Exploring Origin of $[p_T]$ Fluctuations in Ultra-Central Pb+Pb and Xe+Xe Collisions with ATLAS

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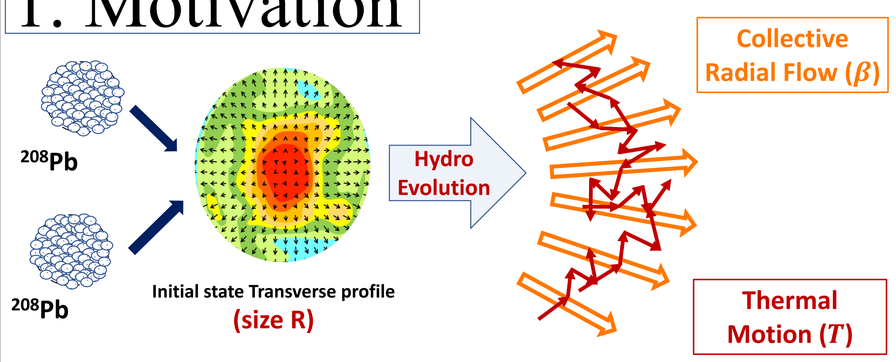
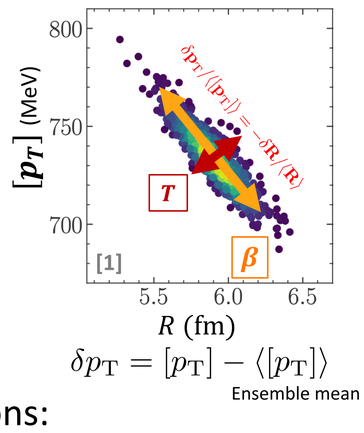
1. Motivation





$\delta p_T = [p_T] - \langle [p_T] \rangle$ Ensemble mean

➢ Two sources of $[p_T]$ fluctuation in heavy ion collisions:

Geometrical fluctuation → Radial Flow fluctuation → Expected to follow a power law

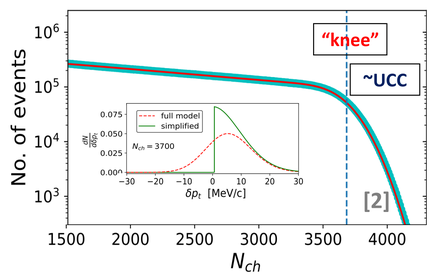
$$\frac{\delta p_T}{\langle [p_T] \rangle} \rightarrow \left(\frac{\delta p_T}{\langle [p_T] \rangle}\right)^2 \propto \left(\frac{\delta R}{\langle R \rangle}\right)^2 \propto \sim \frac{1}{N_{part}}$$

Variance

Non-Geometrical (intrinsic) → Quantum fluc. :IS + Thermal fluc. :QGP

$$\propto \frac{1}{N_{sources}} \sim \frac{1}{N_{part}}$$

➢ **Main idea**: Narrow the size fluctuation and expose the intrinsic fluctuation in UCC.



➢ with ↑ N_{ch} in Ultra-Central Collisions (UCC),

- Geometrical fluctuations are constrained,
- Fluctuations depart from power-law scaling.

↑ Mean, ↓ Variance & ↑ skewness of $[p_T]$ distribution, P($[p_T]$):

➢ **GOAL:** Isolate "*Geometrical*" from "*Intrinsic*" fluctuations using $[p_T]$ cumulants.

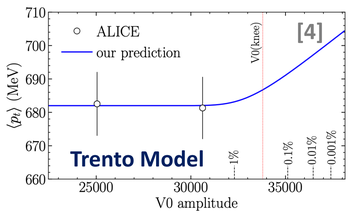
2. Observables and Expectations

- n-particle correlators: $\langle c_2 \rangle = \langle \delta p_{T,i_1} \delta p_{T,i_2} \rangle$ $\langle c_3 \rangle = \langle \delta p_{T,i_1} \delta p_{T,i_2} \delta p_{T,i_3} \rangle$

➢ Cumulants of $[p_T]$ distribution (P($[p_T]$)):

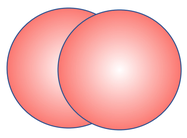
$\langle [p_T] \rangle$ Mean; $k_2 = \frac{\langle c_2 \rangle}{\langle [p_T]^2 \rangle}$ Variance; $k_3 = \frac{\langle c_3 \rangle}{\langle [p_T]^3 \rangle}$ Skewness; $\gamma = \frac{\langle c_3 \rangle}{\langle c_2 \rangle^{(3/2)}}$ [3] Normalized Skewness

1. From Independent source model, expect: $k_n \propto 1/N_{ch}^{(n-1)}$
2. In UCC, larger Radial flow is predicted with ↑ N_{ch} (using Trento).
3. 2D-Gaussian Model: $[p_T]$ fluctuations arise from:

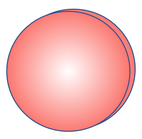


Geometric fluctuations: fluctuations in R at fixed N_{ch}
Intrinsic Fluctuations: fluctuations of N_{ch} at fixed b.
} Both assumed Gaussian

Peripheral to Central collisions:
Geometric + Intrinsic fluctuations have similar contributions

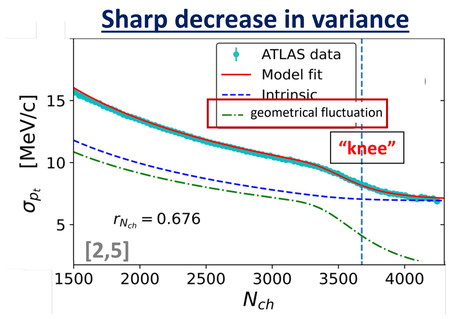


Ultra-Central collisions:
Approaches Max overlap. area , Geometrical fluctuations constrained

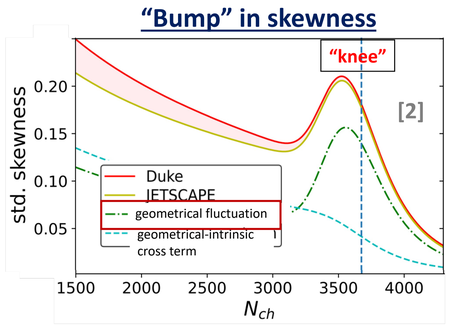


- 2D-Gaussian Model Predicts:

Sharp decrease in variance



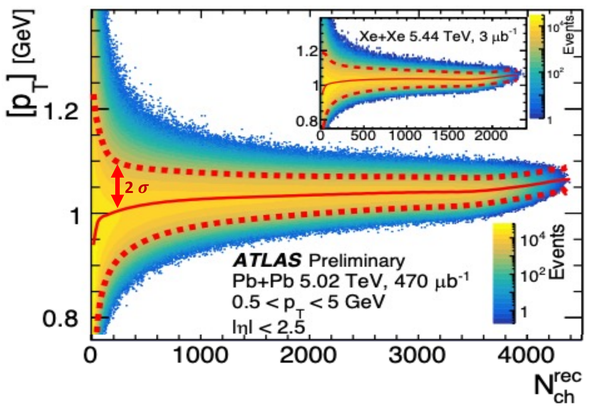
"Bump" in skewness

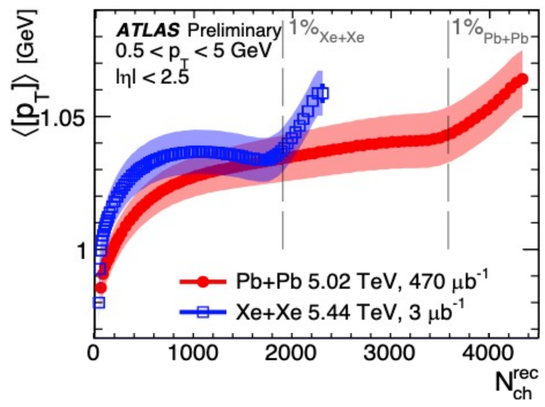


➢ Using $[p_T]$ cumulants, aim to study:
1. Scaling behavior of $[p_T]$ cumulants, k_n according to independent source model.
2. Role of Geometric and Intrinsic fluctuations towards final state $[p_T]$ cumulants.

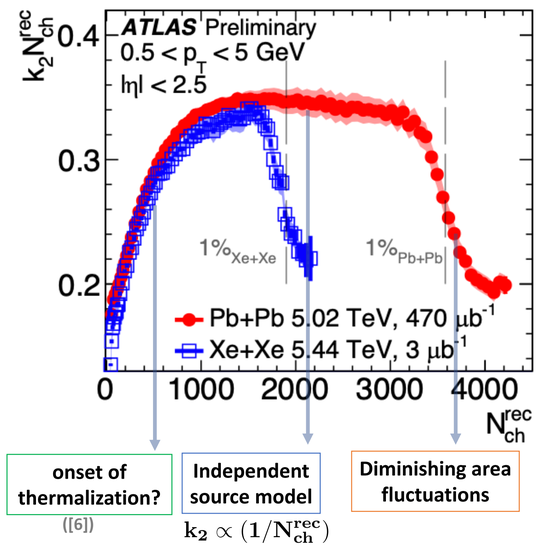
3. Results: Evolution of fluctuations with N_{ch}

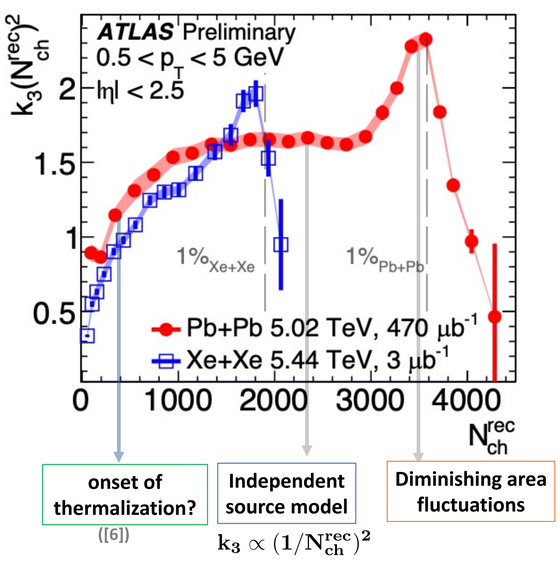
➢ Measurement for Pb+Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV and Xe+Xe collisions at $\sqrt{s_{NN}}$=5.44 TeV.





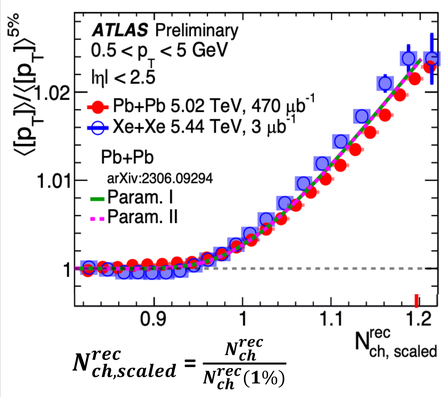
➢ Gradual rise of $\langle [p_T] \rangle$ from peripheral to central collisions, sharp rise in UCC.

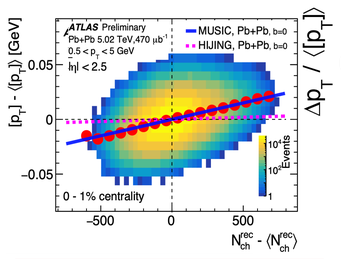




➢ Fluctuations follow expected power law scaling only approximately.

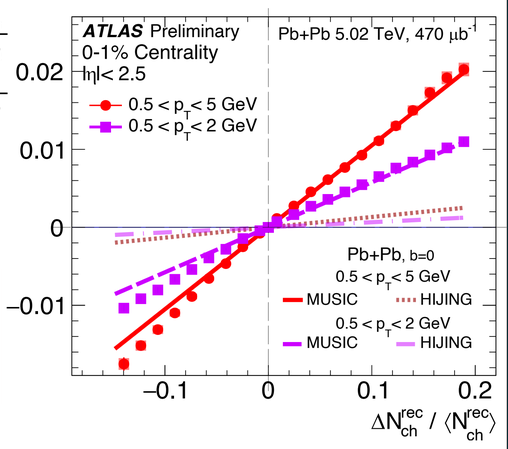
4.Results: Effect of vanishing area fluctuations





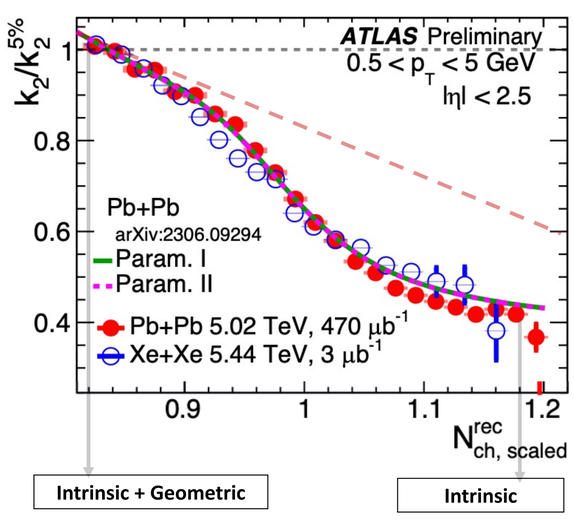
$c_s^2 = \frac{d \ln T}{d \ln s} = k \frac{d \ln [p_T]}{d \ln N_{ch}} = k \frac{\Delta p_T / [p_T]}{\Delta N_{ch} / N_{ch}}$

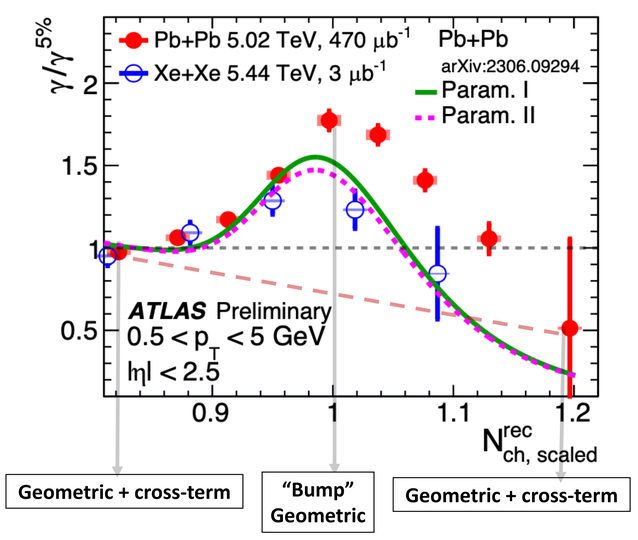
k : dependent on spectra shape and p_T-range



➢ Magnitude of rise in $\langle [p_T] \rangle$ in UCC is dependent on p_T - range of particles.

➢ $\langle [p_T] \rangle$ increase in UCC consistent with Hydro model (Not Hijing).





➢ Clear signatures of Interplay b/w Intrinsic and geometric fluctuations in $[p_T]$ fluctuations.

➢ 2D Gaussian model Comparison: $[p_T]$ fluctuations are approximately Gaussian.

5. Summary & Outlook

➢ Precise measurement of mean, variance and skewness of $[p_T]$ distribution in Pb+Pb and Xe+Xe collisions with ATLAS are presented. The data shows:

1. Variance (k_2) and skewness (k_3) approximately follow independent source scenario $k_n \propto 1/N_{ch}^{(n-1)}$
2. Evolution of purely "Geometric" fluctuation (which gives rise to deviation from overall behavior) with N_{ch} different than "Intrinsic" fluctuations.
   - Difference in overall and UCC behavior of $[p_T]$ cumulants can be used constrain "Geometric" and "Intrinsic" contributions to final state fluctuations
3. Increase in $\langle [p_T] \rangle$ with N_{ch} in UCC captured by MUSIC model. Theoretical input required on $\frac{\Delta T}{T} = k \frac{\Delta p_T}{\langle [p_T] \rangle}$ to reliably extract c_s^2 from $\langle [p_T] \rangle$ rise in UCC.

References: [1] Giacalone, PRC, **102**, 024901 (2020), [2] Samanta et. al, PRC108, 024908 (2023), [3] Bhatta et. al PRC **105**, 024904, [4] Gardim et. al, PLB 809 (2020) 135749, [5] Samanta et. al. 2303.15323, [6] Gavin, PRL.92,162301 (2004).