Soft probes of the quark-gluon plasma in ATLAS

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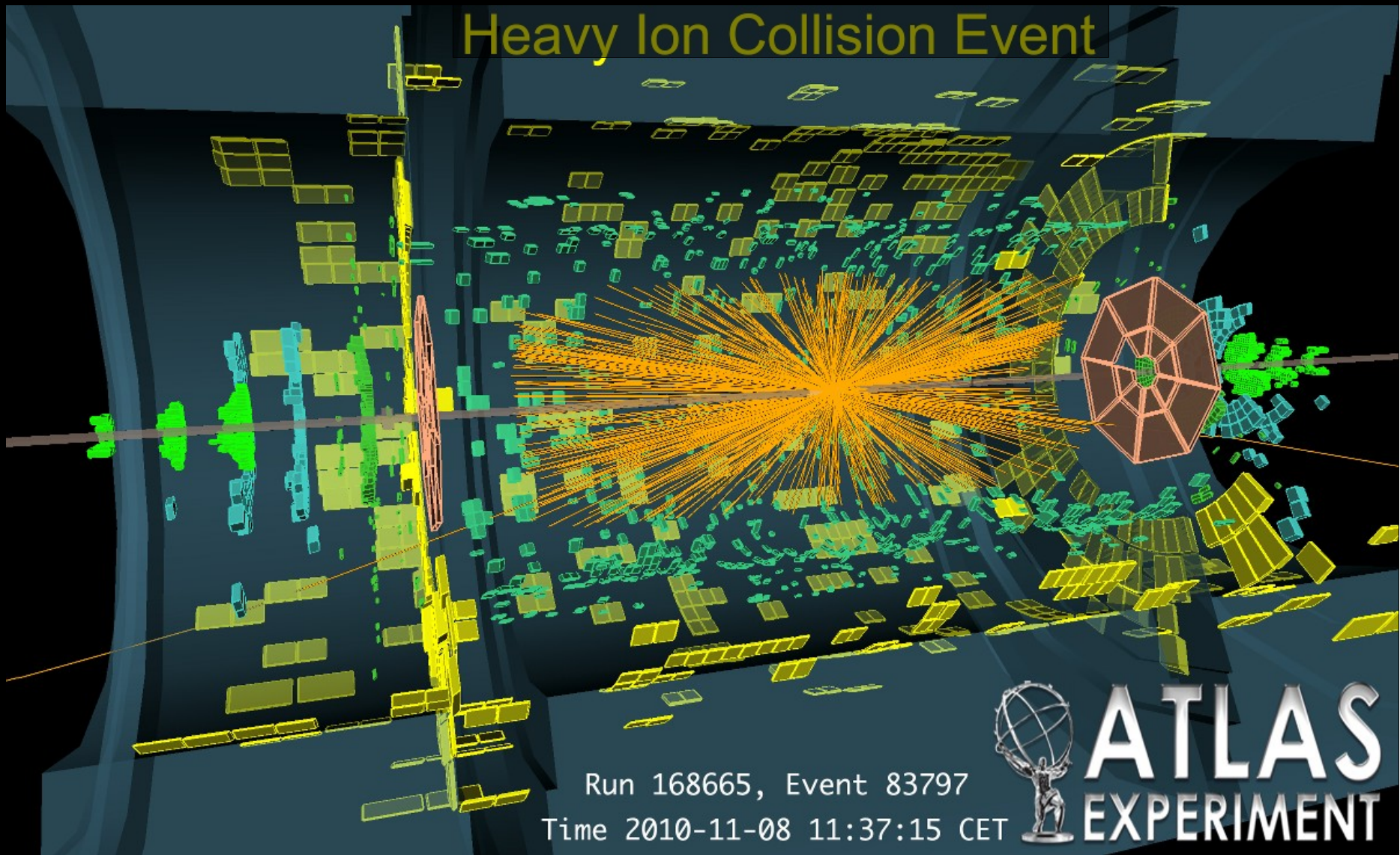
for the ATLAS Collaboration



Outline

Study of Quark-Gluon Plasma initial conditions and evolution

- Integrated elliptic flow
- Flow harmonics from multi-particle cumulants
- Event plane correlations
- Correlations between flow harmonics

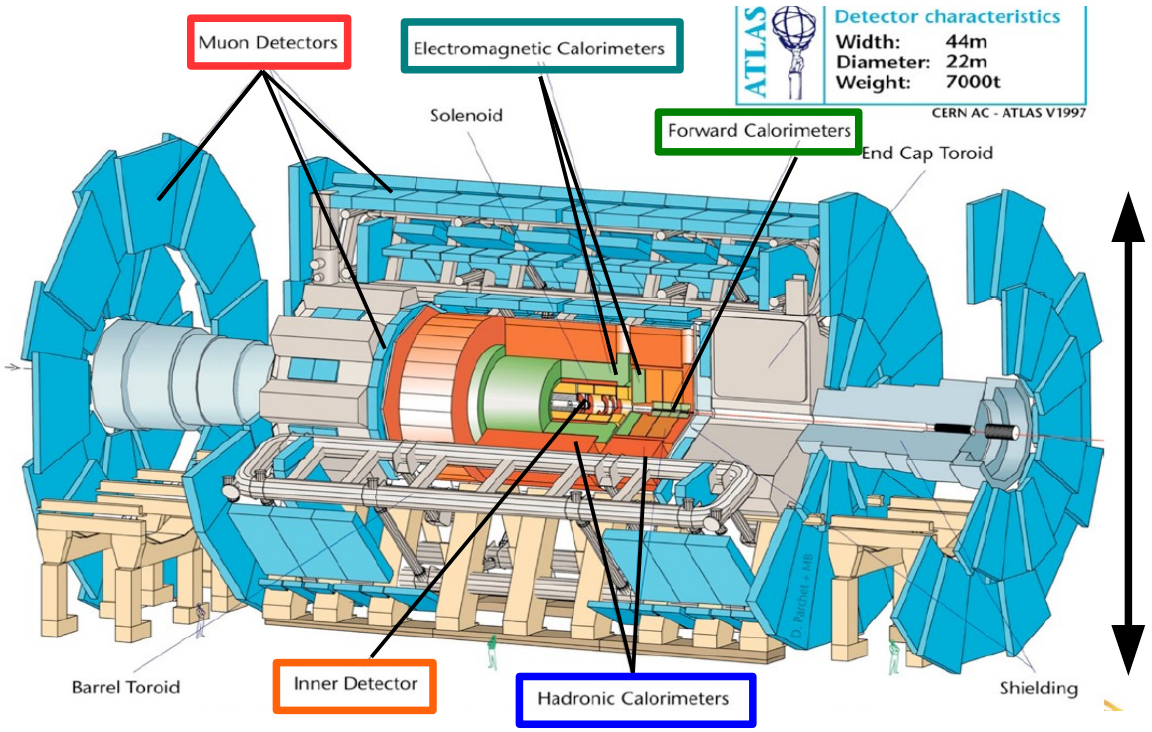
Pb+Pb

- Long range pseudorapidity correlations

p+Pb

More details were given in the earlier talk by Martin Spousta

The ATLAS detector



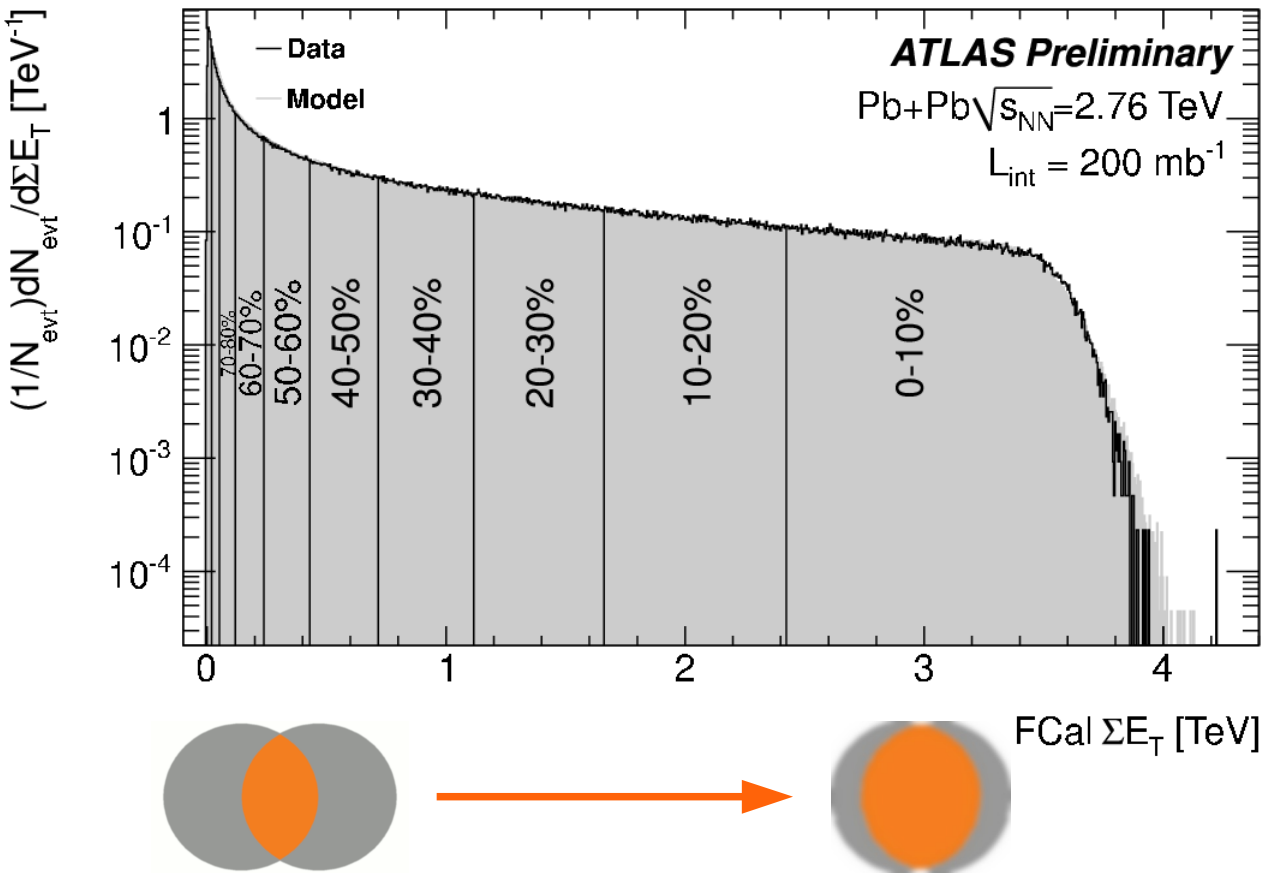
44 m

Inner detector $|\eta|<2.5$

Calorimeter $|\eta|<3.2$

Forward Calorimeter $3.1<|\eta|<4.9$

Centrality of PbPb collisions



Distribution of the signals registered in the Forward Calorimeter (FCal) is divided into bins with appropriate percentage of events .

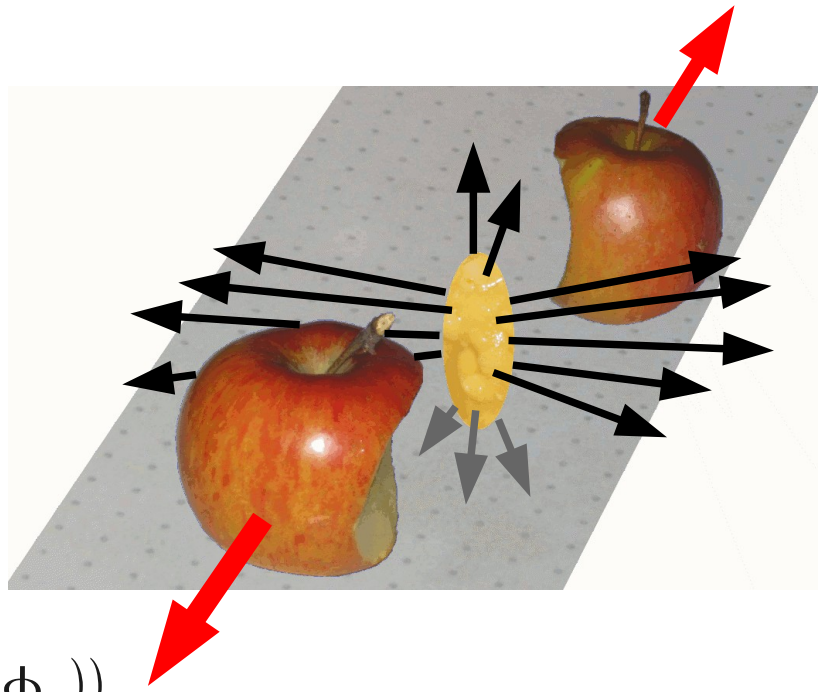
Fraction of the sampled non-Coulomb inelastic cross section after all trigger selection cuts is estimated to be 100% ±2%

Azimuthal correlations decomposition - definitions

Event plane method

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

$$v_n = \langle\cos(n(\phi-\Phi_n))\rangle$$

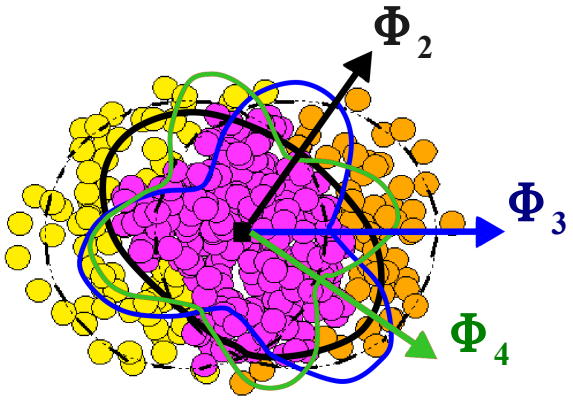


Two-particle correlations method

$$\frac{dN}{d(\phi_a-\phi_b)} \sim 1+2\sum_{n=1}^{\infty} v_{n,n}(p_T^a,p_T^b)\cos(n(\phi_a-\phi_b))$$

$$v_{n,n} = \langle\cos(n(\phi_a-\phi_b))\rangle$$

for flow: $v_{n,n}(p_T^a,p_T^b) = v_n(p_T^a)v_n(p_T^b)$



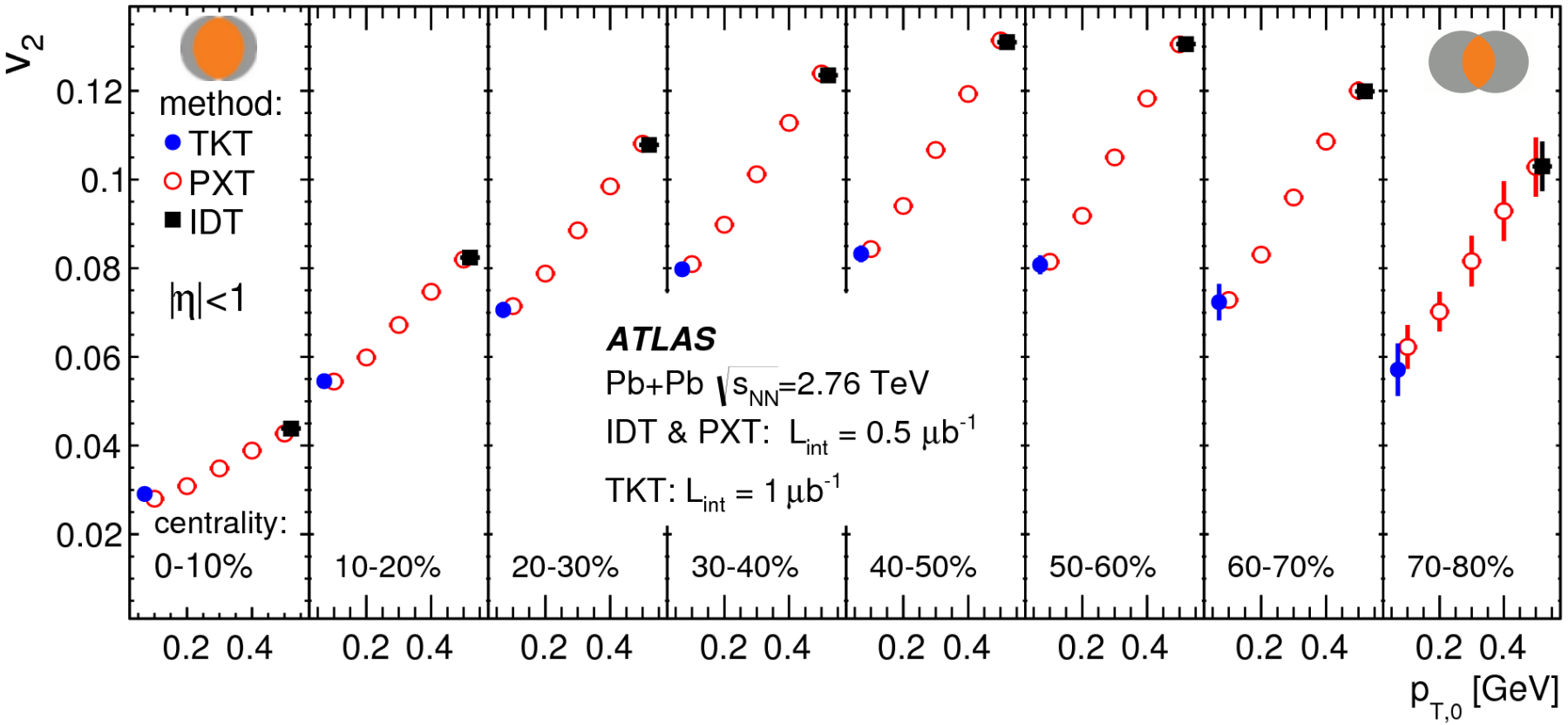
Cumulants from 2k-particle correlations

$$\langle corr_n\{2k\}\rangle = \langle\exp(in(\phi_1+\ldots+\phi_k-\phi_{k+1}+\ldots+\phi_{2k}))\rangle$$

Integrated elliptic flow in Pb+Pb collisions

Integrated elliptic flow:

- from reconstructed tracks **with $p_T > p_T^{min}$, extrapolated to $p_T = 0$**
- **measured down-to very low p_T (p_T>0.07 GeV)** [arXiv:1405.3936v2]



Using pixel tracklets (vertex+2 hits) and pixel tracks ATLAS is reconstructing low-p_T charged primary particles with sufficient efficiency to measure integrated elliptic flow without model dependent corrections

ATLAS, arXiv:1405.3936v2

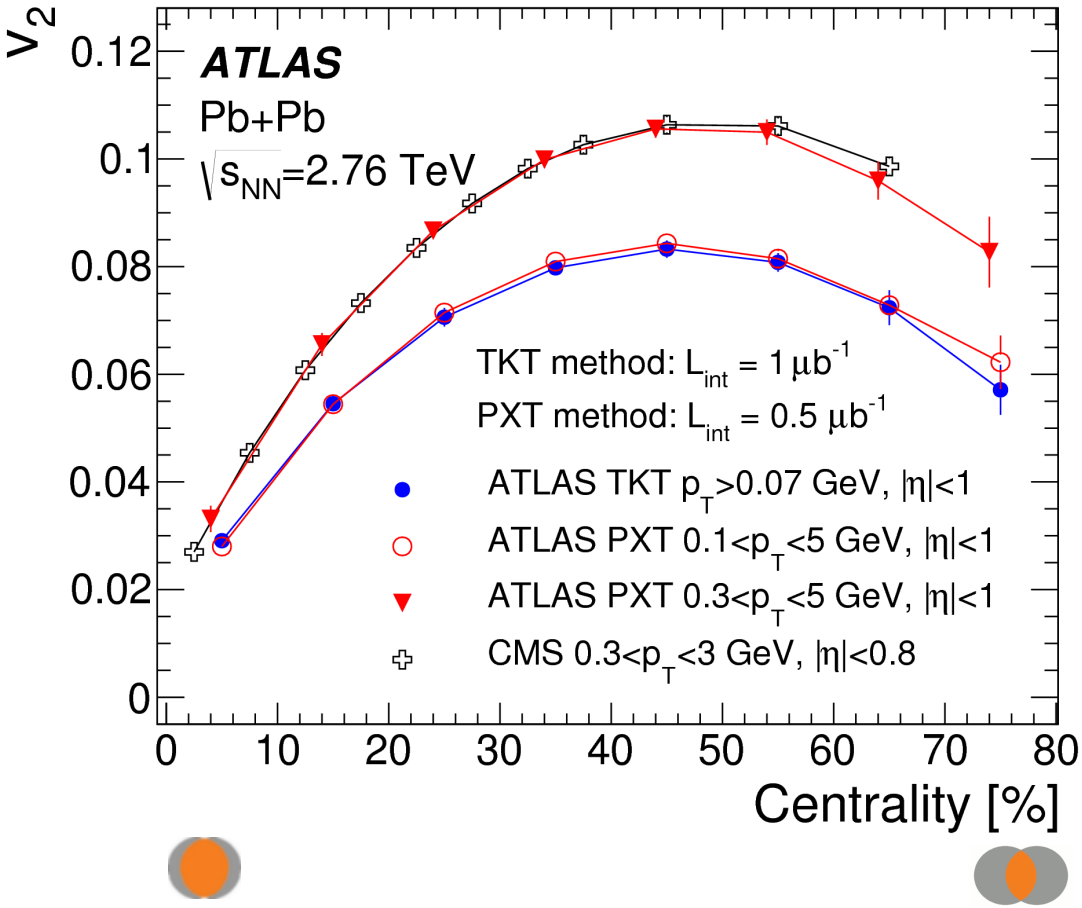
Integrated elliptic flow in Pb+Pb collisions

Integrated elliptic flow:

- from reconstructed tracks with $p_T > p_T^{min}$, extrapolated to $p_T = 0$
- measured down-to very low p_T ($p_T > 0.07$ GeV) [arXiv:1405.3936v2]

Using pixel tracklets (vertex+2 hits) and pixel tracks ATLAS is measuring low-p_T charged primary particles with sufficient efficiency.

Integrated flow is ~20% smaller that the flow calculated from tracks with $p_T > 0.5$ GeV

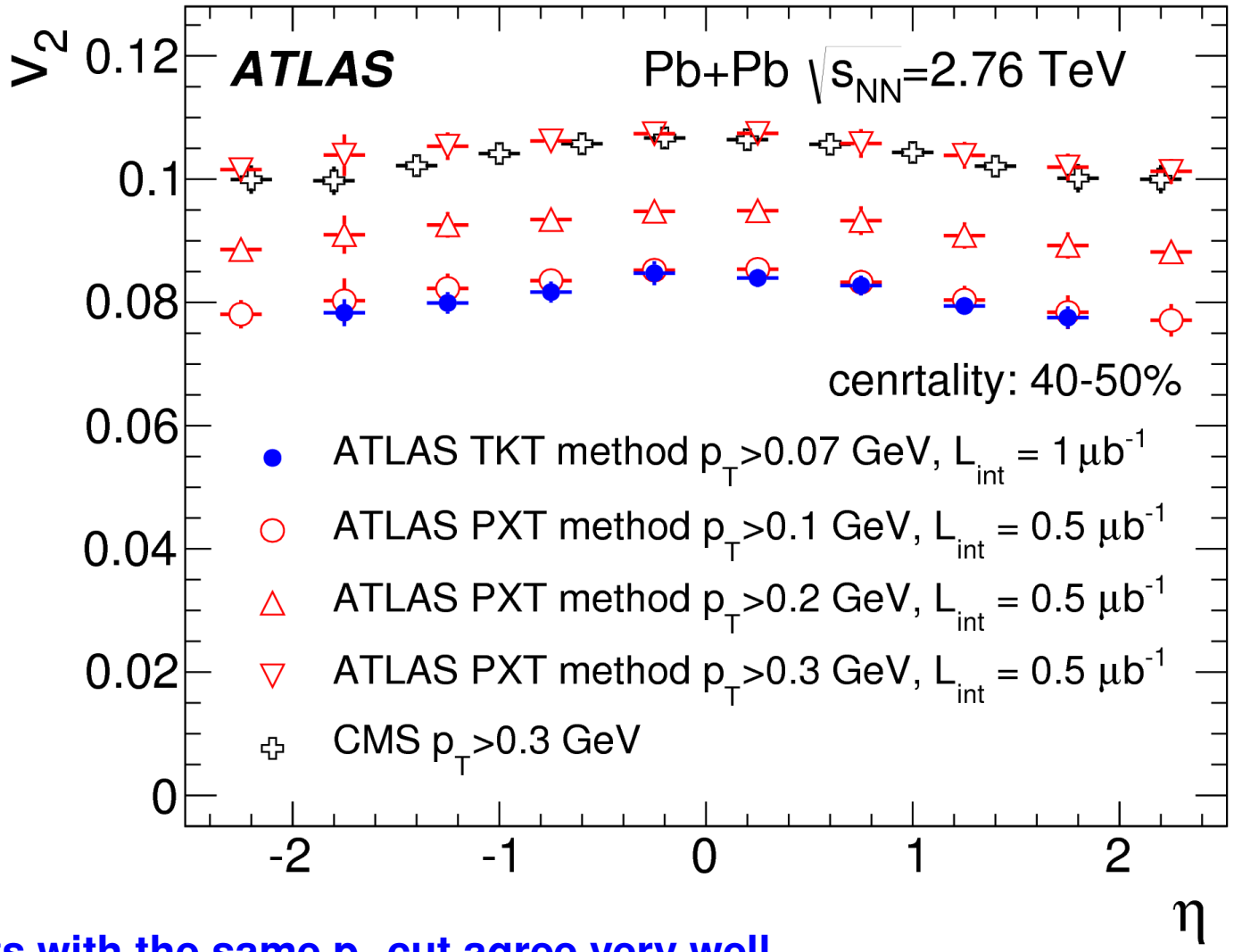


ATLAS, arXiv:1405.3936v2

Integrated elliptic flow in Pb+Pb collisions

Elliptic flow for different p_T cuts:

- $p_T > 0.3$ GeV
- $p_T > 0.2$ GeV
- $p_T > 0.1$ GeV
- $p_T > 0.07$ GeV

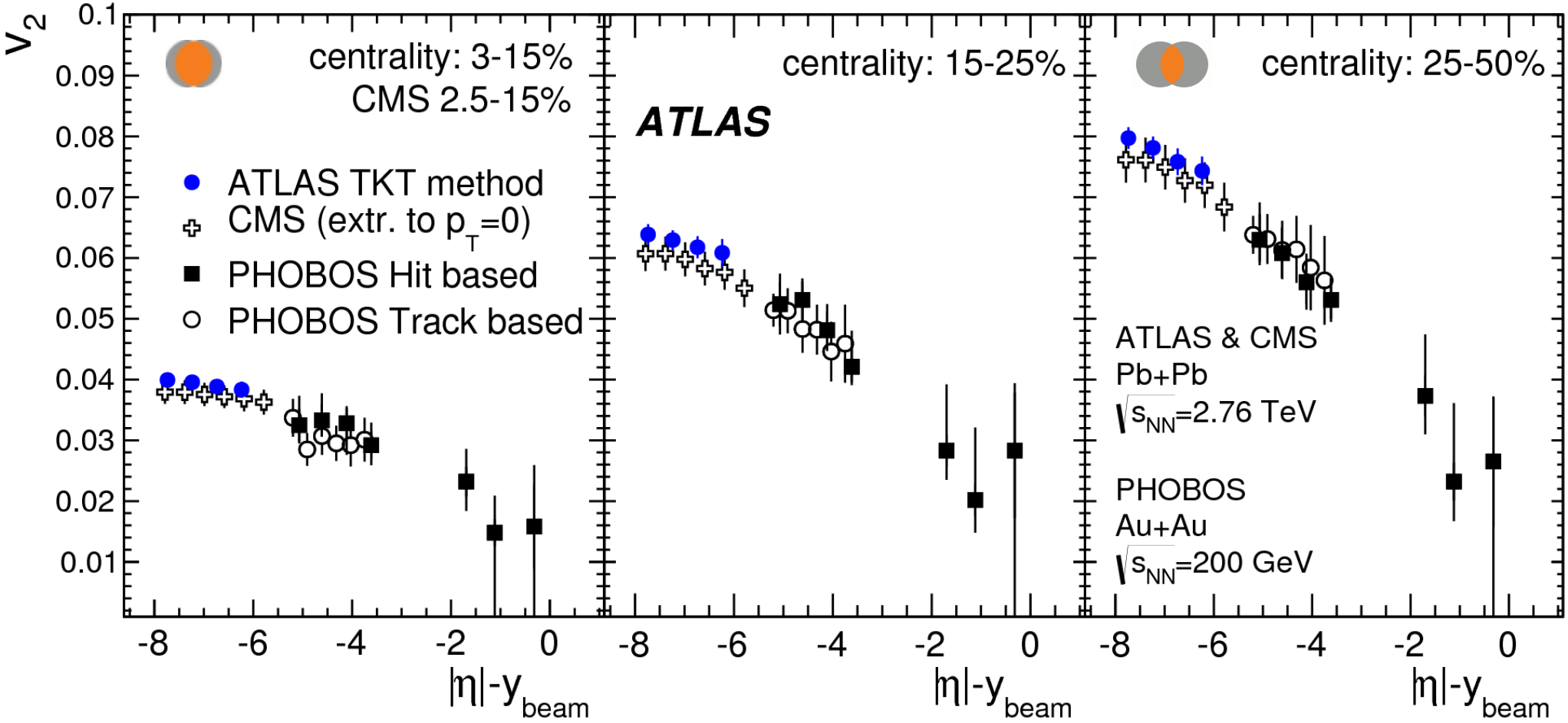


ATLAS and CMS results with the same p_T cut agree very well

ATLAS, arXiv:1405.3936v2

Integrated elliptic flow in Pb+Pb collisions

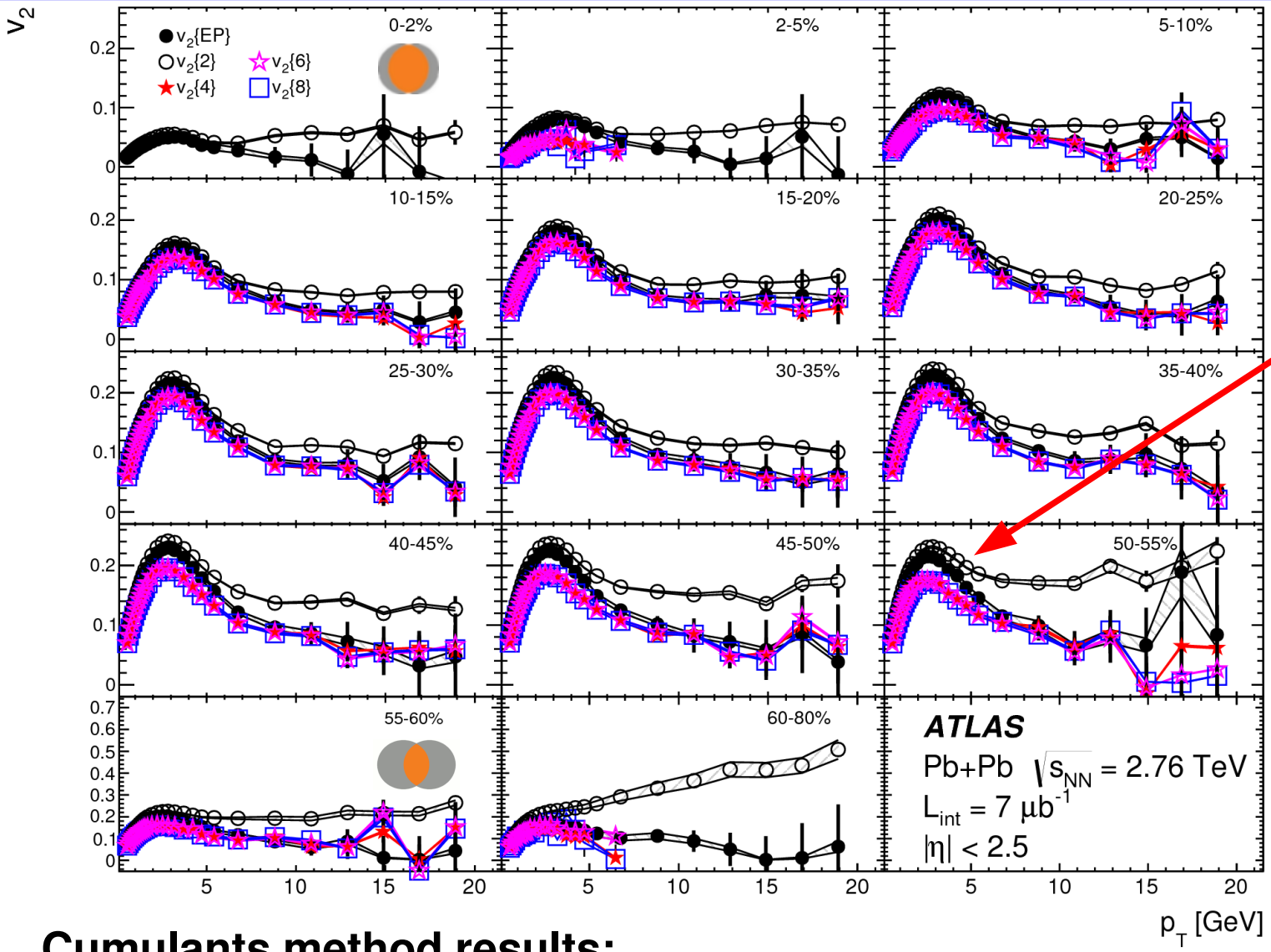
Integrated elliptic flow - after transformation to the rest frame of one of colliding nuclei:



LHC results consistent with the extended longitudinal scaling observed at RHIC

ATLAS, arXiv:1405.3936v2

Flow harmonics with multi-particle cumulants in Pb+Pb collisions



$v_2\{2\} > v_2\{EP\} > v_2\{4\}$

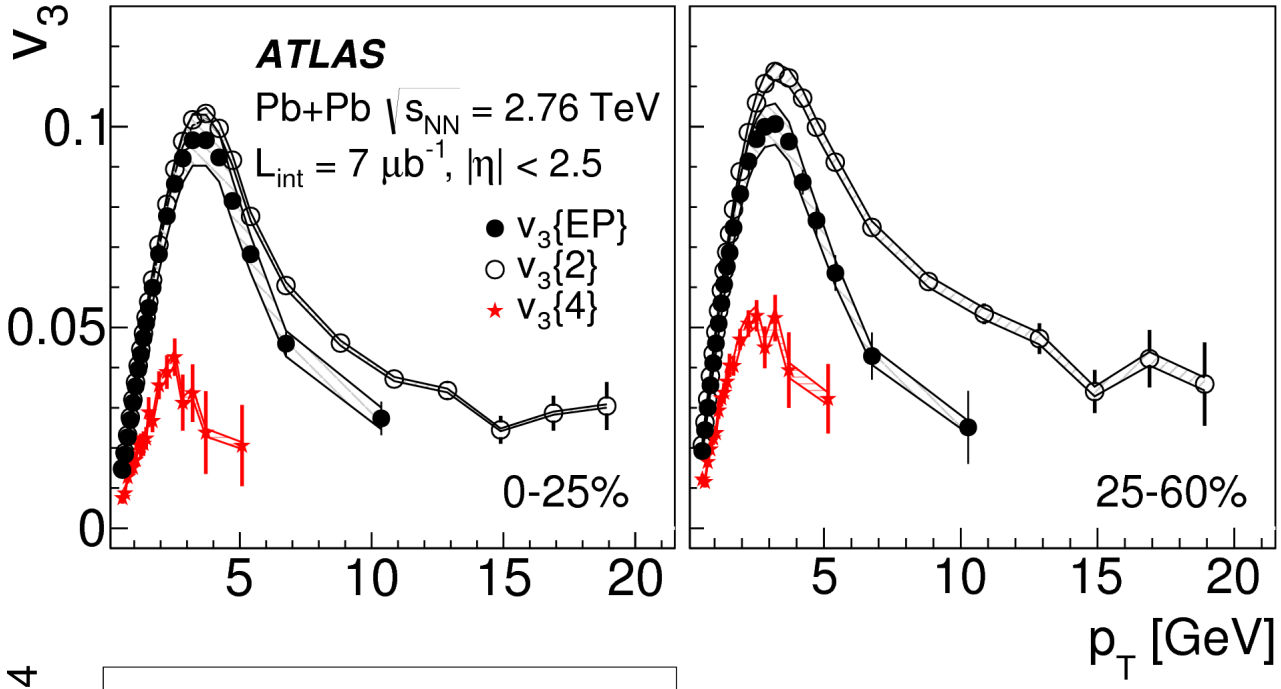
$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$

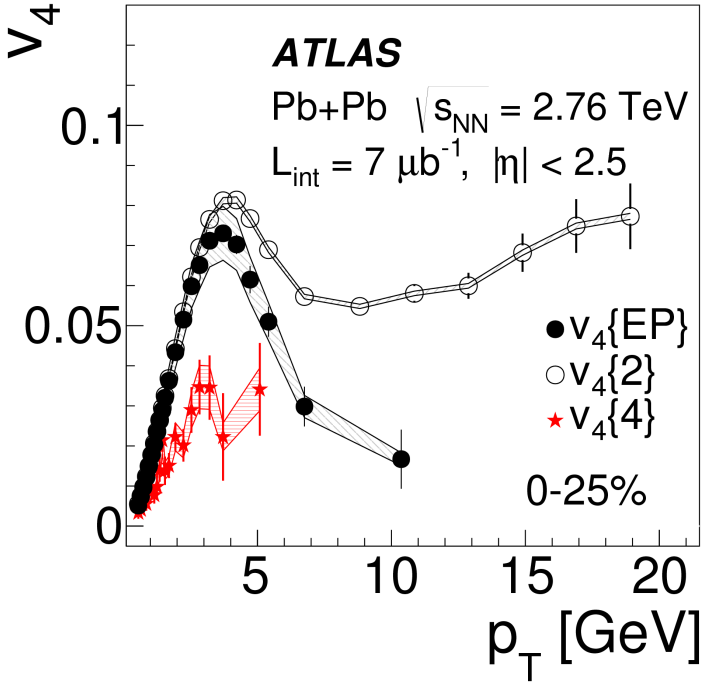
ATLAS, arXiv:1408.4342

Cumulants method results:

$v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$ values of elliptic flow obtained from 4, 6 and 8-particle correlations, in which effects from two-particle correlations are canceled, are significantly smaller than v_2 from two-particle correlations or from event plane method

Flow harmonics with multi-particle cumulants in Pb+Pb collisions





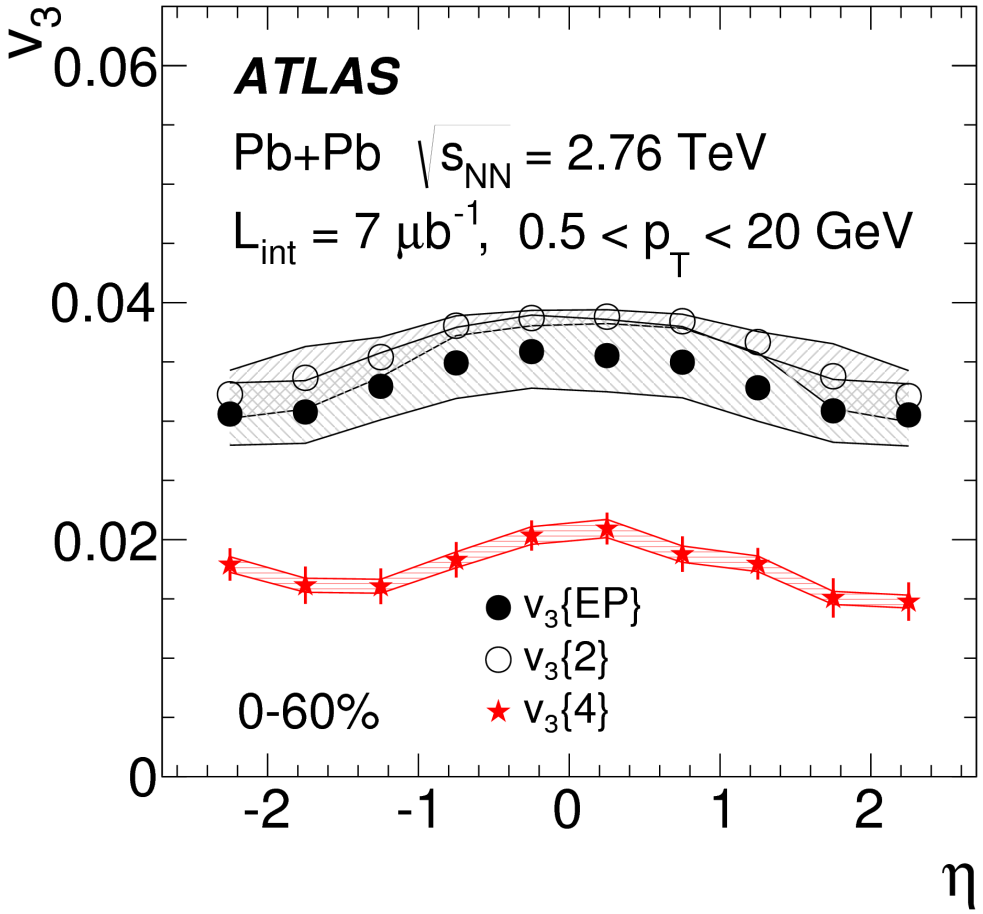
Even stronger relation for higher order harmonics:

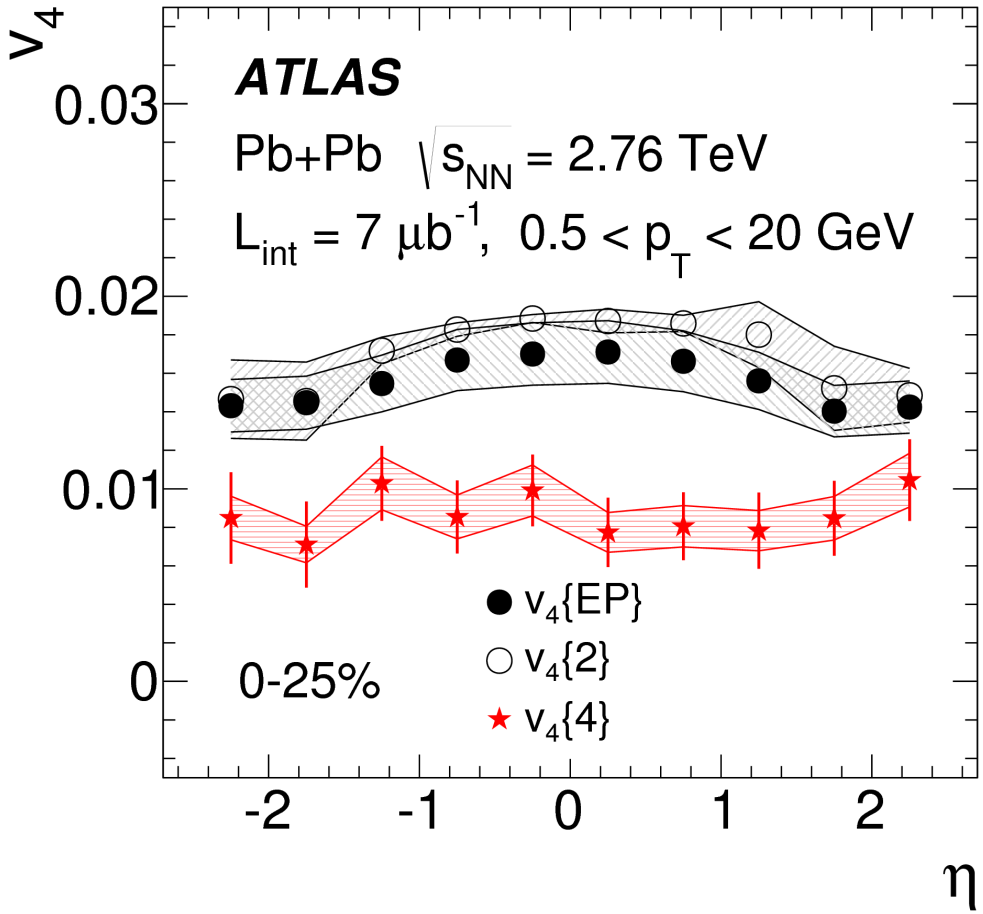
v_n{2} > v_n{EP} >> v_n{4} for n > 2

ATLAS, arXiv:1408.4342

Flow harmonics with multi-particle cumulants in Pb+Pb collisions

Weak pseudorapidity dependence of v_3 and v_4





ATLAS, arXiv:1408.4342

Flow harmonics with multi-particle cumulants in Pb+Pb collisions

Centrality dependence of v_2, v_3 and v_4

Harmonics measured using different methods have similar shape of centrality dependence, but with different magnitude:

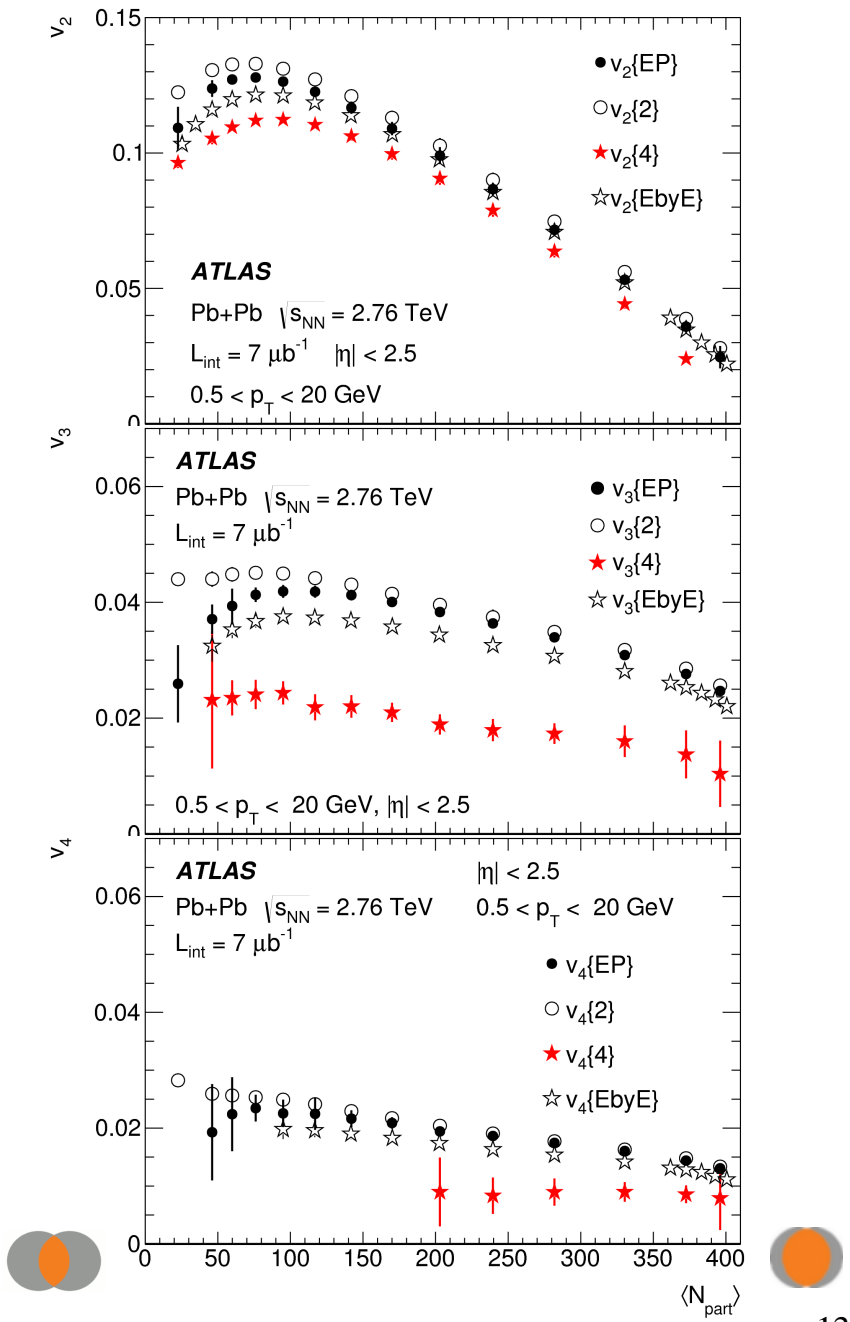
$v_2\{2\} > v_2\{EP\} > v_2\{EbyE\} > v_2\{4\}$

Note:
$v_n\{EbyE\}$ is calculated from the distribution of v_n measured event-by-event

$$v_n(EbyE) = \sum v_n\, p(v_n)$$

$v_2\{2\}$ - contains short range two particle correlations
$v_2\{EP\}$ - increased by flow fluctuations
$v_2\{EbyE\}$ - without these effects
$v_2\{4\}$ - related to the "generic" initial flow effect

ATLAS, arXiv:1408.4342



Event plane correlations in Pb+Pb collisions

Correlation between event planes Φ_n and Φ_m

$$\frac{dN_{events}}{d\left(k\left(\Phi_n-\Phi_m\right)\right)} \propto 1 + 2\sum_{j=1}^{\infty} V_{n,m}^{j}\cos jk\left(\Phi_n-\Phi_m\right)$$

$$V_{n,m}^{j} = \left\langle \cos jk\left(\Phi_n-\Phi_m\right)\right\rangle$$

Event plane angles Φ reconstructed in separated pseudorapidity intervals:
2 planes: (-4.8, -0.5) and (0.5, 4.8)
3 planes: (-2.7, -0.5), (0.5, 2.7) and (3.3, 4.8)

In the correlators combinations of angles Φ_2 to Φ_6 are used. Two methods of calculations are deployed:
EP - event plane method
SP - scalar product method - in which flow vector weights are used

For comparison unweighted or weighted correlators obtained from Glauber model are calculated.

Correlators:

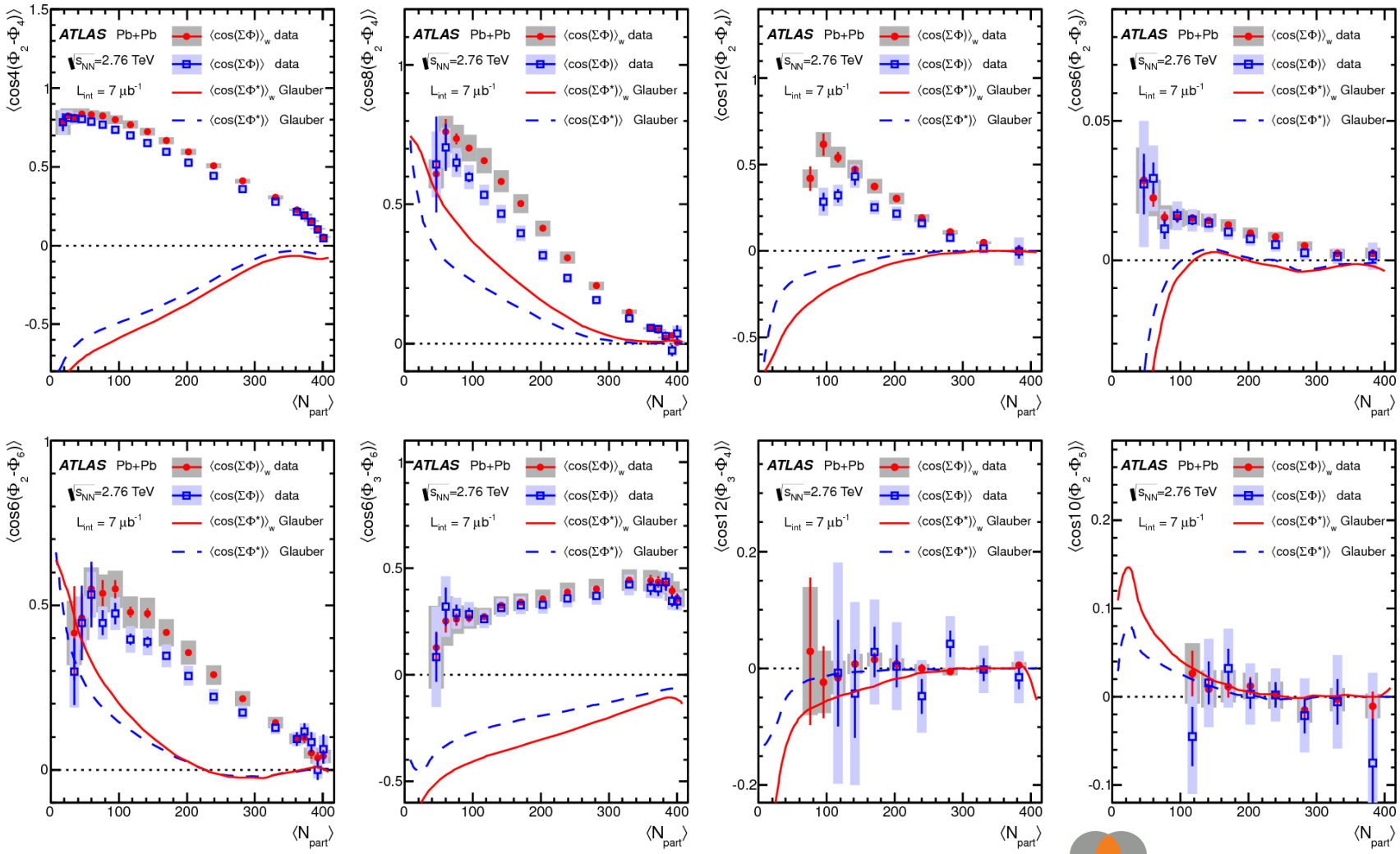
$\left\langle \cos 4\left(\Phi_2-\Phi_4\right)\right\rangle$
$\left\langle \cos 8\left(\Phi_2-\Phi_4\right)\right\rangle$
$\left\langle \cos 12\left(\Phi_2-\Phi_4\right)\right\rangle$
$\left\langle \cos 6\left(\Phi_2-\Phi_3\right)\right\rangle$
$\left\langle \cos 6\left(\Phi_2-\Phi_6\right)\right\rangle$
$\left\langle \cos 6\left(\Phi_3-\Phi_6\right)\right\rangle$
$\left\langle \cos 12\left(\Phi_3-\Phi_4\right)\right\rangle$
$\left\langle \cos 10\left(\Phi_2-\Phi_5\right)\right\rangle$

$\left\langle \cos\left(2\Phi_2+3\Phi_3-5\Phi_5\right)\right\rangle$
$\left\langle cos4\left(-8\Phi_2+3\Phi_3+5\Phi_5\right)\right\rangle$
$\left\langle cos4\left(2\Phi_2+4\Phi_4-6\Phi_6\right)\right\rangle$
$\left\langle cos4\left(-10\Phi_2+4\Phi_4+6\Phi_6\right)\right\rangle$
$\left\langle cos4\left(2\Phi_2-6\Phi_3+4\Phi_4\right)\right\rangle$
$\left\langle cos4\left(-10\Phi_2+6\Phi_3+4\Phi_4\right)\right\rangle$

Event plane correlations in Pb+Pb collisions

Correlation between two event planes Φ_n and Φ_m

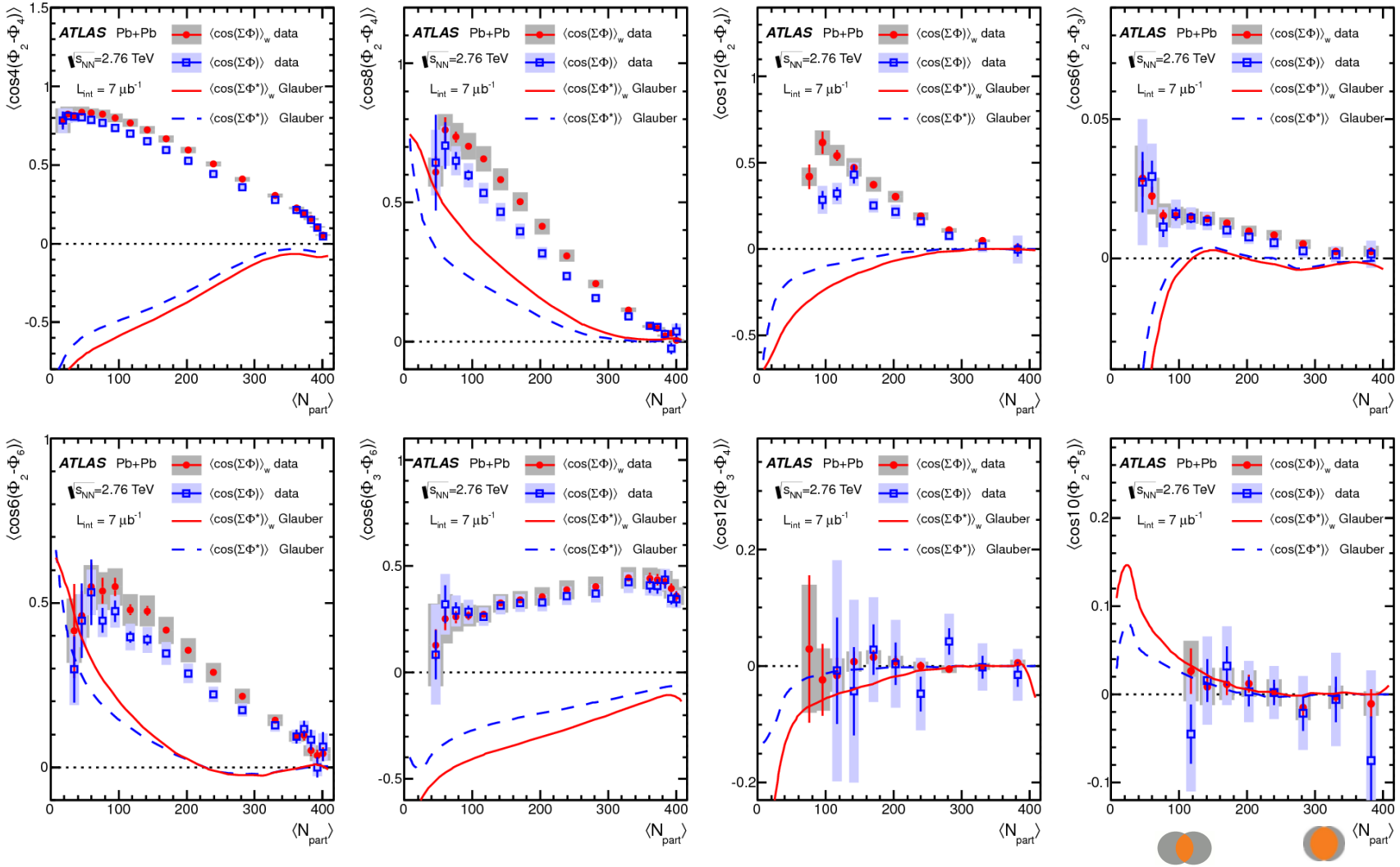
$$\frac{dN_{events}}{d\left(k\left(\Phi_n-\Phi_m\right)\right)} \propto 1 + 2\sum_{j=1}^{\infty} V_{n,m}^{j} \cos jk\left(\Phi_n-\Phi_m\right), \qquad V_{n,m}^{j} = \left\langle \cos jk\left(\Phi_n-\Phi_m\right)\right\rangle$$



ATLAS, arXiv:1403.0489v1 [hep-ex]

Event plane correlations in Pb+Pb collisions

Correlation between two event planes Φ_n and Φ_m



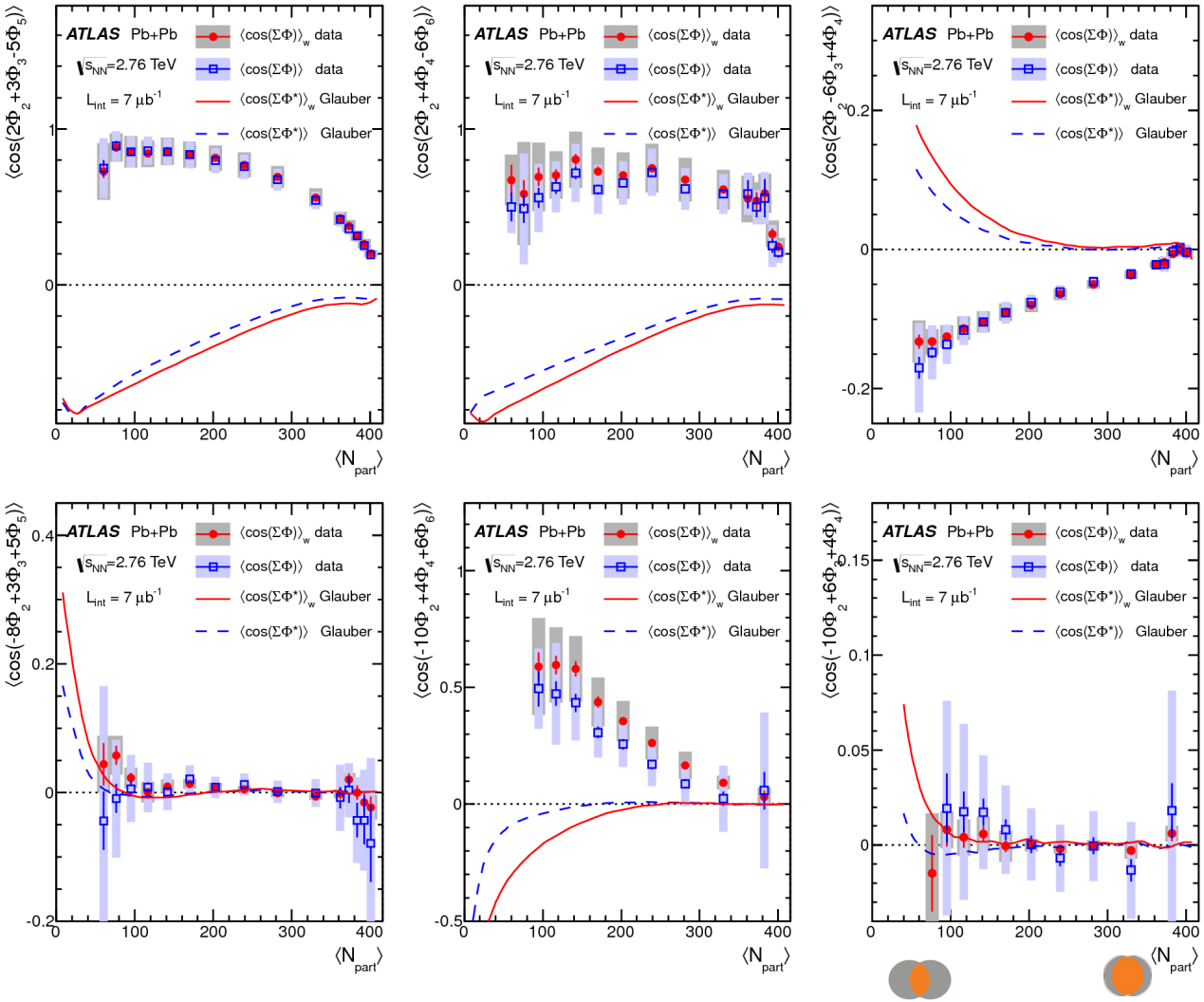
Glauber model does not describe these correlations

ATLAS, arXiv:1403.0489v1 [hep-ex]

Event plane correlations in Pb+Pb collisions

Correlation between three event planes Φ_n, Φ_m and Φ_h

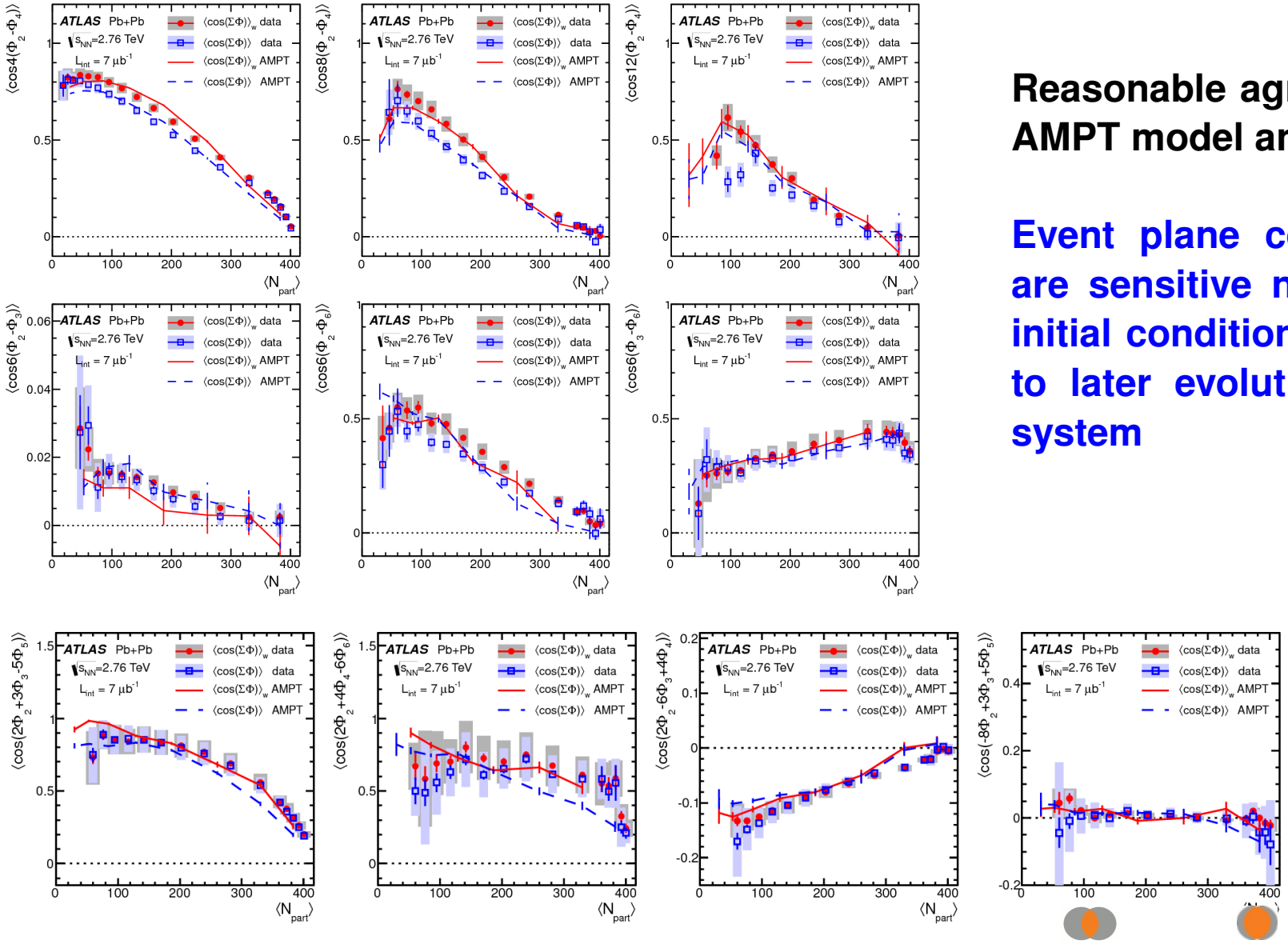
$$\left\langle \cos\left(c_n n\Phi_n + c_m m\Phi_m + c_h h\Phi_h\right)\right\rangle$$



ATLAS, arXiv:1403.0489v1 [hep-ex]

Event plane correlations in Pb+Pb collisions

Comparison with AMPT model predictions



Reasonable agreement of AMPT model and the data

Event plane correlations are sensitive not only to initial conditions but also to later evolution of the system

ATLAS, arXiv:1403.0489v1 [hep-ex]

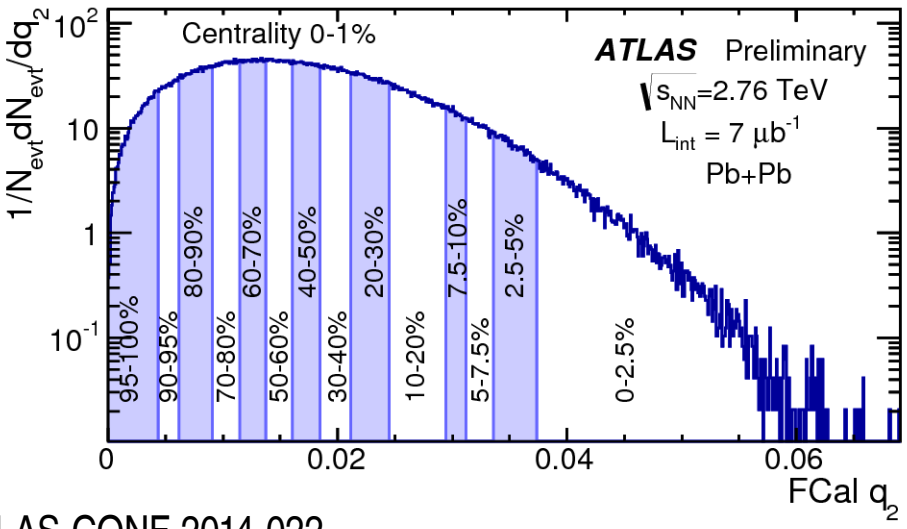
Correlations between flow harmonics in Pb+Pb collisions

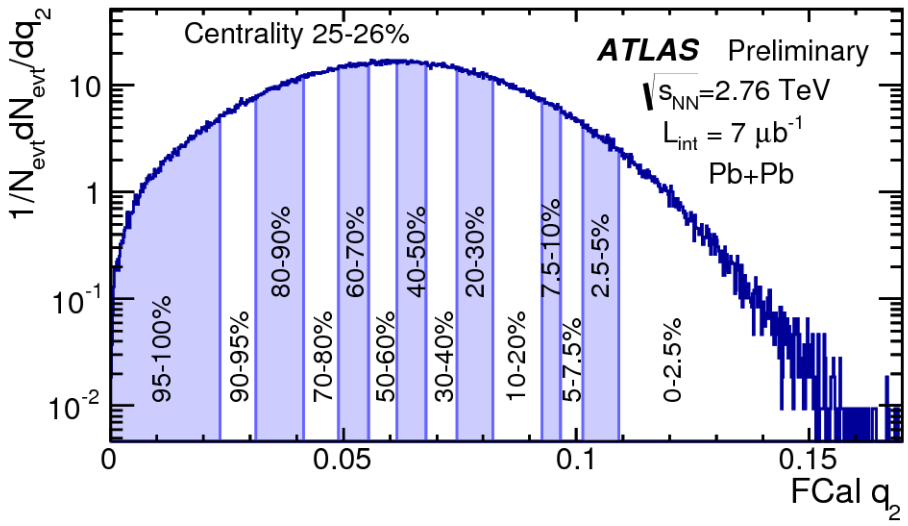
Studies of correlations between v_2 and v_n (n=2-5), obtained from two-particle correlations:

- **as a function of centrality**
- **as a function of p_T**
- **as a function of event shape, characterized by q_2 - flow vector magnitude, measured in 3.3 < |η| < 4.8 interval**

$$\vec{q}_2 = \left(q_{x,2}^2, q_{y,2}^2\right) = \frac{1}{\sum w_i}\left(\sum w_i \cos 2\phi_i, \sum w_i \cos 2\phi_i\right) - \langle \vec{q}_2 \rangle$$

$$q_2 = \sqrt{q_{x,2}^2 + q_{y,2}^2}$$





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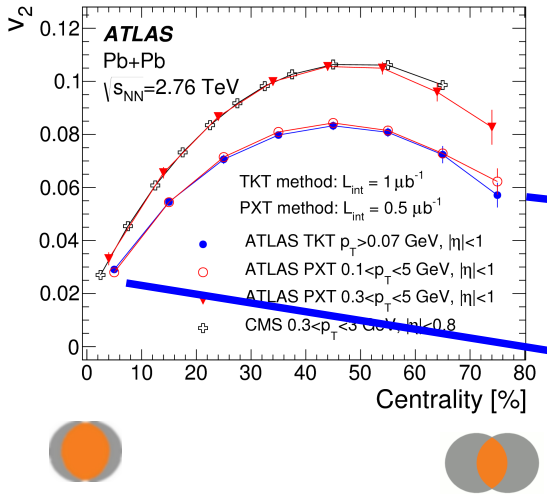
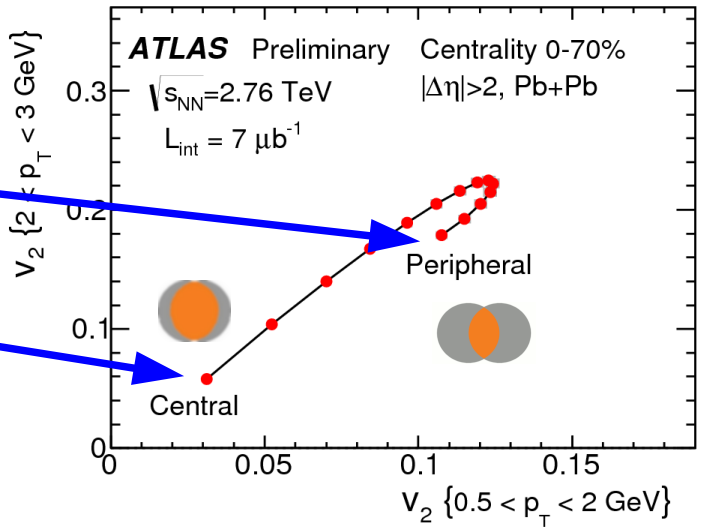
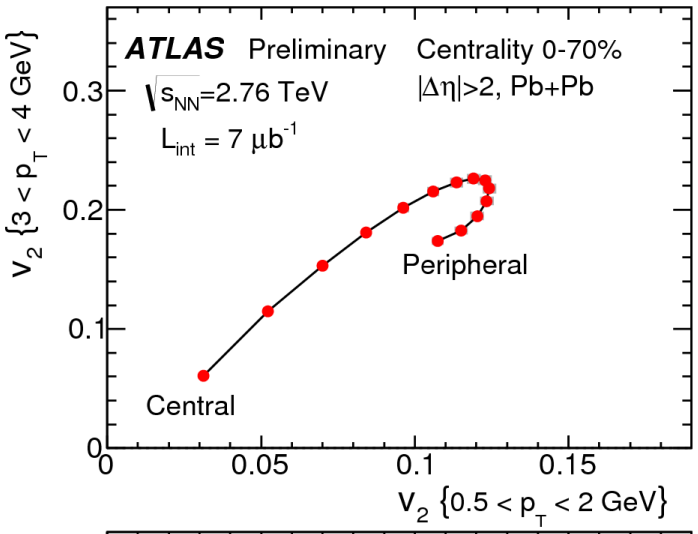
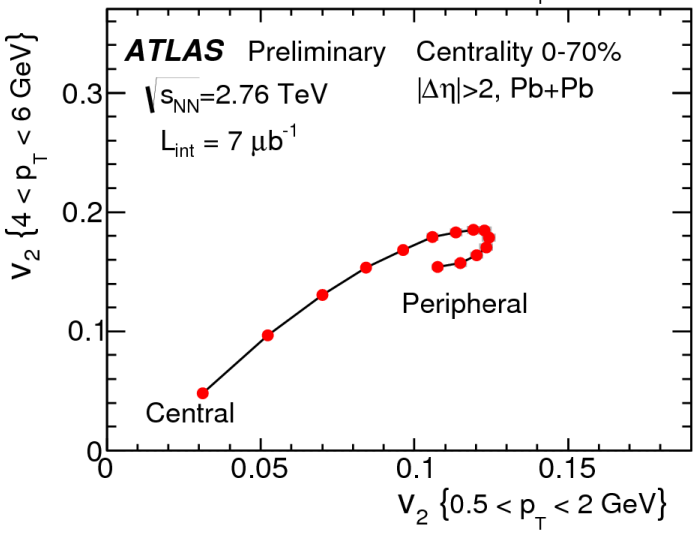
Correlations between flow harmonics in Pb+Pb collisions

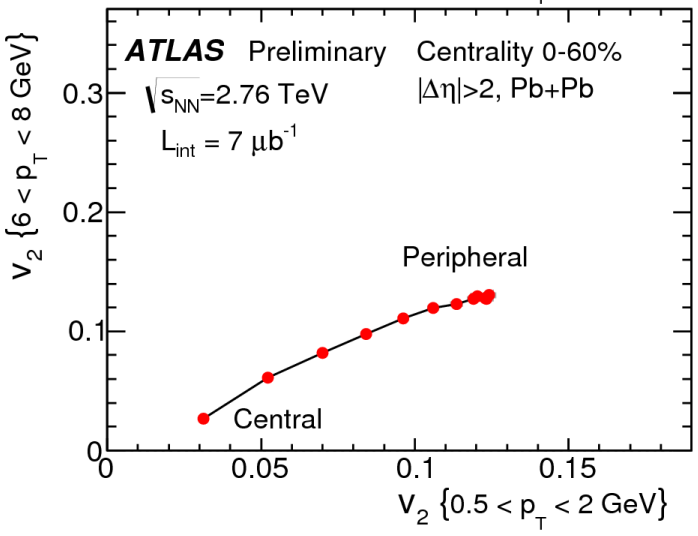
Correlations between v_2 values for different p_T ranges











The "boomerang" shape is consistent with larger viscous-damping effects expected from hydrodynamic calculations

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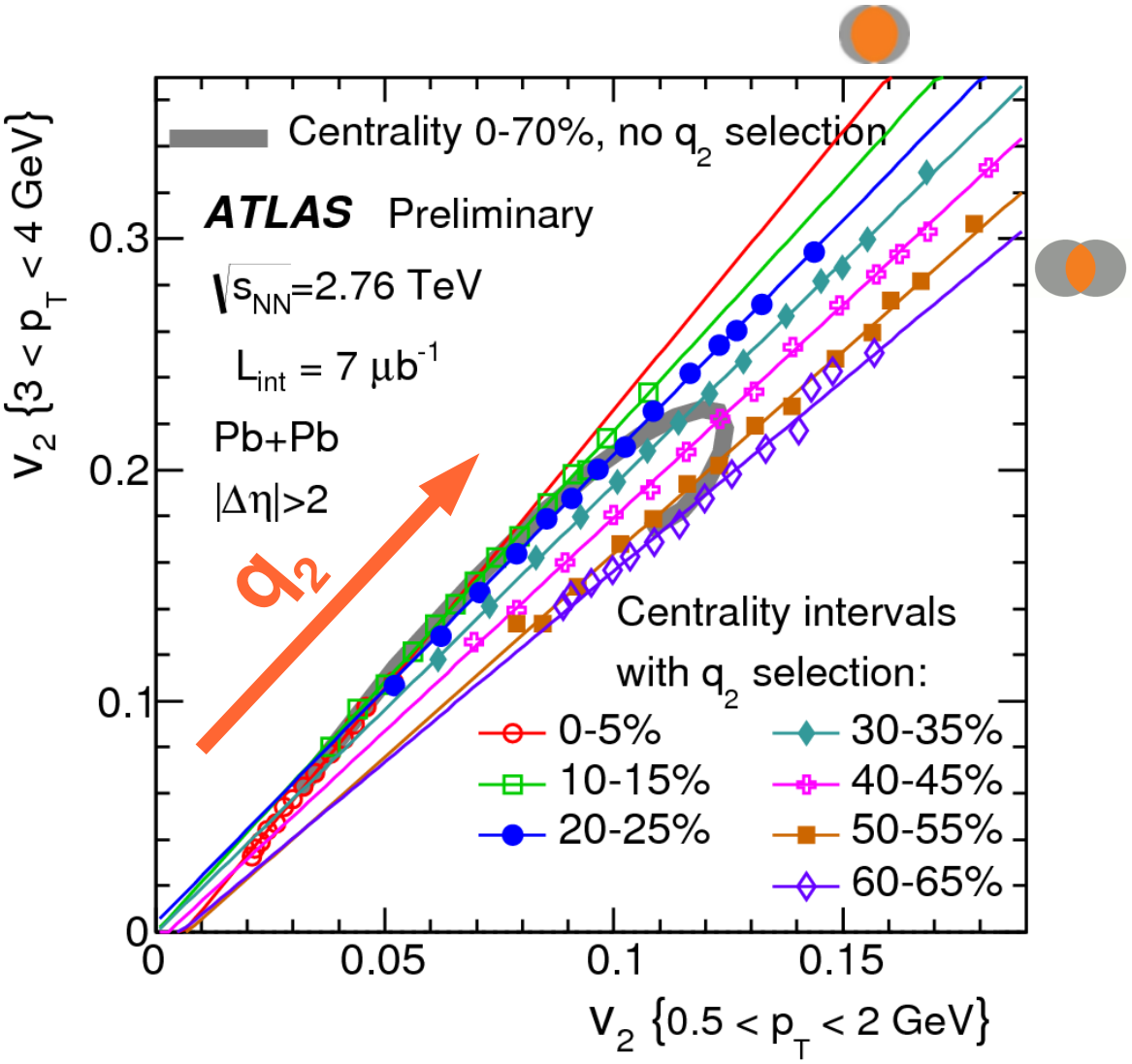
Correlations between flow harmonics in Pb+Pb collisions

Correlations between v_2 values for different p_T ranges

When events in each centrality bin are divided into subsamples according to q_2 values, linear correlations are observed.
For fixed centrality the viscous-damping changes very little with event ellipticity.

Viscous corrections are controlled by the overall system size.



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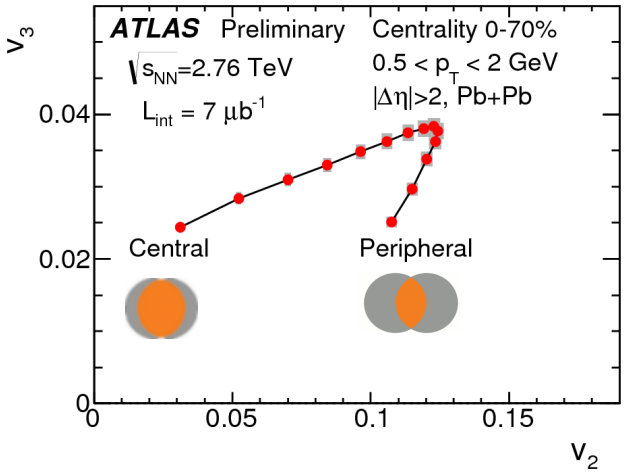
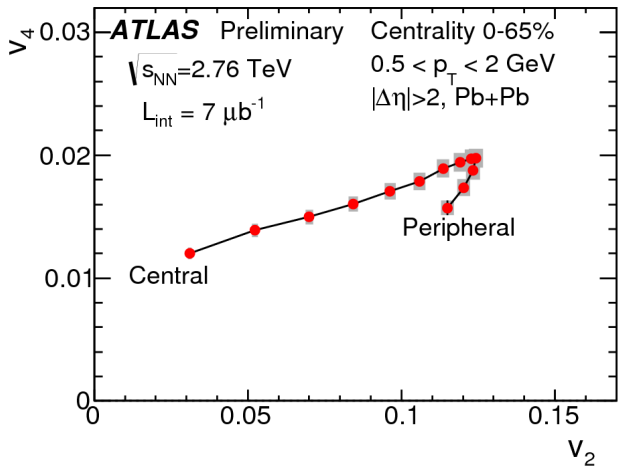
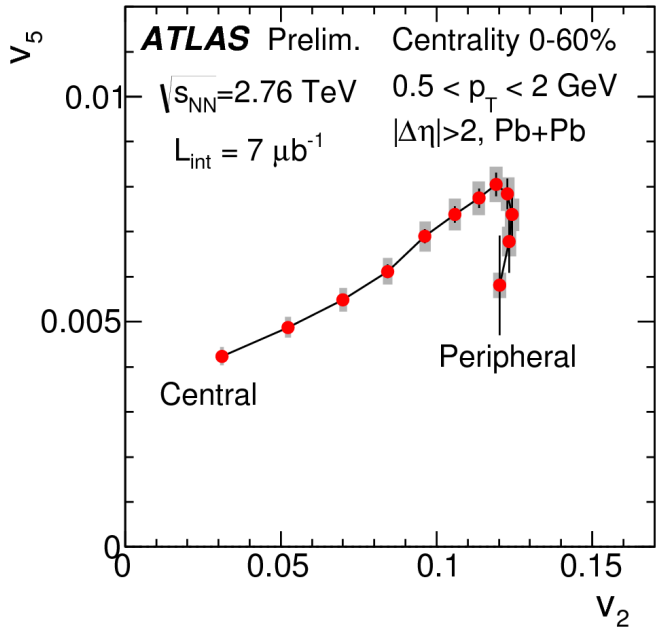
Correlations between flow harmonics in Pb+Pb collisions

Centrality dependence of correlations between v_2 and v_n (n=3-5) measured in the same range of p_T







Similar dependence also at higher p_T

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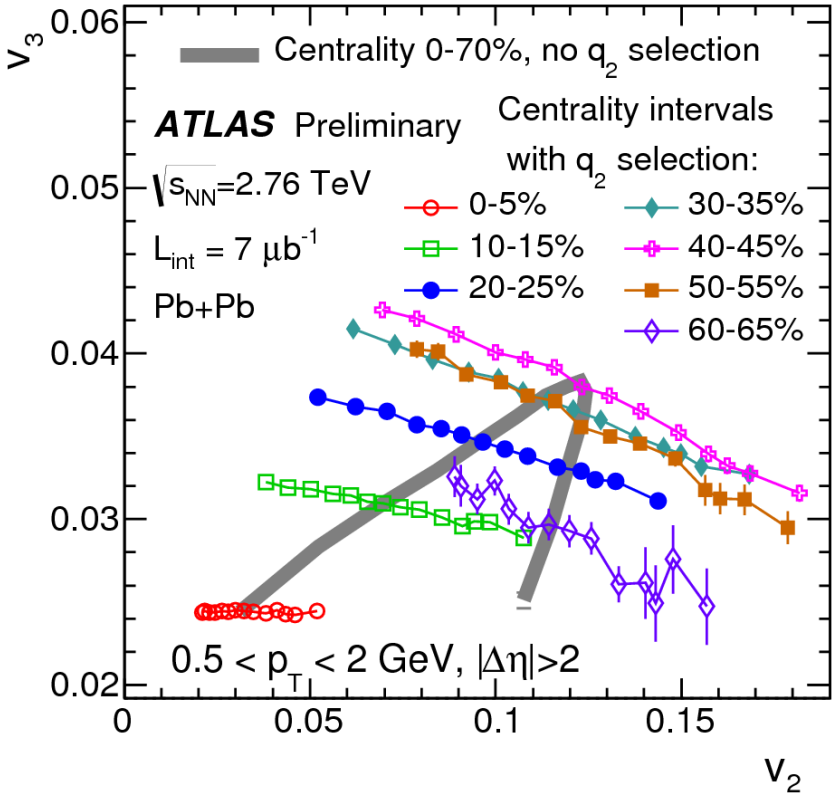
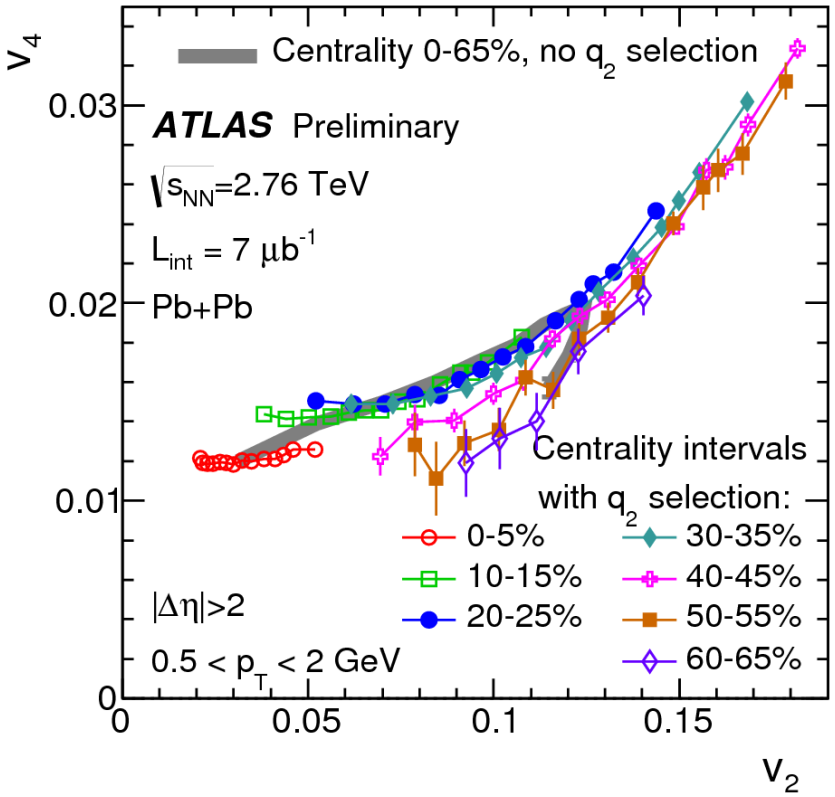
Correlations between flow harmonics in Pb+Pb collisions

Centrality and q_2 dependence of correlations between v_2 and v_3 or v_4





Negative correlation between v_2 and v_3 for changing q_2 within fixed centrality

Positive, non linear correlation between v_2 and v_4 for changing q_2 within fixed centrality

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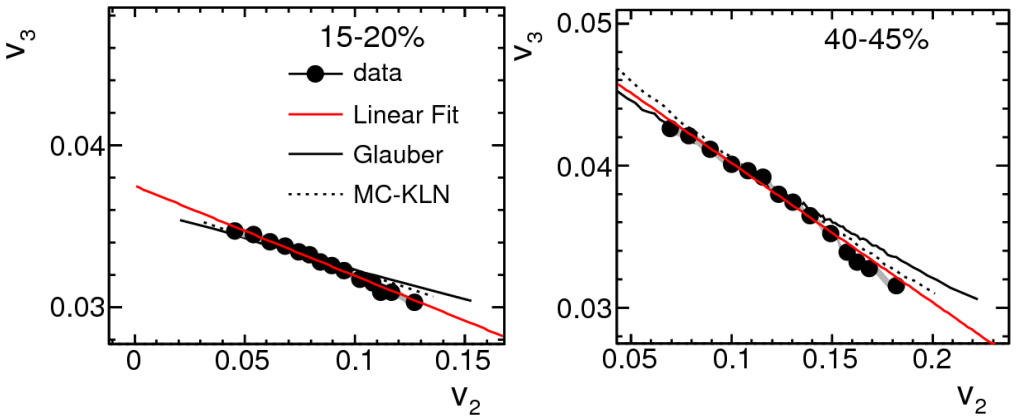
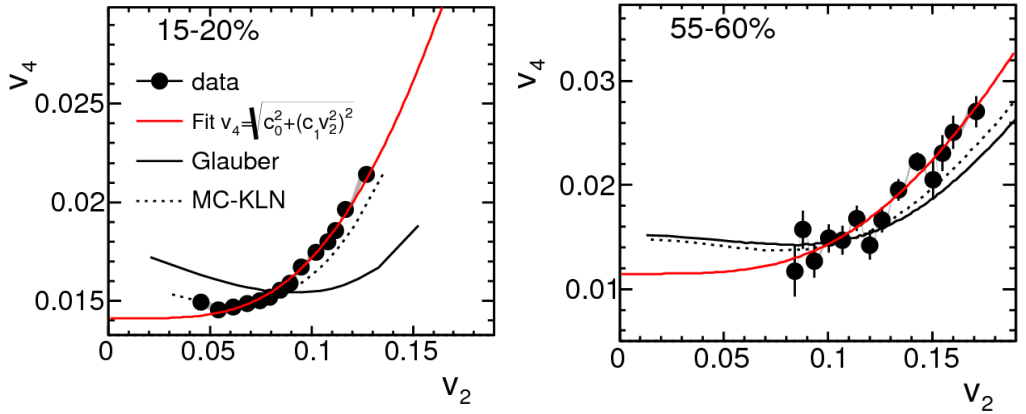
Correlations between flow harmonics in Pb+Pb collisions

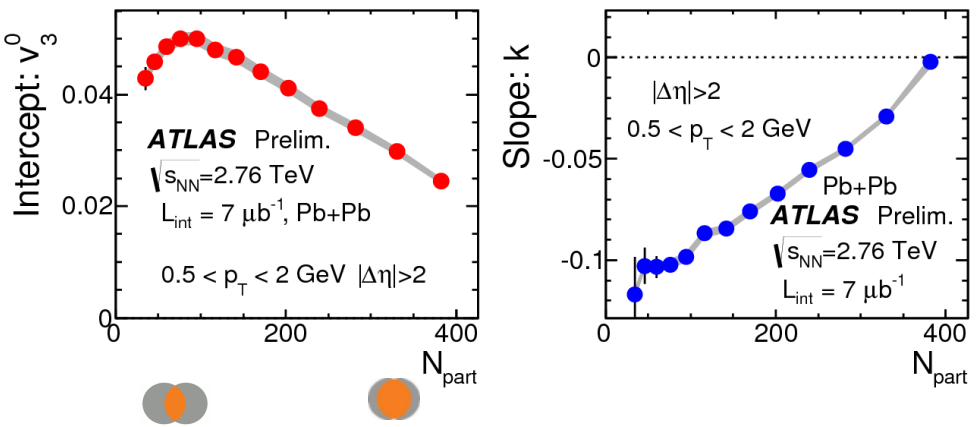
Centrality and q_2 dependence of correlations between v_2 and v_3 or v_4

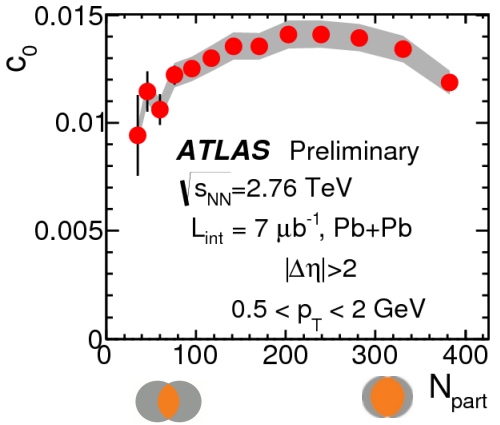


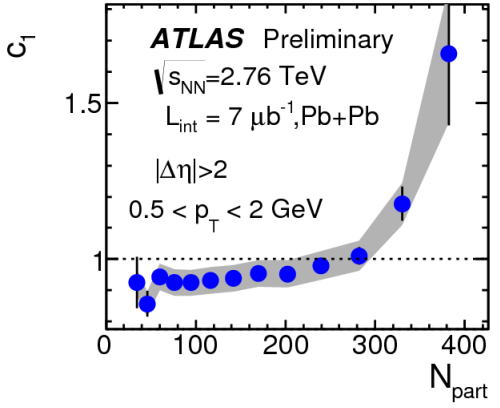


$$fit: \quad v_3 = k\,v_2 + v_3^0$$

$$fit: \quad v_4 = \sqrt{c_0^2 + (c_1 v_2^2)^2}$$







Parameters of the fit can be used to extract linear and non-linear component of v_4

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Correlations between flow harmonics in Pb+Pb collisions

Linear and non-linear terms in v_4

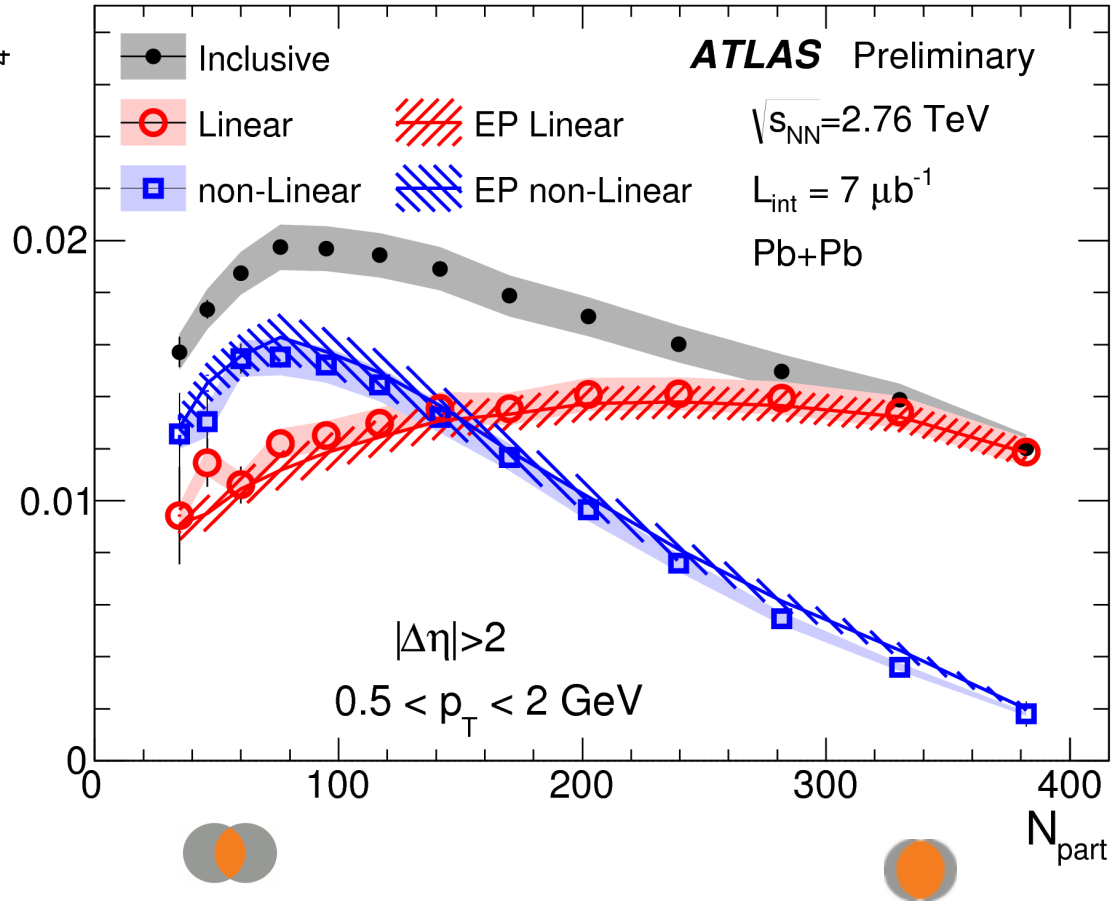
$$fit: \quad v_4 = \sqrt{c_0^2 + (c_1 v_2^2)^2}$$

Parameters of the fit can be used to extract linear and non-linear components of v_4

$$v_4^L = c_0$$
$$v_4^{NL} = \sqrt{v_4^2 - c_0^2}$$

The same components can be calculated using the correlations between event planes

$$v_4^{NL} = v_4 \langle \cos 4(\Phi_2 - \Phi_4) \rangle$$
$$v_4^L = \sqrt{v_4^2 - (v_4^{NL})^2}$$



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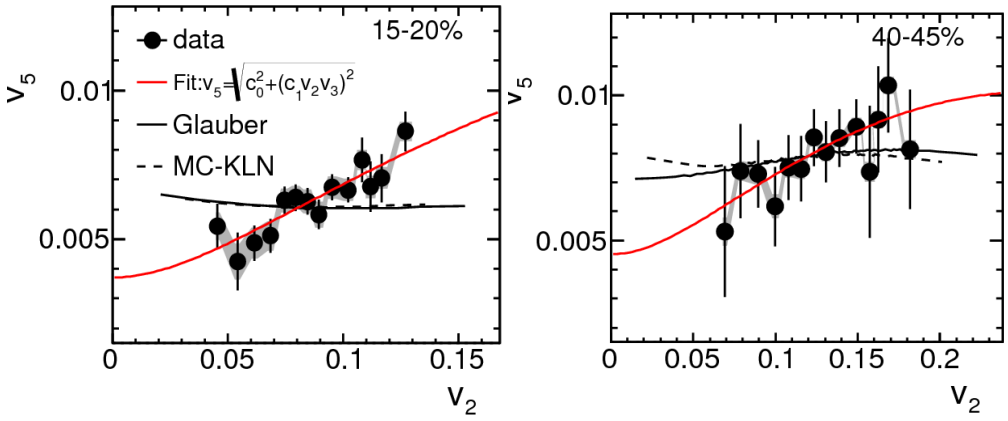
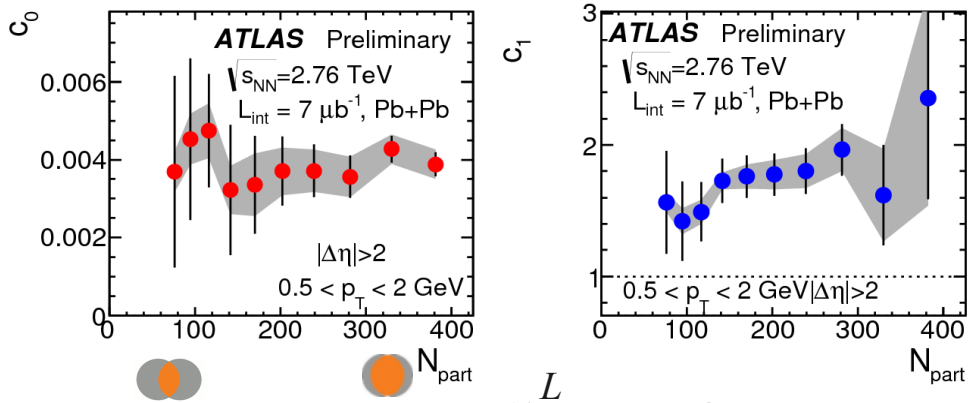
Correlations between flow harmonics in Pb+Pb collisions

Centrality and q_2 dependence of correlations between v_2 and v_5

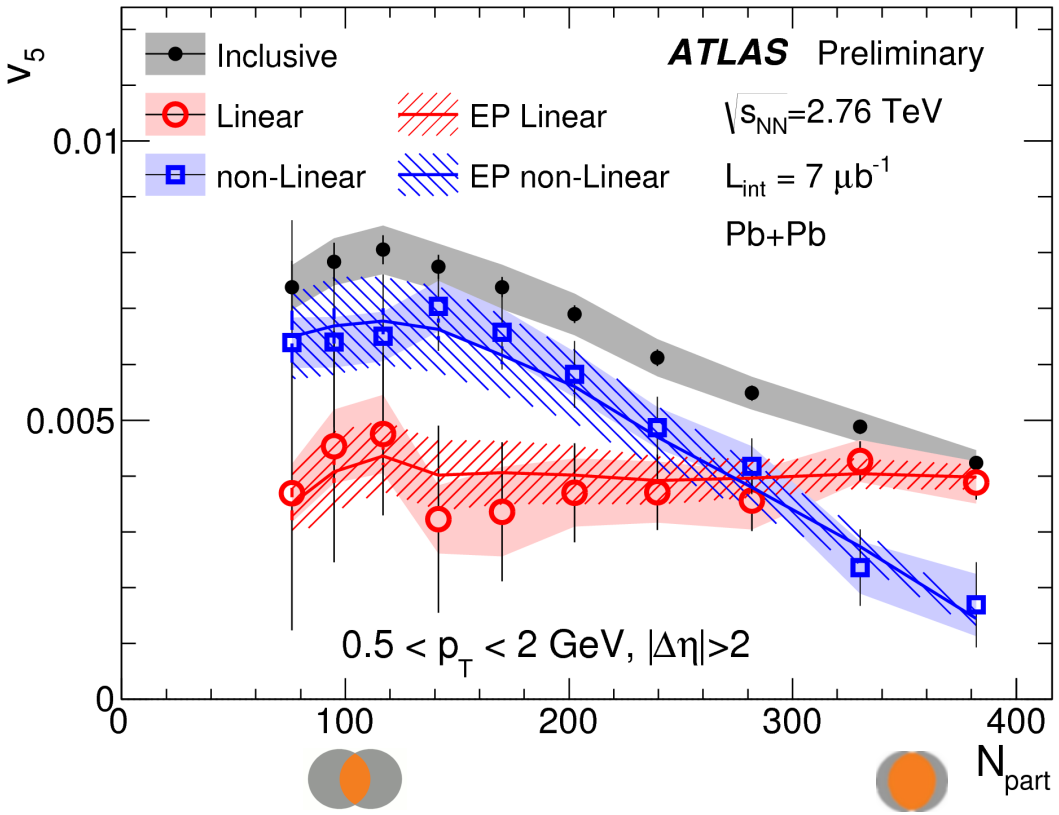


$$fit: \quad v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2}$$



$$v_5^L = c_0$$

$$v_5^{NL} = \sqrt{v_5^2 - c_0^2}$$



Linear and non-linear components of v_5 from event plane correlator:

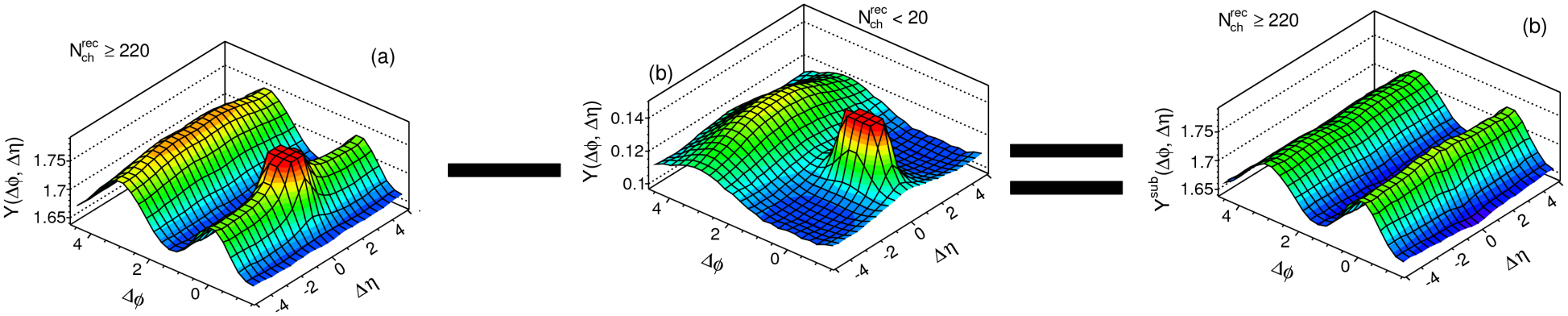
$$v_5^L = v_5 \langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$$

$$v_5^{NL} = \sqrt{v_5^2 - (v_5)^2}$$

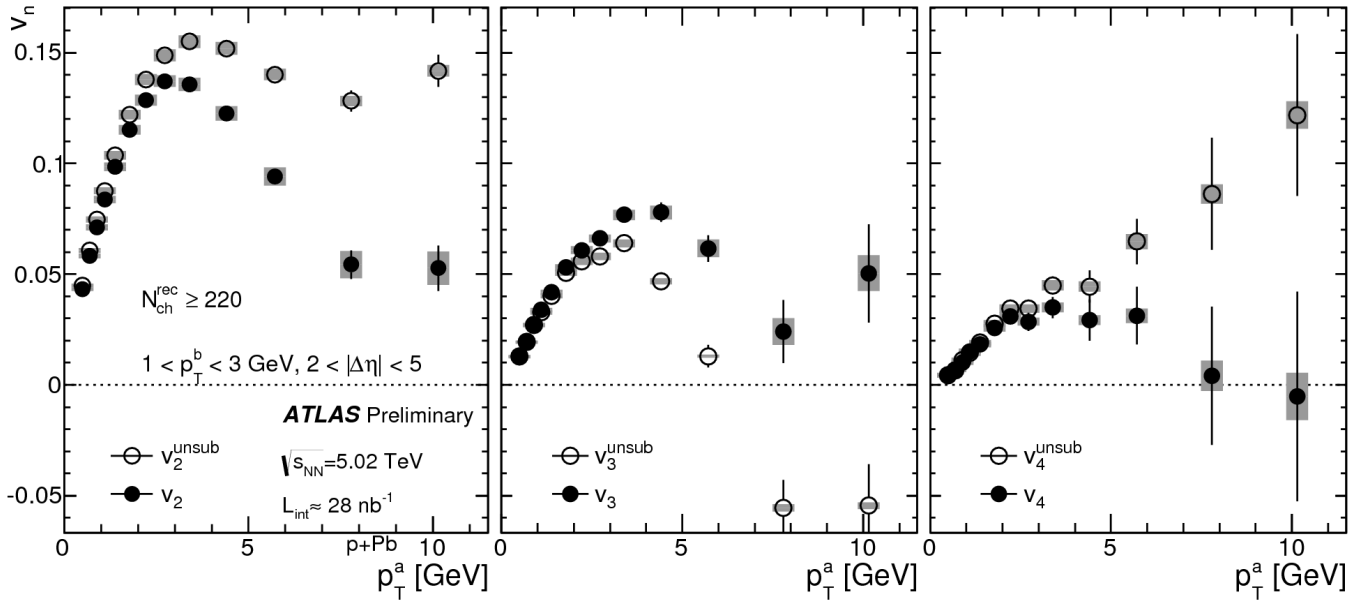
ATLAS-CONF-2014-022

Long-range pseudorapidity correlations in p+Pb collisions

To study long-range effects the yield from peripheral events needs to be subtracted:



Flow harmonics obtained from correlation function without subtraction (v_n^{unsub}) and after subtraction (v_n)



More details were given in the earlier talk by Martin Spousta

ATLAS-CONF-2014-021

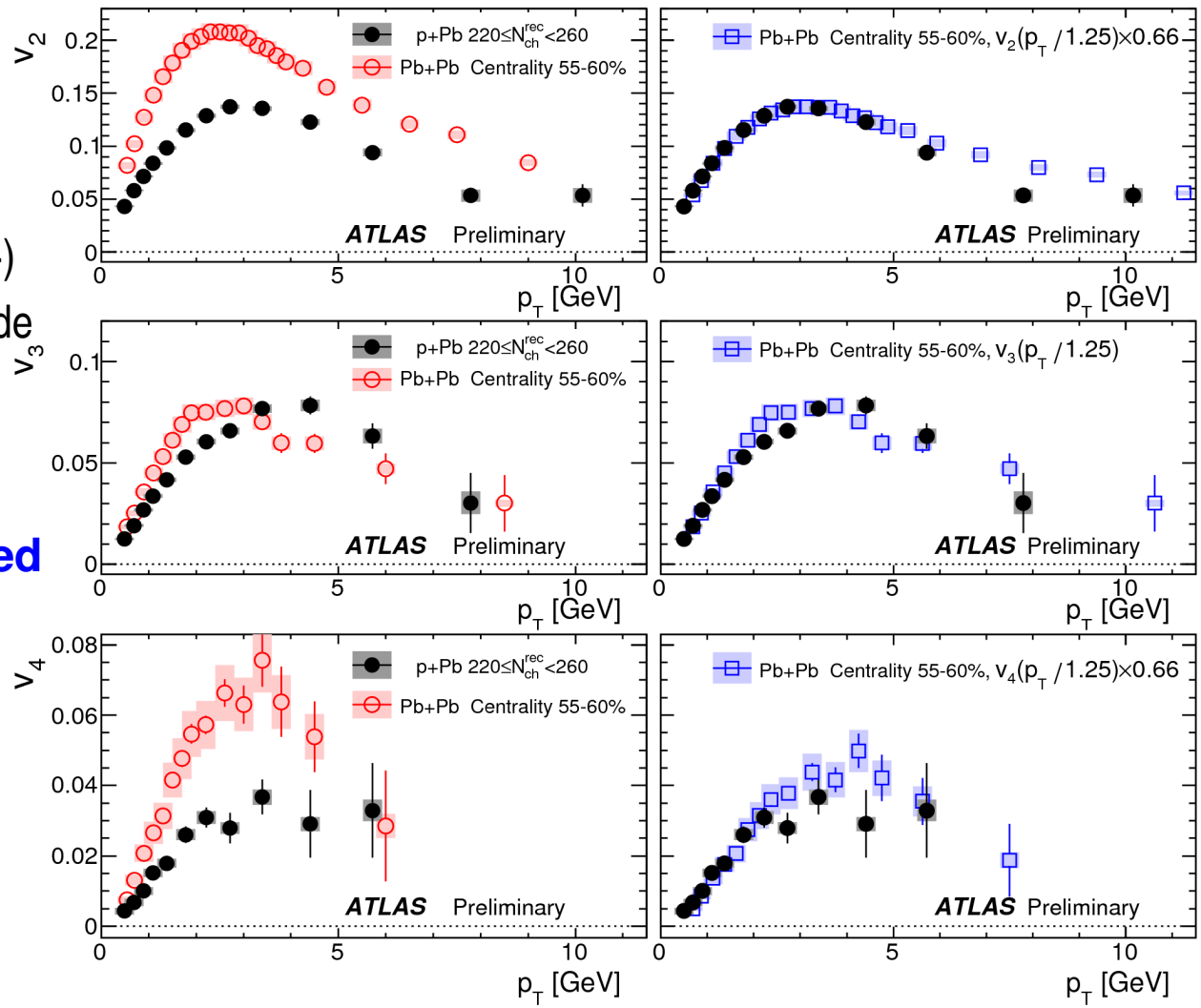
Long-range pseudorapidity correlations in p+Pb collisions

Comparison of $v_n(p_T)$ in p+Pb and Pb+Pb collisions

Rescaling of Pb+Pb harmonics:

- change of p_T by a factor K=1.25 (to account for different values of $\langle p_T \rangle$)
- modification of the absolute magnitude of v_2 and v_4 by a common empirical factor 0.66

Similar shape of $v_n(p_T)$ is obtained



More details were given in the earlier talk by Martin Spousta

ATLAS-CONF-2014-021

Summary

Integrated elliptic flow

- measurement of elliptic flow down-to very low p_T ($p_T > 0.07$ GeV)
- no need for model dependent extrapolations to $p_T=0$

Flow harmonics from multi-particle cumulants

- higher order cumulants insensitive to two-particle correlations
- harmonics obtained from cumulants better represent real flow
- confirmed significant non-flow contribution in v_n from two-particle correlations
- $v_2\{2\} > v_2\{EP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- strong centrality dependence of v_2 and a weak dependence of v_n for n>2

Event plane correlations

- correlations between 2 or 3 event planes studied
- Glauber model inconsistent with the data, AMPT model including final state collective dynamics describes these correlations well

Correlations between flow harmonics

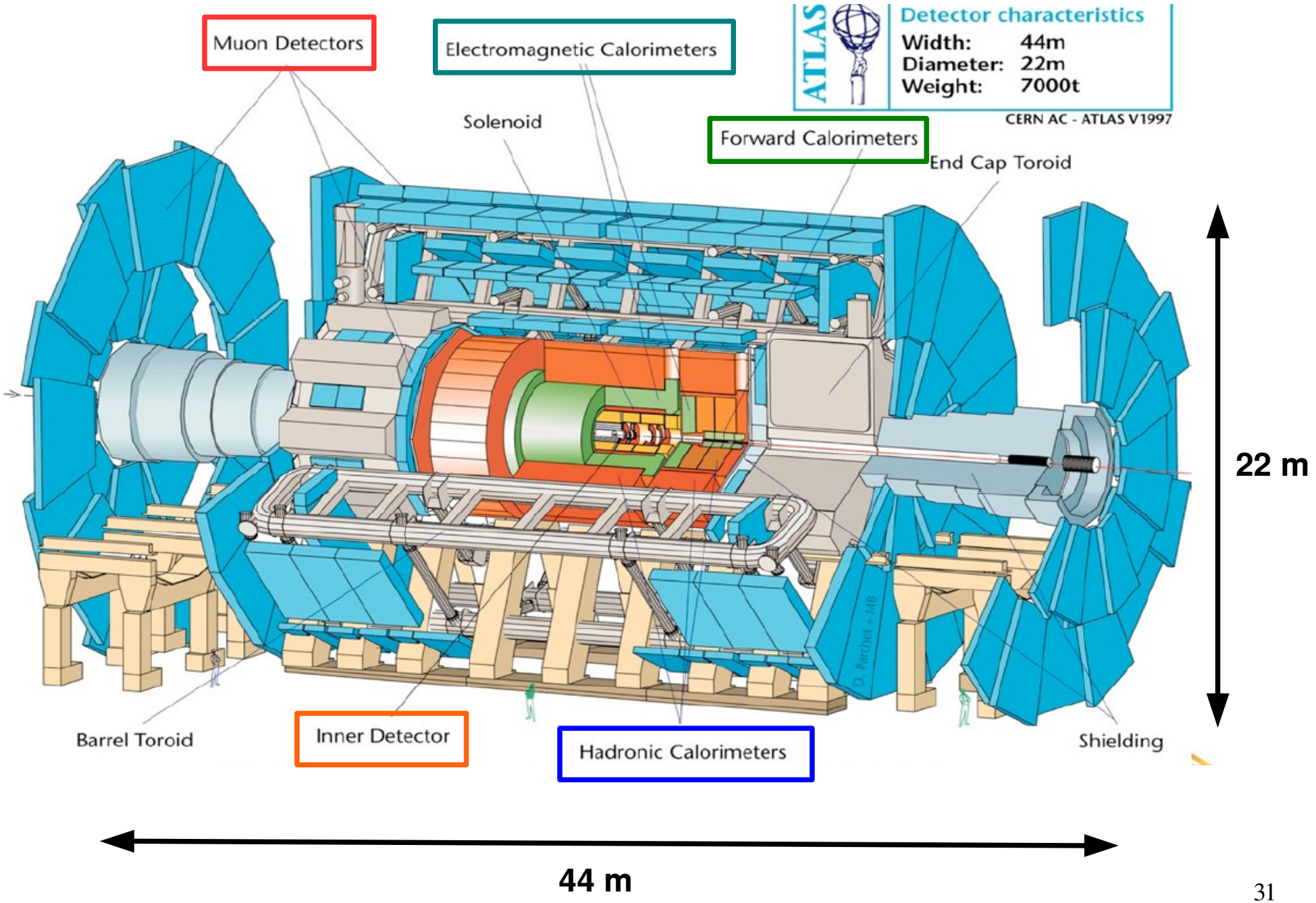
- presence of viscous-damping effects expected from hydrodynamic calculations
- negative correlation between v_2 and v_3 for changing ellipticity within fixed centrality
- positive, non linear correlation between v_2 and v4 for changing q_2 within fixed centrality

Long range pseudorapidity correlations

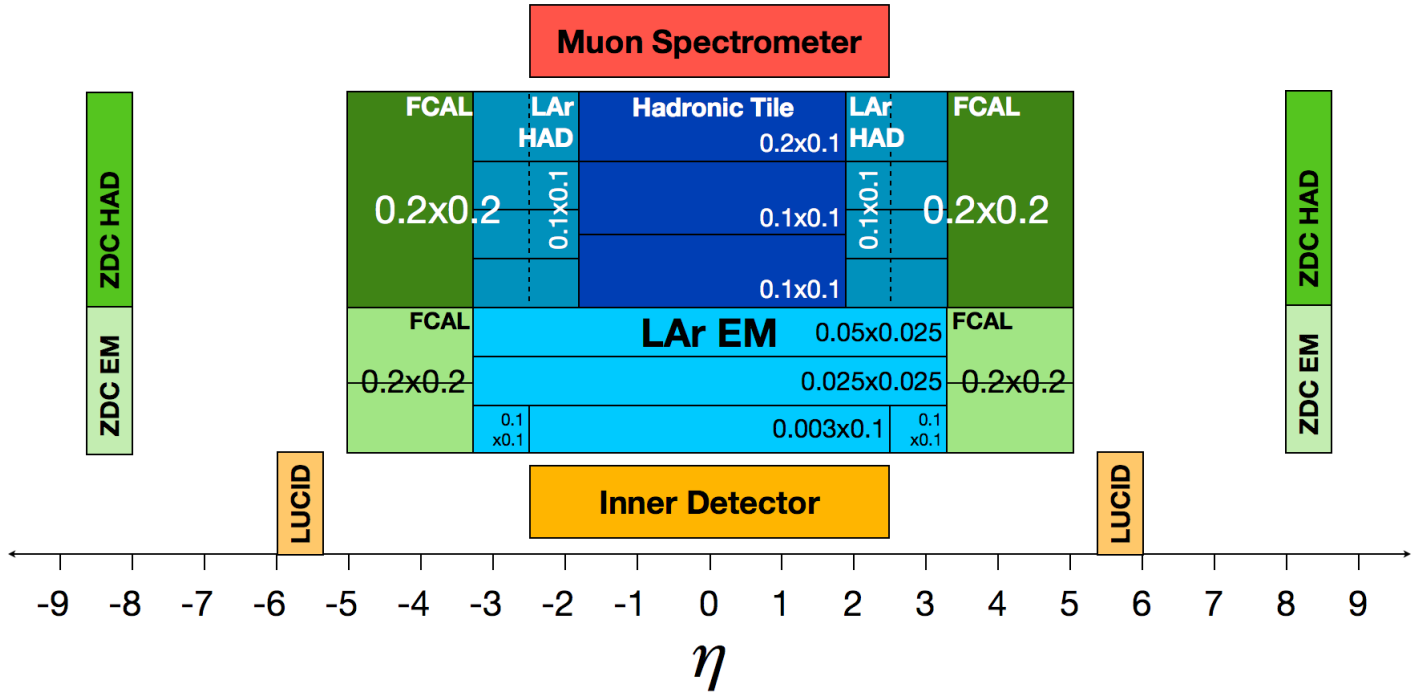
- significant correlations extending to $|\Delta\eta| \approx 5$ present also in the away-side
- extracted $v_n(p_T)$ (n=2-4) in p+Pb collisions similar to those in Pb+Pb collisions after appropriate rescaling

Backup

The ATLAS detector



The ATLAS detector



Inner detector — $|\eta|<2.5$ — **track reconstruction**

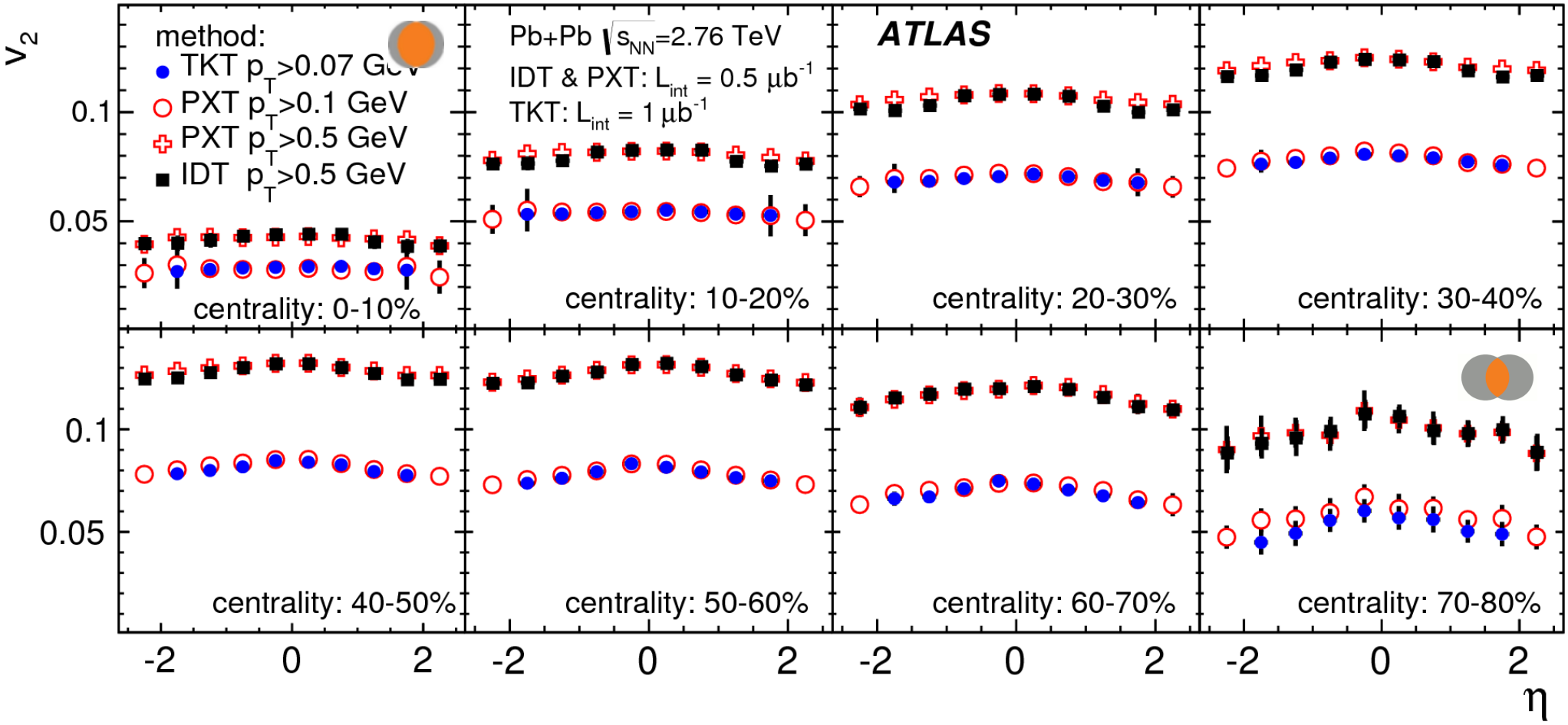
Calorimeter — $|\eta|<3.2$ — **jet reconstruction**

Forward Calorimeter — $3.2<|\eta|<4.9$ — **centrality determination**

Muon spectrometer — $|\eta|<2.7$ — **muon reconstruction**

Integrated elliptic flow in Pb+Pb collisions

Integrated elliptic flow - η dependence:



ATLAS, arXiv:1405.3936v2