Stony Brook University

ATLAS EXPERIMENT

Measurement of the correlation between flow harmonics of different order in lead-lead collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with ATLAS

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(on behalf of the ATLAS collaboration)

[arXiv:1504.01289]

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QUARK MATTER 2015

Introduction and Motivation

- Event shape dependence of flow harmonics.
  - Helps understand change in medium response with event shape.
  - Disentangle system size and system shape dependence.
  - v_2 - v_n and v_3 - v_n correlations (study of non-linear response).

Introduction and Motivation

- Event shape dependence of flow harmonics.
  - Helps understand change in medium response with event shape.
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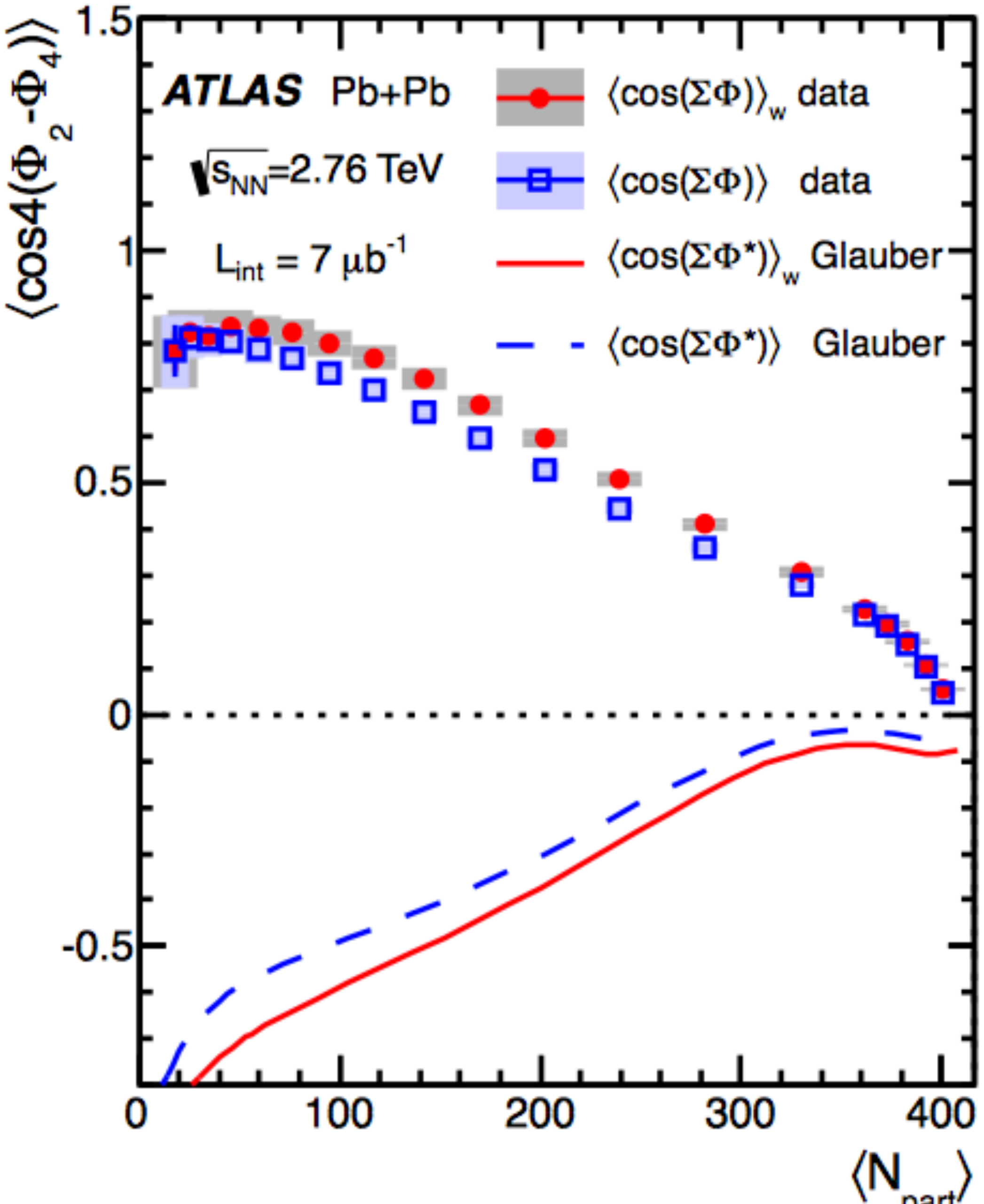
  - v_2 - v_n and v_3 - v_n correlations (study of non-linear response).

- Correlations between Event Planes of different orders studied previously (*ATLAS: PRC 90, 024905 (2014)*).

- Not reproduced by initial state correlations.
- Additional constraints on medium response.

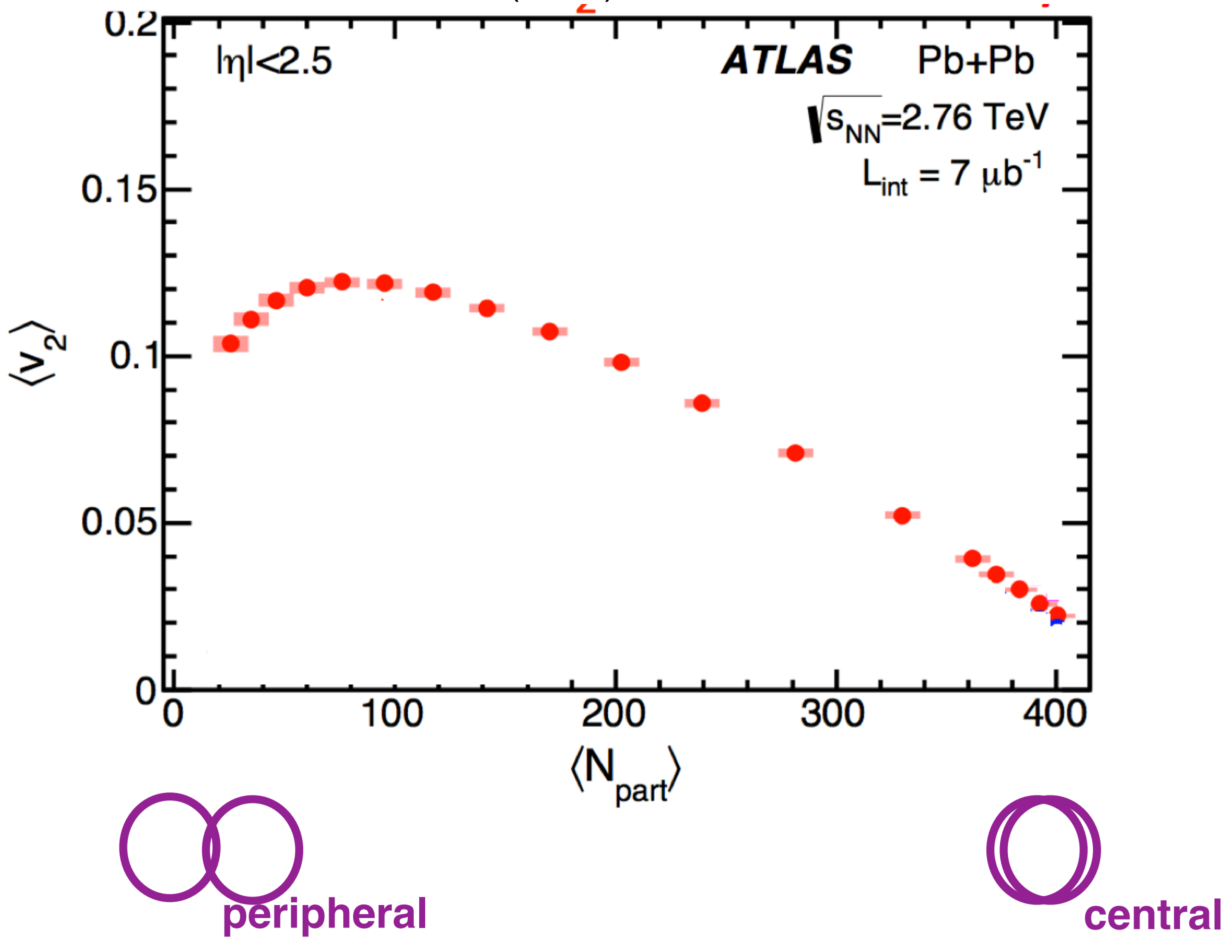
- Event shape selected analysis helps to understand these correlations better.



Event Shape Engineering

JHEP 11 (2013) 183

Average v_2 vs cent



- Both ellipticity and system size change with centrality!

Event Shape Engineering

EbE v_2 at fixed cent

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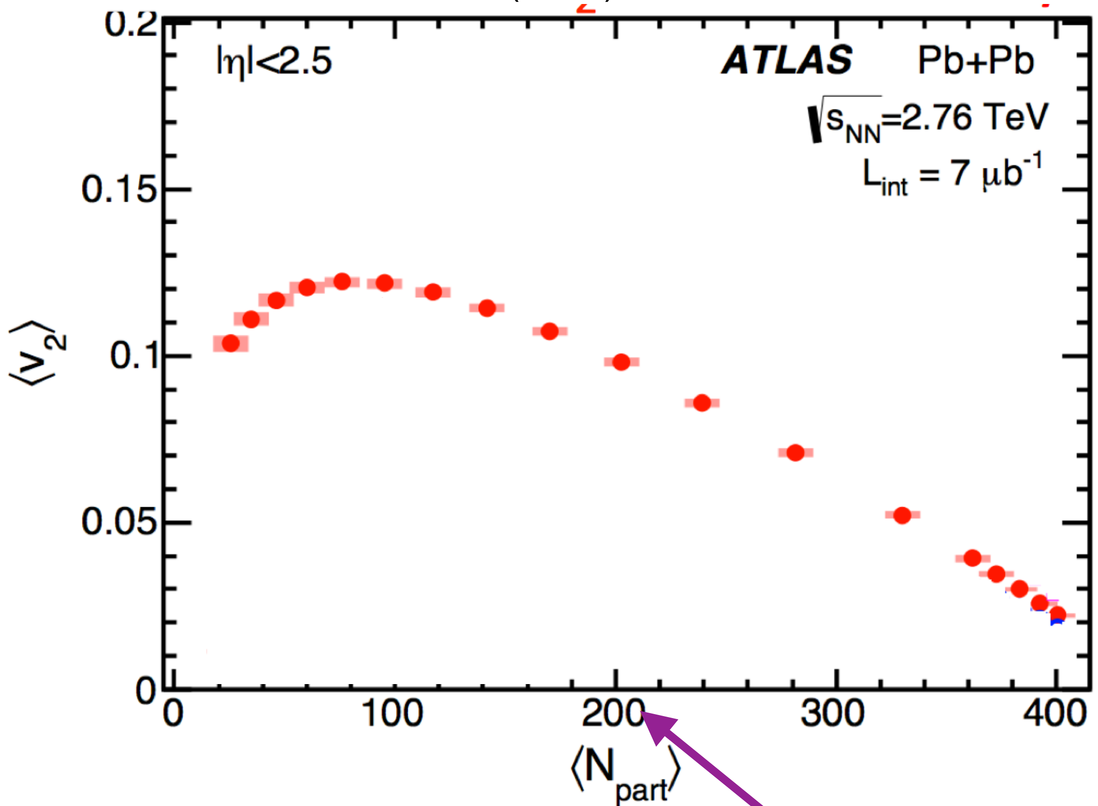

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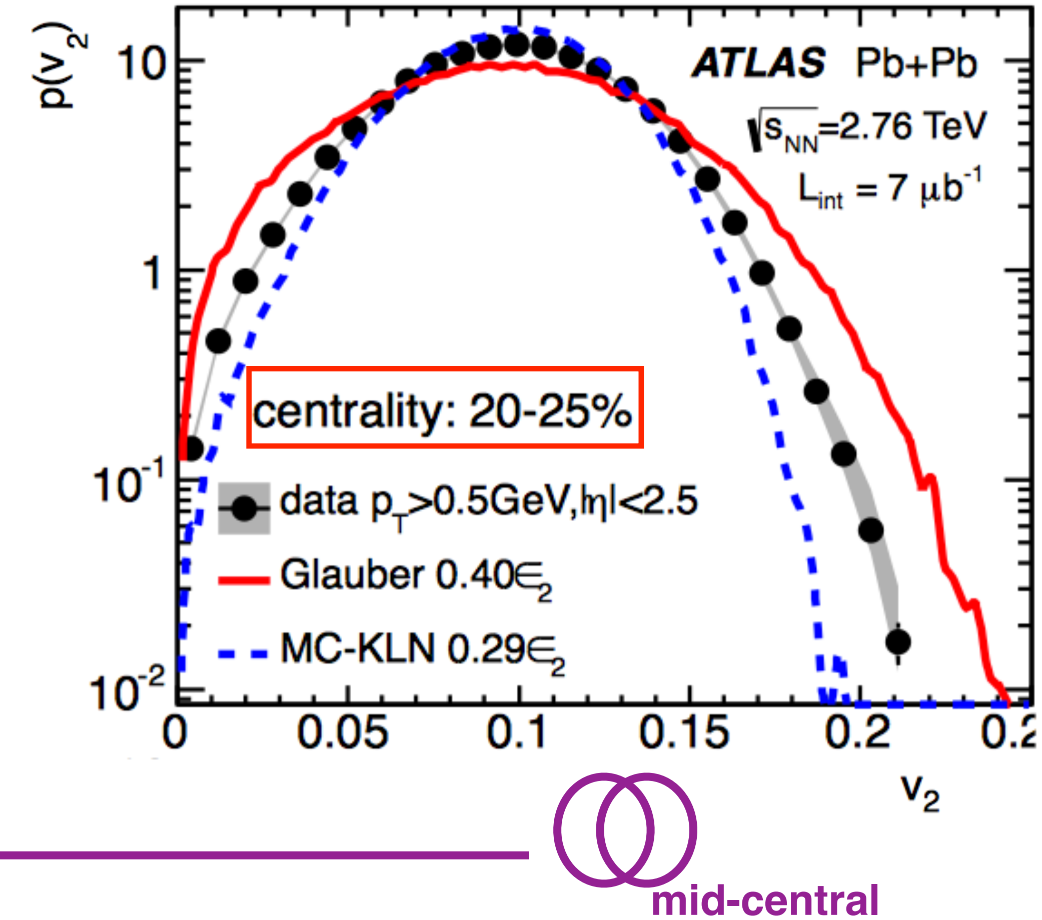
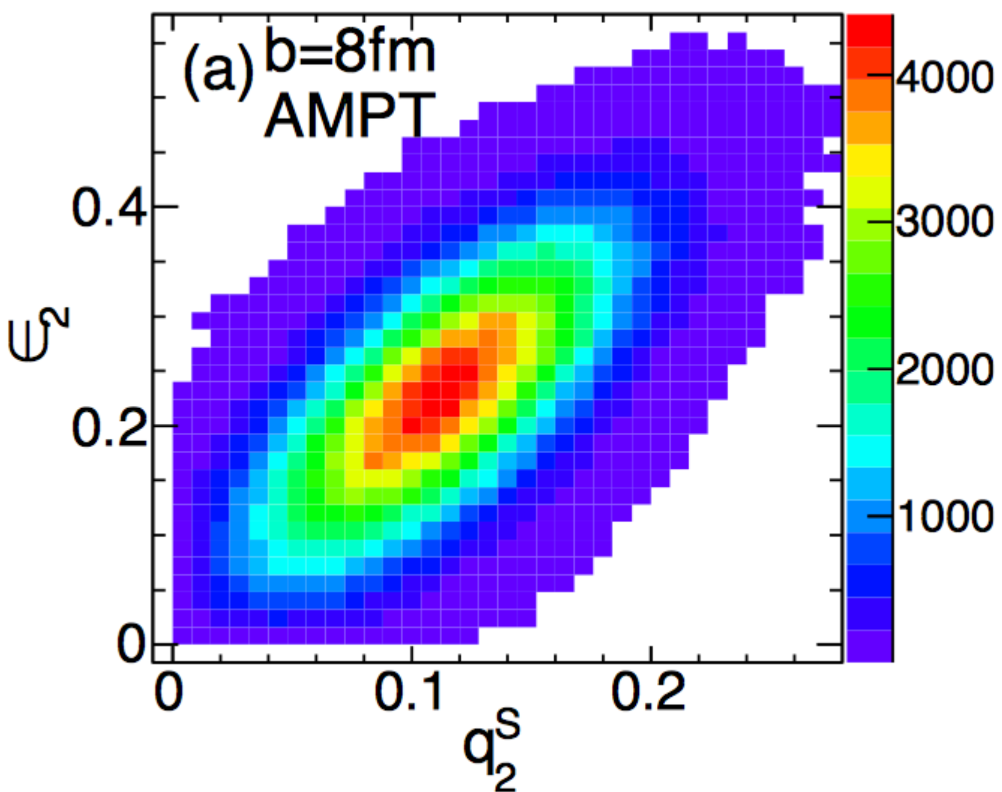


- Both ellipticity and system size change with centrality!
- Within a given centrality v_n varies over a wide range.

Event Shape Engineering

P.Huo,J.Jia,S.Mohapatra, PRC.90.024910



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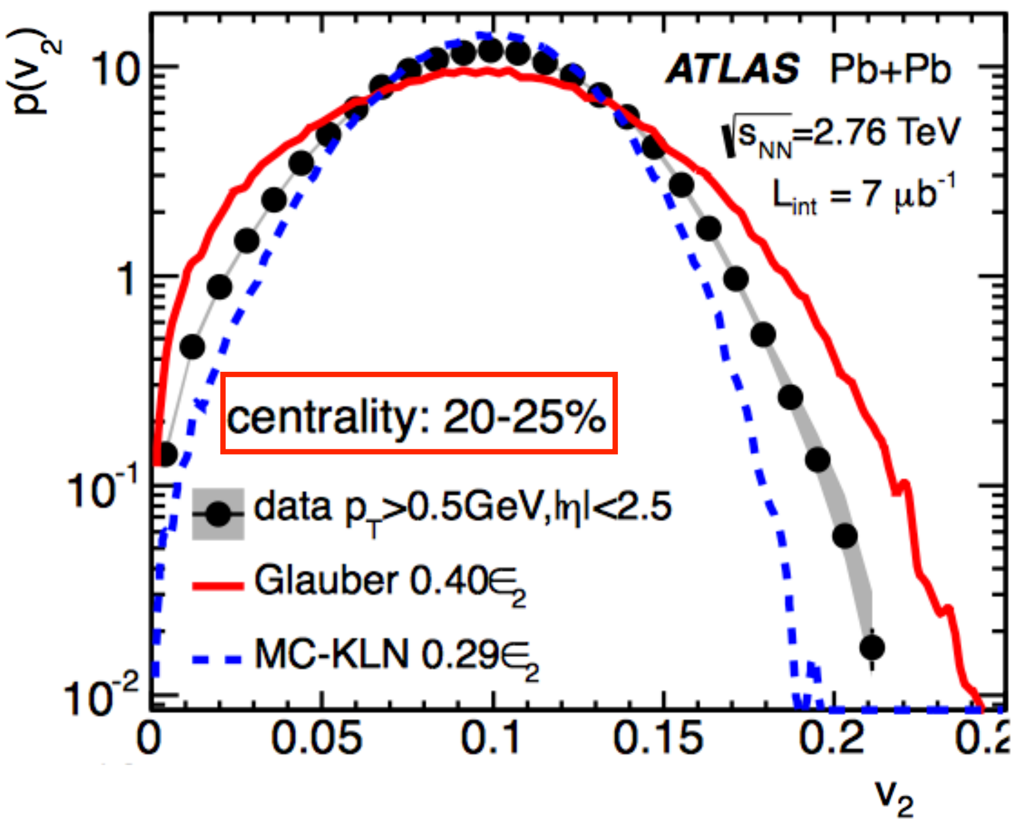
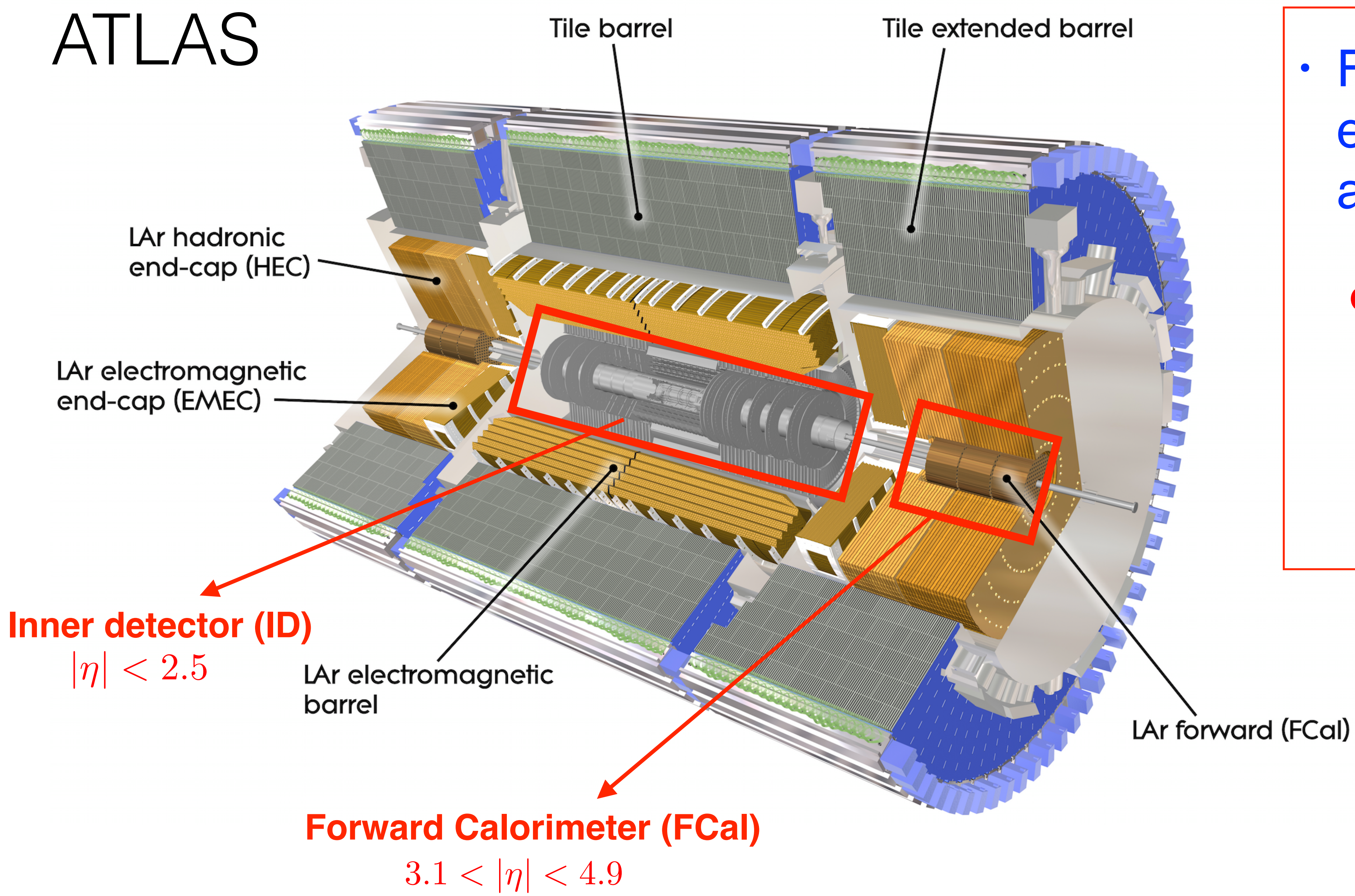


Strong correlation between ϵ_2 and v_2

- Both ellipticity and system size change with centrality!
- Event shape selection allows to control the shape of the events (ellipticity, triangularity etc), but without changing centrality.
- Can study correlations of many observables with the system shape, eg jet properties, flow correlations etc.

Analysis procedure



- FCal used for binning events into centrality and q-vector classes.

$$\mathbf{q}_m = q_m e^{im\Psi_m^{obs}}$$

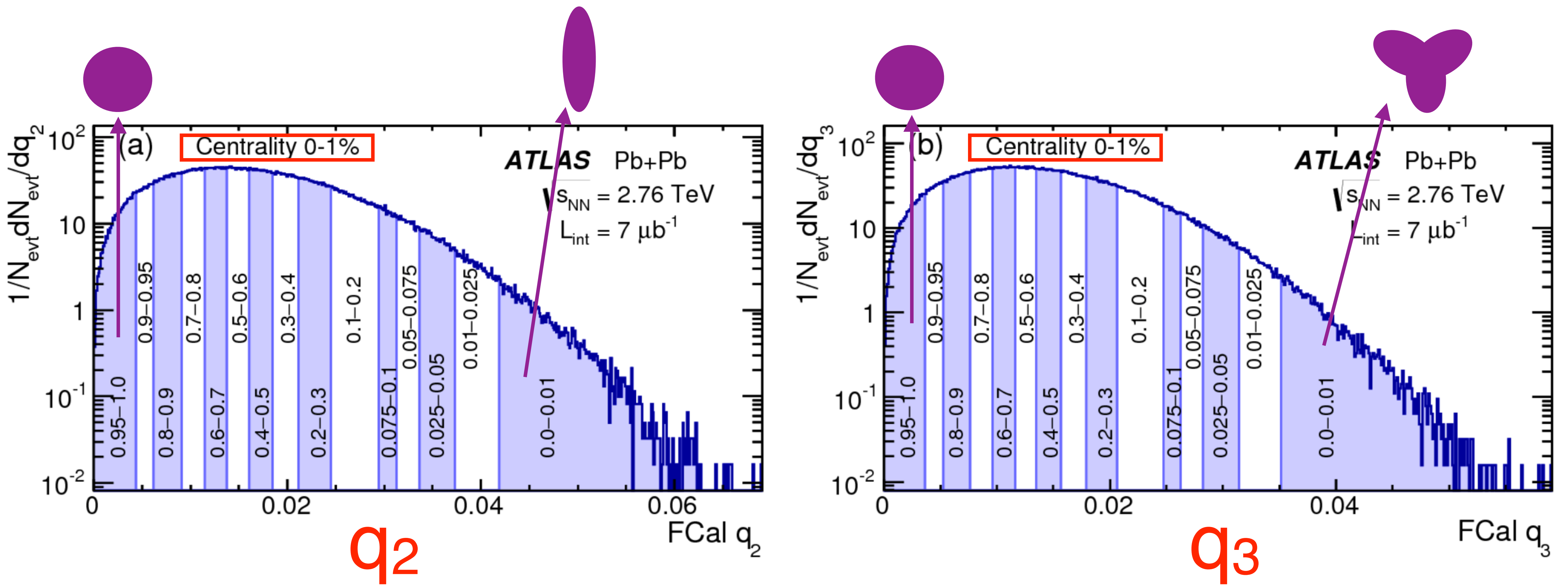
$$= \frac{\sum E_{Tj} e^{-im\phi_j}}{\sum E_{Tj}} - \langle \mathbf{q}_m \rangle_{evts}$$

i) Bin events in centrality classes.

ii) For each centrality class, bin into event-shape classes based on magnitude of q_m vector.

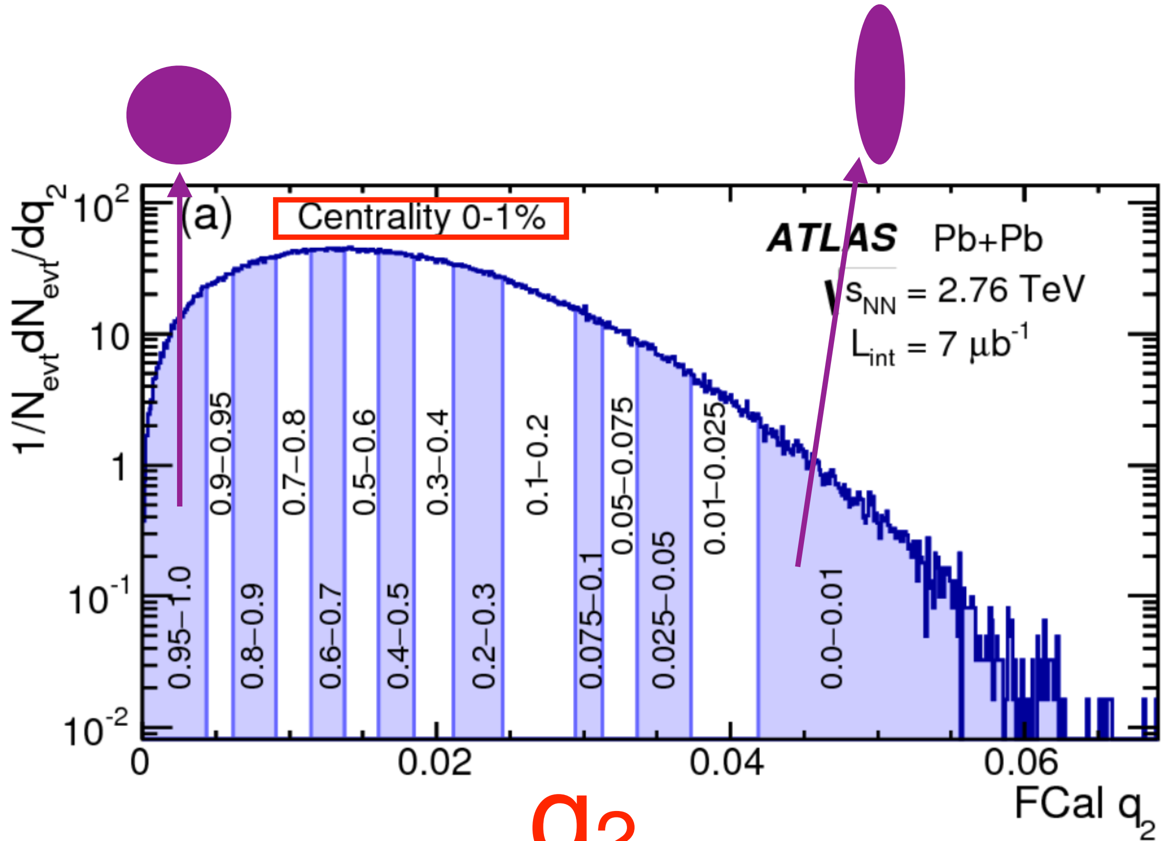
iii) Calculate v_n and v_m - v_n correlations using tracks in ID (using 2PC from pairs with $\Delta\eta > 2$).

Event Shape Selection

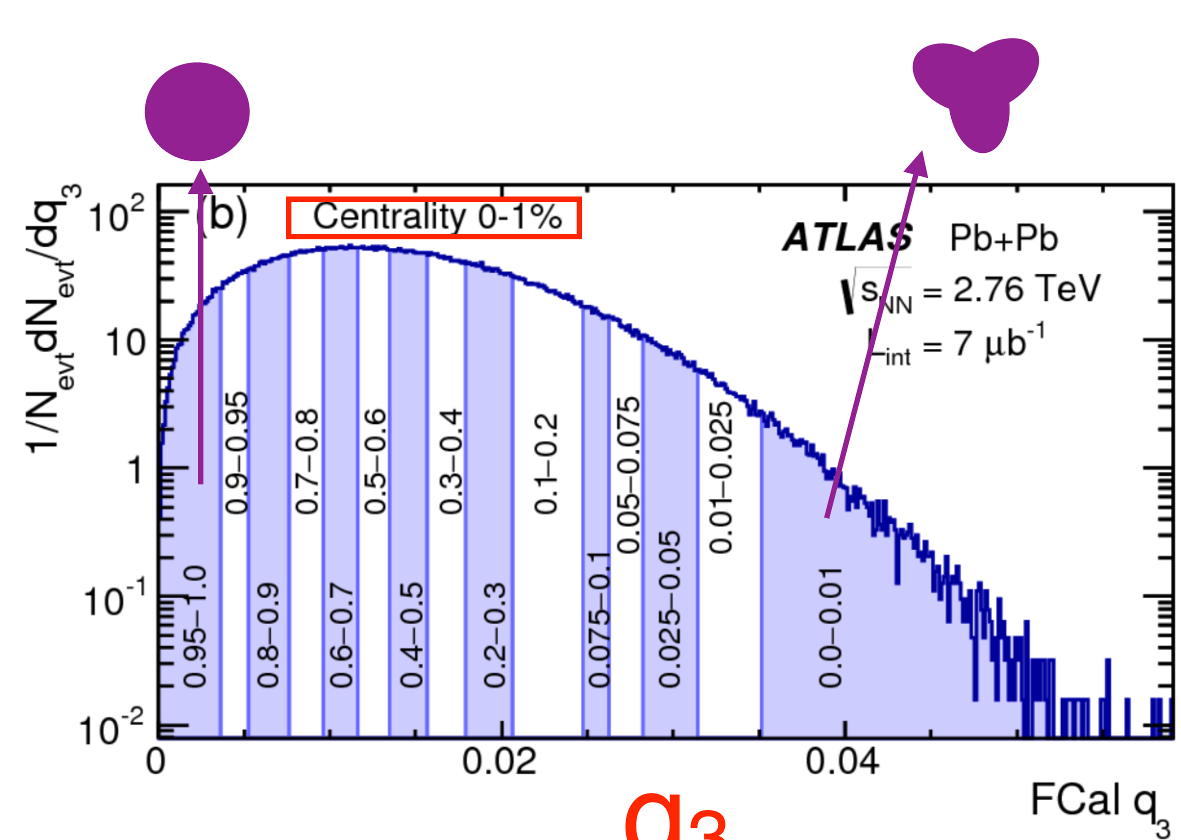


- Events are binned into q-vector classes based on the magnitude of q_2 or q_3 in FCal

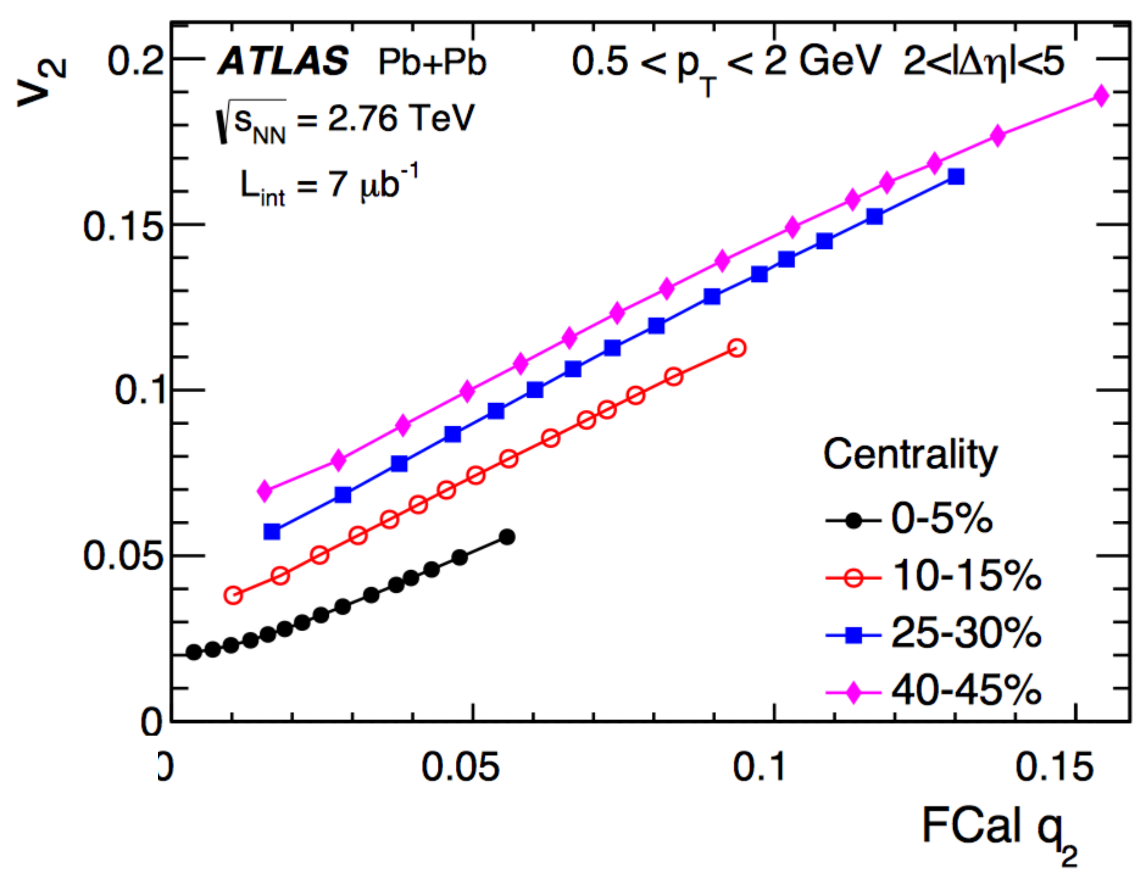
Event Shape Selection



q_2



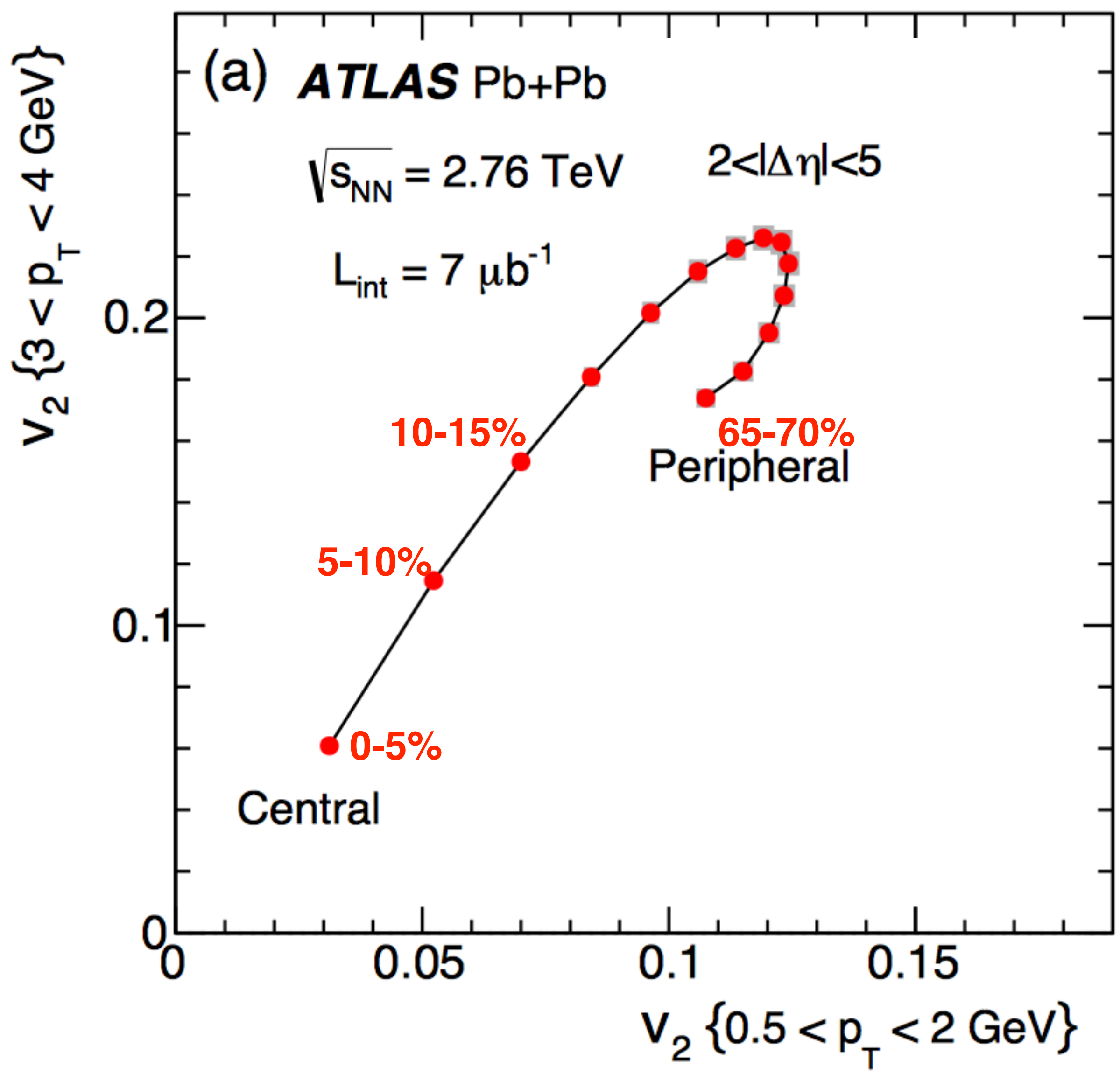
q_3



- Events are binned into q-vector classes based on the magnitude of q_2 or q_3 in FCal
- Good correlation between q_n in forward detector and v_n in mid-rapidity.

System size vs system shape: v_2 - v_2 correlations

v_2 at intermediate p_T

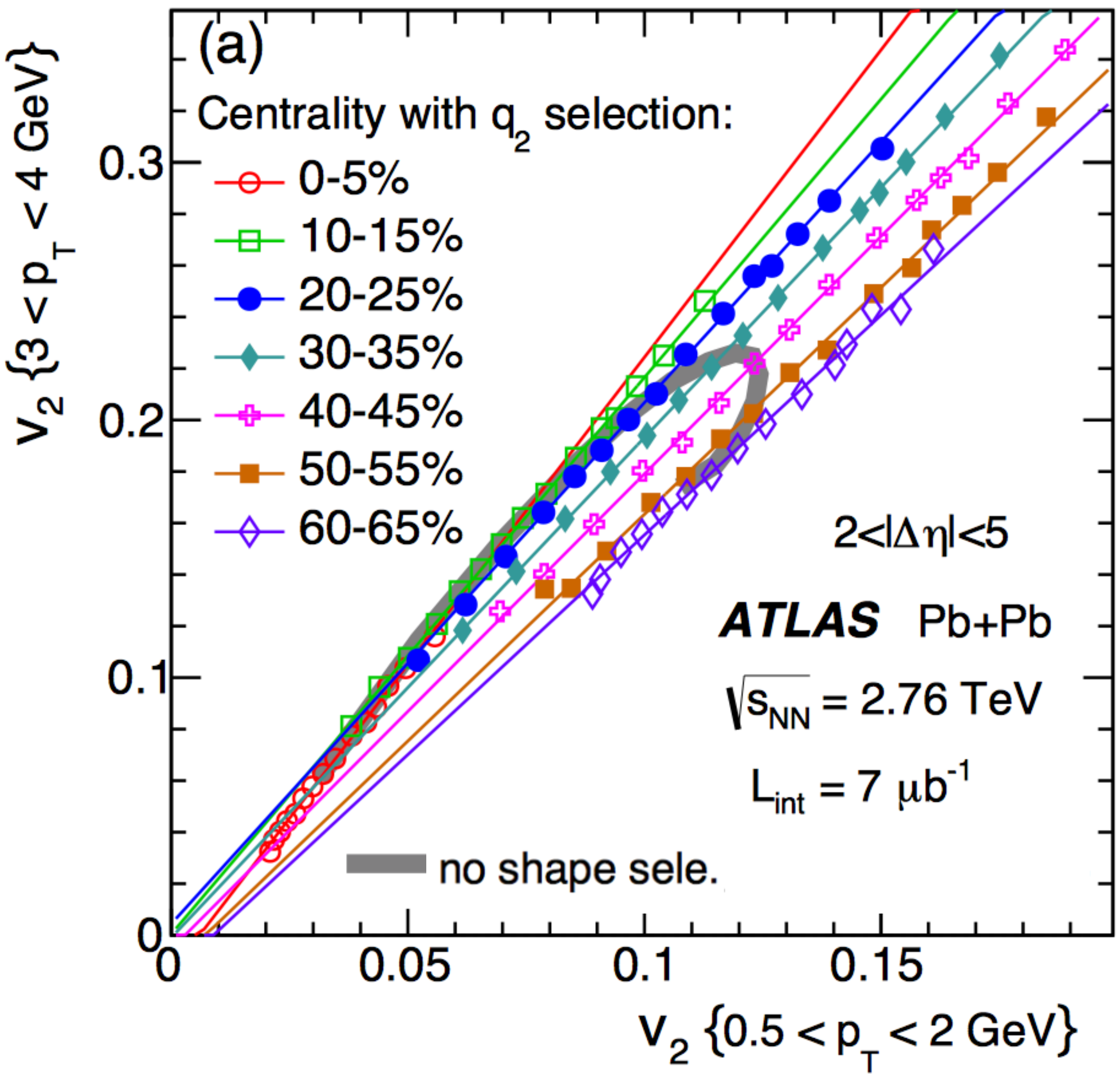


v_2 at low p_T

- v_2 at intermediate p_T plot against v_2 at low p_T. Each point is for a centrality interval.
- For same v_2 at low p_T, smaller v_2 at higher p_T, for peripheral events.
- Effect of larger viscosity in peripheral classes.

Does the correlation depend on event-shape?

System size vs system shape: v_2 - v_2 correlations

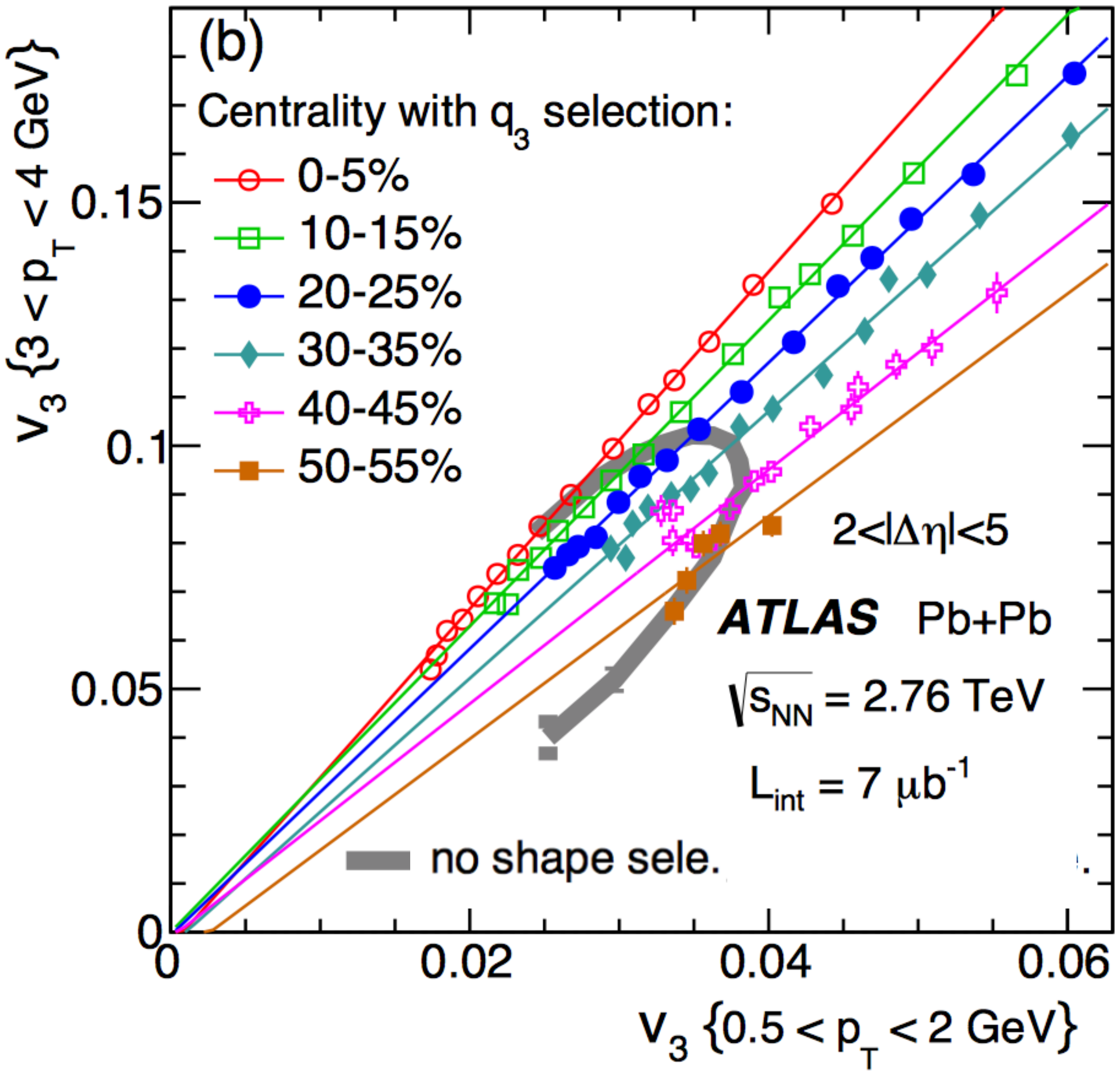


- Similar plot, but now in each centrality many points corresponding to the event-shape classes.

- Within a centrality ratio between low p_T and intermediate p_T v_2 remains same.
- Slope changes with centrality.

- Suggests viscous effects controlled by system size and independent of event ellipticity.

System size vs system shape: v_3 - v_3 correlations



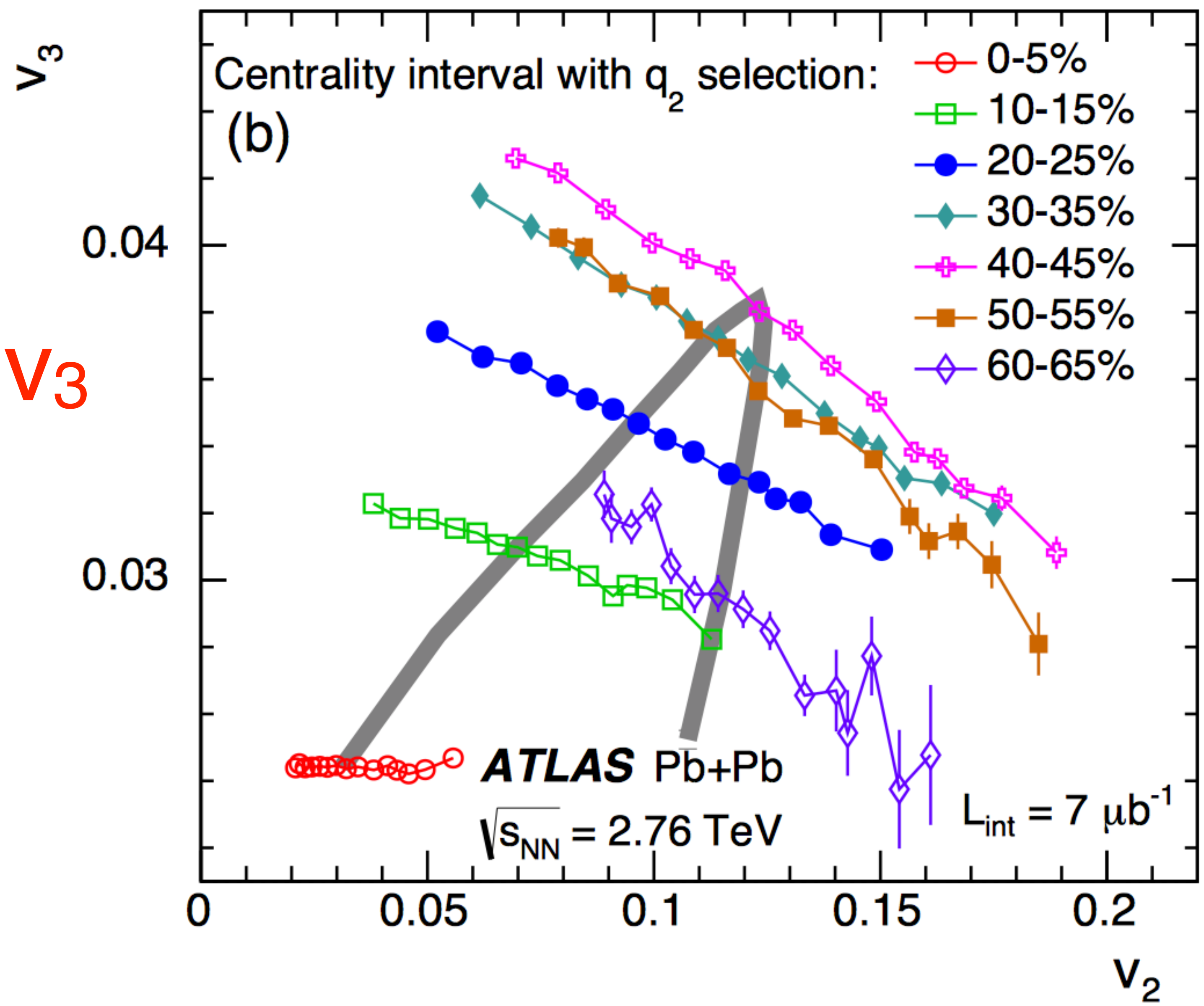
- Similar plot, for v_3.
- Within a centrality ratio between low p_T and intermediate p_T v_3 remains same.
- Slope changes with centrality.

- Suggests viscous effects controlled by system size and independent of event triangularity.

v_2 - v_3 correlation

- Can study v_n as a function of v_m at fixed centralities.

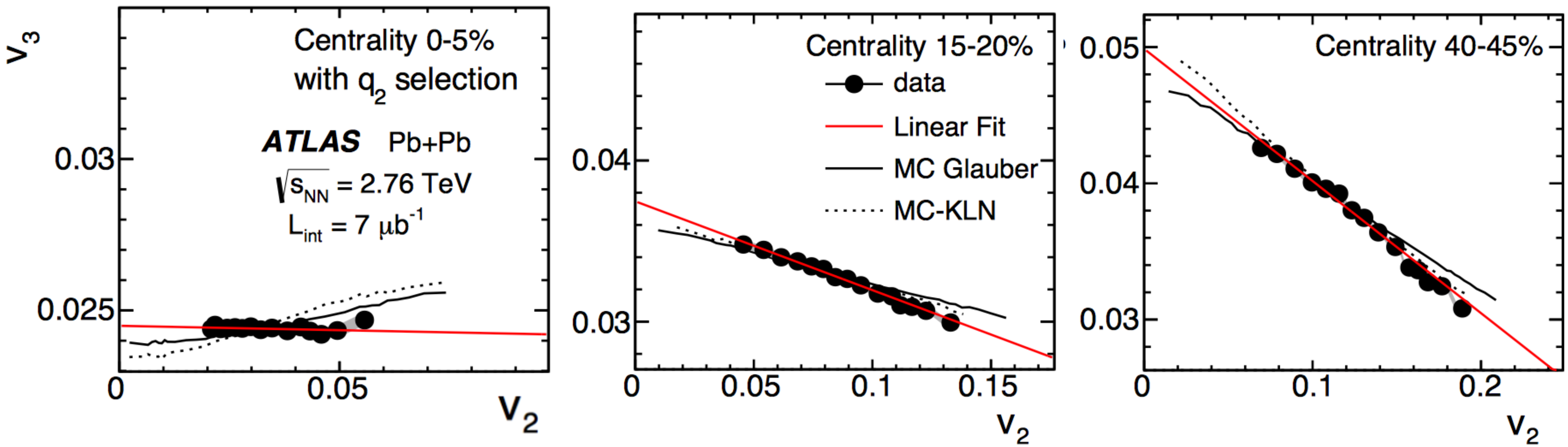
V_3



V_2

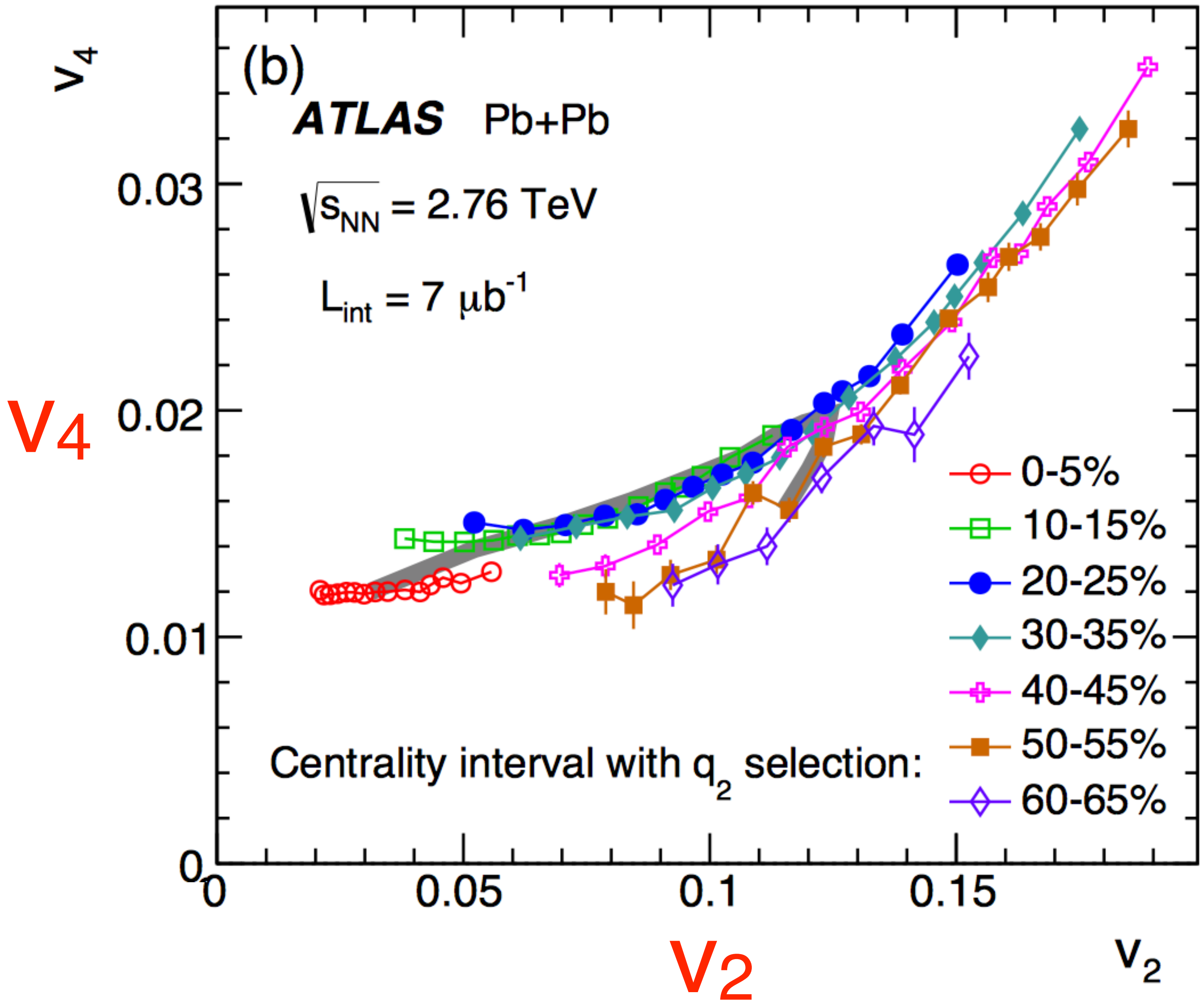
- Colored markers are from different event shape classes.
- Anti-correlation between v_2 and v_3, particularly in mid-central and peripheral event classes.
- Initial state effects or from final state interactions?

v_2 - v_3 correlation: Comparison with initial state correlations



- $\epsilon_2 - \epsilon_3$ correlation from initial state models show similar behavior.
- Some deviations though, particularly in most central classes.

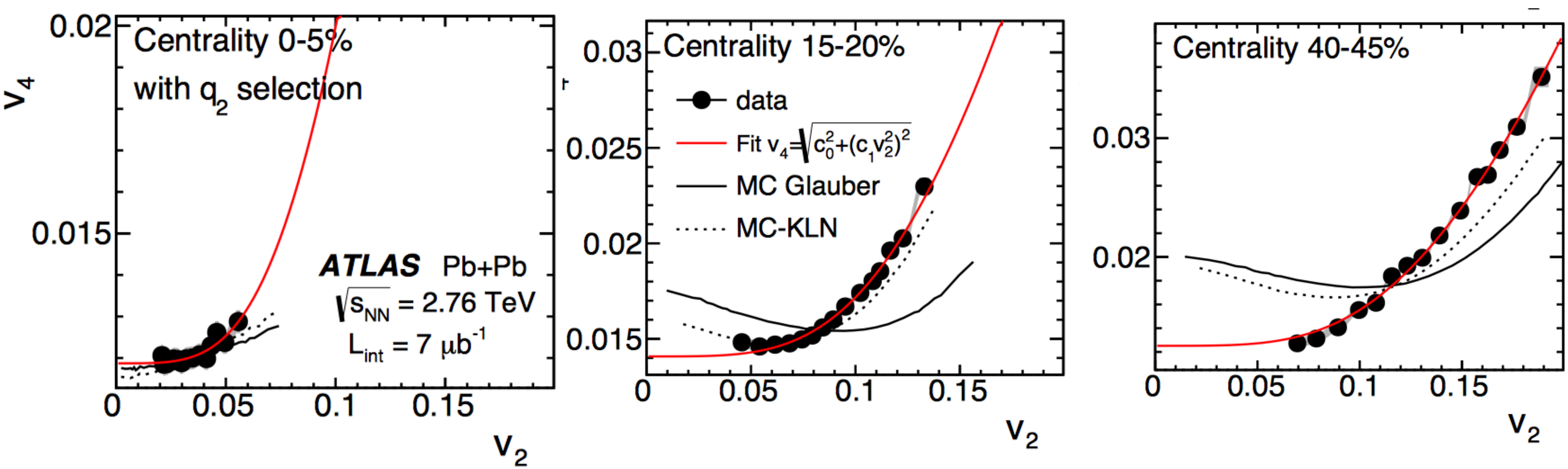
Non linear response: v_2 - v_4 correlation



- Non-linear increase of v_4 with v_2.
- v_4 is expected to have non-linear correlation with v_2, $v_4 \propto v_2^2$
  - From initial geomtry, $\epsilon_4 \propto \epsilon_2^2$
  - Due to non-linear medium response.
  - From freeze-out due to anisotropic flow profile.
- Can also have a contribution from quadrangular geomtry uncorrelated with ϵ_2, ϵ_4^{True}

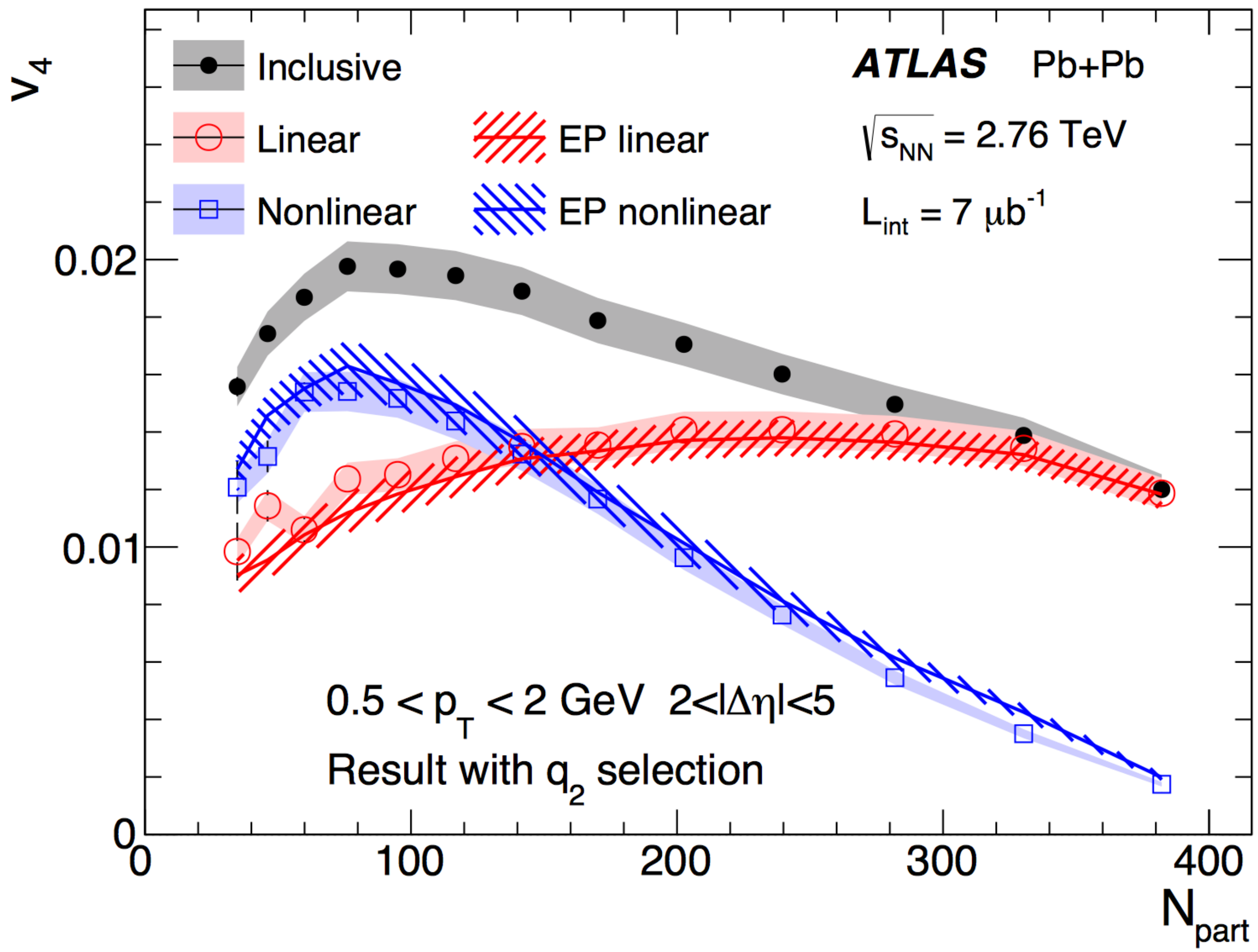
- Do initial state models capture this correlation?

v_2 - v_4 correlation: Comparison with initial state correlations



- v_4 gets two contributions: $v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^{True}} + c_1 v_2^2 e^{i4\Phi_2}$
  c_0 captures response to ϵ_4^{True} and $c_1 v_2^2$, the non-linear contribution.
- v_4 can be fit with a function, $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$
- Fits work quite well to the data
- Also shown are $\epsilon_2 - \epsilon_4$ correlations from MC Glauber and MC-KLN: initial state models fail to describe data.

v_2 - v_4 correlation: Linear and non-linear components

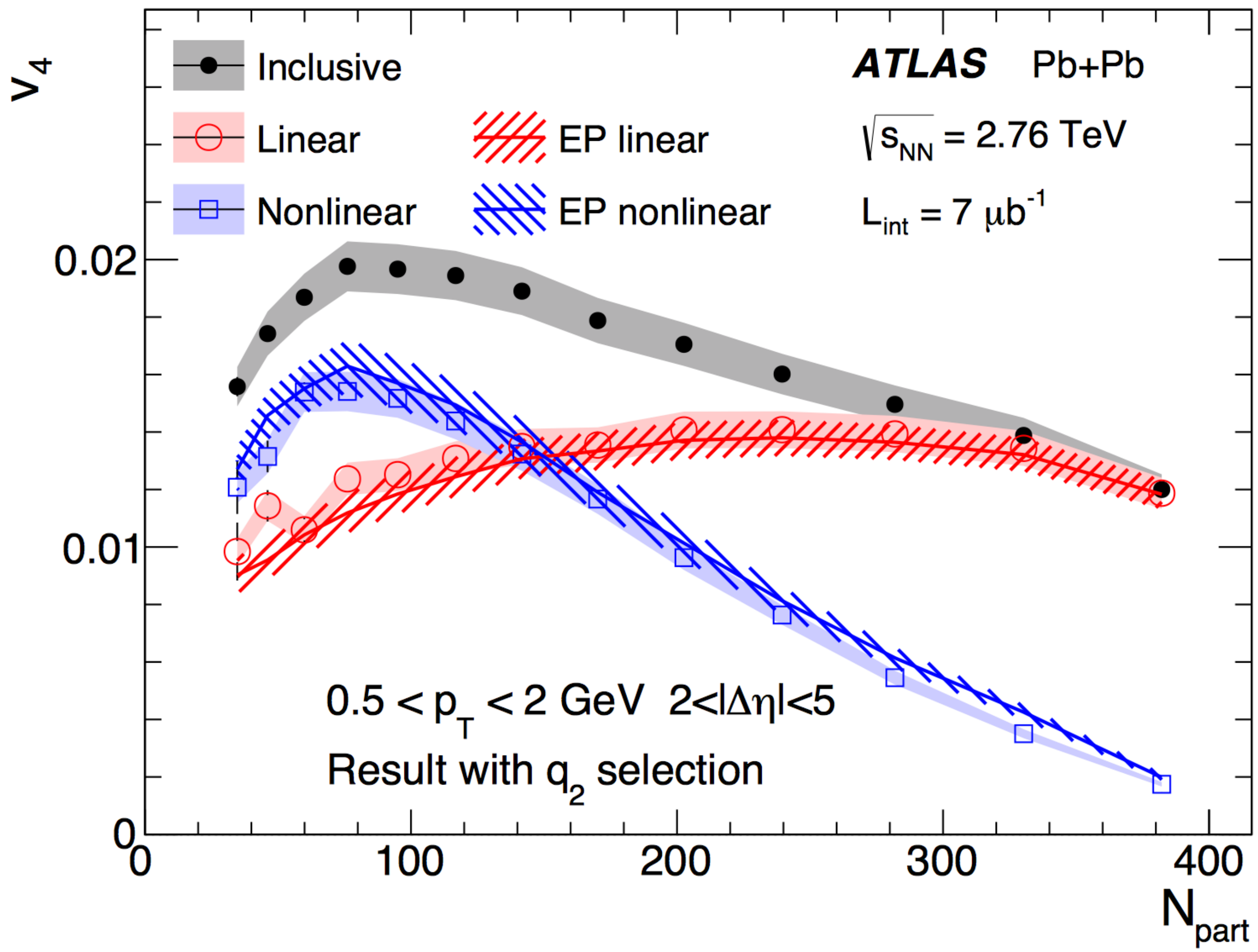


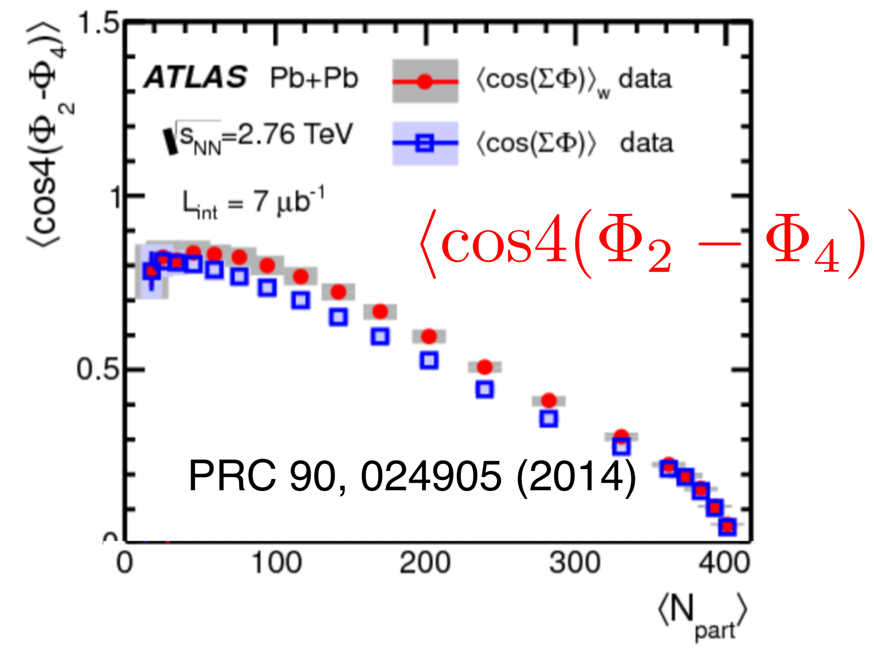
$$v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^{True}} + c_1 v_2^2 e^{i4\Phi_2}$$

$$v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}\ ; \quad v_4^L = c_0, \quad v_4^{NL} = c_1 v_2^2$$

- Weak centrality dependence for the linear component, strong centrality dependence for non-linear component.
- Linear and non-linear terms are argued to have different sensitivities to viscosity (D.Teaney, L.Yan PhysRevC.86.044908)

v_2 - v_4 correlation: Linear and non-linear components





- Linear and non-linear components may also be calculated from EP correlations.

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

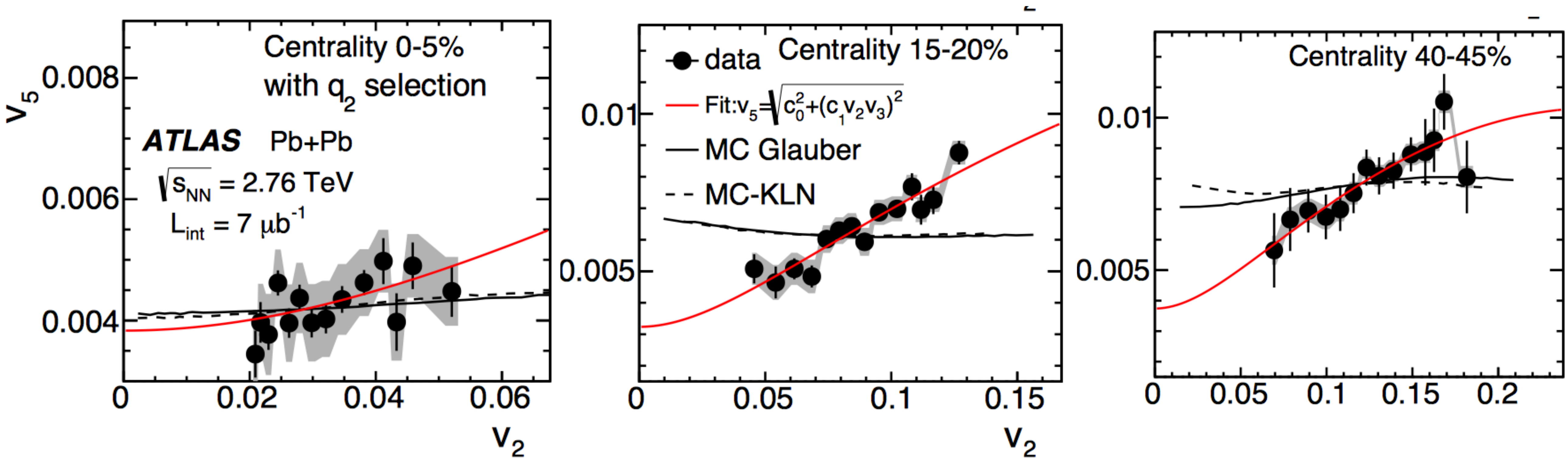
$$v_4^{L} = \sqrt{v_4^2 - (v_4^{NL})^2}$$

$$v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^{True}} + c_1 v_2^2 e^{i4\Phi_2}$$

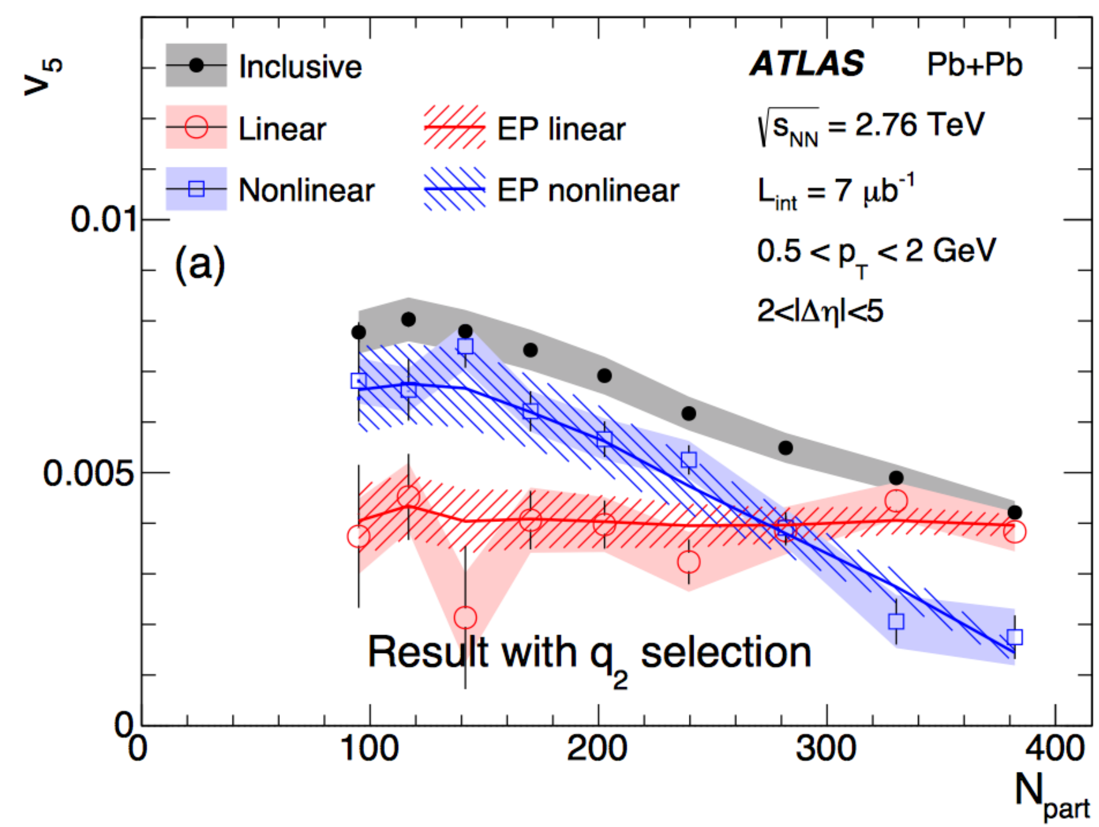
$$v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}\ ;\ \ v_4^L = c_0,\ \ v_4^{NL} = c_1 v_2^2$$

- Consistent results between the two methods!

v_2 - v_5 correlations



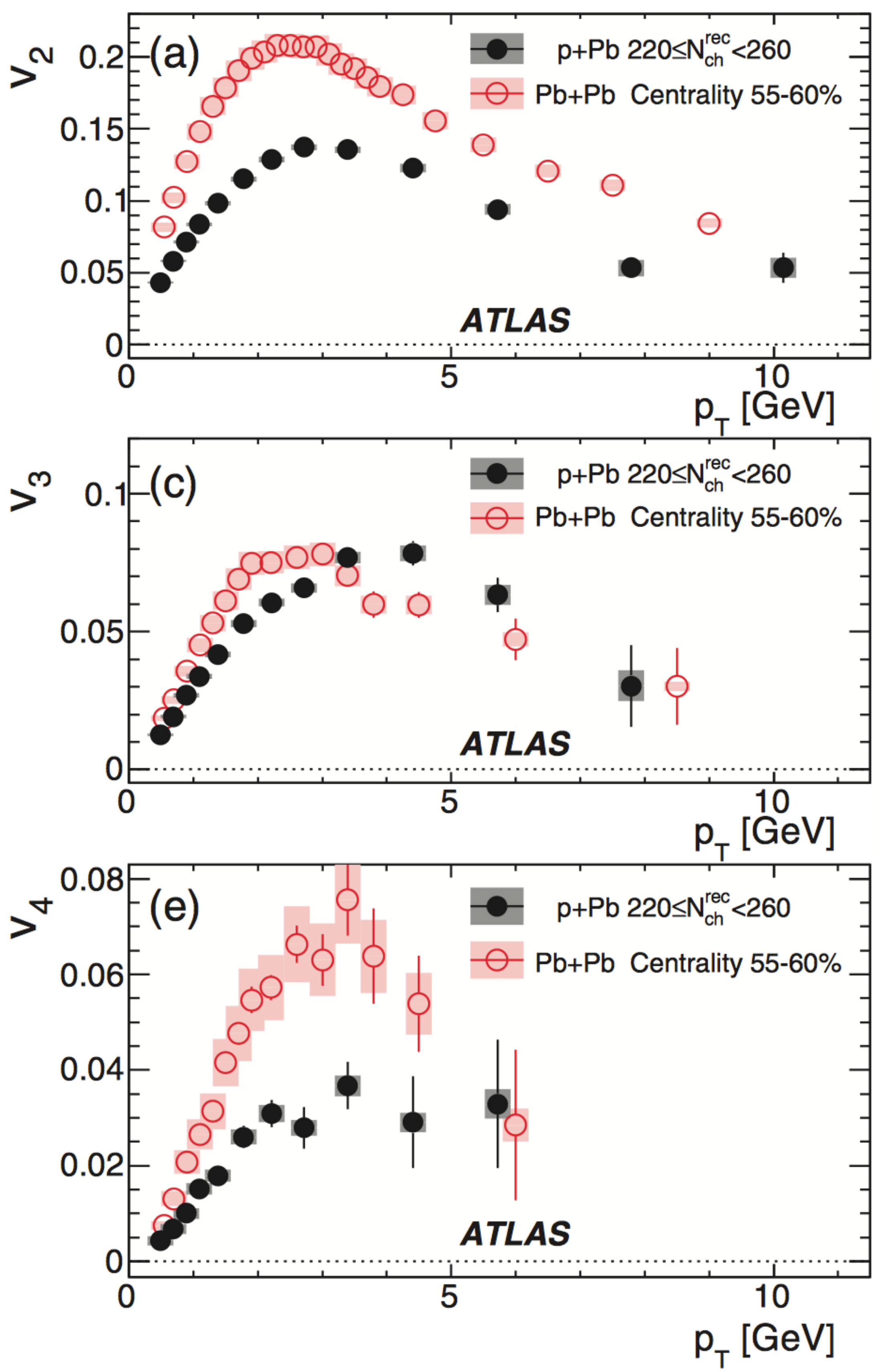
- v_5 gets a contribution also from v_2v_3: $v_5 e^{i5\Phi_5} = c_0 e^{i\Phi_5^{True}} + c_1 v_2 v_3 e^{i(3\Phi_3+2\Phi_2)}$
- $\epsilon_2 - \epsilon_5$ correlations from initial state models do not describe the data.
- The fit, $v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2}$ can be used to extract linear and non-linear components.
- Also good agreement with EP results.



Non-linear response in p+Pb?

PRC 90.044906 (2014)

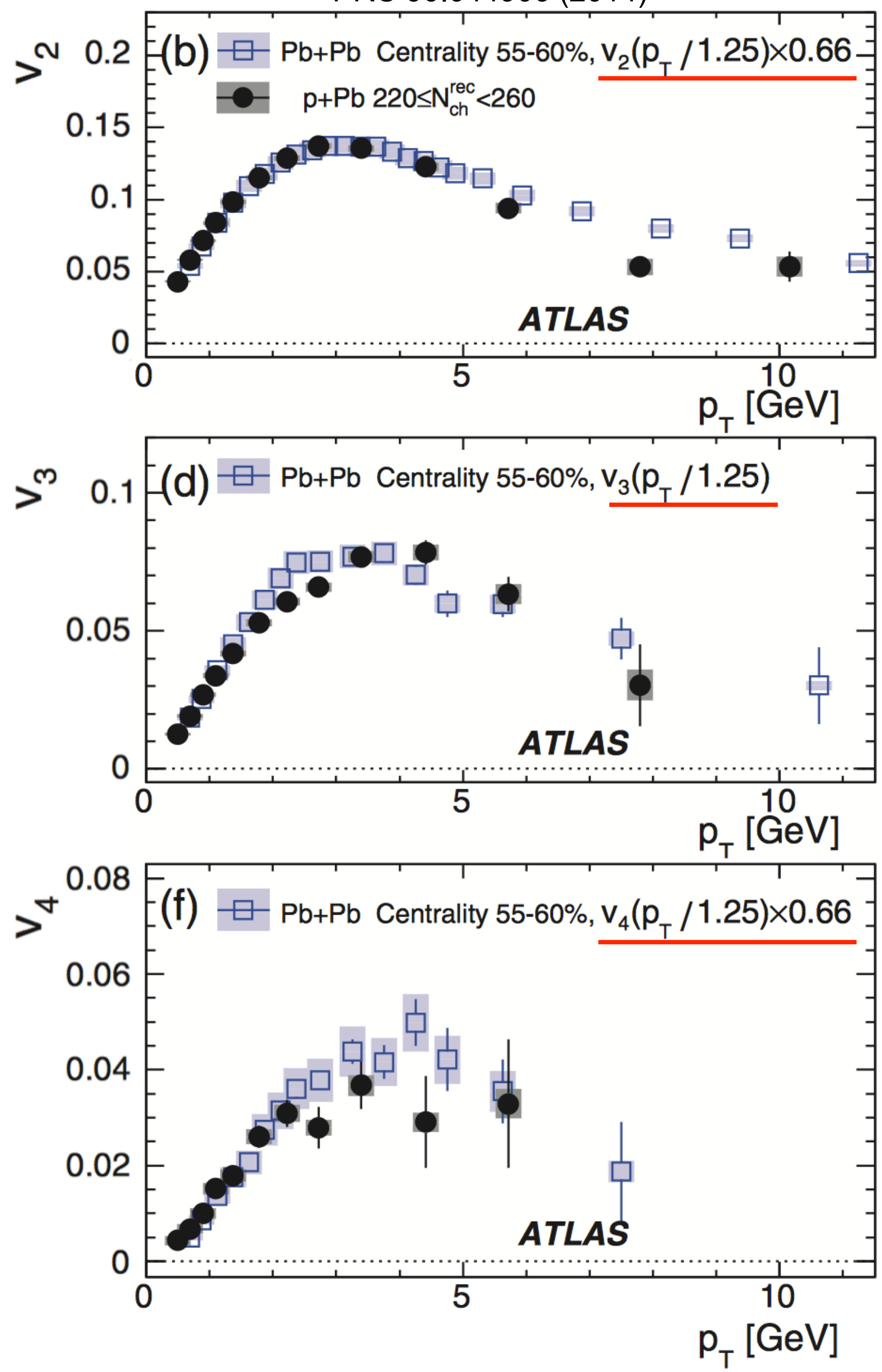
- Significant v_n harmonics observed in p+Pb.
- v_n shown for similar multiplicity event classes.
- Difference in v_2 magnitude reflects difference in initial ellipticity.
- v_3 magnitudes similar since driven by fluctuations in both systems.
- v_4 larger in Pb+Pb than p+Pb.



Non-linear response in p+Pb?

- v_n in p+Pb and Pb+Pb found to have similar p_T dependence.
- v_2 is different by a constant scale factor
  ⟶ change in average geometry.
- v_3 driven by fluctuations, no scale factor needed.
- v_4 driven by fluctuations, but also by v_2
  ⟶ differ by a scale factor (*J.Jia IS2014*).

PRC 90.044906 (2014)



Non-linear response in p+Pb?

- v_4 driven by fluctuations, but also by v_2
  → differ by a scale factor (*J.Jia IS2014*).

$$v_4^2\{\mathrm{pPb}\} = v_4^{L^2}\{\mathrm{pPb}\} + v_4^{NL^2}\{\mathrm{pPb}\}$$

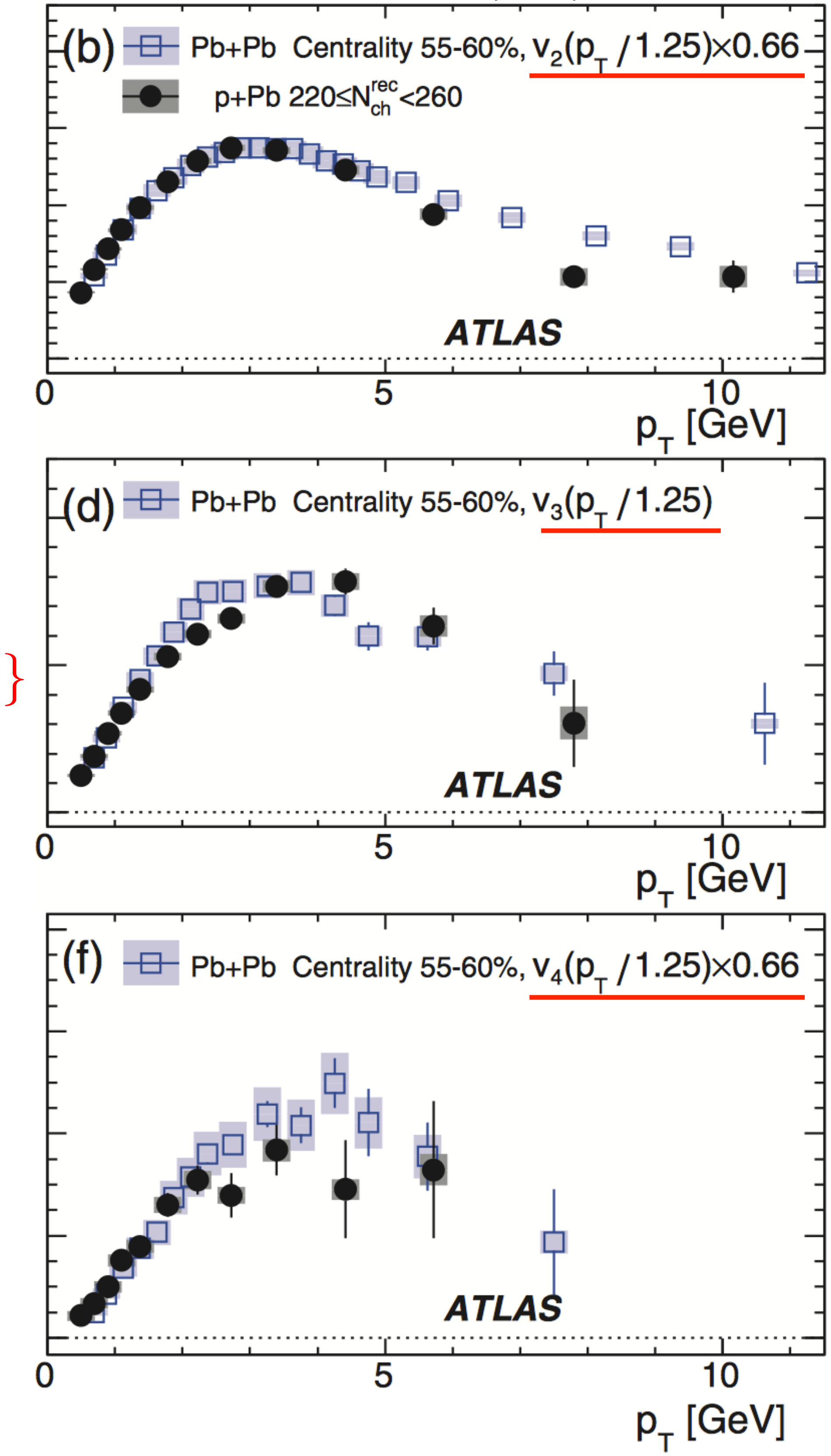
$$= v_4^{L^2}\{\mathrm{PbPb}\} + a^2c^2v_2^4\{\mathrm{PbPb}\}$$

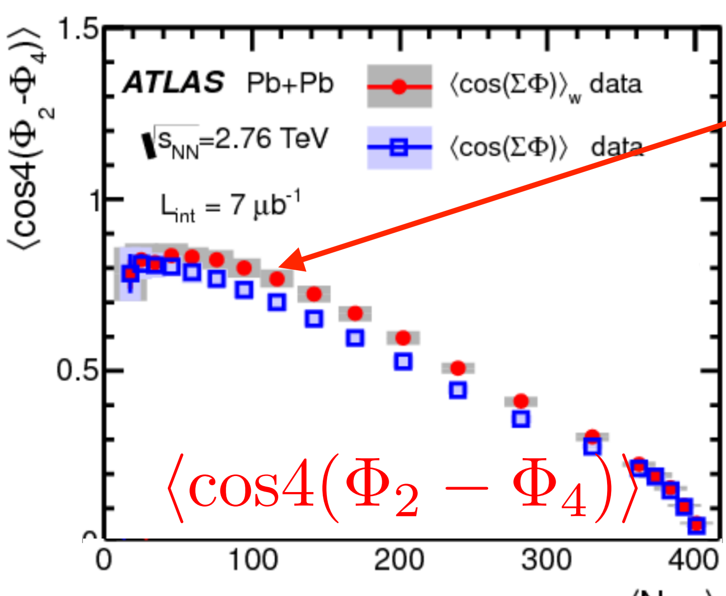
$$= (1-b^2)v_4^2\{\mathrm{PbPb}\} + a^2b^2v_4^2\{\mathrm{PbPb}\}$$

$$= (1-b^2+a^4b^2)v_4^2\{\mathrm{PbPb}\} \approx 0.66^2v_4^2\{\mathrm{PbPb}\}$$

$$a = 0.66,\; b = \langle\cos 4(\Phi_2-\Phi_4)\rangle \approx 0.84$$

PRC 90.044906 (2014)





PRC 90, 024905 (2014)

Summary and Conclusions

Presented results of correlations of flow harmonics with event shape.

- Correlation between v_n at different p_T
  - Correlation between v_2 (v_3) at different p_T has strong centrality dependence.
  - But independent of event shape.
  - Suggests viscous effects controlled by system size, not system shape.

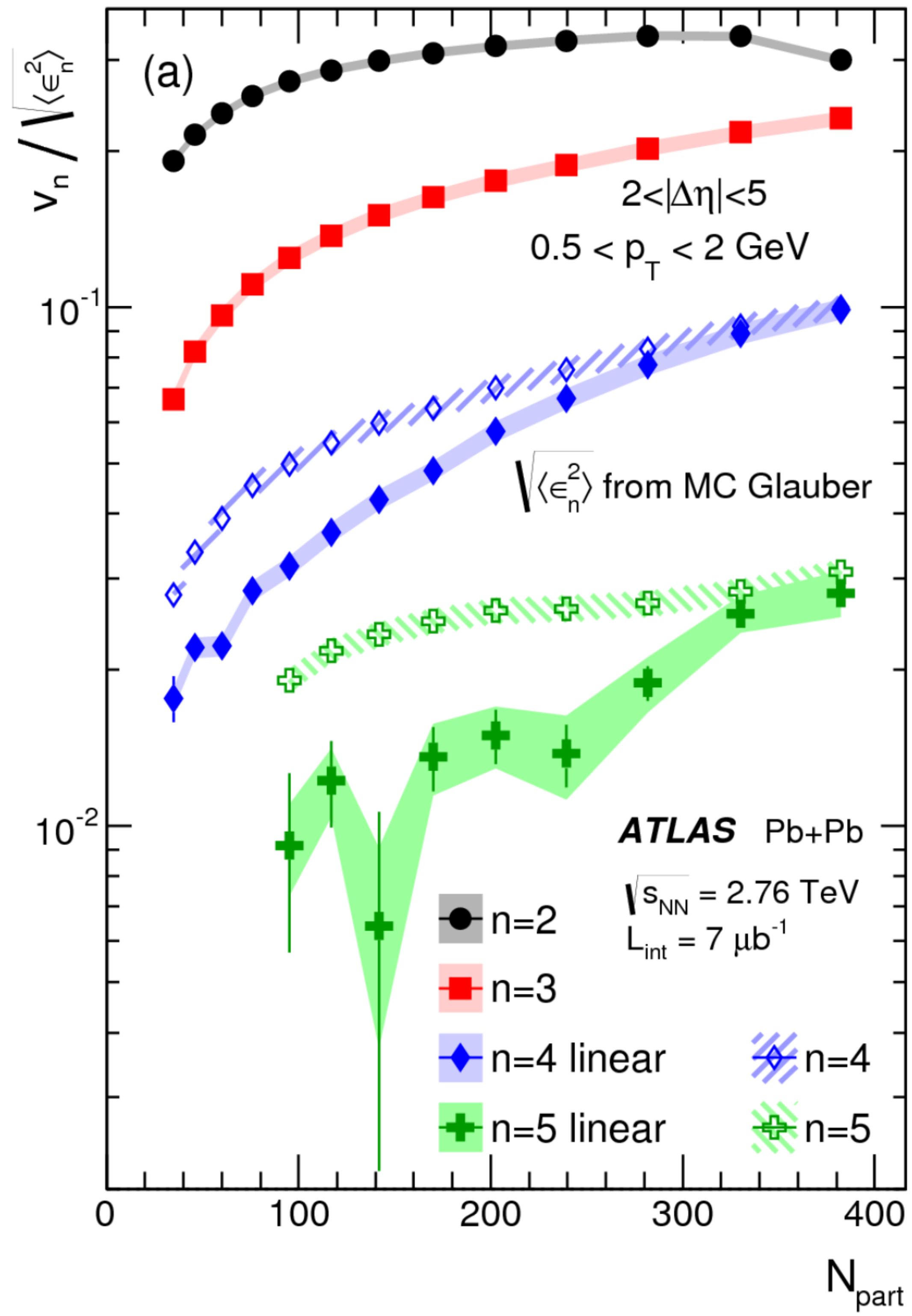
- Anti correlation between v_2 and v_3.
  - Mostly described by $\epsilon_2 - \epsilon_3$ correlations from initial state models.
- Non-linear correlation between v_2 and higher order harmonics.
  - Initial state models fail to describe the observed correlations.
  - Fits with a two component function with linear and non-linear response terms.
  - Linear component has weak centrality dependence, non-linear component has strong centrality dependence.
  - Consistent with results from EP correlations.

- v_4 values from p+Pb also suggest contribution from non-linear response to geometry.
  - Supports the geomtric and collective origin of ridge in p+Pb collisions.

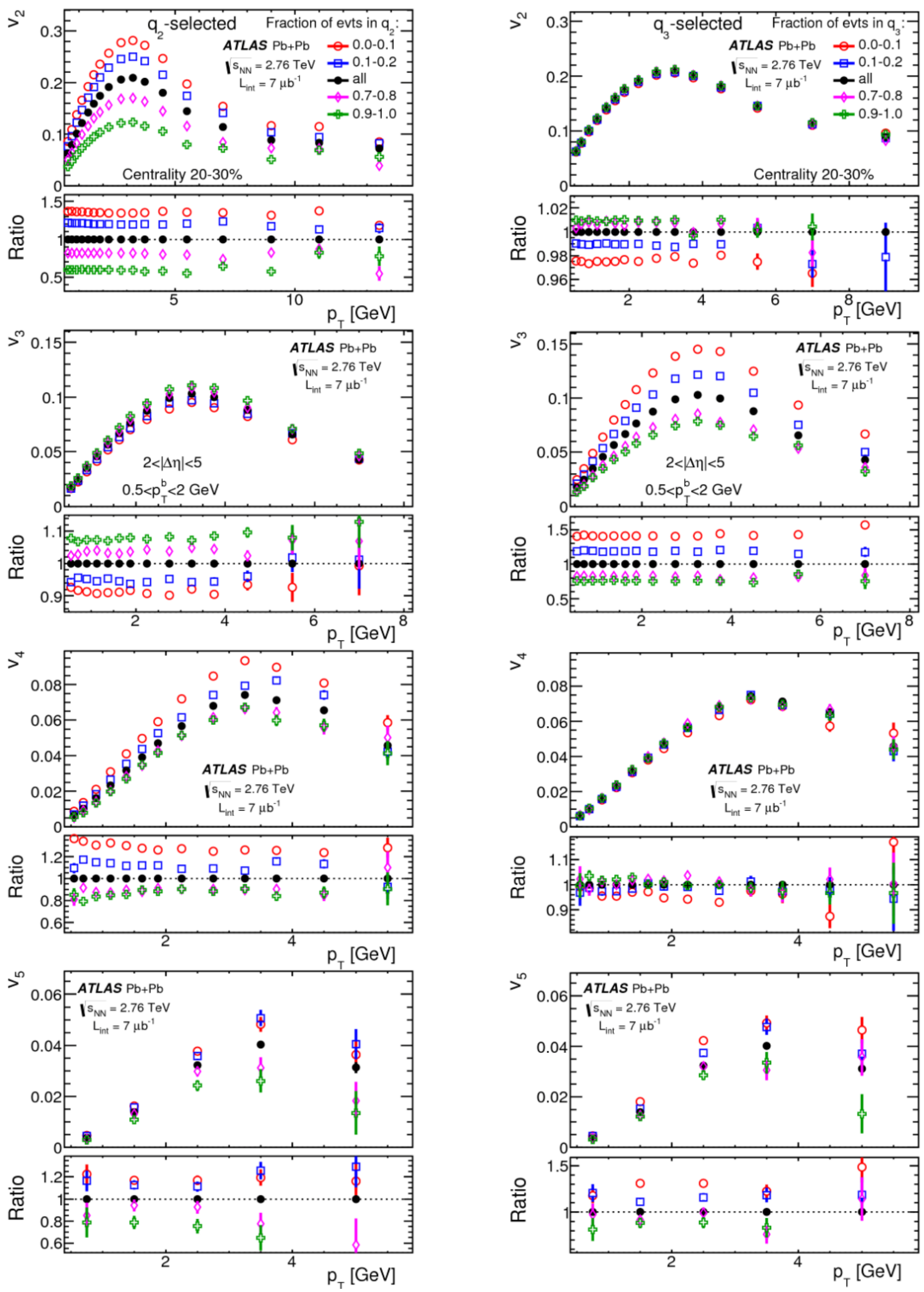
Back Up

scaling

- $v_n/\sqrt{\epsilon_n^2}$ as a function of N_{part}.
- For n=4 and n=5, both linear and total v_n are shown.
- For linear component, larger variation can be seen with centrality.
- Indicates larger viscous damping for higher order harmonics.



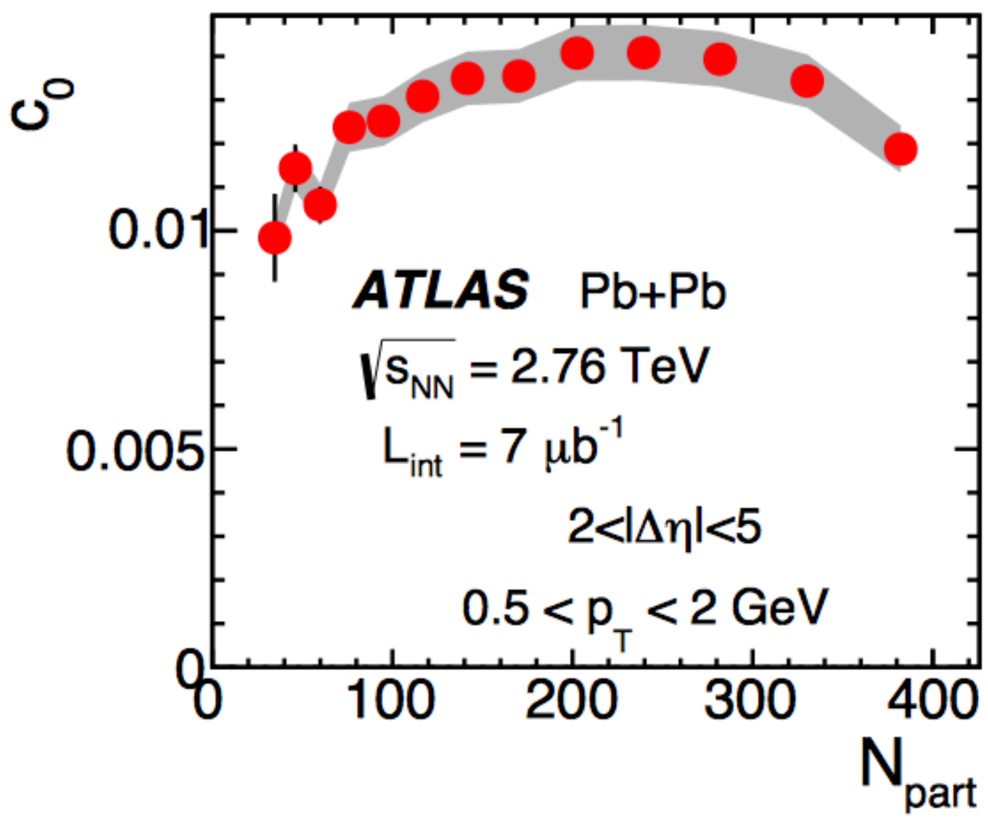
Event shape selection

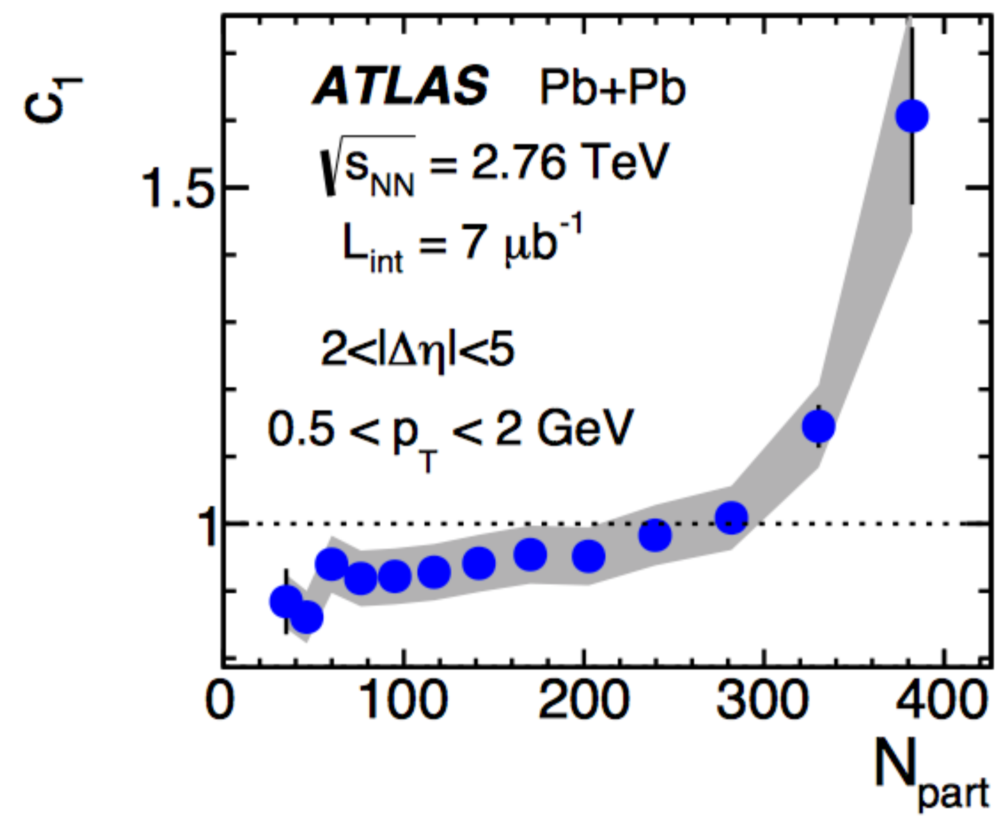


- v_n as function of p_T for different shape selected event classes slected on q_2 (left) and q_3 right.

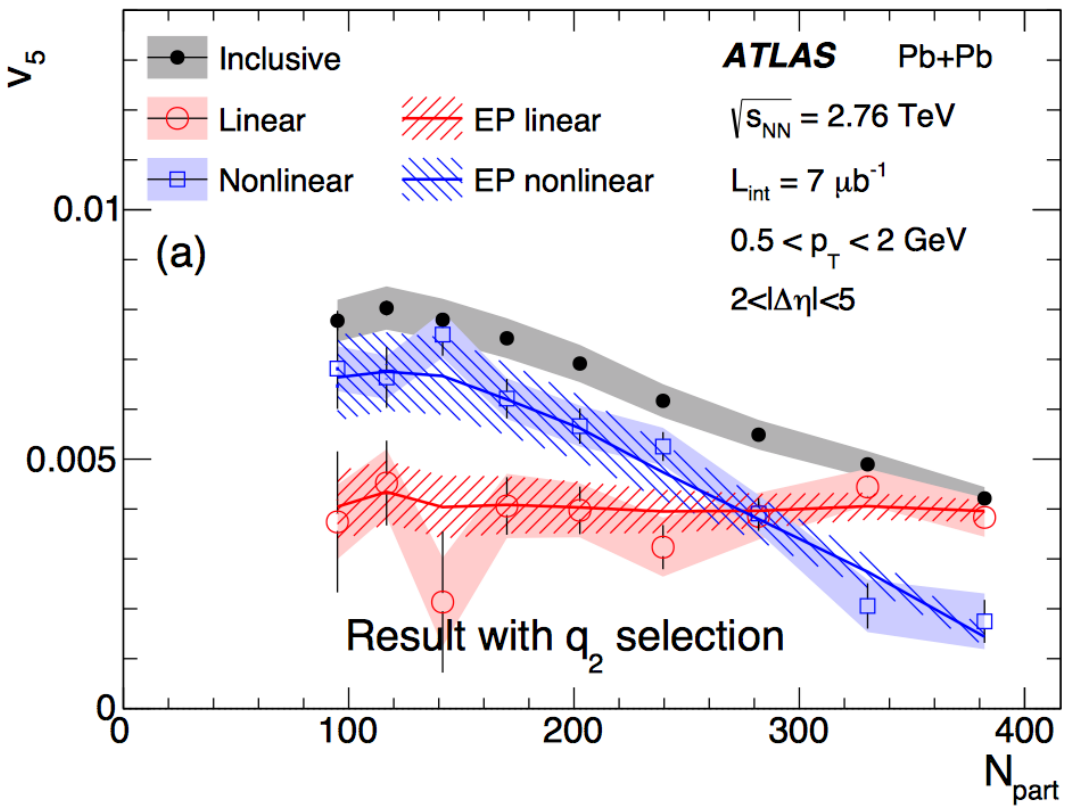
v_2 - v_4 correlation

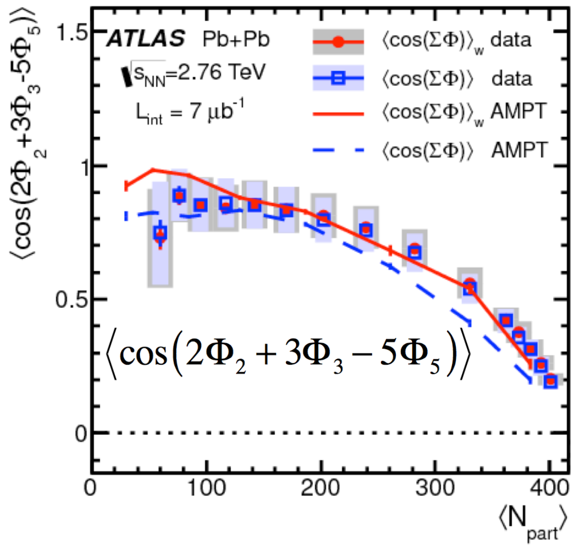
- v_4 gets two contributions: $v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^{True}} + c_1 v_2^2 e^{i4\Phi_2}$
- The fit, $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$ can be used to extract linear and non-linear components.
- Linear and non-linear components are argued to have different sensitivities to viscosity of the medium (D.Teaney, L.Yan PhysRevC.86.044908)





v_2 - v_5 correlation: Linear and non-linear components





- Linear and non-linear components may also be calculated from EP correlations.

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

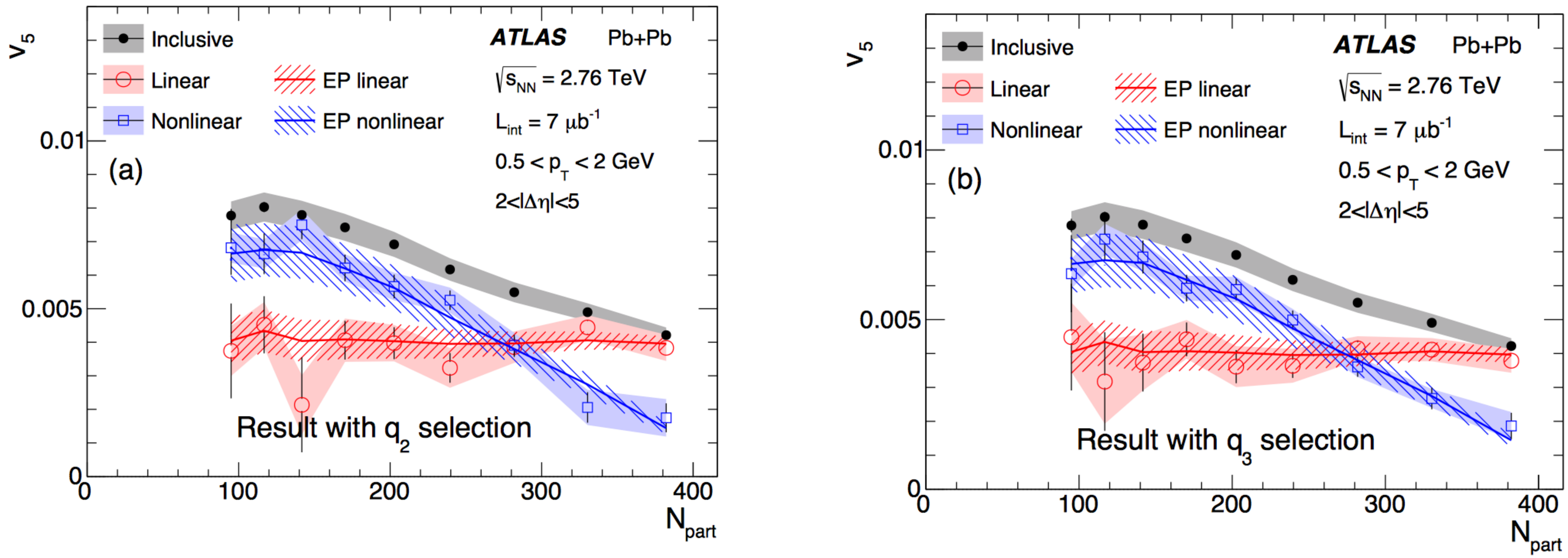
$$v_5^{L} = \sqrt{v_5^2 - (v_5^{NL})^2}$$

$$v_5 e^{i5\Phi_5} = c_0 e^{i\Phi_5^{True}} + c_1 v_2 v_3 e^{i(3\Phi_3+2\Phi_2)}$$

$$v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2} \;\; ; \;\; v_5^L = c_0, \;\; v_5^{NL} = c_1 v_2 v_3$$

- Weak centrality dependence for the linear component, strong centrality dependenc non-linear component.
- Consistent with EP correlation results.

q_3 selected results: v_3 - v_5 correlation



- Similar analysis can be done using q_3 selected events.
- For e.g. can use to extract linear and non-linear components in v_5.
- Gives consistent results!
- More results in (*arXiv:1504.01289*)

$$v_5 e^{i5\Phi_5} = c_0 e^{i\Phi_5^{True}} + c_1 v_2 v_3 e^{i(3\Phi_3 + 2\Phi_2)}$$

$$v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2}\ ;\quad v_5^L = c_0,\quad v_5^{NL} = c_1 v_2 v_3$$