Azimuthal anisotropy in Pb+Pb, Xe+Xe and p+Pb collisions and v_n-p_T correlations in Pb+Pb and p+Pb collisions with the ATLAS experiment

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on behalf of the ATLAS Collaboration

EUROPEAN PHYSICAL SOCIETY HEP2019

Plan

- Correlations of v_n harmonics: with event mean-p_T in Pb+Pb and p+Pb collisions

  arXiv:1907.05176 [nucl-ex]

- Flow measurements in Pb+Pb with multi particle cumulants

  arXiv:1904.04808 [nucl-ex]

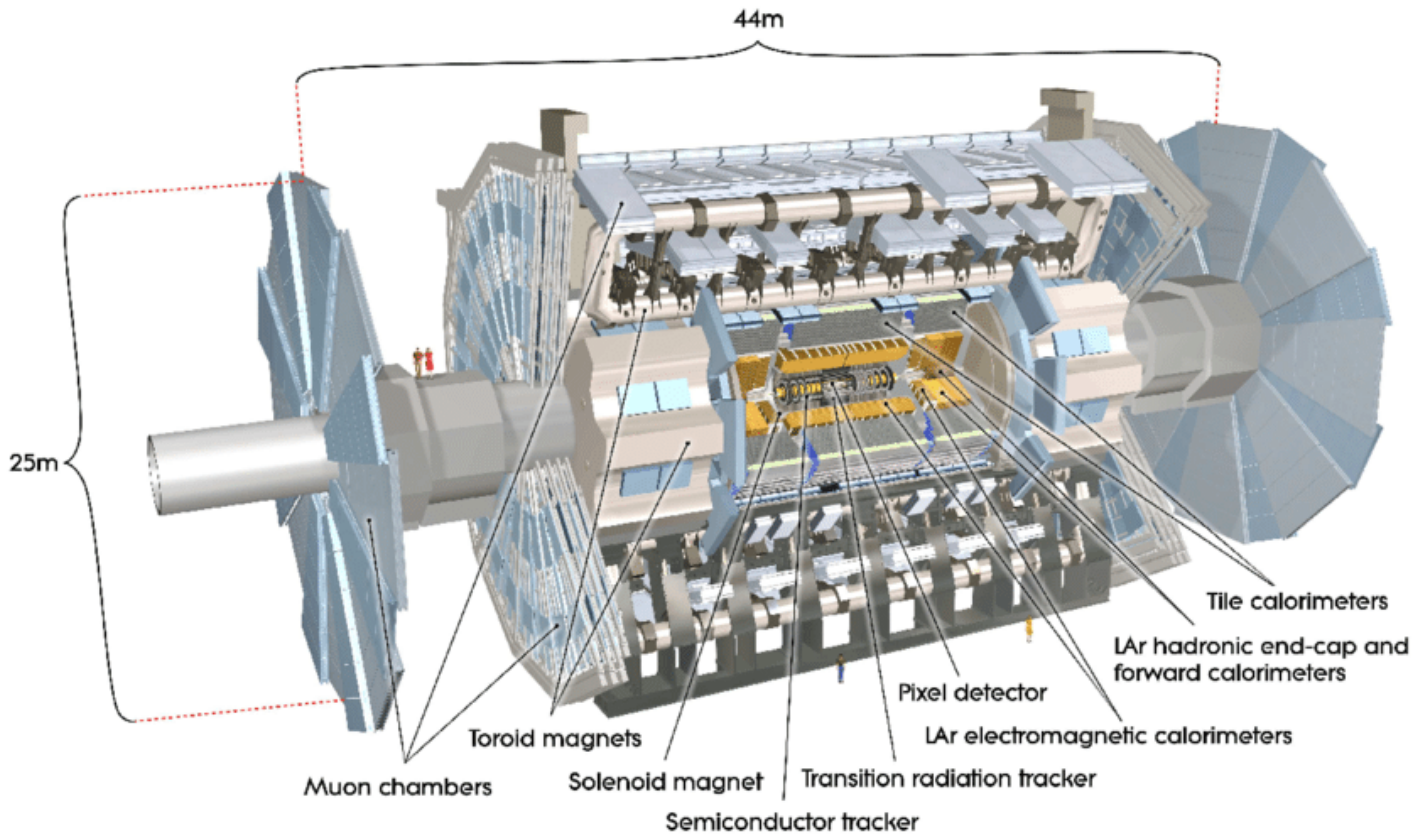
- Flow measurements in Xe+Xe collisions

  ATLAS-CONF-2018-011

- More

  AtlasPublic/HeavyIonsPublicResults

The ATLAS detector



- Measurements mostly based on the Inner Detector tracker (ID) $|\eta|<2.5$ - 5 rapidity units

Mean p_T correlation with flow harmonics in Pb+Pb and p+Pb

arXiv:1907.05176 [nucl-ex]

NEW result from: 11th July

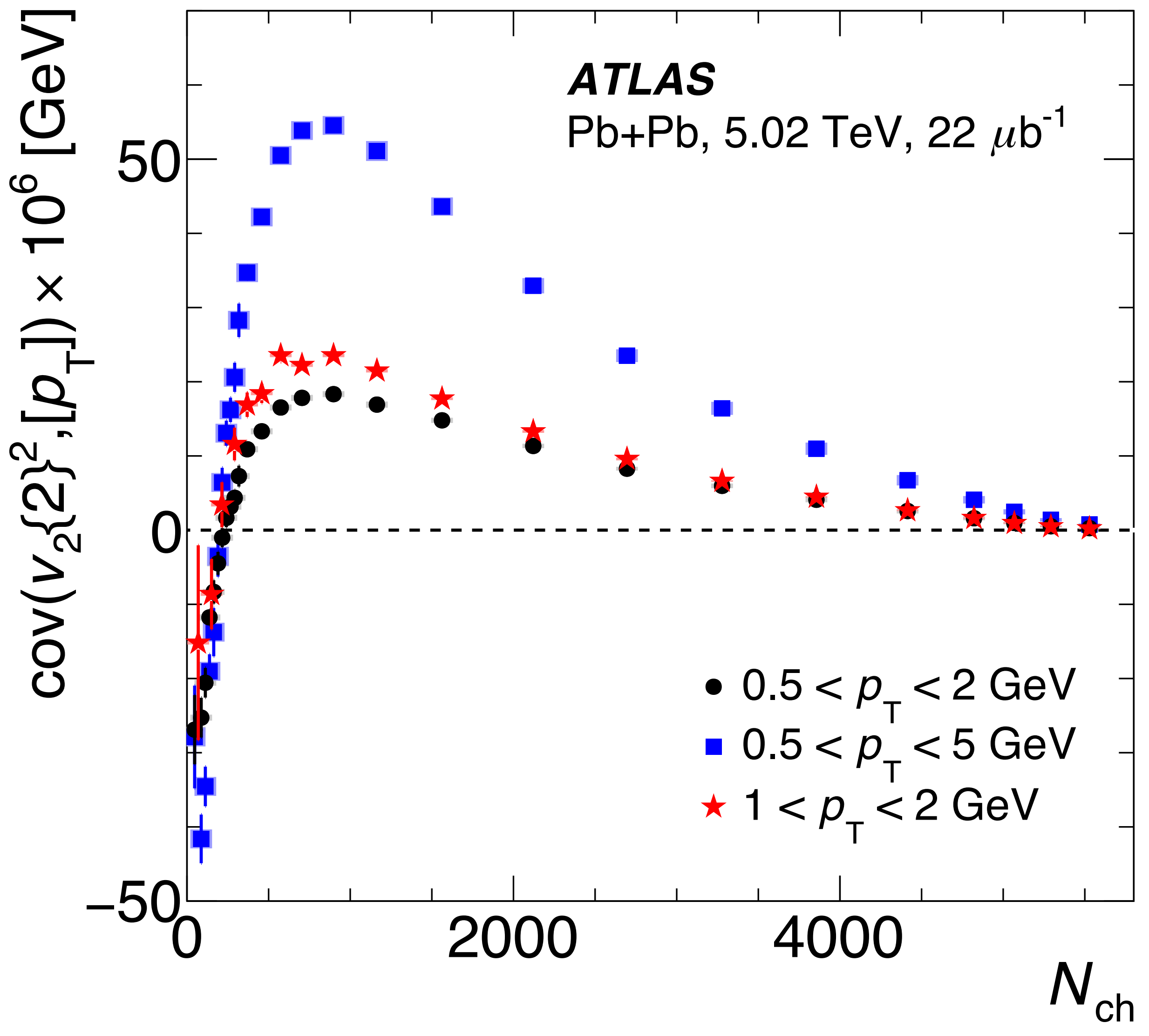
- Relate initial state quantity (event mean $[p_T]$) with evolution towards the final state (flow harmonics)
- Known that the correlation exists (ALICE Collab. Phys. Rev. C **93**, 034916)
- Pearson correlation coefficient distorted by the limited event multiplicity
- A modified correlator proposed (P. Bozek Phys. Rev. C93 (2016) 044908)
  - Replaces variances by dynamic counterparts $\mathrm{Var}_{\mathrm{dyn}}$, c_k
  - Reproduces true R even with limited event multiplicity → detector independent measurement
    - **Is the correlation present & positive or negative? Is it strong? Is it the same for all harmonics? Is it the same in Pb+Pb an p+Pb?**

$$R = \frac{\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)}\sqrt{\mathrm{Var}([p_\mathrm{T}])}},$$

$$\rho = \frac{\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}}\sqrt{c_k}}.$$

$$\mathrm{Var}(v_n\{2\}^2) = \langle corr\{4\}\rangle - \langle corr\{2\}\rangle^2$$

Ingredients of the ρ for v_2



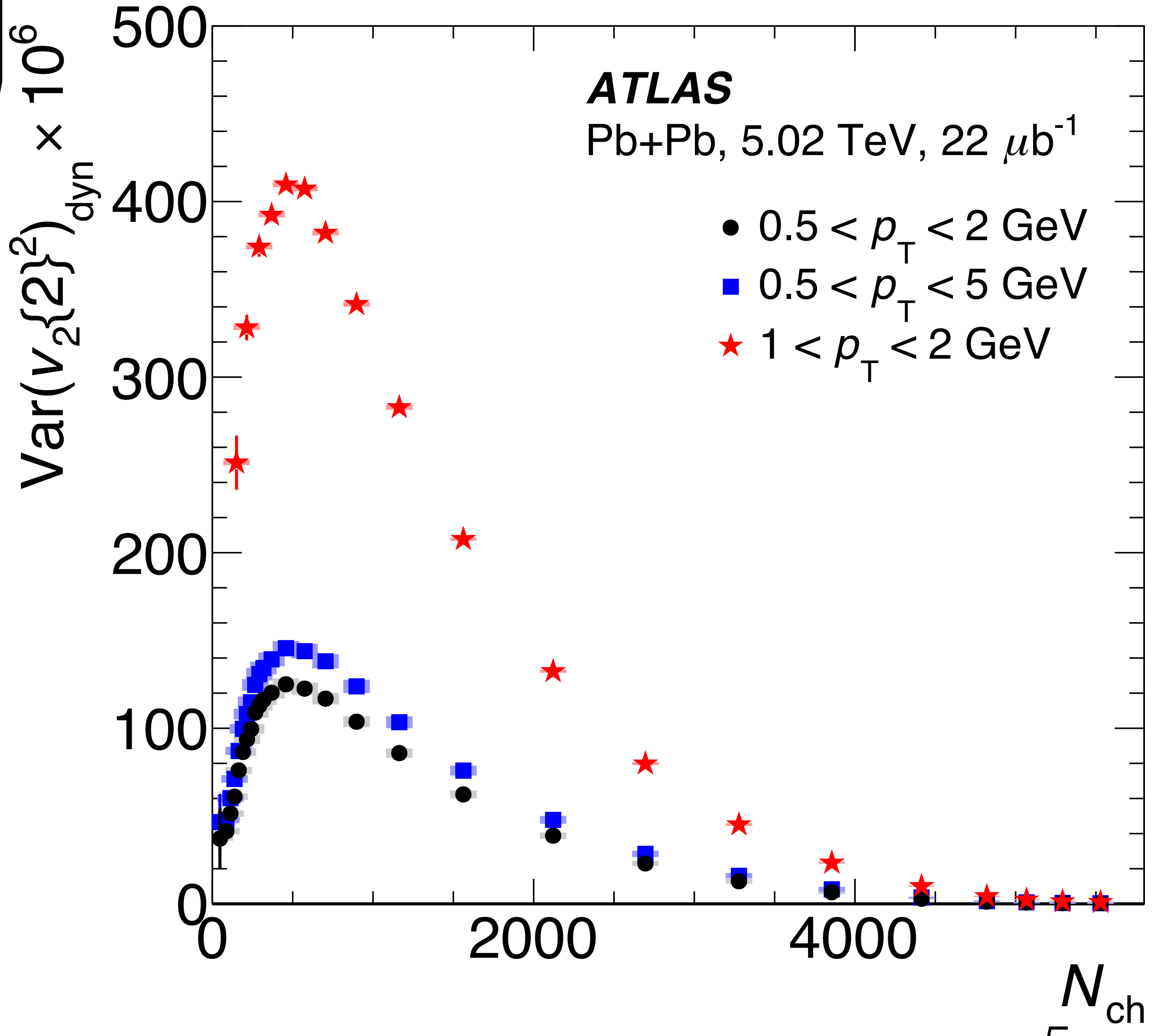
$0.5 < p_T < 5$ GeV, $|\eta| < 2.5$

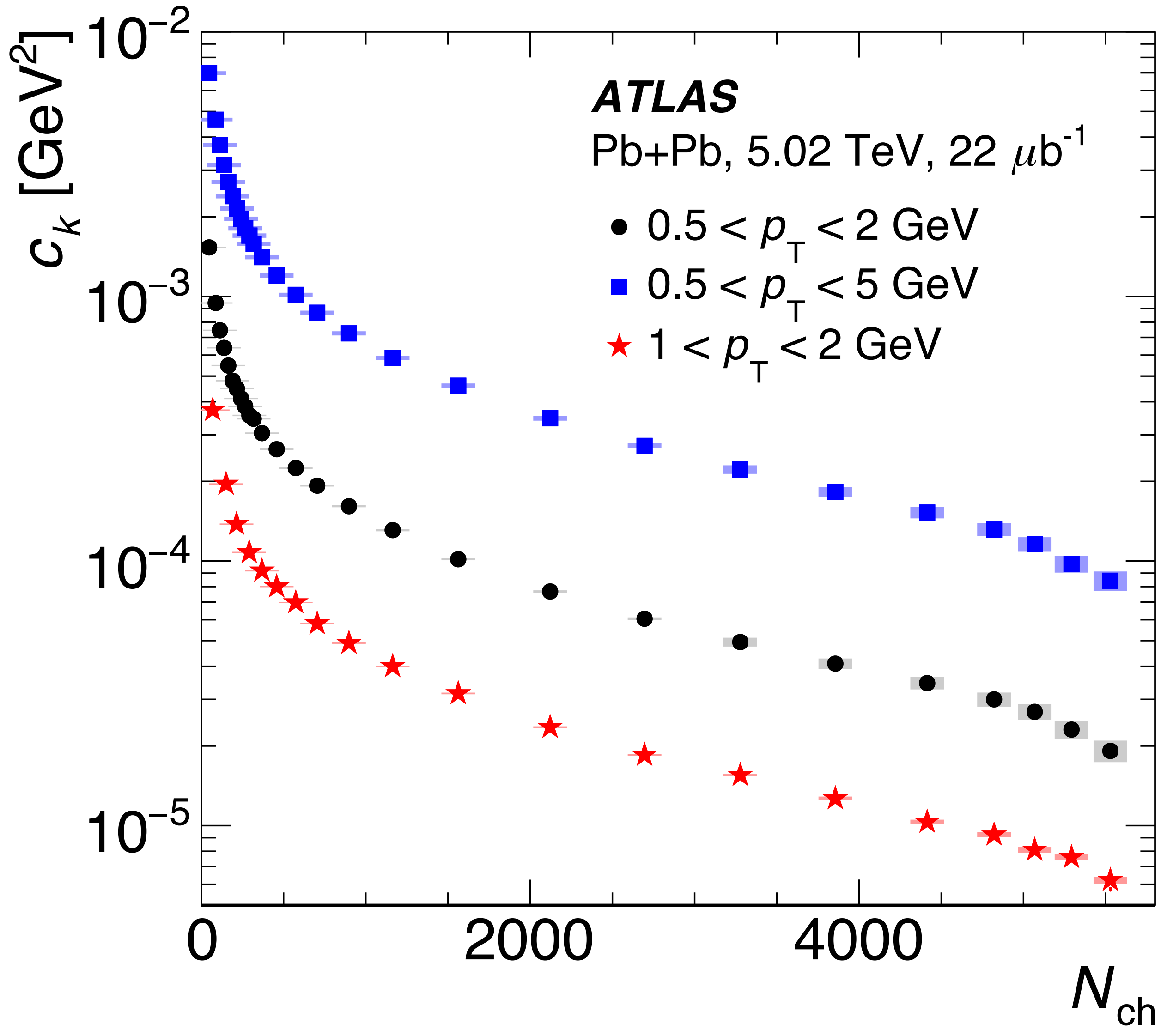
Significant variation with centrality

Trend flows the v_2 magnitude

Negative in peripheral events!

$\rho =$





Magnitude of v_2 fluctuations

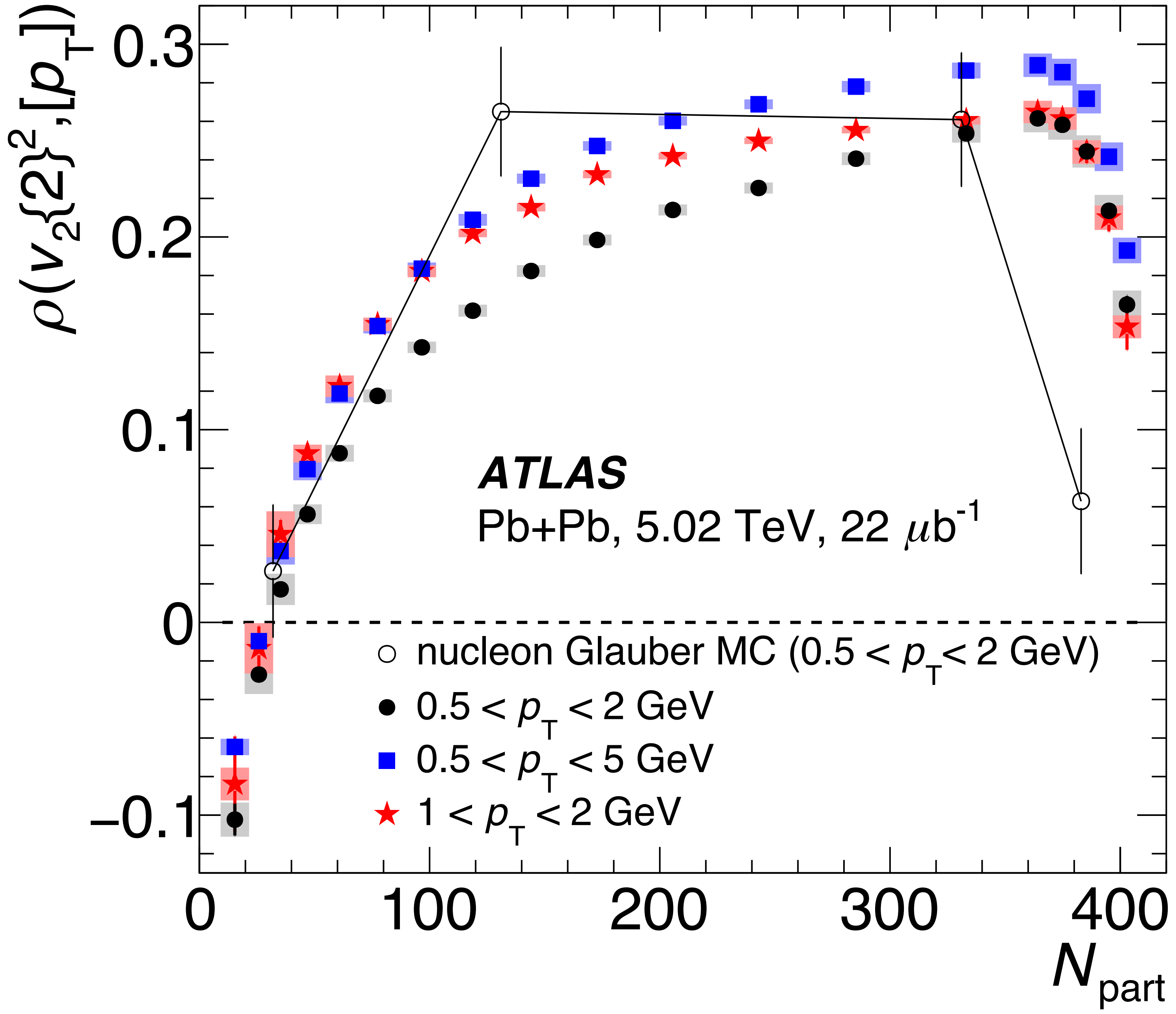
Similar trend to v_2

Different p_T ordering as compared to cov

c_k quantifies magnitude of p_T fluctuations

Nontrivial p_T interval ordering, different than for *cov* and *dyn. var*

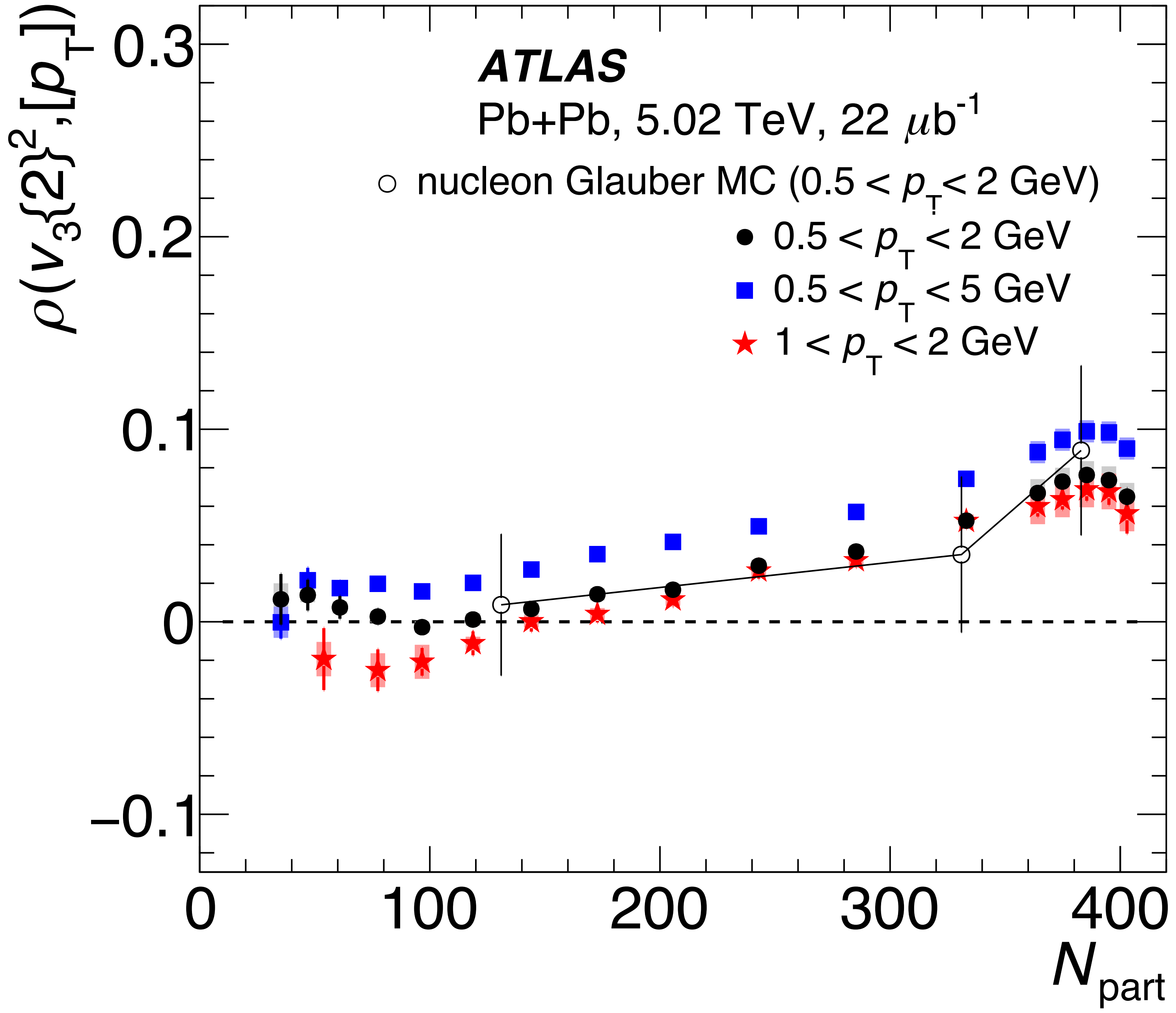
Correlation coefficient ρ



Negative correlation for v_2 in peripheral events
→ related to ecc. ~ 1/r

Gentle rise above → stronger hydrodynamic response to initial eccentricities

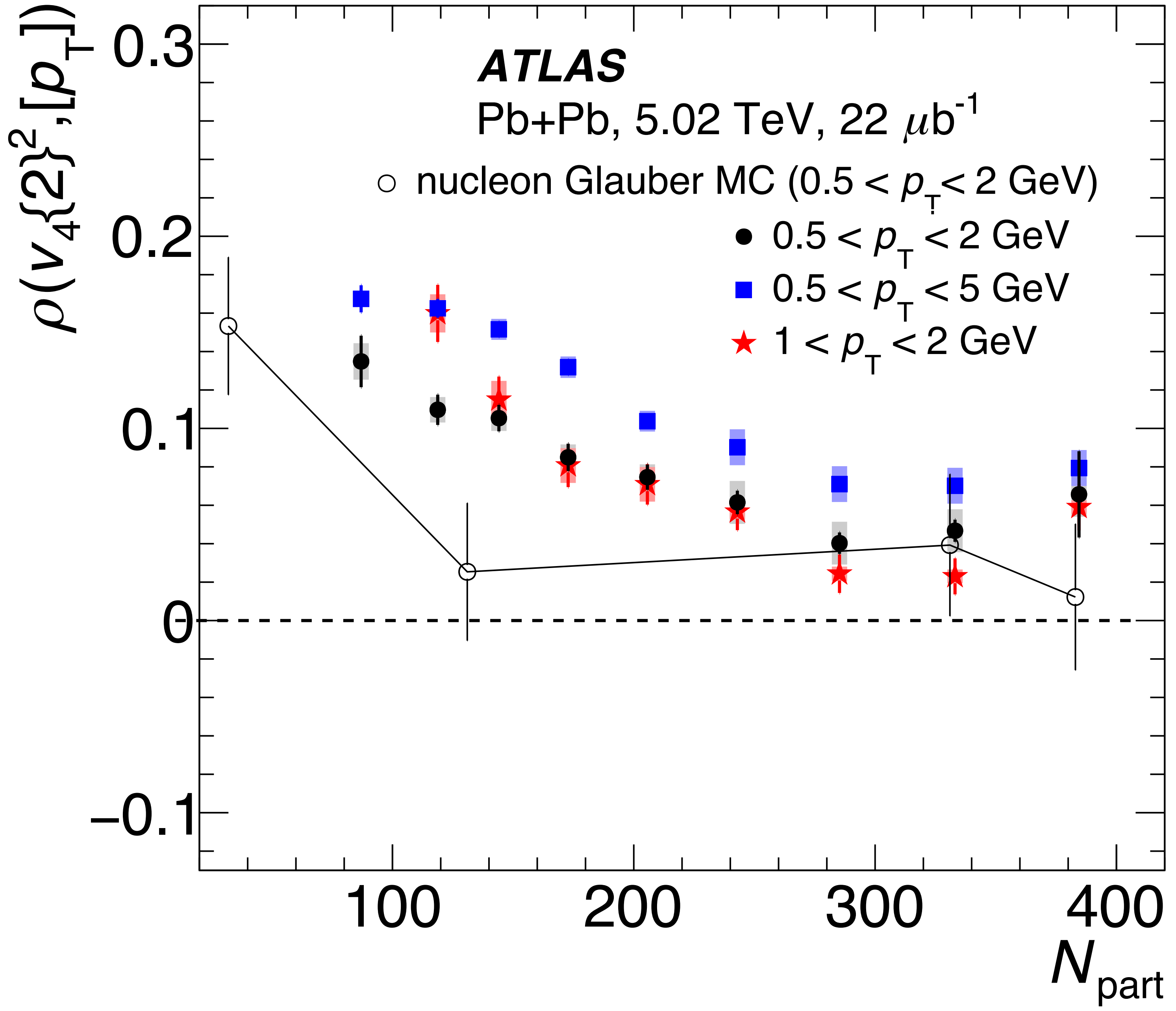
Fall in most central events



Correlation for v_3 is weaker compared to v_2

Positive except for N_{part} < 100 and p_T > 1GeV

Above $N_{part} \simeq$ 100 steady rise



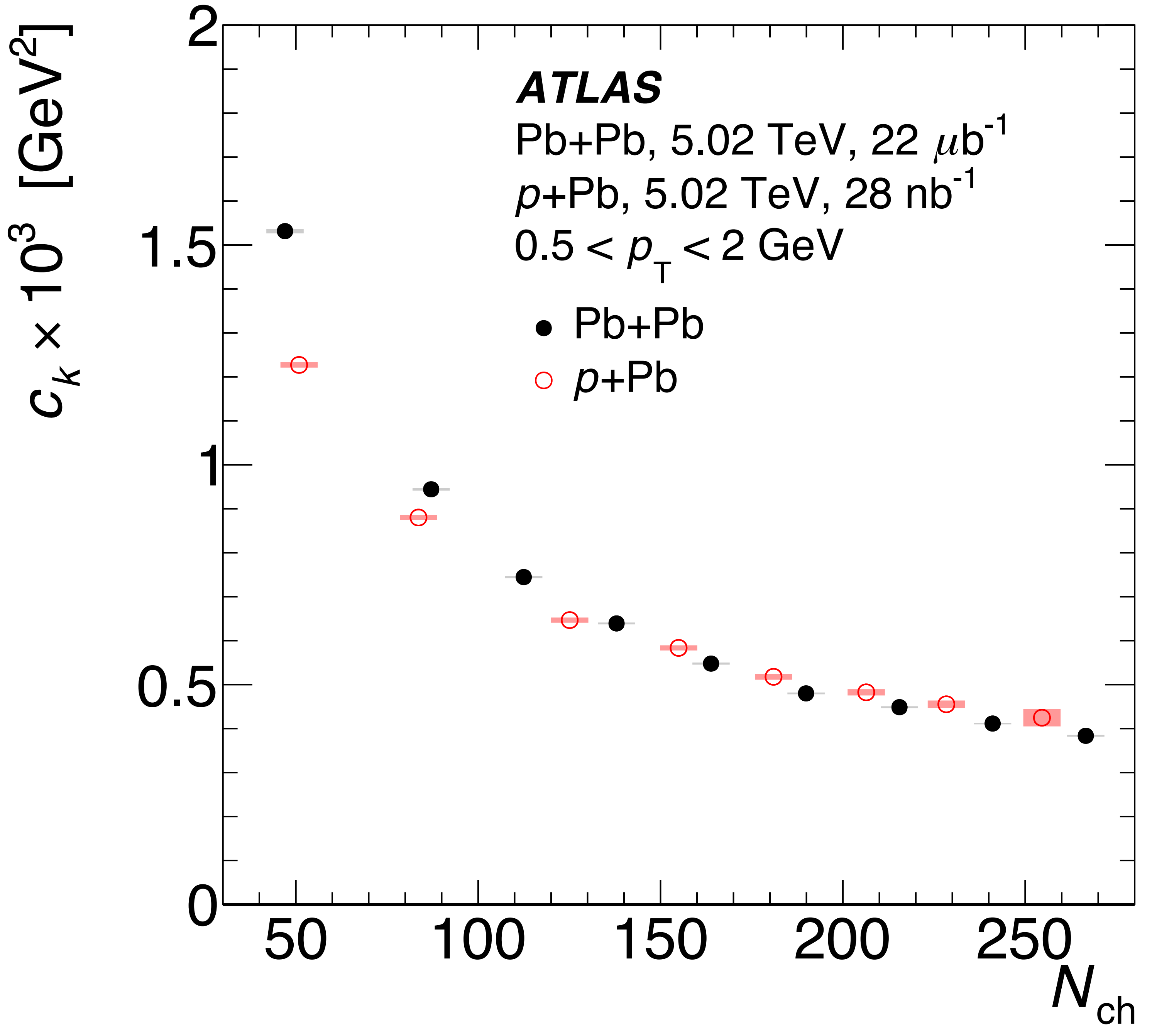
Significant correlation for v_4

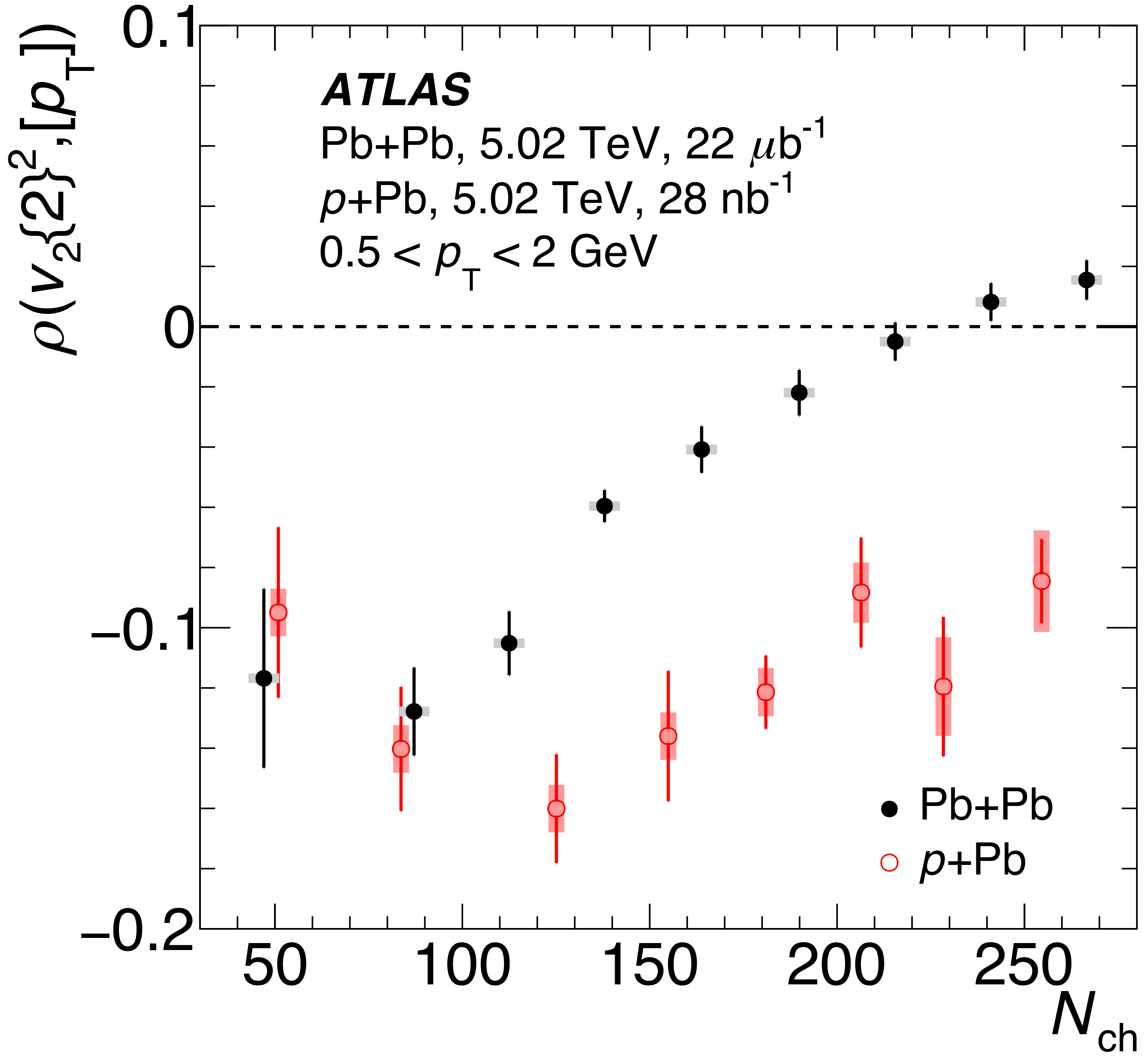
The trend is mostly inverted as compared to v_2 and v_3

Evident change of the trend in central events -> nonlinear hydro response to initial geometry fluctuations?

Hydro 1+3D, reproduces the behaviour qualitatively Phys. Rev. C93 (2016) 044908

The ρ in p+Pb in comparison to Pb+Pb





The ρ for v_2 is negative in high multiplicity p+Pb collisions

Favours small dimensions of the initial state
-> higher pressure ($[p_T]$), low eccentricity (v_2)

No geometry driven trend observed in p+Pb compared to a strong effect in Pb+Pb

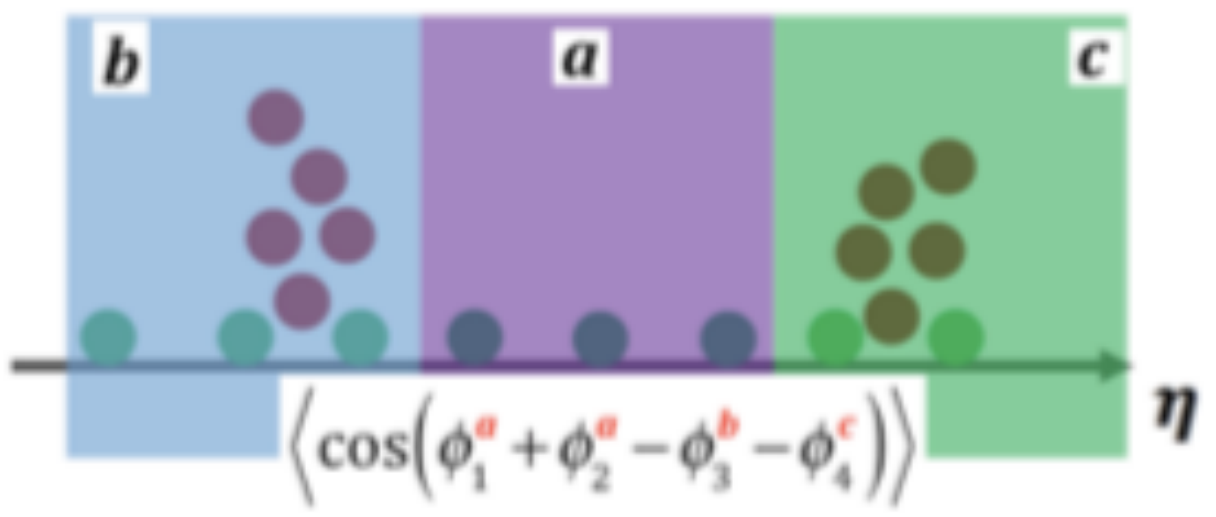
The p_T fluctuations (c_k) are of similar magnitude on p+Pb and peripheral Pb+Pb when matched N_{ch}

The difference in the ρ values driven by the flow

Flow measurements in Pb+Pb collisions with multi particle cumulants

arXiv:1904.04808

- The cumulants methodology can be used to extract the flow harmonics, and correlations between them
  - Result checked with sub-event method to exclude non-flow
- Can answer number of questions about v_n
  - **Is it driven by the initial stage geometry only?**
  - **Are v_n fluctuations an initial state effect or final state effect?**
  - **Is the dipolar flow (v_1) visible in multi particle correlations?**
- + other questions: Does the “centrality definition” affect measured? Are different modes correlated?



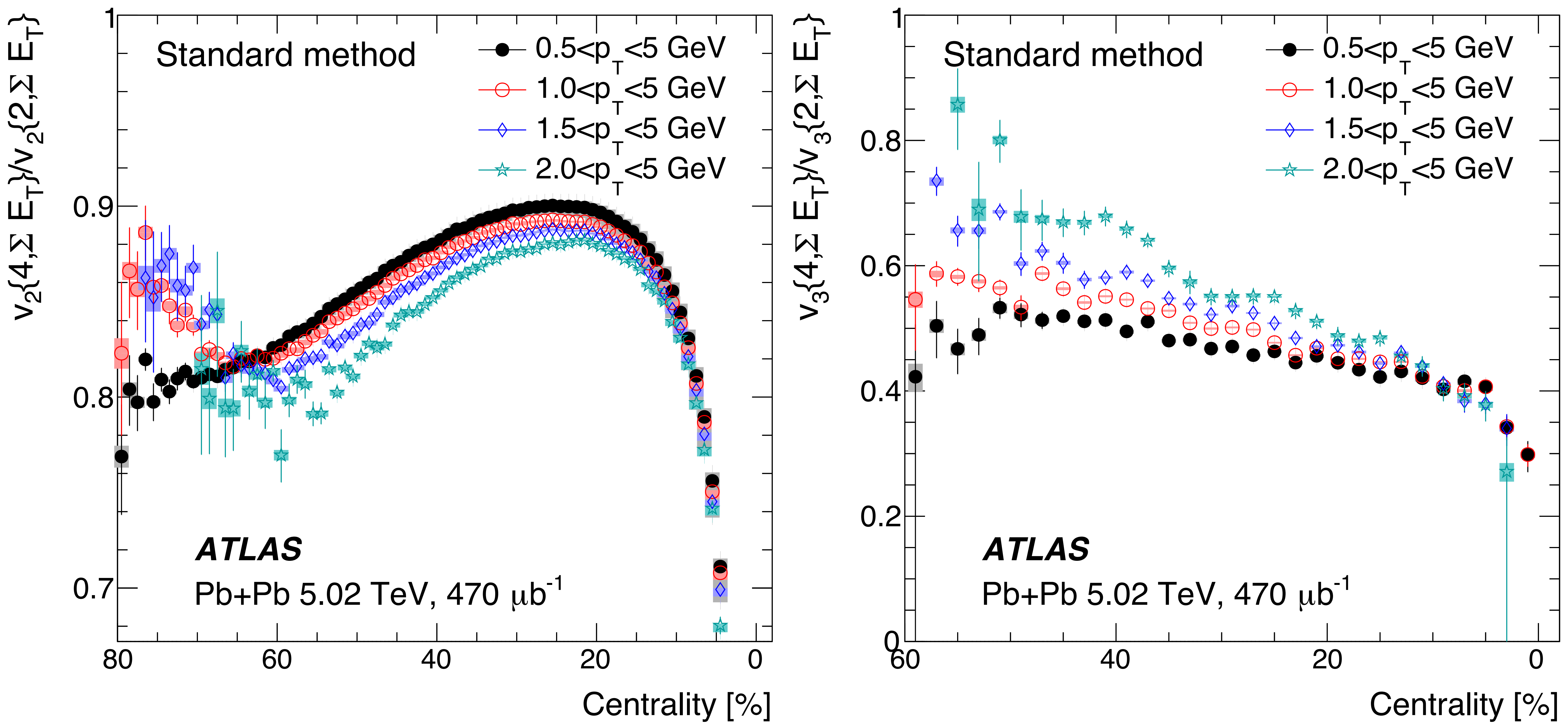
3-subevent method

Geometry only?

The ratio of $\frac{v_n\{2\}}{v_n\{4\}}$ and eccentricities $\frac{\epsilon\{2\}}{\epsilon\{4\}}$ identical. If =1 - only initial shape relevant.

The ratio of eccentricities is not reachable experimentally.

However, we can look if the former exhibits p_T dependence.



Magnitude: ~1 - small fluctuations, ~0 - large fluctuations

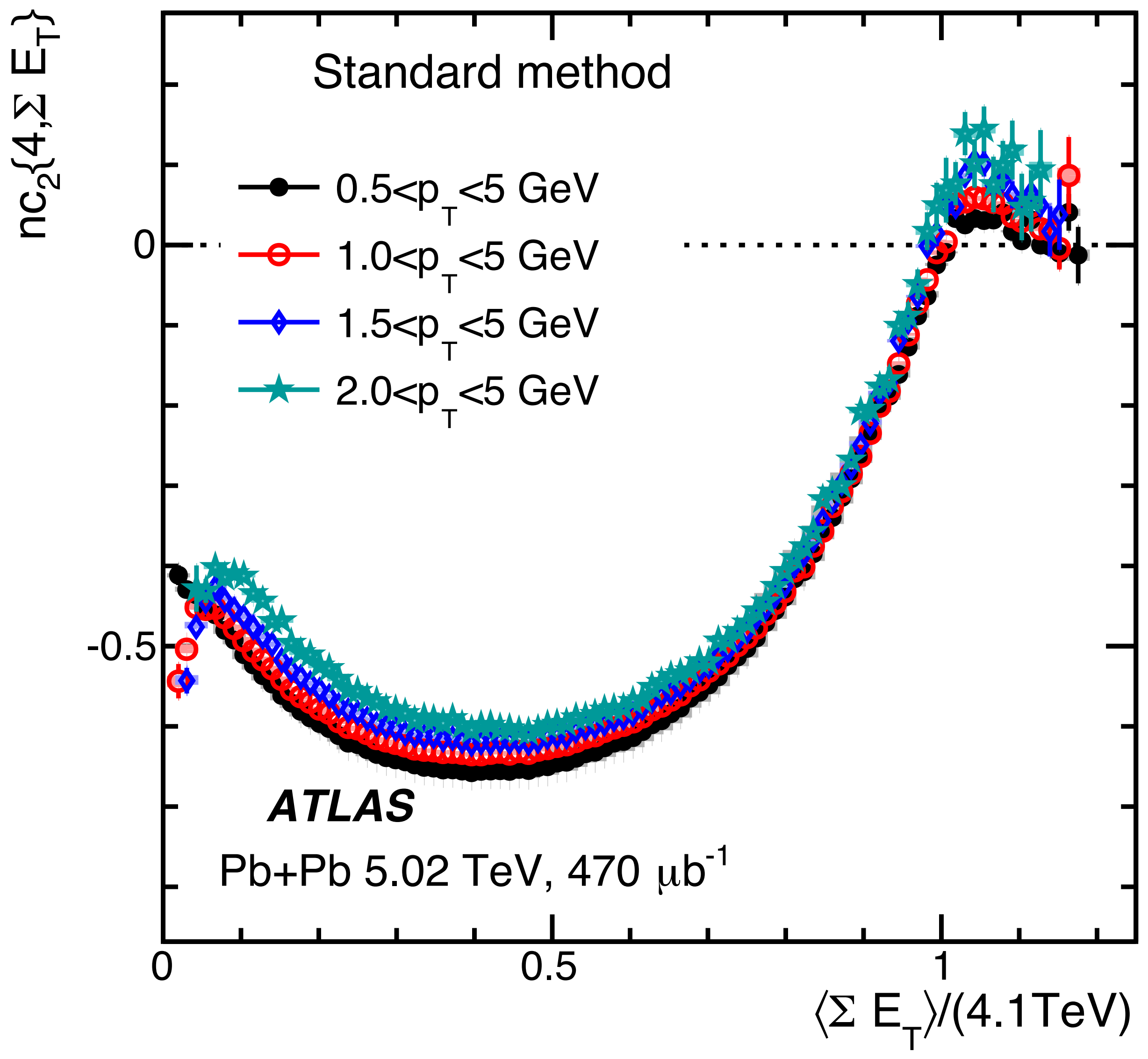
- Evident p_T dependence observed
  - Final state/evolution have an impact on the observed v_2 and v_3
- Fluctuations have a small relative contribution to v_2, and only in central & peripheral collisions,
- larger contribution from fluctuations to observed v_3
- Non-trivial evolution with centrality

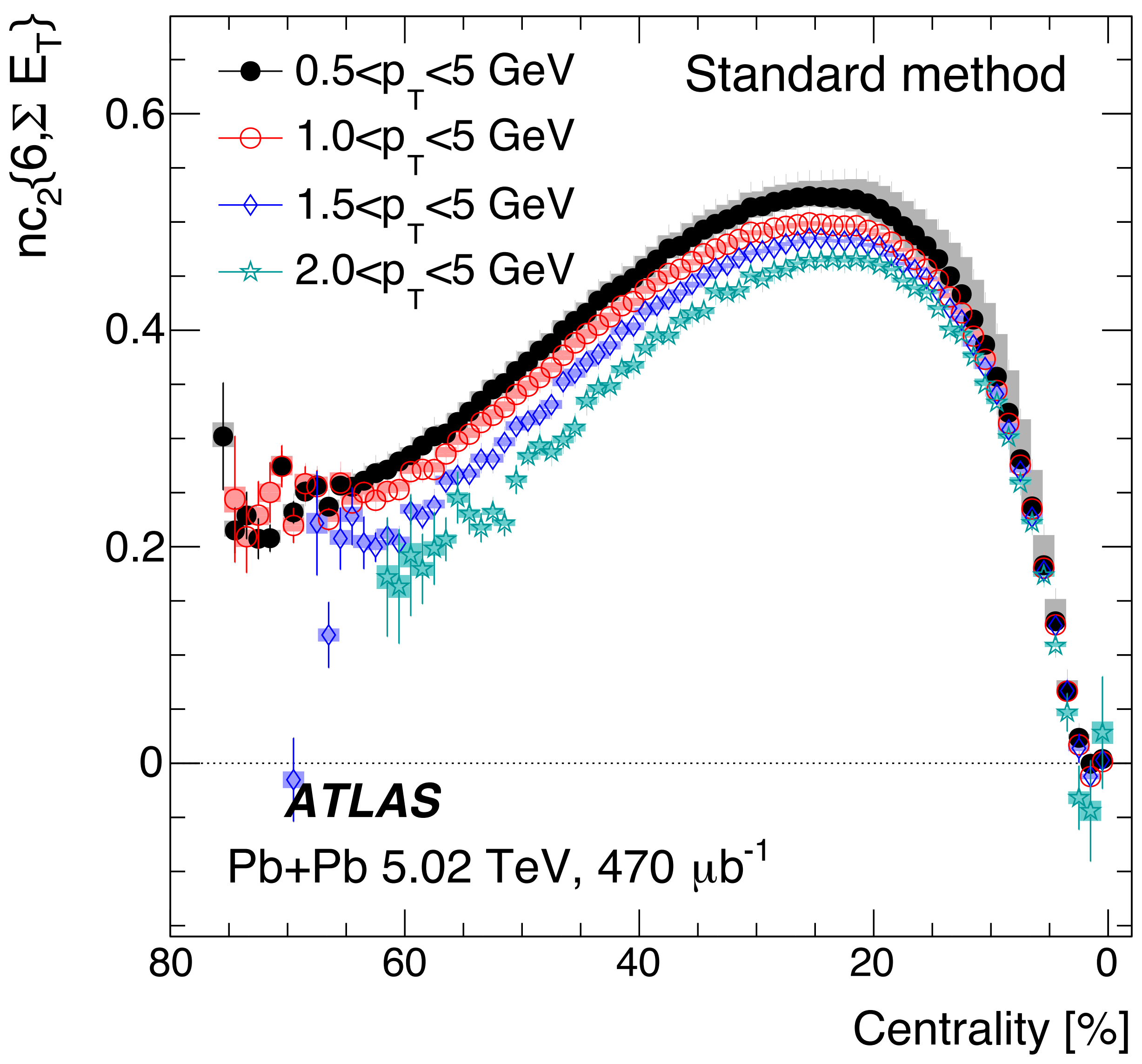
The shape of PDF(v_n)

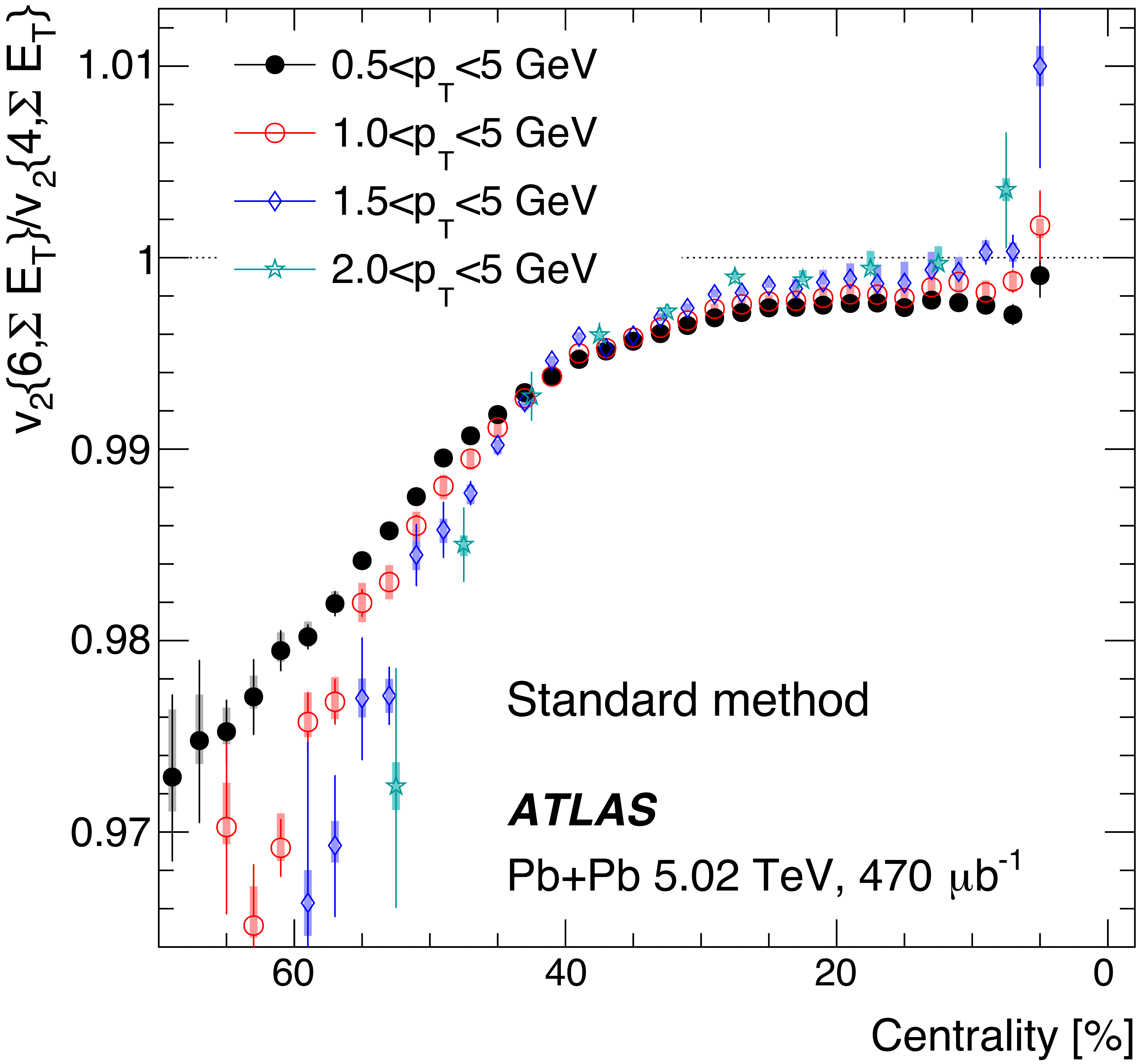
The ratio $\frac{v_v\{4\}}{v_n\{6\}} = 1$ indicate gaussian initial shape fluctuations

If vary with p_T interval indicate final state effects

The ratio is extracted from normalised cumulants $nc_2\{4\}$ and $nc_2\{6\}$



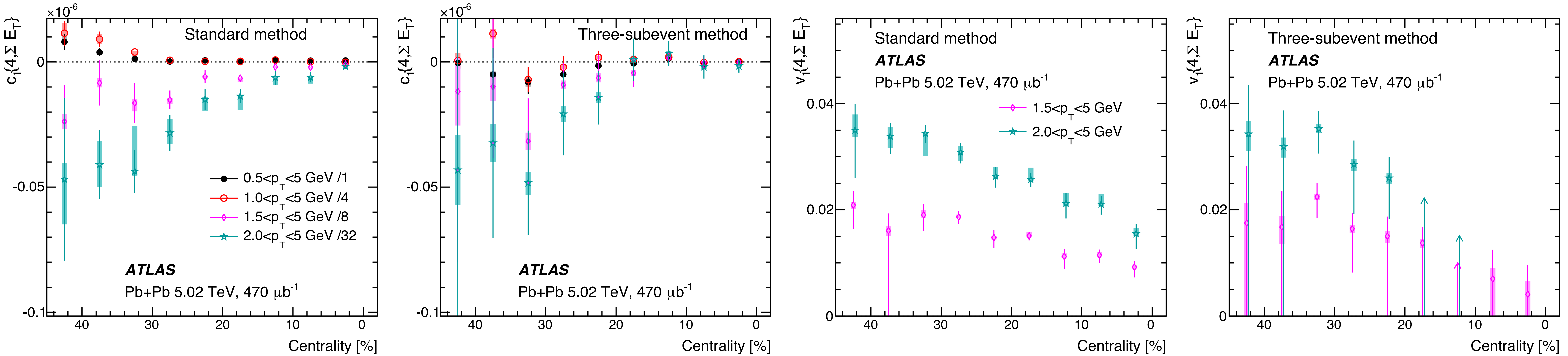




Slight deviation from unity - non gaussian fluctuations

Observable variation with p_T - final state effect

Dipolar flow $v_1\{4\}$



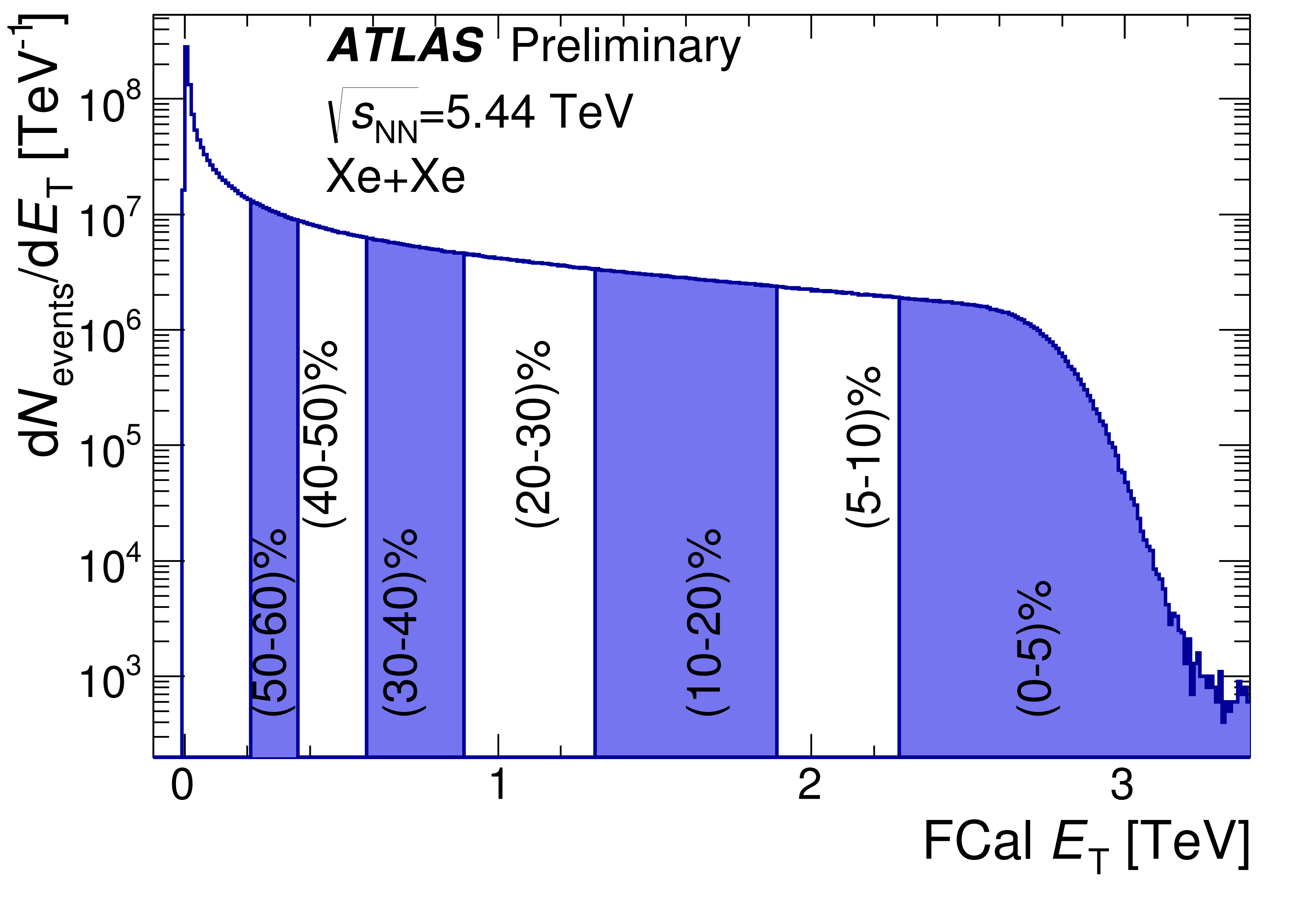
- *Negative* $c_1\{4\}$ —> first published measurement of the $v_1\{4\}$
- Sub-event cumulants to eliminate short-range correlations —> same conclusion
- The $v_1\{4\}$ is most pronounced in the peripheral events and only exits for higher p_T

ATLAS EXPERIMENT

ATLAS-CONF-2018-011

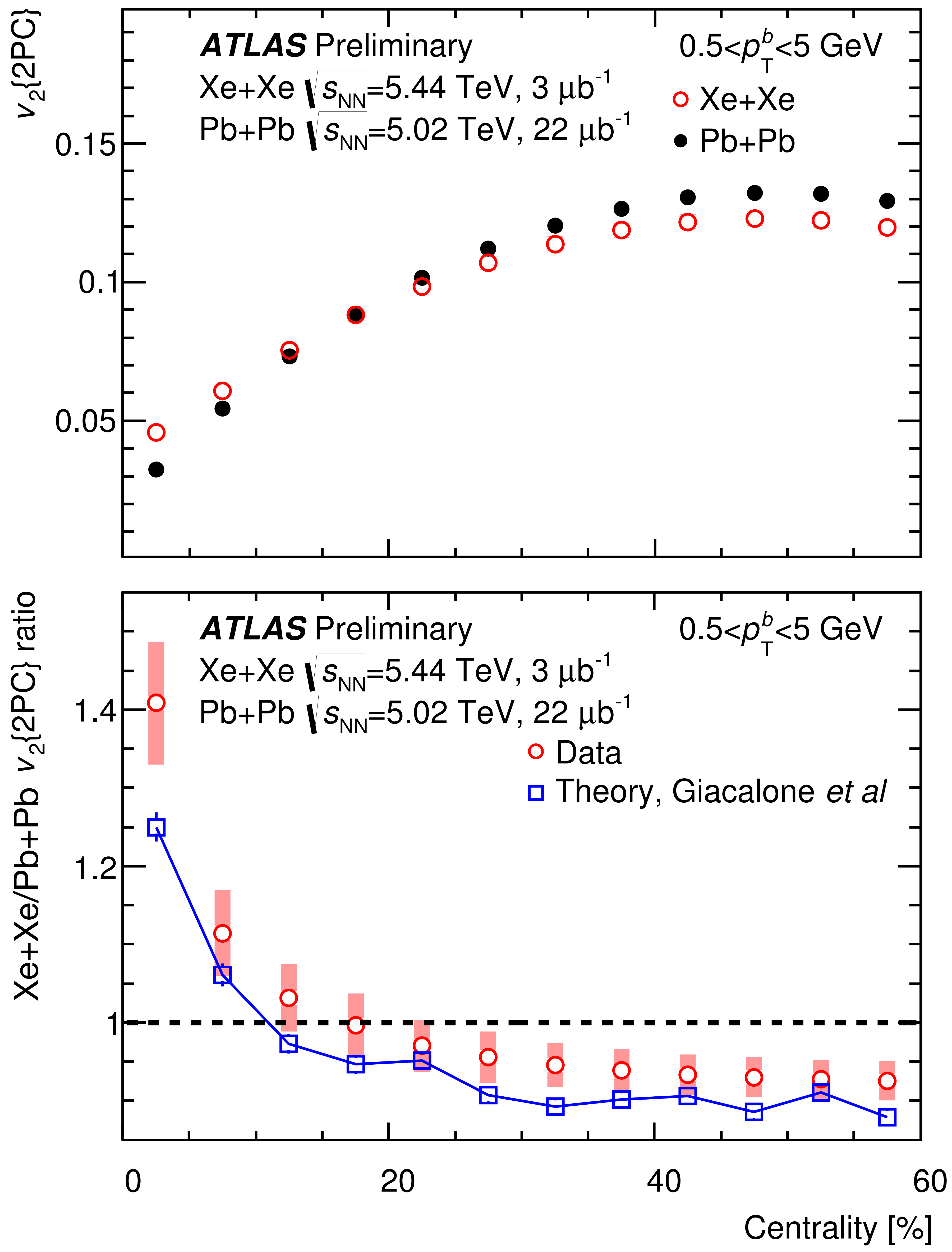
Flow in Xe+Xe collisions

- Goal is to measure the flow in Xe+Xe collisions in comparison to Pb+Pb
  - Centrality dependence
  - Scaling via higher order correlations
- Measurements performed in bins of centrality (0-80%) quantified by E_T in FCal $3.2<|\eta|<4.9$
  - Mapped to N_{part} via Glauber modeling
- **Is the measurement sensitive enough to see geometry change (oblate Xe shape)?**
  How do harmonics scale with centrality (geometry) or N_{part} (size)?



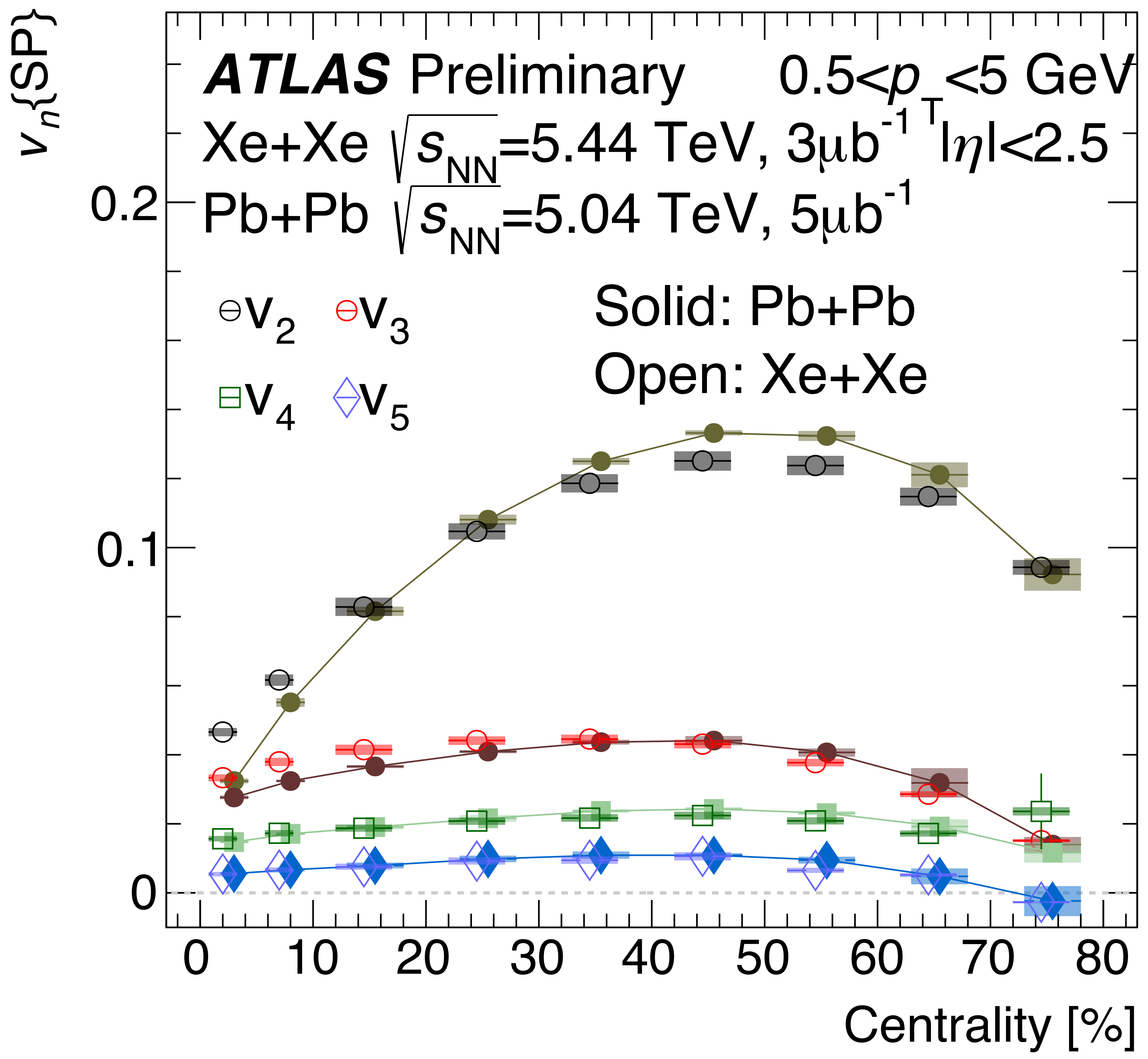
Centrality dependence Xe+Xe vs. Pb+Pb

- The measured flow harmonics resemble those in Pb+Pb
- v_n is higher in most central events for Xe+Xe collisions
  - Elongated Xe shape
  - Smaller N_{part} → larger fluctuations
- Reduced value in mid central and peripheral
  → surface effect → smaller initial eccentricities
  → viscous corrections
- A similar behaviour seen for v_3 and v_4 for different p_T
- Consistent with predictions!

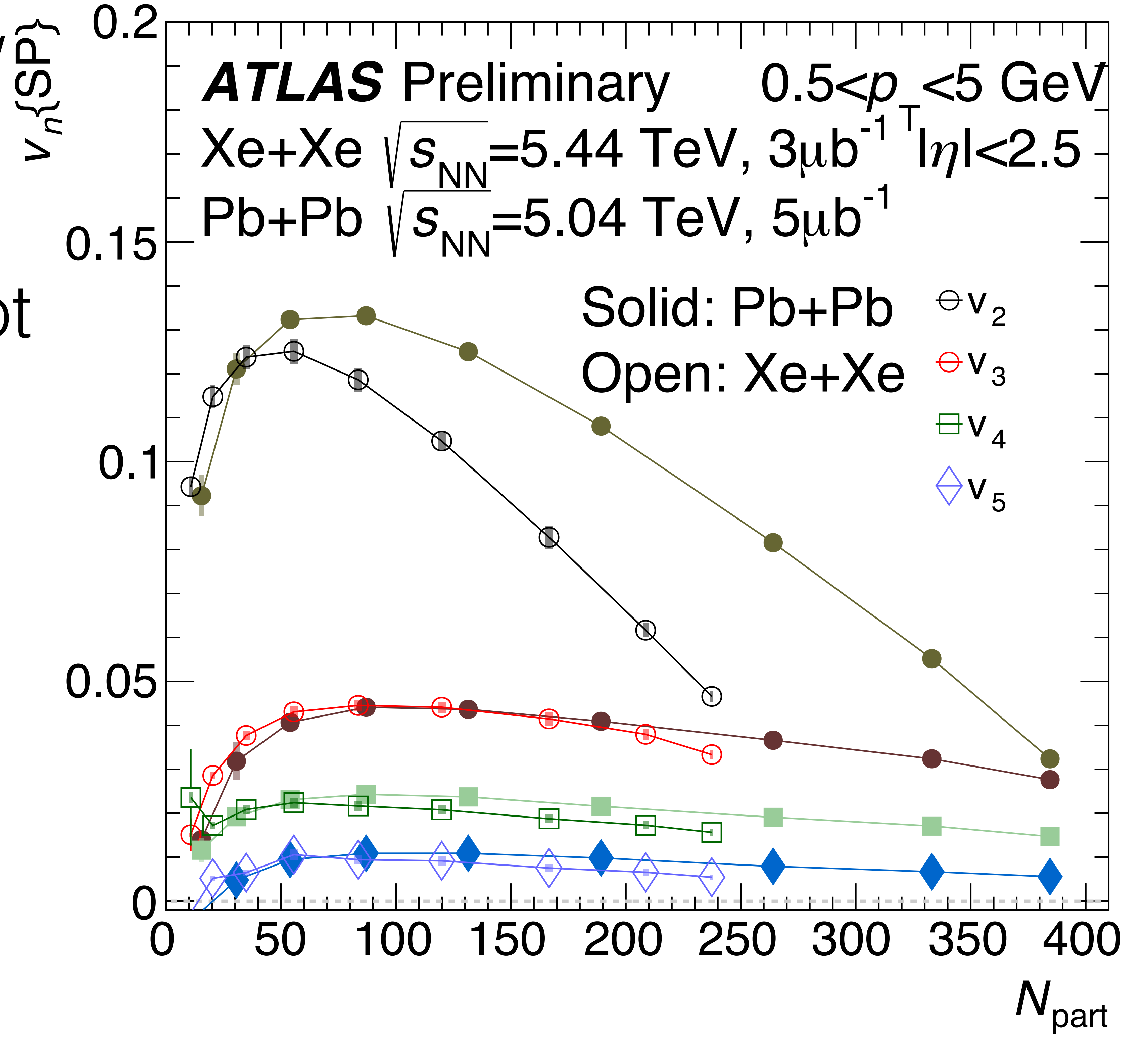


Giacalone et al.
Phys. Rev. C 97, 034904 (2018)

Centrality dependence - geometry scaling



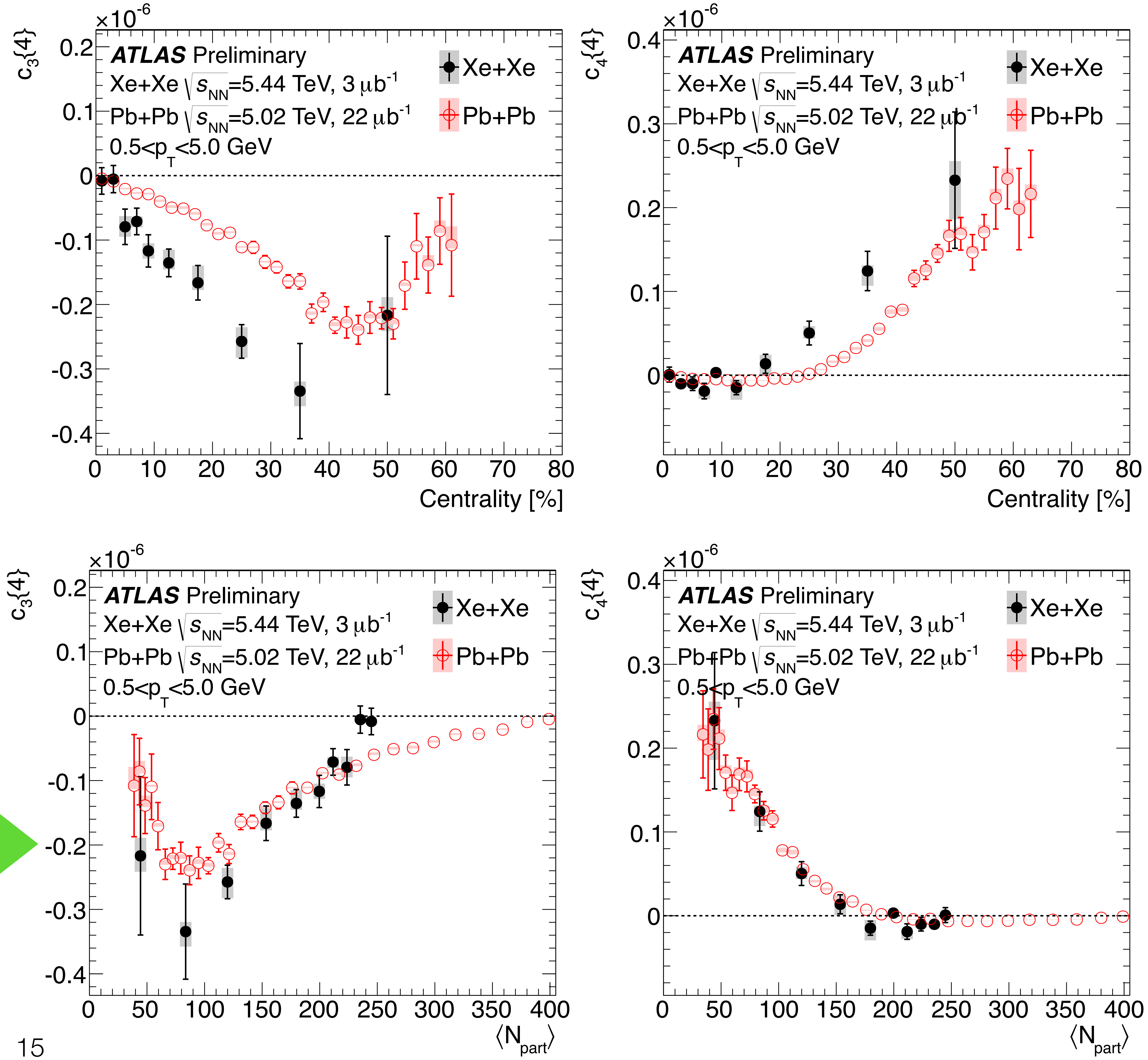
- Typical pattern for centrality/ N_{part} dependence
  - N_{part} scaling for v_2 does not hold however centrality scaling does work: **—> geometric origin of the elliptic flow**
  - Scaling with centrality or N_{part} for the higher order harmonics: **not so obvious**



N_{part} dependence - fluctuations scaling

- A more sensitive variable: 4-particle cumulants to check scaling for 3rd and 4th harmonic
- They scale with $N_{\rm part}$ → v_3, v_4 are fluctuations driven

Better agreement



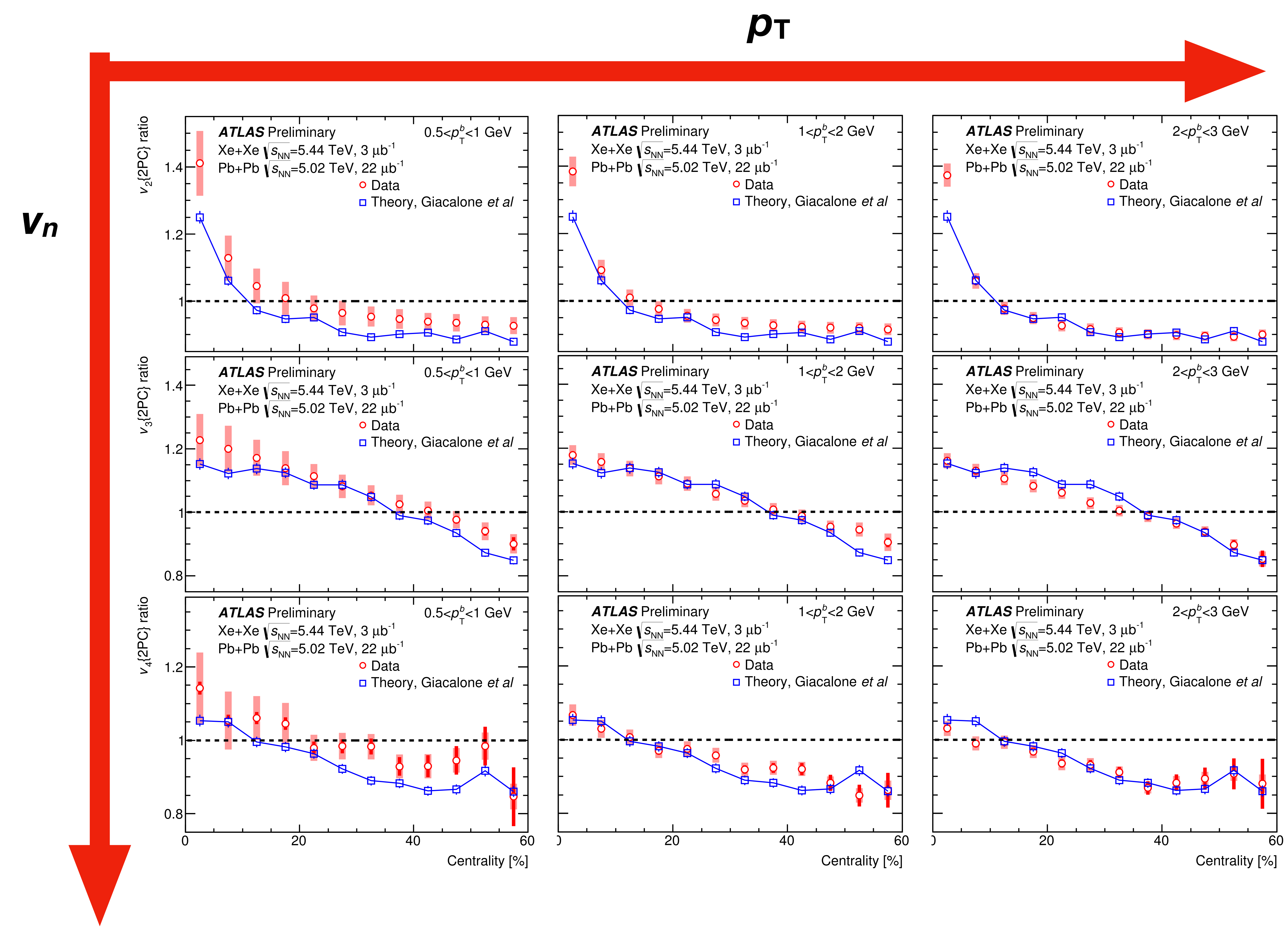
Conclusions

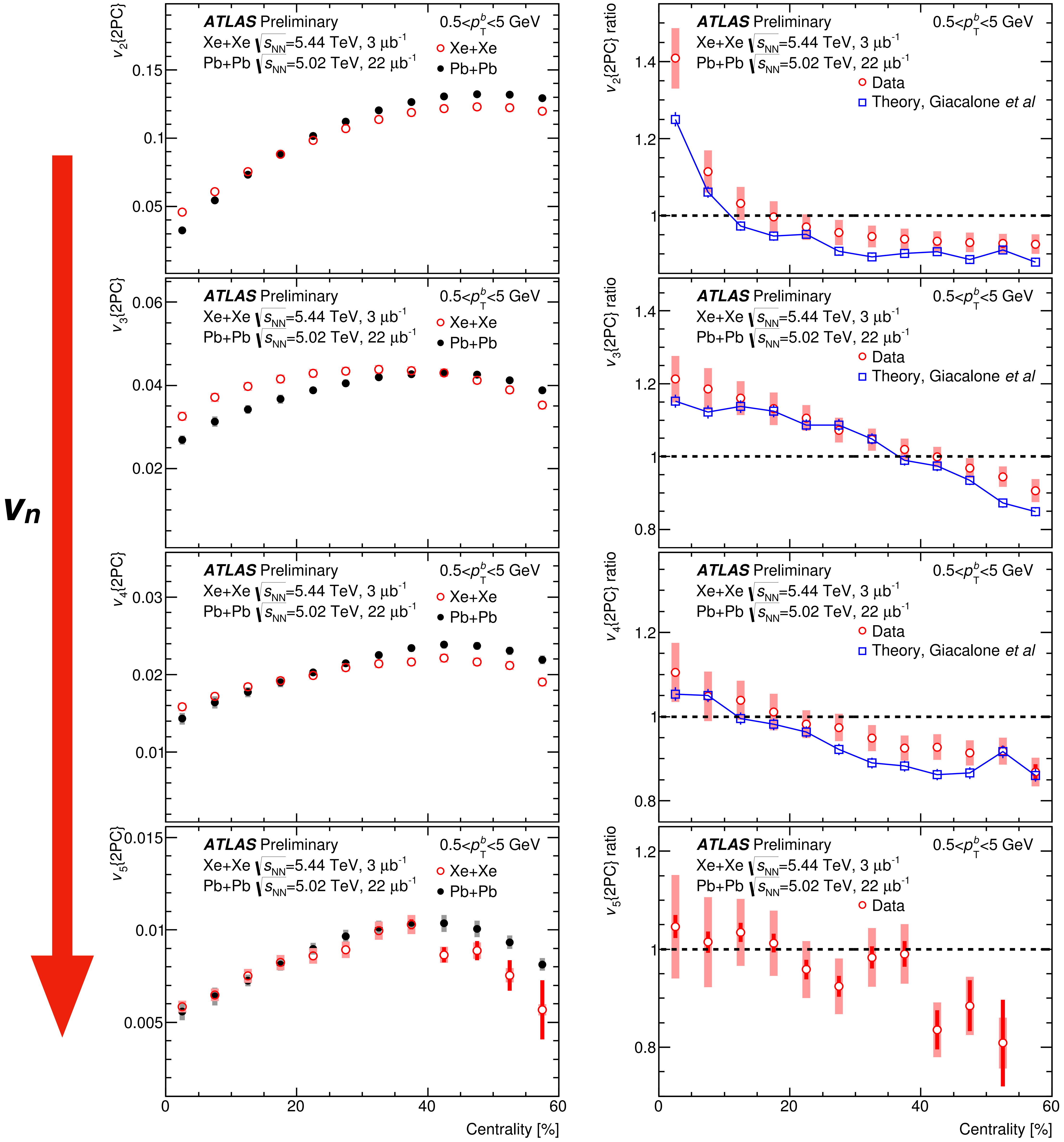
- ATLAS Measured correlations of flow with event mean-p_T in Pb+Pb and p+Pb
  - Significant values for all harmonics in mid central Pb+Pb
  - For peripheral Pb+Pb collisions and p+Pb the v_2-mean-p_T correlation negative
- Using cumulants shed light on the initial and final state effects in observed v_n in Pb+Pb collisions at 5.02 TeV
  - Flow fluctuations, di-polar flow, shape of v_n
- Performed a comprehensive study of flow in Xe+Xe collisions at 5.44 TeV and compared to Pb+Pb at 5.02 TeV
  - The observed v_n are mostly compatible with that in Pb+Pb - slight deviations well predicted by theory
  - Scaling of v_2 and higher higher flow harmonics indicate a different origin of them

Thank you

Backups

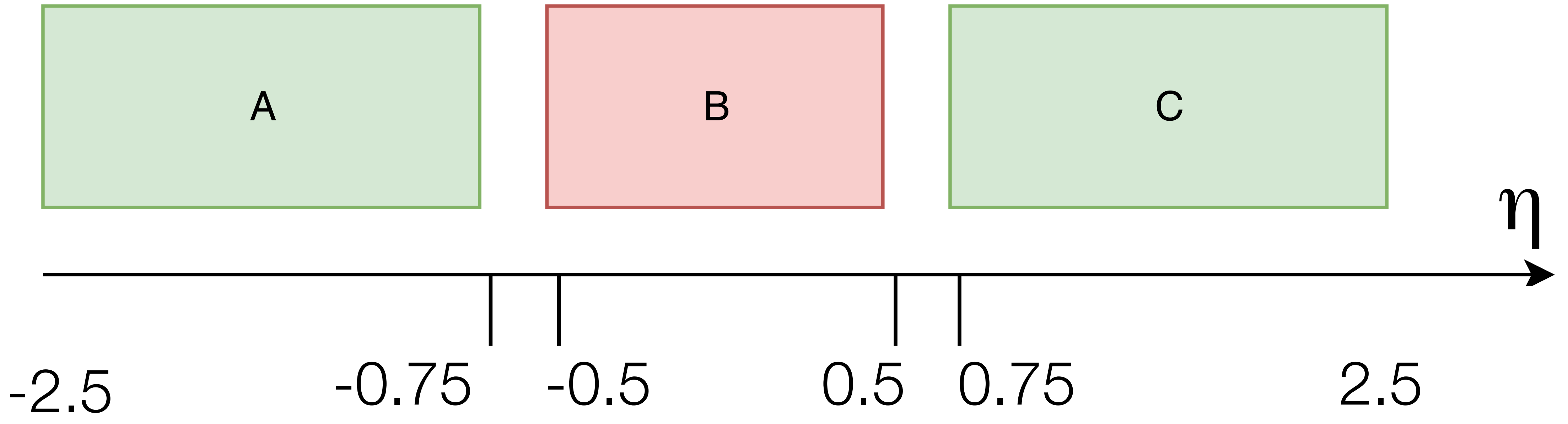
Xe+Xe / Pb+Pb flow harmonics ratio





Backup for v_n-p_T correlations measurement

Measurement details



$$cov(v_n\{2\}^2, [p_\mathrm{T}]) = \left\langle \frac{1}{\sum_{a,c} w_a w_c} \sum_{a,c} w_a w_c e^{in\phi_a - in\phi_c} \frac{1}{\sum_b w_b} \sum_b w_b (p_{\mathrm{T},b} - \langle [p_\mathrm{T}] \rangle) \right\rangle$$

- Distinct sets of particles for $[p_\mathrm{T}]$ and $v_n\{2\}^2$
- Rapidity gaps to suppress non-flow
- Analysis in narrow bins of multiplicity in A+C regions (unconstrained in B)
  - Mapped to charged particle multiplicity N_ch and number of participants N_part
- Several p_T intervals to test hydrodynamics region, energy loss region & sensitivity to multiplicity change

$$[p_\mathrm{T}] = \frac{1}{\sum_b w_b} \sum_b w_b p_{\mathrm{T}b}$$

$$c_k = \left\langle \frac{1}{(\sum_b w_b)^2 - \sum_b w_b^2} \sum_b \sum_{b \neq b'} w_b (p_{\mathrm{T},b} - \langle [p_\mathrm{T}] \rangle) w_{b'} (p_{\mathrm{T},b'} - \langle [p_\mathrm{T}] \rangle) \right\rangle$$

c_k - STAR Collaboration Phys. Rev. C72 (2005) 044902

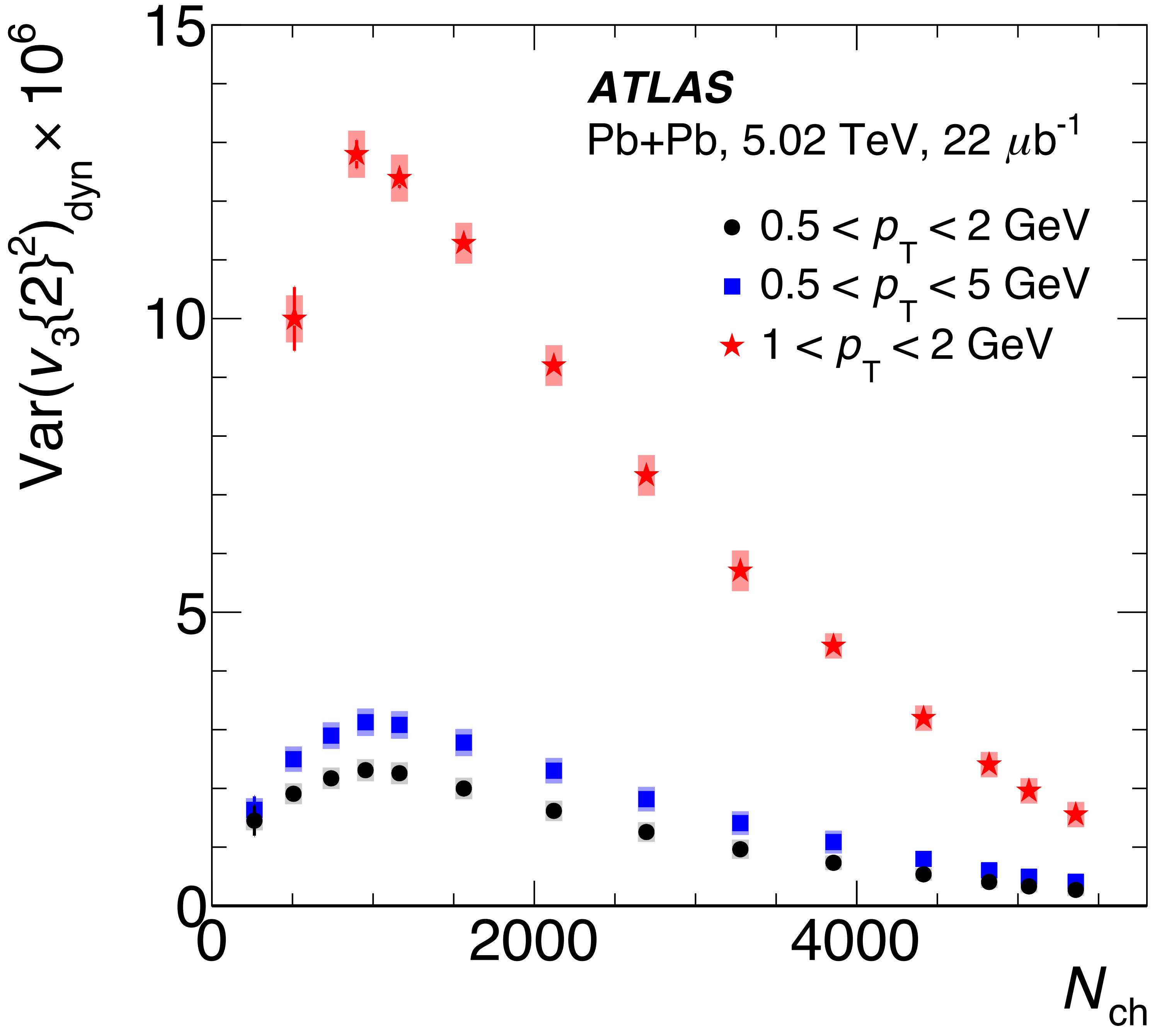
$$var(v_n^2)_{dyn} = \langle corr\{4\} \rangle - \langle corr\{2\} \rangle^2$$

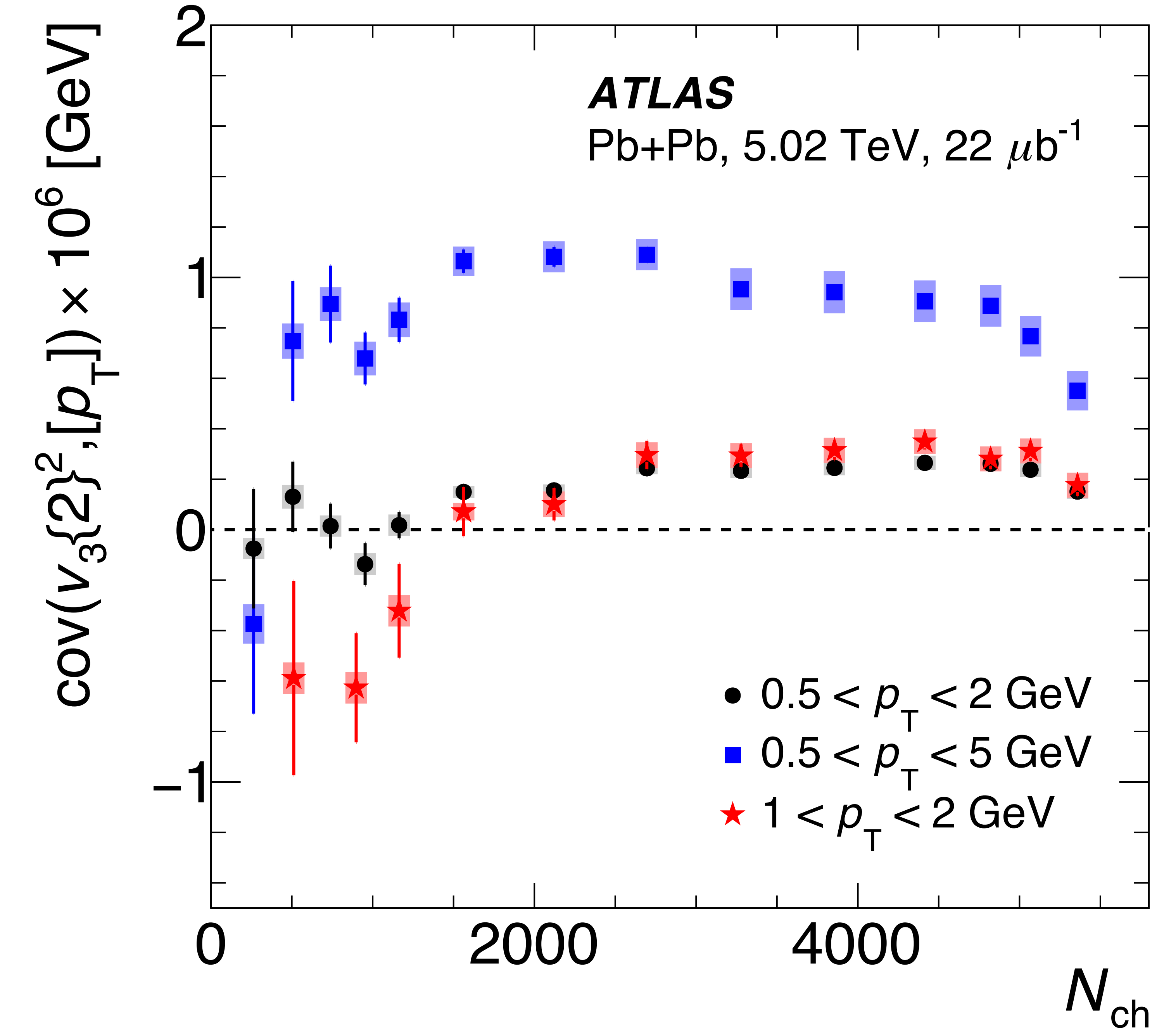
Intermediate results:

V3

- Covariances
  - Flat dependence → very different N_{ch} dependence compared to v_2
  - Very different magnitudes
- Dynamical variance
  - a similar N_{ch} dep. as v_2

- c_k quantifies magnitude of p_T fluctuations
- p_T interval ordering yet different than for *cov* and *dyn. var*

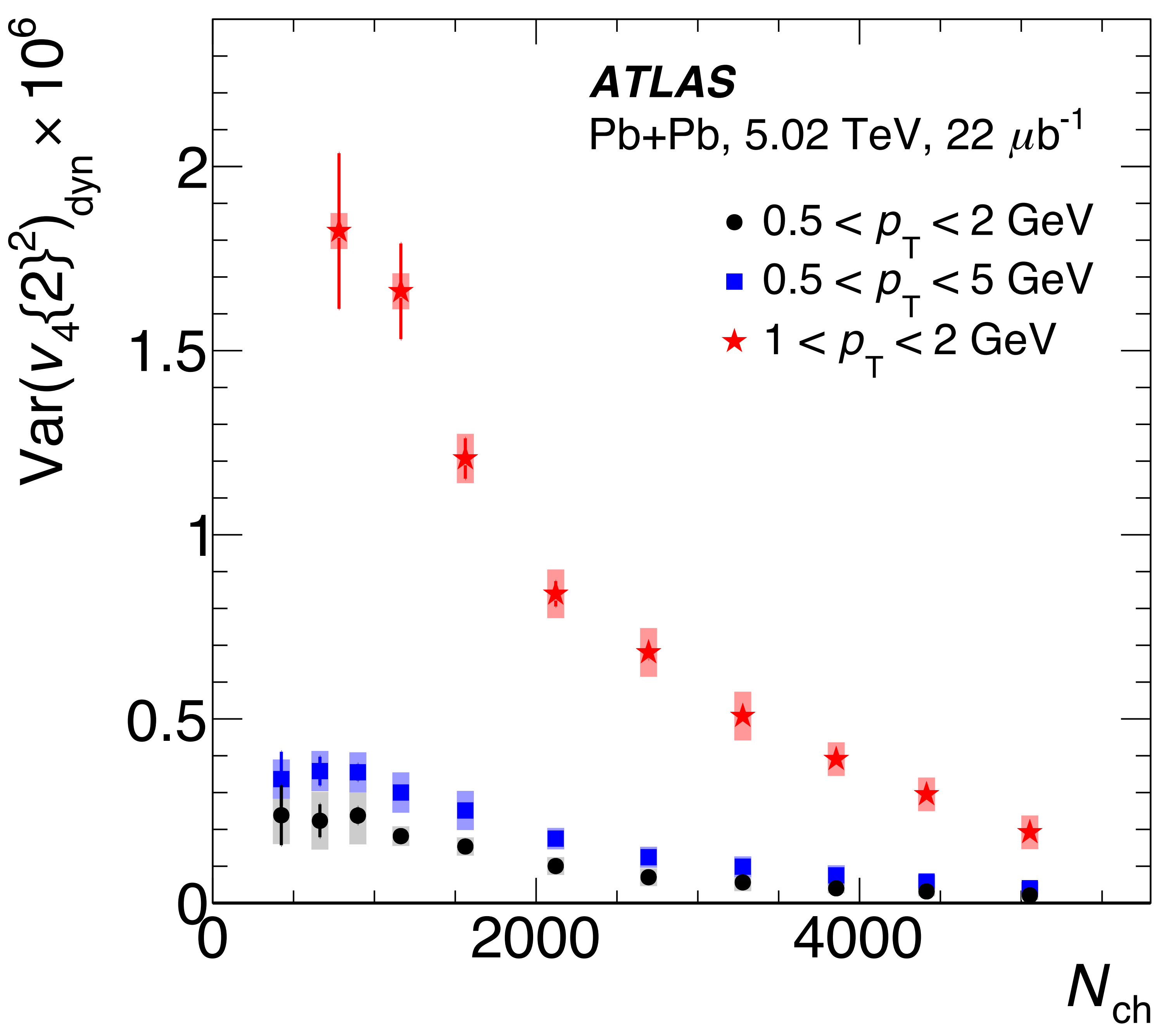




Intermediate results:

v₄

- Covariances and dynamical variances similar behaviour to v_2 except much smaller magnitude
- Low N_{ch} not accessible



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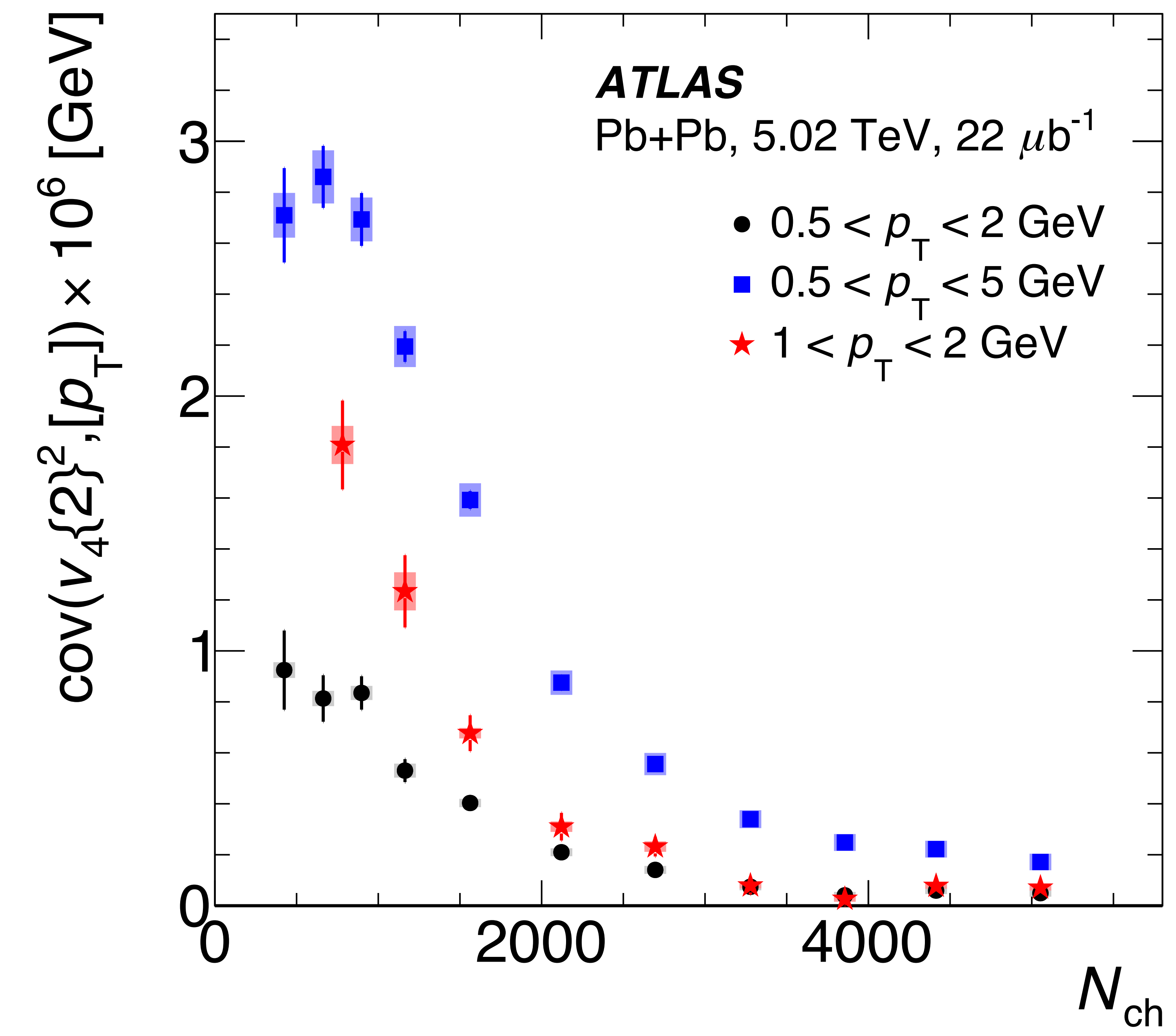

Ingredients of ρ_{v_2} in p+Pb

$$\rho = \frac{\mathrm{cov}(v_2\{2\}^2,[p_T])}{\sqrt{c_k \cdot \mathrm{Var}(v_2\{2\}^2)_{dyn}}}$$