# Measurement of the azimuthal anisotropy of charged particles in 5.02 TeV Pb+Pb and 5.44 TeV Xe+Xe collisions with ATLAS

Tomasz Bold - AGH UST
on behalf of the ATLAS Collaboration

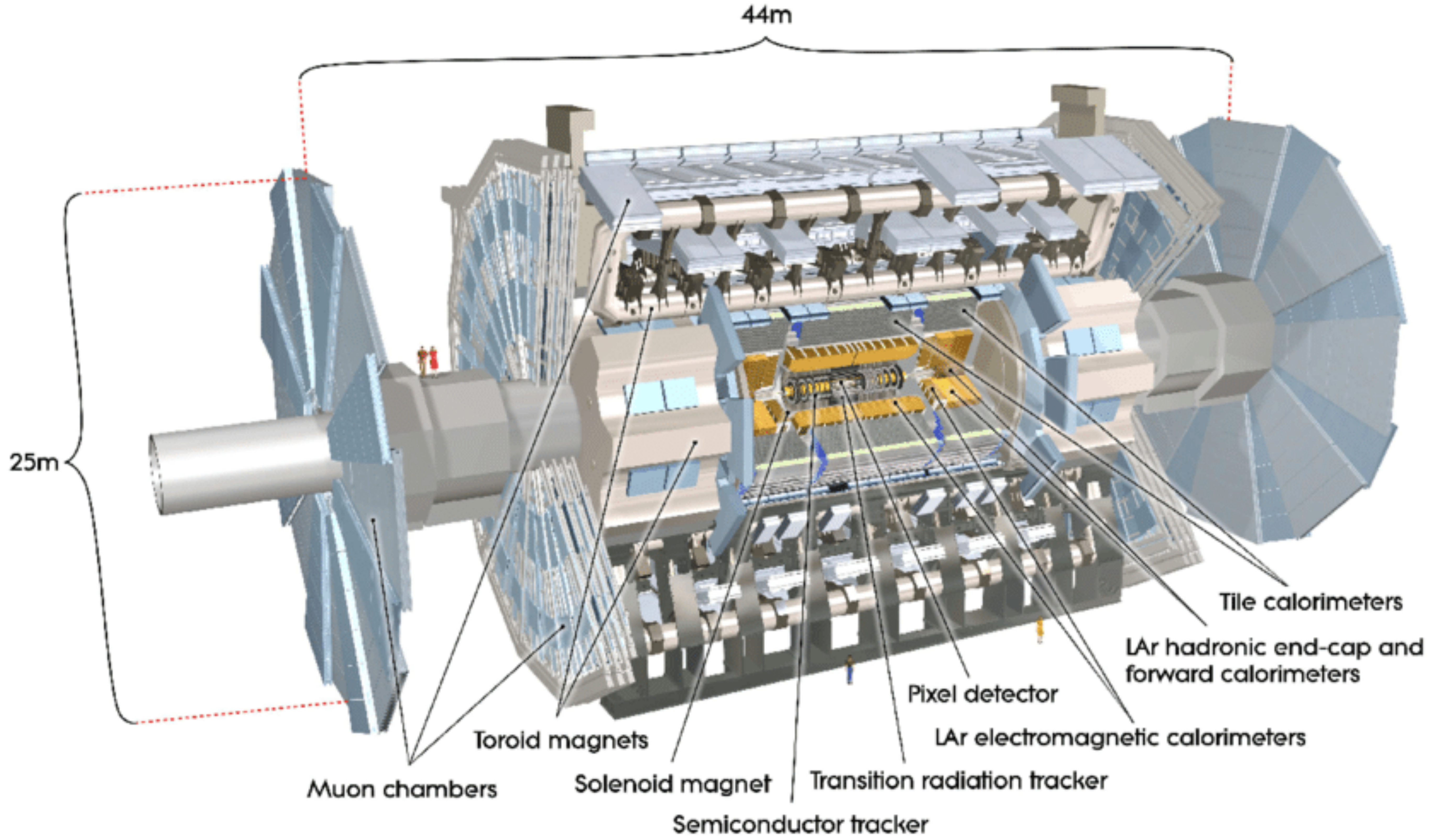
# Plan

- Pb+Pb results
  - Flow measurements — ATLAS-CONF-2016-105
  - Correlations of $v_n$ harmonics: with event mean-$p_T$ — ATLAS-CONF-2018-008
- Xe+Xe results
  - flow harmonics $p_T$ and centrality dependence
  - insight into the initial state fluctuations via multi-particle cumulant measurements
- Comparisons between Pb+Pb & Xe+Xe — ATLAS-CONF-2018-011

**https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults**

ATLAS EXPERIMENT

# The ATLAS detector

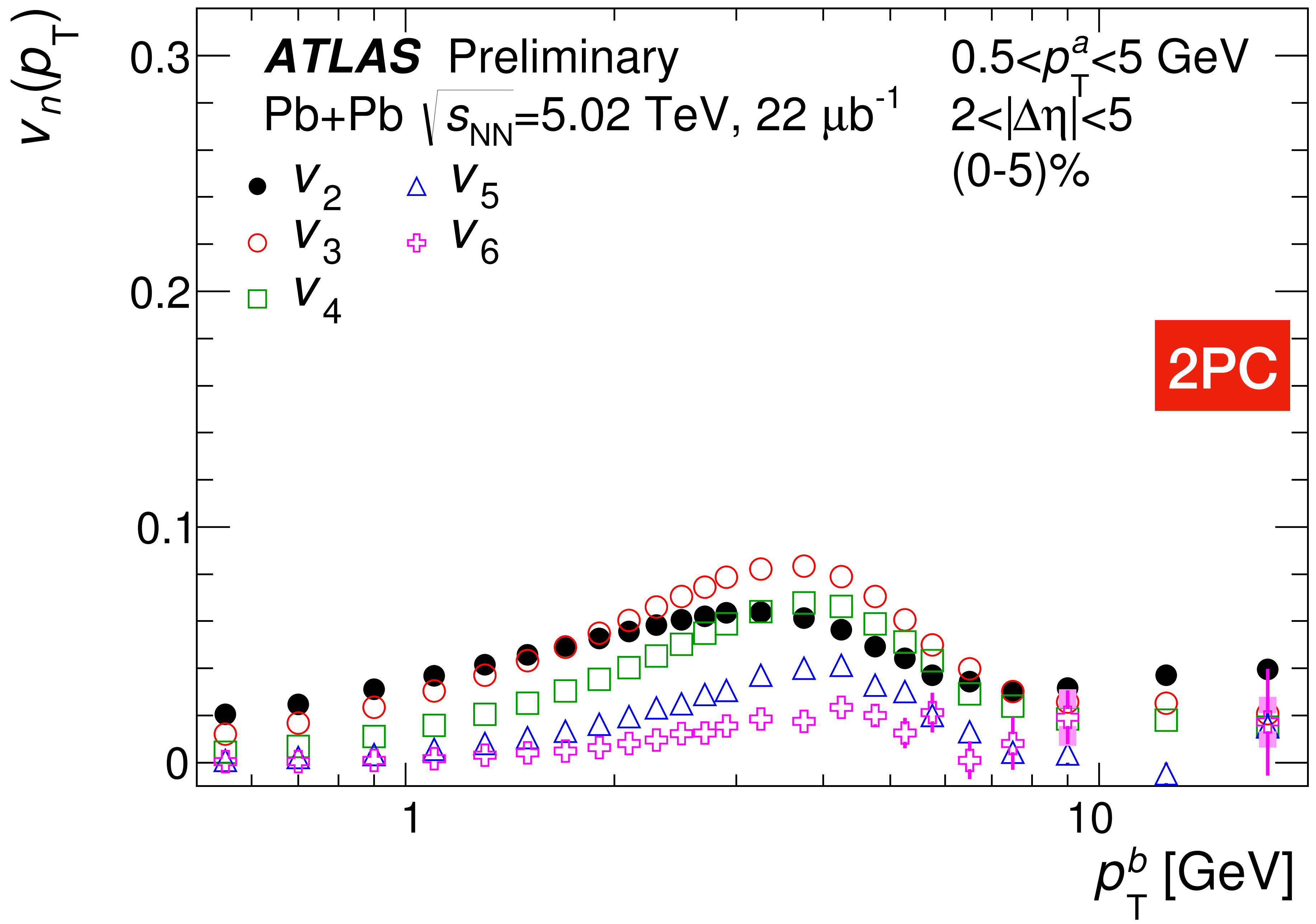


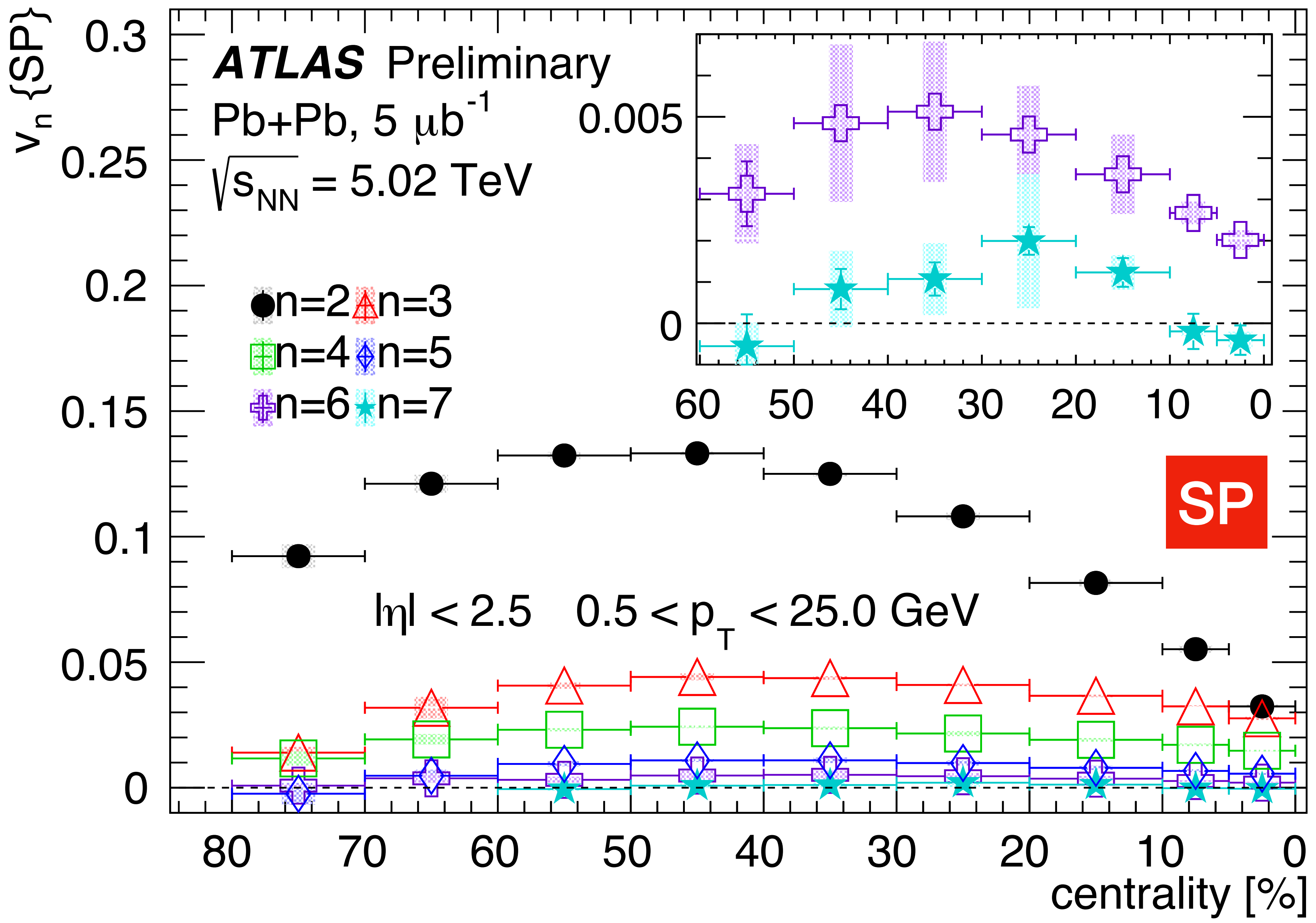

- Measurements reported here use
  - Inner Detector tracker (ID) $|\eta|<2.5$
  - Forward Calorimeter $3.2<|\eta|<4.9$ and ZDC $|\eta|>8.3$

# Flow harmonics at Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV

ATLAS-CONF-2016-105

- Measurement of the $v_n$ in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV allowed to reach high $p_T$ of 25 GeV, study very central collisions
- Harmonics up to *n*=7 with SP
- Weak η dependence
- The $v_n$ at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV energies are similar



# Mean $p_T$ correlation with flow harmonics

ATLAS-CONF-2018-008

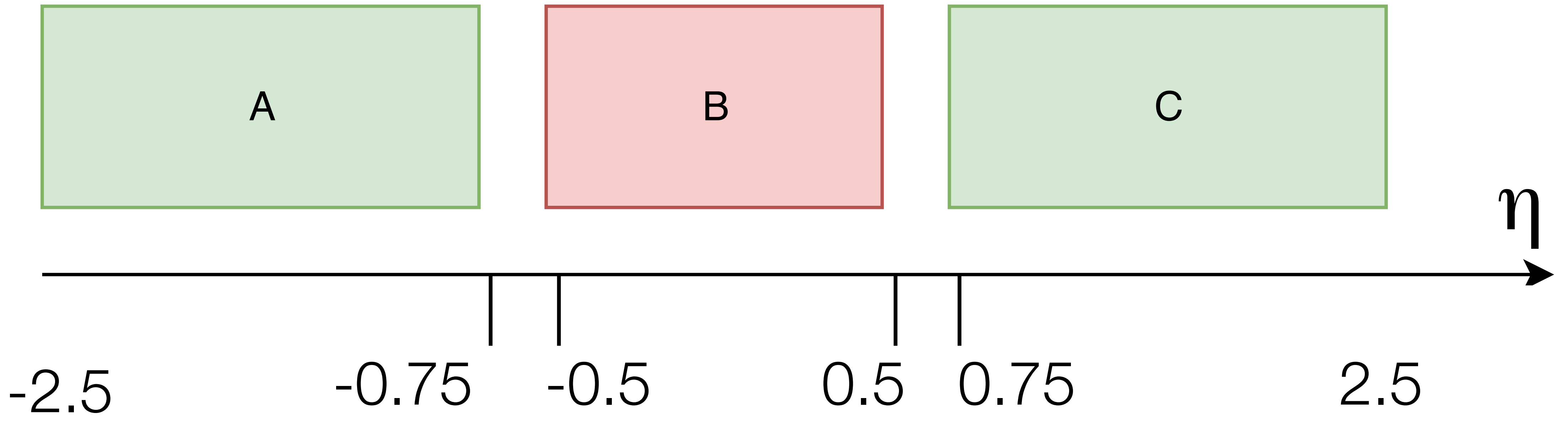
- Known that the correlation exists (ALICE Collab. Phys. Rev. C **93**, 034916)
- Relate initial state quantity (event mean $[p_T]$) and final state evolution (flow harmonics)
- The quantitive measure, i.e. correlation coefficient distorted by the limited event multiplicity
- A modified correlator proposed (P. Bozek Phys. Rev. C93 (2016) 044908)
  - Replaces multiplicity dependent variances by dynamic counterparts $\mathrm{Var}_{dyn}$, $c_k$ → detector independent measurement
  - Reproduces true R

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

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

ATLAS EXPERIMENT

# 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 $N_\mathrm{ch}$ and number of participants $N_\mathrm{part}$
- Four $p_\mathrm{T}$ intervals, 0.5-5, 0.5-2, 1-2, 1-5 GeV
  → significant variation of multiplicities

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

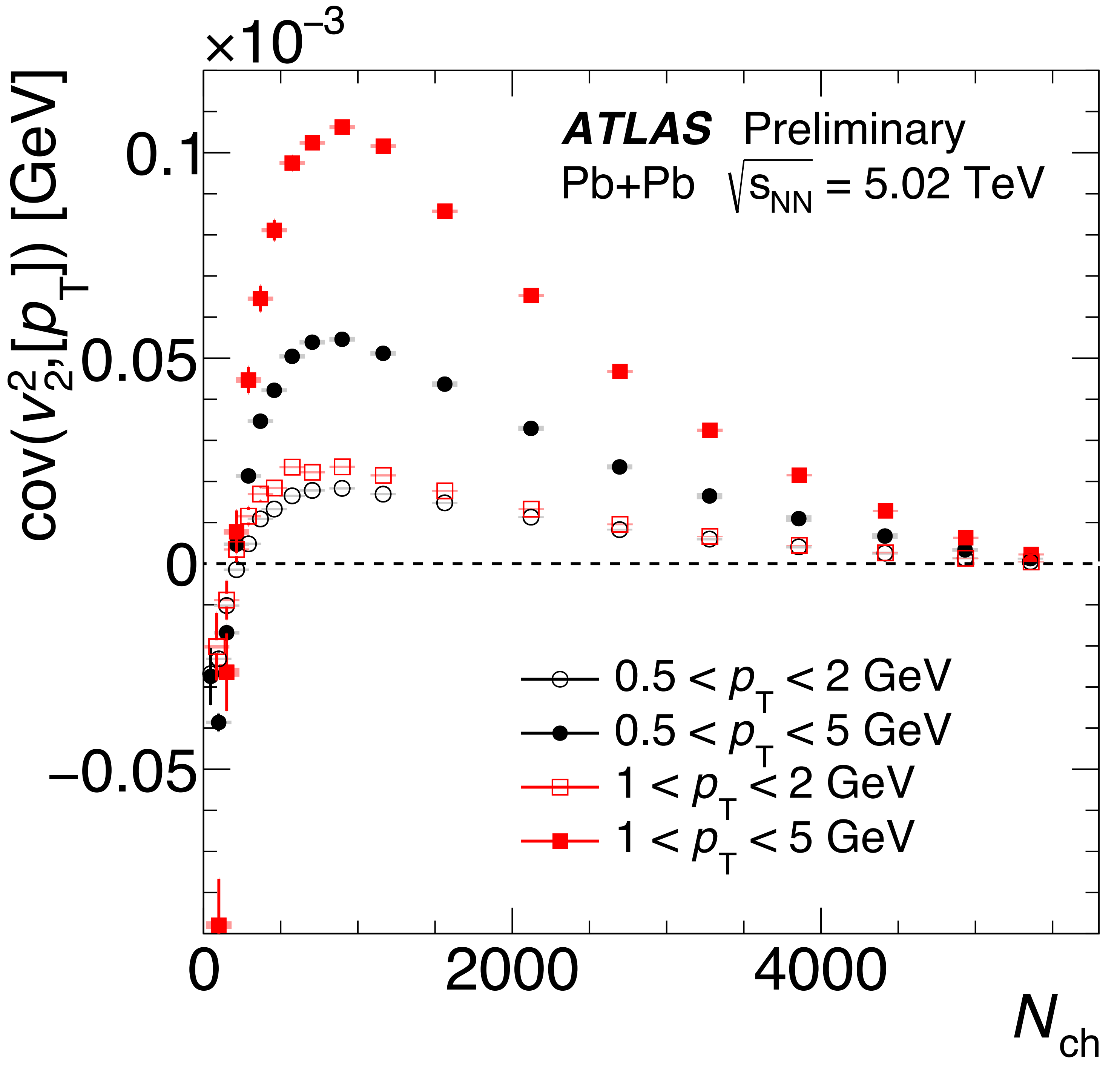
$$c_k = \left\langle \frac{1}{(\sum_b w_b)^2 - \sum_b w_b^2} \sum_b \sum_{b \neq b'} w_b (p_{\mathrm{T},b} - \langle [p_\mathrm{T}] \rangle) w_{b'} (p_{\mathrm{T},b'} - \langle [p_\mathrm{T}] \rangle) \right\rangle$$

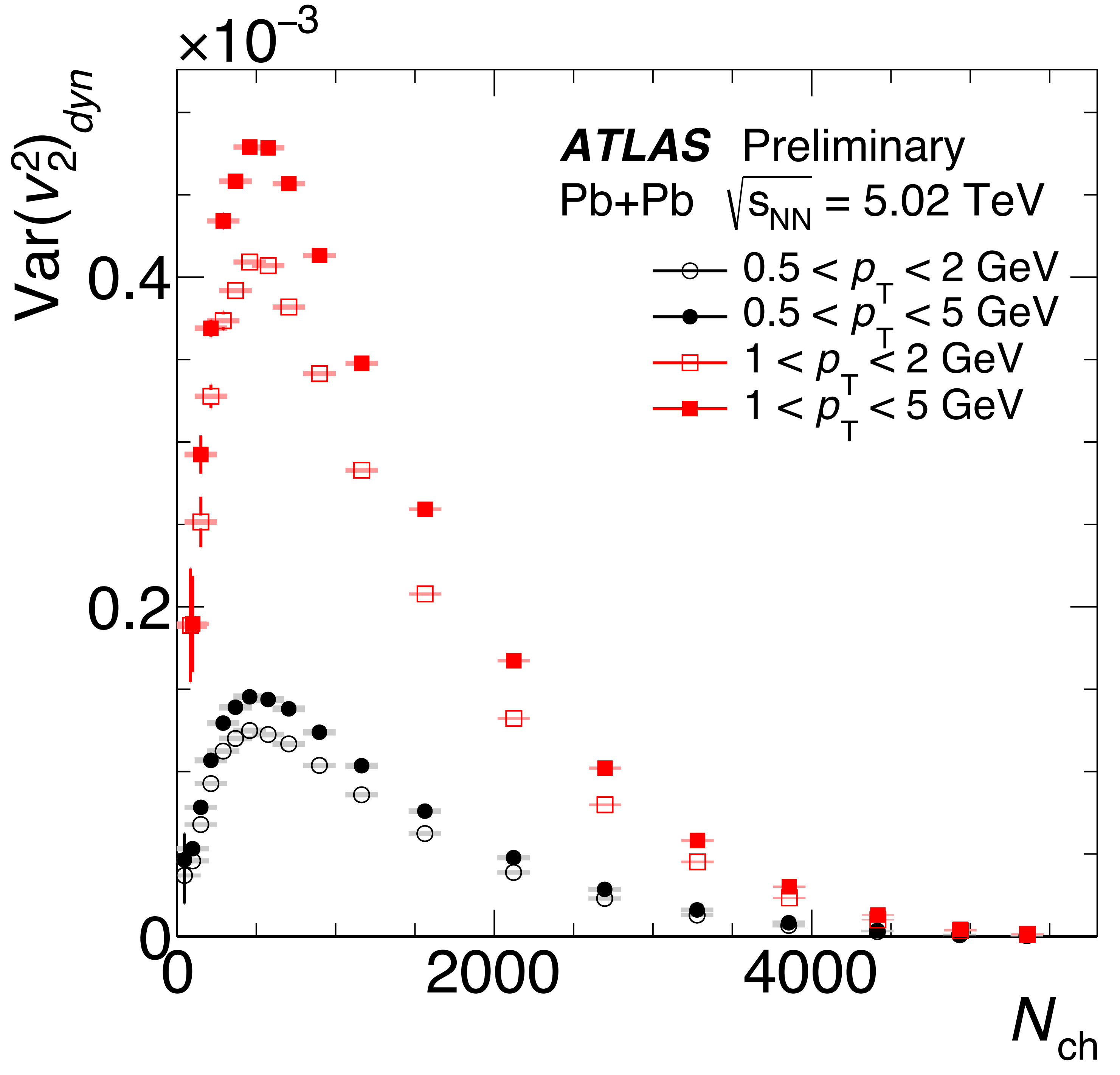
$c_k$ - STAR Collaboration Phys. Rev. C72 (2005) 044902

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

# Intermediate results: $v_2$

- Covariances
  - Significant change with centrality
    - Highest where flow is highest
    - For $v_2$ negative in peripheral events
  - $p_T$ interval affects the multiplicity and thus the the covariance values
- Similar trend for dynamical variance
  - Different $p_T$ ordering

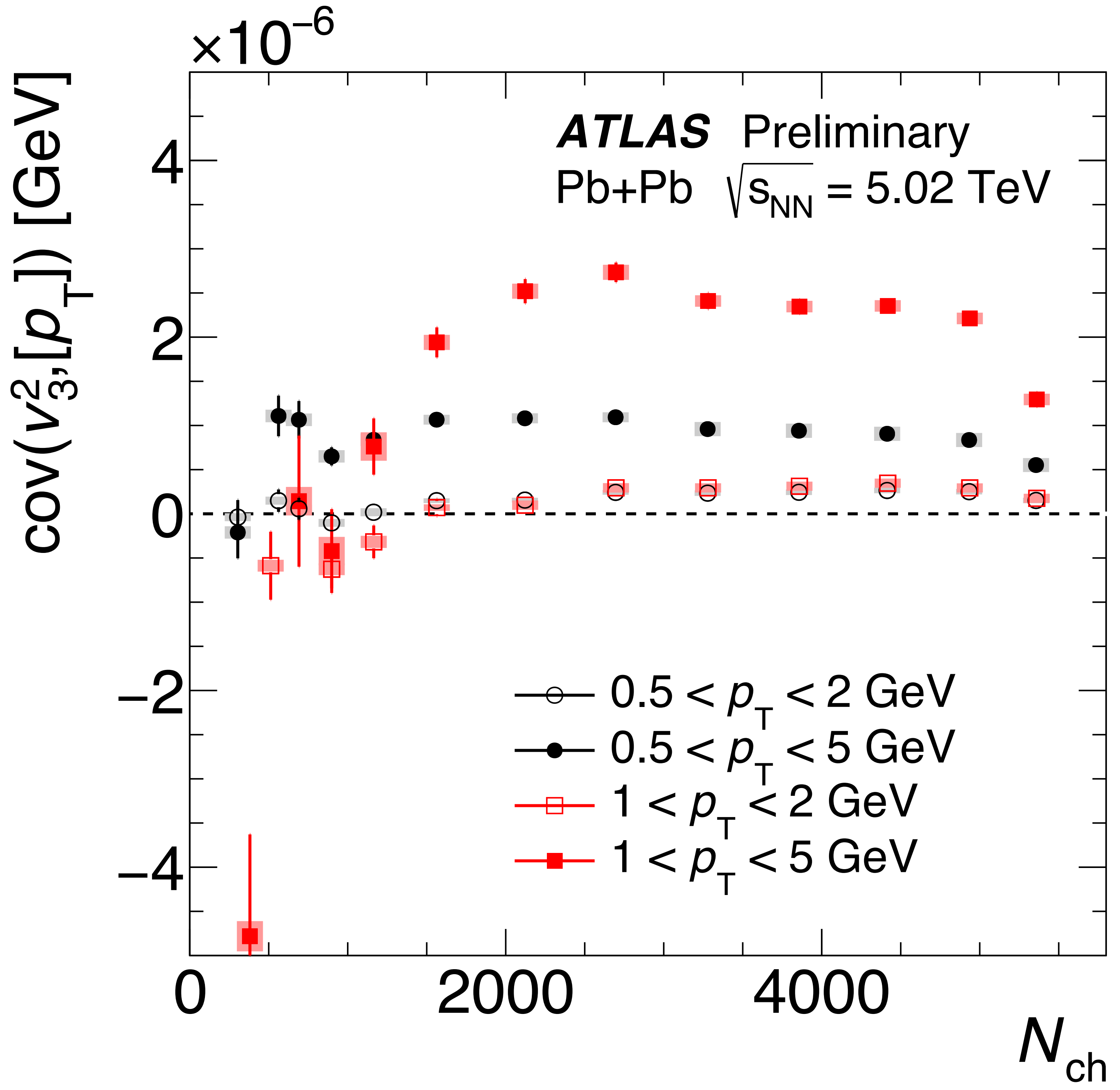


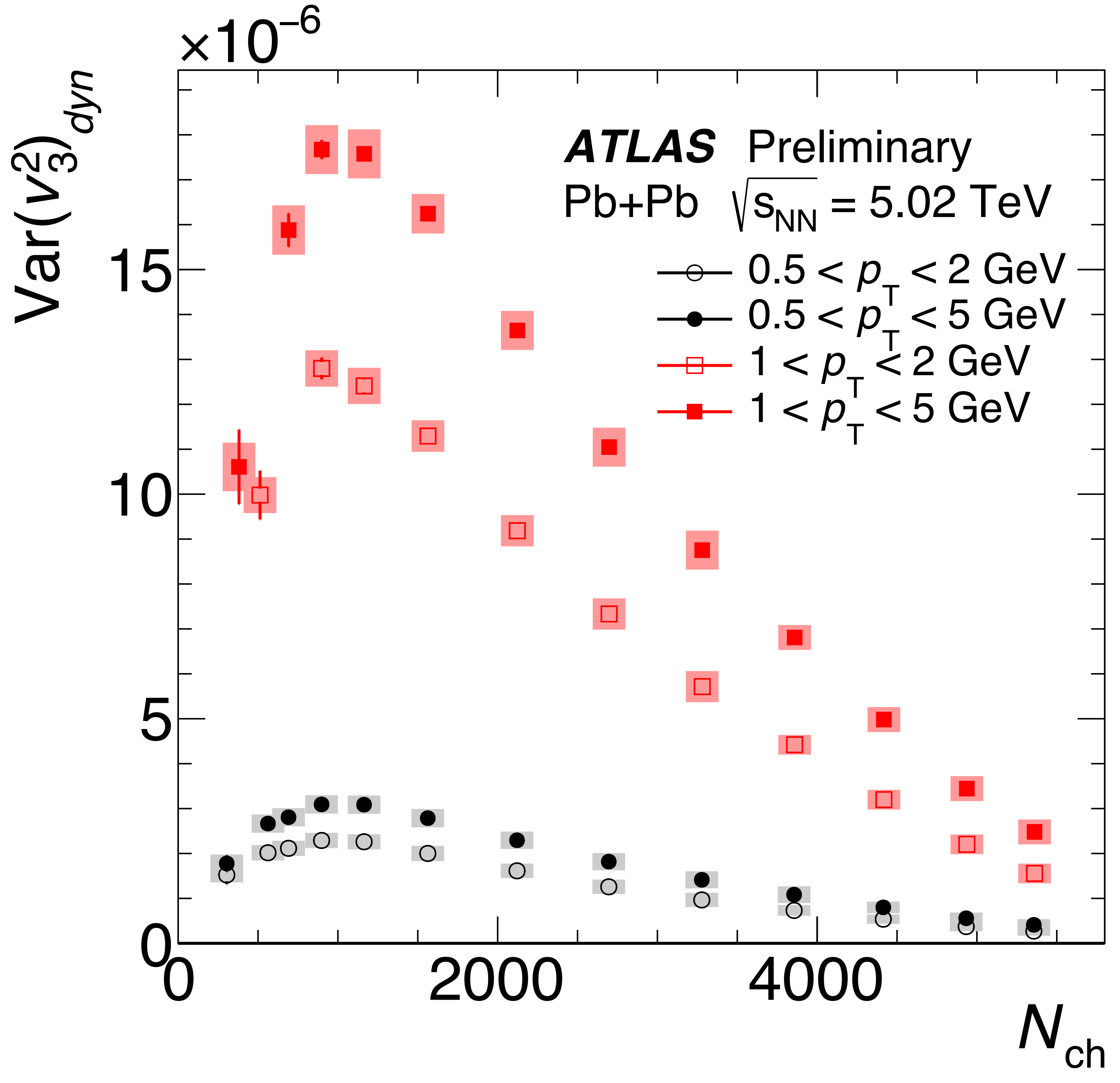




ATLAS EXPERIMENT

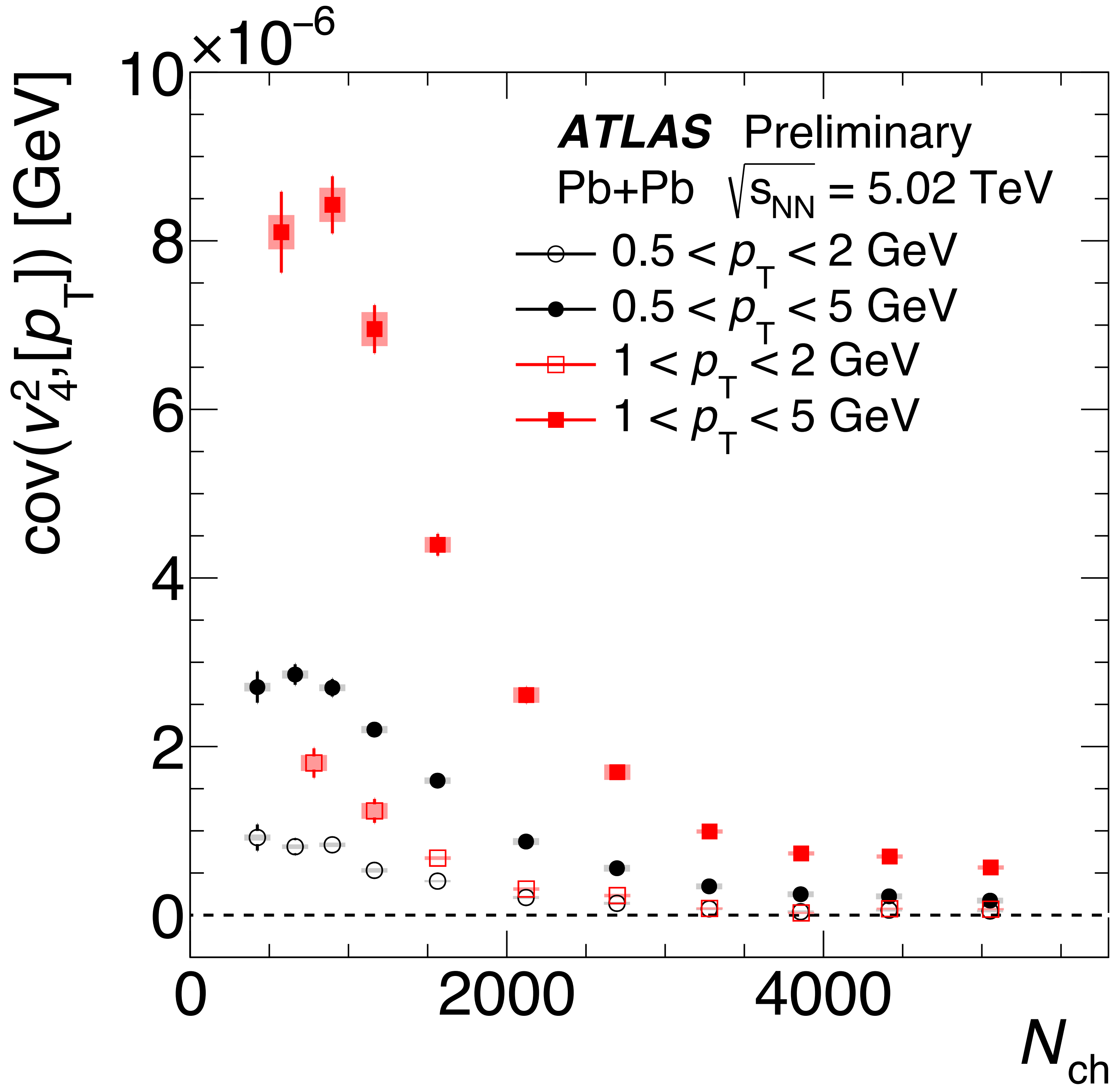
# Intermediate results: $v_3$

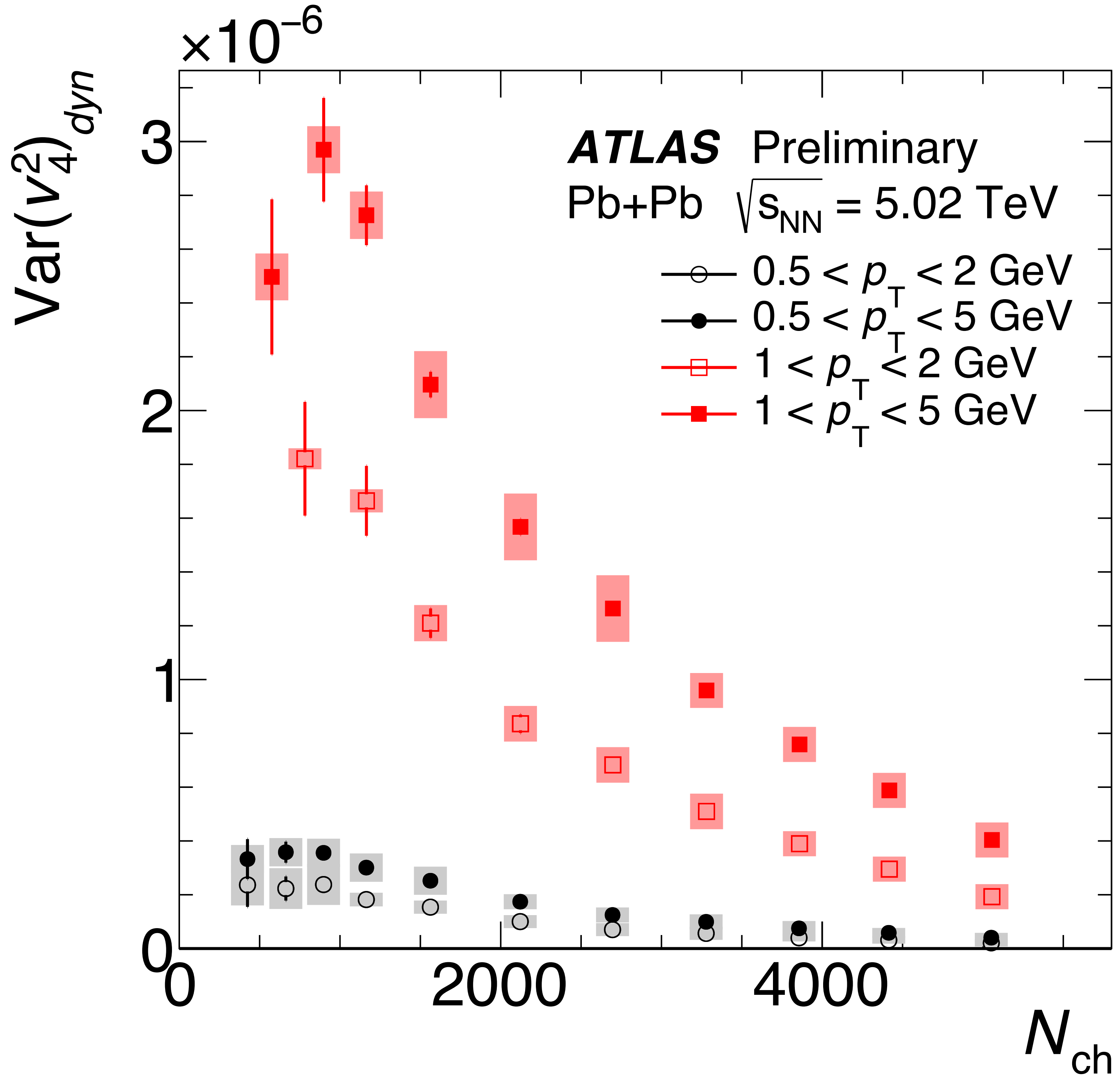
- Covariances
  - Flat dependence → very different $N_{ch}$ dependence compared to $v_2$
  - Very different magnitudes
- Dynamical variance
  - a similar $N_{ch}$ dep. as $v_2$



# Intermediate results: $v_4$

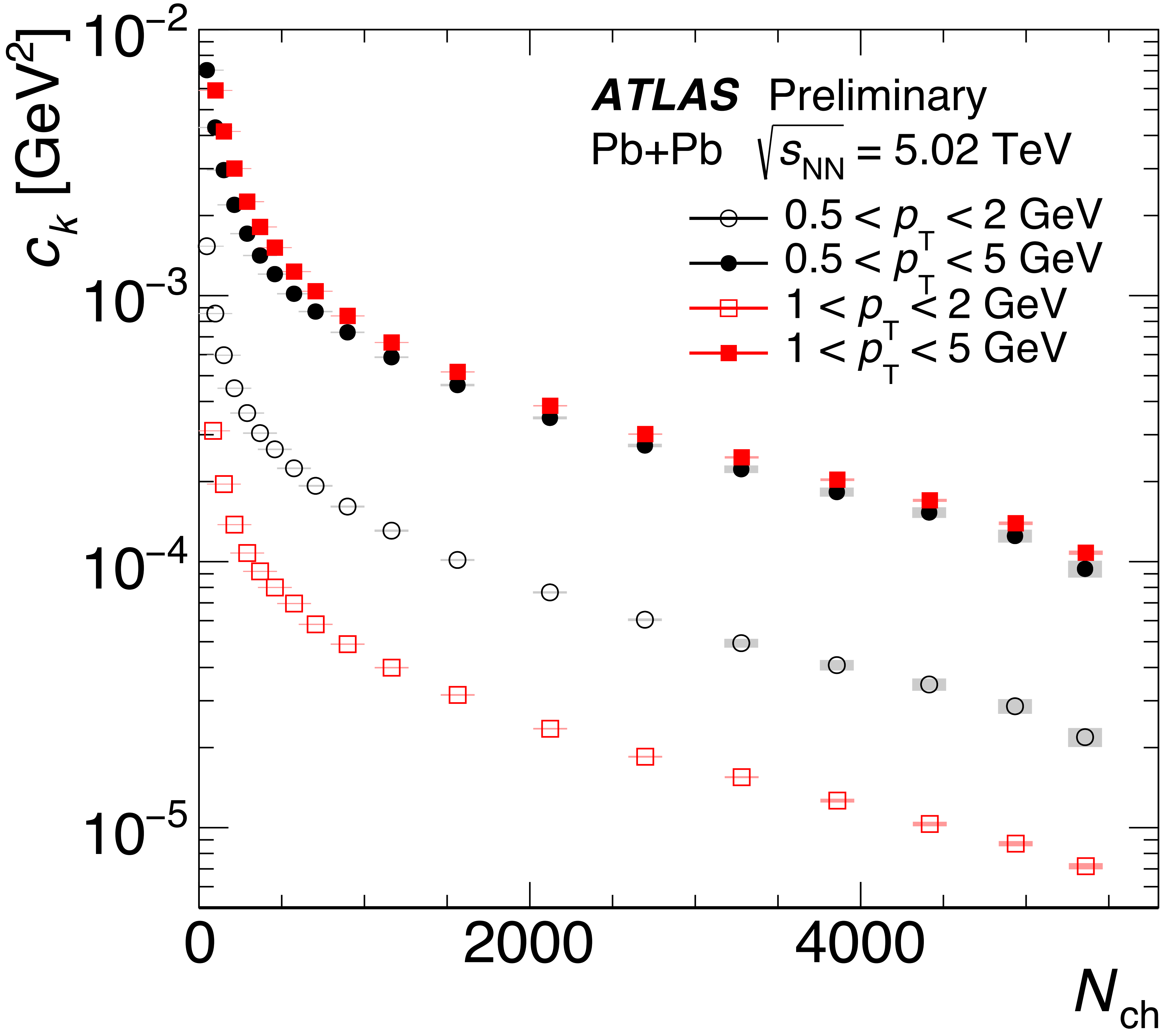



- Covariances and dynamical variances similar behaviour to $v_2$ except much smaller magnitude
- Low $N_{ch}$ not accessible

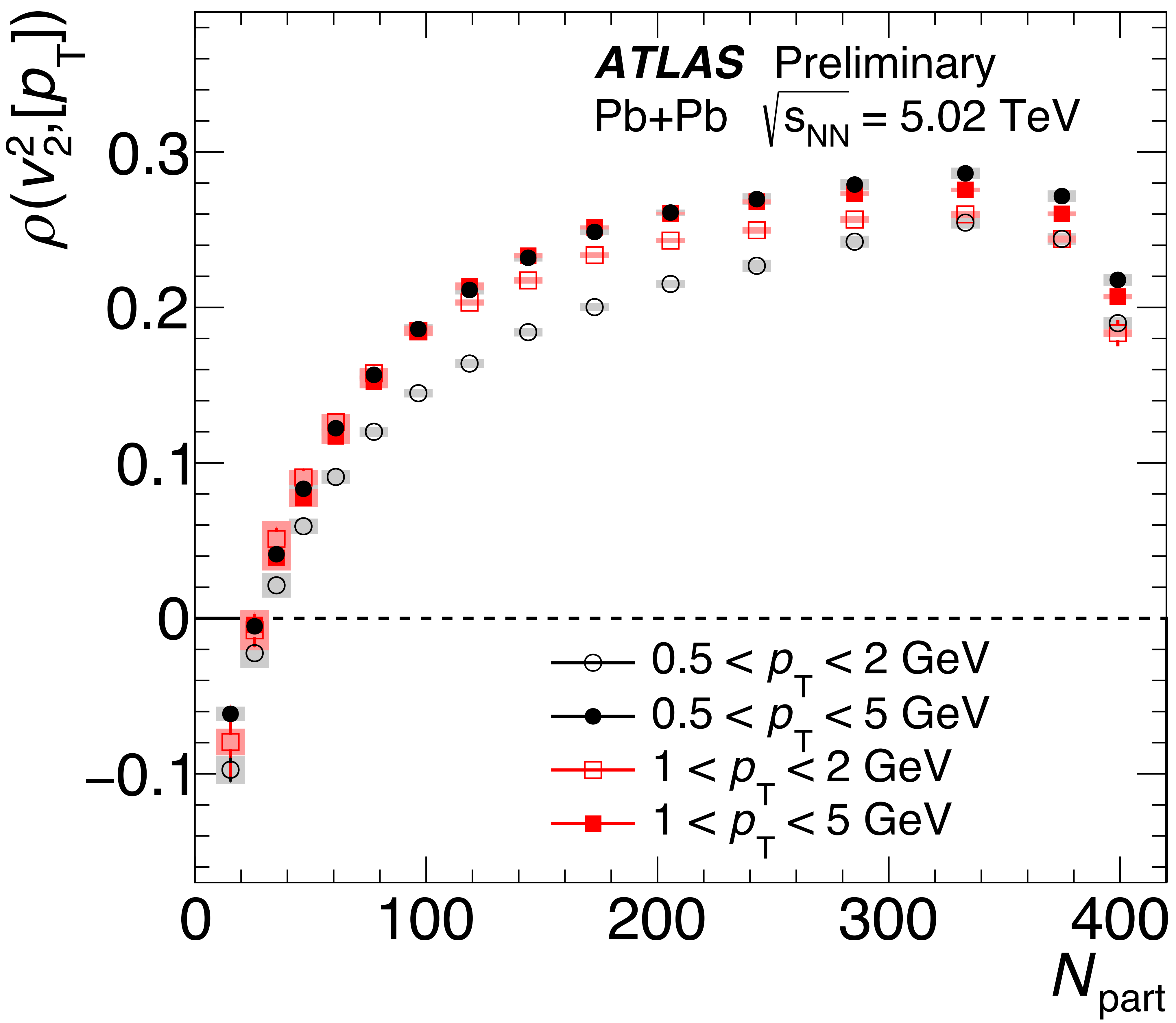
# Intermediate results: $c_k$

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



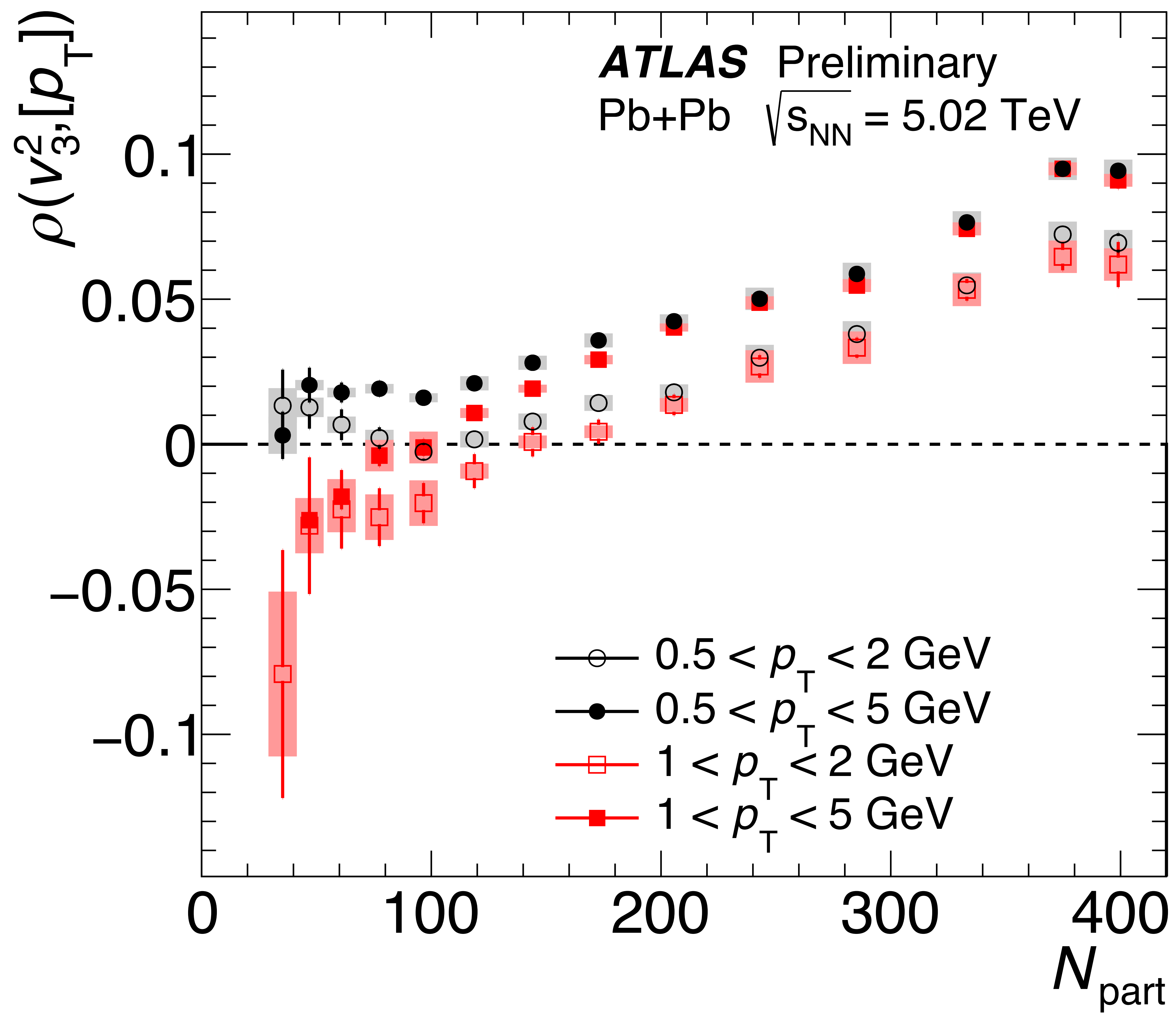
# Correlation coefficient $\rho$ for $v_2$

- Negative correlation for $v_2$ in peripheral events
  → related to ecc. ~ 1/r
- Gentle rise above $N_{part} \simeq 100$ - significant value of ≃0.28
  → stronger hydrodynamic response to initial eccentricities
- Fall in most central events
- Difference between various $p_T$ intervals 10-20%



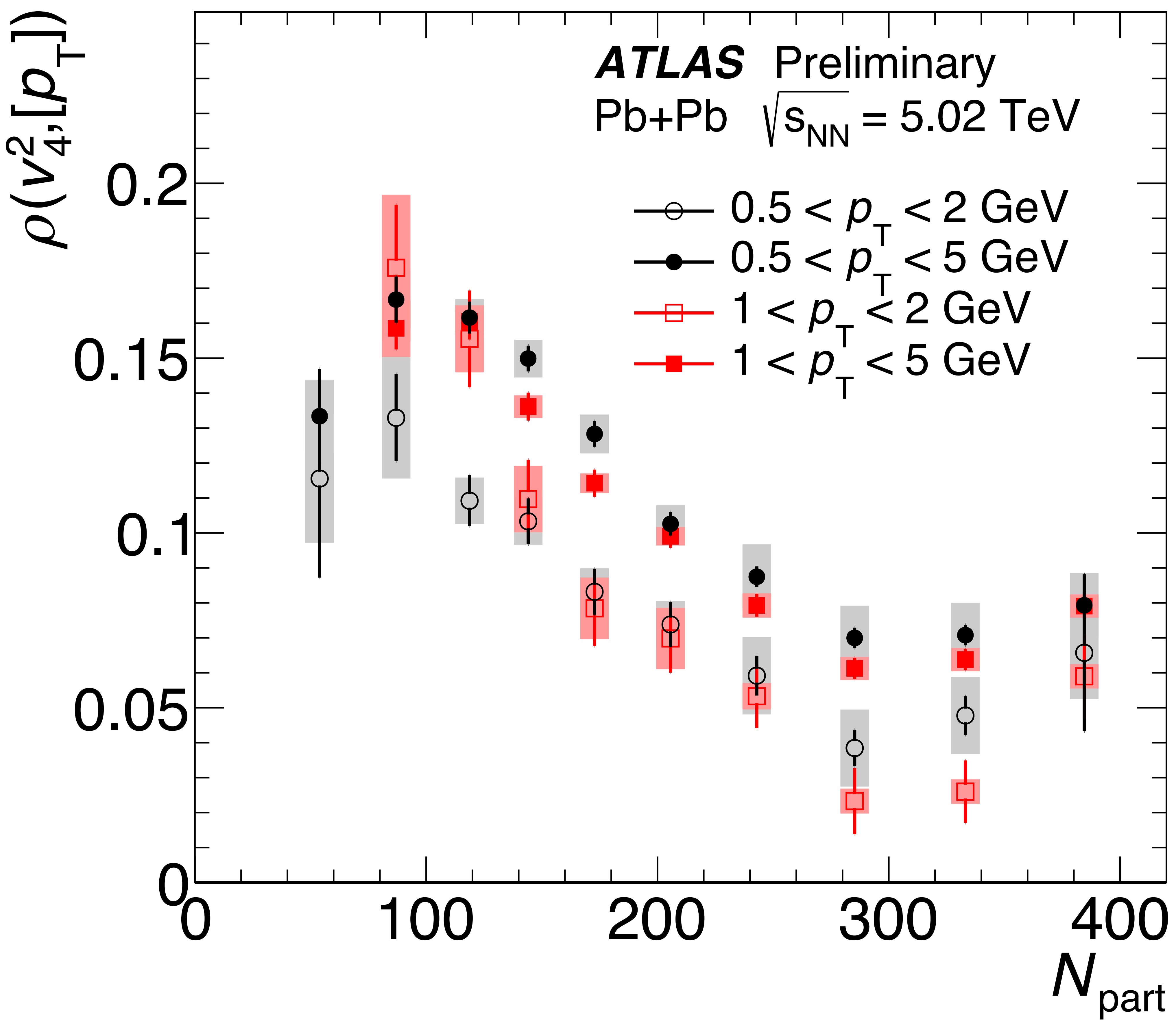
# Correlation coefficient $\rho$ for $v_3$

- Correlation for $v_3$ weaker compared to $v_2$
- Positive except for $p_T$ > 1GeV below $N_{part}$ ≃ 100
- Above $N_{part}$ ≃ 100 steady rise
  - higher $p_T$ threshold translates to higher $\rho$; independent of lower threshold $p_T$
- A hint of decrease in most central 3% events

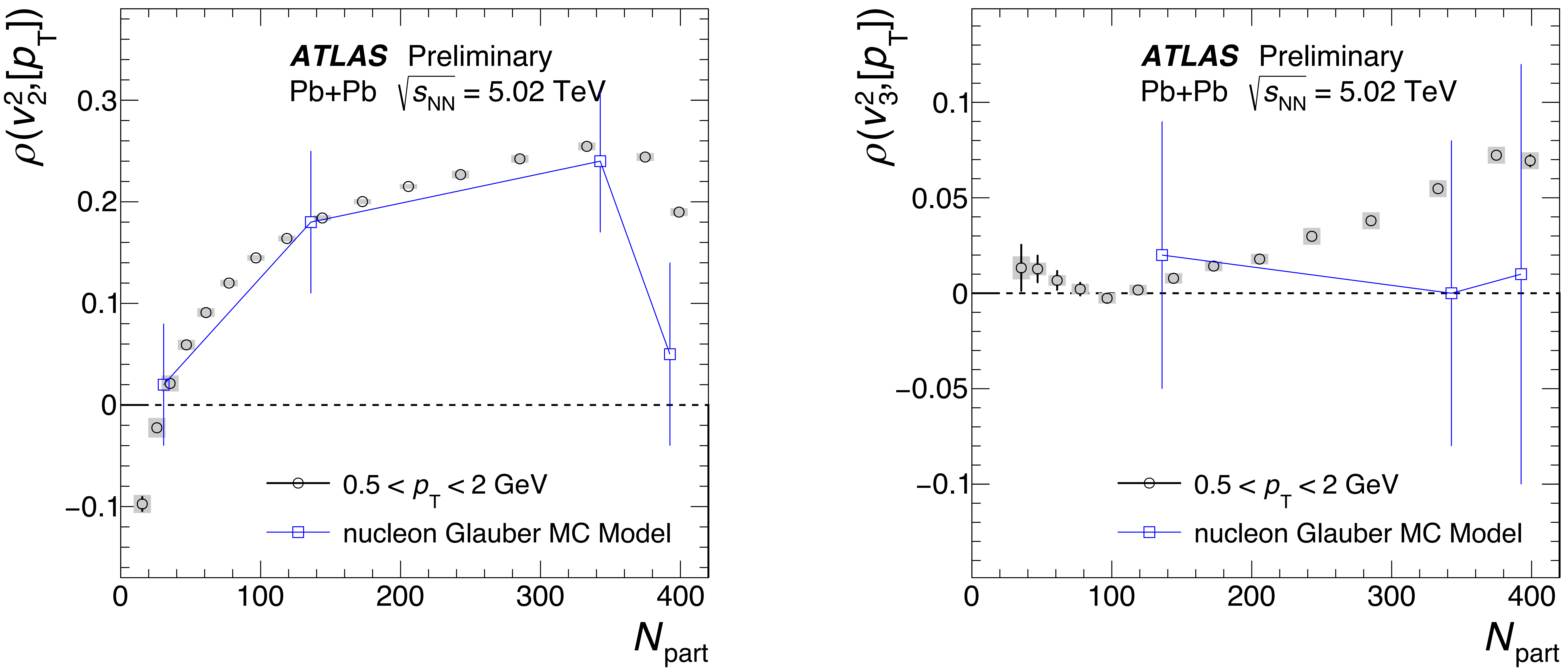


# Correlation coefficient $\rho$ for $v_4$

- Also a significant correlation seen
- A fall with rising centrality for mid central
- Lower in most peripheral - a hint of increase in most central events
- Possible hint of convergence with $v_3$ for most central events



# Theory comparison



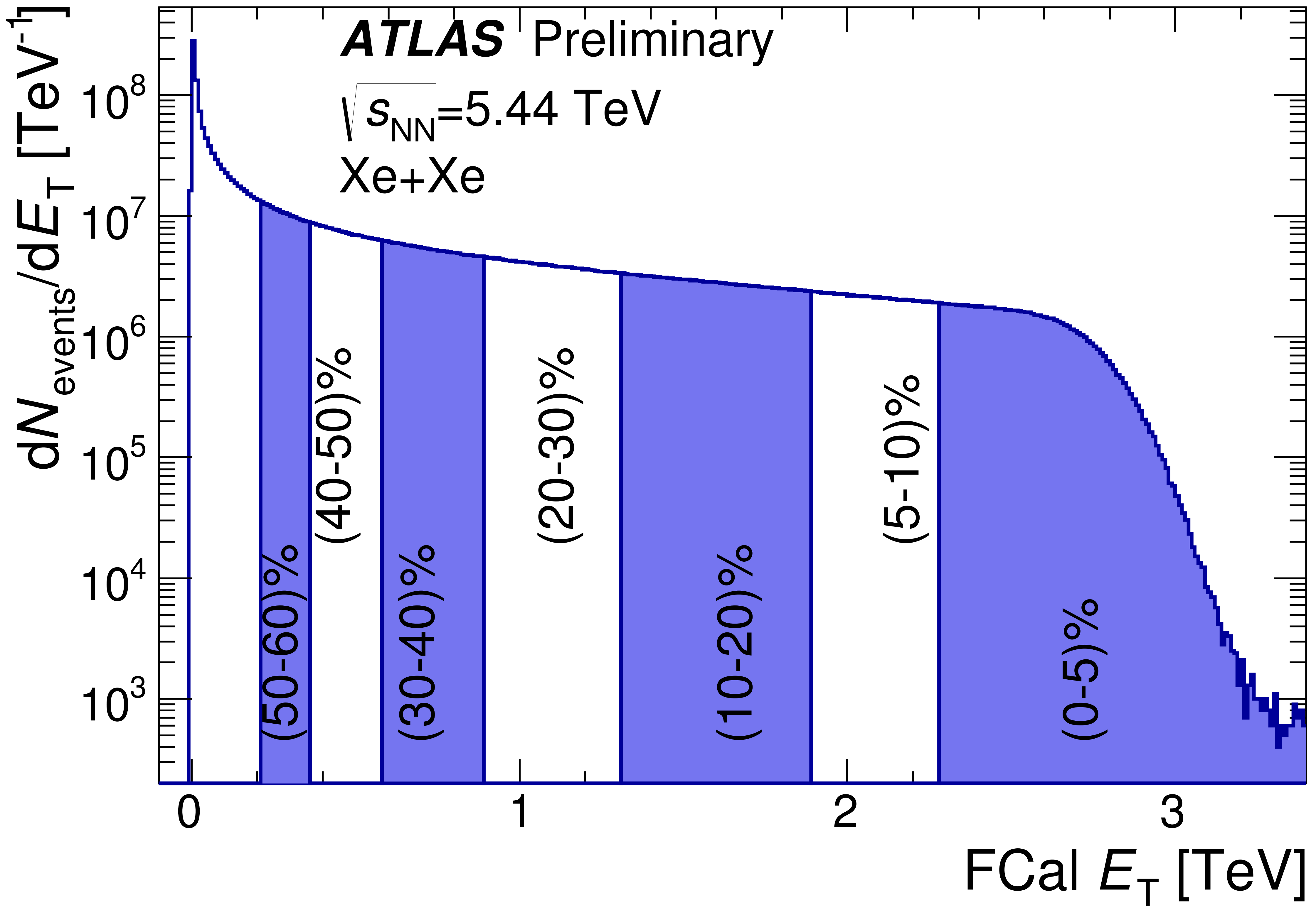

P. Bozek Phys. Rev. C93 (2016) 044908

- Theory predictions qualitatively consistent with data

# Flow in Xe+Xe collisions

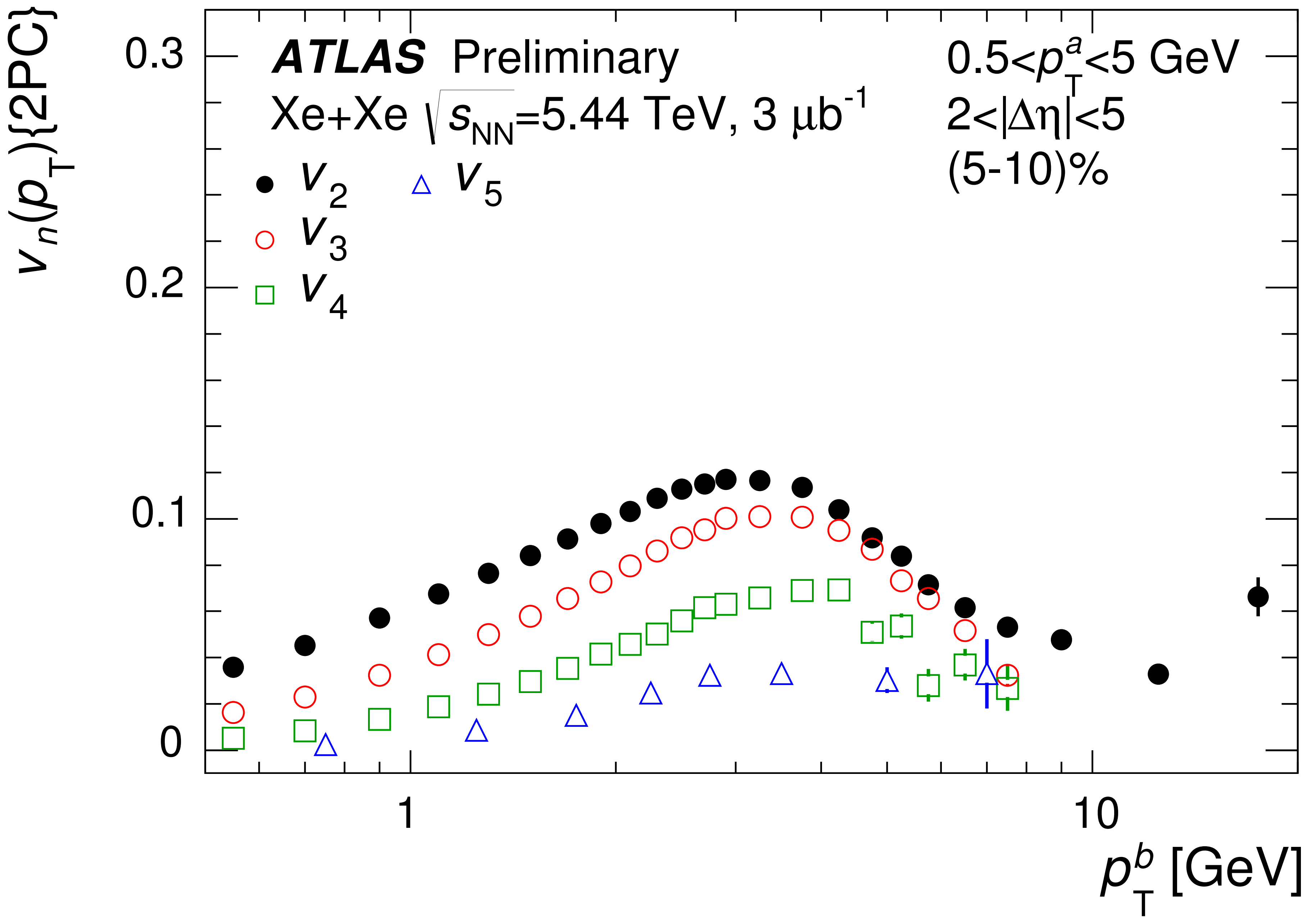
ATLAS-CONF-2018-011

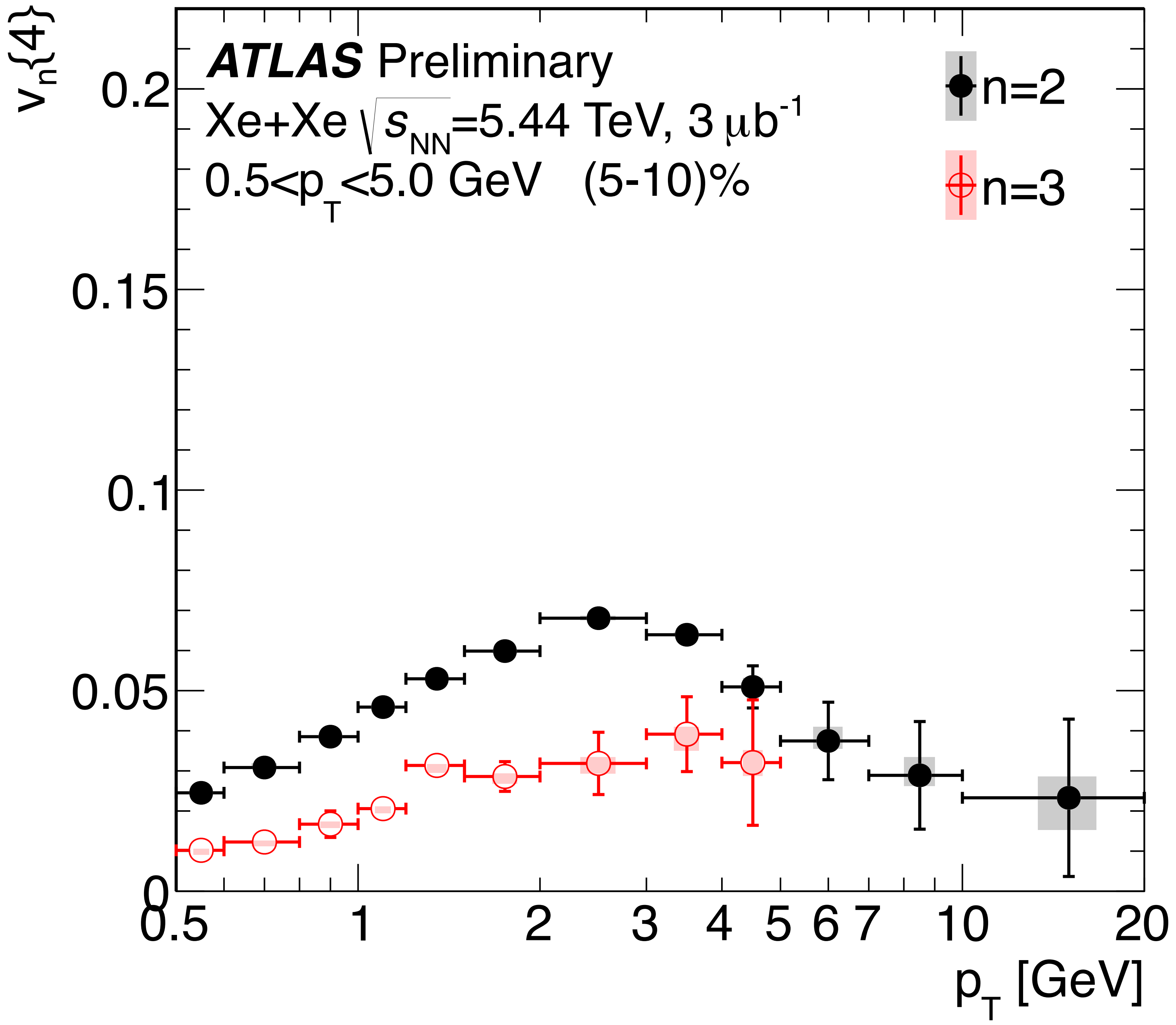
- Goal is to measure the flow in Xe+Xe collisions in comparison to Pb+Pb
- The $p_T$ and centrality dependence
- Event-by-event fluctuations via higher order correlations
- Measurements performed in bins of centrality (0-80%) quantified by $E_T$ in FCal $3.2<|\eta|<4.9$
  - Mapped to $N_{part}$ via Glauber modeling



# The $v_n(p_T)$ dependence in Xe+Xe

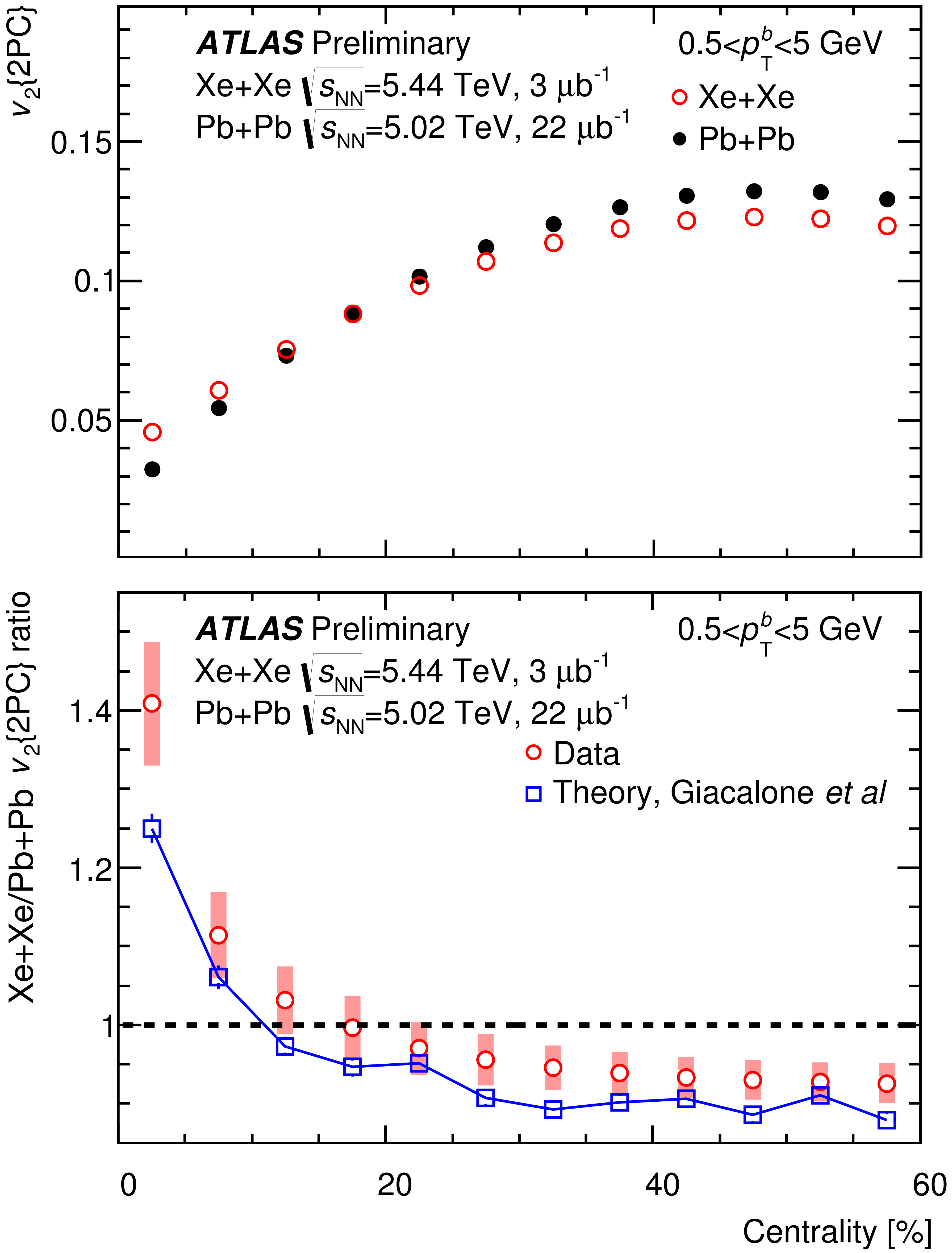
- Measured $v_n$ up to $n$=5, wide $p_T$ range (20 GeV for $v_2$)
- Typical $p_T$ dependence is observed
  - A rise up to 3-4 GeV, then fall, higher order fall harmonics to 0, $v_2$ rises due to non-flow effects
  - $v_2$ dominant except the most central collisions
  - $v_n$ measured with higher order correlations smaller
    → suppressed non-flow
    → impact of fluctuations



# Centrality dependence Xe+Xe vs. Pb+Pb

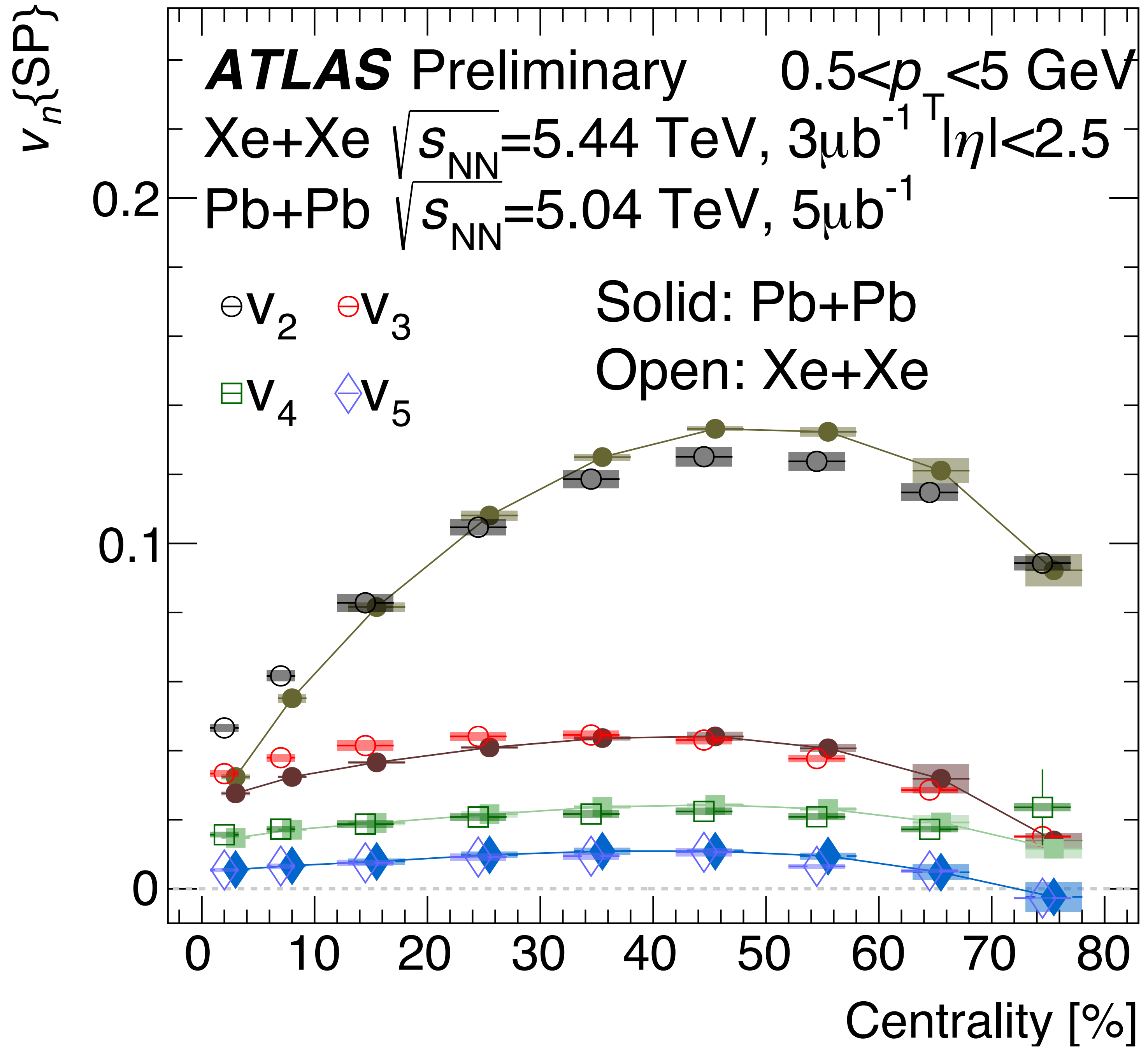
- Integrated $v_2$ is higher in most central events for Xe+Xe collisions
  - Elongated Xe shape
  - Smaller $N_{part}$ → larger fluctuations
- Reduced value in mid central and peripheral → surface effect → smaller initial eccentricities → viscous corrections
- A similar behaviour seen for $v_3$ and $v_4$
  - The increase in most central events is less pronounced
- Ratio is similar for different $p_T$ intervals
- Consistent with predictions

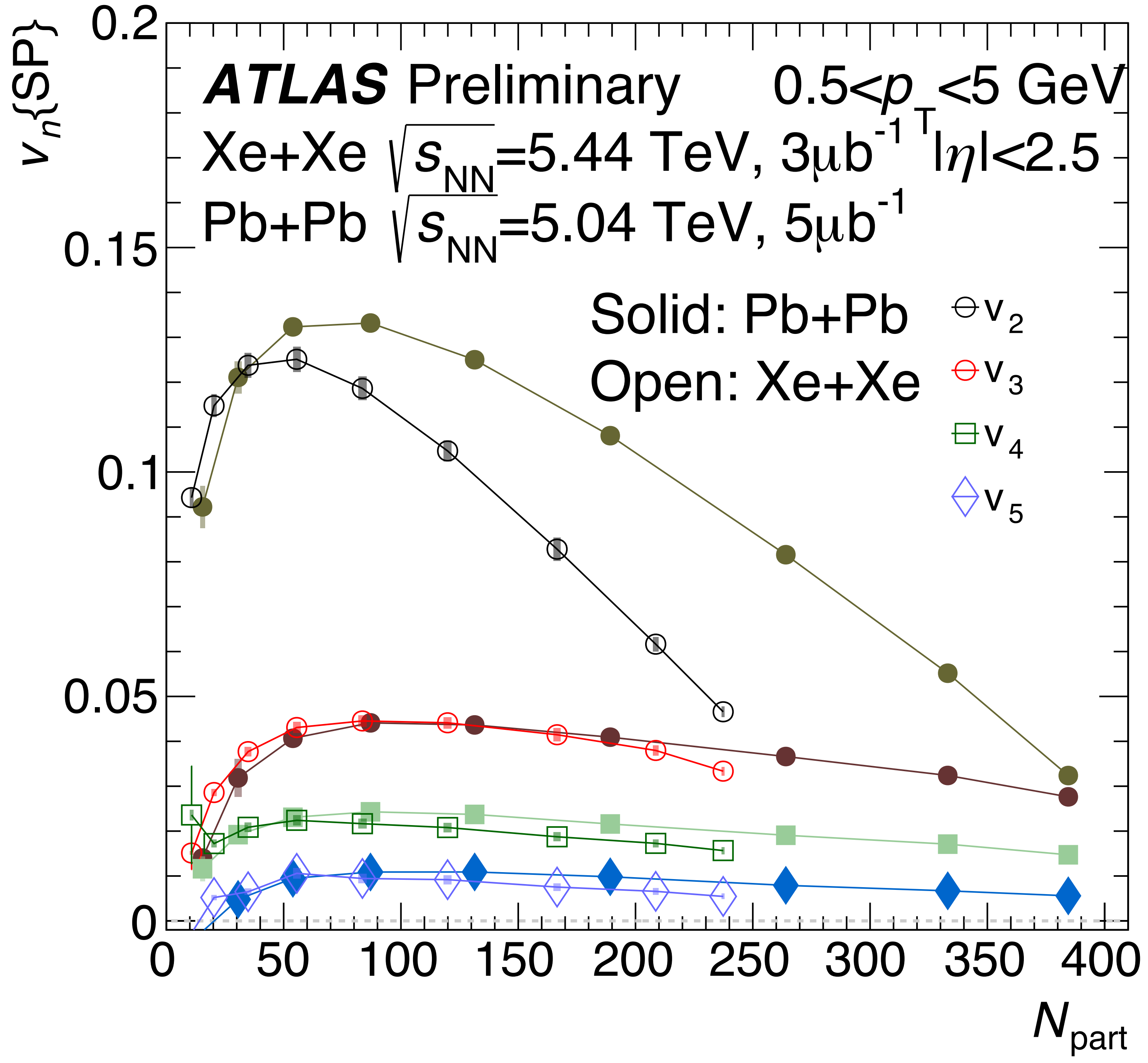



Giacalone *et al.* Phys. Rev. C 97, 034904 (2018)

# Centrality dependence (scaling)

- Typical pattern for centrality/$N_{\mathrm{part}}$ dependence
  - A good matching of $v_2$ as a function of centrality indicates geometric origins of the elliptic flow
  - $N_{\mathrm{part}}$ scaling for $v_2$ does not hold
  - Scaling with centrality or $N_{\mathrm{part}}$ not so obvious for higher order harmonics when looking at $v_n$

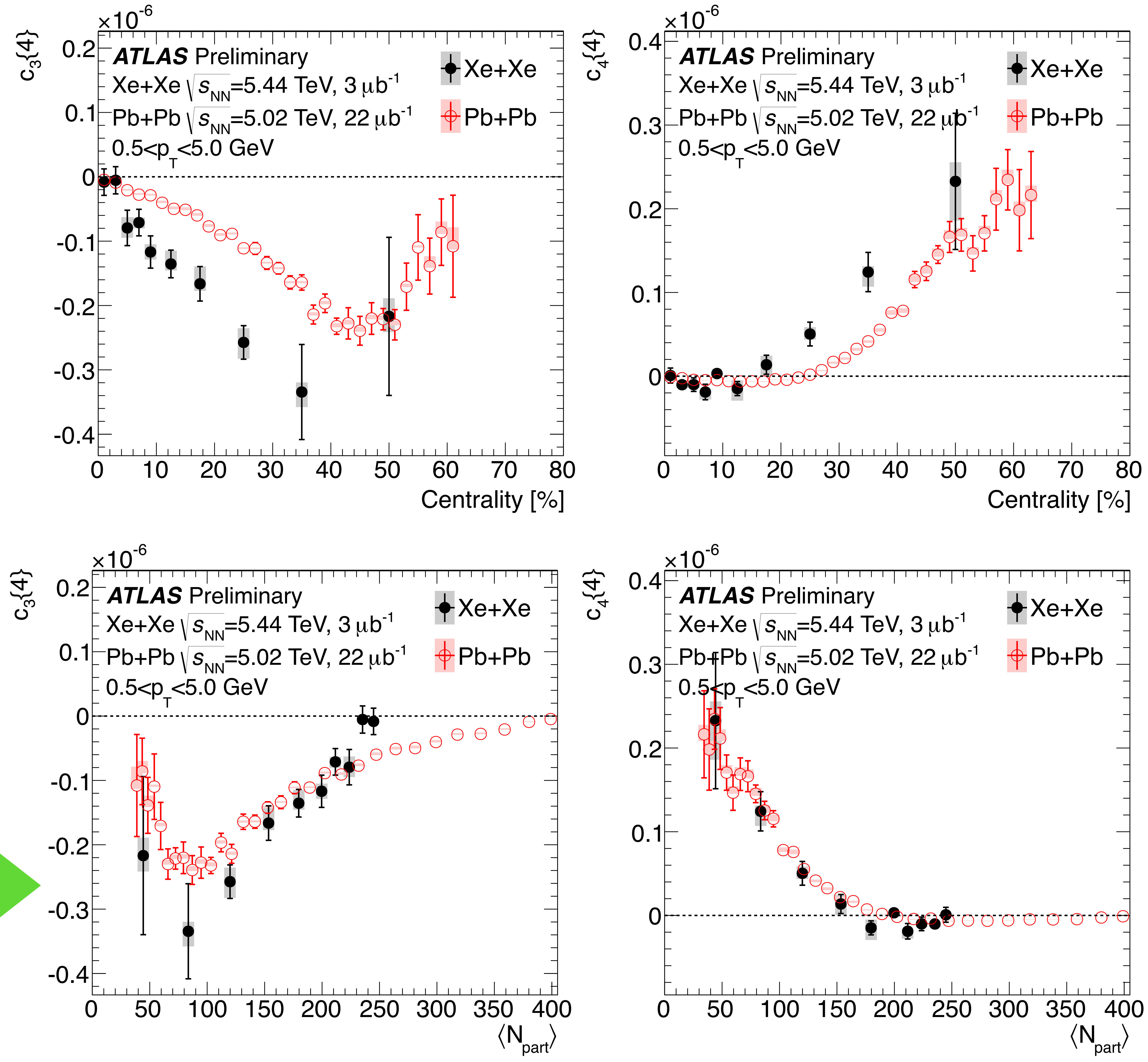


# Centrality dependence (scaling)

- A more sensitive variable: 4-particle cumulants to check scaling for higher order harmonics
- They scale with $N_{part}$ → flow is fluctuations driven

Good agreement

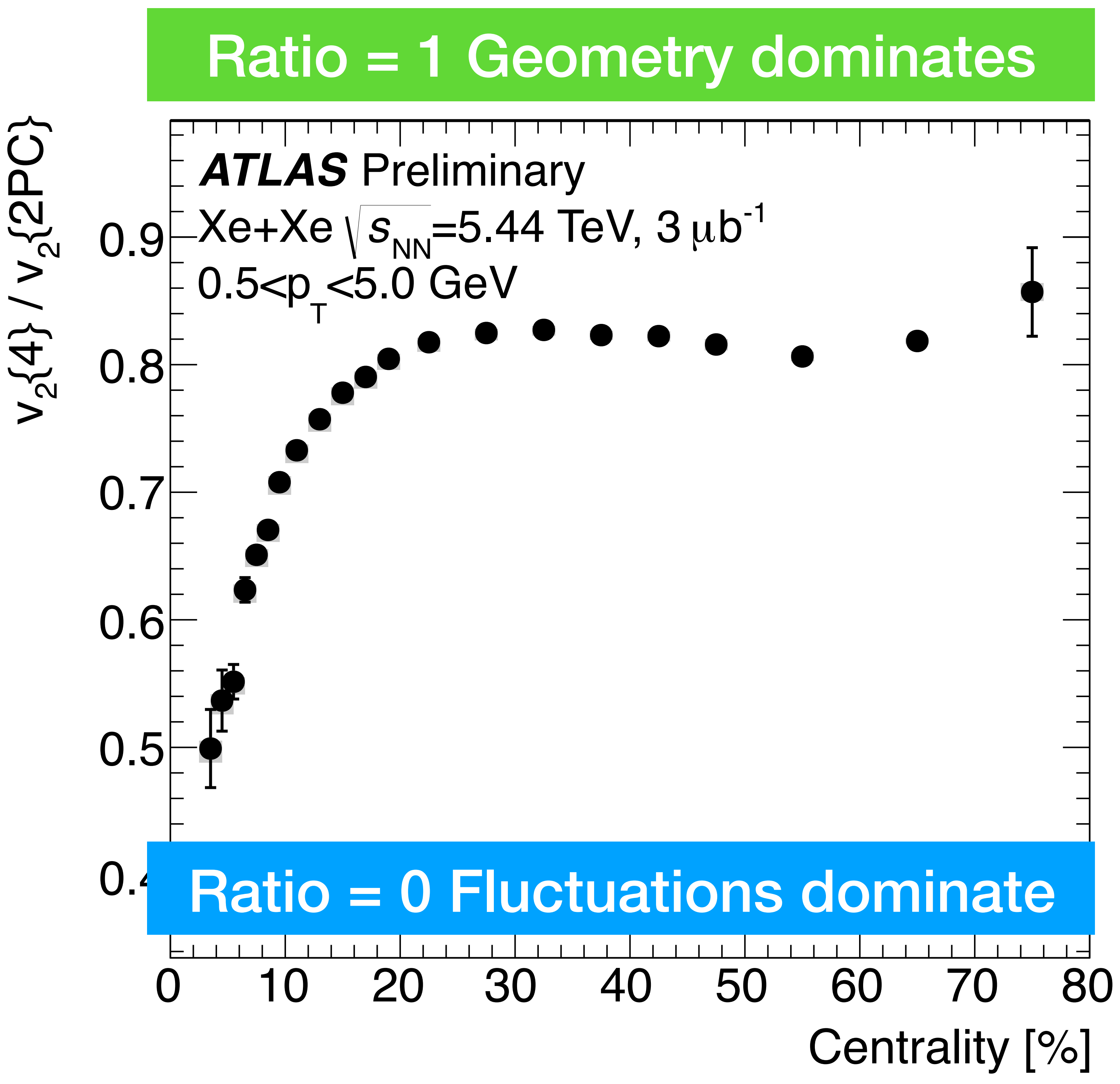


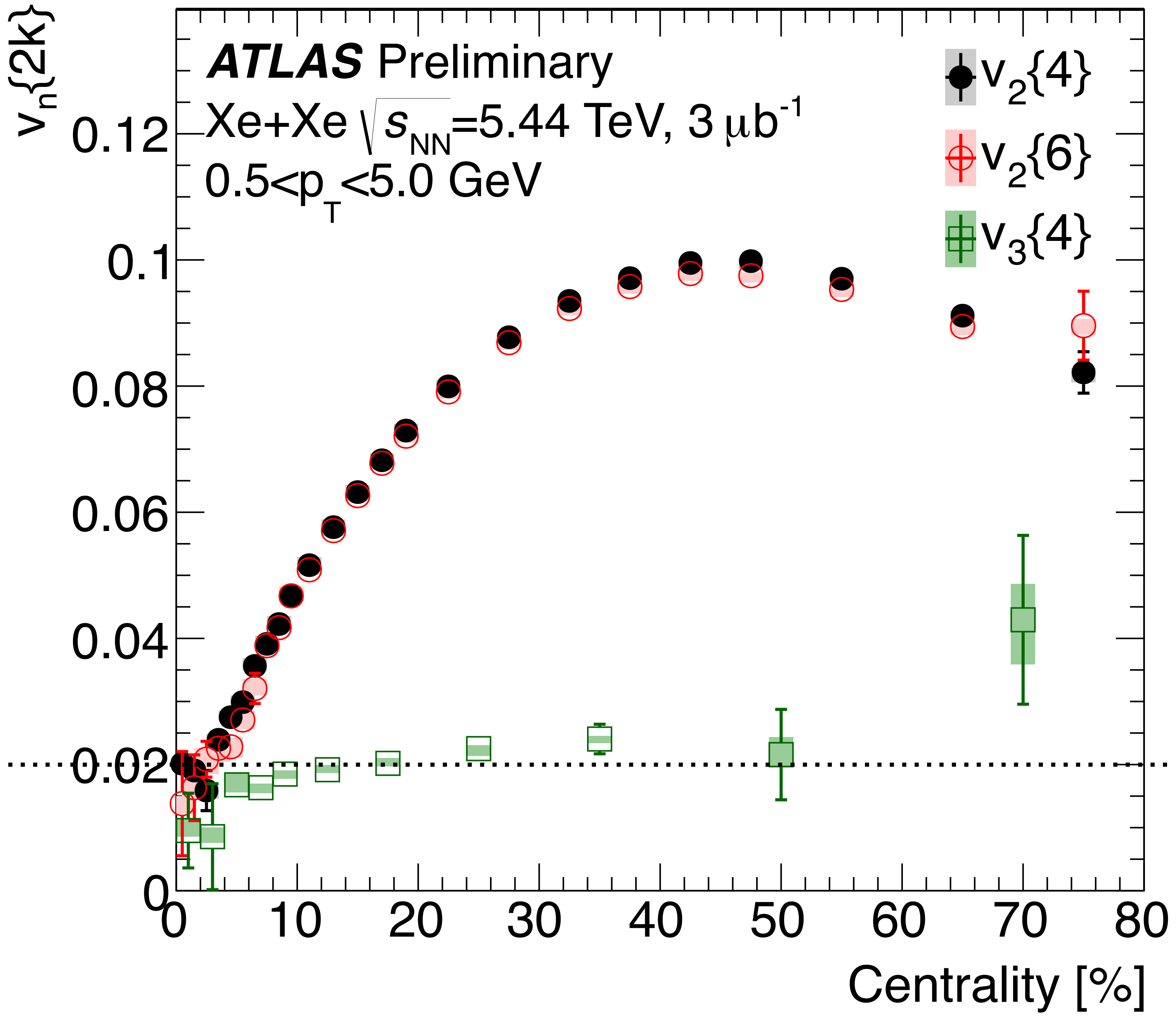
# Flow fluctuations in Xe+Xe

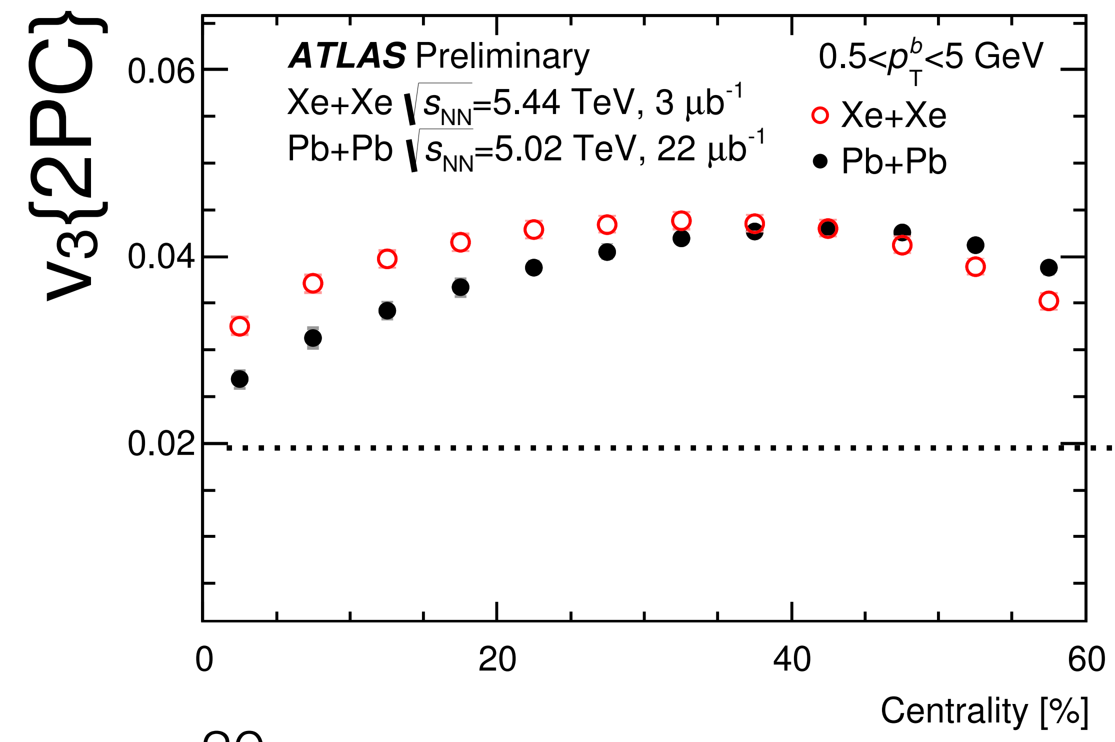
- Comparisons of 2PC/SP to cumulant results:

  $v_2\{2PC/SP\} \gg v_2\{4\}$ (central collisions)

  $v_3\{2PC/SP\} \gg v_3\{4\}$
- Indicate strong flow fluctuations
  - $v_2$ - significant influence of fluctuation
  - $v_3$ - result of fluctuations



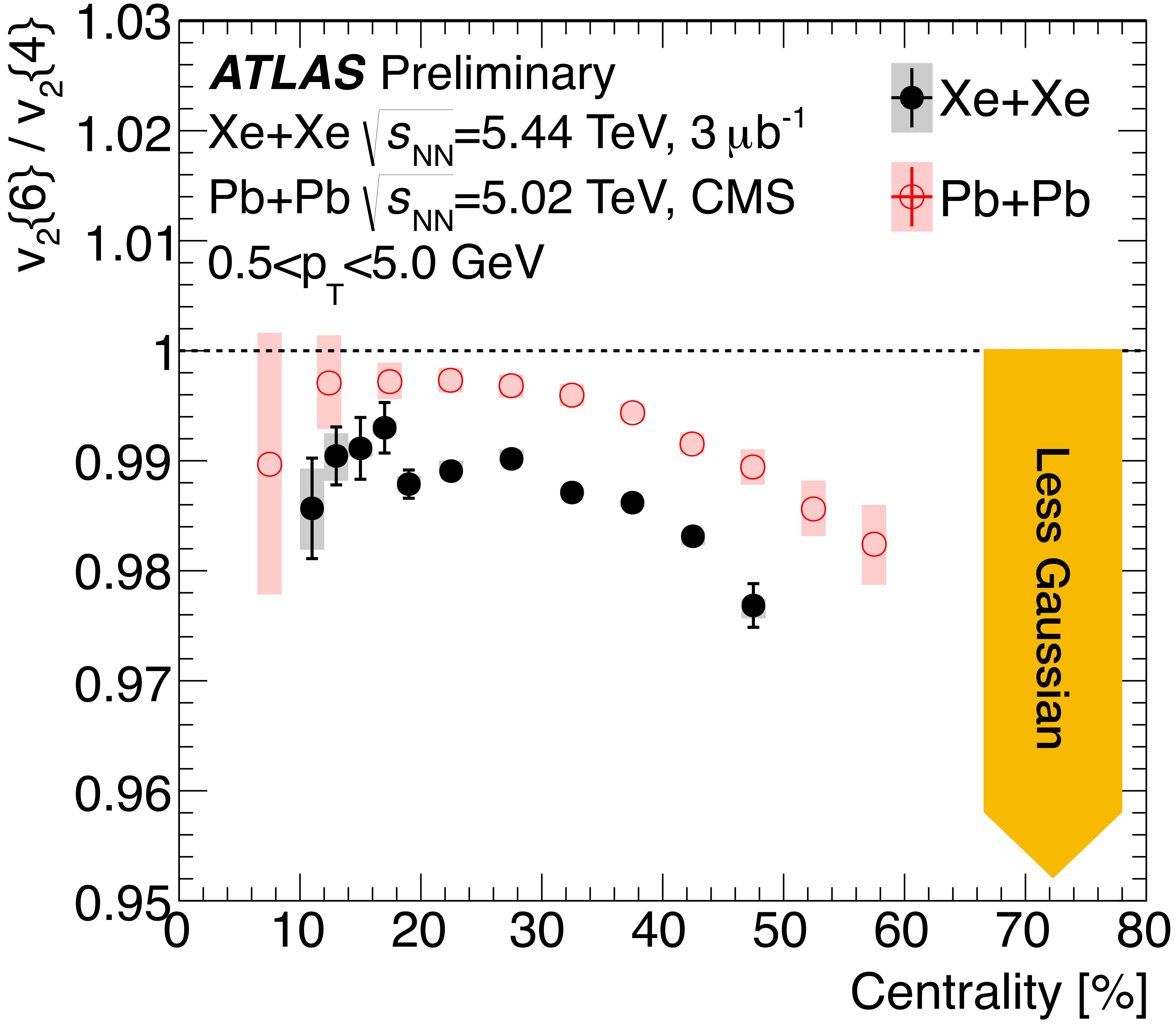
# Flow fluctuations in Xe+Xe and Pb+Pb

- Large number of sources → Gaussian flow fluctuations

$$v_n\{2\} = \sqrt{\bar{v}_n^2 + \delta_n^2},\ v_n\{4\} = v_n\{6\} = \bar{v}_n$$

- Comparison of $v_2\{6\}$ **/** $v_2\{4\}$ allows to check if fluctuations are Gaussian or not

- $v_2\{6\}$ **/** $v_2\{4\} \lesssim 1$ in Xe+Xe smaller than in Pb+Pb
  → less-Gaussian nature of $v_2$ fluctuations



# Conclusions

- Thanks to the excellent ATLAS detector and a rich dataset:
  - Measured flow harmonics up $v_7$ and to a very high $p_\mathrm{T}$ in Pb+Pb
    ATLAS-CONF-2016-105
  - Measured significant correlations of flow harmonics with event mean-$p_\mathrm{T}$ in Pb+Pb
    ATLAS-CONF-2018-008
  - Performed a comprehensive study of flow in Xe+Xe collisions at 5.44 TeV and compared to Pb+Pb at 5.02 TeV
    ATLAS-CONF-2018-011

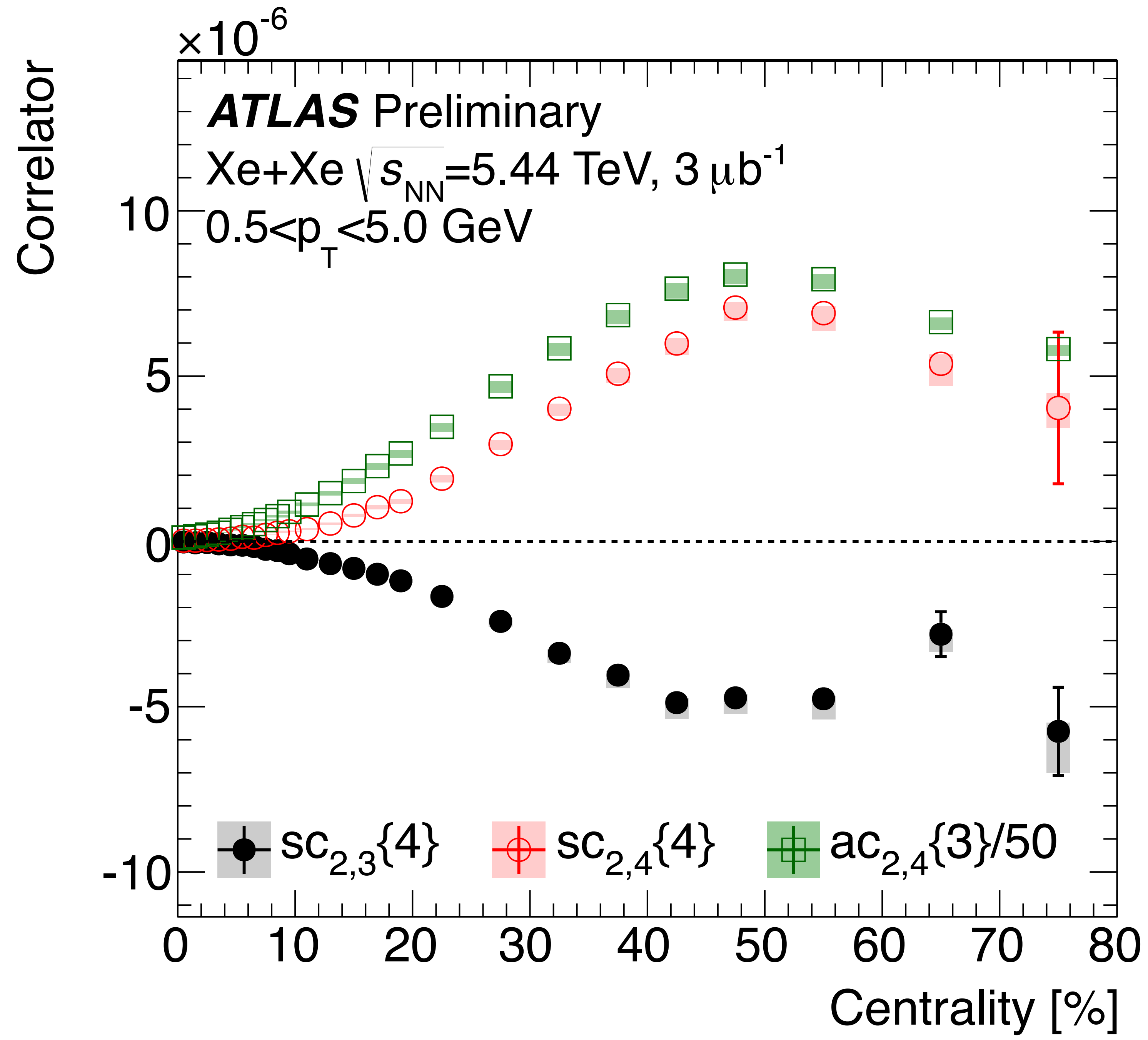
**More on flow measurements in Klaudia Burka's poster**

**More on fluctuations in Minglinag Zhou's talk: 15/05/2018, 15:00**

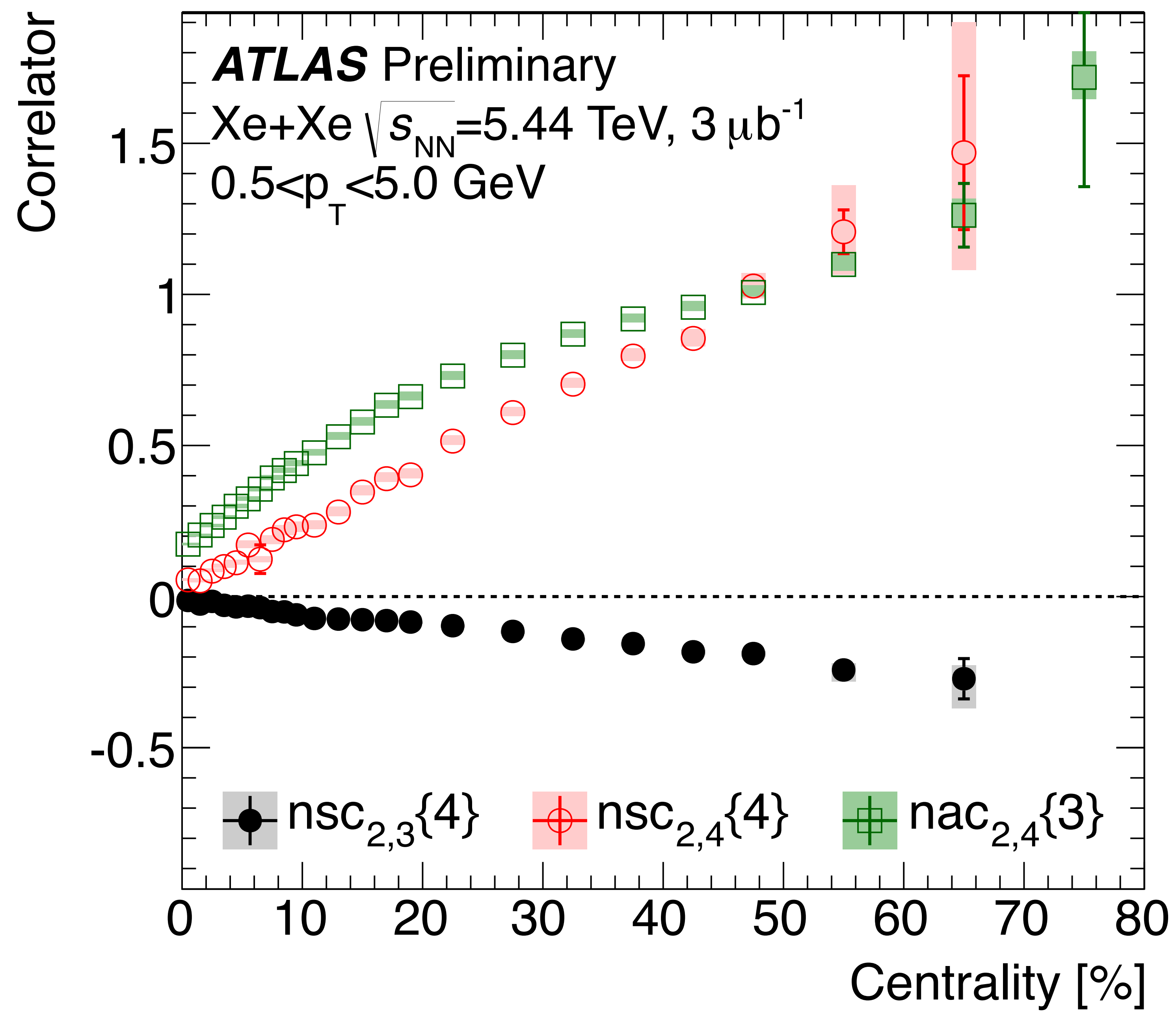
ATLAS EXPERIMENT

# Backups

# (A)-symmetric cumulants




- Detailed checks of correlations through (a)-symmetric and normalised cumulants
  - $v_2$ anti-correlated with $v_3$ ($sc_{2,3}\{4\}$)
  - non-linear $v_2$ correlated with $v_4$ ($sc_{2,4}\{4\}$ & $ac_{2,4}\{3\}$)

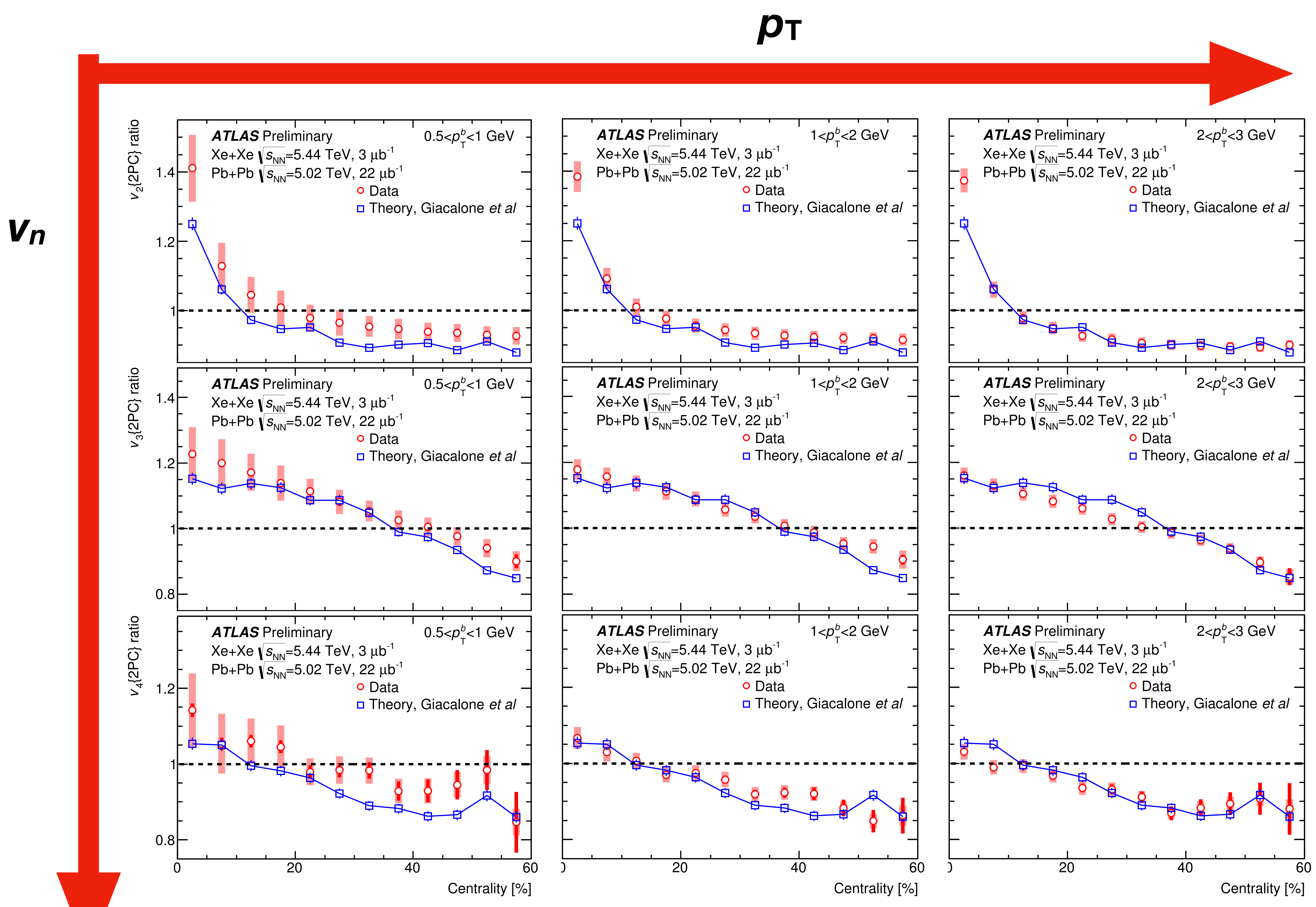


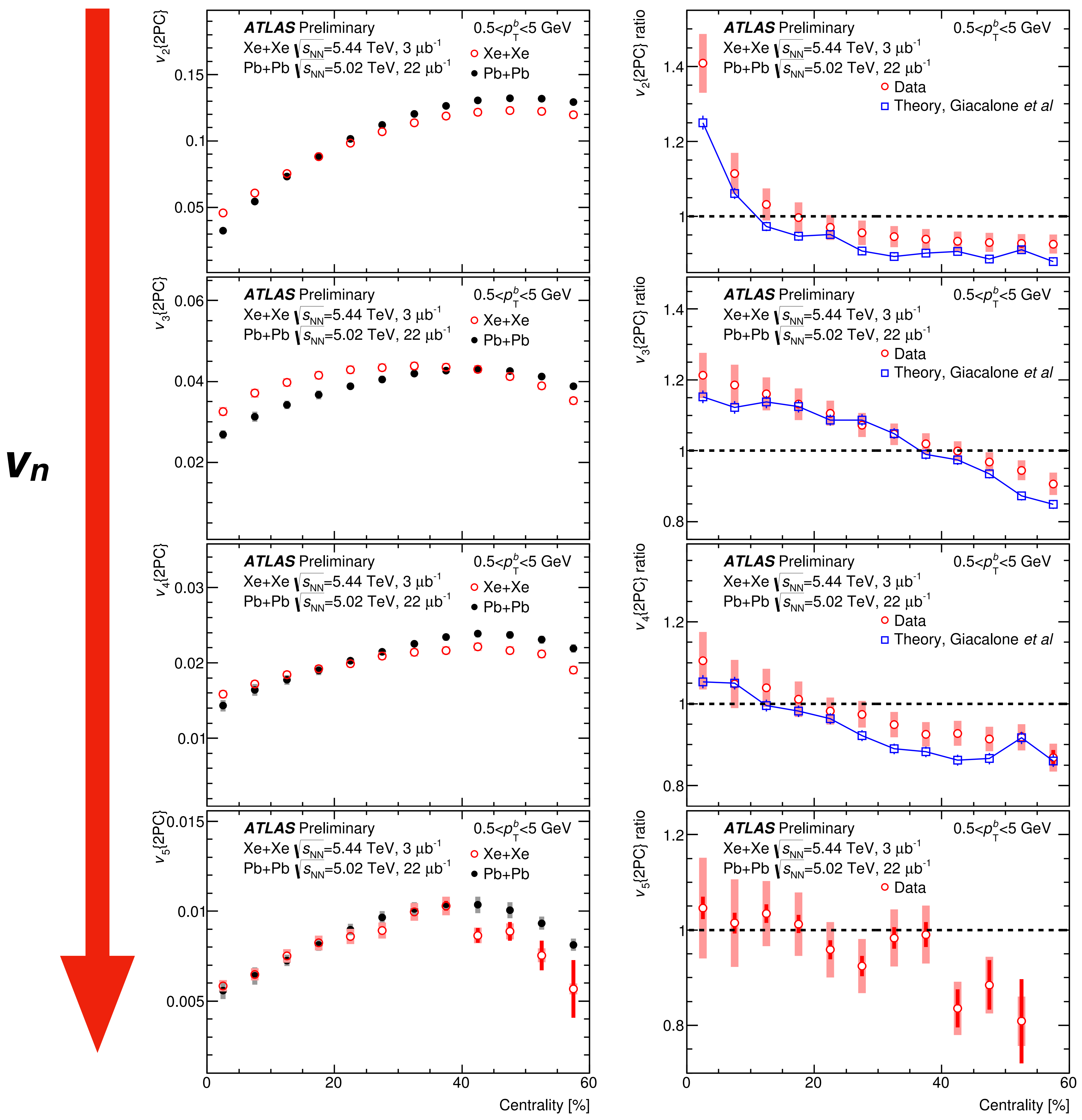
# Xe+Xe flow measurement technologies

- (2,4, and 6) particle and Scalar Product methods
  - 2PC - constructed correlation functions
    in $\Delta\eta$ and $\Delta\phi$ → projected to $\Delta\phi$ → ($\eta$-gap of 2 units)
  - REF $p_T$ range 0.5-5 GeV
  - Fourier analysis
    → di-jets contribution removed by peripheral events subtraction
  - 4/6PC - employed cumulants technology
  - SP - correlated average bearing vectors $Q$ from FCal
    with $q$ vectors from tracks ($\eta$-gap of 3.2)
    → resolution correction
- Integrated quantities weight differential measurement for

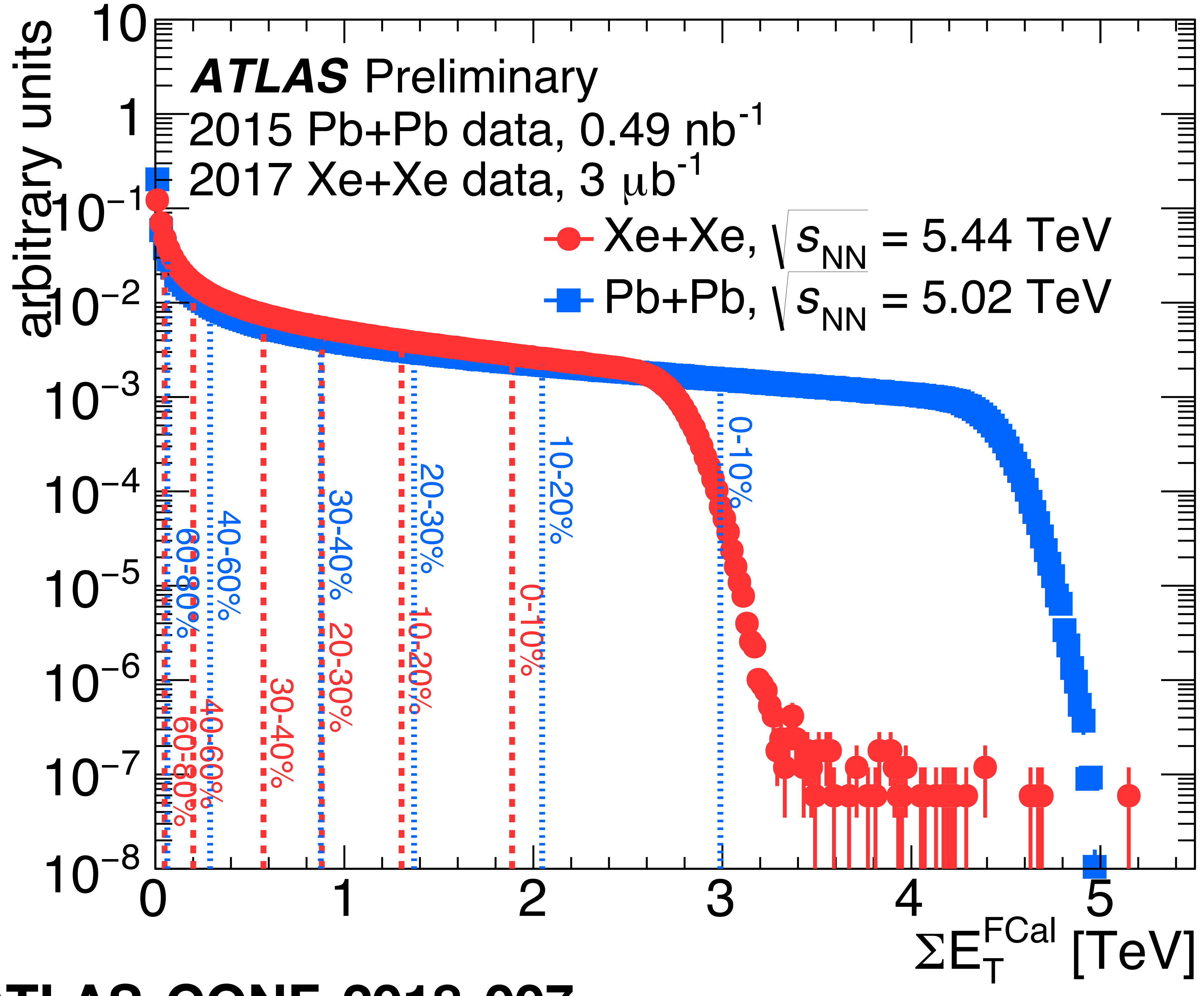
ATLAS EXPERIMENT

# Xe+Xe / Pb+Pb flow harmonics ratio



# Xe+Xe @ 5.44 TeV centrality calibration for QM'18 ATLAS measurements




**ATLAS-CONF-2018-007**

- Characterized with $\Sigma E_T$ in FCal, $|\eta|$ = 3.1-4.9
- Xe-129 nuclear wavefunction from $A^{1/3}$ scaling of Sb-122 Woods-Saxon parameters [1]
  - ➡ alternate descriptions included by systematics [2]
  - ➡ co-dominant $T_{AA}$ uncertainty in 0-50% events
- $\sigma_{NN}$ = 71mb ± 3mb [3]
- Central $T_{AA}$ values from 2CM fit with $x$=0.09
  - ➡ same used for ATLAS Run 1 and Run 2 Pb+Pb
- 82.4% of distribution in range $\Sigma E_T$ > 40 GeV
  - ➡ conservatively free of "non-Glauber" backgrounds
  - ➡ ±1% uncertainty, dominant systematic


[1] "Xes" in v2.4 of PHOBOX MC Glauber

[2] scaling from Xe-132 ("Xe"), reweighed WS in MC Glauber 3.0 ("Xerw")

[3] ATLAS & TOTEM measurements of $\sigma_{tot}$