Measurement of correlations between elliptic and higher order flow in Pb+Pb collisions

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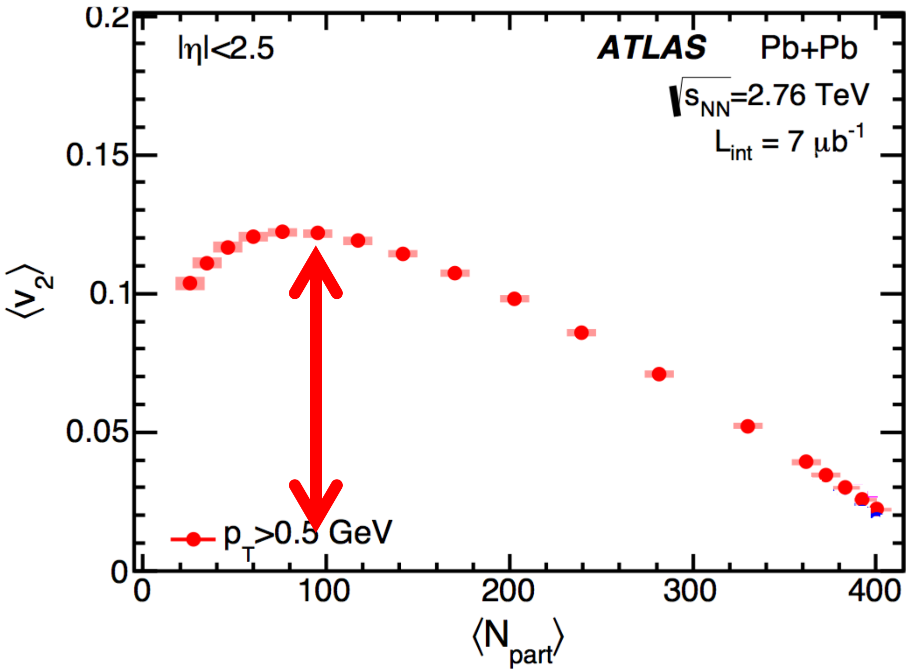
- ATLAS Event-Plane correlation paper: arXiv 1403.0489
- ATLAS flow correlation ConfNote: ATLAS-CONF-2014-022

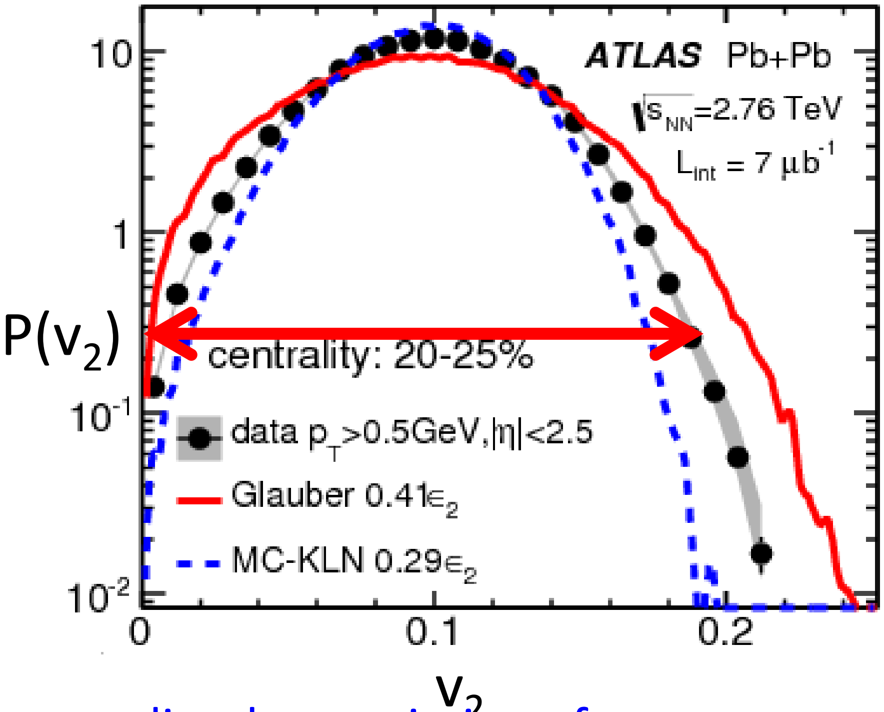
Quark Matter 2014
19-24 May 2014

Motivation-I

- Have previously measured $<v_2>$

JHEP11(2013)183

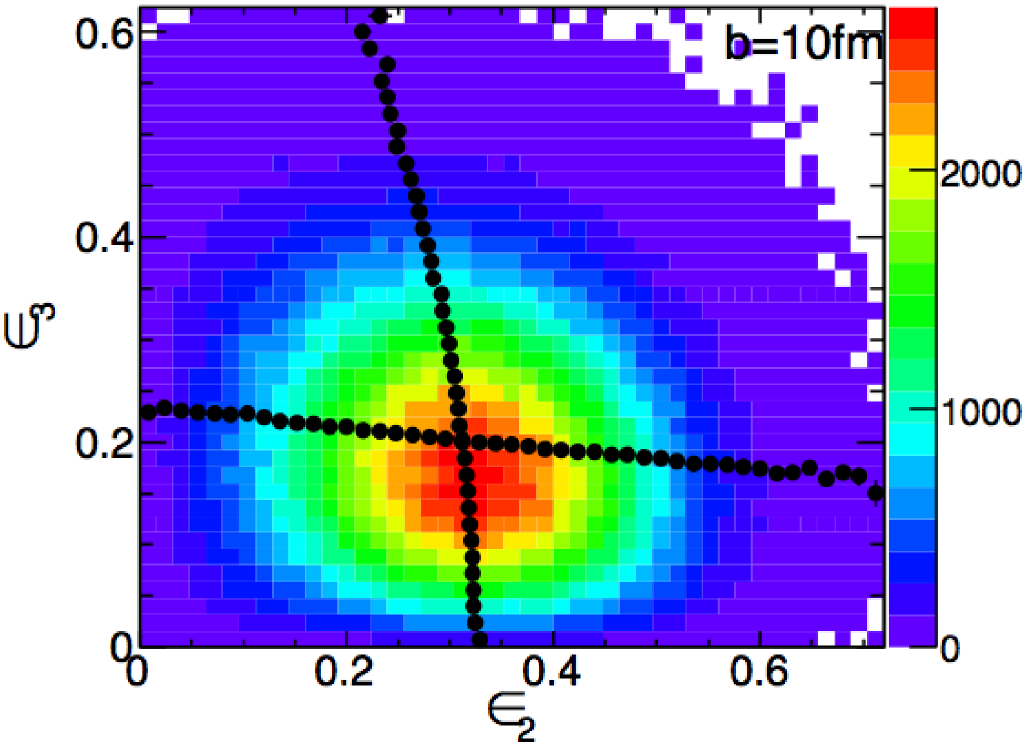




- Much more variation in v_2 within one centrality than variation of mean v_2 across all centralities

- Should also study the variation of v_n at fixed centrality but varying event-geometry: "event-shape-selected v_n measurements" (arXiv 1208.4563 Schucraft et al.)

Motivation-II



Pb+Pb , b_{imp}=10 fm
arXiv 1311.7091
SM, Huo & Jia

ε_2 and ε_3 are anti-correlated at fixed b_{imp} (centrality)

- Event-shape selected measurements can reveal new correlations
- Hidden initial geometry effects.

$$v_2 e^{i2\Phi_2} \propto \epsilon_2 e^{i2\Phi_2^*}, \quad v_3 e^{i3\Phi_3} \propto \epsilon_3 e^{i3\Phi_3^*}$$

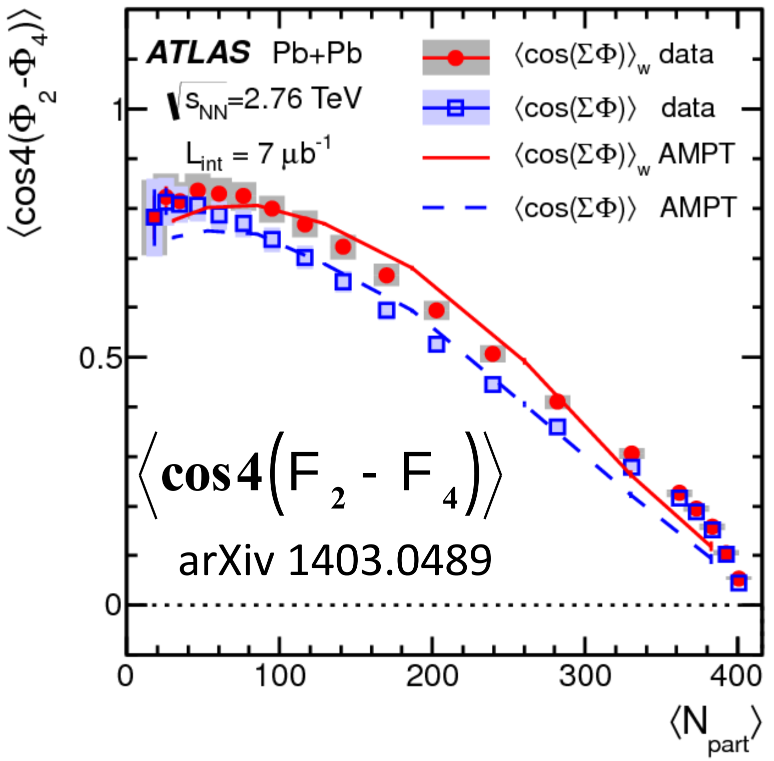
- Measure correlations = Understand geometry of initial state

Motivation-III

- Understand non-linear flow effects:

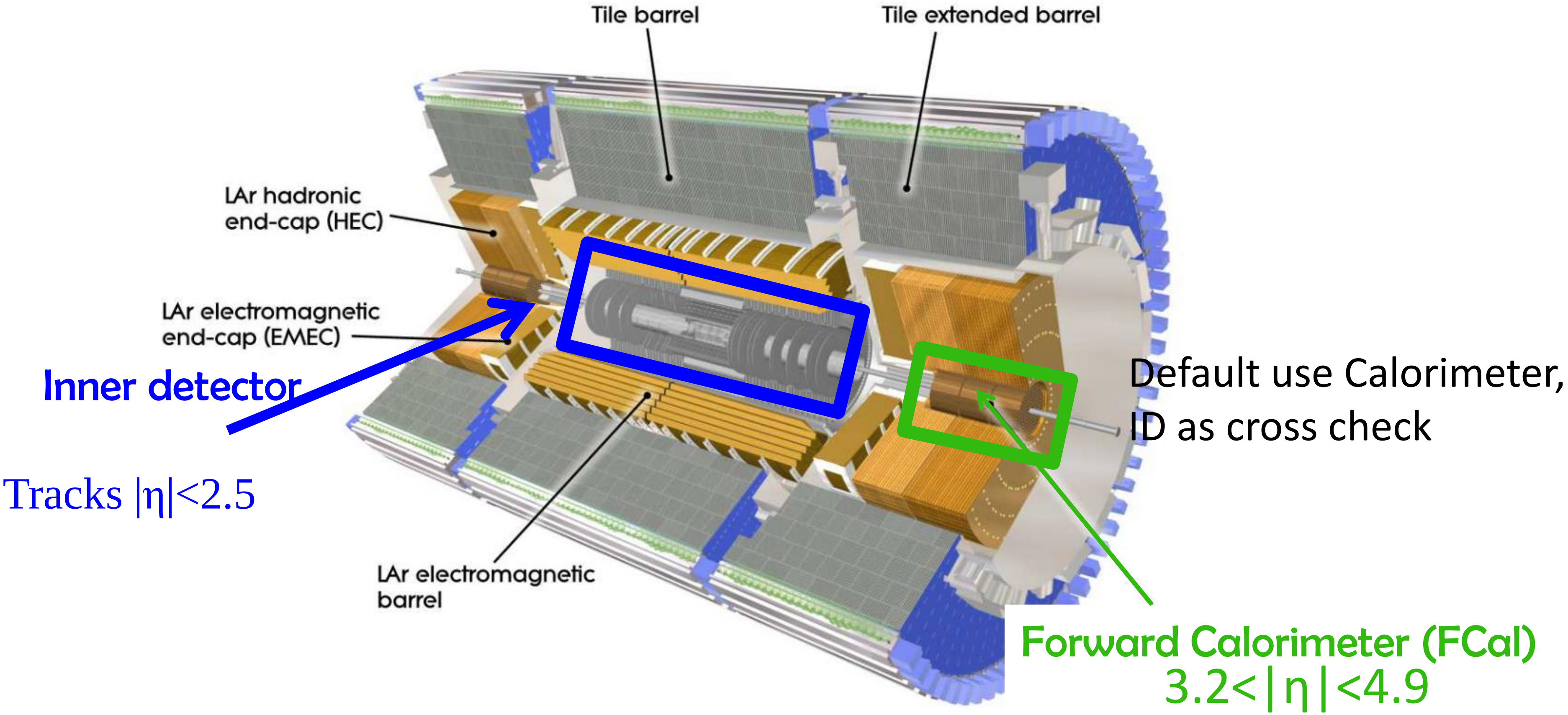
$$v_2 e^{i2\Phi_2} \propto \epsilon_2 e^{i2\Phi_2^*}, \quad v_3 e^{i3\Phi_3} \propto \epsilon_3 e^{i3\Phi_3^*}$$

$$\begin{aligned} v_4 e^{i4\Phi_4} &= a_0\ \epsilon_4 e^{i4\Phi_4^*} + a_1\ \left(\epsilon_2 e^{i2\Phi_2^*}\right)^2 \\ &= c_0\ e^{i4\Phi_4^*} + c_1\ \left(v_2 e^{i2\Phi_2}\right)^2 \end{aligned}$$



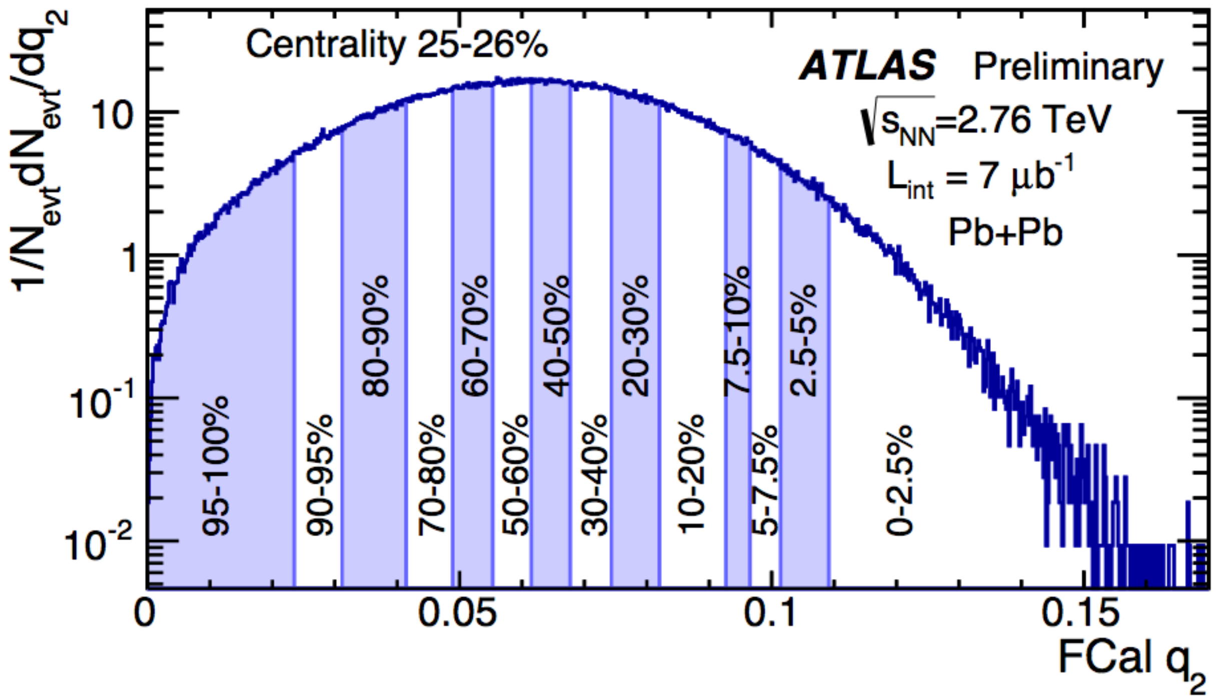
- Have measured correlations between phases Φ_2 & Φ_4.
- Can measure direct correlations between magnitudes of the v_n.
- Measure correlations = Understand hydro response

ATLAS Detector



- FCal coverage : 3.2<|η|<4.9 (determine Centrality, Event-Shape selection)
- Tracking coverage : |η|<2.5 (Track reconstruction, v_n measurement)

Event-shape selection

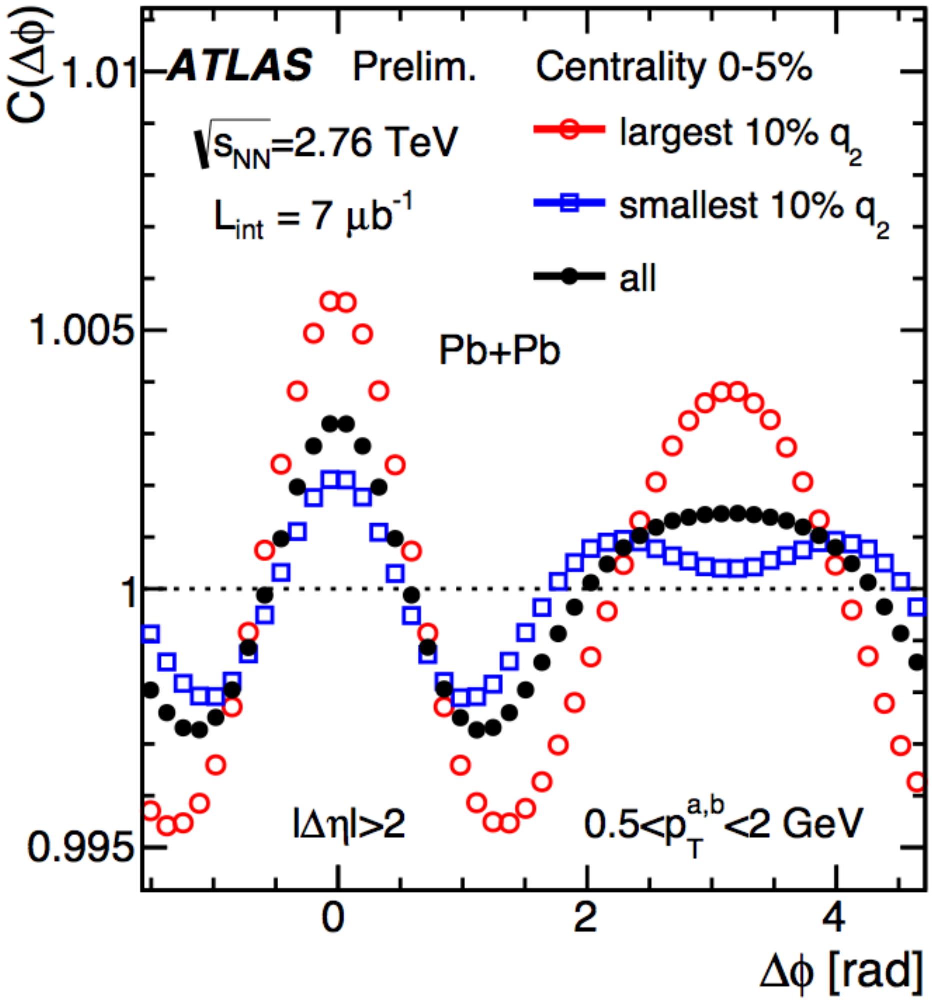


- Slice observed v_2 in FCal (called q_2) to categorize events into q_2-Bins centrality by centrality

- Events with larger q_2 have a geometry that is more elliptic: q_2-bin is bin on ellipticity!

Two-particle corrs (2PC) for different q-classes

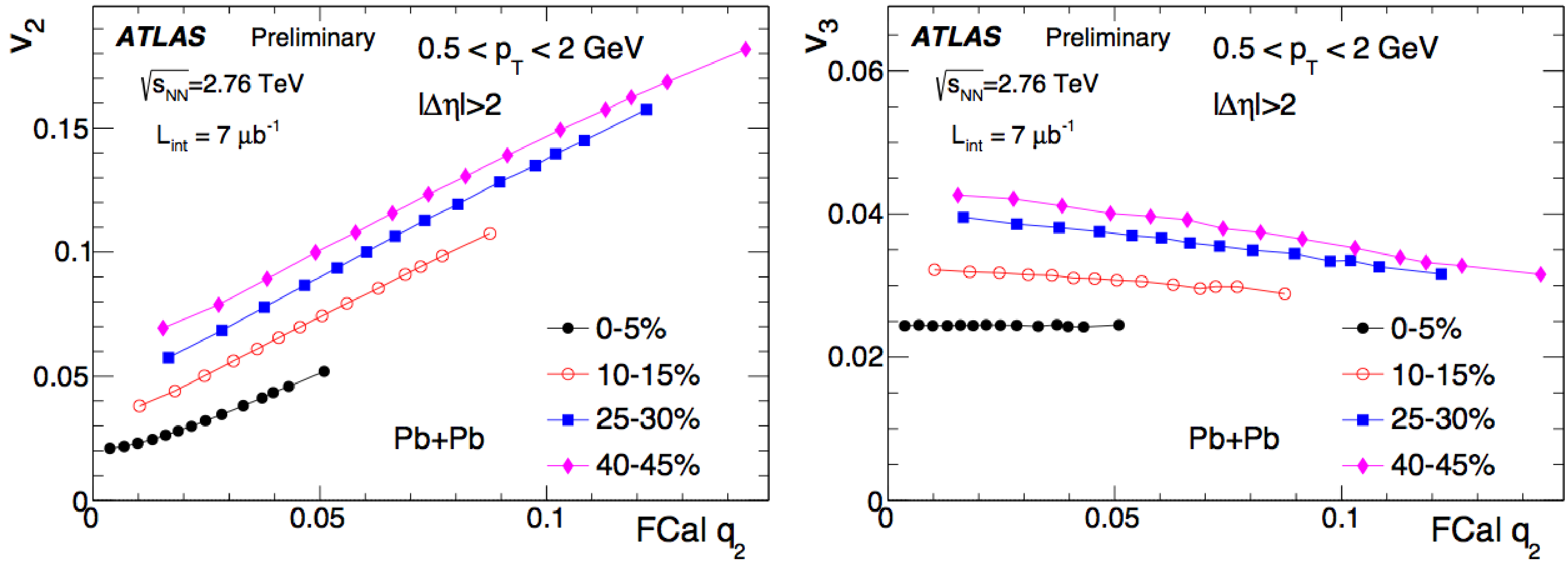
- See clear differences in structure of 2PC for different q-classes at fixed centrality



- Using these 2PC the v_n are extracted for each centrality, q-Bin by q-Bin using the factorization relation: $v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a) v_n(p_T^b)$

n^{th} Fourier components of 2PC=Product of the v_n of the two particles

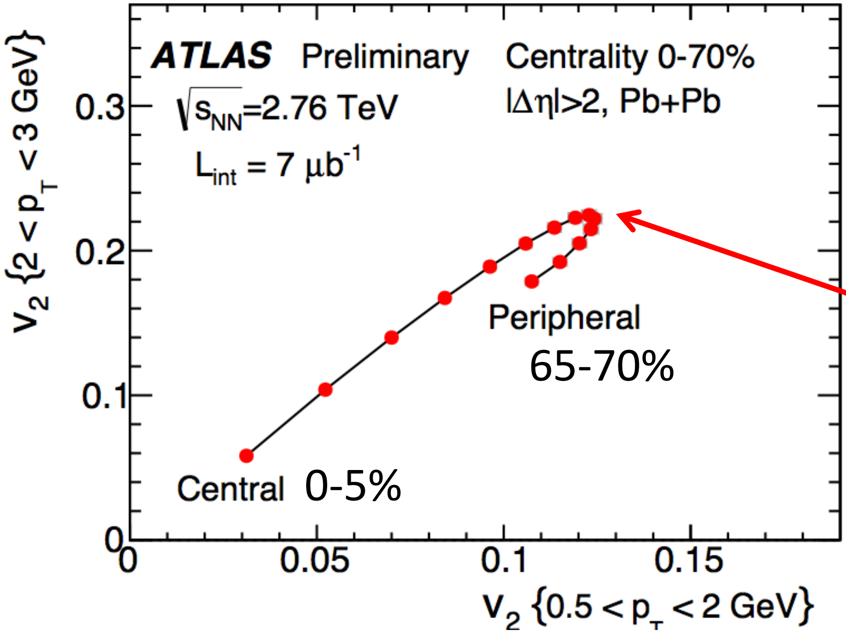
v_n-q_2 Correlations

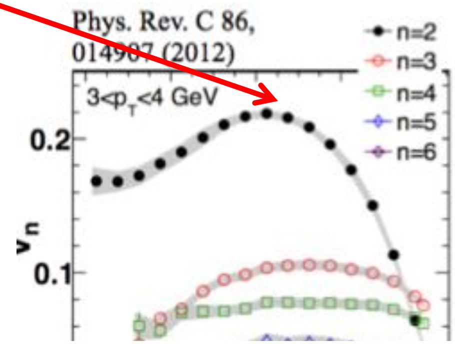


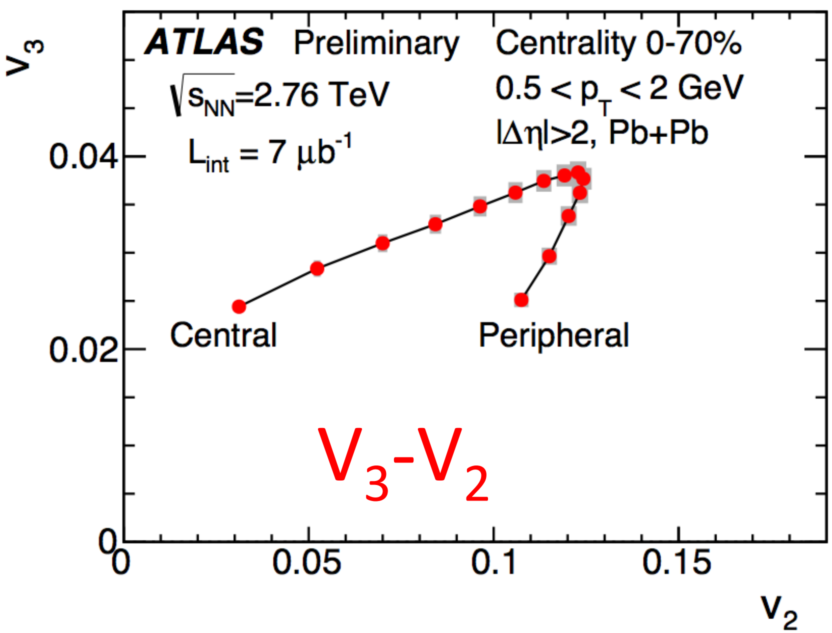
- Plots show variation in v_2 & v_3 with FCal-q_2 at fixed centrality, for several centrality bins
- However a better correlation is v_m-v_2 correlation (both measured in ID)
- Avoid auto-correlation effects: shouldn't bin on q_2 as well as use it in measuring correlations. Also q_2 is an observed quantity (not corrected for resolution)

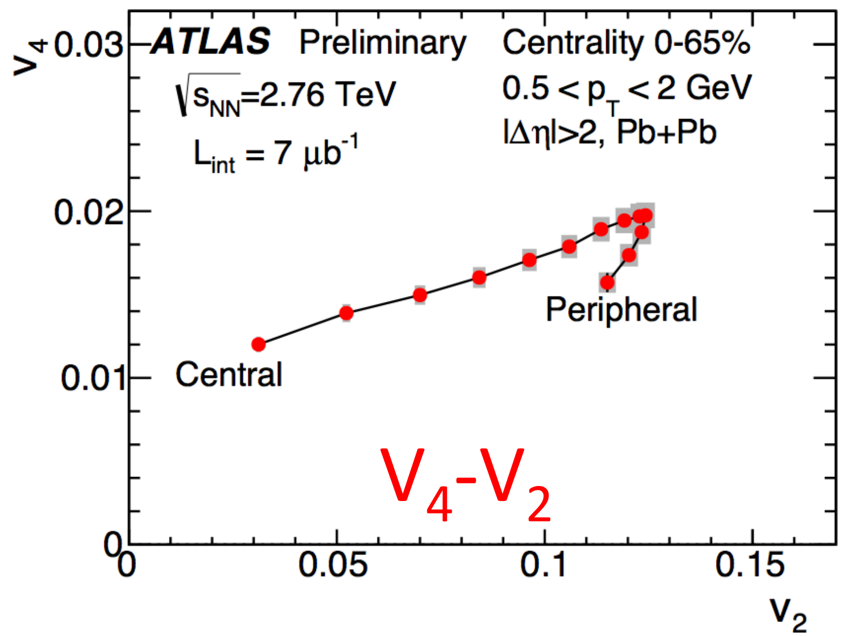
v_m-v_2 correlations : inclusive

- 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

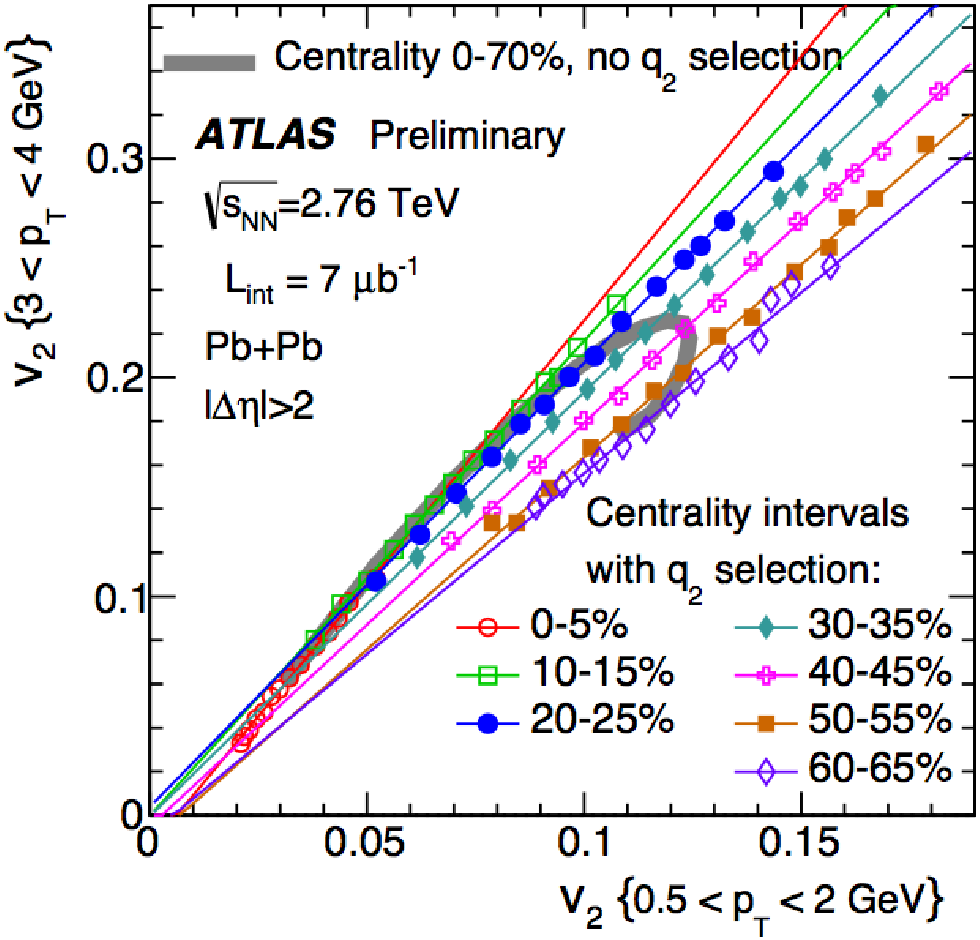






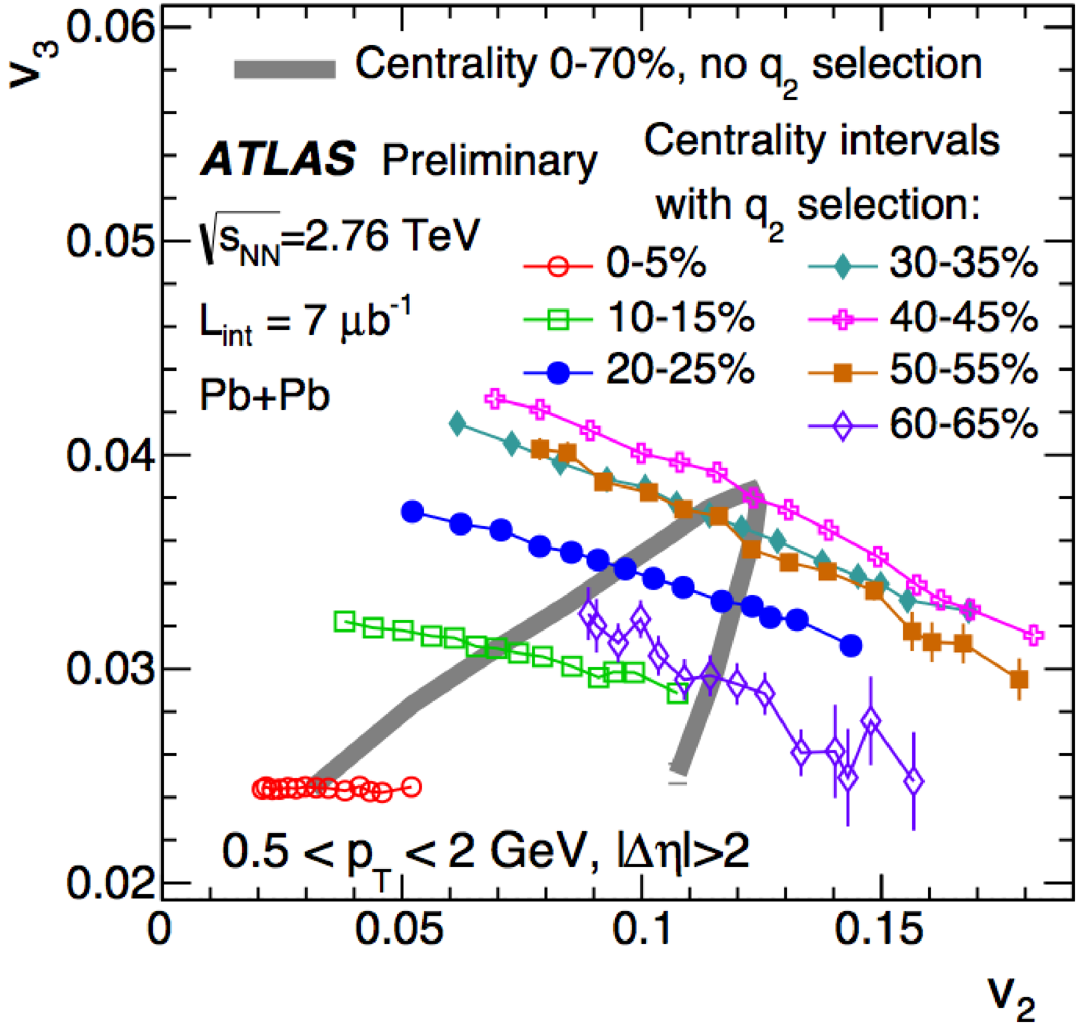


v_2-v_2 correlations : q-bins



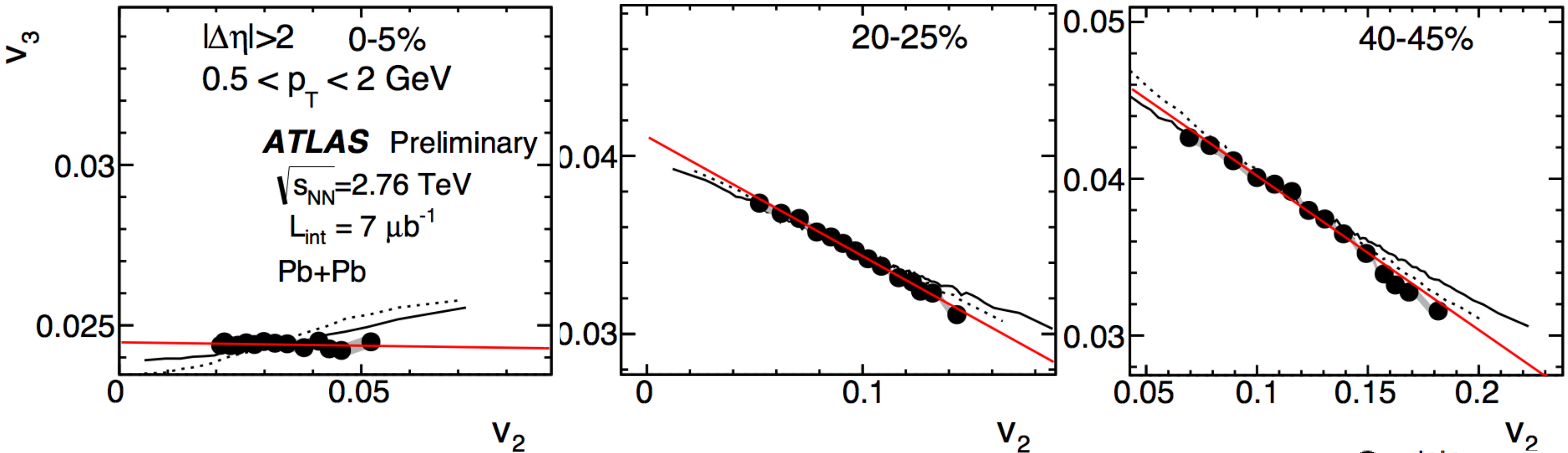
- Saw non-trivial dependence with centrality (boomerang),
  - but within one centrality dependence is linear!
- Indicates that viscous correction mostly controlled by system size, not shape!

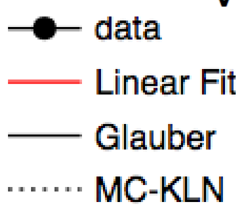
v_3-v_2 correlations : q-bins



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

v_3-v_2 correlations : Glauber & CGC comparison





- 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 $v_3 = kv_2 + v_3^0$

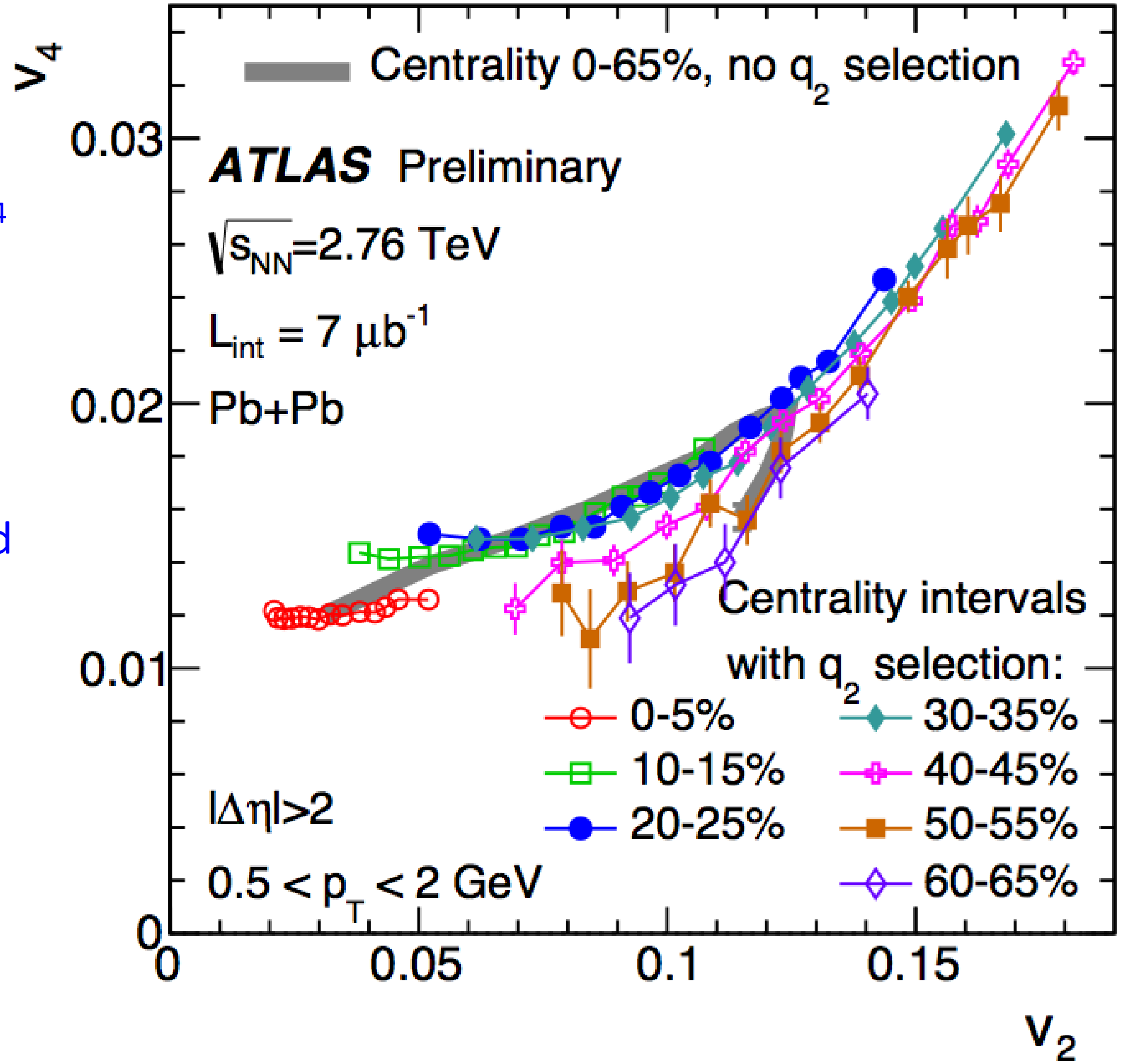
v_4-v_2 correlations : q-bins

- 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

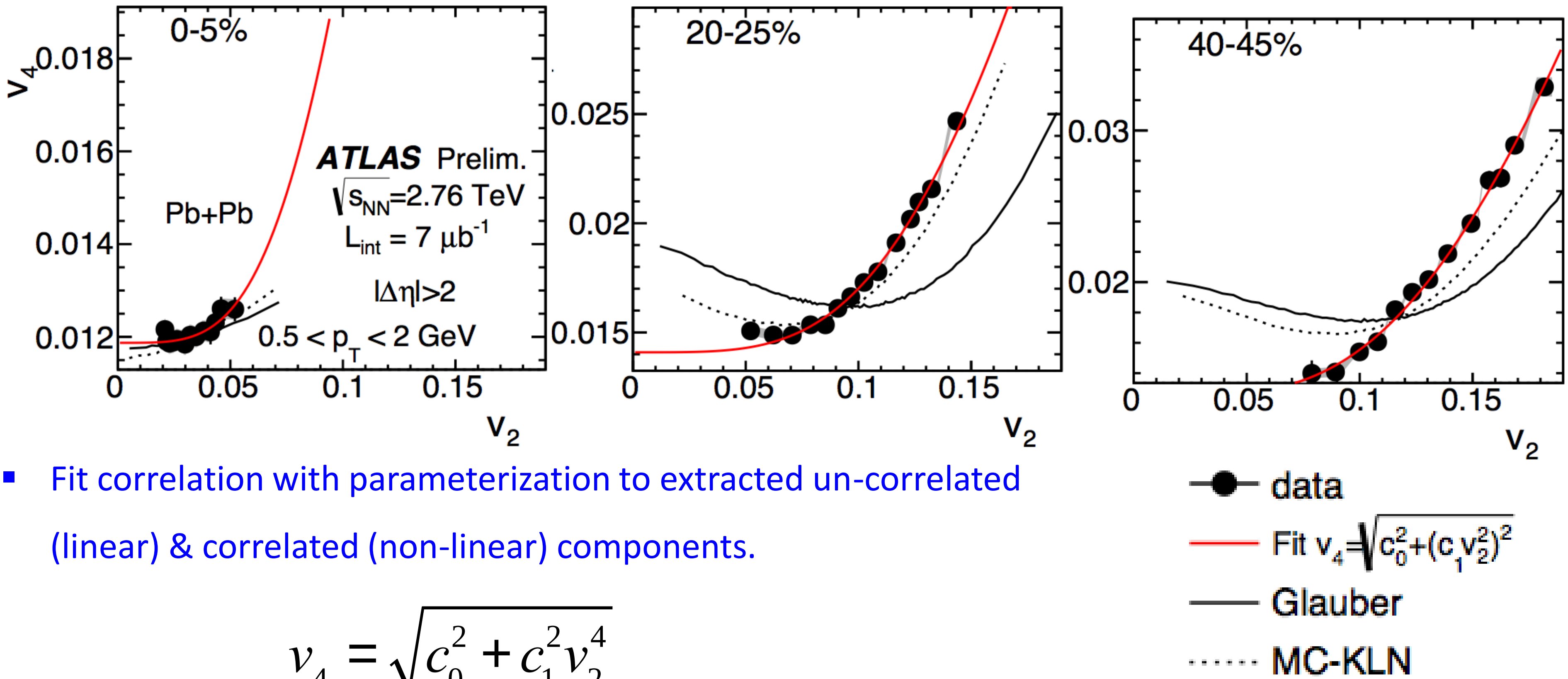
$$v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^*} + c_1 \left(v_2 e^{i2\Phi_2}\right)^2$$

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



- 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

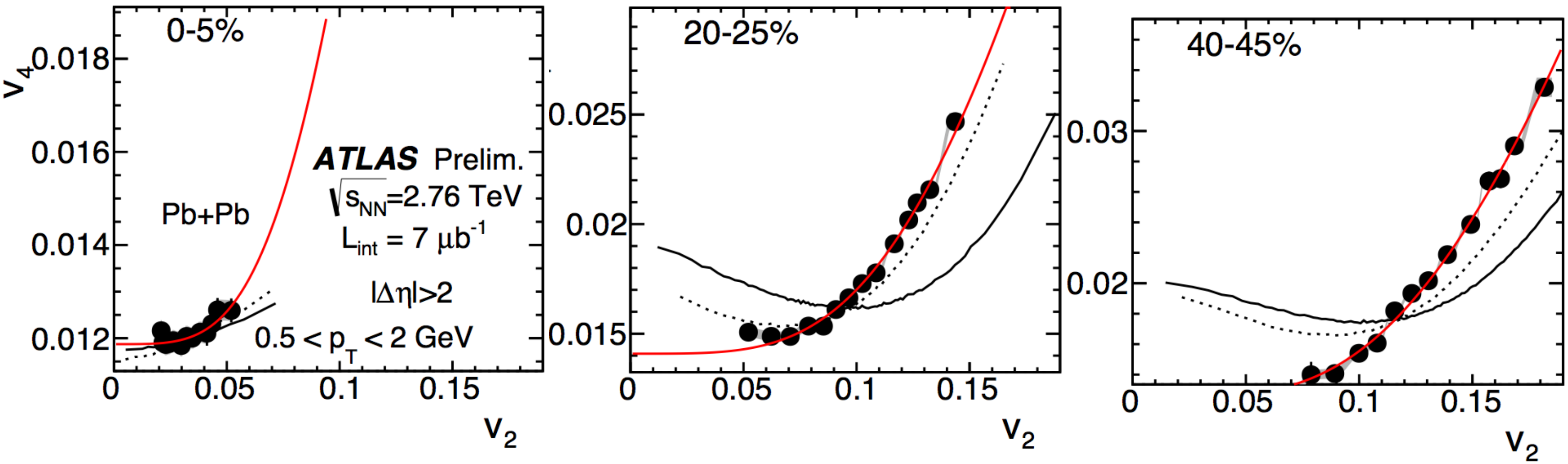


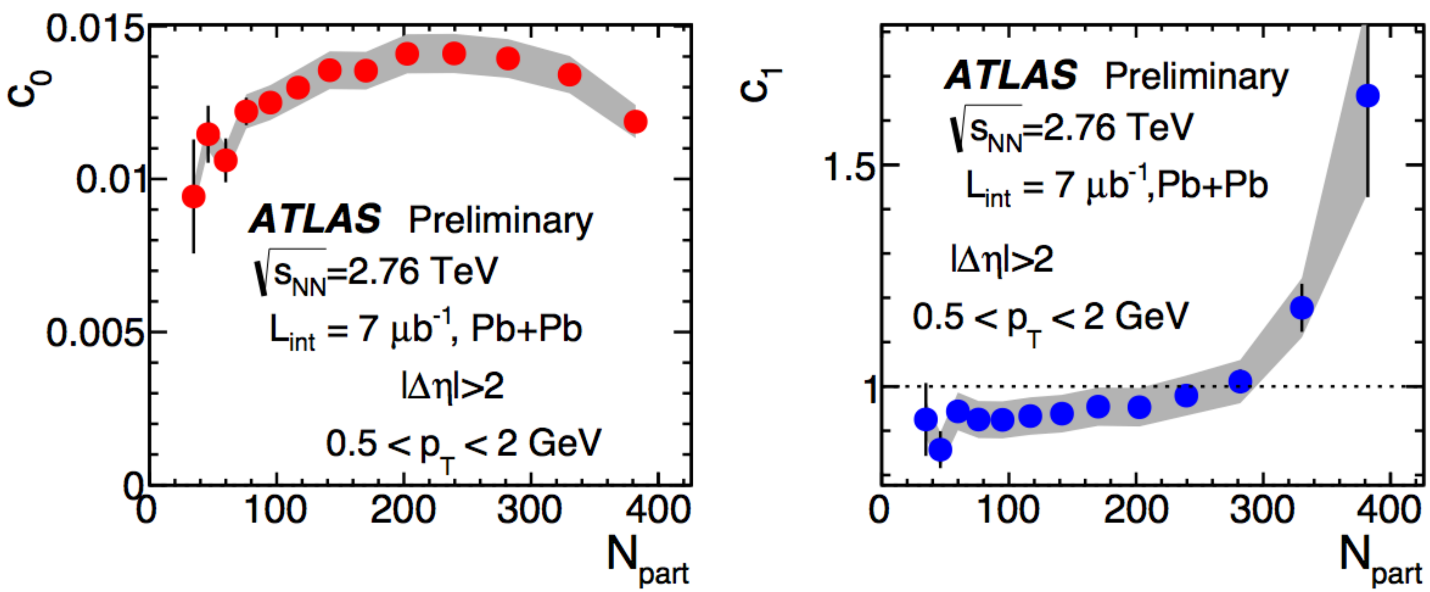
- Fit correlation with parameterization to extracted un-correlated (linear) & correlated (non-linear) components.

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

- 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

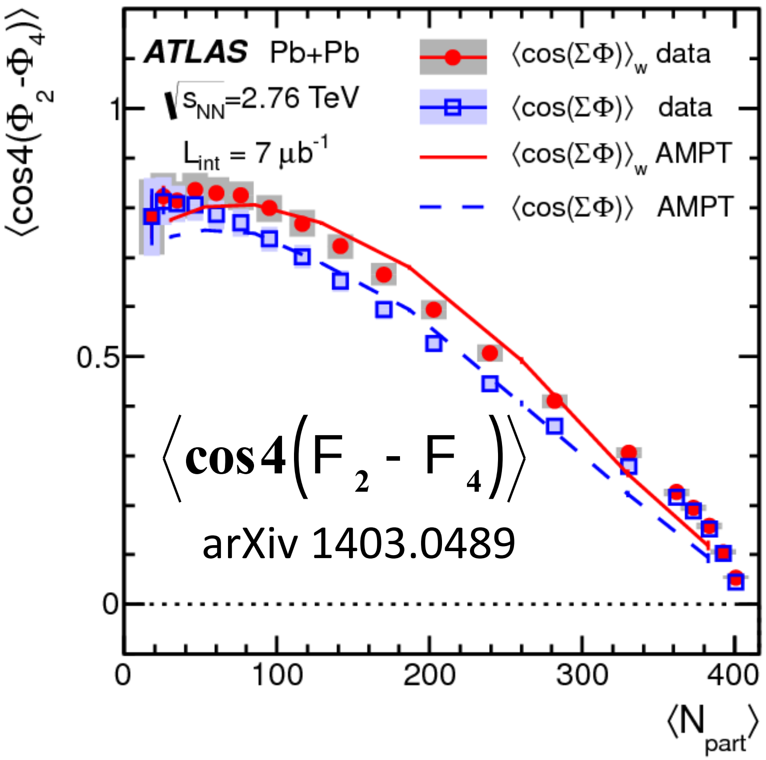


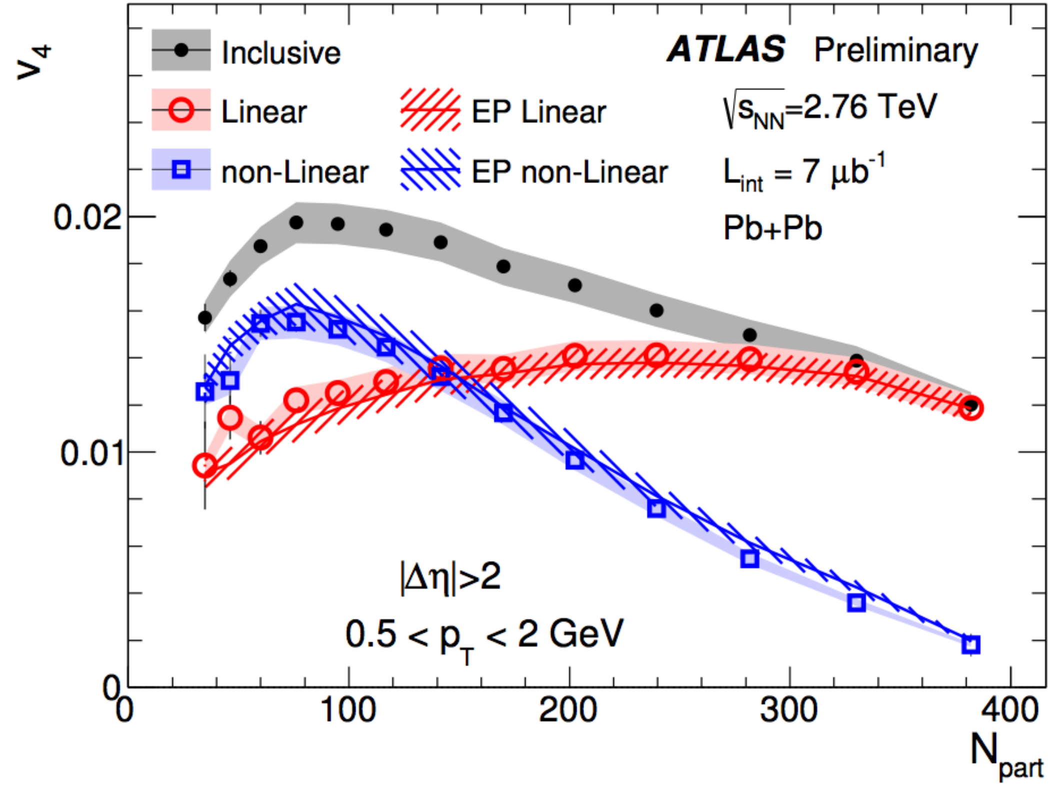


$$v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$$

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

v_4-v_2 correlations : comparison to EP correlations



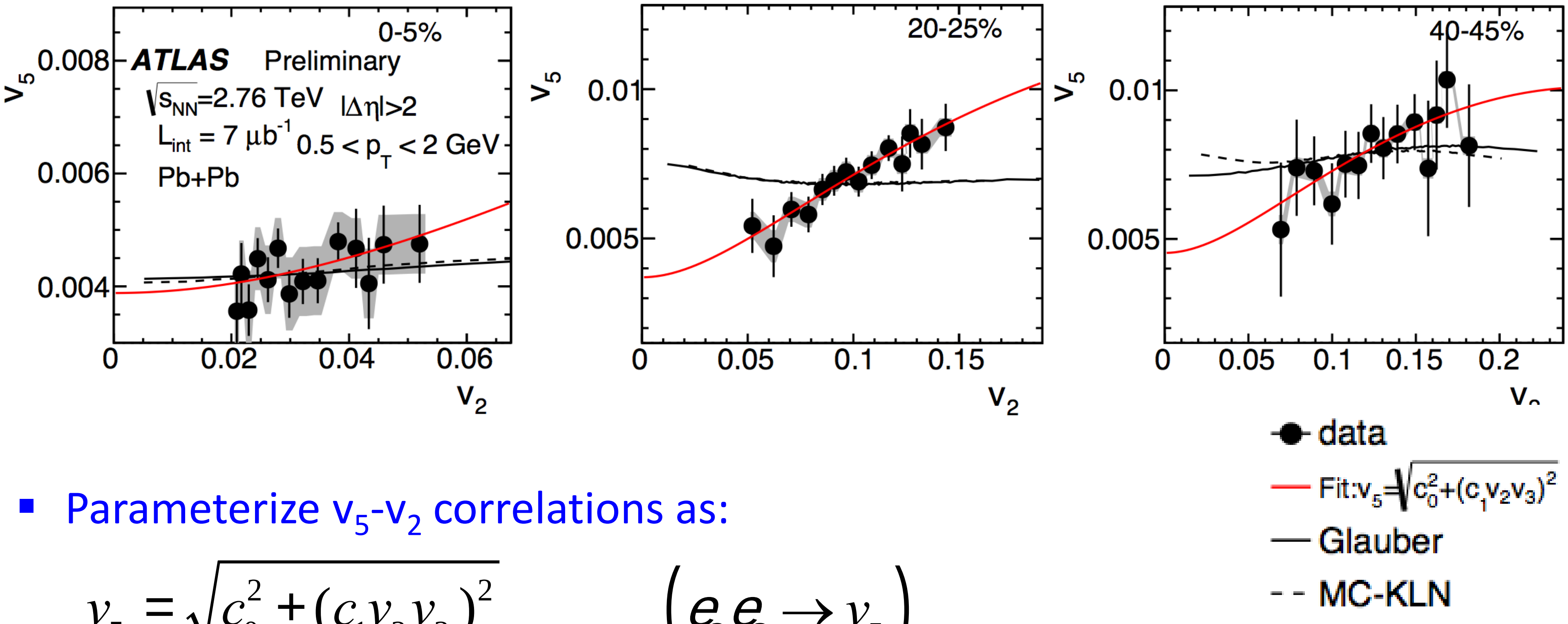


- The non-linear & linear components from EP correlations are obtained as:

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

- 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_{part}~120

v_5-v_2 correlations : q-bins

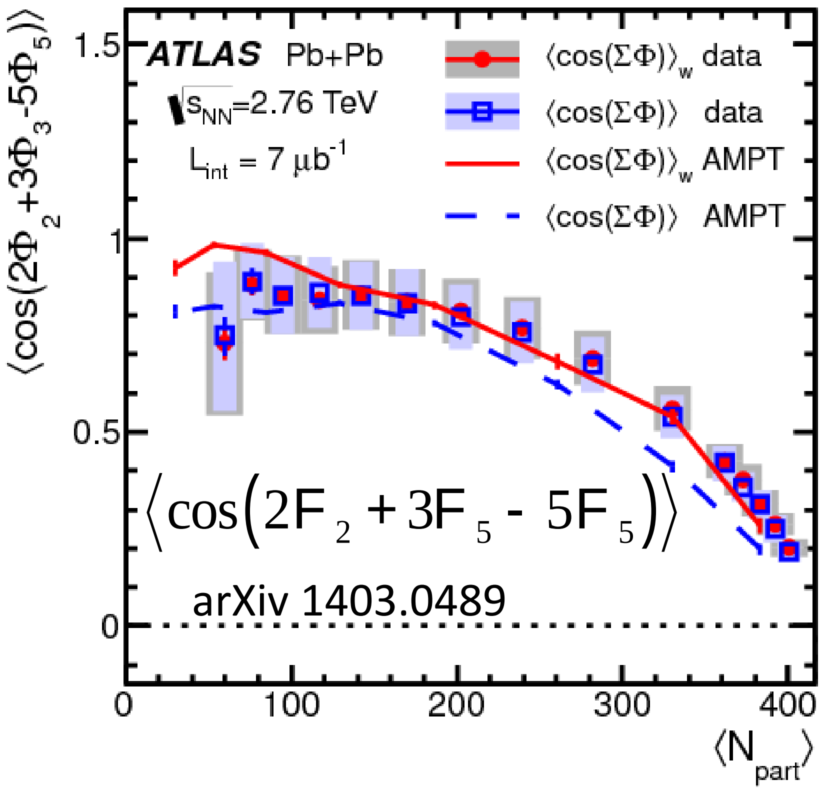


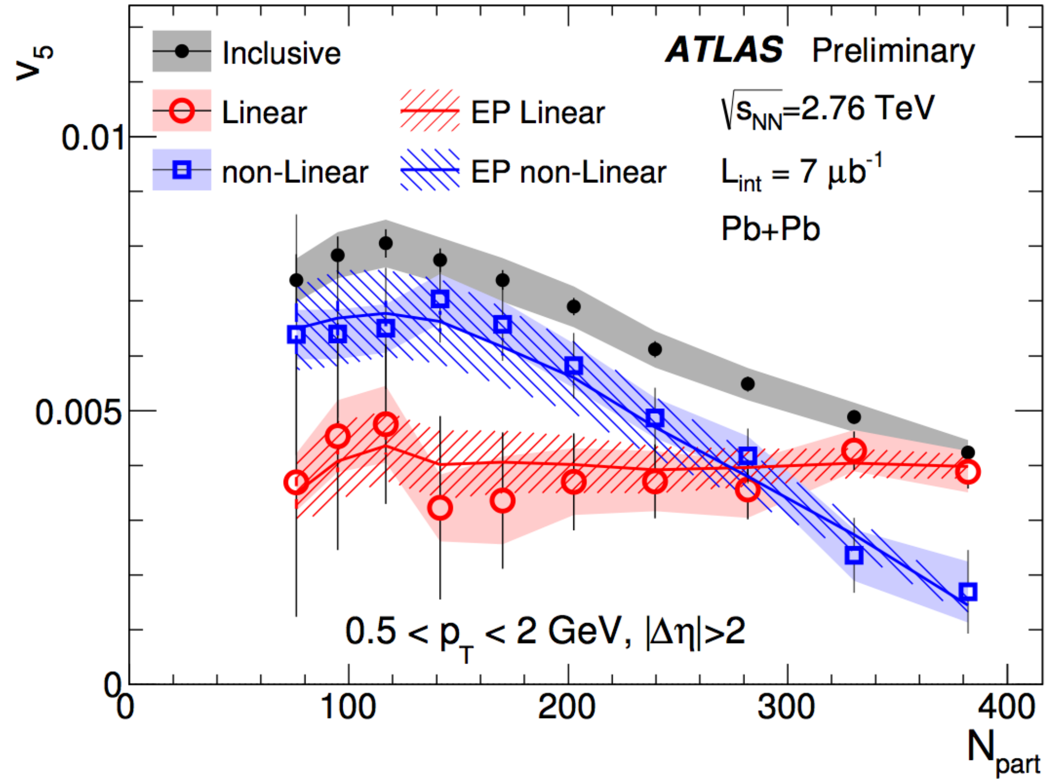
- Parameterize v_5-v_2 correlations as:

$$v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2} \qquad \left(e_2 e_3 \rightarrow v_5\right)$$

- 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



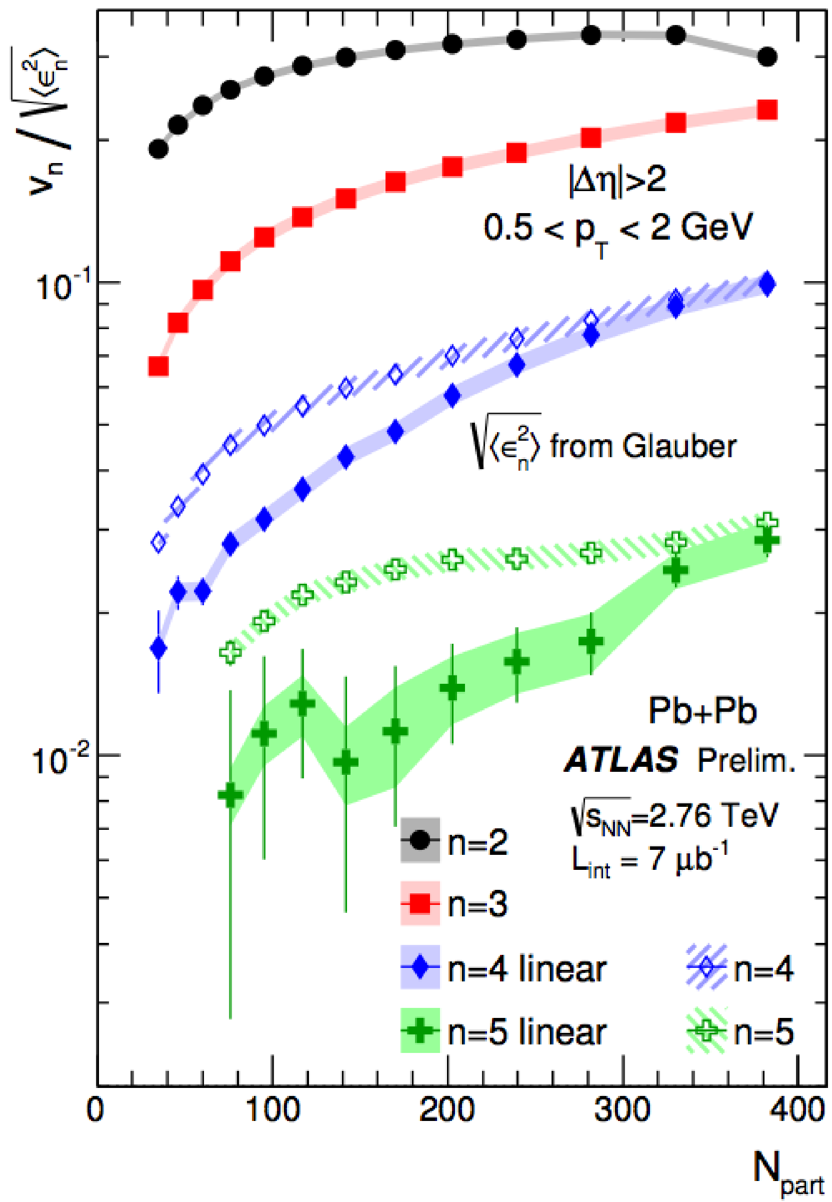


- Compare linear & non-linear components from this analysis to EP correlation results
- The non-linear & linear components from EP correlations are obtained as:

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

ε_n scaling of linear components

- The v_n/rms-ε_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.



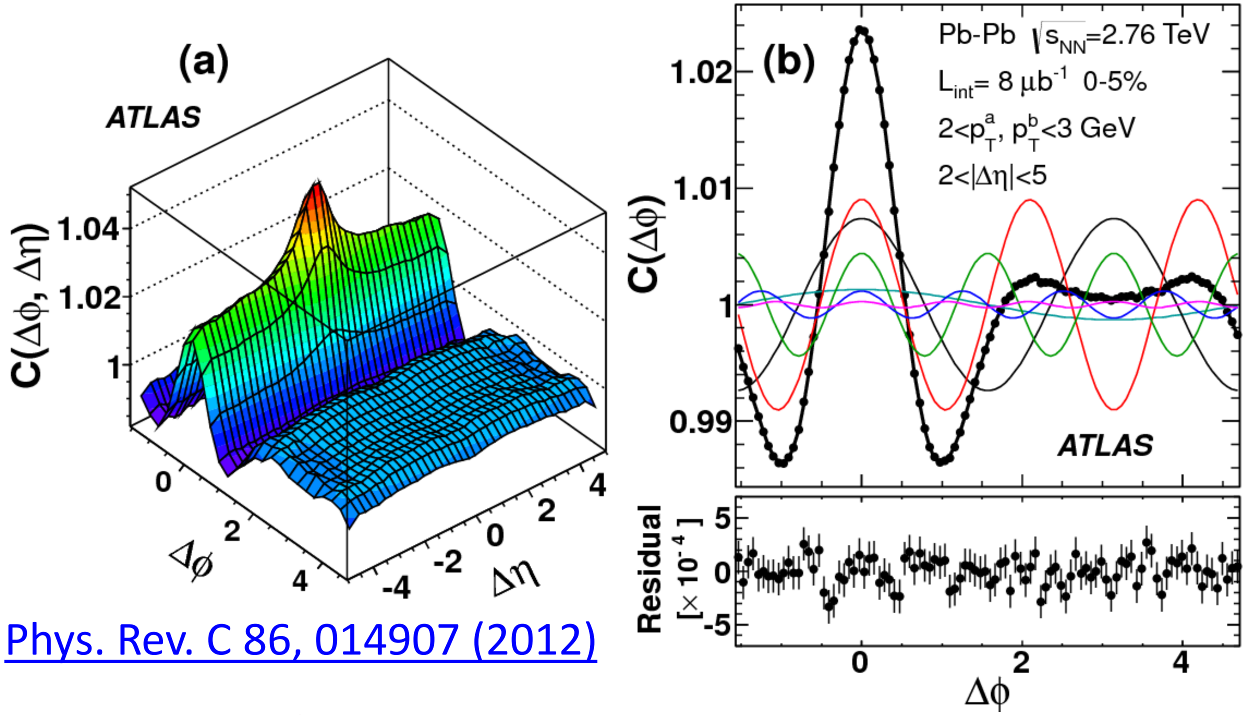
Conclusions

- Measurements:
  - Correlations between v_2 and v_m, m=2-5.
- $v_2(p_T^a)$-$v_2(p_T^b)$ 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 previously published EP correlation results
- Dependence of the linear components on the rms-ε_n were also studied
  - Stronger damping seen for higher order harmonics as expected from hydrodynamics
- v_n-v_m correlations are new flow observables
  - Have much potential in improving our understanding of HI collisions.

Backup

v_n extraction using 2PC

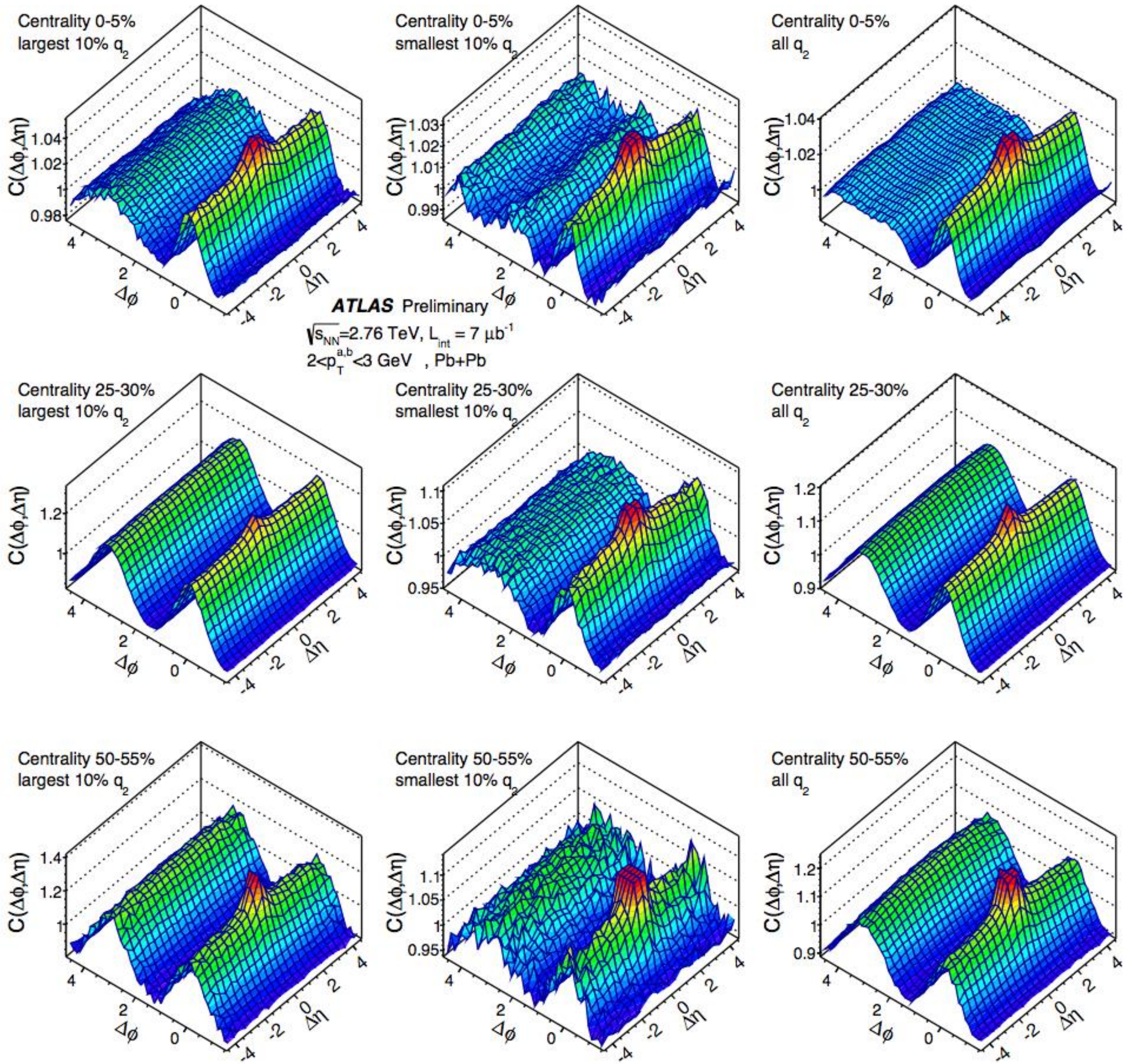
- a) 2PC in Δη-Δφ
- b) Δφ projection for |Δη|>2
- The |Δη|>2 cut removes near-side peak



Phys. Rev. C 86, 014907 (2012)

- Can expand 2PC as Fourier series $\frac{dN^{\text{pairs}}}{d\Delta\phi} = N_0^{\text{pairs}}\left(1+\Sigma_{n=1}^{\infty} v_{n,n}(p_T^a, p_T^b)\cos(n\Delta\phi)\right)$
- The Fourier coefficients $v_{n,n}(p_T^a,p_T^b)$ of the 2PC factorize as: $v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)$
- We can thus evaluate the $v_n(p_T^b)$ as: $v_n(p_T^b) = \frac{v_{n,n}(p_T^a, p_T^b)}{v_n(p_T^a)} = \frac{v_{n,n}(p_T^a, p_T^b)}{\sqrt{v_{n,n}(p_T^a, p_T^a)}}$
- Method was used extensively in previous v_n measurement for same dataset
  - Only change is that now the study is done q-Bin by q-Bin

Physics Plots: 2D corrs q dependence



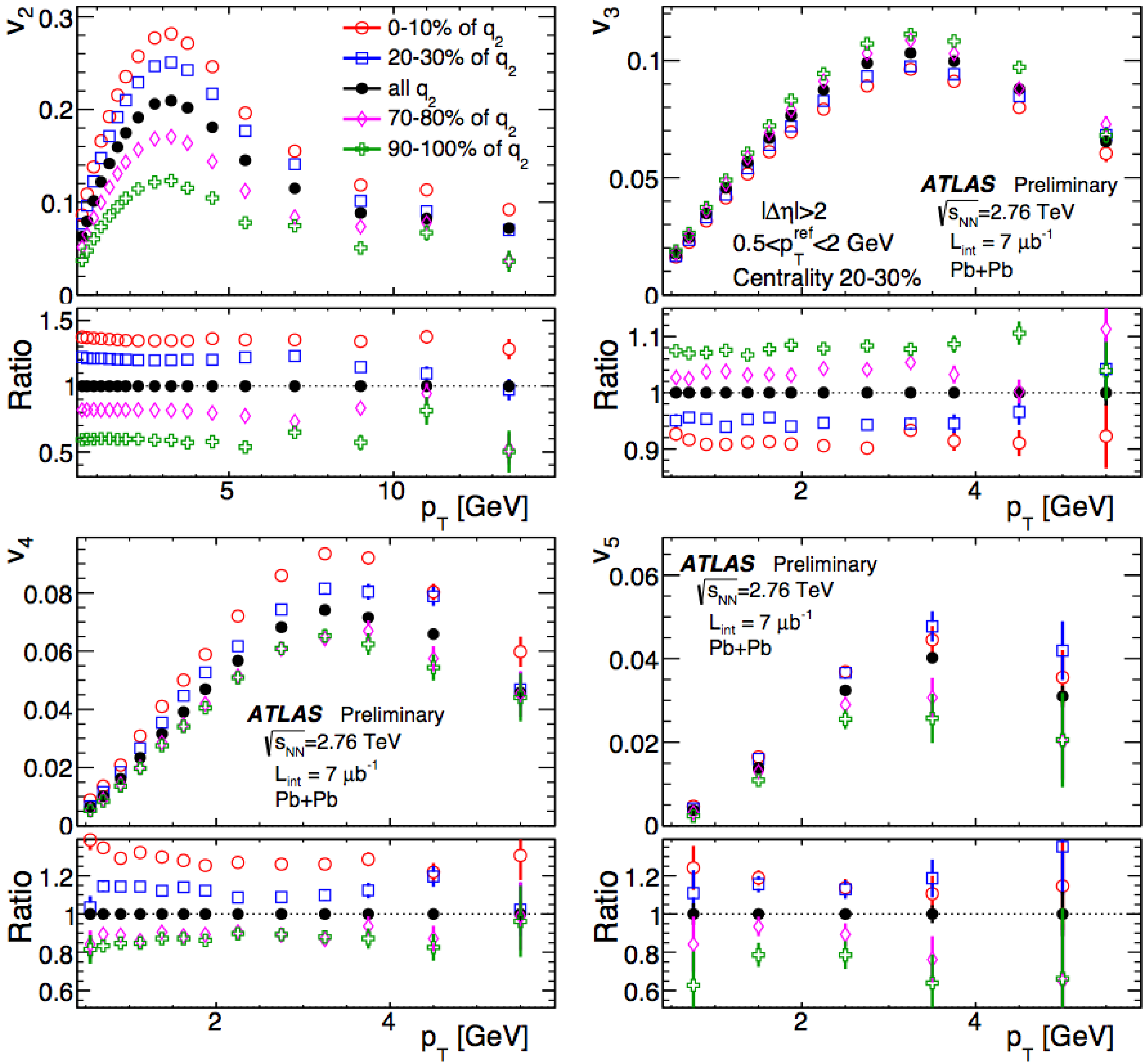
Systematic Errors

	Source	v_2	v_3	v_4	v_5	q_2 dependent
1	Track Selection [%]	0.3	0.3	1.0	2.0	yes
2	Tracking efficiency [%]	0.1-1.0	0.2-1.5	0.2-2.0	0.3-2.5	yes
3	Running Periods [%]	0.3-1.0	0.7-2.1	0.7-2.1	2.3	no
4	Trigger & event Selection [%]	0.5-1.0	0.5-1.5	0.5-1.5	0.5-1.5	yes
5	MC consistency [%]	1.0	1.5	2.0	3.5	yes
	Total [%]	1.2-2.0	1.8-3.4	2.4-4.0	4.6-5.5	yes

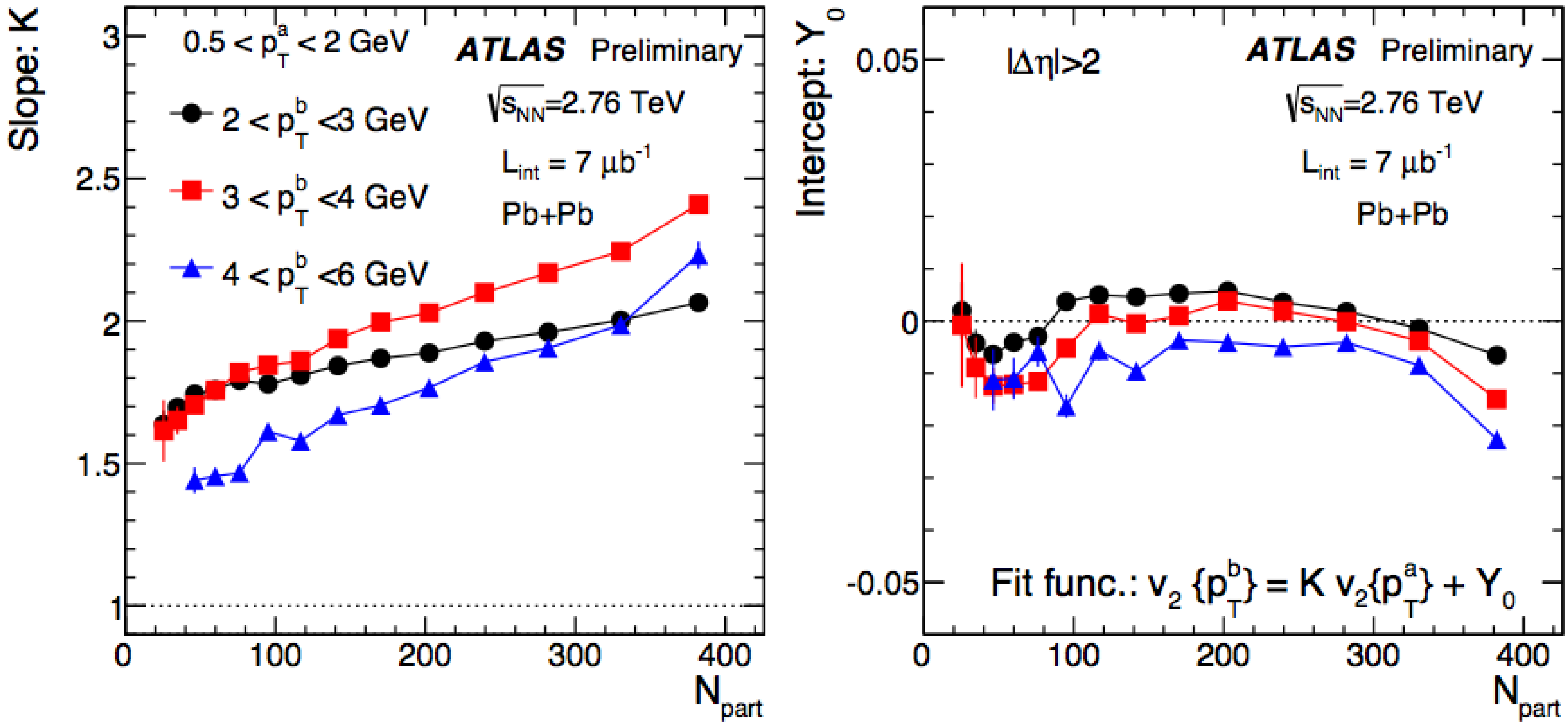
Items 1,3,4,5 were evaluated in previous paper on v_n measurement Phys. Rev. C 86, 014907 (2012) (internal note at https://cds.cern.ch/record/1349038)

Item 2 was evaluated in previous paper on Event-by-event flow JHEP11(2013)183

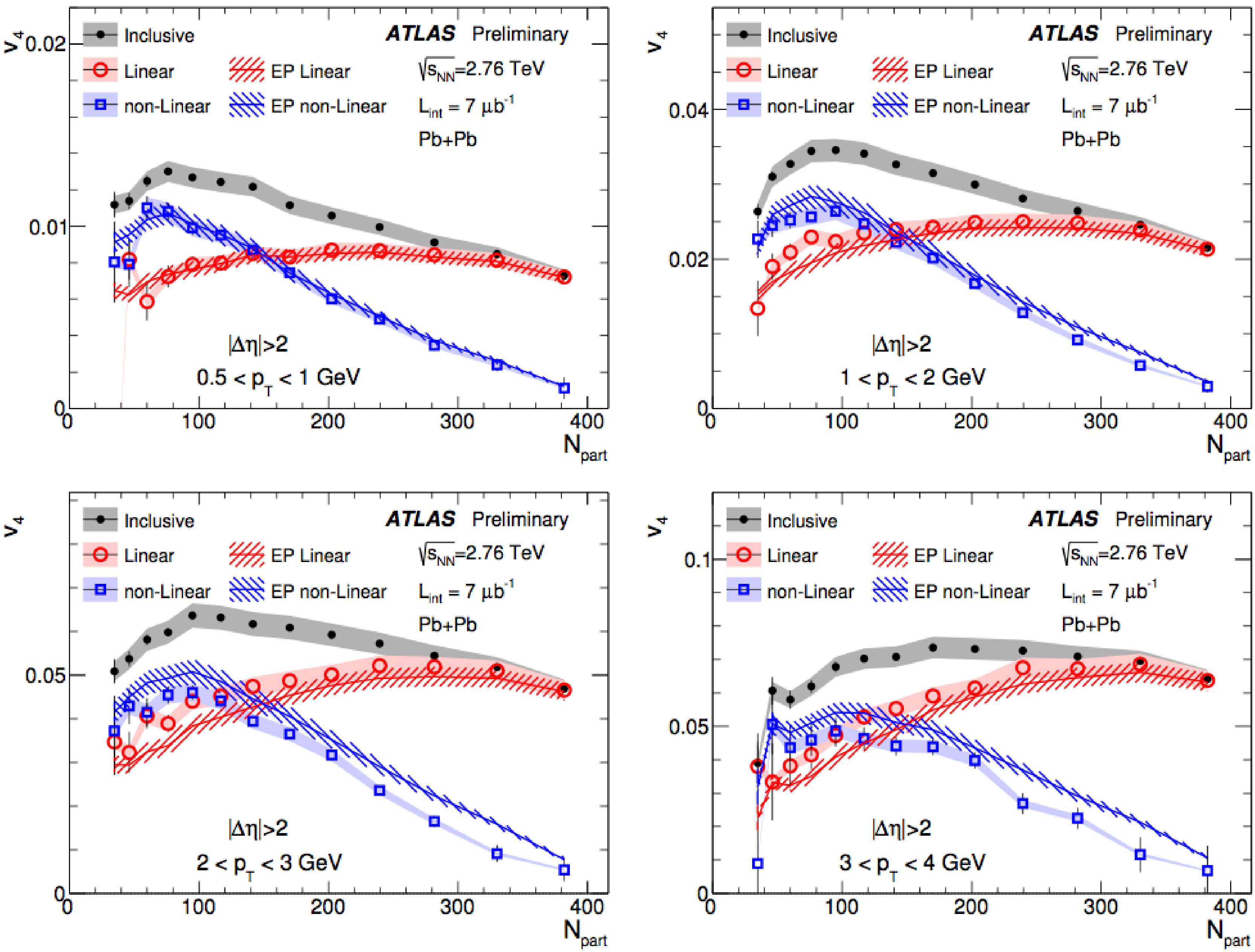
Physics Plots: qBins pT dependence



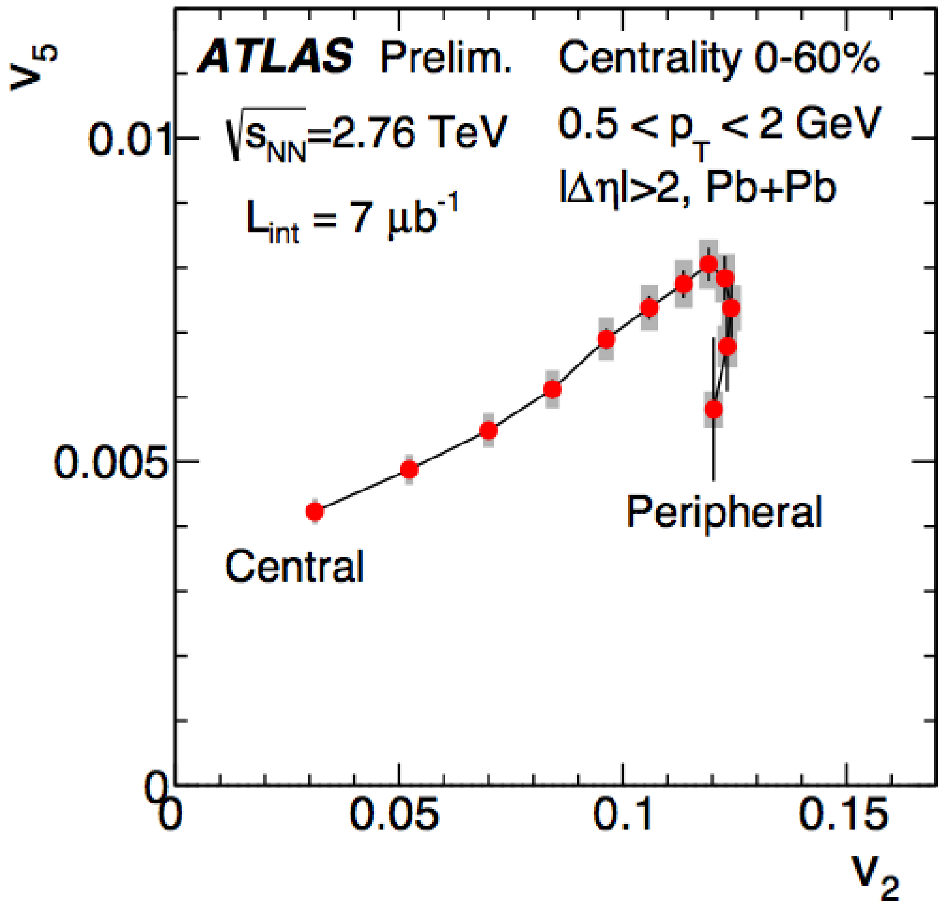
Physics Plots: v2-v2 corrs fit params

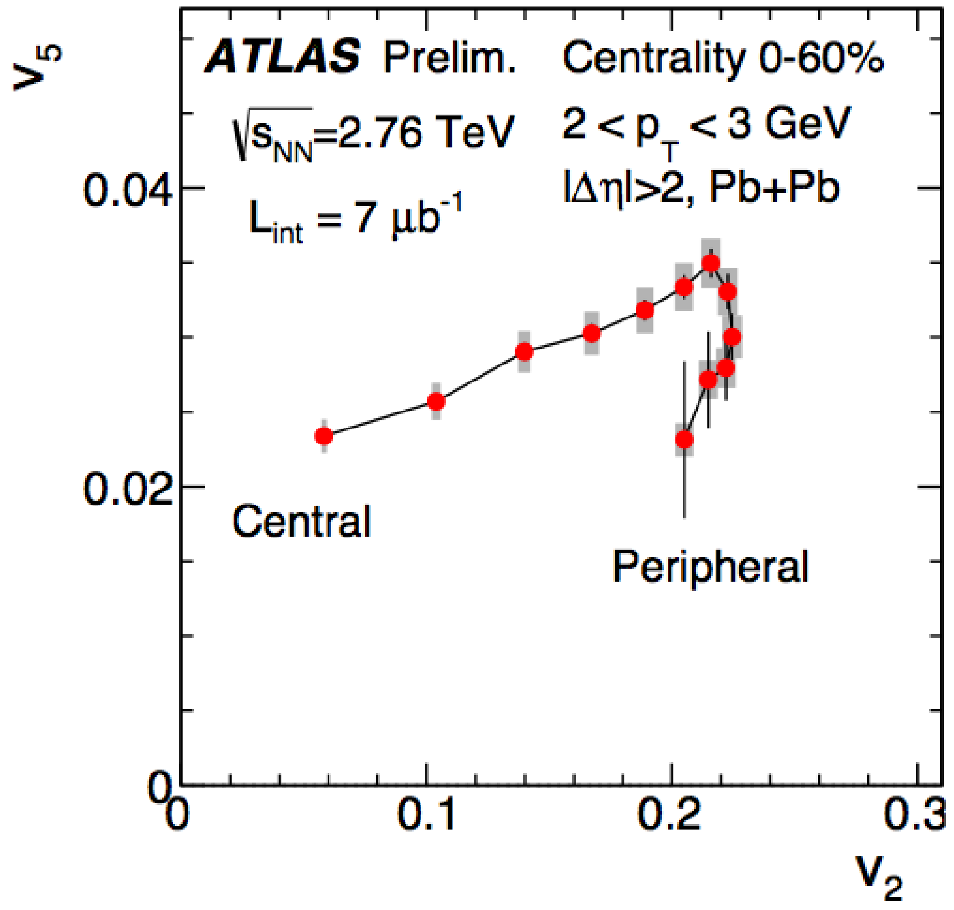


Physics Plots: v4 liner & non-linear



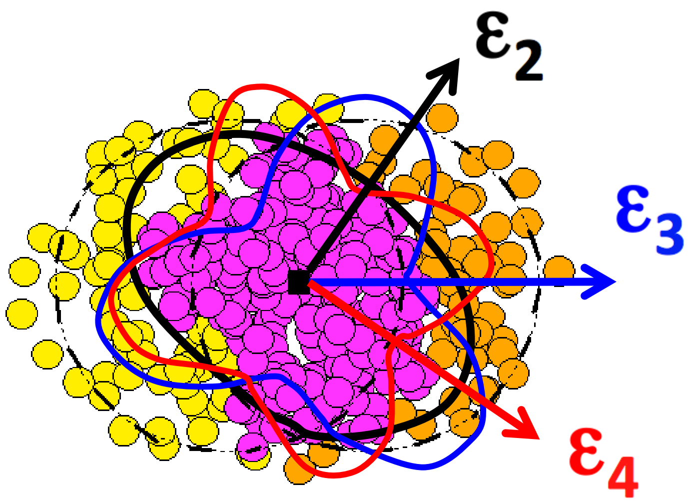
Physics Plots: v5 inclusive qbins





Introduction

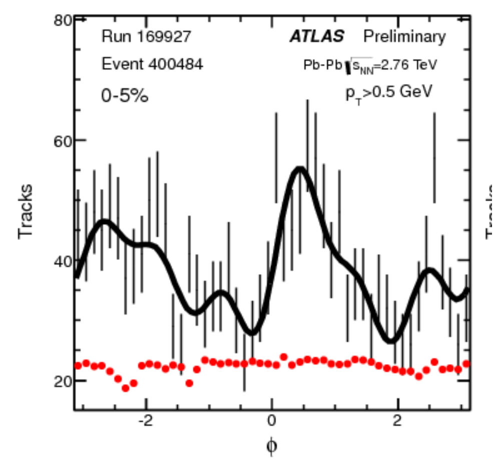
- Initial spatial fluctuations of nucleons lead to higher moments of deformations in the fireball, each with its own orientation.
- The spatial anisotropy is transferred to momentum space by collective flow.



$$\varepsilon_n = \sqrt{\frac{\langle r^n \cos(n\phi)\rangle + \langle r^n \sin(n\phi)\rangle}{r^n}}$$

$$\tan(n\Phi_n) = \frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle}$$

Final particles: $\frac{dN}{d\phi} \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n} \cos n(\phi - \Phi_n)$



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

Motivation-I

- Have previously measured $<v_n>$

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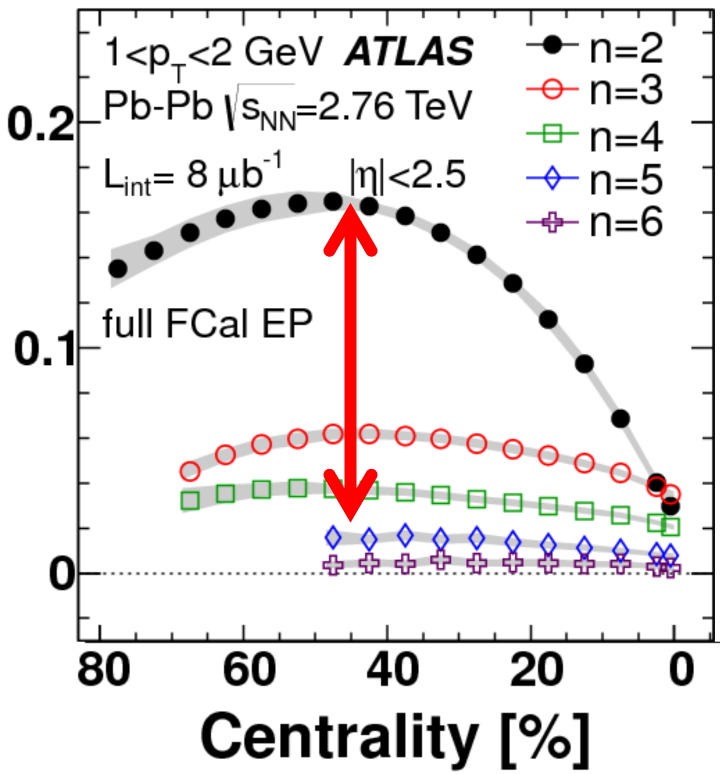

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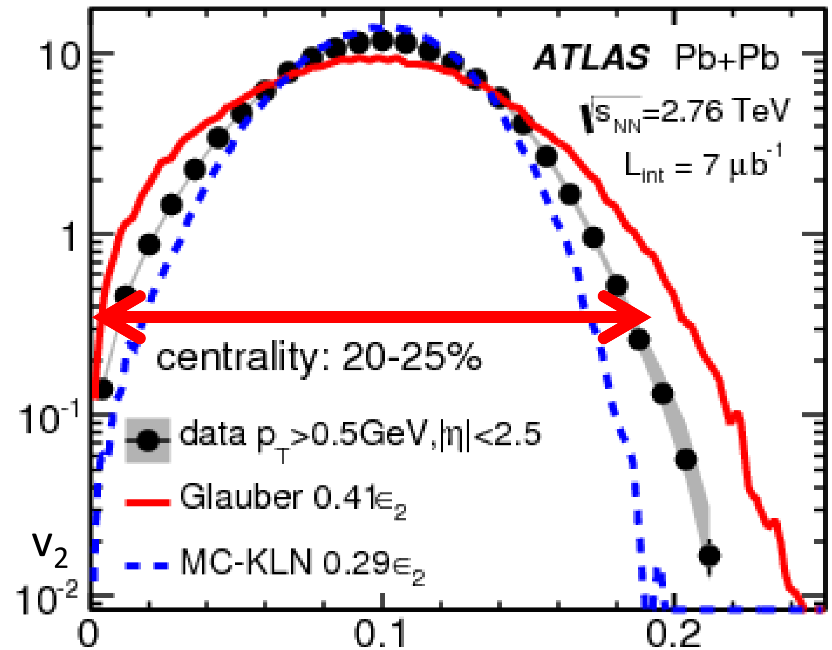
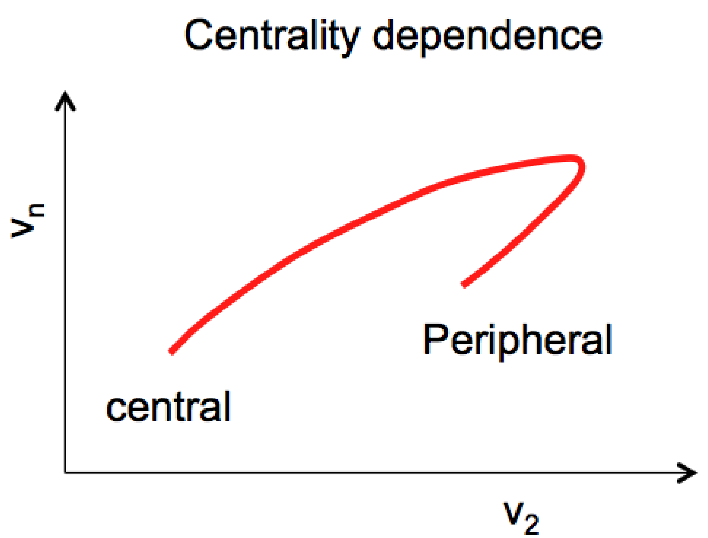


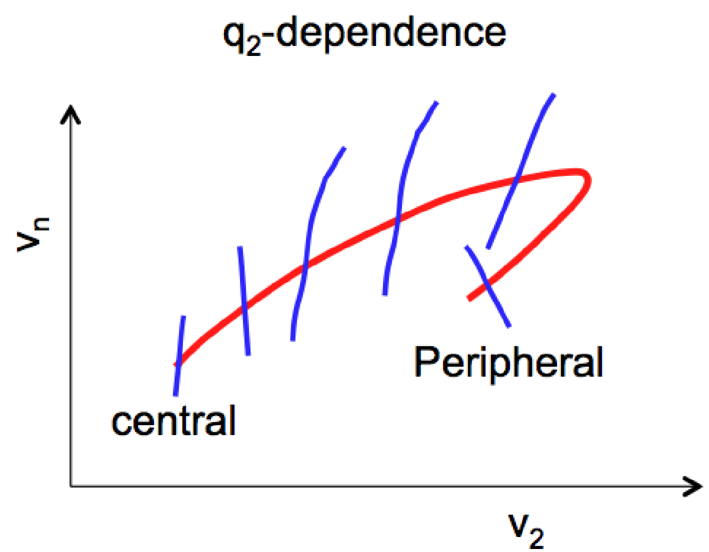
- Much more variation in v_n within one centrality than variation of mean v_n across all centralities
- Should also study the variation of v_n at fixed centrality but varying event-geometry: “event-shape-selected v_n measurements”

Presentation strategy

- Present the results as direct correlations:
  - Correlations between v_2 and v_m in the same p_T range.

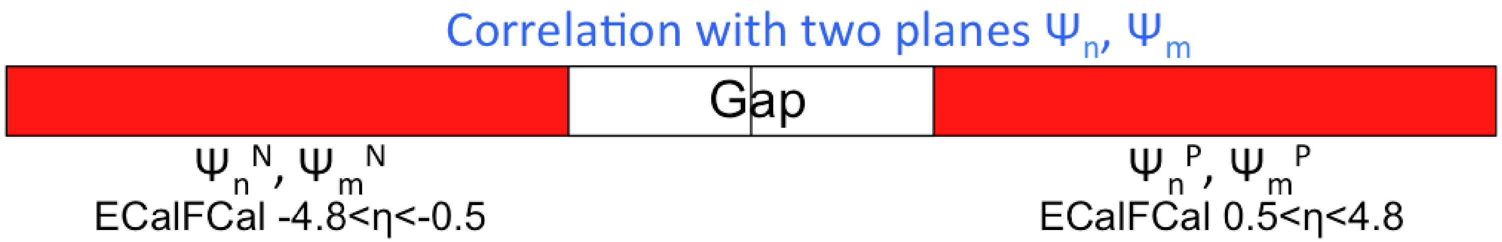
- Will first show the inclusive centrality dependence and then overlay with q dependence

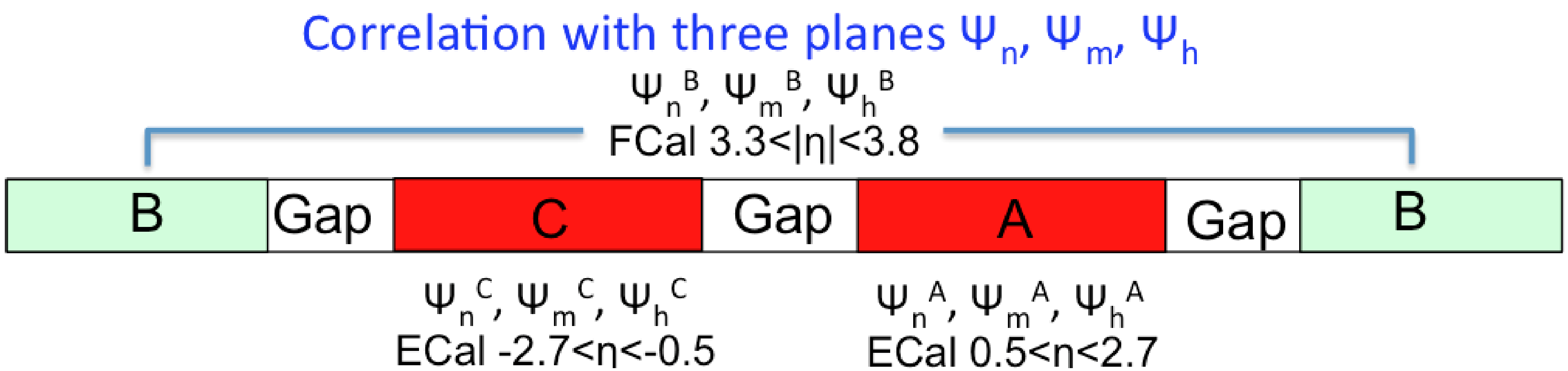




Note the centrality dependence can be obtained entirely from the published data

event-plane correlations : methodology

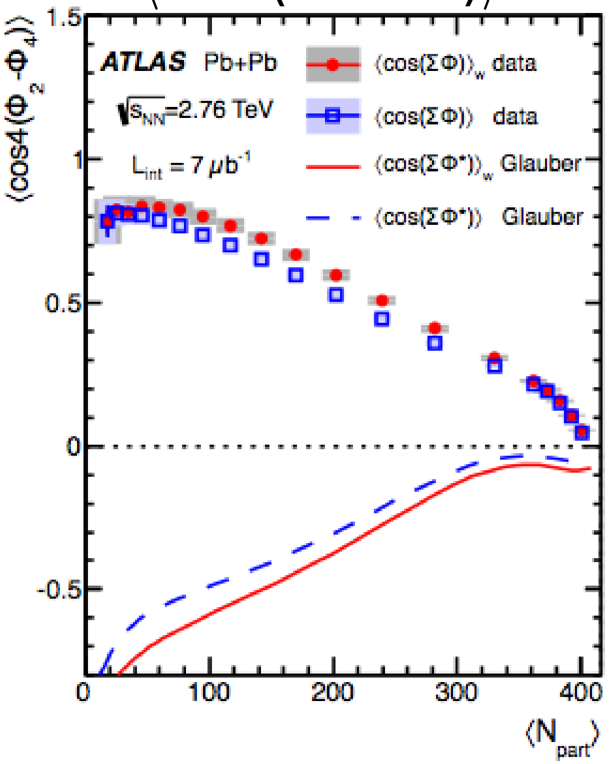




- η-gap is required to remove autocorrelations.
- Correlations measured via both event-plane (EP) & scalar-product (SP) methods

Correlation between Φ_2 and Φ_4

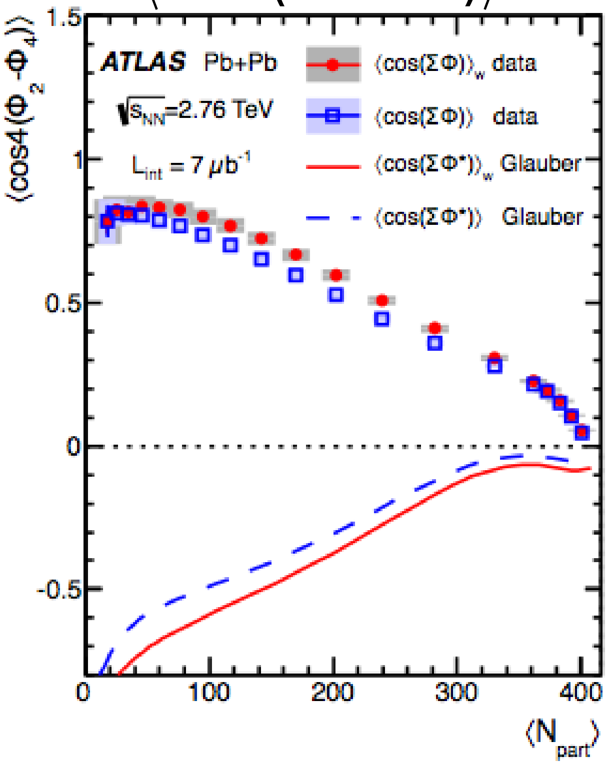
$$\left\langle \cos 4\left(F_2 - F_4\right)\right\rangle$$



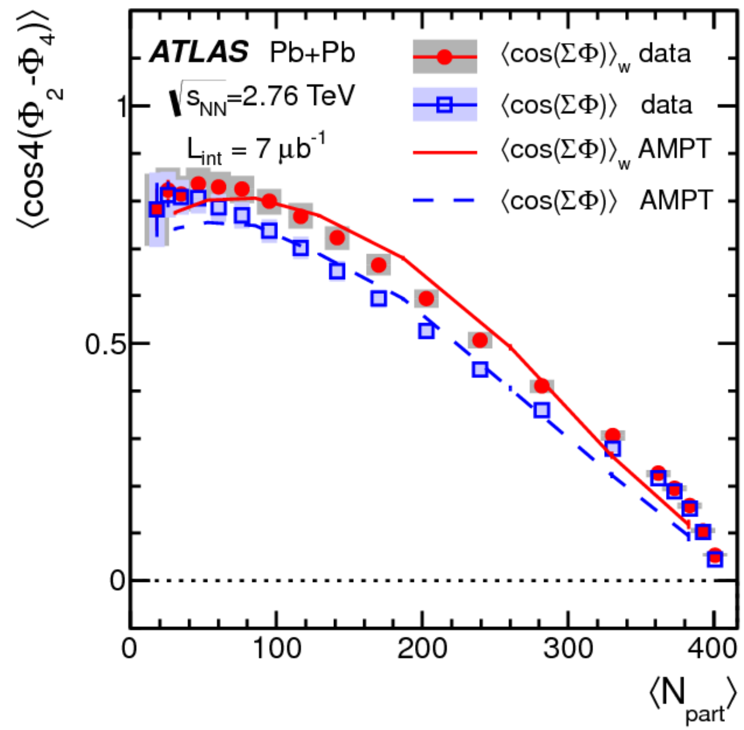
- Results expressed as function of N_{part}.
- Very different from correlations in initial state (Glauber)
- What happens if we include final-state-interactions?

Correlation between Φ_2 and Φ_4

$\langle \cos 4(F_2 - F_4) \rangle$

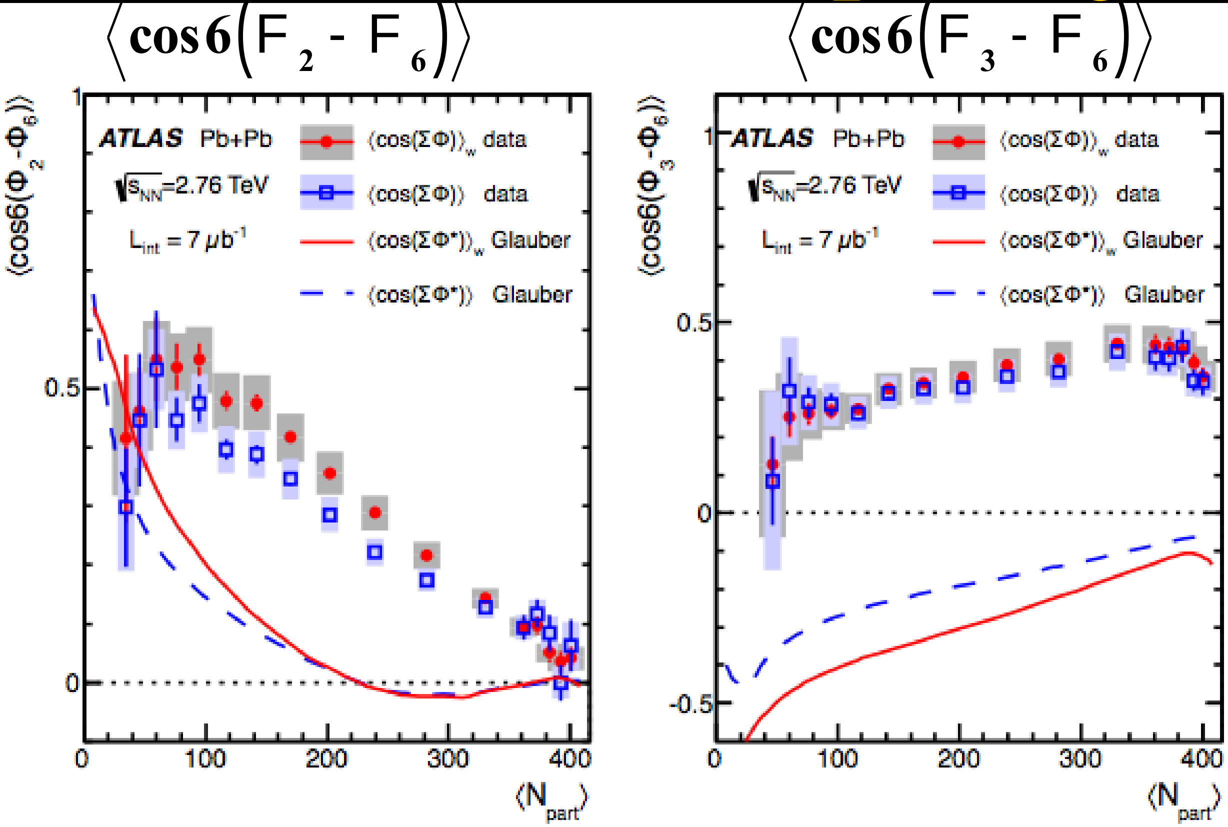


$\langle \cos 4(F_2 - F_4) \rangle$



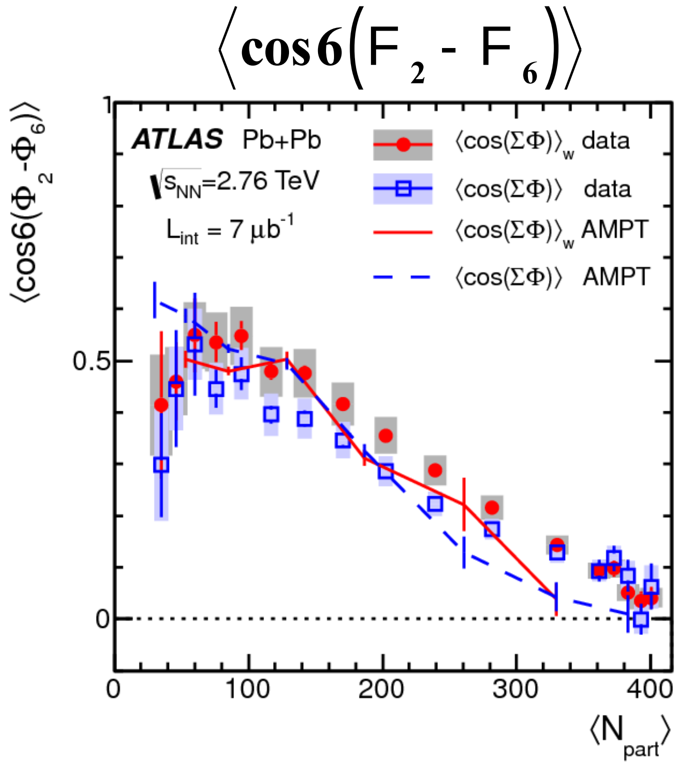
- Results expressed as function of N_{part}.
- Very different from correlations in initial state (Glauber)
- What happens if we include final-state-interactions?
- Correlations well reproduced in AMPT model
  - AMPT results from **arXiv:1307.0980** (Bhalerao et. al.)
- Conclusion: large fraction of v_4 originates from ε_2 during hydrodynamic expansion !!!

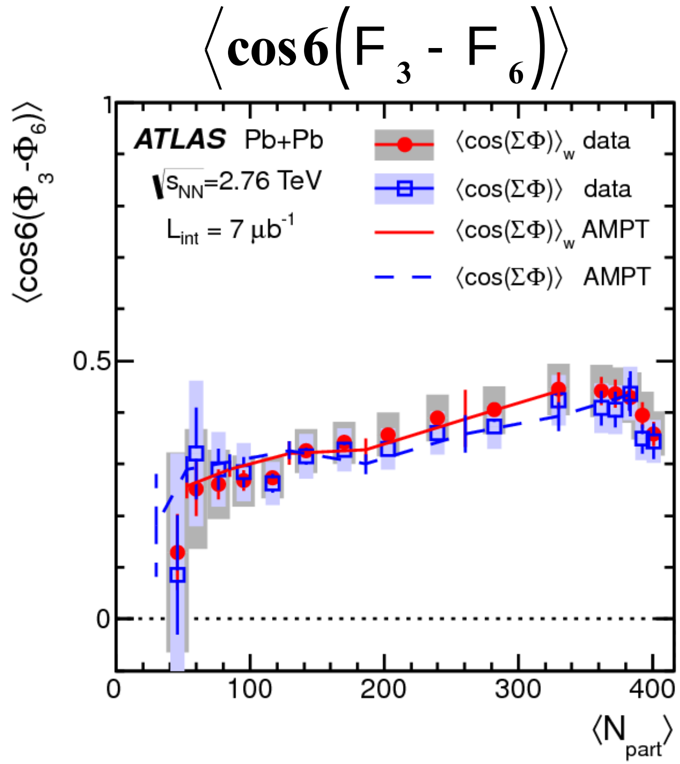
Correlation of Φ_2 or Φ_3 with Φ_6



- Φ_2 and Φ_3 both strongly correlated with Φ_6
- They show opposite centrality dependence though:
  - Φ_2-Φ_6 correlation may due to average geometry..
  - But Φ_3-Φ_6 correlation?
  - v_6 dominated by non-linear contribution: v_2^3, v_3^2 ?

Correlation of Φ_2 or Φ_3 with Φ_6



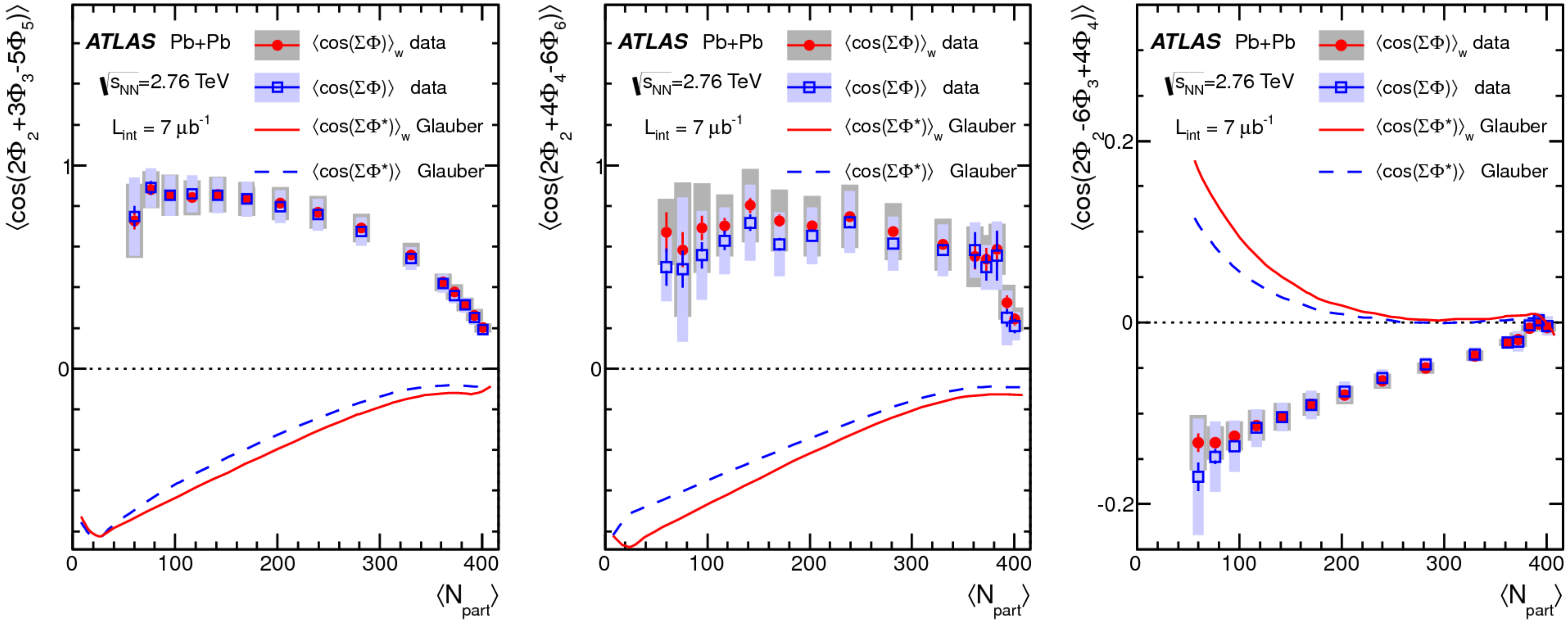


- Final state interactions reproduce the correlations

- Conclusion: large contribution to v_6 from $(\varepsilon_2)^3$ & $(\varepsilon_3)^2$ during hydrodynamic expansion !!!

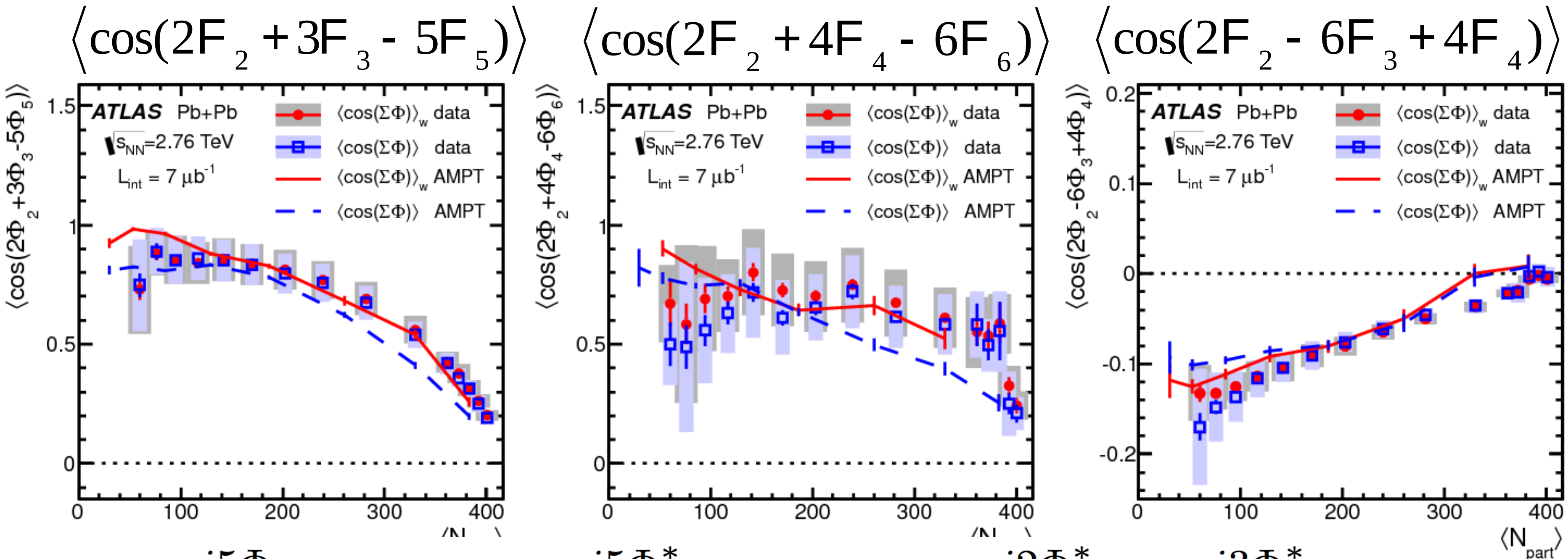
Three-plane correlations

$\left\langle \cos(2F_2 + 3F_3 - 5F_5) \right\rangle$ $\left\langle \cos(2F_2 + 4F_4 - 6F_6) \right\rangle$ $\left\langle \cos(2F_2 - 6F_3 + 4F_4) \right\rangle$



- See rich centrality dependent correlation patterns
- Not described by Initial geometry models (Glauber)

Three-plane correlations : AMPT comparison



$$v_5 e^{-i5\Phi_5} = \alpha_5 \epsilon_5 e^{-i5\Phi_5^*} + \alpha_{2,3,5}\, \epsilon_2 e^{-i2\Phi_2^*} \epsilon_3 e^{-i3\Phi_3^*} + \ldots.$$

$$= \alpha_5 \epsilon_5 e^{-i5\Phi_5^*} + \beta_{2,3,5}\, v_2 v_3 e^{-i(2\Phi_2 + 3\Phi_3)} + \ldots.$$

- Correlations recovered in AMPT model !! (Final state interactions)
- Non-linear effects are very important in understanding HI collisions
- 2-3-5 Correlation ~0.8 in peripheral events
  - Larger fraction of v_5 comes from $\varepsilon_2 * \varepsilon_3$ and not from ε_5.