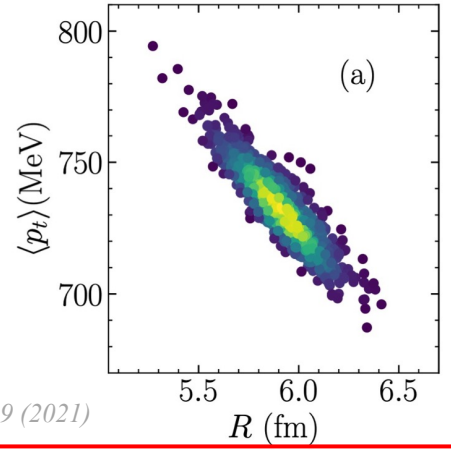
$\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$

R_0 a_0 β_n

Observables $\frac{d^2N}{d\phi dp_T} = N(p_T)\left(\sum_n V_n e^{-in\phi}\right)$

linear responses:

$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$$

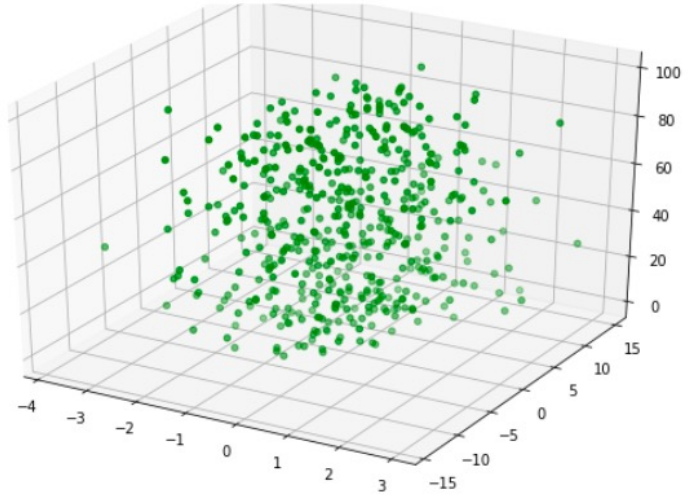


G. Giacalone et al., *PRC 103, 024909 (2021)*

Key: 1) fast snapshot, 2) linear response, 3) large multiplicity for many-body correlation

New observables: mean transverse momentum fluctuations

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



Event-by-event temperature 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)*

Mean: $\langle\langle p_{\mathrm{t}}\rangle\rangle = \dfrac{\sum_{k=1}^{N_{\mathrm{events}}} \langle p_{\mathrm{t}}\rangle_k}{N_{\mathrm{events}}}$ where $\langle p_{\mathrm{t}}\rangle_k = \dfrac{\sum_i w_i p_{\mathrm{t},i}}{\sum_i w_i}$

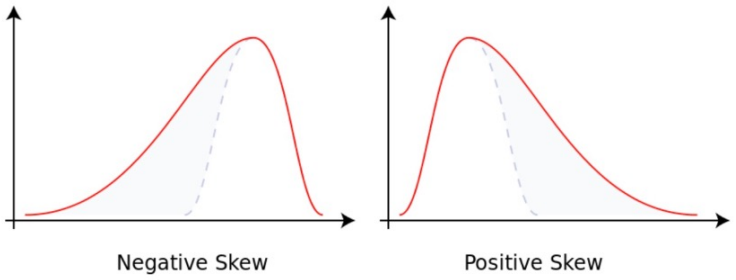
w_i is the detector efficiency

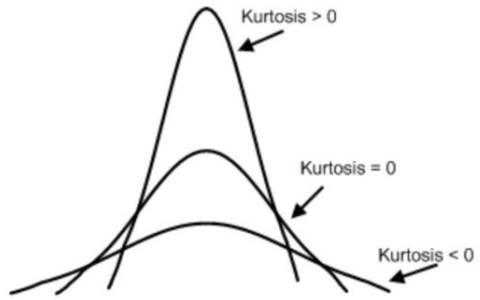
Variance: $\left\langle (\delta p_T)^2 \right\rangle = \dfrac{\sum_i \sum_{j\neq i} \omega_i\omega_j \left(p_{T,i} - \langle [p_T]\rangle\right)\left(p_{T,j} - \langle [p_T]\rangle\right.}{\sum_i \sum_{j\neq i} \omega_i\omega_j},$

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

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

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



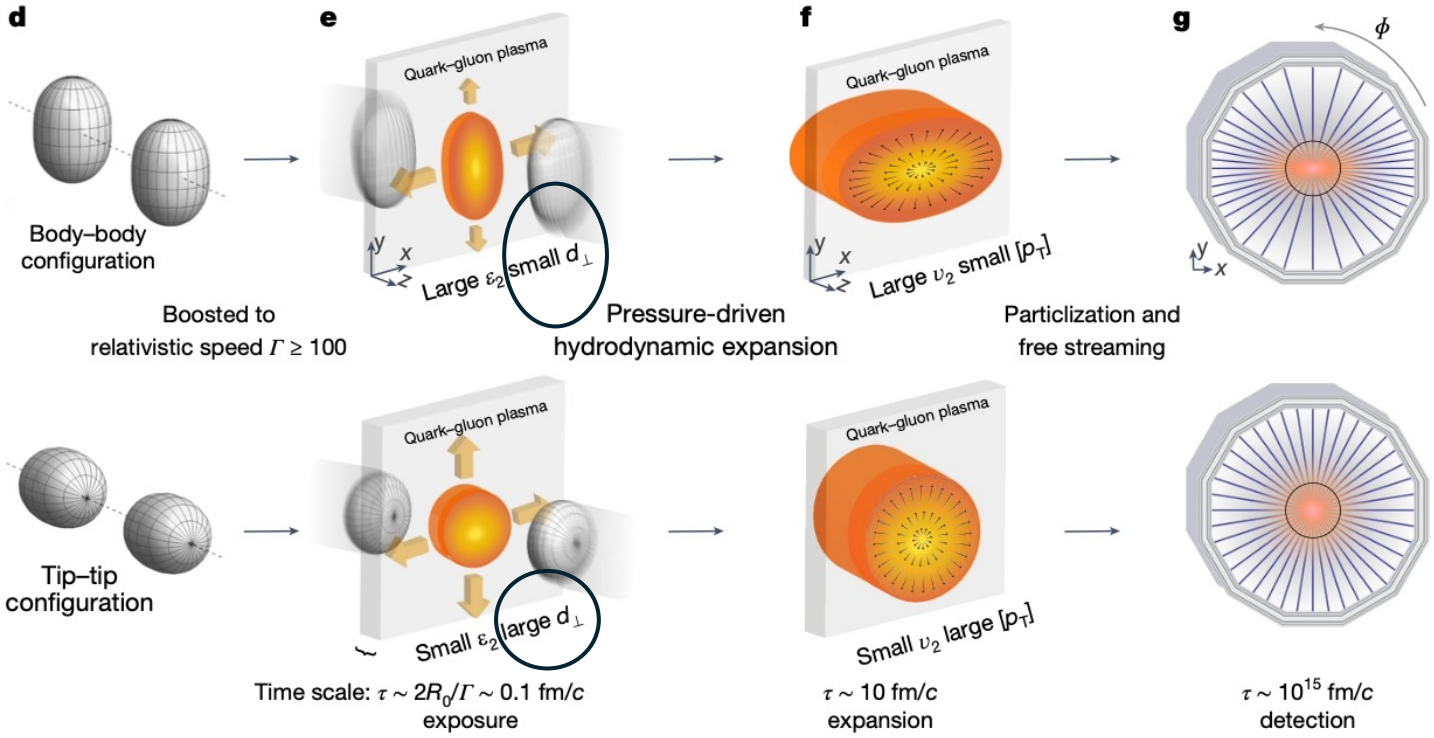


S. Gavin, *PRL 92, 162301 (2004)*

❑ Imaging nuclear structure in high-energy collisions

I. Nuclear structure in ^{238}U, ^{96}Ru/^{96}Zr

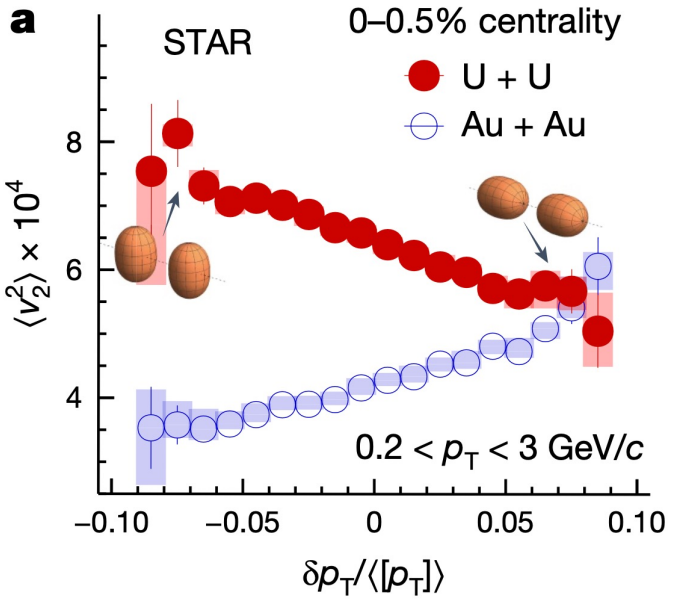
Imaging nuclear shape in high-energy snapshot



Nuclear deformation across energy scales

STAR, *Nature 635, 67-72 (2024)*

Body-body: v_2 ↗ p_T ↘



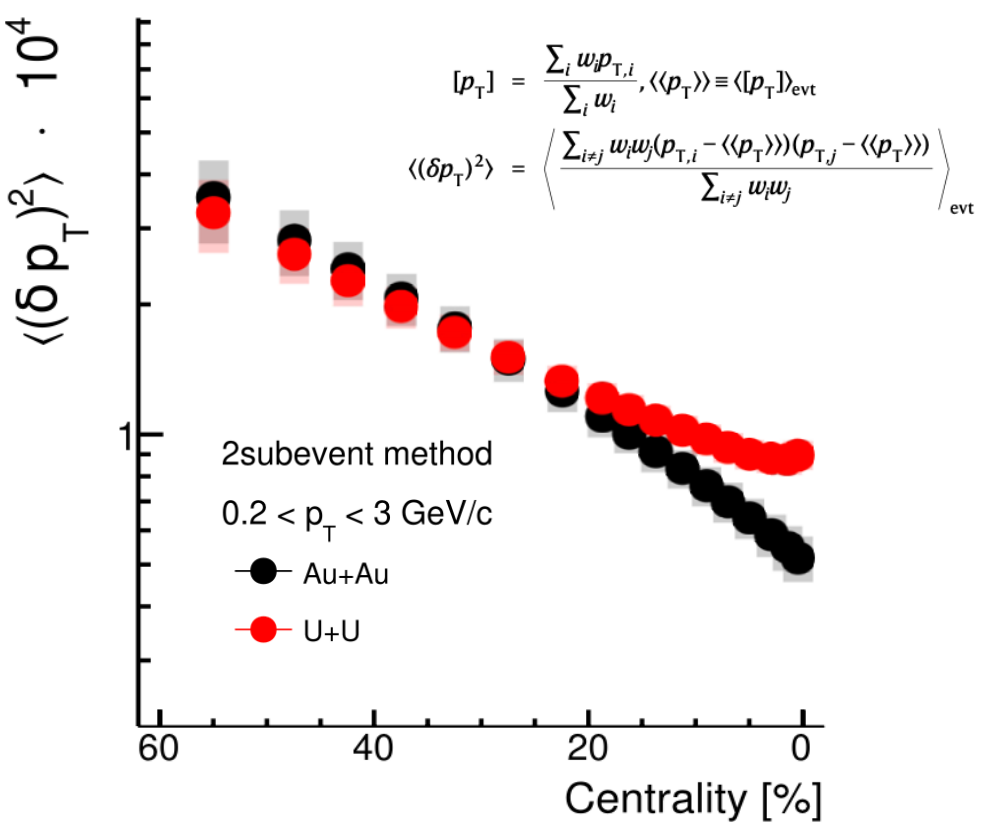
Tip-tip: v_2 ↘ p_T ↗

Shape-frozen like a snapshot during nuclear crossing (10^{-25}s << rotational time scale 10^{-21}s)

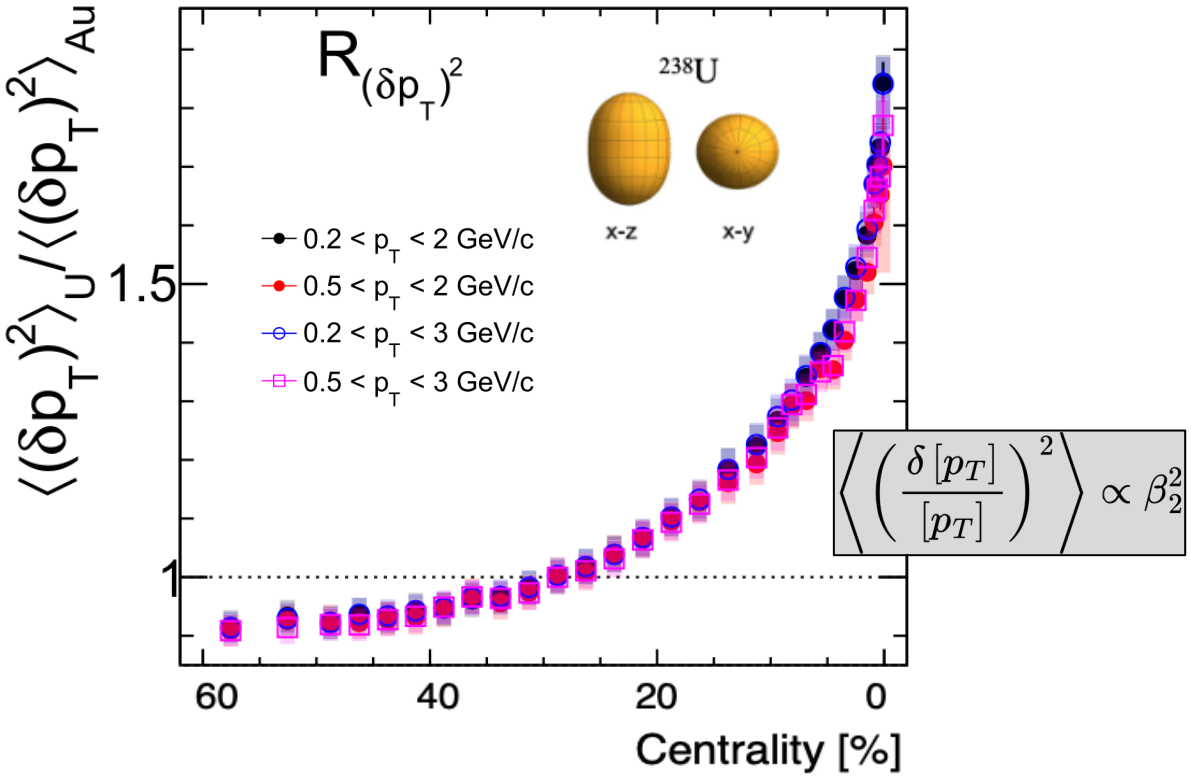
probe entire mass distribution in the intrinsic frame via multi-point correlations

$\langle(\delta p_T)^2\rangle$ sensitive to nuclear deformation

STAR, *Nature 67, 635 (2025)*



STAR, *Rep. Prog. Phys. 88,108601 (2025)*



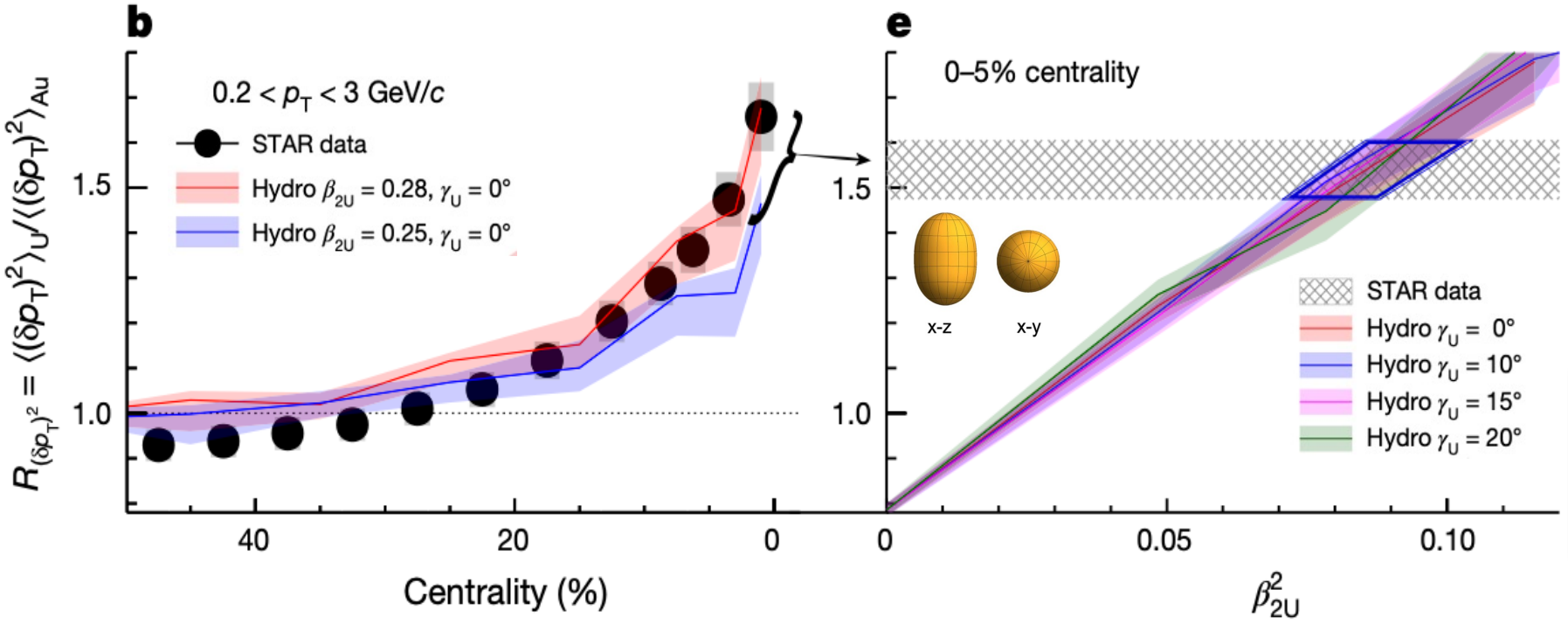
large enhancement in mean and variance ⟶ size fluctuations enhanced

A good probe to image nuclear deformation.

ALICE, *PLB 850, 138541 (2024);* ATLAS, *PRL 133, 252301 (2024);* G. Giacalone, J. Jia, C. Zhang, *PRL 127, 242301 (2021)*

Constraining the ground-state ^{238}U: $\beta_{2,U}$ and γ_U

STAR, *Nature 635, 67-72 (2024)*



Relation confirmed by hydro

$$R_{(v_2^2)} \approx 1 + \frac{b_1}{a_1}\beta_2^2,$$
$$R_{\langle(\delta p_T)^2\rangle} \approx 1 + \frac{b_2}{a_2}\beta_2^2,$$
$$R_{\langle v_2^2 \delta p_T\rangle} \approx 1 - \frac{b_3}{a_3}\beta_2^3\cos(3\gamma)$$

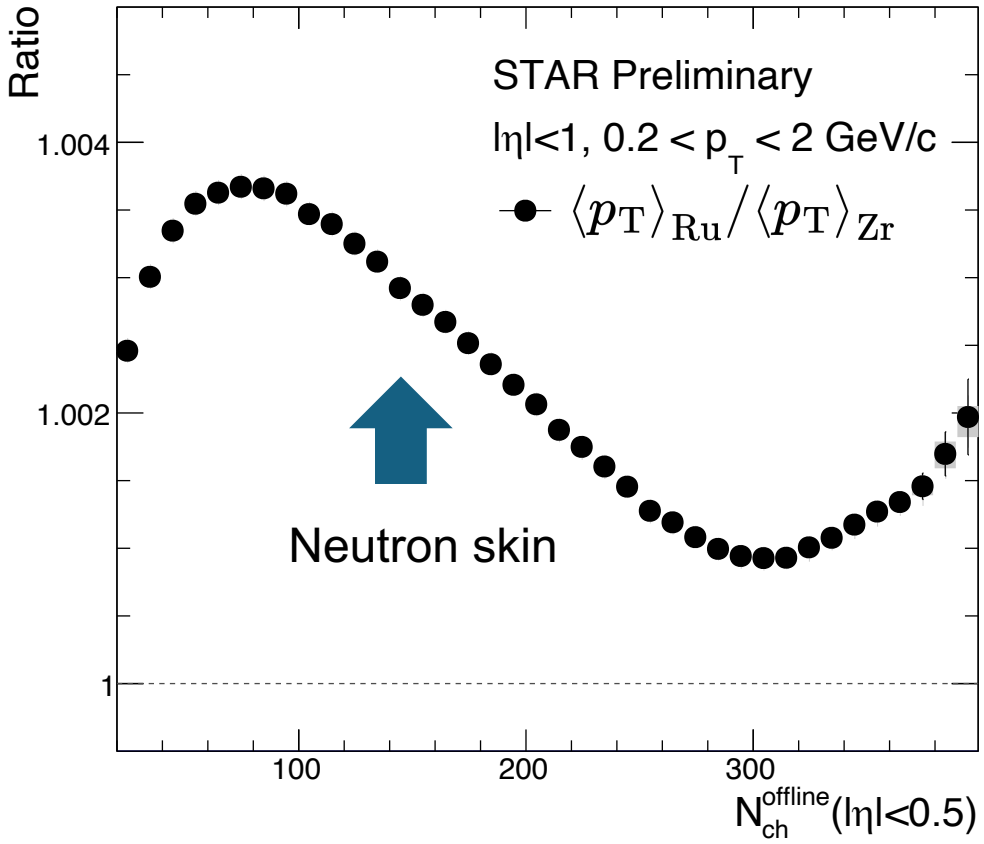
High-energy estimate
(*IP-Glasma+MUSIC* and *Trajectum*)

$$\beta_{2U} = 0.286 \pm 0.025$$
$$\gamma_U = 8.5° \pm 4.8°$$

A large deformation with a slight deviation from axial symmetry in the nuclear ground-state

$\langle p_T \rangle$ sensitive to nuclear skin

C. Zhang (STAR), *QM2022*



The nonmonotonic trend reflects the neutron skin effect.

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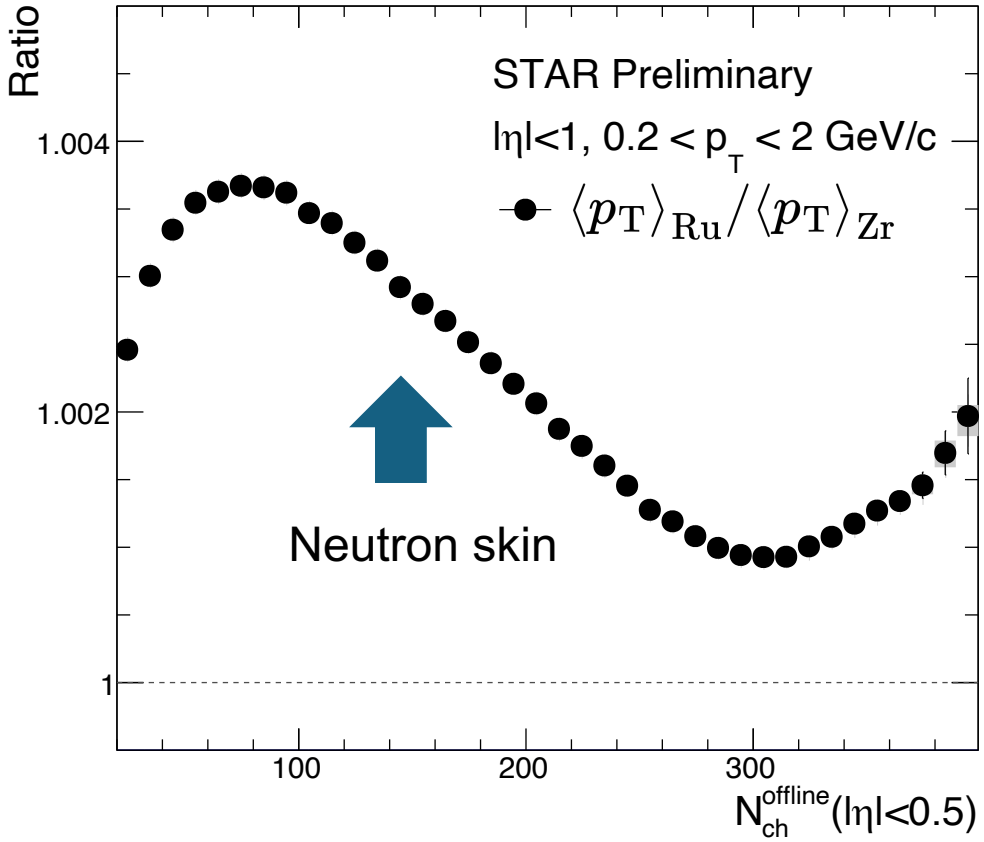
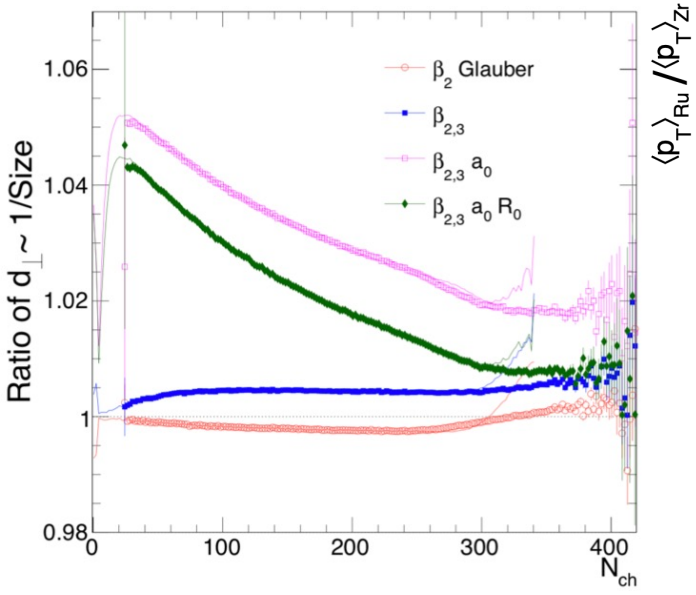
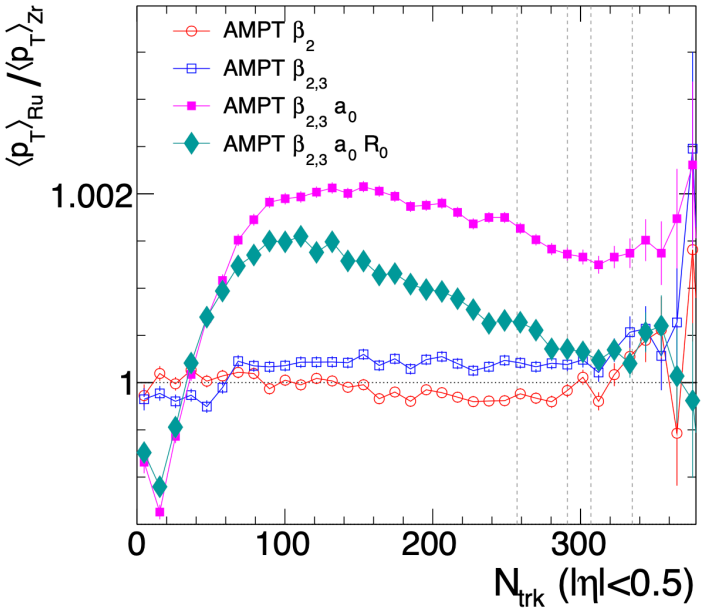
C. Zhang (STAR), *QM2022*



Initial-state Glauber and final-state AMPT



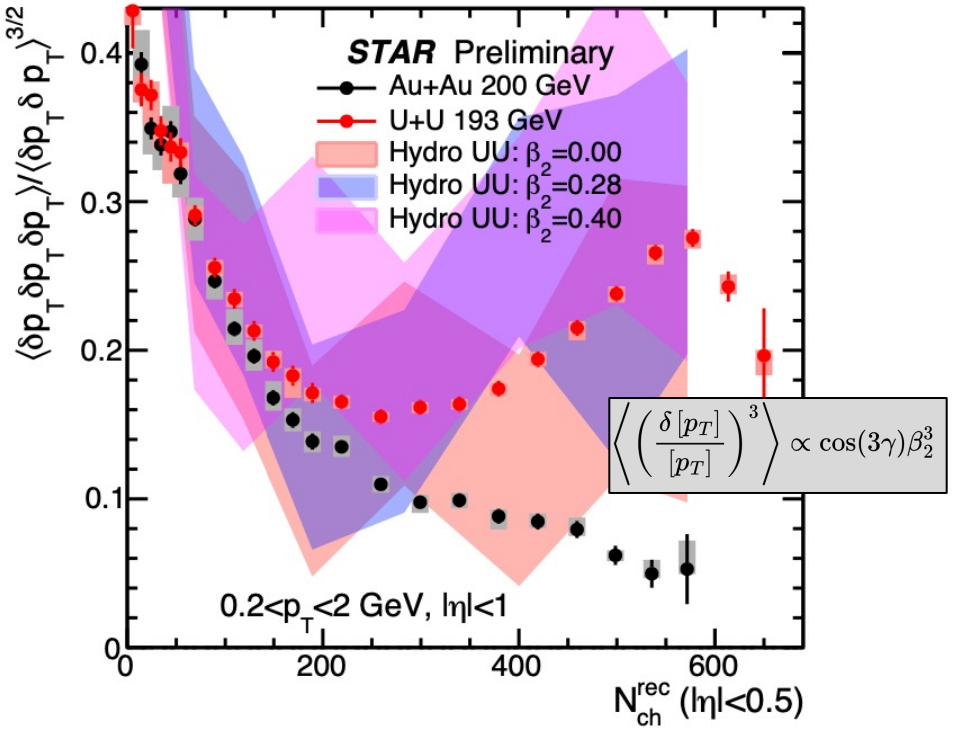


J. Jia, *PRC 105, 044905 (2022*
H.J. Xu et al., PRC 108, L011902 (2023)

The nonmonotonic trend reflects the neutron skin effect.

$\langle(\delta p_T)^3\rangle$ and $\langle(\delta p_T)^4\rangle$ sensitive to nuclear deformation

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



Independence source model: following $1/N_s^{n-1}$ within power-law decrease in high-order

M. Cody et. al., *Phys. Rev. C 107, (2023)*

Size fluctuations enhanced: large enhancement in skewness and **sign-change** in kurtosis

Confirmed by hydro, will update the hydro statistics.

ALICE, *PLB 850, 138541 (2024);* ATLAS, *PRL 133, 252301 (2024);* G. Giacalone, J. Jia, C. Zhang, *PRL 127, 242301 (2021)*

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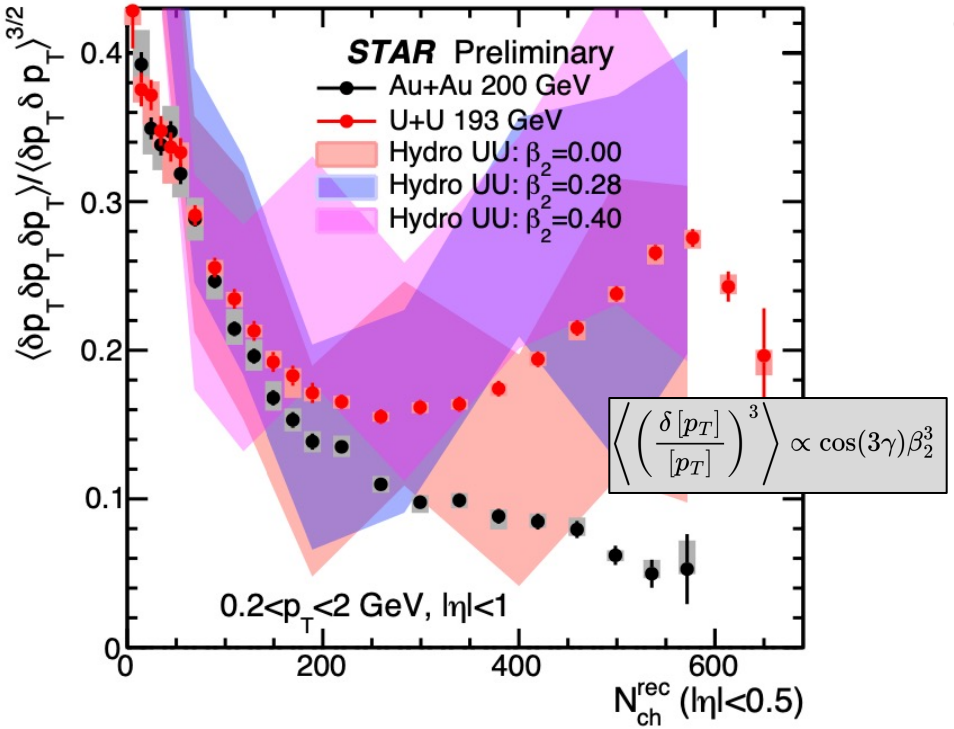

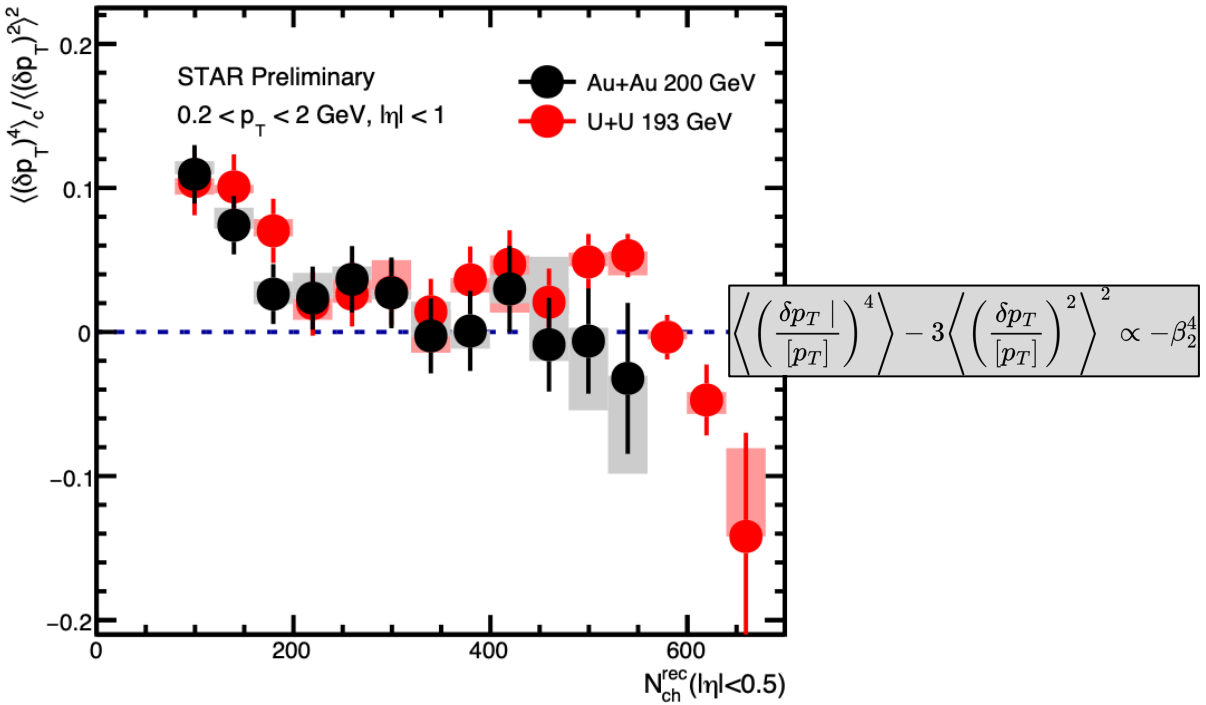

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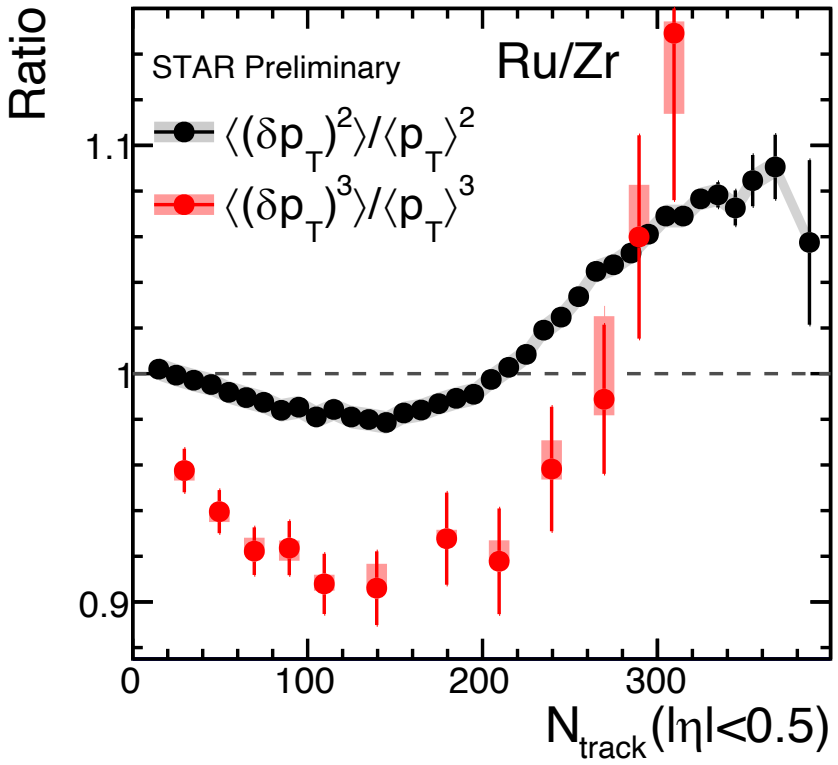
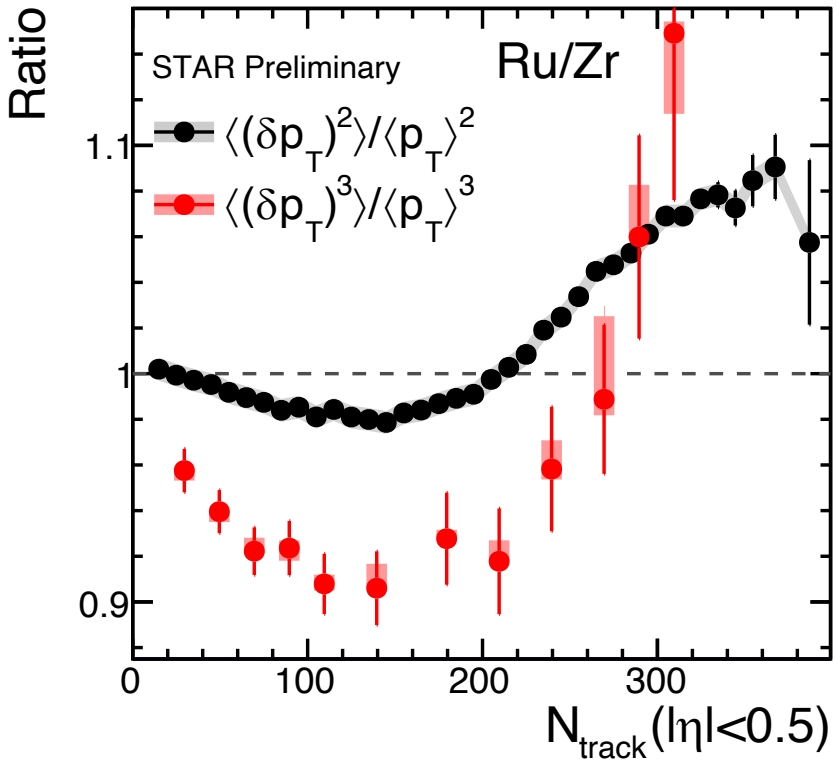
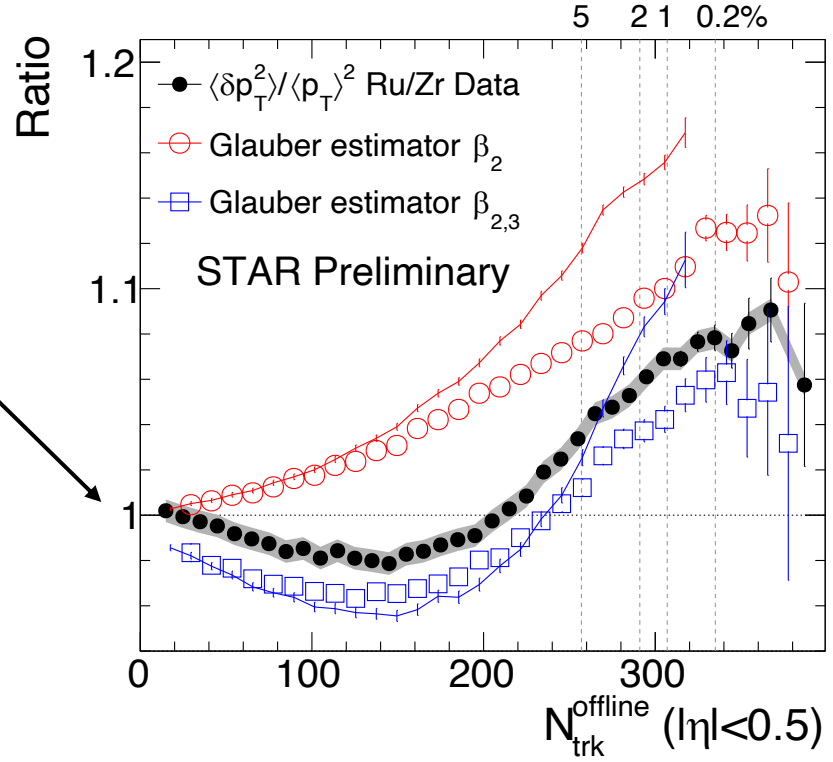
$\langle(\delta p_T)^2\rangle$ and $\langle(\delta p_T)^3\rangle$ are sensitive to nuclear deformation in ^{96}Ru and ^{96}Zr



Octupole deformation: large enhancement in skewness and sign-change in kurtosis

$\langle(\delta p_T)^2\rangle$ and $\langle(\delta p_T)^3\rangle$ are sensitive to nuclear deformation in ^{96}Ru and ^{96}Zr





$$\left\langle \left(\frac{\delta [p_T]}{[p_T]} \right)^2 \right\rangle \propto \beta_2^2$$

$$\left\langle \left(\frac{\delta [p_T]}{[p_T]} \right)^3 \right\rangle \propto \cos(3\gamma)\beta_2^3$$

$$\frac{\langle \delta p_T^2 \rangle_{\mathrm{Ru}}}{\langle \delta p_T^2 \rangle_{\mathrm{Zr}}} \approx 1 + \frac{b_0}{a_0}\left(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2\right) - \frac{b_{0,3}}{a_0}\beta_{3,\mathrm{Zr}}^2$$

Cancelation expected in non-central collisions

C. Zhang, J. Jia, *PRL 128, 022301 (2022)*

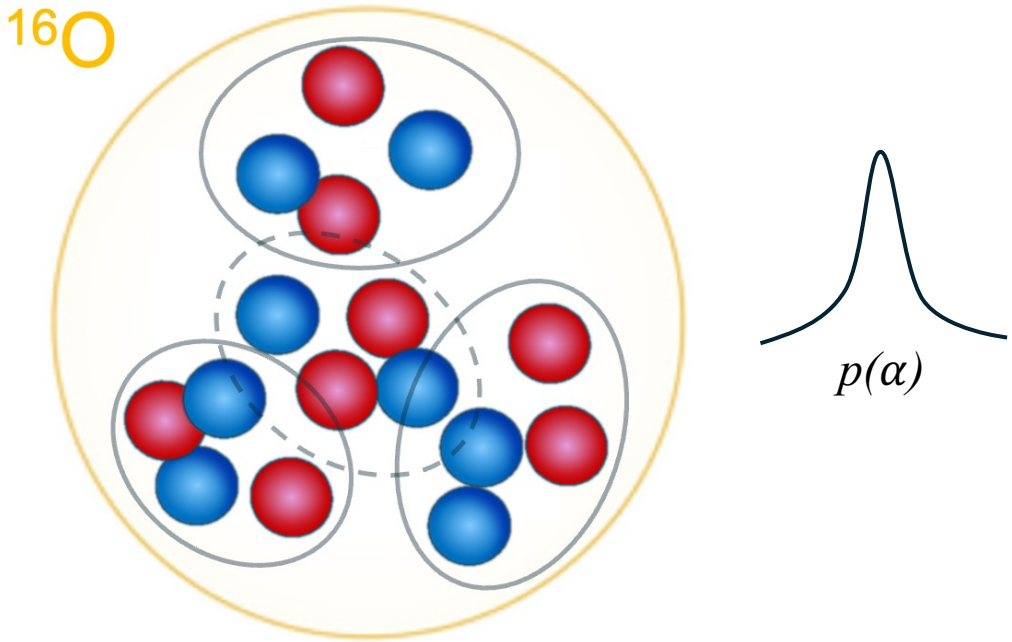
Octupole deformation: large enhancement in skewness and sign-change in kurtosis

II. Geometry effect and subnucleon fluctuations in ^{16}O

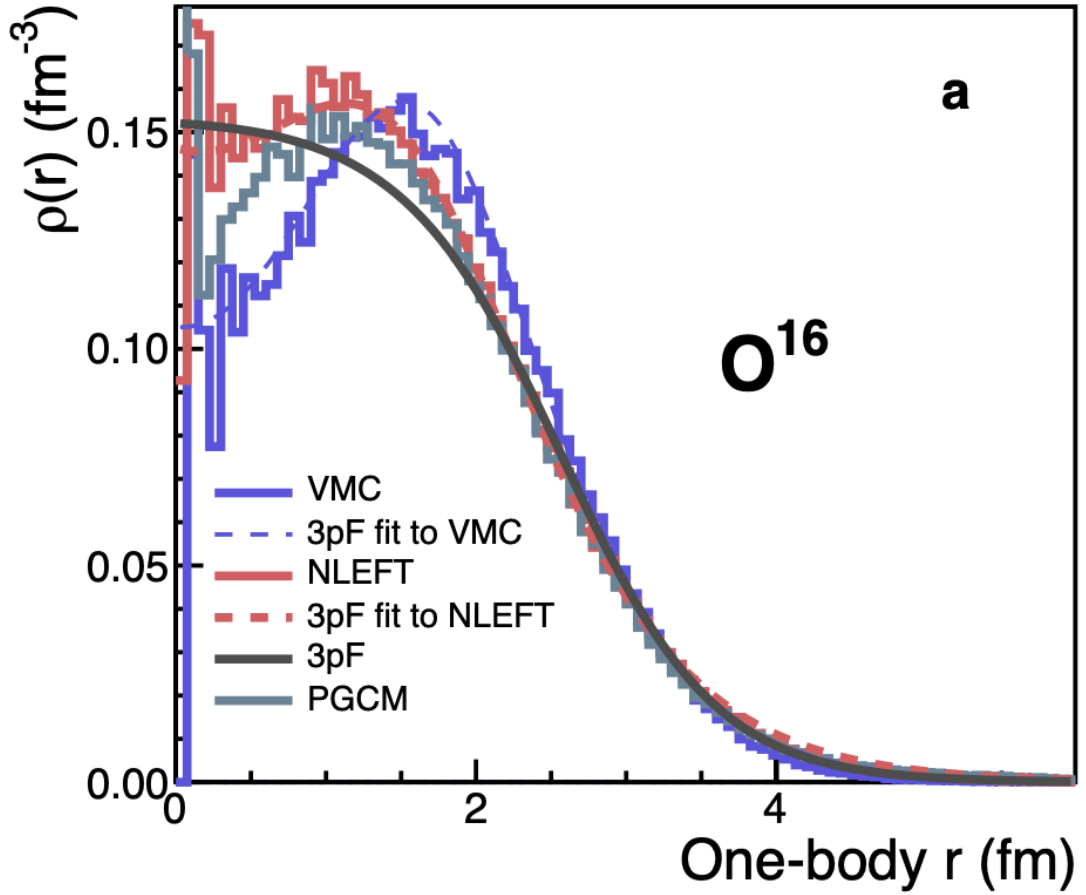
Light nuclei: geometry and many-nucleon correlations

"Double magic number" in $^{16}_{8}O$ nuclei, possible alpha cluster in low-energy studies.

NN correlation (cluster pattern)



ab initio calculations

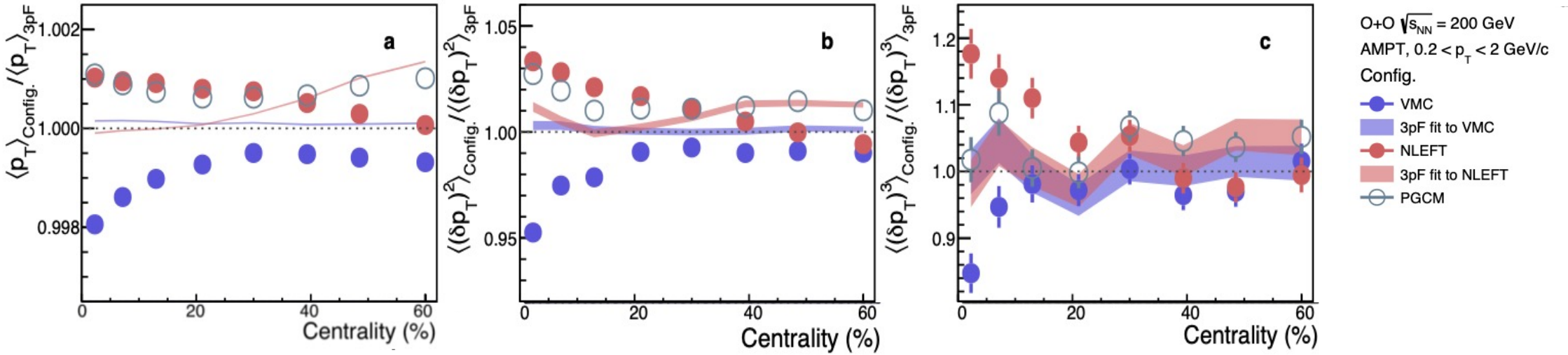


Nuclear inputs: VMC / AFDMC, NLEFT, and PGCM. C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *PLB 862, 139322 (2025)*

Ab-initio NN correlations and their impact on p_T fluctuations

C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *PLB 862, 139322 (2025)*

Multiple final-state observables

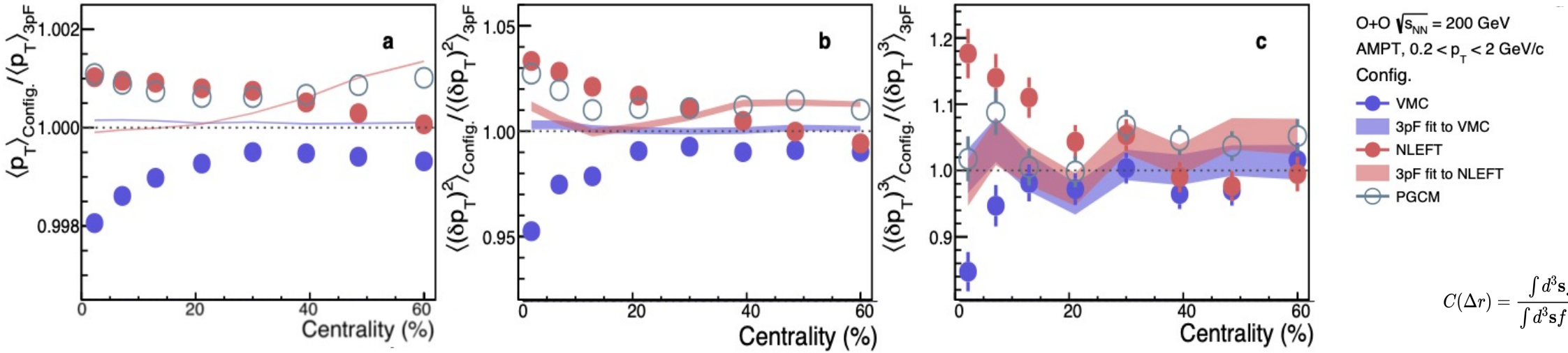


- 3pF as the baseline can NOT capture the NN correlations.
- Distinct differences are observed between VMC and NLEFT/PGCM.
- Central collision is prominent.

Ab-initio NN correlations and their impact on p_T fluctuations

C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *PLB 862, 139322 (2025)*

Multiple final-state observables



$$C(\Delta r) = \frac{\int d^3\mathbf{s} f\left(\mathbf{s}+\frac{\mathbf{r}}{2}, \mathbf{s}-\frac{\mathbf{r}}{2}\right)}{\int d^3\mathbf{s} f\left(\mathbf{s}+\frac{\mathbf{r}}{2}\right) f\left(\mathbf{s}-\frac{\mathbf{r}}{2}\right)}$$

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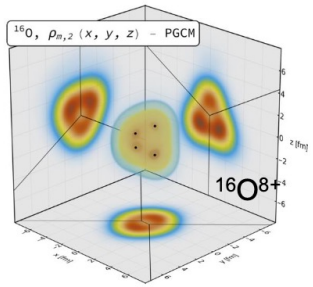
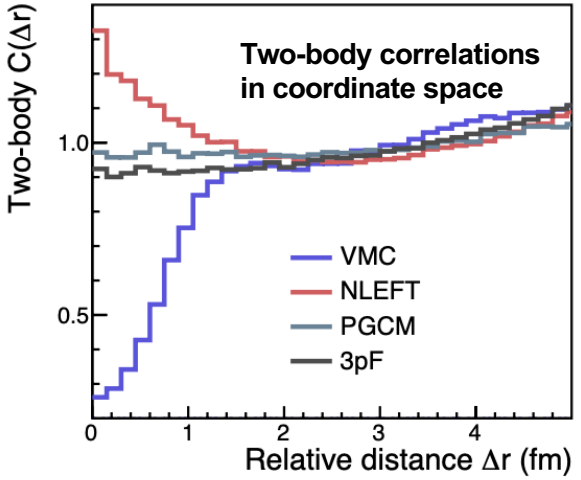


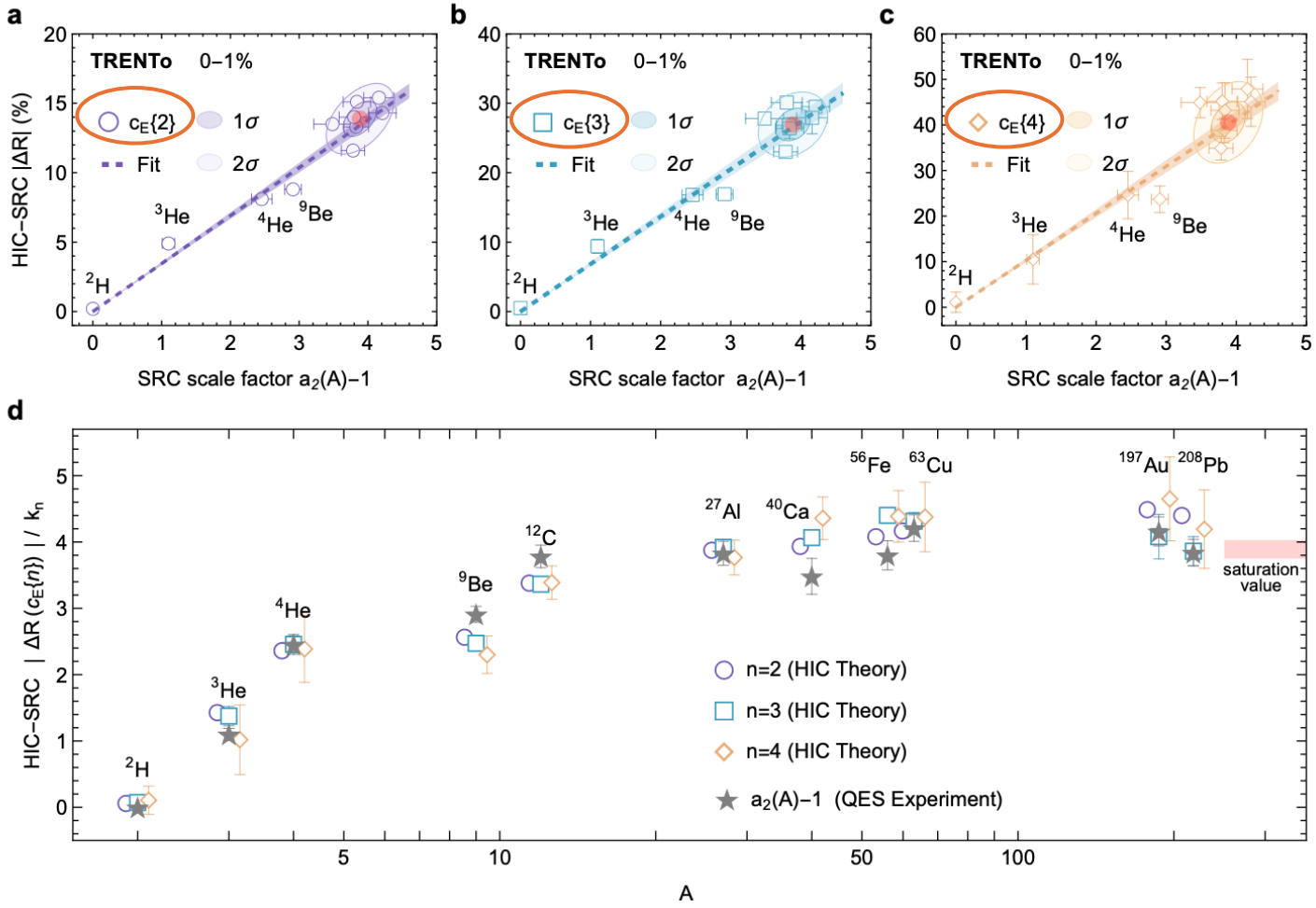
α cluster



High-orders p_T fluctuations as a possible SRC probe

$$p_{\mathrm{T}} \propto E/S \propto d_{\perp}$$

P. Li, K.J. Sun, B. Zhou, G.-L. Ma, *2511.23293v2 (2025)*



Input NN-SRC in initial-state fluctuations.

Predicted sensitivity is stronger at the third and fourth order p_T flucutations: $c_{E/S}\{3\}$ and $c_{E/S}\{4\}$.

$$c_d\{2\} = \langle(\frac{\delta d_\perp}{d_\perp})^2\rangle,$$

$$c_d\{3\} = \langle(\frac{\delta d_\perp}{d_\perp})^3\rangle,$$

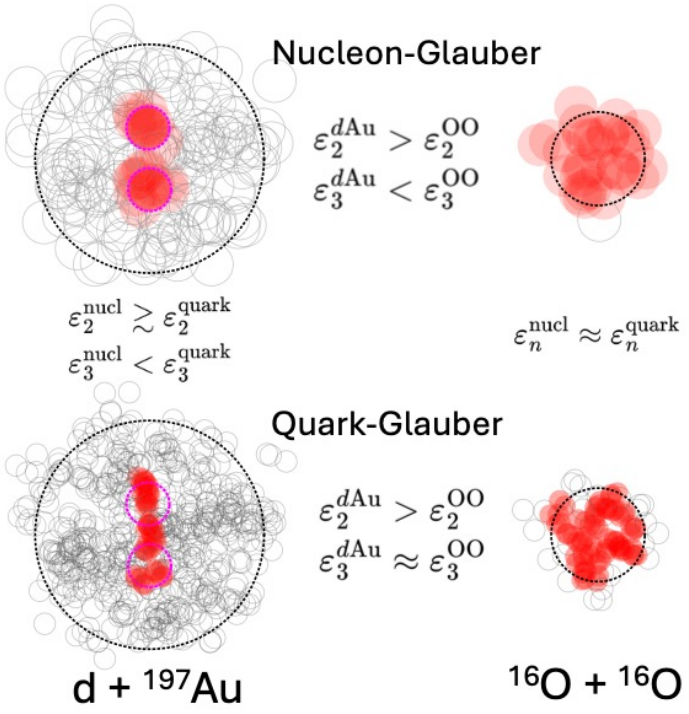
$$c_d\{4\} = \langle(\frac{\delta d_\perp}{d_\perp})^4\rangle - 3\langle(\frac{\delta d_\perp}{d_\perp})^2\rangle^2.$$

Higher-order mean-p_T fluctuations offer a complementary SRC probe.

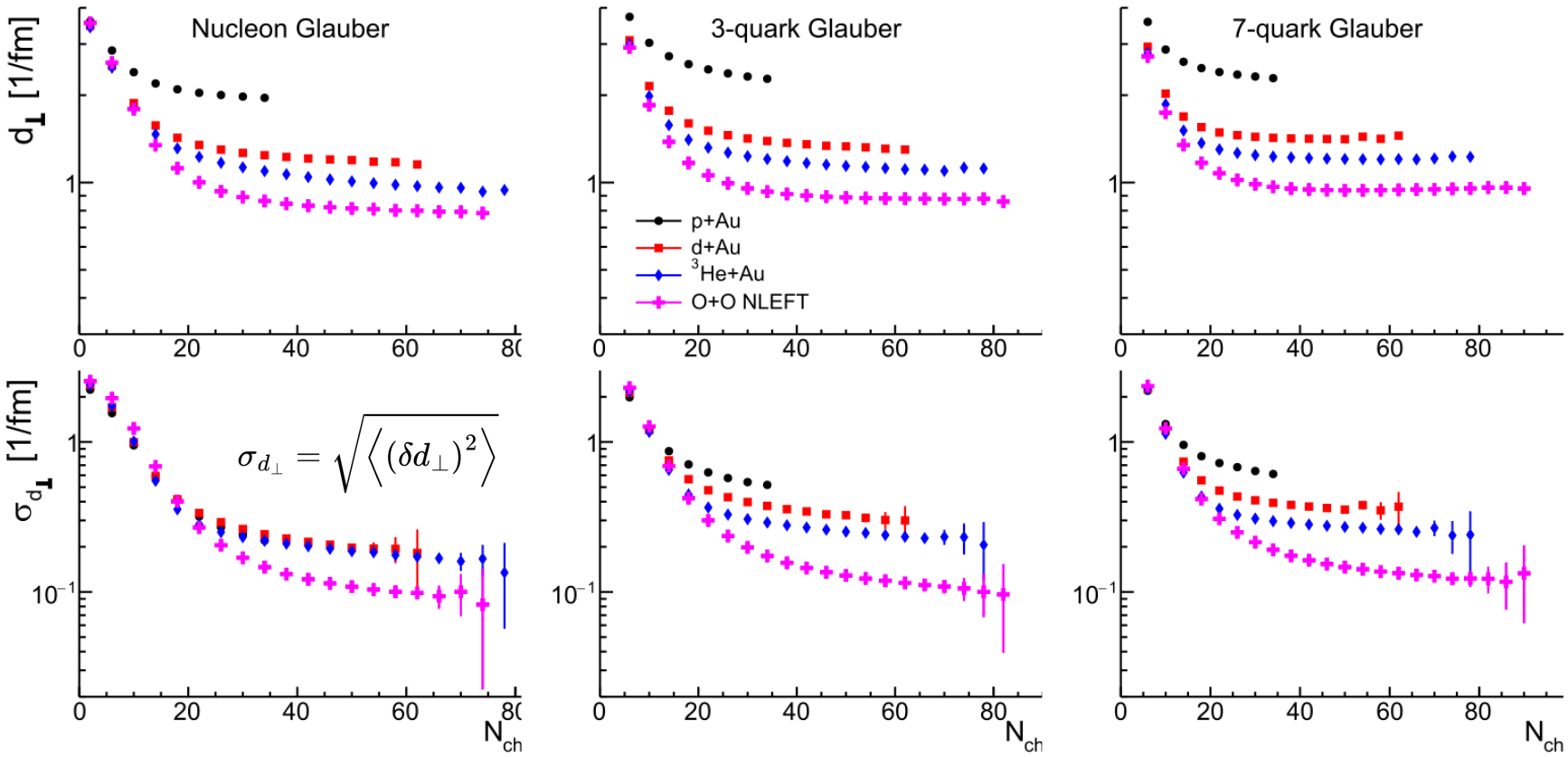
Nucleon/sub-nucleon fluctuation vs. *NN* correlations

$d_\perp = 1/\sqrt{[x^2]\,[y^2]}$ $\quad \delta d_\perp = d_\perp - \langle d_\perp \rangle$

S. Huang, J. Jia, C. Zhang, *PLB 870, 139926 (2025)*



STAR, *2510.19645 (under review in PRL)*



The variance of $[p_T]$ should be significantly enhanced in d+Au collisions compared to O+O collisions at the same $N_{ch.}$

$\sigma_{d\perp}$ values are similar among asymmetric collisions in the nucleon Glauber model, while they show a clear hierarchy in the quark-Glaubermodel.

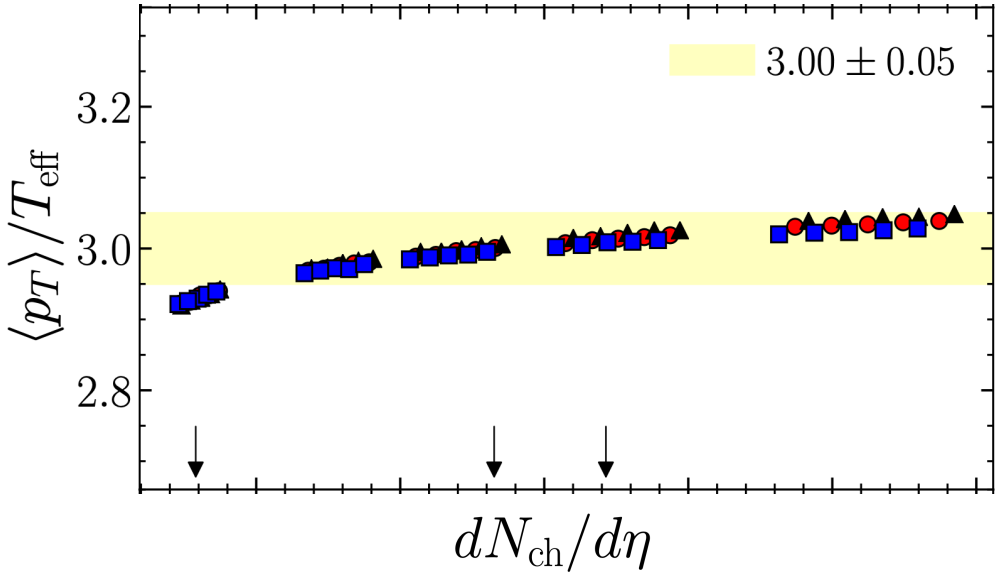
An independent test of geometry-driven interpretation of the radial flow.

❑ Probing QCD matter properties

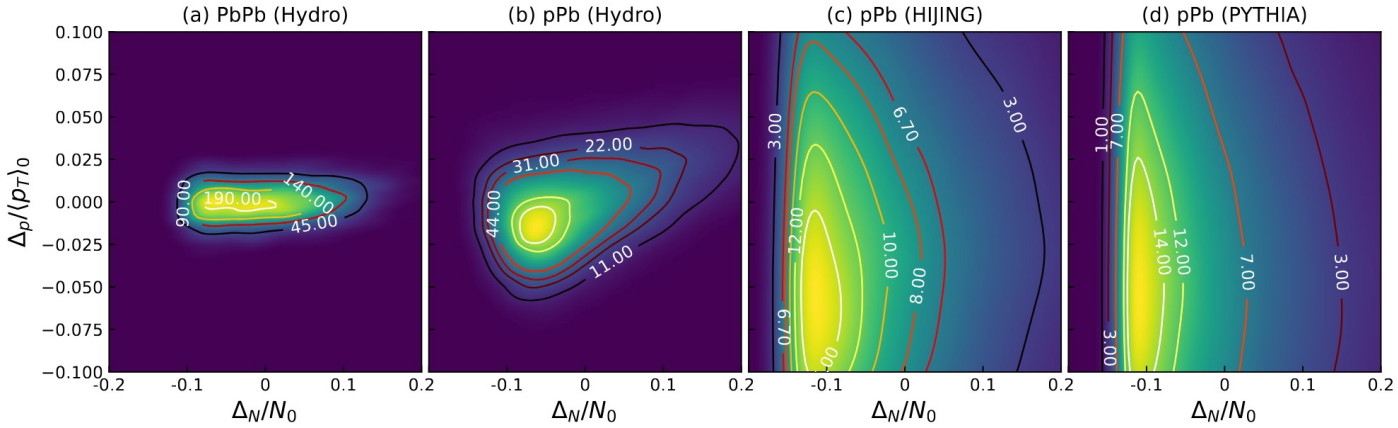
I. Energy dependence of second-order p_T fluctuation in ^{197}Au + ^{197}Au collisions

Momentum fluctuations and medium response

F. G. Gardim, A.V. Giannini, J. Y. Ollitrault., PLB 856, 138937 (2024)



Y.-S. Mu, L. Yan, X.-G. Huang, PRL 135, 162301 (2025)



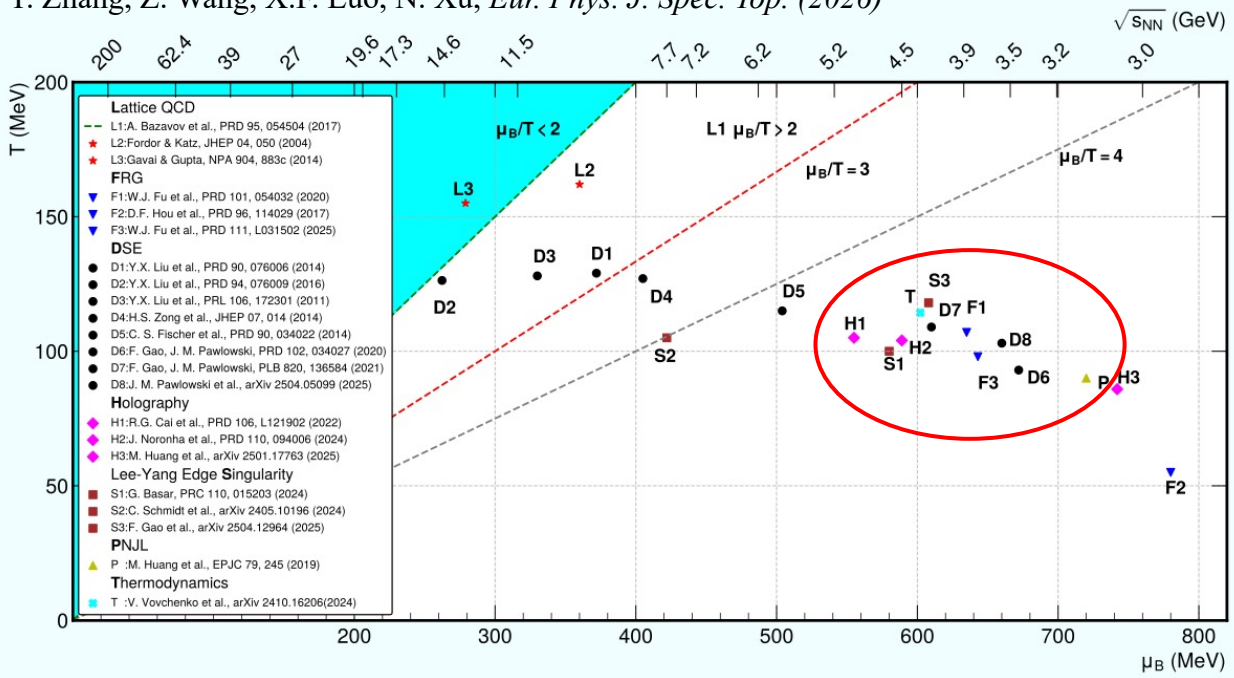
$$\frac{\Delta_p}{\langle p_T \rangle_0} = c_s^2 \frac{\Delta_N + \delta}{N_0} \qquad (c_s^2)^3 \frac{\{\Delta_N^3\}}{N_0^3} - 3(c_s^2)^2 \frac{\{\Delta_N^2 \Delta_p\}}{N_0^2 \langle p_T \rangle_0} + 3c_s^2 \frac{\{\Delta_N \Delta_p^2\}}{N_0 \langle p_T \rangle_0^2} - \frac{\{\Delta_p^3\}}{\langle p_T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

- In ultra-central Pb–Pb collisions, $\langle p_T \rangle$ provides an approximate measure of the effective temperature
- Event-by-event fluctuations in $\langle p_T \rangle$, combined with multiplicity fluctuations, can provide information about the thermodynamic response of the QCD medium

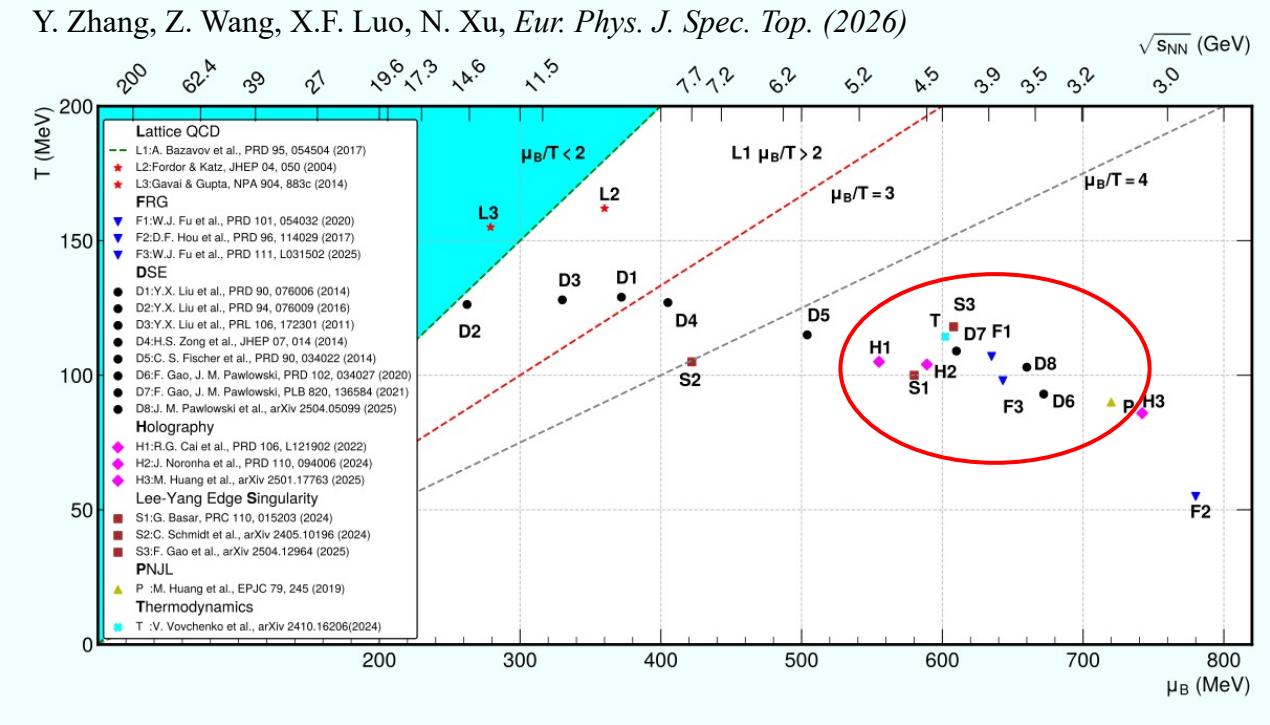
May help constrain the QCD equation of state at high baryon density

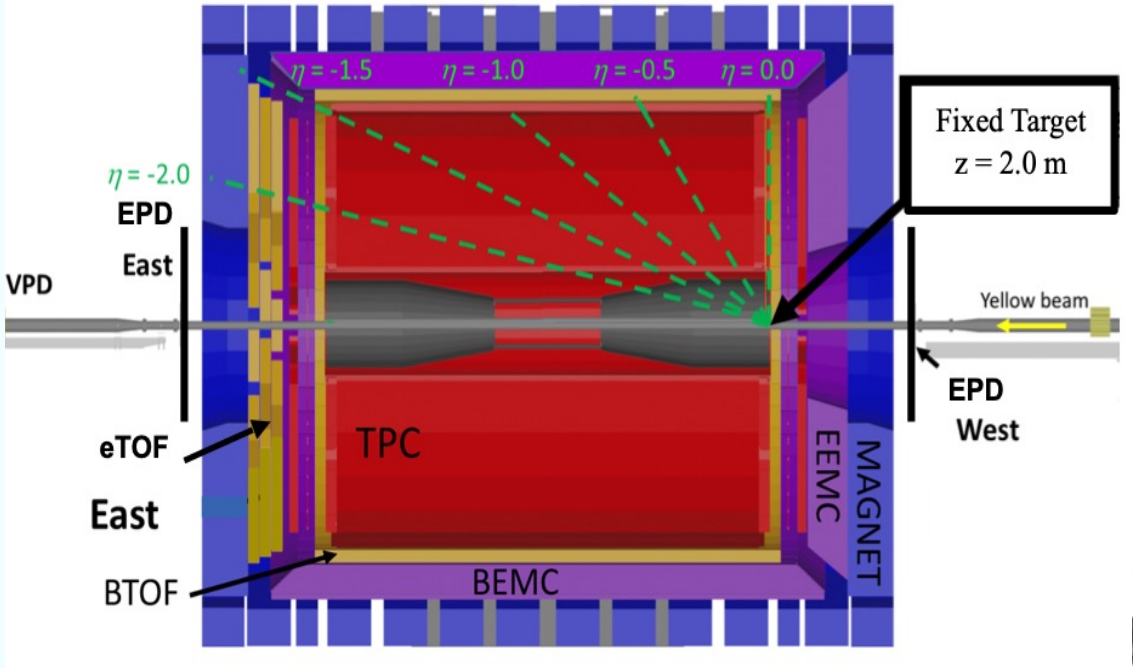
The BES-II Upgrades and fixed-target (FXT) mode

Y. Zhang, Z. Wang, X.F. Luo, N. Xu, *Eur. Phys. J. Spec. Top. (2026)*

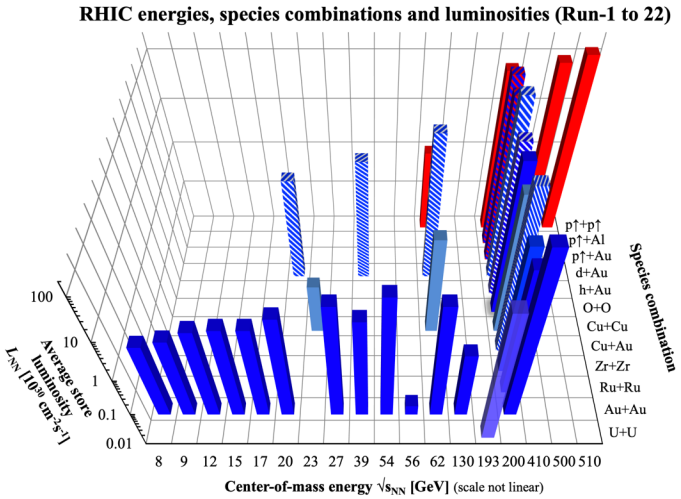


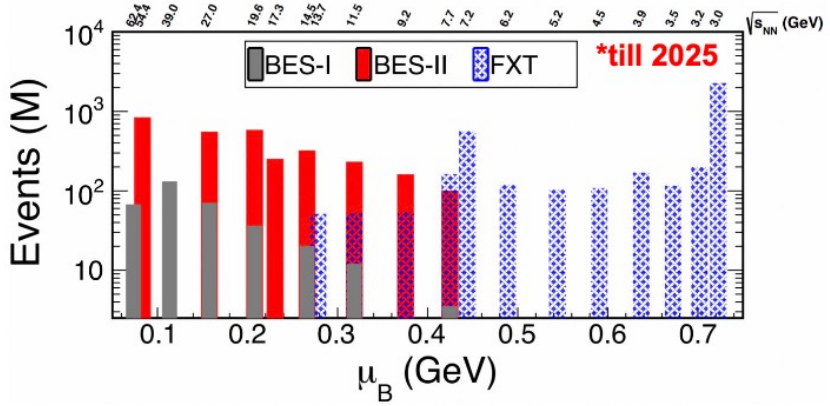
The BES-II Upgrades and fixed-target (FXT) mode





Mid-rapidity for 3.0 GeV is y = 1.049



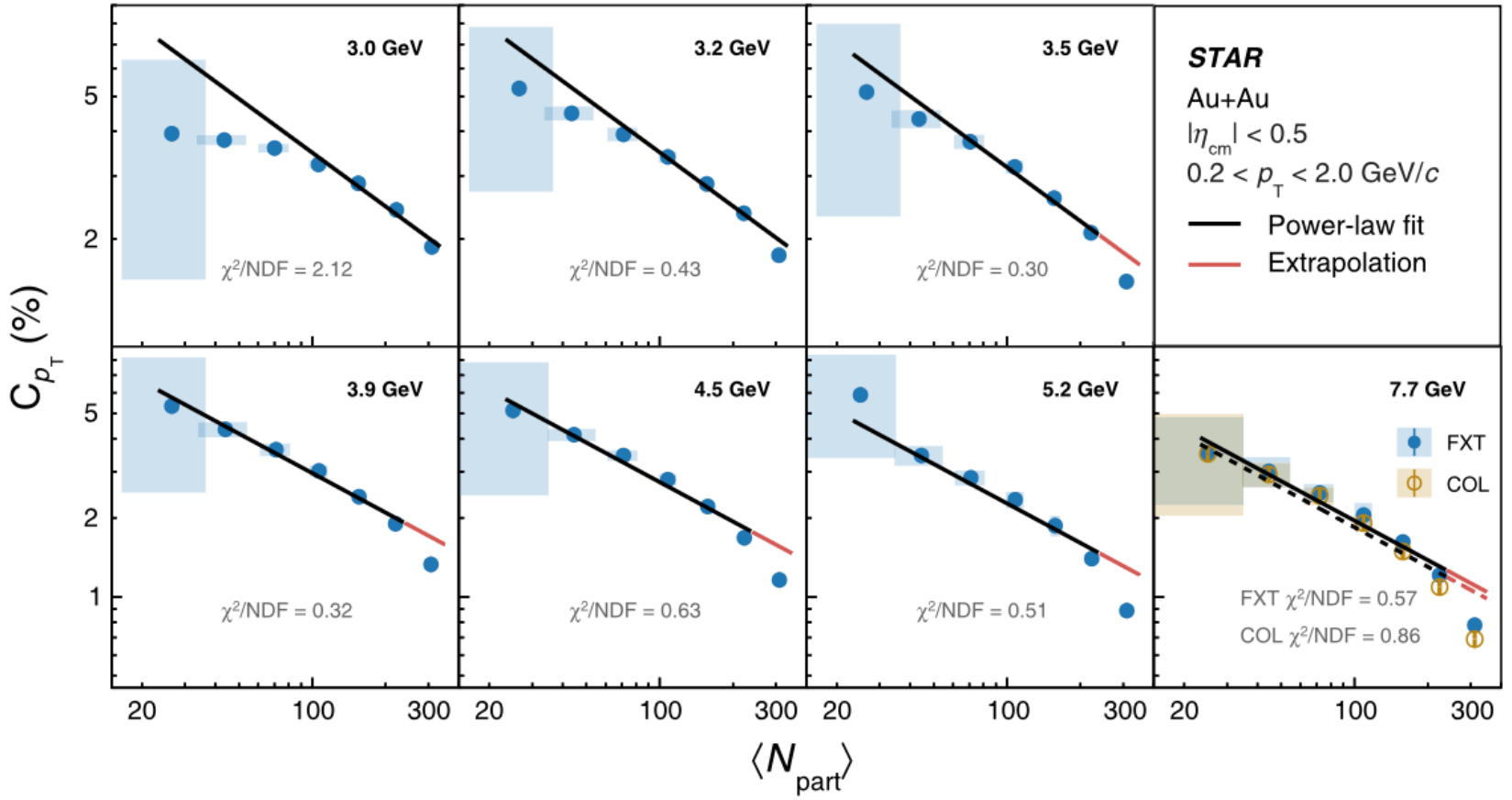


A strong convergence of predicted points within the 3–6 GeV energies

Large datasets with iTPC upgrade ~10 X BES-I

$\sqrt{\langle(\delta p_T)^2\rangle}/\langle\langle p_T\rangle\rangle$ vs centrality in FXT mode

Zheng Liu, *ATHIC2026* STAR, *PRL 137, 132301 (2026)*

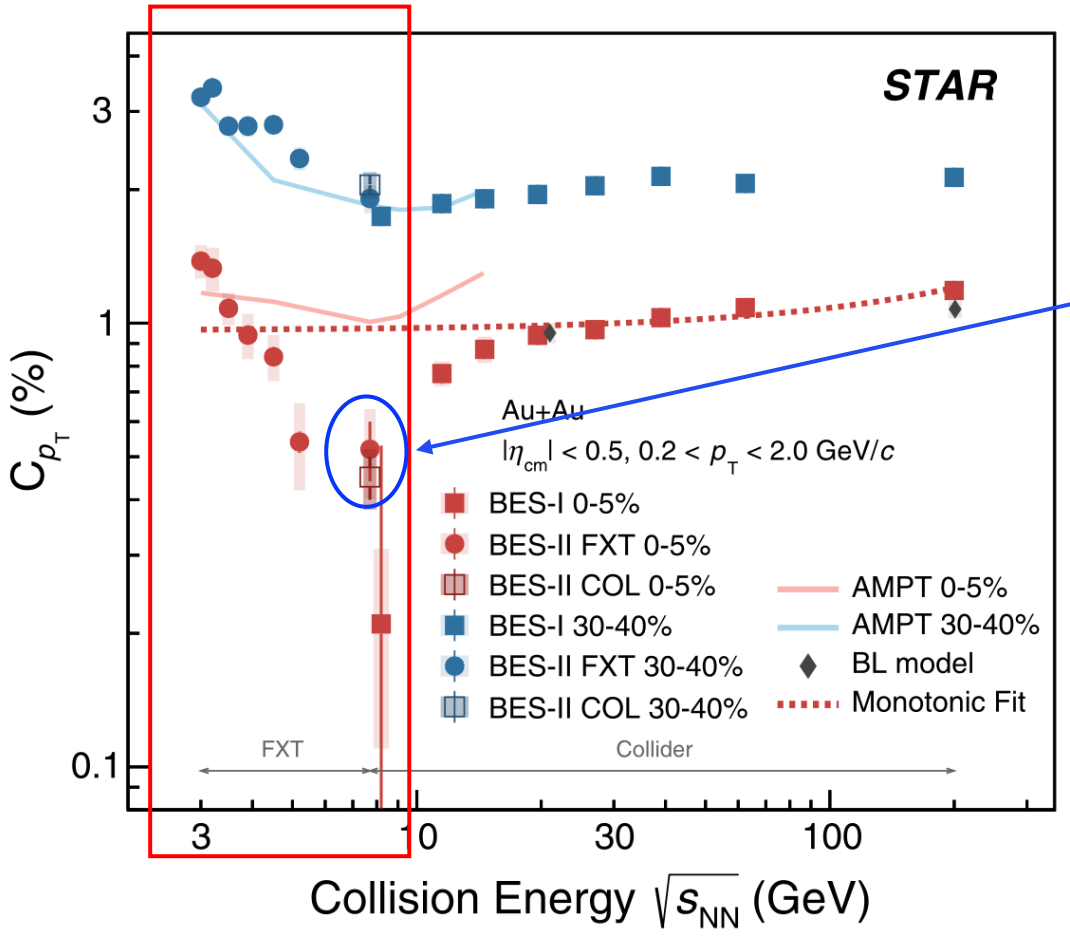


- Correlations larger in the peripheral collisions and decrease with centrality
- Measurements deviate from power-law behavior, implying that the centrality dependence does not follow a simple superposition scenario
- Independent of the collision mode: good agreement between measurements made at 7.7 GeV in FXT and collider modes.

Nonmonotonicity of $\sqrt{\langle(\delta p_T)^2\rangle}/\langle\langle p_T\rangle\rangle$ vs collision energy in FXT mode

μ_B ~ 400 - 600 MeV

STAR, *PRL 137, 132301 (2026)*



No acceptance effect: at 7.7 GeV, BES-II is consistent with BES-I.

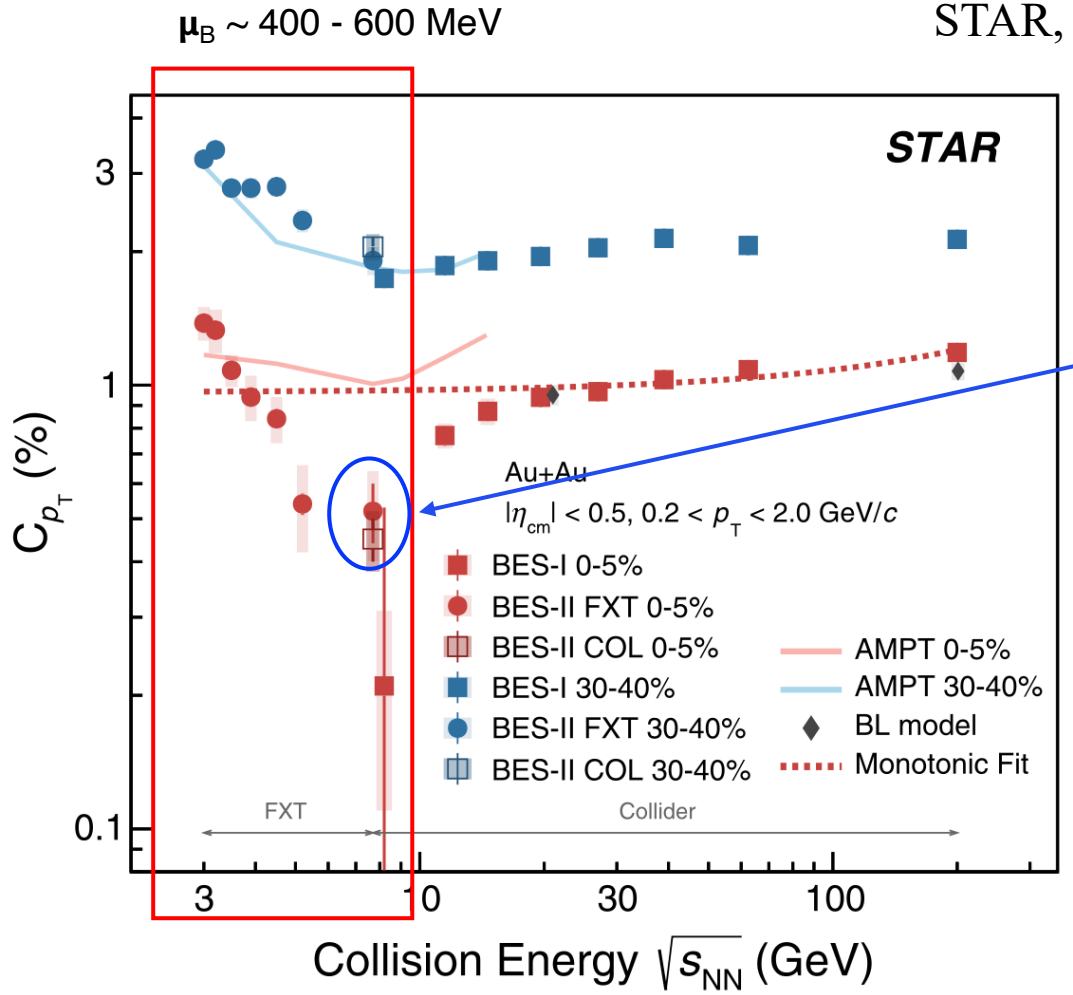
Useful for constraining EoS and understanding the phase diagram.

Nonmonotonicity of $\sqrt{\langle(\delta p_T)^2\rangle}/\langle\langle p_T\rangle\rangle$ vs collision energy in FXT mode

STAR, *PRL 137, 132301 (2026)*

BES-II results show a **significant non-monotonic behavior** in 0–5% central collisions, but not in 30–40%.

STAR 0-5 %	~5.5 σ
AMPT 0-5 %	~1.4 σ
STAR 30-40 %	~2 σ



No acceptance effect: at 7.7 GeV, BES-II is consistent with BES-I.

Useful for constraining EoS and understanding the phase diagram.

Ongoing: PID (pion/kaon/proton) STAR

Boltzmann–Langevin model: S. Gavin et. al., *PRC 95, 064901 (2017)*

Lipei Du, *PLB 874, 140225 (2026)*

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

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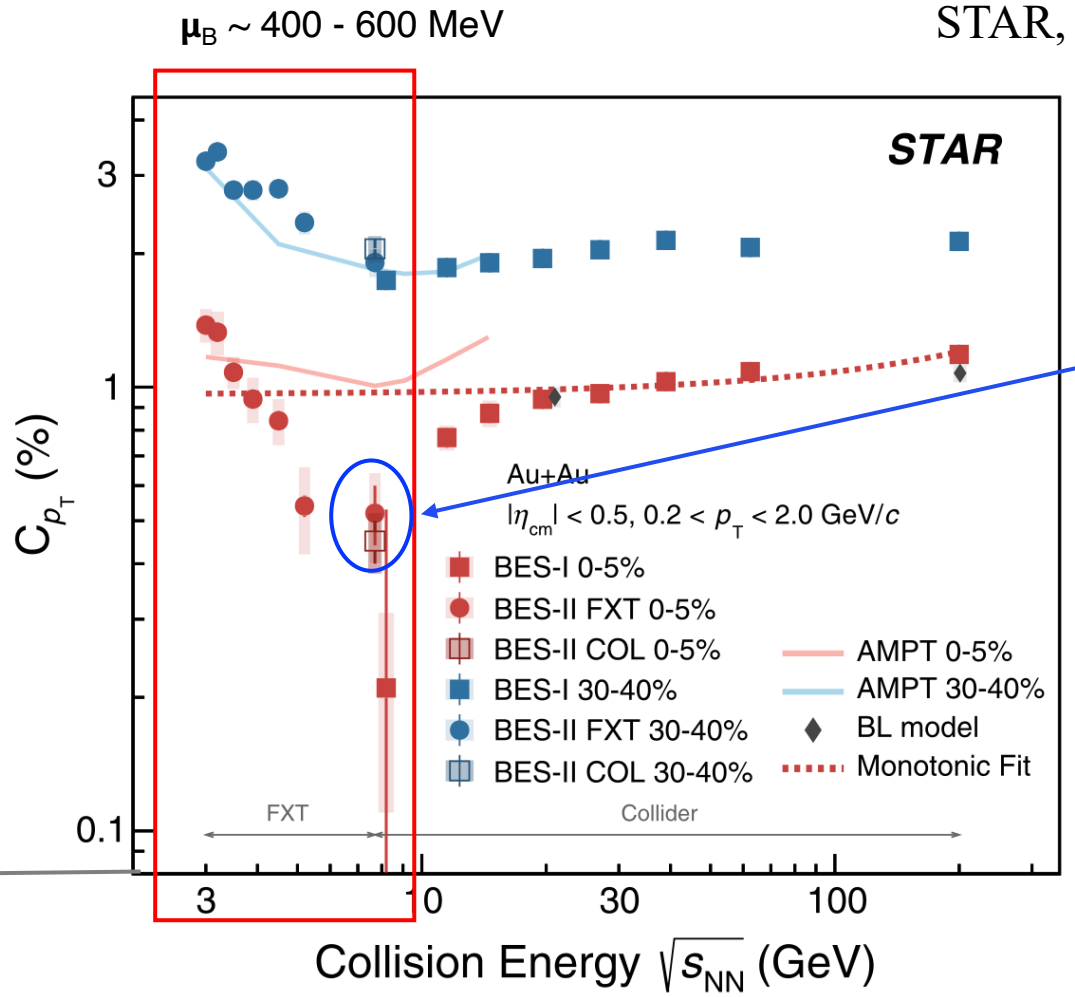


No acceptance effect: at 7.7 GeV, BES-II is consistent with BES-I.

Lower-energy reaction measurable:

Nuclear liquid-gas phase transition region?

100 MeV — 1 GeV

Y.-G. Ma, *PRL 83, 3617 (1999)*

Useful for constraining EoS and understanding the phase diagram.

Ongoing: PID (pion/kaon/proton) STAR

Boltzmann–Langevin model: S. Gavin et. al., *PRC 95, 064901 (2017)*

Lipei Du, *PLB 874, 140225 (2026)*

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

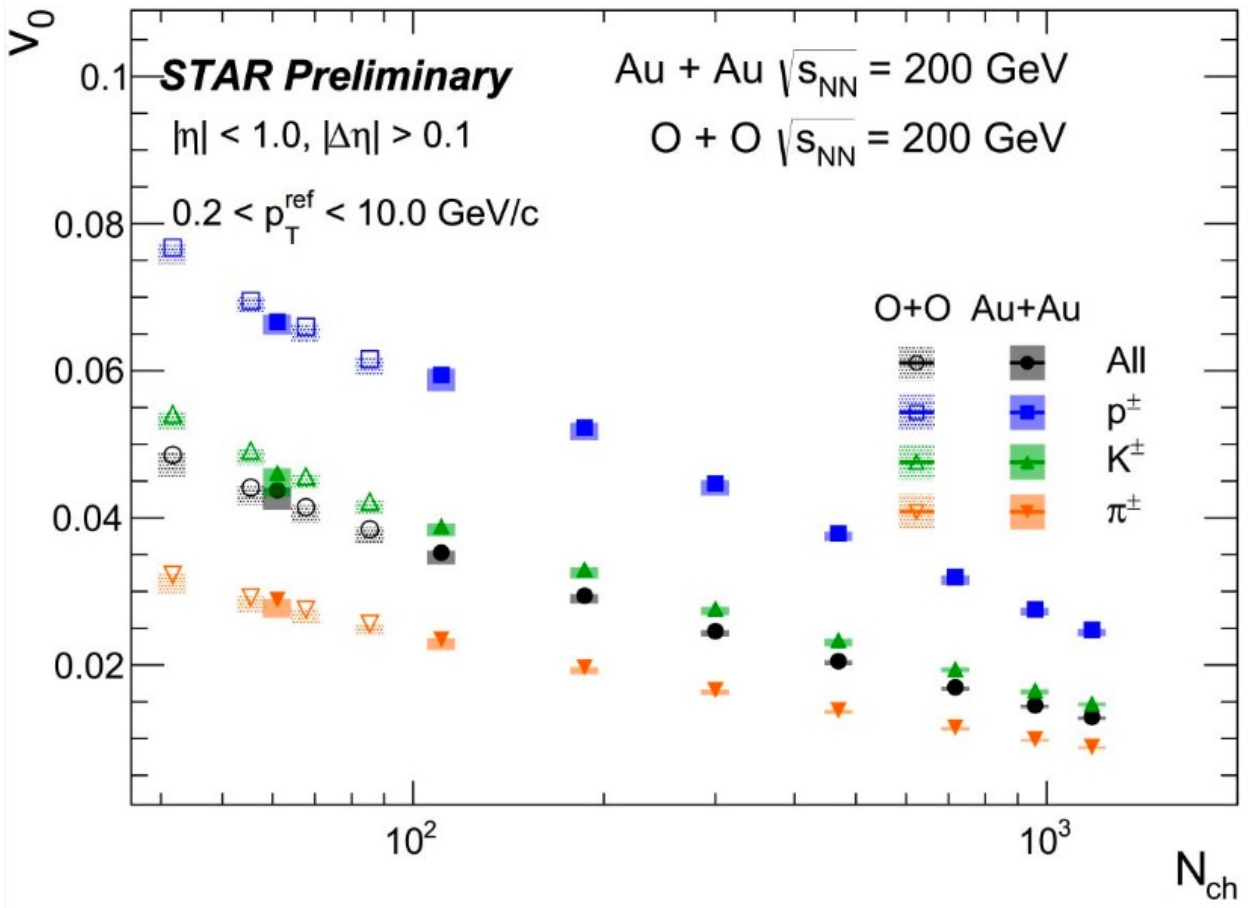
Integral p_T fluctuation v_0 at 200 GeV

Zaining Wang, *sQM2026*

$$v_{0,\mathrm{PID}} = \frac{\langle \delta[p_\mathrm{T}]_\mathrm{PID} \delta[p_\mathrm{T}]_h \rangle}{\langle [p_\mathrm{T}] \rangle_h}$$

- Measured for charged hadrons, protons, kaons and pions in O+O to Au+Au.
- larger fluctuation signals for heavier particles.
- v_0 follows an approximate power scaling

$$\mathrm{v}_0 \sim 1/\sqrt{N_\mathrm{ch}}$$

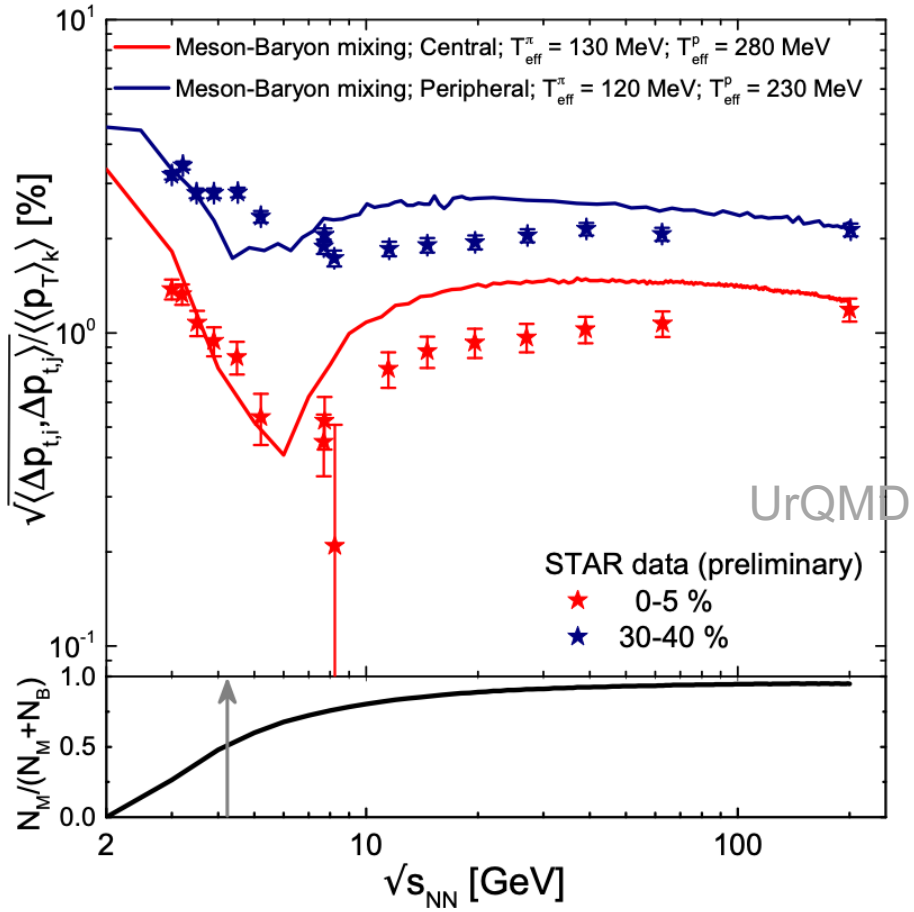


ATLAS, *PRL 136, 032301 (2026),* ALICE, *PRL 136, 032302 (2026)*

Interpretations: Baryon–Meson Composition

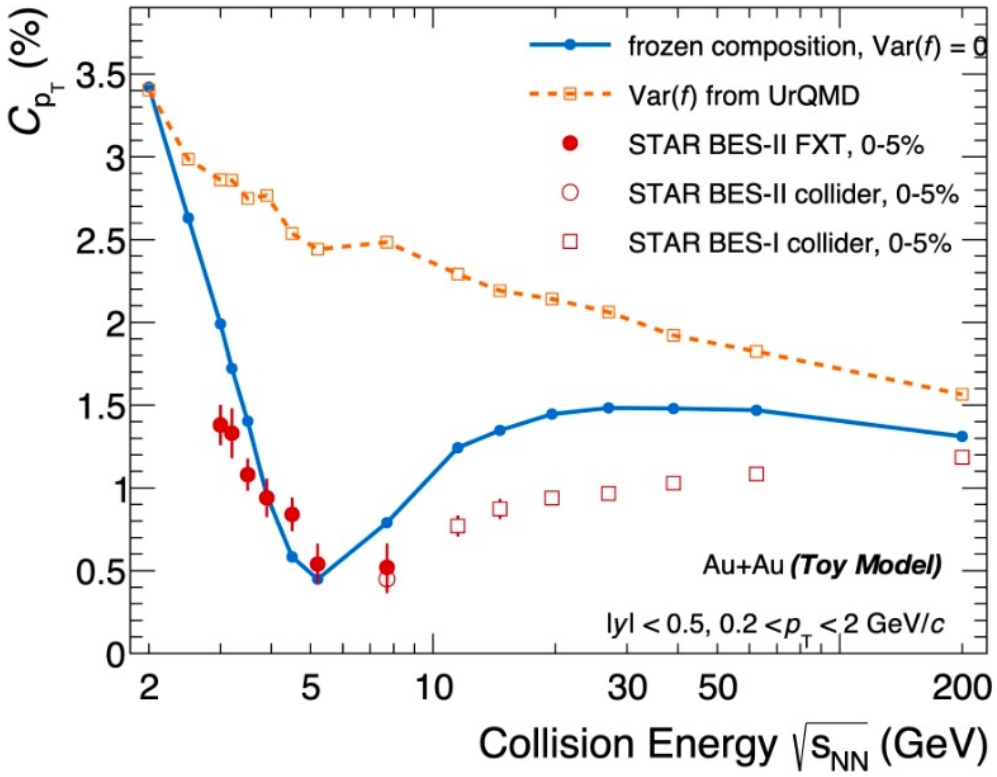
$$\langle \Delta p_{\mathrm{T},i} \Delta p_{\mathrm{T},j} \rangle = -\frac{N_M N_B}{N_k^2 (N_k - 1)} (\mu_M - \mu_B)^2$$

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



Baryon–meson mixing can reproduce the observed non-monotonic energy dependence.

R. Manikandhan, R. Bellwied, *2610.32790.*

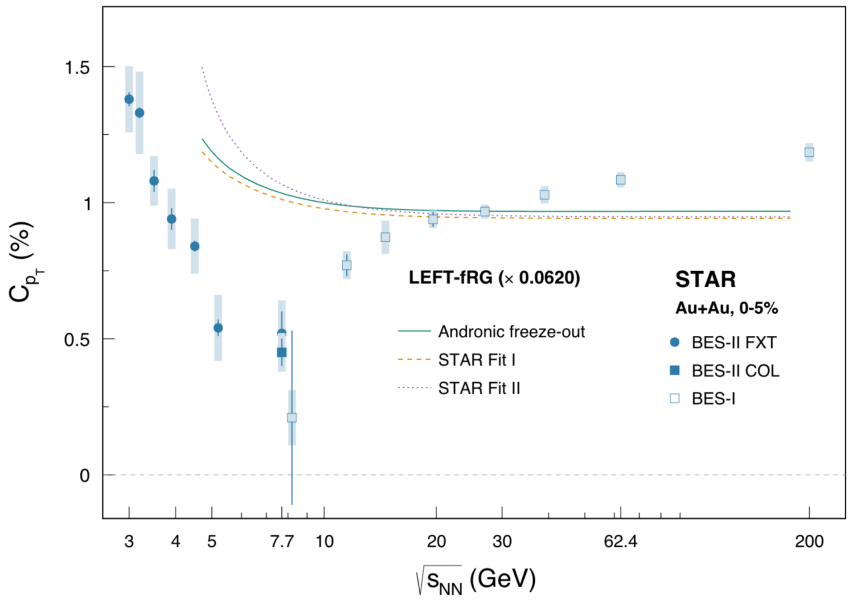


Including event-by-event composition fluctuations can wash out the dip.

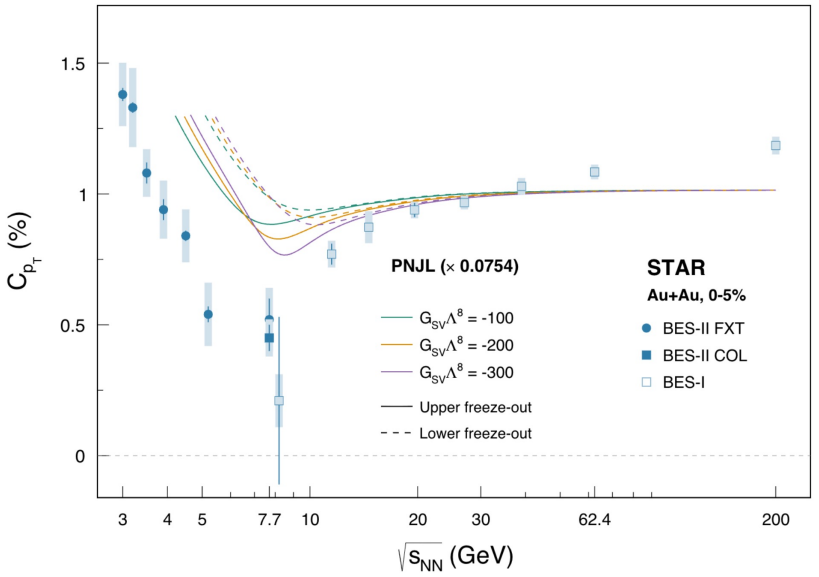
The non-monotonicity is sensitive not only to the mean baryon–meson composition, but also to its event-by-event fluctuations

Interpretations: Temperature fluctuations

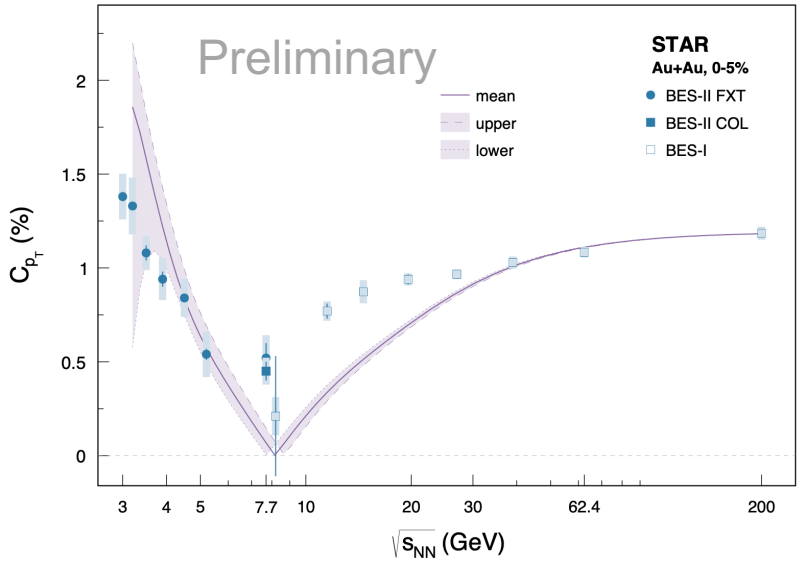
J. Chen, W. Fu, S. Yin, C. Zhang, *PRD 114, 014064 (2026)*



H. Liu, P. Wu, H.M. Liu, P.C. Chu, *2607.16275*



Y. Lu, F. Gao, J. M. Pawlowski, C. Zhang



Reflecting their sensitivity to the QCD equation of state and freeze-out conditions

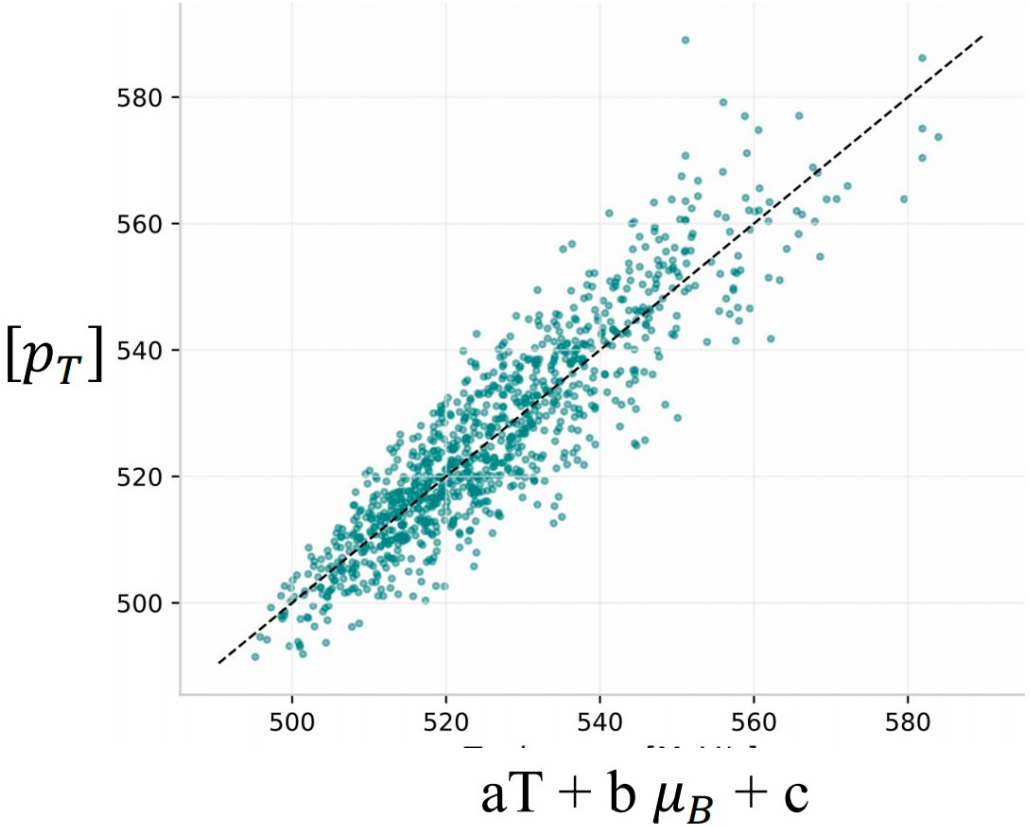
If the event-wise mean transverse momentum tracks the effective temperature, temperature fluctuations may contribute to the observed dynamical p_T correlations

Requires full dynamical modeling

Detailed interpretation in Weijie's talk

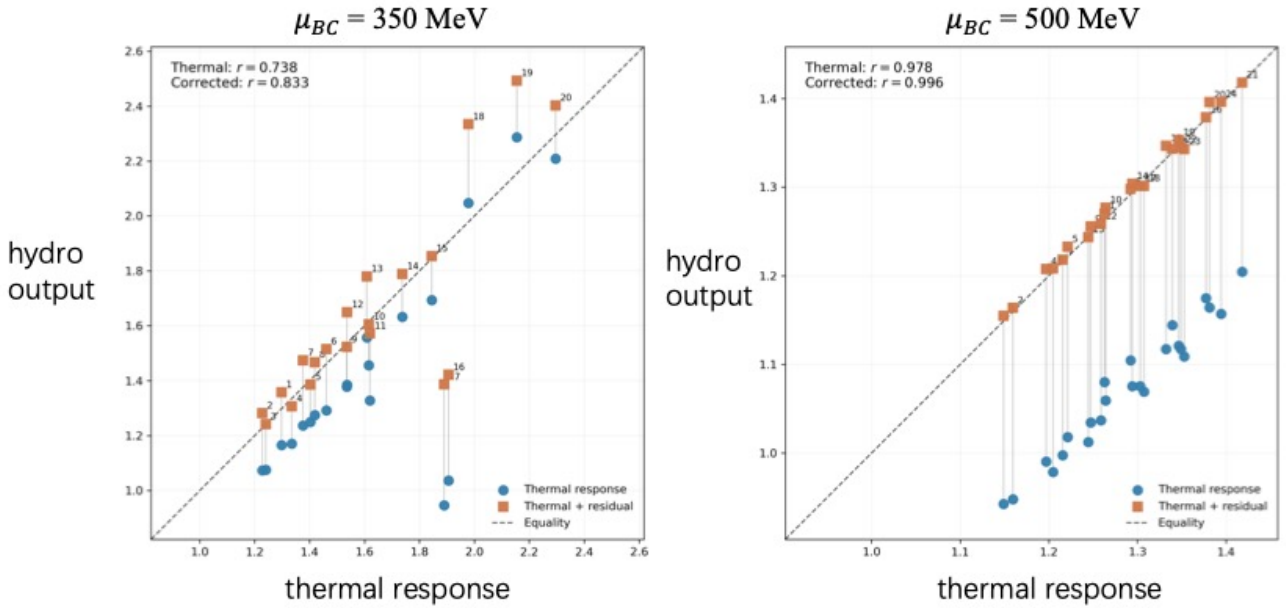
Interpretations: Hydrodynamic calculations

Hydrodynamic + EOS



Yushan Mu, C3NT, Searching for the QCD critical end point through fluctuations of intensive quantities

Numerical test of the thermal response in HIC: c_{p_T}



Fluctuations of $[p_T]$ is a sensitive probe of QCD EoS

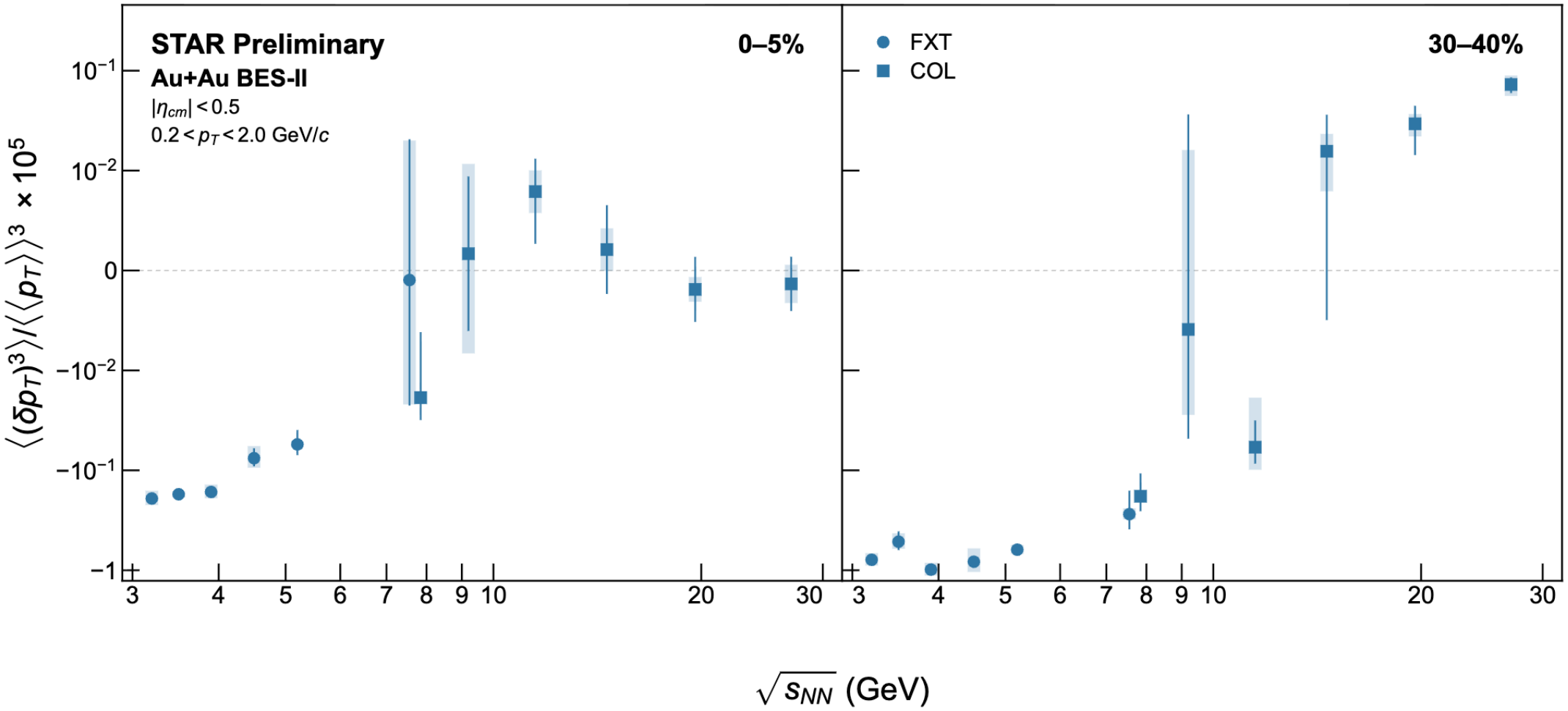
Carry out event-by-event hydro simulations at finite muB with EoS embedded with CEP.

Require more theoretical understandings and calculations

II. Energy dependence of high-order p_T fluctuations in $^{197}Au+^{197}Au$ collisions

High-order $\langle(\delta p_T)^3\rangle/\langle p_T\rangle^3$ vs Energy

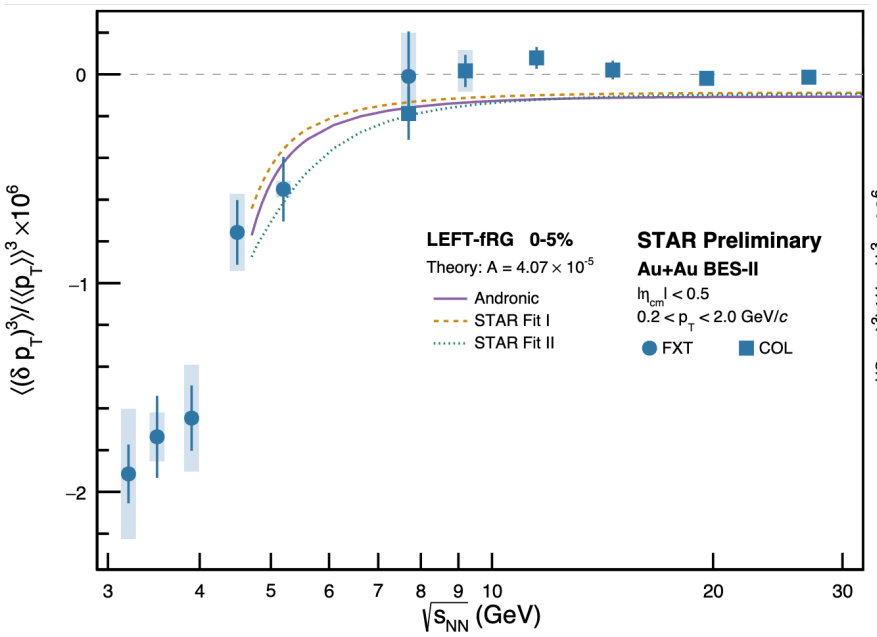
Yining Gao, *ATHIC2026*



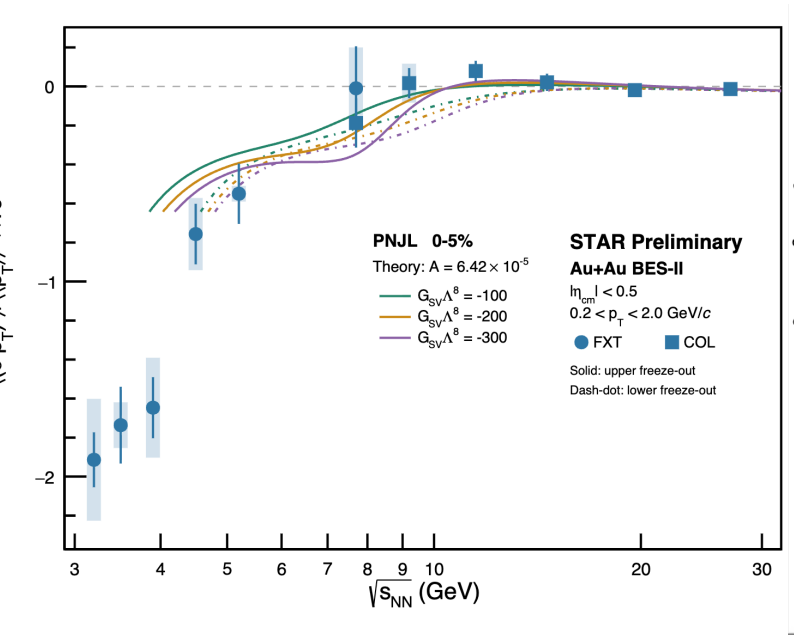
A pronounced negative-to-positive evolution is observed in 30–40% collisions, in contrast to the near-zero correlations at higher energies in 0–5%

Interpretations: Temperature fluctuations

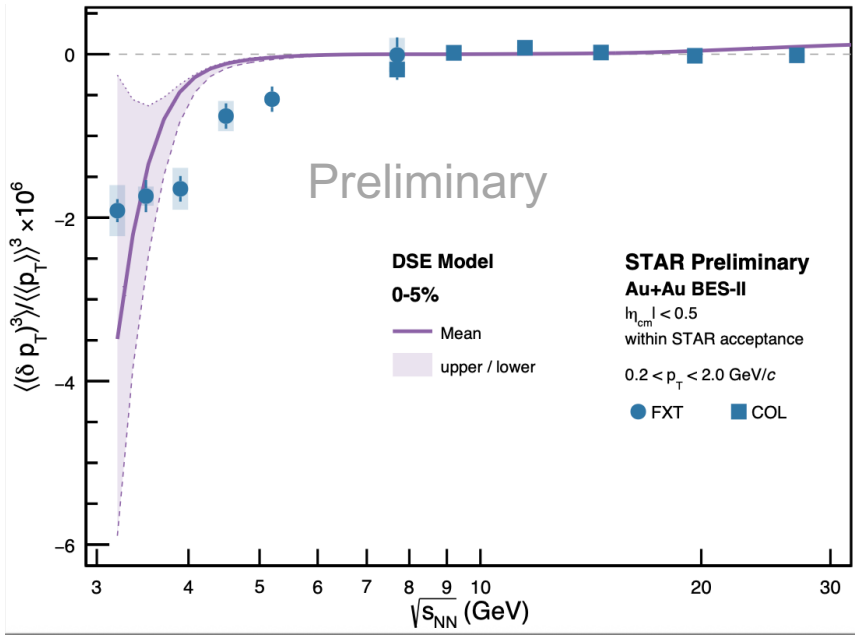
J. Chen, W. Fu, S. Yin, C. Zhang, PRD 114, 014064 (2026)



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



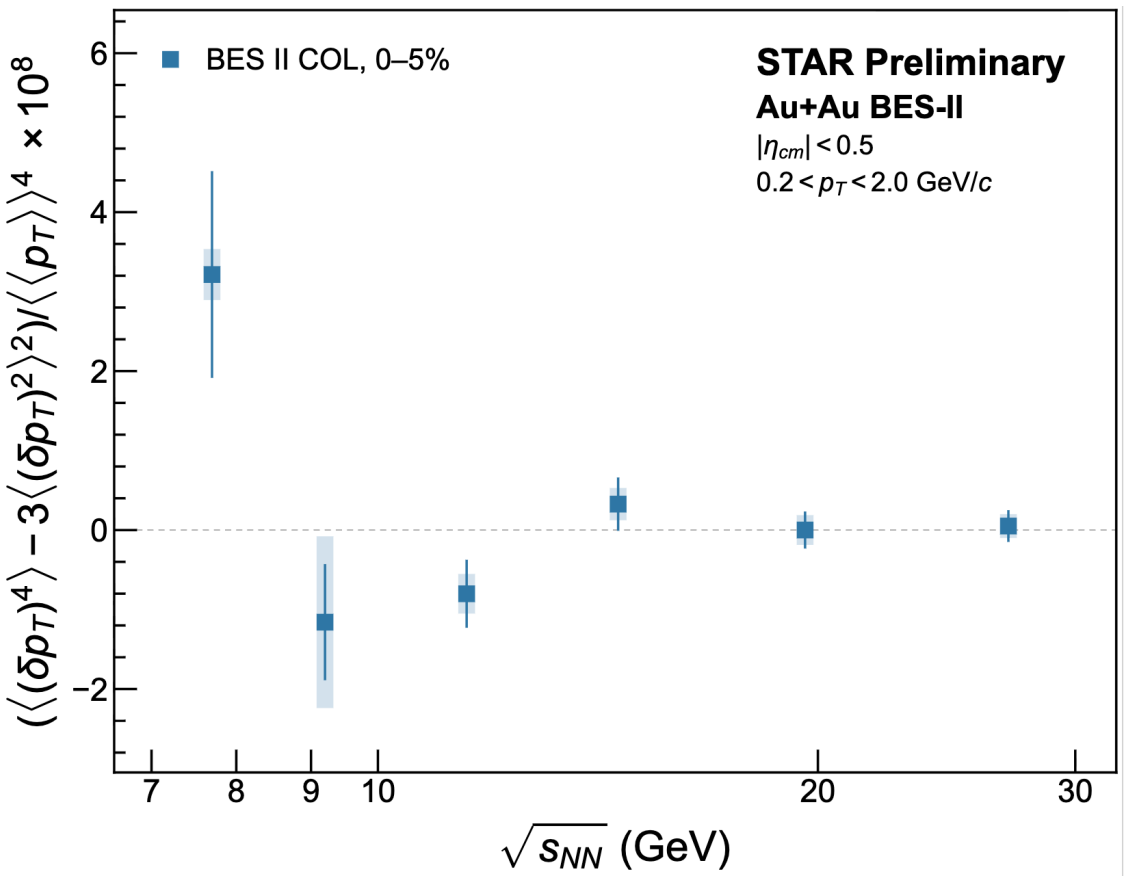
Y. Lu, F. Gao, J. M. Pawlowski, C. Zhang

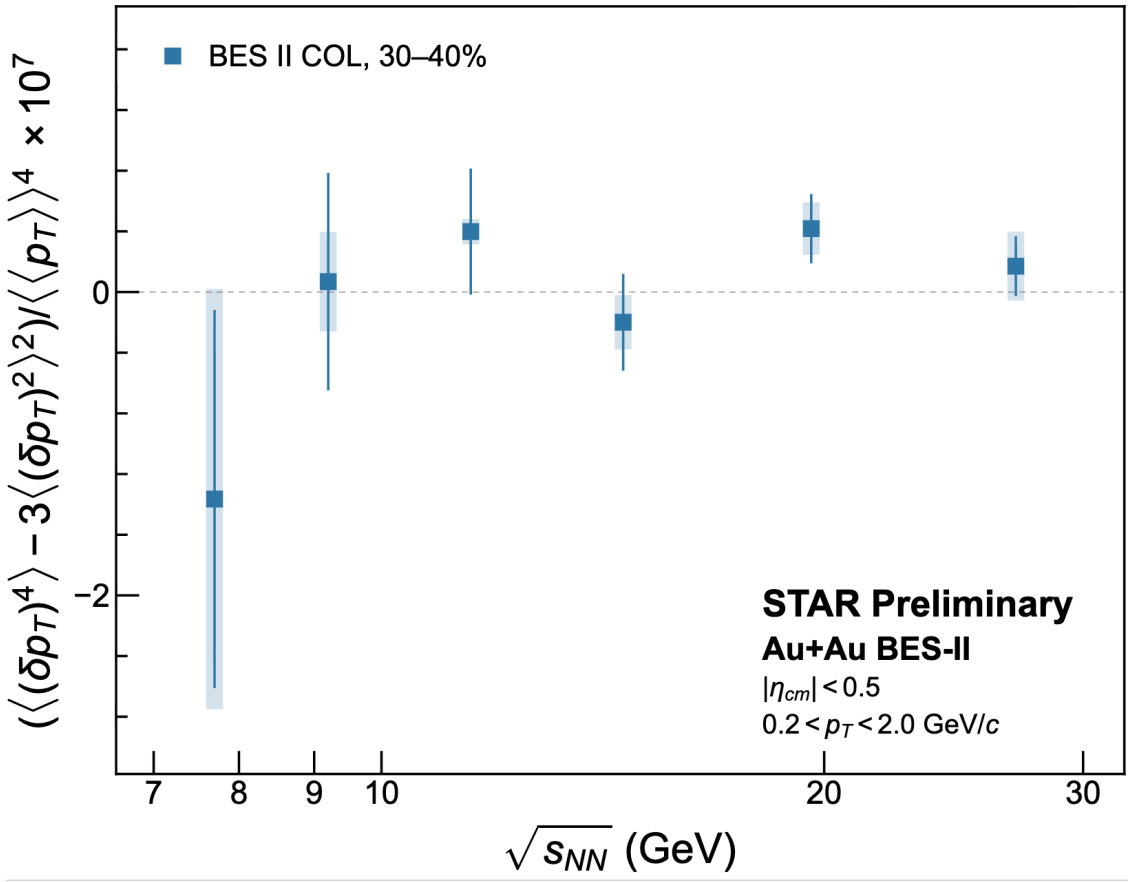


- Both predict negative third-order temperature cumulants at low collision energies
- Qualitatively consistent with the overall trend of the STAR measurements
- Additional dynamical effects are useful for a comprehensive comparison in future

Detailed interpretation in Weijie's talk

High-order $(\langle(\delta p_T)^4\rangle - 3\langle(\delta p_T)^2\rangle^2)/\langle p_T\rangle^3$ vs Energy

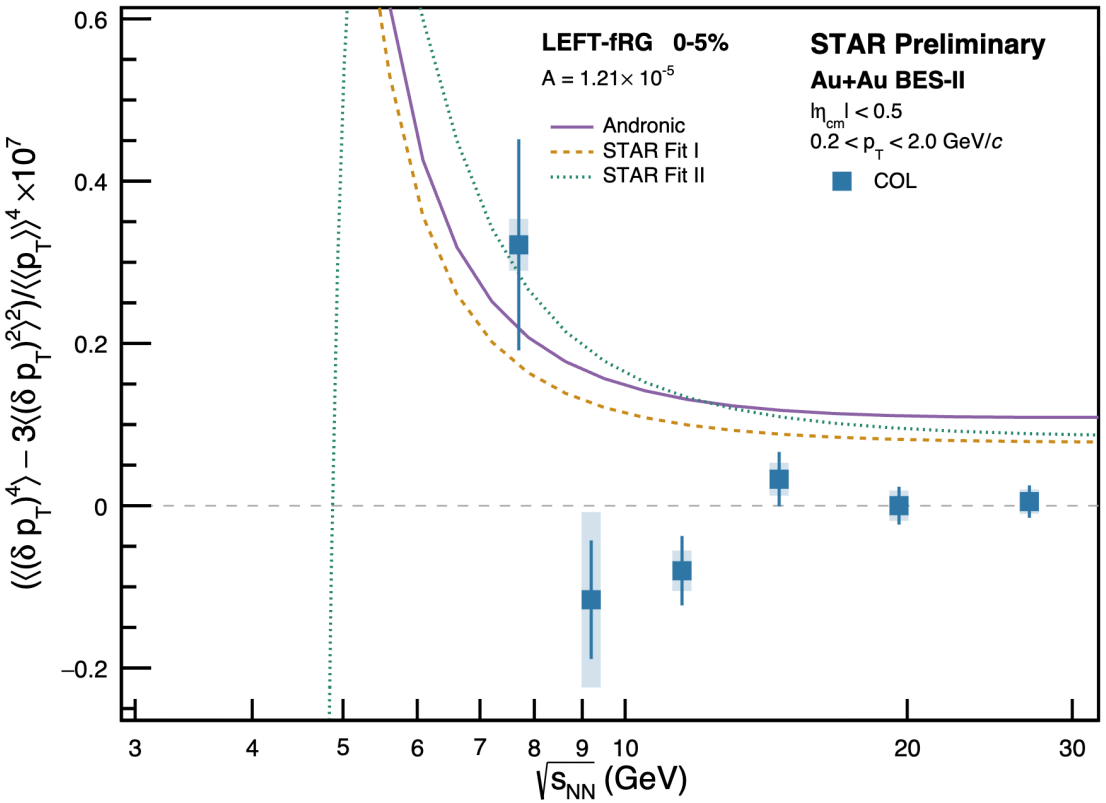




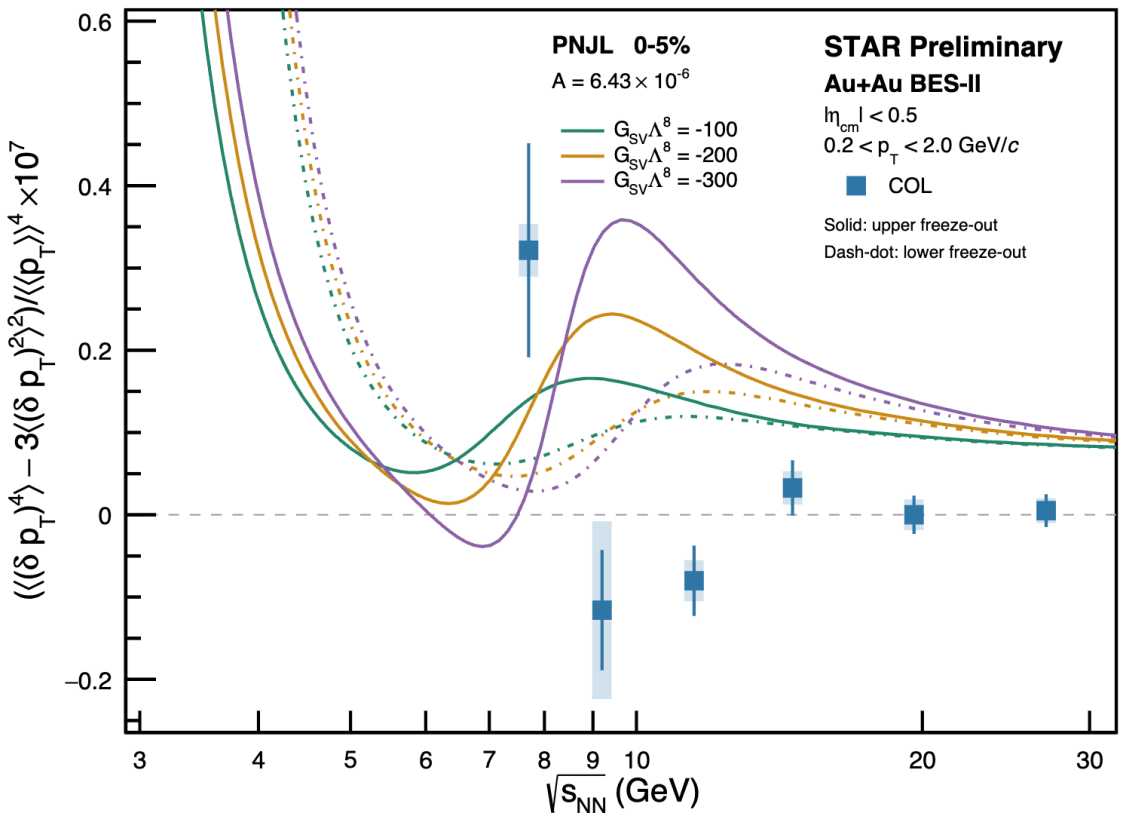
- 0–5%: Possible enhancement at low collision energies, with fourth-order cumulants approaching zero at higher energies
- 30–40%: Larger fourth-order correlations, fluctuating around zero

Interpretations: Temperature fluctuations

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



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



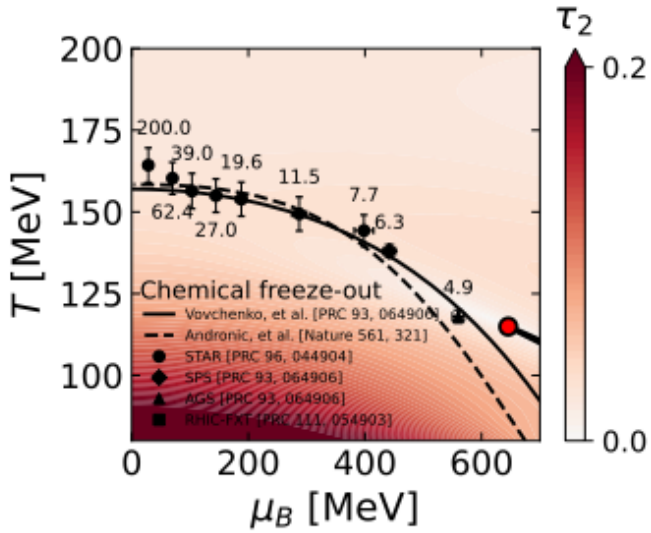
- LEFT-fRG: Positive fourth-order temperature cumulants, with a strong enhancement toward lower collision energies
- PNJL: Predicts non-monotonic peak–dip structures, sensitive to model parameters and freeze-out conditions

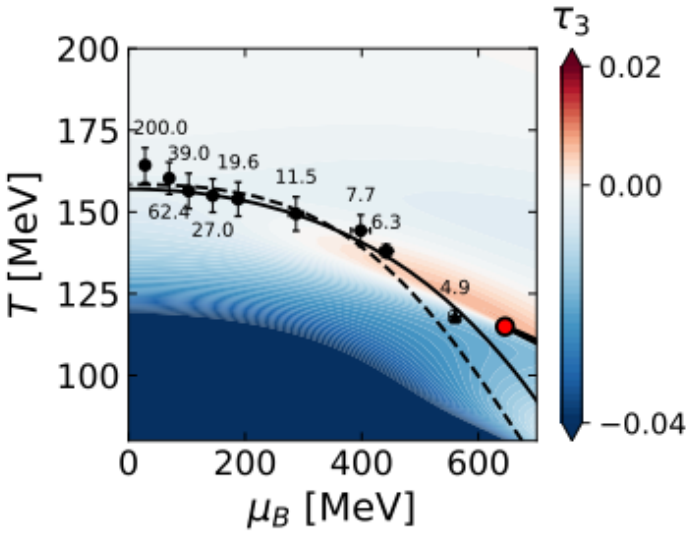
Qualitatively comparable with the overall trend of the STAR measurements

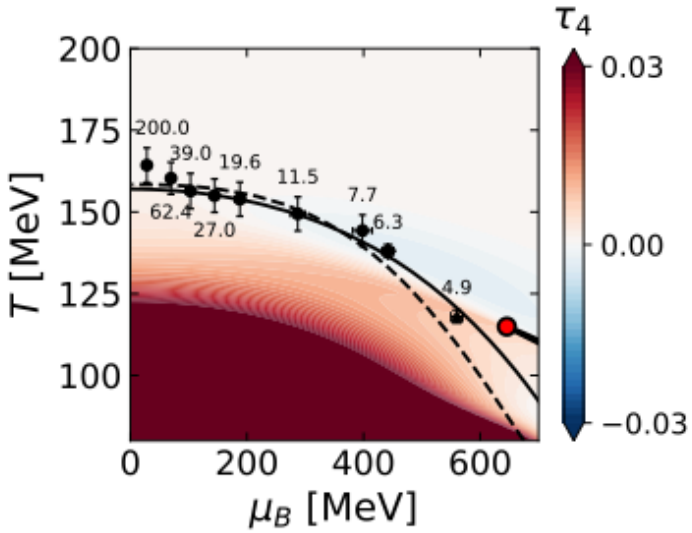
Detailed interpretation in Weijie's talk

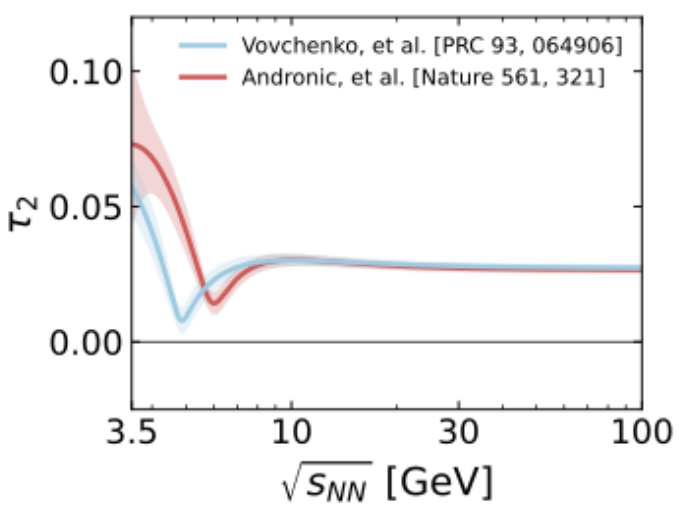
Interpretations: Temperature fluctuations

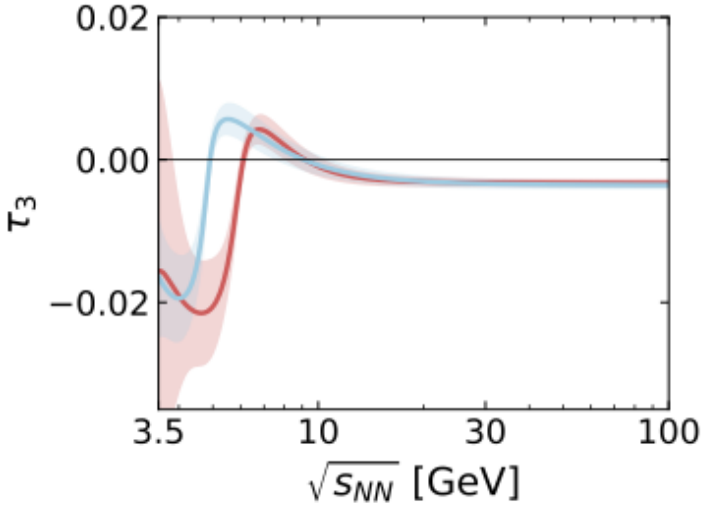
T. Gyure, H. Shah, L. Formaggio, F. D. Clemente, M. Hippert ,C. Ratti, V. Vovchenko, 2610.20806

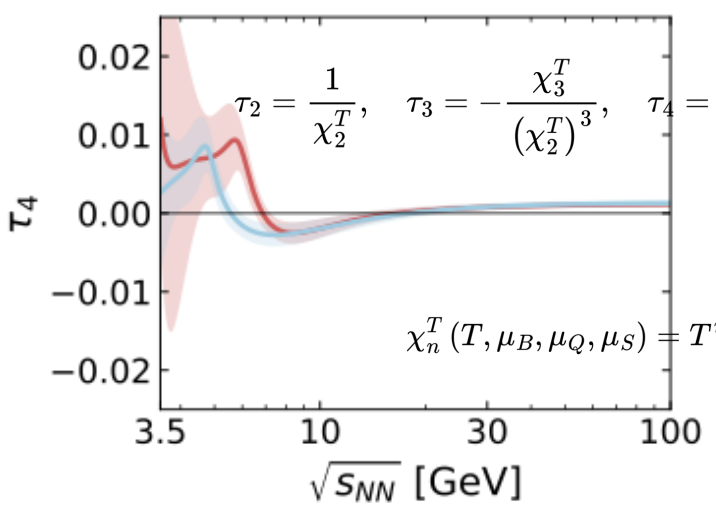












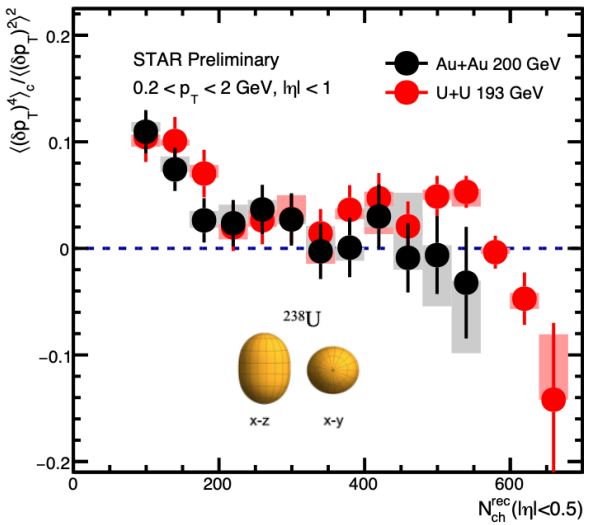
$$\tau_2 = \frac{1}{\chi_2^T}, \quad \tau_3 = -\frac{\chi_3^T}{(\chi_2^T)^3}, \quad \tau_4 = \frac{3(\chi_3^T)^2}{(\chi_2^T)^5} - \frac{\chi_4^T}{(\chi_2^T)^4}$$

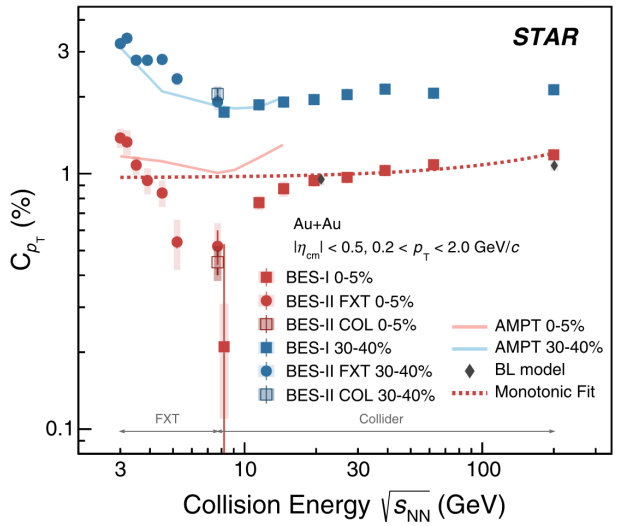
$$\chi_n^T(T, \mu_B, \mu_Q, \mu_S) = T^{n-4}\left(\frac{\partial^n p}{\partial T^n}\right)_{\mu_B, \mu_Q, \mu_S}$$

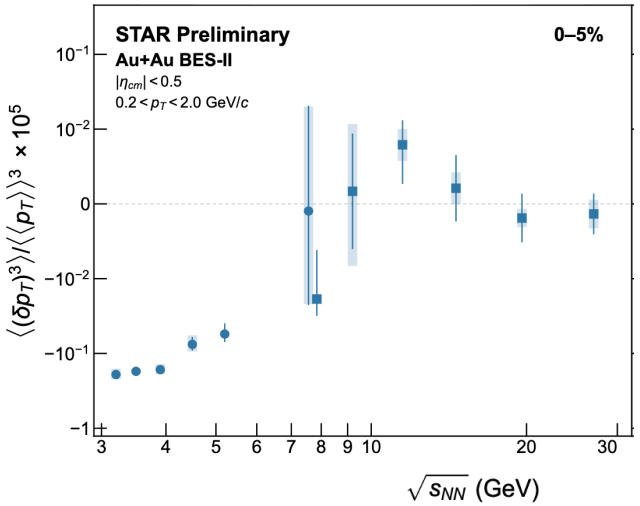
help distinguish critical behavior from a non-critical hadronic baseline around freeze-out lines approach the critical region of our equation of state.

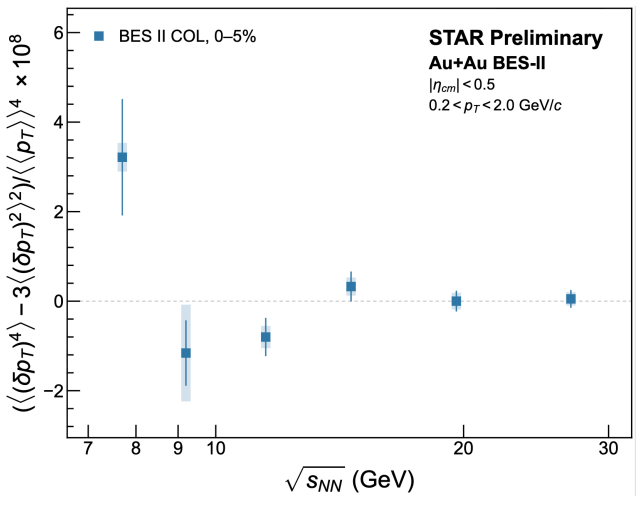
Conclusions

- **Mean p_T fluctuations: a potential smoking gun probing nuclear structure and QCD properties.**
- **Negative kurtosis** in highly deformed ^{238}U indicates the nuclear structure effect.
- Light ion collisions is a good connection to investigate **NN correlations and subnucleon fluctuations**.
- **Nonmonotonic dependence** of second-order mean p_T fluctuations at high μ_B.
- **High-order mean p_T fluctuations** serve as complementary probes of the properties of QCD matter.





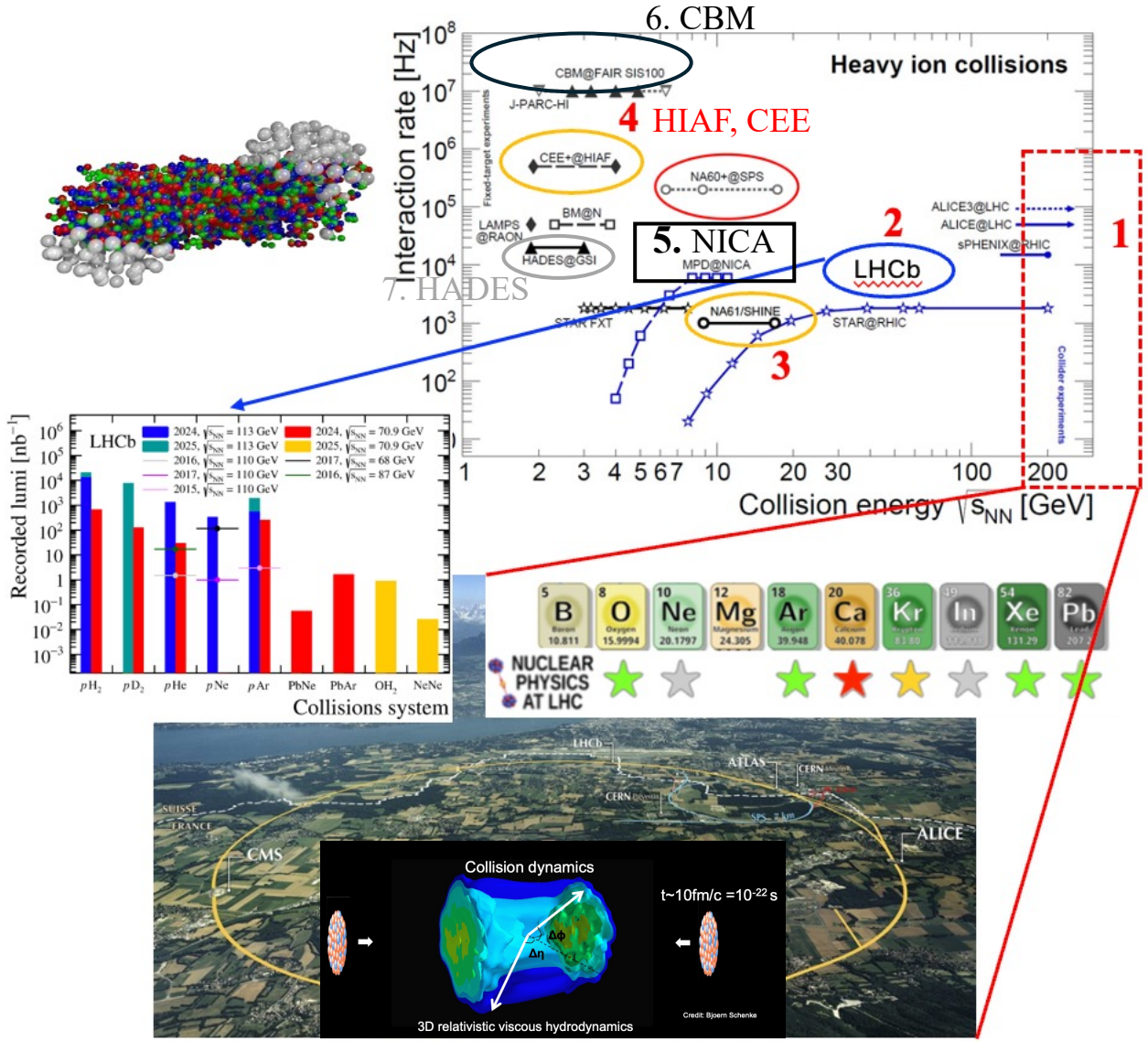




STAR, *PRL 137, 132301 (2026)*

Outlooks

1) Energy evolution and system scan in high baryon density



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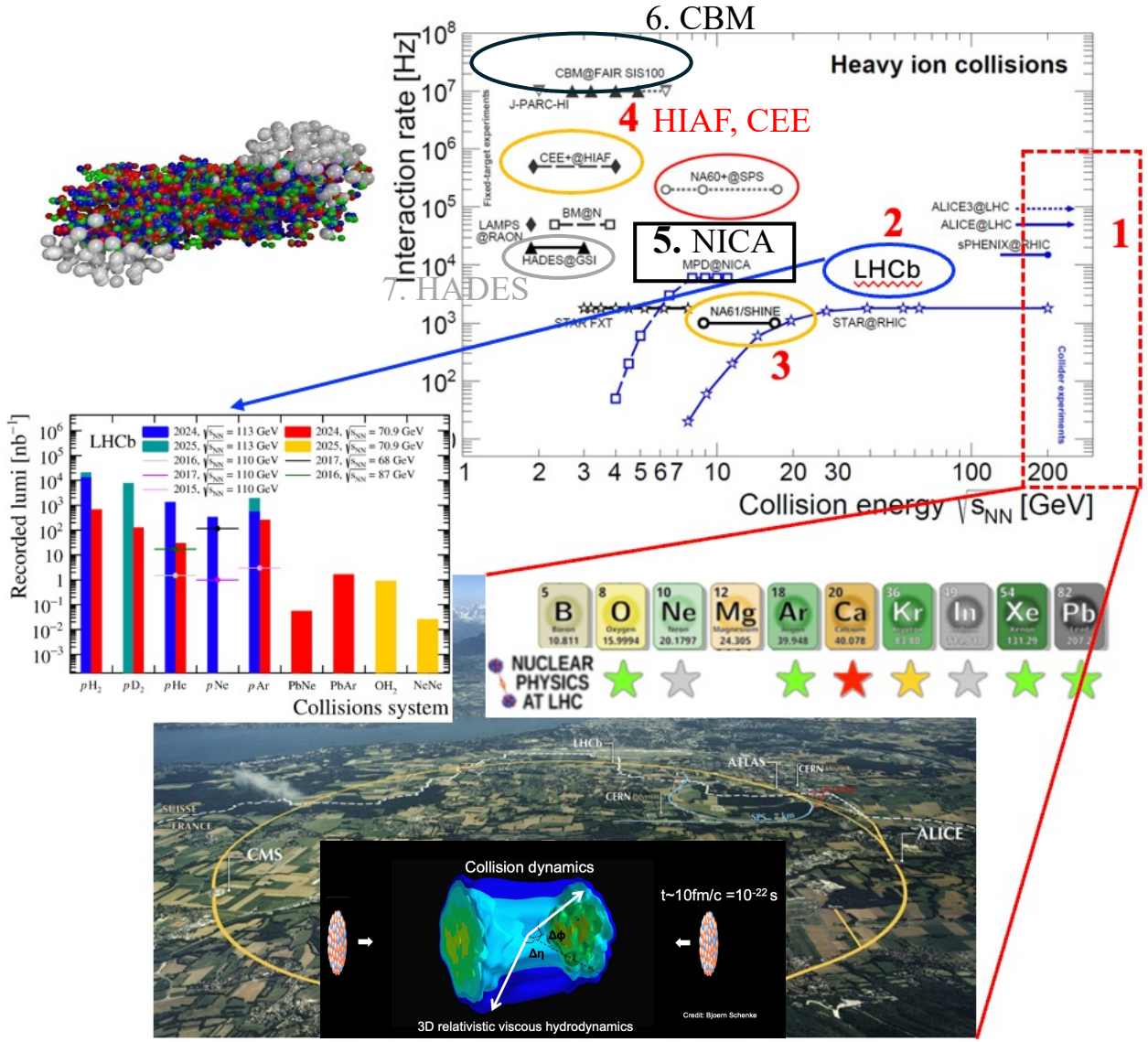
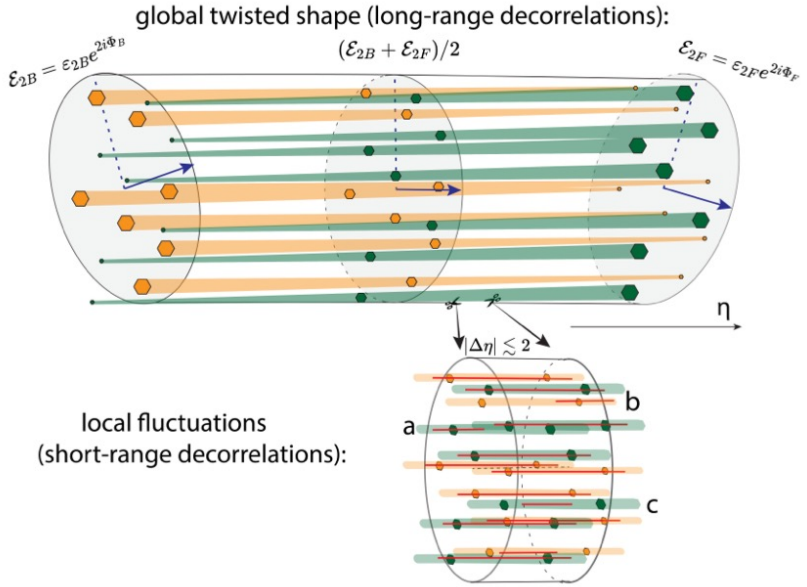


2) Longitudinal structure QGP initial conditions



Decorrelation map:

v_n decorrelations (deformation-induced component):

J. Jia, C. Zhang, S. Huang, *2405.08749*

J. Jia, S. Huang, C. Zhang, S. Bhatta, *PRL 137, 202301 (2026)*

p_T decorrelations and EoS:

L. Liu, J. Chen, X.-G. Huang, J. Jia, C. Shen, C. Zhang, *2511.11094*

J. Zhu, X.-Y. Wu, G.-Y. Qin, *2602.04148*

S. Jahan, Roch, C. Shen, *PRC 113, 024919 (2026)*

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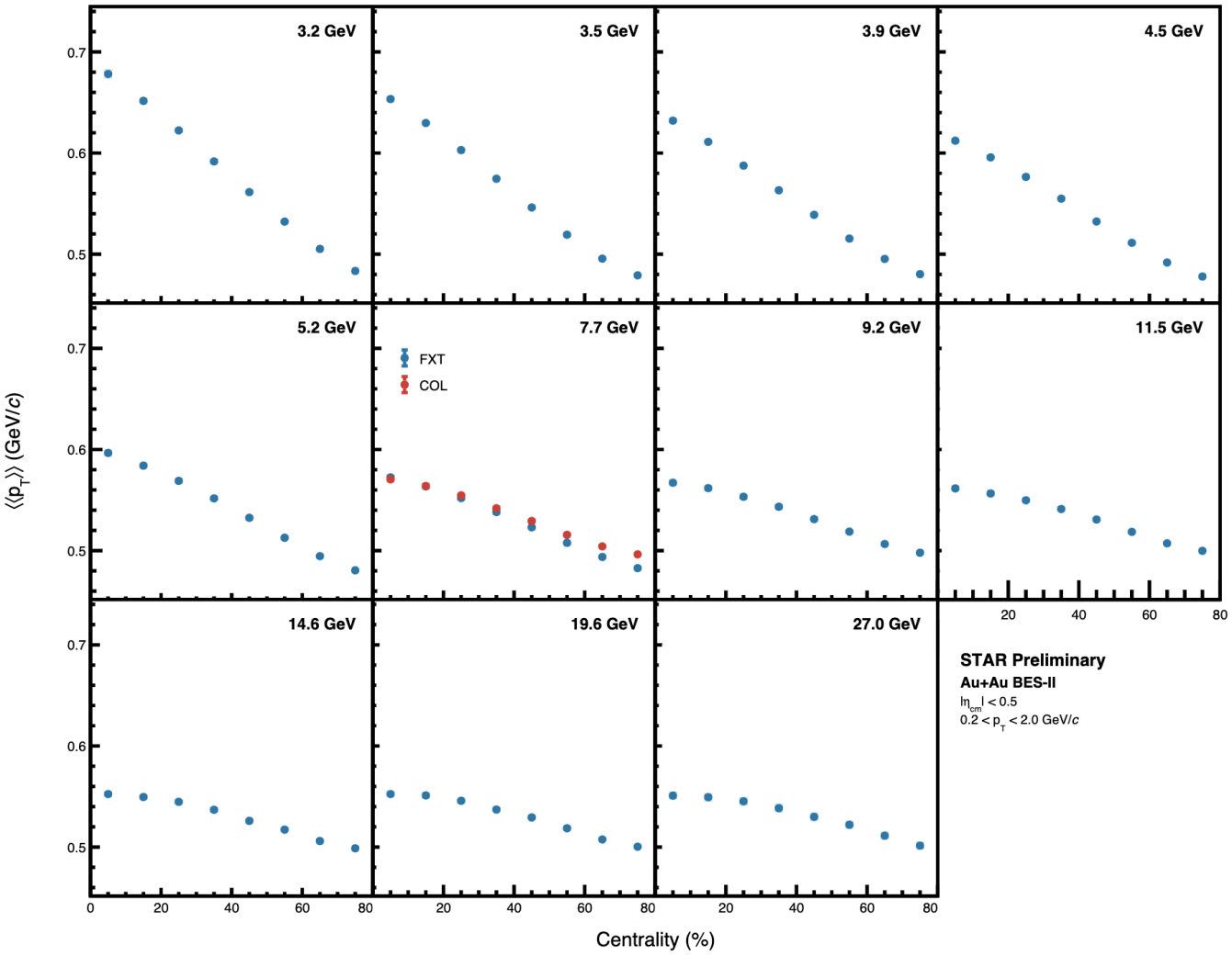
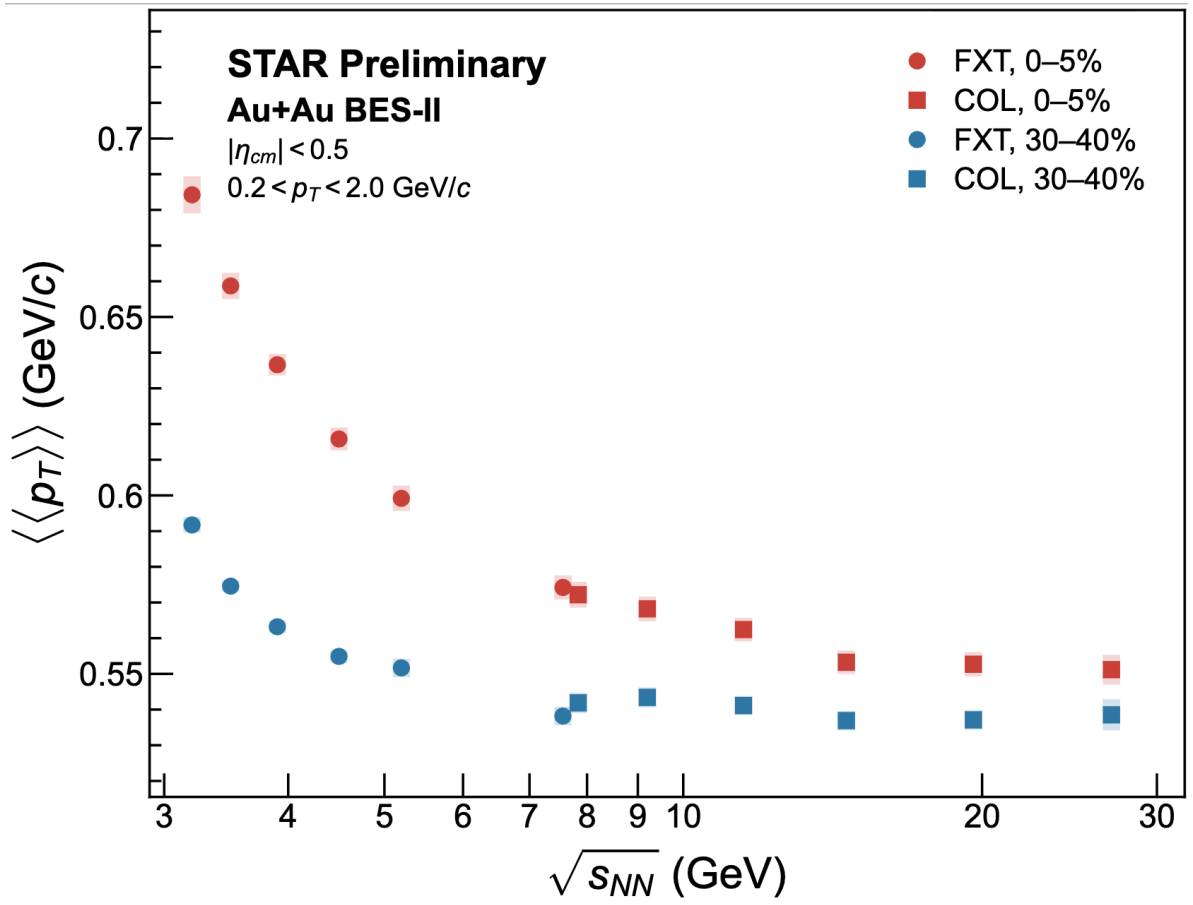
Thank you for your attention!

Centrality and Energy dependence of $\langle p_T \rangle$



Stronger Centrality dependence at lower energies.



Mean p_T decreases rapidly at low collision energies and shows a much weaker variation above 11.5 GeV