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

Physical Review C 111, 024911 (2025)

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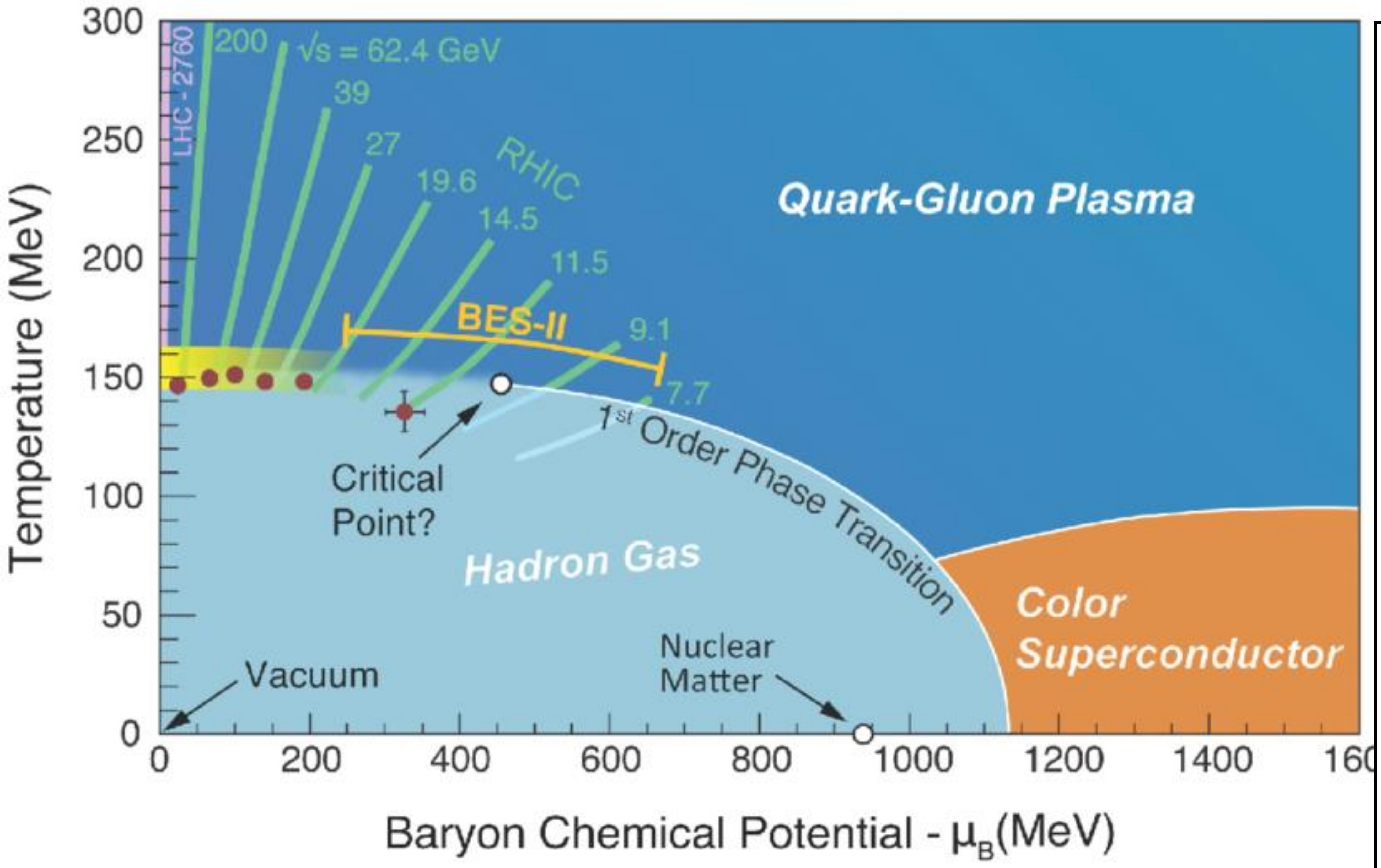
# Motivation

The evidence of Quark-Gluon Plasma (QGP) existence: searching critical point and 1st order boundary.




Sensitive observables :

- Collectivity: long-range correlation.
- Chirality: polarization.
- Criticality: net proton/charge/strange fluctuation, light nucleus yield ratios fluctuation.

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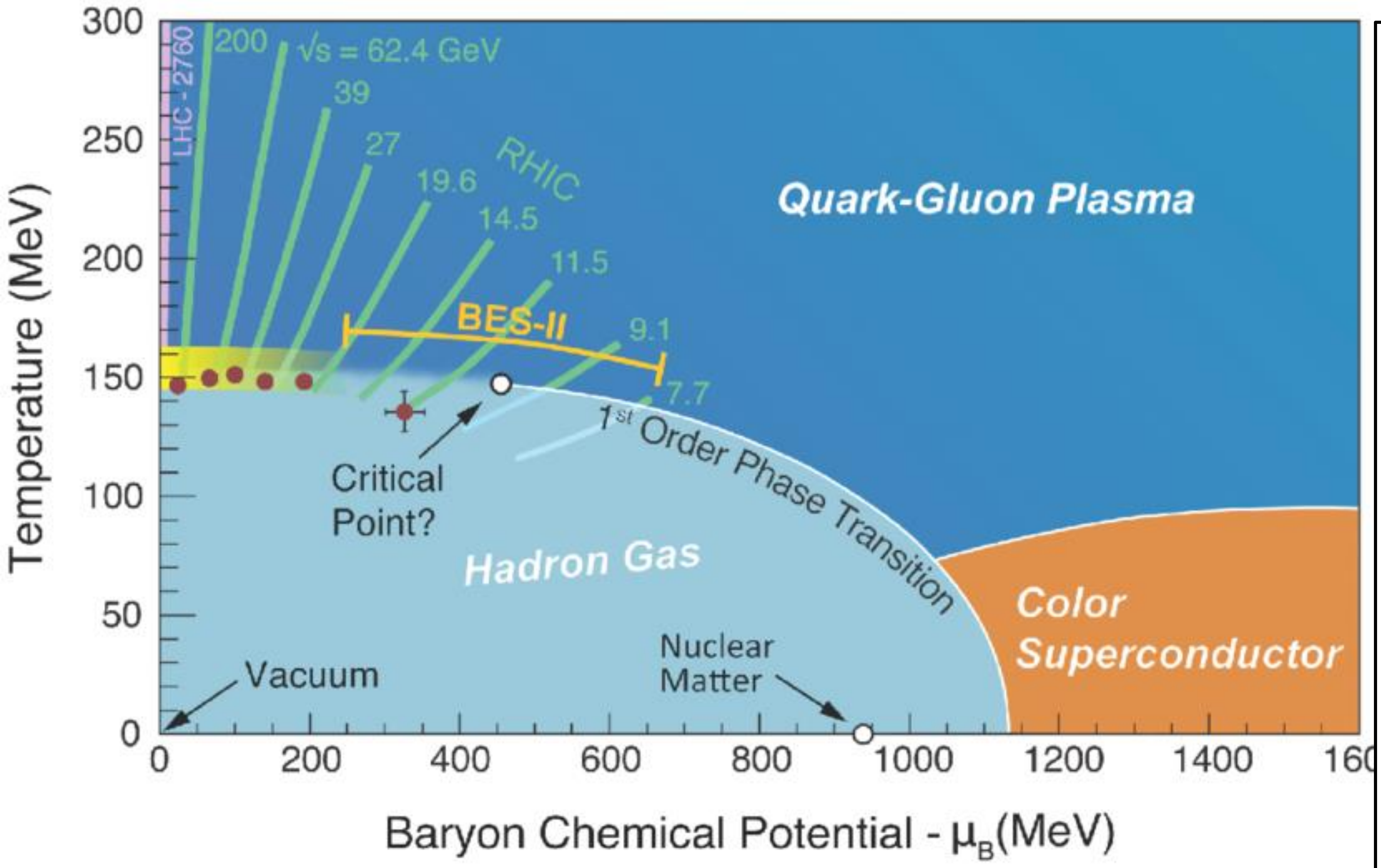


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**EbE $\langle p_T \rangle$ fluctuations**

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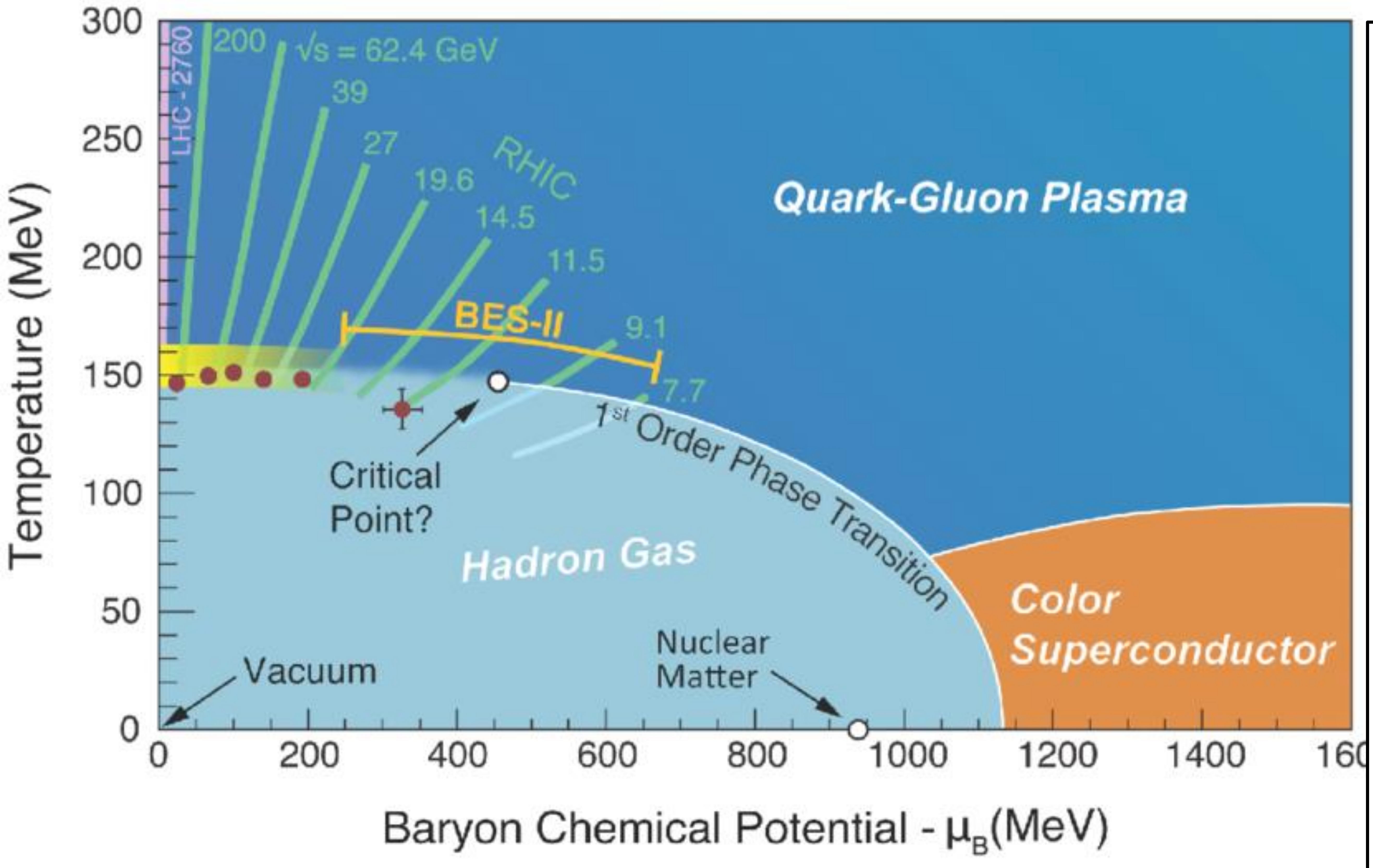


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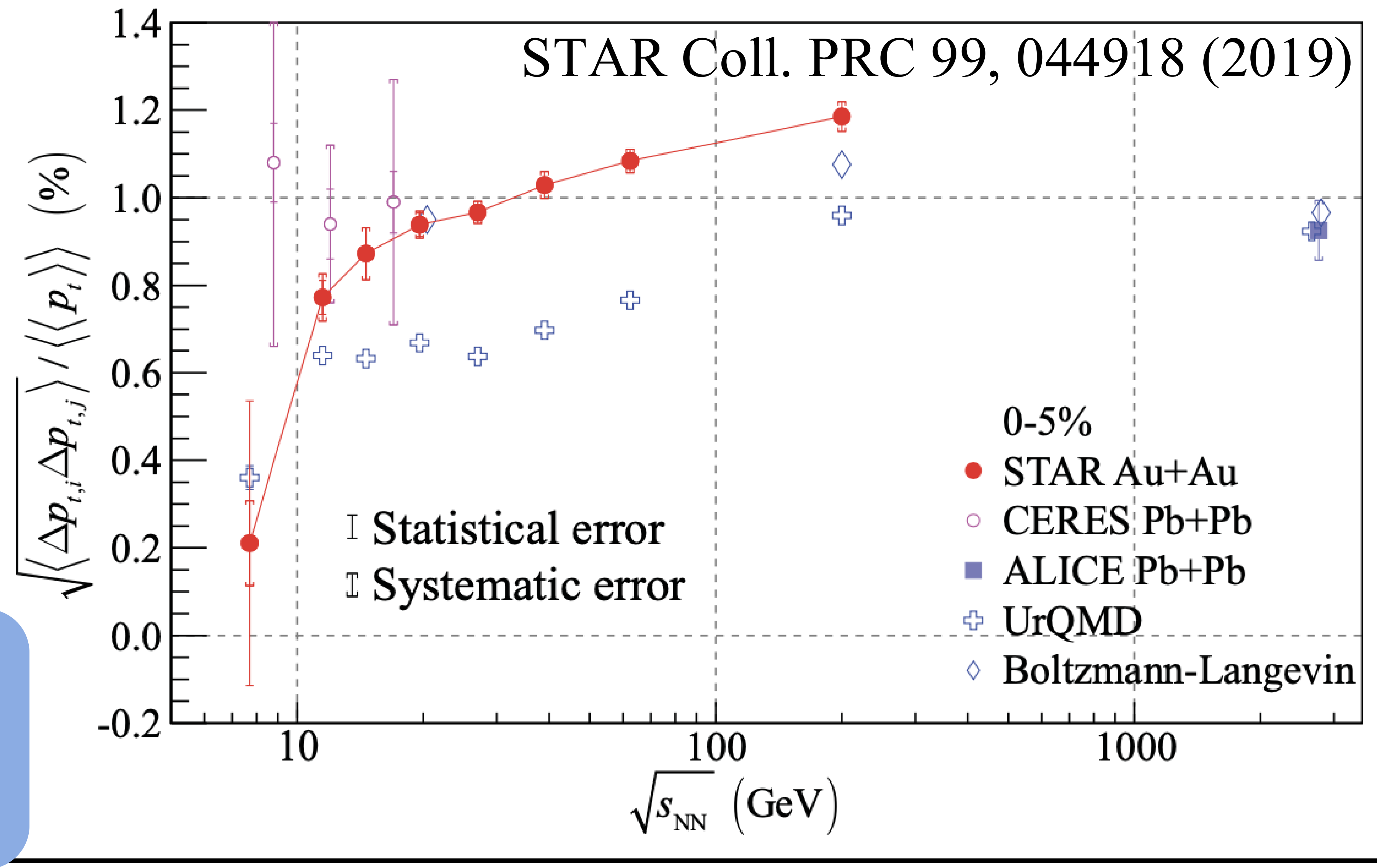
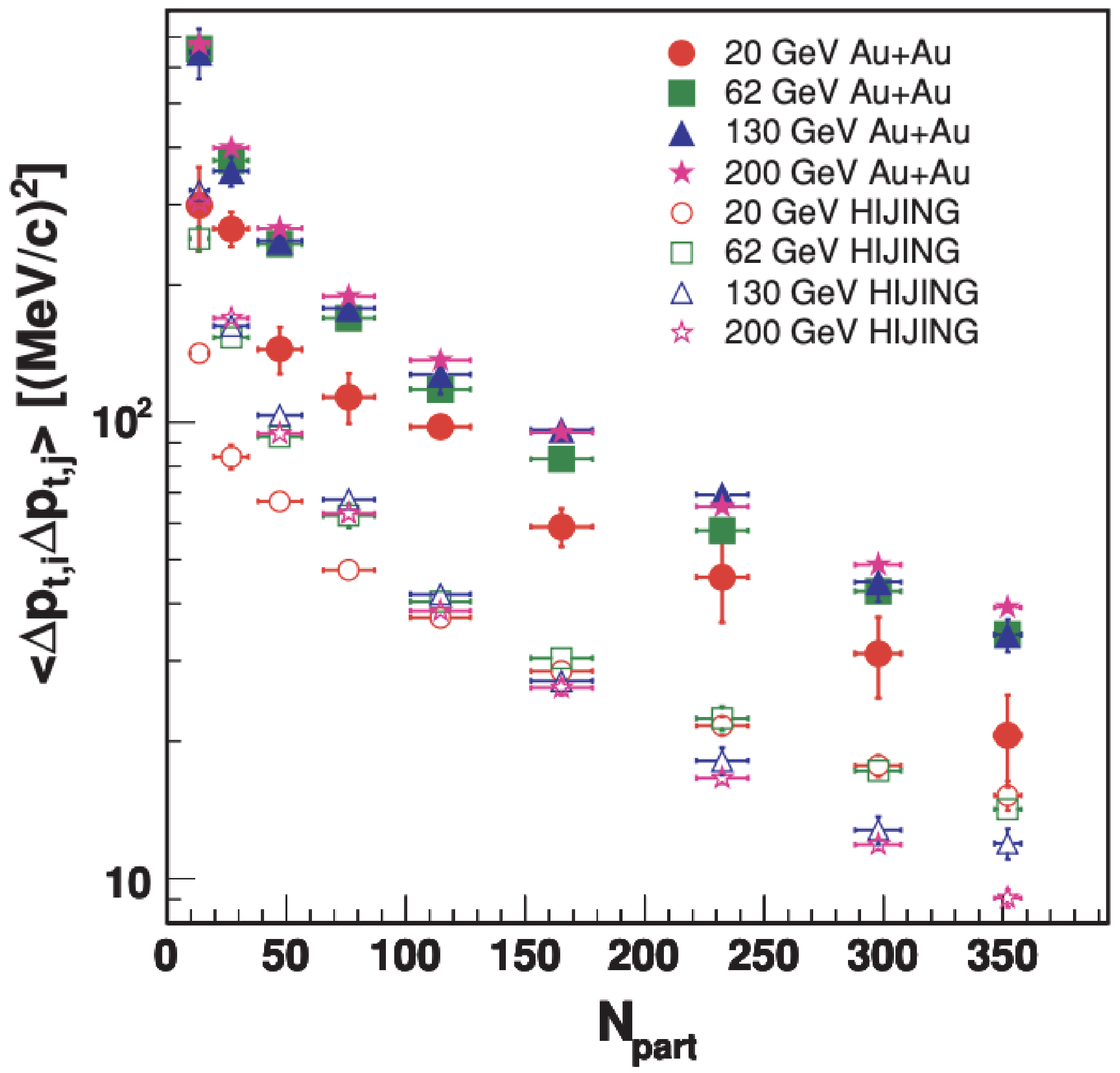



A non-monotonic behavior of $\langle p_T \rangle$ fluctuations as a function of centrality or incident energy was suggested as one of the possible signals of the QGP

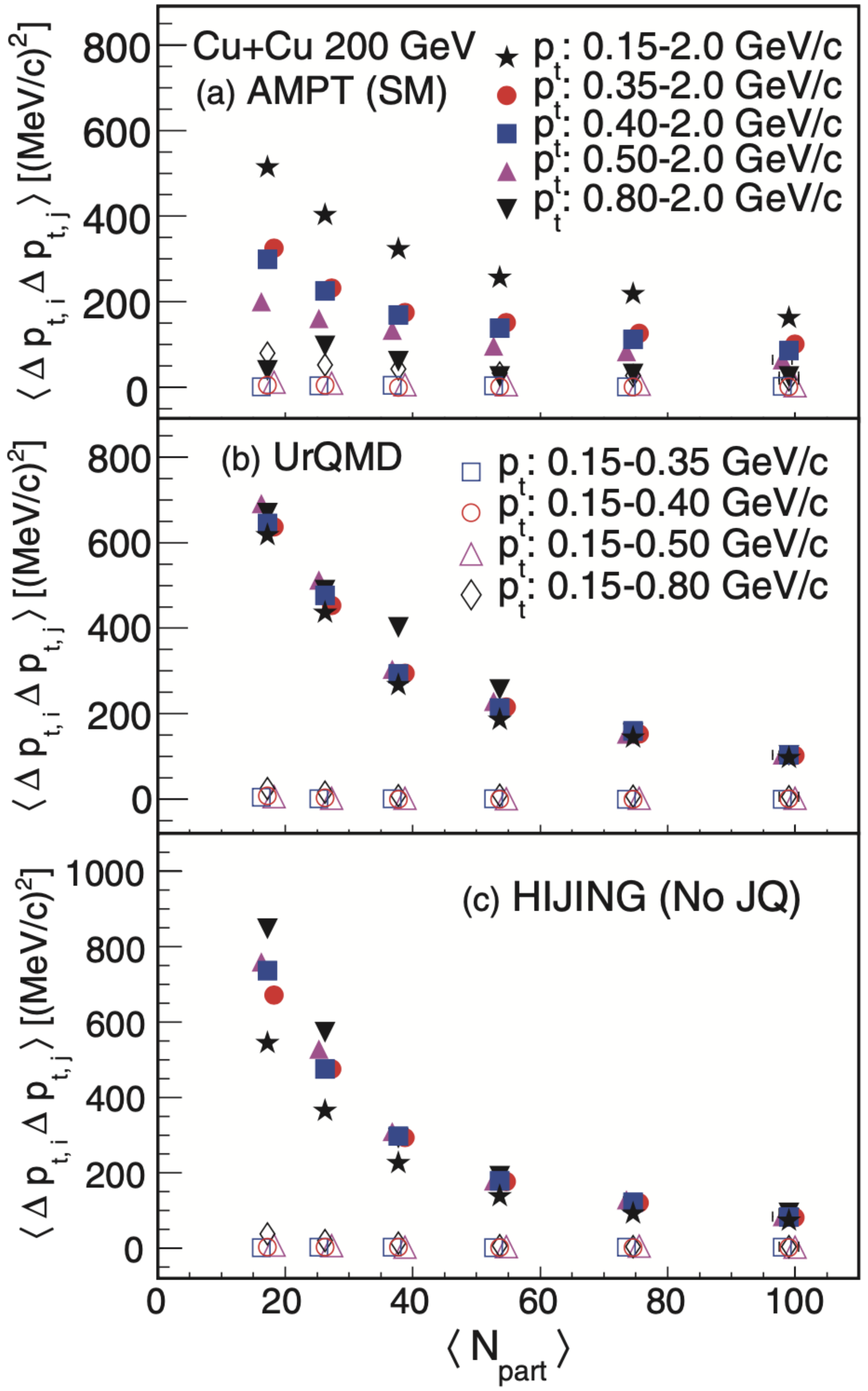
# Motivation



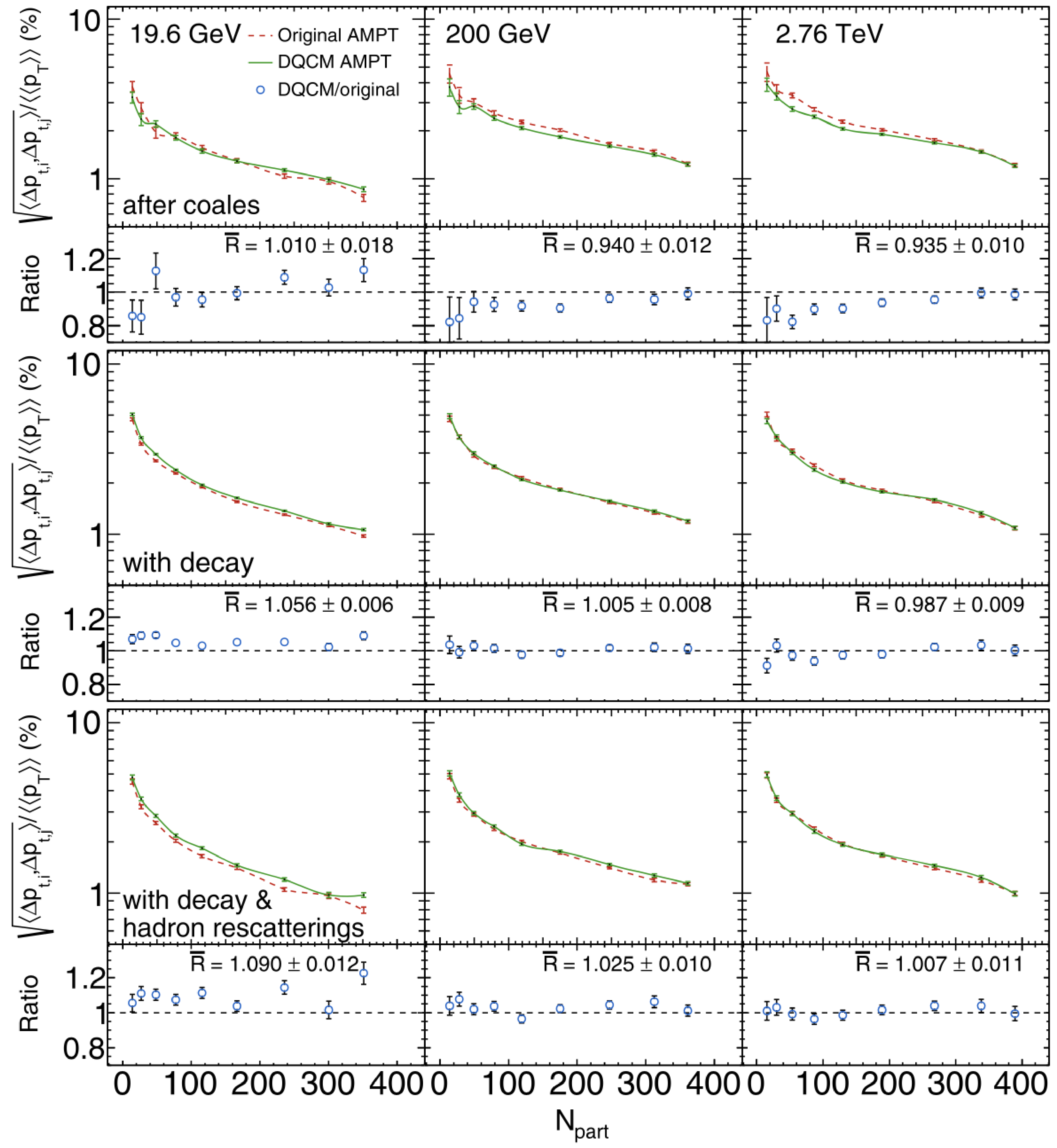
PRC **72**, 044902 (2005)




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




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




The higher-order $\langle p_{\mathrm{T}} \rangle$ fluctuations need to be systematically explored considering the BES program.

# $\langle p_T \rangle$ trend：AMPT optimization



1) vs centrality, 2) vs incident energy

Two key parameters in hadronization mechanisms in the AMPT model:

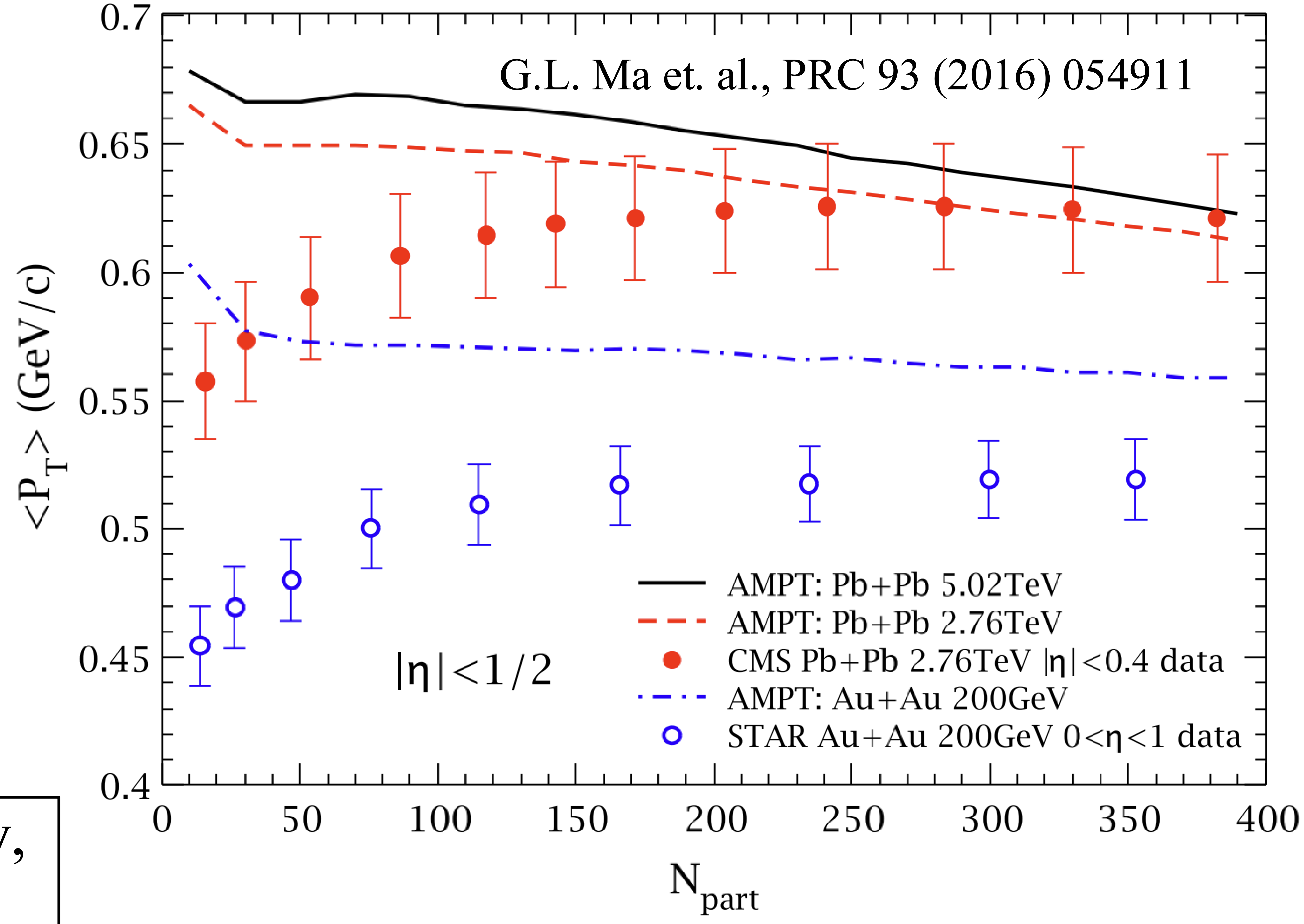
$\boldsymbol{a_L}$, $\boldsymbol{b_L}$: which are inversely related to $\langle p_T \rangle^2$ of hadrons.

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

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.

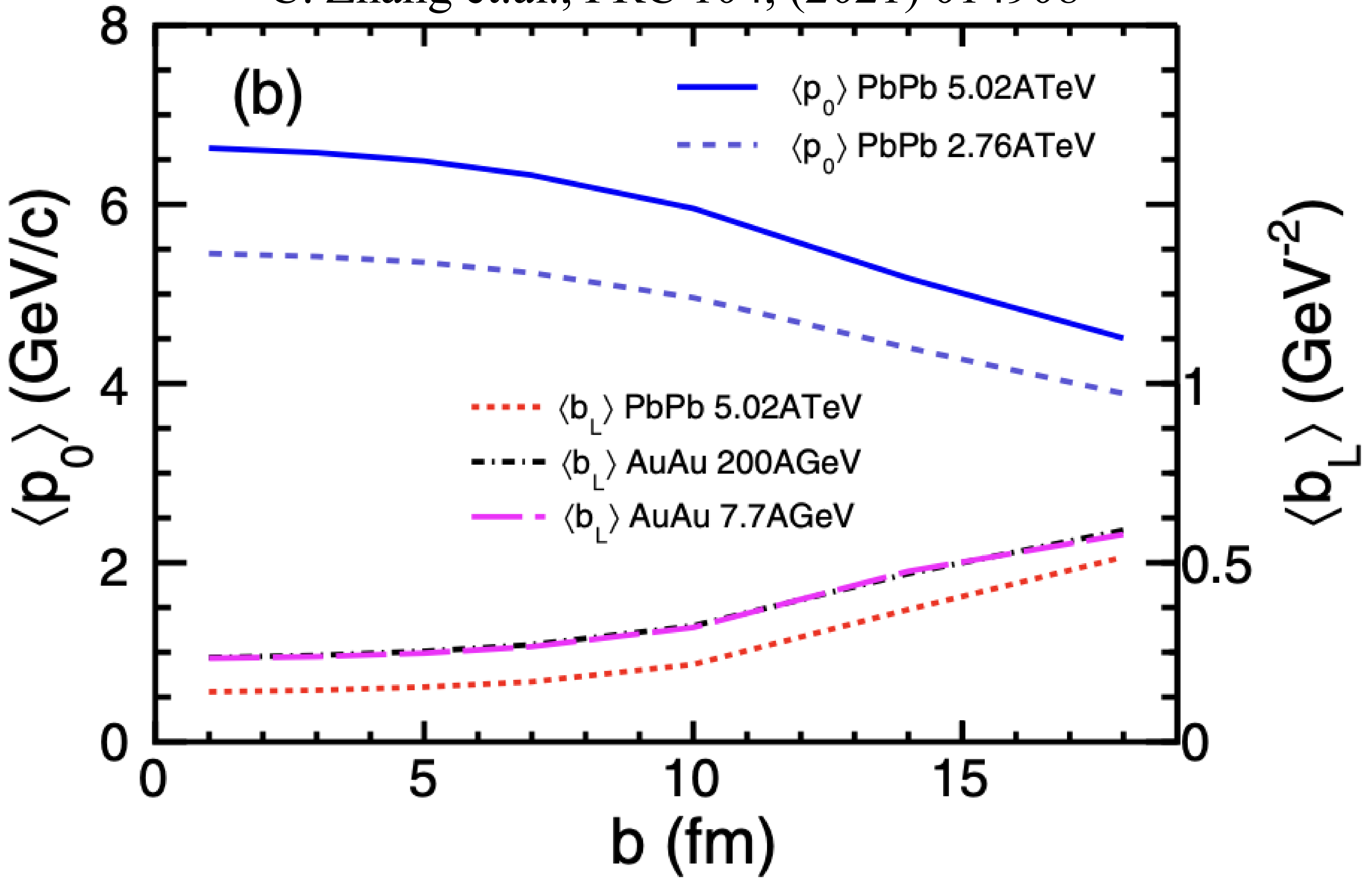
# $\langle p_T \rangle$ trend : AMPT optimization



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.

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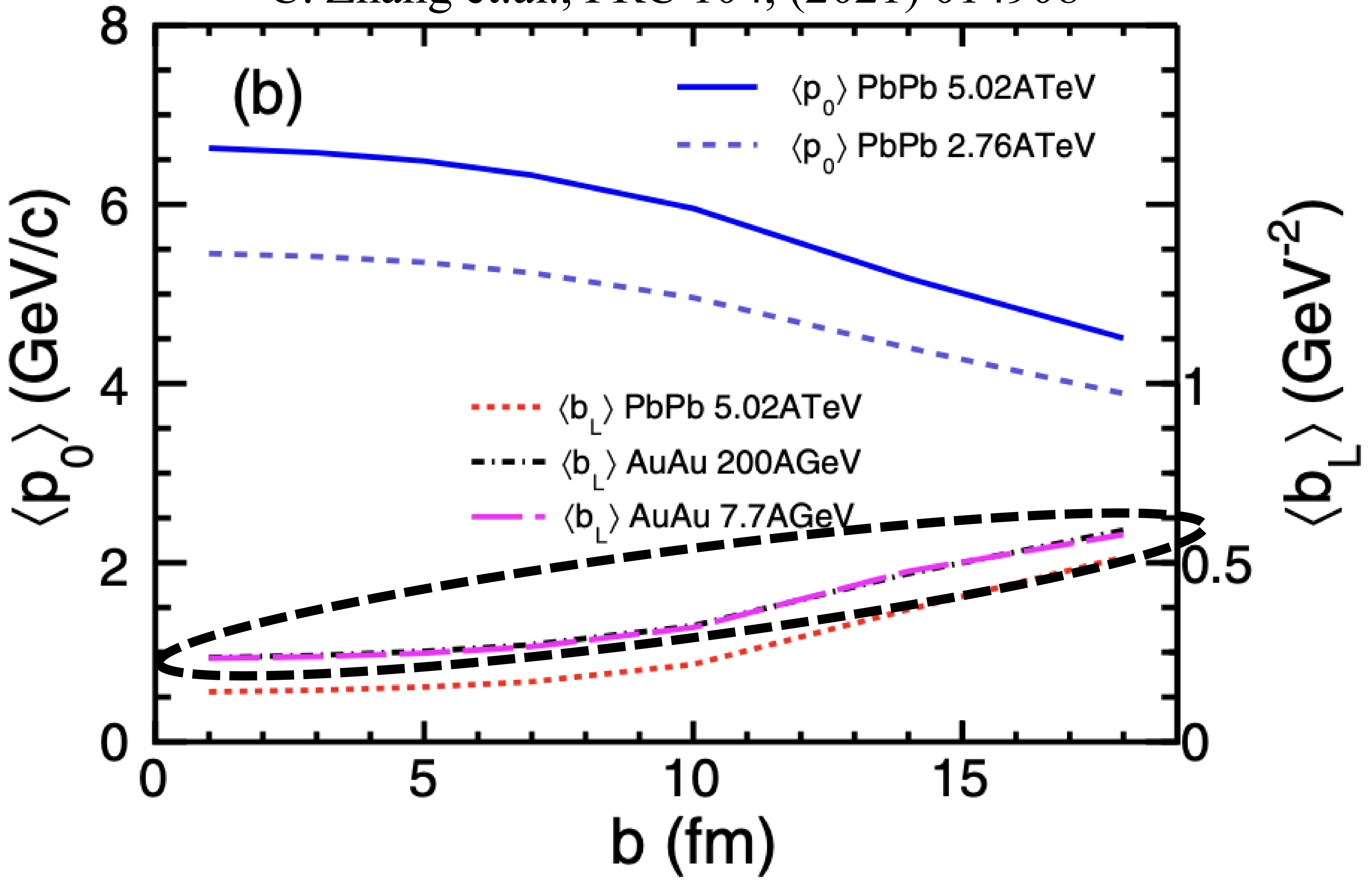


Based on the published work, we adopt:

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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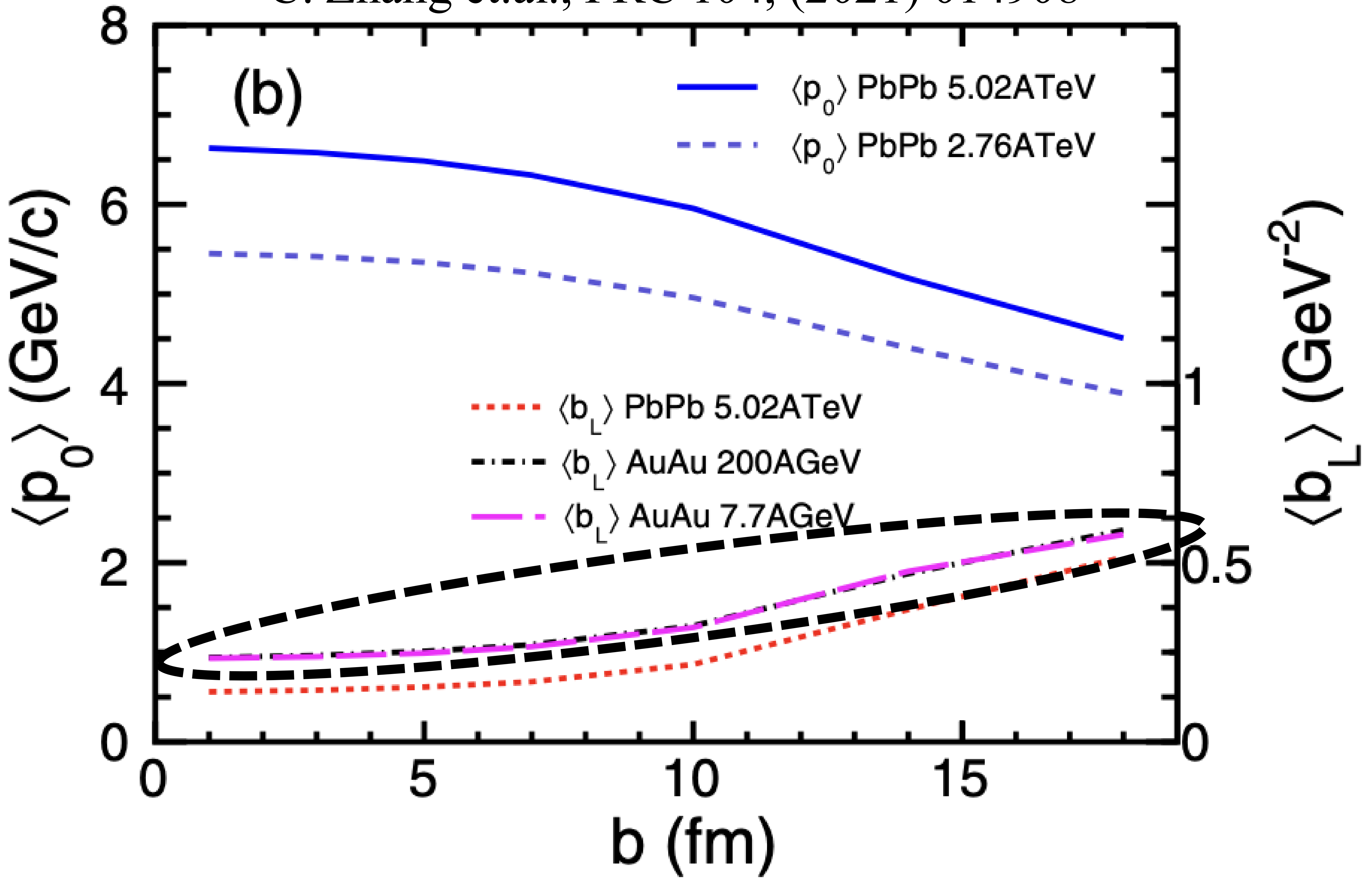



Based on the published work, we adopt:

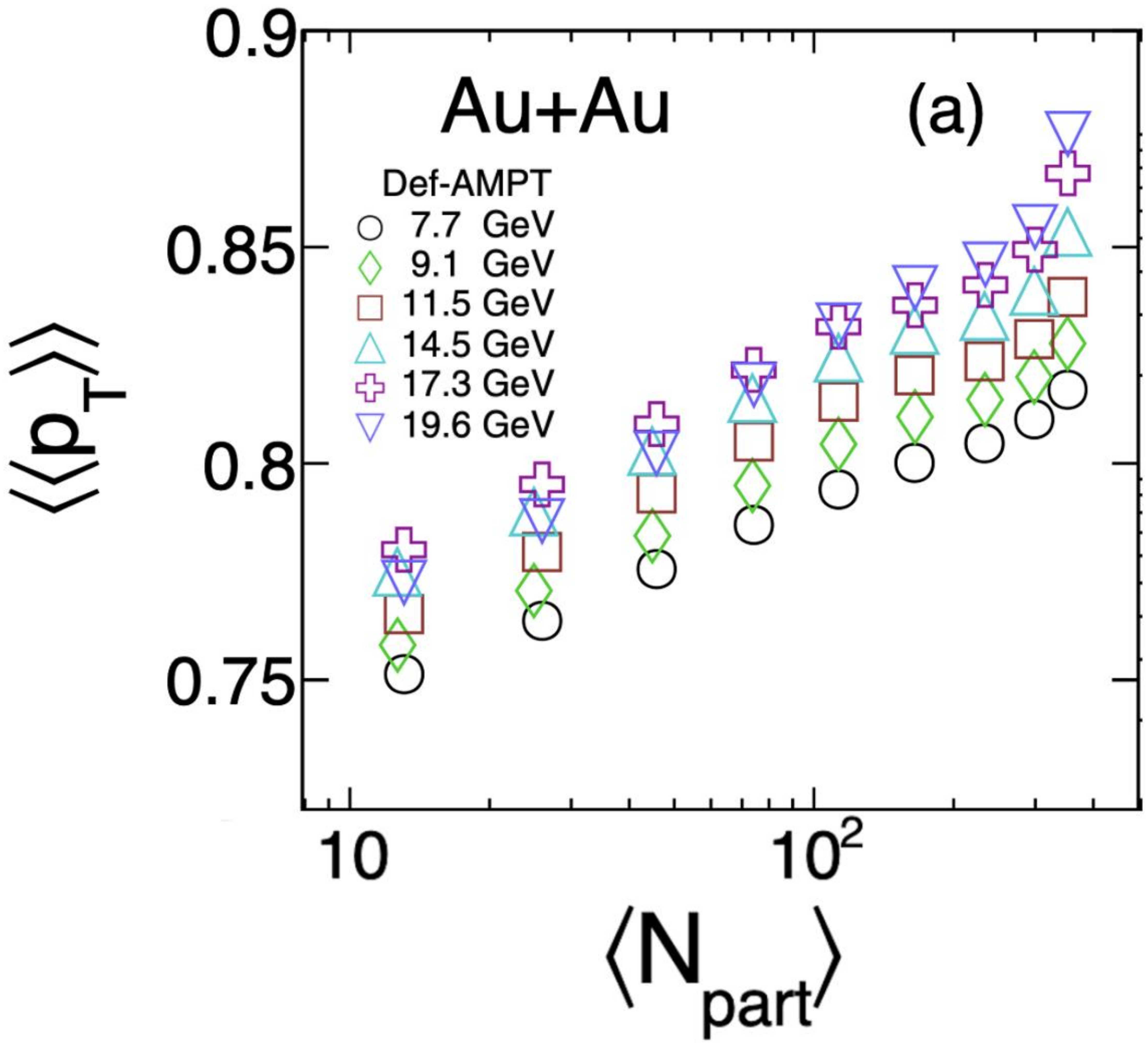
a) $b_L$ has approximate linear dependence on the b.

→ 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.

# $\langle p_T \rangle$ trend：AMPT optimization

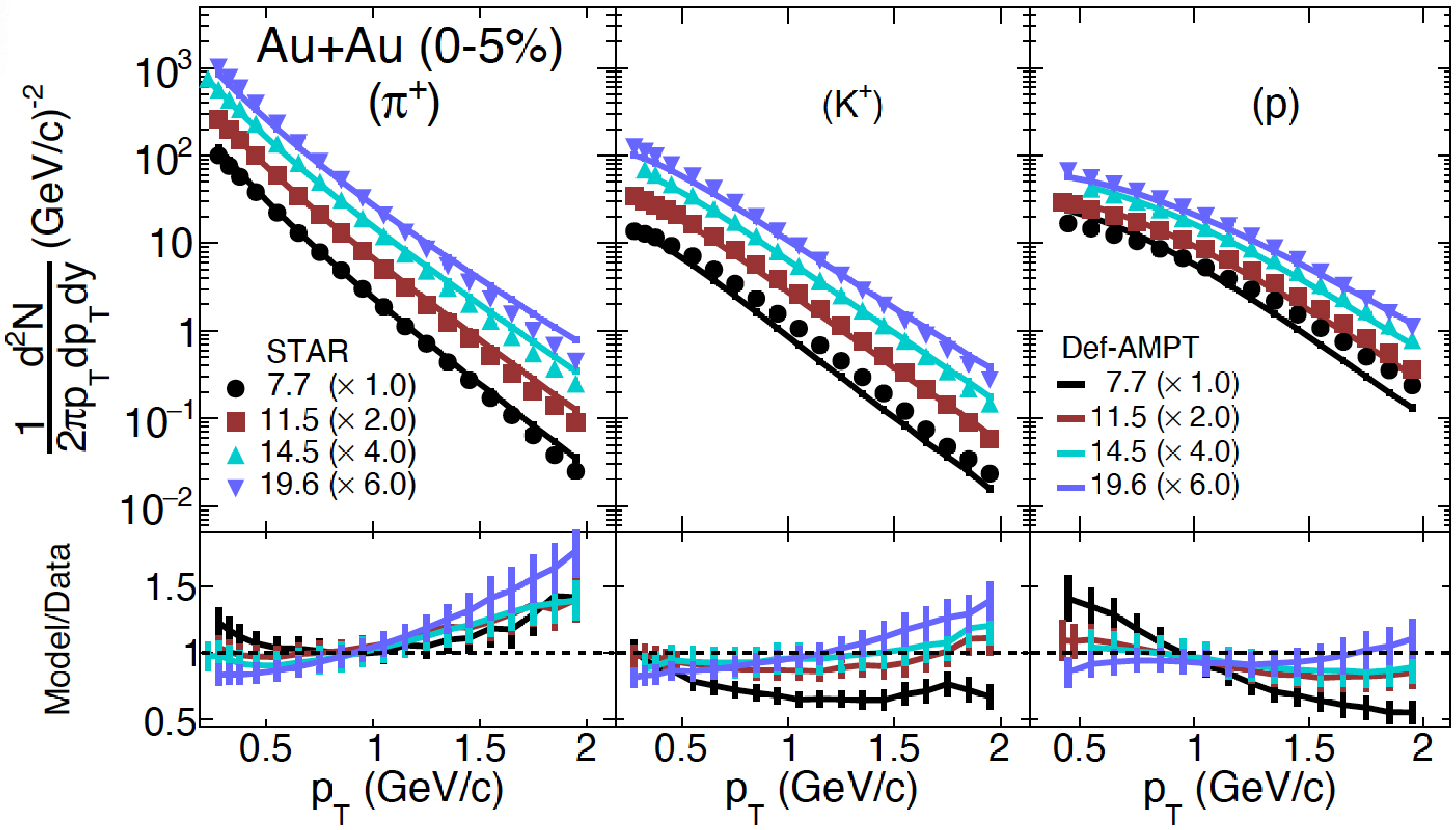



Combine the optimization (a) and (b), the $\langle\langle p_T \rangle\rangle$ distributions from the enhanced AMPT exhibit:

- ✓ A reasonable centrality dependence, verified the expectation that higher initial temperatures in more central collisions.
- ✓ A significant energy dependence is observed across beam energy scan, with larger $\langle\langle p_T \rangle\rangle$ values at higher incident energy due to enhanced collective effects.

# The AMPT validity

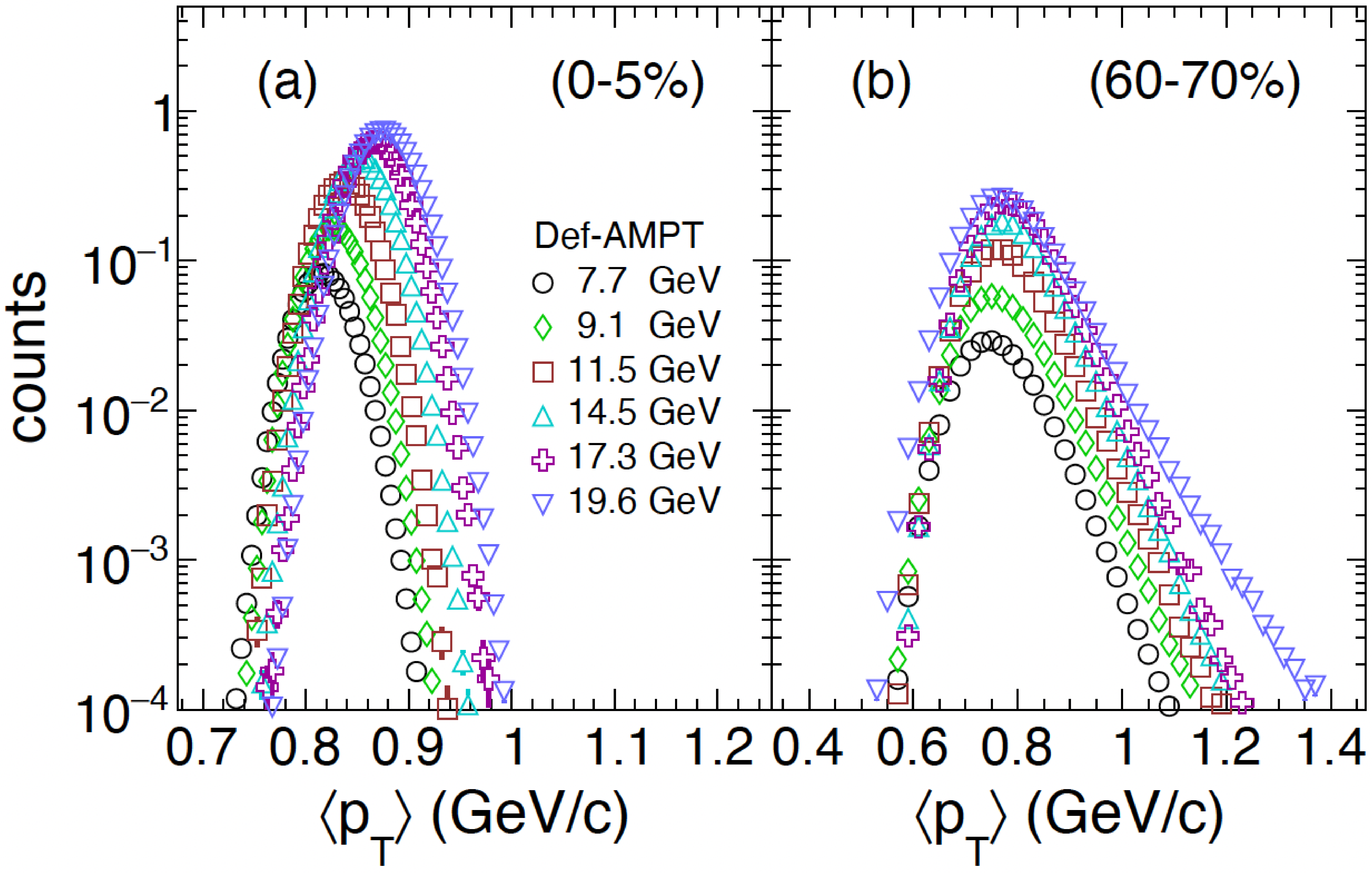





The improved AMPT model qualitatively produces the experimental data across a broad $p_T$ spectrum, spanning a variety of incident energy.

# Event-wise $\langle p_T \rangle$ distribution

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

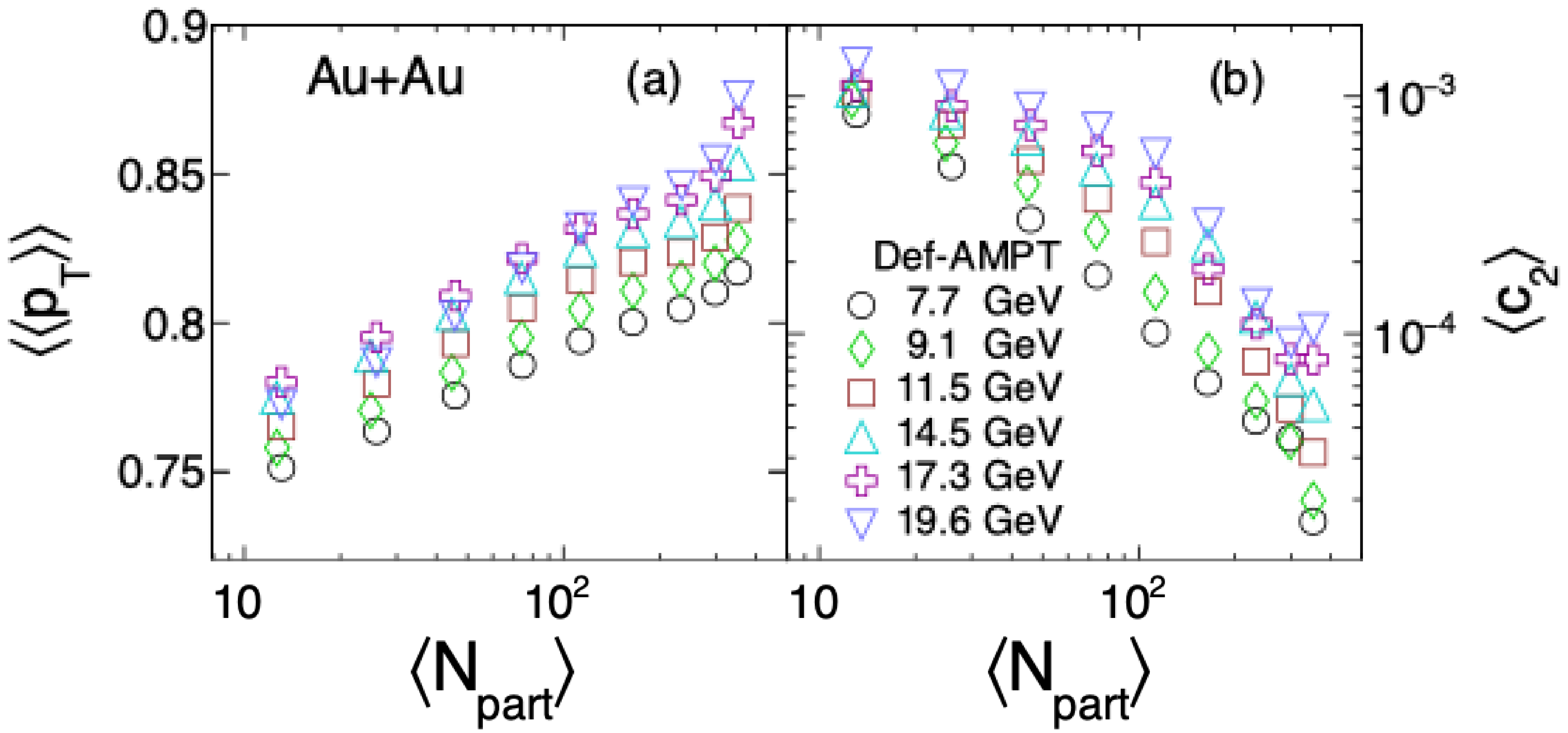



The peripheral collisions (60-70%) compared to central collisions (0-5%) ):

- the $\langle p_T \rangle$ distributions exhibit greater variances, indicating enhanced fluctuations.
- the $\langle p_T \rangle$ distributions show a significant rightward tail, suggesting positive skewness.

# Second-order $p_T$ cumulants

Variance($\langle c_2 \rangle$)



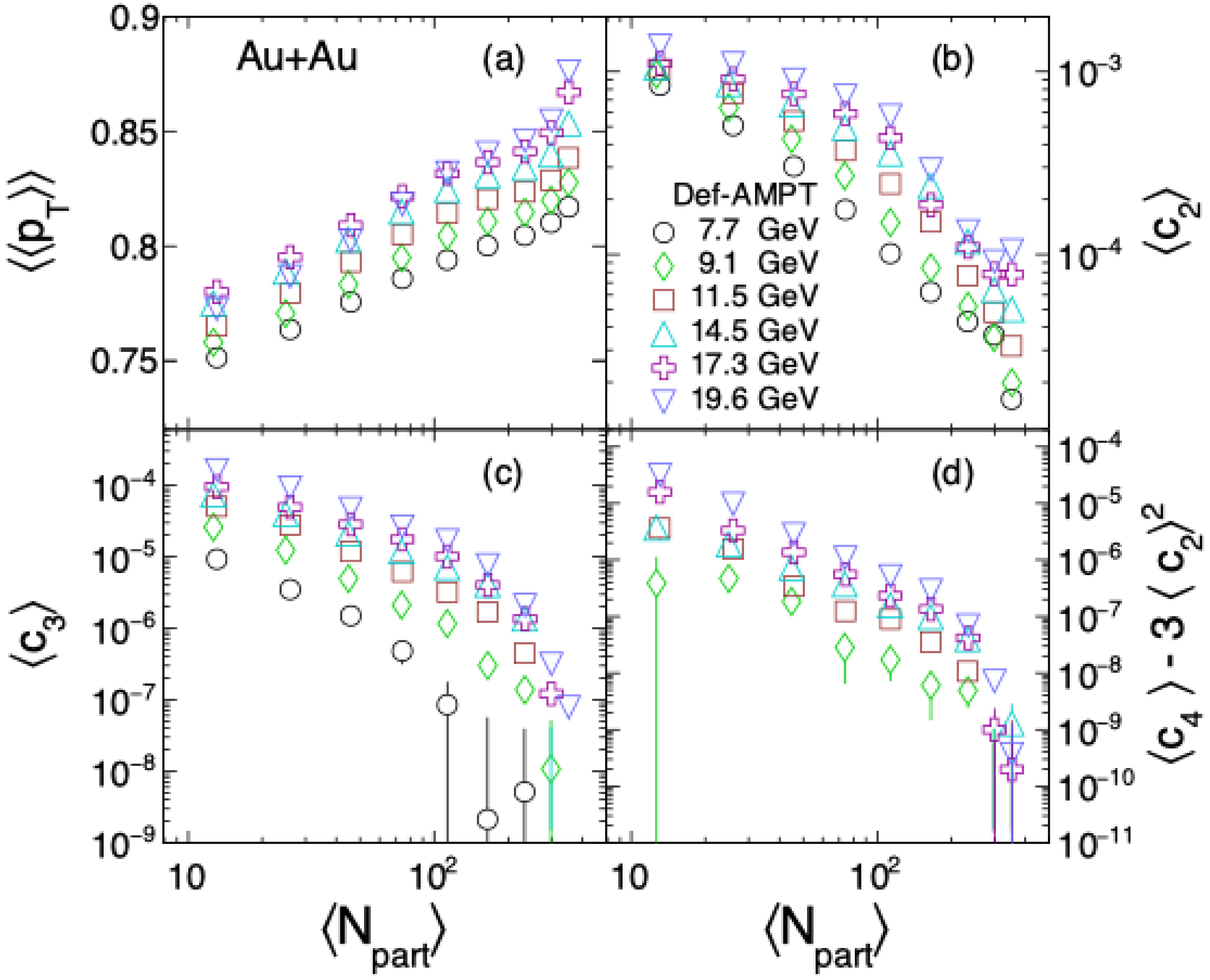

$\langle c_2 \rangle$ (cent.) vs energy

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.

# Higher-order $p_T$ cumulants

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




Share significant dependence on cent. and energy:

their magnitudes decrease by more than one order of magnitude with increasing centrality classes.

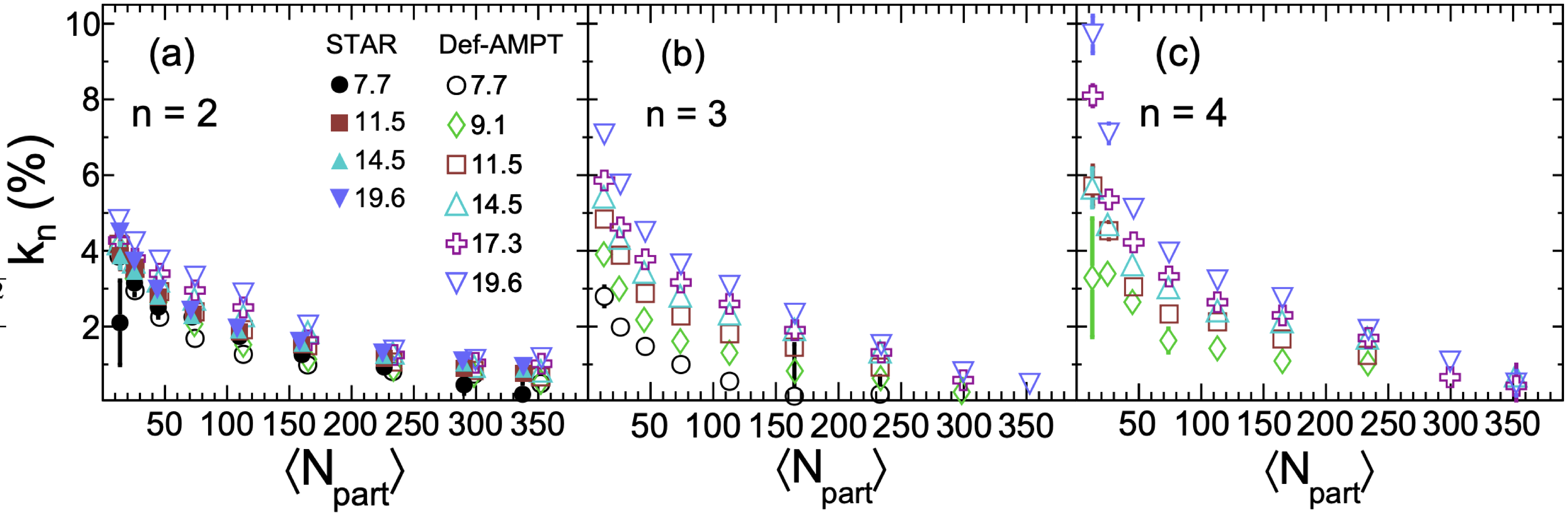
# Scaled $p_T$ cumulants

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

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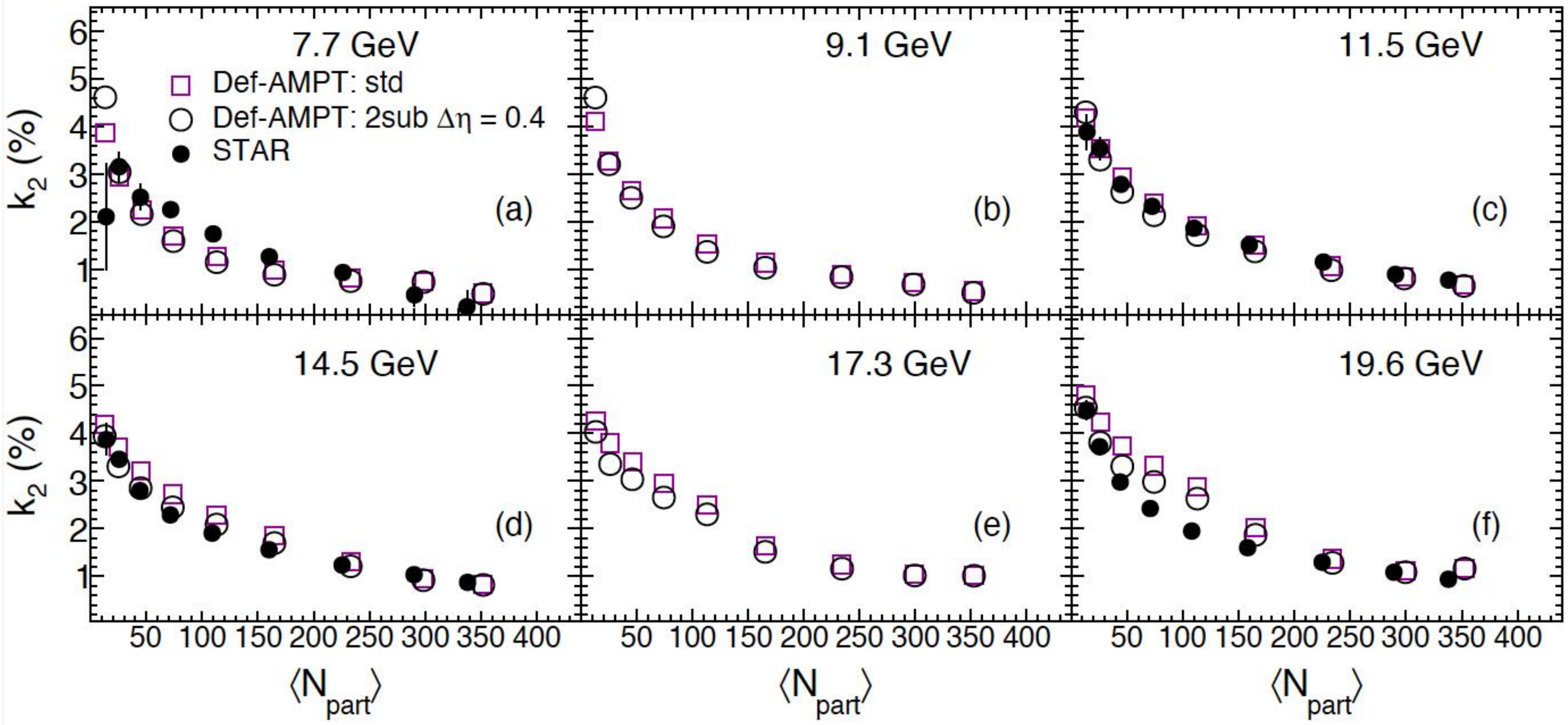
The scaled $p_T$ cumulants by a two-subevent method: to minimize the impact of short-range correlations.




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

# Scaled $p_T$ cumulants: baryon Vs meson

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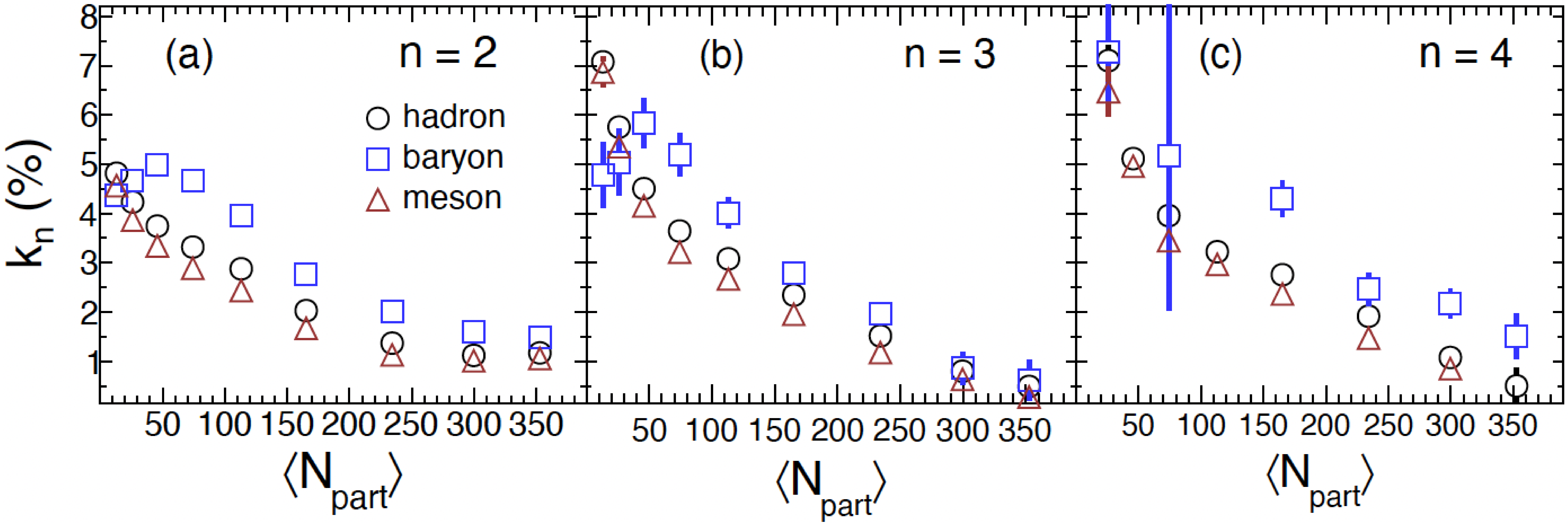
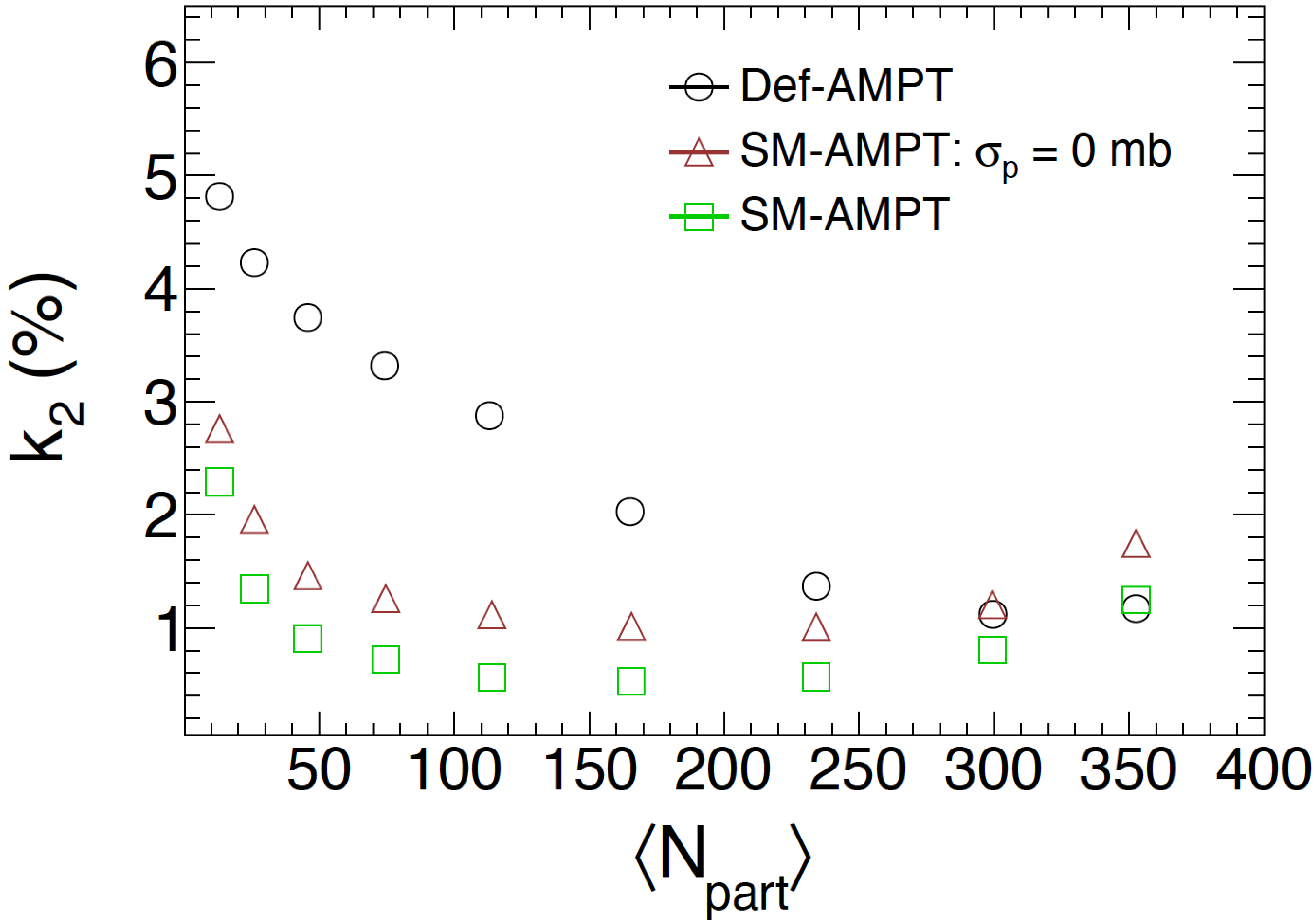
To further explore the radial flow mechanism.




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

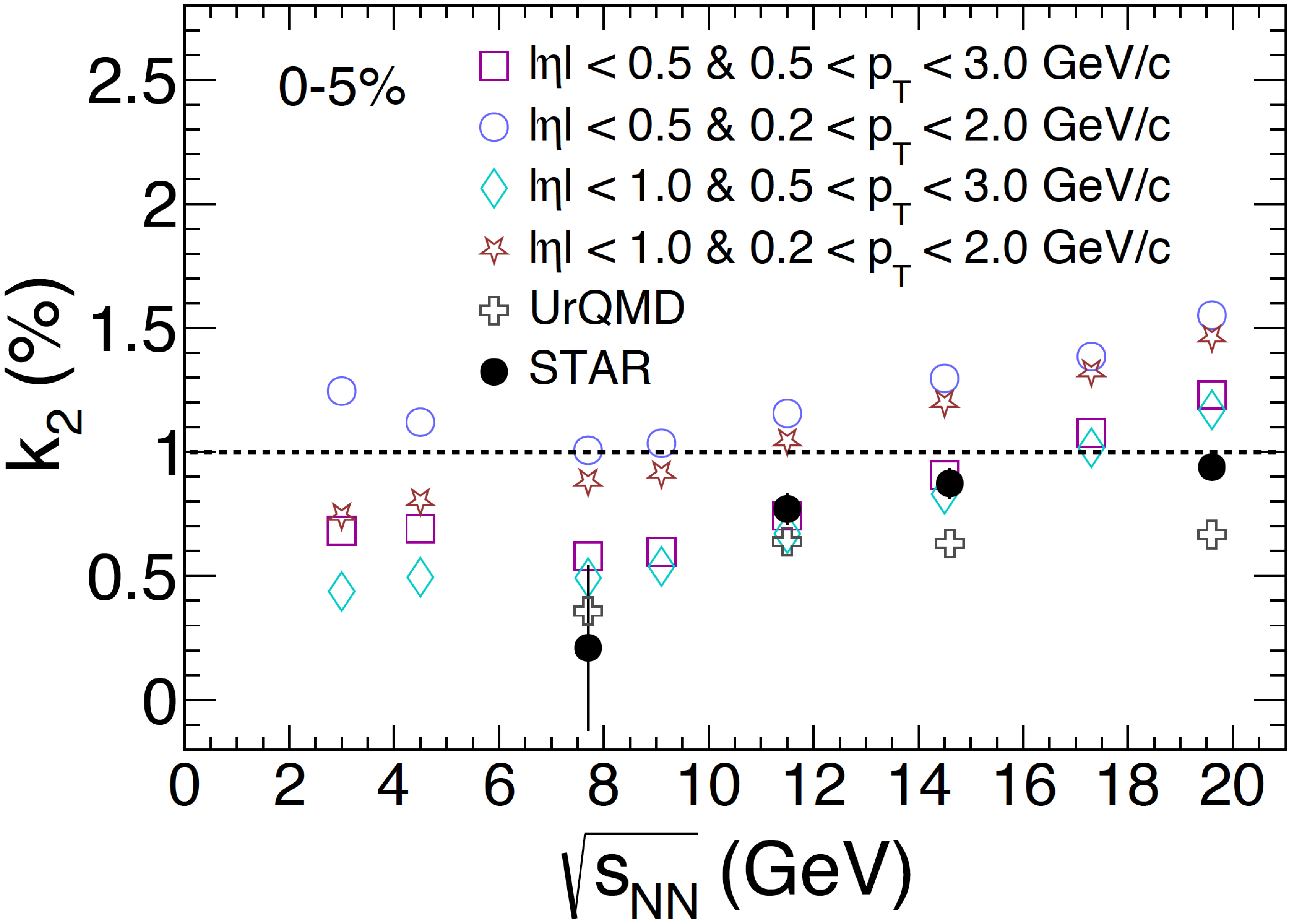



- The default configuration exhibits more pronounced $\langle p_T \rangle$ fluctuations than SM version with and without partonic interactions.

  → likely different hadronization mechanisms.

- Partonic evolution slightly suppress the EbE fluctuations.

# Scaled $p_T$ cumulants: vs energy




- $k_2$ is more sensitive to $p_T$ variations than $\eta$ acceptance.
- $0.5 < p_T < 3.0$ GeV: quantitatively consistent with STAR measurements.
- extend to 3.0 GeV, $k_2$ exhibits a significant abnormal increase, indicating an enhancement of dynamical correlations at lower collision energies.

# Summary and outlook



- A comprehensive systematic study of higher-order dynamical $p_T$ cumulants up to fourth order.
- Higher-order $p_T$ cumulants with and without normalization exhibit a strong dependence on centrality across 3.0-19.6 GeV.
- Our finding provides variable references for the experimental measurements.
- The inner mechanism from acceptance or decorrelation need further to be explored.

Thank you !!!

# Backup

# Methodology: n-particle $p_T$ correlator

$$c_n = \frac{\sum_{i_1 \neq \cdots \neq i_n} w_{i_1} \cdots w_{i_n} \left(p_{\mathrm{T},\mathrm{i}_1} - \langle\langle p_{\mathrm{T}} \rangle\rangle\right) \cdots \left(p_{\mathrm{T},\mathrm{i}_n} - \langle\langle p_{\mathrm{T}} \rangle\rangle\right)}{\sum_{i_1 \neq \cdots \neq i_n} w_{i_1} \cdots w_{i_n}}$$

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

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