

Initial and final state effects on the higher order fluctuations of the mean transverse momentum at LHC

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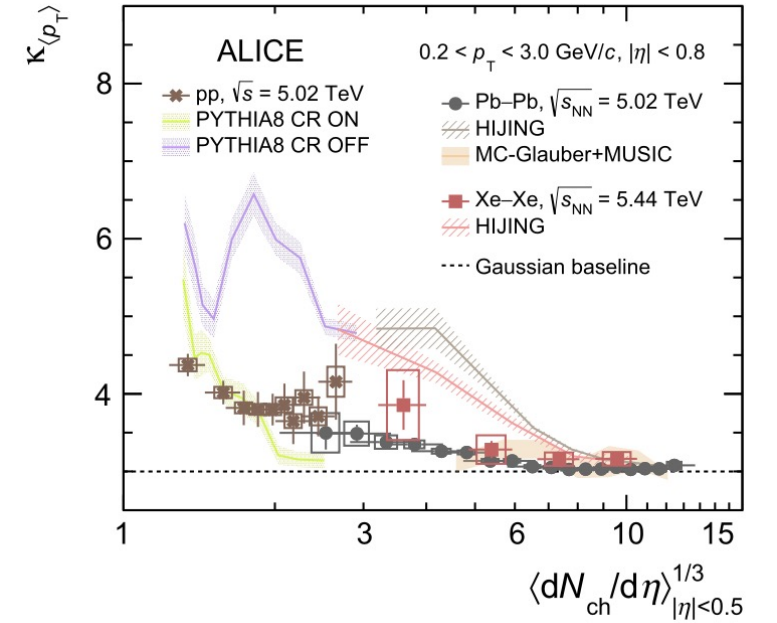
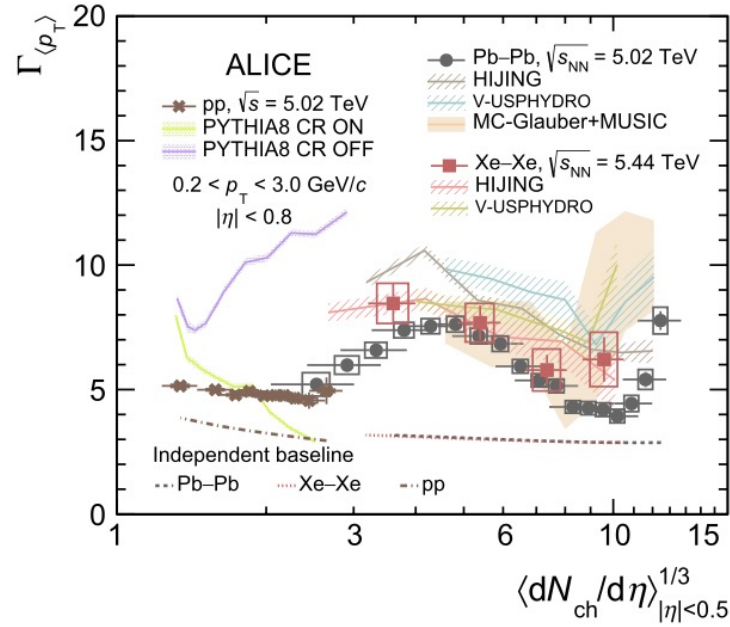
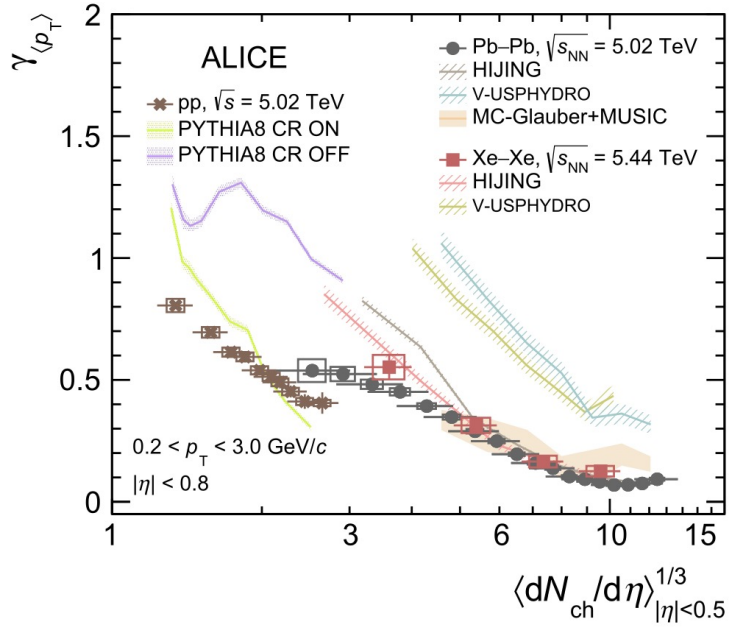


The 16th Workshop on QCD Phase Transition and Relativistic
Heavy-Ion Physics (QPT 2025), Guilin, Oct 24 – 28, 2025

Outline

- Motivation
- Improvement on the multi-phase transport model
- The final state effects on the mean p_T fluctuations
- Summary

Motivation



1. The standard skewness $\gamma_{\langle p_T \rangle}$, intensive skewness $\Gamma_{\langle p_T \rangle}$ and the kurtosis $\kappa_{\langle p_T \rangle}$ of charged particle mean transverse momentum in Pb+Pb, Xe+Xe and pp collisions are reported by the ALICE collaboration.
2. A decreasing trend in $\gamma_{\langle p_T \rangle}$ and $\kappa_{\langle p_T \rangle}$ in general are observed with increasing centrality, while the $\Gamma_{\langle p_T \rangle}$ exhibits a non-monotonic behavior

Method

The multiparticle p_T correlators method is used in this analysis:

$$\langle \Delta p_{T,i} \Delta p_{T,j} \rangle = \left\langle \frac{\sum_{\substack{i,j \\ i \neq j}}^{N_{\text{ch}}} (p_{T,i} - \langle \langle p_T \rangle \rangle) (p_{T,j} - \langle \langle p_T \rangle \rangle)}{N_{\text{ch}}(N_{\text{ch}} - 1)} \right\rangle = \left\langle \frac{Q_1^2 - Q_2}{N_{\text{ch}}(N_{\text{ch}} - 1)} \right\rangle - \left\langle \frac{Q_1}{N_{\text{ch}}} \right\rangle^2,$$

$$\begin{aligned} & \langle \Delta p_{T,i} \Delta p_{T,j} \Delta p_{T,k} \rangle \\ &= \left\langle \frac{\sum_{\substack{i,j,k \\ i \neq j \neq k}}^{N_{\text{ch}}} (p_{T,i} - \langle \langle p_T \rangle \rangle) (p_{T,j} - \langle \langle p_T \rangle \rangle) (p_{T,k} - \langle \langle p_T \rangle \rangle)}{N_{\text{ch}}(N_{\text{ch}} - 1)(N_{\text{ch}} - 2)} \right\rangle = \left\langle \frac{Q_1^3 - 3Q_2Q_1 + 2Q_3}{N_{\text{ch}}(N_{\text{ch}} - 1)(N_{\text{ch}} - 2)} \right\rangle - 3 \left\langle \frac{Q_1^2 - Q_2}{N_{\text{ch}}(N_{\text{ch}} - 1)} \right\rangle \end{aligned}$$

$$\begin{aligned} \langle \Delta p_{T,i} \Delta p_{T,j} \Delta p_{T,k} \Delta p_{T,l} \rangle &= \left\langle \frac{\sum_{\substack{i,j,k,l \\ i \neq j \neq k \neq l}}^{N_{\text{ch}}} (p_{T,i} - \langle \langle p_T \rangle \rangle) (p_{T,j} - \langle \langle p_T \rangle \rangle) (p_{T,k} - \langle \langle p_T \rangle \rangle) (p_{T,l} - \langle \langle p_T \rangle \rangle)}{N_{\text{ch}}(N_{\text{ch}} - 1)(N_{\text{ch}} - 2)(N_{\text{ch}} - 3)} \right\rangle \\ &= \left\langle \frac{Q_1^4 - 6Q_4 + 8Q_1Q_3 - 6Q_1^2Q_2 + 3Q_2^2}{N_{\text{ch}}(N_{\text{ch}} - 1)(N_{\text{ch}} - 2)(N_{\text{ch}} - 3)} \right\rangle - 4 \left\langle \frac{Q_1^3 - 3Q_2Q_1 + 2Q_3}{N_{\text{ch}}(N_{\text{ch}} - 1)(N_{\text{ch}} - 2)} \right\rangle \left\langle \frac{Q_1}{N_{\text{ch}}} \right\rangle \\ &+ 6 \left\langle \frac{Q_1^2 - Q_2}{N_{\text{ch}}(N_{\text{ch}} - 1)} \right\rangle \left\langle \frac{Q_1}{N_{\text{ch}}} \right\rangle^2 - 3 \left\langle \frac{Q_1}{N_{\text{ch}}} \right\rangle^4. \end{aligned}$$

$$\gamma_{\langle p_T \rangle} = \frac{\langle \Delta p_{T,i} \Delta p_{T,j} \Delta p_{T,k} \rangle}{\langle \Delta p_{T,i} \Delta p_{T,j} \rangle^{3/2}},$$

$$\Gamma_{\langle p_T \rangle} = \frac{\langle \Delta p_{T,i} \Delta p_{T,j} \Delta p_{T,k} \rangle \langle \langle p_T \rangle \rangle}{\langle \Delta p_{T,i} \Delta p_{T,j} \rangle^2}.$$

$$\kappa_{\langle p_T \rangle} = \frac{\langle \Delta p_{T,i} \Delta p_{T,j} \Delta p_{T,k} \Delta p_{T,l} \rangle}{\langle \Delta p_{T,i} \Delta p_{T,j} \rangle^2}$$

With $Q_n = \sum_{i=1}^{N_{\text{ch}}} p_{T,i}^n$, the standard skewness, intensive skewness and kurtosis are then defined with:

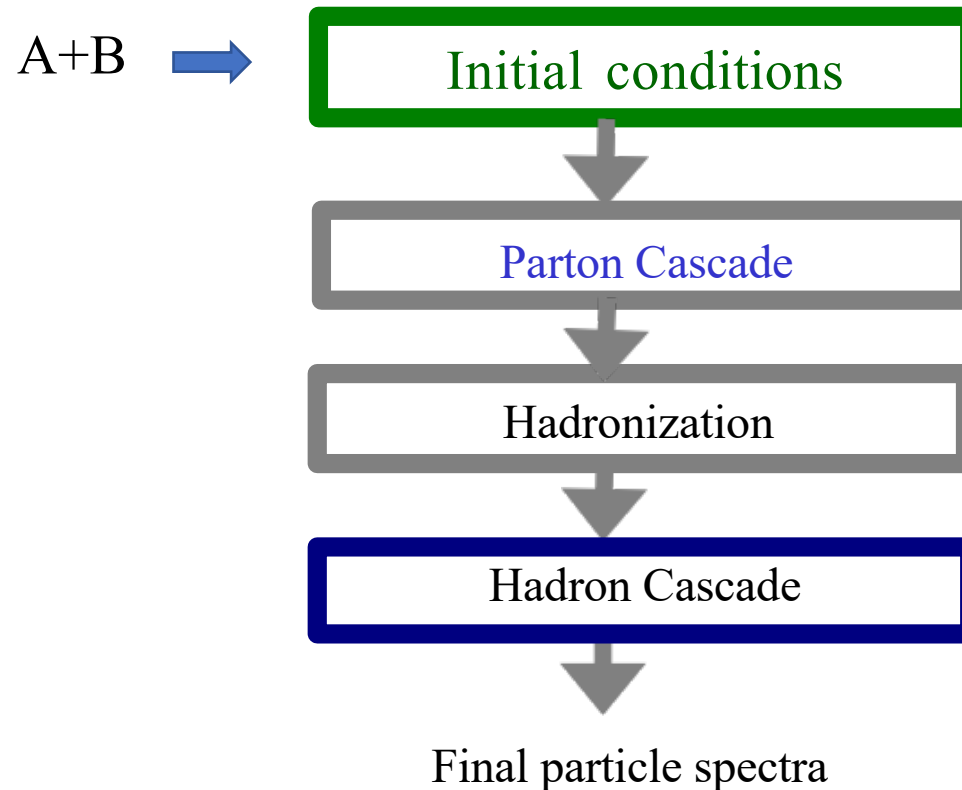
Improvement on the multi-phase transport model

We use a multi-phase transport (AMPT) model for this study.

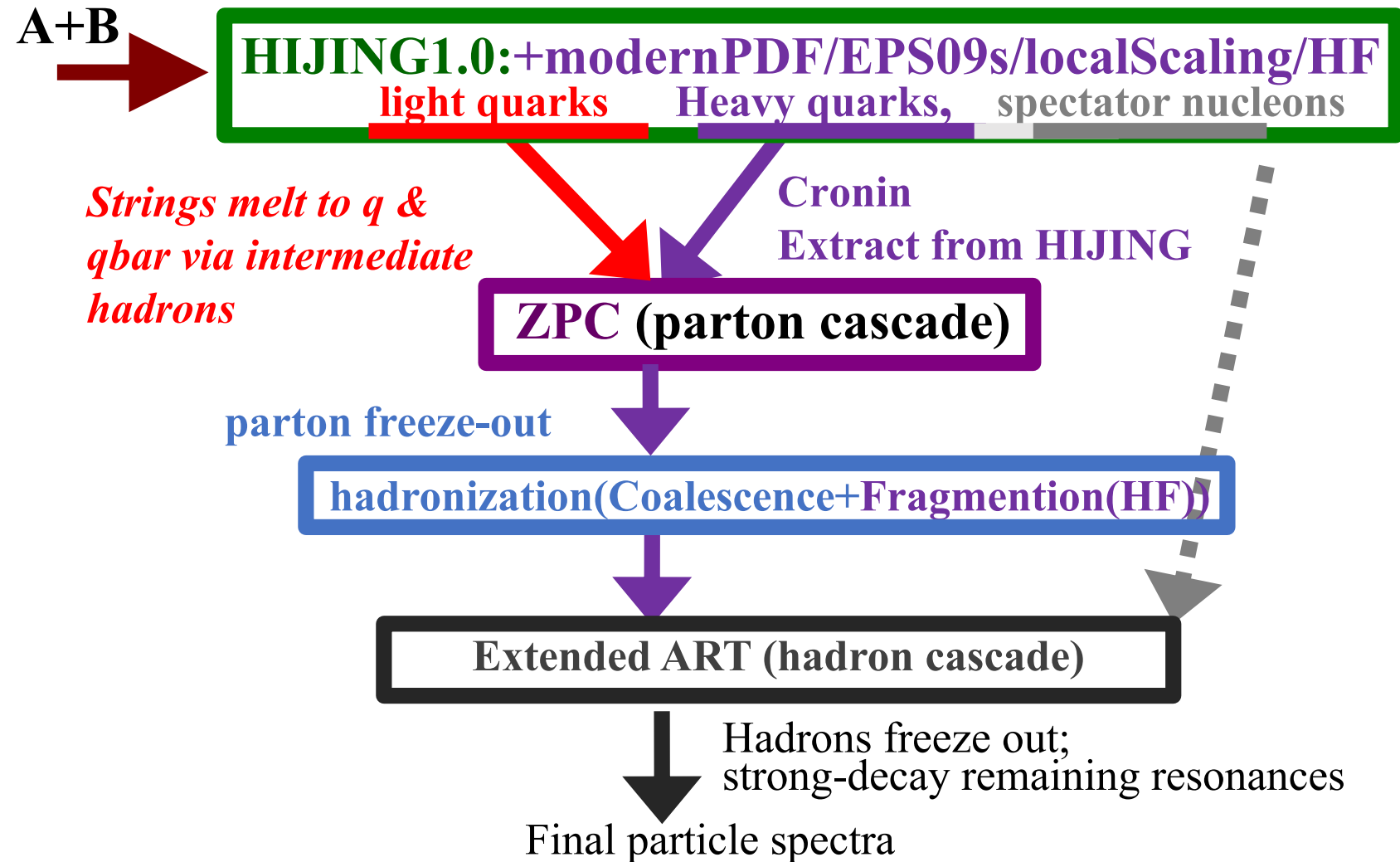
It was constructed as a self-contained kinetic description of heavy ion collisions:

- evolves the system from initial condition to final observables;
- particle productions of all flavors from low to high p_T ;
- addresses non-equilibrium evolution/dynamics (*more important for smaller systems*).

ZWL, Ko, Li, Zhang & Pal, PRC (2005);
ZWL & Zheng, NST (2021)



Structure of improvedAMPT (String Melting version)



The AMPT model used in this study contains all these improvements

Local scaling for self-consistent size dependence in AMPT

Lund symmetric string fragmentation function: $f(z) \propto z^{-1}(1-z)^{a_L} e^{-b_L m_T^2/z}$

b_L typical values (in $1/\text{GeV}^2$):

~ 0.58 (PYTHIA6.2), 0.9 (HIJING1.0), 0.7 - 0.9 (AMPT for pp)

$b_L \sim 0.15$ is needed for string melting AMPT to describe
the bulk matter at high energy AA collisions.

ZWL, PRC (2014)

This corresponds to a much higher string tension:

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

ZWL et al. PRC (2005)

pp and AA collisions need different values of b_L ;

Chao Zhang et al. PRC (2019)

same for minijet cutoff p_0 (for modern PDFs, is related to $Q_s \propto A^{1/6}$)

Zheng et al. PRC (2020)

→ We scale them with local nuclear thickness functions:

$$b_L(s_A, s_B, s) = \frac{b_L^{pp}}{[\sqrt{T_A(s_A)T_B(s_B)}/T_p]^{\beta(s)}}$$

$$p_0(s_A, s_B, s) = p_0^{pp}(s) [\sqrt{T_A(s_A)T_B(s_B)}/T_p]^{\alpha(s)}$$

Chao Zhang et al. PRC (2021)

We fit charged hadron $\langle p_T \rangle$ in pp to determine $b_L^{pp} = 0.7$,

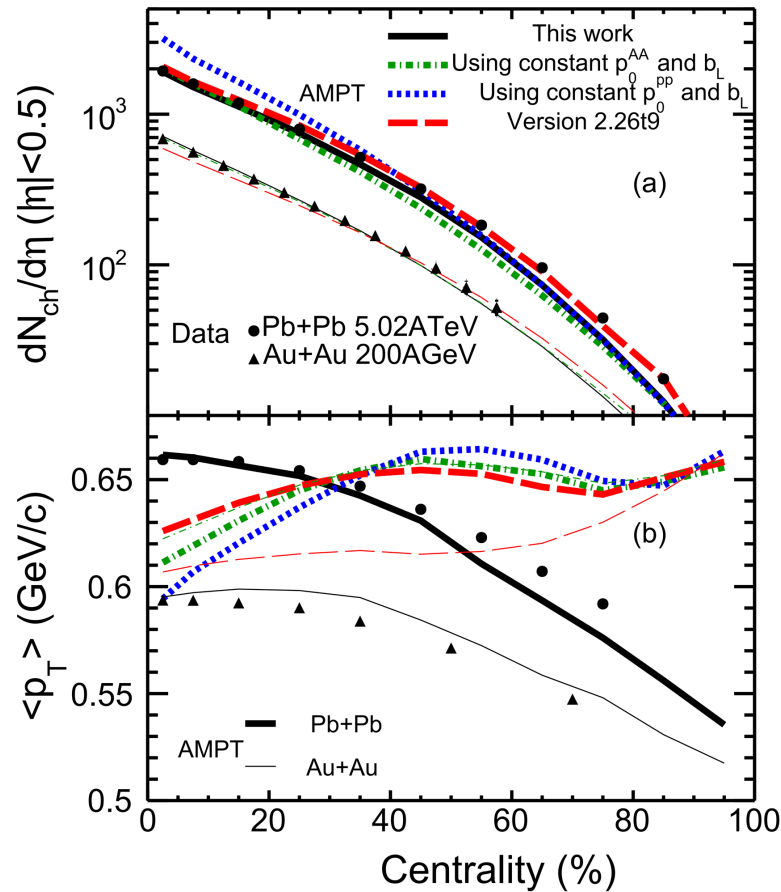
then used central AuAu/PbPb $\langle p_T \rangle$ data to determine $\alpha(s)$, $\beta(s)$ versus energy

Local scaling for self-consistent size dependence in AMPT

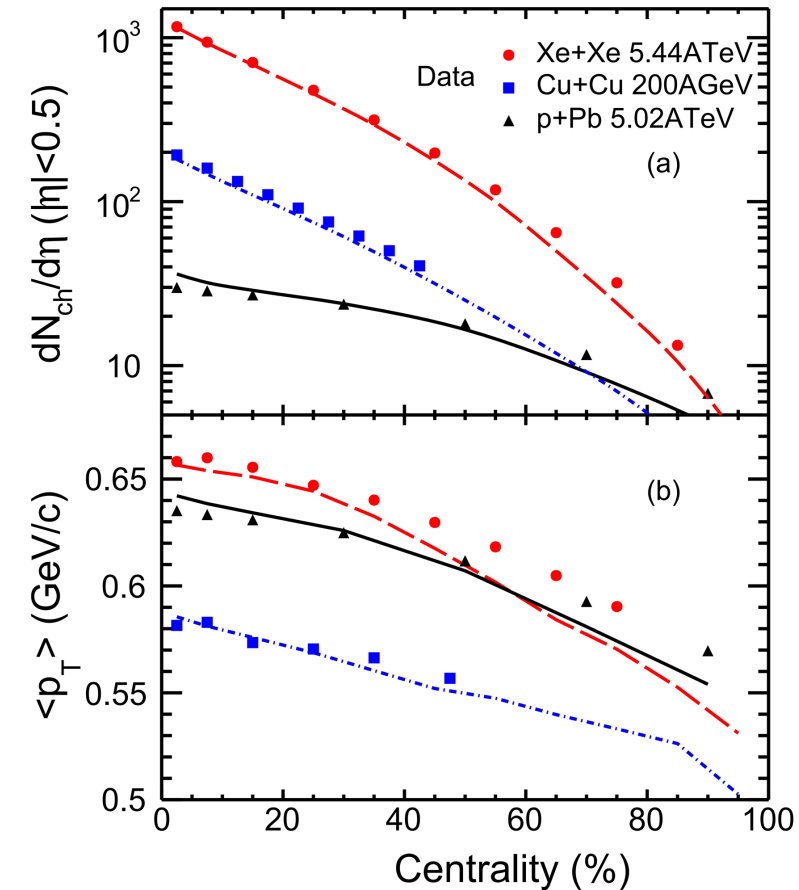
The scaling allows AMPT to self-consistently describe the system size dependence,

including centrality dependences of AuAu & PbPb:

Chao Zhang et al. PRC (2021)

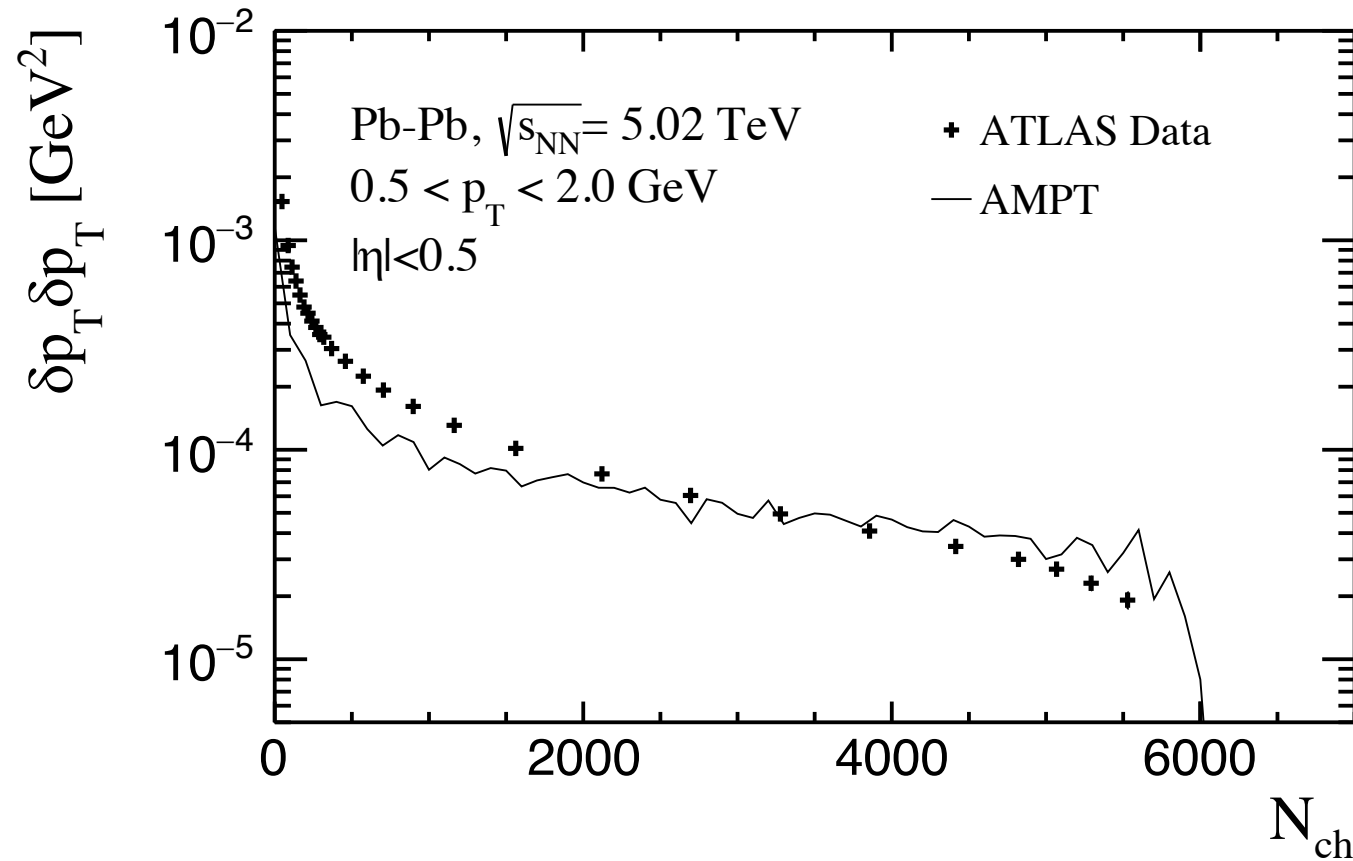


Centrality dependence of $\langle p_T \rangle$ is now reasonable, while previous/public AMPT (v2.26t9) fails



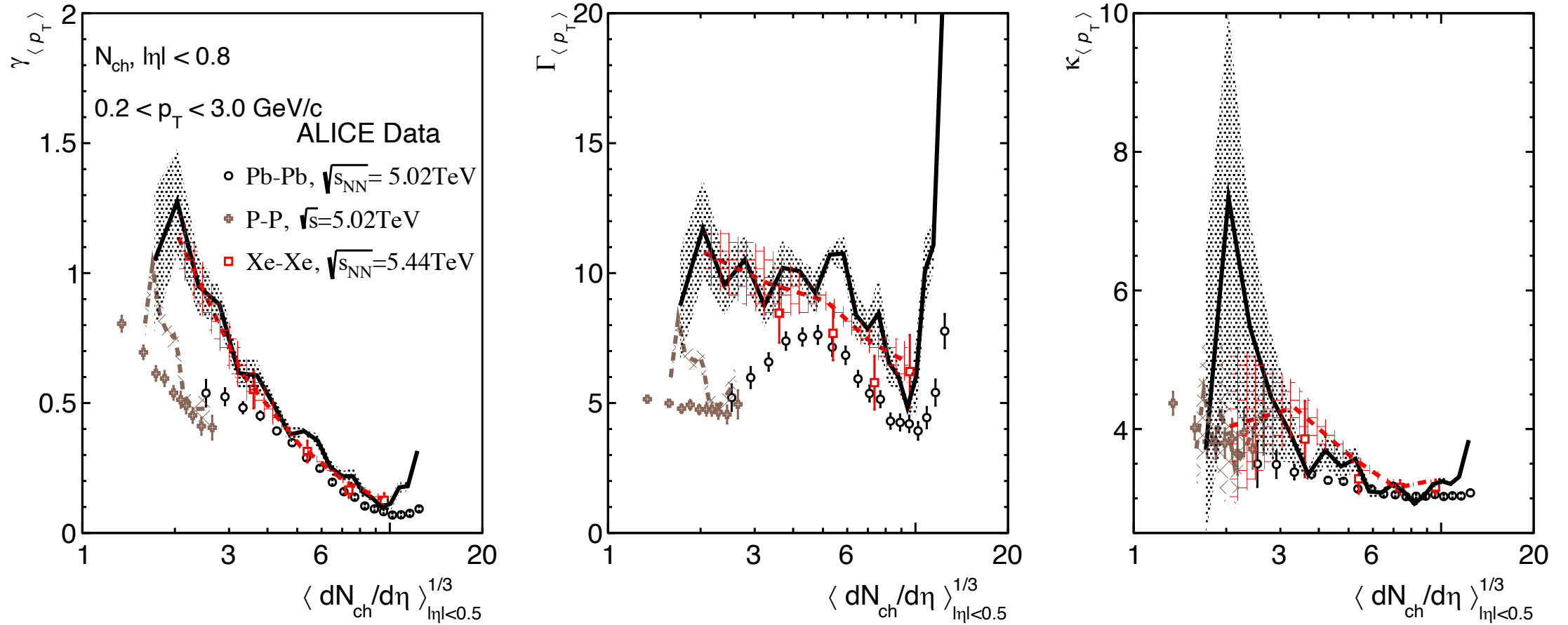
Also works for smaller systems

The variance



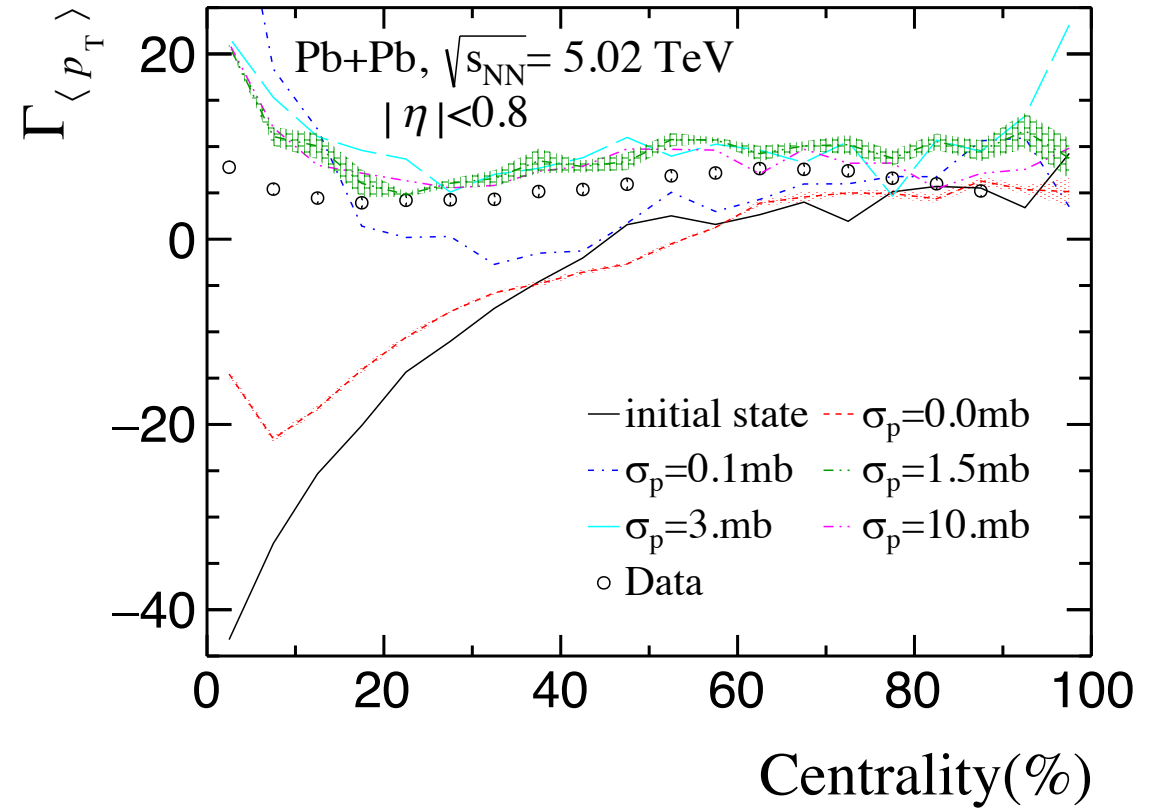
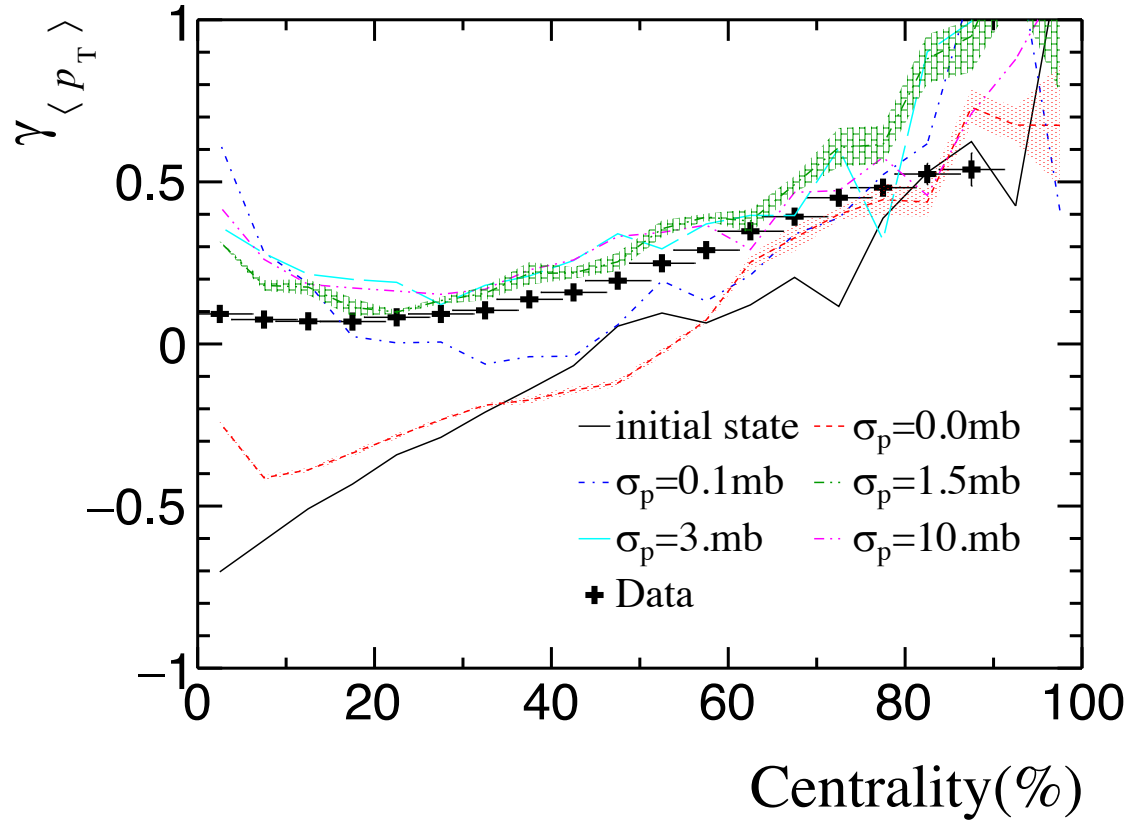
- The AMPT model can reasonably describe the variance of mean transverse momentum fluctuations at LHC.

Results



- Black: Pb+Pb collisions, Red: Xe+Xe collision, brown: pp collisions
- The AMPT model can reasonably describe the experimental data across all three systems, although it tends to overestimate the $\Gamma_{\langle p_T \rangle}$ for Pb+Pb collisions.
- AMPT model captures the non-monotonic behavior of the $\Gamma_{\langle p_T \rangle}$ as function of centrality.

The final state effects

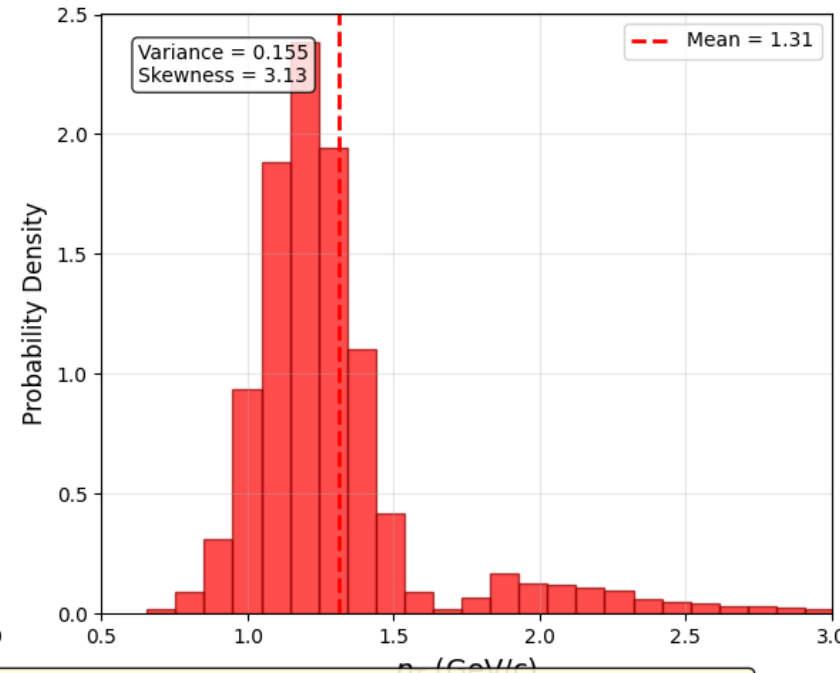
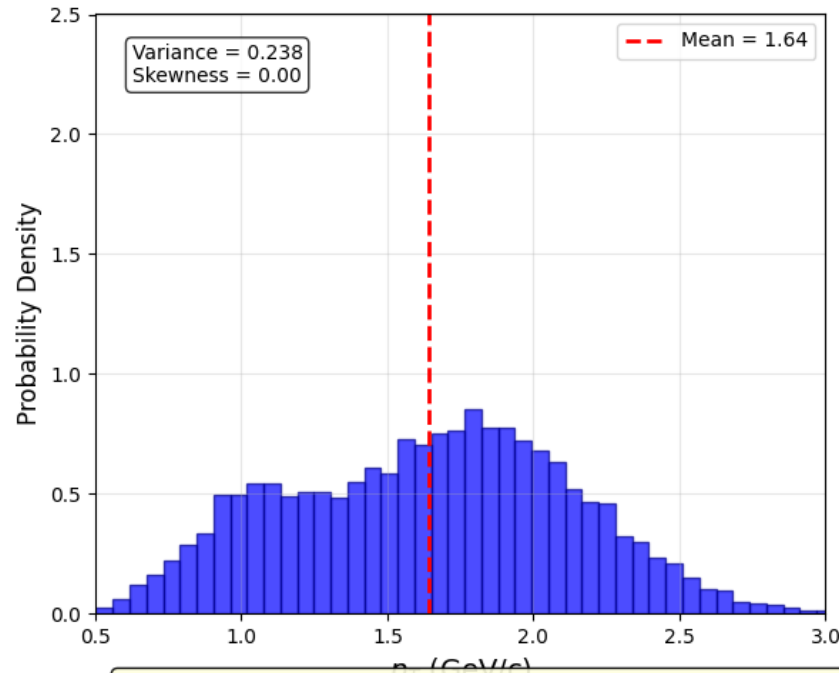
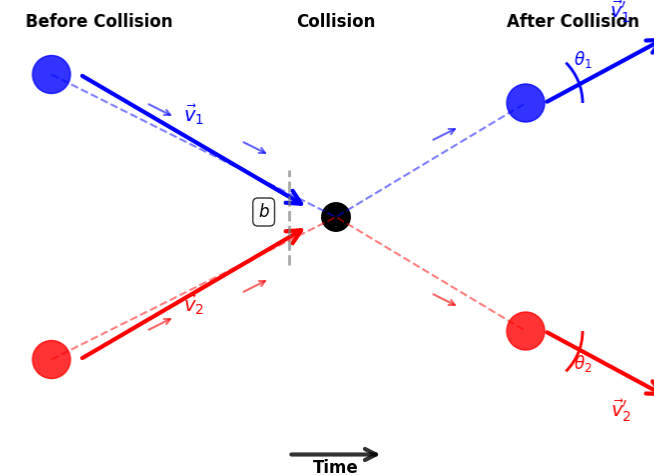


- The initial state: effectively turning off the ZPC and ART.
- The final state effects leads to the increase of both $\Gamma_{\langle p_T \rangle}$ and $\gamma_{\langle p_T \rangle}$ for most central collision

More on final state Effects

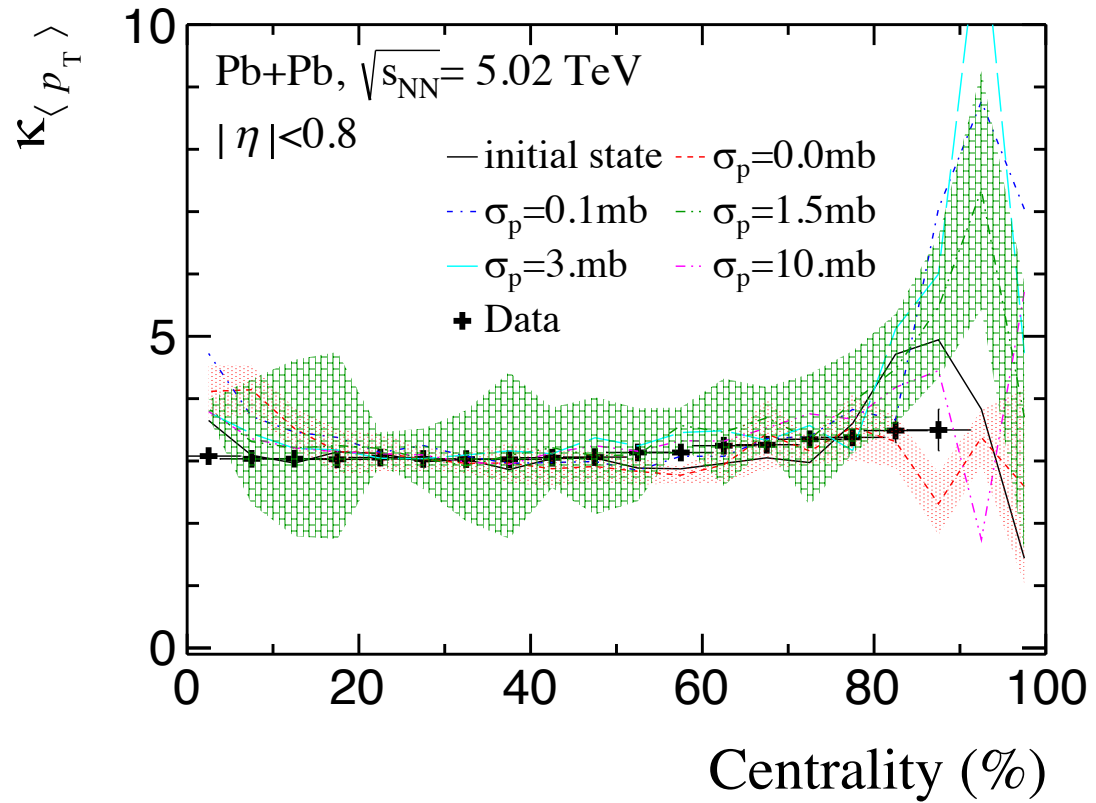
- The soft particle (low p_T) dominates leads to a negative skewness when there is no final state interactions.
- Parton scatterings thermalize the system, resulting in a reduction of both $\langle p_t \rangle$ and its variance.
- In contrast, rare hard scatterings generate high- p_t particles, leading to a positive skewness in the distribution.

Laboratory Frame: Two Moving Particles, Non-Central Collision



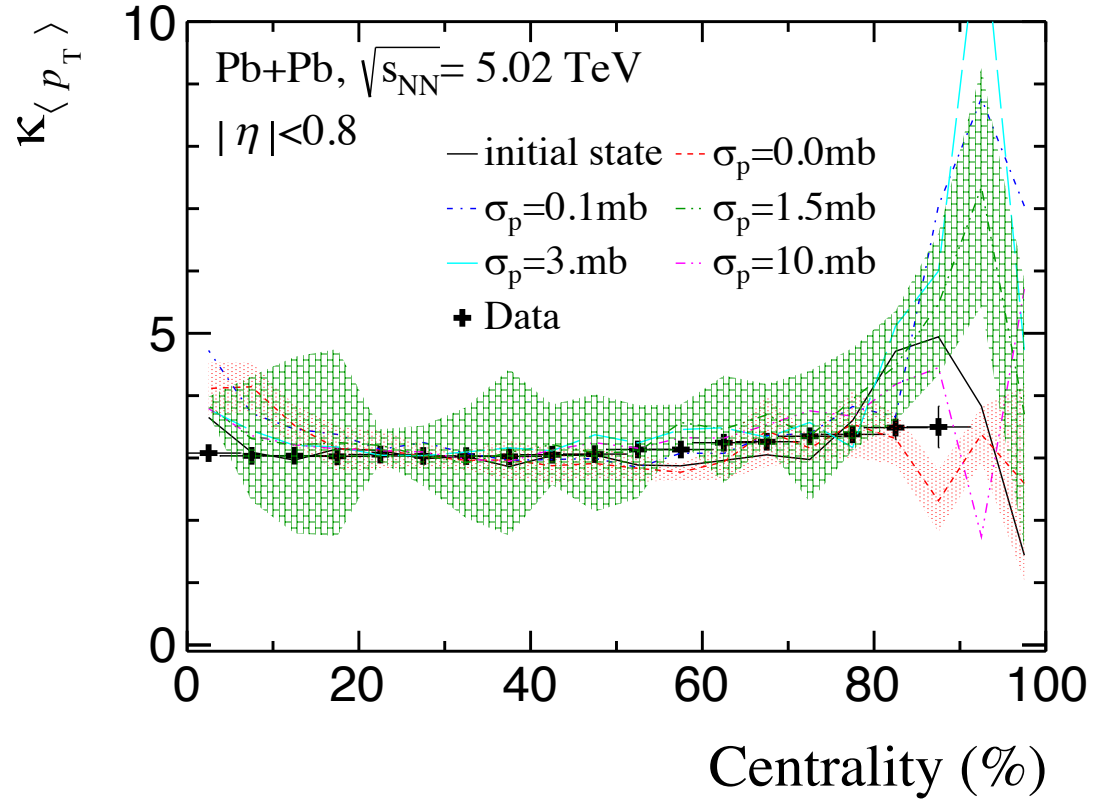
Final state interactions thermalizes the bulk (reducing mean p_T and variance) while creating rare hard kicks (producing positive skew)

The kurtosis

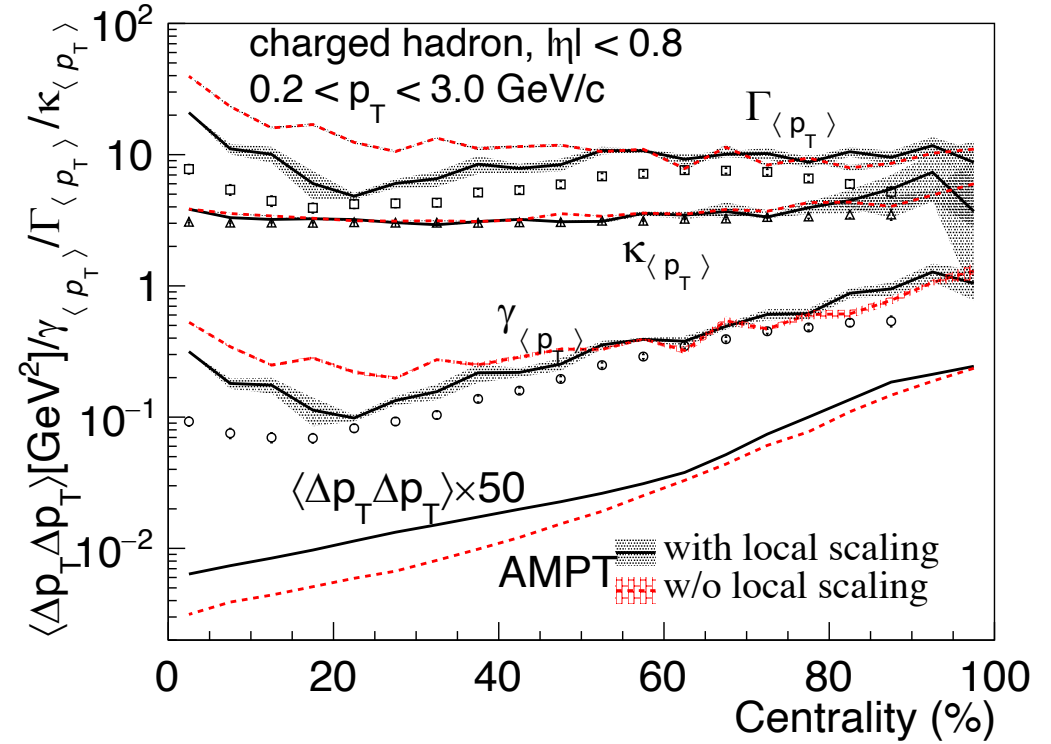


- The kurtosis is not sensitive to the final state effects.

The local scaling Effects



- The kurtosis is not sensitive to the final state effects.



- The variance of $\langle p_T \rangle$ increase with local scaling due to the fluctuation of string tension.
- The $\Gamma_{\langle p_T \rangle}$ and $\gamma_{\langle p_T \rangle}$ decreases with local scaling due to the increase of variance

Summary

- We have studied the skewness and kurtosis of mean transverse momentum fluctuations in Pb+Pb, Xe+Xe and pp collisions at LHC energies with an improved multi-phase transport model;
- The improved AMPT model can provide a reasonable description of the data in all three collision systems;
- The final state effects is found important in reproducing the centrality dependence of the skewness.

Workshop on Transport Approaches for Extreme Nuclear Matter at RHIC-BES and Beyond

Dec 19 – 22, 2025

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The **Workshop on Transport Approaches for Extreme Nuclear Matter at RHIC-BES and Beyond** will be held in Wuhan, Hubei, on December 19–22, 2025. The workshop is jointly organized by Central China Normal University, Wuhan University of Technology, China University of Geosciences (Wuhan) and Wuhan Textile University, with Central China Normal University serving as the local host.

This workshop is dedicated to advancing the development, application, and critical assessment of **transport models** in the study of nuclear matter under extreme conditions, particularly in the context of relativistic heavy-ion collisions at RHIC-BES and future experimental programs. Transport approaches play a vital role in describing the dynamical evolution of these collisions across a broad energy range, especially where nonequilibrium effects and complex microscopic interactions dominate.

The workshop will bring together a diverse community of theorists and experimentalists to exchange ideas on the current state of transport modeling, including hadronic and partonic transport, hybrid frameworks, and the treatment of rare probes and fluctuations. Through focused discussions and collaborative sessions, the workshop aims to foster cross-model comparisons, highlight areas for improvement, and identify key observables and strategies that can guide future model development and experimental analyses. The ultimate goal is to strengthen the theoretical foundations and predictive power of transport models in support of current and next-generation heavy-ion collision programs.

Date:

- December 19: Registration and free discussion
- December 20–21: Workshop on Transport Approaches for Extreme Nuclear Matter at RHIC-BES and Beyond
- December 22: Free discussion and departure

Venue: Room 9409 (on 4th floor) of Bldg. 9 at CCNU

Accommodation: Accommodation at Guiyuan Hotel can be booked at the registration page.

Website: <https://indico.ihep.ac.cn/event/26058/>

Registration Fee: 1500 RMB (教师/博后), 1000RMB (学生) (collected at the registration)

Registration Period: September 4 – December 15, 2025

Abstract Submission Deadline: September 4 – December 15, 2025

Conference registration and abstract submission are now open. We warmly welcome you to register and submit your presentation title.



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