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NAGASAKI

Investigating initial state of heavy-ion collisions using $[p_T]$ fluctuations and $v_n - [p_T]$ correlations in ATLAS

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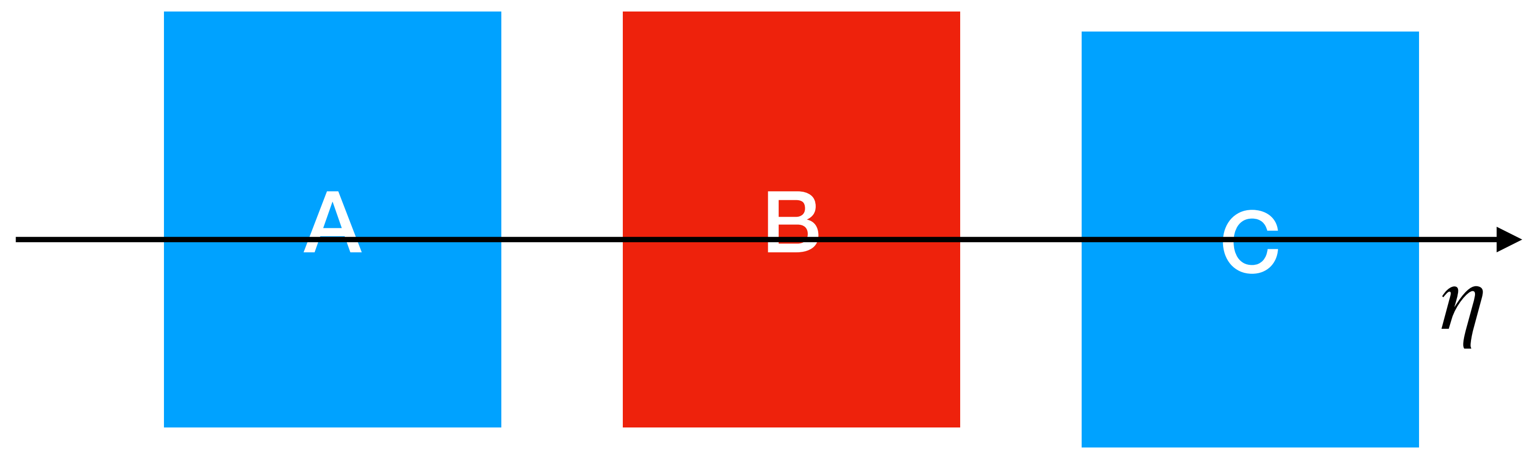
ATLAS EXPERIMENT

Correlations between flow and transverse momentum in Xe+Xe and Pb+Pb collisions at the LHC with the ATLAS detector: a probe of the heavy-ion initial state and nuclear deformation

PHYSICAL REVIEW C 107, 054910 (2023) / arXiv:2205.00039

- ATLAS measured $v_n - [p_T]$ correlation coefficient ρ in Pb+Pb (and p+Pb)
    - Precise tool for initial stage imaging - sensitive to correlation between energy density & initial state deformation - not so much on details of QGP evolution (e.g. Giacalone et al Phys. Rev. C 103, 024909 (2021))
- The measurement of ρ in Xe+Xe relative to Pb+Pb indicated difference between them - attributed to the shape of Xe nuclei
- The $[p_T]$ & c_k also exhibit an interesting evolution: investigated in followup measurement

Measurement details



$$\rho_n = \frac{\mathrm{cov}_n}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{c_k}}, \qquad \mathrm{cov}_n = \left\langle\!\left\langle v_n^2 \delta p_{\mathrm{T}} \right\rangle\!\right\rangle,$$

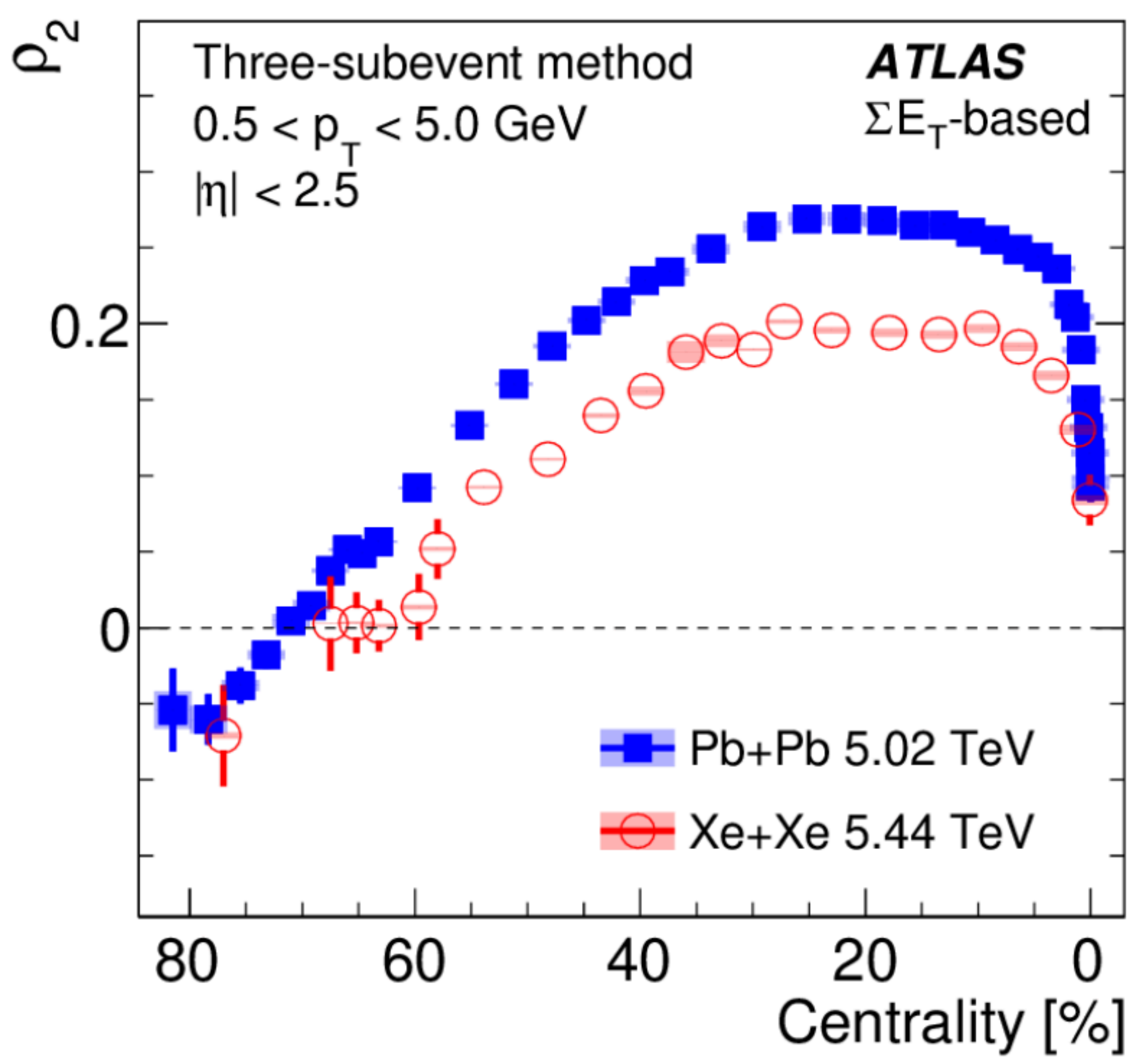
$$\mathrm{var}\left(v_n^2\right) = \left\langle v_n^4 \right\rangle - \left\langle v_n^2 \right\rangle^2, \qquad c_k = \langle\langle \delta p_{\mathrm{T}} \delta p_{\mathrm{T}} \rangle\rangle.$$

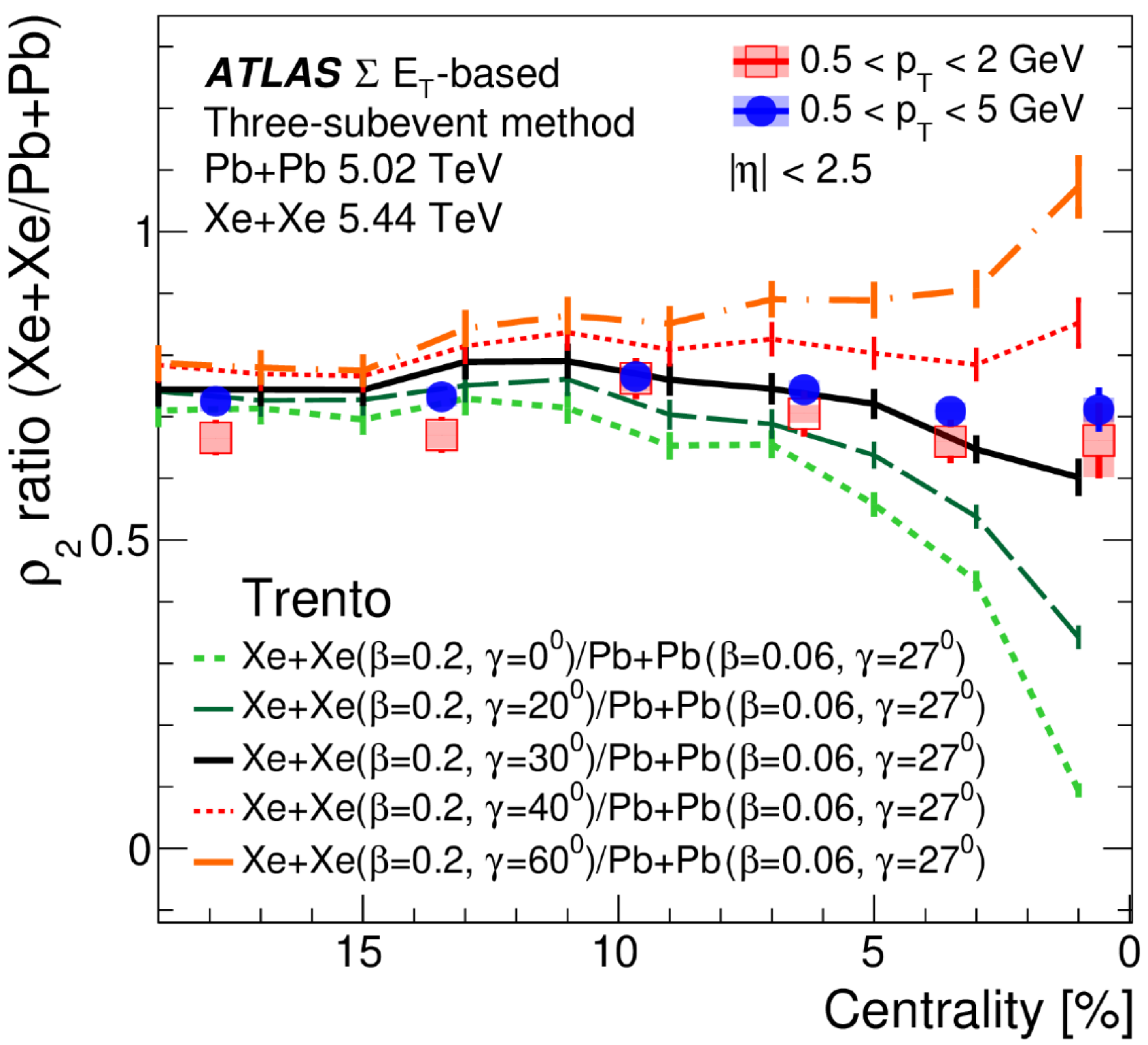
Where: $\delta p_T = p_T - \left\langle [p_T] \right\rangle$

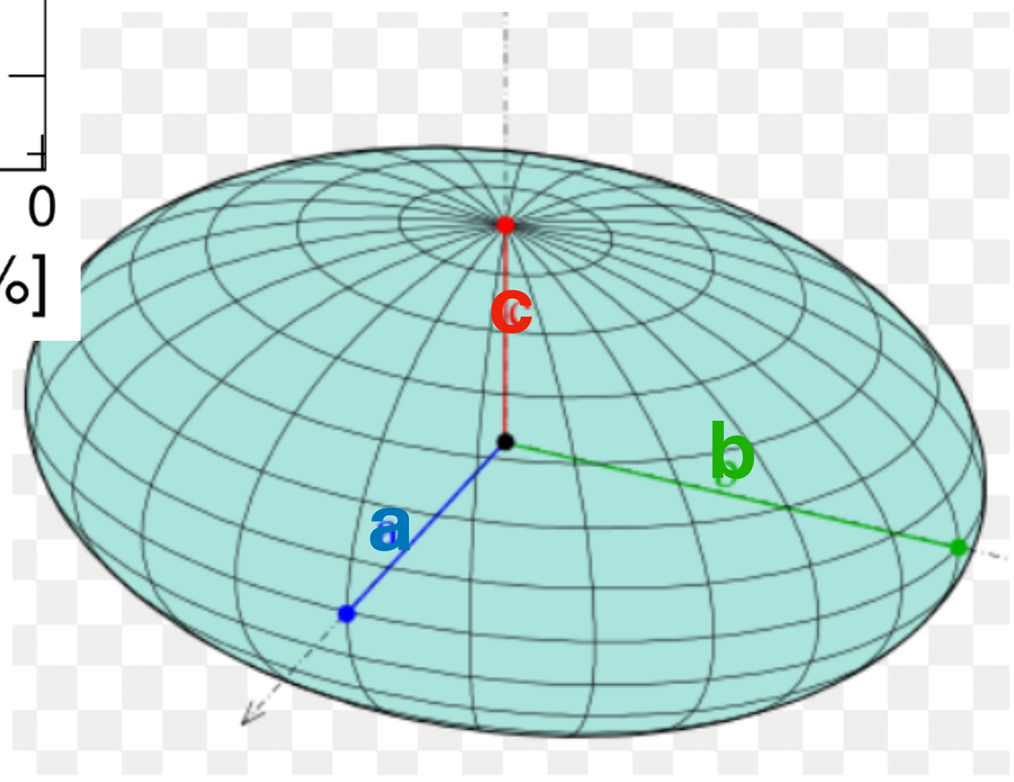
Various methods to combined information from sub-events:
standard - all particles used,
2 sub-events only A & C
3 sub-events A & C for $v_n\{2\}$ and B for c_k

ρ_2 in Pb+Pb, Xe+Xe and its ratio

PHYSICAL REVIEW C 107, 054910 (2023)





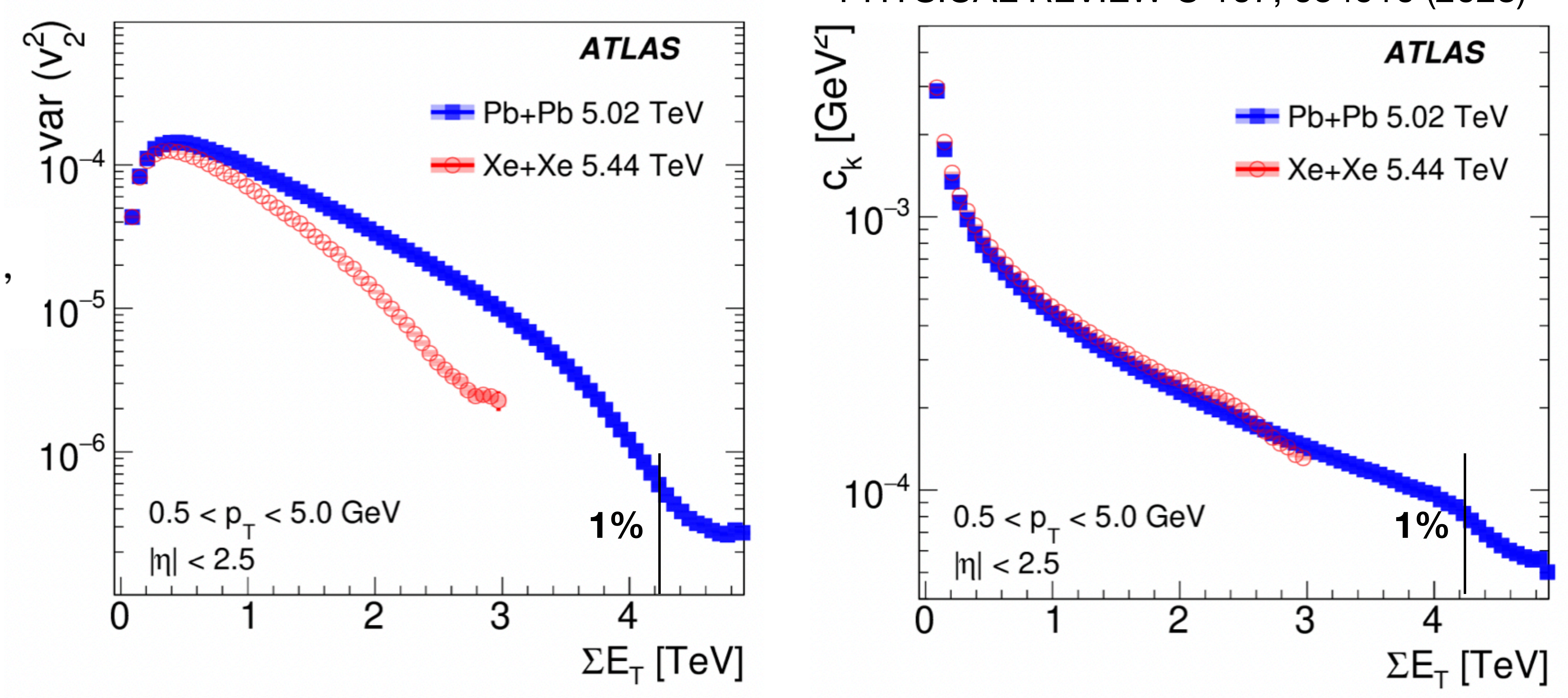


- Significant variation with centrality
- Different between the Xe+Xe and Pb+Pb, yet the ratio almost constant
- The ratio sensitive to initial projectiles shape
  - a very good description in simulation (Trento) allowed data to discern Xe nuclei shape - it is strongly triaxial: $a \neq b \neq c$

The Ultra Central events (UCC)

PHYSICAL REVIEW C 107, 054910 (2023)

$$\rho_n = \frac{\mathrm{cov}_n}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{c_k}},$$



- In the UCC, $b \rightarrow 0$, (about 1.5% most central) the trends of ρ but also Var, c_k change behaviour
- The $b \rightarrow 0$ reduces the initial geometry fluctuations and thus reduced variance of flow harmonics
- Trend in c_k (measure of momentum fluc.) also change, reduced fluctuations - investigated further

b - impact parameter

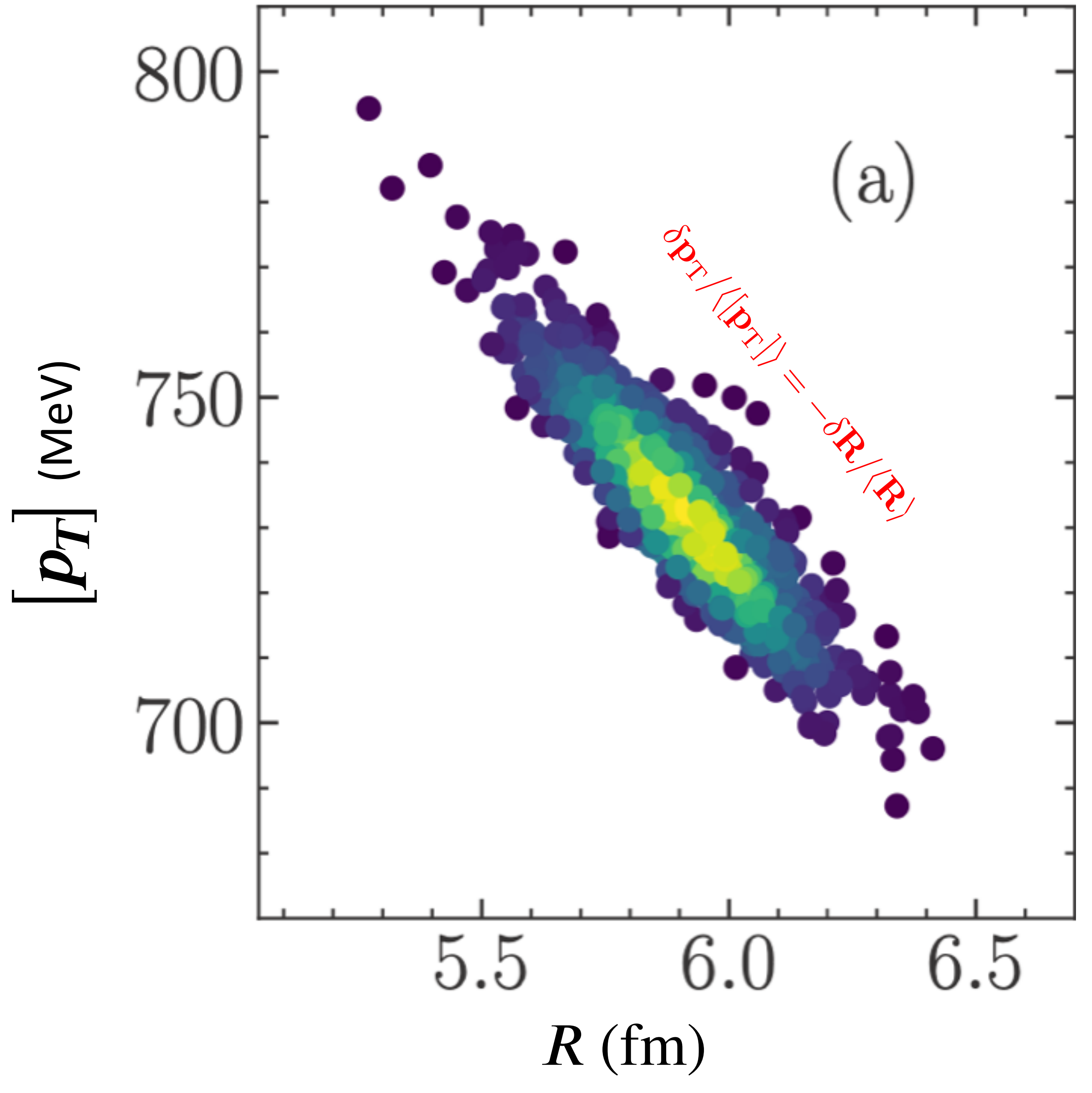
Disentangling sources of momentum fluctuations in Xe+Xe and Pb+Pb collisions with the ATLAS detector

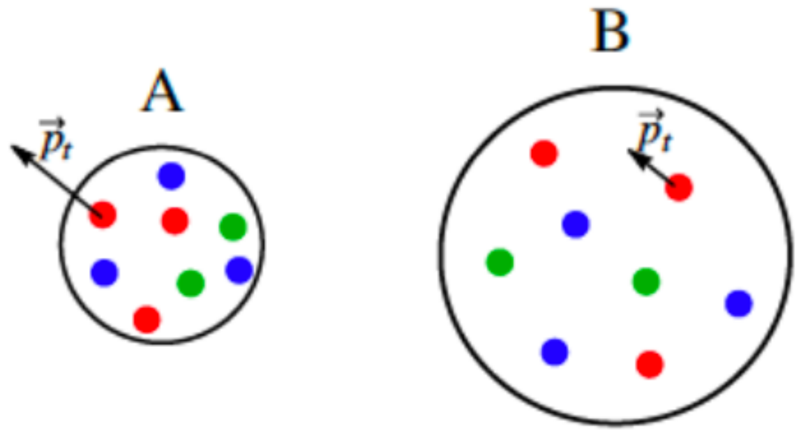
HION-2021-20 / arXiv:2407.06413

- Evolution of $[p_T]$ distribution moments with centrality (N_{ch} scaling)
- A close look at the evolution of moments of $[p_T]$ in UCC
- Pb+Pb & Xe+Xe comparison
- Comparison to models aiming at description of $[p_T]$ fluctuation

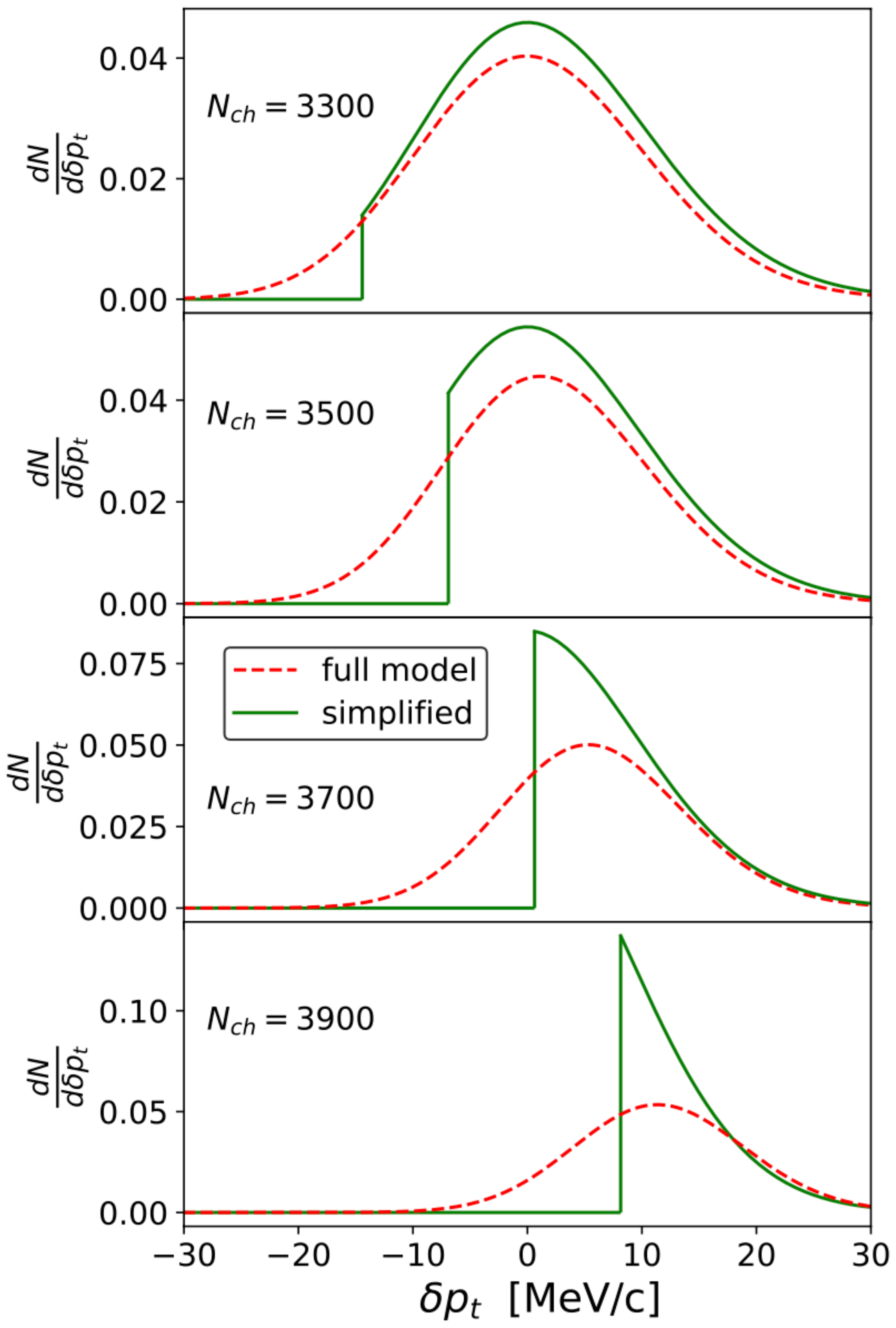
Motivation

Giacalone, PRC, **102**, 024901 (2020)





R. Samanta et al Phys. Rev. C 108, 024908



- Two contributions to $[p_T]$ fluctuations
  - Geometric fluctuation - radial flow
  - Intrinsic fluctuations - quantum (initial state) + thermal (evolution)
- By constraining size fluctuations - going to UCC - access the magnitude of intrinsic part

Measured quantities

- An n-particle transverse momentum correlator defined:

$$c_n = \frac{\sum_{i_1 \neq \dots \neq i_n} w_{i_1}..w_{i_n}(p_{\mathrm{T},i_1} - \langle [p_{\mathrm{T}}] \rangle)\dots(p_{\mathrm{T},i_n} - \langle [p_{\mathrm{T}}] \rangle)}{\sum_{i_1 \neq \dots \neq i_n} w_{i_1}\dots w_{i_n}}$$

- Moments: central $\left\langle [p_T] \right\rangle$, dimensionless scaled variance k_2, scaled skewness k_3, intensive skewness Γ

Where:
$[p_T]$ - mean momentum of particles in an event
$\left\langle [p_T] \right\rangle$ - mean over a class of events

- Averaged over activity class:
  N_{ch}^{rec} - in number of reconstructed charged particles in ATLAS ID
  ΣE_T^{FCal} - energy in ATLAS Forward calorimeter (default centrality estimator)

$$k_2 = \frac{\langle c_2 \rangle}{\langle [p_{\mathrm{T}}] \rangle^2}, \quad k_3 = \frac{\langle c_3 \rangle}{\langle [p_{\mathrm{T}}] \rangle^3}, \quad \Gamma = \frac{\langle c_3 \rangle \langle [p_{\mathrm{T}}] \rangle}{\langle c_2 \rangle^2}$$

  - Estimators scaled for comparison by values in the 0-1% centrality bin, or to the value at 5%

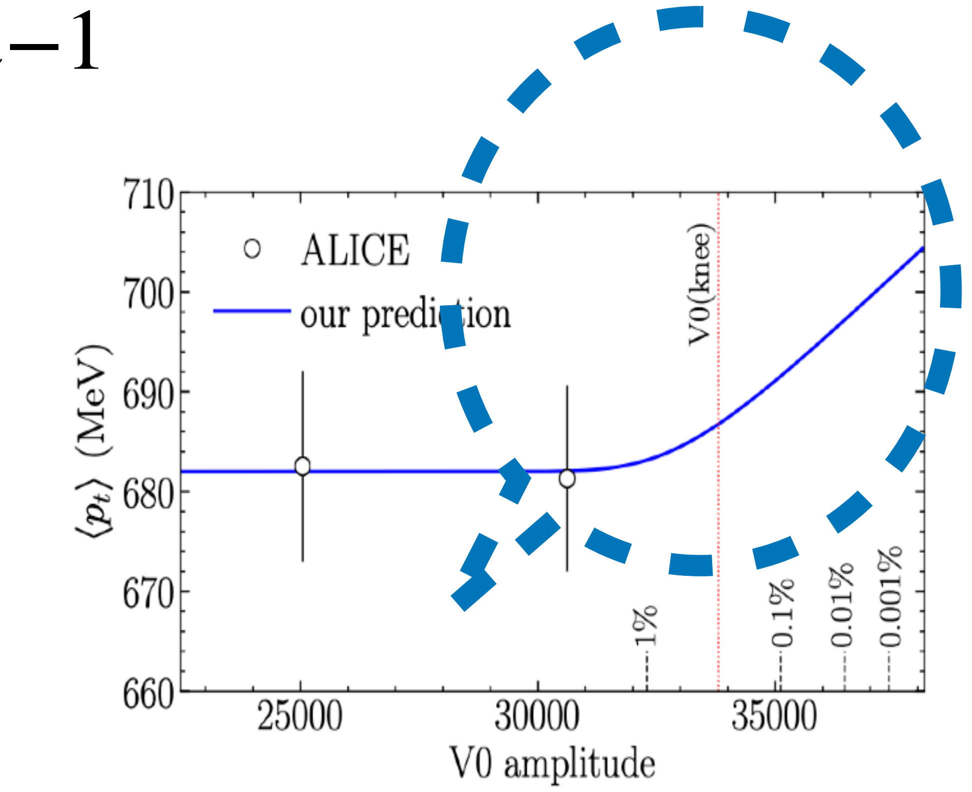
Predictions

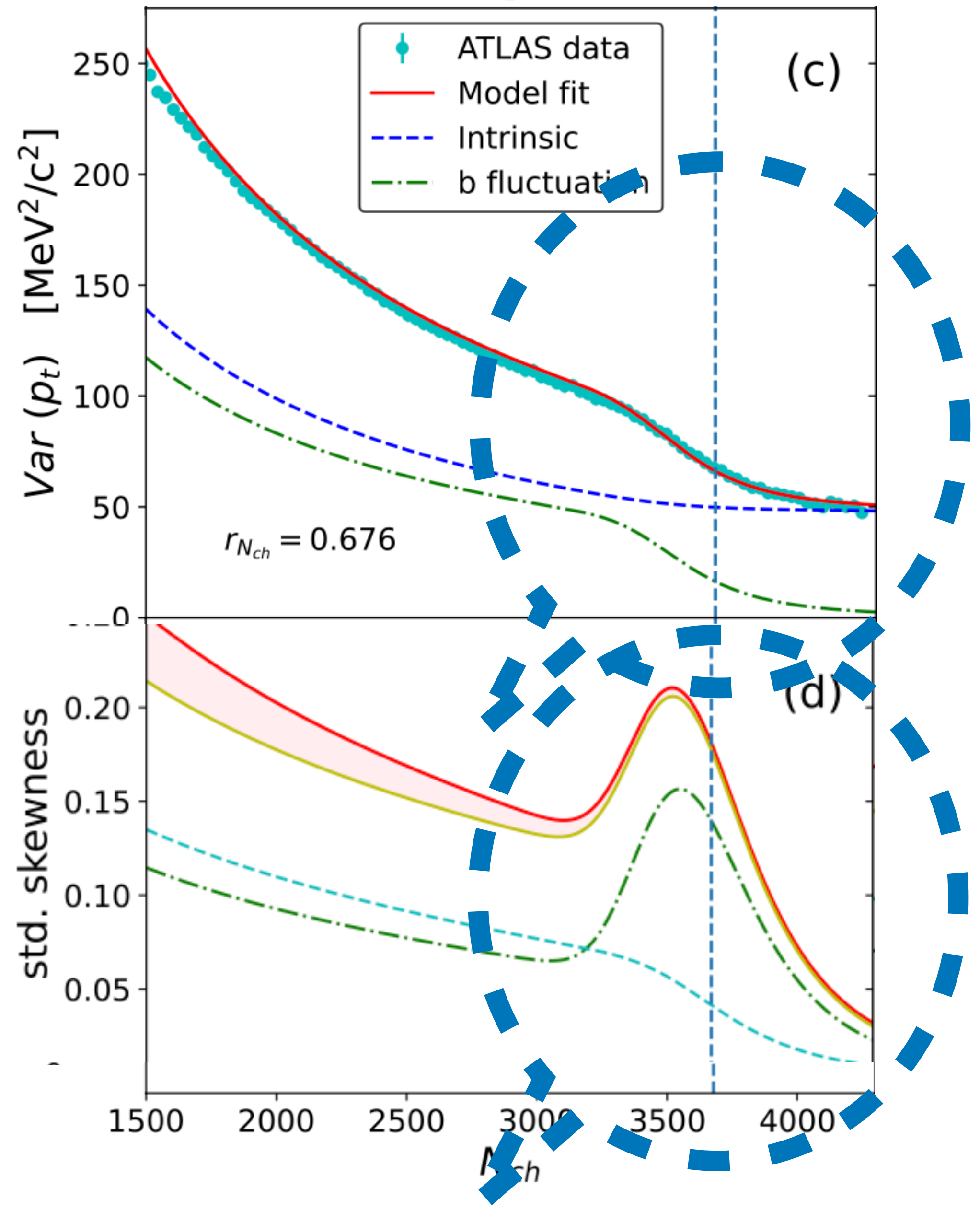
- Independent sources picture - k_n -should evolve with multiplicity following $k_n \propto N^{n-1}$

- In UCC the $[p_T]$ is predicted to rise with centrality 1% -> 0.1% …
and the sound speed in QGP c_s^2 can be obtained from that
F.G. Gardim et al Phys.Lett.B 809 (2020) 135749

- The origin of $[p_T]$ fluctuations proposed to be correlated with b and N_{ch} (2D Gaussian model) captures evolution of moments in mid-central & UCC
R. Samanta et al Phys. Rev. C 109 (2024) L051902

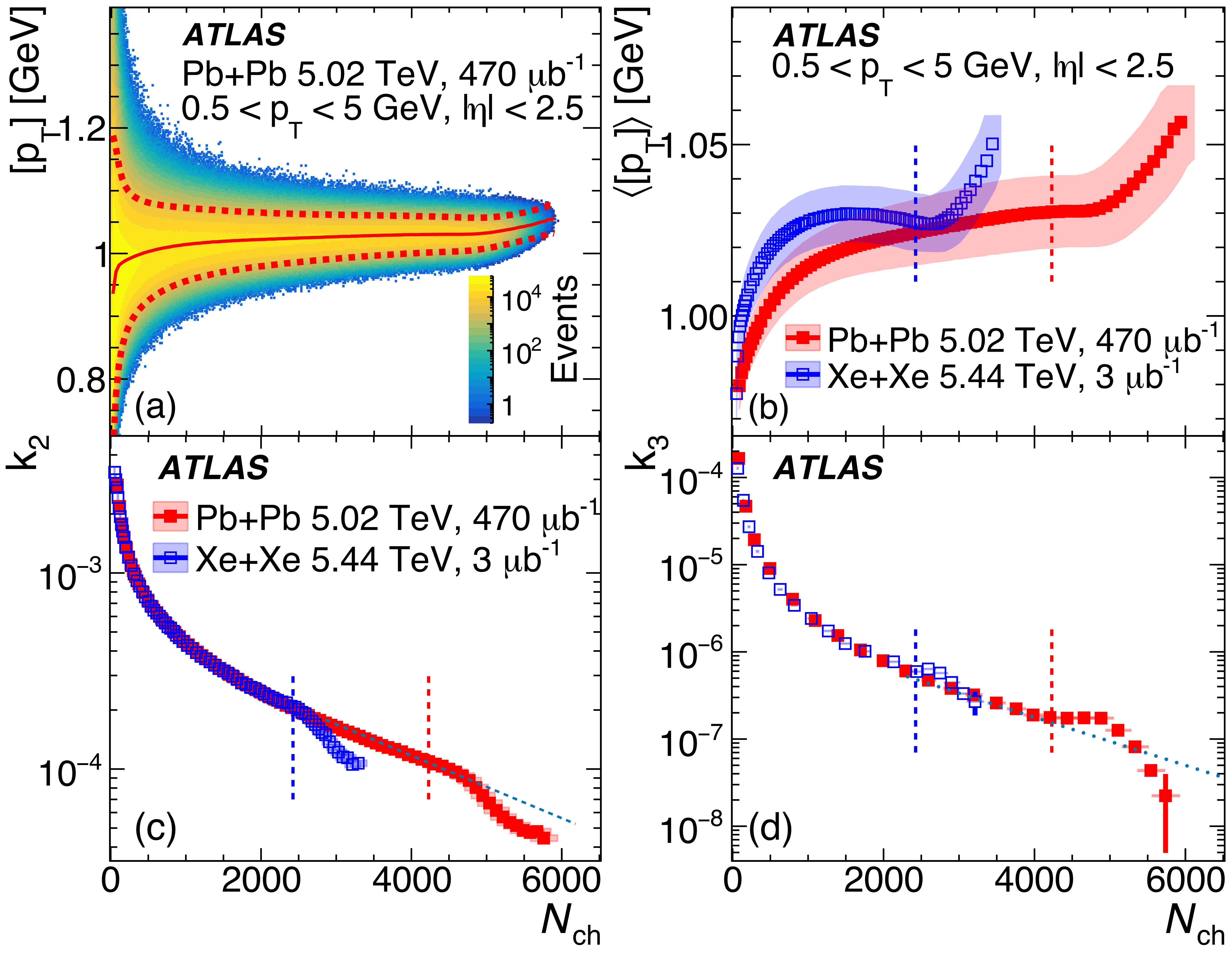
- Within the 2D Gaussian model lower limit on b leads to skewed $[p_T]$ in UCC
R. Samanta et al Phys. Rev. C 108, 024908





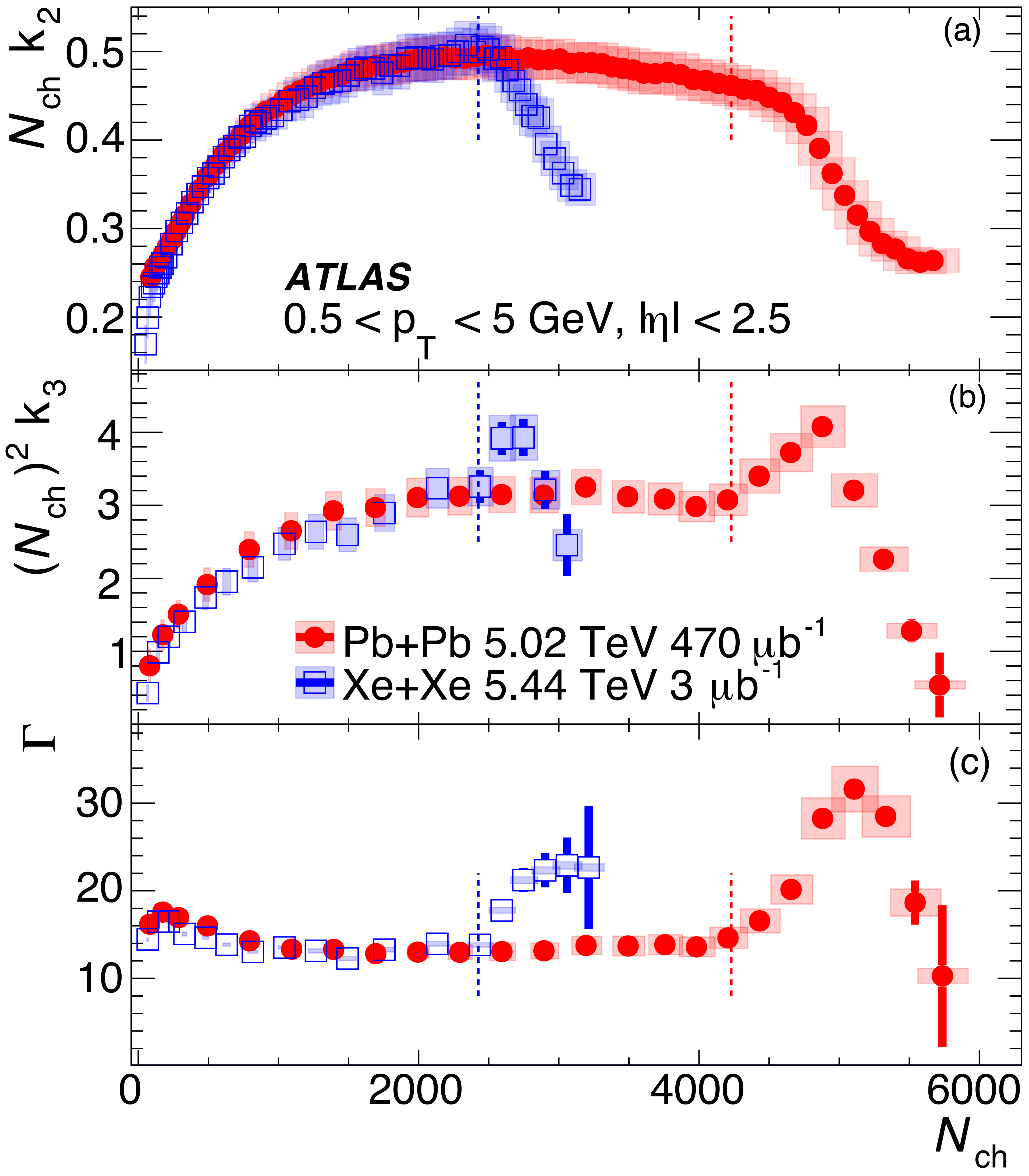
Moments N_{ch}^{rec} dependence

- Shown are $P([p_T], N_{ch})$, $\langle [p_T] \rangle$ and moments evolution with multiplicity
- The $\langle [p_T] \rangle$:
  a turn on of radial flow in peripheral collisions
  plateau-like in mid-central
  a rapid rise in UCC
- The k_2 and k_3: power law driven decrease with centrality, additional component in UCC
- Xe+Xe and Pb+Pb exhibit similar features



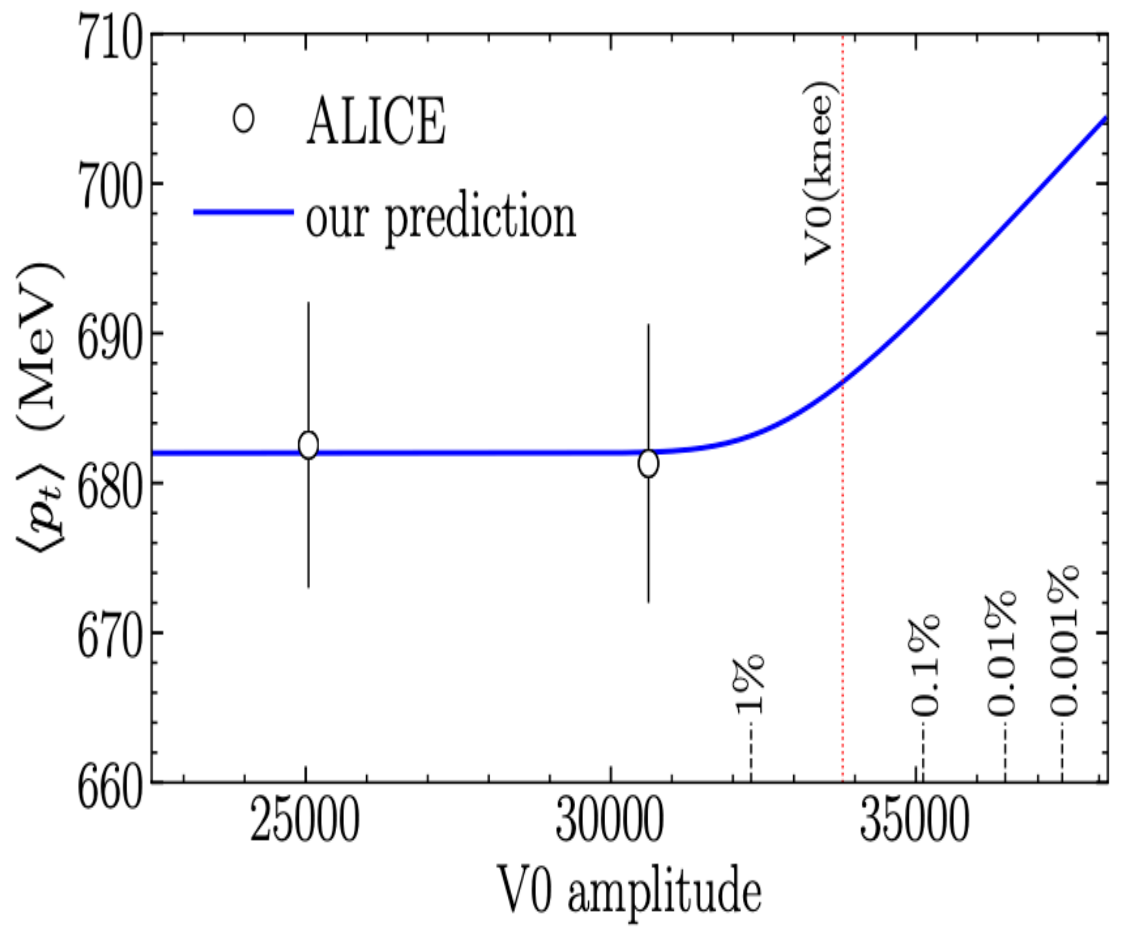
Power-law evolution of moments

- The rise (consistent with earlier observations) in peripheral coll. attributed to the onset of thermalisation
- The scaling (const in $N_{\rm ch}$) holds for broad range of N_{ch}^{rec} for Pb+Pb (not for Xe+Xe) and both k_2
- The drop in UCC due to $b \to 0$ (reducing initial geometric & leaving mostly intrinsic fluctuations)
- Skewness evolution qualitatively similar to k_2 in peripheral collisions
- The rise around the knee also due to truncation of b distribution (k_3 becomes non monotonic)



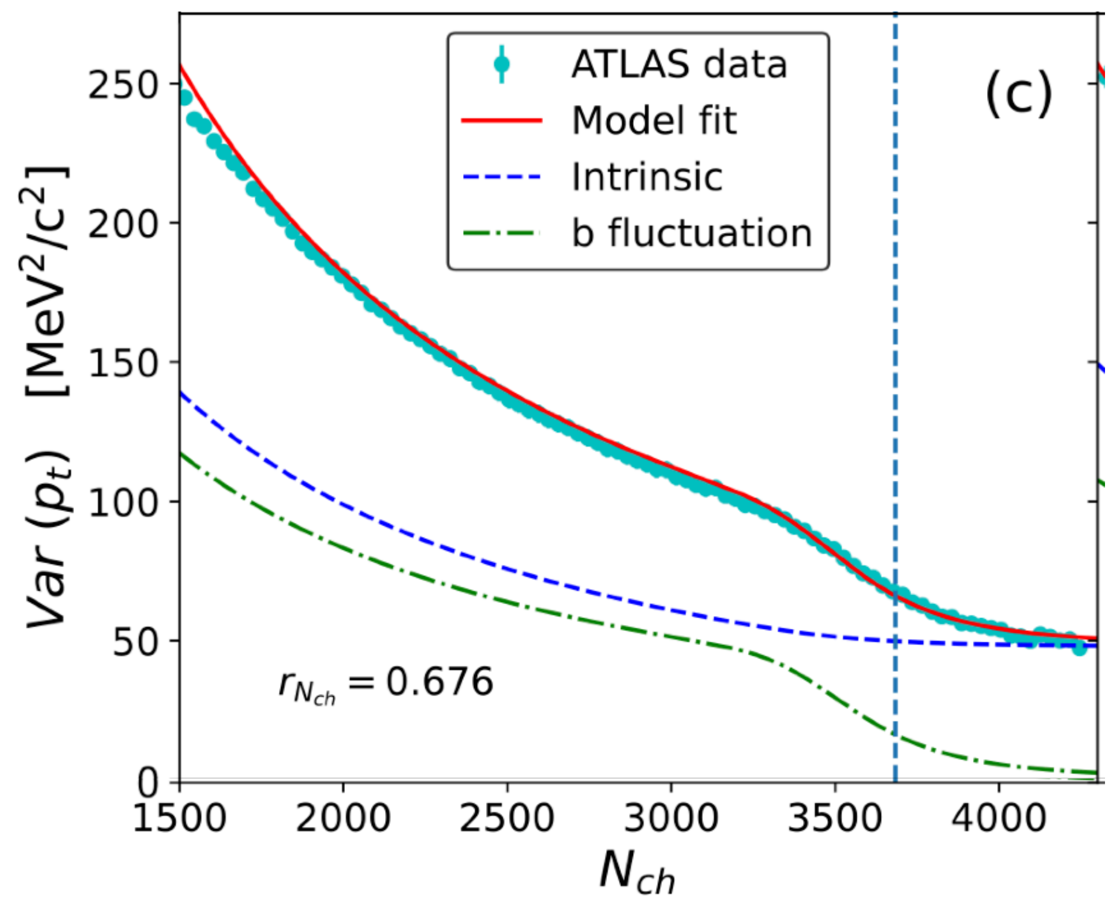
Quantitative comparisons

F.G. Gargim et al Phys.Lett.B 809 (2020) 135749



- A very clear rise by about 2% of $\left\langle [p_T] \right\rangle$ in 1% central collisions

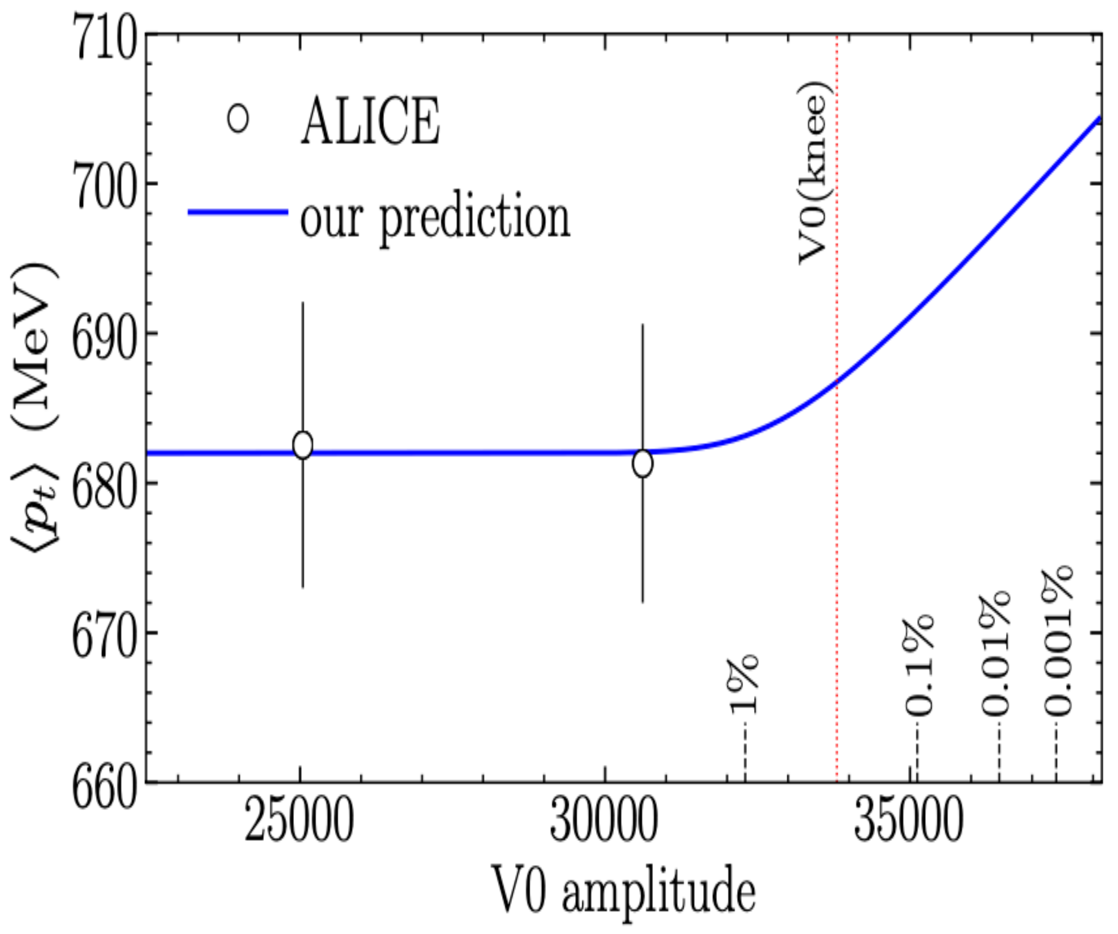
R.Samanta et al Phys. Rev. C 109 (2024) L051902

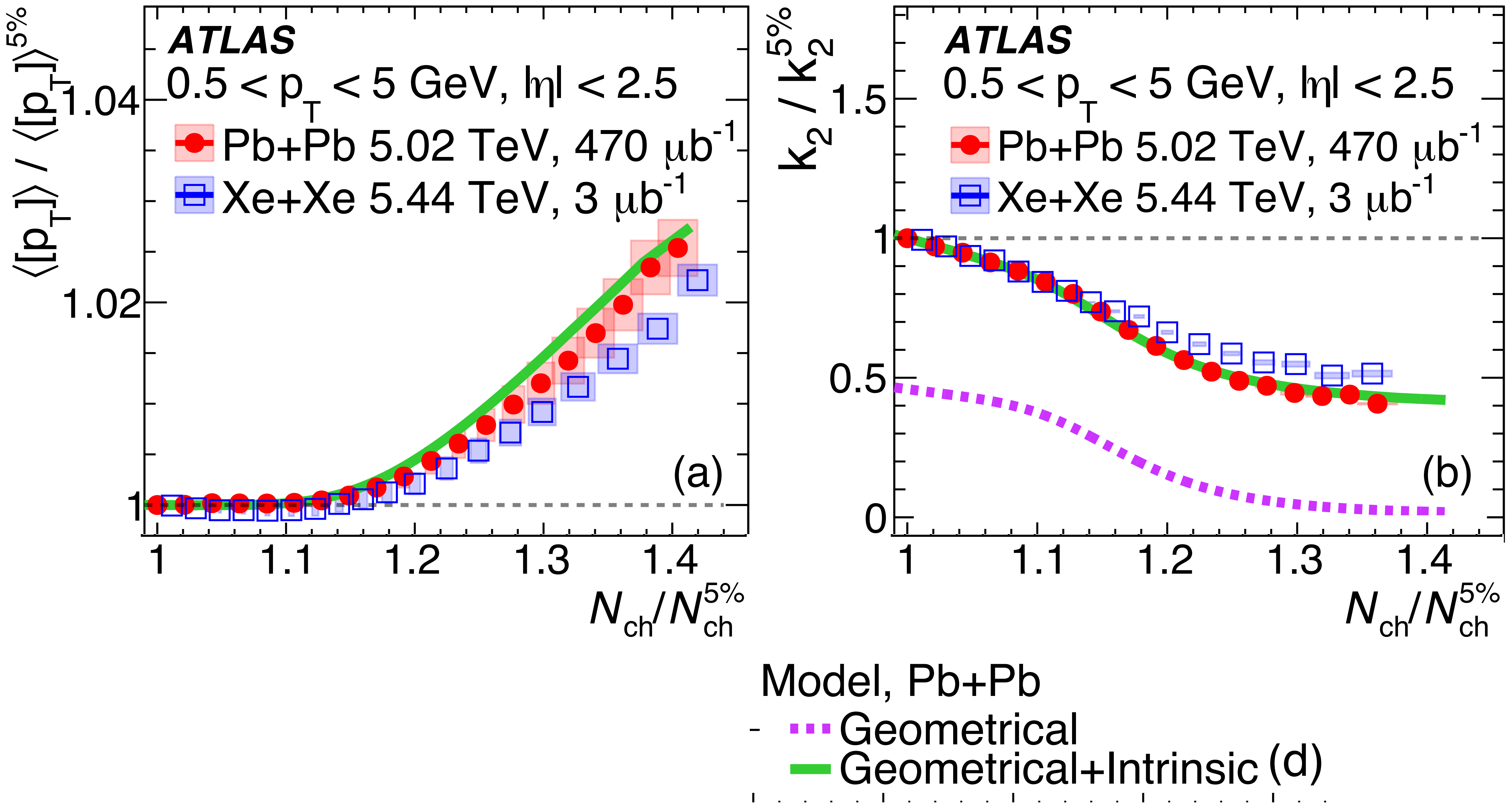


- A phenomenological model (2D Gaussian model) of fluctuations predicts sudden drop of fluctuations magnitude in 1% central

Quantitative comparisons

F.G. Gargim et al Phys.Lett.B 809 (2020) 135749





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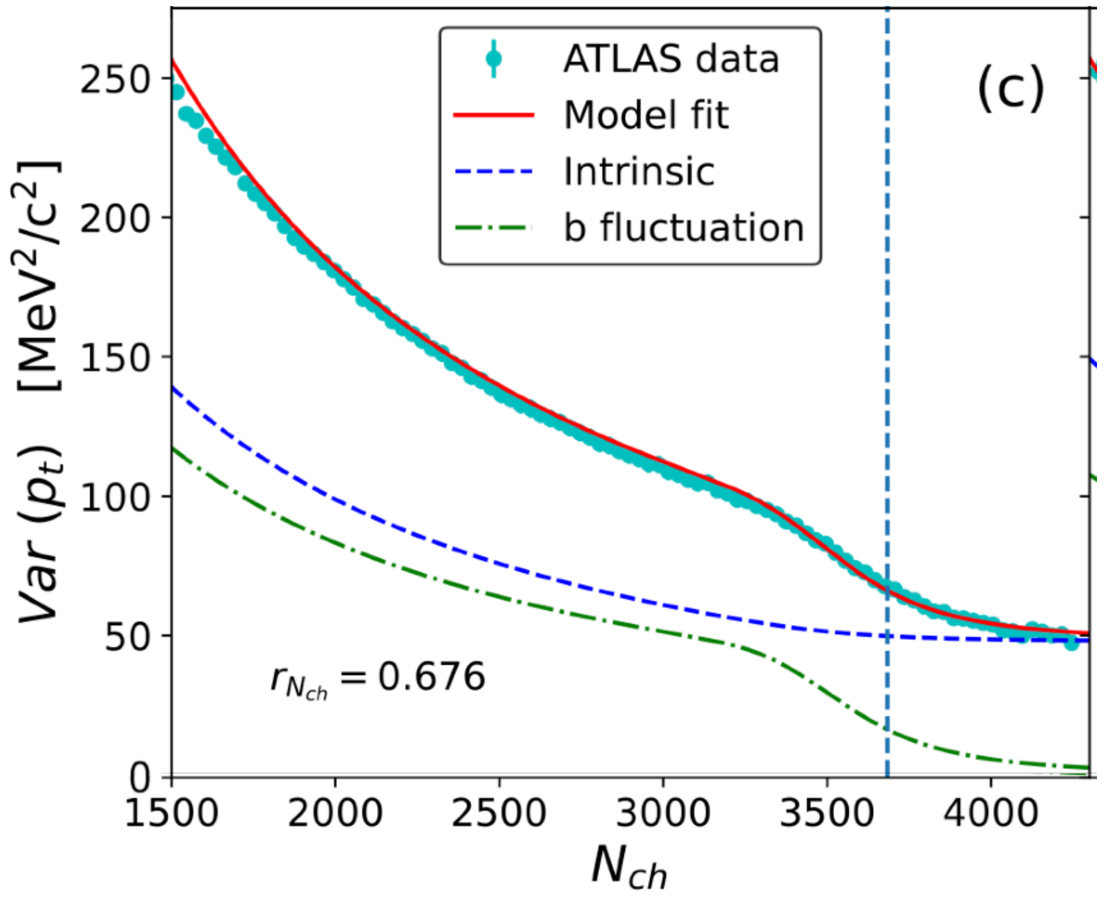
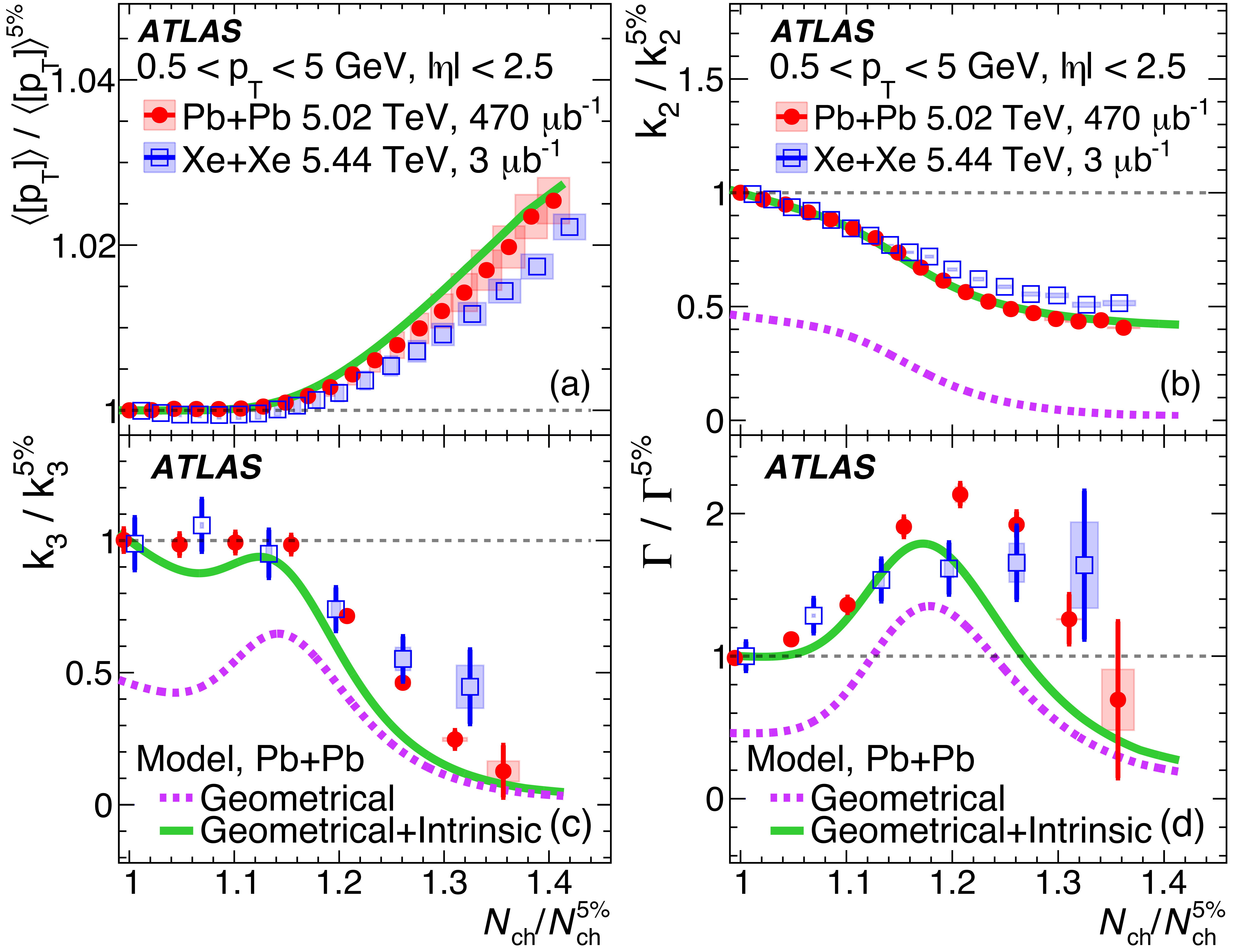


- A very clear rise by about 2% of $\langle [p_T] \rangle$ in 1% central collisions

A very good agreement with predictions

- A phenomenological model (2D Gaussian model) of fluctuations predicts sudden drop of fluctuations magnitude in 1% central

Higher order moments



- Third moment exhibits a non-monotonic behaviour
- Well described by the 2D gaussian model
- The two components of fluctuations needed and describe the data satisfactory

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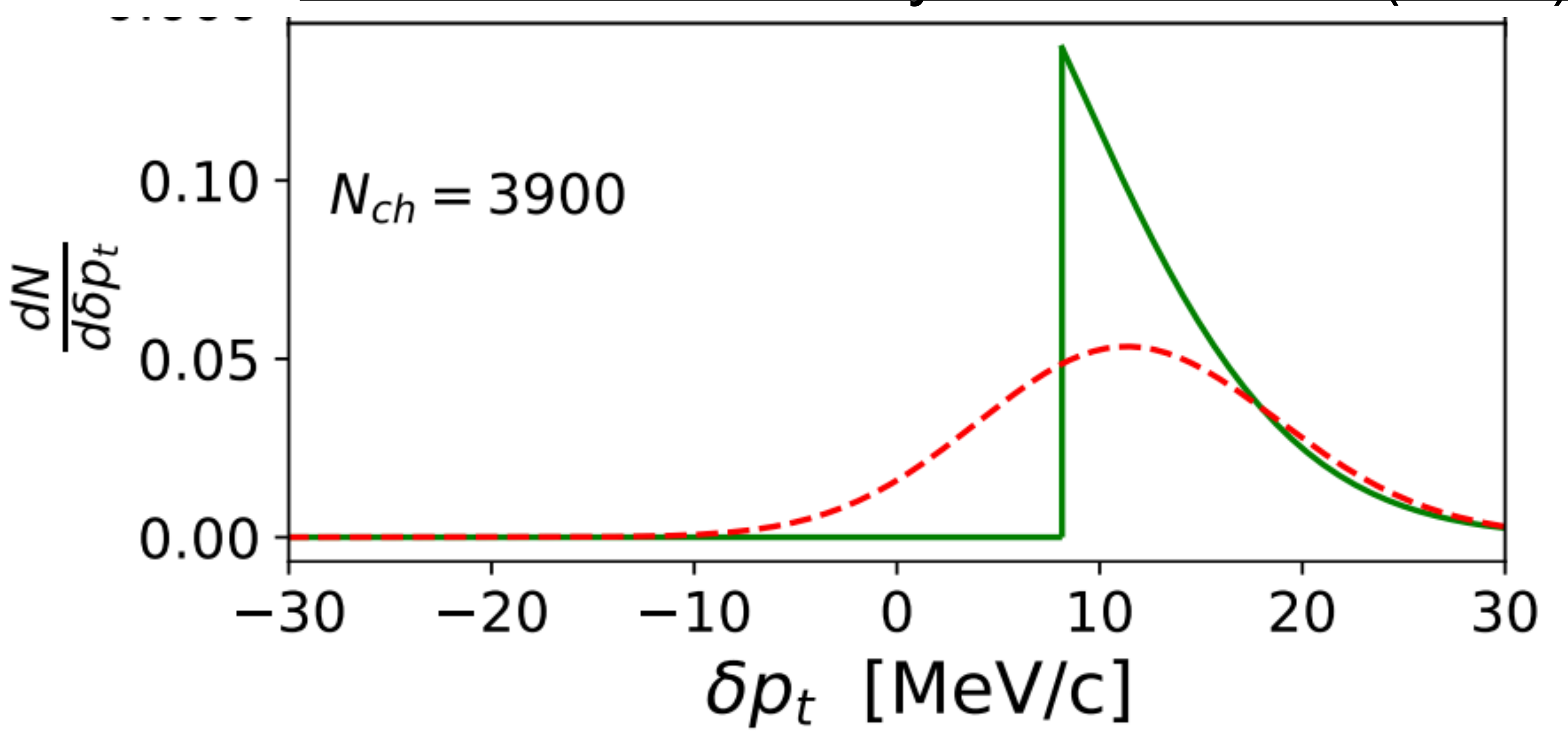

Direct correlation measurement

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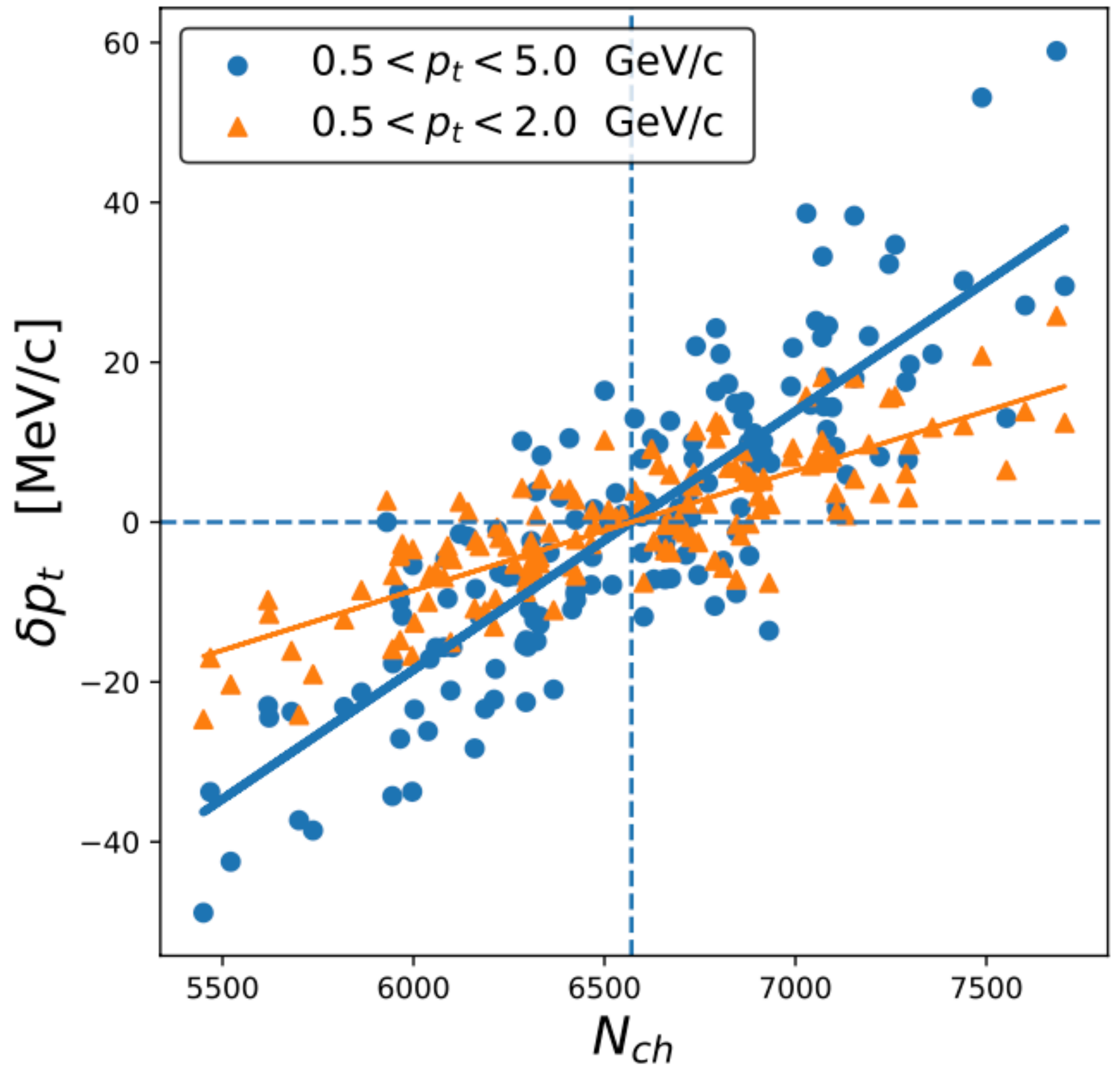

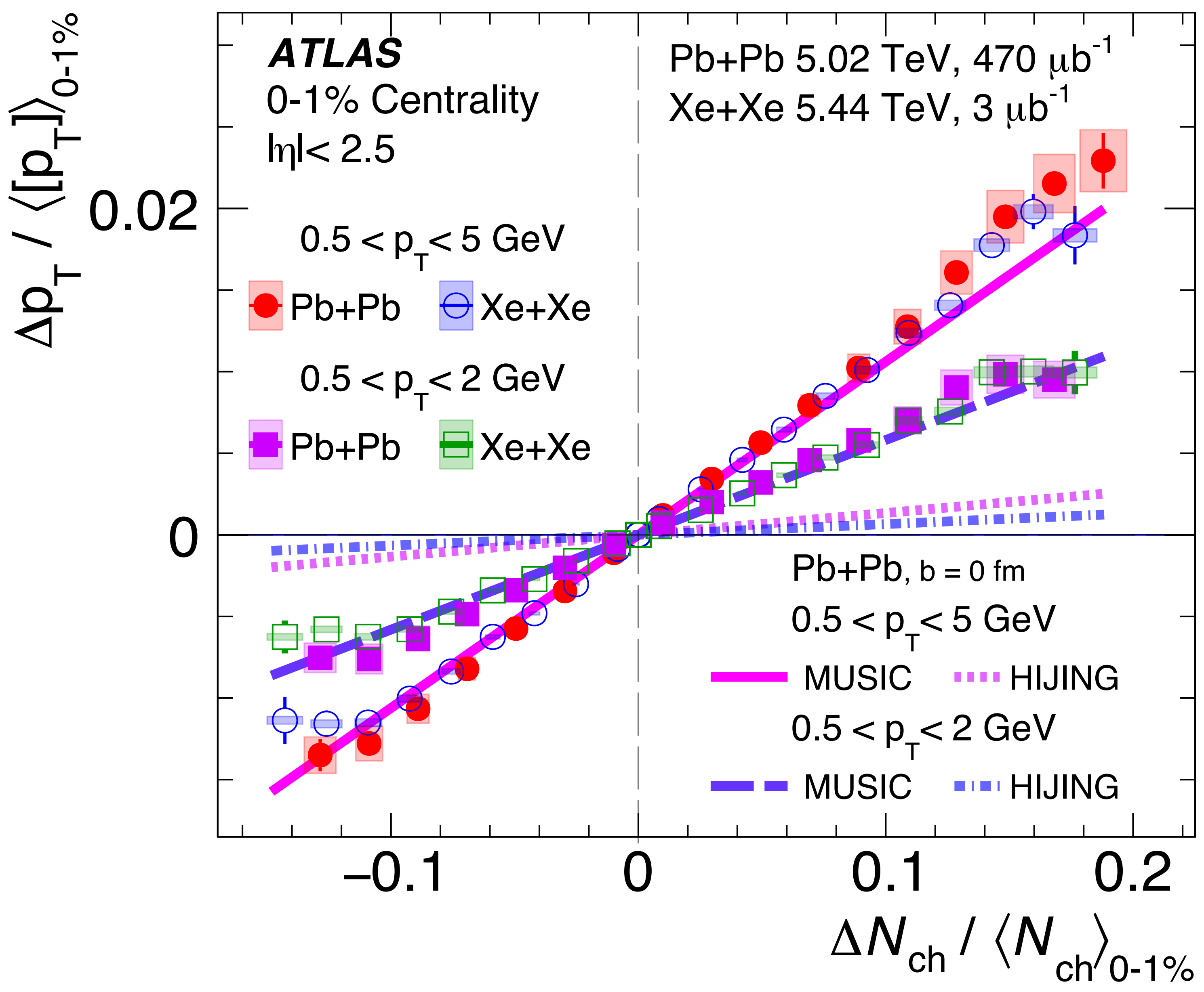

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$$c_s^2 = \frac{d \ln T}{d \ln s} = k \frac{d \ln [p_T]}{d \ln N_{ch}}$$

$$= k \frac{\Delta p_T / [p_T]}{\Delta N_{ch} / N_{ch}}$$

k : dependent on spectra shape and p_T-range

- Restricted impact parameter using ΣE_T^{FCal} estimator: $\langle [p_T] \rangle$ measured in slices of N_{ch}^{rec}
- Prediction: the slope of the correlation proportional to speed of sound c_s^2 in QGP
- Predictions by MUSIC (initial entropy destr. from TRENTO, $T_{eff} \approx 222\ MeV$ and $c_s^2 \approx 0.23$) model are in excellent agreement for Pb+Pb and Xe+Xe, unlike the HIJING

Relation to hard probes programme

- The UCC Pb-Pb events provide well controlled environment: fixed transverse area, fluctuating T & s (accessible experimentally via $[p_T]$ & $[N_{ch}]$)
    - Could be used to study jet-quenching & overall hard particles spectra modification as a function of T & s
    - A high sensitivity of $v_n - [p_T]$ to the initial conditions calls of the study of this correlation in the presence of hard probes
- Pursuing such ideas would greatly benefit from theory input

Summary

- ATLAS explored measurement of $v_n - [p_T]$ correlations:
    - measured precisely the Xe nucleus shape (triaxial)
    - and hinted interesting behaviour in the UCC
- and $[p_T]$ fluctuations:
    - variance and skewness follow independent source scenario in wide centrality range (driven by geometry)
    - “geometric” and “intrinsic” contributions evolutions in N_{ch} are different
        - departure from independent-source trend in UCC allow to disentangle them (also in non UCC)
    - Increase of $\langle [p_T] \rangle$ with N_{ch} captured by simulations allow two extract speed of sound in QGP
- Both of these measurements indicate that Pb+Pb Ultra Central Collisions are excellent setting to study hard-probes - ideas are welcome