极端条件下的QCD研讨会

重离子碰撞中径向流与平均横动量涨落的实验研究

张春健

复旦大学

烟台大学，2026年8月18-20日

Outline

- **Introductions:** mean transverse momentum fluctuations

- Imaging nuclear structure in heavy ion physics

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

  STAR, *Nature 67, 635 (2024), Rep. Prog. Phys. 88,108601 (2025)*

  II. Cluster pattern and geometry effect in ^{16}O

  STAR, *arXiv: 2510.19645 (under review at PRL)*

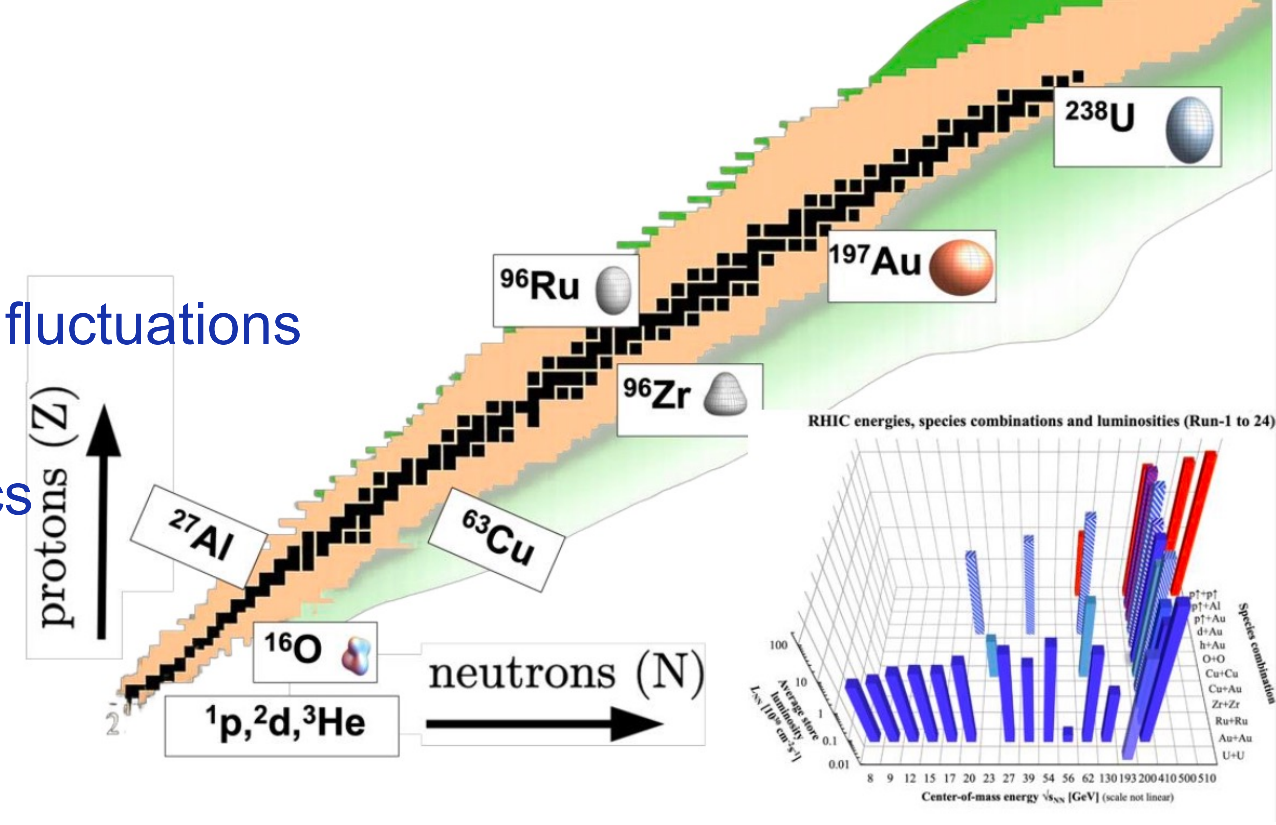
- Energy dependence and universal features of radial-flow response

  I. Second-order fluctuation in ^{197}Au + ^{197}Au collisions at FXT energies

  STAR, *arXiv: 2604.06434 (PRL in press)*

  II. Energy dependence of High-order fluctuations

  III. Radial-flow response from large to small collisions: *universal features?*



❑ **Introductions:** mean transverse momentum fluctuations

Imaging by smashing method and event-by-event fluctuations

Take a snapshot

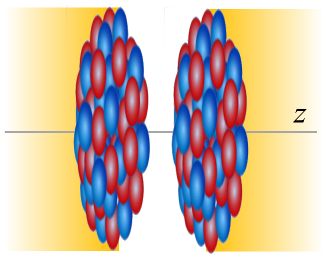
Evolution

Measurement

Nuclei collisions $T_{\mu\nu}(\tau = 0)$

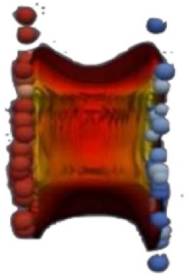
$\partial_\mu T^{\mu\nu} = 0$, EOS, viscosity…

$T_{\mu\nu}(\tau = \infty)$

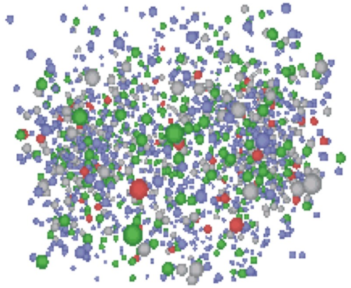


Pressure-driven expansion of

Quark-gluon plasma (QGP)



free-streaming



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

$\tau \sim 10\text{fm}/c$
expansion

$\tau \sim 10^{15}\text{fm}/c$
detection

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

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

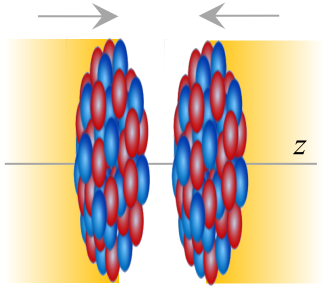
$\beta_2 \longrightarrow$ quadrupole deformation
$\beta_3 \longrightarrow$ octupole deformation
$\gamma \longrightarrow$ triaxiality
$a_0 \longrightarrow$ surface diffuseness
$R_0 \longrightarrow$ nuclear size

ab initio theory/shell model/DFT

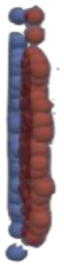
Imaging by smashing method and event-by-event fluctuations

Take a snapshot | Evolution | Measurement

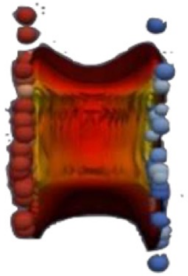
Nuclei collisions $T_{\mu\nu}(\tau=0)$ $\quad$ $\partial_\mu T^{\mu\nu}=0$, EOS, viscosity… $\quad$ $T_{\mu\nu}(\tau=\infty)$



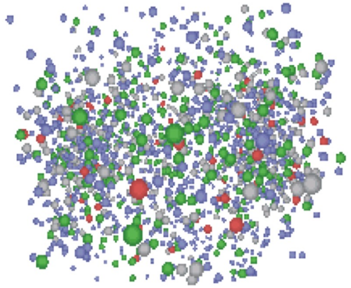
$\longrightarrow$



Pressure-driven expansion of $\longrightarrow$ Quark-gluon plasma (QGP)



free-streaming $\longrightarrow$



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

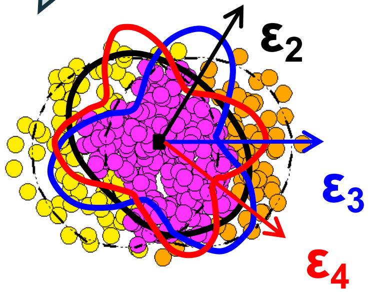
$\tau\sim 10\mathrm{fm}/c$ expansion

$\tau\sim 10^{15}\mathrm{fm}/c$ detection

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

- $\beta_2 \rightarrow$ quadrupole deformation
- $\beta_3 \rightarrow$ octupole deformation
- $\gamma \rightarrow$ triaxiality
- $a_0 \rightarrow$ surface diffuseness
- $R_0 \rightarrow$ nuclear size

ab initio theory/shell model/DFT



size & shape

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

$\boxed{R_\perp^2 \propto \langle r_\perp^2\rangle}$

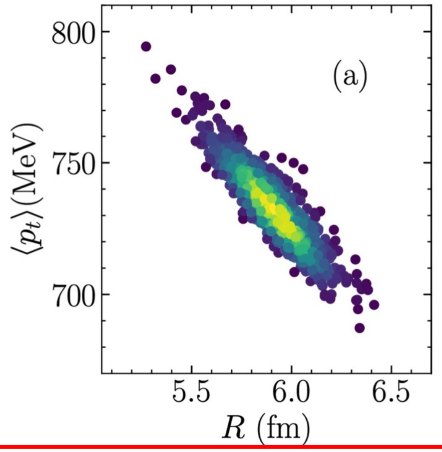
$\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi}\rangle$

R_0 $\quad$ a_0 $\quad$ β_n

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

linear responses:

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

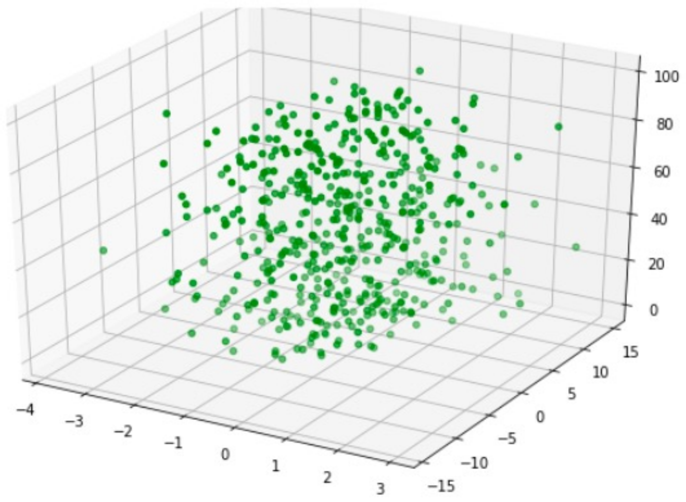


Key: 1) fast snapshot, 2) linear response, 3) large multiplicity for many-body correlation

New observables: mean transverse momentum fluctuations

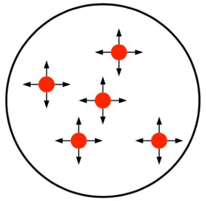
J. Jia, S. Huang, C. Zhang, *PRC 105 , 014906 (2022)*
S. Bhatta, C. Zhang, J. Jia, *PRC106, L031901 (2022)*
C. Zhang, A. Behera, S. Bhatta, J. Jia, *PLB 822, 136702 (2021)*

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



Event-by-event temperature fluctuations

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

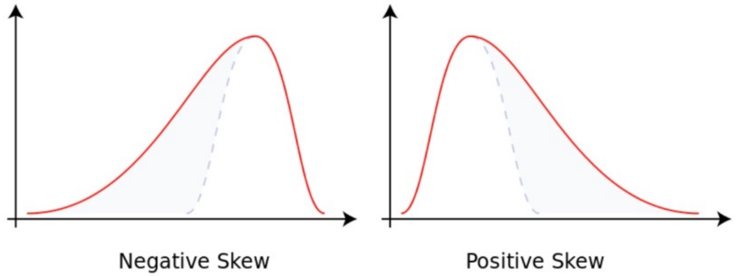


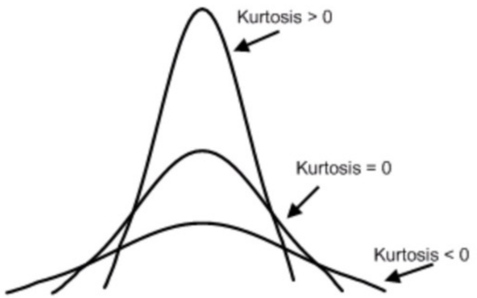
Variance: $$\left\langle\left(\delta p_T\right)^2\right\rangle = \frac{\sum_i \sum_{j\neq i}\omega_i\omega_j\left(p_{T,i}-\langle[p_T]\rangle\right)\left(p_{T,j}-\langle[p_T]\rangle\right)}{\sum_i\sum_{j\neq i}\omega_i\omega_j},$$

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

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

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





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

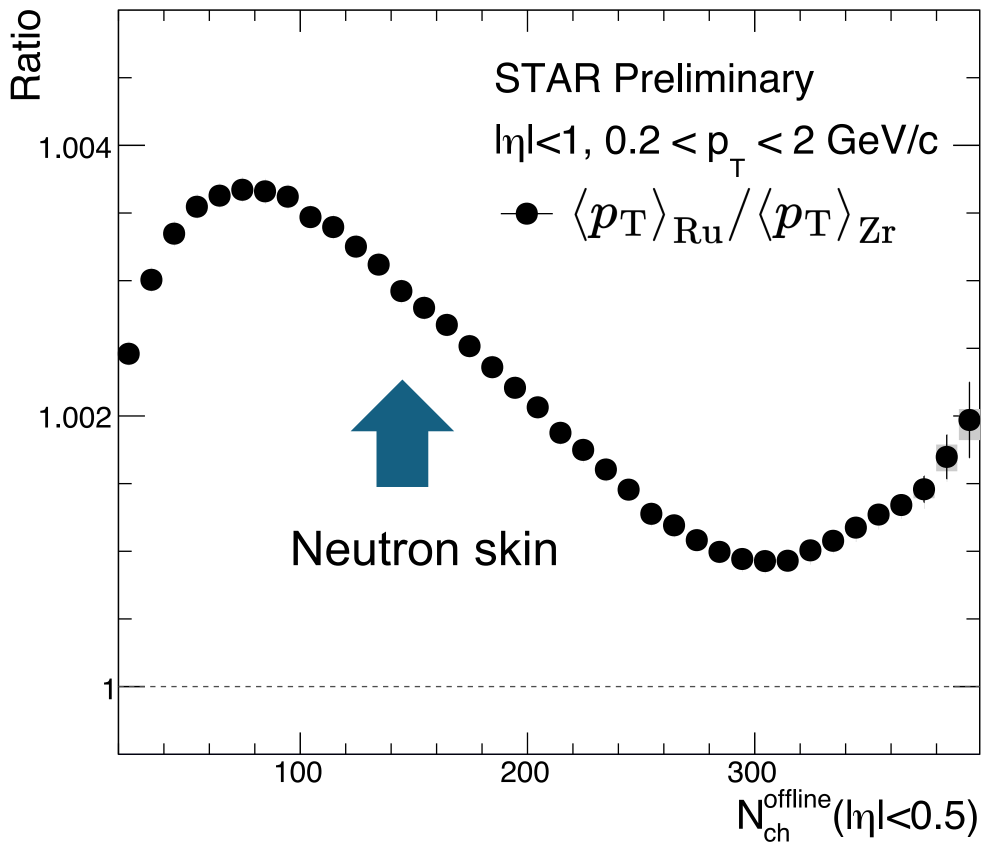
❑ Imaging nuclear structure in heavy ion physics

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

STAR, *Nature 67, 635 (2024), Rep. Prog. Phys. 88,108601 (2025)*

Size fluctuation sensitive to nuclear skin

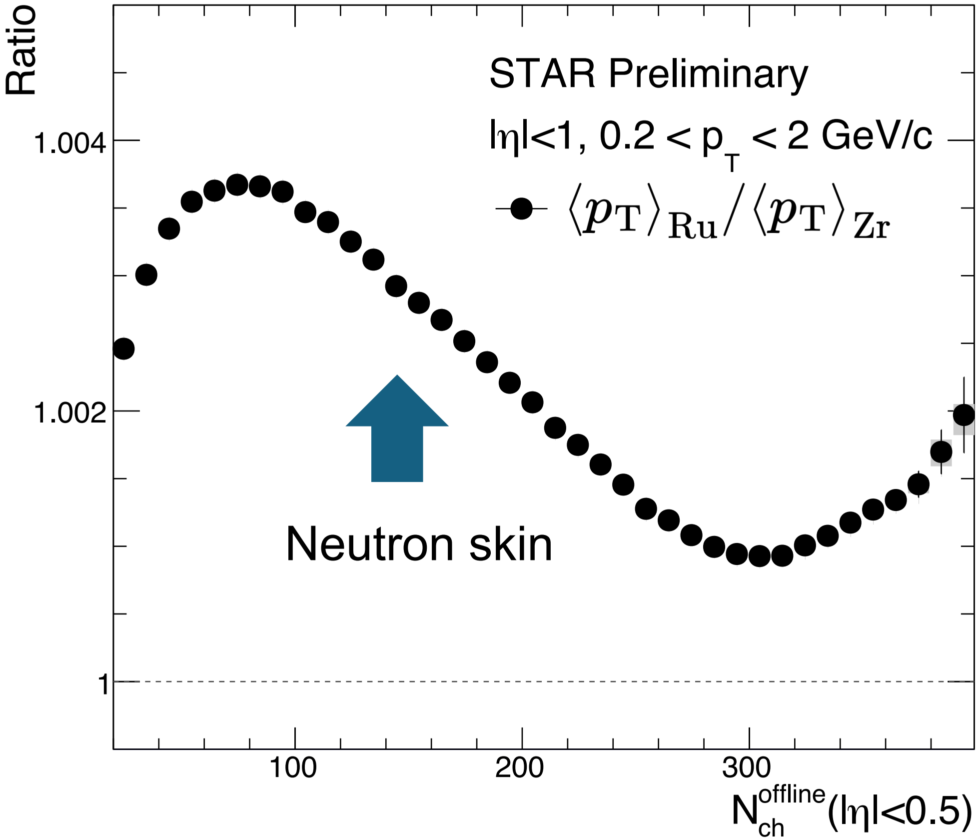
C. Zhang (STAR), *QM2022*



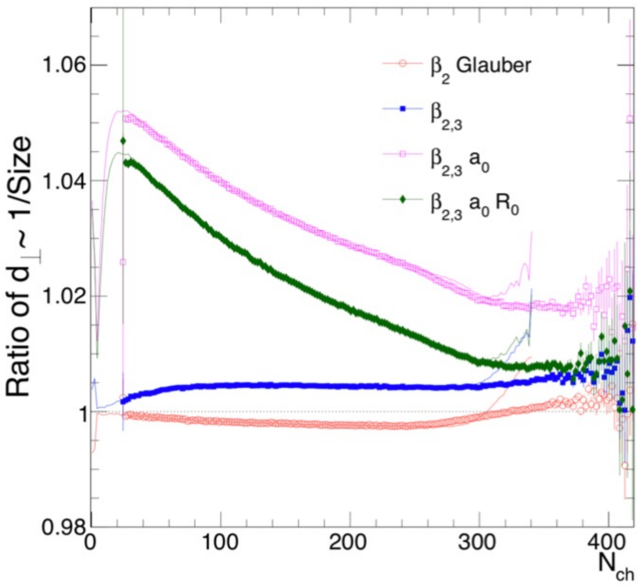
The nonmonotonic trend reflects the neutron skin effect.

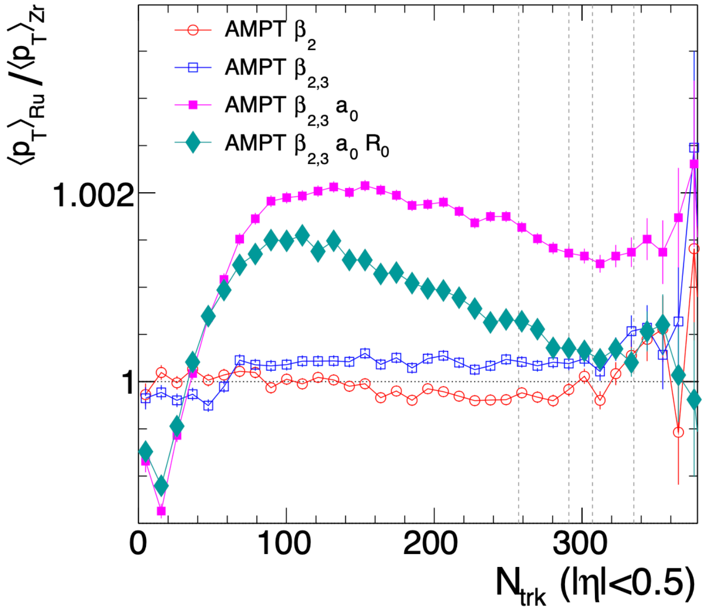
Size fluctuation sensitive to nuclear skin

C. Zhang (STAR), *QM2022*



Initial-state Glauber and final-state AMPT



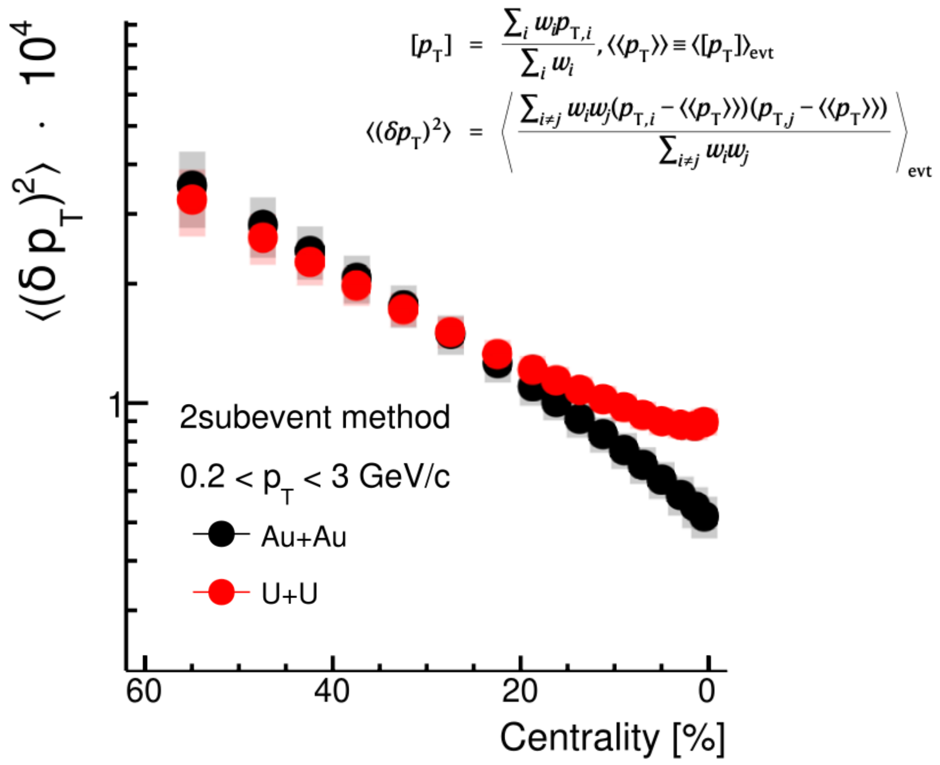


J. Jia, *PRC 105, 044905 (2022)*

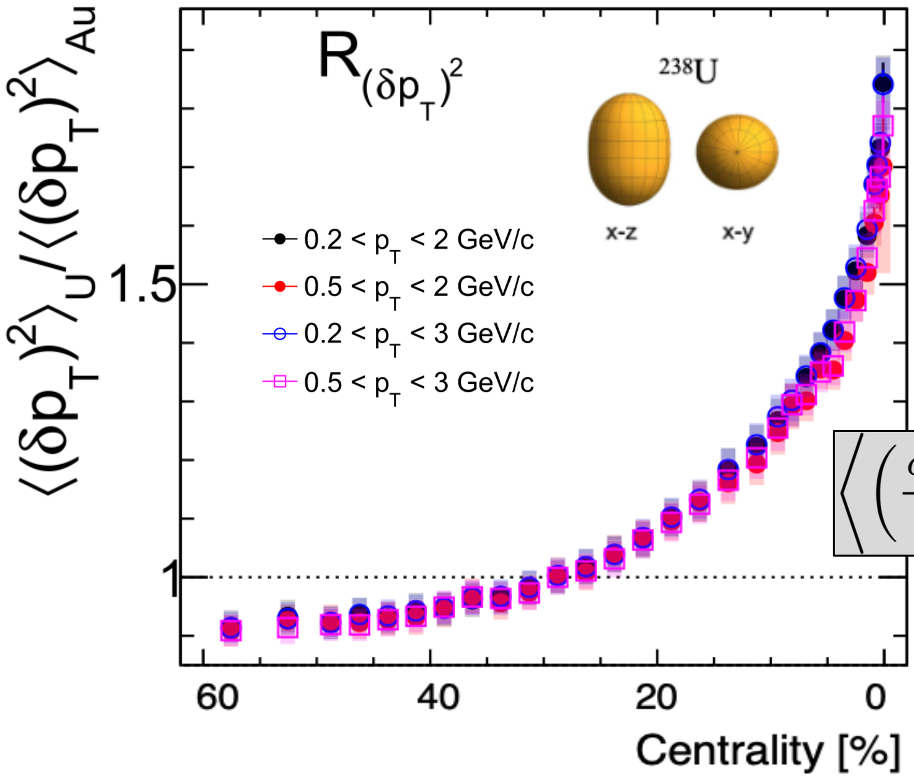
The nonmonotonic trend reflects the neutron skin effect.

Size fluctuation sensitive to nuclear deformation

STAR, *Nature 67, 635 (2025)*



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



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

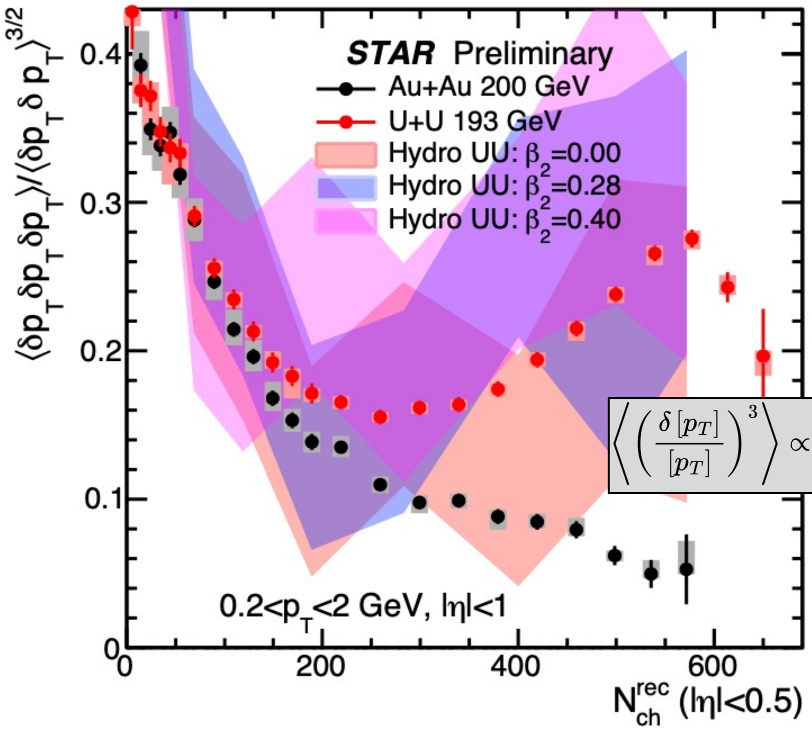
large enhancement in mean and variance ⟶ size fluctuations enhanced

A good probe to image nuclear deformation.

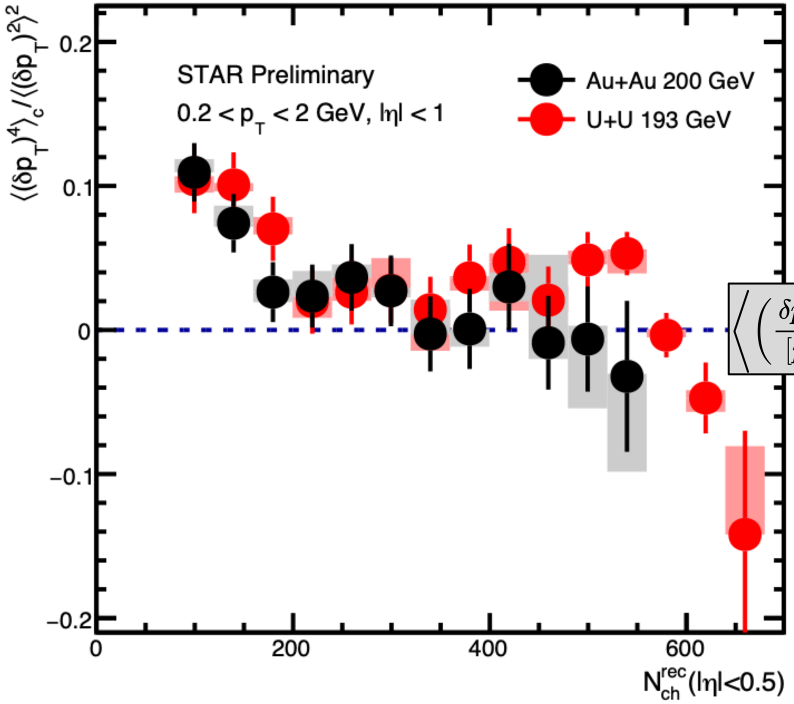
ALICE, *PLB 850, 138541 (2024);* ATLAS, *PRL 133, 252301 (2024);* G. Giacalone, J. Jia, C. Zhang, *PRL 127, 242301 (2021)*

Size fluctuation sensitive to nuclear deformation

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



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



$$\left\langle \left(\frac{\delta p_T}{[p_T]}\right)^4 \right\rangle - 3\left\langle \left(\frac{\delta p_T}{[p_T]}\right)^2 \right\rangle^2 \propto -\beta_2^4$$

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

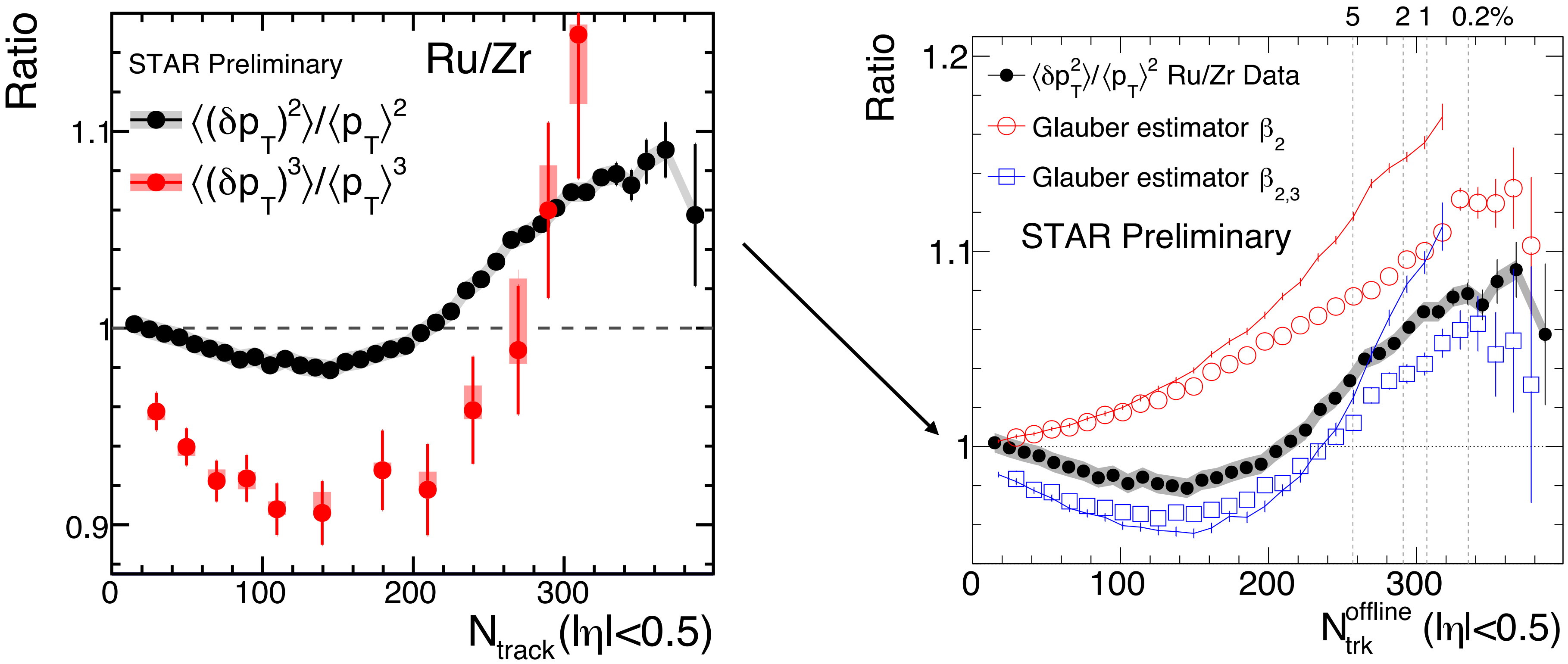
M. Cody et. al., *Phys. Rev. C 107, (2023)*

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

Confirmed by hydro, but statistics hungry.

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

Size fluctuation sensitive to nuclear deformation



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

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

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

Cancelation expected in non-central collisions

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

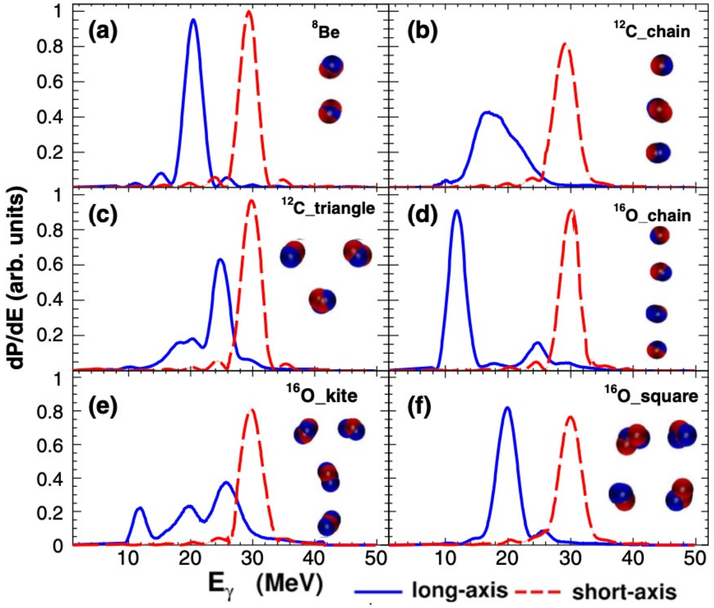
Octupole deformation: large enhancement in skewness and sign-change in kurtosis

II. Cluster pattern and geometry effect in ^{16}O

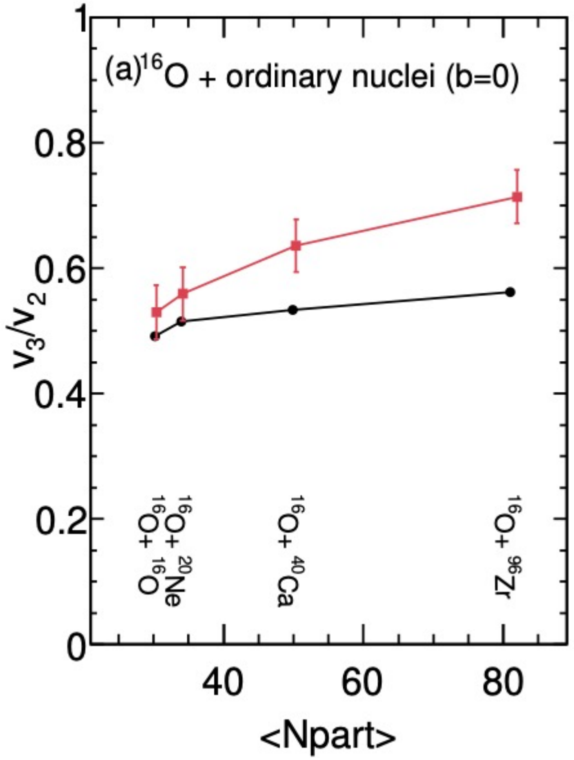
STAR, *arXiv: 2604.06434 (Under review at PRL)*

Pioneer theory instructions of the nucleonic clustering

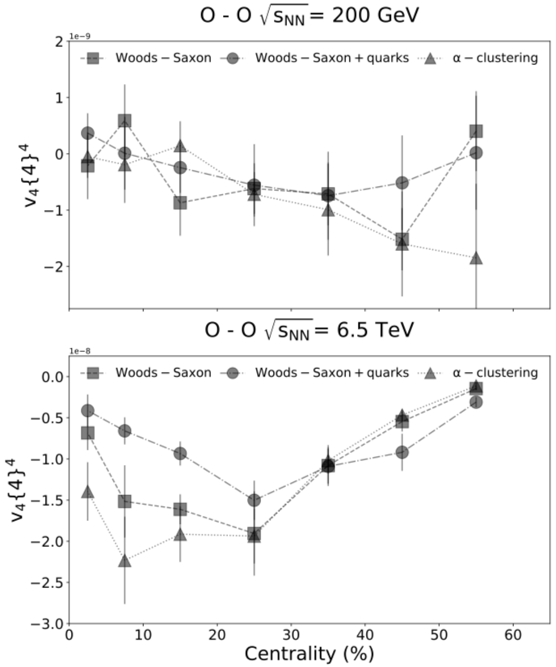
"Double magic number" in $^{16}_{8}$O nuclei, possible alpha cluster in low-energy studies.



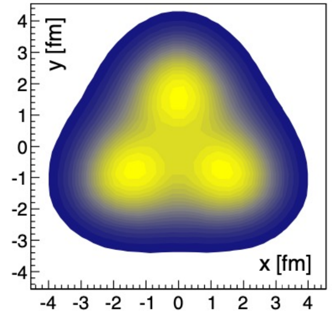
W. He, Y.-G. Ma et al., *PRL 113, 032605 (2014)*

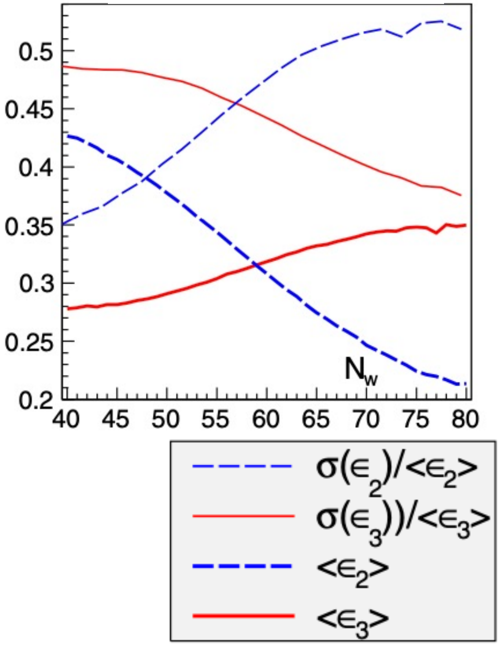


Y.-G. Ma and S. Zhang, *Handbook of Nuclear Physics,* 2206.08218



Nicholas et al., *PRC 104, L041901 (2021)*





W. Broniowski, E. Arriola, *PRL 112, 112501 (2014)*

- ^{16}O nucleus could have different intrinsic topological structures.
- The initial configurations straightforwardly affect the final state observables in high energies.

Nucleon-nucleon (NN) correlations in quantum many-body system

Possible cluster in ground-state $^{16}_{8}O$ nuclei in low energy

***1) Woods-Saxon:** without many-body nuclear correlation*

2) Nuclear Lattice Effective Field theory (NLEFT):
model with many-nucleon correlation including α clusters

Lu et al., *PLB 797, 134863 (2019)*
M. Freer et al., *Rev. Mod. Phys. 90, 035004 (2018)*
S. Elhatisari et al., *Nature 630, 59 (2024)*

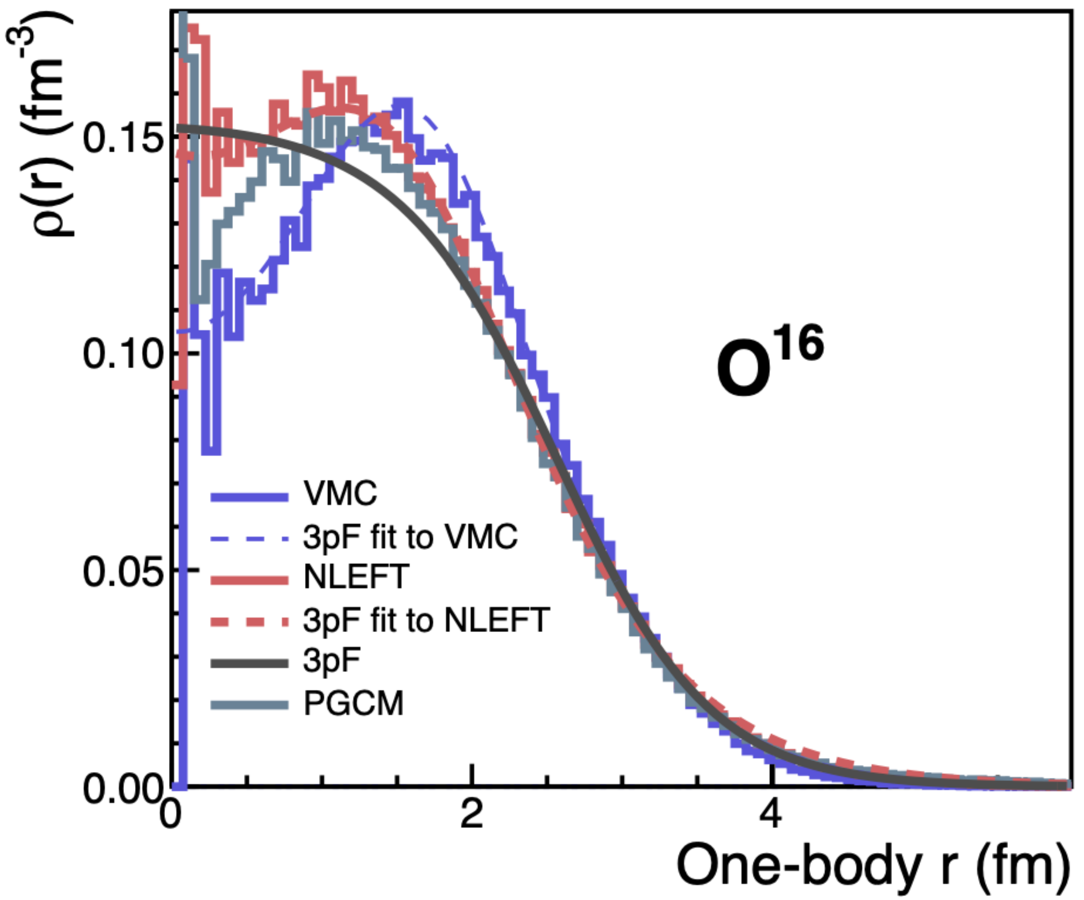
3) Variational auxiliary field diffusion Monte Carlo (VMC):
MC solution of Schrödinger eq. from the time evolution of trial wave function.

A. Lonardoni et al., *PRC 97, 044318 (2018)*
J. Carlson and R. Schiavilla, *Rev. Mod. Phys. 70, 743 (1998)*

4) ab-initio Projected Generator Coordinate Method (PGCM):
Wave function from variational calculation (as in density functional theory)

Frosini et al., *EPJA 58, 62 (2022); EPJA 58, 63 (2022); EPJA 58, 64 (2022)*

5) Some other micro models…

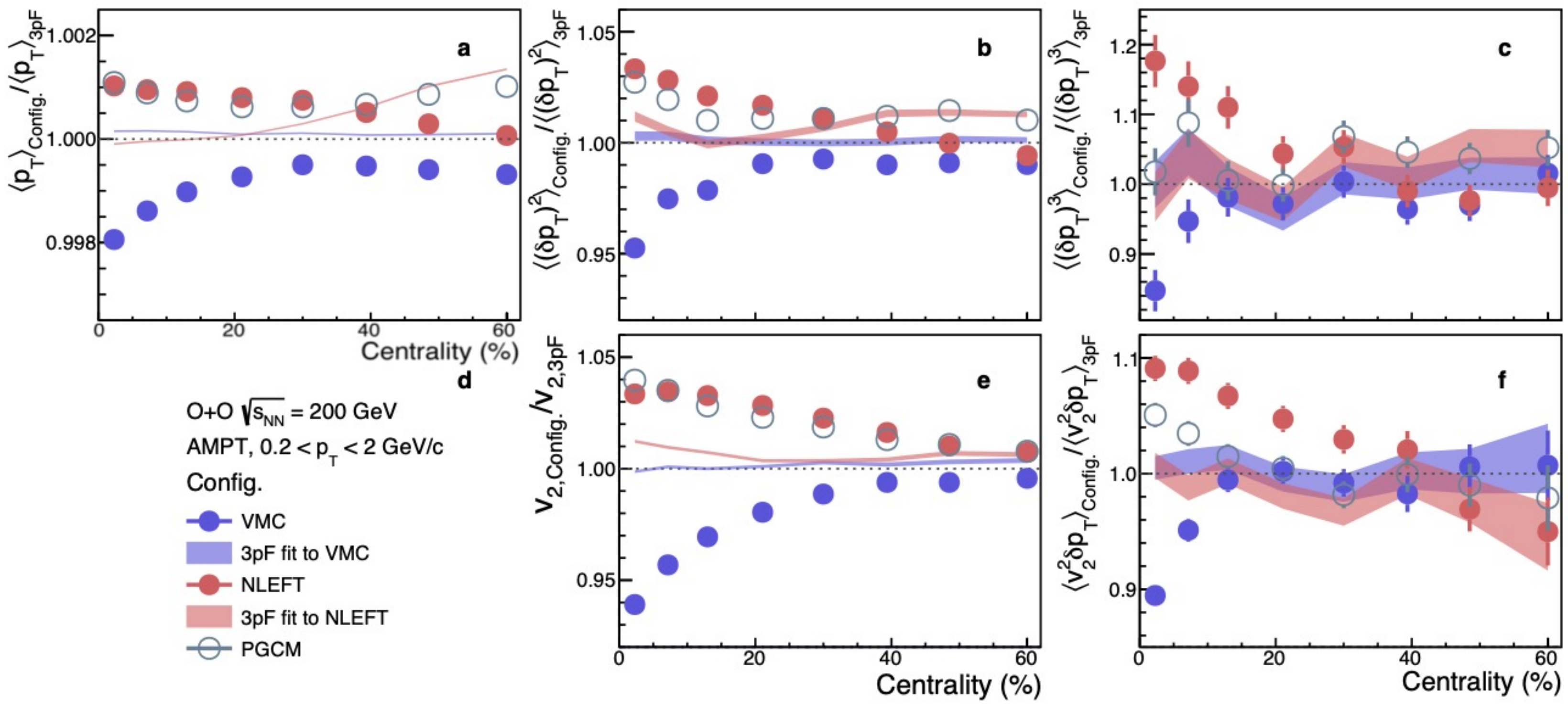


C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *PLB 862, 139322 (2025)*

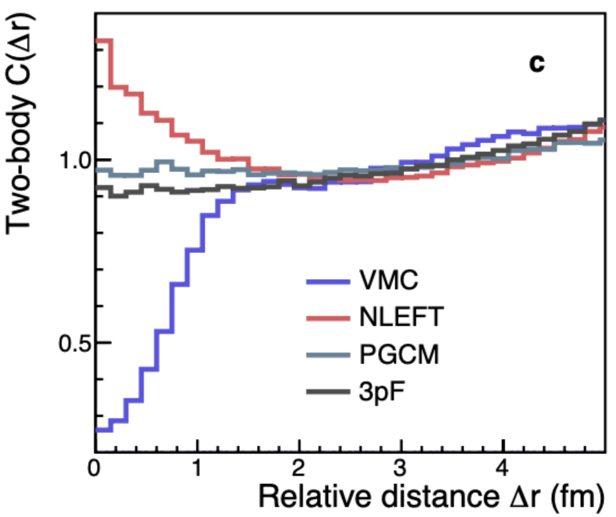
Ab-initio NN correlations and their impact on high-energy

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

Multiple final-state observables

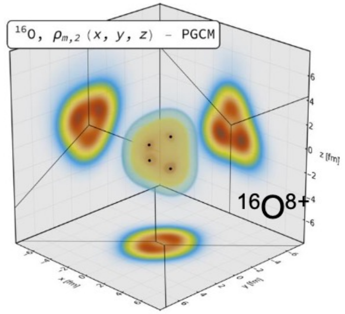


Two-body correlations in coordinate space



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

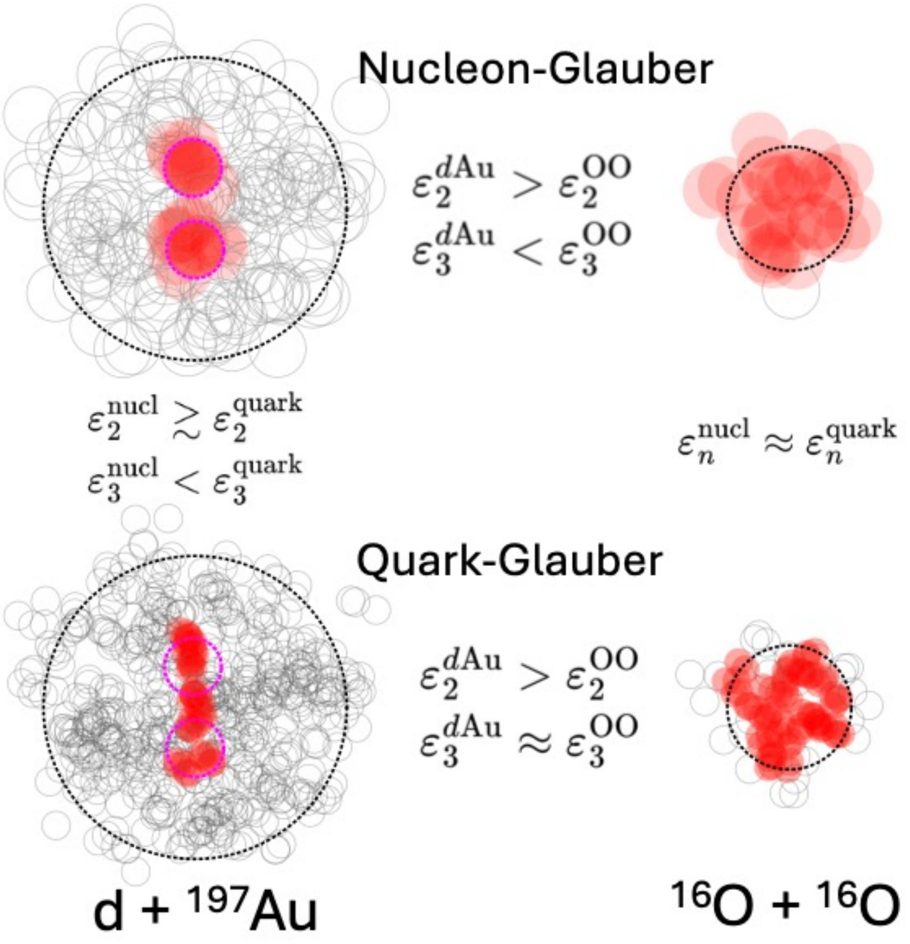
- 3pF as the baseline can NOT capture the NN correlations.
- Distinct differences are observed between VMC and NLEFT/PGC
- Central collision is prominent.



α cluster

More nuclear structure models are needed.

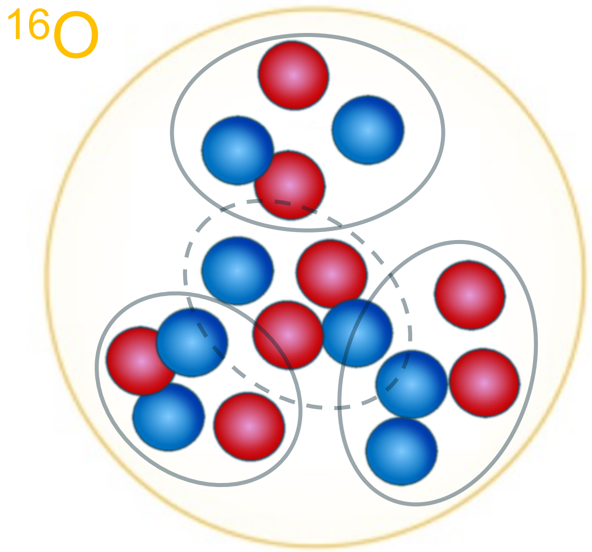
Nucleon/sub-nucleon fluctuation vs. nucleon-nucleon correlations

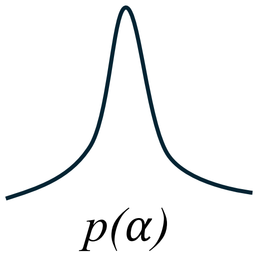


STAR, *PRL 130, 242301 (2023)*

STAR, *PRC 110, 064902 (2024)*

NN correlation (cluster pattern)





ab initio calculations

Y.-G. Ma, S. Zhang, *Handbook of Nuclear Physics (2022)*

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

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

X. Zhao, G. Ma. Y. Zhou, Z. Lin and C. Zhang, *PLB 874, 140254 (2026)*

P. Li, B. Zhou, G.-L. Ma, *PRL 136, 082302 (2026)*

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

Y. Wang, S. Zhao, B. Cao, H. Xu and H. Song, *PRC 109, L051904 (2024)*

H. Wang, S. Li, J. Xu, Z. Ren, *PLB 866, 139516 (2025)*

J. Hu, H. Xu, X. Wang, S. Pu, *2507.01493*

...

d+Au collision, 200 GeV ⟷ Nearly same N_{ch} ⟷ O+O collision, 200 GeV

Benchmarking geometric tomography of ^{16}O nucleus

STAR, *2510.19645 (under review at PRL)*

Small fluctuation in d+Au

$$\frac{v_2^{dAu}\{4\}}{v_2^{dAu}\{2\}} \approx \frac{\varepsilon_2^{dAu}\{4\}}{\varepsilon_2^{dAu}\{2\}} \approx 0.9$$

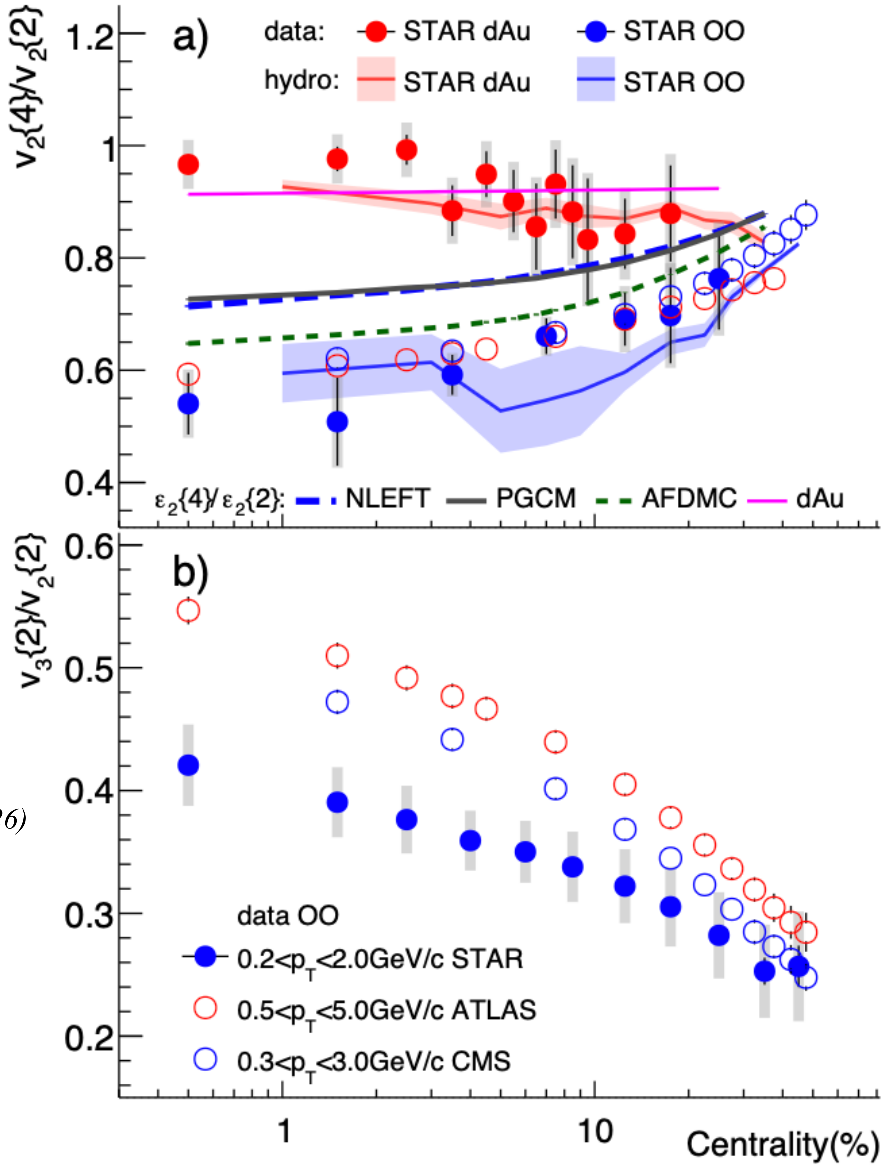
large fluctuation in O+O

$$\frac{v_2^{OO}\{4\}}{v_2^{OO}\{2\}} \approx \frac{\varepsilon_2^{OO}\{4\}}{\varepsilon_2^{OO}\{2\}} \sim 0.6$$

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

NLEFT from D. Lee

PGCM from B. Bally, T. Duguet



$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from three models:

AFDMC vs. EFT/PGCM has a visible difference.

Nucleon-nucleon correlations impact initial-state fluctuations.

Y.-G. Ma, S. Zhang, *Handbook of Nuclear Physics (2022)*

C. Zhang et al., *PLB 862, 139322 (2025)*

G. Giacalone, B. Bally, et al., *PRL 135, 012302 (2025)*

G. Giacalone, W. Zhao et al., *PRL 134, 082301 (2025)*

P. Li, B. Zhou, G.-L. Ma, *PRL 136, 082302 (2026)*

ATLAS, *2509.05171, PRC*

ALICE, *2509.06428, PRL*

CMS, *2510.02580, PRL*

d+Au is flat; Large enhancement in O+O with continuous decrease

Benchmarking geometric tomography of ^{16}O nucleus

STAR, *2510.19645 (under review at PRL)*

Small fluctuation in d+Au

$$\frac{v_2^{dAu}\{4\}}{v_2^{dAu}\{2\}} \approx \frac{\varepsilon_2^{dAu}\{4\}}{\varepsilon_2^{dAu}\{2\}} \approx 0.9$$

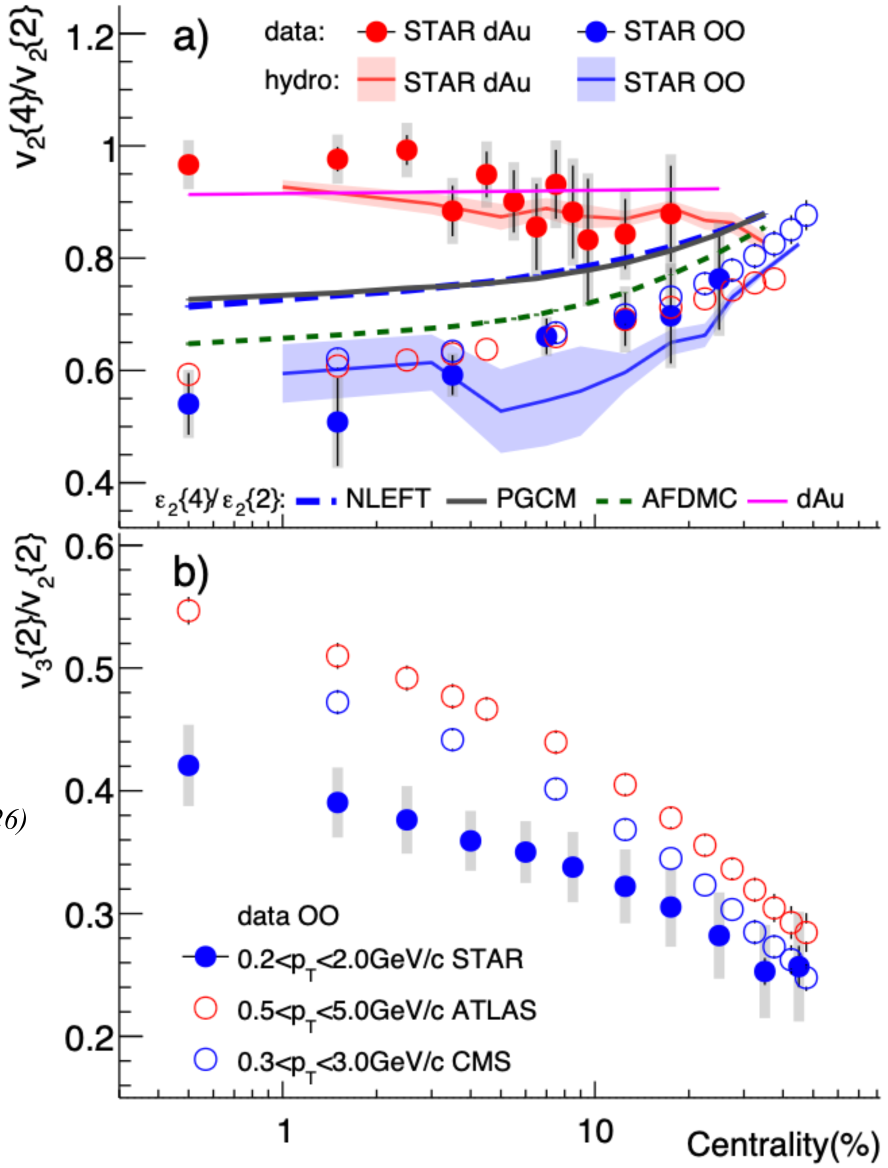
large fluctuation in O+O

$$\frac{v_2^{OO}\{4\}}{v_2^{OO}\{2\}} \approx \frac{\varepsilon_2^{OO}\{4\}}{\varepsilon_2^{OO}\{2\}} \sim 0.6$$

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

NLEFT from D. Lee

PGCM from B. Bally, T. Duguet



$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from three models:

AFDMC vs. EFT/PGCM has a visible difference.

Nucleon-nucleon correlations impact initial-state fluctuations.

Y.-G. Ma, S. Zhang, *Handbook of Nuclear Physics (2022)*
C. Zhang et al., *PLB 862, 139322 (2025)*
G. Giacalone, B. Bally, et al., *PRL 135, 012302 (2025)*
G. Giacalone, W. Zhao et al., *PRL 134, 082301 (2025)*
P. Li, B. Zhou, G.-L. Ma, *PRL 136, 082302 (2026)*
ATLAS, *2509.05171, PRC*
ALICE, *2509.06428, PRL*
CMS, *2510.02580, PRL*

The interplay between nucleon/sub-nucleon fluctuations and many-nucleon correlation.

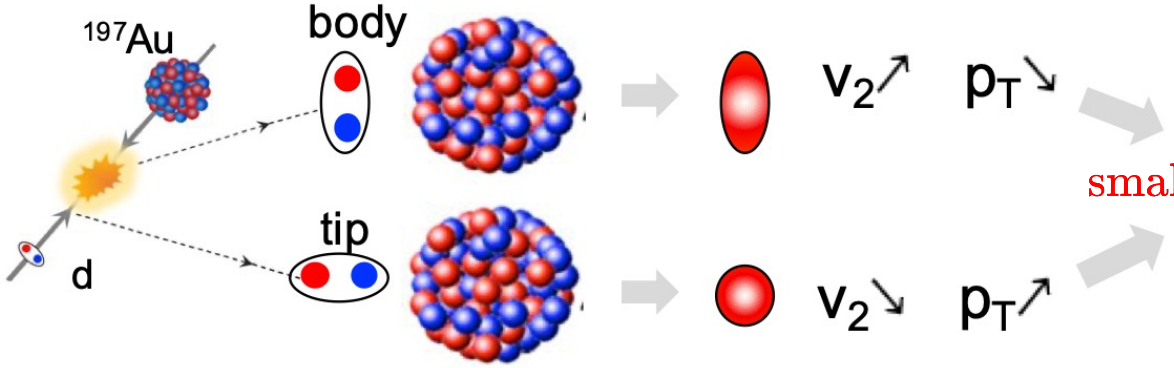
STAR, *PRL 130, 242301 (2023)*
S. Huang, J. Jia, C. Zhang, *PLB 870, 139926 (2025)*

Geometric scan elucidates nuclear tomography and strong nuclear force?

New 2025-2026 dataset: ~10 X High multiplicity

d+Au is flat; Large enhancement in O+O with continuous decrease

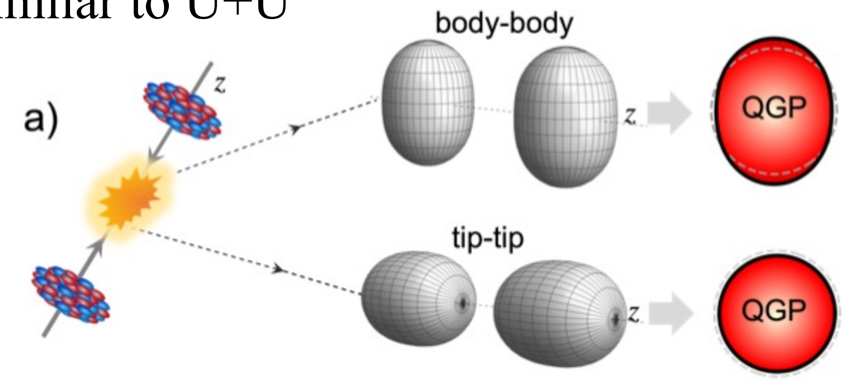
Prolate shape of *deuteron* vs. ^{16}O



smaller $< v_2^2 \delta p_T >$

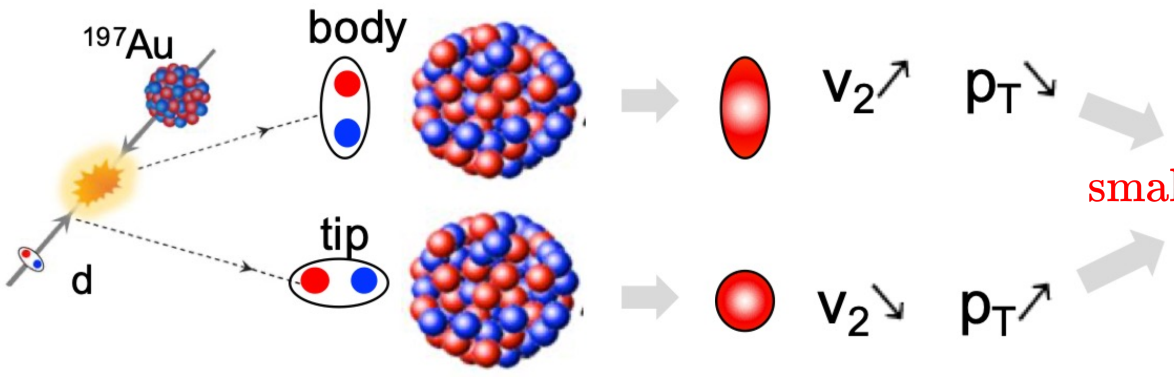
$\langle v_2^2 \delta p_T \rangle = a - b\beta_2^3$

Similar to U+U



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

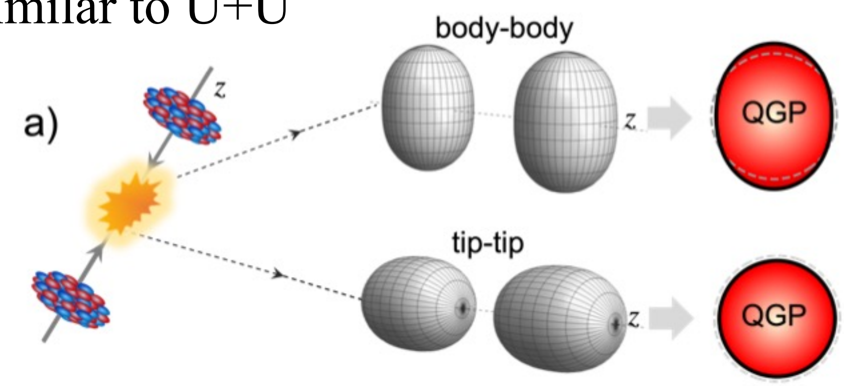
Prolate shape of *deuteron* vs. ^{16}O



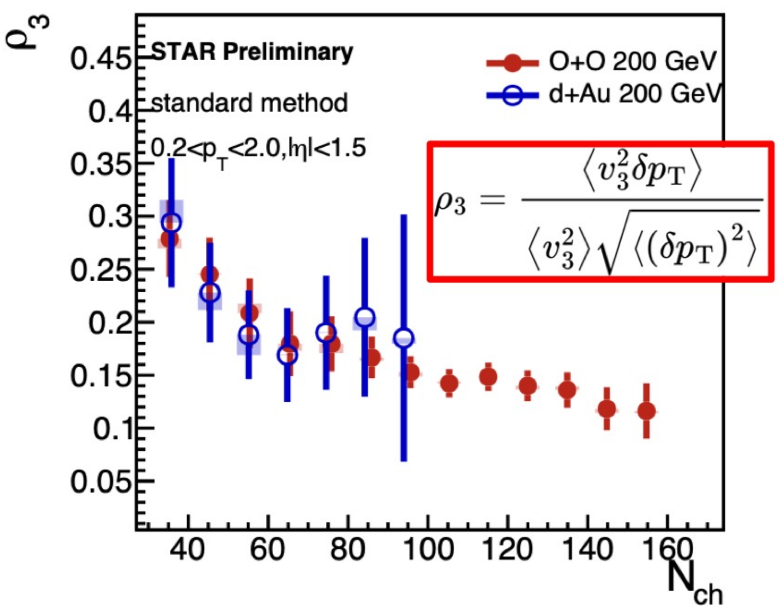
smaller $<v_2^2\delta p_T>$

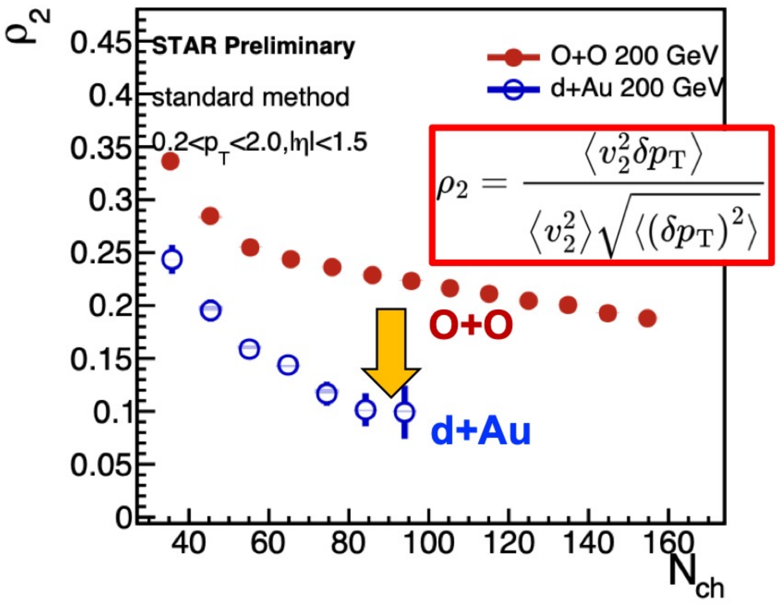
$$\langle v_2^2\delta p_T\rangle = a - b\beta_2^3$$

Similar to U+U



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





The deuteron wave function is fixed.

^{16}O structure might be important.

Behavior of $\langle v_2^2\delta p_T\rangle$ consistent with QGP response to the prolate shape of deuteron

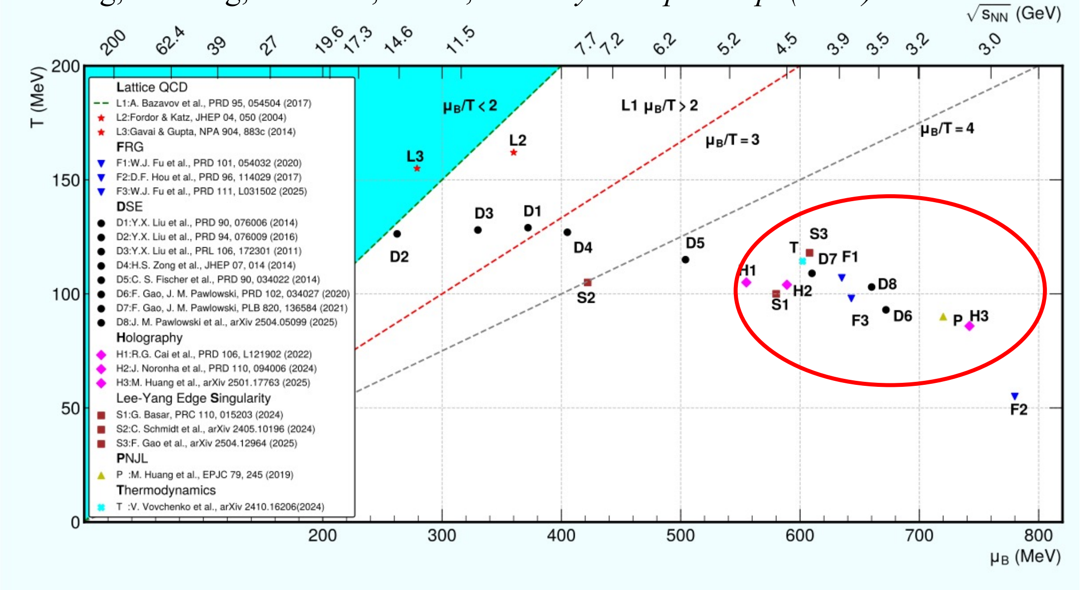
❑ Energy dependence and universal features of radial-flow response

I. Second-order fluctuation in ^{197}Au + ^{197}Au collisions at FXT energies

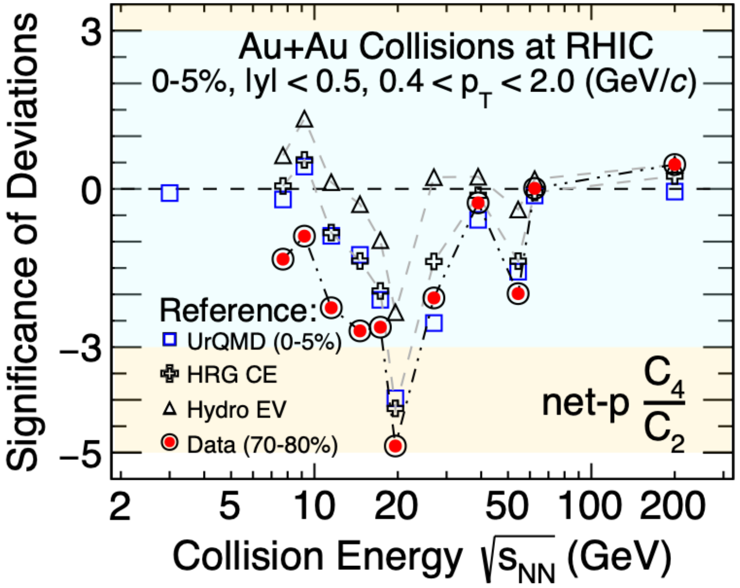
STAR, *arXiv: 2604.06434 (PRL In press)*

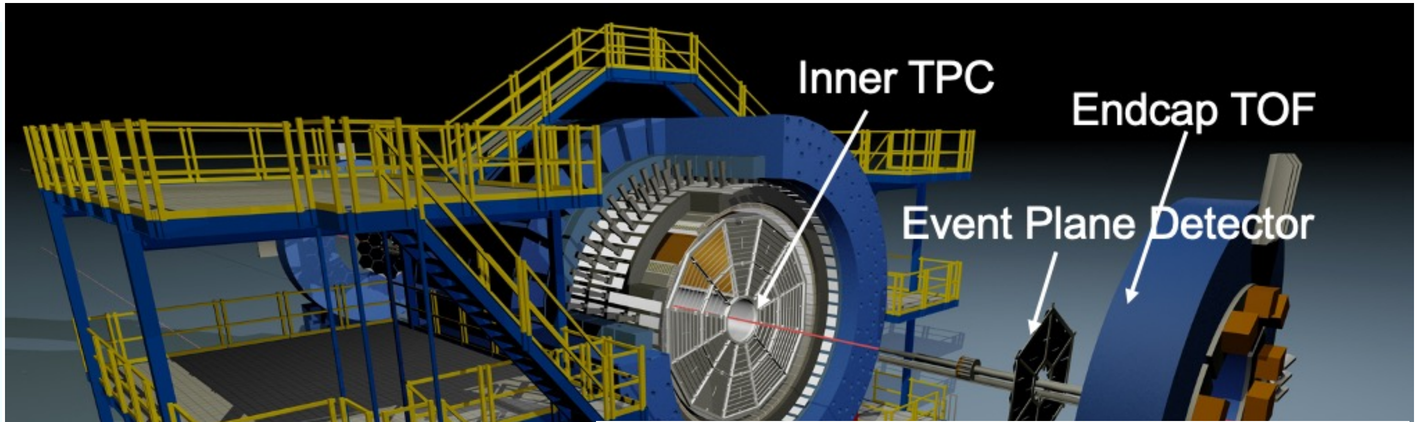
The BES-II Upgrades and fixed-target (FXT) mode

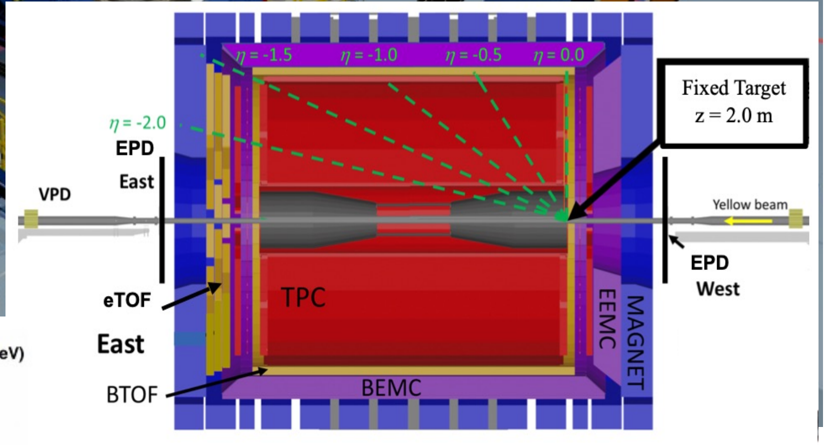
Y. Zhang, Z. Wang, X.F. Luo, N. Xu, *Eur. Phys. J. Spec. Top. (2026)*

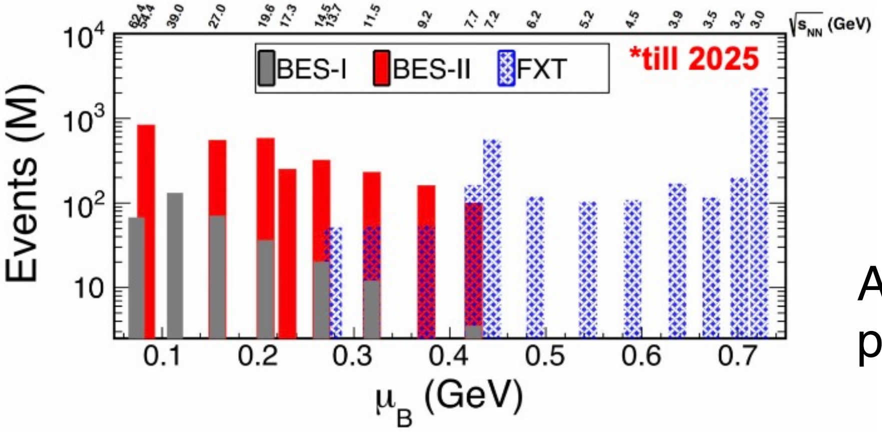


STAR, *PRL 135, 142301 (2025)*









Mid-rapidity for 3.0 GeV is y = 1.049

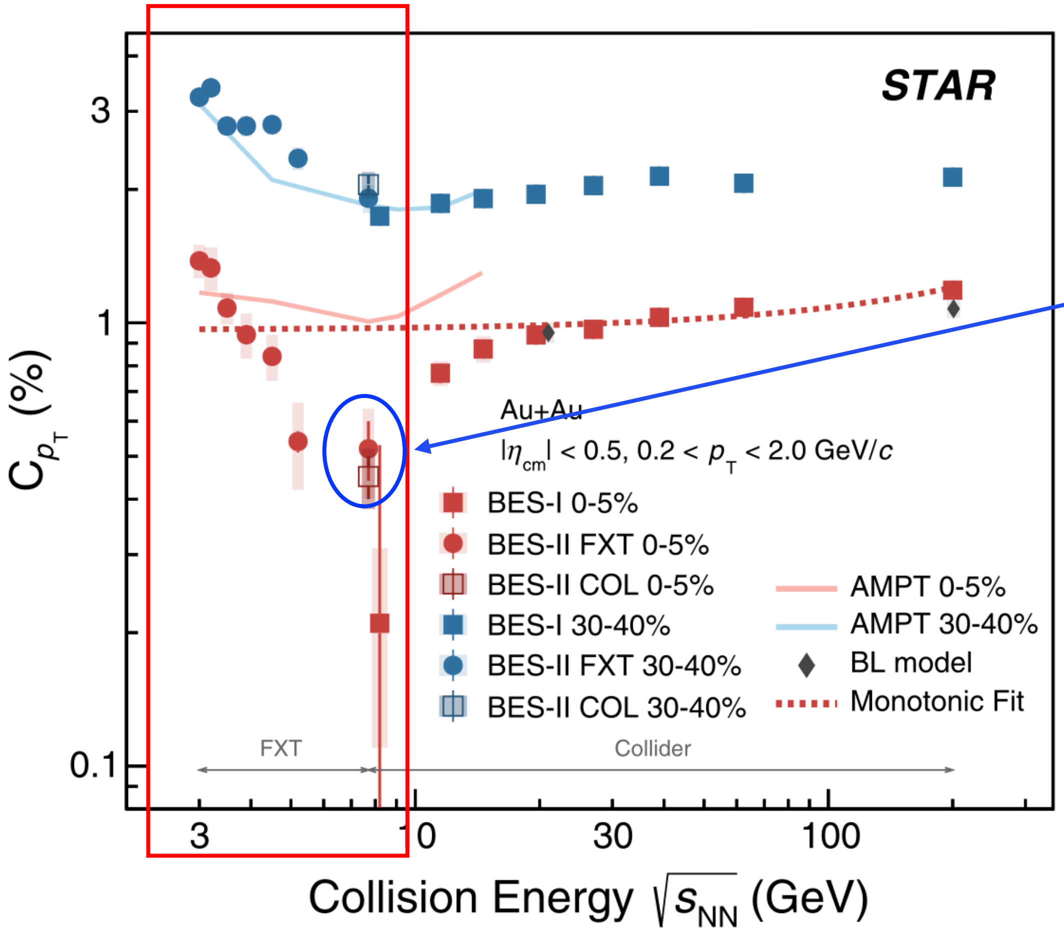
A strong convergence of predicted points within the 3–6 GeV energies

Large datasets with iTPC upgrade ~10 X BES-I

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

STAR, *arXiv: 2604.06434 (PRL in press)*

$\mu_B \sim 400$ - 600 MeV



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

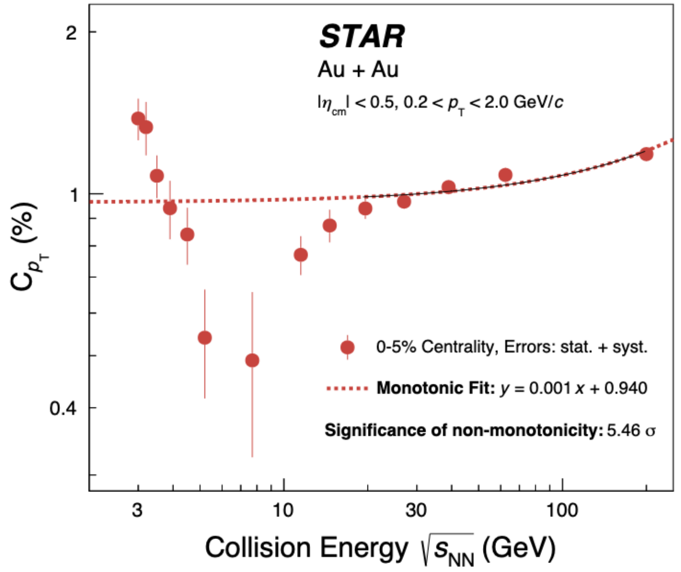
Useful for constraining EoS and understanding the phase diagram.

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

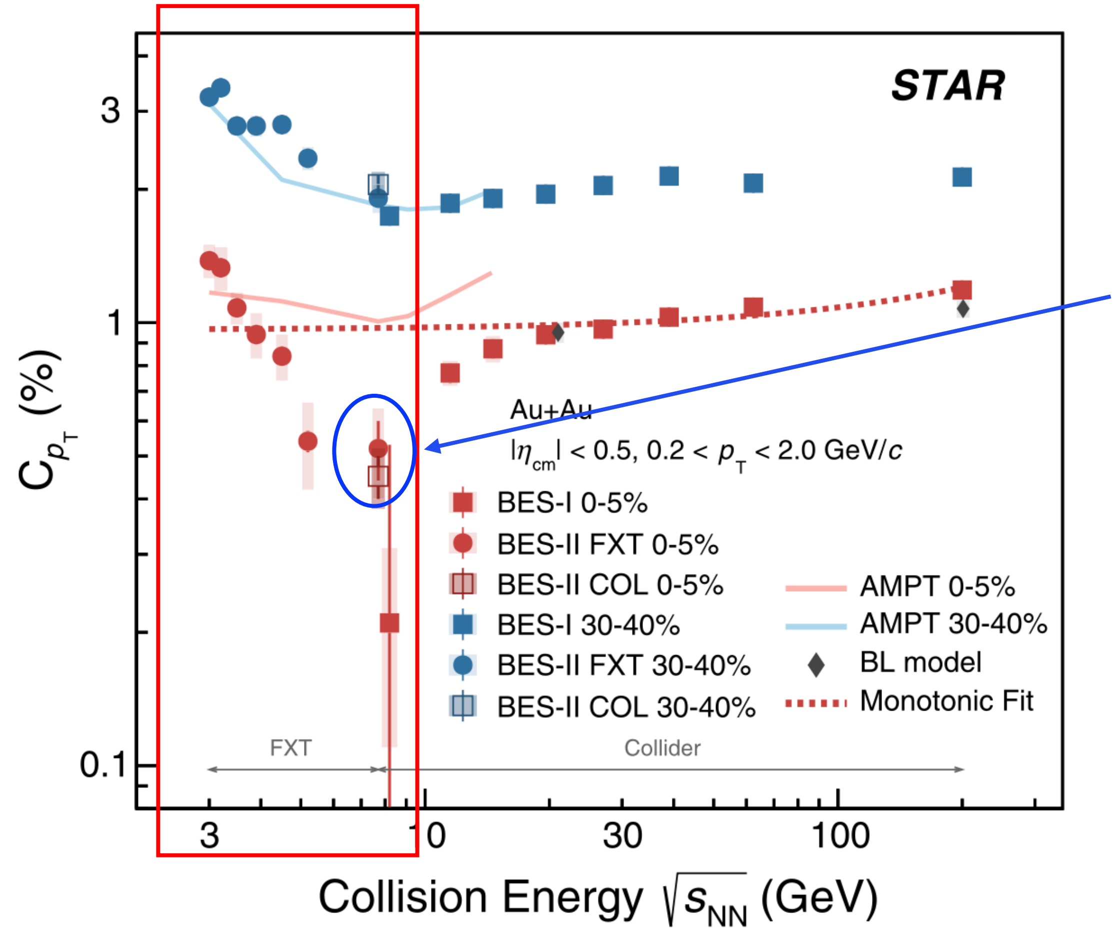
STAR, *arXiv: 2604.06434 (PRL in press)*

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**



μ_B ~ 400 - 600 MeV



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

Useful for constraining EoS and understanding the phase diagram.

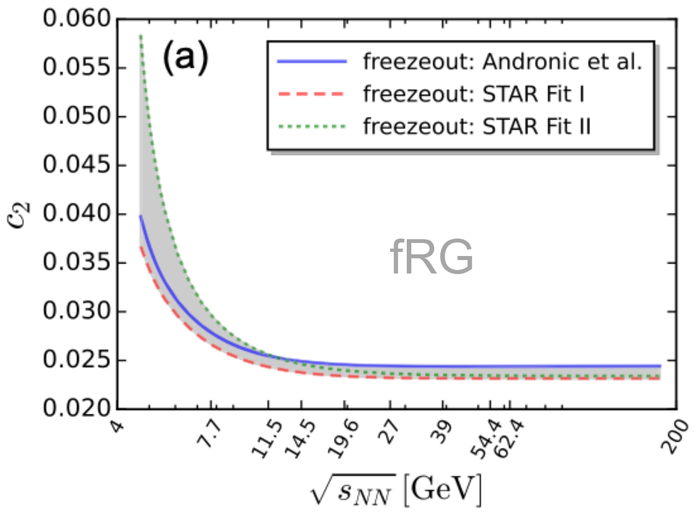
Boltzmann–Langevin model: S. Gavin et. al., PRC *95, 064901 (2017)*

Next: PID/high-order matters.

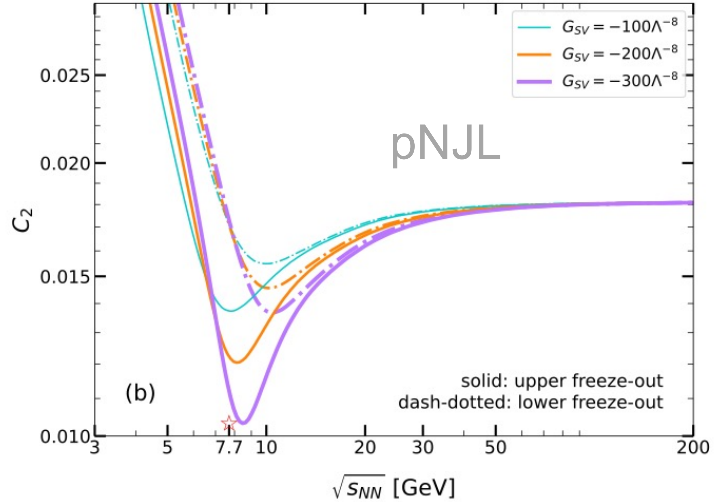
AMPT: L. Zhang, J. Chen, C. Zhang, *PRC 111, 024911 (2025)*; R.X. Cao, S. Zhang, Y.-G. Ma, *PRC 106, 014910 (2022)*

Unsettled interpretations: recent model studies

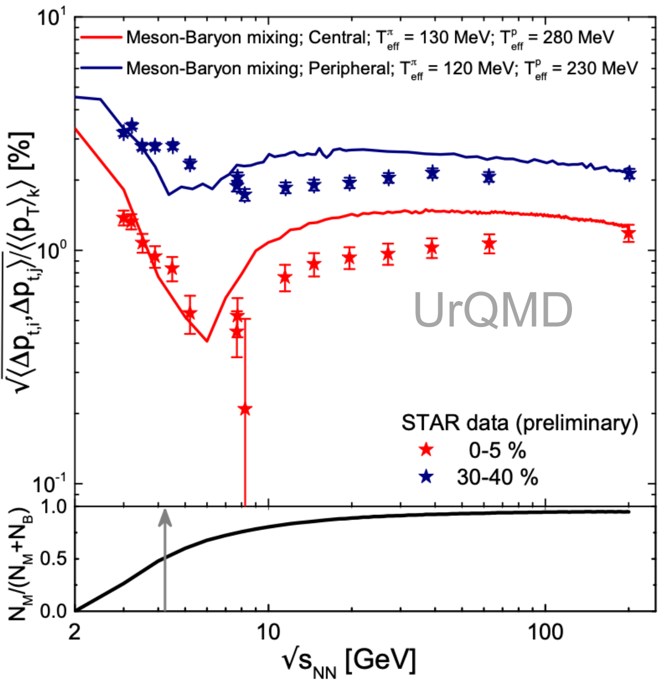
J. Chen, W. Fu, S. Yin, C. Zhang, *PRD 114, 014064 (2026)*



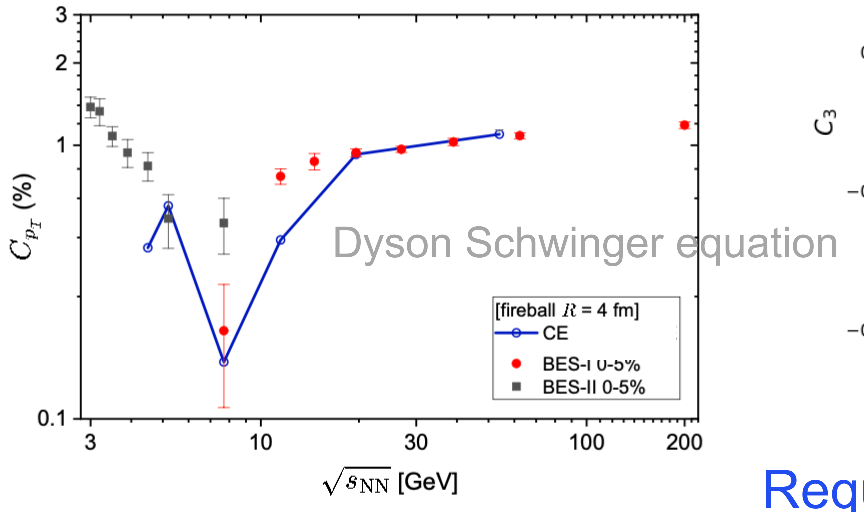
H. Liu, P. Wu, H.M. Liu, P.C. Chu, *2607.19275*

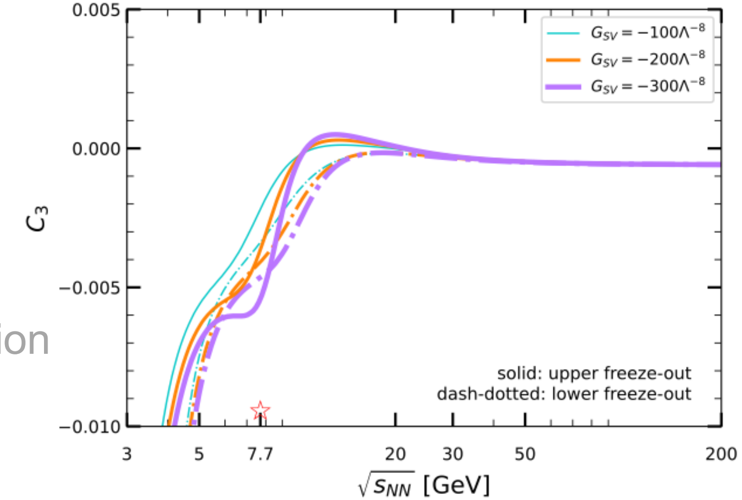


T. Reicherte, J. Steinheimera,b, M. Bleicher, *2606.03294*

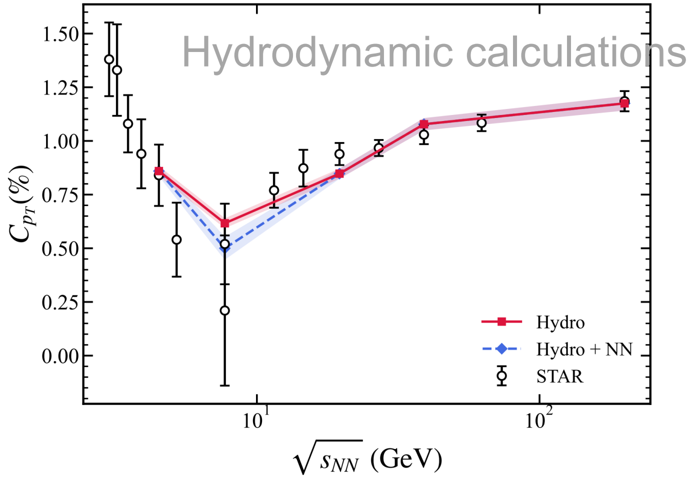


Y. Lu, F. Gao, C. Zhang, *Preliminary results*





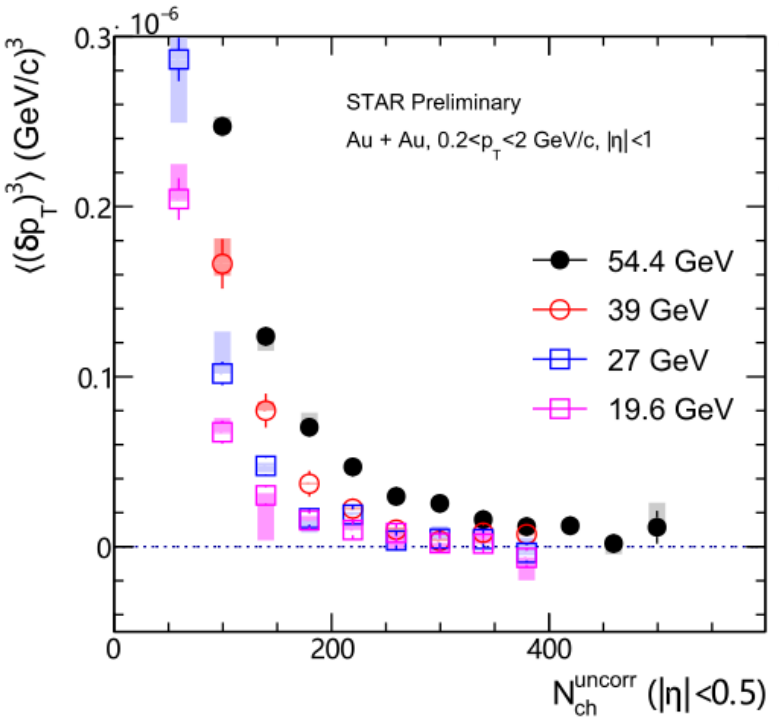
L. Yan, Y.S. Mu, X.G. Huang, YITP 2026 workshop

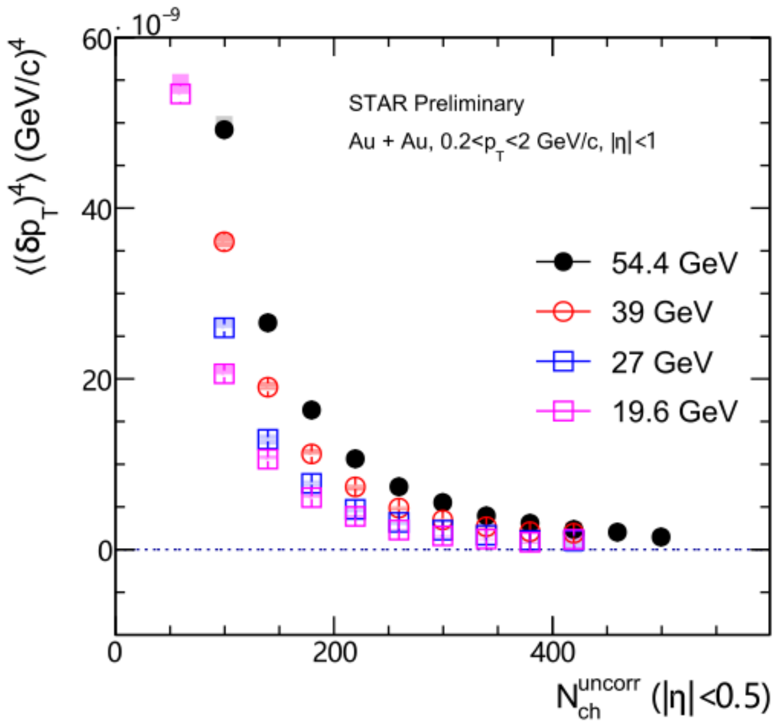


Require more theoretical understandings and calculations

II. Energy dependence of High-order fluctuations

High-order $\langle(\delta p_T)^n\rangle$ vs centrality



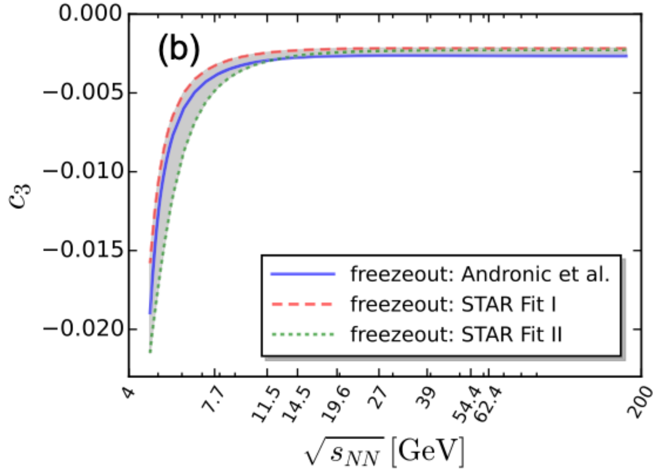


Efficiency-uncorrected N_{ch}

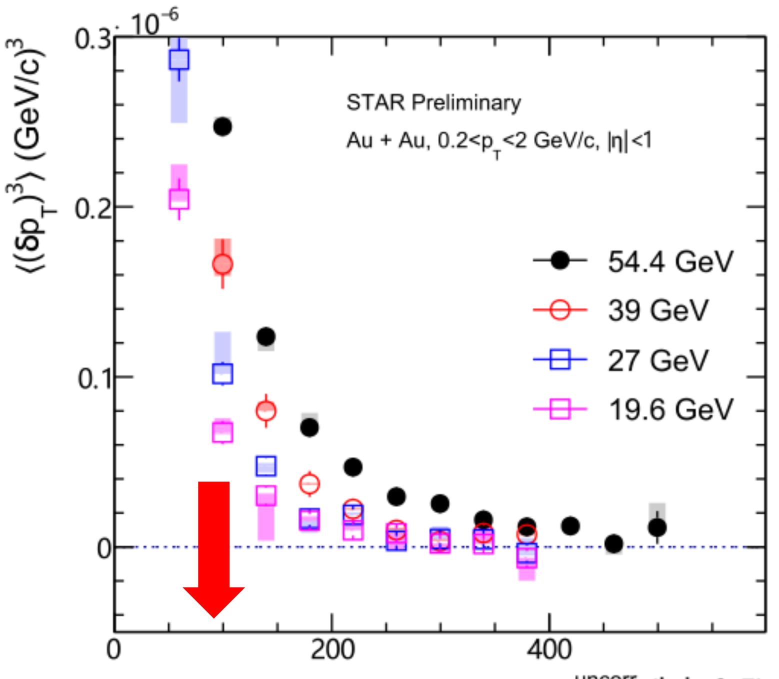
- Values of correlators of variance, skewness and kurtosis increase towards peripheral collisions.
- Slight energy dependence is observed.

High-order $\langle(\delta p_T)^n\rangle$ vs centrality

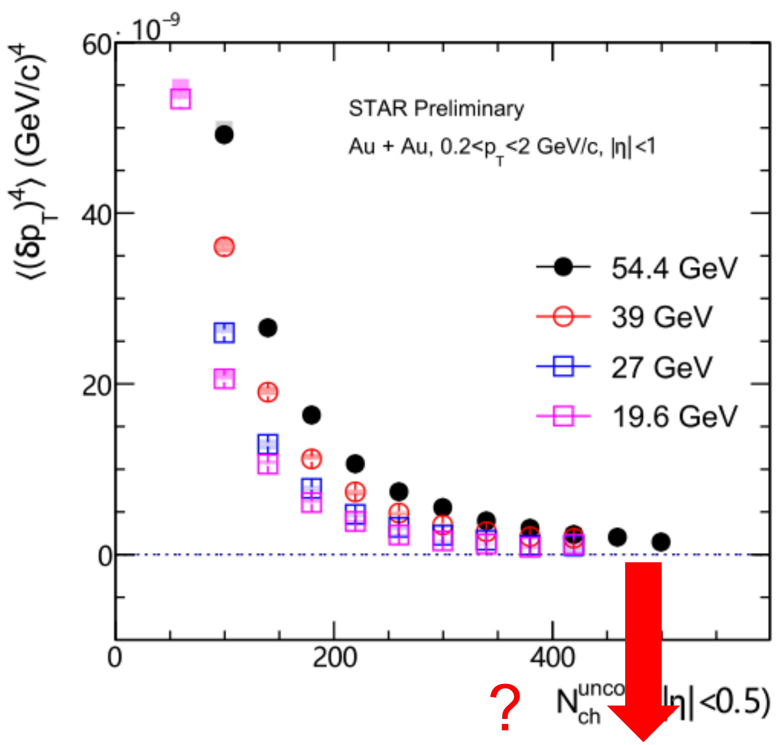
Negative skewness



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



data confirmed

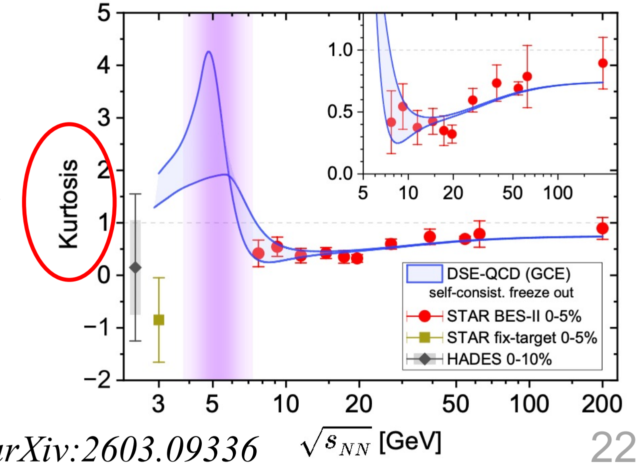


?

Efficiency-uncorrected N_{ch}

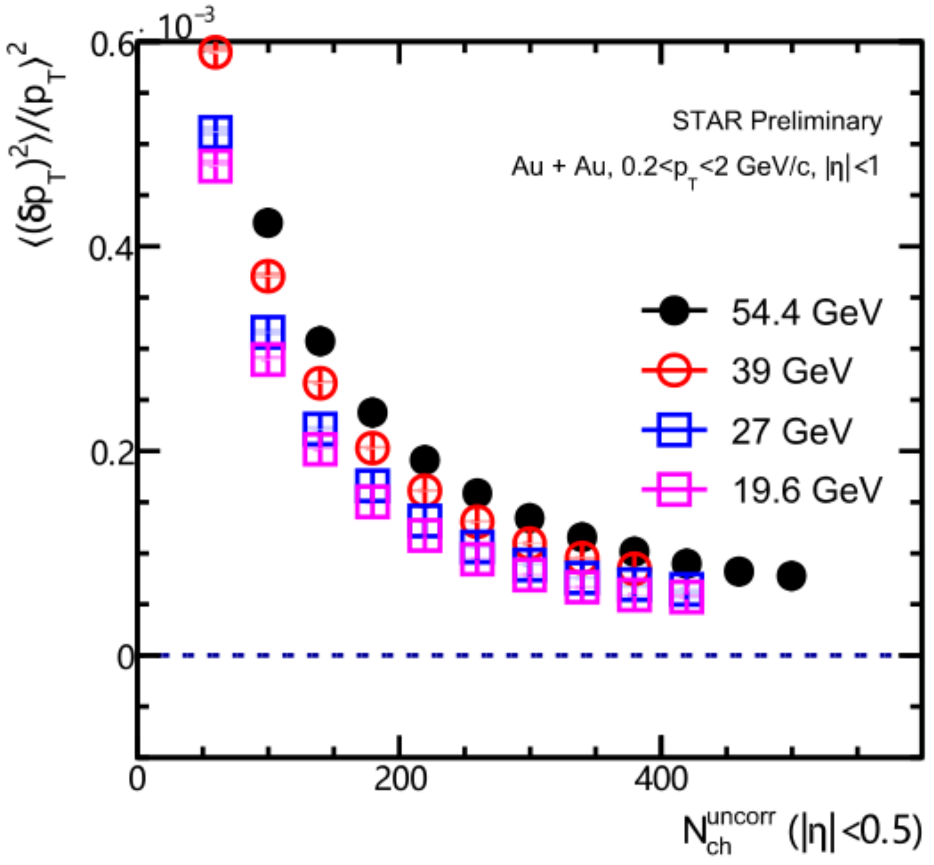
- Values of correlators of variance, skewness and kurtosis increase towards peripheral collisions.
- Slight energy dependence is observed.

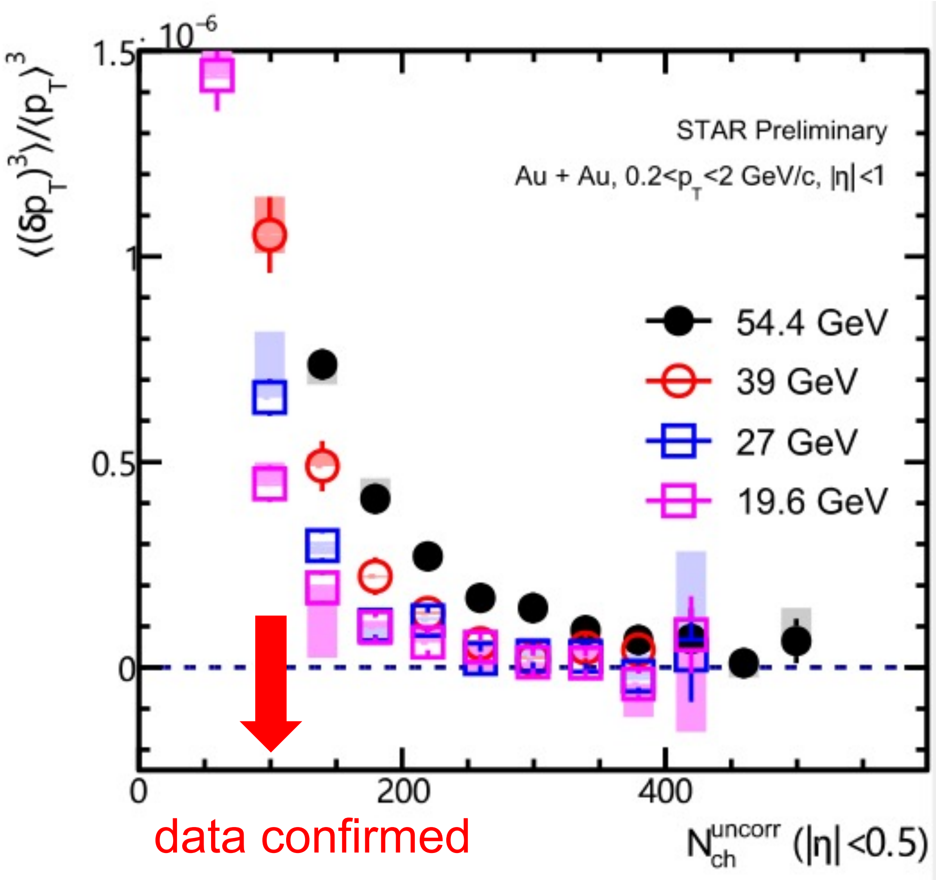
Analog: Interesting to study such energy dependence



Y. Lu, C.S. Fischer, F. Gao, Y.X. Liu, J.M. Pawlowski, *arXiv:2603.09336*

High-order $\langle(\delta p_T)^n\rangle$ vs centrality





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

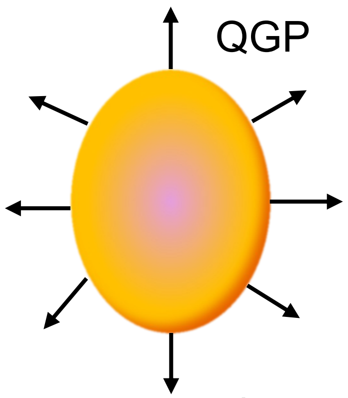
- With increasing charge-multiplicity, the normalized correlators of variance and skewness decrease in magnitudes.
- Energy dependence that increases towards peripheral collisions are observed.

Further understand initial conditions and EbE fluctuations across different collision energies.

III. Radial-flow response from large to small collisions: *universal features?*

New measurement: radial flow $v_0(p_T)$

Radial expansion: the n=0 modulation

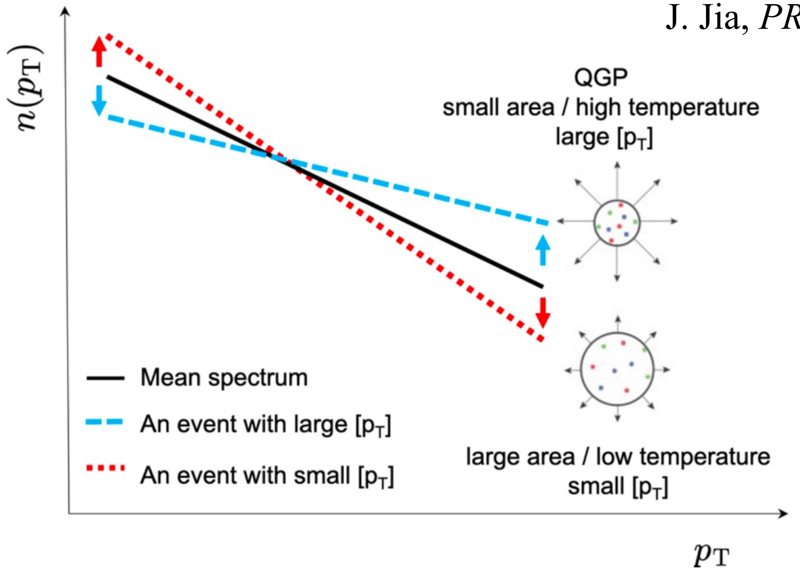


ζ/s and EoS sensitive

Response to size fluctuations

$$\delta p_{\mathrm{T}}/\langle[p_{\mathrm{T}}]\rangle \approx -\delta R/\langle R\rangle$$

J. Jia, *PRL 136, 112301 (2026)*



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 $[p_T]$:** $\langle \delta n\,(p_T)\delta\,[p_T]\rangle$

Calculated within a reference range, p_T-independent.

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

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

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

Remove influence from global fluctuations

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, *PRC 113, 014901 (2026)*
J. Zhu, X.-Y. Wu, G.-Y. Qin, *2602.04148*

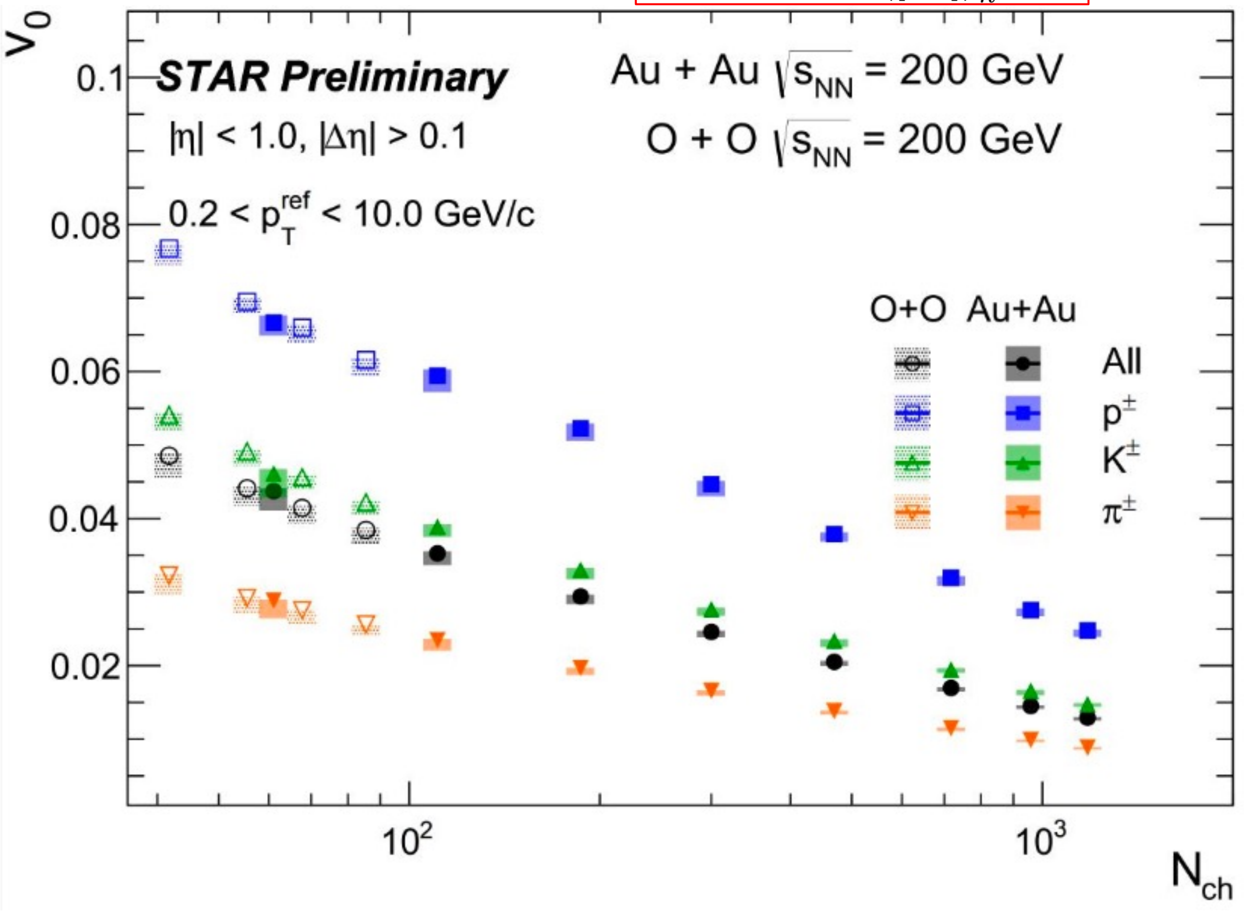
Verify the signatures of radial flow, like for anisotropic flow (n≥1)

System comparisons in integral p_T fluctuation v_0

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

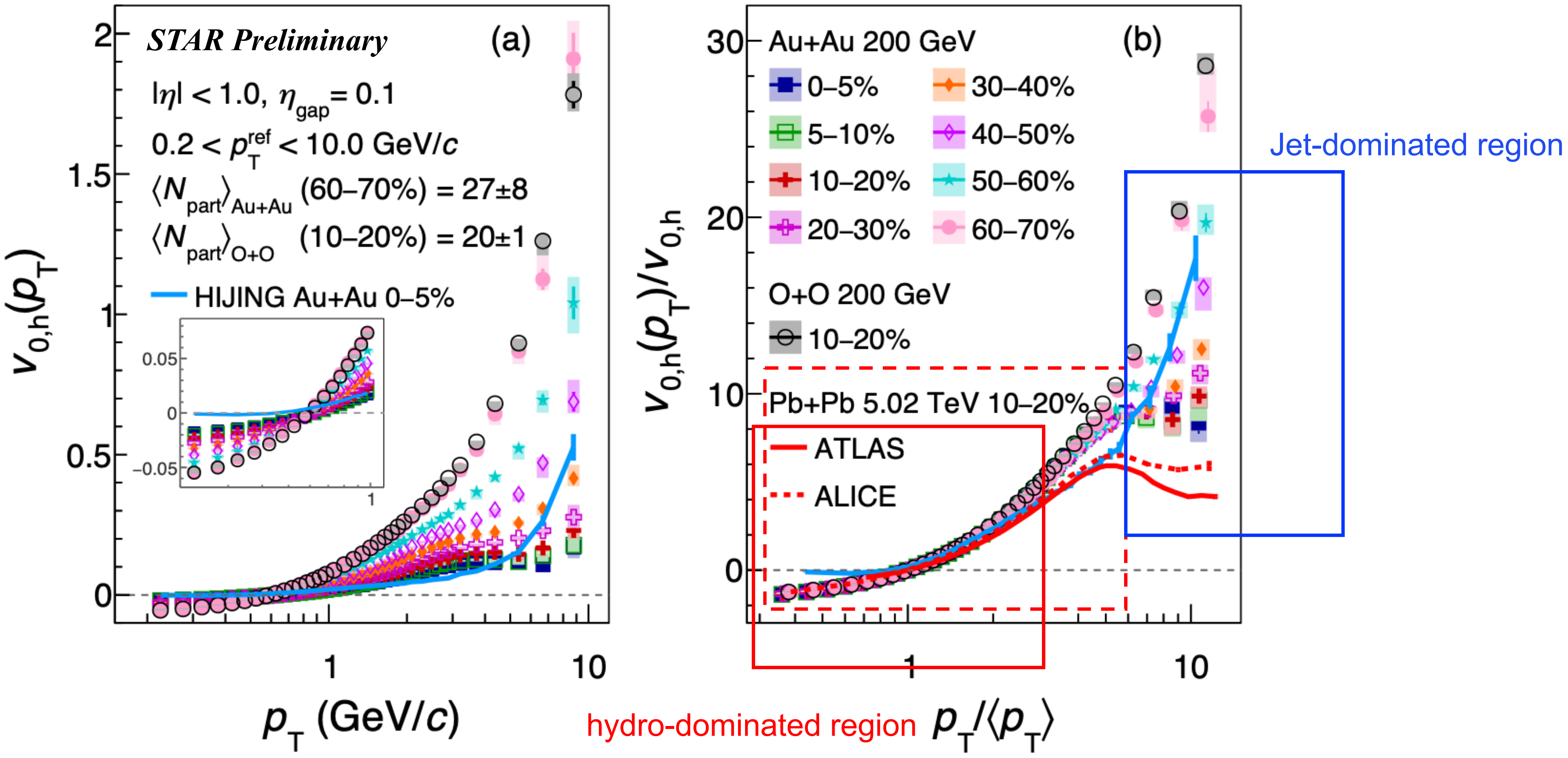
- First measurement for charged hadrons, protons, kaons, and pions in O+O to Au+Au.
- larger fluctuation signals for heavier particles.
- v_0 follows an approximate power scaling

$$v_0 \sim 1/\sqrt{N_\mathrm{ch}}$$



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

$v_0(p_T)$ from large (Au+Au) to small (O+O) collisions at 200 GeV



Strong centrality-dependence: size-driven radial flow fluctuations

$$\frac{\delta[p_T]}{\langle[p_T]\rangle} = \kappa_0\left(-\frac{\delta R}{R}\right)$$

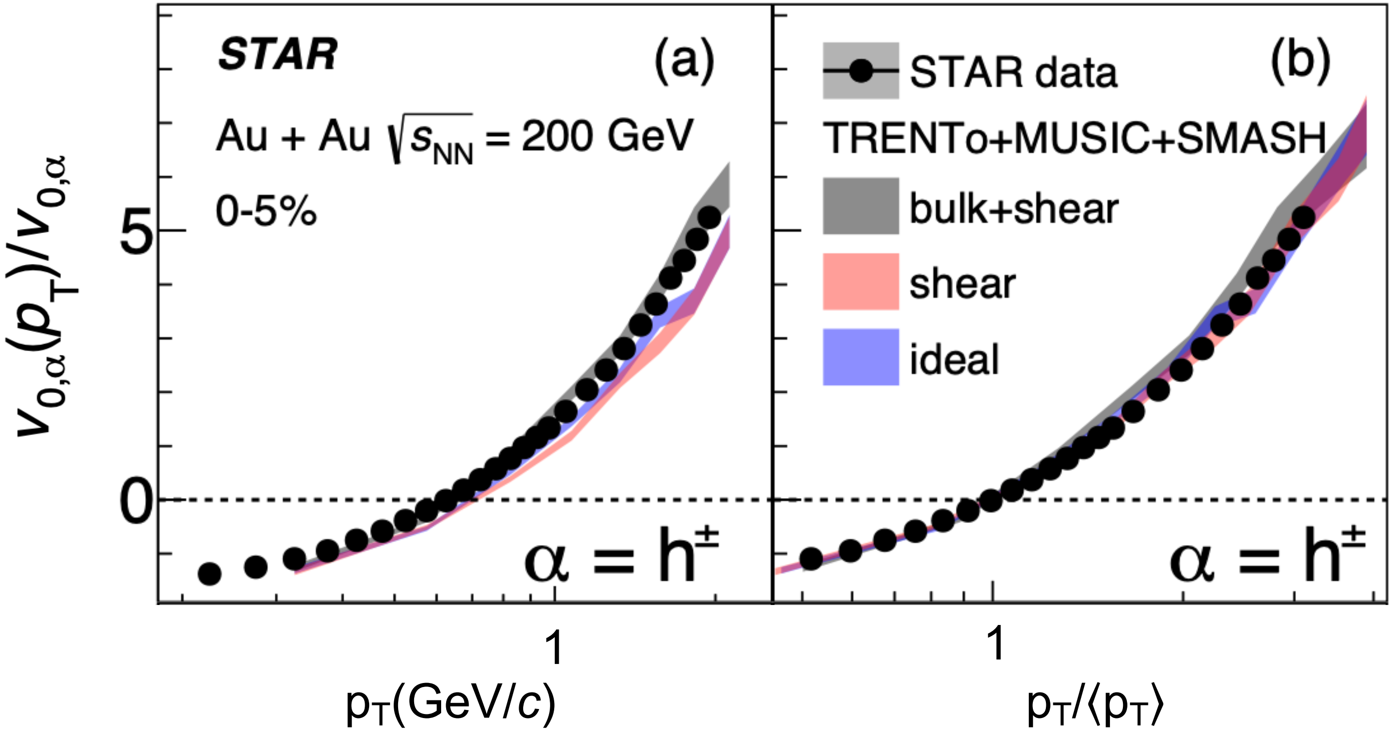
$$\boxed{\begin{gathered} v_0(p_T) = \kappa_0(p_T)\left(-\frac{\delta R}{R}\right) \\ v_0 = \kappa_0\left(-\frac{\delta R}{R}\right)\end{gathered}}$$

$$\frac{v_0(p_T)}{v_0} = \frac{\kappa_0(p_T)}{\kappa_0}$$

Access medium properties

Universal features across centrality, collisions system, and energy at low p_T

Sensitive to bulk properties ζ/s



$$\frac{v_0\,(p_{\mathrm{T}})}{v_0} = \frac{\kappa_0\,(p_T)}{\kappa_0}$$

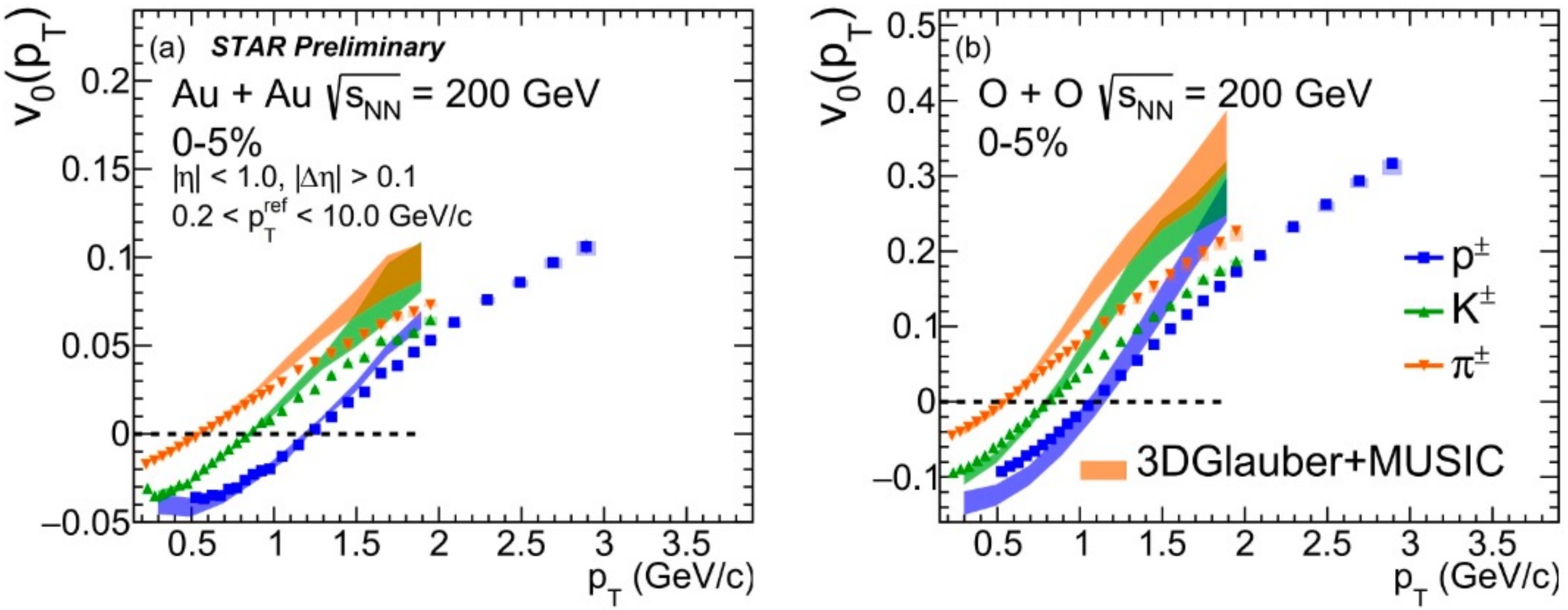
Access medium properties

Providing a new approach to constrain bulk properties in hydrodynamic models.

Trento+MUSIC+Smash: L. Du, *PRC 113, 014901 (2026)*

Particle mass-ordering and model comparison

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

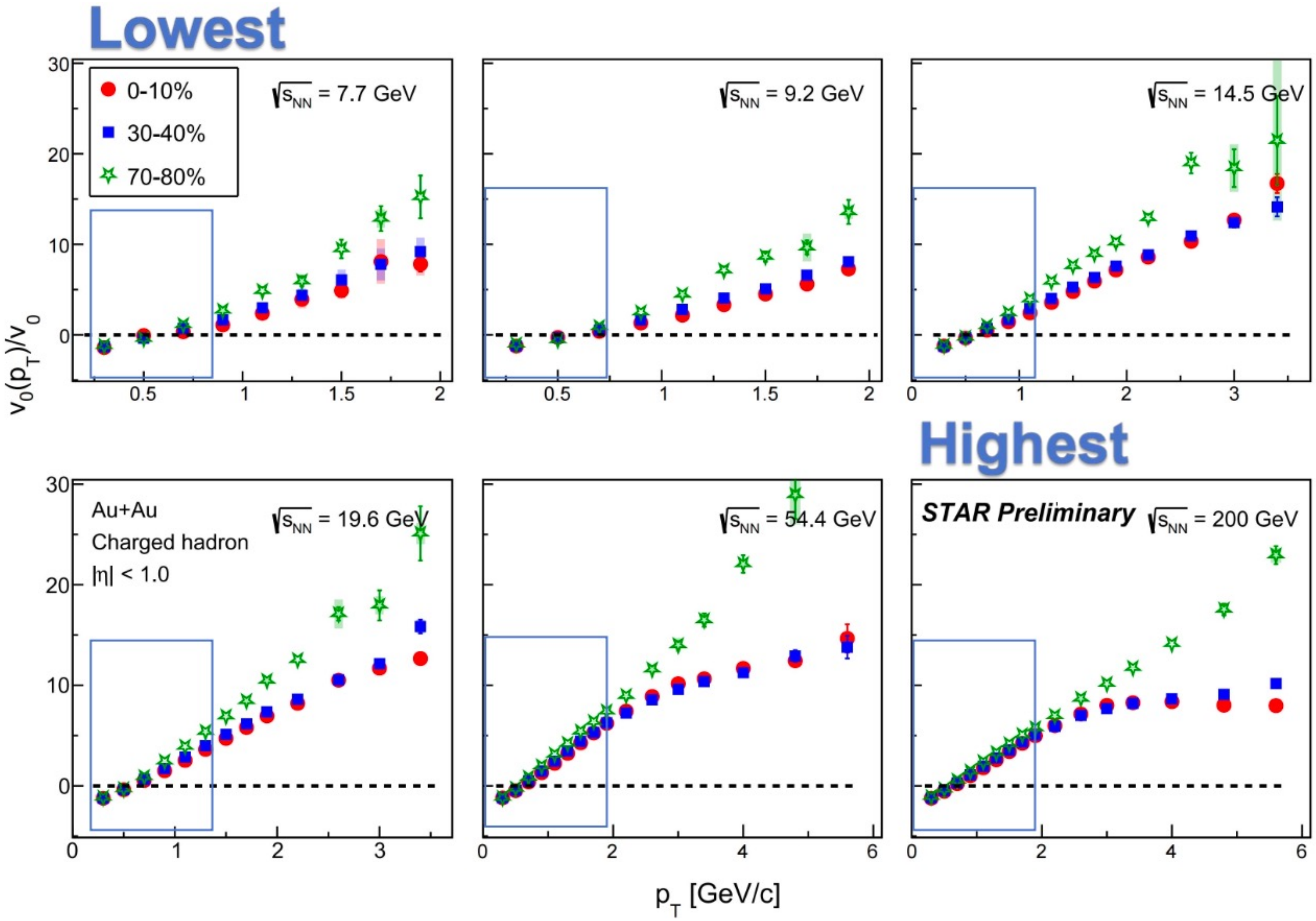


The stronger boost experienced by heavier particles gives rise to a clear mass ordering

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

3D-Glauber+MUSIC+UrQMD: S.A. Jahan, H. Roch, C. Shen, *PRC 113, 024919 (2026)*

Energy-dependence of radial expansion in Au+Au collisions

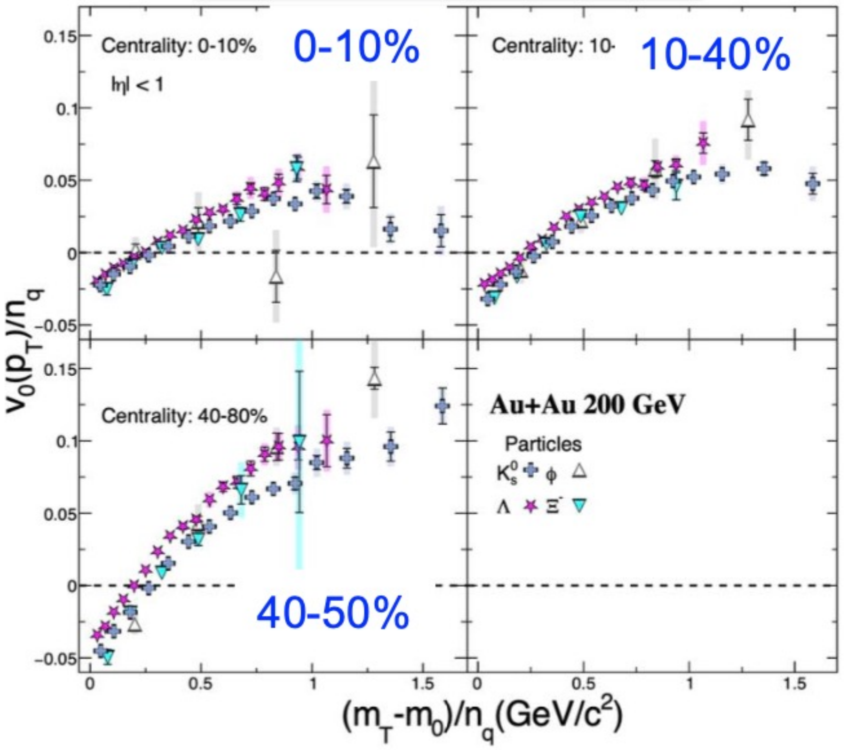


Structure persists down to lower energies: with response coefficients similar to those at higher energies.

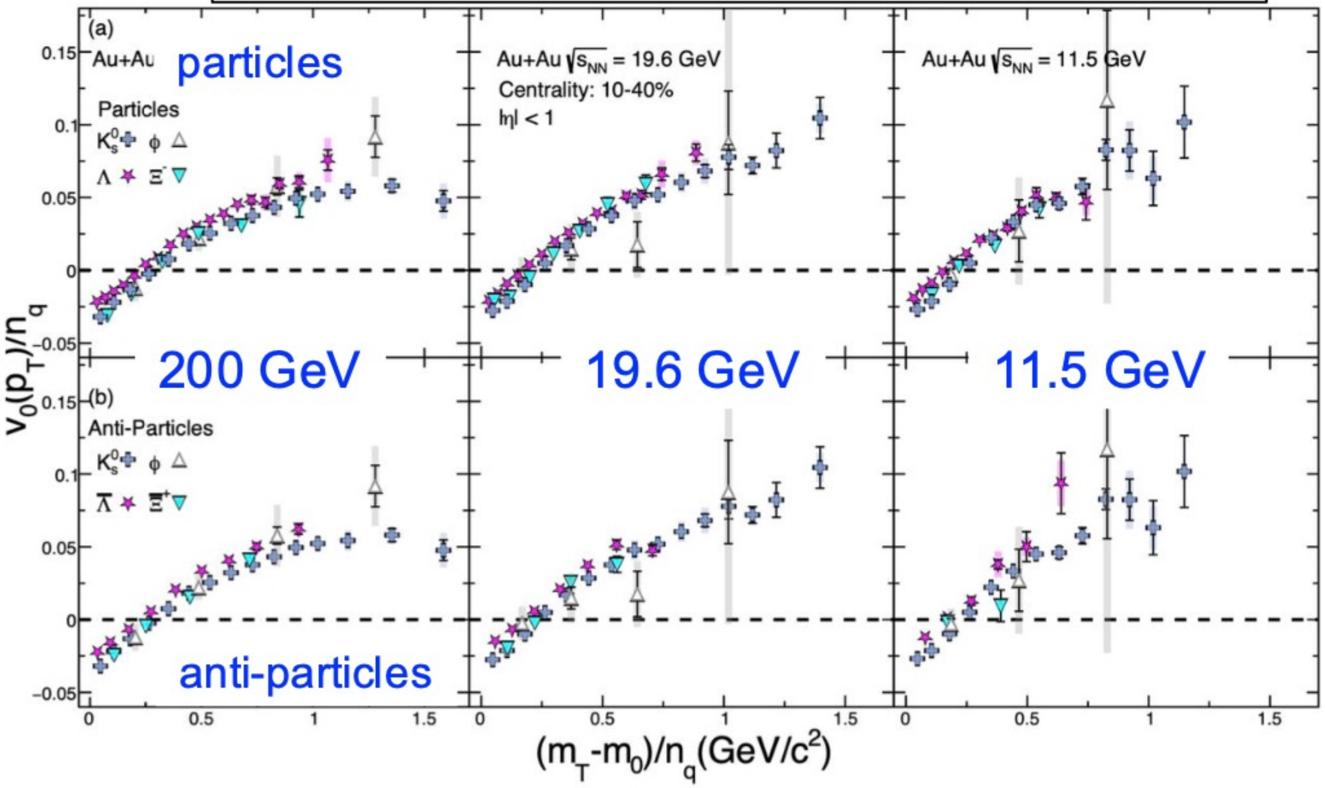
Strange hadrons and its energy dependence in Au+Au collisions

PID (strange meson and baryons) dependence allows a detailed test of NCQ scaling

Centrality dependence at 200 GeV



Energy dependence in 10-40% centrality collisions



deviation in more peripheral collisions

approximately hold in broad $\sqrt{S_{NN}}$ range

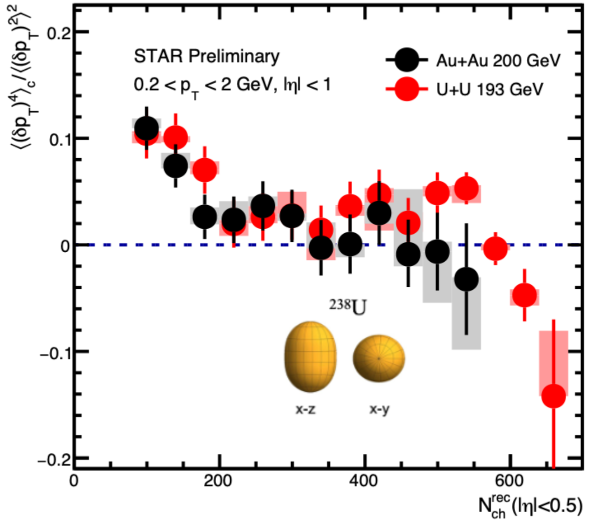
signal also change weakly with $\sqrt{S_{NN}}$ range

Conclusions and Outlooks

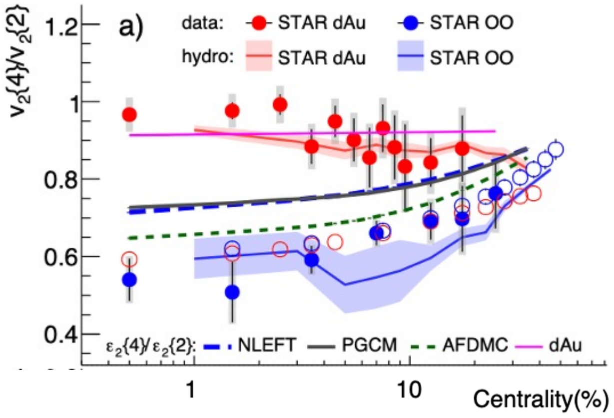
Data: nature of mean p_T fluctuations

Theoretical model calculations

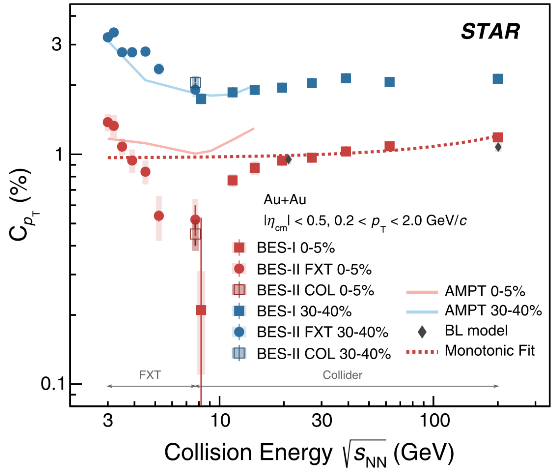
- **Negative kurtosis** in highly deformed ^{238}U indicates the nuclear structure effect.
- Light ion ^{16}O is a good connection to investigate **nucleon-nucleon correlations and cluster patterns**.
- **Nonmonotonic dependence** of second-order mean p_T fluctuations at high μ_B.
- $v_0(p_T)$ as a new approach to constrain bulk properties in energy-, system-size, and PID-dependences.



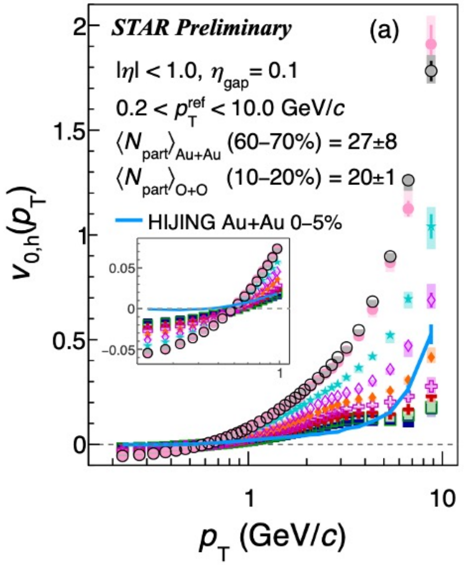
STAR, Nature 67, 635 (2024)
STAR, *Rep. Prog. Phys. 88,108601 (2025)*



STAR, *arXiv: 2510.19645*
(under review at PRL)



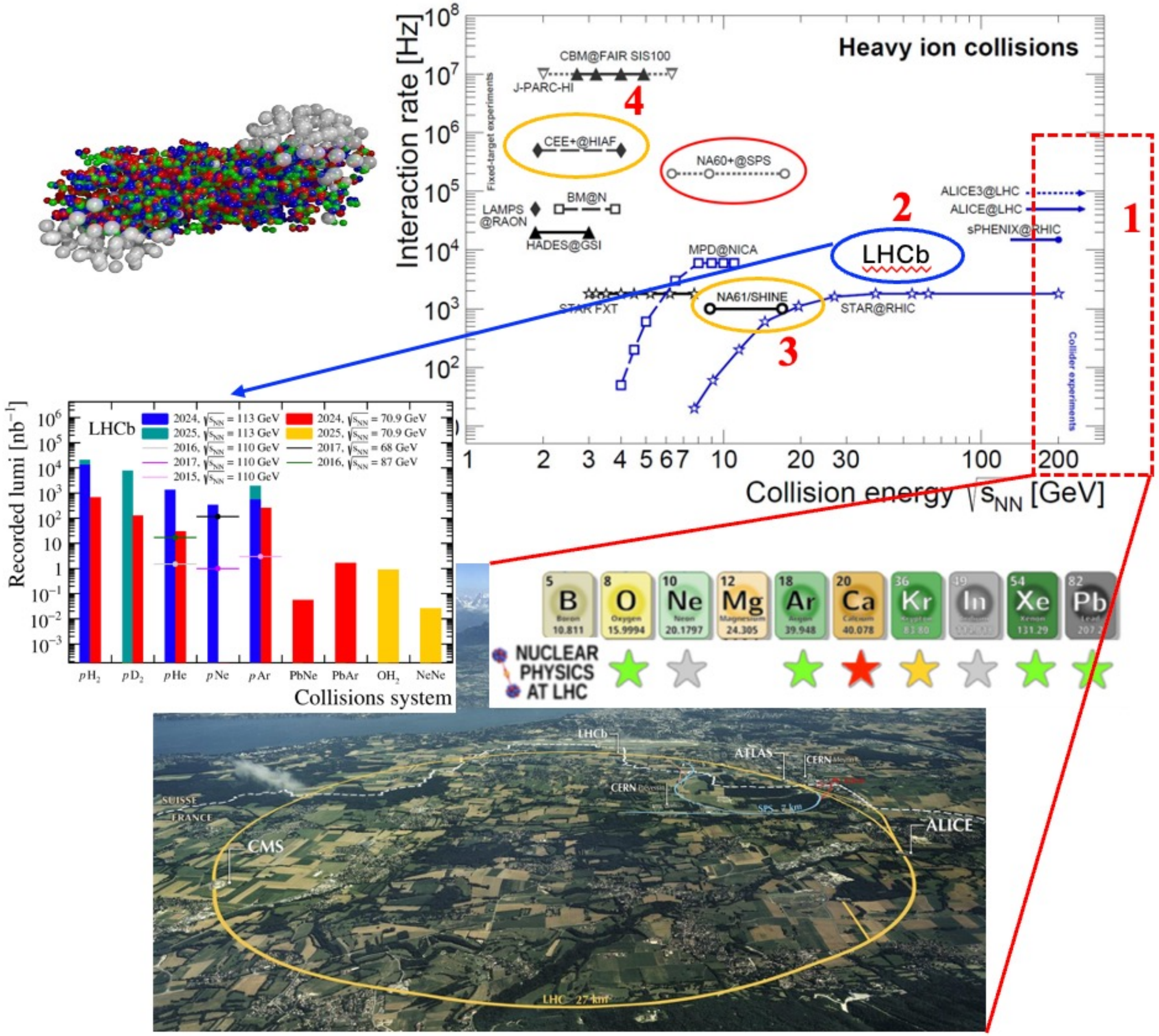
STAR, *arXiv: 2604.06434*
(PRL in press)



$v_0(p_T)$ measurement at RHIC

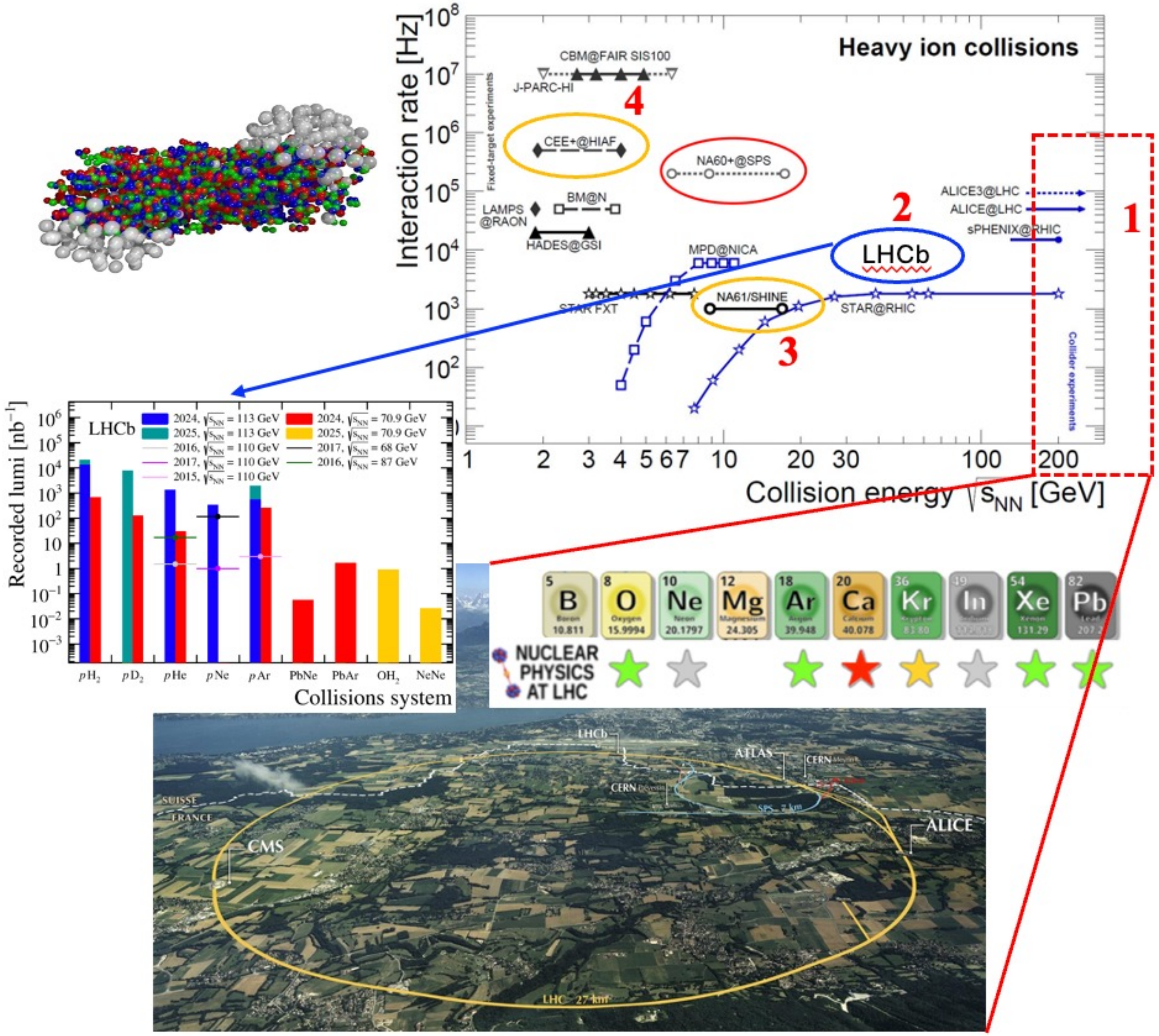
Conclusions and Outlooks

1) Energy evolution and system scan in high baryon density

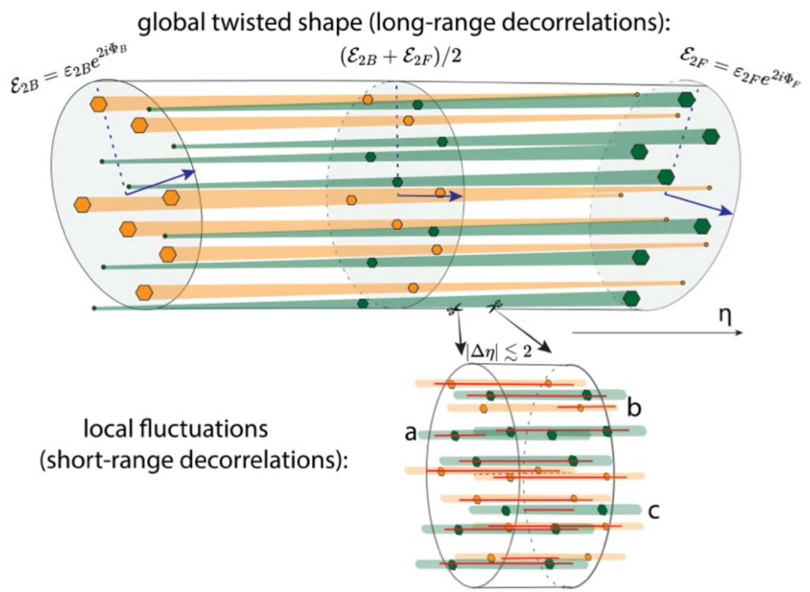


Conclusions and Outlooks

1) Energy evolution and system scan in high baryon density



2) Longitudinal structure QGP initial conditions



Decorrelation map:

v_n decorrelations (deformation-induced component):

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

J. Jia, S. Huang, C. Zhang, S. Bhatta, *2408.15006*

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*

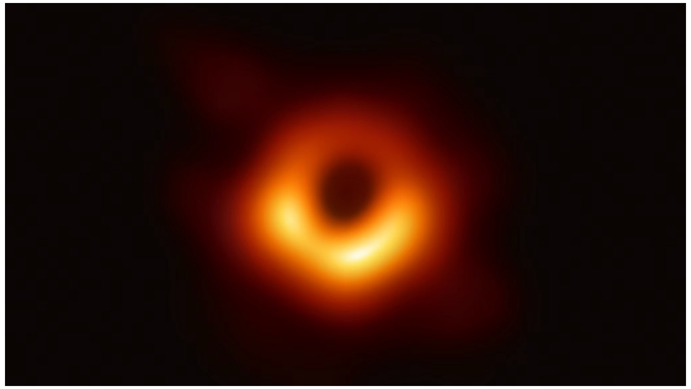
S. Jahan, Roch, C. Shen, *PRC 113, 024919 (2026)*

…

Thank you for your attention!

Analogy to the snapshot imaging technique

First-ever image of a black hole



MRI CT image

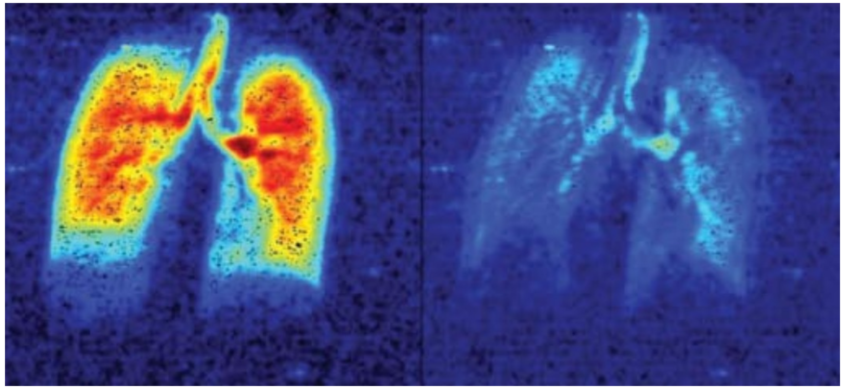
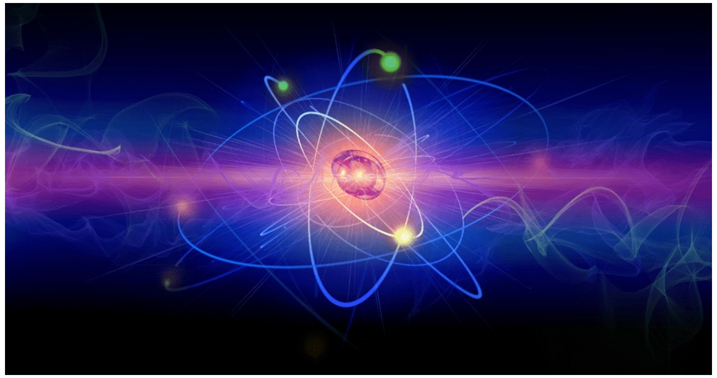


Image of electrons at attosecond

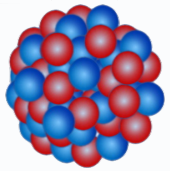


Astronomical scale → **Microscopic scale**

J. Jia et al., *Nucl. Sci. Tech. 35, 220 (2024), G. Giacalone, EPJA 59, 297 (2023), T. Duguet et al., PRL 135, 182301 (2025)* W. Ke, *2509.09549, …*

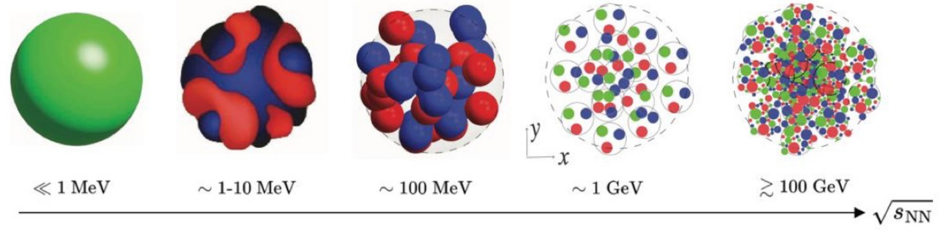
Emergent seeing shape directly require access to instantaneous nucleon distributions

$\Psi\left(\mathbf{r}_1, \mathbf{r}_2 \ldots\right)$



Will see all DOFs longer than exposure timescale:

nucleons, hadrons, quark, gluons, gluon saturations



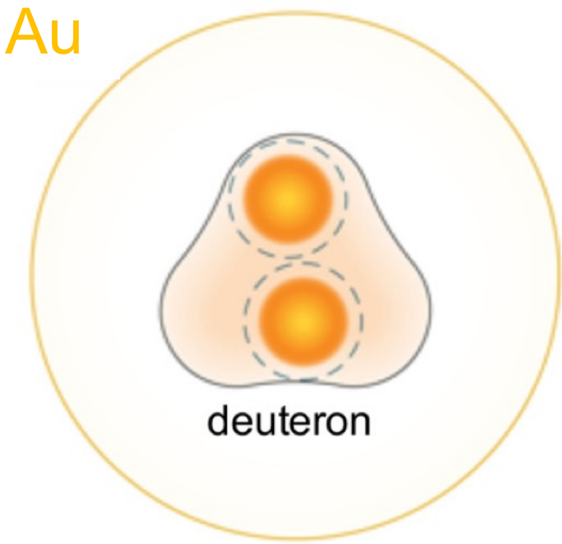
Yoctosecond scale

$$1\mathrm{fm}/c = 3\times10^{-24}\ \text{seconds} = 3\times10^{-6}\ \text{attoseconds} = 3\ \text{yoctoseconds}$$

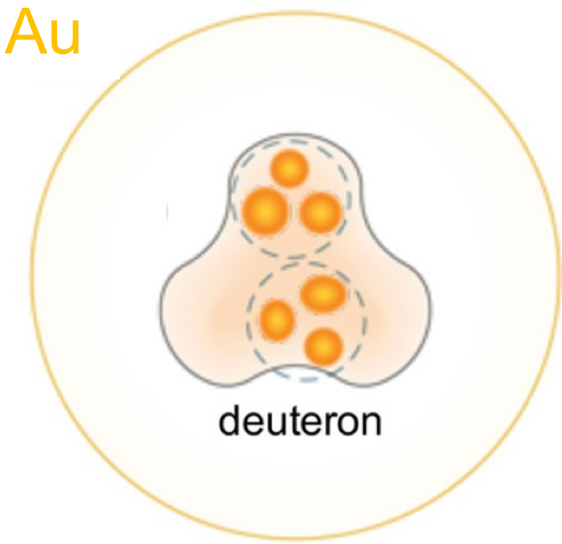
A new, complementary, and independent of low-energy experiments

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

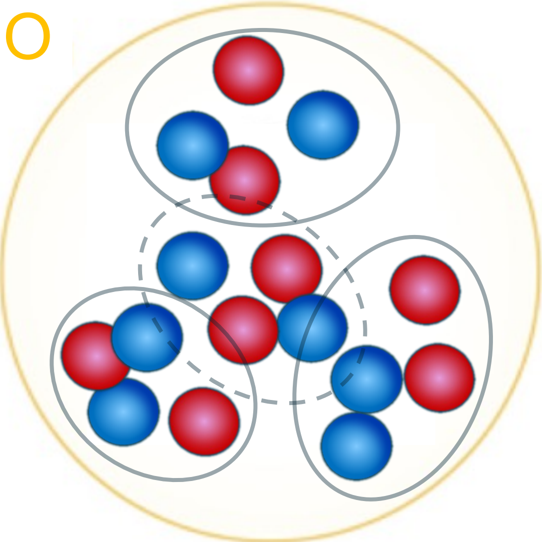
Nucleon fluctuation

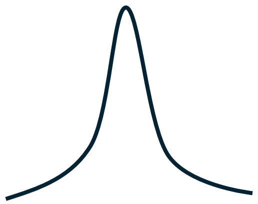


subnucleon fluctuation



NN correlation (cluster pattern)





ab initio calculations

STAR, *PRL 130, 242301 (2023)*

STAR, *PRC 110, 064902 (2024)*

Y.-G. Ma, S. Zhang, *Handbook of Nuclear Physics (2022)*

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

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

X. Zhao, G. Ma. Y. Zhou, Z. Lin and C. Zhang, *PLB 874, 140254 (2026)*

P. Li, B. Zhou, G.-L. Ma, *PRL 136, 082302 (2026)*

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

Y. Wang, S. Zhao, B. Cao, H. Xu and H. Song, *PRC 109, L051904 (2024)*

H. Wang, S. Li, J. Xu, Z. Ren, *PLB 866, 139516 (2025)*

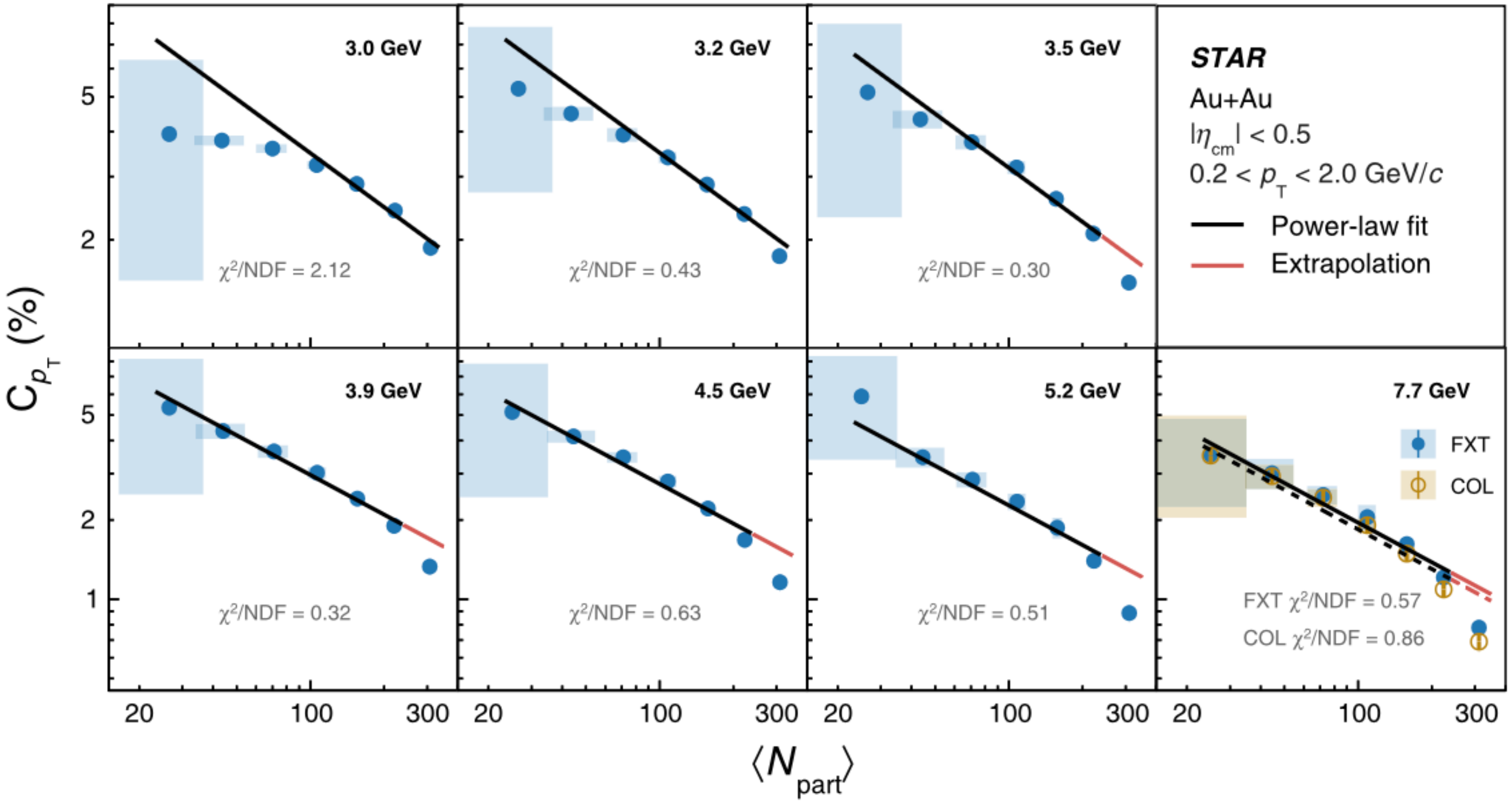
J. Hu, H. Xu, X. Wang, S. Pu, *2507.01493*

...

d+Au collision, 200 GeV ⟷ Nearly same N_{ch} ⟷ O+O collision, 200 GeV

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

STAR, *arXiv: 2604.06434 (PRL)*



- 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.