INPC 2025

May 25-30, 2025
DCC, Daejeon, Korea

Energy dependence of transverse momentum fluctuations in Au+Au collisions from a multiphase transport model

Physical Review C 111, 024911 (2025)

Liuyao Zhang[1]

In collaboration with Jinhui Chen[2], Chunjian Zhang[2]

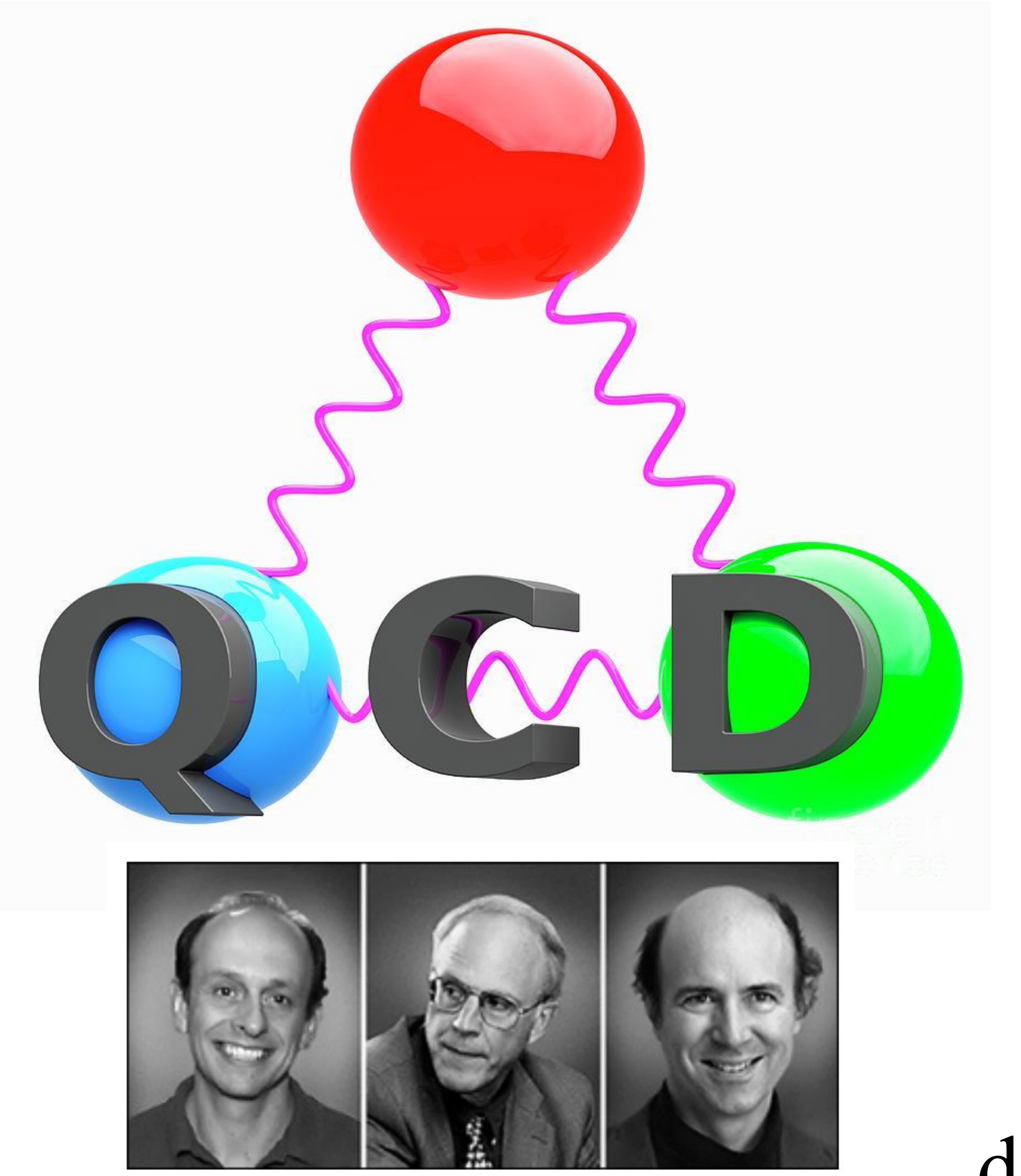
1. Institute of Nuclear Science and Technology, Henan Academy of Sciences

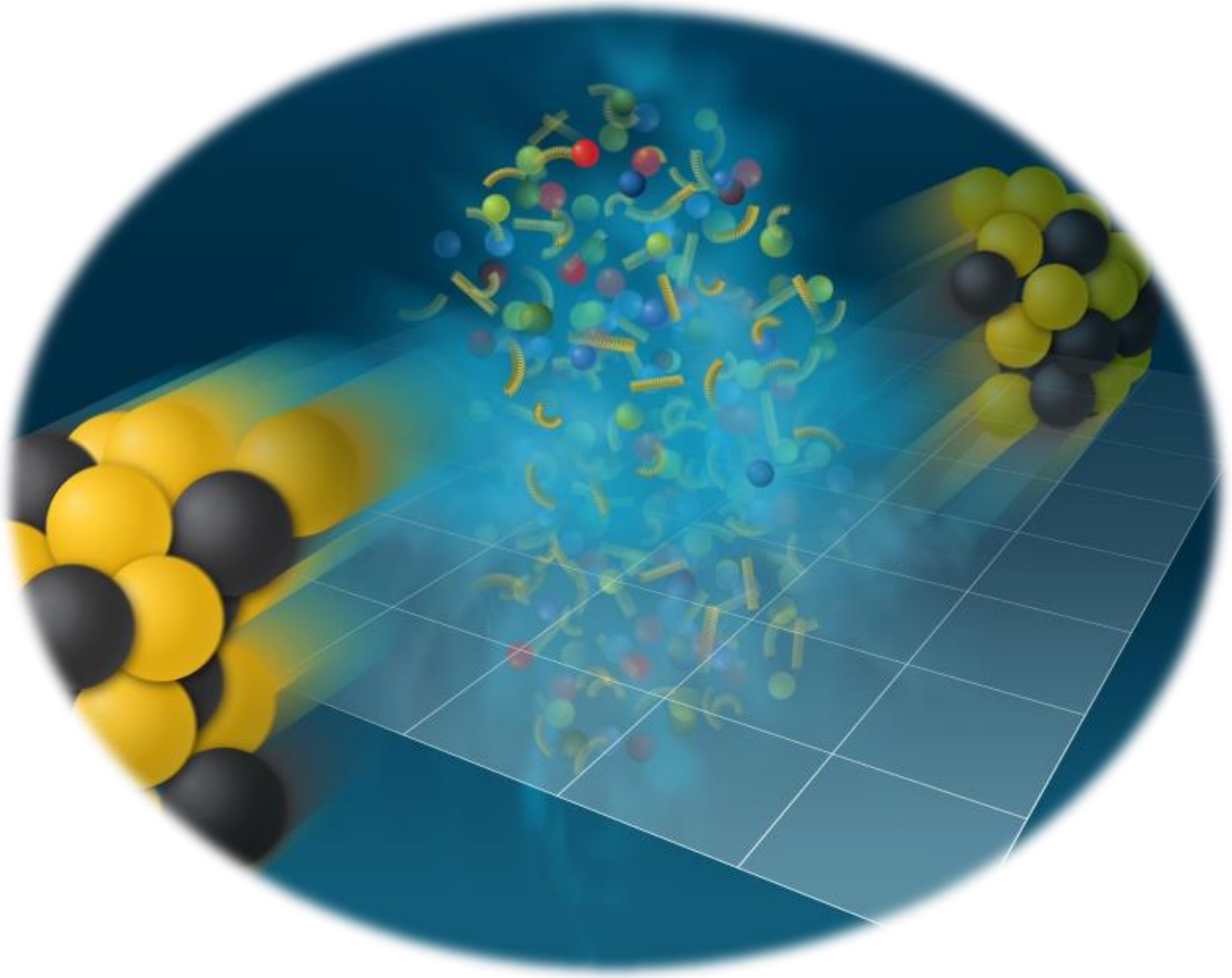
2. Fudan University

The 29th International Nuclear Physics Conference (INPC2025), Daejeon, Korea

Motivation

Quantum **C**hromo**D**ynamics (**QCD**):
the theory of strong interactions governing the behavior of quarks and gluons.

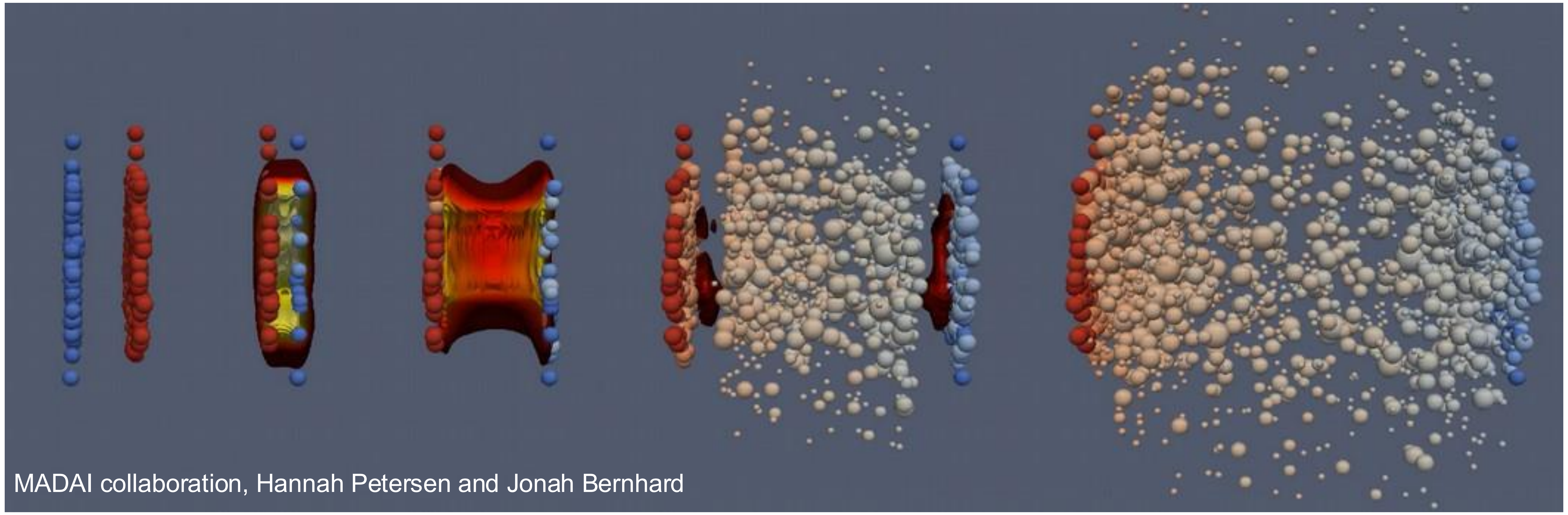


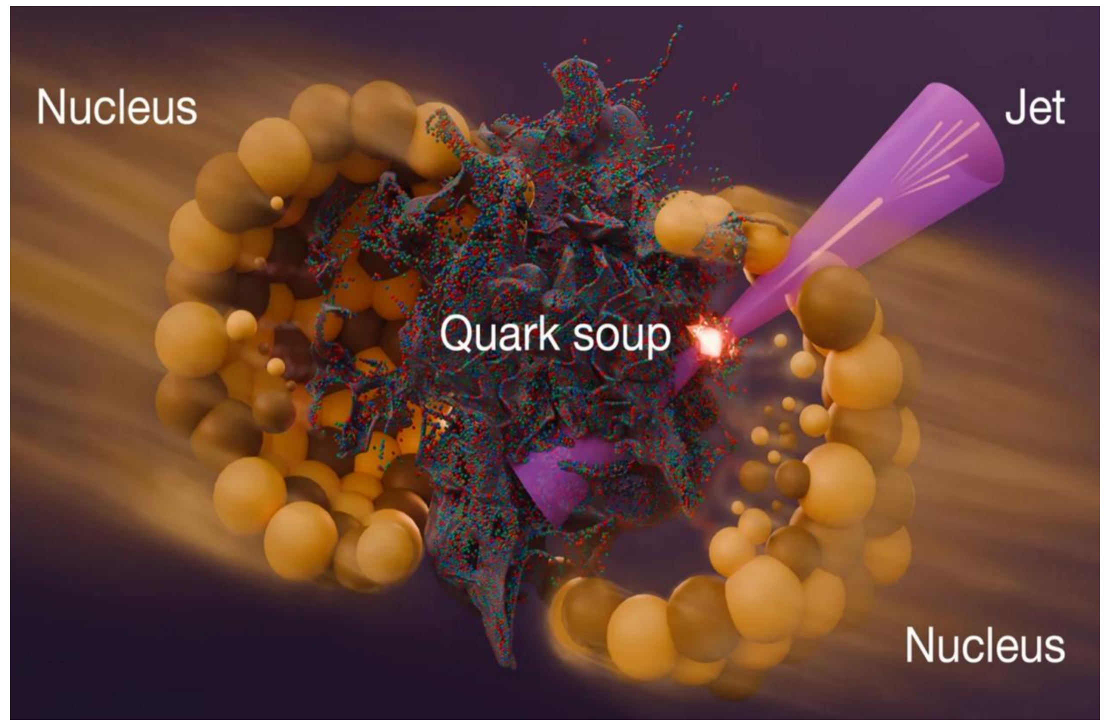


Quark **G**luon **P**lasma (**QGP**):
deconfined state under extreme conditions of temperature and density.

Motivation

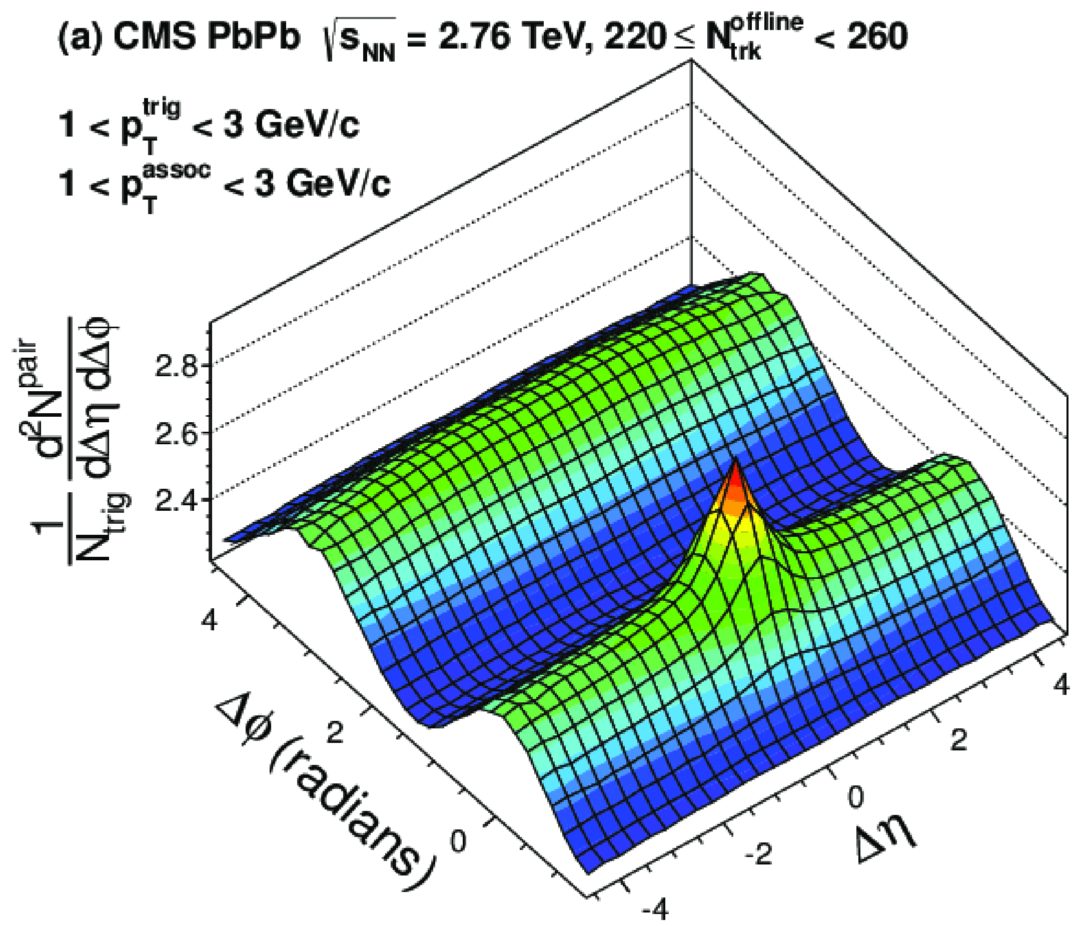
In the laboratory, the QGP could be generated in heavy-ion collisions.





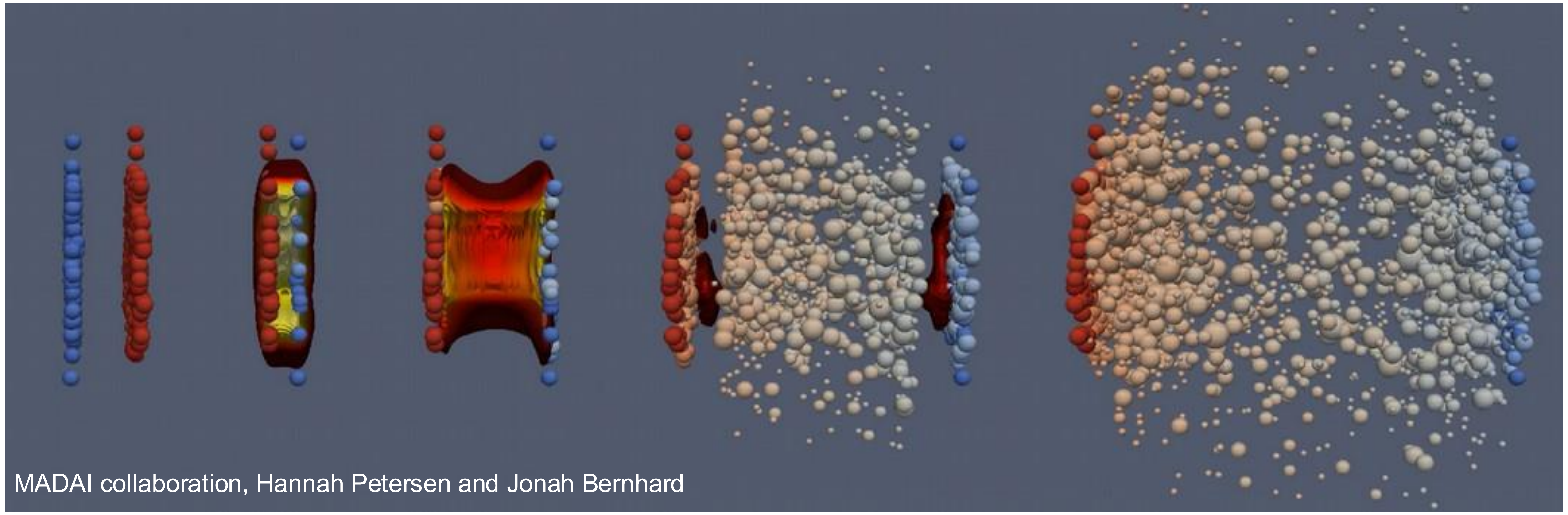
Hard Probes:
Jets,
Large p_T hadrons,
Heavy quark/hadrons,
Quarkonia,
...

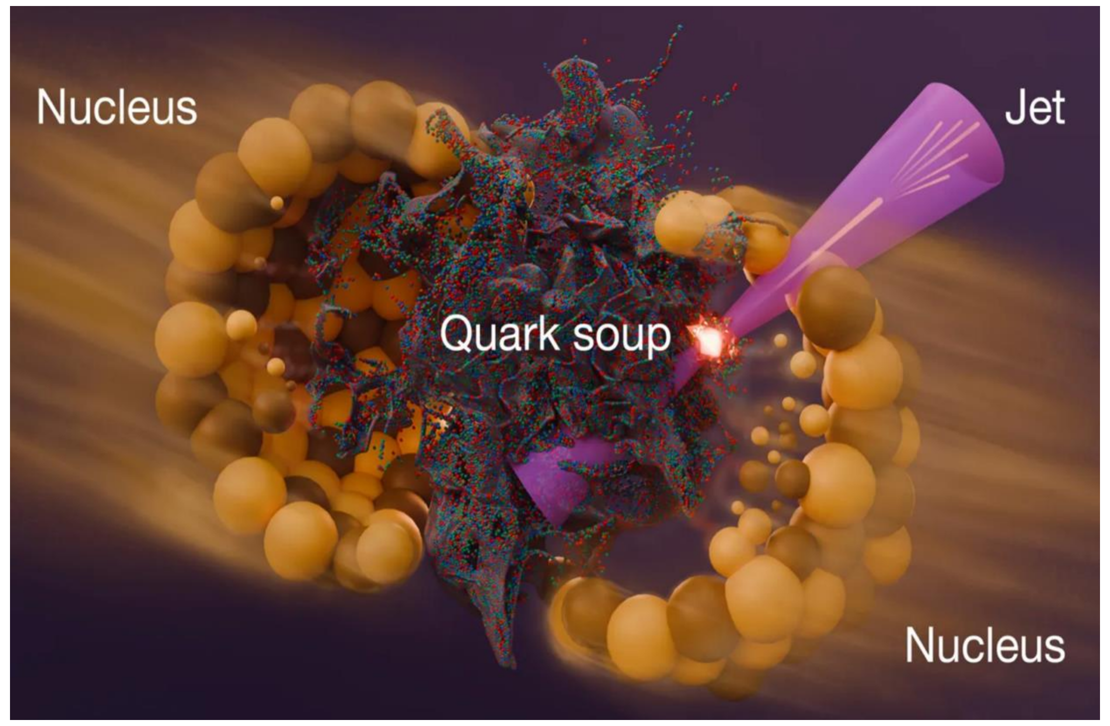
Soft Probes:
Yields/Spectra,
Flows,
Correlations,
Decorrelations,
Fluctuations,
...



Motivation

In the laboratory, the QGP could be generated in heavy-ion collisions.





Hard Probes:
Jets,
Large p_T hadrons,
Heavy quark/hadrons,
Quarkonia,
...

Soft Probes:
Yields/Spectra,
Flows,
Correlations,
Decorrelations,
Fluctuations,
...

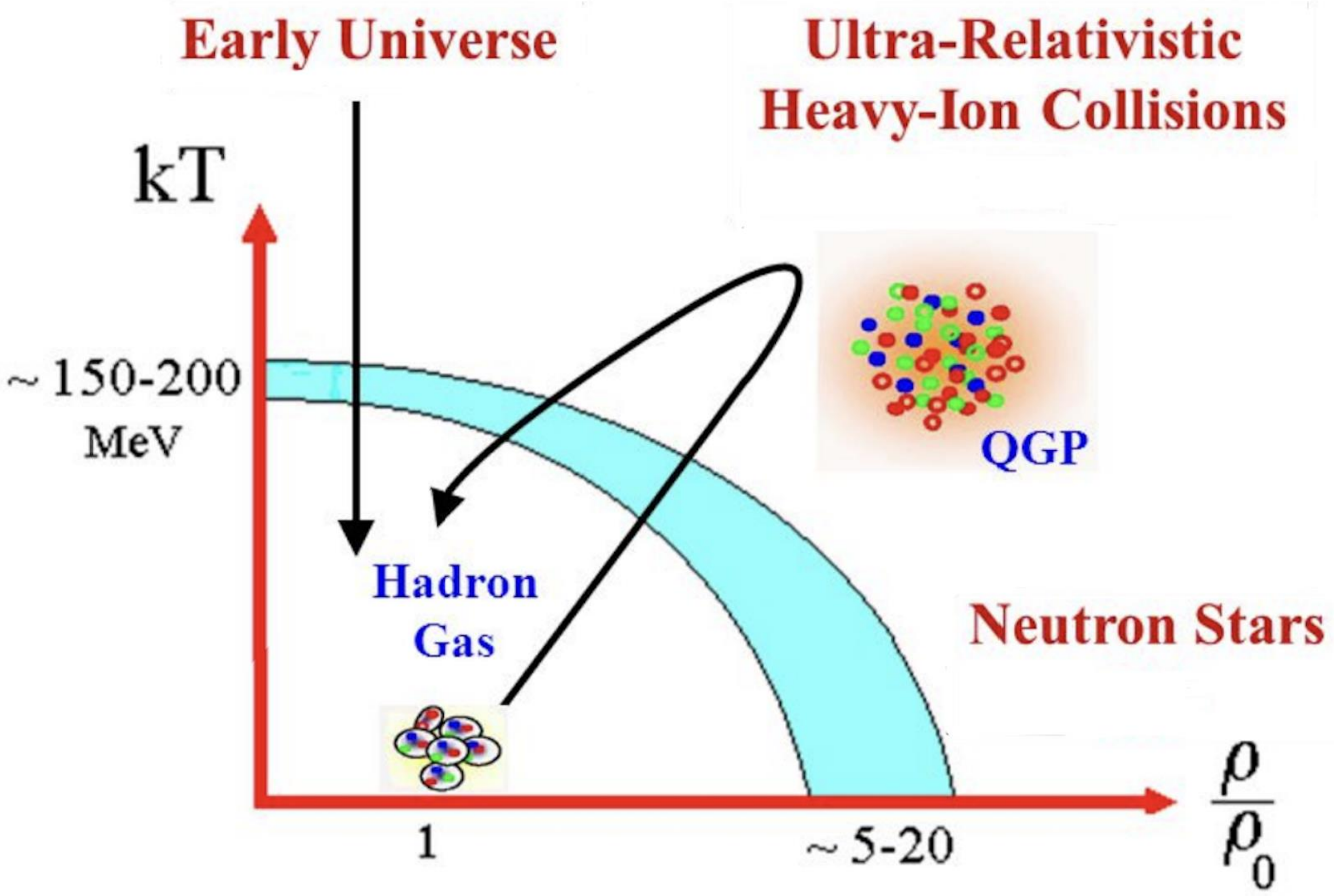
Nu Xu: Tue (16:30)

Conserved Quantities: net charge/proton...

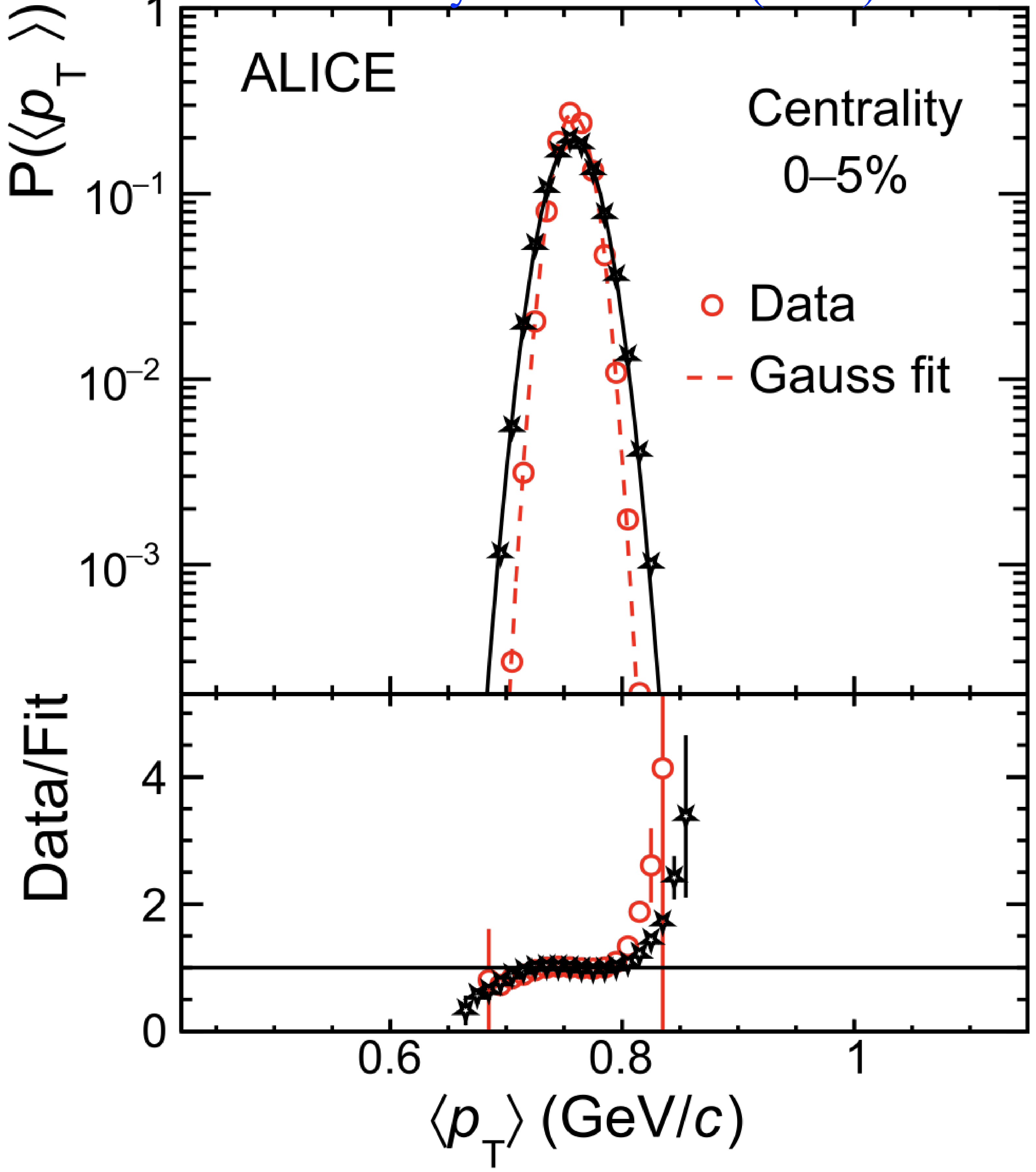
Event-by-Event $\langle p_T \rangle$.

Motivation

Phase transition (QGP to Hadron Gas) → Thermodynamics quantity (T): critical fluctuation. → dynamical $\langle p_T \rangle$ fluctuations

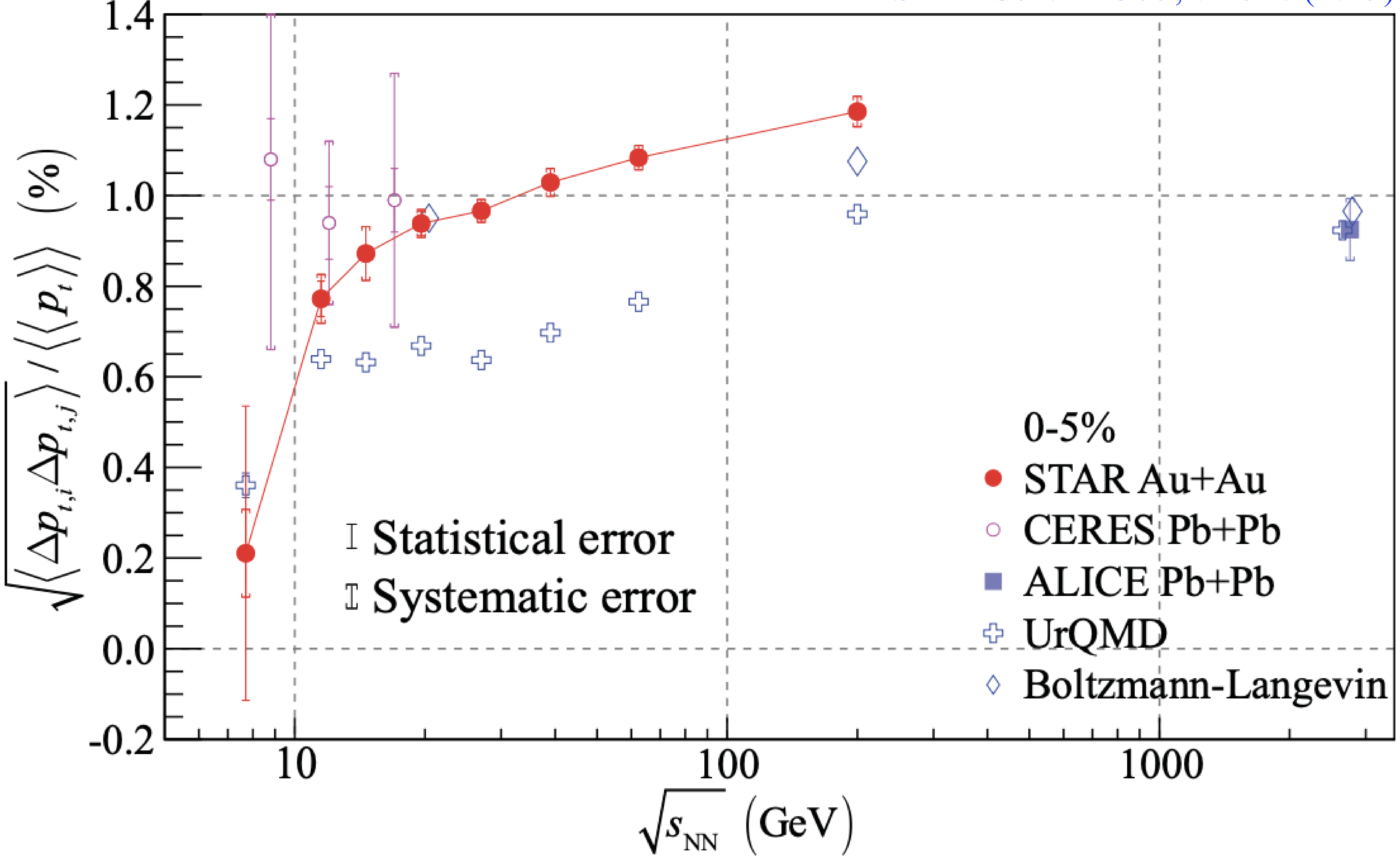


Phys. Lett. B 850 (2024) 138541



Motivation

STAR Coll. PRC 99, 044918 (2019)



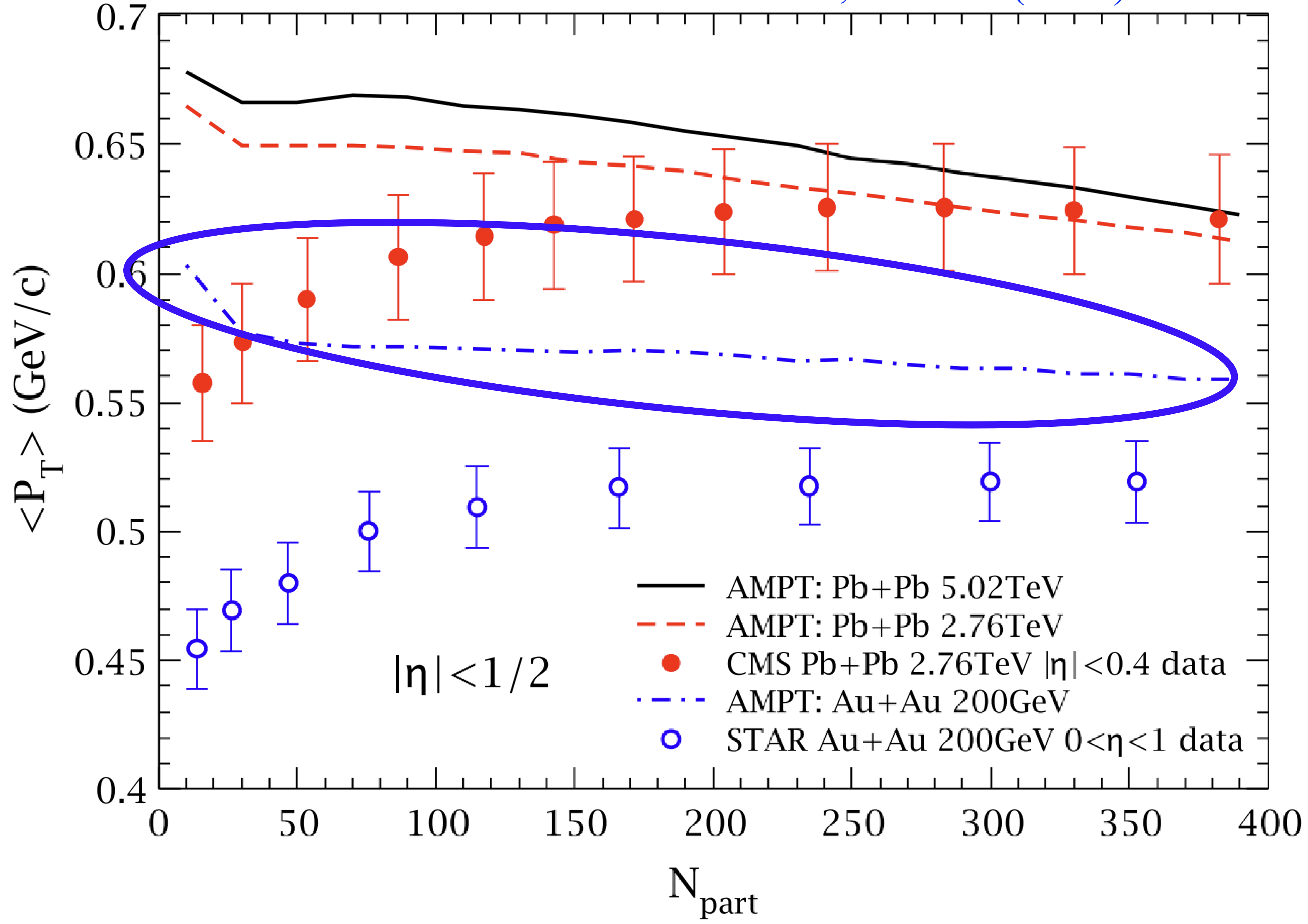
A non-monotonic behavior of $\langle p_T \rangle$ fluctuations as a function of centrality or incident energy was suggested as one of the possible signals of the QGP.

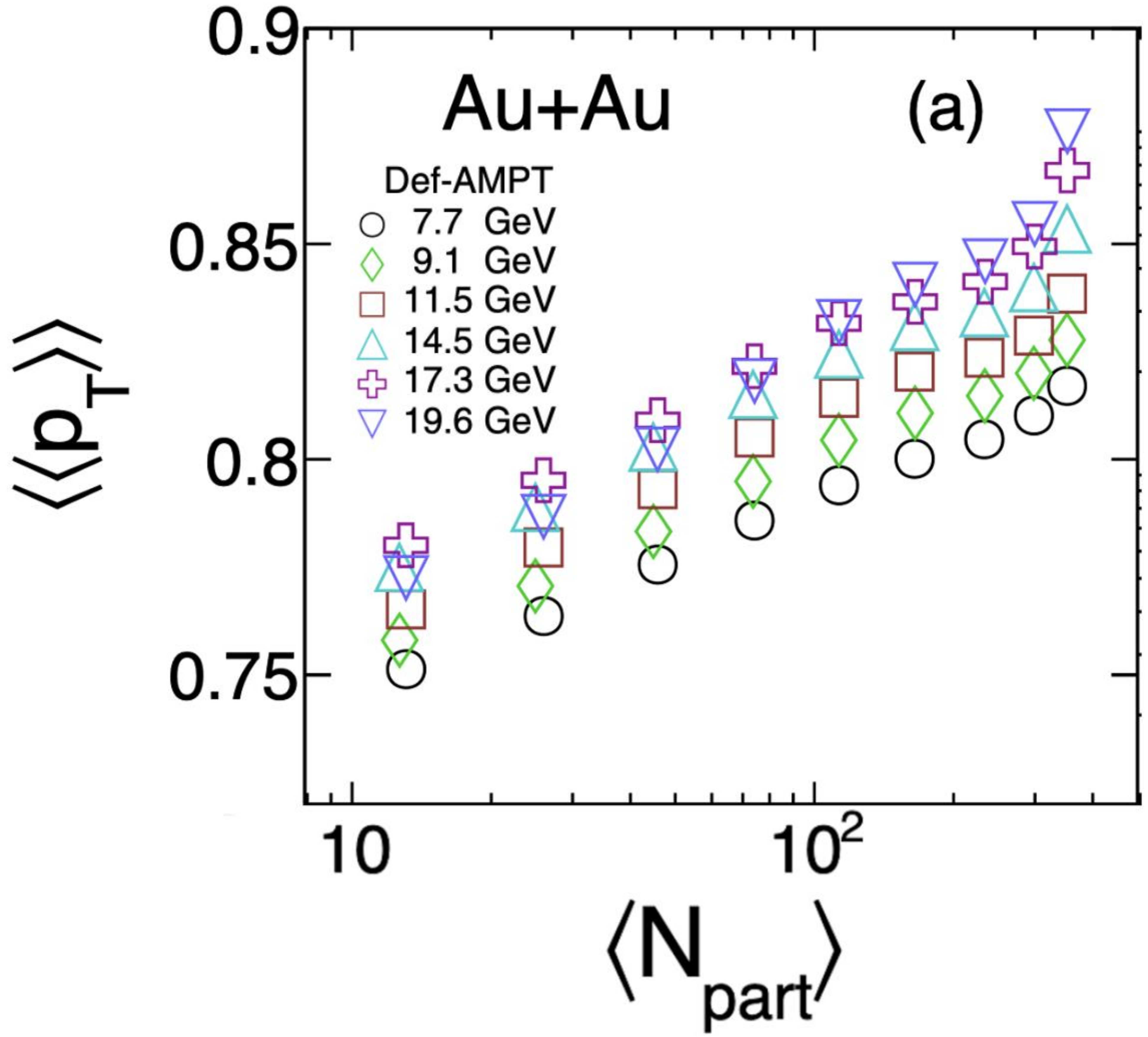
$\langle p_T \rangle$ trend：AMPT optimization

Two key parameters ($\boldsymbol{a_L}$, $\boldsymbol{b_L}$) in hadronization mechanisms are tuned:

fixed value → variable (based on impact parameter)

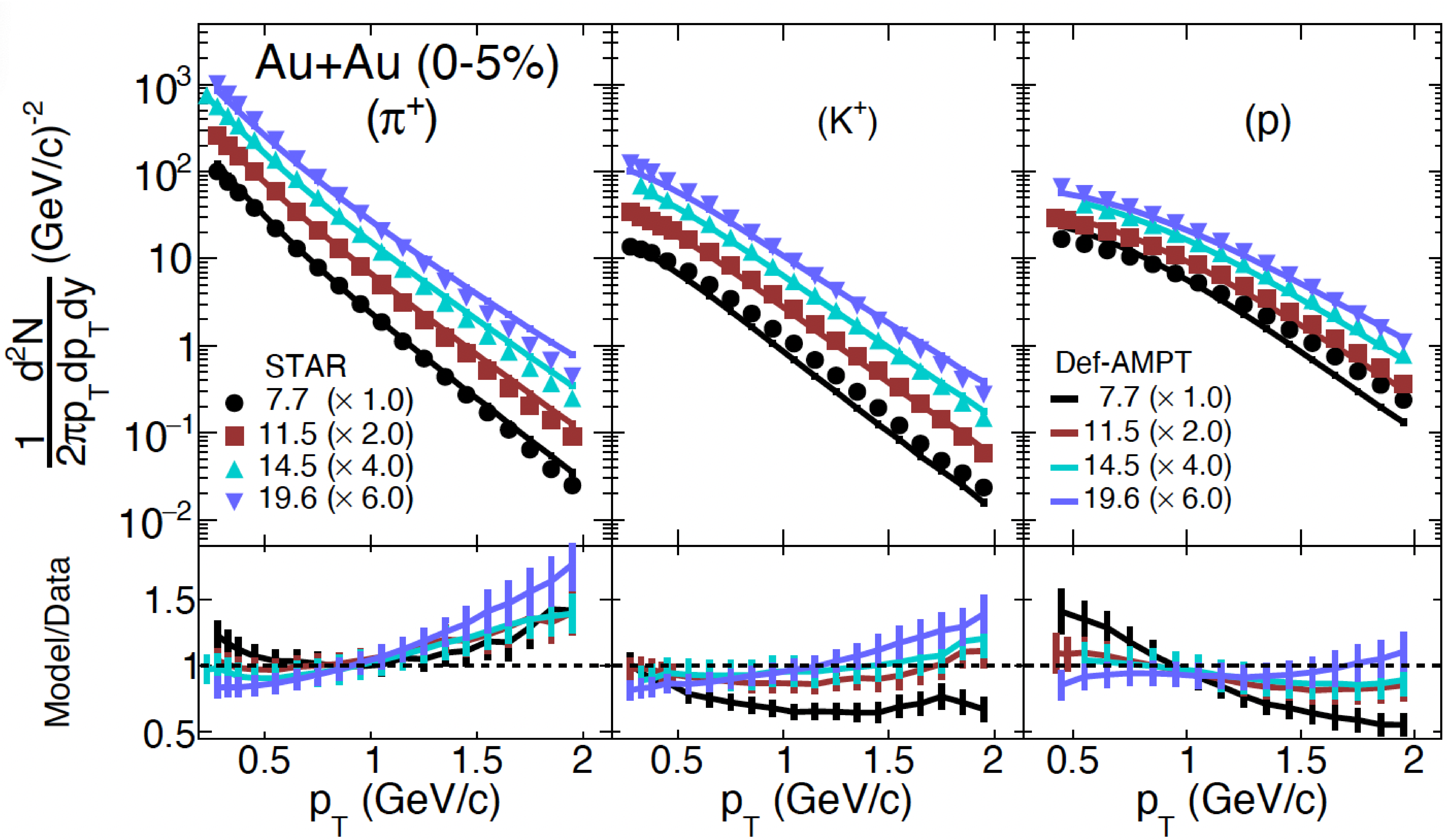
G.L. Ma et. al., PRC 93 (2016) 054911





$\langle\langle p_T \rangle\rangle$ tends to increase with centrality, which are more **reasonable expectation**.

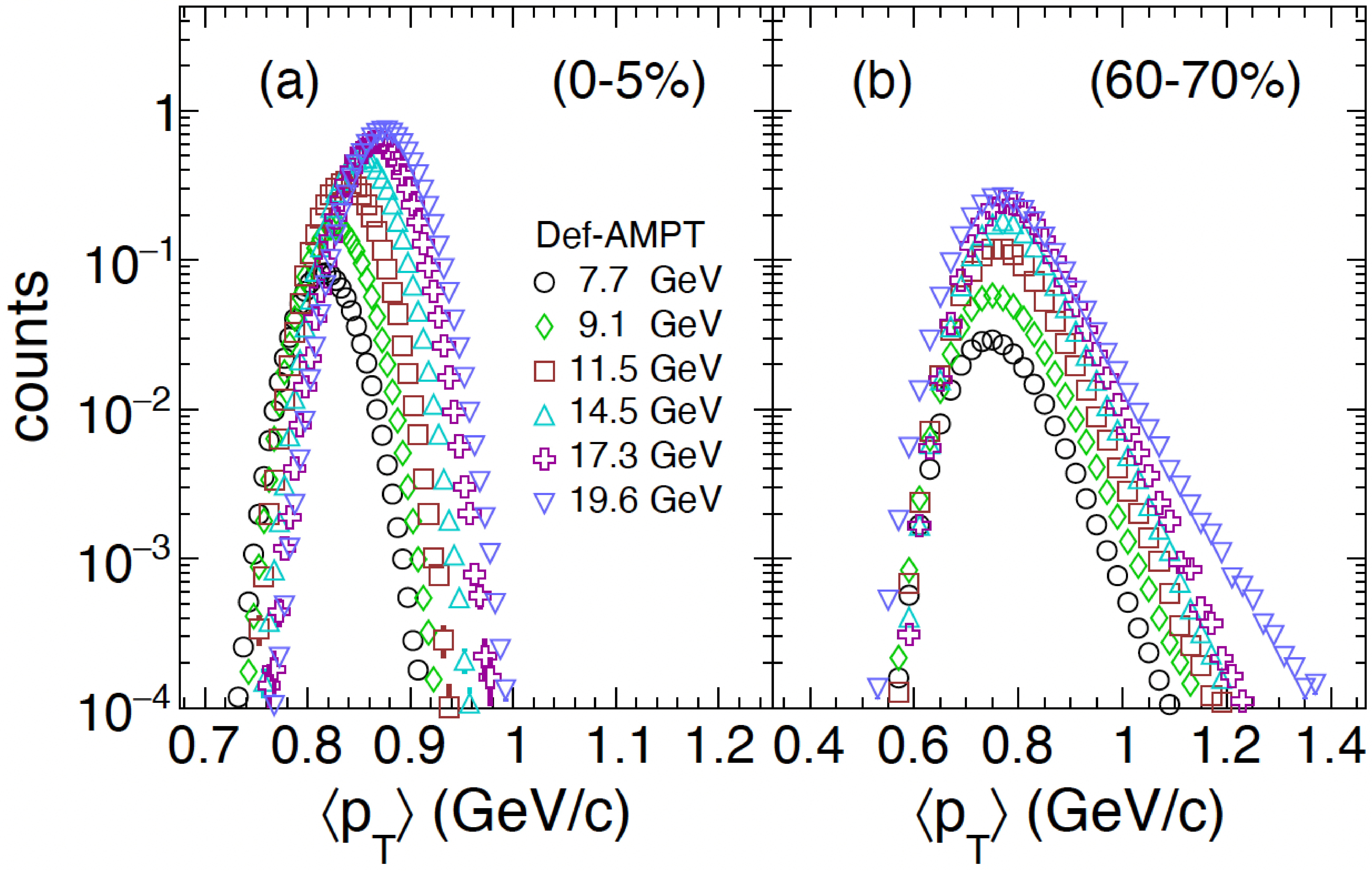
The AMPT validity



The improved AMPT qualitatively produces the experimental data across a broad p_T spectrum.

Event-wise $\langle p_T \rangle$ distribution

The $\langle p_T \rangle$ fluctuations can be straightforwardly studied by its event-wise distributions.

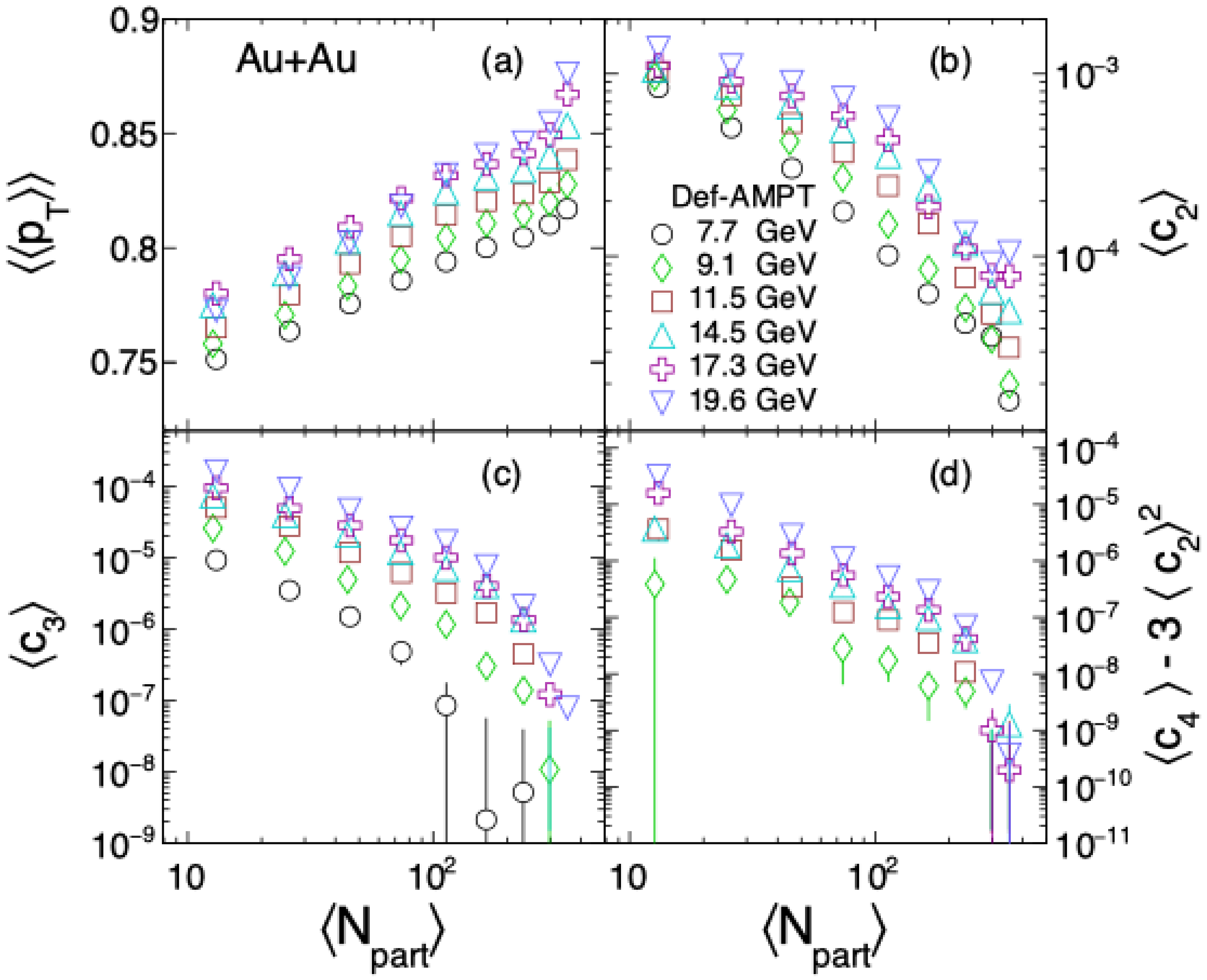


At peripheral collisions:

- ➢ greater variances:
  indicating enhanced fluctuations.
- ➢ more significant rightward tail:
  suggesting positive skewness.

Higher-order p_T cumulants

Variance($\langle c_2 \rangle$), Skewness ($\langle c_3 \rangle$), Kurtosis($\langle c_4 \rangle$-3$\langle c_2 \rangle^2$)



- Share significant dependence on:
  a) **centrality**, b) **incident energy**;
- An inverse dependence on centrality:
  a reduction in particle-pair correlations if they are dominated by particles originating from the same nucleon-nucleon collisions.

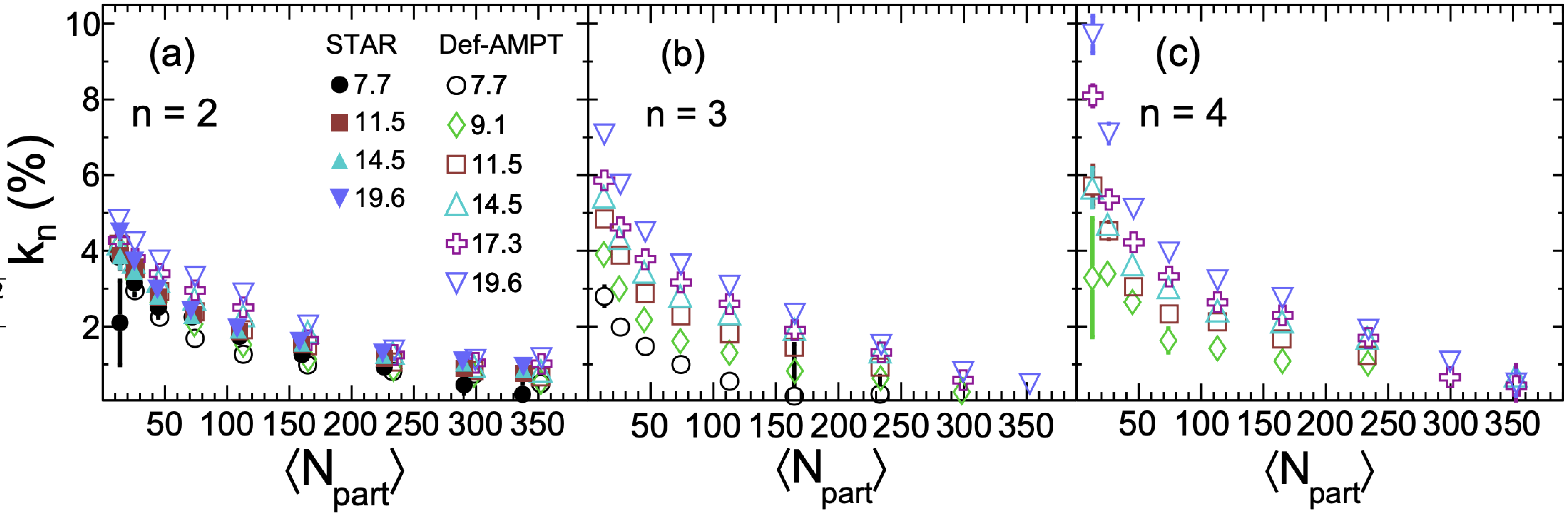
Scaled p_T cumulants

To mitigate the influence on the cumulants in $\langle\langle p_T\rangle\rangle$ with centrality or incident energy.

$$k_2 = \frac{\sqrt{\langle c_2\rangle}}{\langle\langle p_T\rangle\rangle},$$

$$k_3 = \frac{\sqrt[3]{\langle c_3\rangle}}{\langle\langle p_T\rangle\rangle},$$

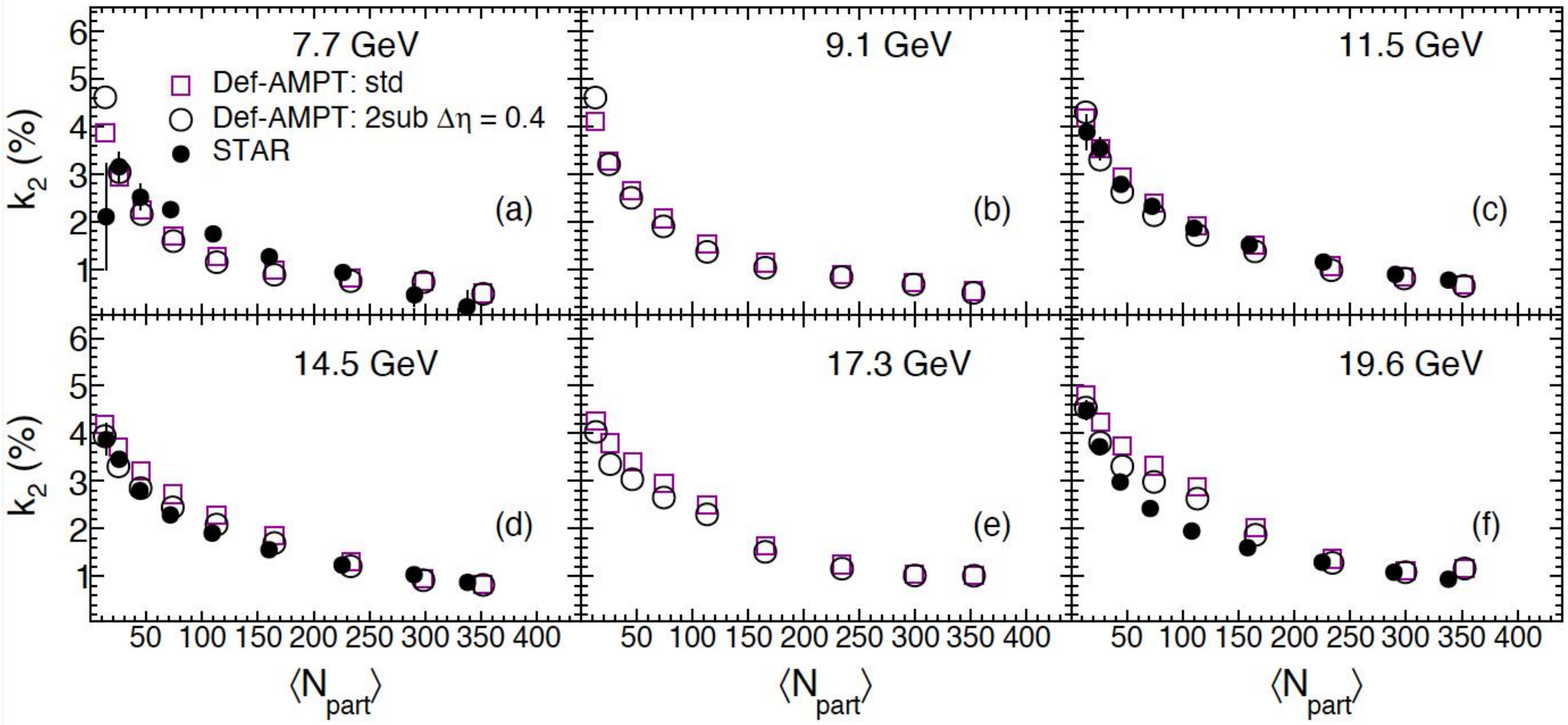
$$k_4 = \frac{\sqrt[4]{\langle c_4\rangle - 3\langle c_2\rangle^2}}{\langle\langle p_T\rangle\rangle}$$



- ➢ k_2 qualitatively produce the trends of STAR experiment.
- ➢ k_n (n=2,3,4) exhibits significant centrality and energy dependence;
- ➢ k_n (n=2,3,4) exhibit an approximate power-law behavior.

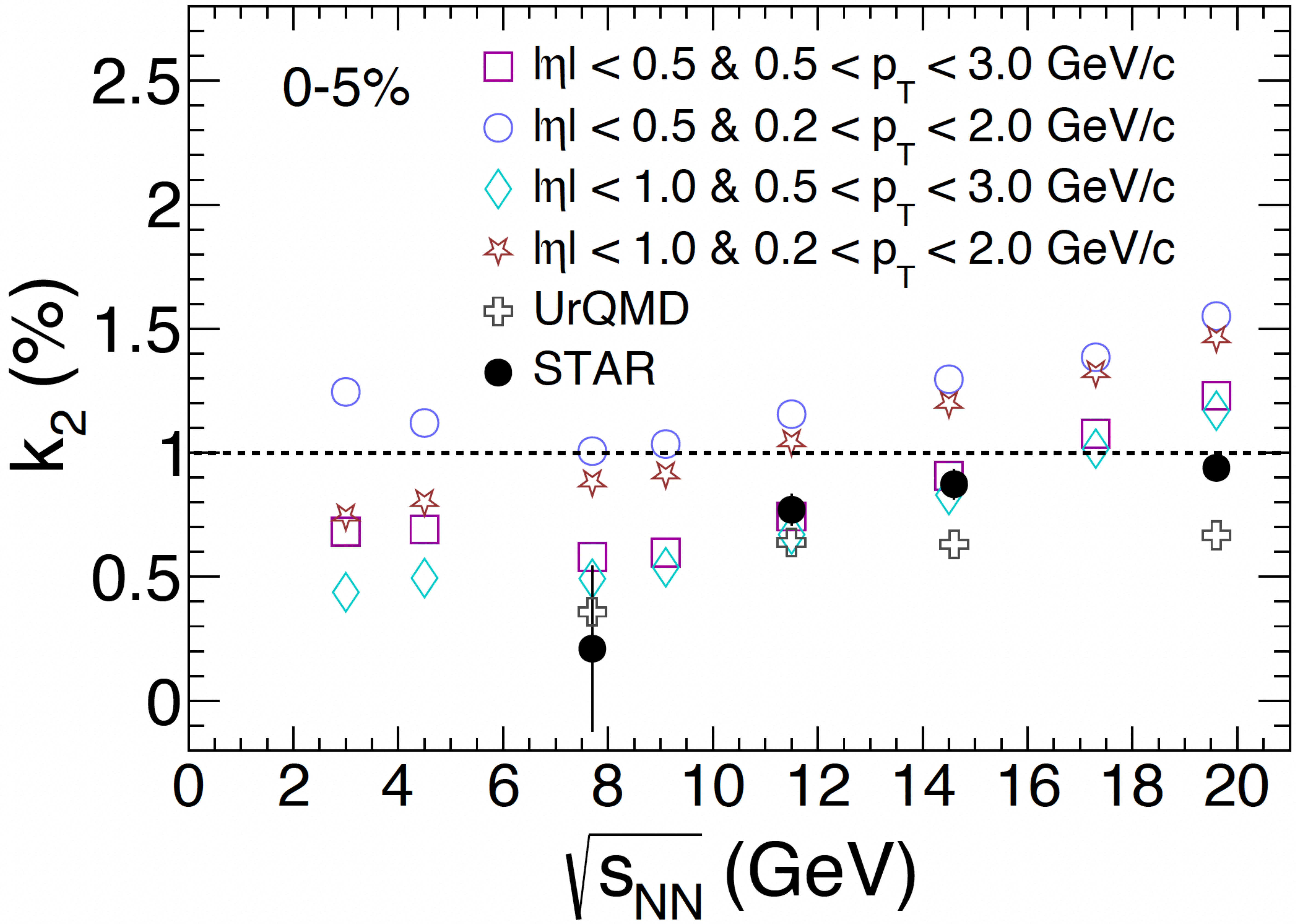
Scaled p_T cumulants: the short-range correlations

Two-subevent method:



All values from two-subevent method are slightly suppressed compared to the standard method.

Scaled p_T cumulants: vs energy



- More sensitive to p_T variations than η.
- $0.5 < p_T < 3.0$ GeV/c: quantitatively consistent with STAR measurements.
- extend to 3.0 GeV/c:
  a significant abnormal increase, indicating an enhancement of dynamical correlations at lower collision energies.

Summary and outlook

- A systematic study of higher-order dynamical p_T cumulants up to fourth order.
- Higher-order p_T cumulants w/o normalization exhibit a strong dependence on centrality.
- Our finding provides variable references for the experimental measurements.
- The inner mechanism from acceptance or decorrelation need further to be explored.

Thank you for your attention !!!

Backup

Methodology: n-particle p_{T} correlator

$$c_n = \frac{\sum_{i_1 \neq \cdots \neq i_n} w_{i_1} \cdots w_{i_n} \left(p_{\mathrm{T,i_1}} - \langle\langle p_{\mathrm{T}} \rangle\rangle\right) \cdots \left(p_{\mathrm{T,i_n}} - \langle\langle p_{\mathrm{T}} \rangle\rangle\right)}{\sum_{i_1 \neq \cdots \neq i_n} w_{i_1} \cdots w_{i_n}}$$

$$p_{mk} = \sum_i w_i^k p_i^m / \sum_i w_i^k, \quad \tau_k = \frac{\sum_i w_i^{k+1}}{\left(\sum_i w_i\right)^{k+1}}$$

$\langle p_{\mathrm{T}} \rangle$ cumulant

$$c_2 = \frac{\bar{p}_{11}^2 - \tau_1 \bar{p}_{22}}{1 - \tau_1},$$

$$c_3 = \frac{\bar{p}_{11}^3 - 3\tau_1 \bar{p}_{22}\bar{p}_{11} + 2\tau_2 \bar{p}_{33}}{1 - 3\tau_1 + 2\tau_2},$$

$$c_4 = \frac{\bar{p}_{11}^4 - 6\tau_1 \bar{p}_{22}\bar{p}_{11}^2 + 3\tau_1^2 \bar{p}_{22}^2 + 8\tau_2 \bar{p}_{33}\bar{p}_{11} - 6\tau_3 \bar{p}_{44}}{1 - 6\tau_1 + 3\tau_1^2 + 8\tau_2 - 6\tau_3}$$

S. Bhatta, C, Zhang, and J. Jia, PRC 105, 024904 (2022)

$\langle p_T \rangle$ trend：AMPT optimization

1) vs centrality, 2) vs incident energy

Two key parameters in hadronization mechanisms in the AMPT model:

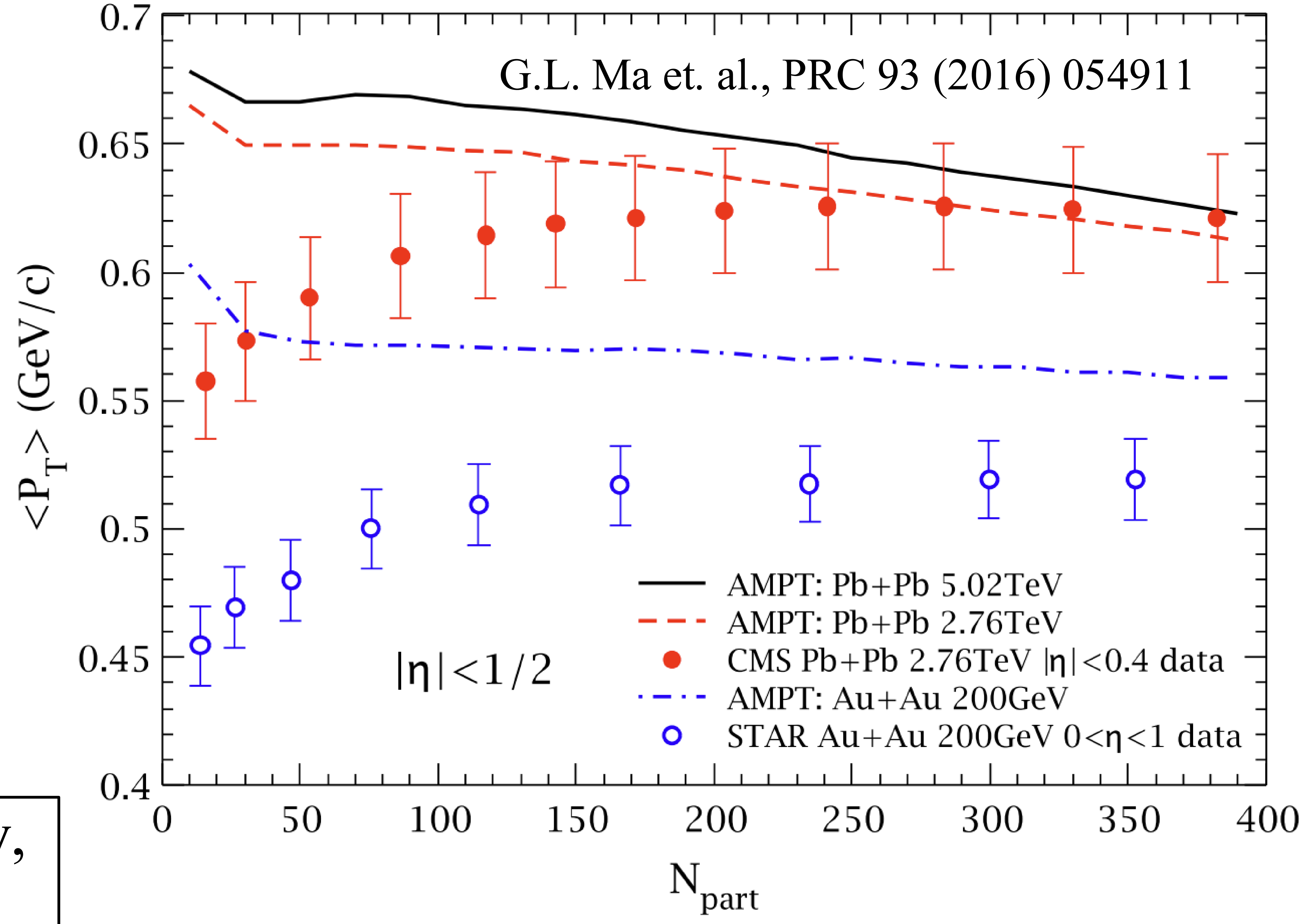
$\boldsymbol{a_L}, \boldsymbol{b_L}$: which are inversely related to $\langle p_T \rangle^2$ of hadrons.

$$\langle p_T^2 \rangle = \frac{1}{b_L(2 + a_L)}$$

Traditionally, a_L, b_L are constant values, e.g.

RHIC@200 GeV: $a_L = 0.55$, $b_L = 0.15$

LHC@2.75/5.02 TeV: $a_L = 0.3$, $b_L = 0.15$



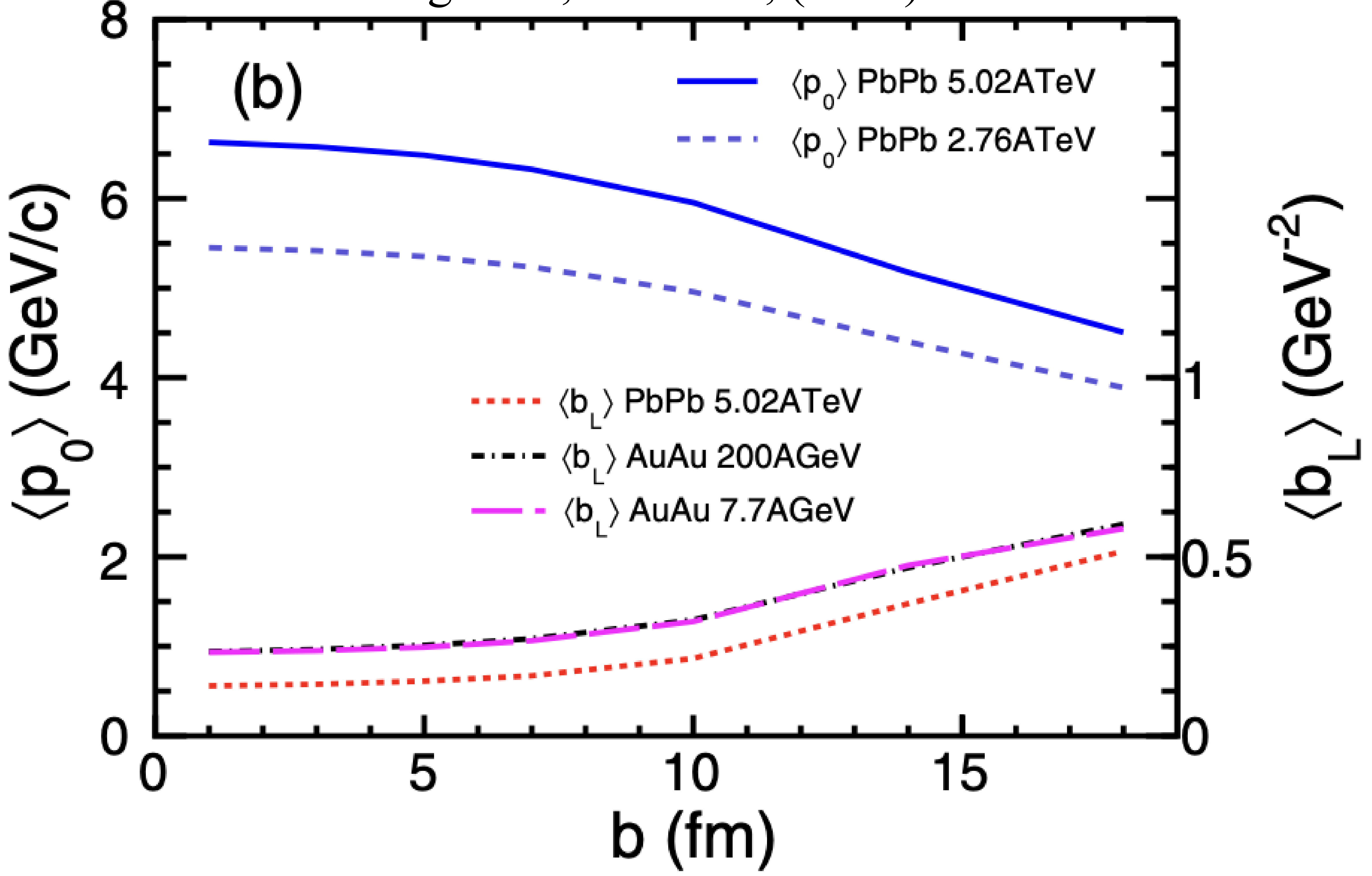
The $\langle p_T \rangle$(cent.) is inconsistent with the data. Actually, the $\langle p_T \rangle$ is expected to increase with centrality due to higher initial temperature in more central collisions.

$\langle p_T \rangle$ trend：AMPT optimization

A possible solution:

Make b_L a local variable, which has a dependence on the transverse position of the corresponding excited string in each event.

C. Zhang et.al., PRC 104, (2021) 014908



At 200 GeV and 7.7GeV:

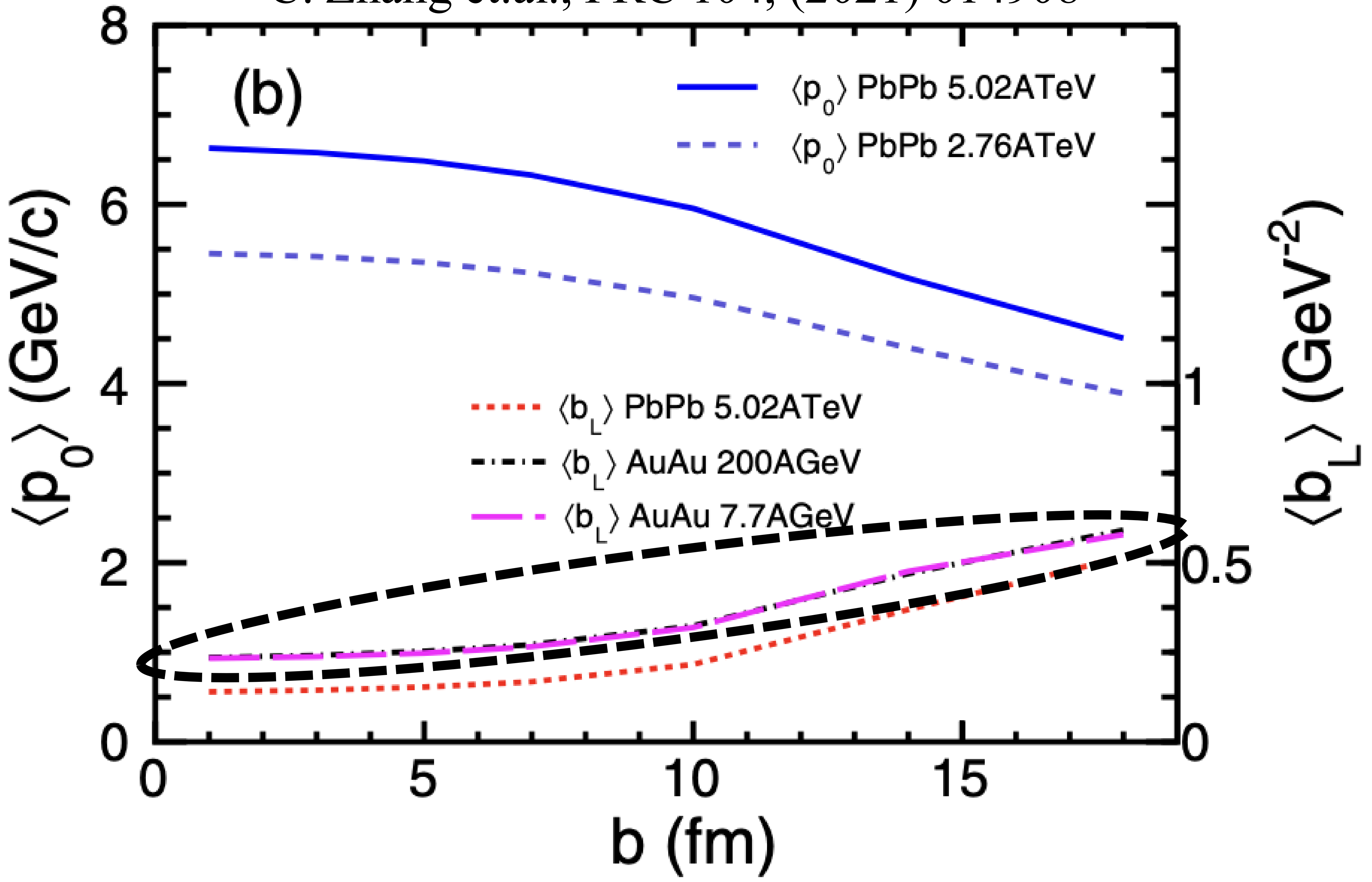
C. Zhang's work reveals b_L has approximate linear dependence on the impact parameter.

$\langle p_T \rangle$ trend：AMPT optimization

A possible solution:

Make b_L a local variable, which has a dependence on the transverse position of the corresponding excited string in each event.

C. Zhang et.al., PRC 104, (2021) 014908



Based on the published work, we adopt:

a) b_L has approximate linear dependence on the b.

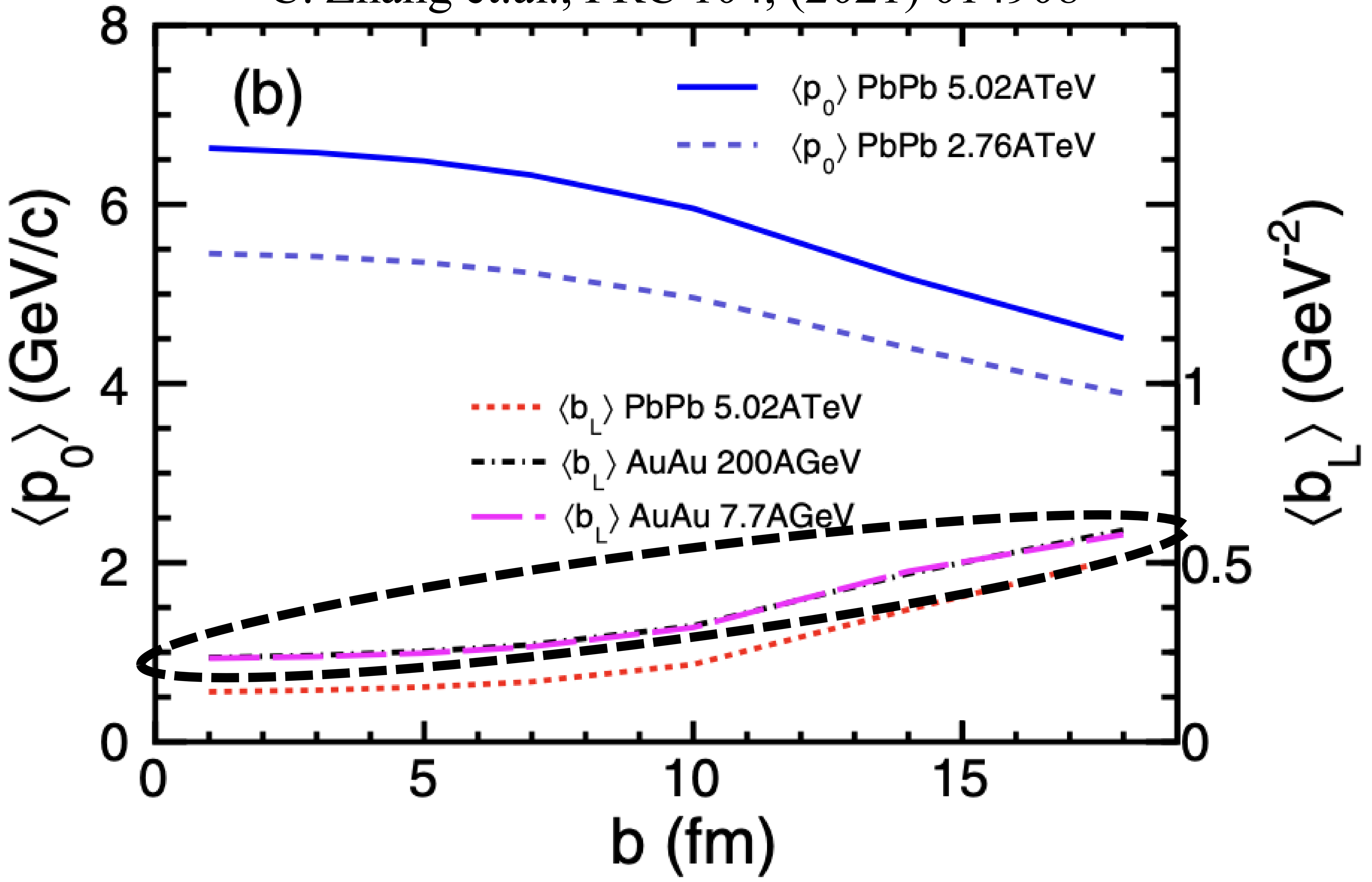
→ Distribution of $\langle p_T \rangle$(cent.) have a reasonable trend.

$\langle p_T \rangle$ trend : AMPT optimization

A possible solution:

Make b_L a local variable, which has a dependence on the transverse position of the corresponding excited string in each event.

C. Zhang et.al., PRC 104, (2021) 014908



Based on the published work, we adopt:

a) b_L has approximate linear dependence on the b.

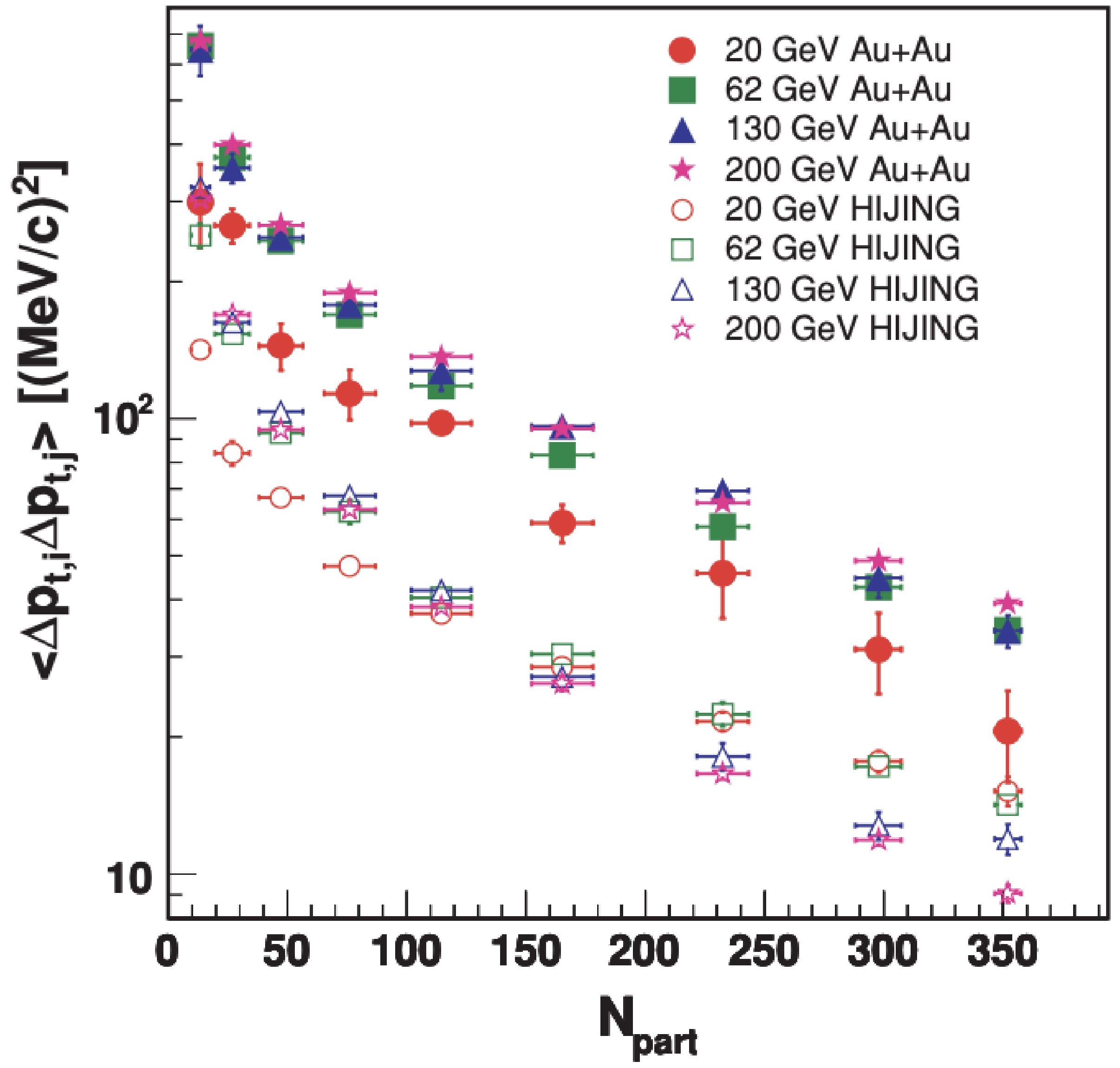
→ Distribution of $\langle p_T \rangle$(cent.) have a reasonable trend.

b) b_L is systematically increased with E.

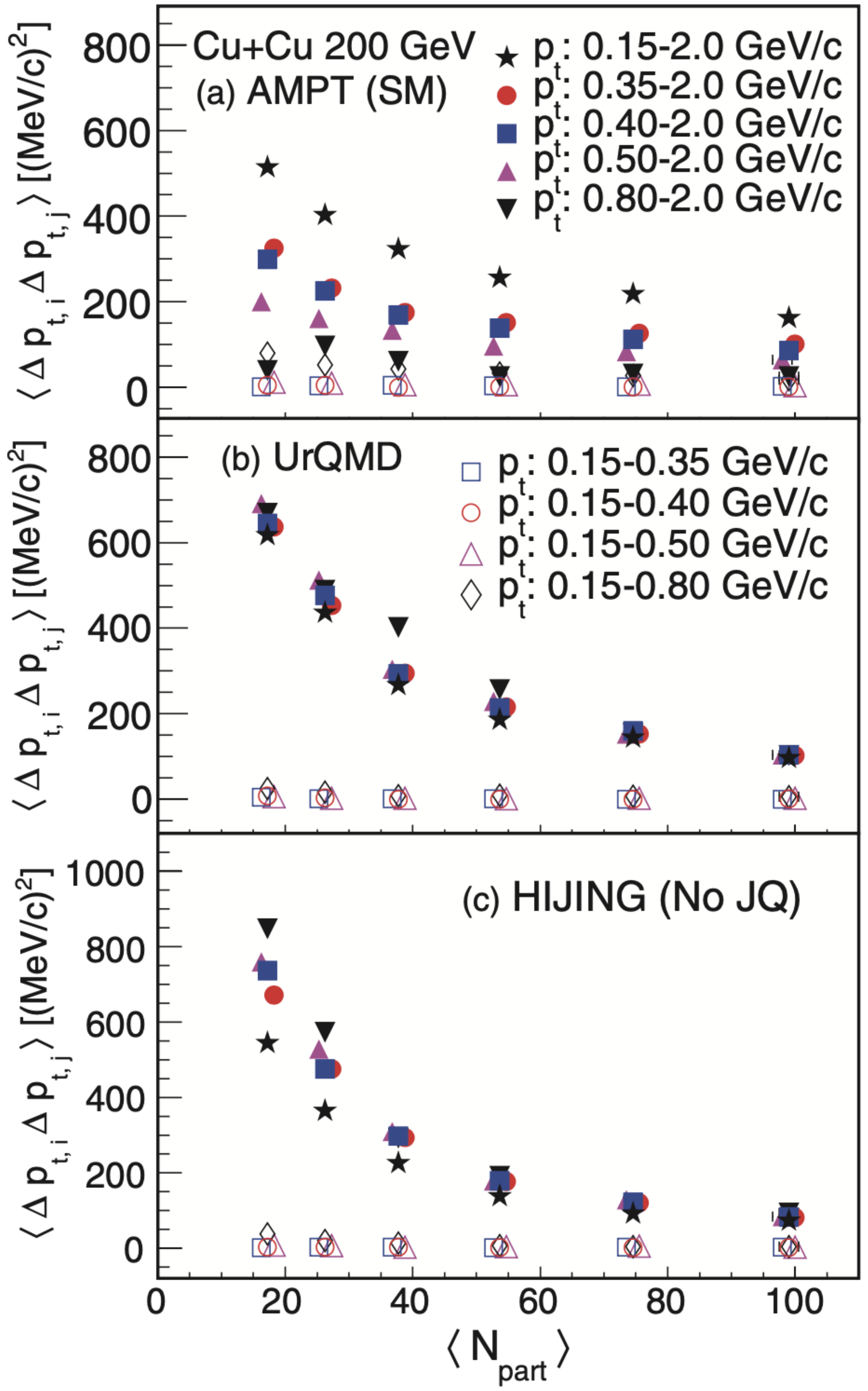
→ Distribution of $\langle p_T \rangle$(cent.) is higher at higher incident energy due to enhanced collective effects.

Motivation

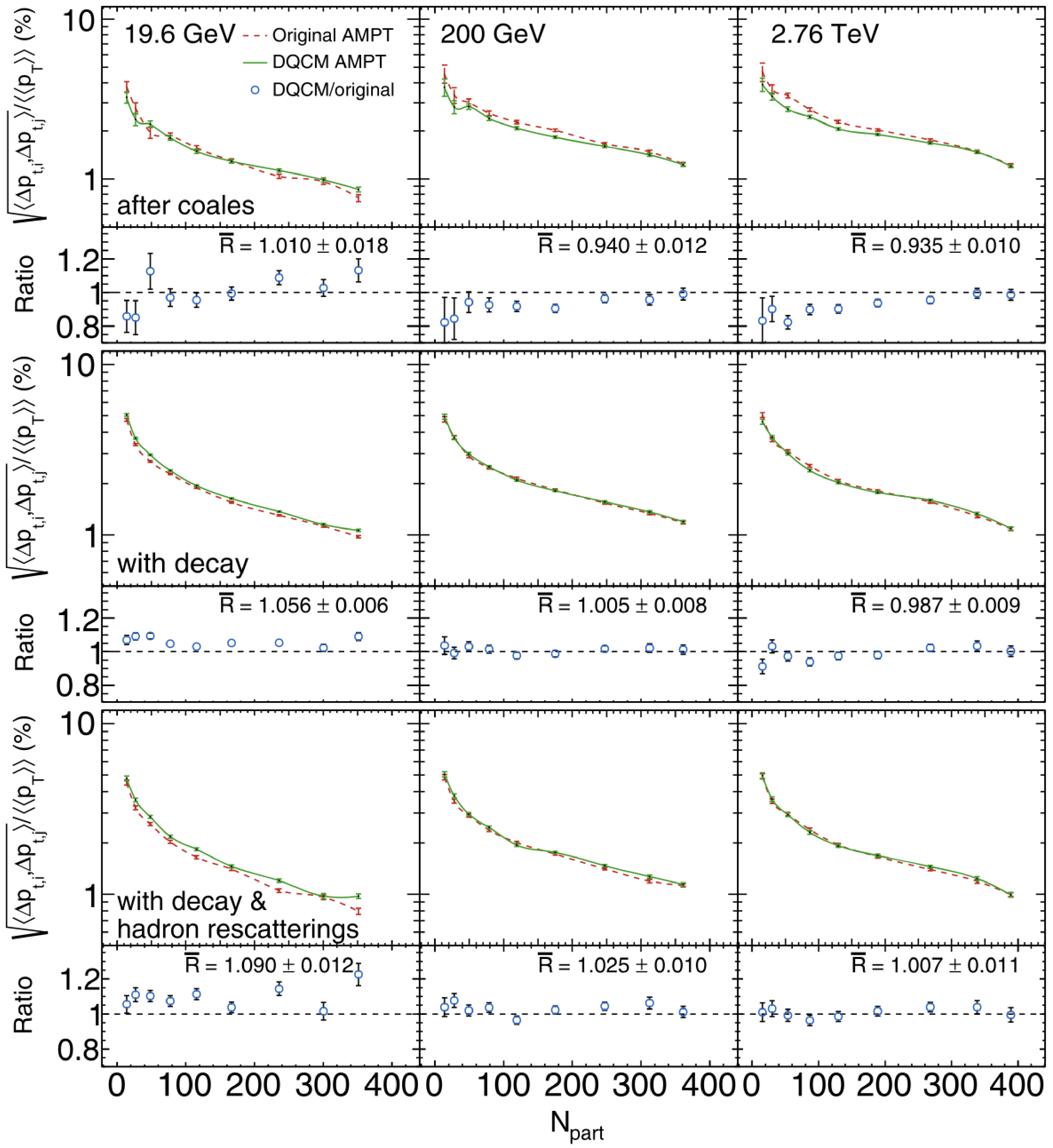
PRC **72**, 044902 (2005)



PHYSICAL REVIEW C **87**, 064902 (2013)



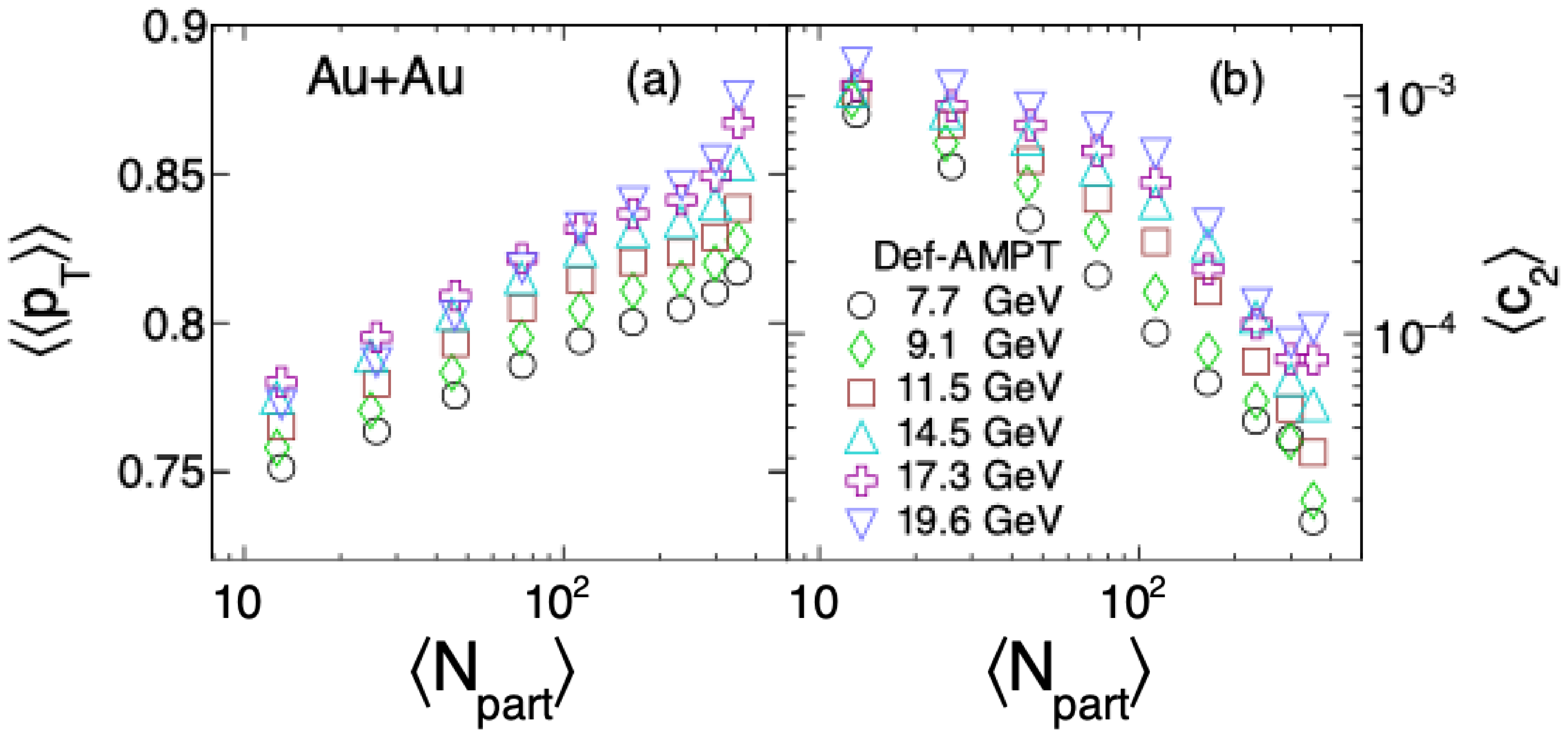
Zhenyu Xu et al 2020 J. Phys. G: Nucl. Part. Phys. 47 125102



The higher-order $\langle p_T \rangle$ fluctuations need to be systematically explored considering the BES program.

Second-order p_T cumulants

Variance($\langle c_2 \rangle$)



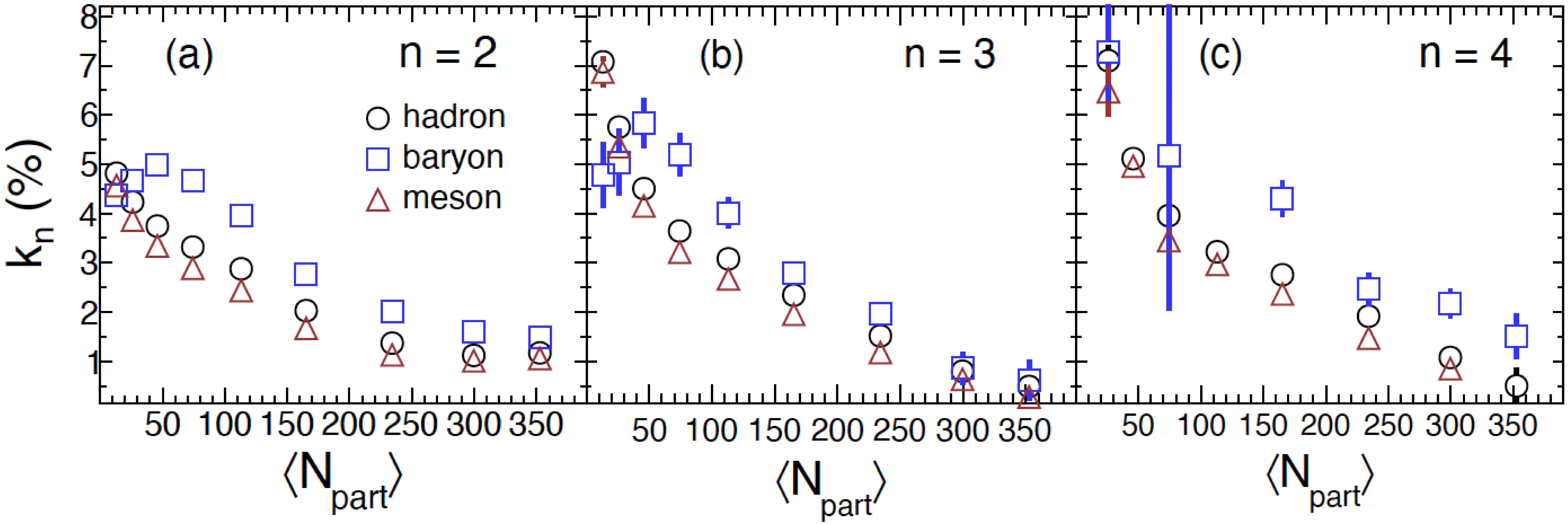
$\langle c_2 \rangle$ (cent.) vs energy

An inverse dependence on centrality is conserved across all energies.

May from a reduction in particle-pair correlations if they are dominated by particles originating from the same NN collisions.

Scaled p_T cumulants: baryon Vs meson

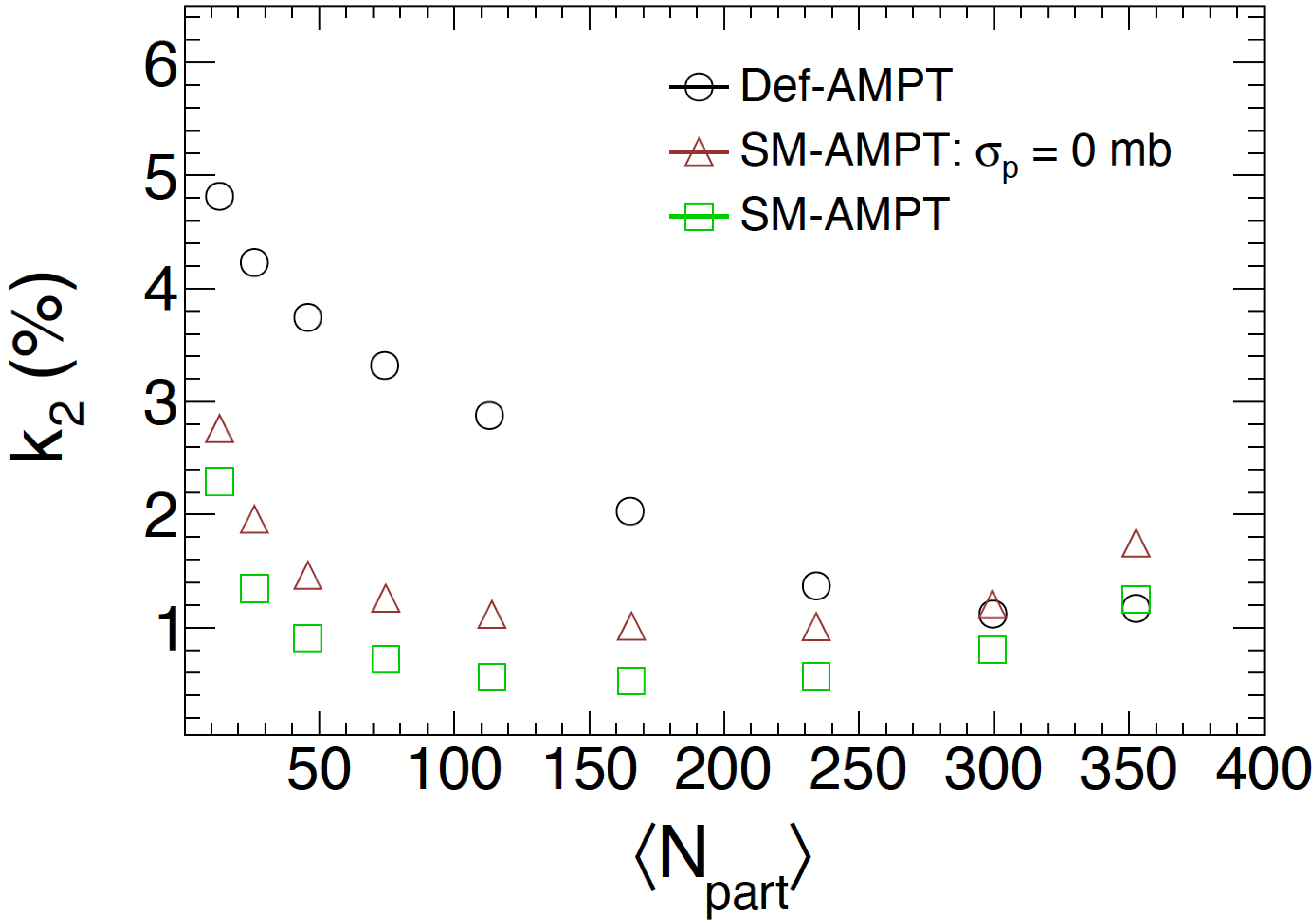
To further explore the radial flow mechanism.



Baryons exhibit more pronounced fluctuations in all scaled variance, skewness and kurtosis compared to mesons.

→ this behavior might be attributed to the effects of radial flow.

Scaled p_T cumulants: SM- Vs default-AMPT



- The default configuration exhibits more pronounced $\langle p_T \rangle$ fluctuations than SM version with and without partonic interactions.

  → likely different hadronization mechanisms.

- Partonic evolution slightly suppress the EbE fluctuations.