ATLAS measurement of mean momentum fluctuations and correlations with the flow in Xe+Xe, and Pb+Pb

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AGH UNIVERSITY OF KRAKOW

$v_n - [p_T]$ correlation measurement

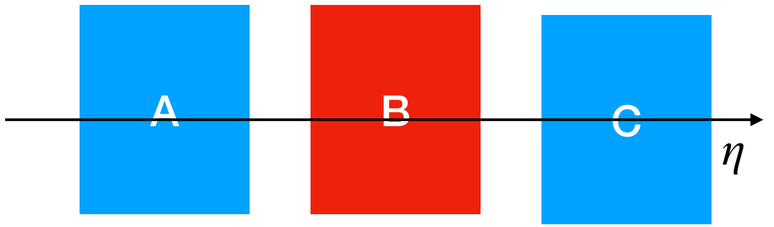
- ATLAS measured $v_n - [p_T]$ correlation coefficient ρ in Pb+Pb (and p+Pb)
  - Precise tool for initial stage imaging - sensitive to correlation between energy density & initial state deformation - not so much on details of QGP evolution
- The measurement of ρ in Xe+Xe relative to Pb+Pb indicated difference attributed to the shape of Xe nuclei
- The $[p_T]$ & c_k also exhibit an interesting evolution: investigated in followup measurement shown in this talk

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

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

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

Various methods to combined information from sub-events



ρ_2 in Pb+Pb, Xe+Xe and its ratio

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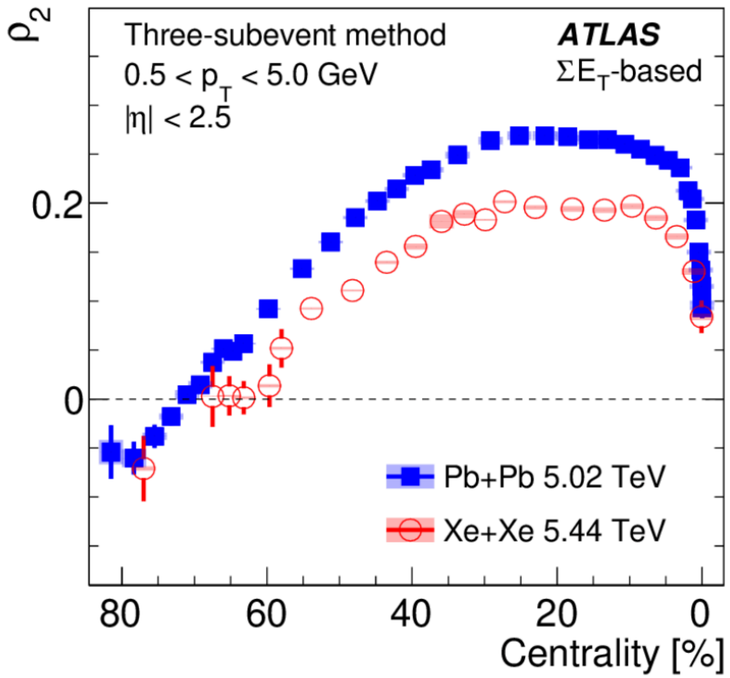

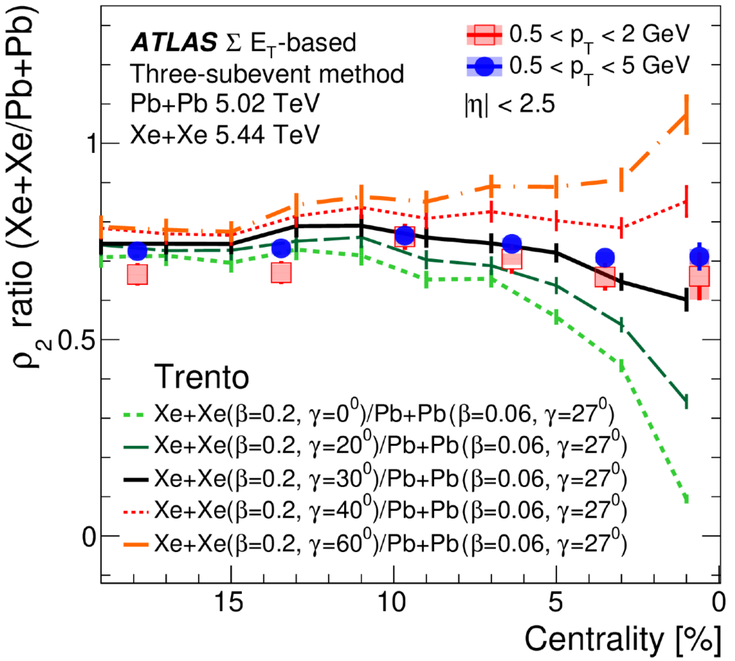

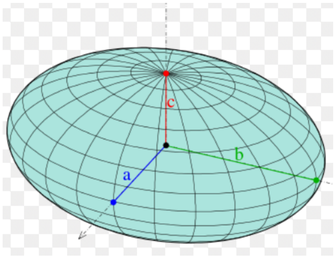

- Significant variation with centrality
- Different between the Xe+Xe and Pb+Pb, yet the ratio almost constant
- The ratio sensitive to initial shape projectiles shape
  - a very good description in simulation (Trento) allowed data to discern Xe nuclei shape - it is strongly triaxial

The UCC events

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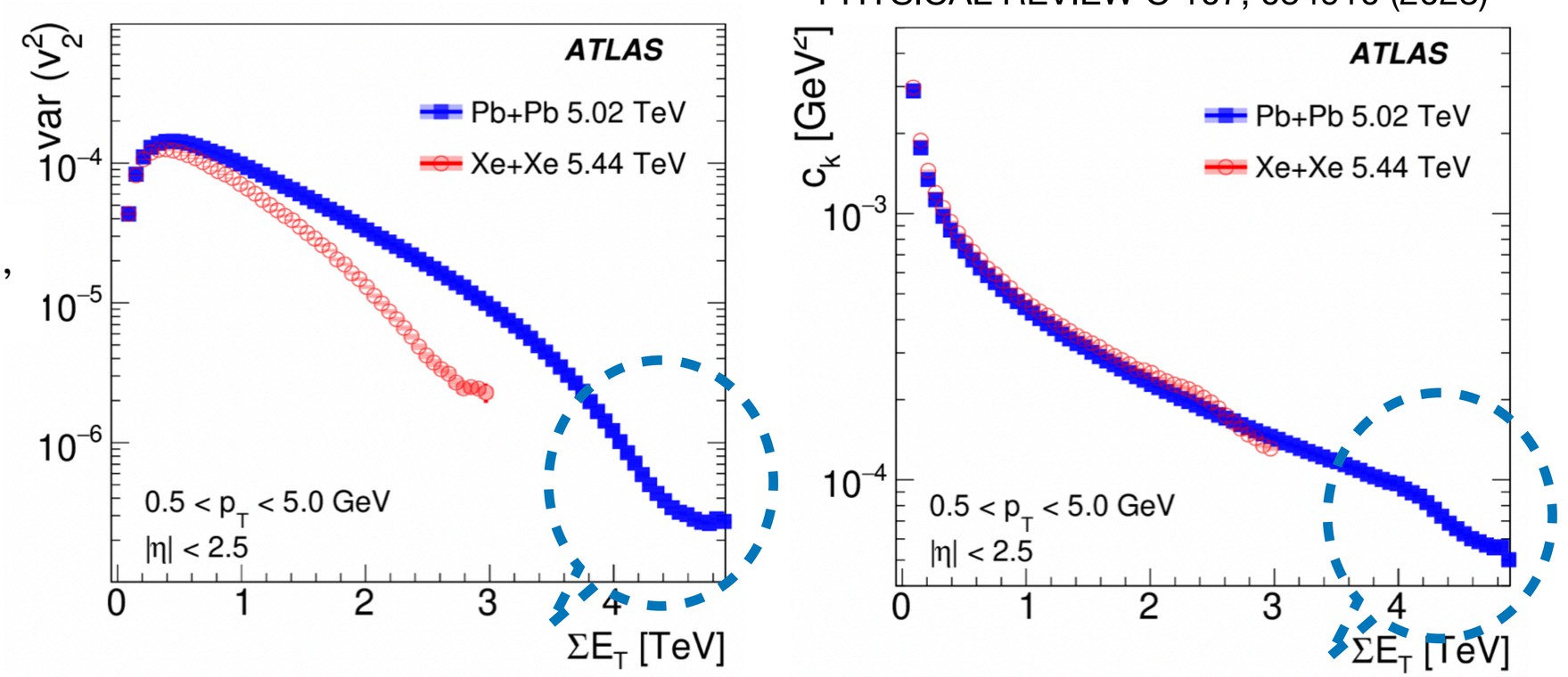
$$\rho_n = \frac{\mathrm{cov}_n}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{c_k}},$$



- In the UCC, $b \to 0$, (about 1.5% most central) the trends of ρ, cov, Var, c_k change behaviour
- The $b \to 0$ 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**

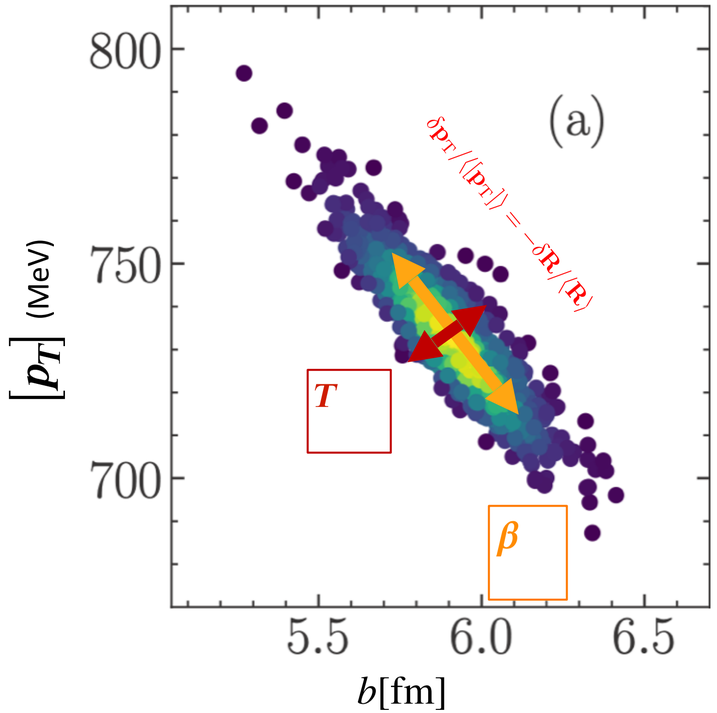
Constraining Initial State in Xe+Xe and Pb+Pb using $[p_T]$ Fluctuations with ATLAS

ATLAS-CONF-2023-061

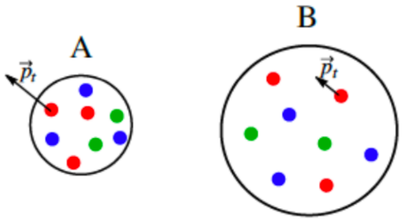
- Evolution of $[p_T]$ distribution moments with centrality (N_{ch} scaling)
- A close look at the evolution of moments of $[p_T]$ in UCC
- Pb+Pb & Xe+Xe comparison
- Comparison to models aiming at description of $[p_T]$ fluctuation

Motivation

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



- 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:

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

- Moments: central $\langle [p_T] \rangle$, scaled variance k_2, scaled skewness k_3, normalised skewness γ

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

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

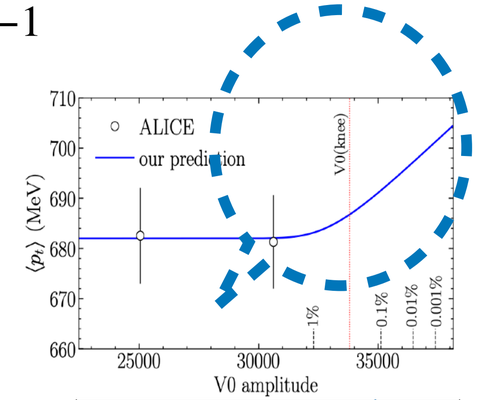
$$k_2 = \frac{\langle c_2 \rangle}{\langle [p_{\mathrm{T}}] \rangle^2}, \quad k_3 = \frac{\langle c_3 \rangle}{\langle [p_{\mathrm{T}}] \rangle^3}, \quad \gamma = \frac{\langle c_3 \rangle}{\langle c_2 \rangle^{(3/2)}}$$

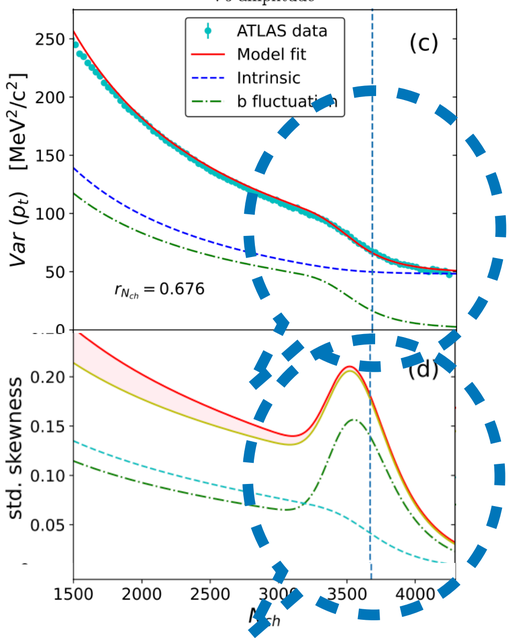
  - Estimators scaled for comparison by values in the 0-1% centrality bin

Skewness normalised to variance of unit value

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
  the sound speed in QGP c_s^2 can be obtained from that $\mathbf{c_s^2 = \frac{d\ ln\ T}{d\ ln\ s} = k\frac{d\ ln\ [p_T]}{d\ ln\ N_{ch}} = k\frac{\Delta p_T/[p_T]}{\Delta N_{ch}/N_{ch}}}$
  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 arxiv 2303.15323
- 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

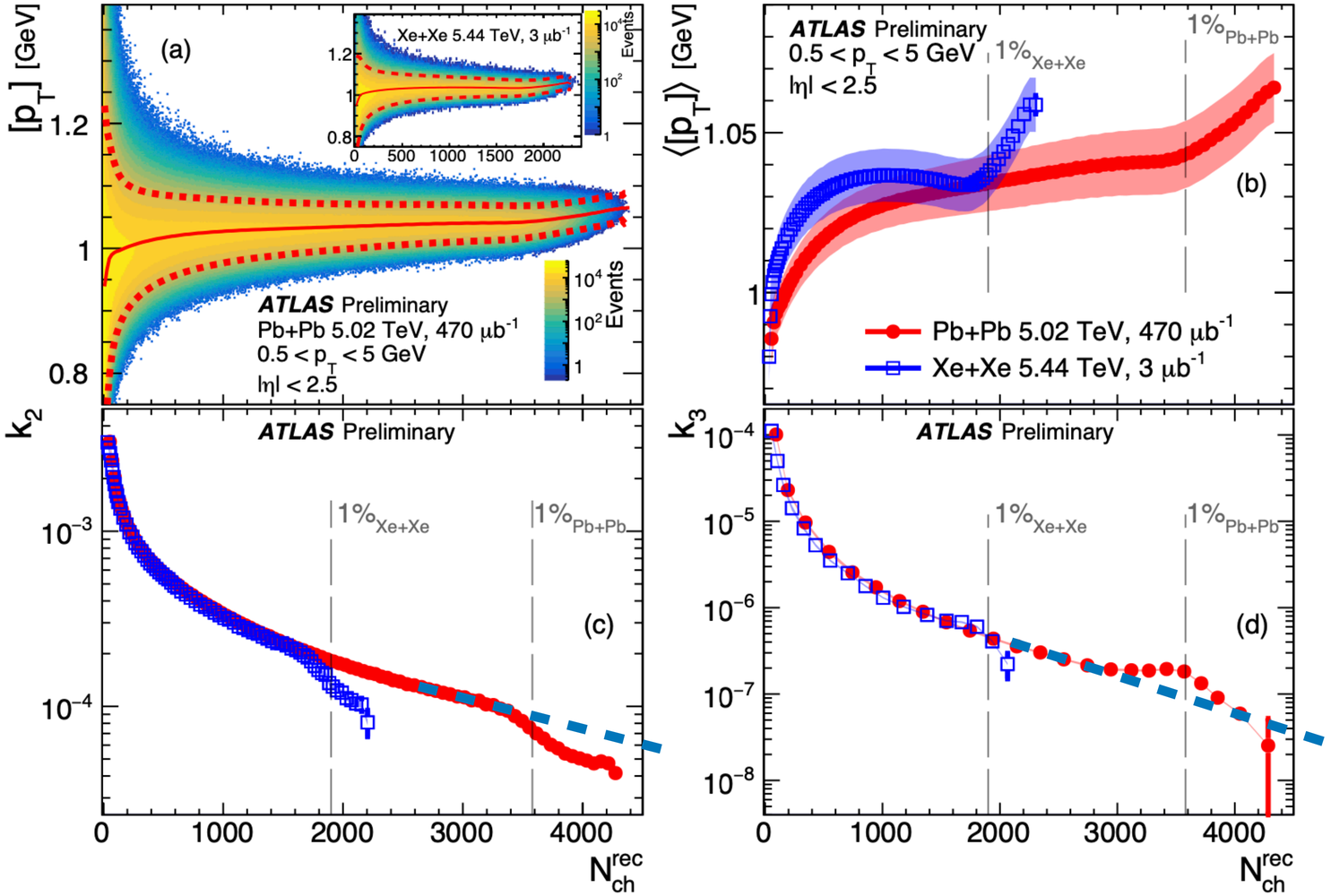




See R. Samanta talk yesterday

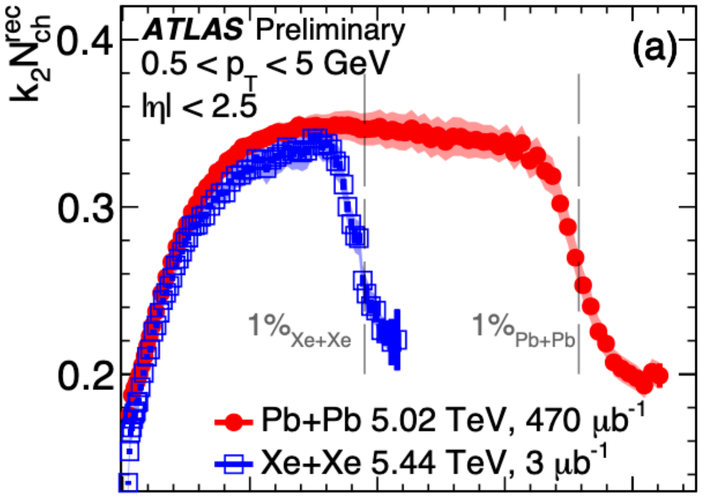
Moments N_{ch}^{rec} dependence

- Shown are $P([p_T], N_{ch})$, $\langle [p_T] \rangle$ and moments evolution with mult.
- 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 modifications UCC
- Xe+Xe and Pb+Pb exhibit similar features

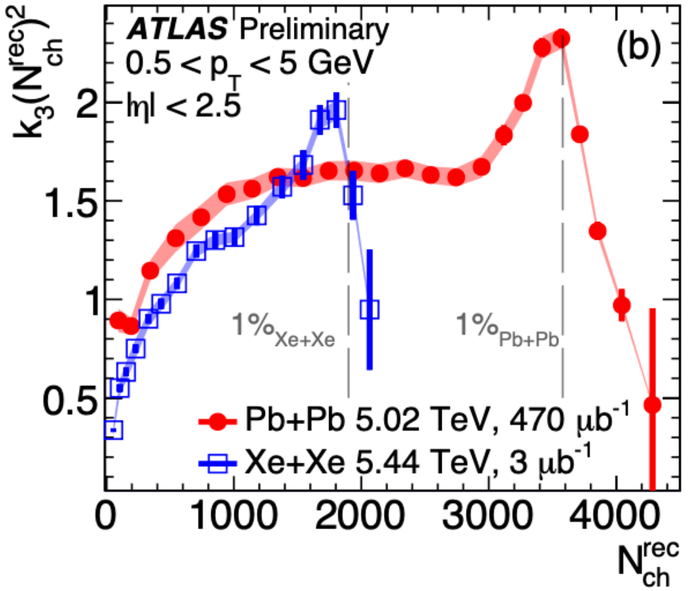


Power-law evolution of moments

- The rise (consistent with earlier observations) in peripheral coll. attributed to the onset of thermalisation
- The scaling 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 & left only intrinsic fluctuations)



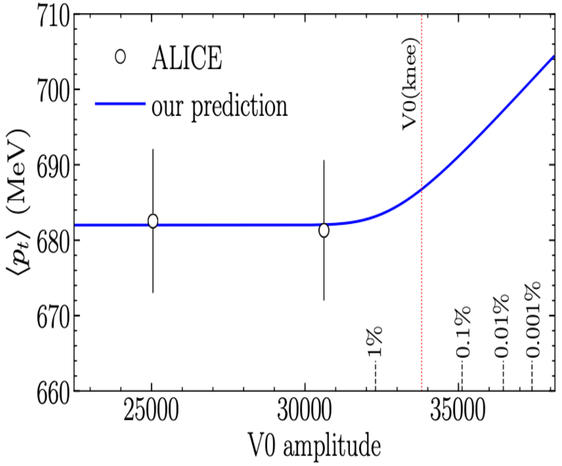
- Skewness evolution qualitatively similar to k_2 in peripheral collisions
- The rise around the knee also due to truncation of b distribution (k_3 becomes non monotonic)

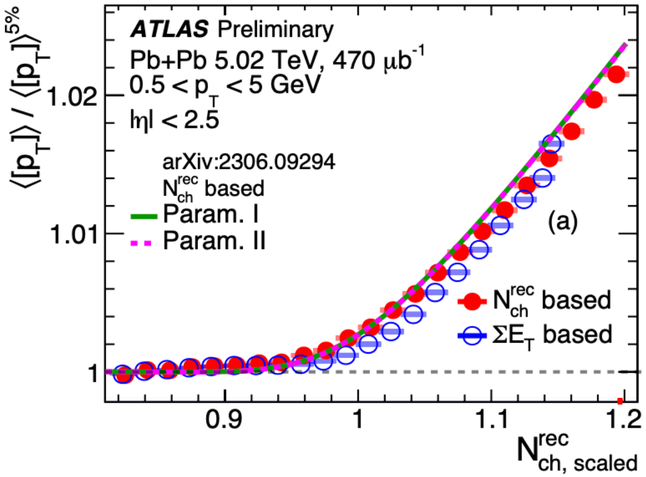


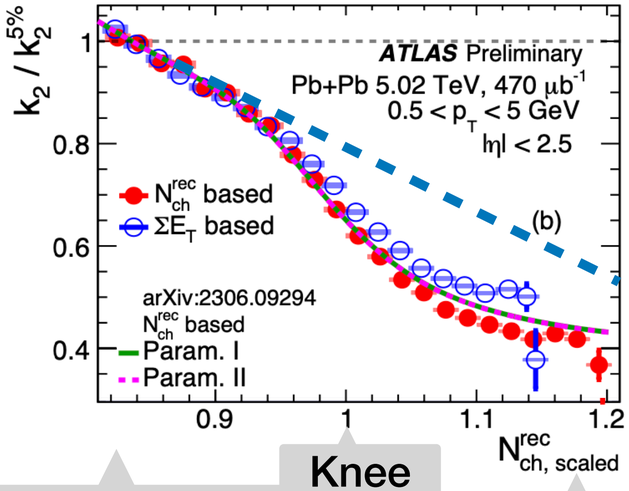
Moments evolution in UCC

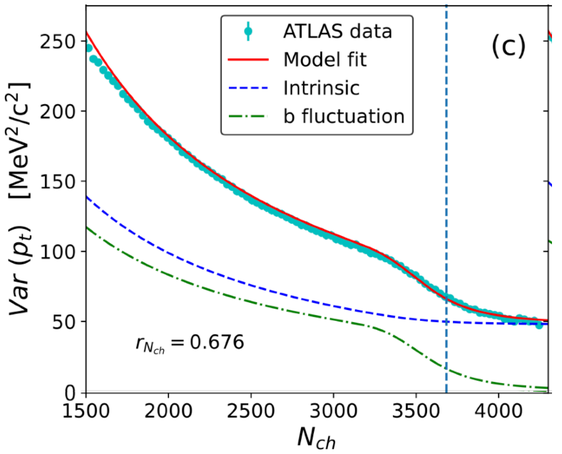
F.G. Gargim et al Phys.Lett.B 809 (2020) 135749

R.Samanta et al arxiv 2303.15323









Geometric + Intrinsic

Knee

Intrinsic

- A very clear rise by about 2% of $\langle [p_T] \rangle$ and a significant drop in k_2 (width)
- The ΣE_T estimator allows variation in N_{ch}^{rec} with which $[p_T]$ is correlated: larger k_2 & smaller $\langle [p_T] \rangle$
- A phenomenological model (2D Gaussian model) of fluctuations predicts the the trends very well - and isolates two contributions to $[p_T]$ fluctuations

Direct correlation measurement

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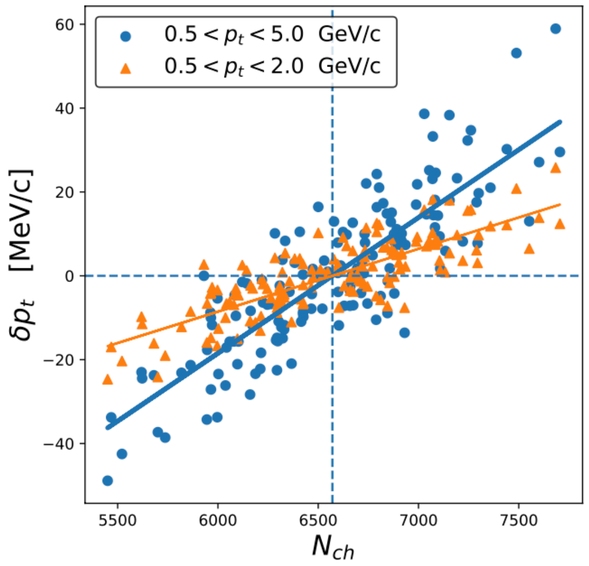
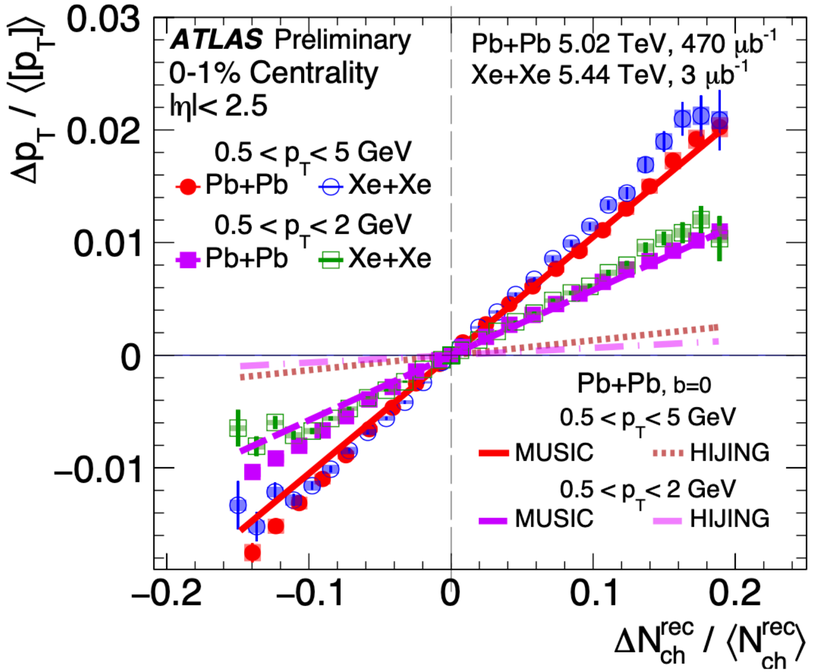




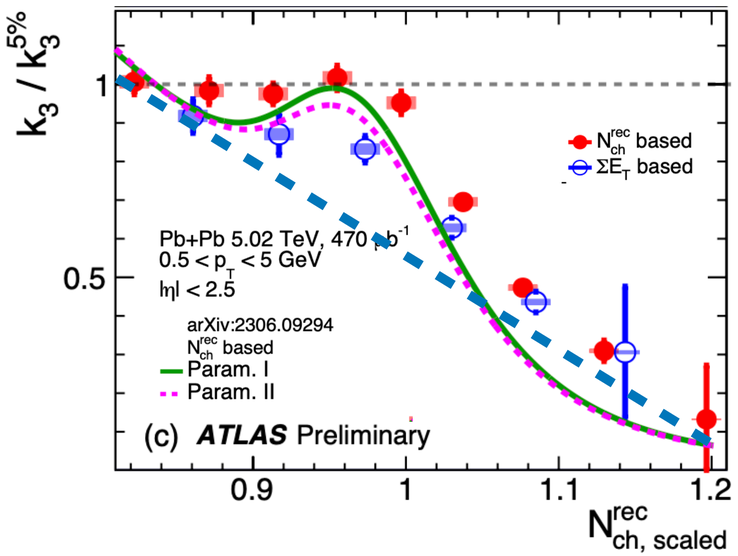
$$c_s^2 = \frac{d\ \ln\ T}{d\ \ln\ s} = k\frac{d\ \ln\ [p_T]}{d\ \ln\ N_{ch}}$$

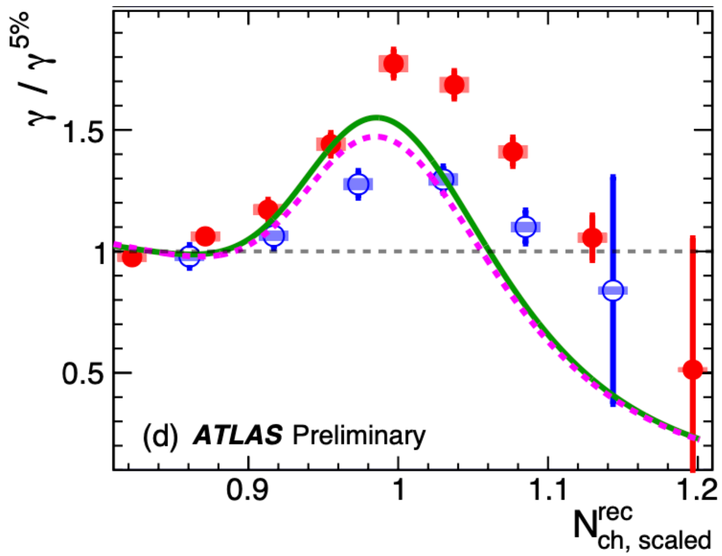
$$= k\frac{\Delta p_T/[p_T]}{\Delta N_{ch}/N_{ch}}$$

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 in QGP
- Predictions by MUSIC (initial entropy destr. from TRENTO) model are in excellent agreement for Pb+Pb and Xe+Xe, unlike the HIJING

Skewness





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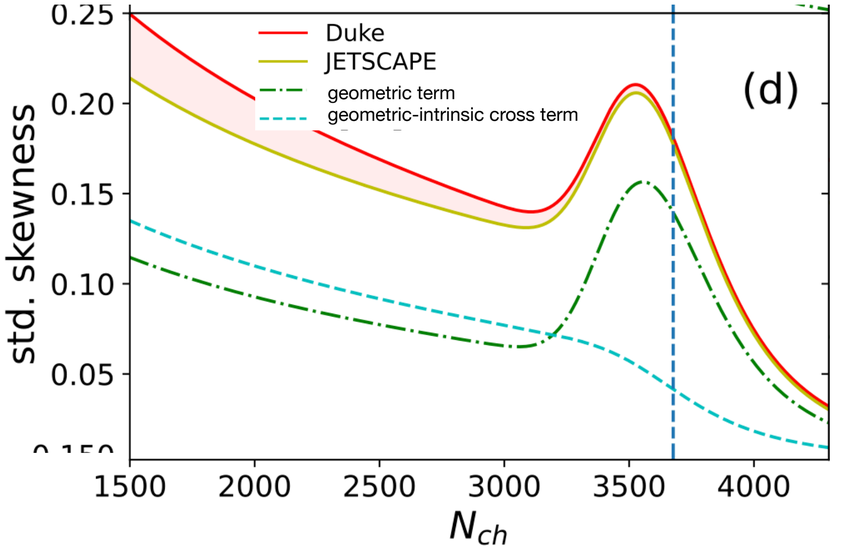


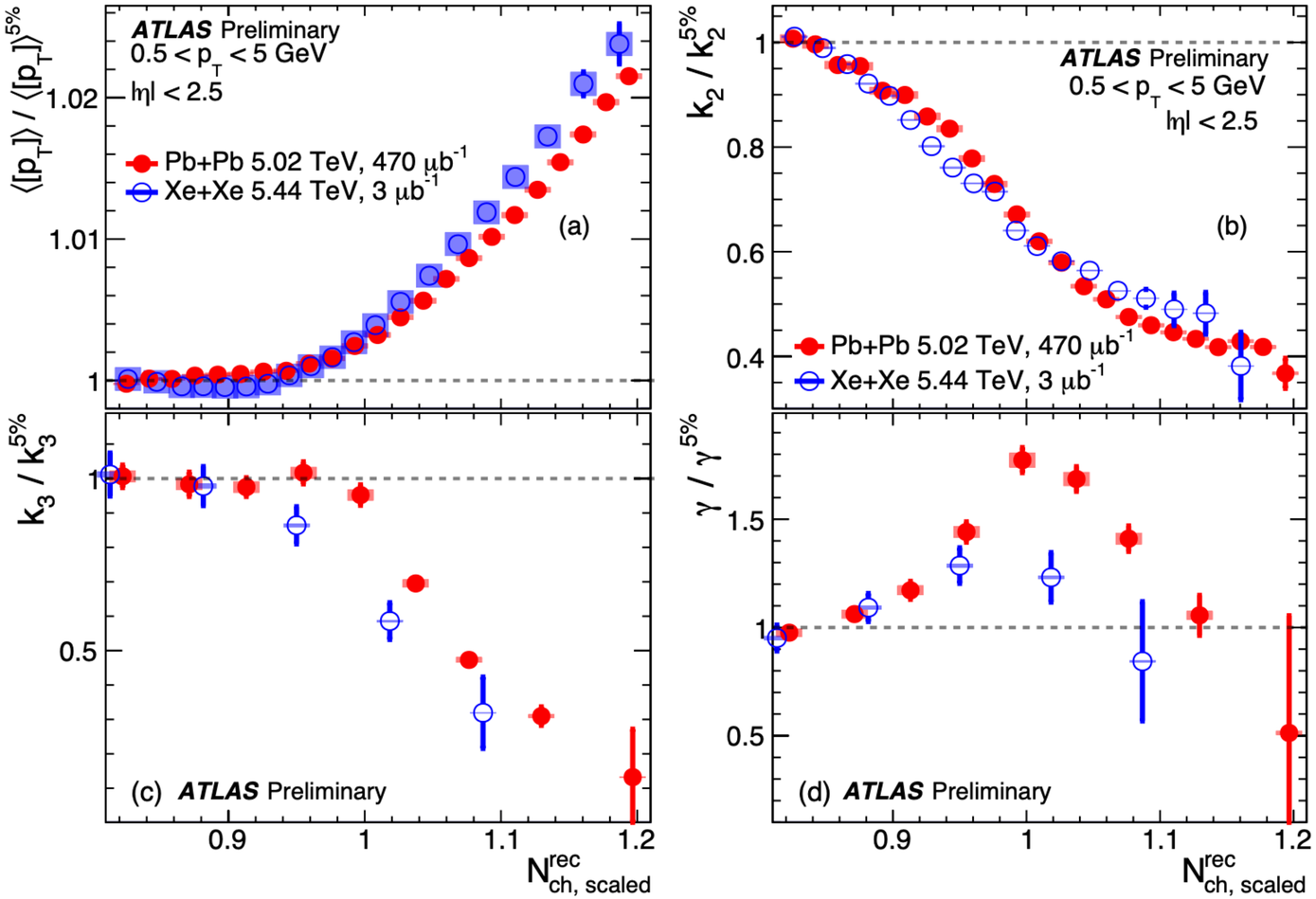
- Significant $[p_T]$ distribution skewness variation in UCC
- The rise around the knee: $[p_T]$ distributions starts to “feel” lower limit on impact parameter
- 2D Gaussian fluctuations model provide good qualitative description of observed quantities

Summary

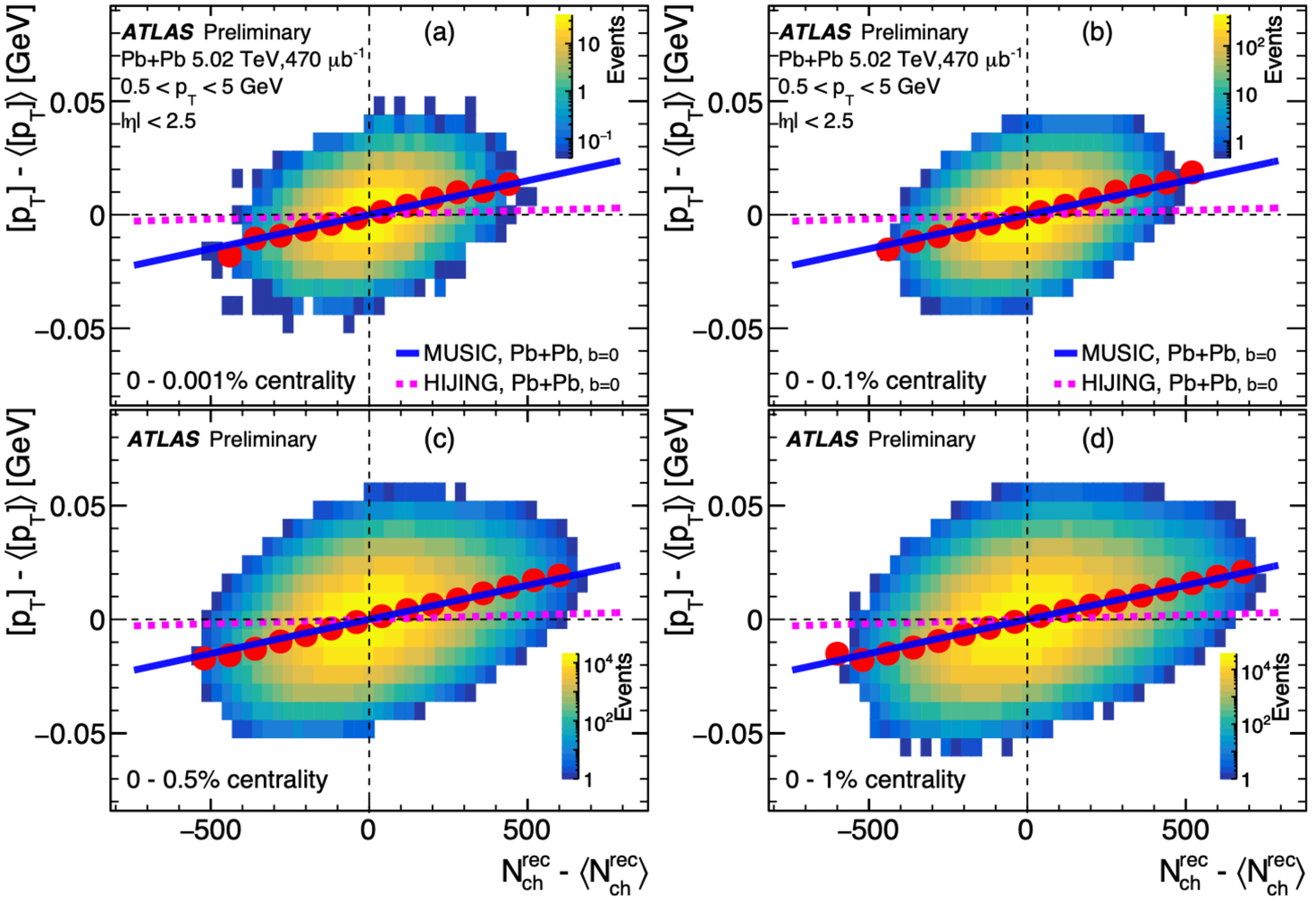
- ATLAS measured $v_n - [p_T]$ correlations:
  - precise constraints of the Xe nucleus shape (triaxial)
  - … and initiated new research opportunities see J. Jia talk at this Conf.
- and $[p_T]$ fluctuations:
  - variance and skewness follow independent source scenario in wide centrality range (driven 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 MUSIC. Further theory input needed to reliably extract c_s^2

See poster No. 578 by: **Somadutta Bhatta**
Exploring the origin of [pT] fluctuations in ultra-central heavy ion collisions:
Higher order [pT] correlations in ATLAS

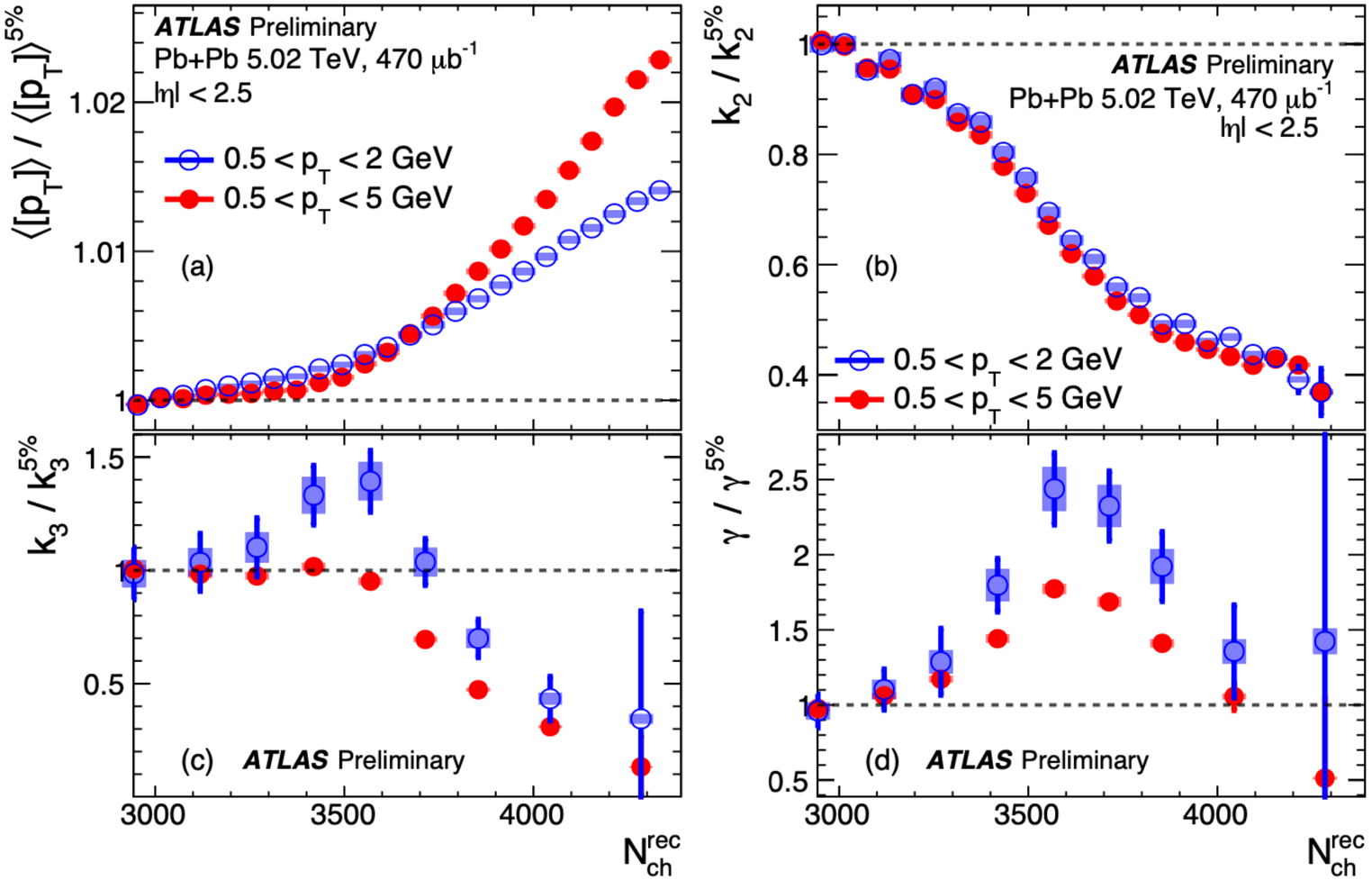
Backup



- Comparison of moments between Pb+Pb and Xe+Xe



- Correlation between N_{ch} and $[p_T]$ in UCC



- Moments dependence on p_T limits