



QPT 2025
Guilin, China

Energy dependence of p_T fluctuations across RHIC energies in Au+Au collisions

Physical Review C 111, 024911 (2025)

Liuyao Zhang¹

In collaboration with Jinhui Chen², Chunjian Zhang²

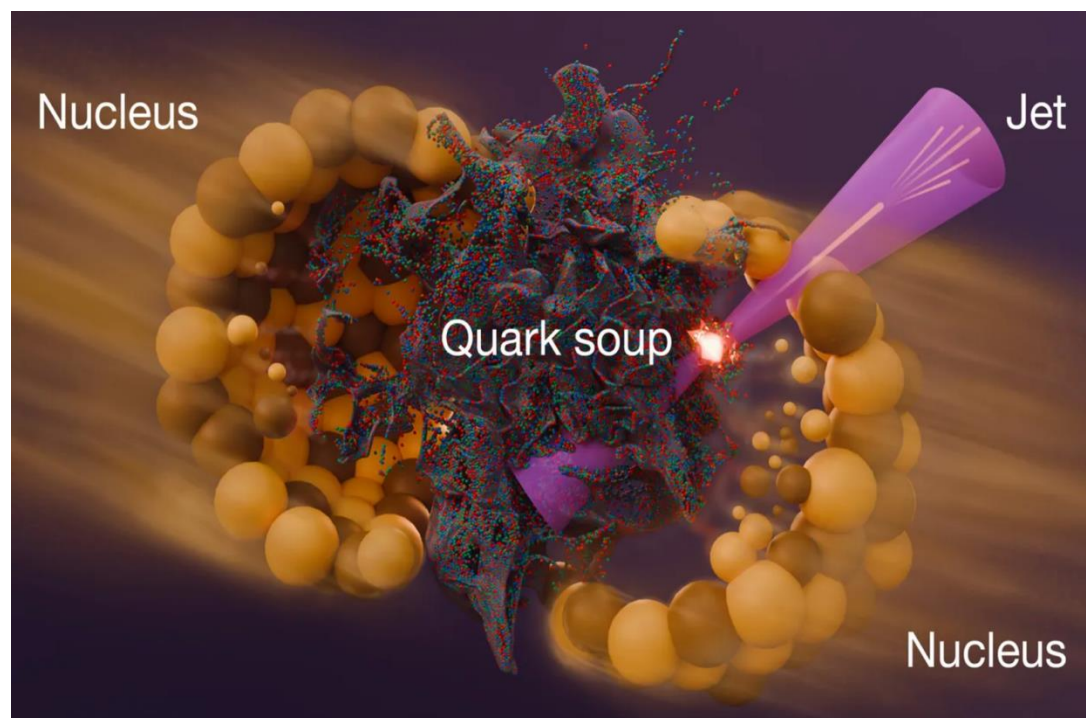
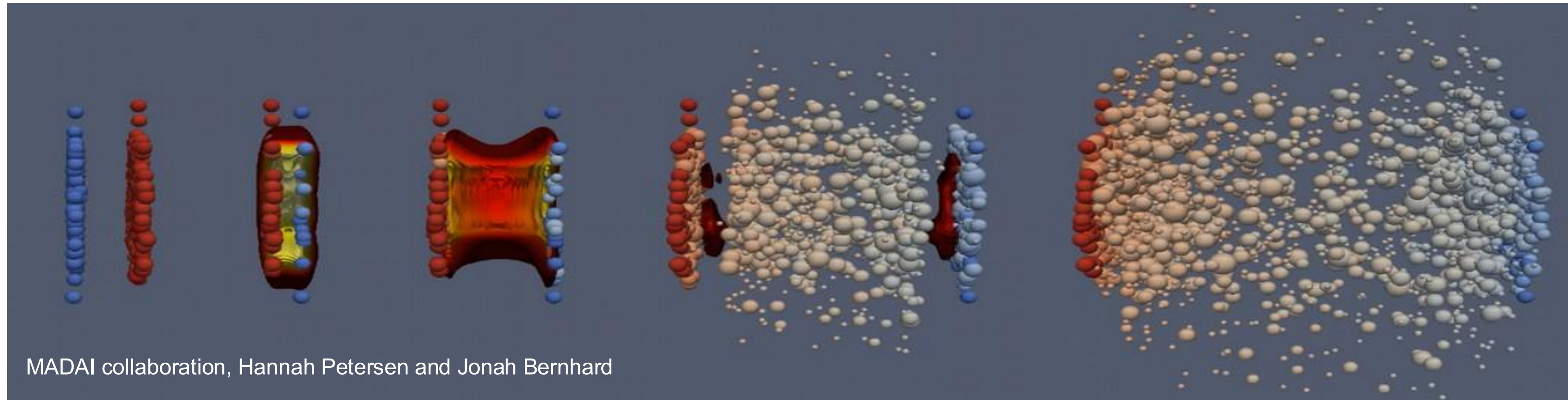
1. Institute of Nuclear Science and Technology, Henan Academy of Sciences

2. Fudan University

QPT2025, Guilin

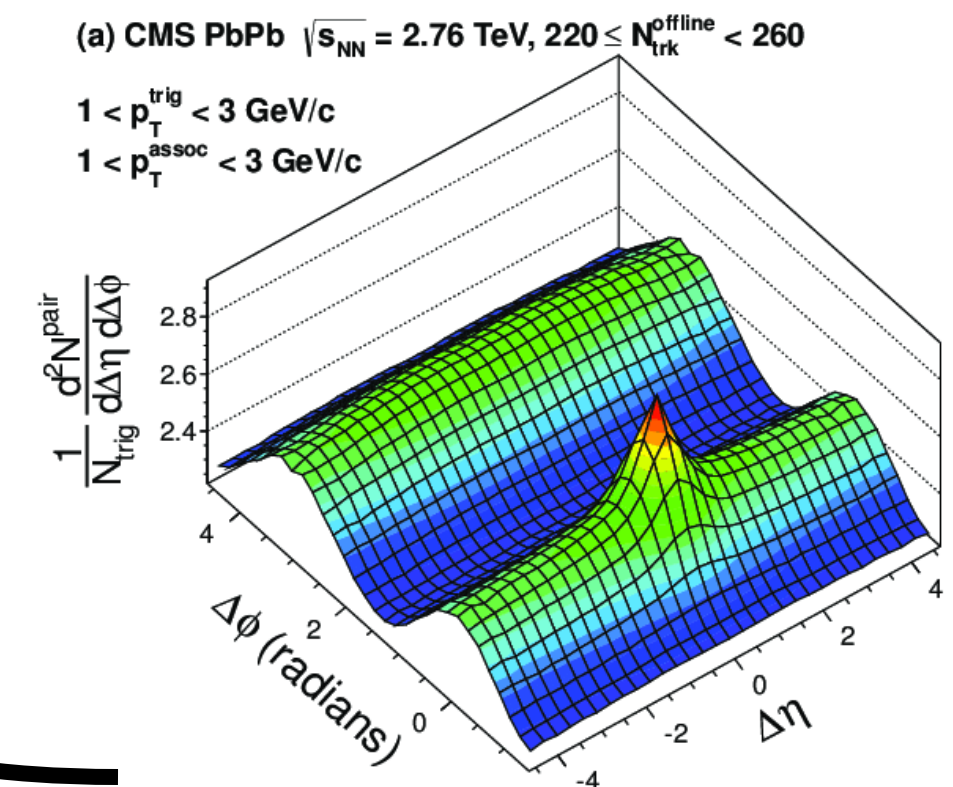
24-28, October

Quantum ChromoDynamics (QCD) $\rightarrow$ Quark Gluon Plasma (QGP) $\rightarrow$ Heavy Ion Collision (HIC)

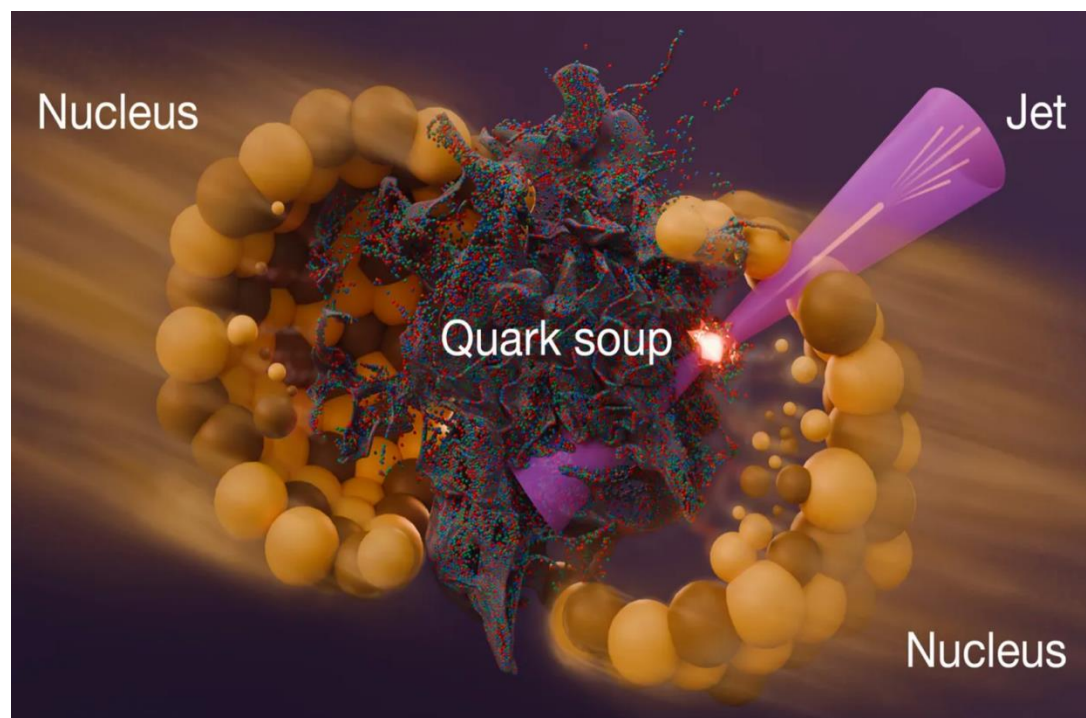
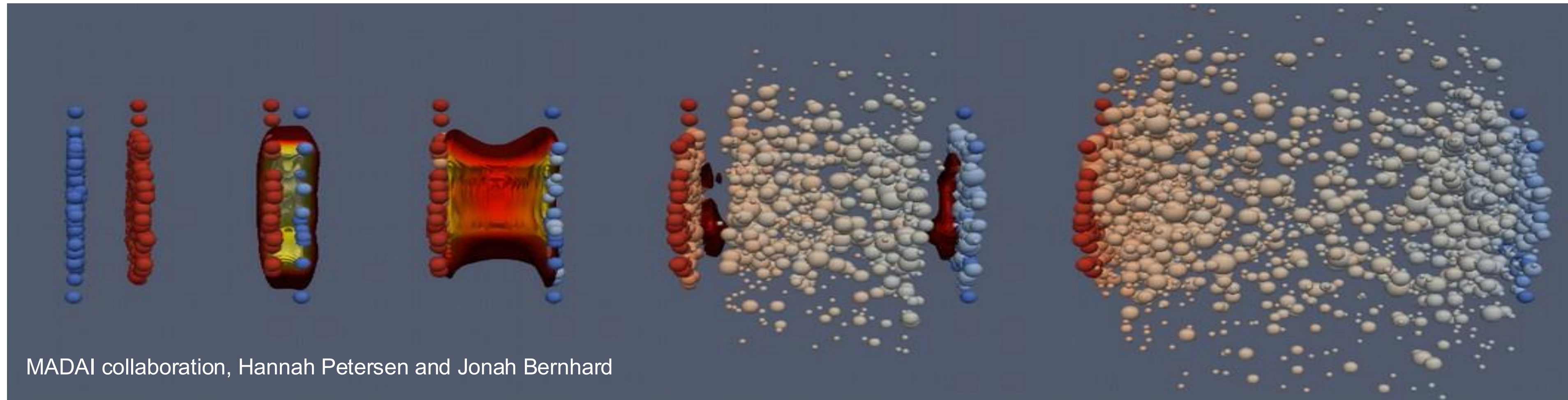


Hard Probes:
Jets,
Large p_T hadrons,
Heavy quark/hadrons,
Quarkonia,
...

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



Quantum ChromoDynamics (QCD) $\rightarrow$ Quark Gluon Plasma (QGP) $\rightarrow$ Heavy Ion Collision (HIC)

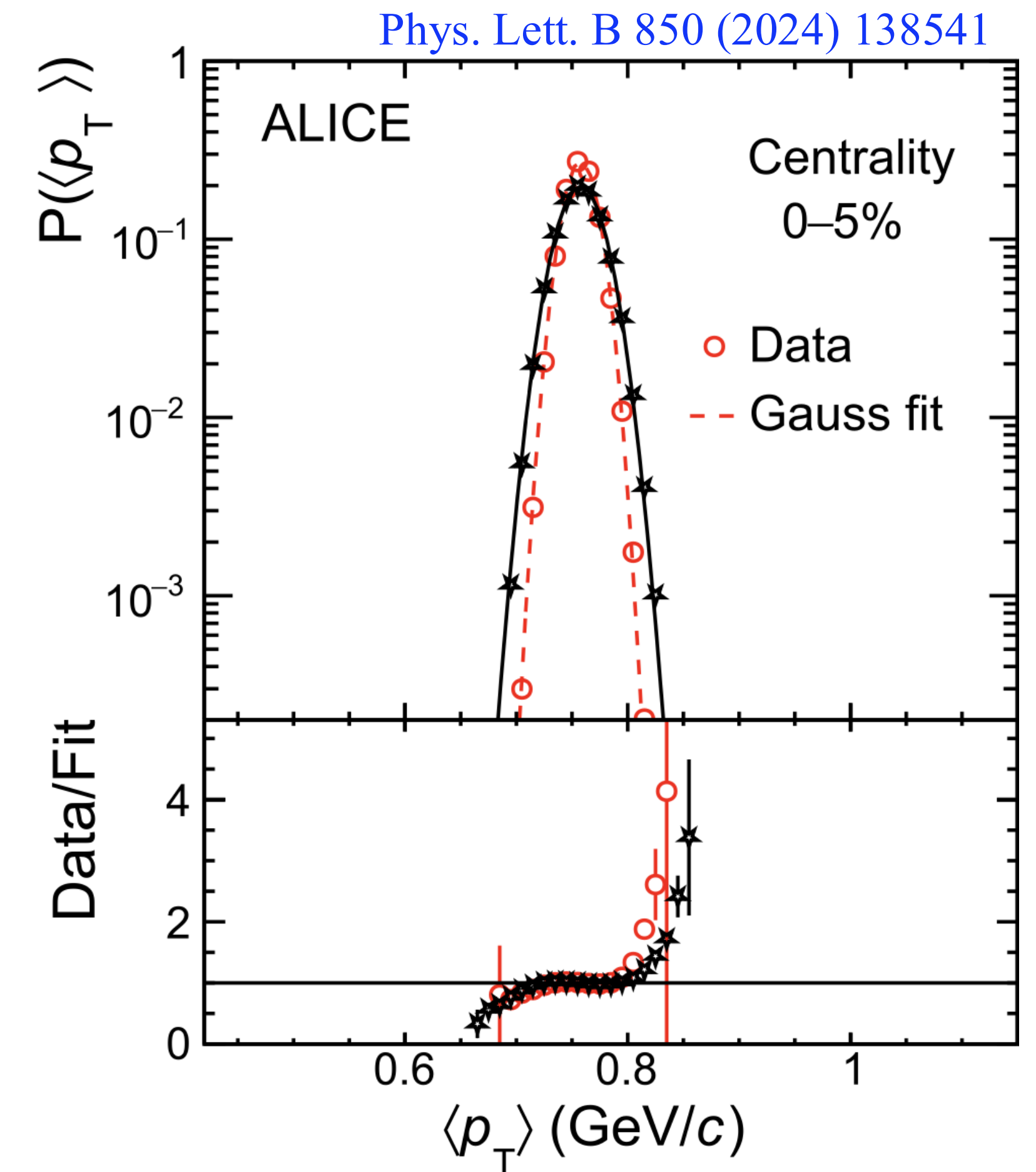
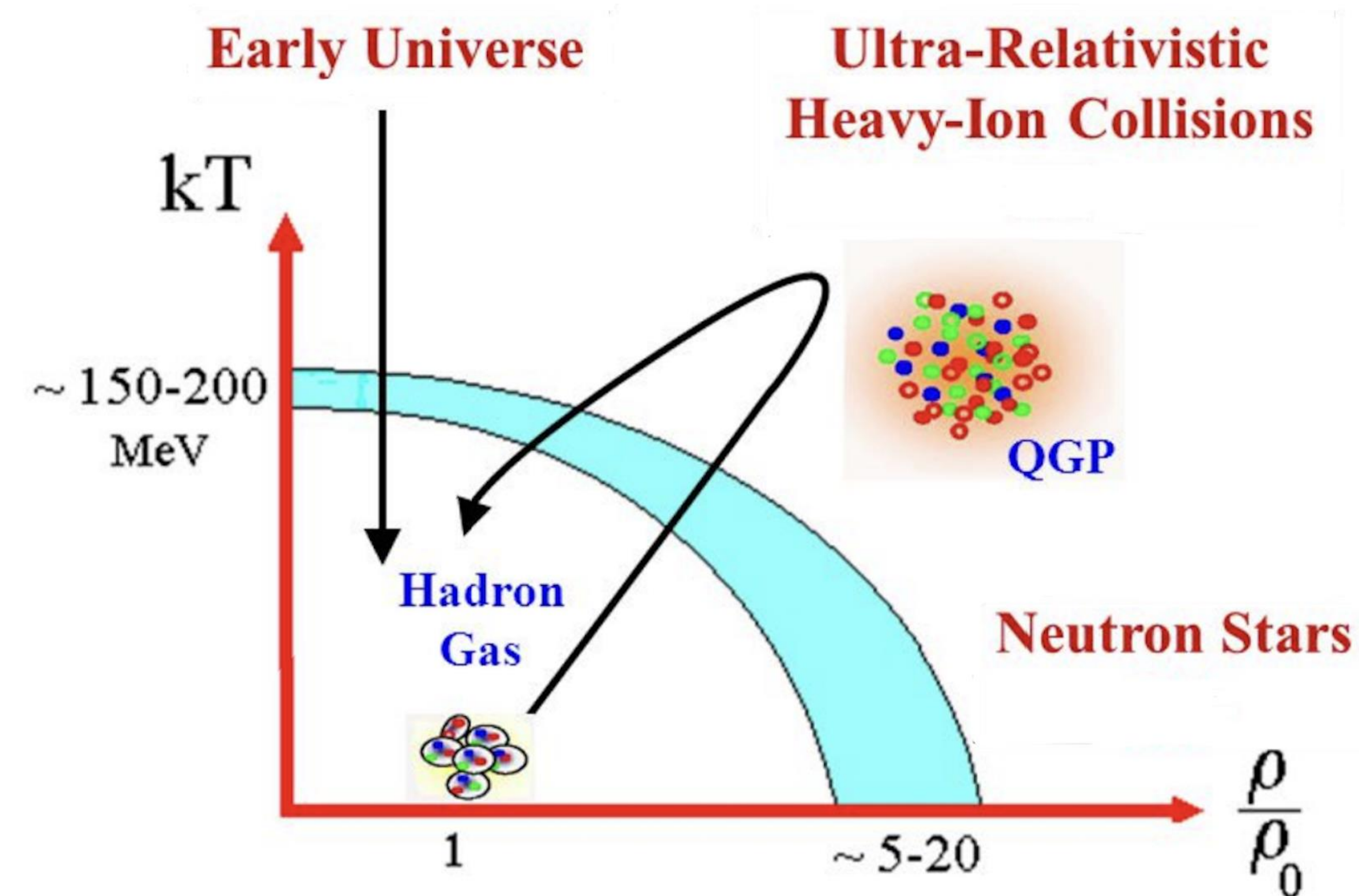
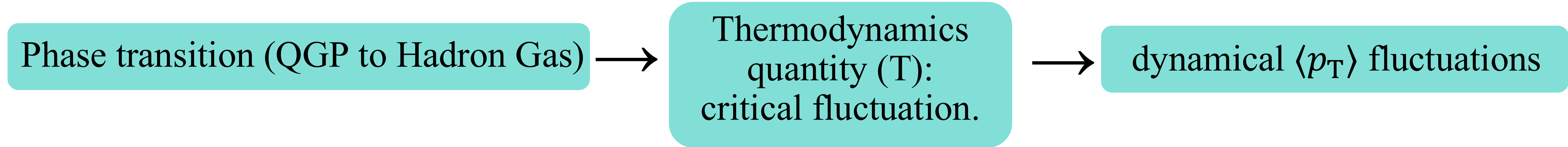


Hard Probes:
Jets,
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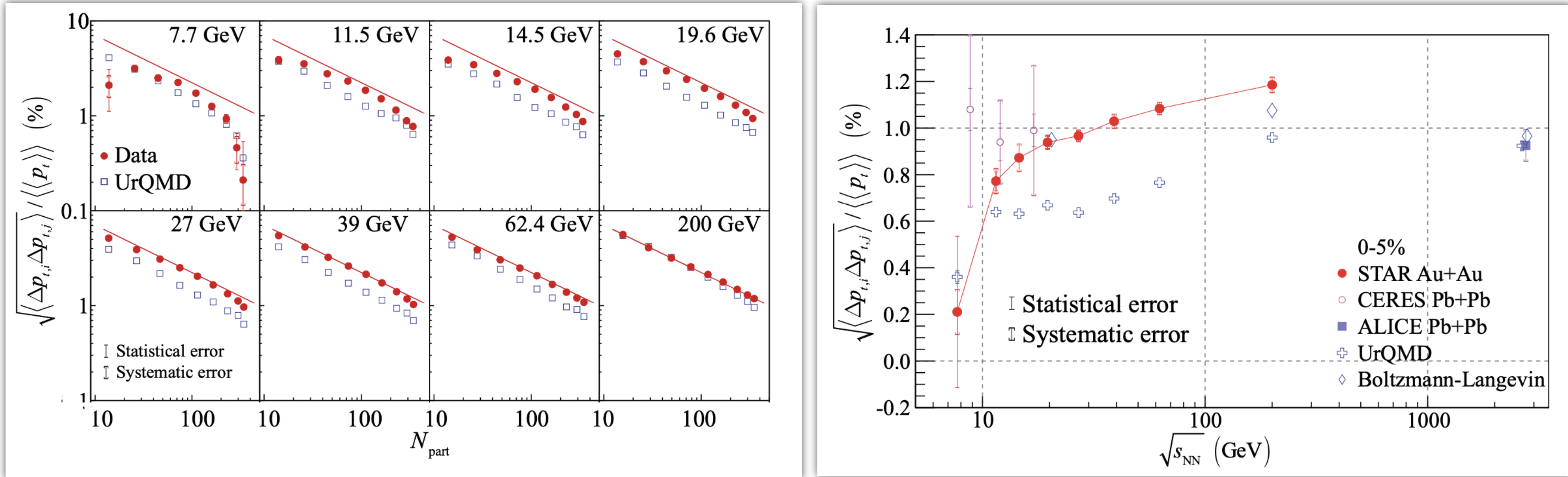
Soft Probes:
Yields/Spectra,
Flows,
Correlations,
Decorrelations,
Fluctuations (conserved),
...

Net-proton fluctuations:
Yu Zhang: Oct.25 (11:45)
Yige Huang: Oct.26 (11:40)
EbE $\langle p_T \rangle$:
Chao Zhang: Oct.26 (12:00)

Motivation



STAR PRC 99, 044918 (2019)

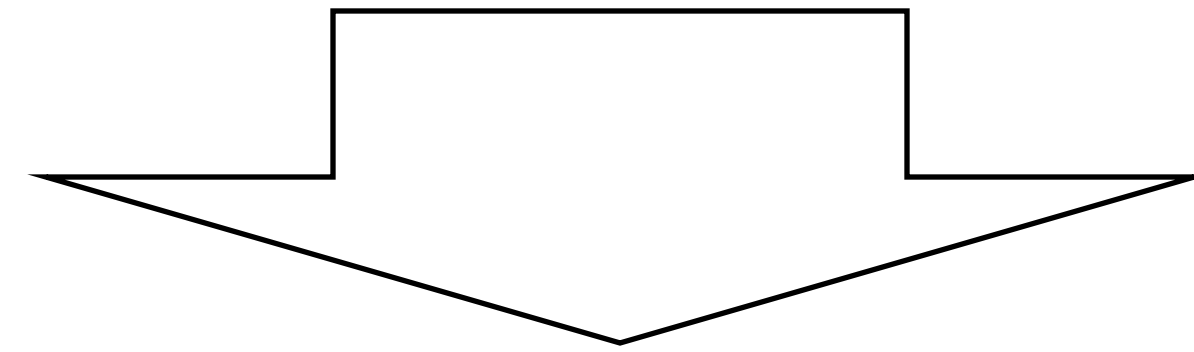


A non-monotonic behavior of $\langle p_T \rangle$ fluctuations as a function of **centrality** or **incident energy** was suggested as one of the possible signature of the critical point.

Methodology: n-particle p_T correlator

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

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



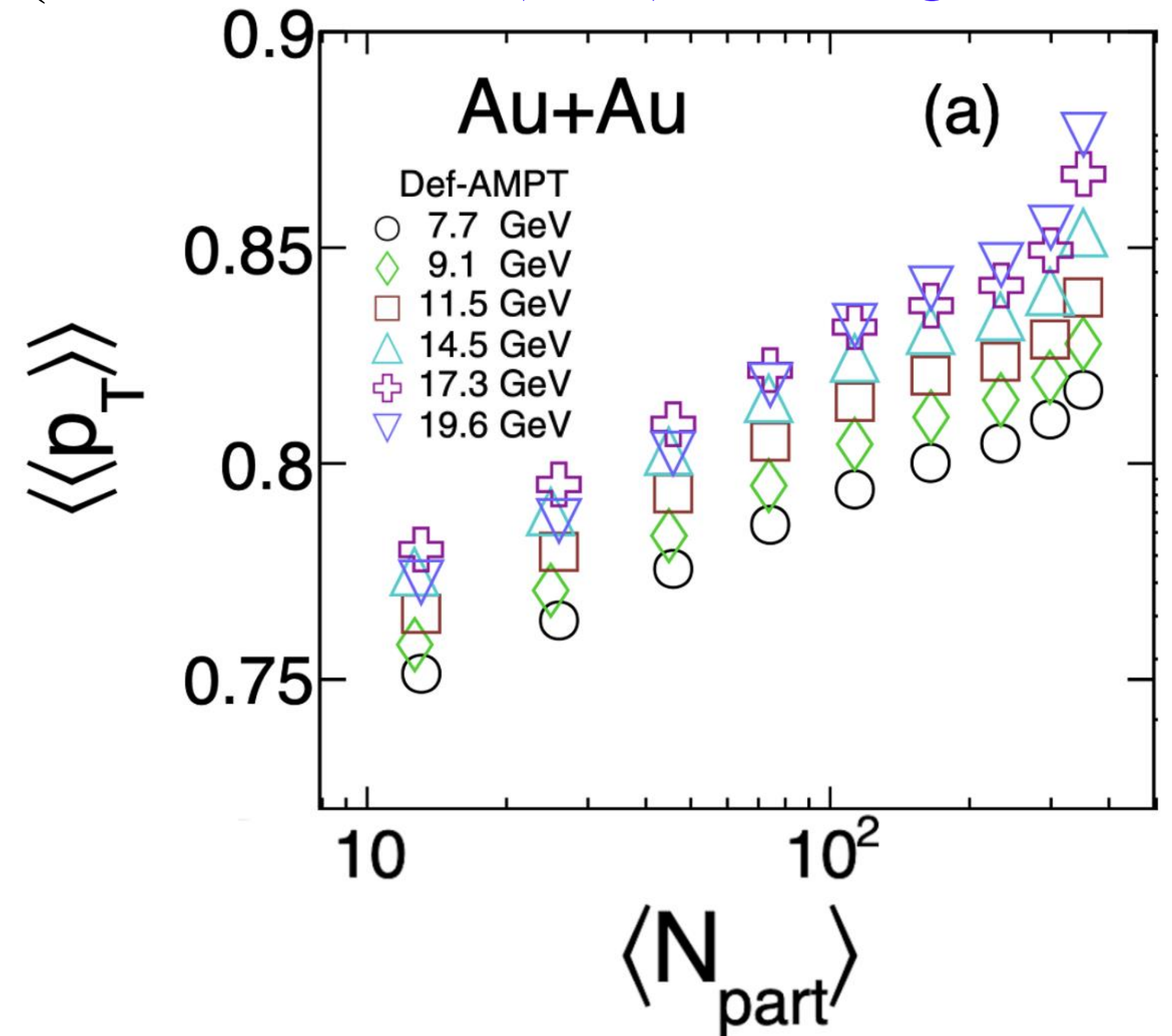
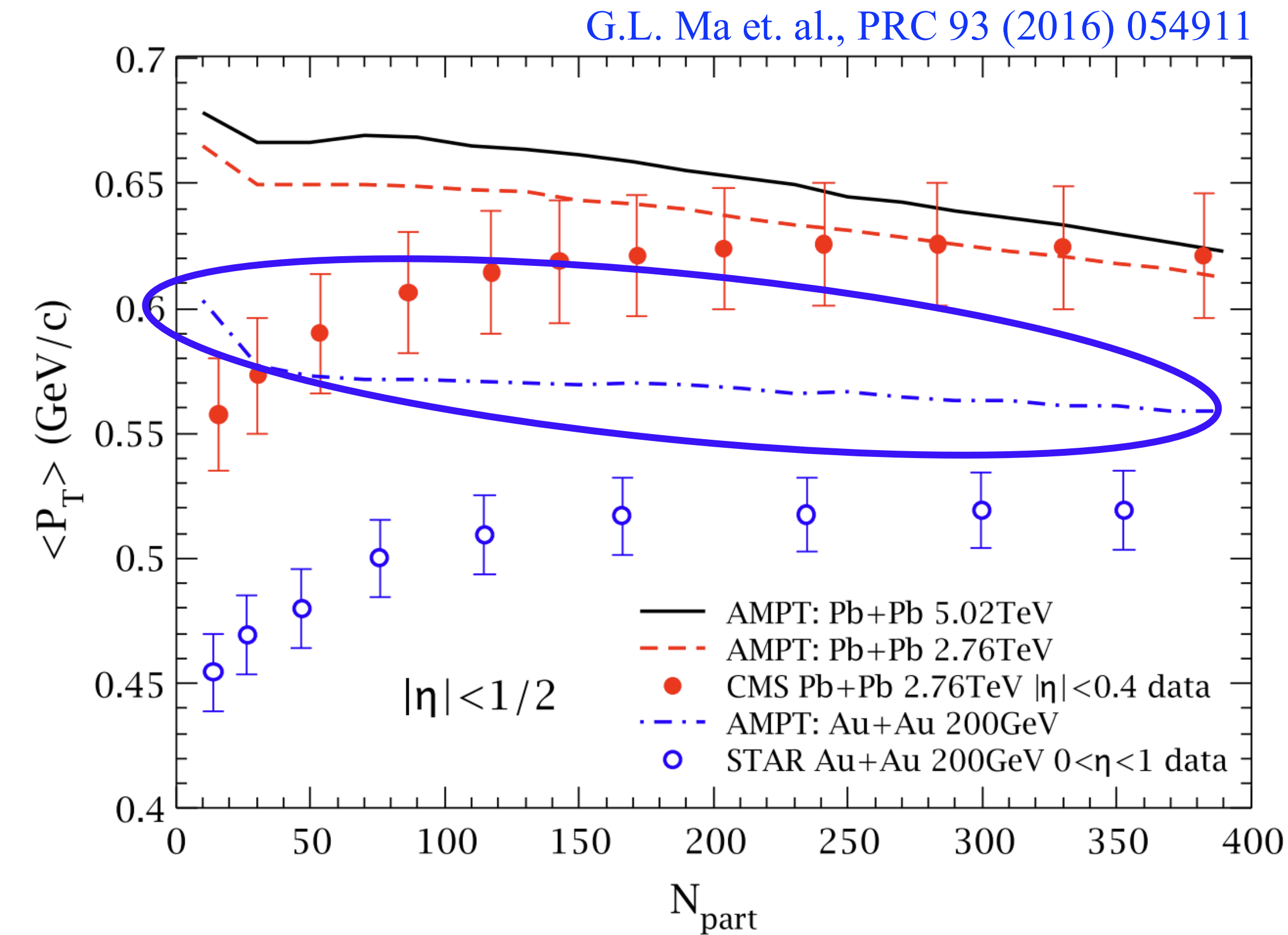
$$\begin{aligned} c_2 &= \frac{\bar{p}_{11}^2 - \tau_1 \bar{p}_{22}}{1 - \tau_1}, \\ c_3 &= \frac{\bar{p}_{11}^3 - 3\tau_1 \bar{p}_{22} \bar{p}_{11} + 2\tau_2 \bar{p}_{33}}{1 - 3\tau_1 + 2\tau_2}, \\ c_4 &= \frac{\bar{p}_{11}^4 - 6\tau_1 \bar{p}_{22} \bar{p}_{11}^2 + 3\tau_1^2 \bar{p}_{22}^2 + 8\tau_2 \bar{p}_{33} \bar{p}_{11} - 6\tau_3 \bar{p}_{44}}{1 - 6\tau_1 + 3\tau_1^2 + 8\tau_2 - 6\tau_3} \end{aligned} \quad \langle p_T \rangle \text{ cumulant}$$

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

$\langle p_T \rangle$ trend : AMPT optimization

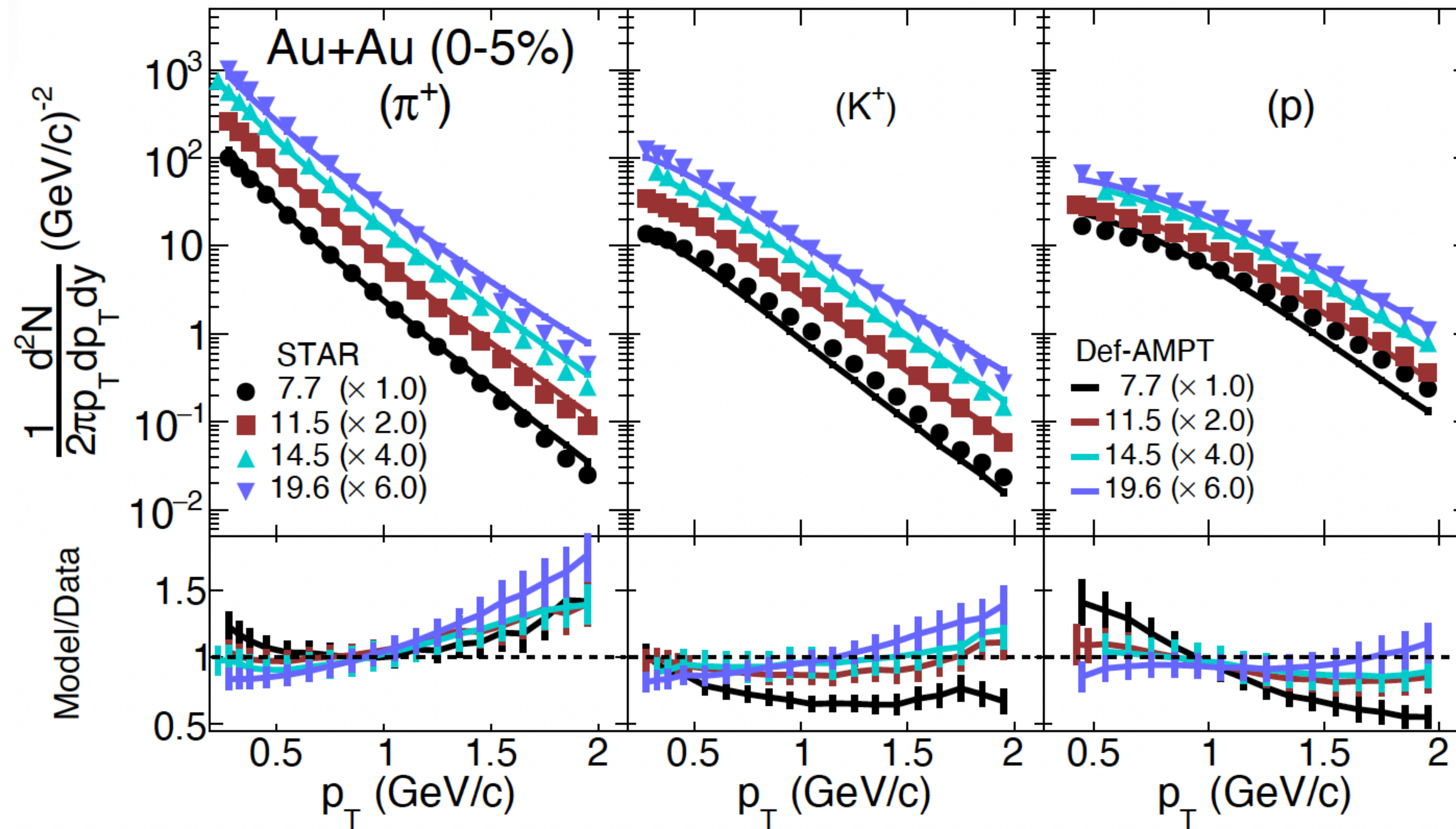
Two key parameters (a_L , b_L) in hadronization mechanisms are tuned:

fixed value $\rightarrow$ variable (based on impact parameter) (*PRC 104, 014908 (2021): C. Zhang, L. Zheng*)



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

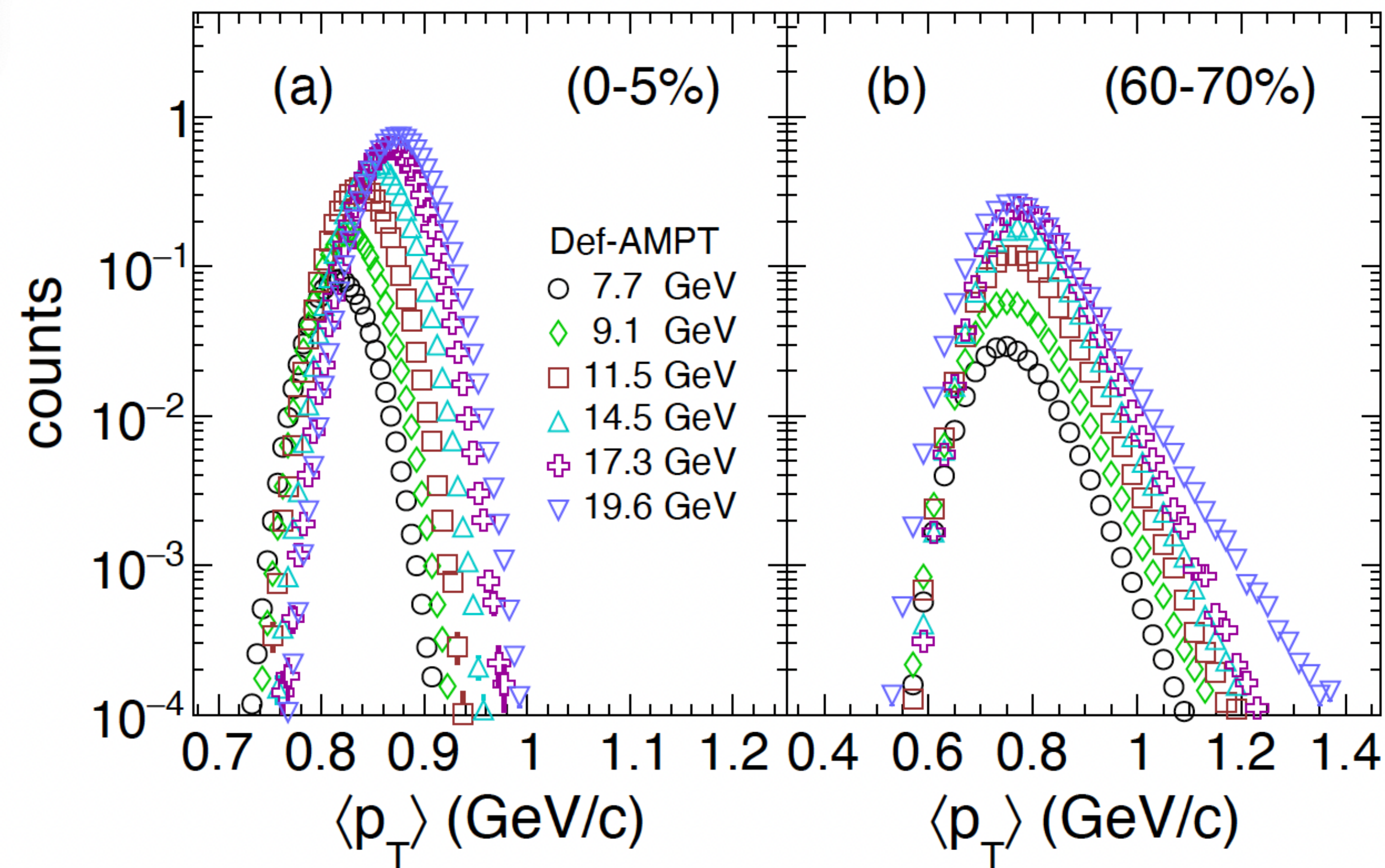
The AMPT validity



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.

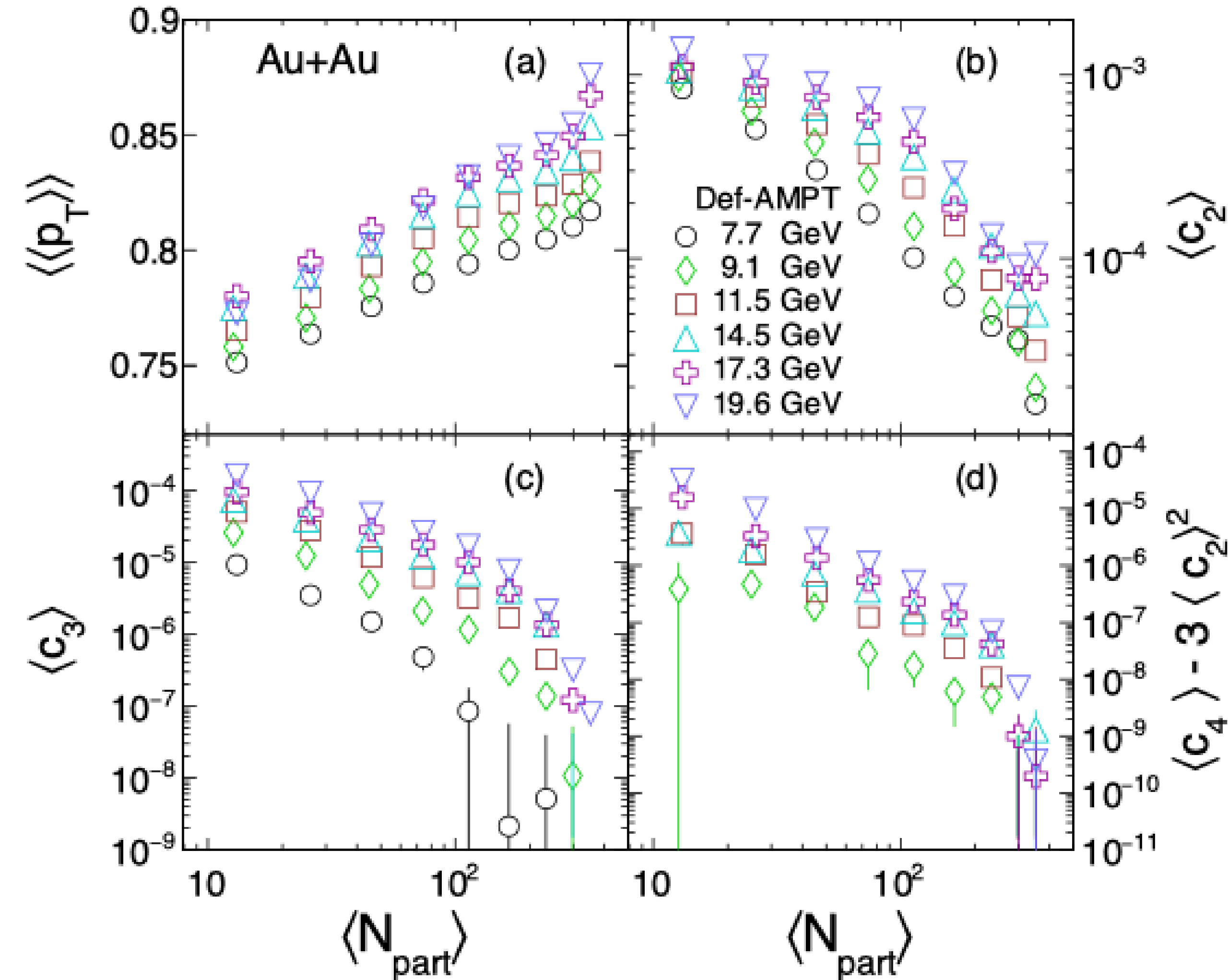


At peripheral collisions:

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

Higher-order p_T cumulants

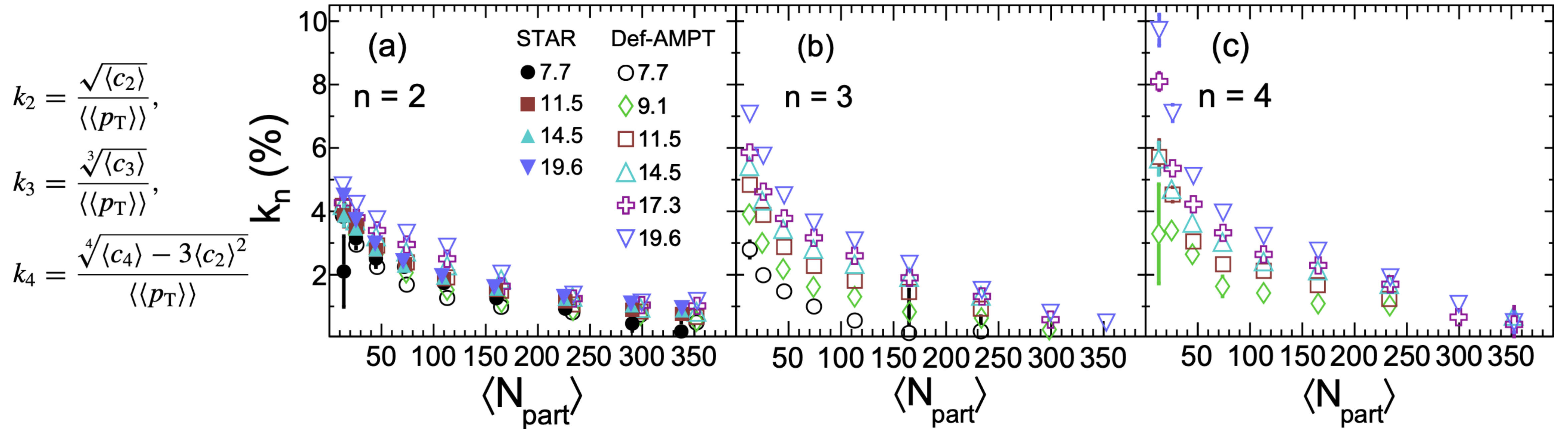
Variance($\langle c_2 \rangle$), Skewness ($\langle c_3 \rangle$), Kurtosis($\langle c_4 \rangle - 3\langle c_2 \rangle^2$)



- 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

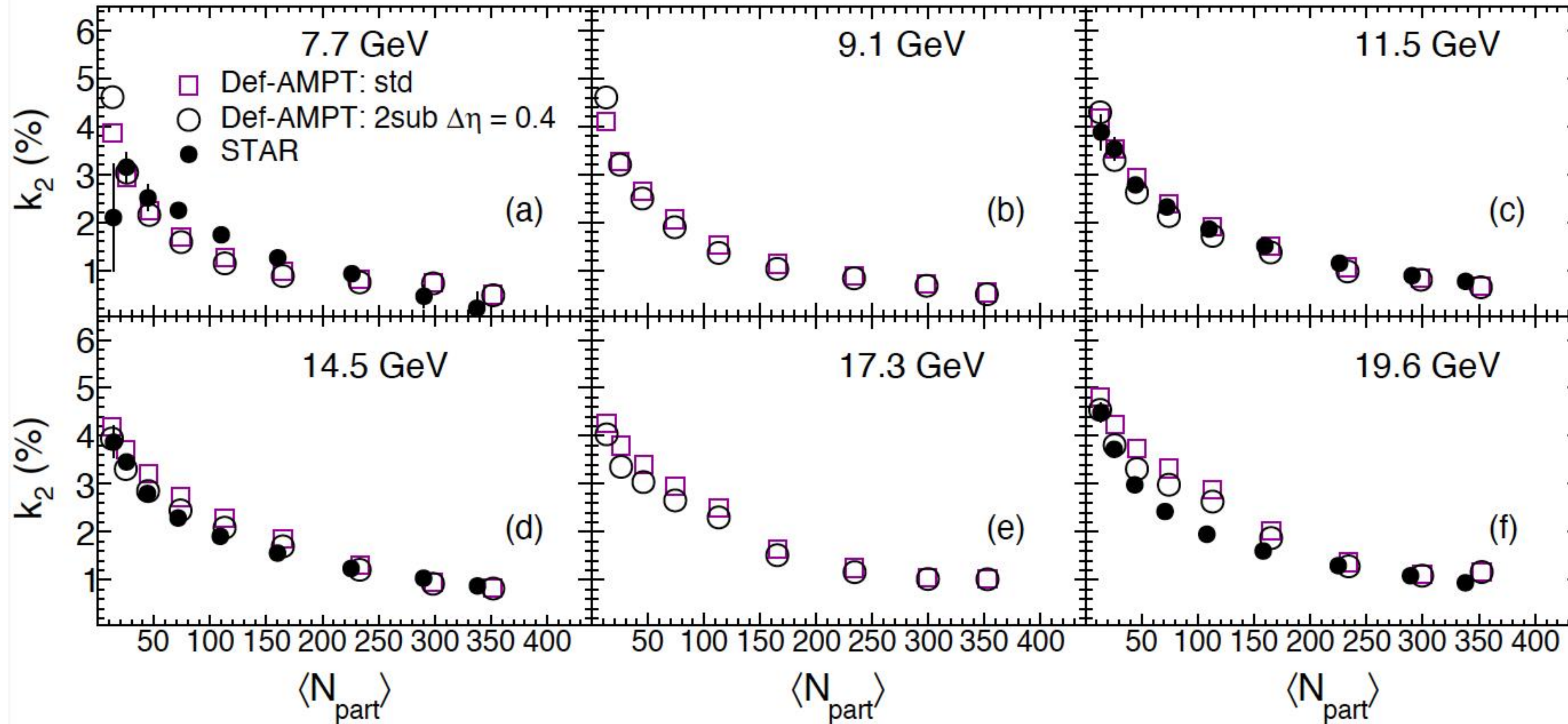
To mitigate the influence on the cumulants in $\langle\langle p_T \rangle\rangle$ with centrality or incident energy.



- k_2 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

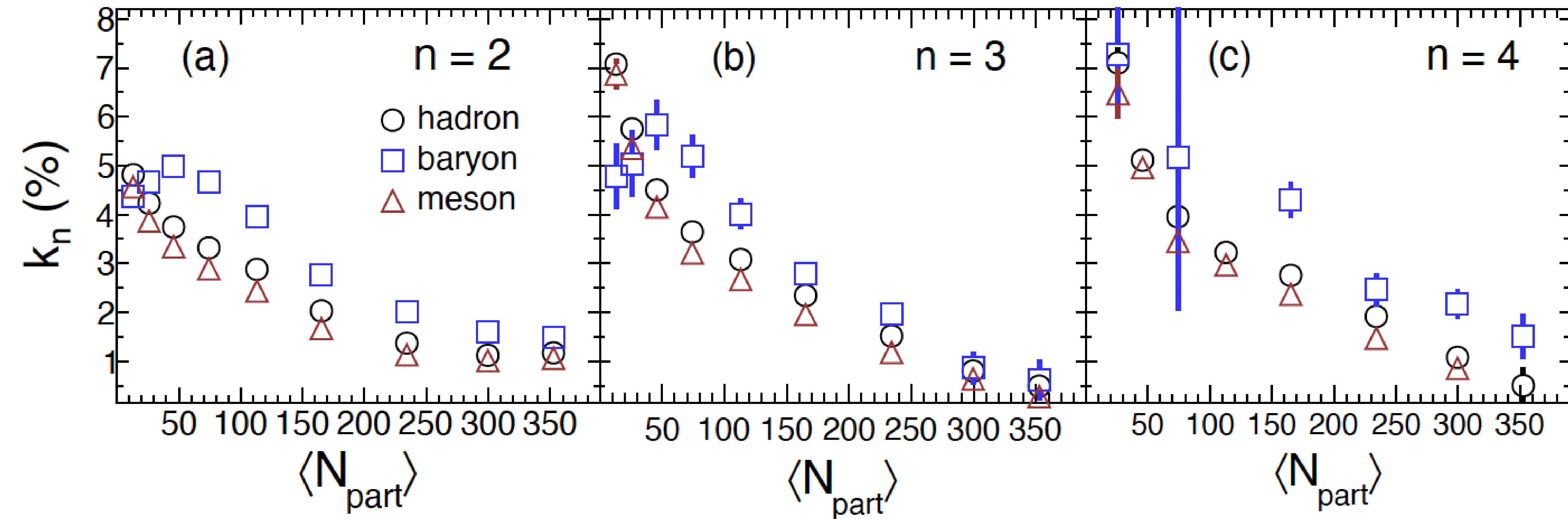
Two-subevent method:



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

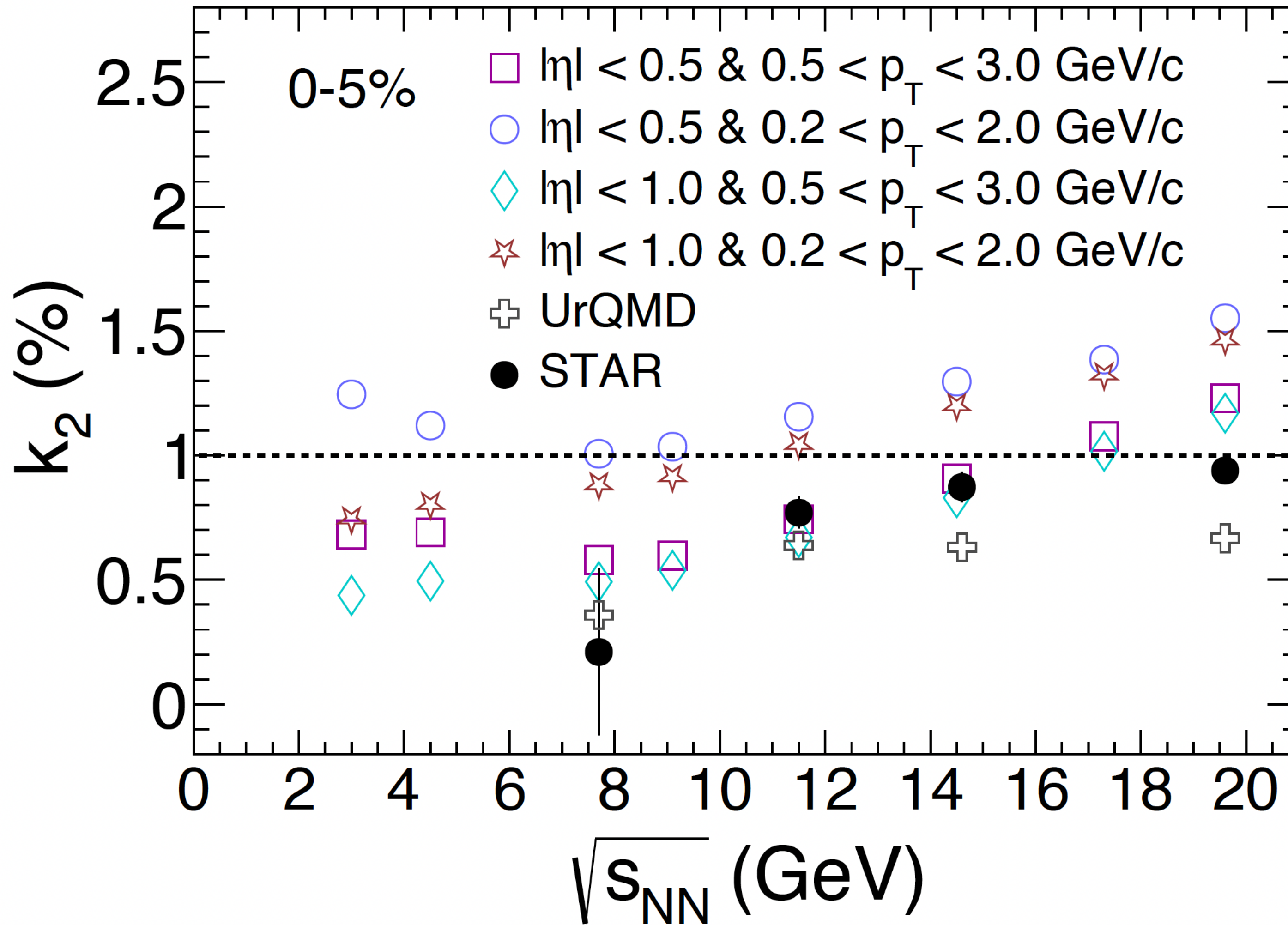
Scaled p_T cumulants: baryon Vs meson

To further explore the radial flow mechanism.



More pronounced fluctuations in all scaled variance, skewness and kurtosis for baryons than mesons.
 → this behavior might be attributed to the effects of radial flow.

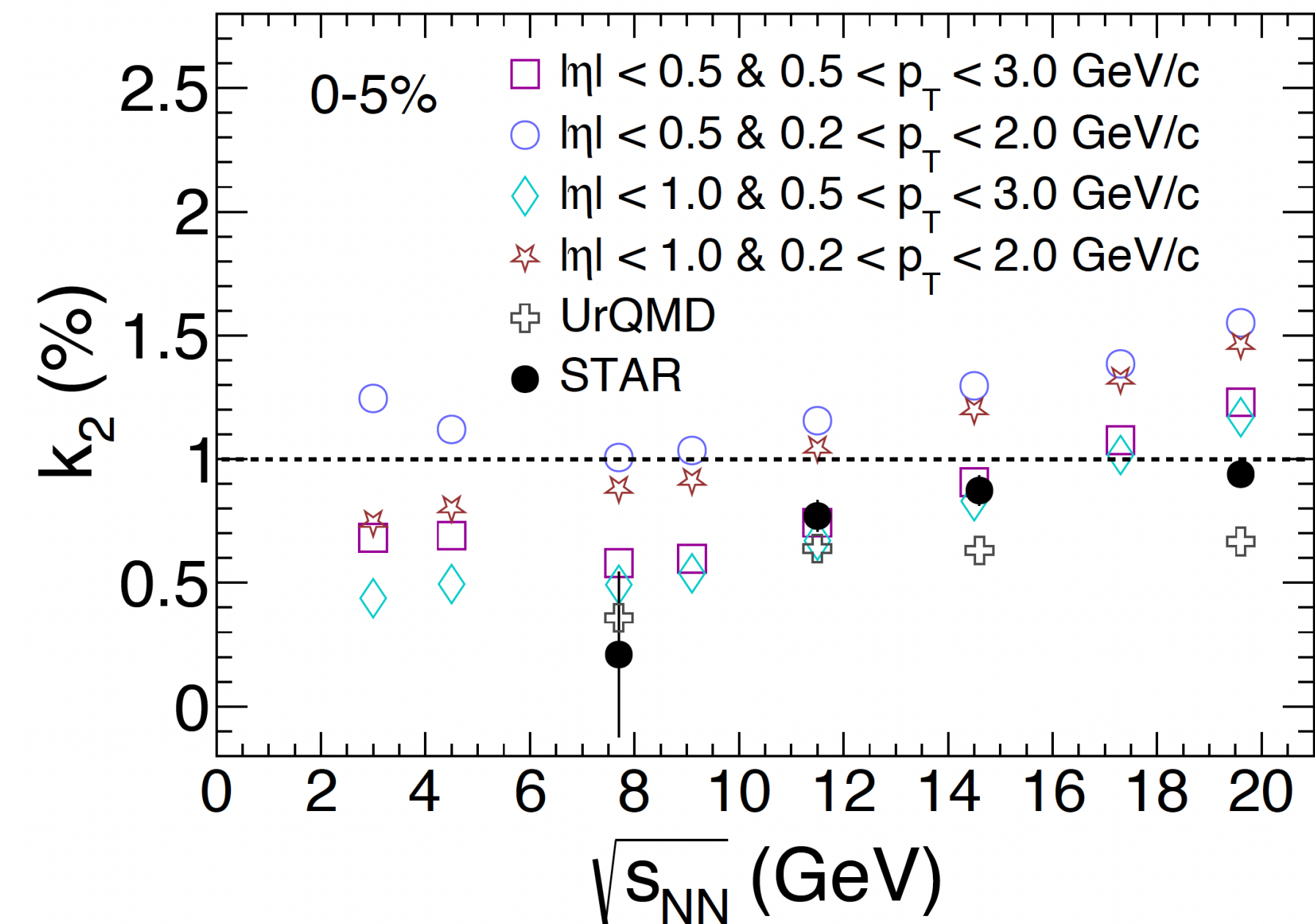
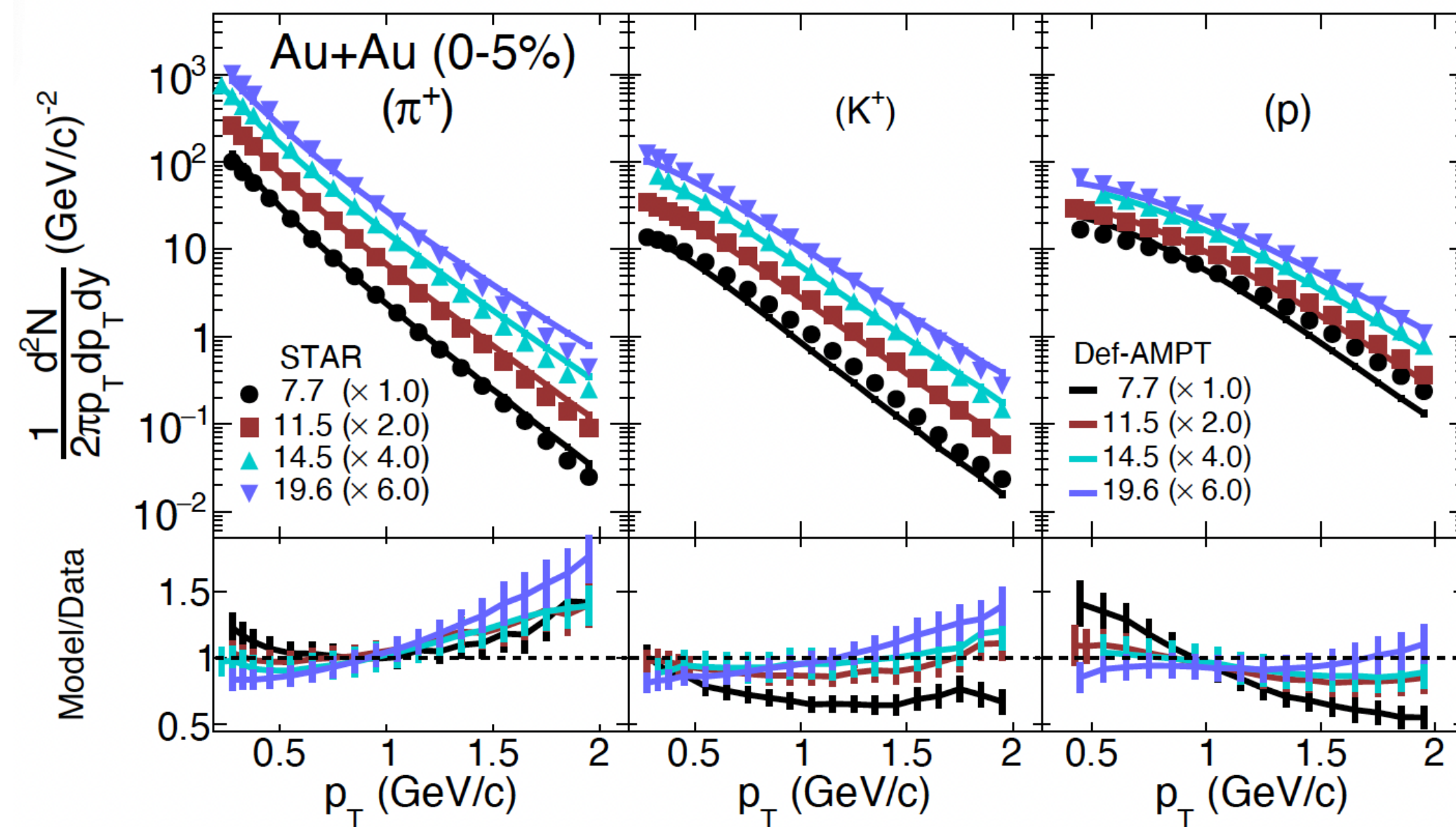
Scaled p_T cumulants: vs energy



- 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.



Backup

$\langle p_T \rangle$ trend : AMPT optimization

1) vs centrality, 2) vs incident energy

Two key parameters in hadronization mechanisms in the AMPT model:

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

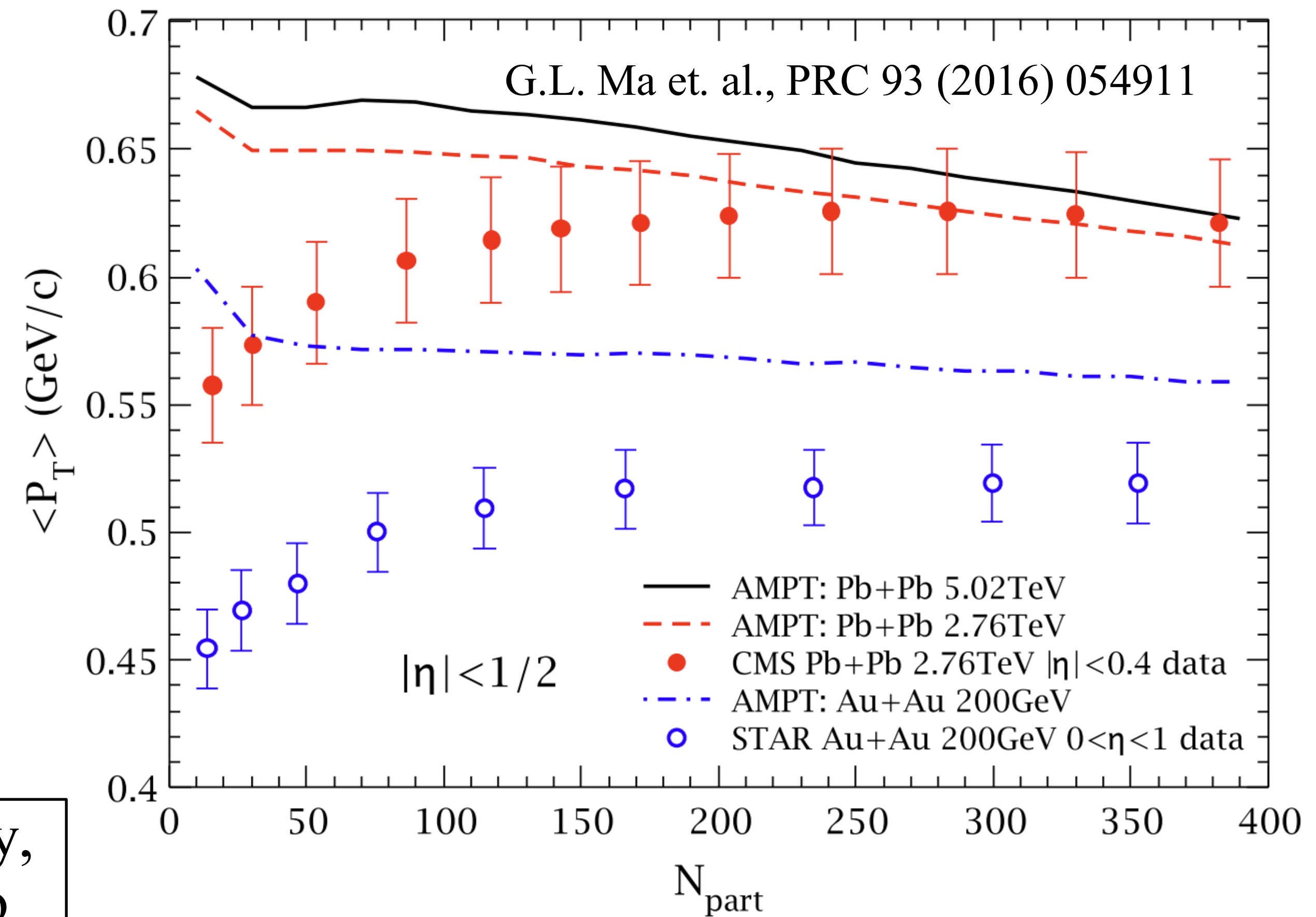
$$\langle p_T^2 \rangle = \frac{1}{b_L(2 + a_L)}$$

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: $a_L = 0.3, b_L = 0.15$

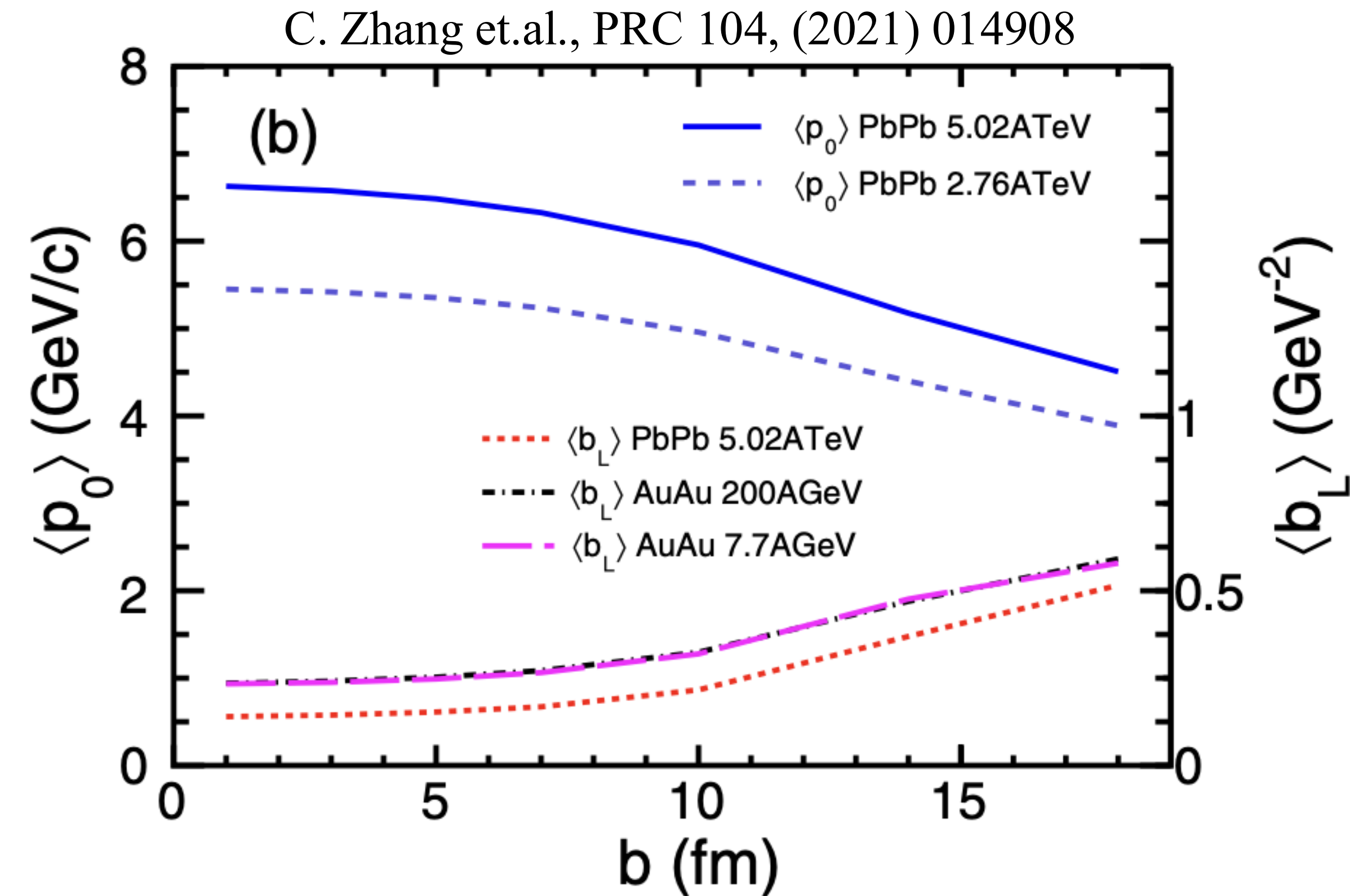
The $\langle p_T \rangle$ (cent.) is inconsistent with the data. Actually, the $\langle p_T \rangle$ is expected to increase with centrality due to higher initial temperature in more central collisions.



$\langle p_T \rangle$ 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.



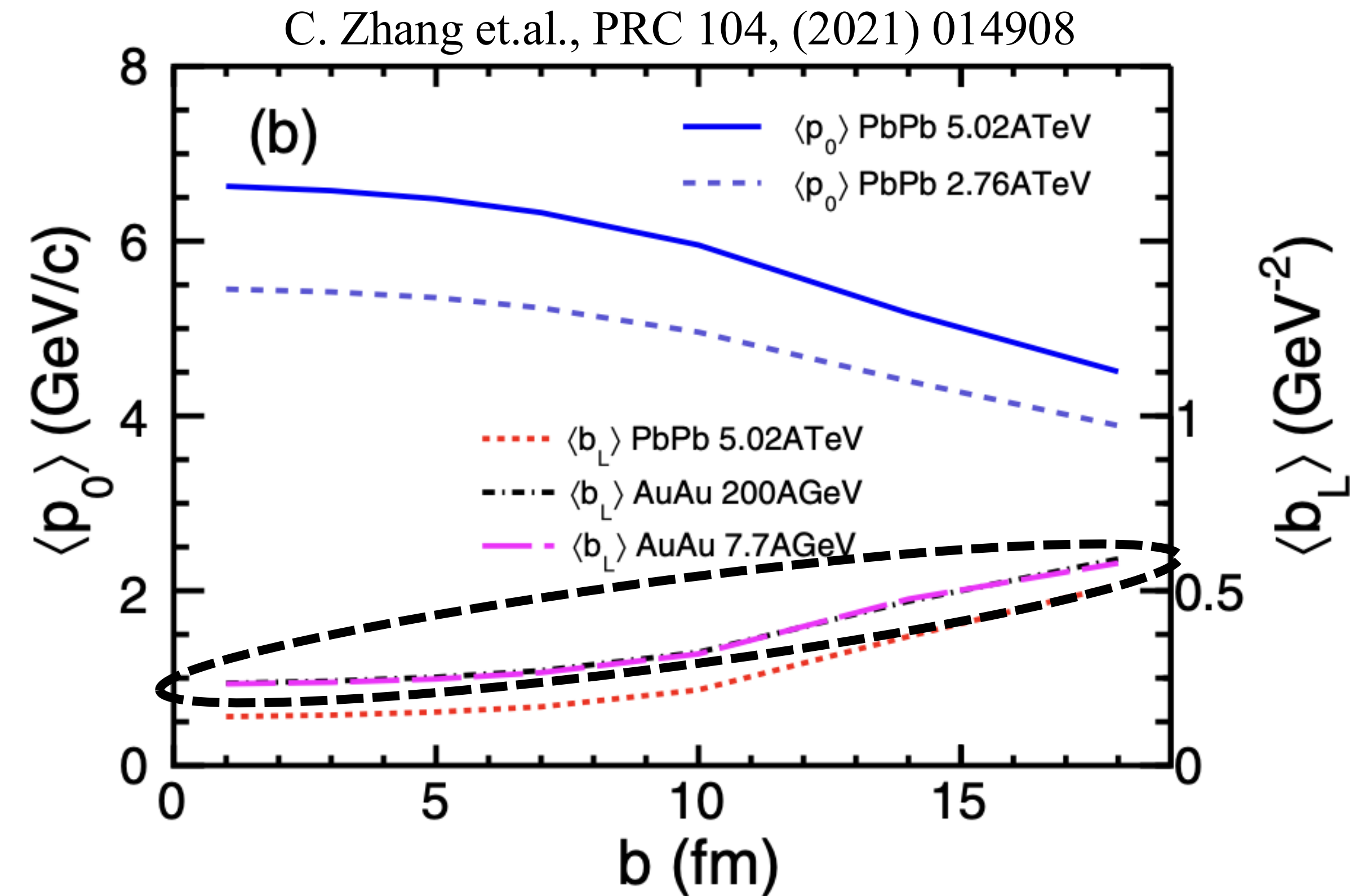
At 200 GeV and 7.7 GeV:

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.



Based on the published work, we adopt:

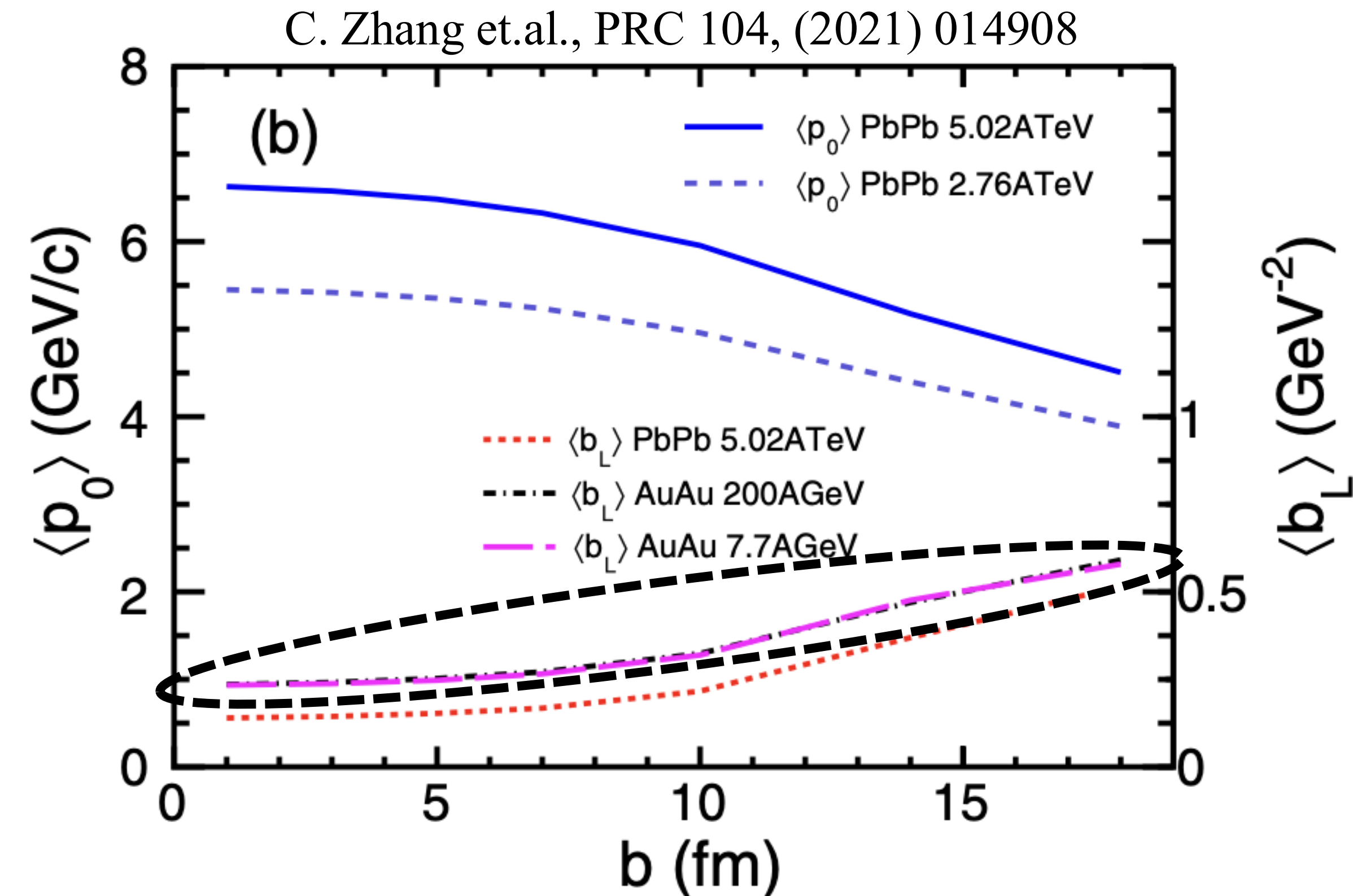
a) b_L has approximate linear dependence on the b .

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

$\langle p_T \rangle$ trend : AMPT optimization

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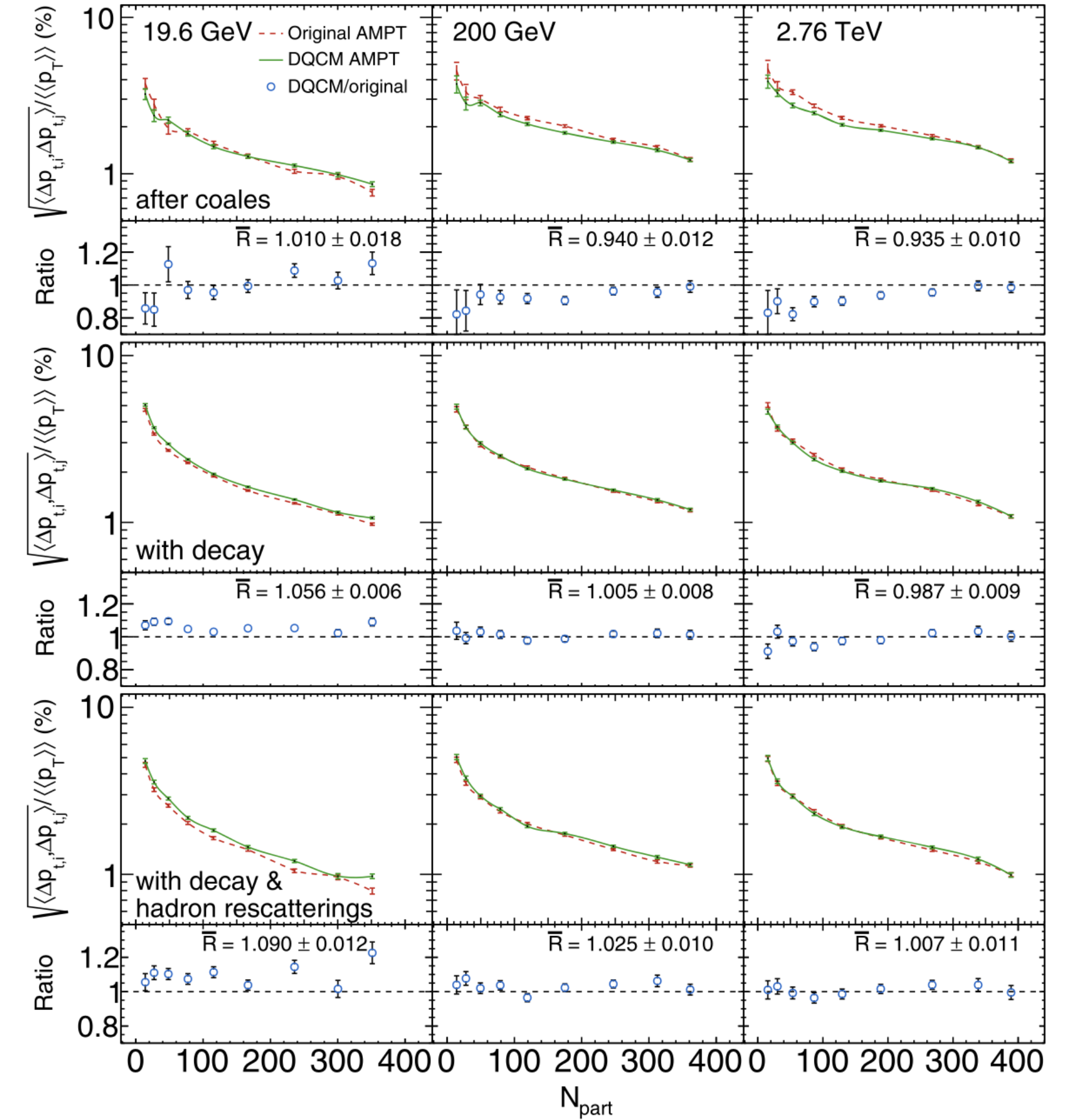
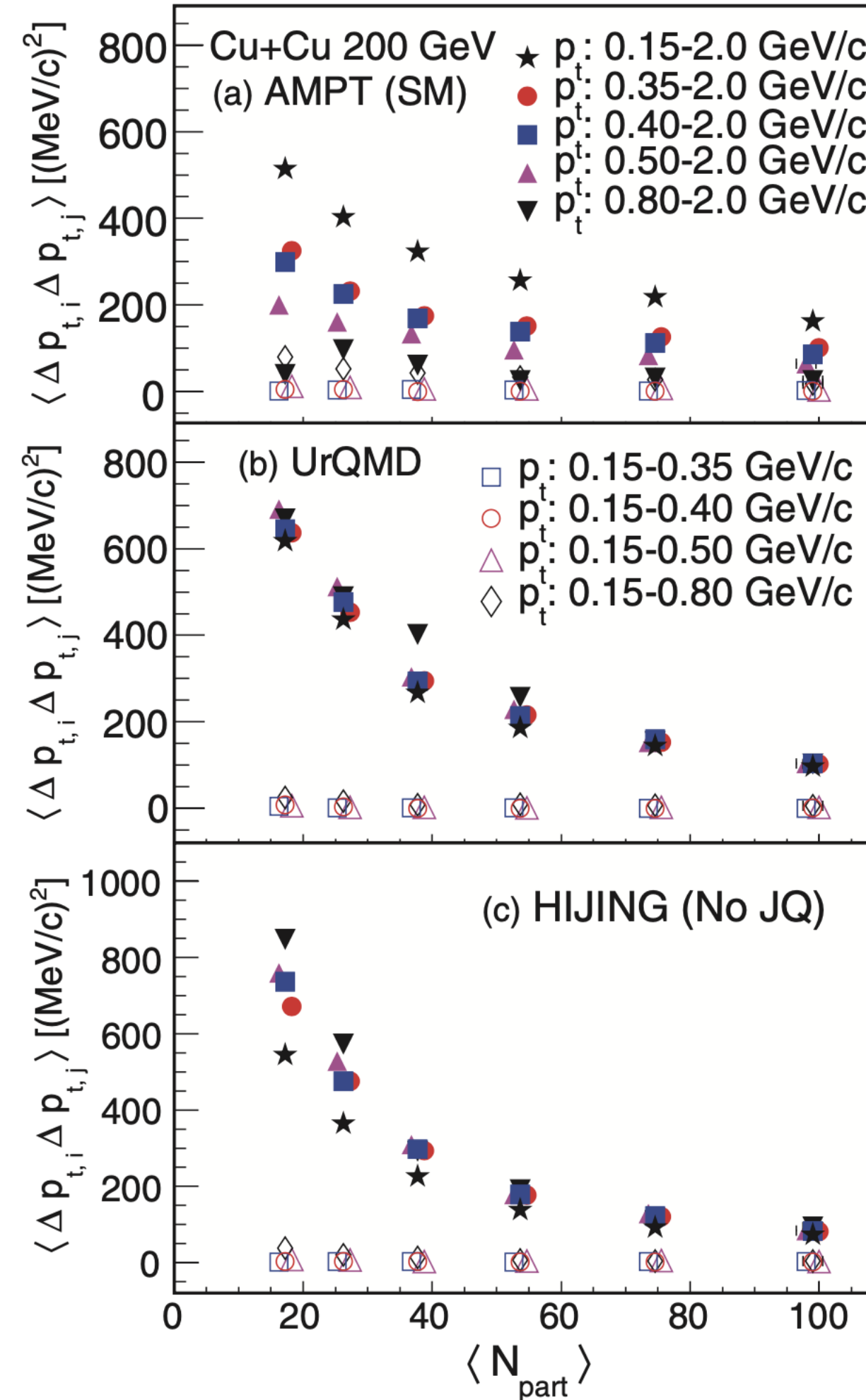
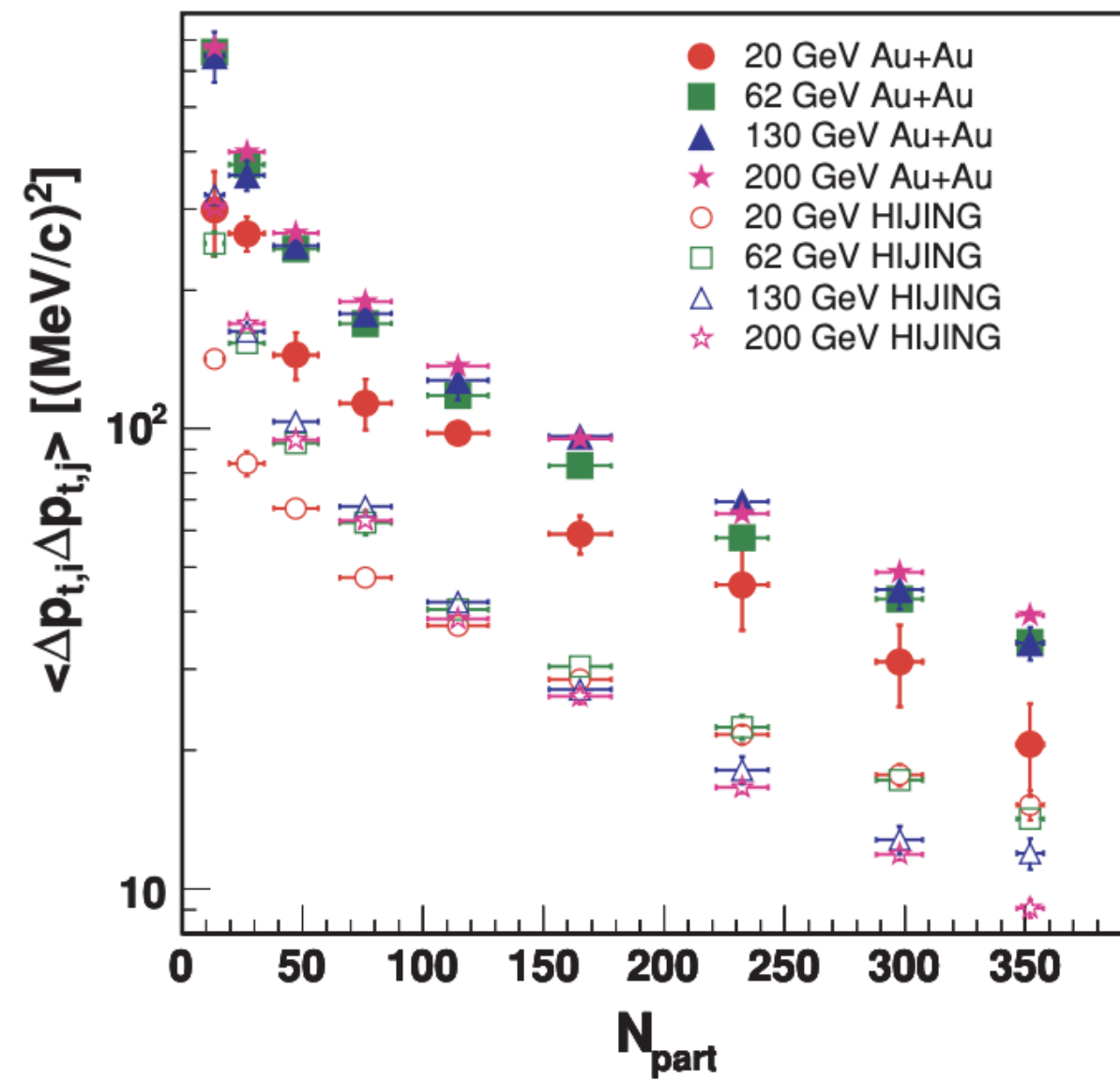
b) b_L is systematically increased with E .

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

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

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

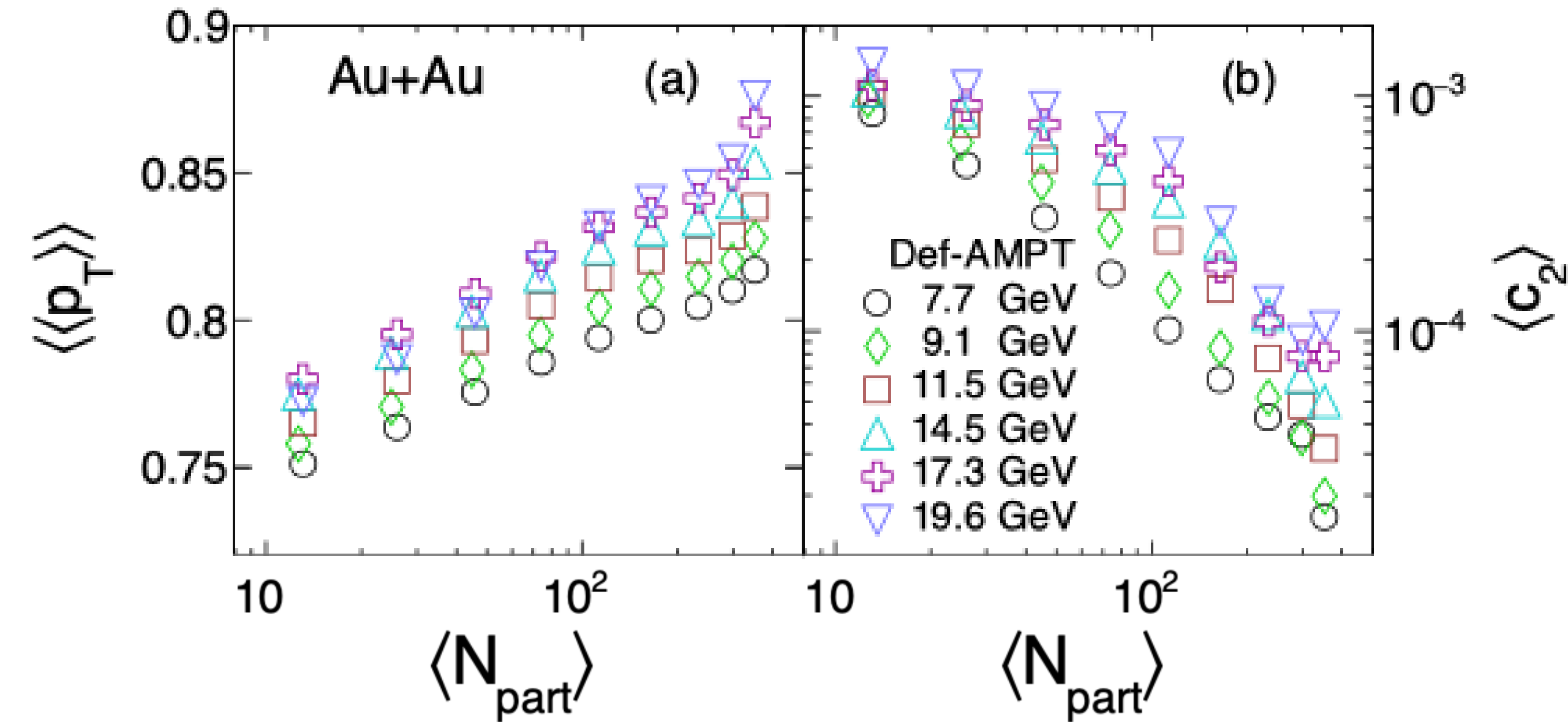
PRC **72**, 044902 (2005)



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

Second-order p_T cumulants

Variance($\langle c_2 \rangle$)

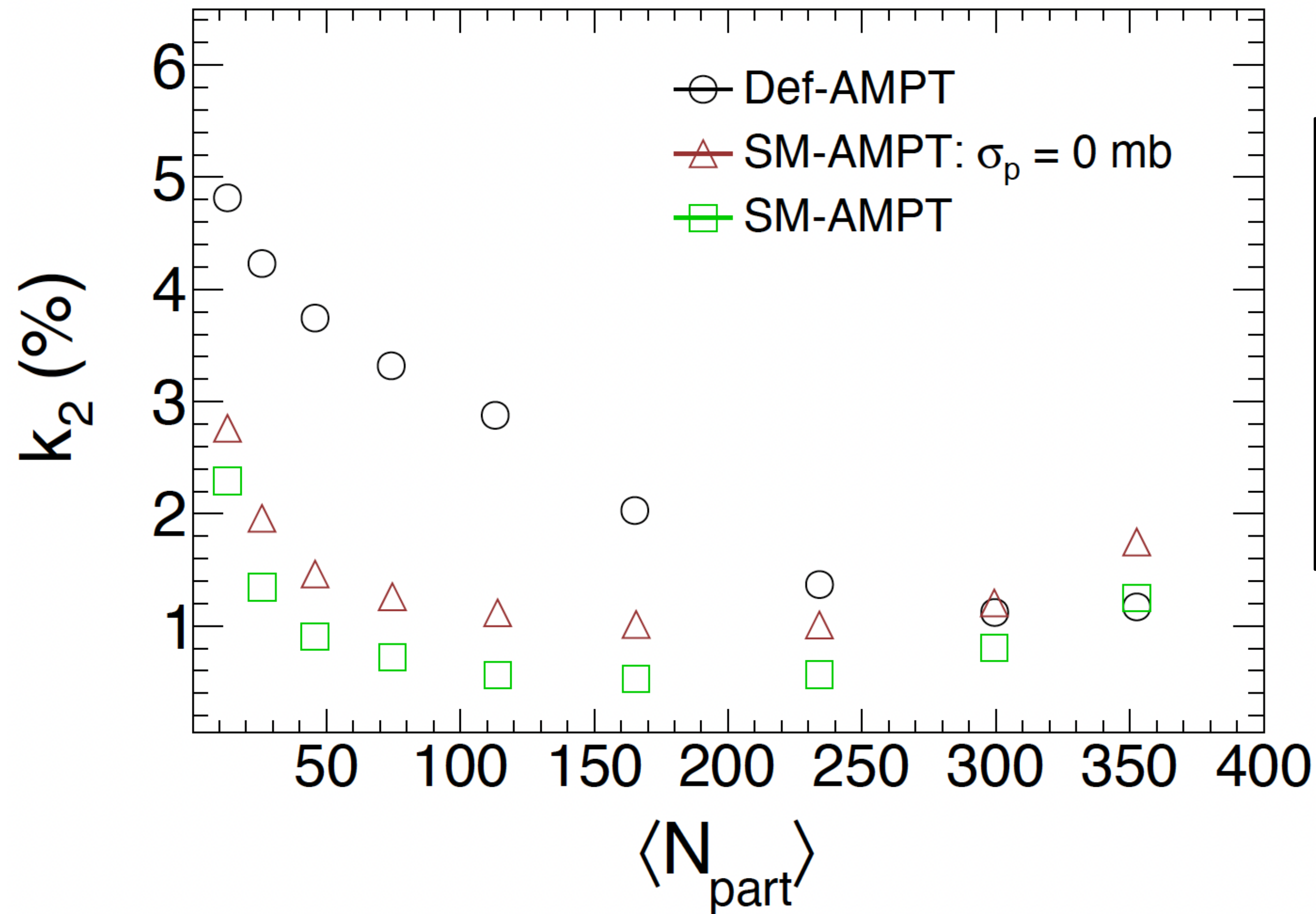


$\langle c_2 \rangle$ (cent.) vs energy

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: 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.