Measurements of mean particles momentum fluctuations in HI collisions by ATLAS and flow-momentum correlations as a tool for nuclear shapes imagining

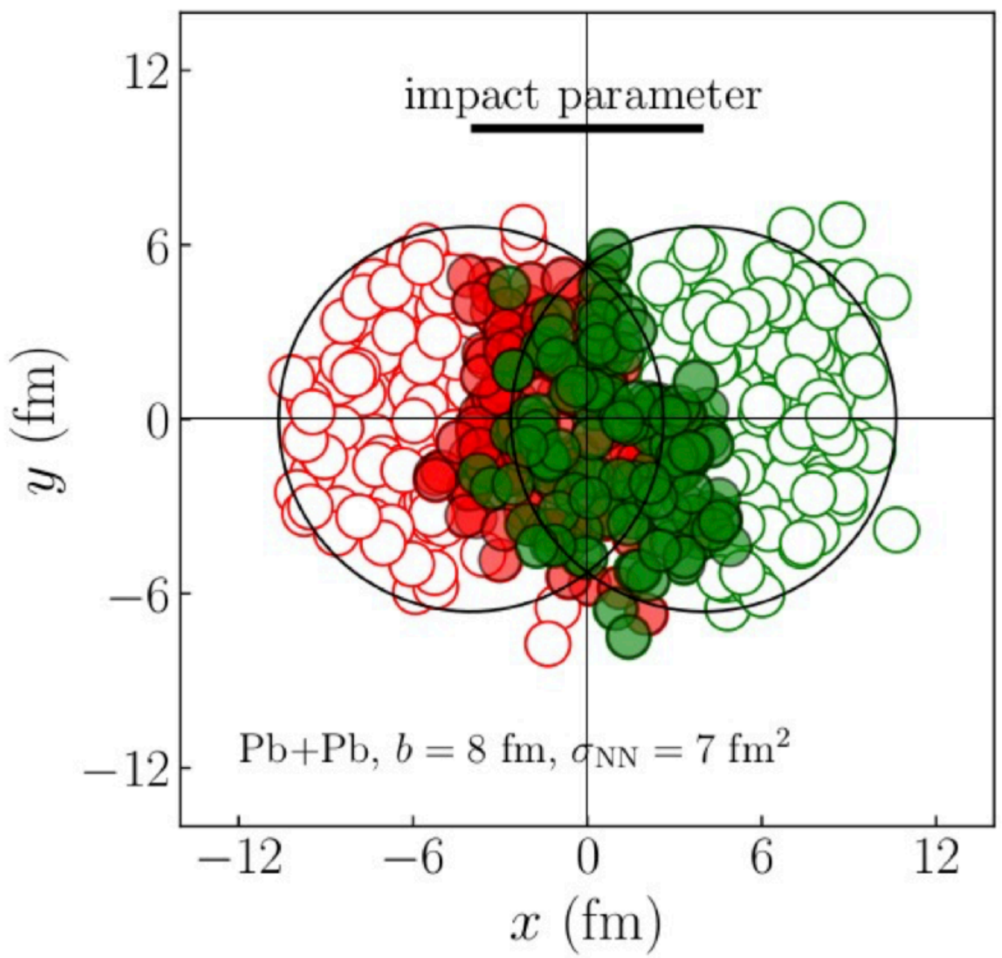
Tomasz Bołd

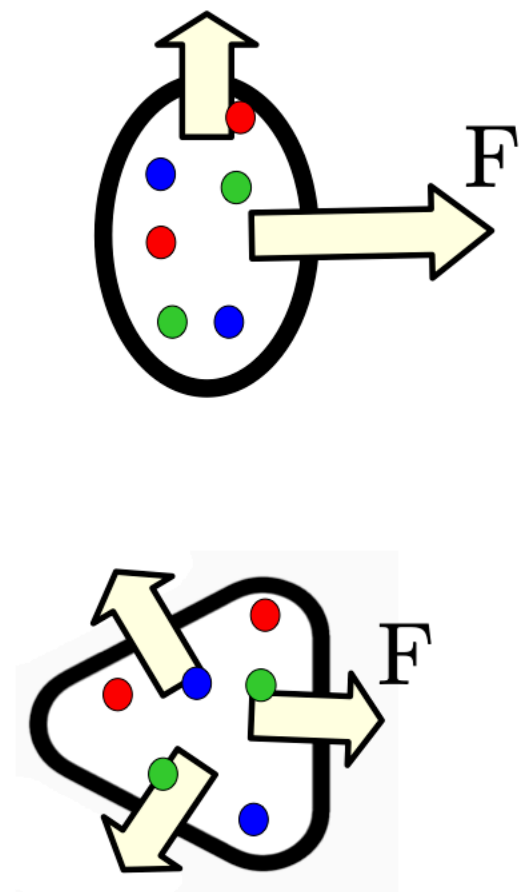
- **Historical interlude**
- **The $v_n - [p_T]$ correlation**
- **Momentum fluctuations**

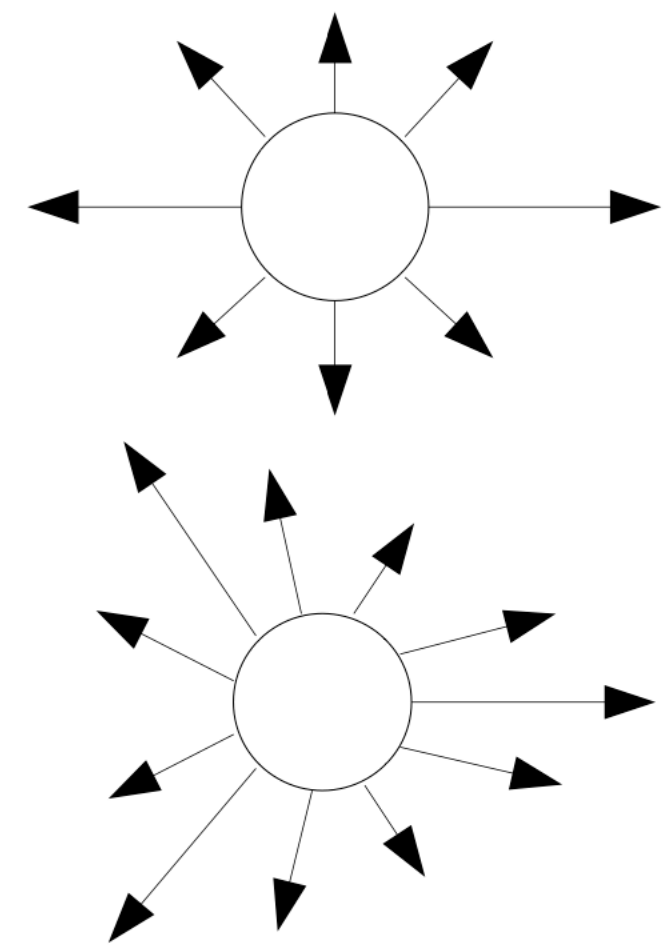
AGH University of Krakow

30 years of discovery · 1992-2022 ATLAS EXPERIMENT

Flow harmonics







$$\frac{d^2N}{dp_T d\phi} = \frac{dN}{2\pi dp_T}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)\right)$$

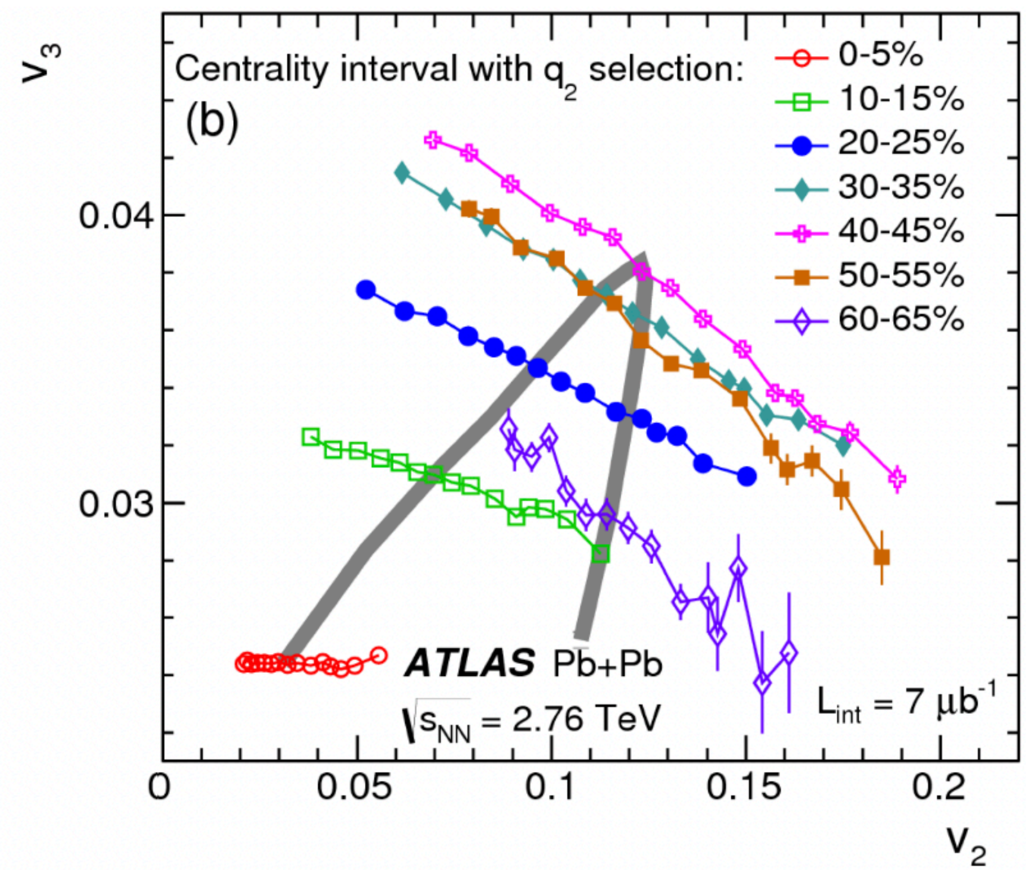
Correlations between harmonics

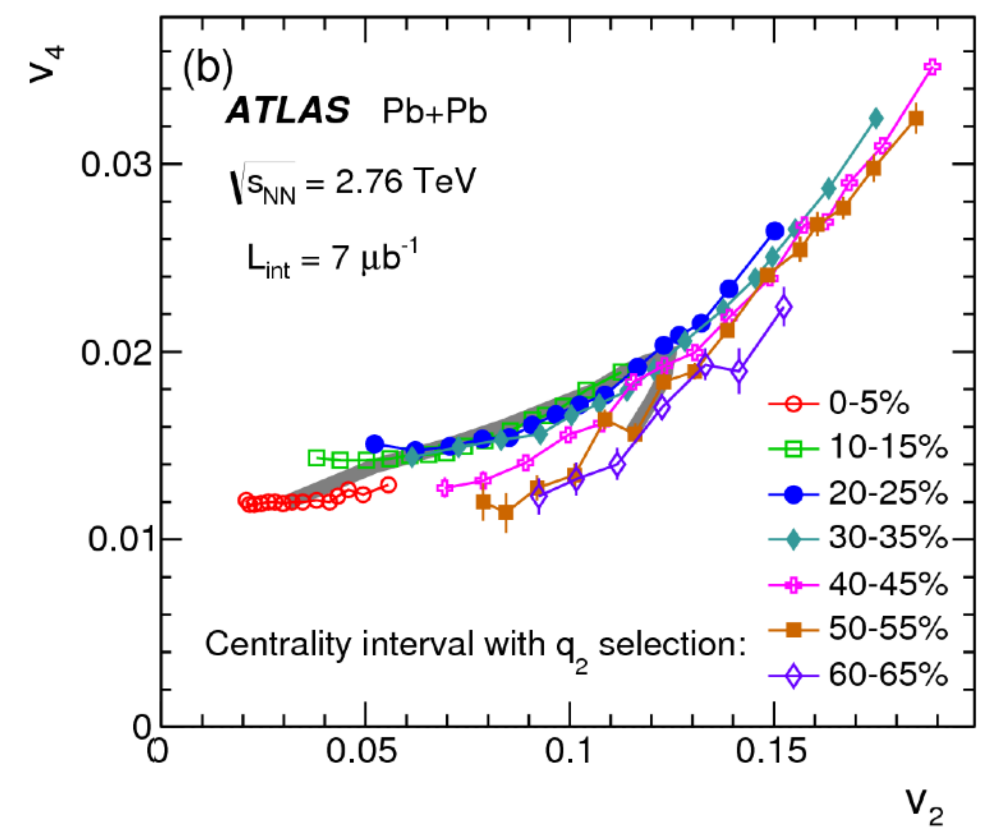
$$v_n \propto q_n = \sum_k e^{-in\phi_k}$$

n- **harmonic order**

k **- particles of choice**
(e.g. of a given momentum range)

- Per event estimates are averaged in various ways: $v_n(\,\%\,), v_n(p_T)\ldots$
- They can also be correlated: magnitudes, angles

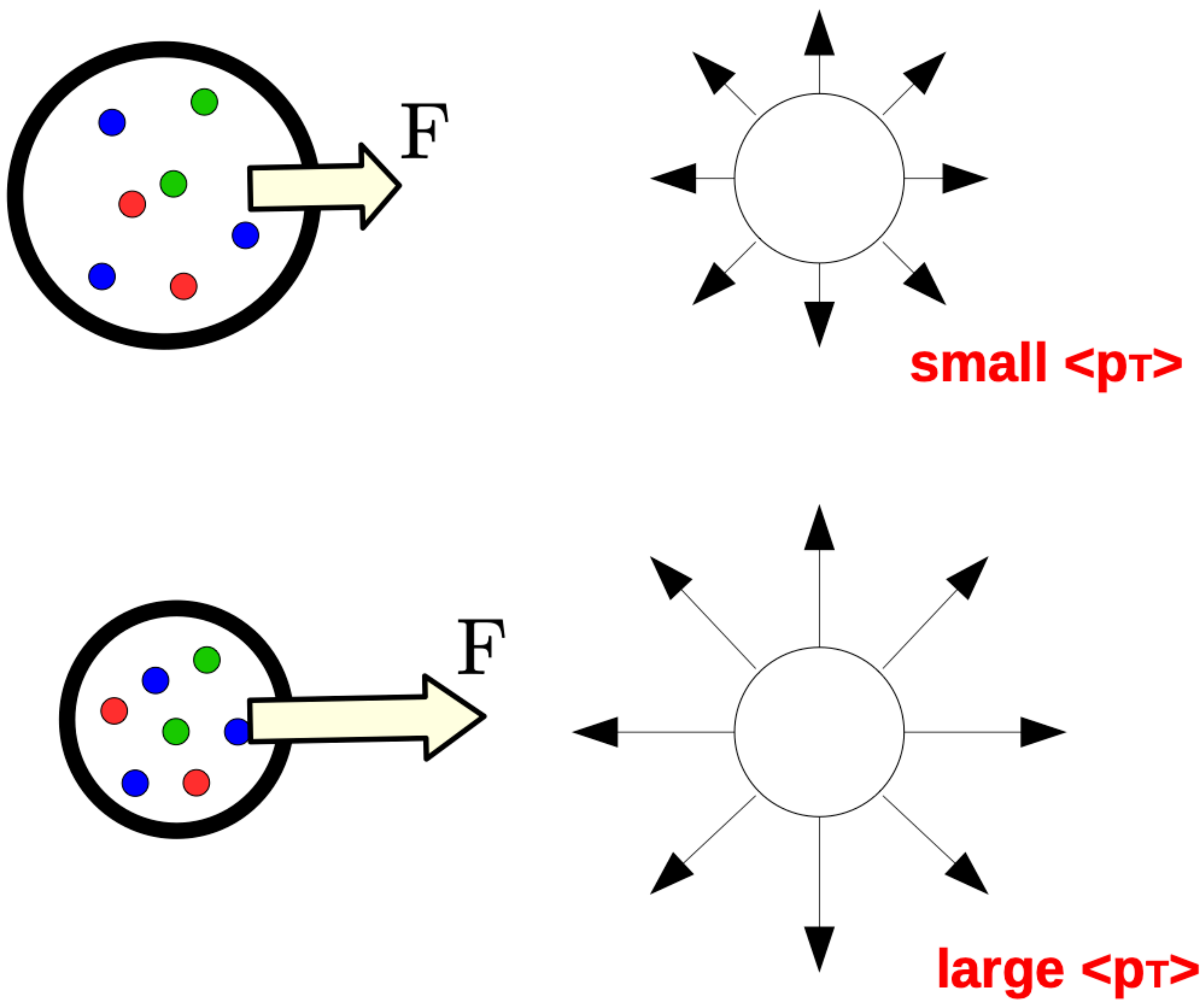




[Phys. Rev. C 92, 034903 (2015)]

Mean event momenta

W. Broniowski, M. Chojnacki, and Ł. Obara Phys. Rev. C **80**, 051902(R)



PHYSICAL REVIEW C **93**, 044908 (2016)

Transverse-momentum–flow correlations in relativistic heavy-ion collisions

Piotr Bożek*
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Krakow, Poland
(Received 25 January 2016; published 21 April 2016)

The correlation between the transverse momentum and the azimuthal asymmetry of the flow is studied. A correlation coefficient is defined between the average transverse momentum of hadrons emitted in an event and the square of the elliptic or triangular flow coefficient. The hydrodynamic model predicts a positive correlation of the transverse momentum with the elliptic flow, and almost no correlation with the triangular flow in Pb-Pb collisions at LHC energies. In *p*-Pb collisions the new correlation observable is very sensitive to the mechanism of energy deposition in the first stage of the collision.

DOI: 10.1103/PhysRevC.93.044908

$v_n - [p_T]$ correlation measurement

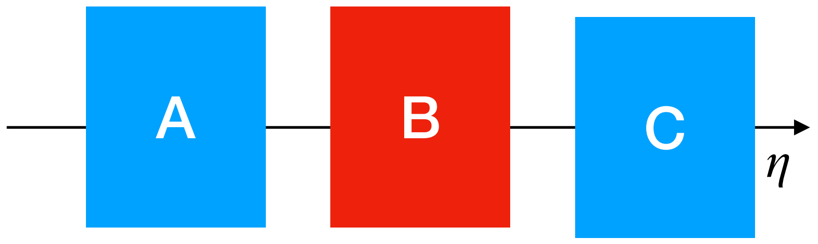
$$\rho(v_n\{2\}^2,[p_\perp]) = \frac{\mathrm{cov}(v_n\{2\}^2,[p_\perp])}{\sqrt{\mathrm{Var}\left(v_n^2\right)_{\mathrm{dyn}} C_{p_\perp}}} .$$

Where:

$$\mathrm{cov}(v_n\{2\}^2,[p_\perp]) = \left\langle \frac{1}{N_{\mathrm{pairs}}N} \sum_{i\neq k\neq j} e^{in\phi_i} e^{-in\phi_k} (p_j - \langle [p_\perp] \rangle) \right\rangle.$$

$$C_{p_\perp} = \left\langle \frac{1}{N(N-1)} \sum_{i\neq j} (p_i - \langle [p_\perp] \rangle)(p_j - \langle [p_\perp] \rangle) \right\rangle.$$ renamed later to c_k

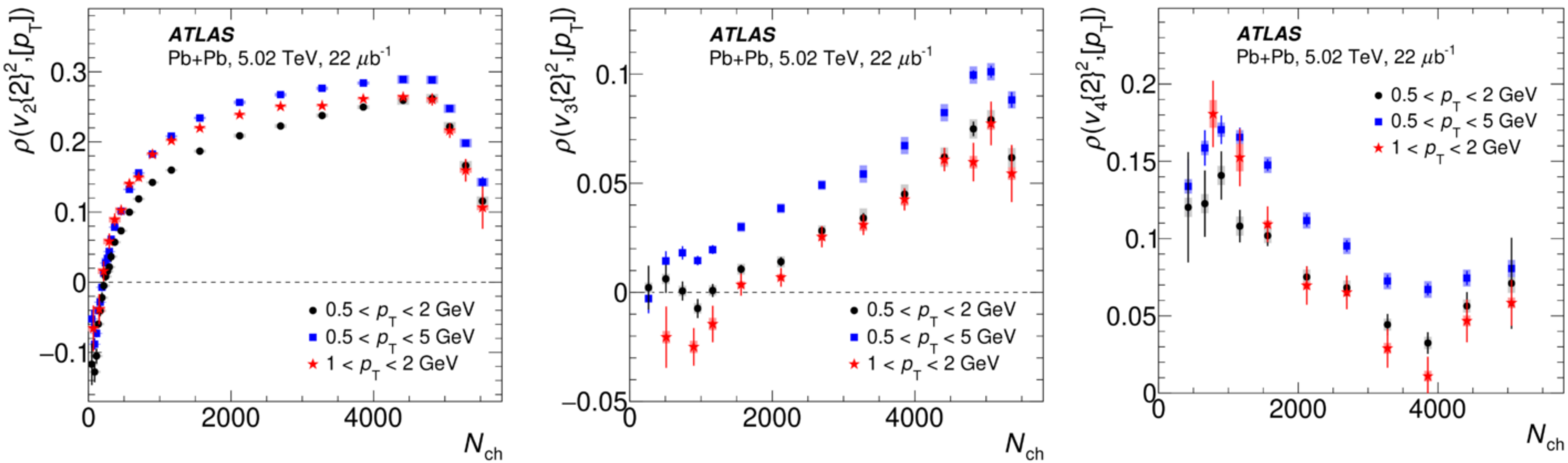
$$\mathrm{Var}(v_n^2)_{\mathrm{dyn}} = \left\langle \frac{1}{N_A(N_A-1)N_B(N_B-1)} \times \sum_{i\neq j\in A} \sum_{k\neq l\in B} e^{in\phi_i + in\phi_j} e^{-in\phi_k - in\phi_l} \right\rangle - \left\langle \frac{1}{N_A N_B} \sum_{i\in A, k\in B} e^{in\phi_i} e^{-in\phi_k} \right\rangle^2$$



Various methods to combine information from sub-events
Various momentum intervals

First measurement by ATLAS: Pb-Pb

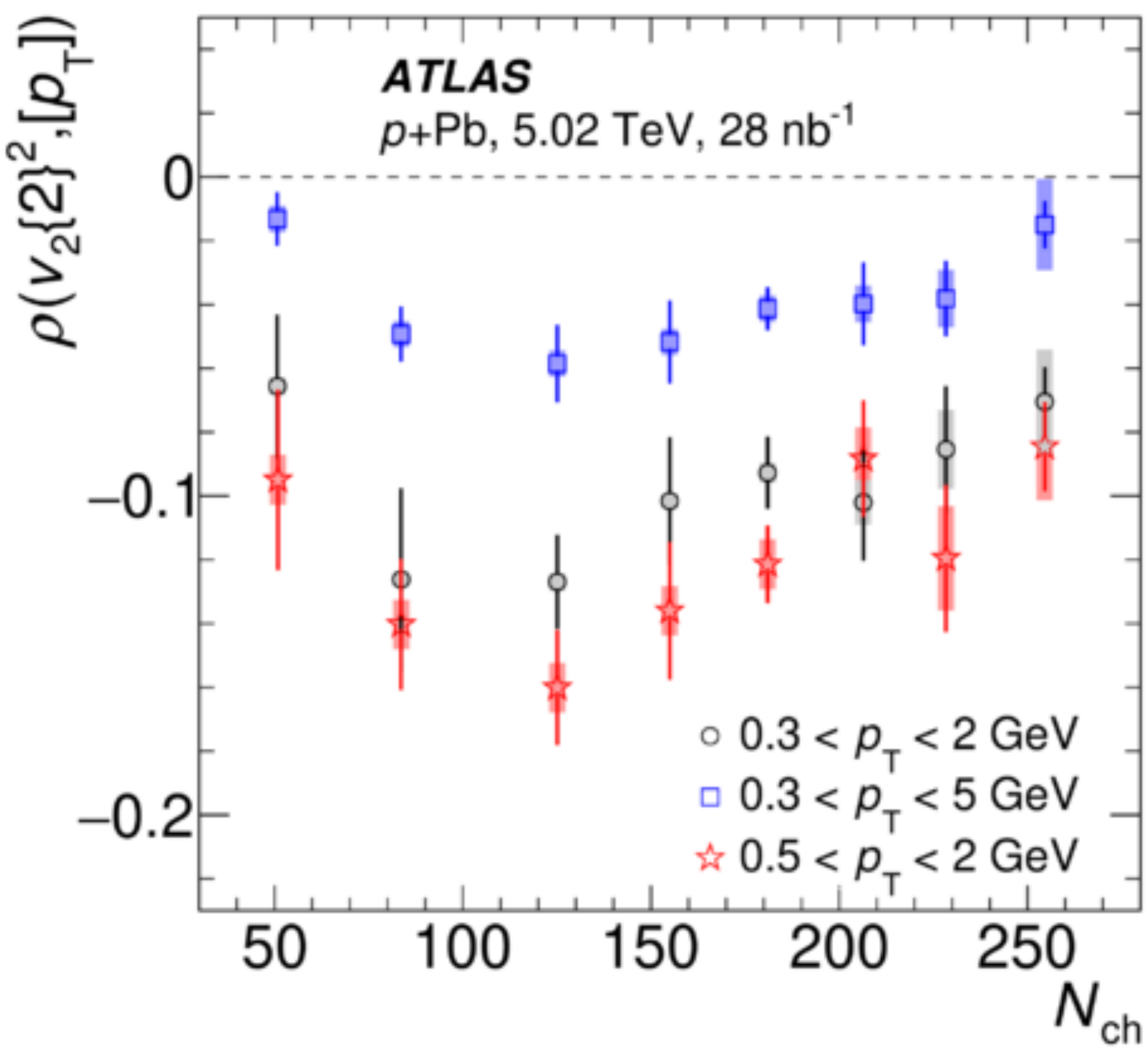
Eur. Phys. J. C 79 (2019) 985

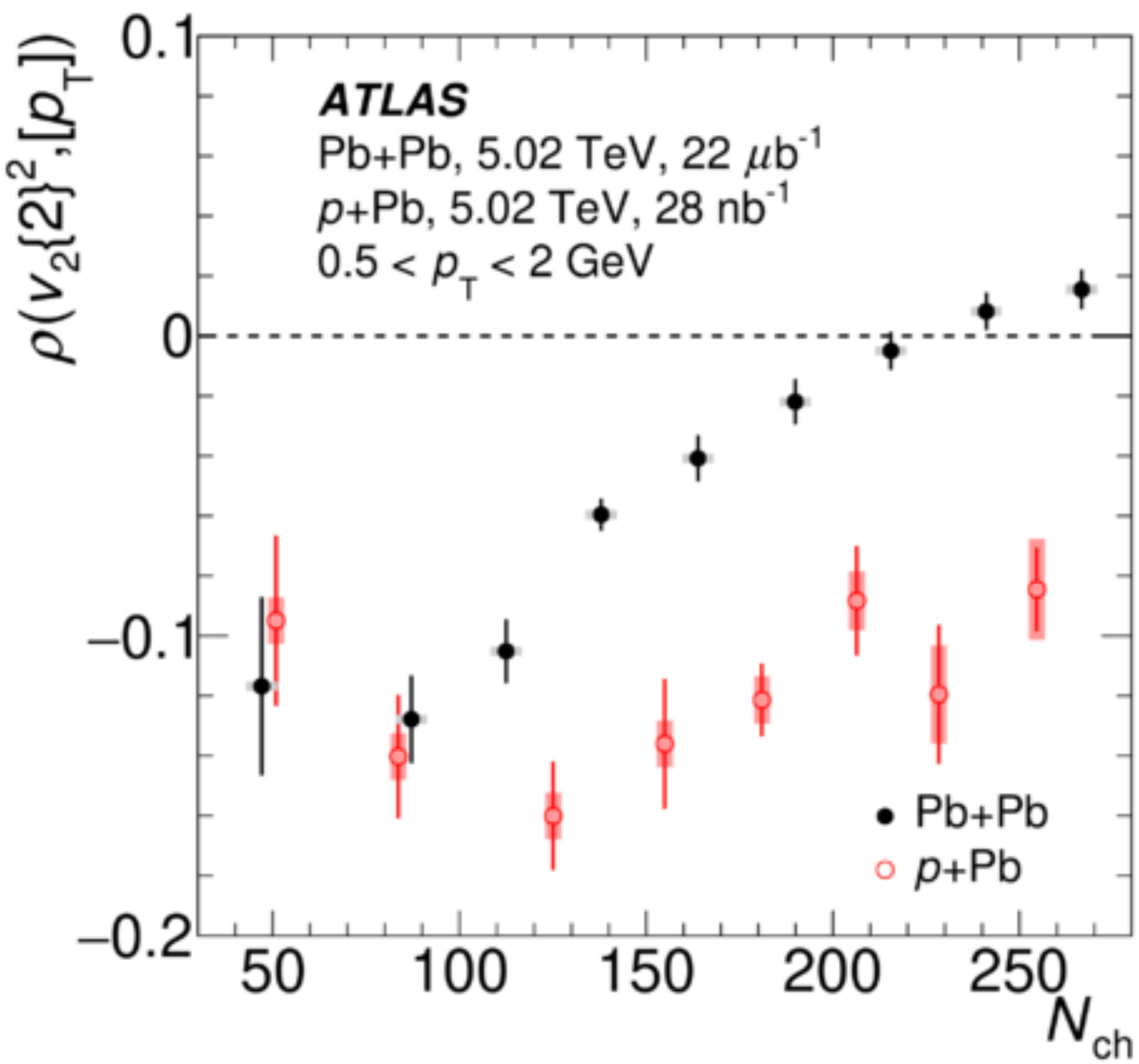


- Very interesting patterns across centralities - ρ_2 - not always positive, ρ_3 - small but not negligible

First measurement by ATLAS: p-Pb

[Eur. Phys. J. C 79 (2019) 985]

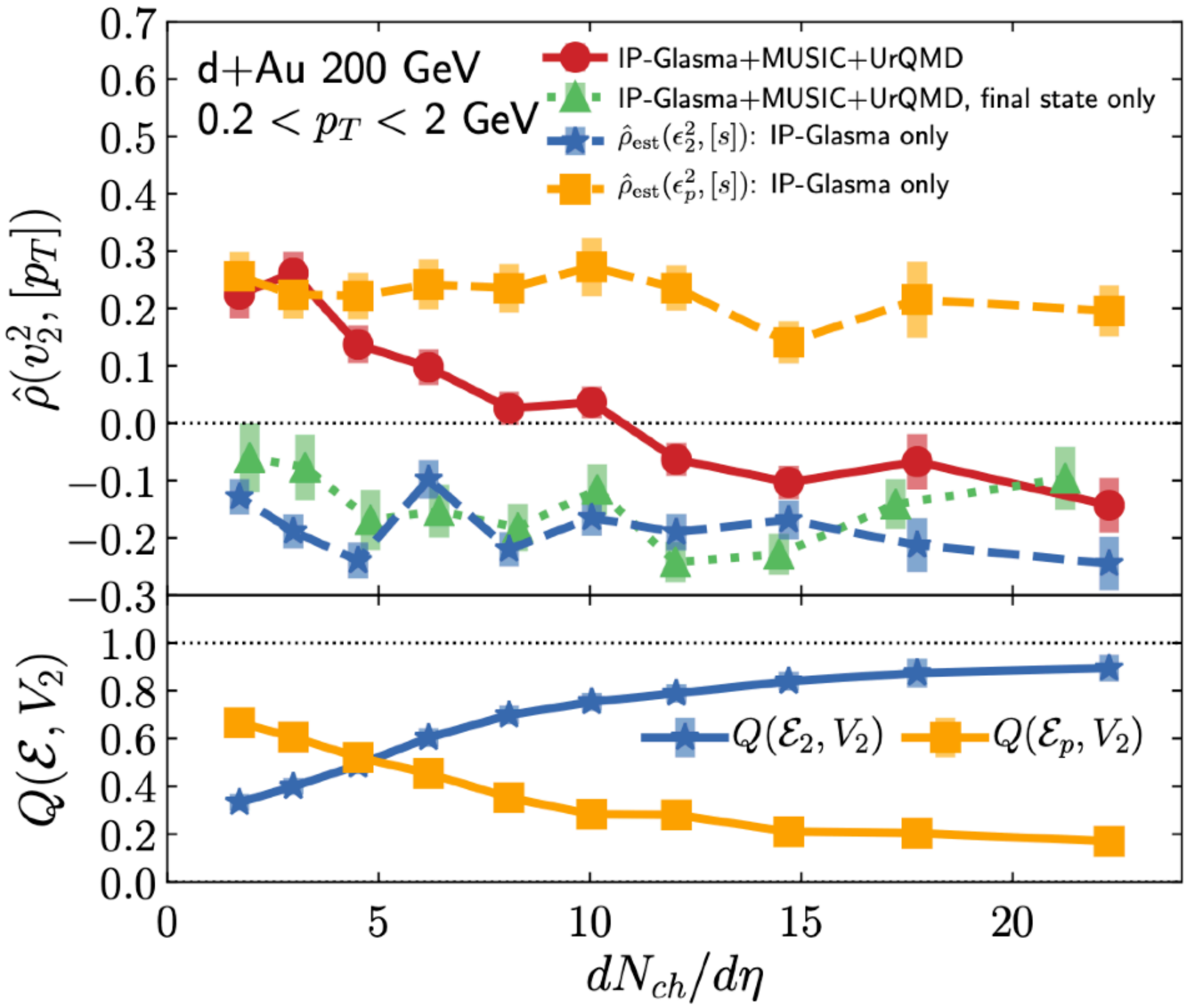




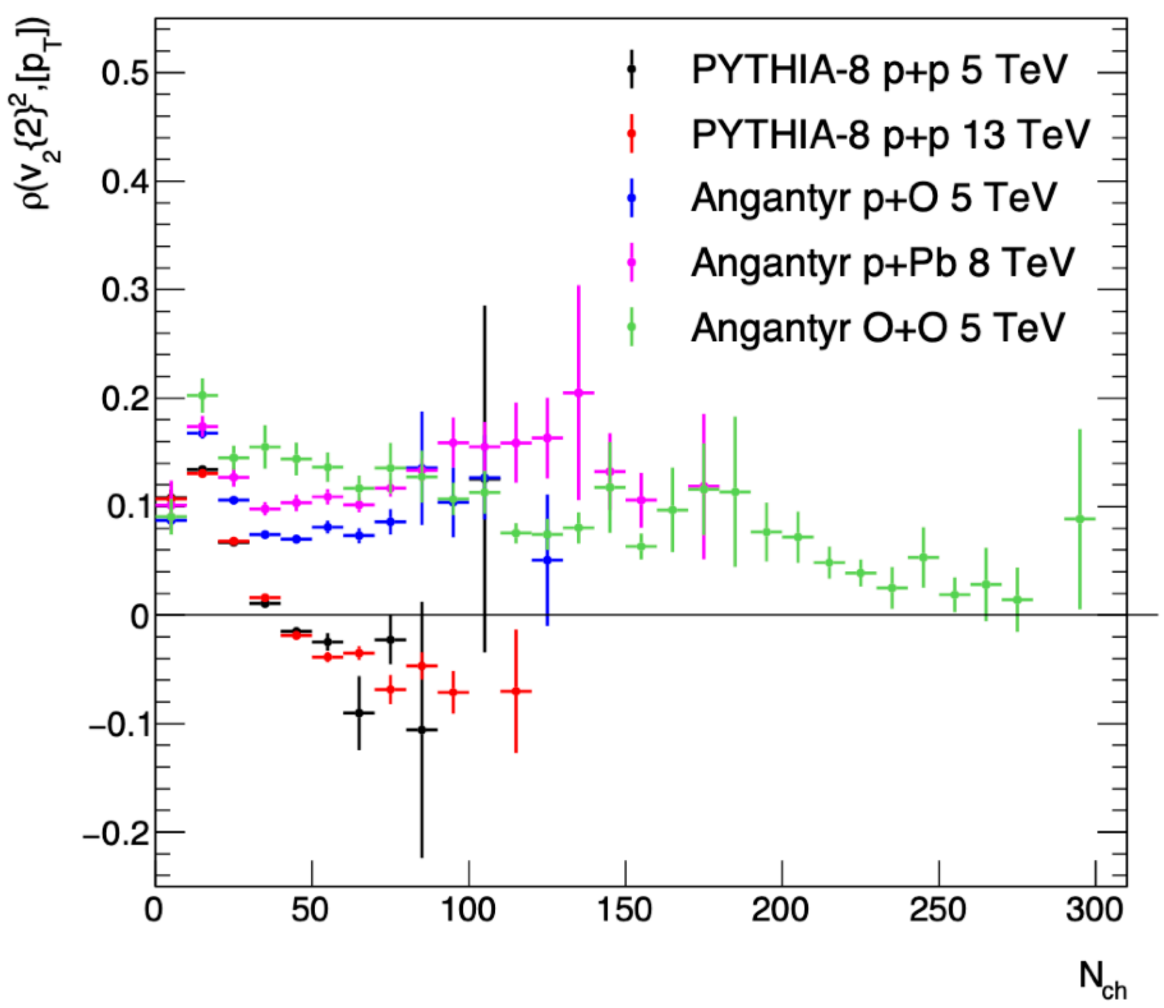
- Anti-correlation in p-Pb, with non monotonic behaviour

Color Glass Condensate predictions for small systems

G. Giacalone, .. Phys. Rev. Lett. 125, 192301 (2020)



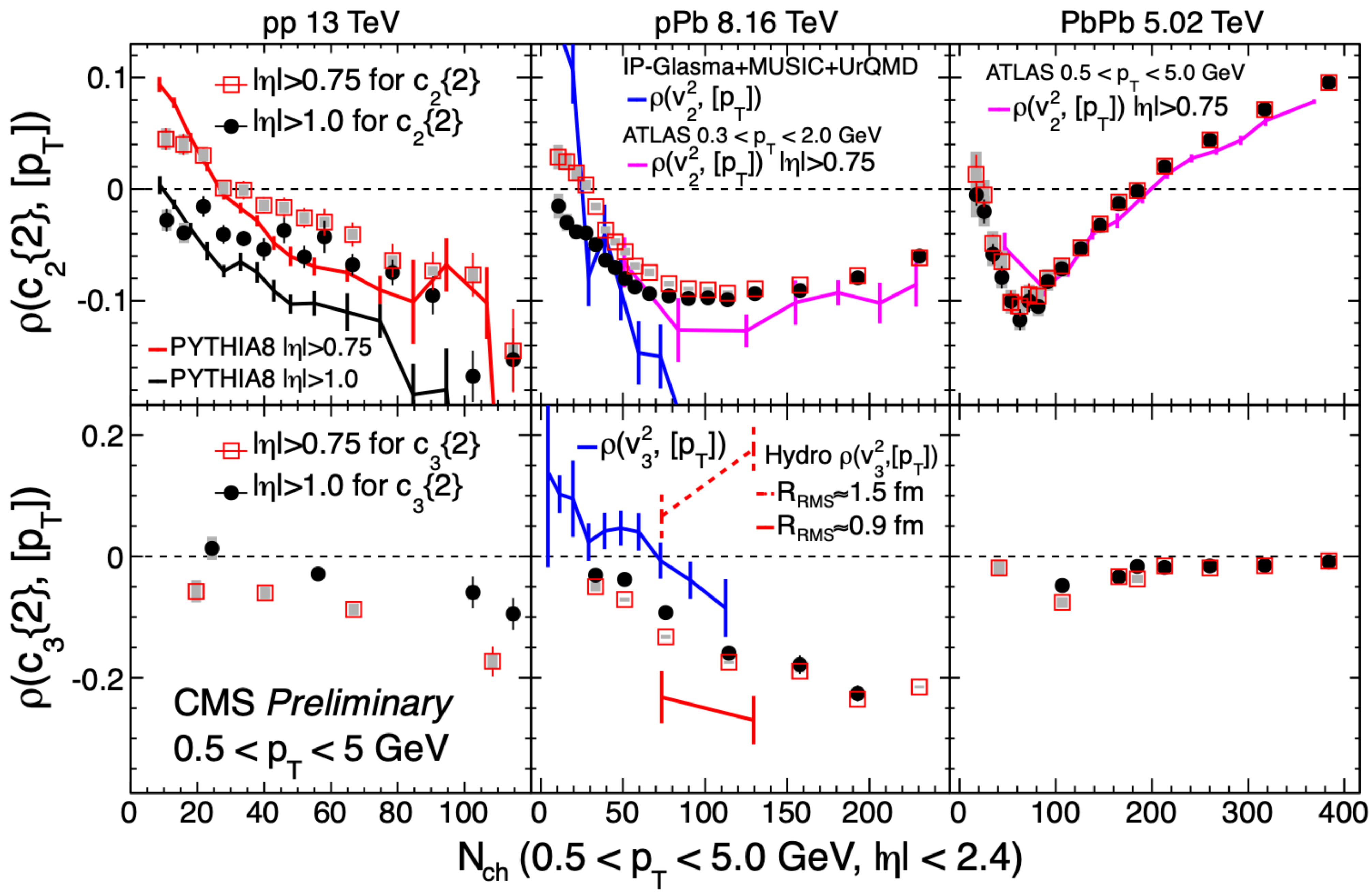
SH Lim, J. Nagle Phys. Rev. C 103, 064906 (2021)



- The rise (sign change) at $N_{ch} \to 0$ proposed as indication of initial state momentum anisotropies

ρ measurements in small systems

CMS-PAS-HIN-21-012

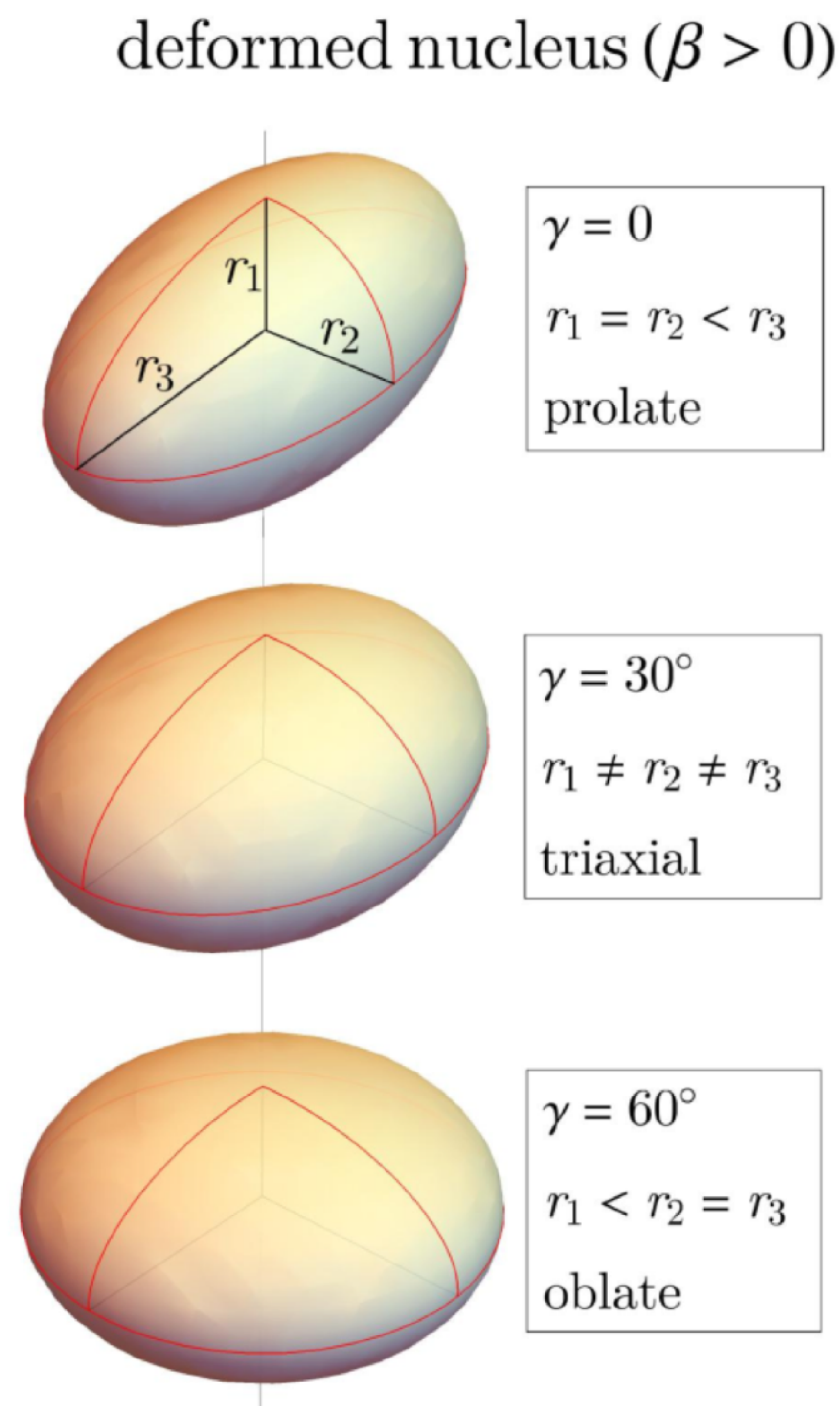


ρ in Xe-Xe collisions

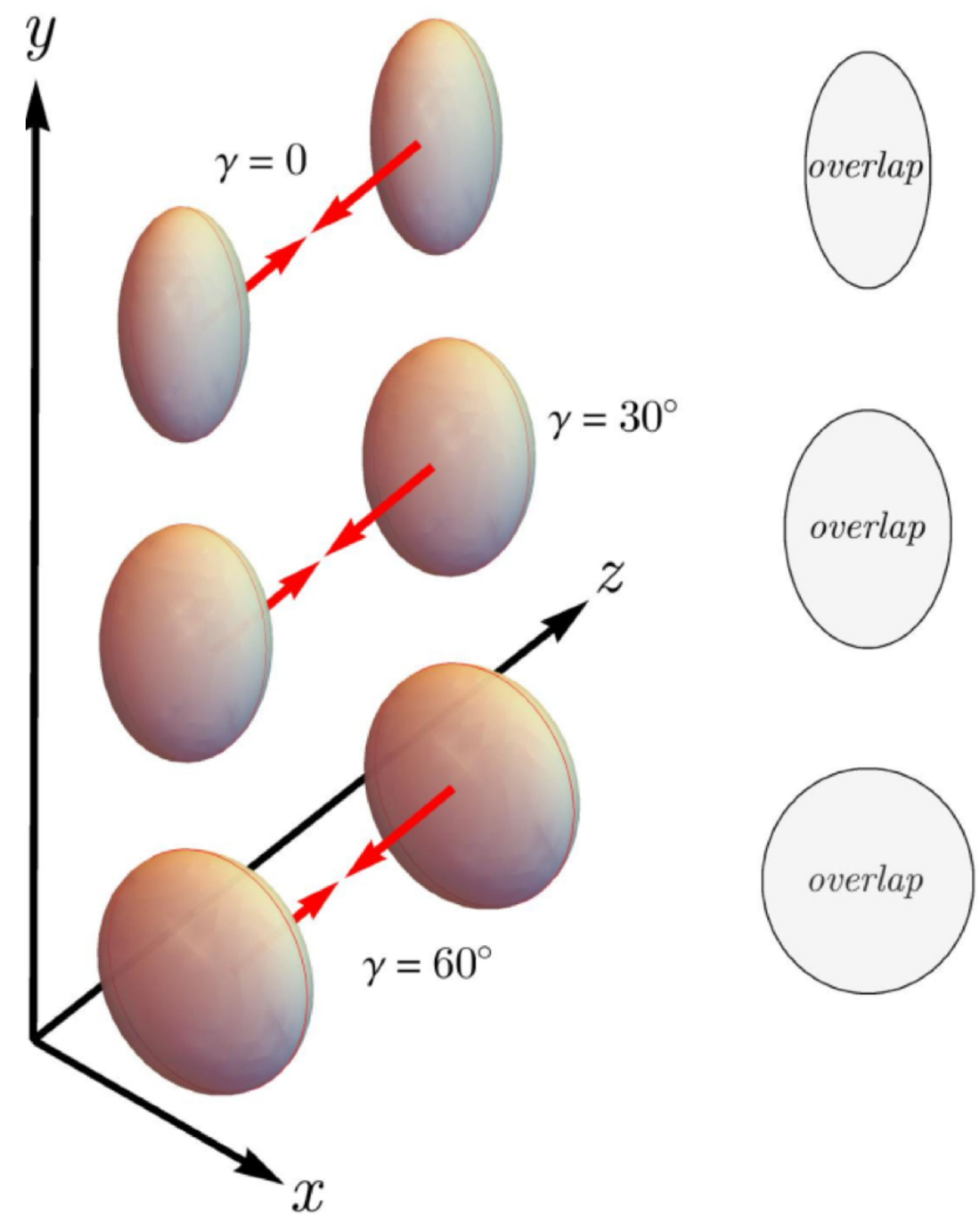
$$R(\theta, \phi) = R_0 \left(1 + \beta[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}]\right)$$

- Flow harmonics measurements predicted and already known to be different (predictions & measurements) -
  Is it dues to initial deformed shape?
  Or QGP evolution?
  Or both?

- For ρ found (in simulations) basically independent on QGP evolution - pure initial geometry probe!

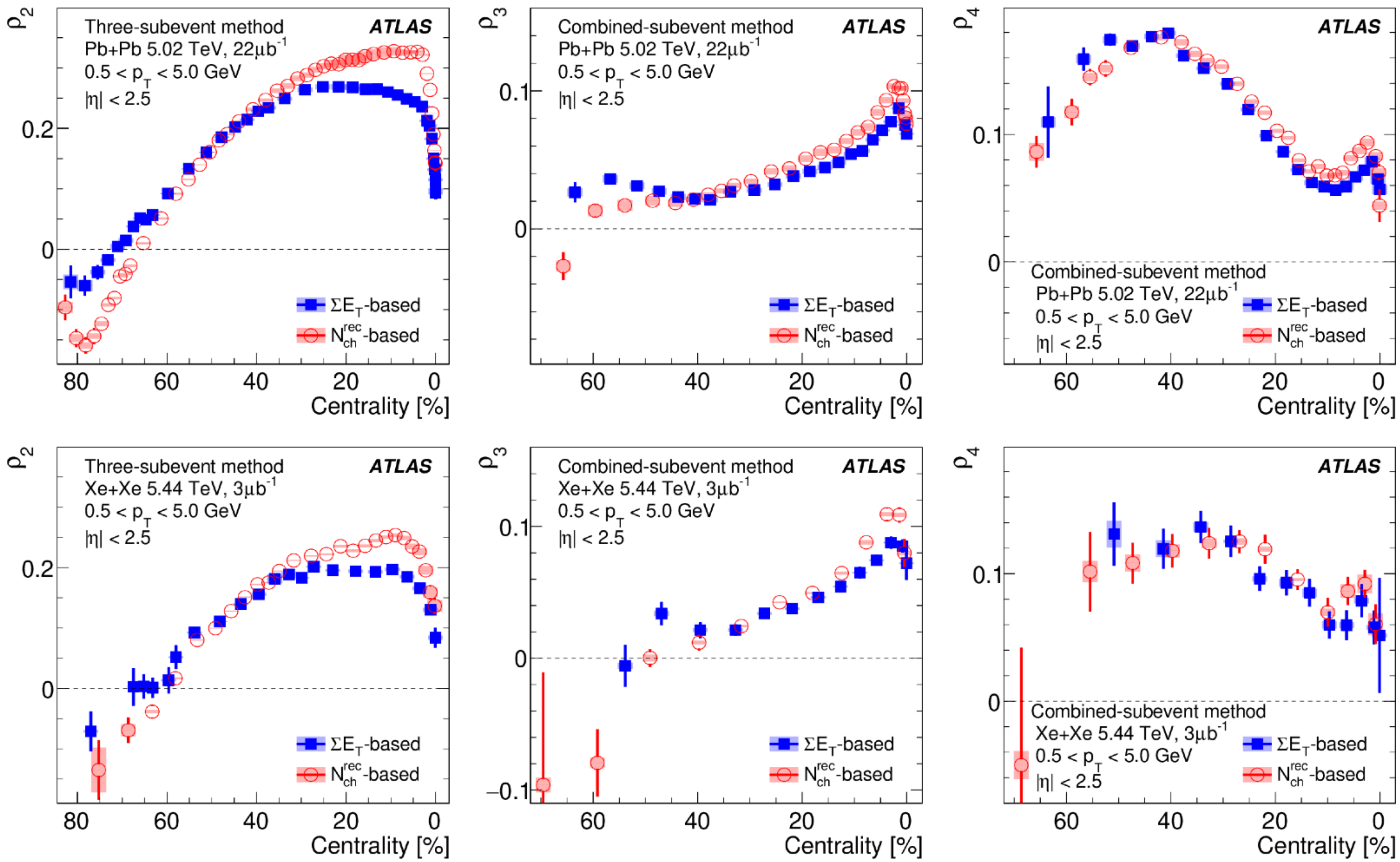


Collisions



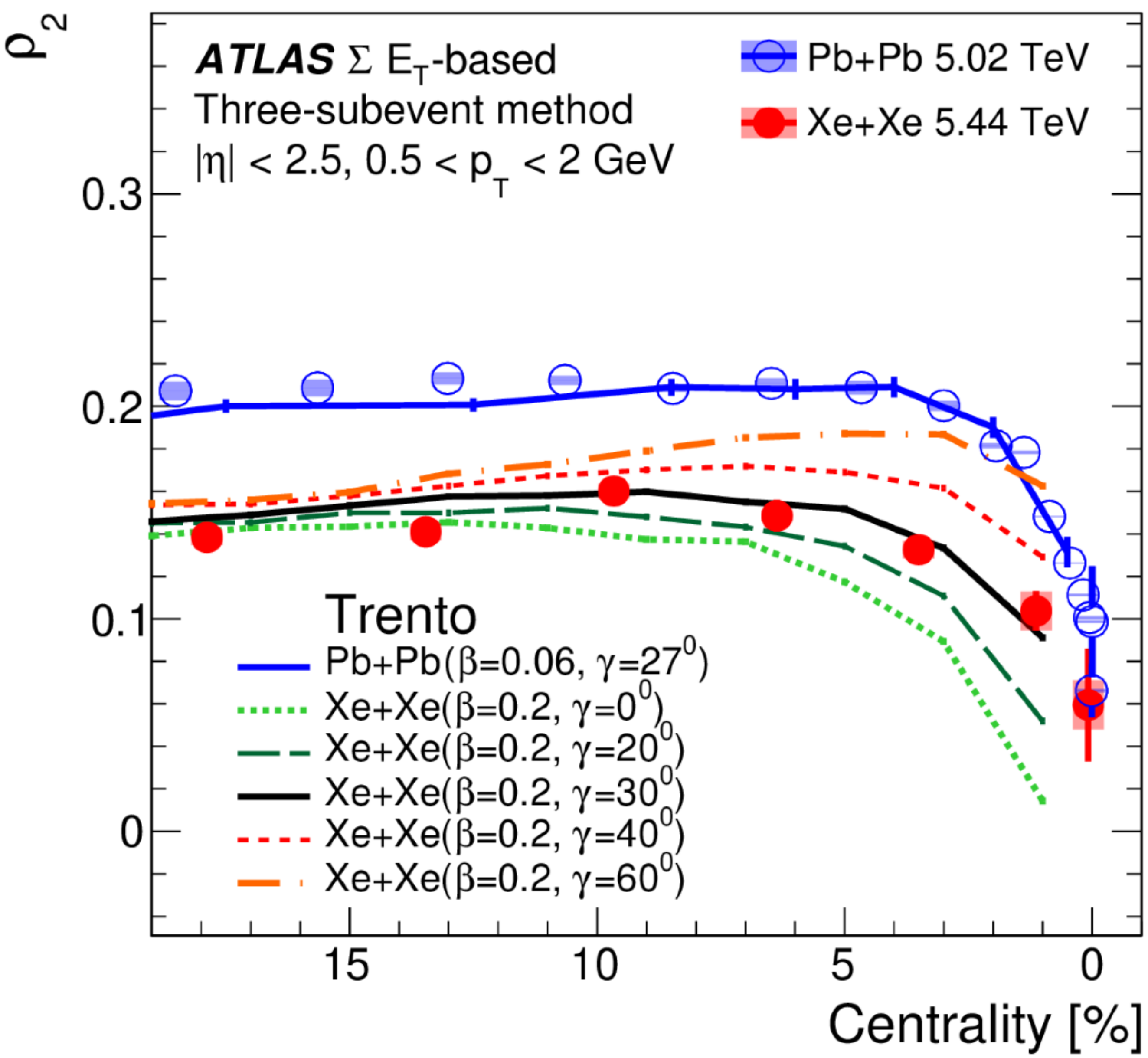
y
$\gamma = 0$
$\gamma = 30^{\circ}$
z
$\gamma = 60^{\circ}$
x
overlap
overlap
overlap

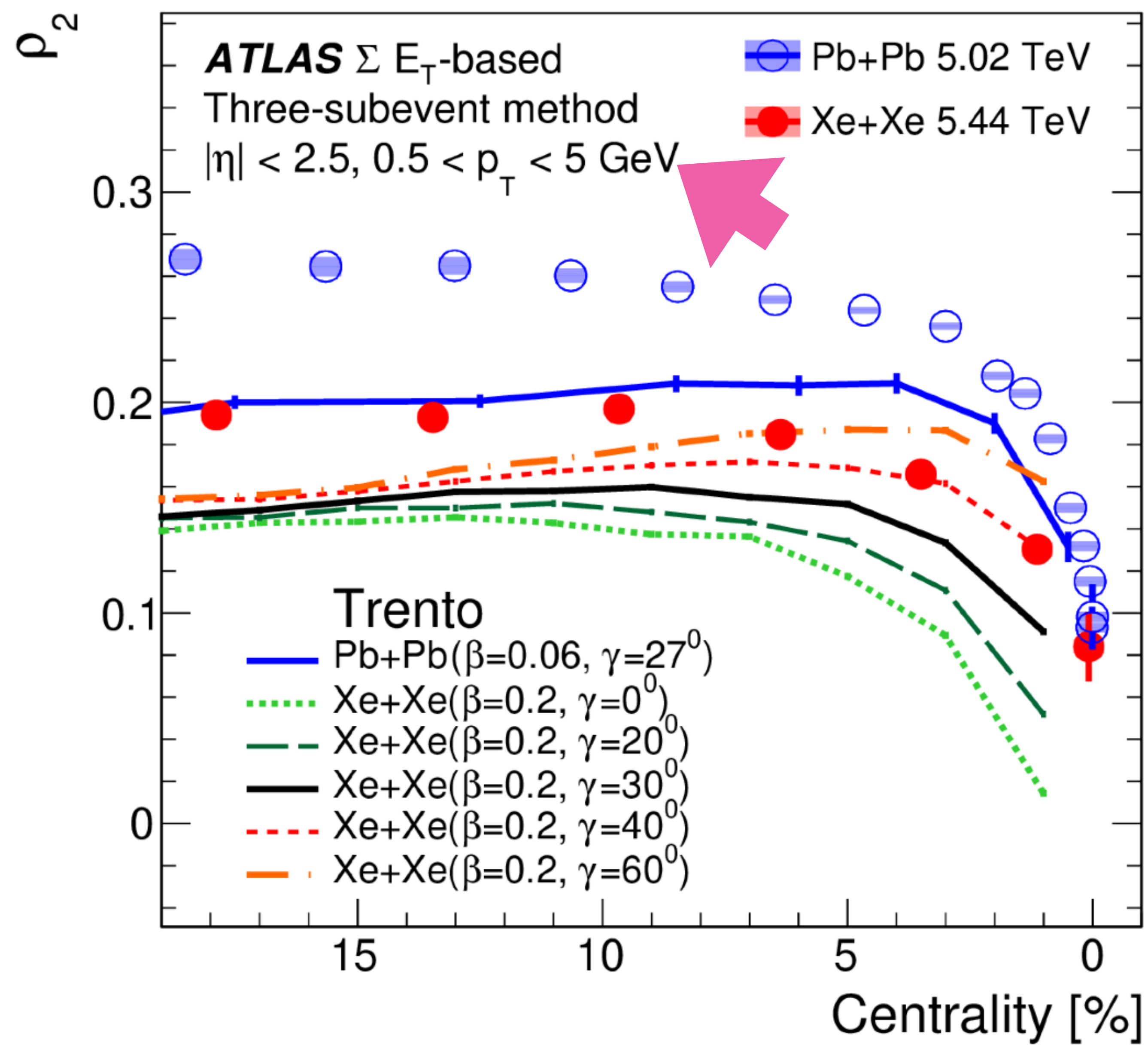
Measurement in Xe-Xe



PHYSICAL REVIEW C 107, 054910 (2023)

Theory comparisons

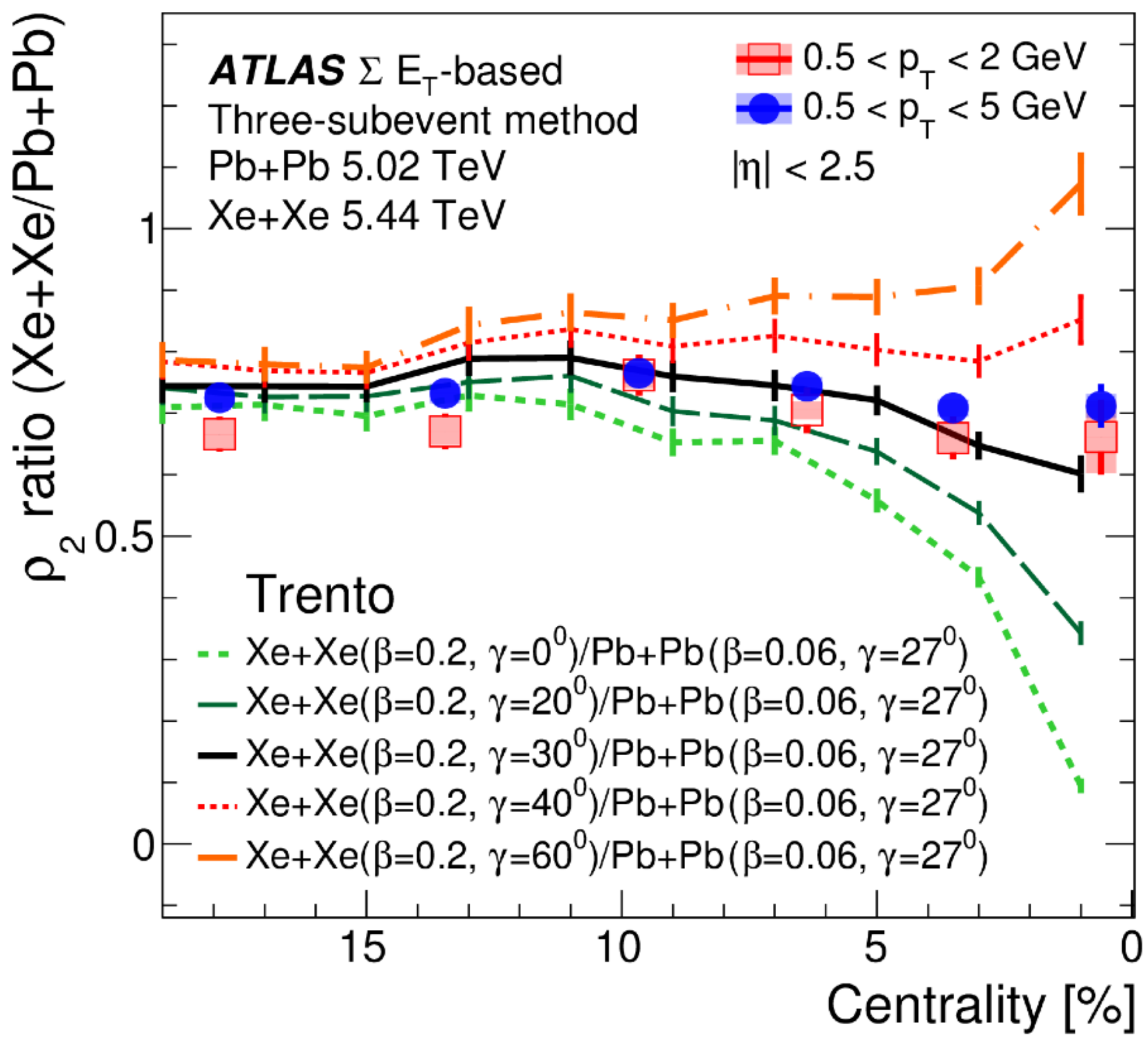




PHYSICAL REVIEW C 107, 054910 (2023)

ρ_2 ratio

PHYSICAL REVIEW C 107, 054910 (2023)



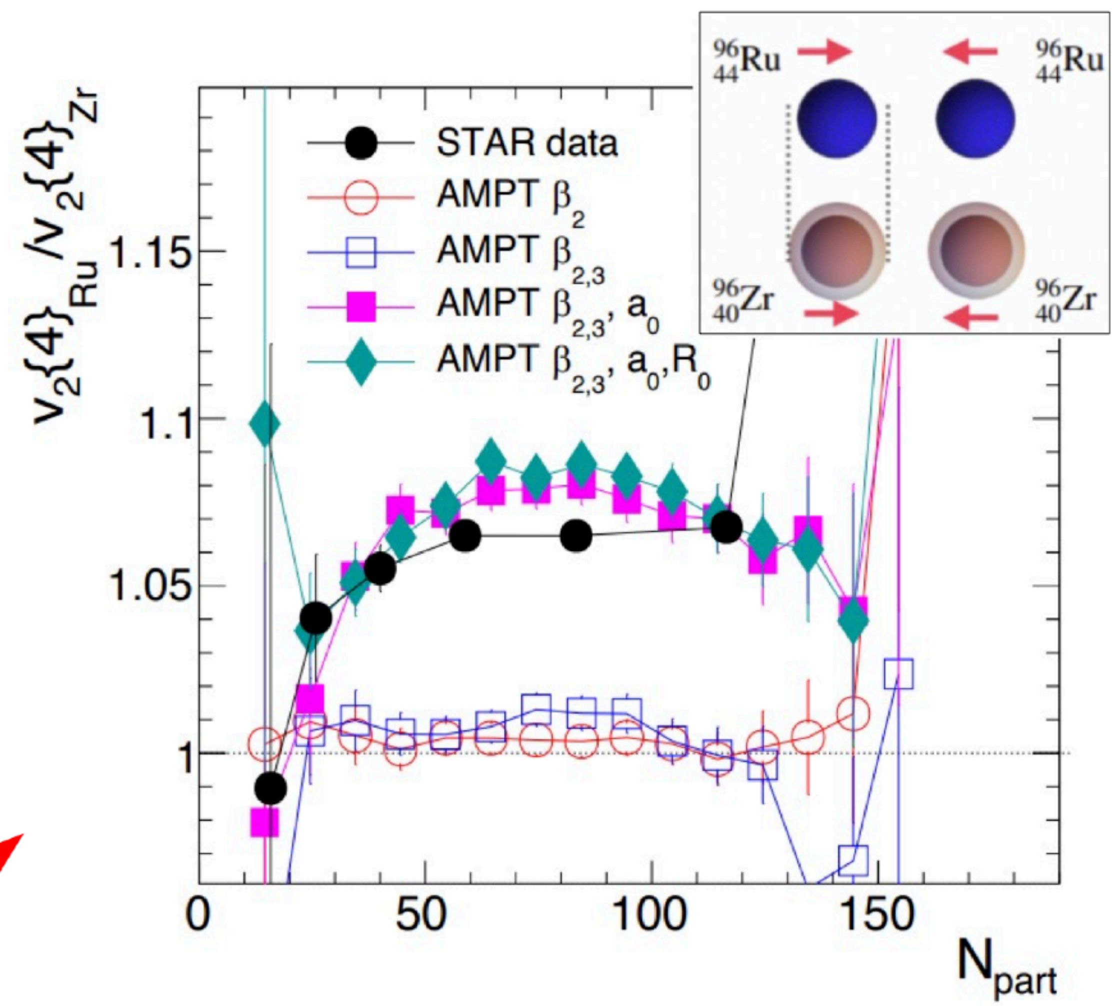
p_T **interval irrelevant**

- 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

Connection to low energy nuclear physics

- New experimental tool to for nuclear shapes imagining
- Especially precise for “relative” deformations
- Multiple workshops e.g: https://www.int.washington.edu/programs-and-workshops/23-1a
- Wouldn’t it be possible to see nuclear shapes by looking at peripheral collisions?

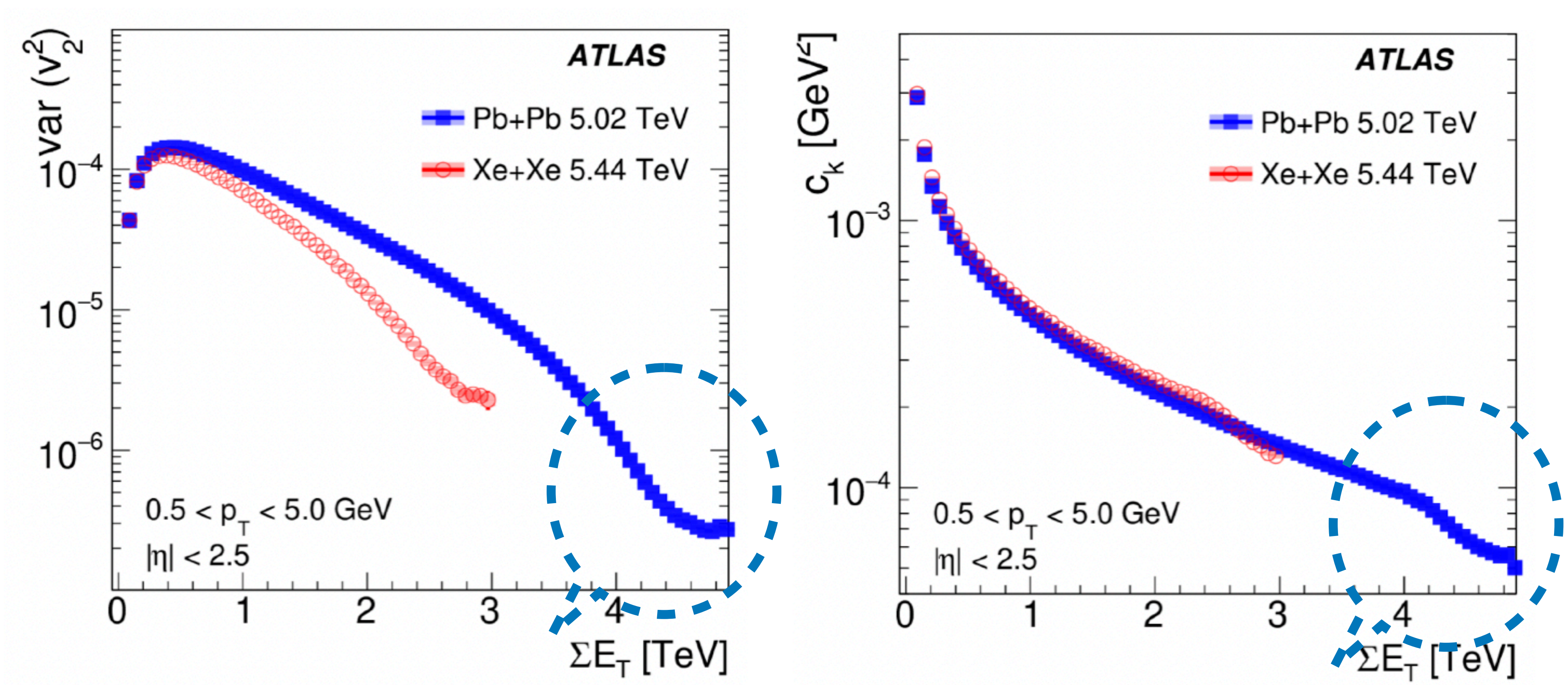
[Jia, Giacalone, Zhang, arXiv:2206.10449]



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

The UCC events

PHYSICAL REVIEW C 107, 054910 (2023)



- 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

ATLAS-CONF-2023-061

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

- 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

Measured quantities

- An n-particle transverse momentum correlator defined:

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

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

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

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

Skewness normalised to variance of unit value

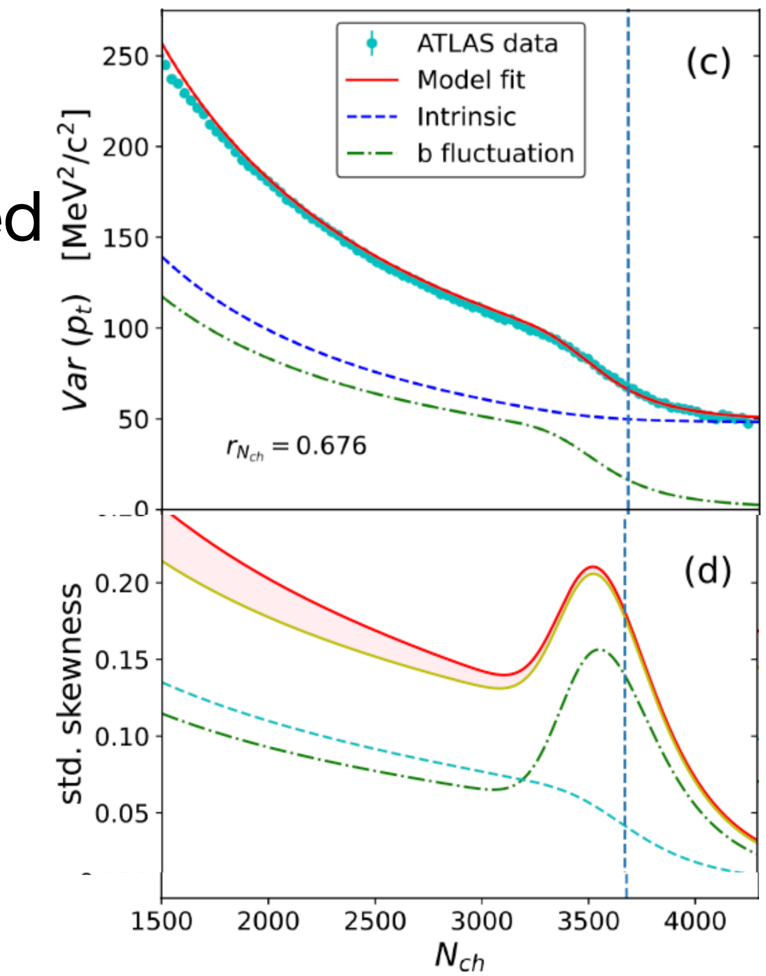
- Averaged over activity class: N_{ch}^{rec} - number of reconstructed charge particlesΣE_T^{FCal} - energy in ATLAS Forward calorimeter (default centrality estimator)
  - Estimators scaled for comparison by values in the 0-1% centrality bin

Predictions

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

- 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



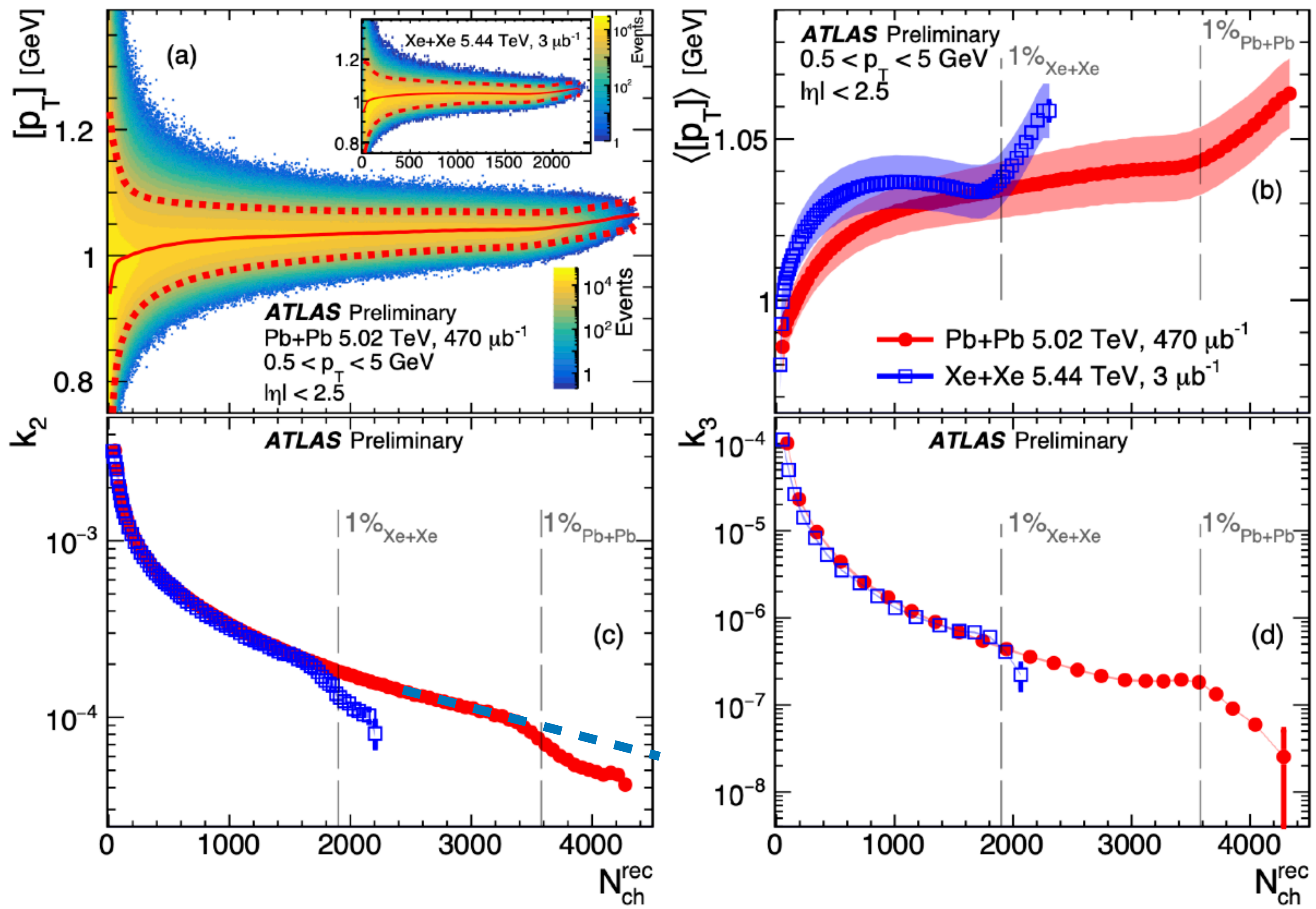
Moments N_{ch}^{rec} dependence

- 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

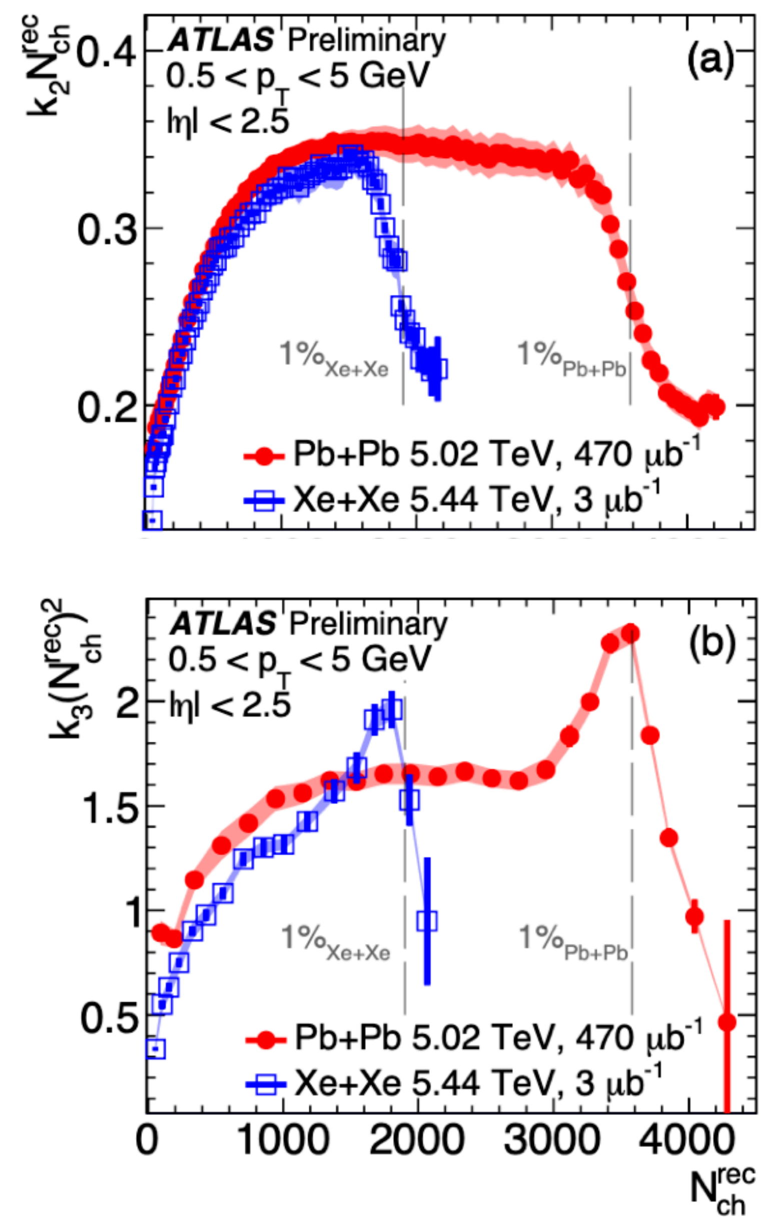
- Xe+Xe and Pb+Pb exhibit similar features



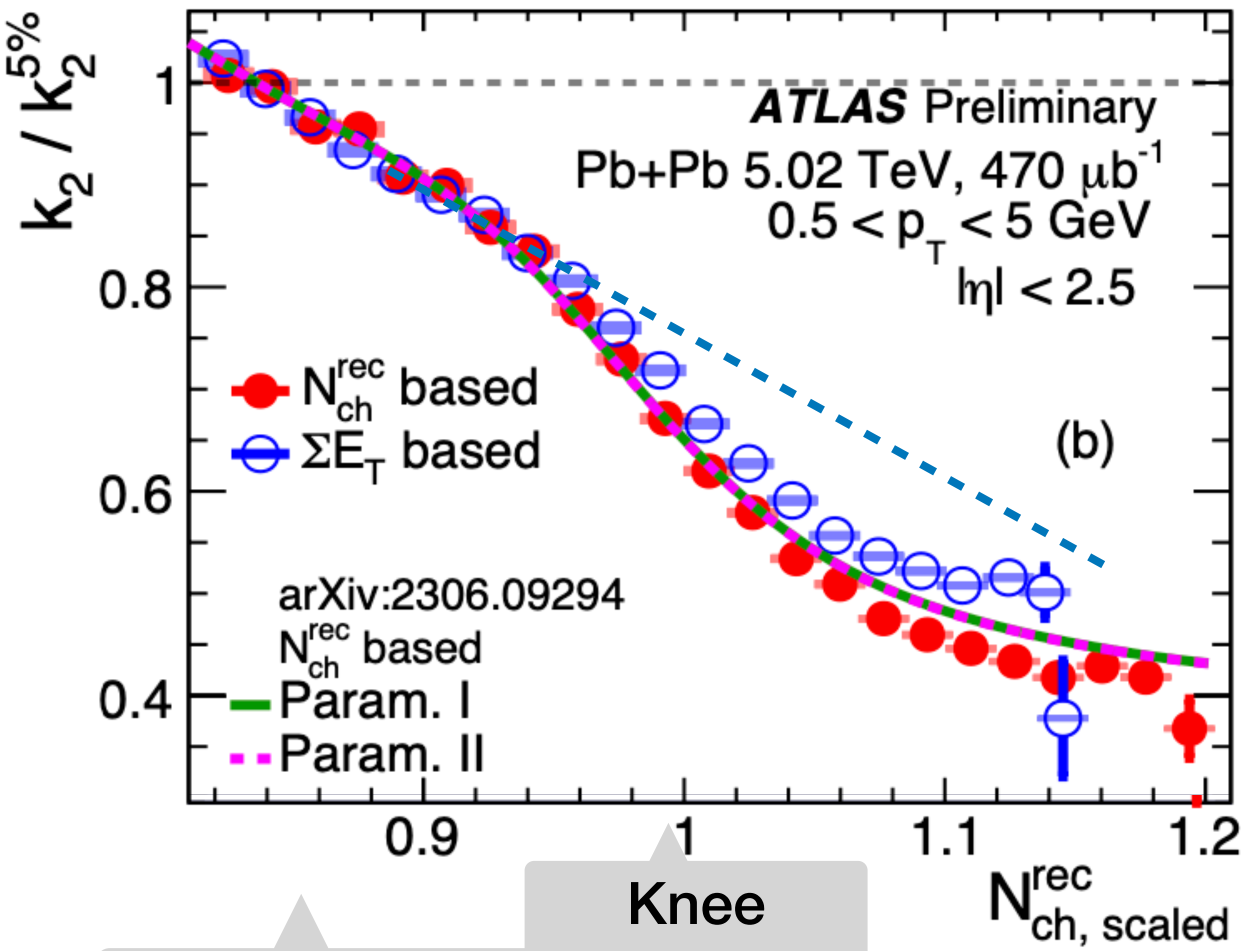
Power-law evolution of moments

- 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)



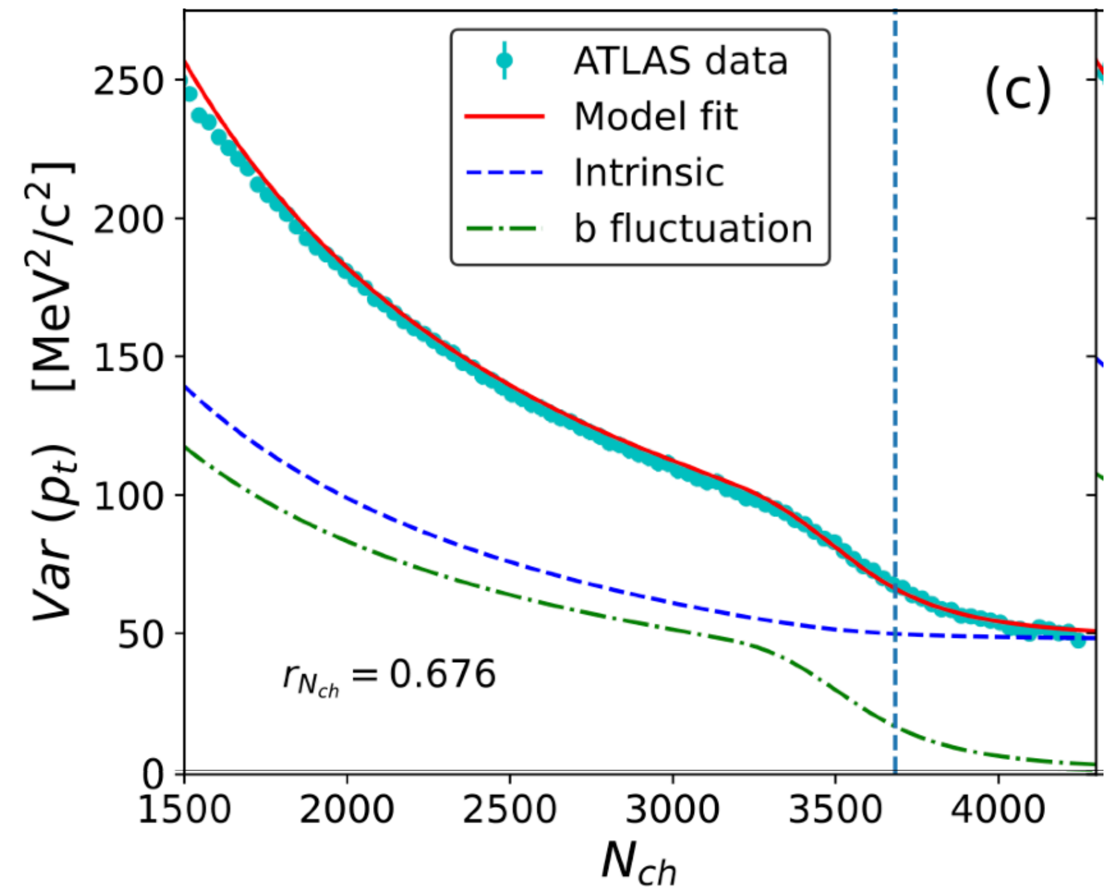
Moments evolution in UCC



Knee

Geometric + Intrinsic

Intrinsic

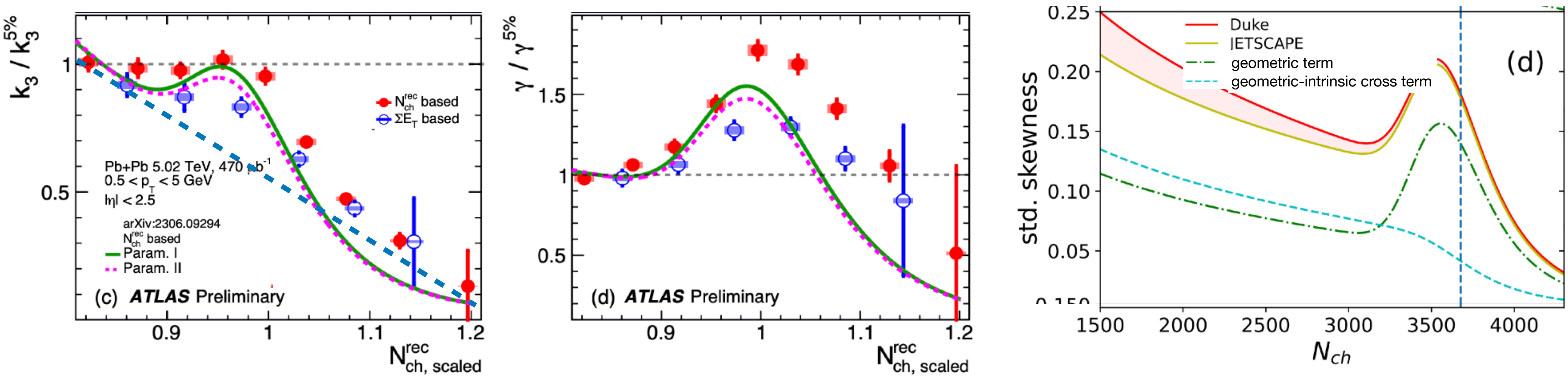


R.Samanta et al arxiv 2306.09294

- A significant drop in k_2 (width of $[p_T]$)
- A phenomenological model (2D Gaussian model) of fluctuations predicts the the trends very well and isolates two contributions to $[p_T]$ fluctuations

Skewness

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



- 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

Speed of sound extraction

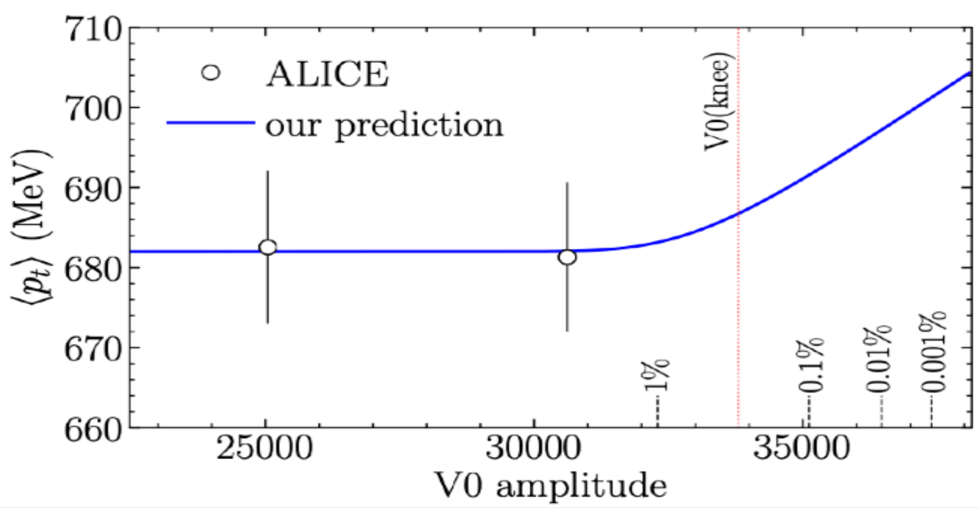
F. Gardim, G. Giacalone, M. Luzum Y.-I. Olitrault
Nature Physics 16 (2020) 615

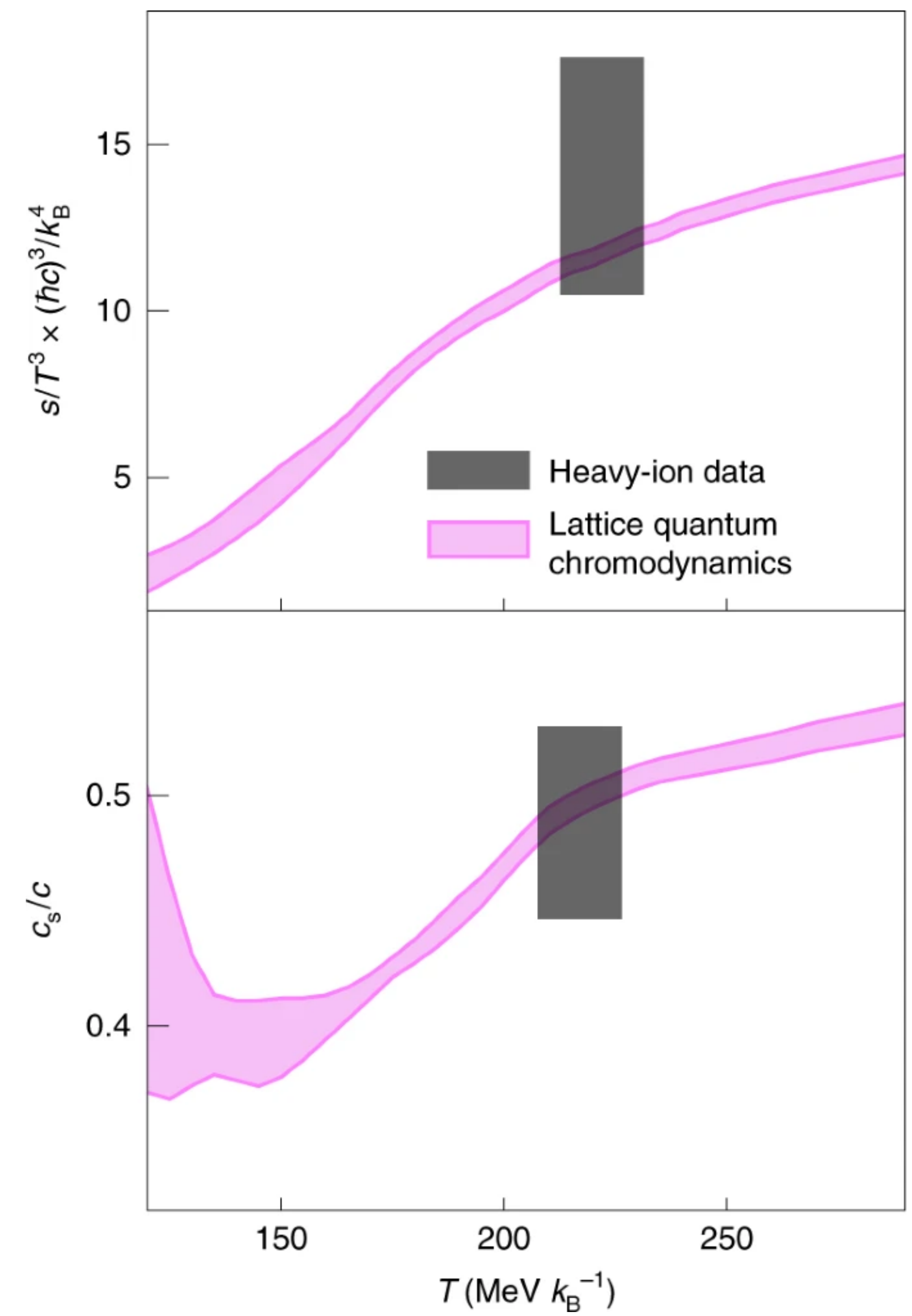
$$c_s^2(T_{\rm eff}) = \frac{dP}{d\varepsilon} = \frac{sdT}{Tds}\Big|_{T_{\rm eff}} = \frac{d\ln\langle p_{\rm T}\rangle}{d\ln(dN_{\rm ch}/d\eta)} = 0.24 \pm 0.04$$

- Assumptions: effective temperature T_{eff} in the QGP phase related to $\langle p_T \rangle = 3 \cdot T_{eff}$, and entropy to N_{ch}

$$\frac{\mathrm{d}s(T_{\rm eff})}{s(T_{\rm eff})} = \frac{\mathrm{d}N_{\rm ch}}{N_{\rm ch}}, \qquad \frac{\mathrm{d}T_{\rm eff}}{T_{\rm eff}} = \frac{\mathrm{d}\langle p_{\rm t}\rangle}{\langle p_{\rm t}\rangle}$$

- Followup: Ultra Central Collisions the $[p_T]$ is predicted to rise with centrality
  the sound speed in QGP c_s^2 can be obtained from that
  F.G. Gardim et al Phys.Lett.B 809 (2020) 135749





CMS analysis

Shown at QM 23 by Cesar Bernardes from CMS

Analysis method - observables

The c_s^2 depends on the relative variation of $\langle p_T \rangle$ vs N_{ch}

- Can be extracted using
  - $\frac{\langle p_T \rangle}{\langle p_T \rangle^0} \sim \left(\frac{N_{ch}}{N_{ch}^0}\right)^{c_s^2}$, where $\langle p_T \rangle^0$ and N_{ch}^0 are obtained in 0-5%

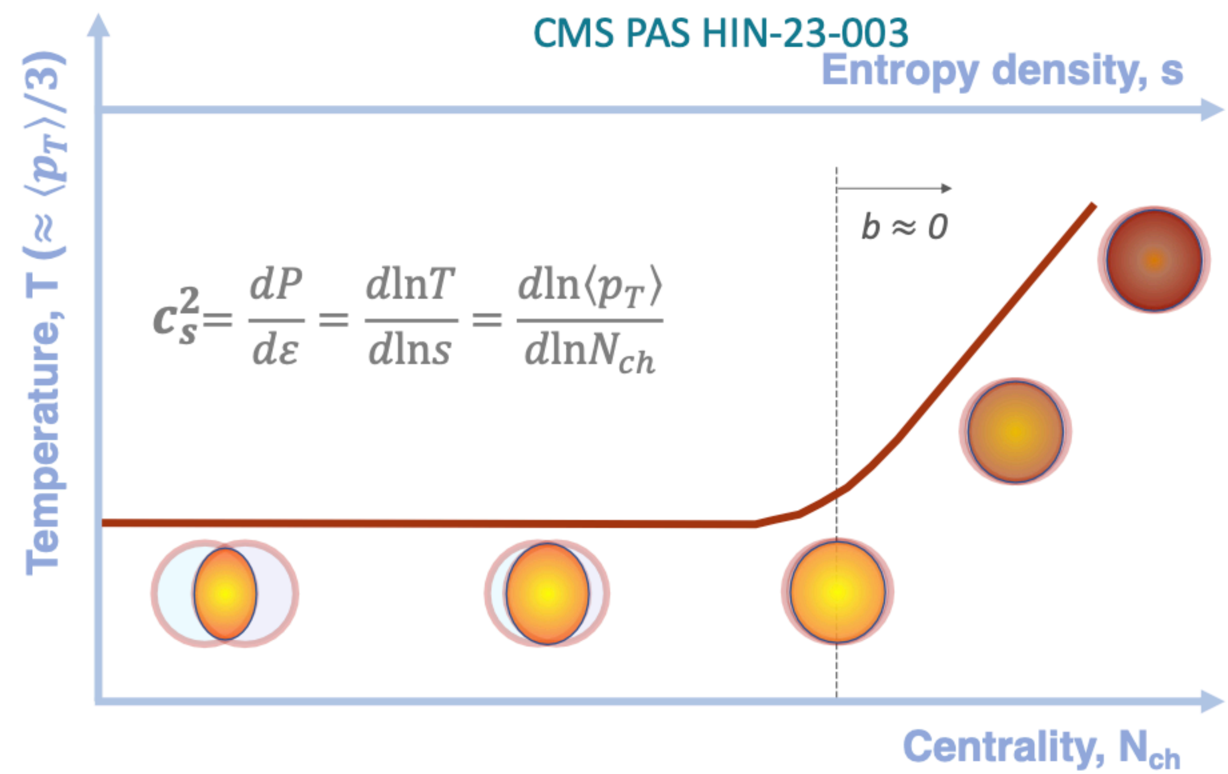
Analysis observables

$\langle p_T \rangle^{norm} = \frac{\langle p_T \rangle}{\langle p_T \rangle^0}$ vs $N_{ch}^{norm} = \frac{N_{ch}}{N_{ch}^0}$

$\langle p_T \rangle^0$ (used to estimate T_{eff})

Fit $\langle p_T \rangle^{norm}$ vs N_{ch}^{norm} using

- $\langle p_T \rangle^{norm} = \left(\frac{N_{ch}^{norm}}{\text{Prob}(N_{ch}^{norm})}\right)^{c_s^2}$



Spectra extrapolation

Analysis method - p_{T} extrapolation to zero

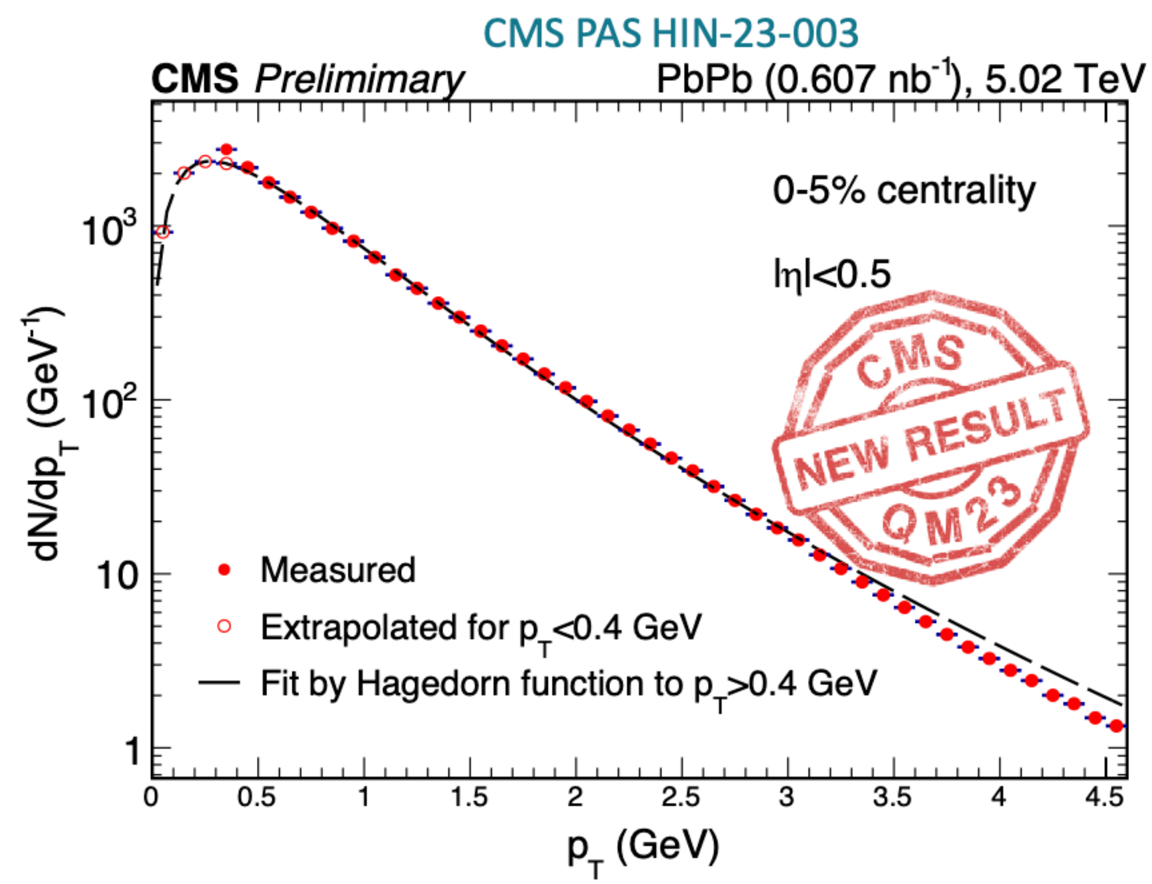
$\langle p_{\mathrm{T}} \rangle$ and N_{ch} are corrected for tracking efficiency

Extrapolation to $p_{\mathrm{T}} \approx 0$ by fitting the spectrum in $p_T > 0.4$ GeV

- Hagedorn function

$$\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}} = p_{\mathrm{T}} \left(1 + \frac{1}{\sqrt{1 - \langle \beta_{\mathrm{T}} \rangle^2}} \frac{\left(\sqrt{p_T^2 + m^2} - \langle \beta_{\mathrm{T}} \rangle p_{\mathrm{T}} \right)}{nT} \right)^{-n}$$

- m is the pion mass and $\langle \beta_{\mathrm{T}} \rangle$, n, T are free parameters



After corrections. for each bin of $E_{\mathrm{T,sum}}^{\mathrm{HF}}$ → $\langle p_{\mathrm{T}} \rangle^{\mathrm{norm}}$ vs $N_{\mathrm{ch}}^{\mathrm{norm}}$

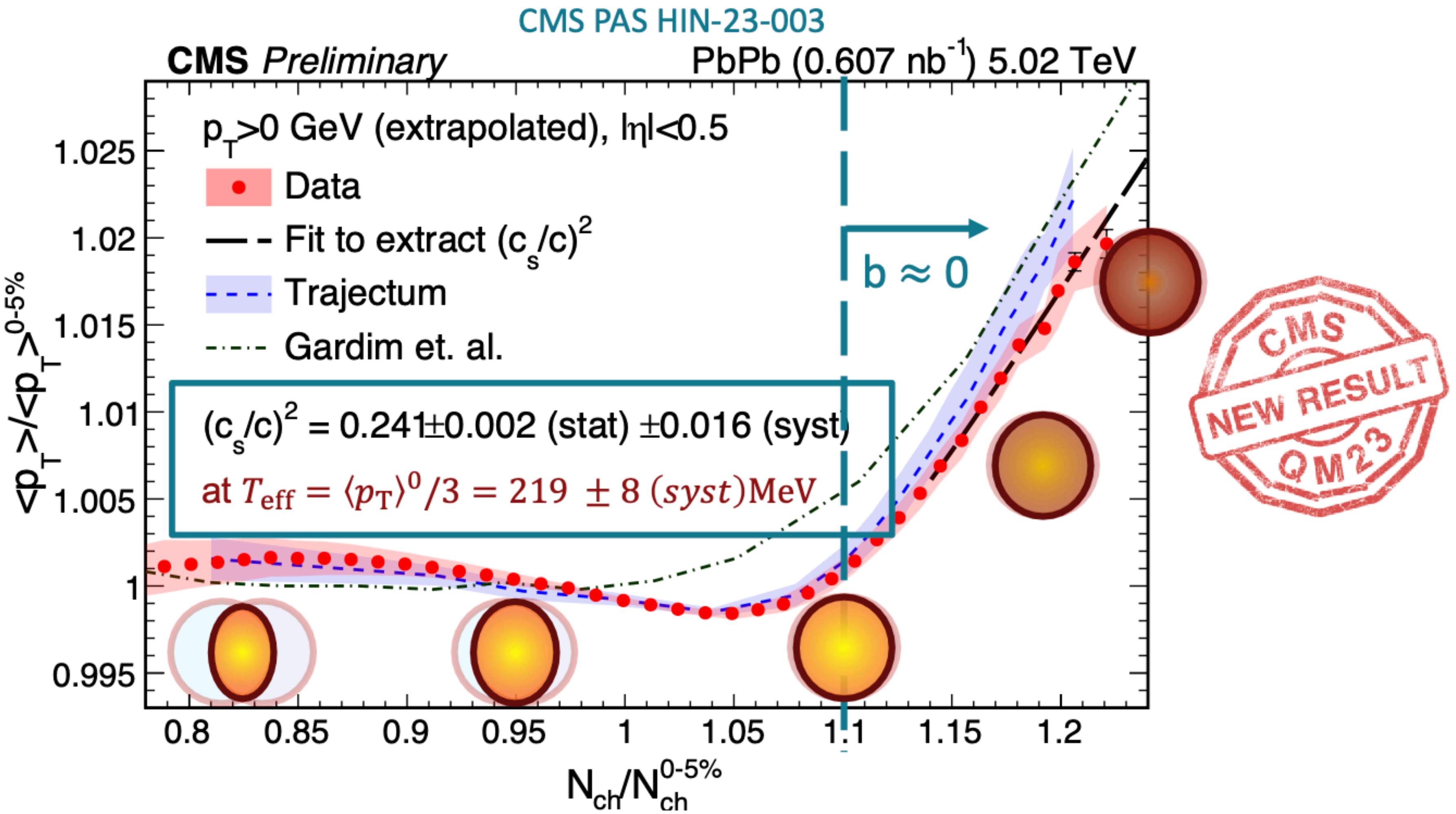
Track selection: $p_{\mathrm{T}} > 0.3$ GeV, $|\eta| < 0.5$

- Better tracking performance

Results

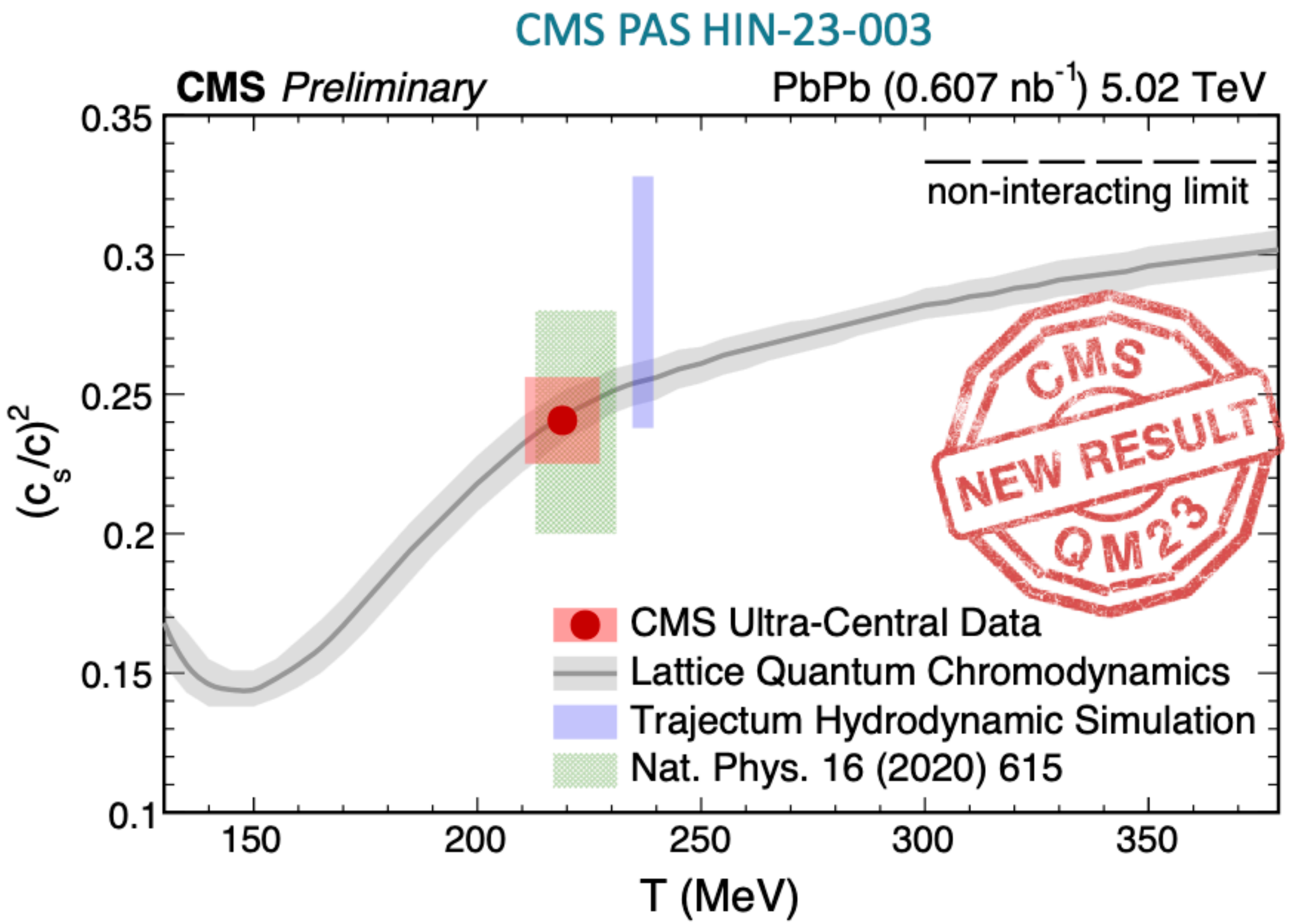
Results

Significant increase of $\langle p_{\mathrm{T}} \rangle$ toward UCC events as predicted by the simulations

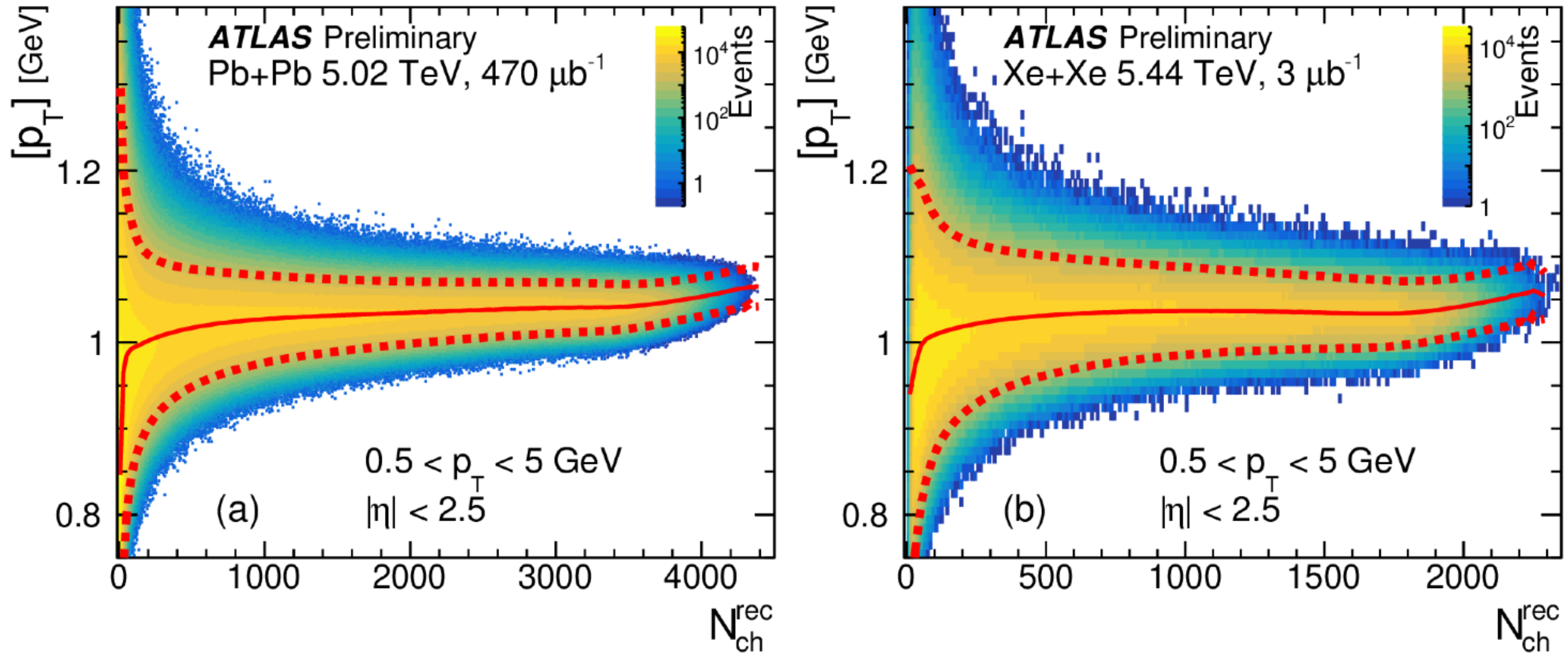


Speed of sound extracted from the fit and T_{eff} from $\langle p_{\mathrm{T}} \rangle^0$

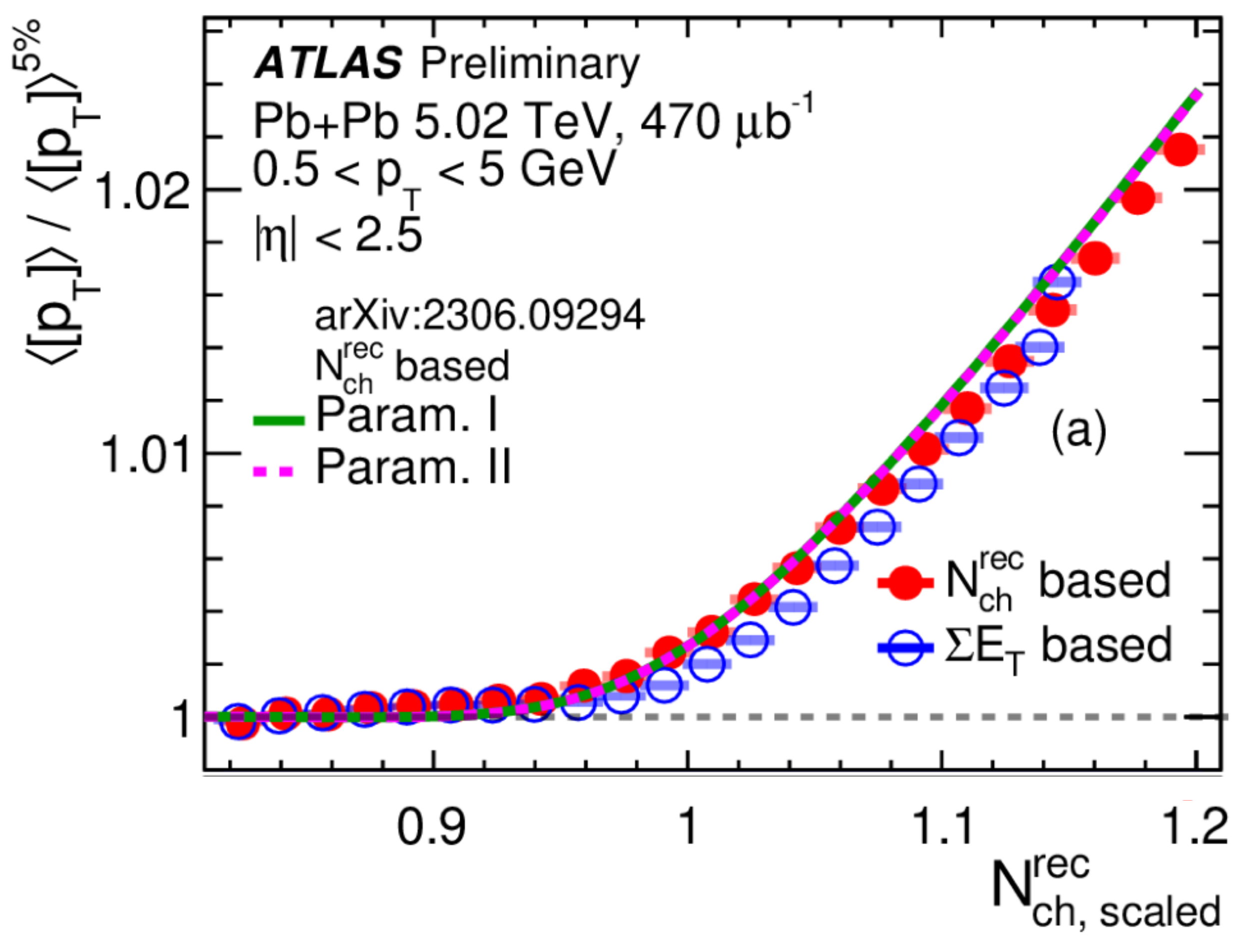
The money plot



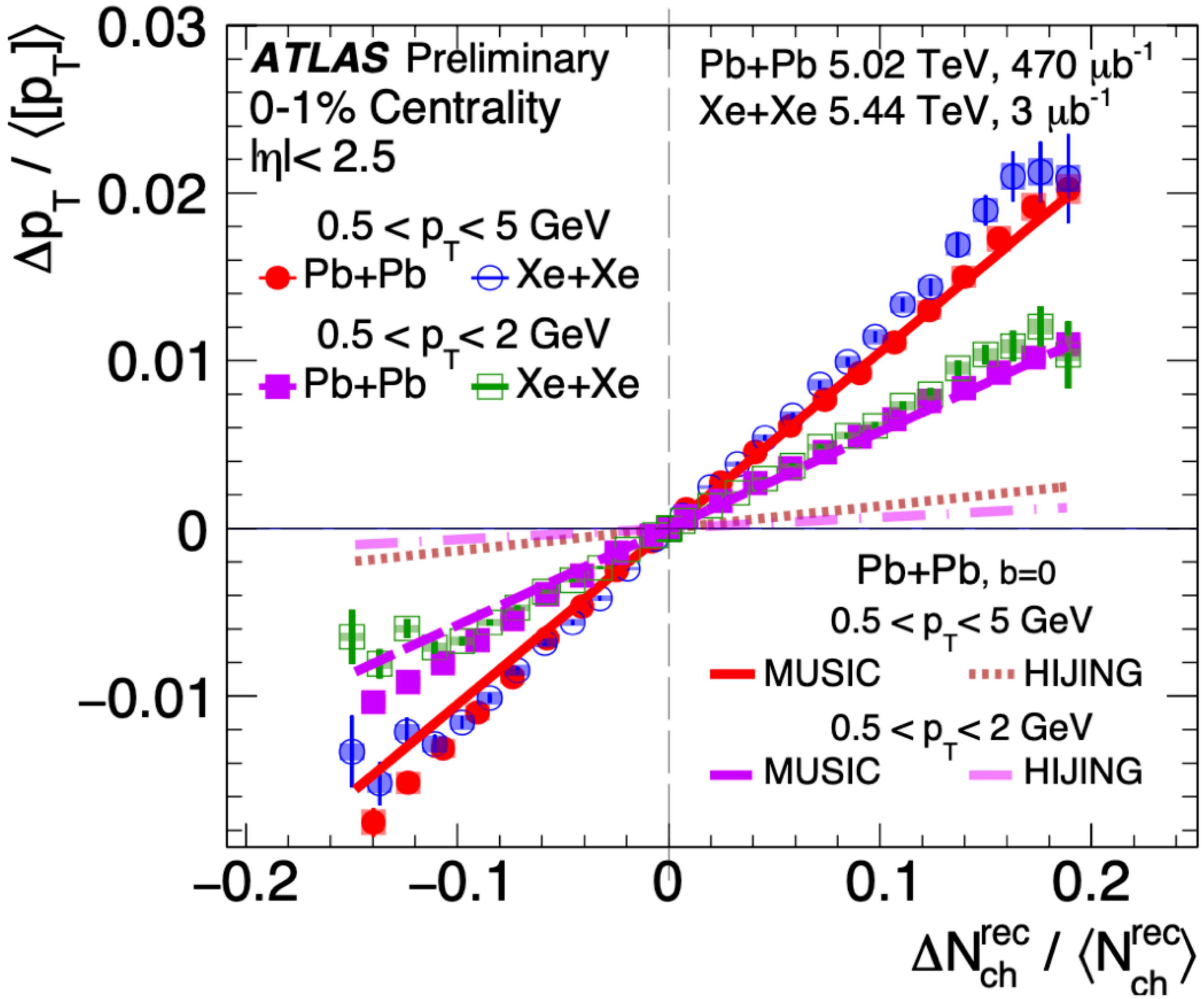
ATLAS analysis



- Similar procedure:
- Momentum range for $[p_T]$ compatible with our earlier measurements - wide η
- Extraction of: $[p_T](N_{ch})$ or $[p_T](E_T)$ - slightly different scaling
- No extrapolations of spectra



Direct correlation measurement



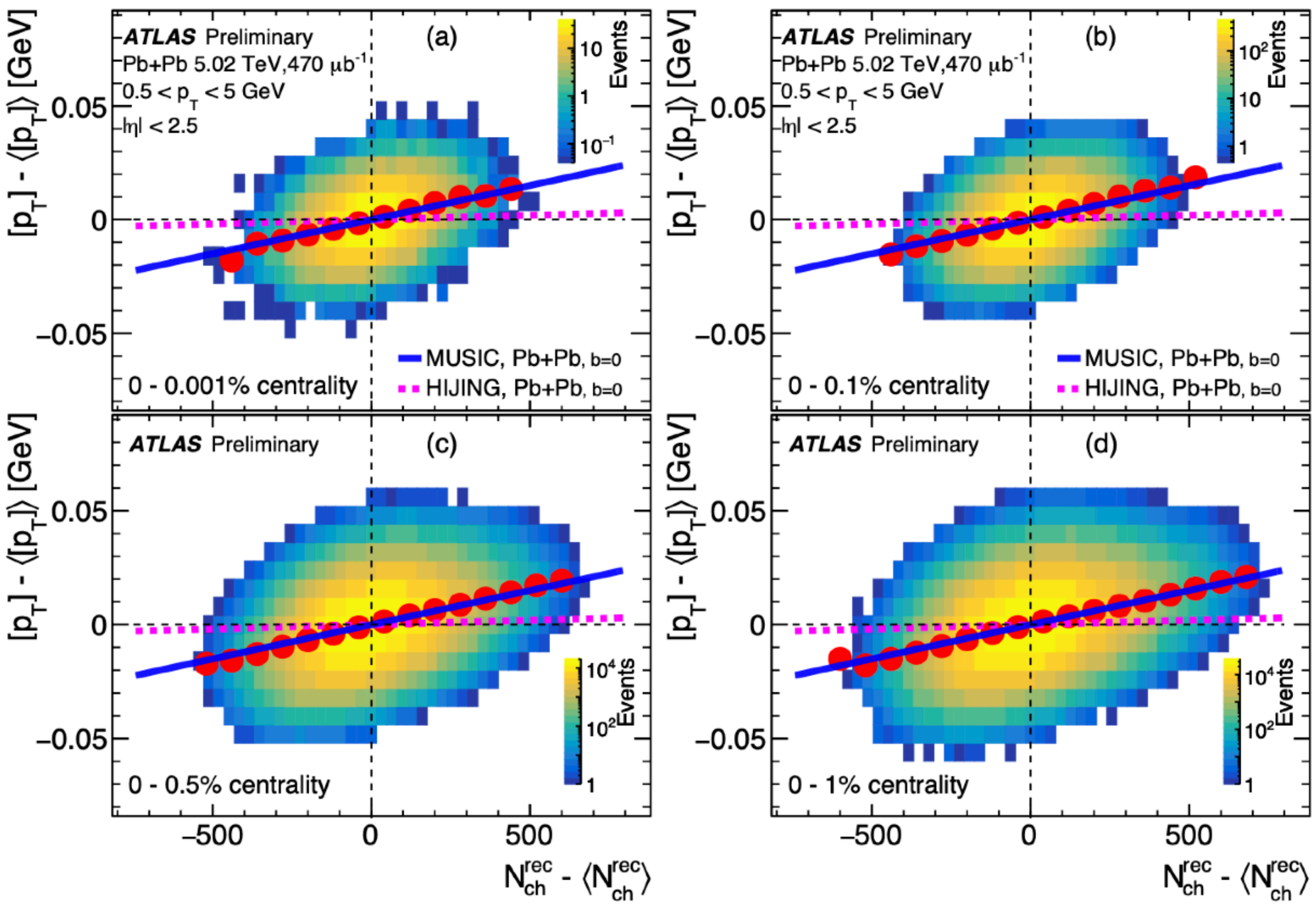
$$c_s^2 = \frac{d \ln T}{d \ln s} = k\frac{d \ln [p_T]}{d \ln N_{ch}}$$

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

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}
- The slope parameter proportional to speed of sound in QGP - but not just equal
- Predictions by MUSIC (initial entropy destr. from TRENTO) - default settings - model in excellent agreement for Pb+Pb and Xe+Xe, unlike the HIJING

A crosscheck in narrower centralities



Summary

- Seemingly simple proposal by P. Bożek to measure correlation between two already well studied quantities v_n and $[p_T]$ proved to be very fruitful
- Due to insensitivity to QGP evolution details became useful tool for imagining initial collision geometry
    - Now a very intense programme of nuclear shapes measurements is developing
- Features of momentum developement found in precise measurements in UCC (thanks to large LHC statistics) may have significant impact on constraining QGP equation of state parameters (speed of sound for now)
- The story will continue …