Measurements of multi-particle correlations and collective flow with the ATLAS detector

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on behalf of the ATLAS Collaboration

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Correlation measurements in ATLAS experiment

- Detailed measurements of correlations in the Pb-Pb system

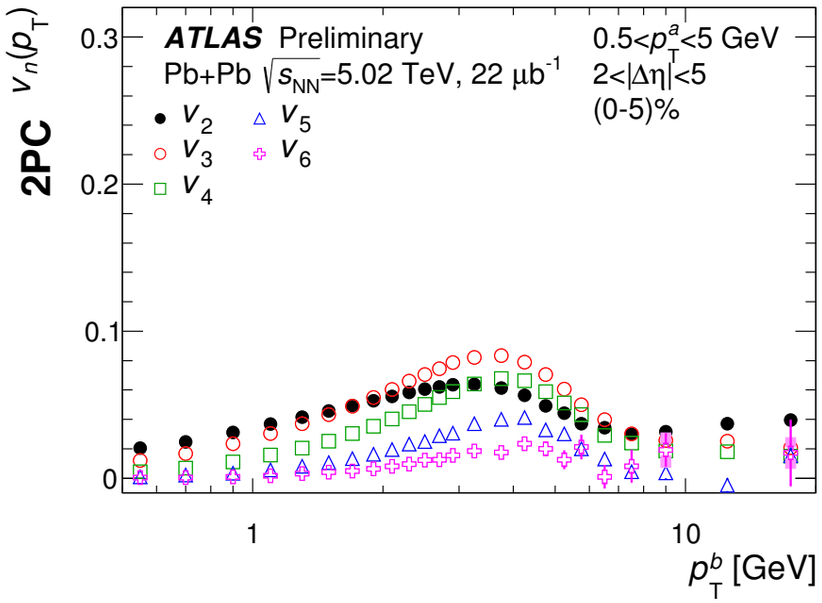
- Measurement to answer fundamental question of correlations origin in small system

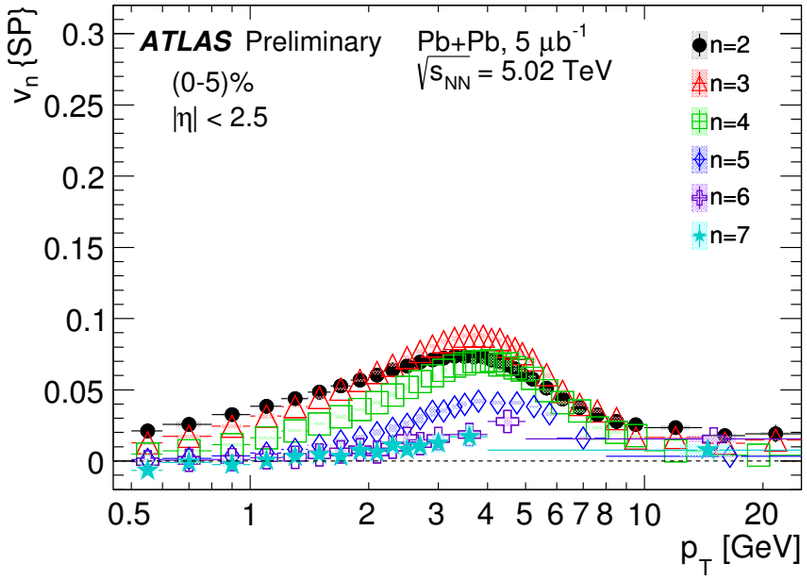
- In this talk only highlights from recent Pb-Pb results and new results for small systems

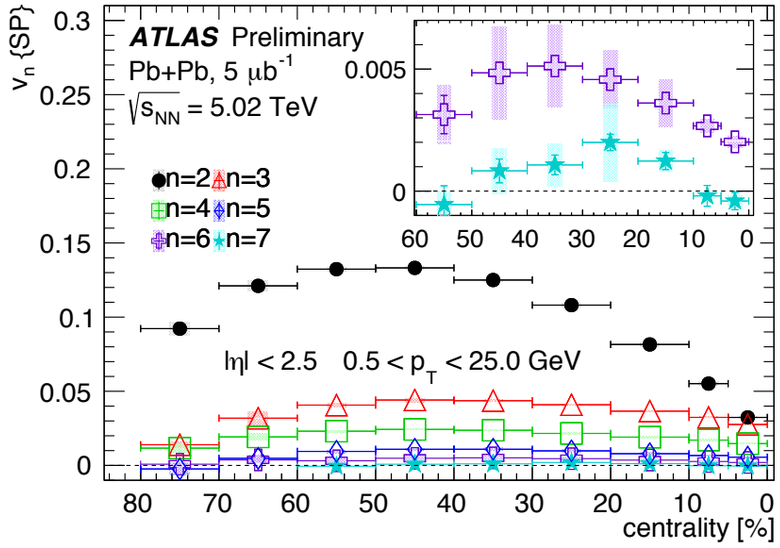
- All results can be found in: **https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults**

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

- 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 and measure harmonics up to n=7 [ATLAS-CONF-2016-105]







- Similar p_T dep. in all harmonics up to 10 GeV,
  - Above only v_2{SP} is non-0 (slow fall), rise in 2PC measurement
- Weak η dependence
- The SP and EP method differ for v_2 only (~3%),
- The v_n at $\sqrt{s_{NN}}$ =2.76 and 5.02 TeV energies are similar

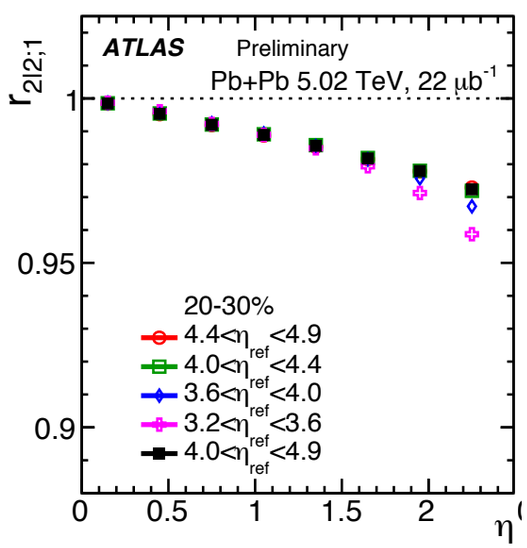
Pb-Pb v_n decorrelation

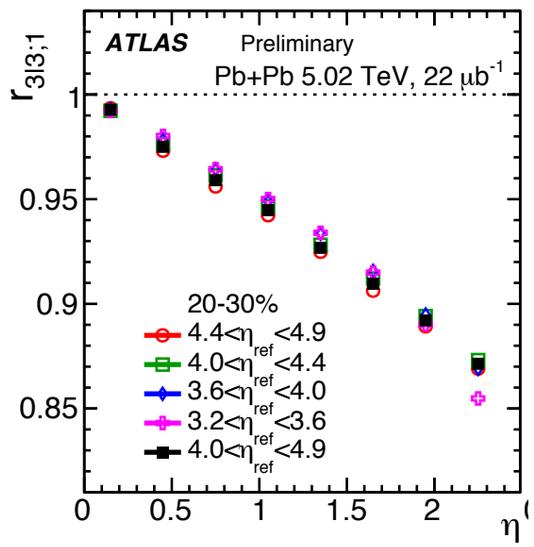
- Majority of flow studies assume boost invariance in longitudinal direction
- The role/importance of the η dependent fluctuations
- ATLAS measured new observables „correlation between v_n in bins of η" in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV [ATLAS-CONF-2017-003]
- $r_{n|n;k}$ expected 1 if longitudinal flow fluctuations not present, k=1,2,3

$$r_{n|n;k}(\eta) = \frac{\langle q_n^k(-\eta) q_n^{*k}(\eta_{\mathrm{ref}}) \rangle}{\langle q_n^k(\eta) q_n^{*k}(\eta_{\mathrm{ref}}) \rangle}$$

CMS [Phys. Rev. C 92 (2015) 034911]

- $R_{n,n|n,n}$ sensitive to the event-plane twist



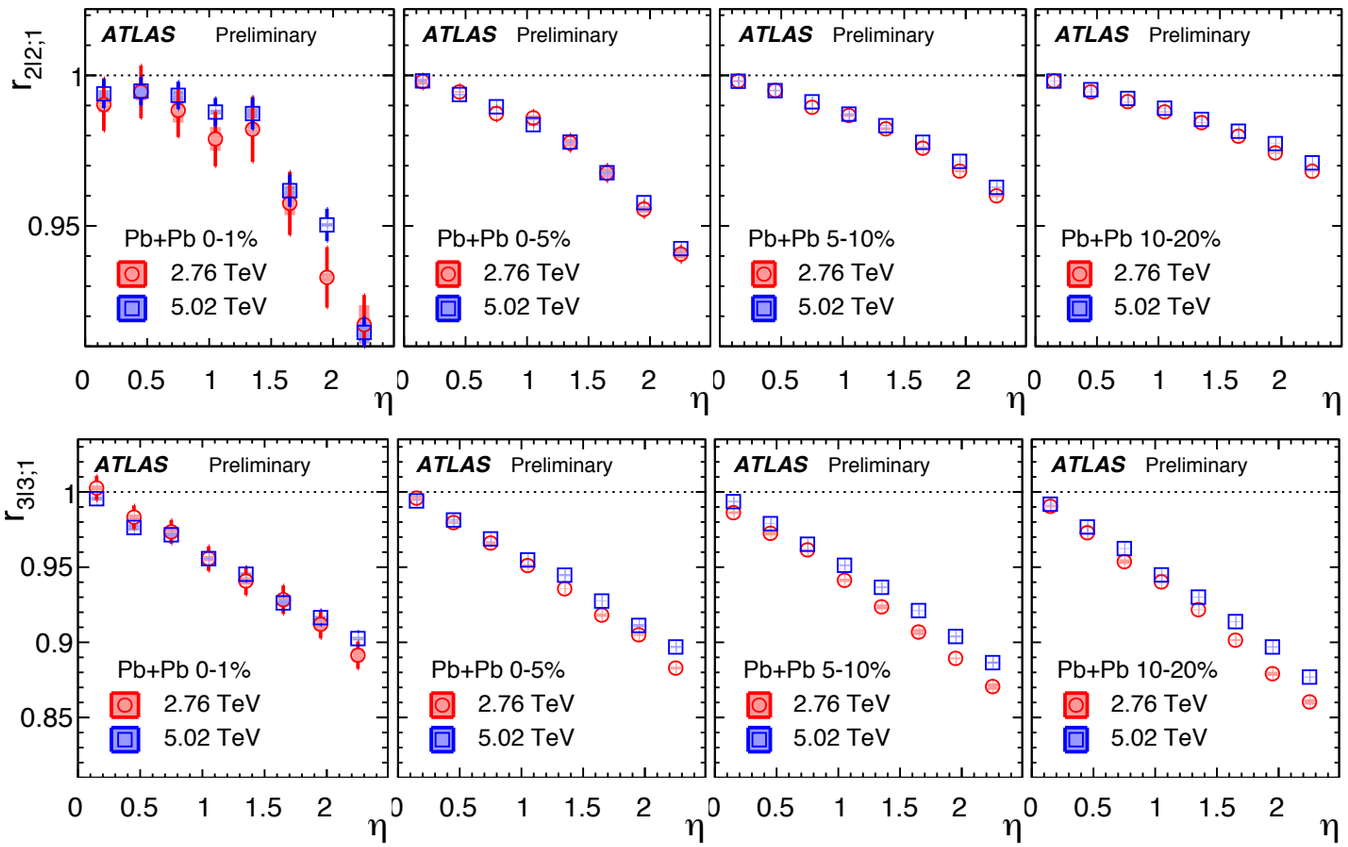


$$R_{n,n|n,n}(\eta) = \frac{\langle q_n(-\eta_{\mathrm{ref}}) q_n(-\eta) q_n^*(\eta) q_n^*(\eta_{\mathrm{ref}}) \rangle}{\langle q_n(-\eta_{\mathrm{ref}}) q_n^*(-\eta) q_n(\eta) q_n^*(\eta_{\mathrm{ref}}) \rangle}$$

Both variables robust against detector effects (ratios),

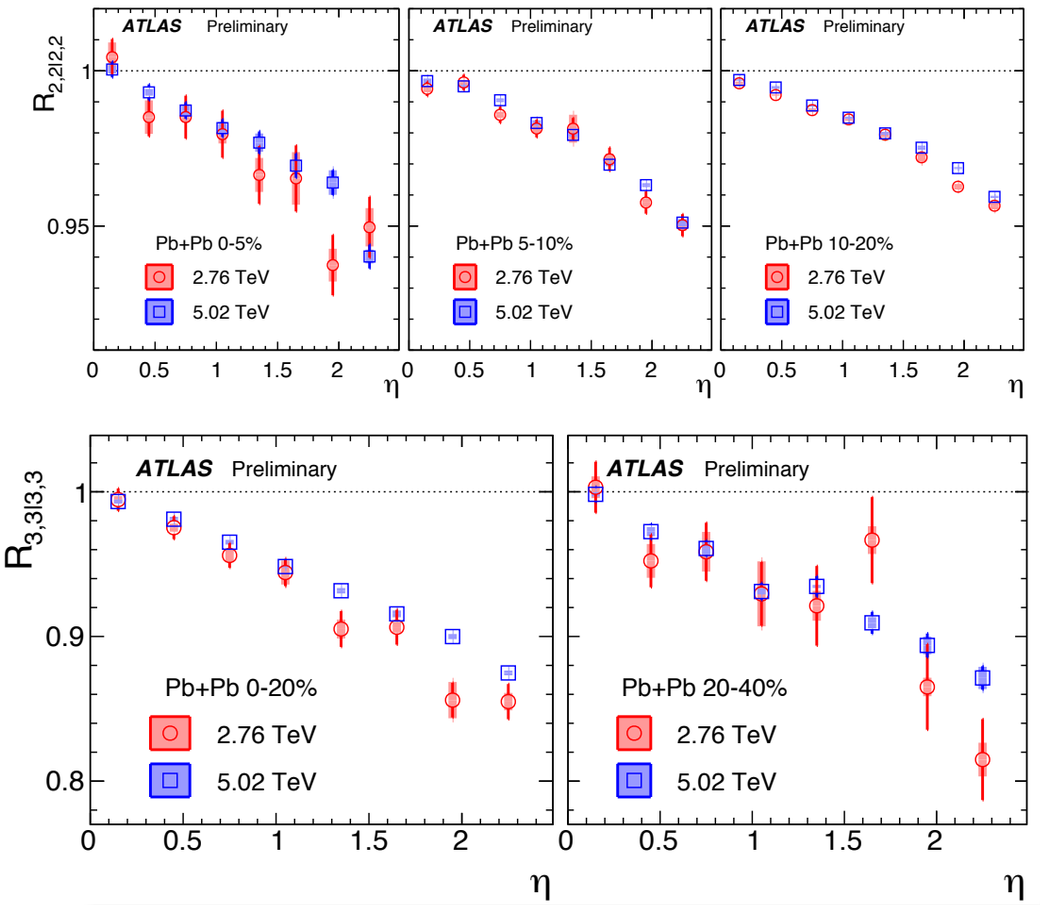
Observed no dependence on η_{ref} reference

Pb-Pb v_n decorrelation



- Factorisation of two particle v_{nn} into single particle v_n broken as function of η
- Effects slightly stronger for $\sqrt{s_{NN}}$=2.76TeV
- Centrality dependence for $r_{2|2;1}$ unlike higher n
- Event plane twist effect comparable to magnitude change
- Higher order indicate: v_2 v_3 long. fluct. independent, $v_4 \propto c\, v_2^2$, $v_5 \propto v_2 v_3$
- $r_{2|2;k} \neq r_{2|2;1}^k$

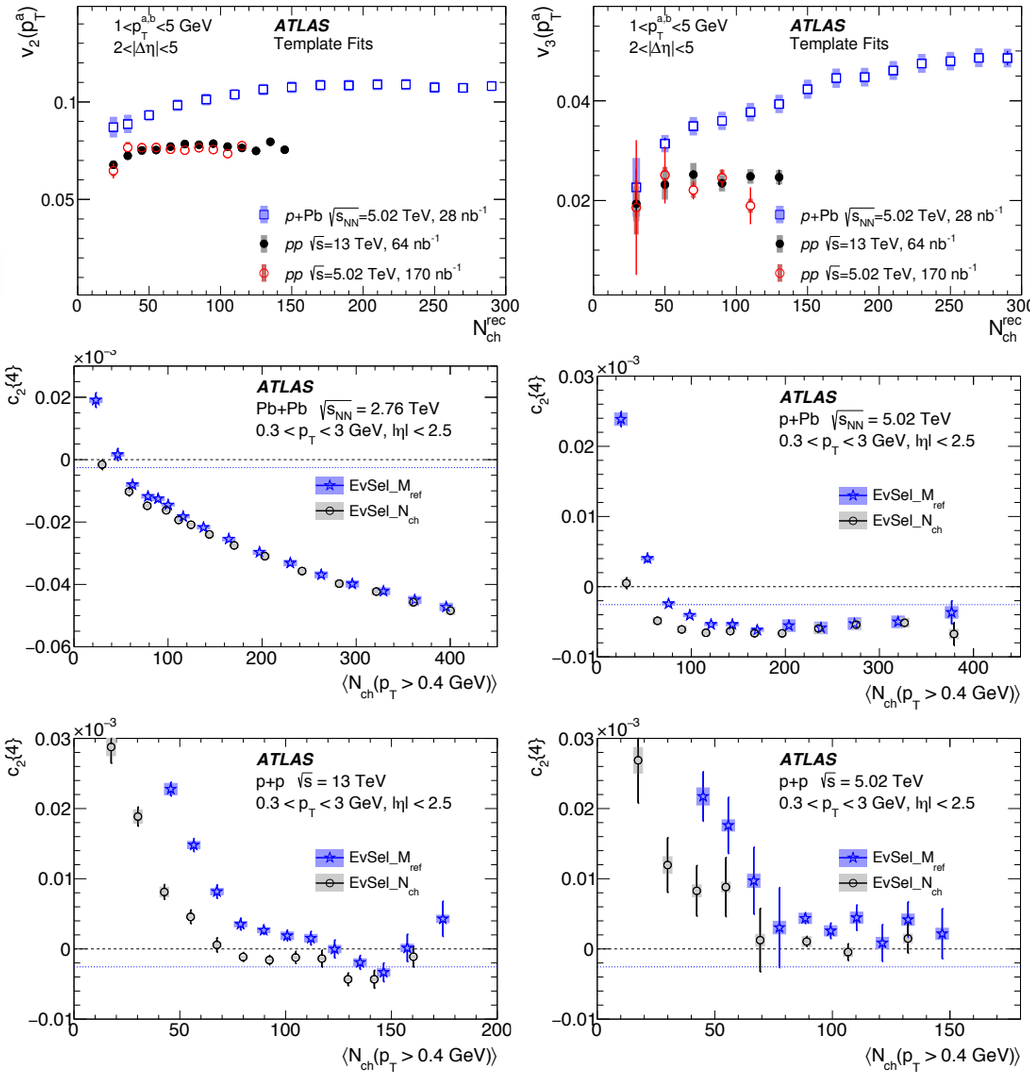
<— The $v_2(\eta)$ decolerrates with centrality while $v_3(\eta)$ - and higher does not



Event plane twist has sizeable contribution - the v_2 decorrelation changing with centrality not caused by twist of event-plane.

Small systems measurements

- The observation of the ridge structure in 2PC in p-p opened discussion on the small systems:
  - Initial stage effect CGS: PRD 87 (2013) 094034 or Collectivity in the evolution (formation of QGP): Phys. Rev. C 88, 014903 (2013)
- Robust method required for long-range correlation measurements in small systems
  - 2PC method require elaborate non-flow subtraction [arXiv:1609.0621
  - Standard multiparticle cumulants suggest: maybe no collectivity in pp
    (measurement depends on arbitrary choice of reference particles)
    [Eur. Phys. J. C 77 (2017) 428]
- „Orthogonal" measurement: azimuthal HBT analysis



Standard and sub-event cumulant methods

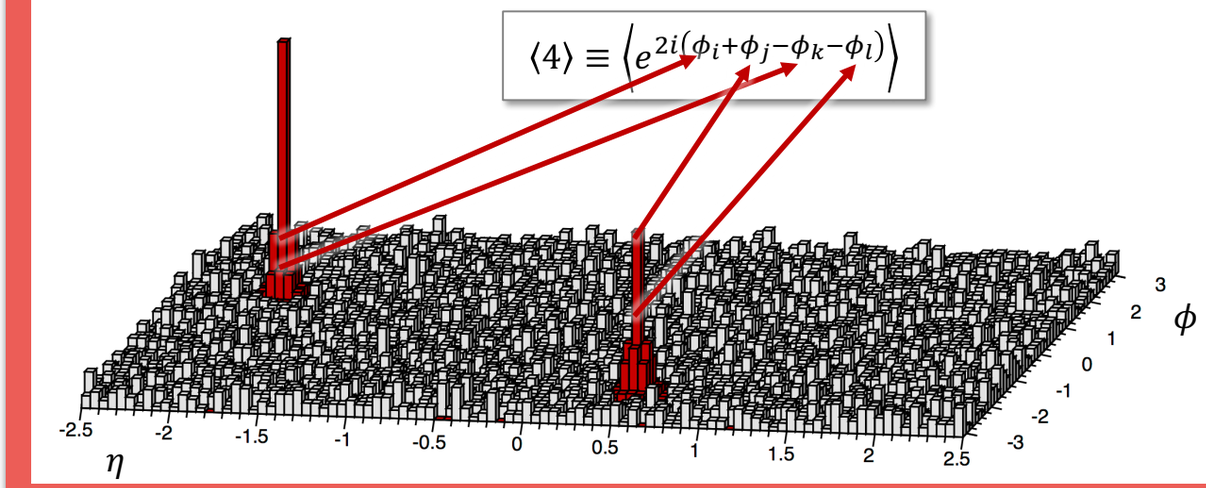
$$v_n\{2\}_n = \sqrt{c_n\{2\}},\ v_n\{4\}_n = \sqrt[4]{-c_n\{4\}}$$

Negative $C_2\{4\}$ indicates collectivity

Standard cumulant

$$\langle\{2\}_n\rangle = \left\langle e^{in(\phi_1-\phi_2)}\right\rangle,\ \langle\{4\}_n\rangle = \left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle$$

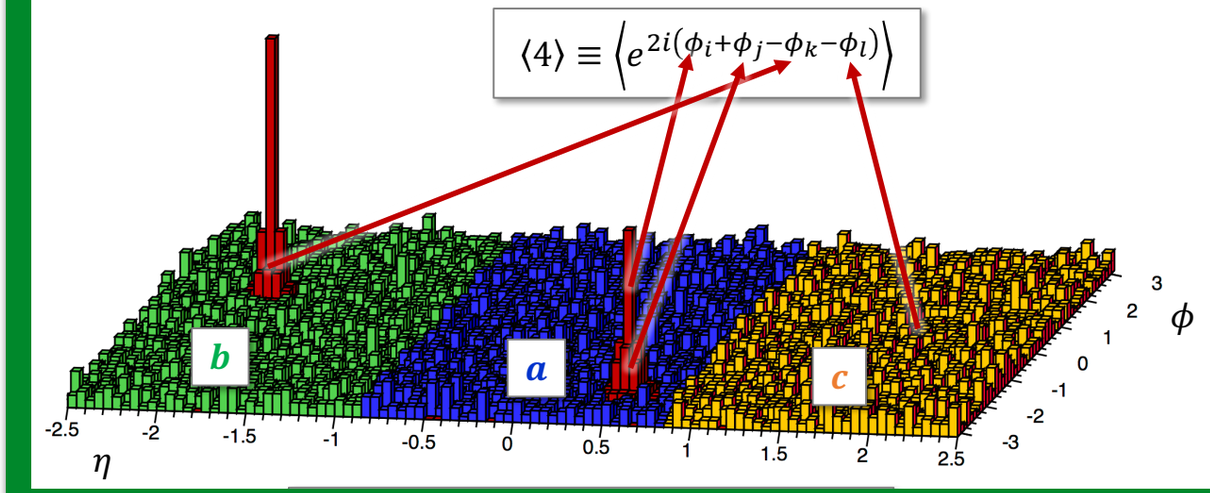
$$c_n\{2\} = \langle\langle\{2\}_n\rangle\rangle,\ c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2$$



Sub-event cumulant

$$\langle\{2\}\rangle_{a|b} = \left\langle e^{in(\phi_1^a-\phi_2^b)}\right\rangle,\langle\{4\}_n\rangle_{2a|b,c} = \left\langle e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^c)}\right\rangle$$

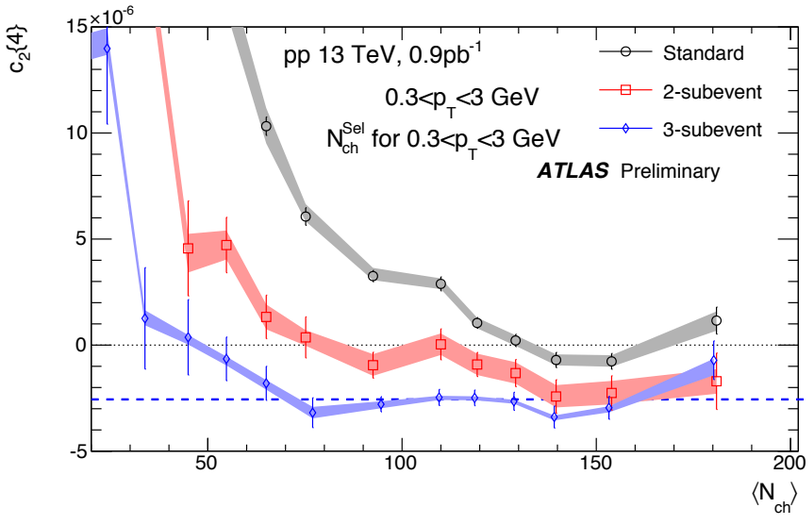
$$c_n^{2a|b,c}\{4\} = \langle\langle\{4\}_n\rangle\rangle_{2a|b,c} - 2\langle\langle\{2\}_n\rangle\rangle_{a|b}\langle\langle\{2\}_n\rangle\rangle_{a|c}$$

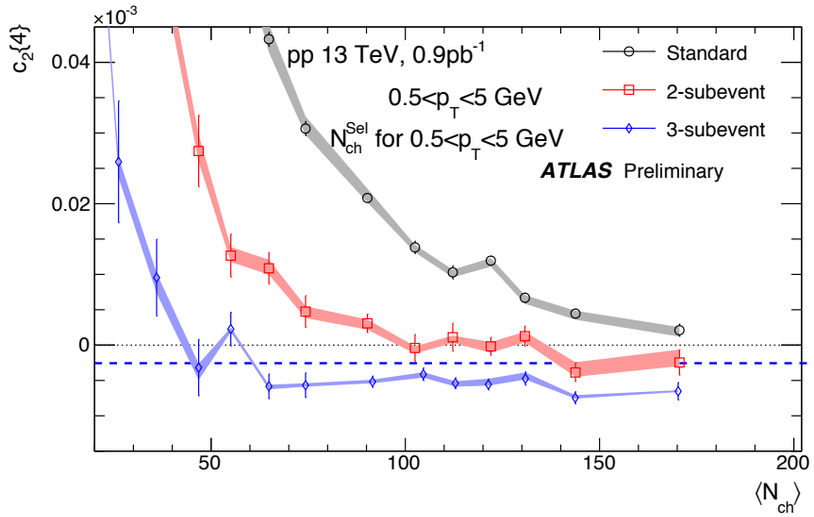


By correlating particles from rapidity separated sub-events the self-correlation (mostly di-jets) is mostly suppressed

arXiv: 1701:03830

$C_2\{4\}$ from sub-event cumulants



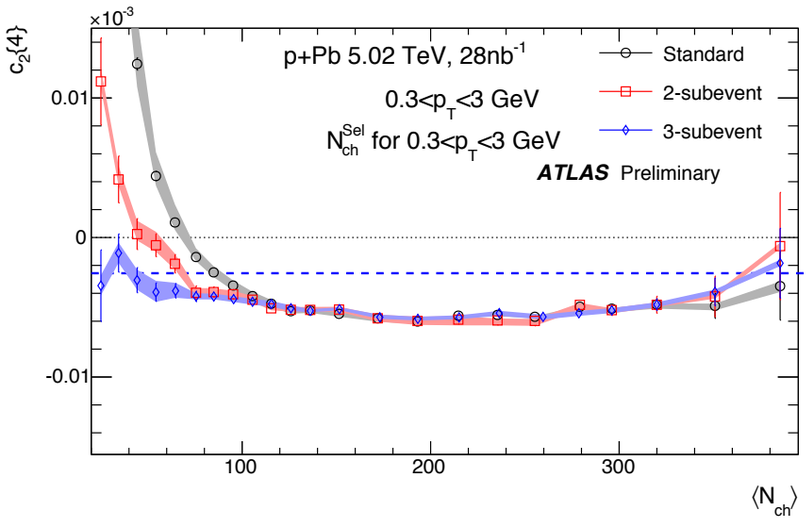


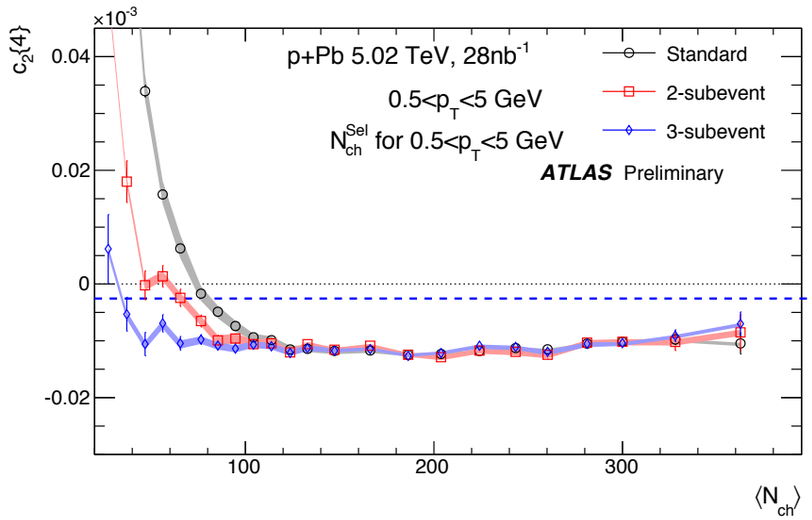
Negative $C_2\{4\}$ indicates collectivity

Standard cumulant meth. indicates no $v_2\{4\}$ unless for very specific reference particles choice and event multiplicity.

Signs of improvement in 2 sub-event cumulant. Weakly dependent on the choice of reference particles.

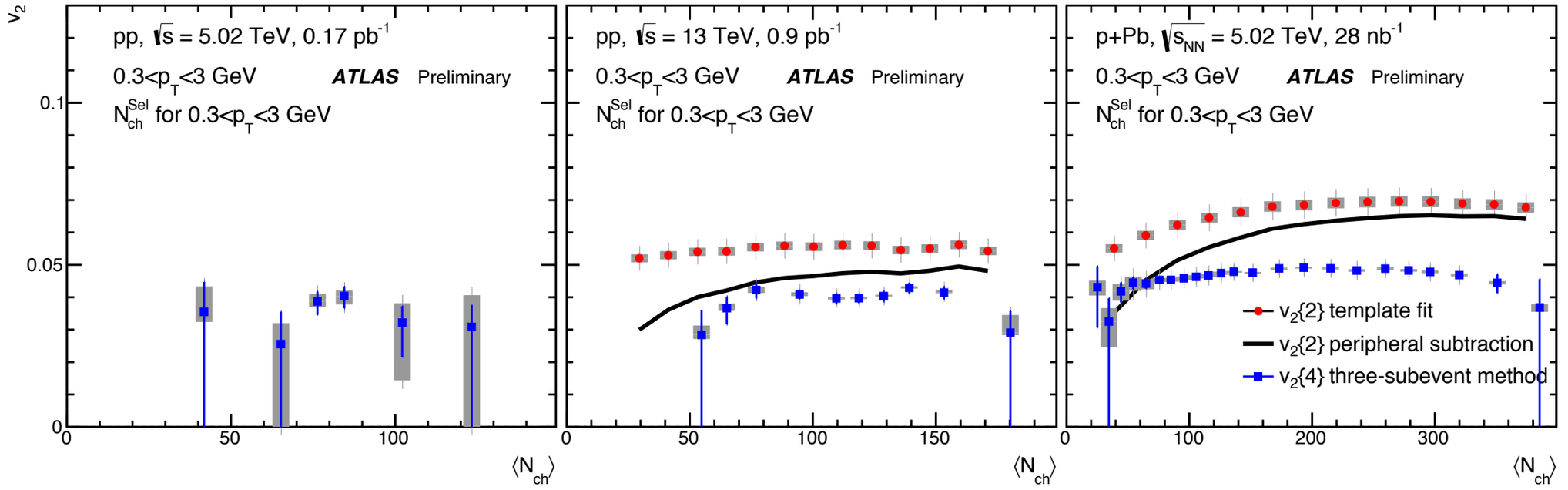
The 3 sub-event cumulant: Consistently below 0. Independent on the choice of reference particles. Negative $C_2\{4\}$ at low mult.





All methods consistent in p-Pb.
Tests on MC indicate suppression of the non-flow v_2=0.

Sub-event cumulant results



The $v_2\{4\}$ obtained in p-p (wide multiplicity range) and p-Pb.
Nearly independent of ev. multiplicity in three systems, very little $\sqrt{s_{NN}}$ dep. in p-p

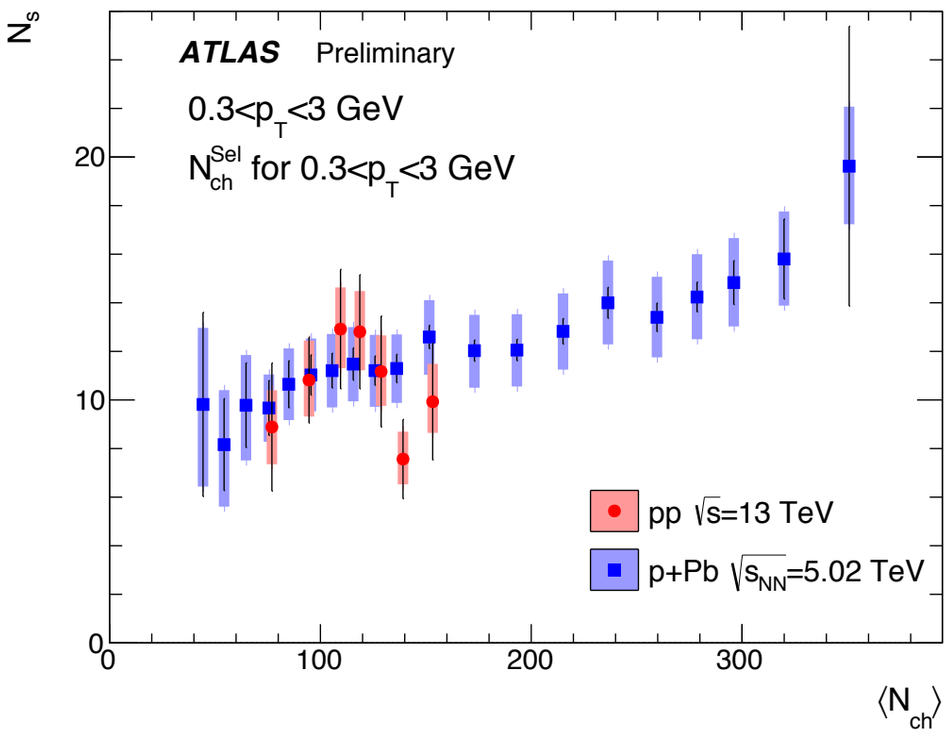
The v_2 with reduced non-flow contributions lower than measured previously

The v_3 consistent with 0

$v_2\{4\}/v_2\{2\}$ estimate number of sources (model dependent: [Phys. Rev. Lett. 112, 082301 (2014)])

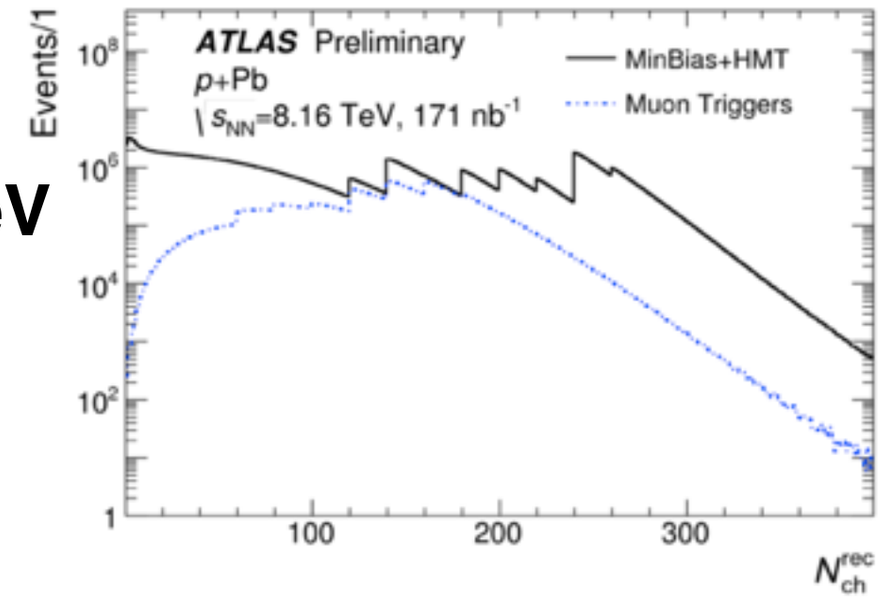
Same multiplicity = same number of sources irrespectively of the collision system!

Consistent with F-B multiplicity correlation results [PRC 95 (2017) 064914]

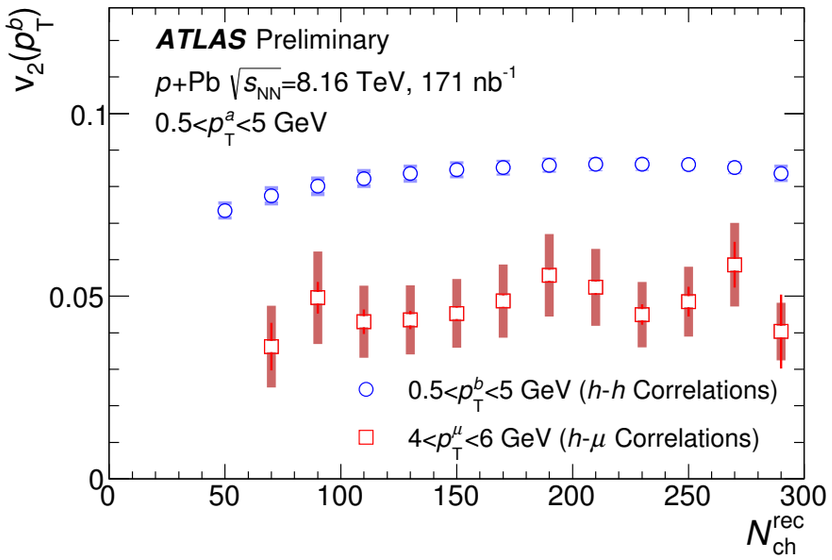


Muon-hadron correlations

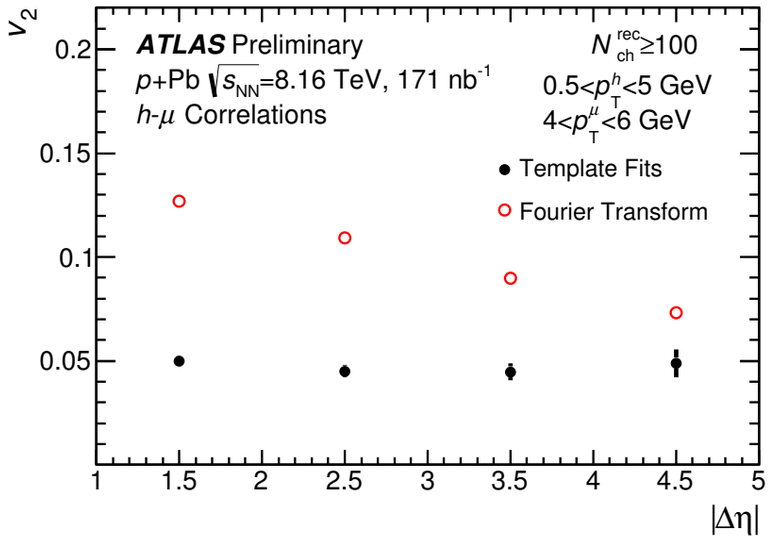
- Heavy flavour long range correlations studied through muon-hadron correlation
- ATLAS measured the azimuthal muon-hadron correlations in Pb-Pb collisions at 2.76 TeV [ATLAS-CONF-2015-053]
  - observed v_2 in range of $4<p_T<12$ GeV from 6 to~0%
- **Now also measured in p-Pb at $\sqrt{s_{NN}}$ =8.16 TeV**
  - high-multiplicity + muon trigger to collect the sample
  - 2PC method with template fits to subtract non-flow contribution [ATLAS-CONF-2017-006]



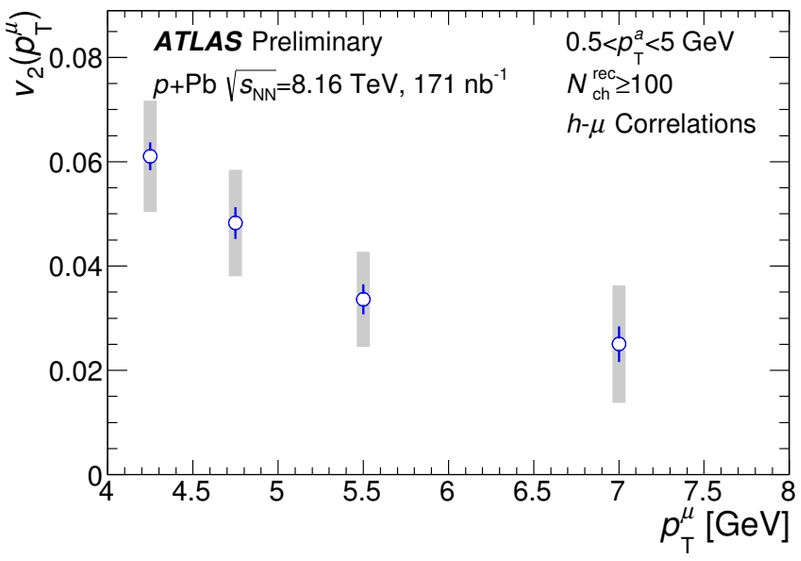
Results: muon-hadron correlation



A significant h-μ v_2 observed (about 60% lower than h-h - mind p_T range difference)
Independent of event multiplicity



After proper removal of dijet contribution flat η dependence —> long range correlation.



The p_T dependence resembles h-h v_2 at high p_T (mind that muons are from HF decays - additional kinematics to take into account before comparison)

Significant azimuthal anisotropy of HF particles observed in p-Pb

Summary

In correlation measurements ATLAS concentrates on:

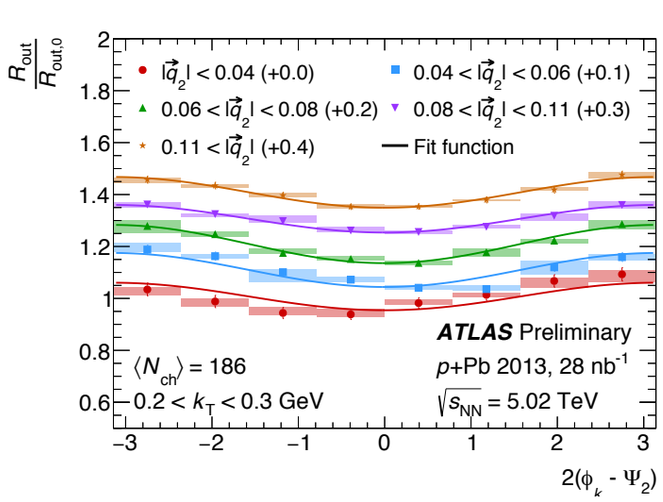
- **Detailed understanding of correlations properties in Pb-Pb collisions**
  - High precision thanks to large statistics available
  - New observables: short & long range component in FB multiplicity correlations, v_n decorrelations
- **Advanced methods to answer the question on the origin of correlations in small systems**
  - Advancing non-flow components removal, novel sub-event cumulant provides robust results
  - Performed muon-hadron correlation analysis

    (in backup: observation of azimuthal modulation of source size)

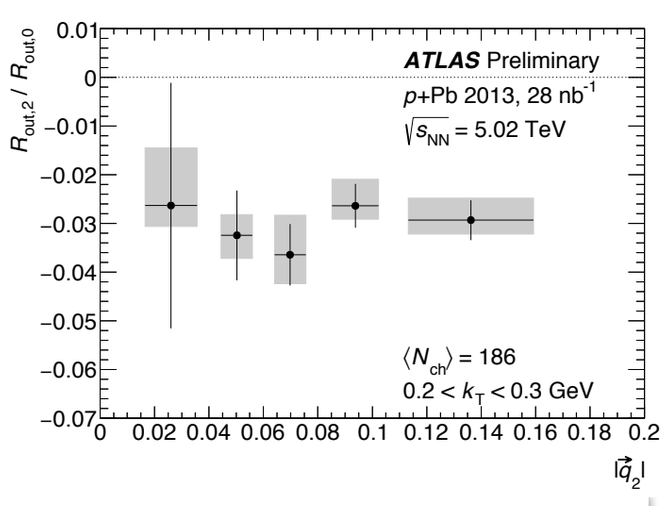
Backup

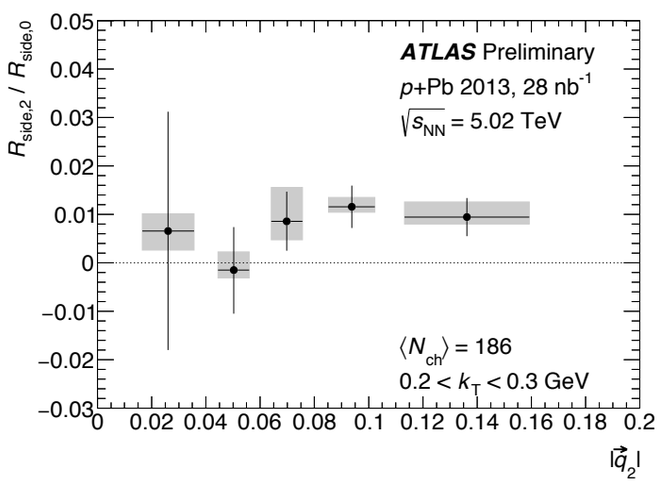
Azimuthal HBT results

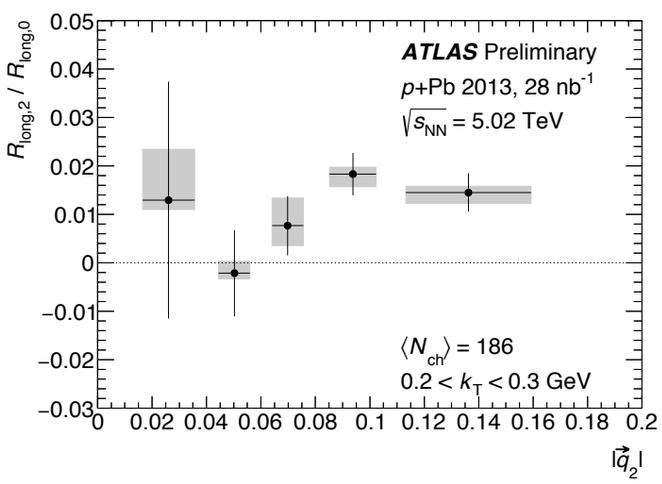
- Modulation of source radii in small system favours evolution scenario
- **Now performed azimuthal HBT analysis** [ATLAS-CONF-2017-008] (inclusive [arXiv:1704.01621])
  - Data set enhanced by high-multiplicity events, Event Plane(EP) established in „forward" calorimeter region, results corrected for EP resolution
  - Measured are relative radii change as function of distance from the EP and its scaling with overall azimuthal asymmetry (magnitude of the elliptic flow vector $|\mathbf{q}_2|$)



cos/sin fit to the data and amplitude extracted (taking into account N bins size & EP resolution)







Modulation visible in all radii
Highest for events with large $|q_2|$
Strong suggestion of collective evolution