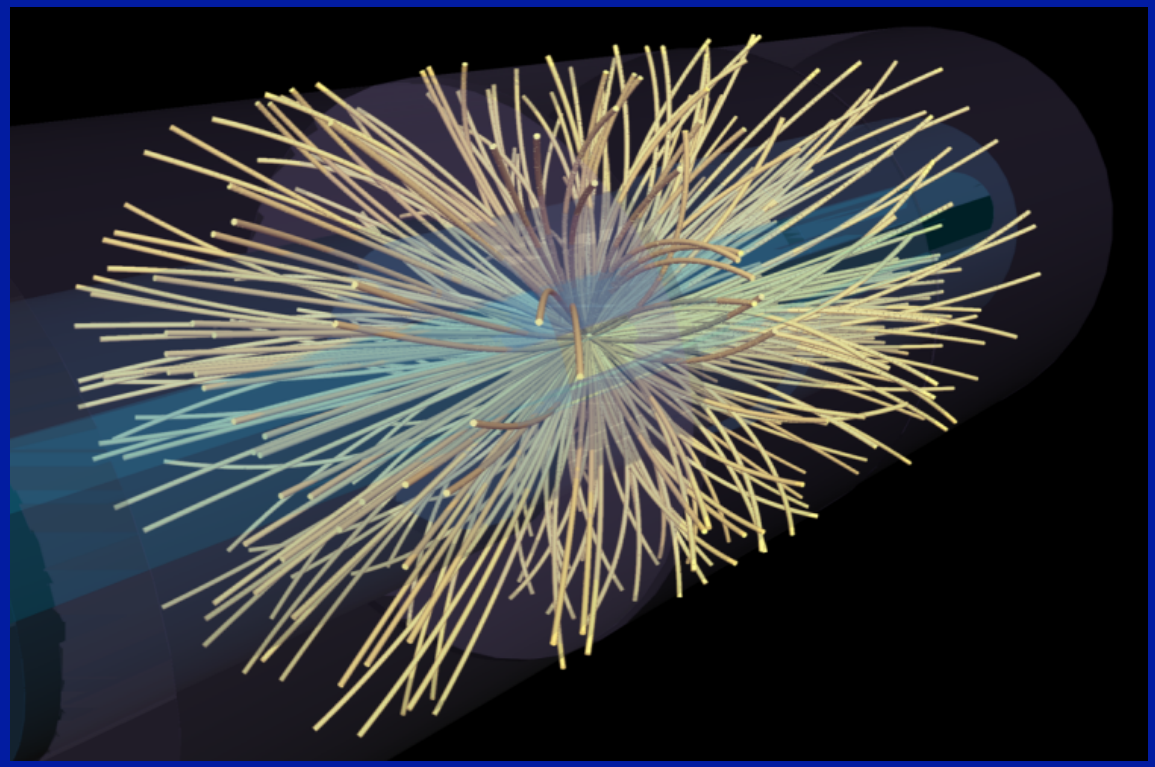
Recent results on flow and correlations from the ATLAS experiment



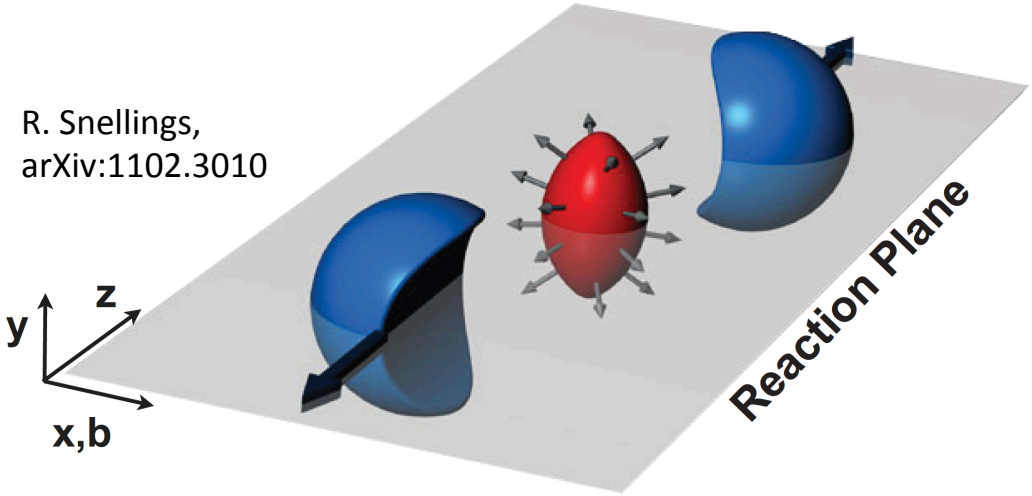
Adam Trzupek on behalf of the ATLAS experiment
Institute of Nuclear Physics PAS, Kraków, Poland

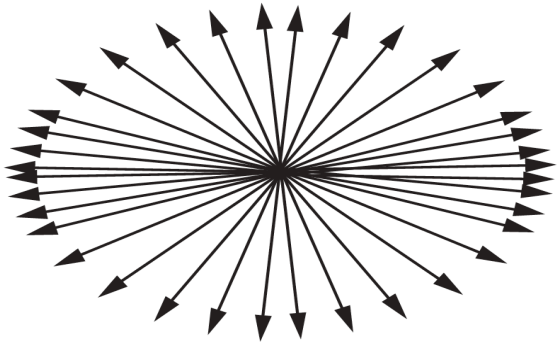
XIII Workshop on Particle Correlations and Femtoscopy, WPCF 2018
Kraków, Poland, May 22-26, 2018

Motivation

- Large azimuthal anisotropy observed at RHIC and the LHC is one of the main signatures of quark-gluon plasma (QGP) formed in heavy-ion collisions

R. Snellings, arXiv:1102.3010





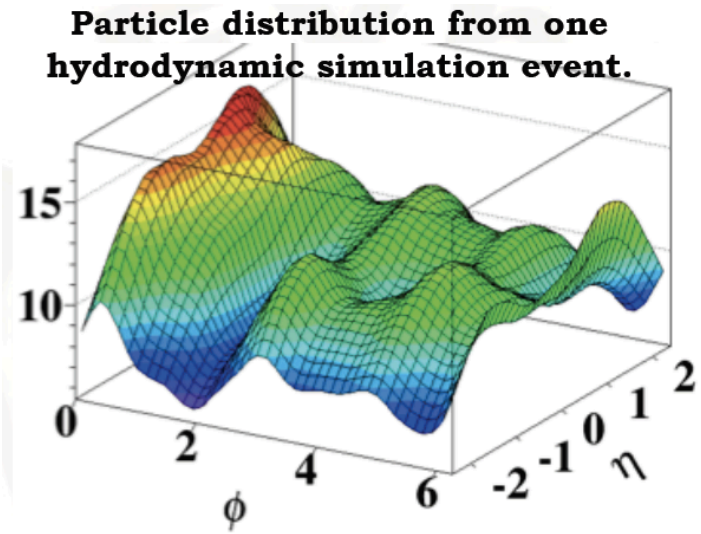
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$

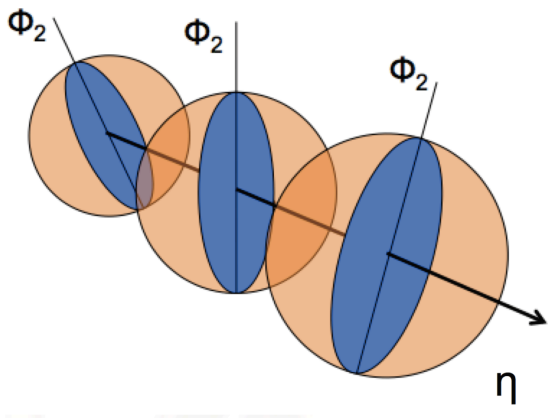
Flow harmonics

Azimuthal anisotropy is "driven" by asymmetry in initial geometry

- Space–time evolution of QGP described by hydrodynamic models
  - Transport parameters (viscosity, η/s ,..)
  - Equation of state (EOS) – nonlinearities
- QGP dynamics is constrained by flow harmonics and their correlations

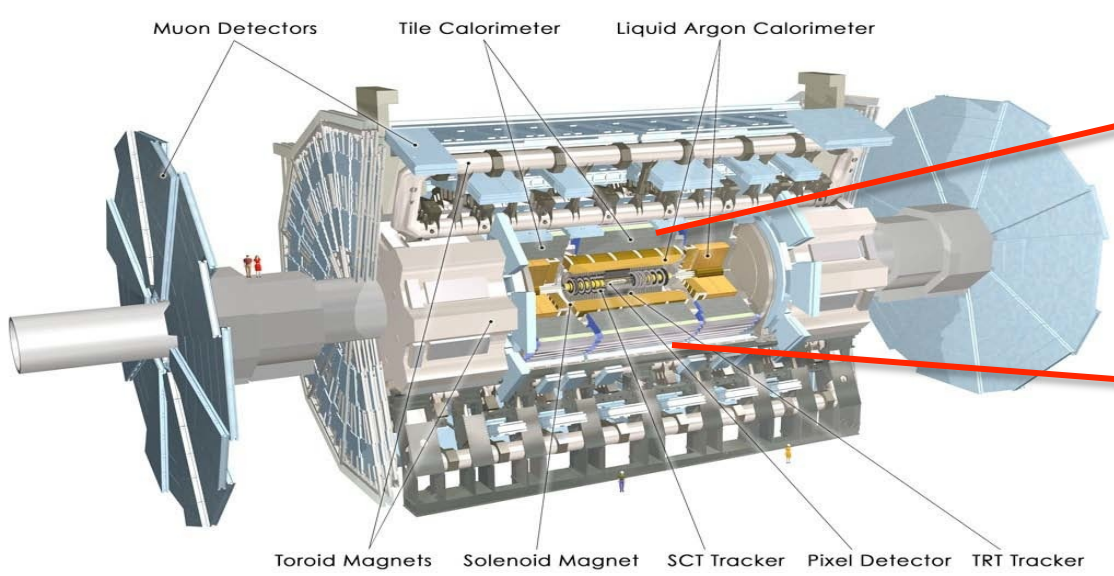
Recent ATLAS azimuthal flow measurements

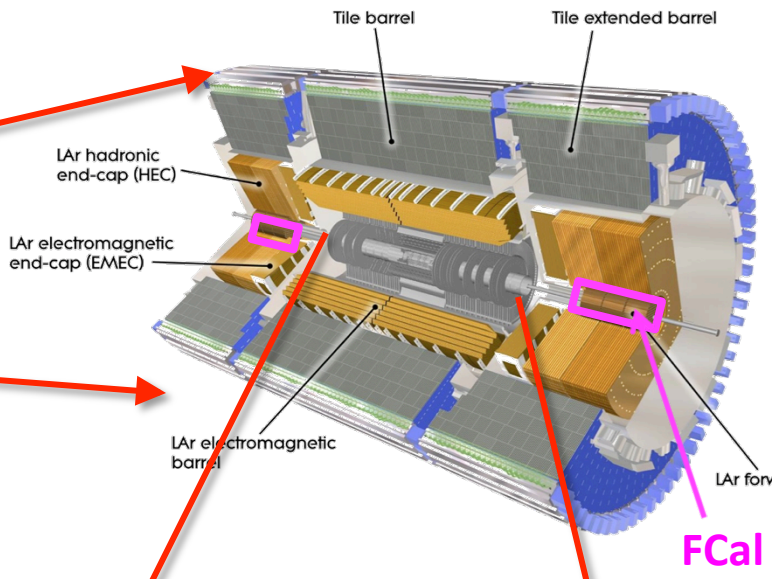




- Flow harmonics from multi-particle correlations in 5.44 TeV Xe+Xe and 5.02 TeV Pb+Pb collisions
  ATLAS-CONF-2018-011
- Flow decorrelations in 2.76 TeV and 5.02 TeV Pb+Pb collisions
  ATLAS, Eur. Phys. J. C 76 (2018) 142
- v_n – mean p_T correlations in 5.02 TeV Pb+Pb collisions
  ATLAS-CONF-2018-008

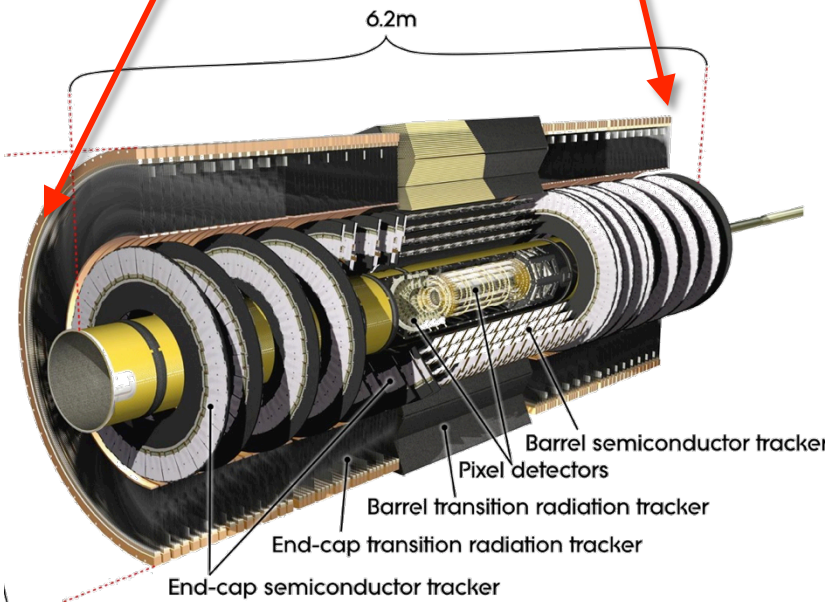
ATLAS Detector





Three main subsystems:

- Inner Detector (ID)–tracking |η|<2.5
- Calorimetry – |η|<4.9
  - FCal 3.1<|η|<4.9
- Muon Spectrometer - |η|<2.7



Fast trigger systems:

- Level 1 (L1)
- High Level Trigger (HLT)

$v_n\{4\}$ (n=2,3) harmonics – p_T dependence

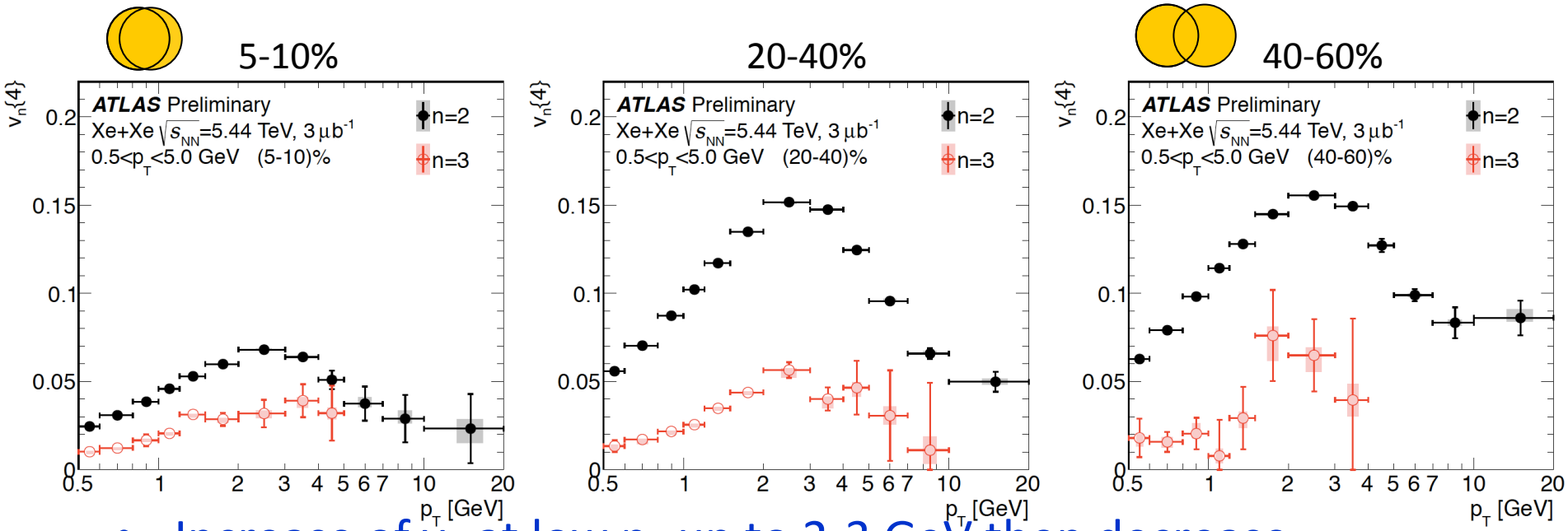
- Recently ATLAS has measured v_n using multiparticle correlations in 5.44 TeV Xe+Xe and 5.02 TeV Pb+Pb collisions

$$\left\langle corr_n\{2k\}\right\rangle \equiv \left\langle \cos[n(\varphi_1 + \ldots - \varphi_{k+1} - \ldots.)]\right\rangle = \left\langle v_n^{2k}\right\rangle$$

- Using cumulants suppresses "non-flow" correlations, e.g.

$$c_n\{4\} = \left\langle\left\langle corr_n\{4\}\right\rangle\right\rangle - 2\left\langle\left\langle corr_n\{2\}\right\rangle\right\rangle^2 \qquad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

negative



- Increase of v_n at low p_T up to 2-3 GeV then decrease
- v_2 strongly depends on centrality interval (≠0 at high p_T)
- v_3 only weakly depends on centrality

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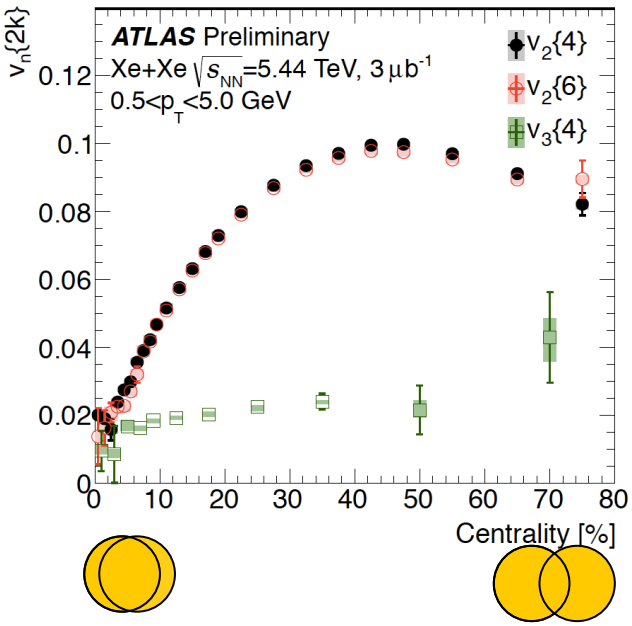
Event-by-Event v_n fluctuations

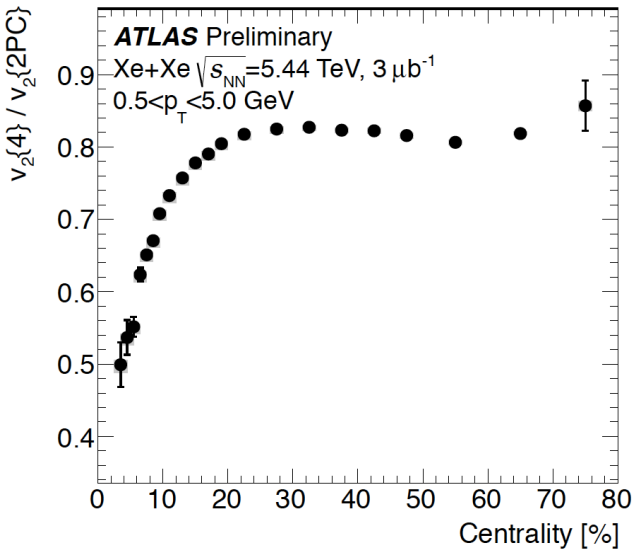
Comparison of $v_2\{4\}$ to $v_2\{2PC\}$ and $v_2\{6\}$

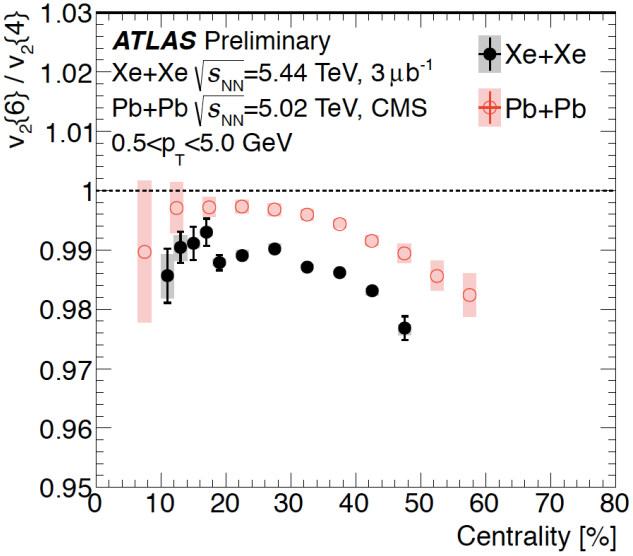
$$v^2_2\{2\} = \langle v_2 \rangle^2 + \sigma^2_v$$

$$v^2_2\{4\} \approx \langle v_2 \rangle^2 - \sigma^2_v$$

Gaussian fluct. → $v_2\{2\} > v_2\{4\} = v_2\{6\}$







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- $v_2\{4\}/v_2\{2PC\} \approx 0.5$ -0.7 for Xe+Xe collisions
  - Significant fluctuations in initial geometry (PRL 112 (2014) 082301)
- For Xe+Xe collisions $v_2\{6\}/v_2\{4\}$, ~ 0.98-0.99 and smaller than for Pb+Pb collisions → $p(v_n)$ not fully described by Gaussian function

$c_n\{4\}$ cumulants in Xe+Xe and Pb+Pb collisions

$$c_n\{4\} = \langle\langle corr_n\{4\}\rangle\rangle - 2\langle\langle corr_n\{2\}\rangle\rangle^2 \qquad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

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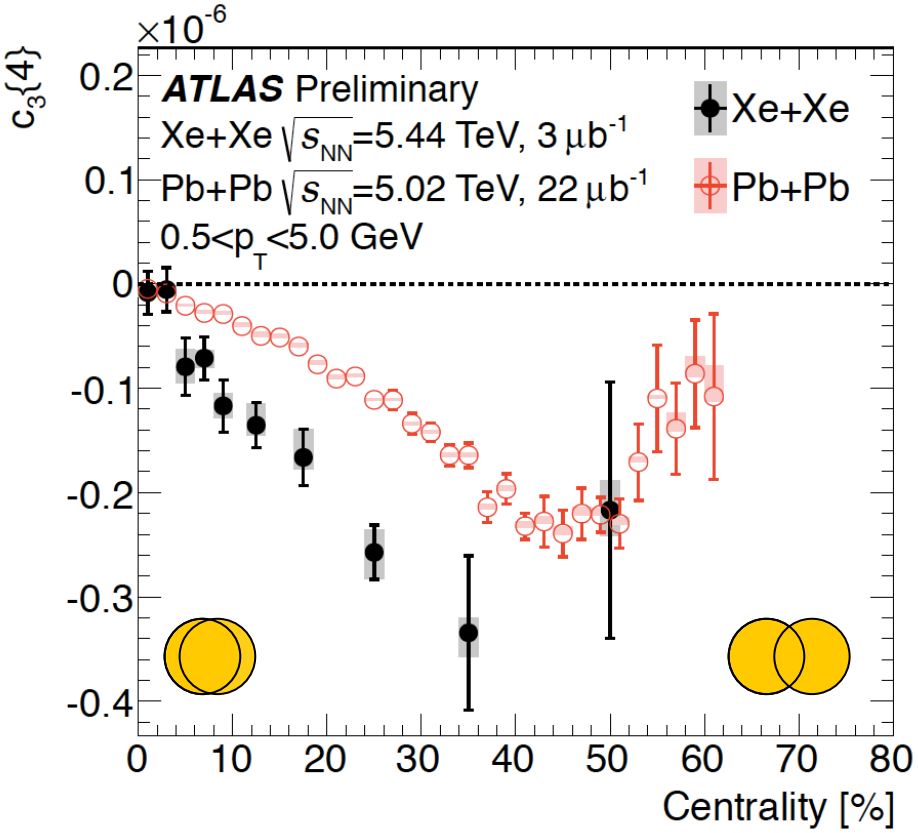
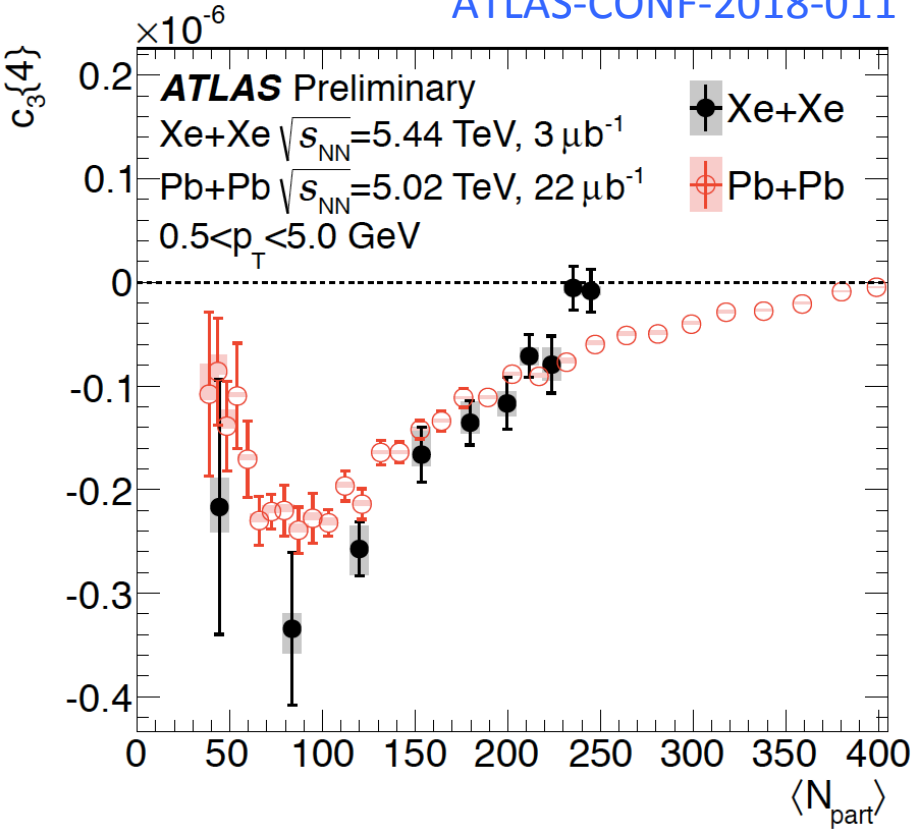




- $c_3\{4\}$ scale better with N_{part}
  - Fluctuations driven by # of sources
- Similar scaling is observed for $c_4\{4\}$

Symmetric and asymmetric cumulants

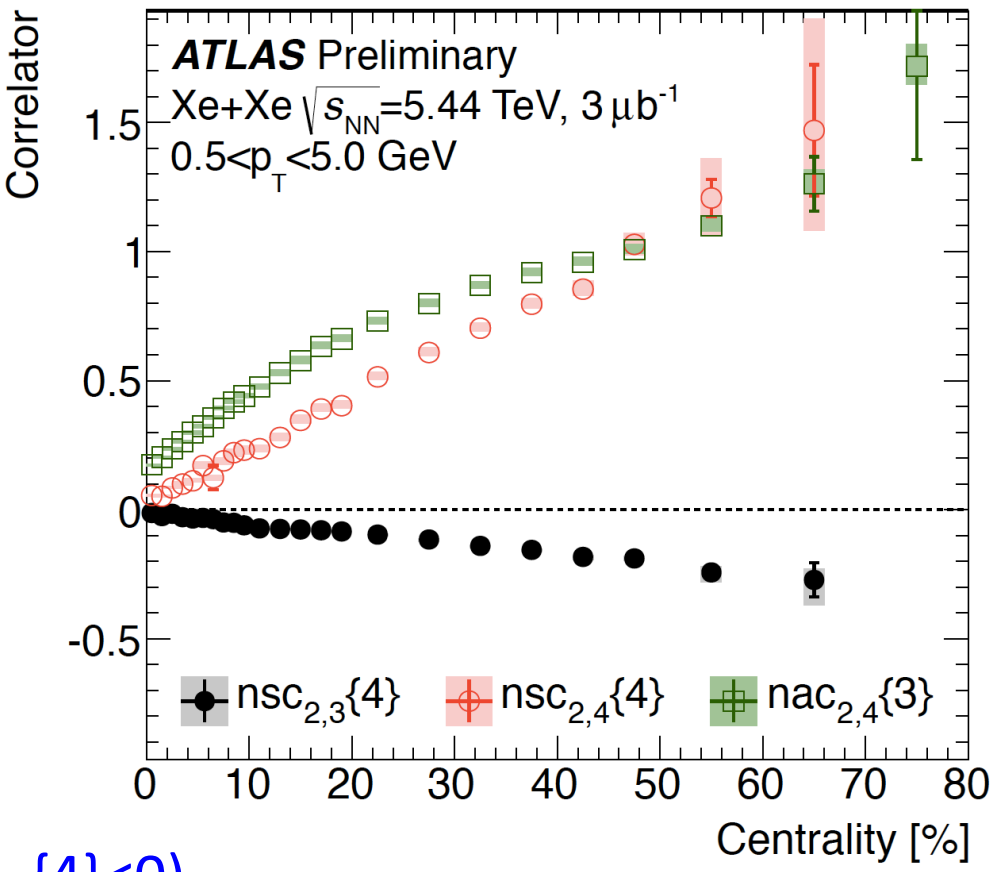
- Study correlations v_2-v_3 and v_2-v_4 through symmetric cumulants

$$sc_{n,m}\{4\} = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

- Asymmetric cumulants used to study v_2-v_4

$$ac_{2,4} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle$$

- Cumulants normalised by corresponding $\langle v_n^2 \rangle$



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- v_2 anti-correlated with v_3 (nsc$_{2,3}${4}<0)
- non-linear v_2 correlated with v_4 (nsc$_{2,4}${4} & nac$_{2,4}${3}>0)

Measurement of flow decorrelation

- Flow vectors measured with charged particle tracks over $|\eta| < 2.5$

$$\boldsymbol{q}_n \equiv \frac{\sum_i w_i e^{in\phi_i}}{\sum_i w_i}$$

Flow vector defines event plane angle Φ_n

At forward rapidity reference flow vector measured from the energy deposits in FCal calorimeter towers, $|\eta_{ref}| > 4$

- The decorrelation between flow vectors (harmonics) is measured at $-\eta$ and η with respect to η_{ref} with correlator Eur. Phys. J. C 76 (2018) 142

$$r_{n|n;k}(\eta) = \frac{\left\langle \boldsymbol{q}_n^k(-\eta)\boldsymbol{q}_n^{*k}(\eta_{\mathrm{ref}})\right\rangle}{\left\langle \boldsymbol{q}_n^k(\eta)\boldsymbol{q}_n^{*k}(\eta_{\mathrm{ref}})\right\rangle}$$

- r is sensitive to breakdown of the factorization of two-particle flow harmonics into single-particle flow harmonics
  - w/o decorrelation: $r = 1$

Elliptic flow de-corelations in Pb+Pb collisions

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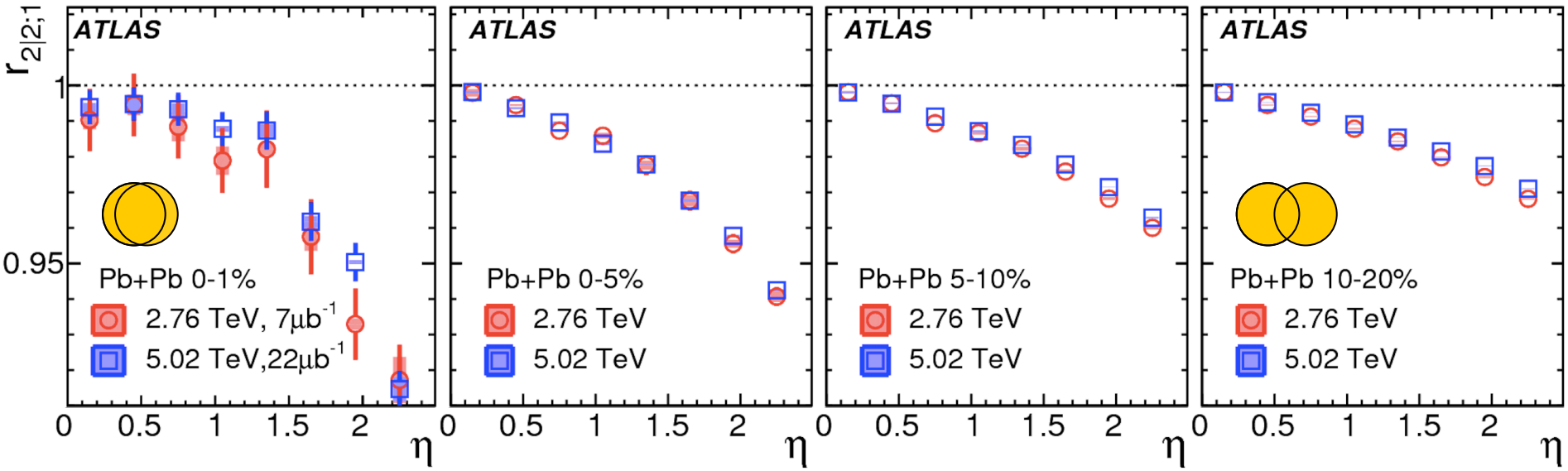

- $r_{2|2;1}$ show significant magnitude of decorrelation (r<1)
- $r_{2|2;1}$ show a linear decrease with η - except in the most central collisions

$$r_{n|n;k}(\eta) \approx 1 - 2F^{\mathrm{r}}_{n;k}\eta$$

- Linear decrease of $r_{n|n;1}$ with η also observed for n = 3 & 4

Centrality and energy dependence of flow decorrelation

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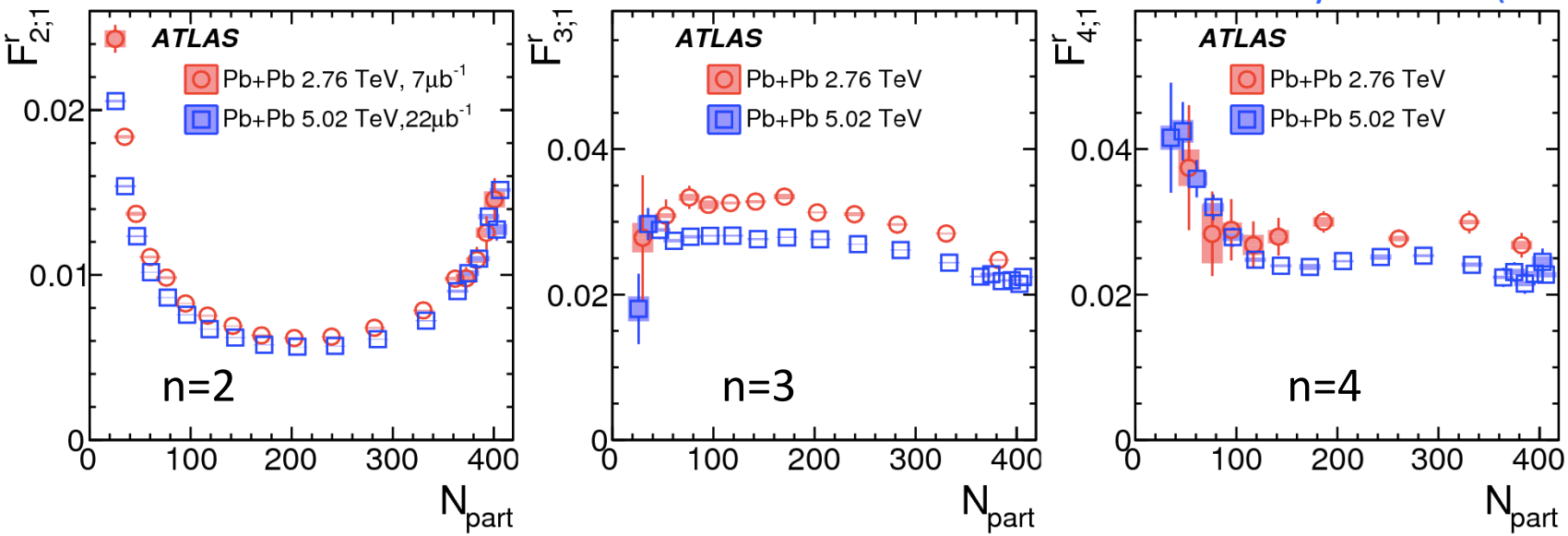
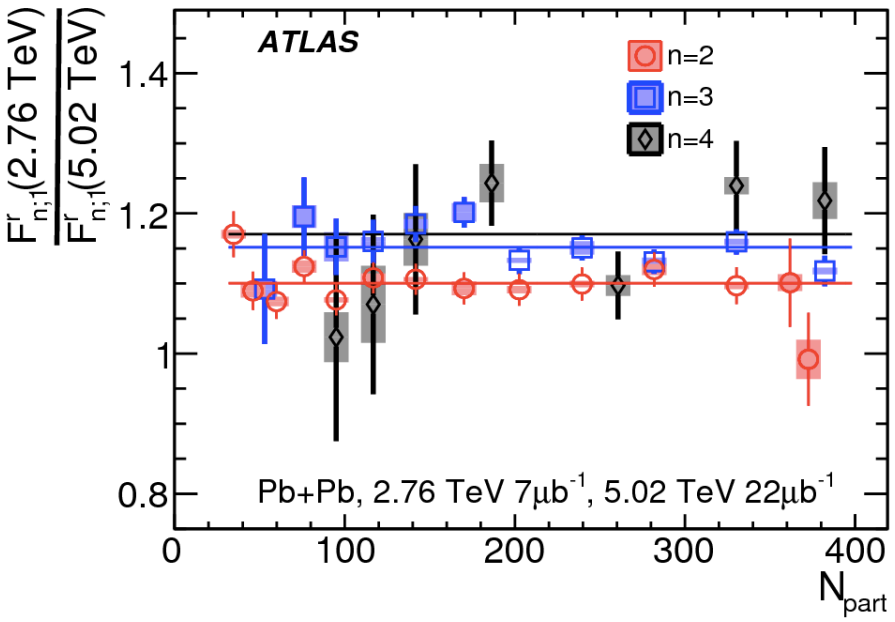


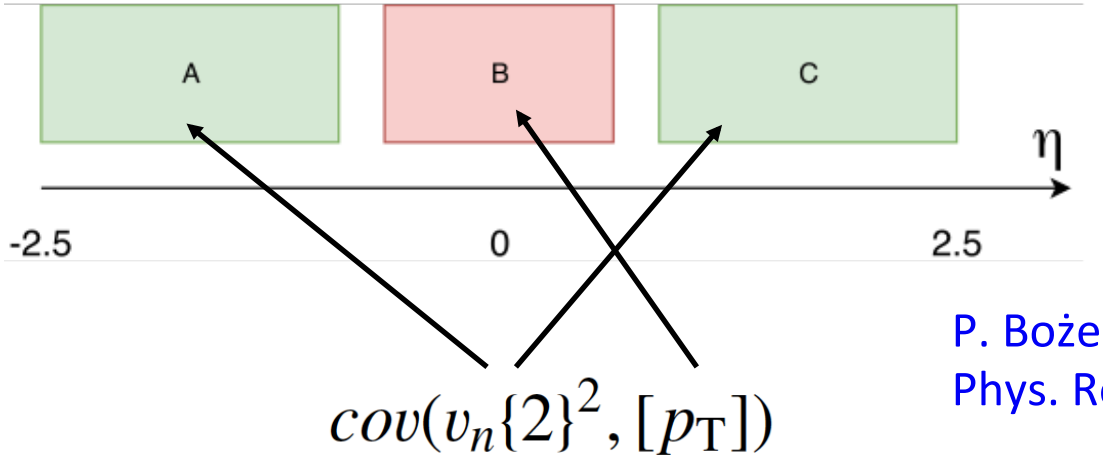


- Decreasing trend is the weakest around the 20-30% centrality range
- For v_3 and v_4 decorrelation is approximately independent of N_{part}
- Slopes for higher order harmonics are significantly larger than for n=2
- Decorrelation is 10-20% stronger in 2.76 TeV than in 5.02 TeV Pb+Pb

v_n- mean p_T correlations in 5.02 TeV Pb+Pb collisions

$$\rho = \frac{cov(v_n\{2\}^2, [p_T])}{\sqrt{var(v_n\{2\}^2)_{dyn}}\sqrt{c_k}}$$

The modified Pearson's coefficient



event mean p_T

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

P. Bożek,
Phys. Rev. C93 (2016) 044908

Dynamical (physical) v_n^2 fluctuations, var_{dyn} EPJ. C74 (2014) 3157

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

Dynamical mean transverse momentum fluctuations PRC 72 (2005) 044902

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

$\langle\rangle$ - denotes averaging over events

Covariance $cov(v_n^2,[p_T])$

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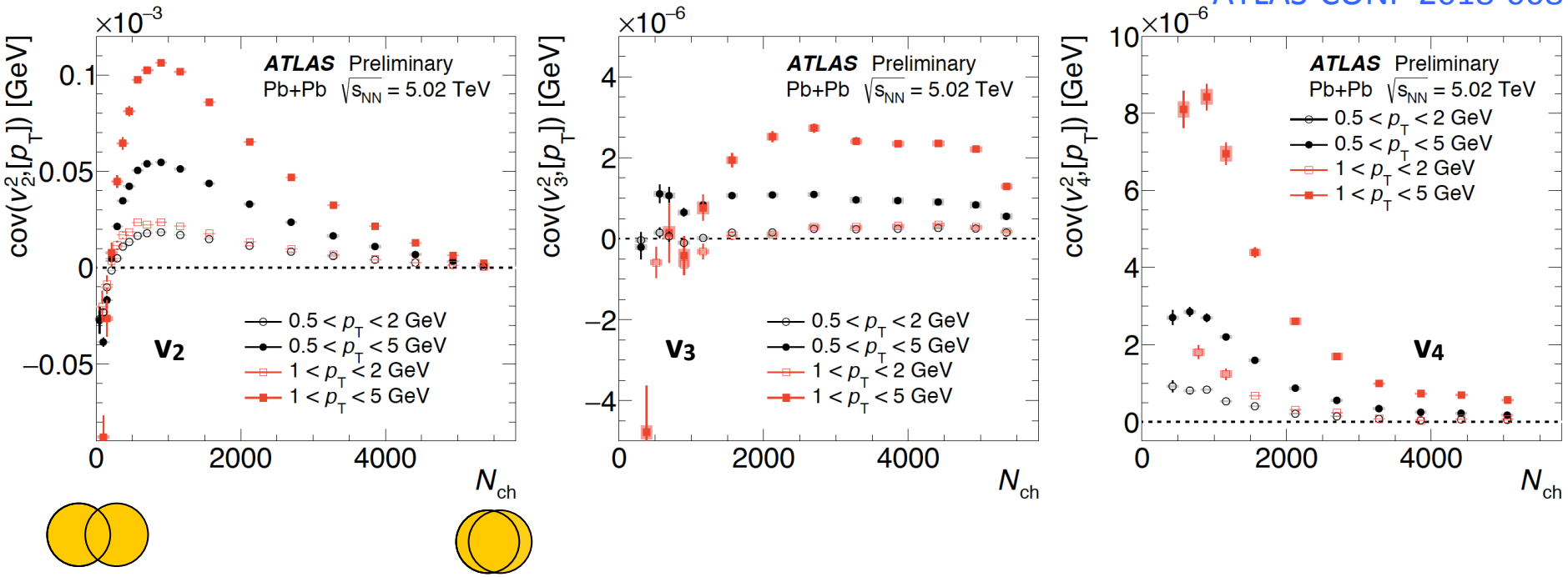

- Covariance $cov(v_n^2,[p_T])$ obtained in 4 p_T ranges
- A rapid increase with N_{ch} from negative value in peripheral events is observed for $cov(v_2^2,[p_T])$
- The $cov(v_3^2,[p_T])$ is weakly changing with N_{ch}
- The N_{ch}-dependence of $cov(v_4^2,[p_T])$ is similar to $cov(v_2^2,[p_T])$

Dynamical transverse momentum and v_n^2 fluctuations

- c_k decreases with increasing N_{ch}
- $Var(v_n^2)$ after an increase with N_{ch} at low multiplicity, a maximum is reached. For higher N_{ch} a decrease is observed - similar dependence to v_n vs N_{ch}

$$var(v_2\{2\}^2)_{dyn} > var(v_3\{2\}^2)_{dyn} > var(v_4\{2\}^2)_{dyn}$$

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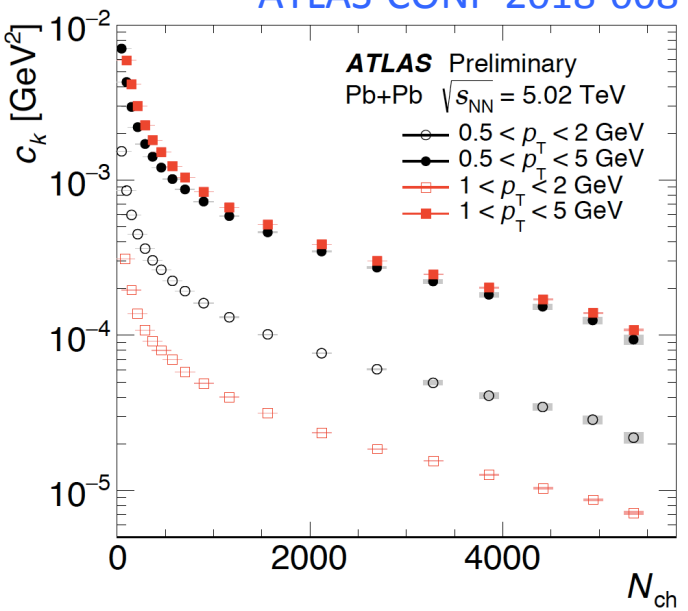

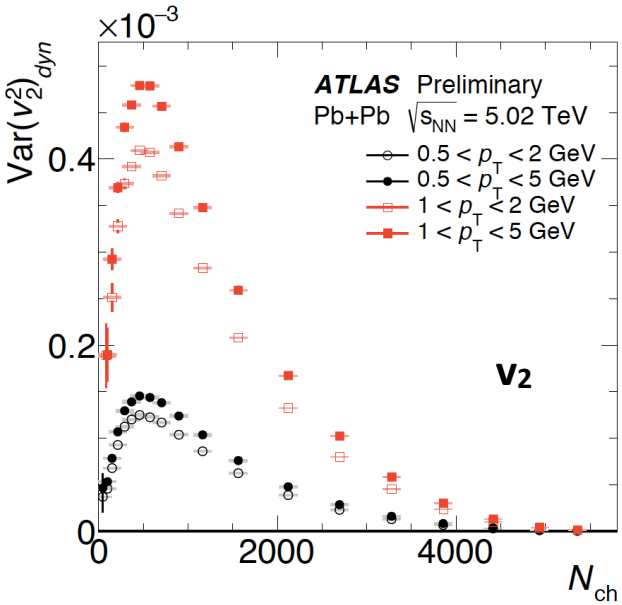

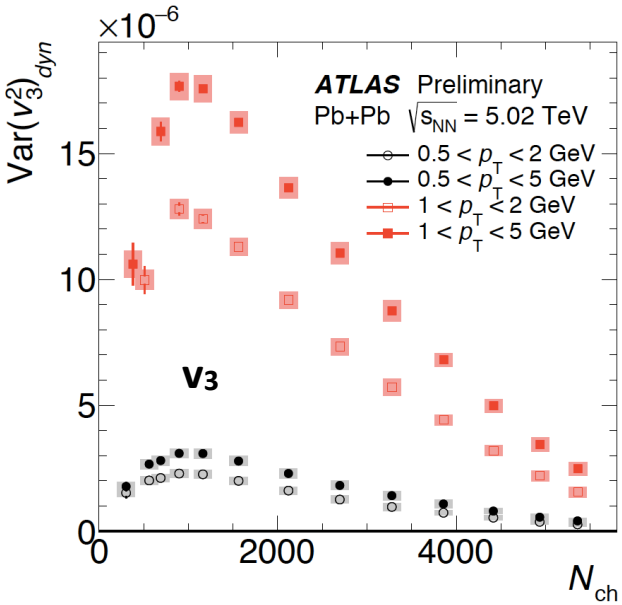

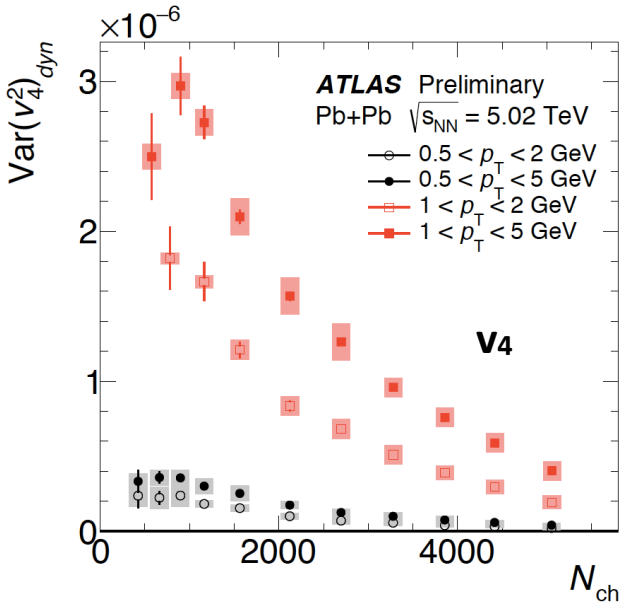

The modified Pearson's coefficient (N_{part})

$$\rho = \frac{cov(v_n\{2\}^2, [p_T])}{\sqrt{var(v_n\{2\}^2)_{dyn}}\sqrt{c_k}}$$

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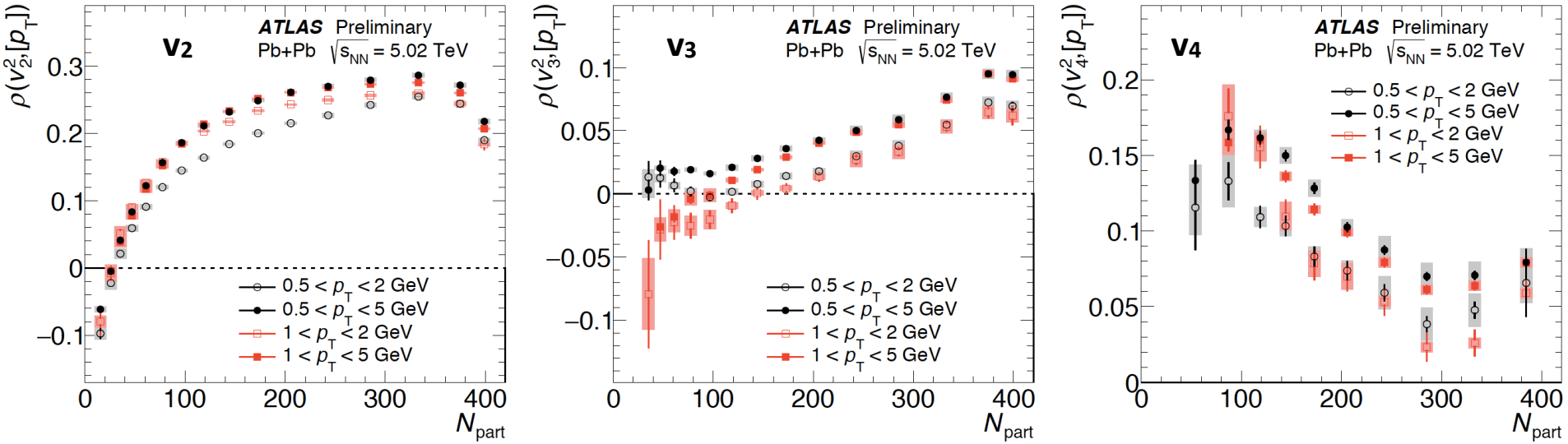

- For v_2: negative at low N_{part}, then rapid rise with maximum $\rho(320) \sim 0.25$ and fall in the most central collisions
- For v_3: values are much lower than for v_2, also low/or negative at low N_{part} , above N_{part}>100 a weak rise
- For v_4: significant positive correlations at low N_{part} then decrease with N_{part} and slow increase for N_{part} > 300

Theory comparison

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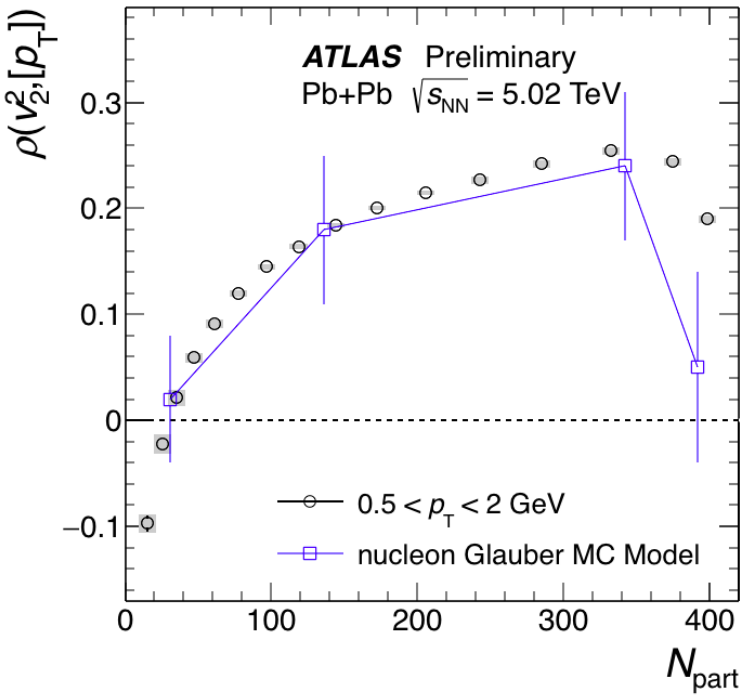
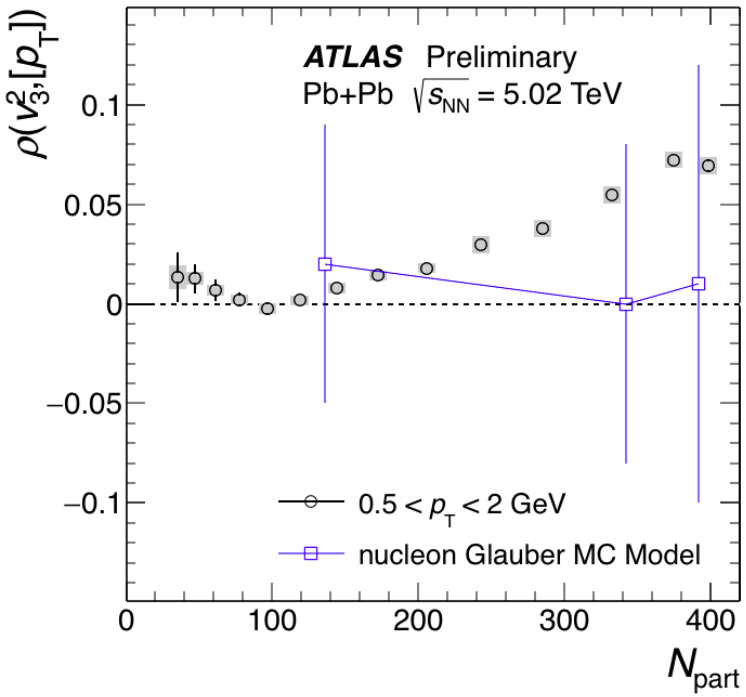




- Comparison of ρ for v_2 and v_3 from hydro simulation of the nucleon Glauber MC model for one p_T interval: 0.5-2 GeV
- Predictions for ρ for v_2 and v_3 consistent with data. Experimental results have much better precision

Summary

- Significant flow harmonics fluctuations observed in 5.44 TeV Xe+Xe and in 5.02 TeV Pb+Pb collisions
  - Results indicate almost Gaussian fluctuations, largest in central collisions and "driven" by fluctuations in initial geometry
- Four-particle symmetric cumulants $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ show negative/positive correlations between v_2-v_3/v_2-v_4
- The magnitude of flow decorrelation increases linearly with the rapidity separation between two particles
- Significant values of modified Pearson's correlation coefficients ρ between $v_n\{2\}^2$ and $[p_T]$ in 5.02 TeV Pb+Pb collisions were measured
  - For peripheral collisions ρ for v_2 is negative. For other centralities the coefficient is positive and dominant
  - The ρ for v_4 shows non-monotonic behaviour with N_{part}
- Hydrodynamic model predictions are consistent with measured ρ for v_2

Backup

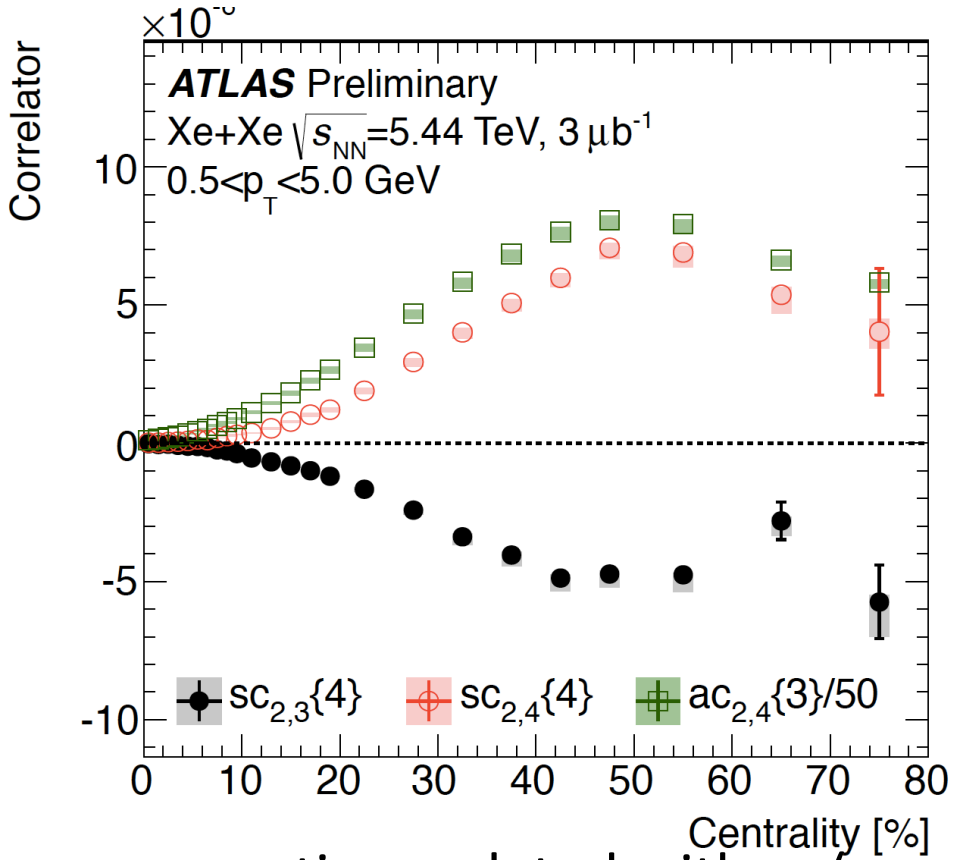
Symmetric and asymmetric cumulants

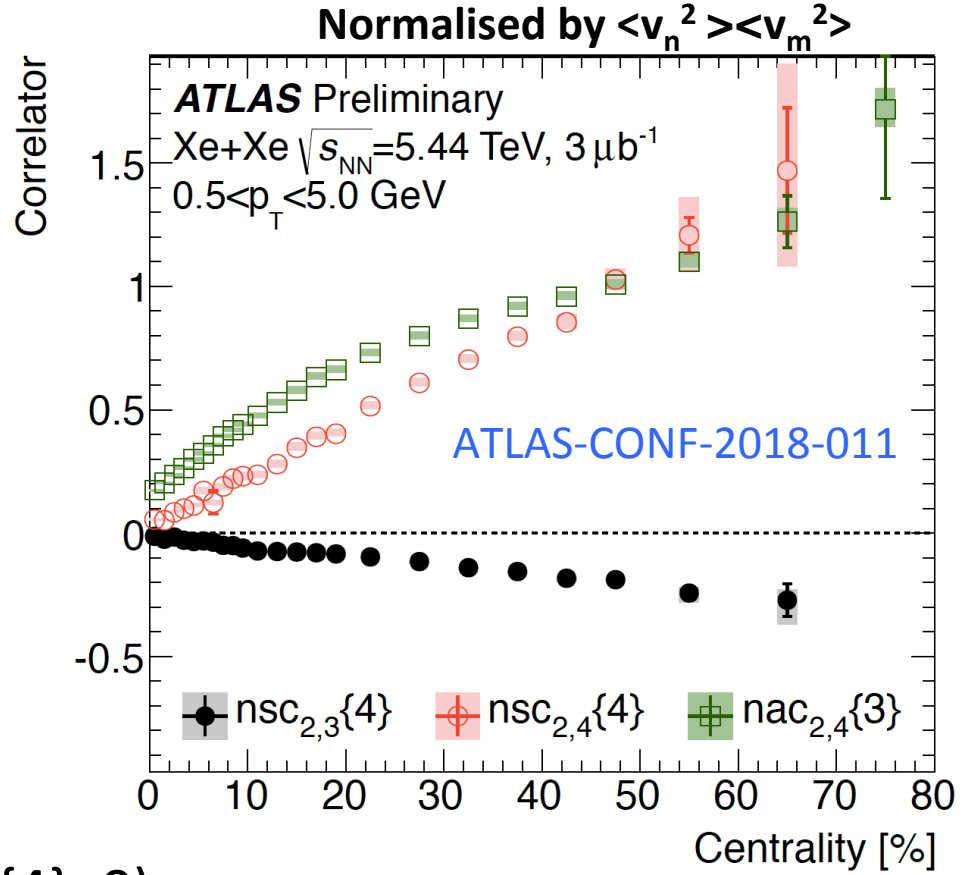
Study correlations v_2-v_3 and v_2-v_4 through (a)symmetric cumulants

$$sc_{n,m}\{4\} = \langle corr_{n,m}\{4\}\rangle - \langle corr_n\{2\}\rangle\langle corr_m\{2\}\rangle = \langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle$$

$$\langle corr_{n,m}\{4\}\rangle = \langle\langle \cos(m\phi_1 + n\phi_2 - m\phi_3 - n\phi_4)\rangle\rangle$$

$$ac_{n,2n}\{3\} = \langle corr_{n,2n}\{3\}\rangle$$





- v_2 anti-correlated with v_3 ($sc_{2,3}\{4\}<0$)
- non-linear v_2 correlated with v_4 ($sc_{2,4}\{4\}$ & $ac_{2,4}\{3\}>0$)