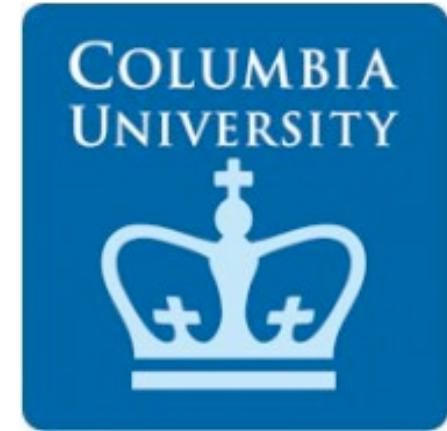


Recent results on flow and correlations from the ATLAS experiment



Soumya Mohapatra
Columbia University

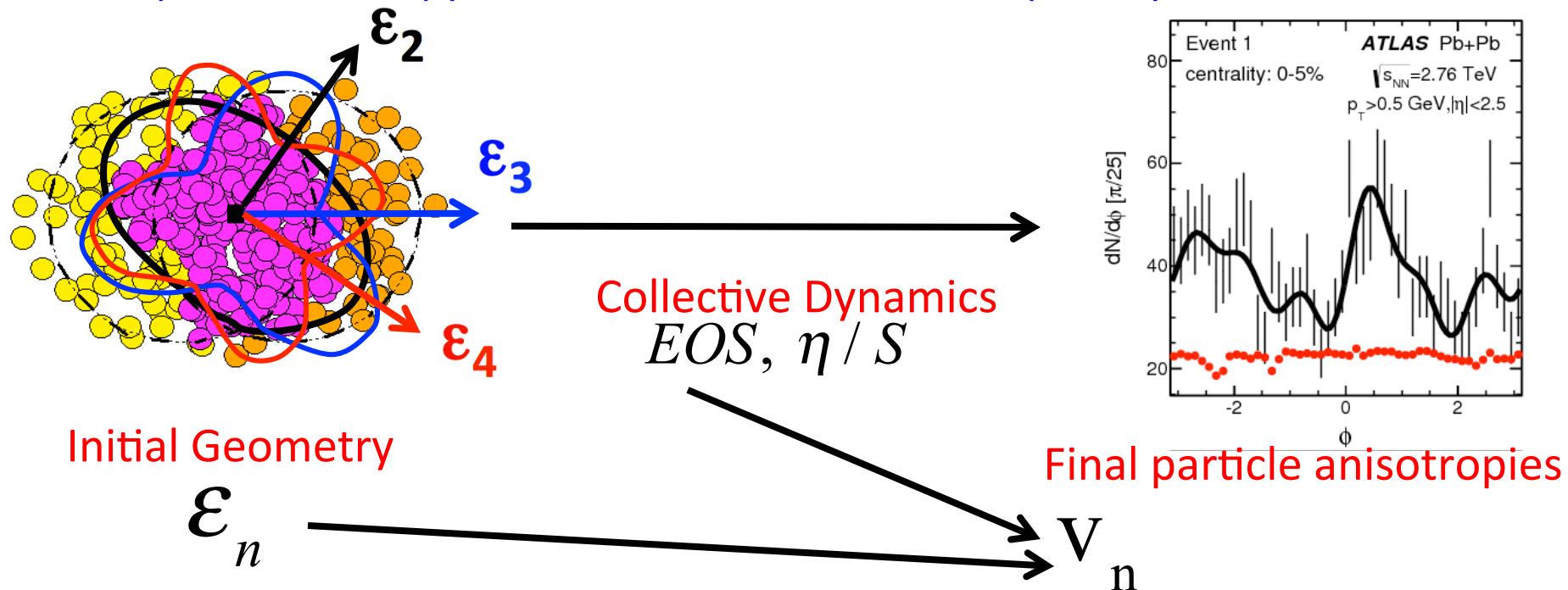
For the ATLAS Collaboration



- ATLAS Event-by-Event v_n paper: JHEP11(2013)183
- ATLAS Event-Plane correlation paper: Phys. Rev. C 90, 024905 (2014)
- ATLAS flow correlation paper: arXiv:1504.01289

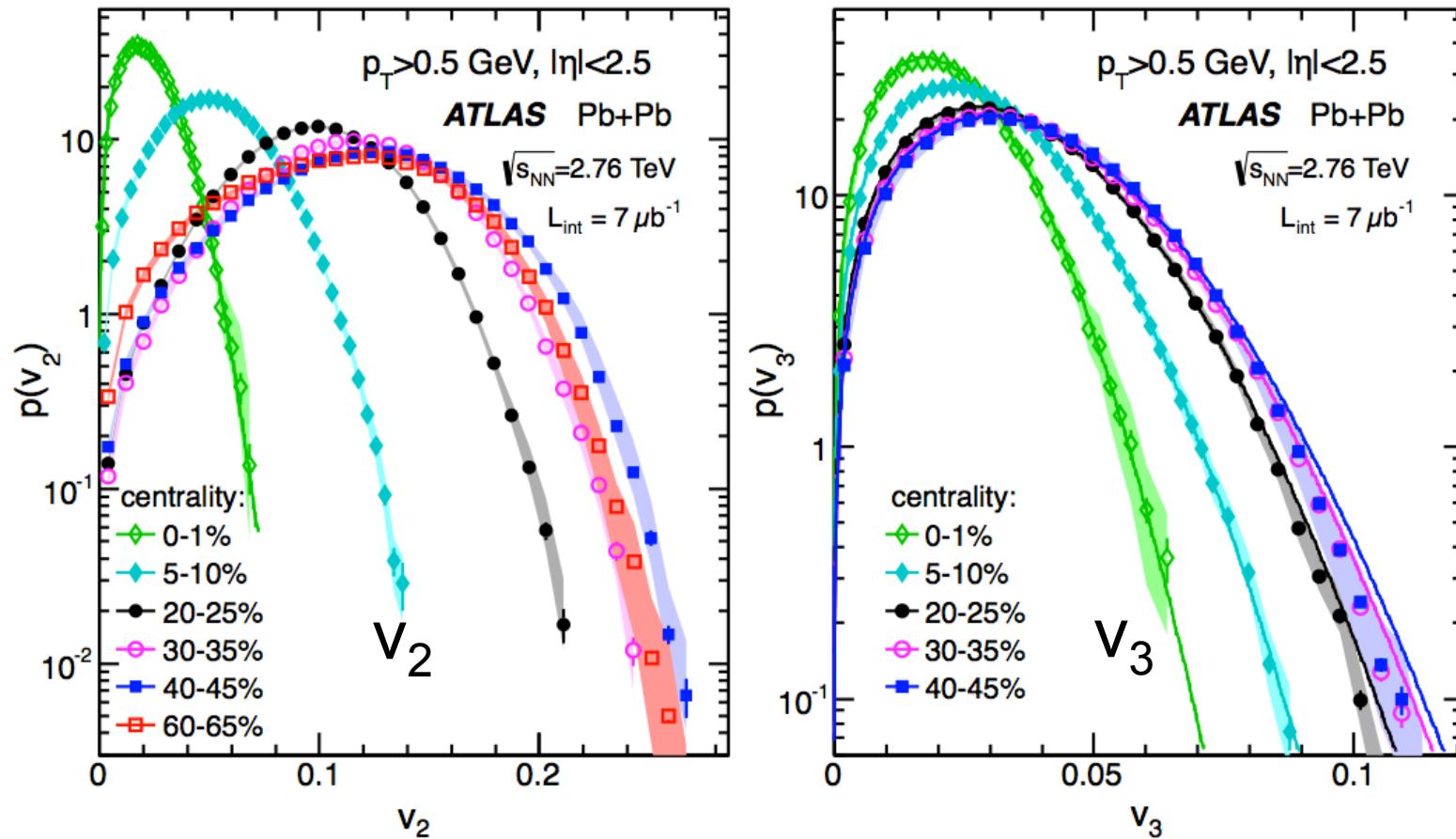
Introduction

- Initial spatial fluctuations of nucleons lead to higher moments of deformations in the fireball, each with its own orientation.
- The spatial anisotropy is transferred to momentum space by collective flow.



- The harmonics v_n carry information about the medium: initial geometry, η/s .
- Measuring harmonics = Understanding initial geometry & medium properties

v_2 - v_3 probability distributions

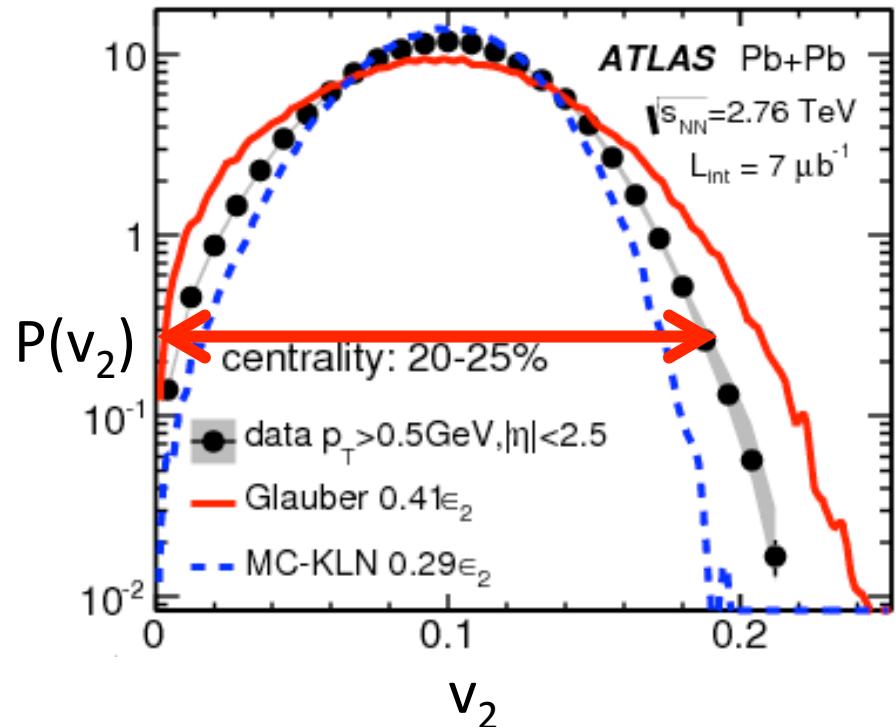
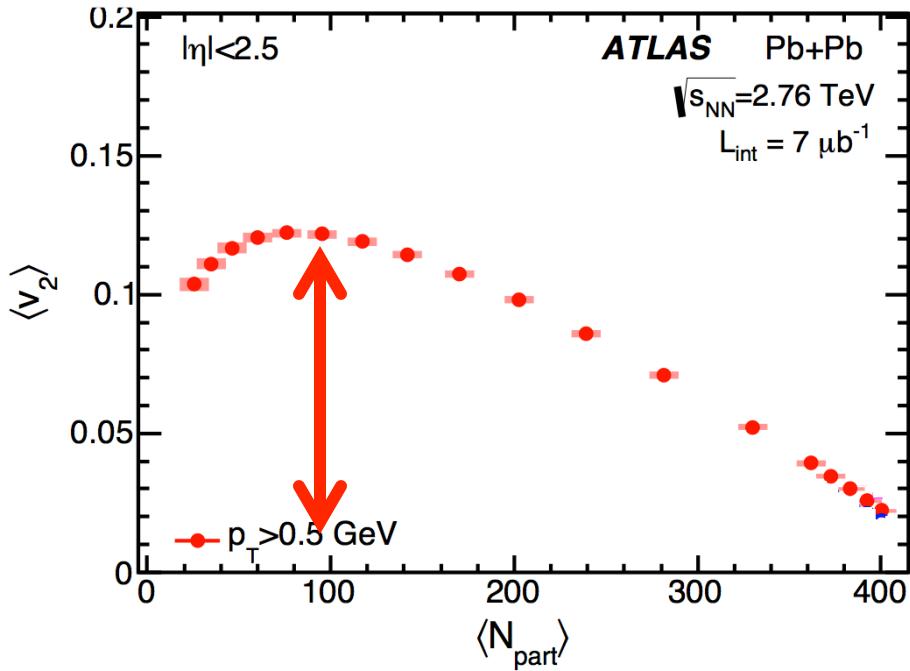


Comprehensive flow measurements: Event-by-Event Probability distributions for flow harmonics

JHEP11(2013)183

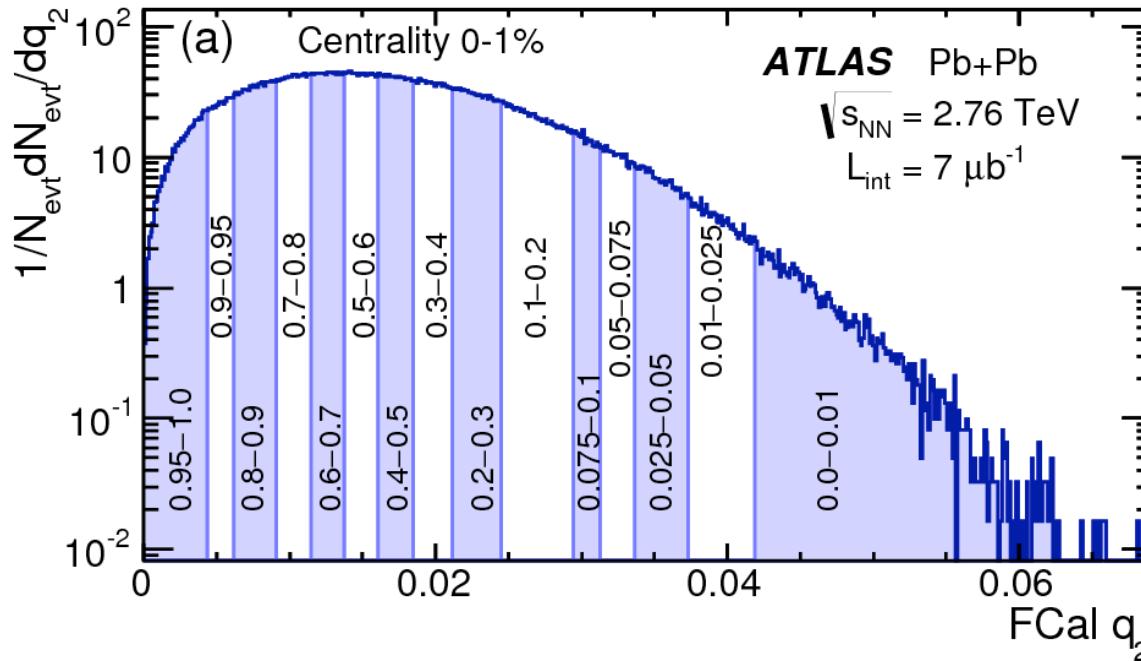
Fluctuations in v_n distributions

JHEP11(2013)183



- Much more variation in v_2 within one centrality than variation of mean v_2 across all centralities
- Traditionally centrality is used as proxy for geometry
- Entangles “event-shape” effects with “event-size” effects

Event-shape selection

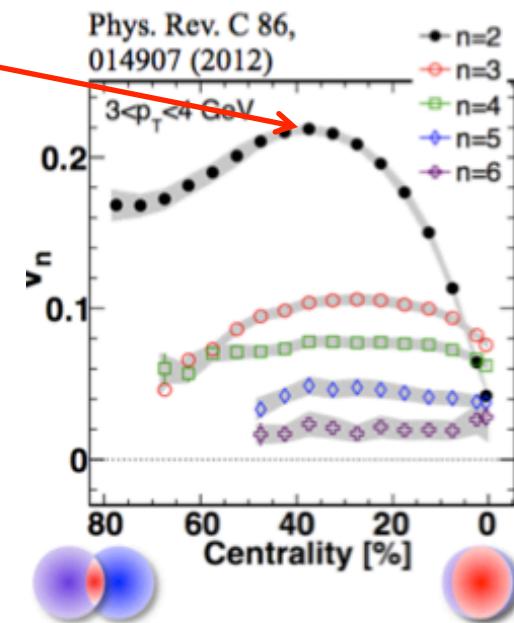
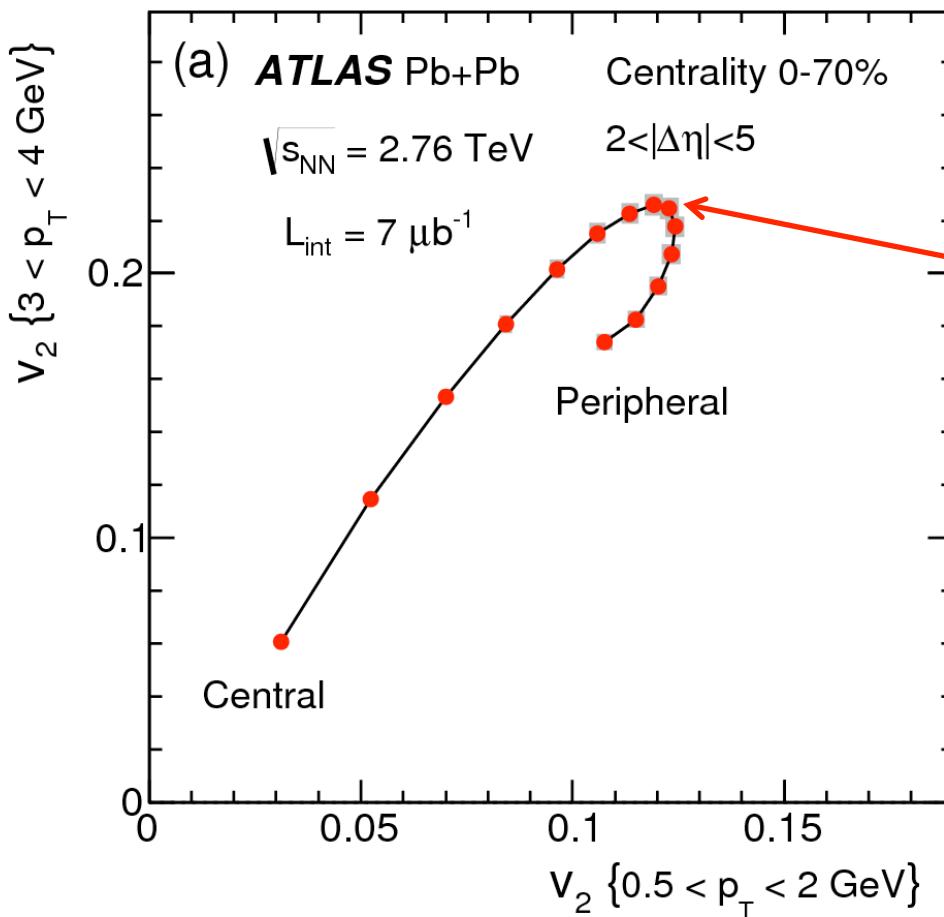


arXiv:1504.01289

- Select events within same centrality that have different geometries : different ellipticity or triangularity.
- Make geometry bins using integrated v_2 or v_3 measured in Forward detectors
- Such “shape selected” measurements reveal insights into correlations in the initial geometry and hydro response
- Obtained via measuring correlations between flow harmonics

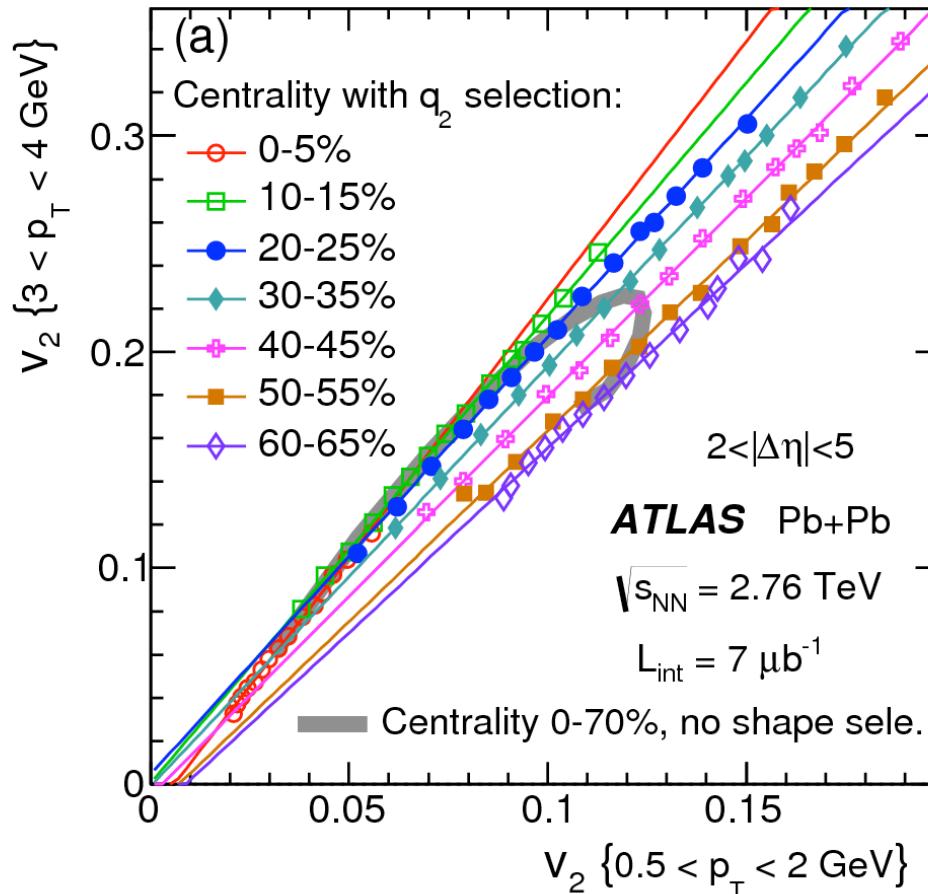
v_2 - v_2 correlations : Centrality bins only

arXiv:1504.01289



- Plot shows low- p_T v_2 intermediate- p_T v_2 correlation as centrality varies
- See non-trivial dependence with centrality (boomerang-curve),
- Indicates that viscous correction larger in peripheral events

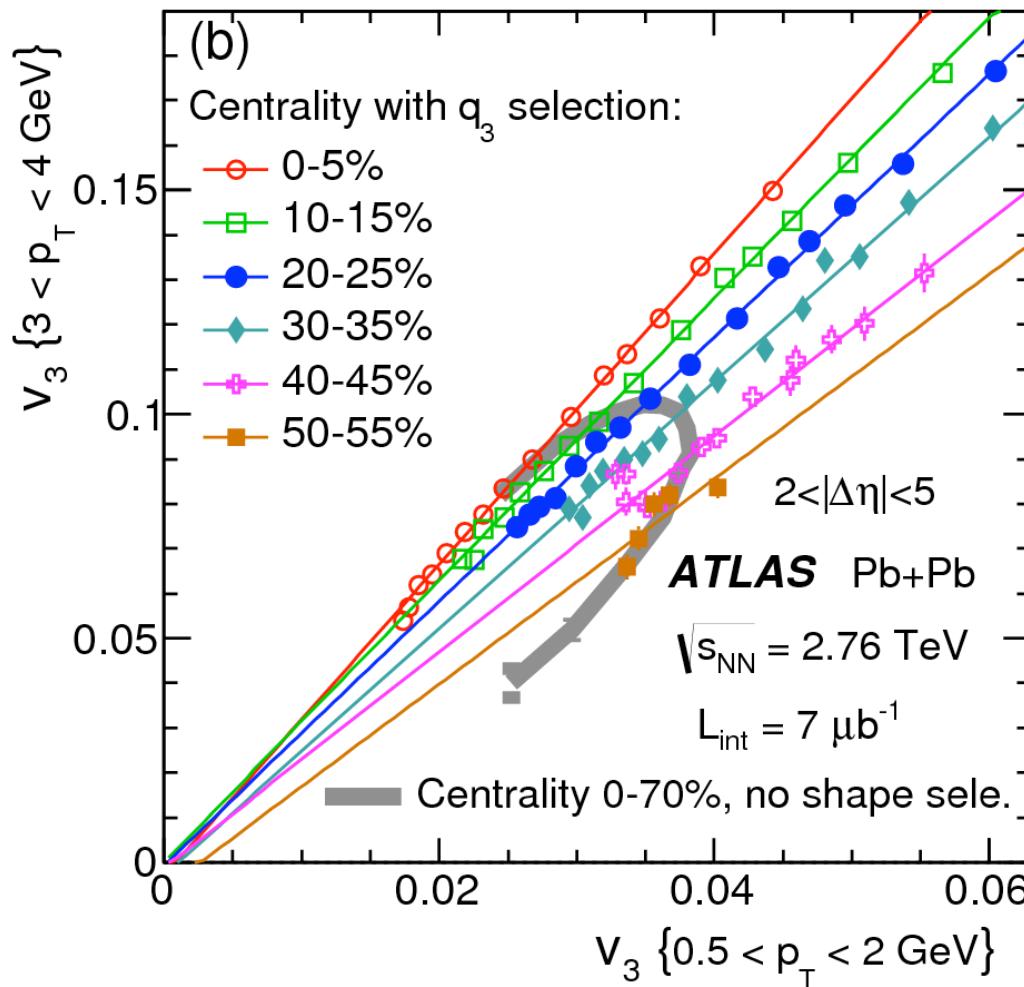
v_2 - v_2 correlations : q_2 -bins



arXiv:1504.01289

- Now for each centrality binning in event geometry (ellipticity) as well
- Saw non-trivial dependence with centrality (boomerang),
 - but within one centrality dependence is linear!
- Indicates that viscous correction mostly controlled by system size, not shape!

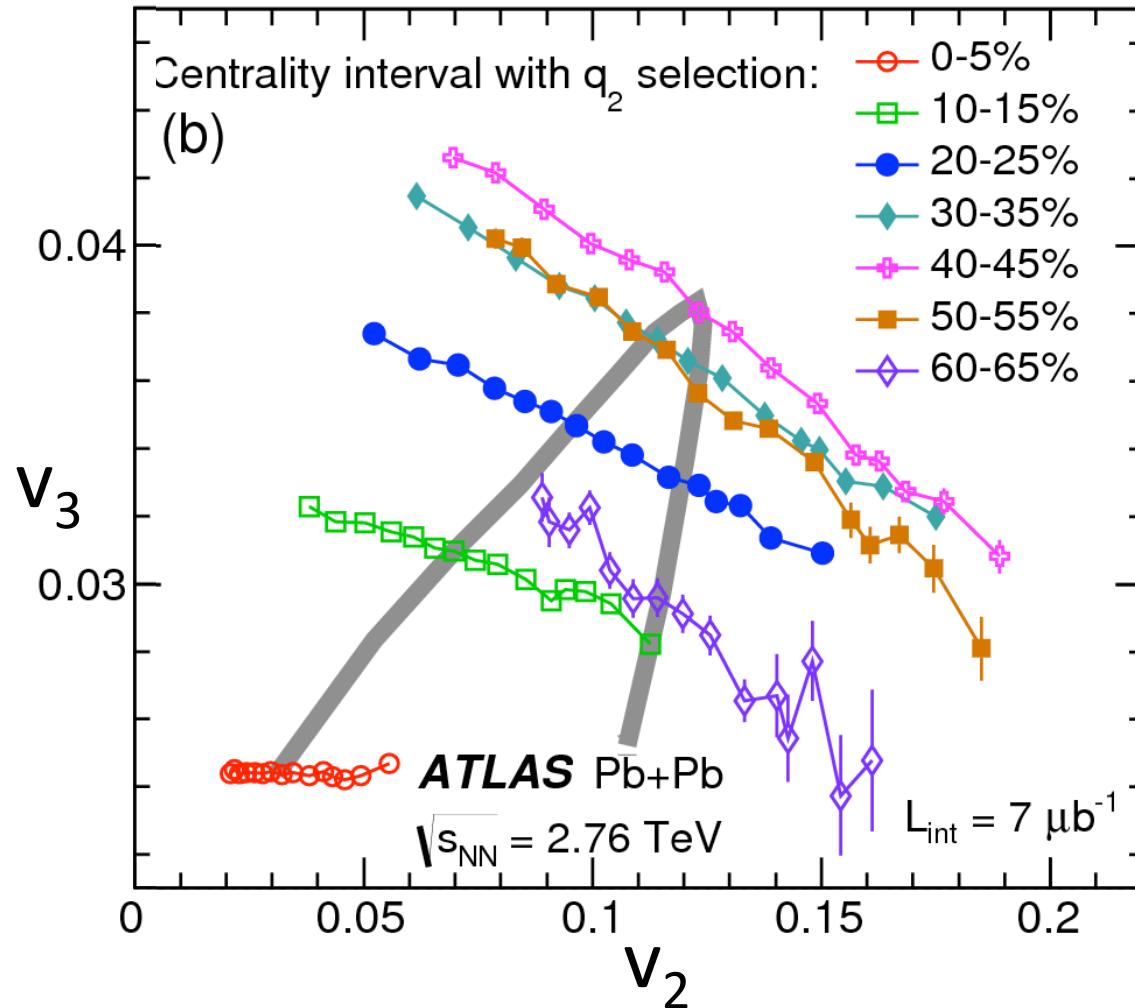
v_3 - v_3 correlations : q_3 -bins



arXiv:1504.01289

Same conclusions for v_3 - v_3 correlations when binning in event triangularity

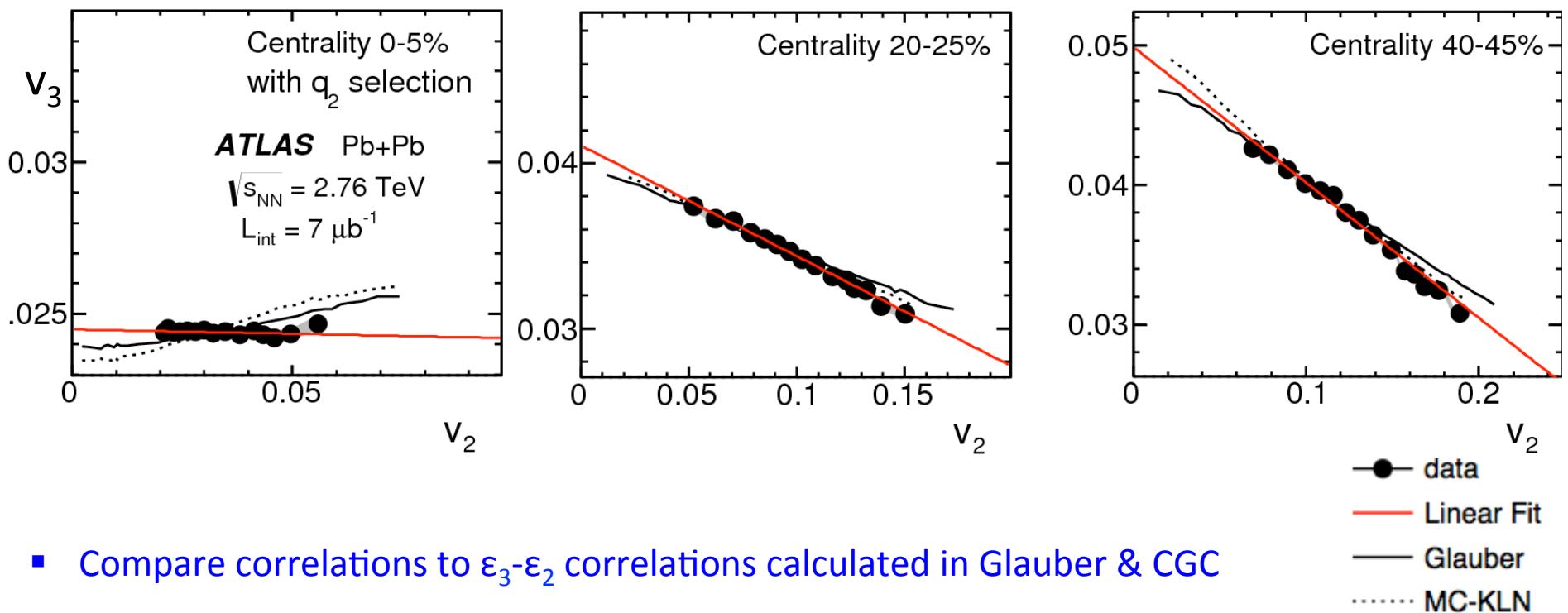
v_3 - v_2 correlations : q_2 -bins



- See anti-correlation between v_2 and v_3 at fixed centrality!
- Initial geometry effect?

v_3 - v_2 correlations : Glauber & CGC comparison

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- Compare correlations to ε_3 - ε_2 correlations calculated in Glauber & CGC models

$$(\varepsilon_3 - \varepsilon_2) \text{ correlation} \propto (v_3 - v_2) \text{ correlation}$$

- See good agreement in most centralities but some deviation in (0-5)% central events
- Measurements can constrain initial geometry models
- Lines are linear fits $v_3 = kv_2 + v_3^0$

v_4 - v_2 correlations : q_2 -bins

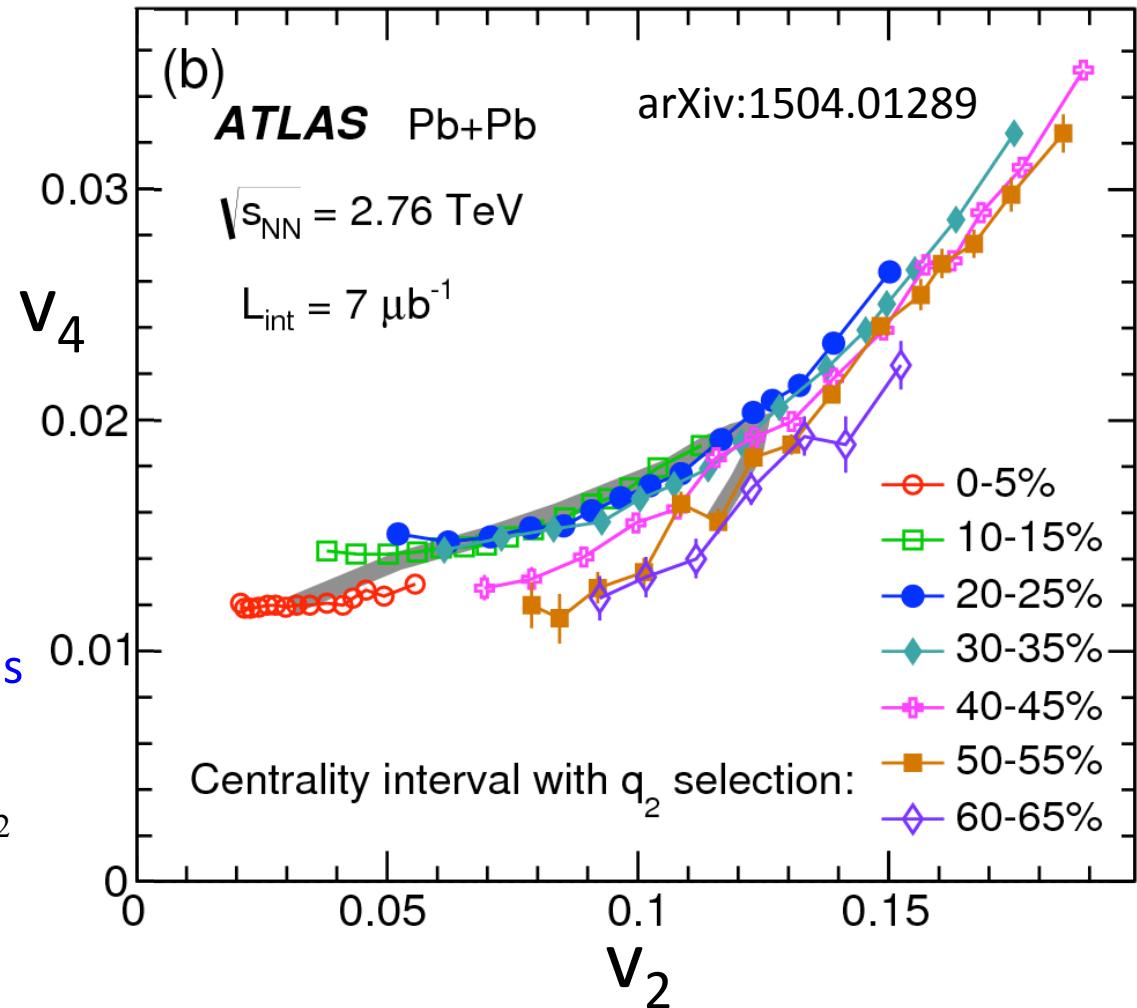
- Clear non-linear correlations seen in v_4 - v_2 case: upward bending of v_4 at large v_2 .

- Can parameterize v_4 into two components, one that is correlated to v_2 and one that is independent

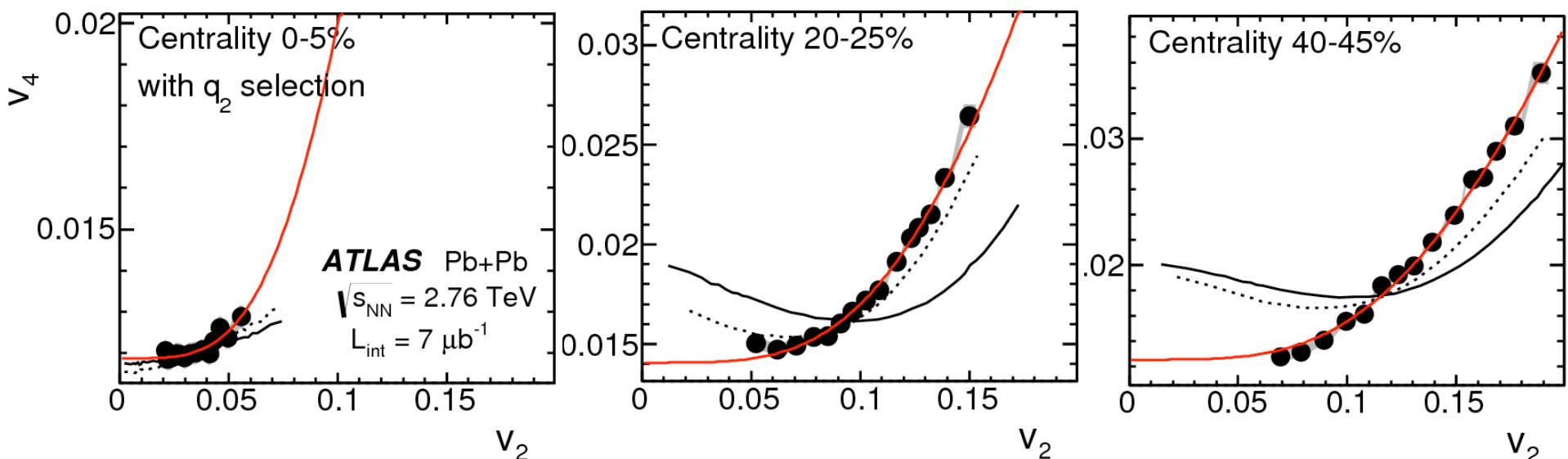
$$v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^*} + c_1 \left(v_2 e^{i2\Phi_2} \right)^2$$

$$\Rightarrow v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$$

- The c_0 component is driven by ϵ_4 while the c_1 component is driven by ϵ_2 .



v_4 - v_2 correlations : linear & non-linear components ¹²



- Fit correlation with parameterization to extracted un-correlated (linear) & correlated (non-linear) components.

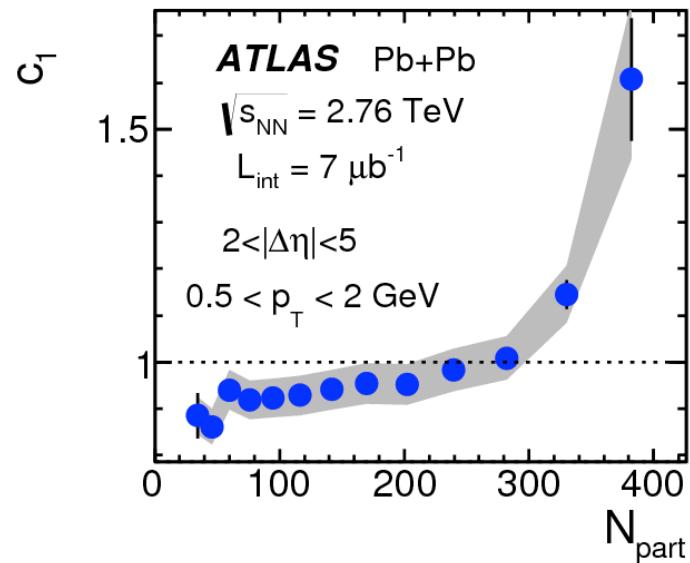
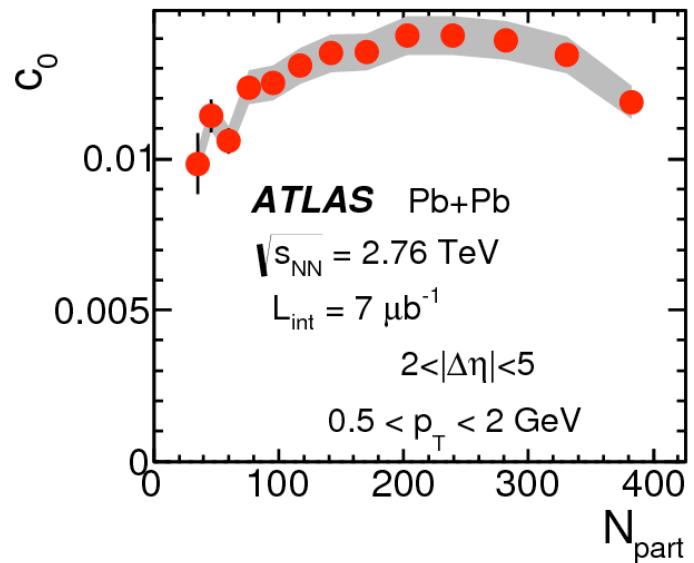
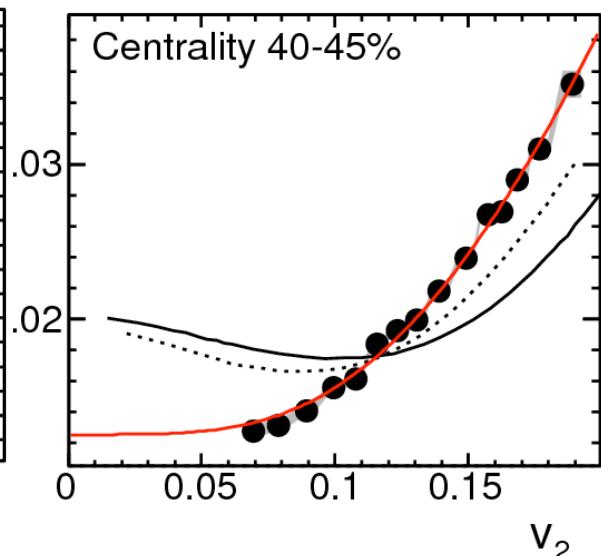
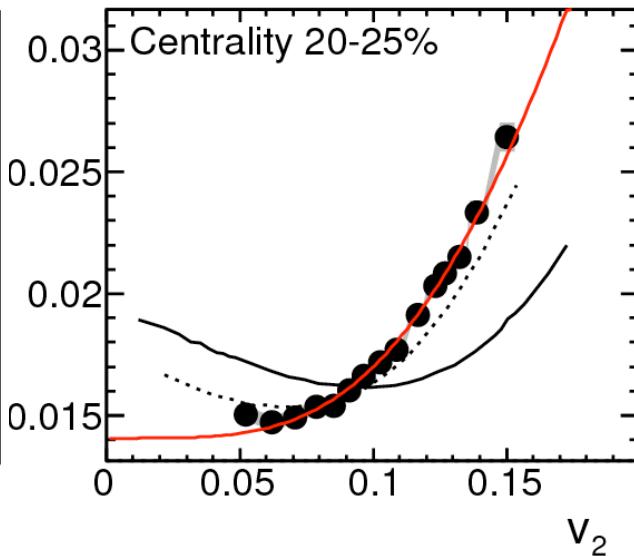
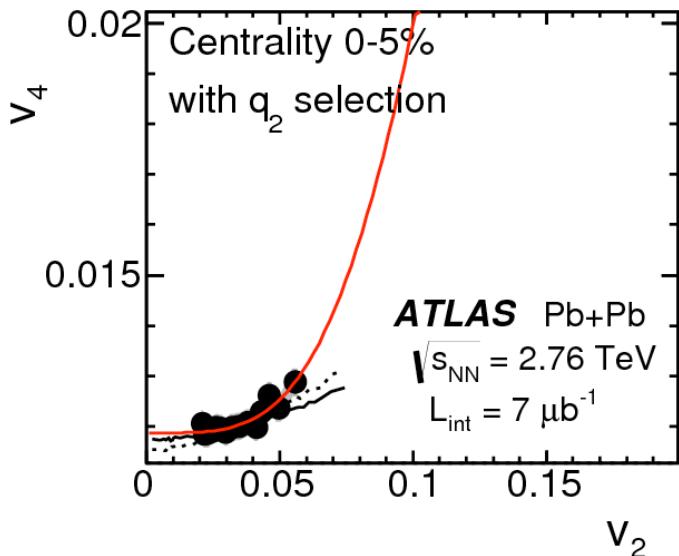
$$v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$$

- data
- Fit $v_4 = \sqrt{c_0^2 + (c_1 v_2^2)^2}$
- Glauber
- MC-KLN

- Also compare correlations to (rescaled) ϵ_4 - ϵ_2 correlations calculated in Glauber & CGC models
 - Fits work quite well, but initial geometry models do not
 - Indicate that non-linear dynamical mixing produces these correlations

v_4 - v_2 correlations : linear & non-linear components

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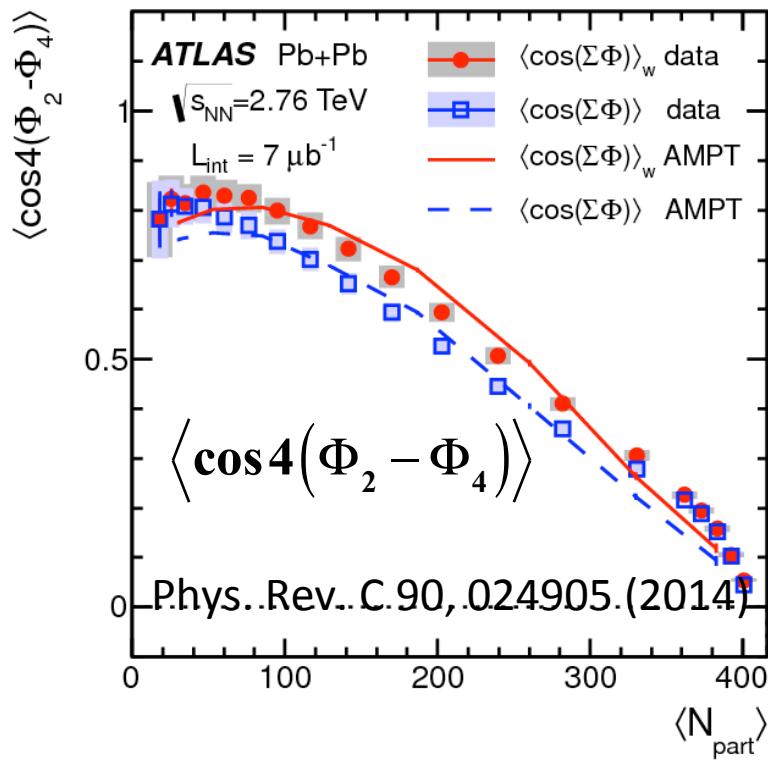


$$v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$$

Each N_{part} point corresponds to 5% centrality bin

v_4 - v_2 correlations : comparison to EP correlations

14



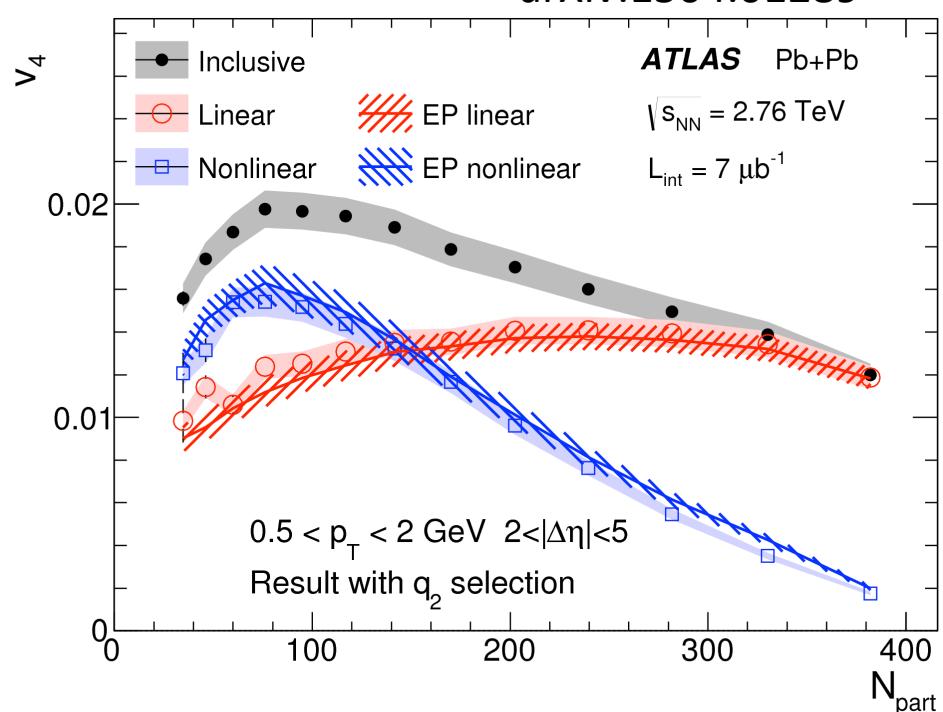
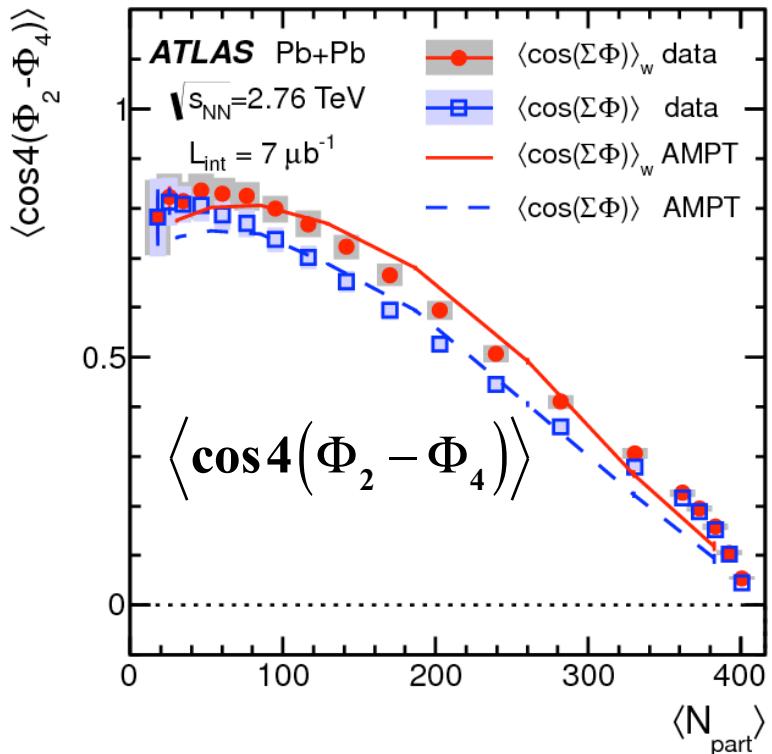
- The non-linear & linear components from EP correlations are obtained as:

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

v_4 - v_2 correlations : comparison to EP correlations

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arXiv:1504.01289

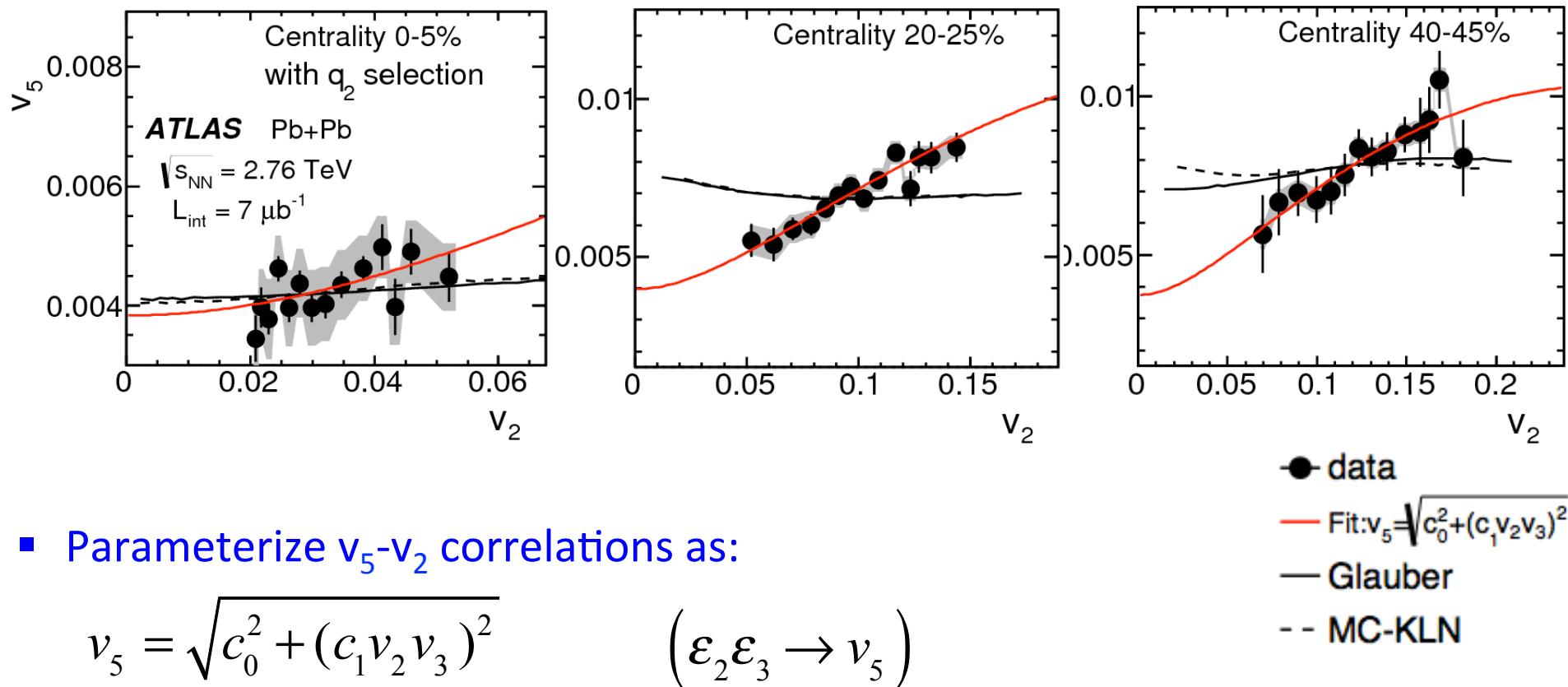


- The non-linear & linear components from EP correlations are obtained as:

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

- The results from the two procedures compare quite well
- In most central cases almost all v_4 is uncorrelated with v_2
- Correlated component gradually increases and overtakes linear component as $N_{\text{part}} \sim 120$

v_5 - v_2 correlations : q-bins



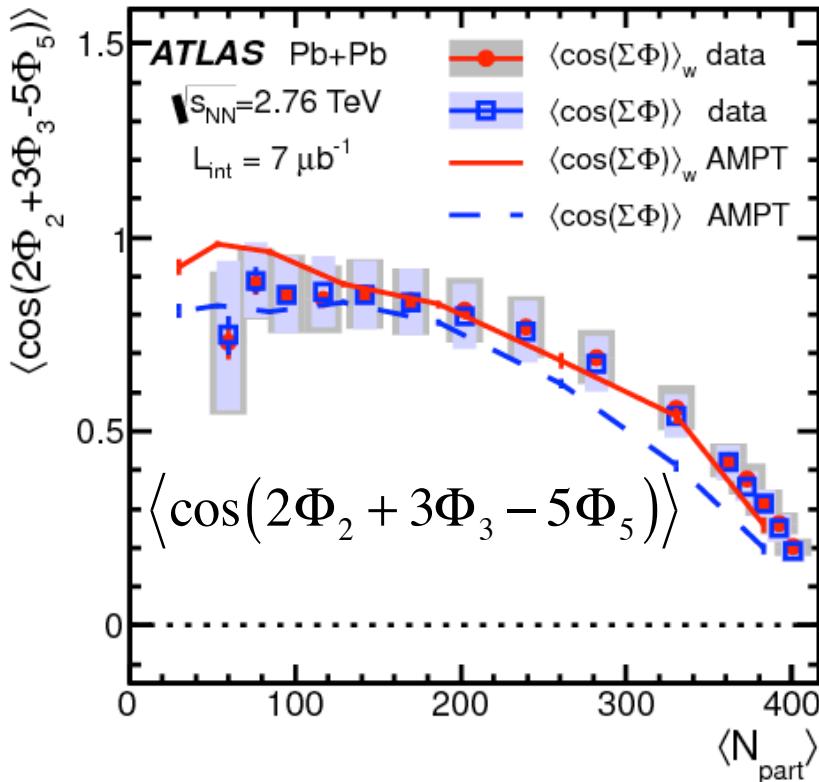
- Parameterize v_5 - v_2 correlations as:

$$v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2} \quad (\mathcal{E}_2 \mathcal{E}_3 \rightarrow v_5)$$

- Fit v_5 - v_2 correlation with above functional form to extract linear & non-linear components
- Comparison to Glauber & CGC models also shown, don't do a good job in describing data

v_5 - v_2 correlations : comparison to EP correlations

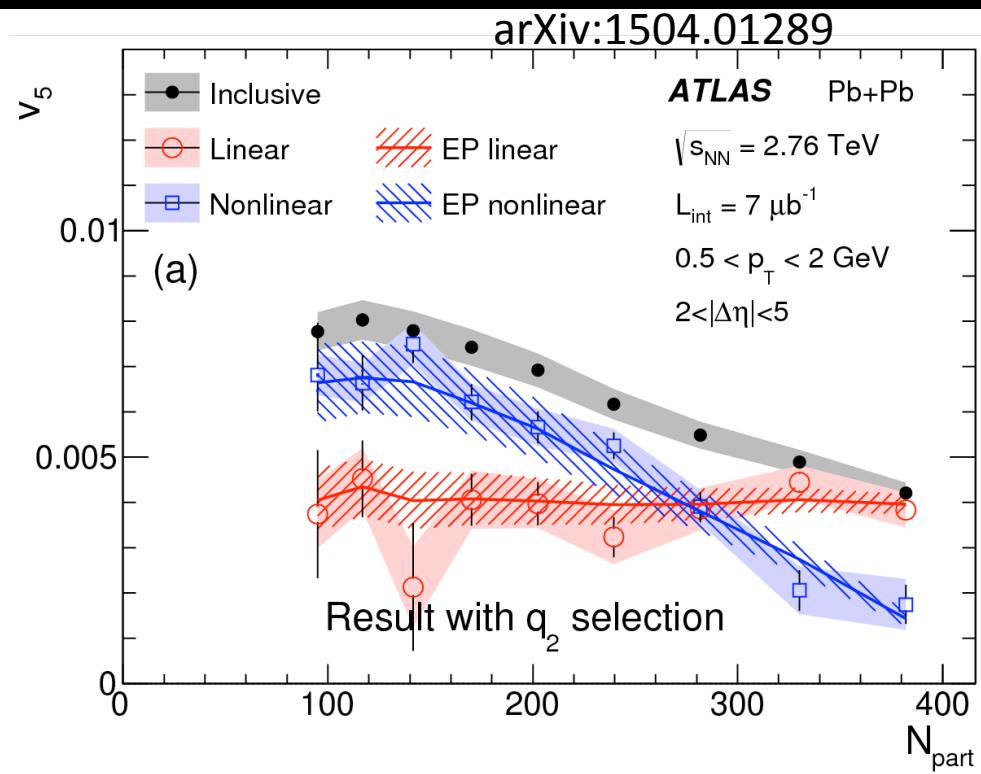
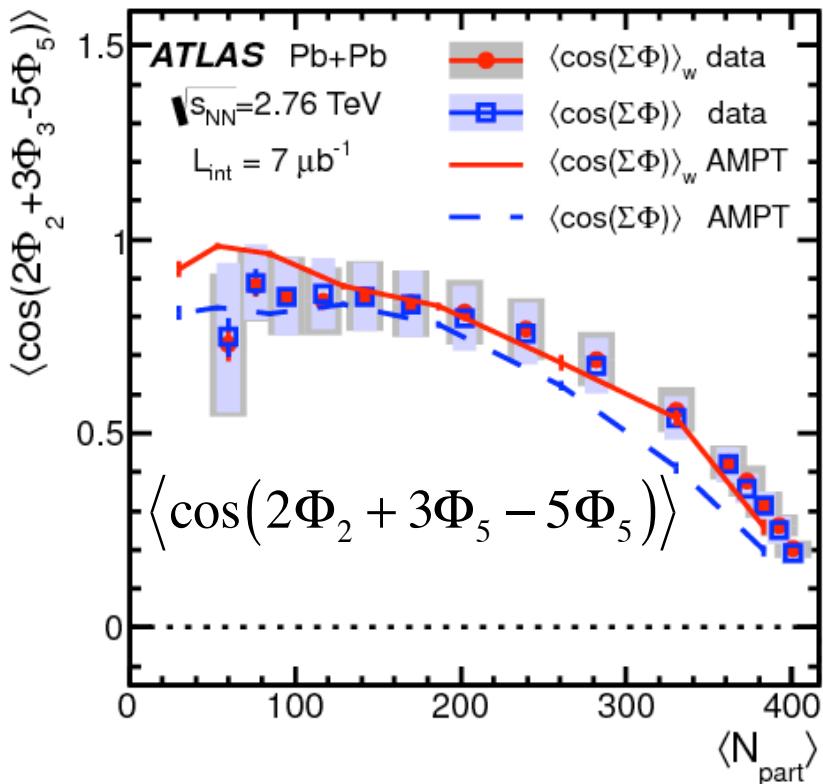
17



- Compare linear & non-linear components from this analysis to EP correlation results
- The non-linear & linear components from EP correlations are obtained as:

$$v_5^{\text{NL}} = v_5 \langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle, \quad v_5^{\text{L}} = \sqrt{v_5^2 - (v_5^{\text{NL}})^2}$$

v_5 - v_2 correlations : comparison to EP correlations

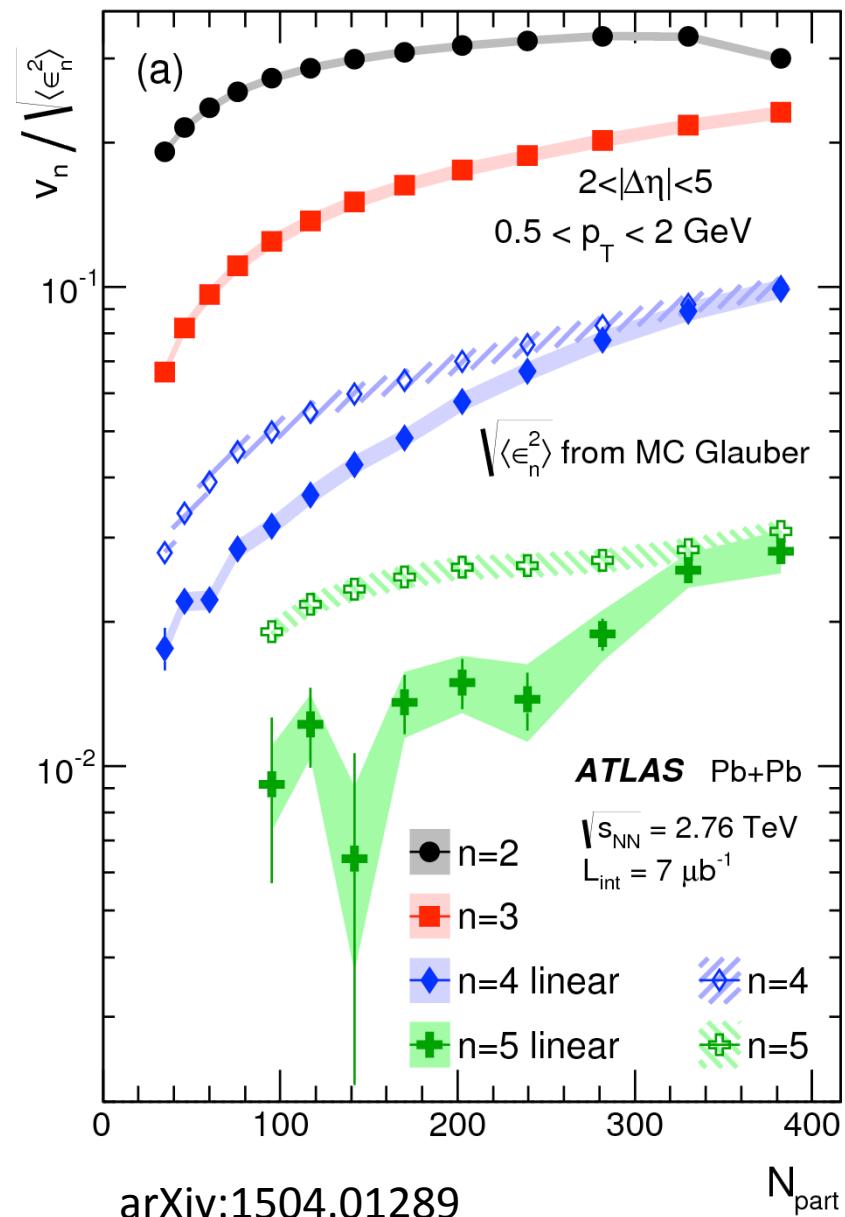


- Compare linear & non-linear components from this analysis to EP correlation results
- The non-linear & linear components from EP correlations are obtained as:

$$v_5^{\text{NL}} = v_5 \langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle, \quad v_5^L = \sqrt{v_5^2 - (v_5^{\text{NL}})^2}$$

ε_n scaling of linear components

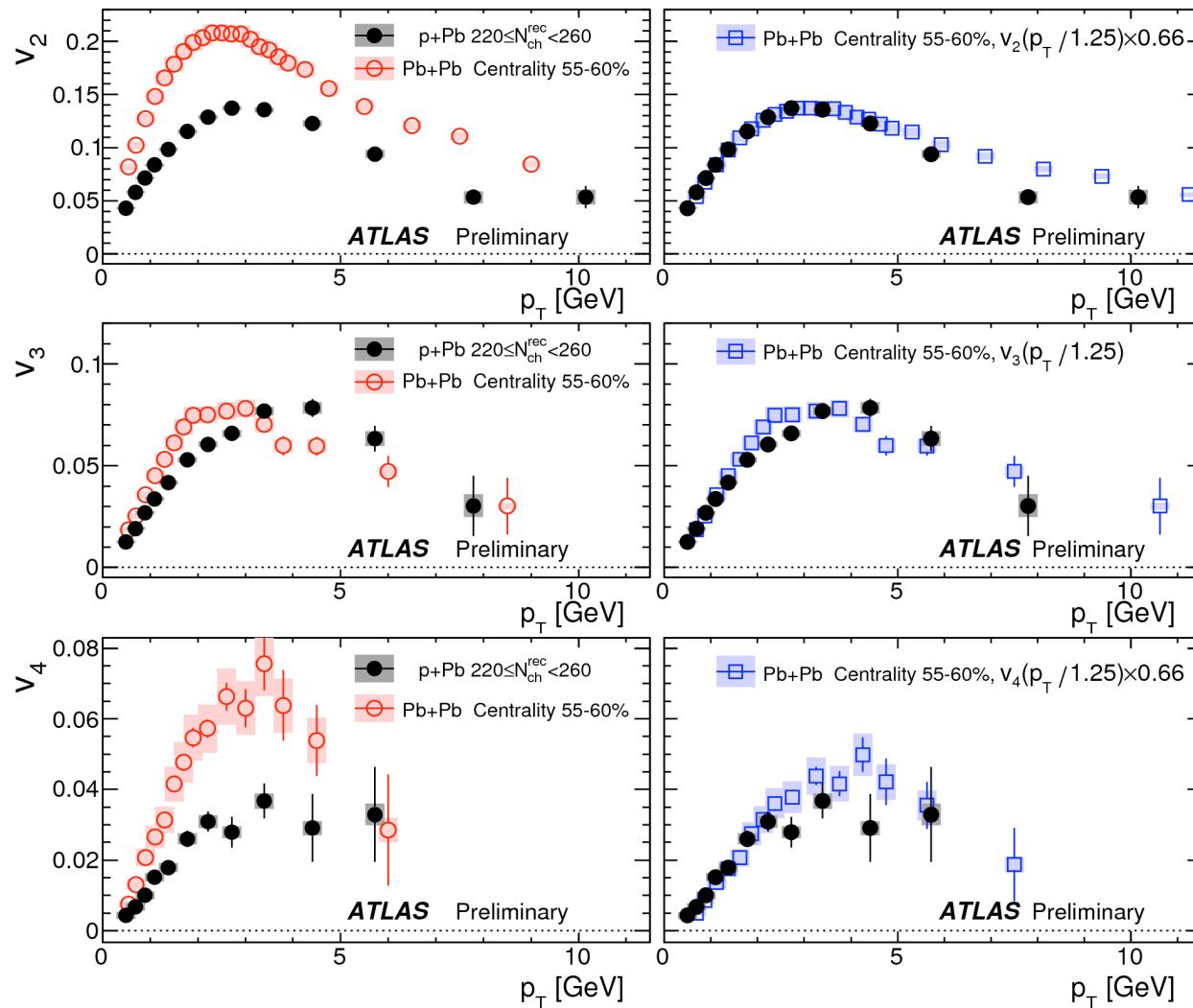
- The $v_n/\text{rms-}\varepsilon_n$ ratios are shown as a function of centrality
- For v_4 & v_5 , the ratio is shown for the linear component as well as the total v_n .
- The linear component show greater variation
- indicates larger viscous dampening for higher harmonics, with decreasing centrality.



Summary

- Measurements:
 - EbE Probability distributions
 - Event-plane correlations
 - Correlations between v_2 and v_m , $m=2-5$.
- $v_n(p_T^a) - v_n(p_T^b)$ correlations indicate viscous effects controlled by system size
 - Not system shape!!!
- See small anti-correlation between magnitudes of v_2 & v_3
 - Initial geometry effect, reasonably weak described by CGC & Glauber models
- See strong correlation between v_4-v_2 and v_5-v_2 .
 - Indicate non-linear response to initial geometry (not described by initial geometry models)
 - Extracted linear & non-linear contributions by two component fits
 - Correlated with v_2 incase of v_4-v_2 correlation
 - Correlated with both v_3 and v_2 incase of v_5-v_2 correlation
- Results show good agreement with independent EP correlation results
- Dependence of the linear components on the $\text{rms}-\varepsilon_n$ were also studied
 - Stronger damping seen for higher order harmonics as expected from hydrodynamics
- v_n-v_m and EP correlations are new flow observables
 - Have much potential in improving our understanding of HI collisions.

Compare p+Pb with Pb+Pb v_n



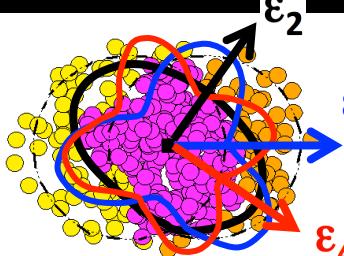
Right panels adjust $p+Pb$ p_T scale by 4/5 to account for difference in $\langle p_T \rangle$ (Teany et al arXiv:1312.6770)

$Pb+Pb v_2$ and v_4 multiplied by 0.66 to match $p+Pb$

Good agreement between $p+Pb$ and $Pb+Pb$ when including p_T and v_2 , v_4 rescaling

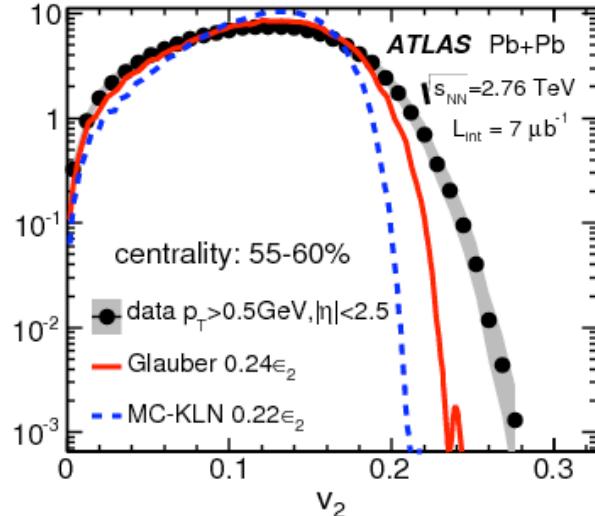
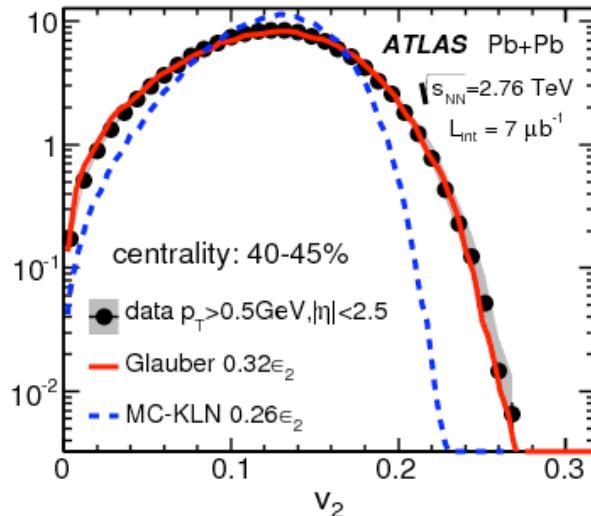
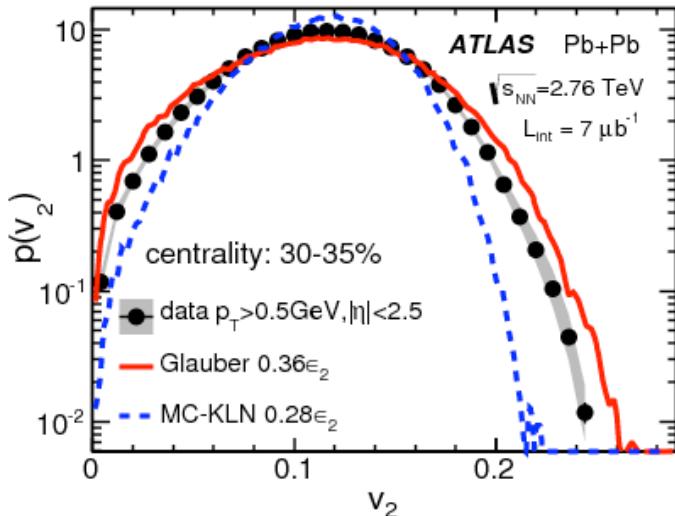
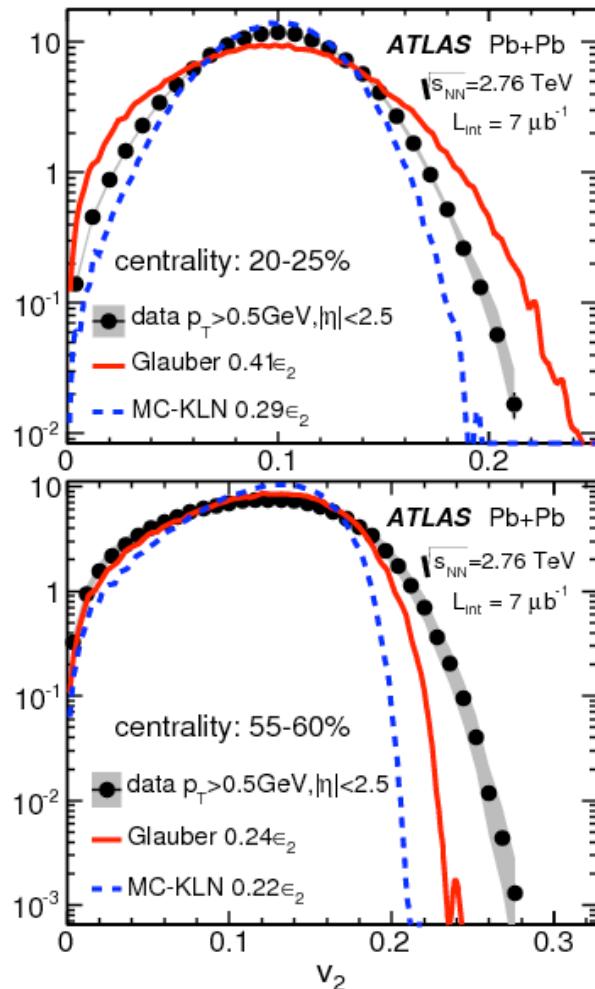
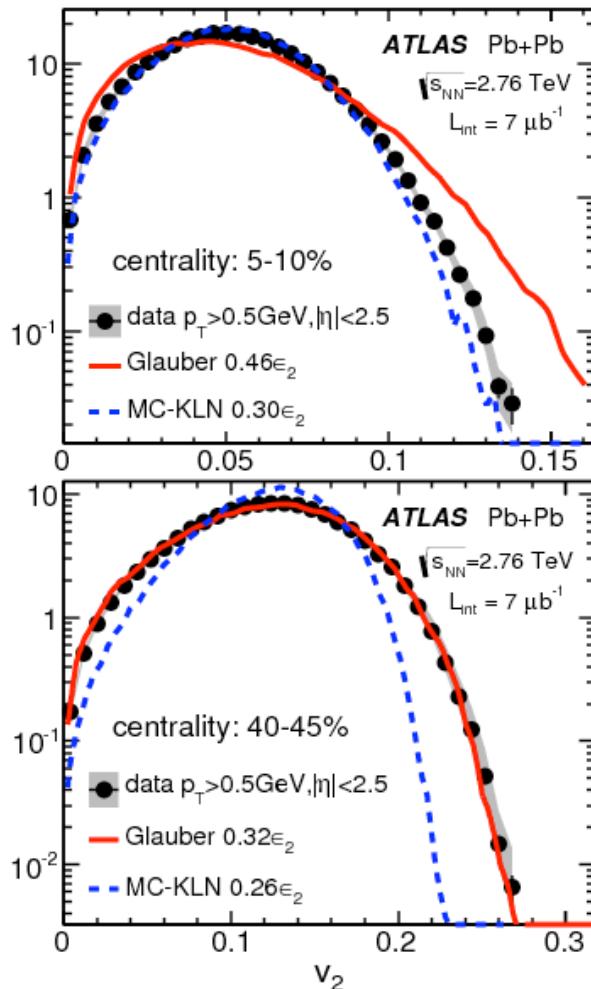
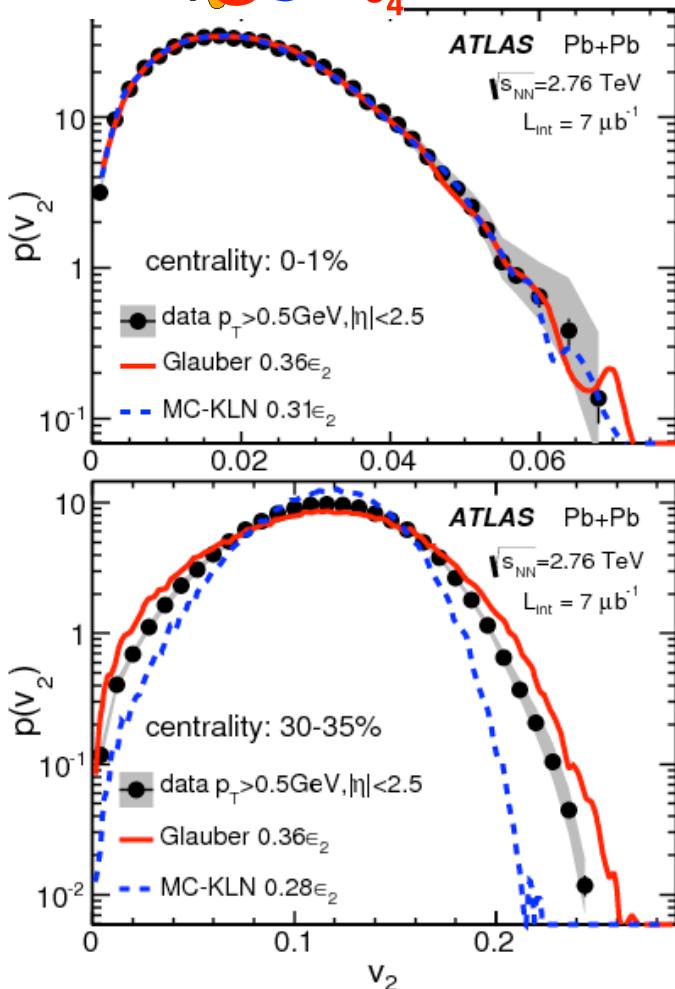
Backups

Measuring the hydrodynamic response: v_2^{23}



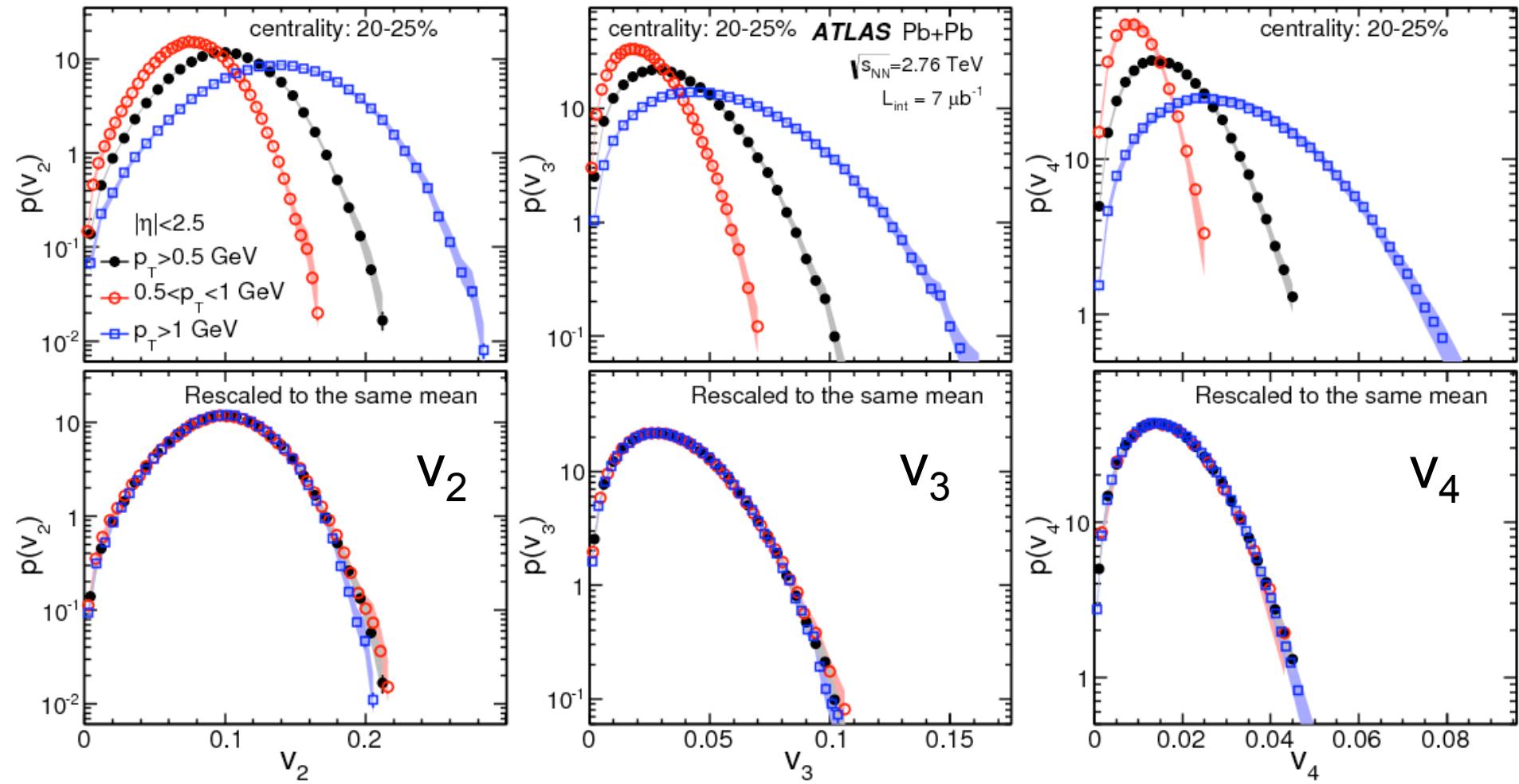
$$v_n \propto \epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$$

For Glauber and CGC mckIn



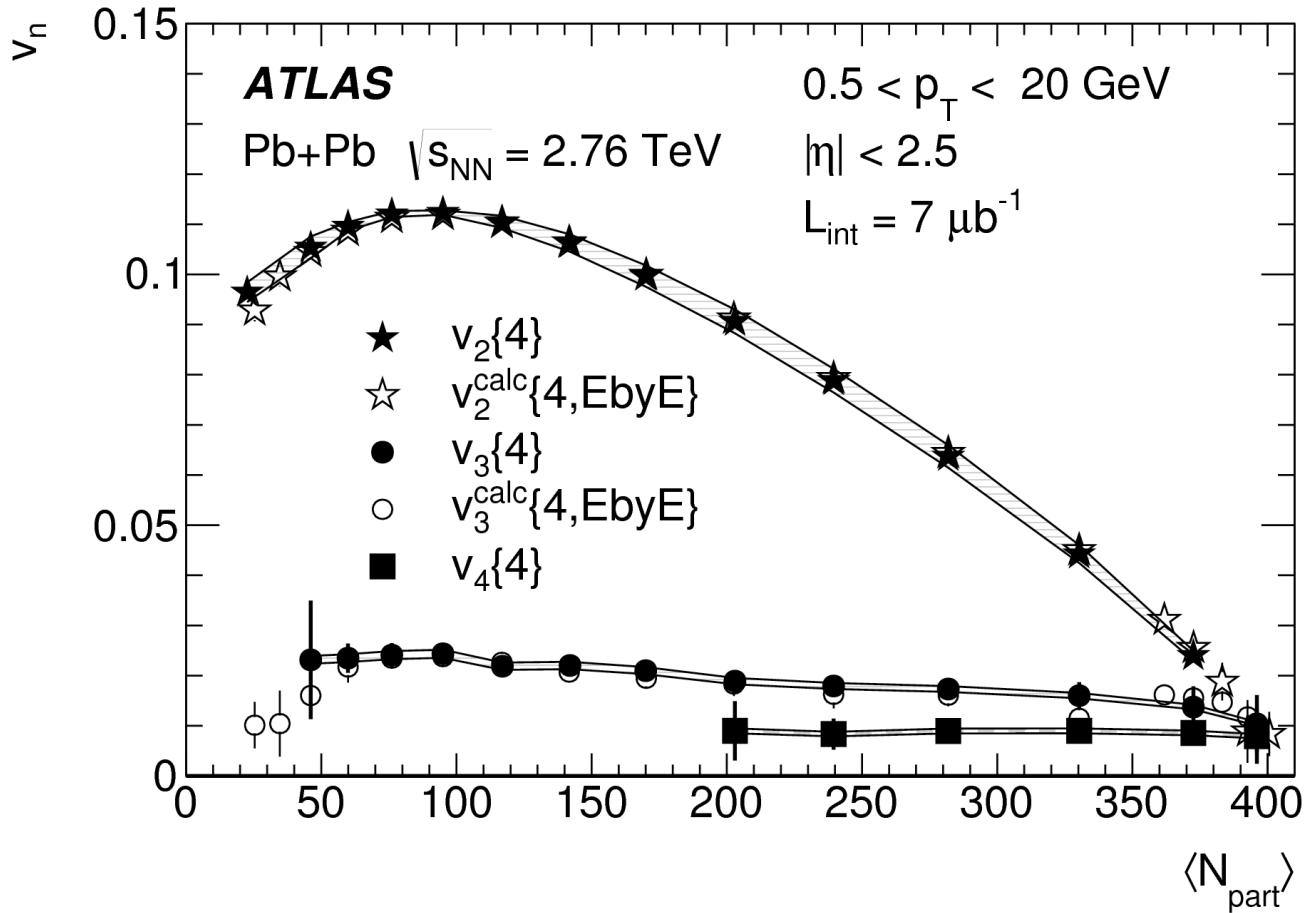
Both models fail describing $p(v_2)$ across the full centrality range

Unfolding in different p_T ranges: 20-25%²⁴



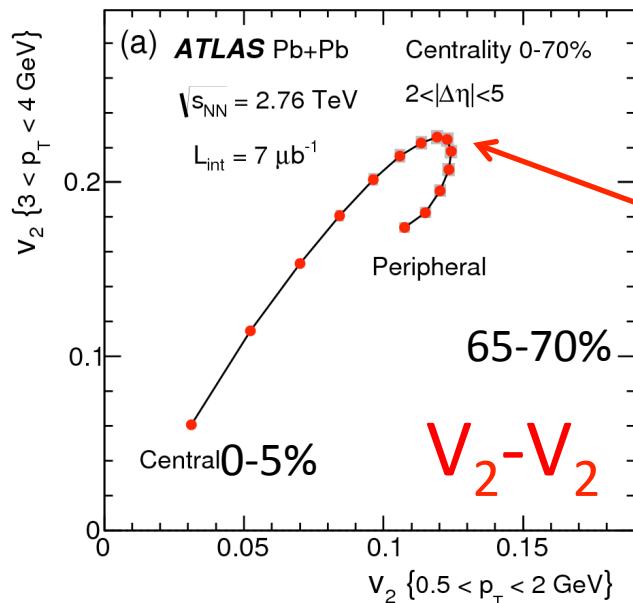
Distributions for higher p_T bin is broader, but they all have \sim same reduced shape. **Hydrodynamic response factorizes into a p_T dependent and geometry dependent part.**

Cumulant measurements

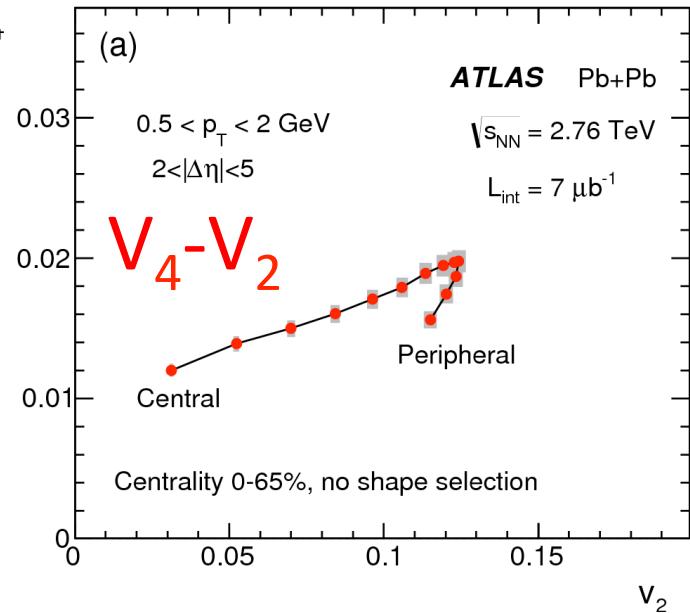
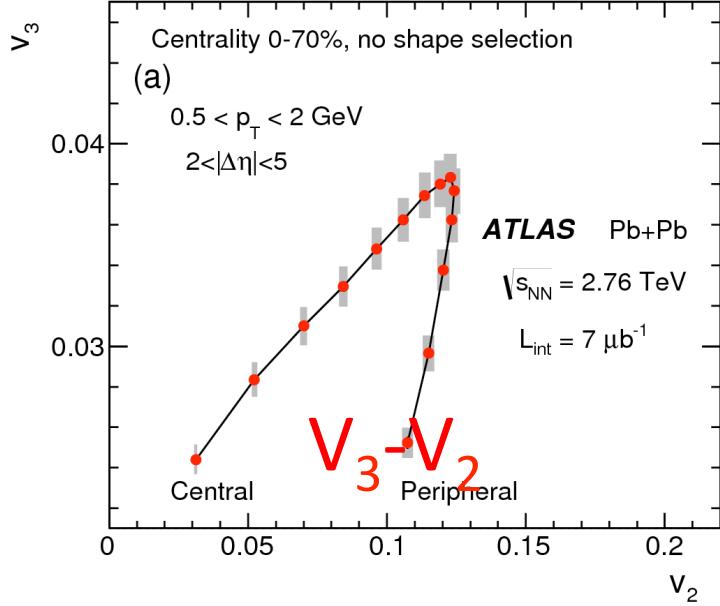
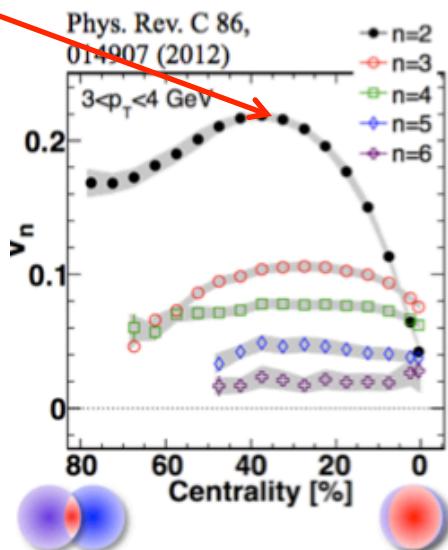


Can directly calculate cumulants from EbyE v_n measurements and compare

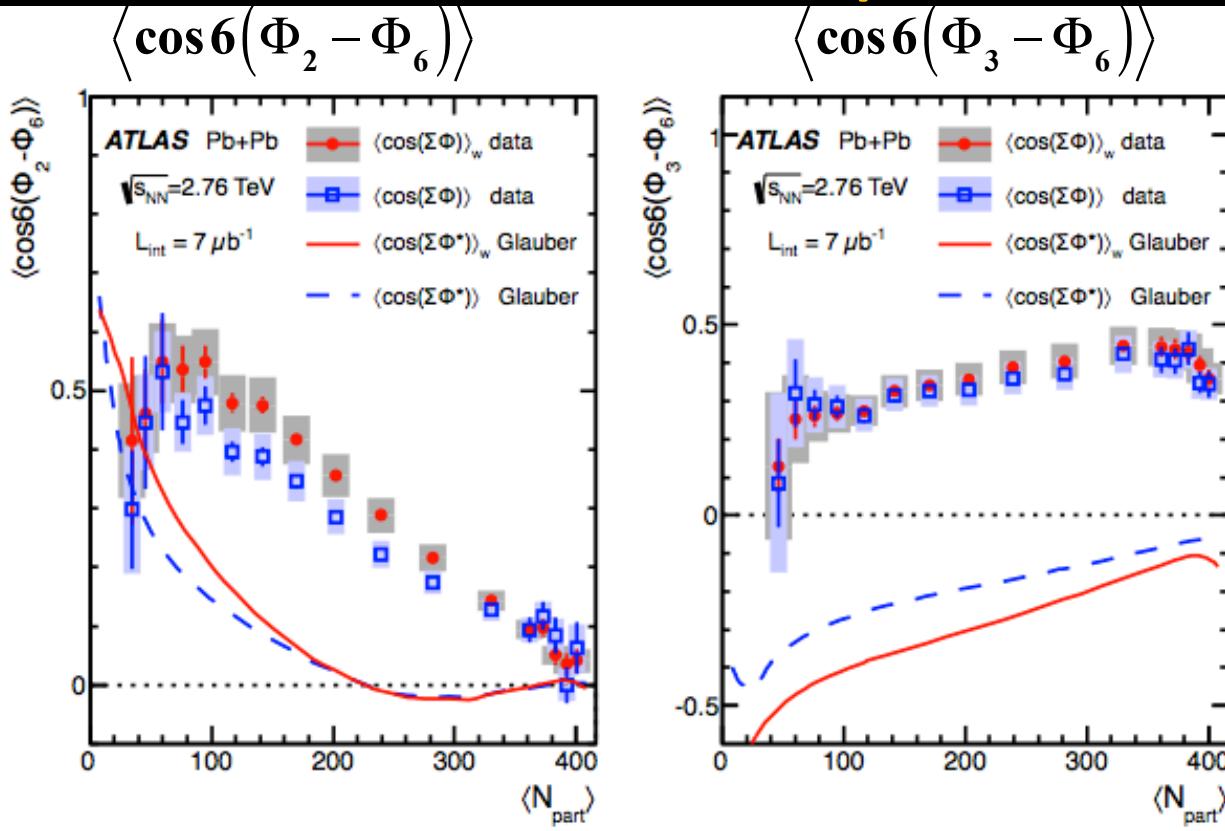
v_m - v_2 correlations : inclusive



- v_2 - v_2 correlation at different p_T
- v_m - v_2 correlation in the same p_T range
 - Reflects different centrality dependence of v_n

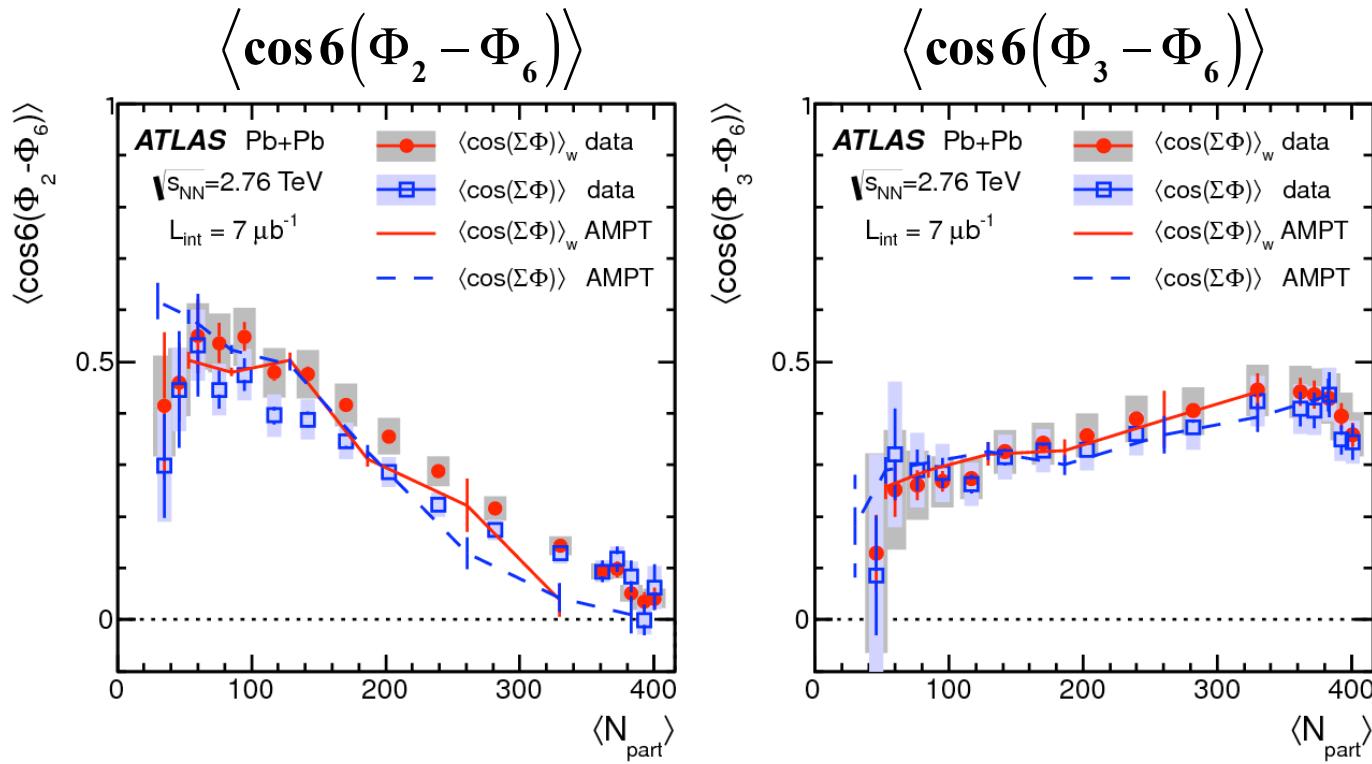


Non-linear response for v_6



- Φ_2 and Φ_3 weakly correlated, but both strongly correlated with Φ_6 .
- They show opposite centrality dependence
 - v_6 dominated by non-linear contribution: v_2^3, v_3^2 ?

Non-linear response for v_6



- Final state interactions reproduce the correlations