Precision studies of collective dynamics in lead-lead and proton-lead collisions with the ATLAS detector

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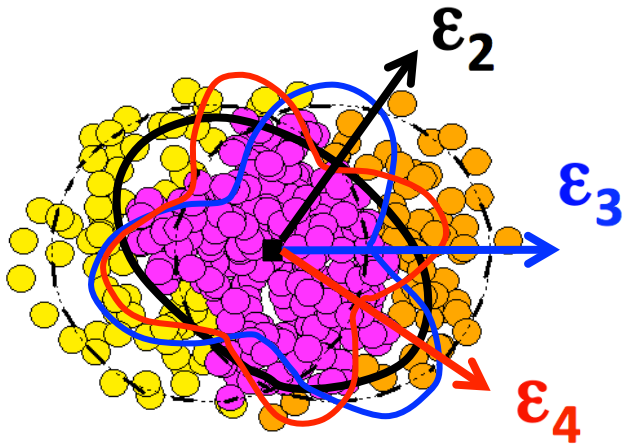
Introduction

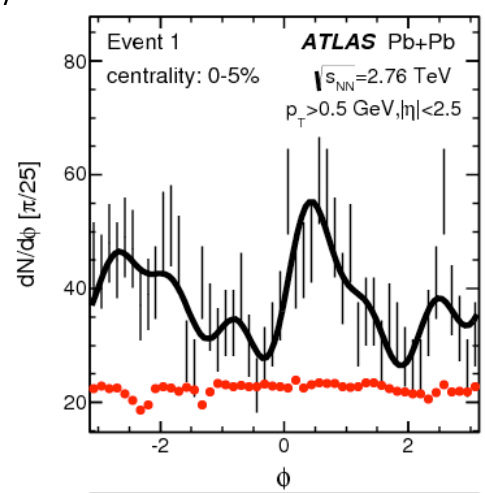
- Initial spatial fluctuations of nucleons lead to higher moments of deformations in the fireball, each with its own orientation.
- The spatial anisotropy is transferred to momentum space by collective flow.



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

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

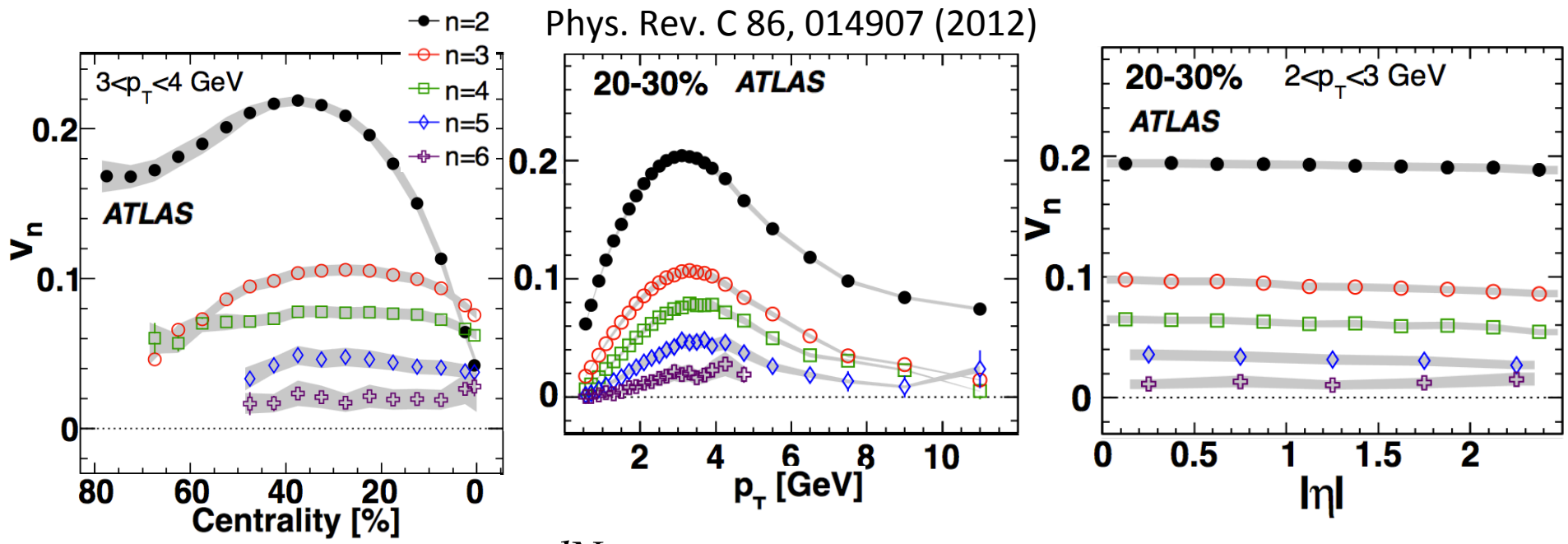
Final particles: $\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Phi_n)$



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

Centrality, p_T & η dependence of $\langle v_n \rangle$

Phys. Rev. C 86, 014907 (2012)



$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Phi_n)$$

- Features of Fourier coefficients
  - v_n coefficients rise and fall with centrality.
  - v_n coefficients rise and fall with p_T.
  - v_n coefficients are ~boost invariant.

ATLAS Unique measurements

Event-by-Event v_n measurements

$v_n - v_m$ correlations

$\Phi_n - \Phi_m$ correlations

Event by Event flow measurements

Track distribution in three central events

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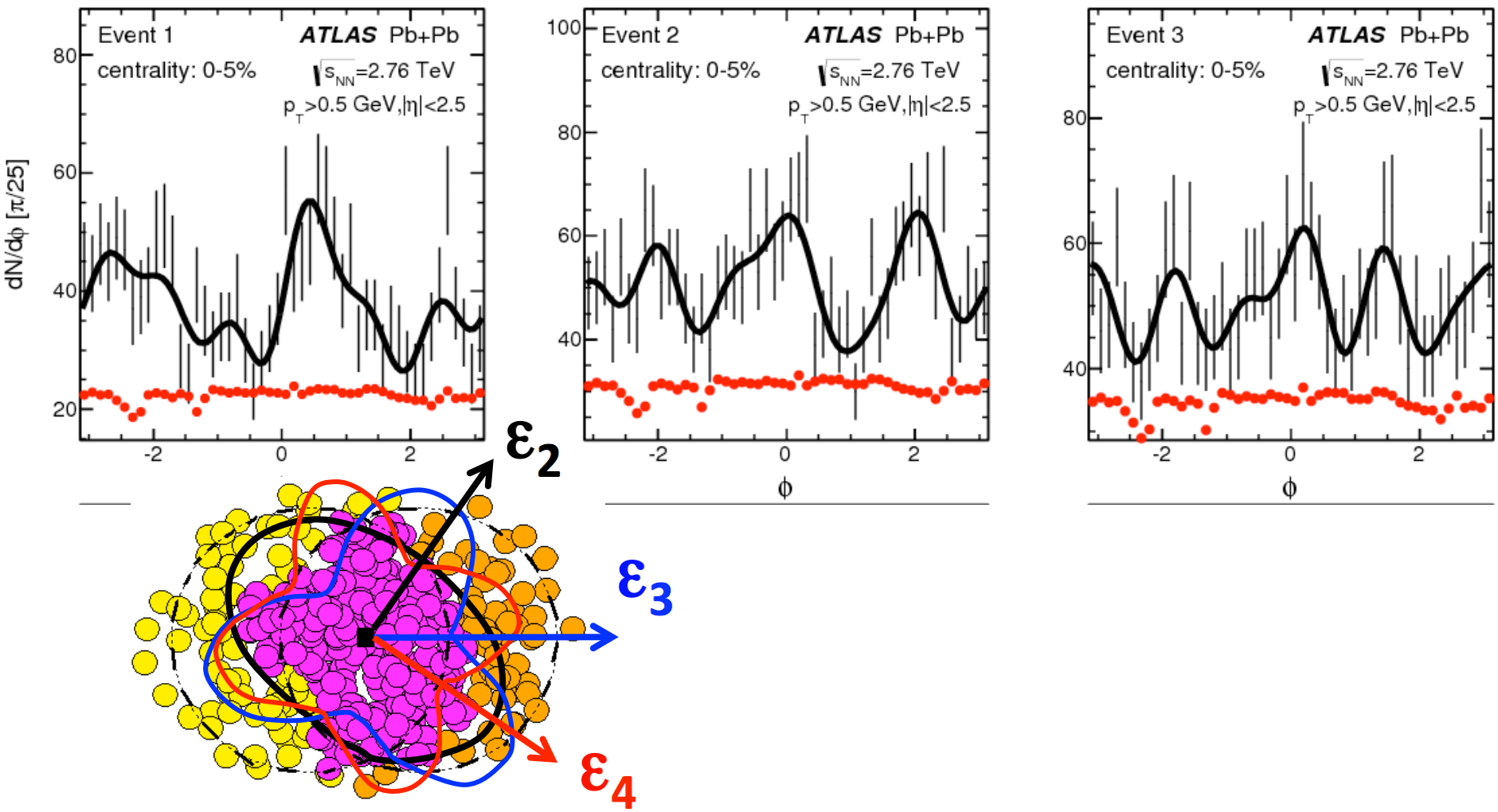
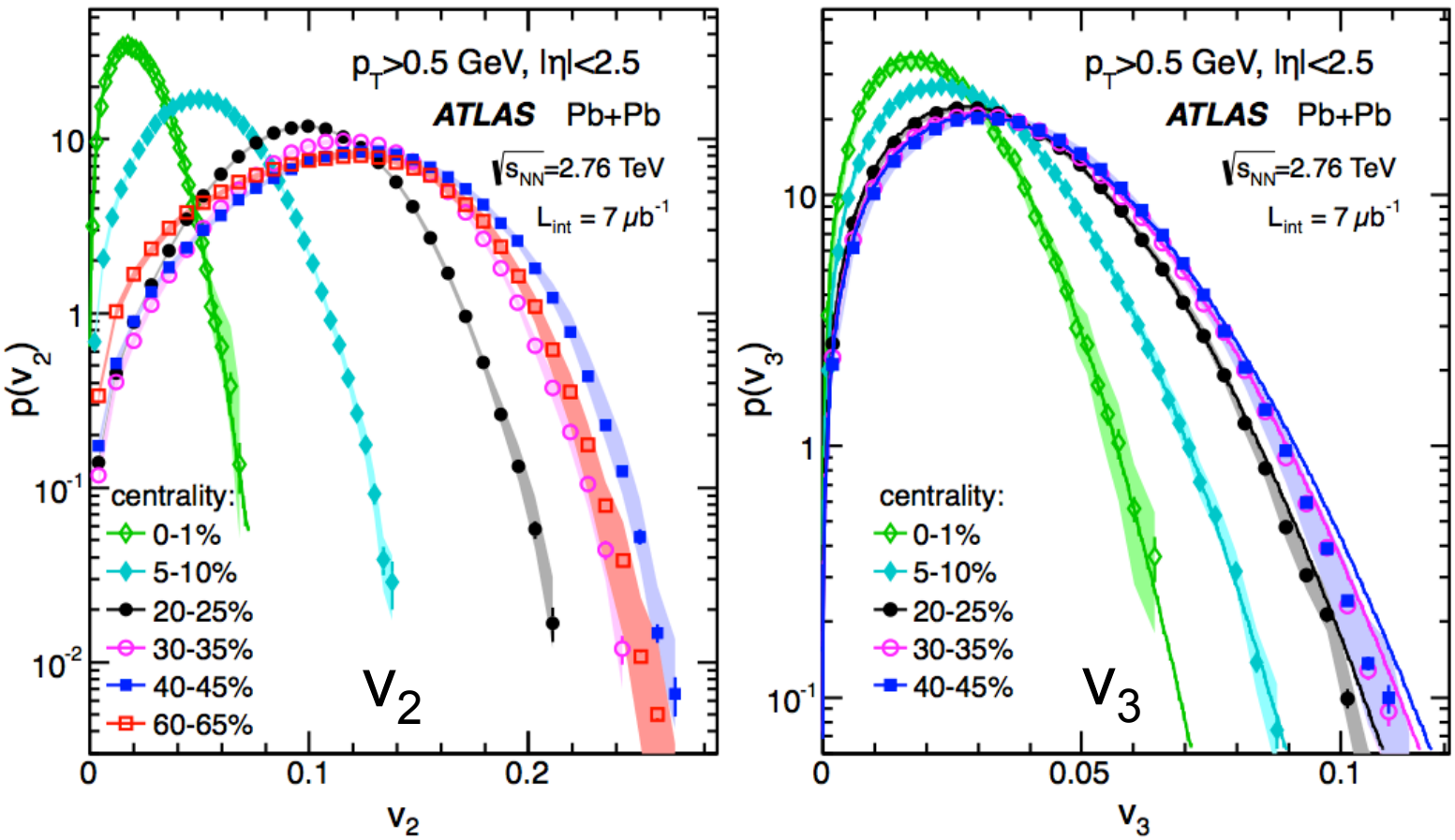


The large acceptance of the ATLAS detector and large multiplicity at LHC makes EbE v_n measurements possible for the first time.

v_2-v_3 probability distributions

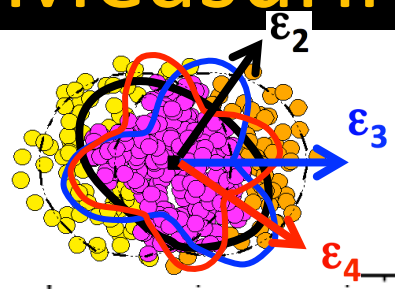


v_3 distributions are consistent with pure Gaussian fluctuations $p(v_n) \propto v_n \exp\left(\frac{-v_n^2}{2\delta_n^2}\right)$

deviations in the tail (increases central->midcentral)

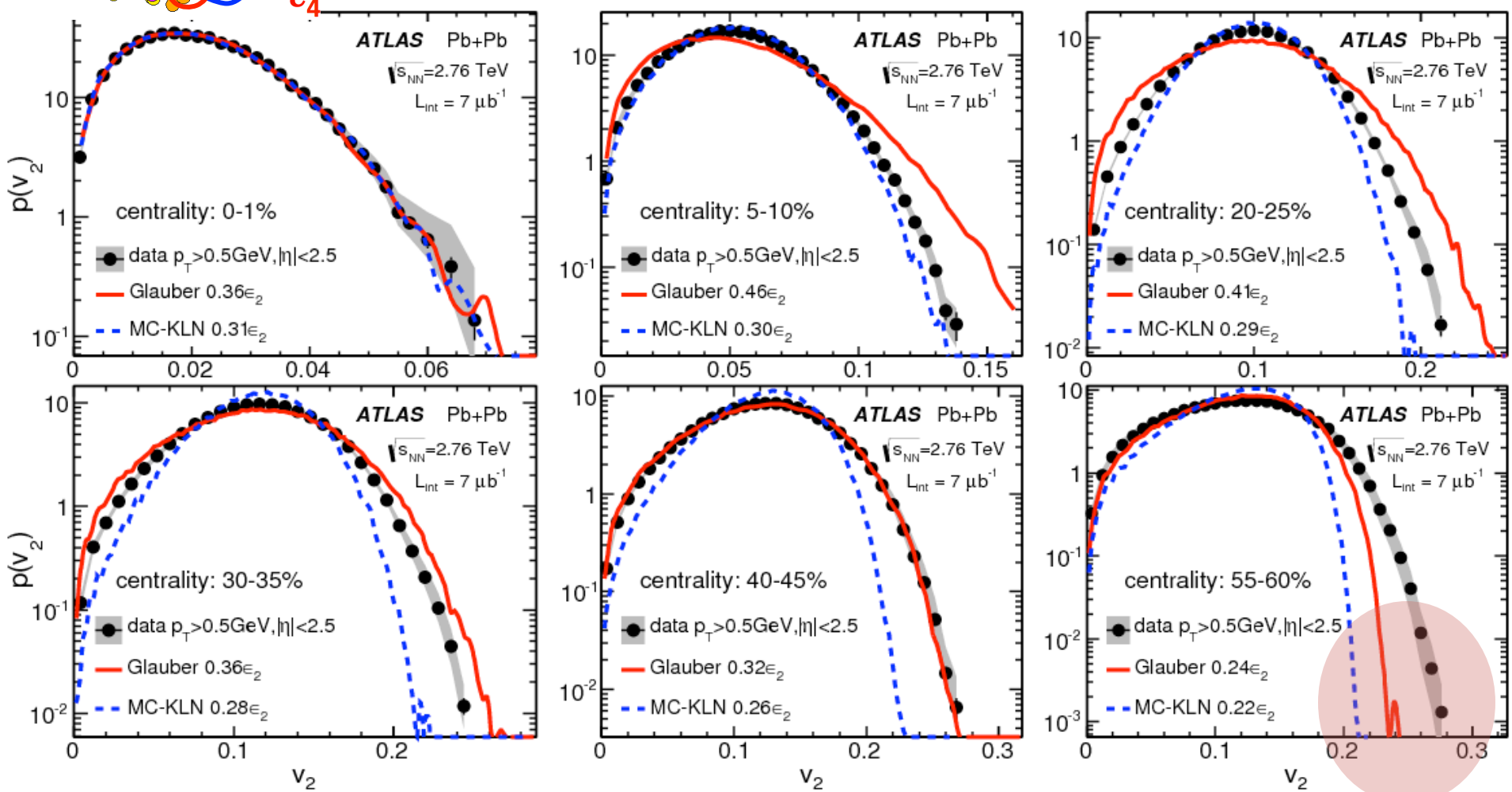
For v_2 pure Gaussian fits only work for most central (2%) events

Measuring the hydrodynamic response: v_2



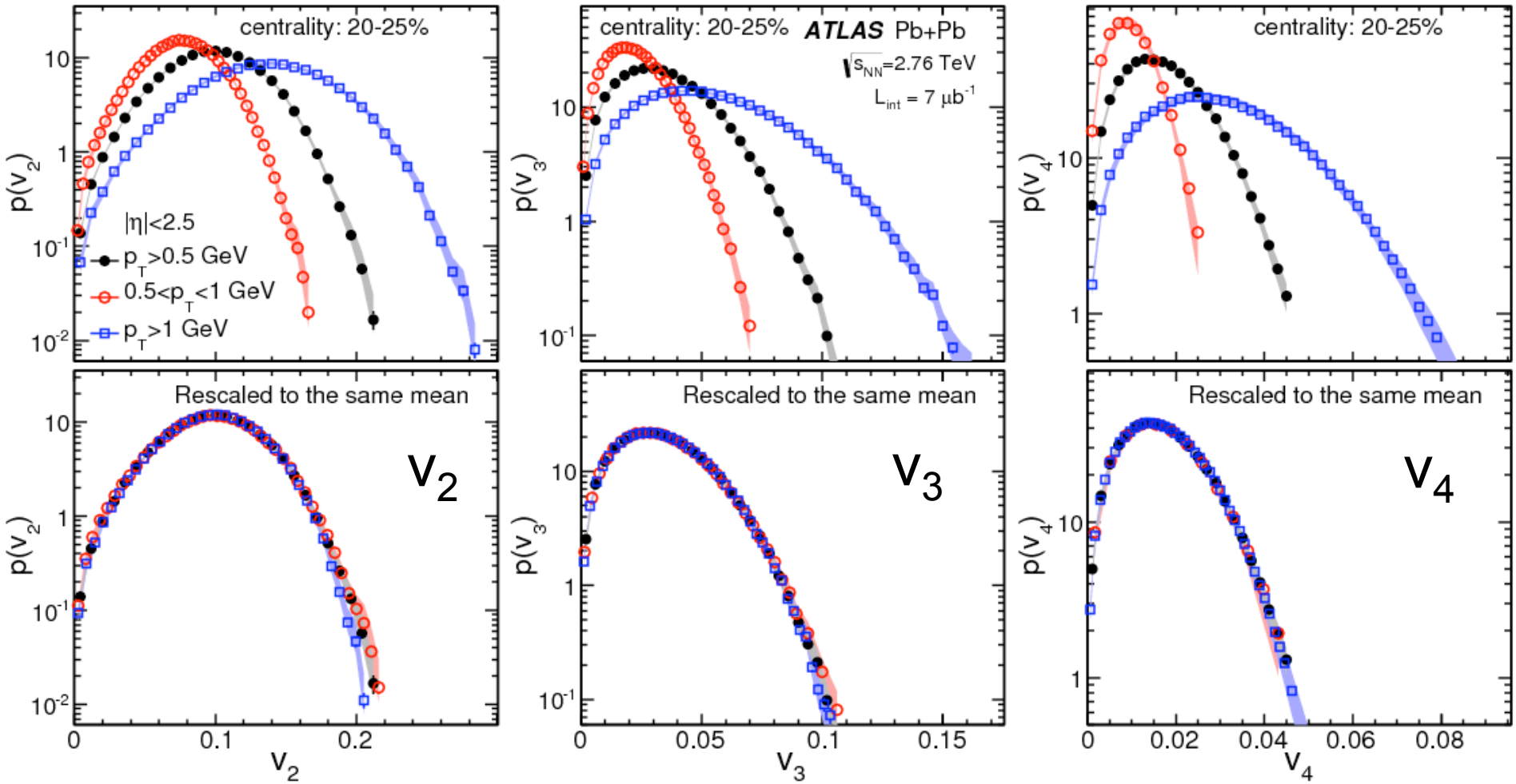
$$v_n \propto \epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$$

For Glauber and CGC mckln



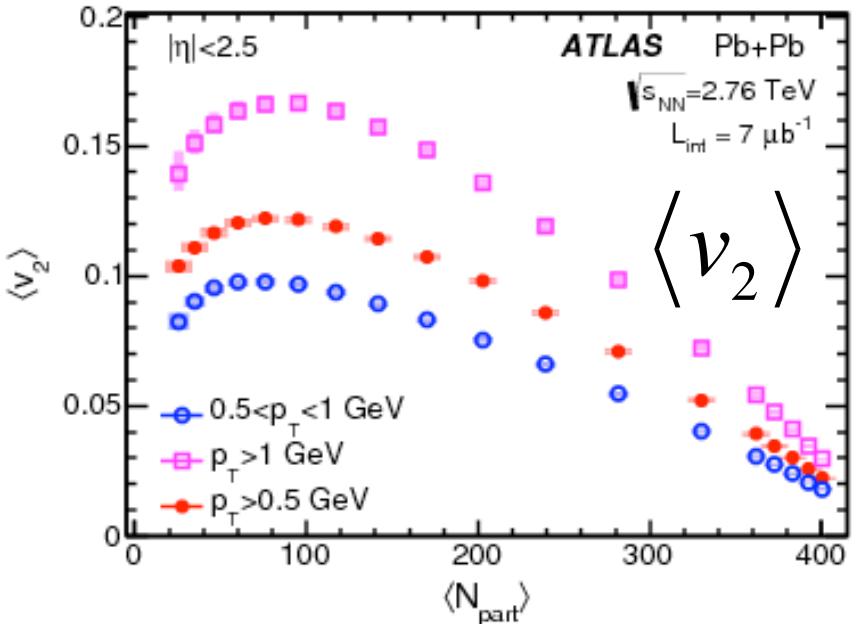
Both models fail describing $p(v_2)$ across the full centrality range

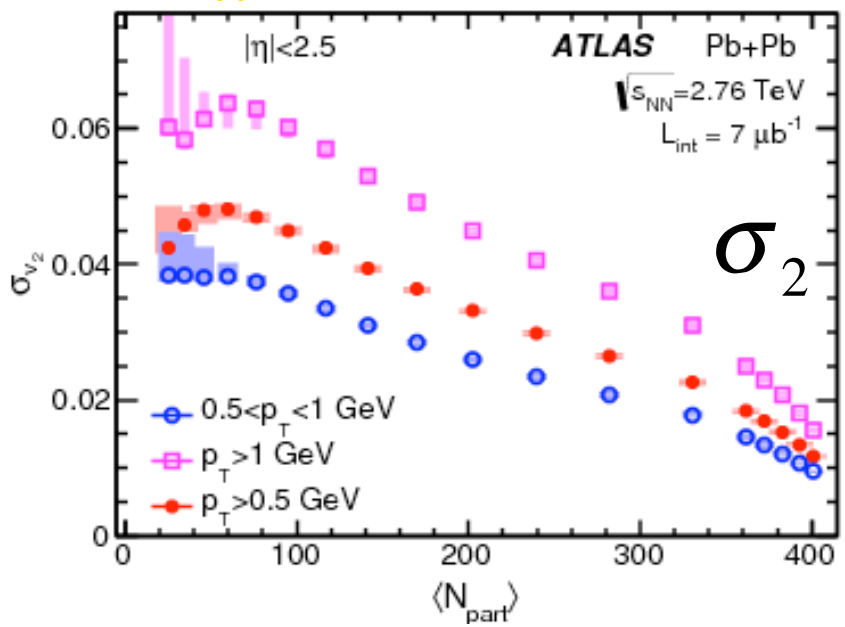
Unfolding in different p_T ranges: 20-25%

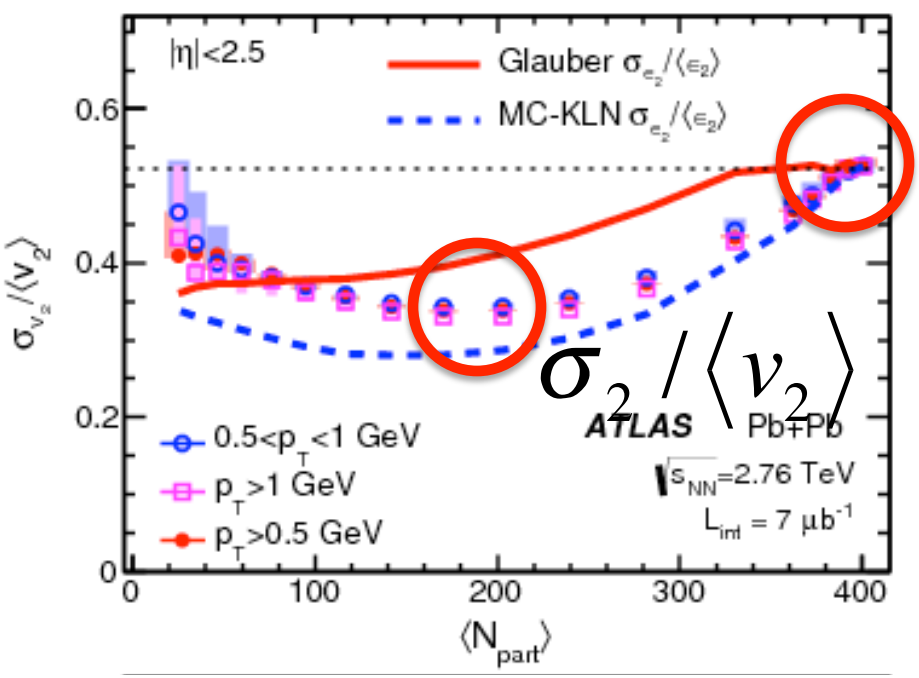


Distributions for higher p_T bin is broader, but they all have ~same reduced shape. Hydrodynamic response factorizes into a p_T dependent and geometry dependent part.

Mean and sigma of v_n distributions



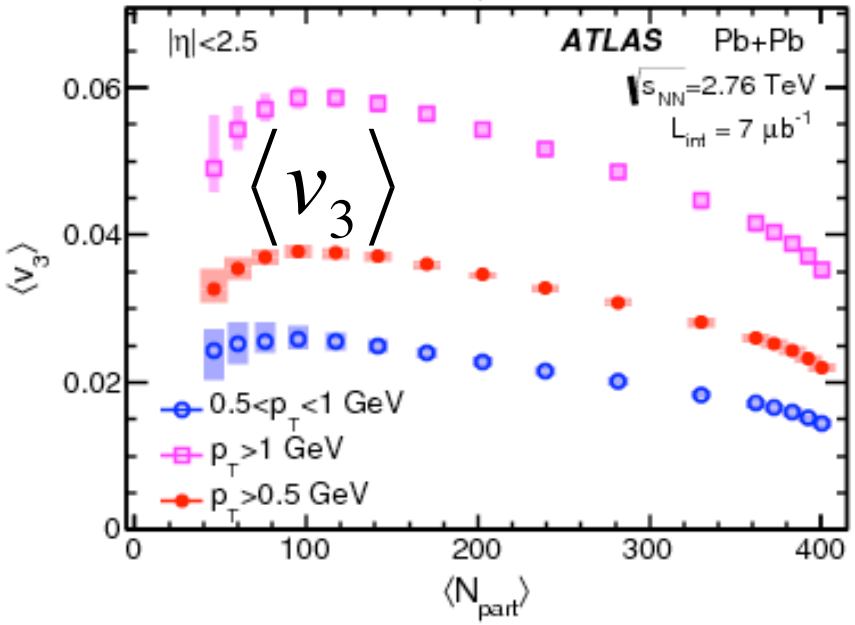


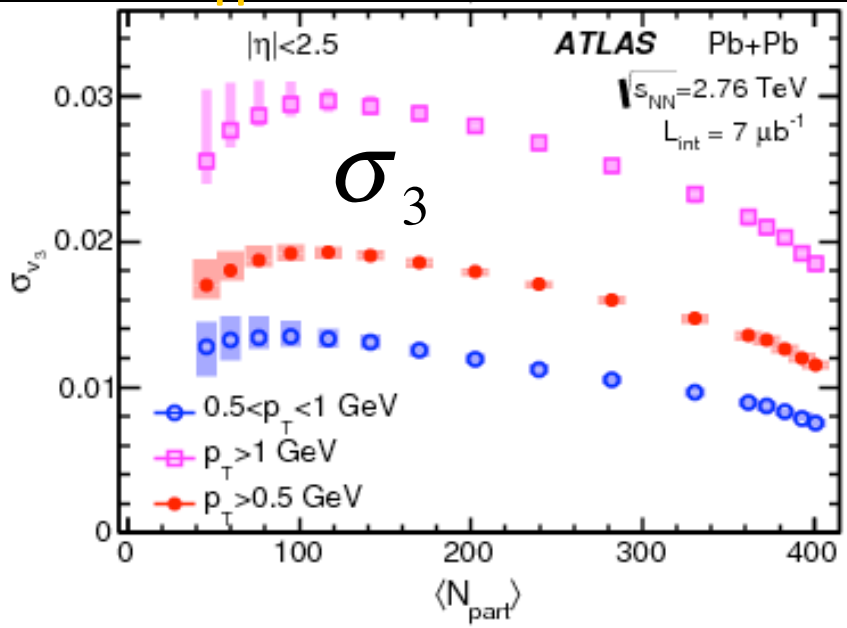


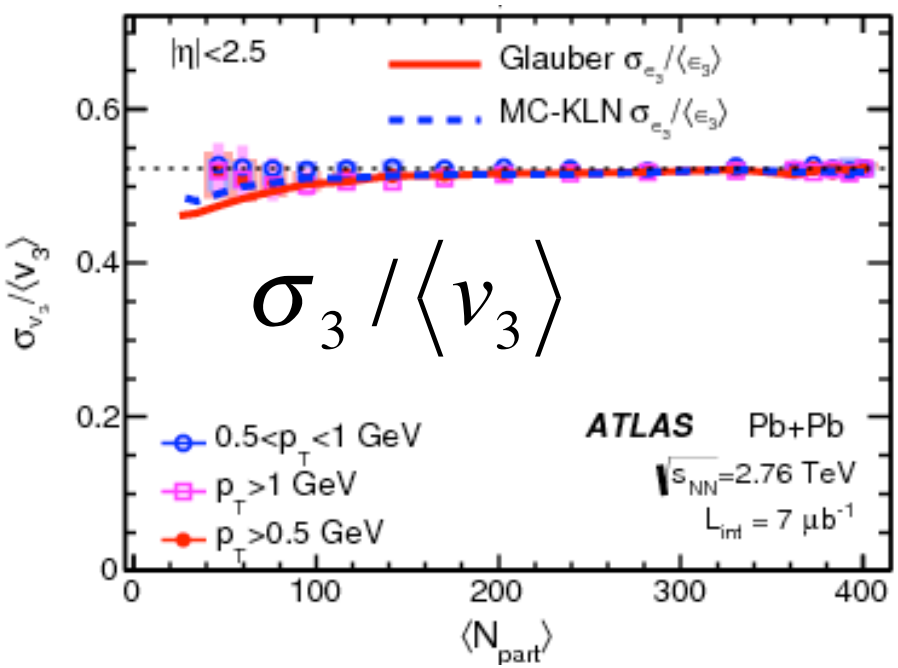
$$\sigma_2 / \langle v_2 \rangle$$

for gaussian fluctuations : $\sigma_n / \langle v_n \rangle \approx 0.523$

Mean and sigma of v_n distributions

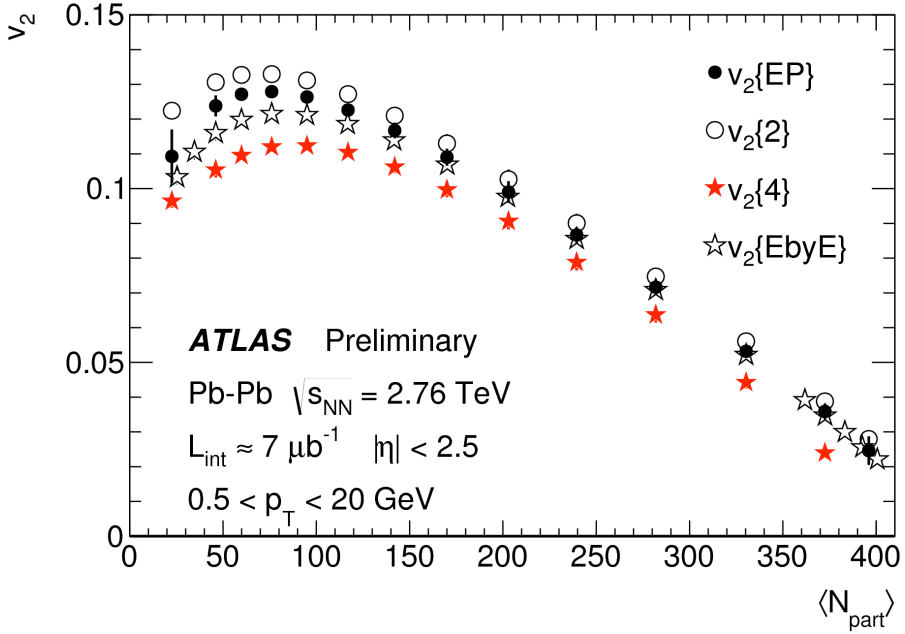


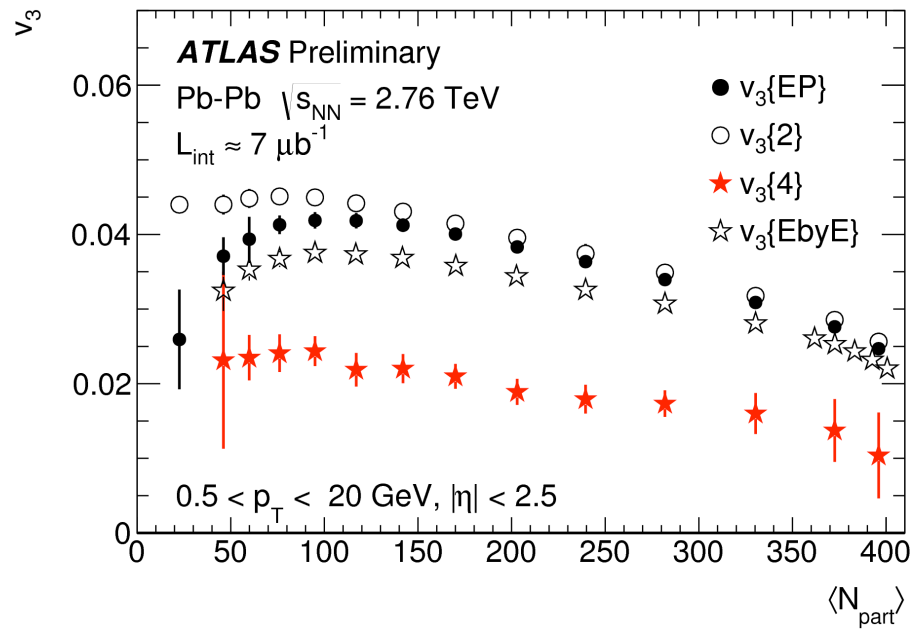


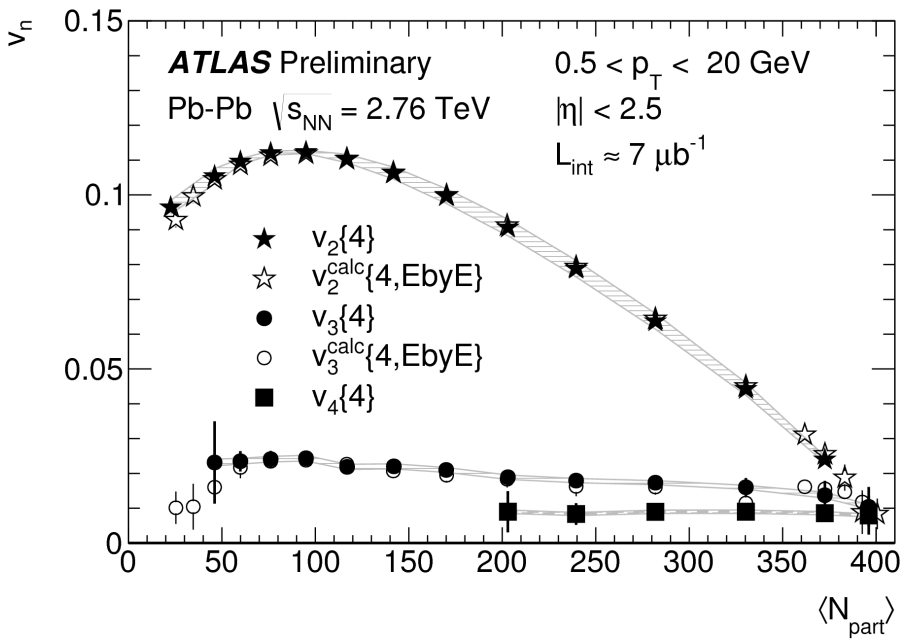


for gaussian fluctuations : $\sigma_n / \langle v_n \rangle \approx 0.523$

Cumulant measurements







Different methods give different results as each is affected differently by fluctuations

Can directly calculate cumulants from EbyE v_n measurements and compare

Event-shape selected v_n measurements

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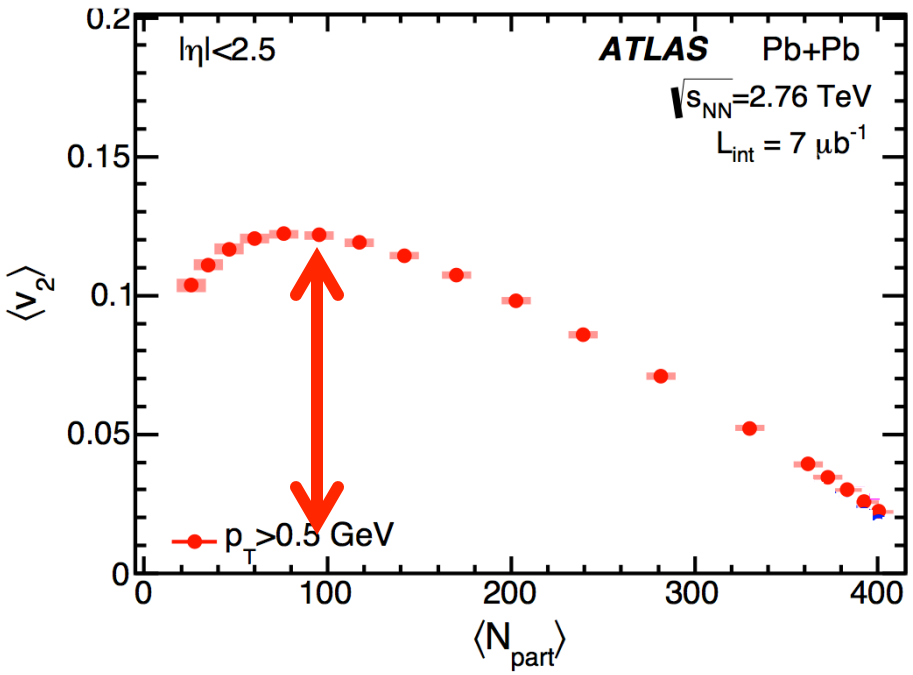
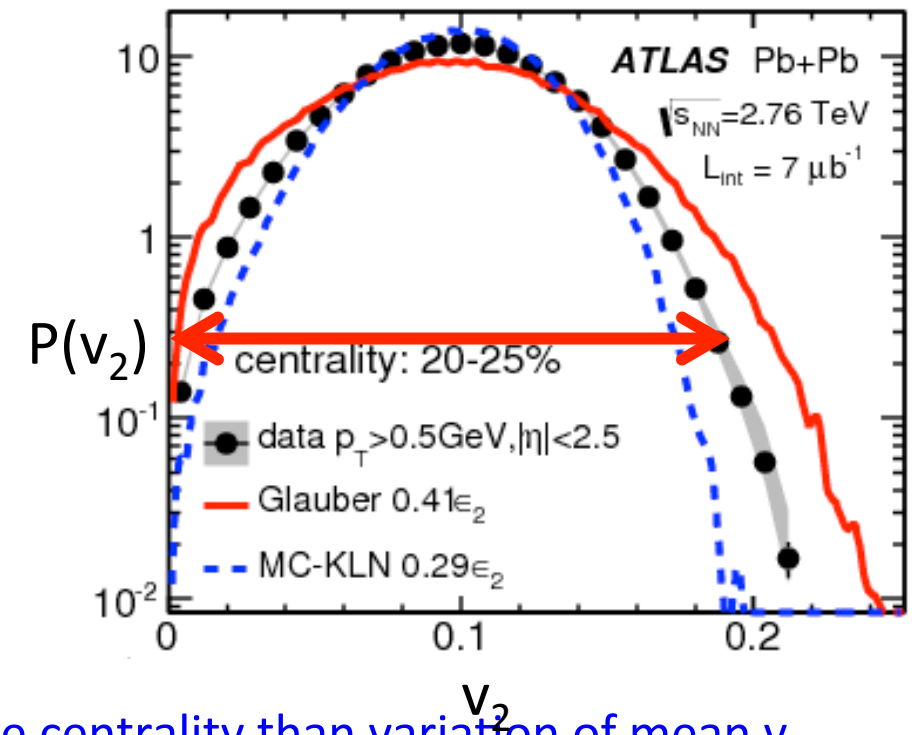




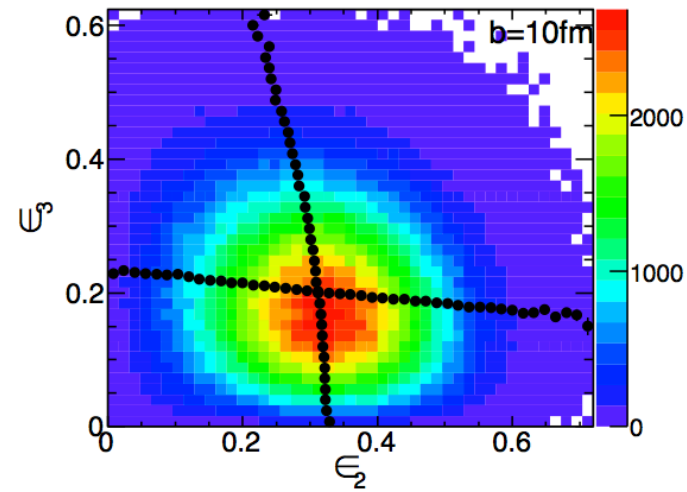
- Much more variation in v_2 within one centrality than variation of mean v_2 across all centralities

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

v_n-v_2 correlations

- Correlations can arise from initial geometry effects.
- Glauber calculations show anti-correlations between ε_2 and ε_3 that can lead to anti-correlations between v_2 and v_3.

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



Pb+Pb , b_{imp}=10 fm
arXiv 1311.7091

- Measure correlations = Understand geometry of initial state
- Correlations can arise from non-linear response to ε_n.

Eccentricities of initial geometry

$$v_4 e^{i4\Phi_4} = a_0\, \epsilon_4 e^{i4\Phi_4^*} + a_1 \left(\epsilon_2 e^{i2\Phi_2^*}\right)^2 + \ldots$$

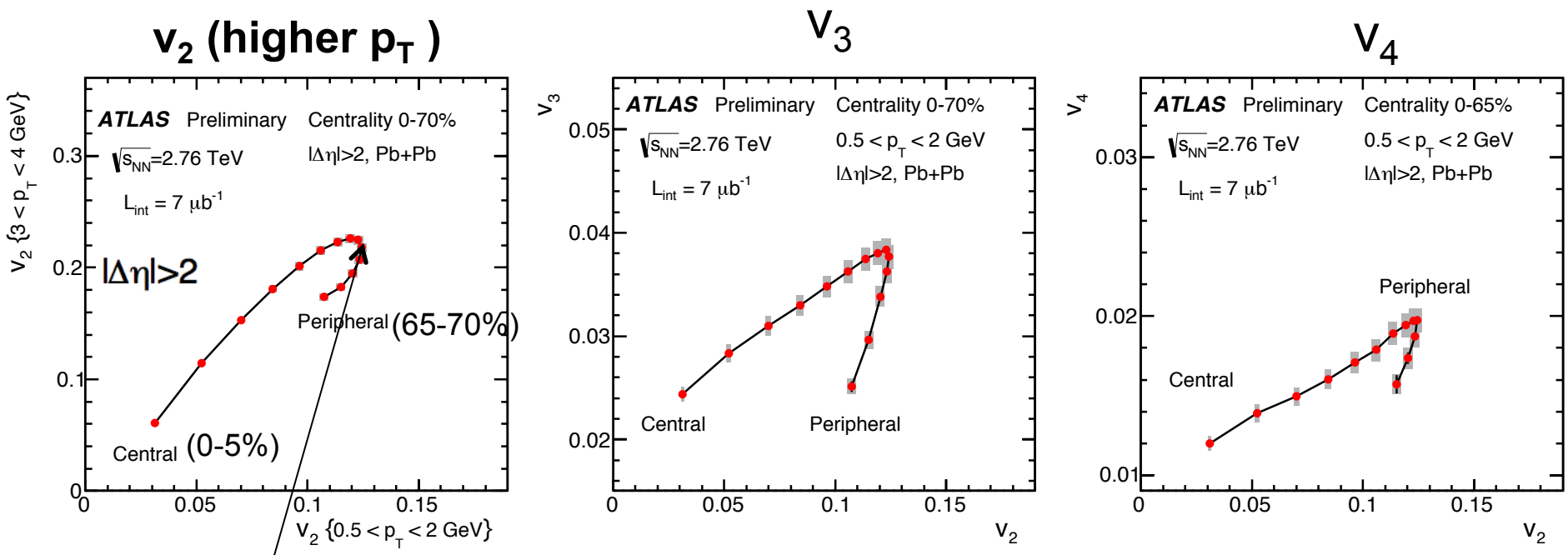
Collective response to eccentricities

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

- Measure correlations = Understand hydro response

v_n-v_2 correlations: centrality dependence

- First correlation without event v_2-selection, 5% steps

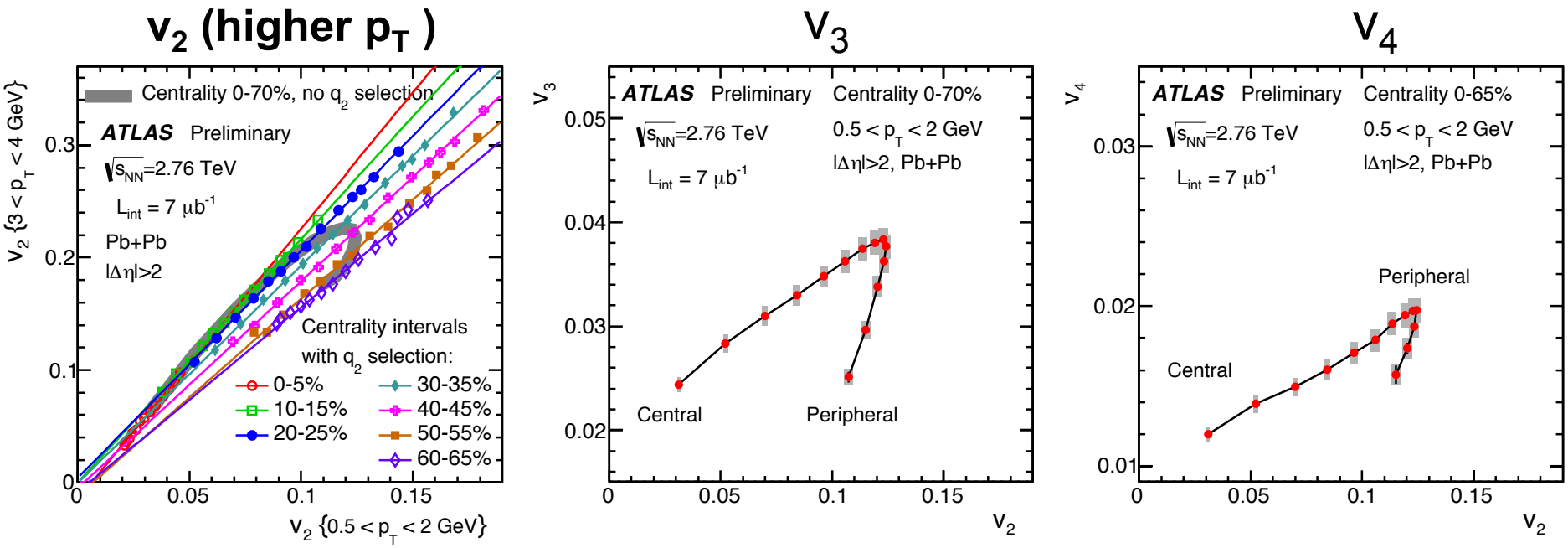


"Boomerang" reflects stronger viscous damping at higher p_T and peripheral

v_n-v_2 correlations: within fixed centrality

- Fix system size and vary the ellipticitiy!

Probe $p(v_n,v_2)$



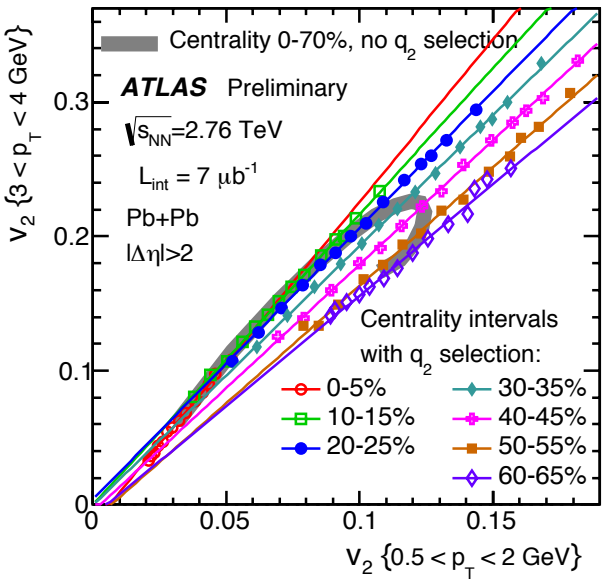
Linear correlation within a given centrality→viscous damping controlled by system size, not shape

v_n-v_2 correlations: within fixed centrality

- Fix system size and vary the ellipticitiy!
- Overlay ε_3-ε_2 and ε_4-ε_2 correlations, rescaled

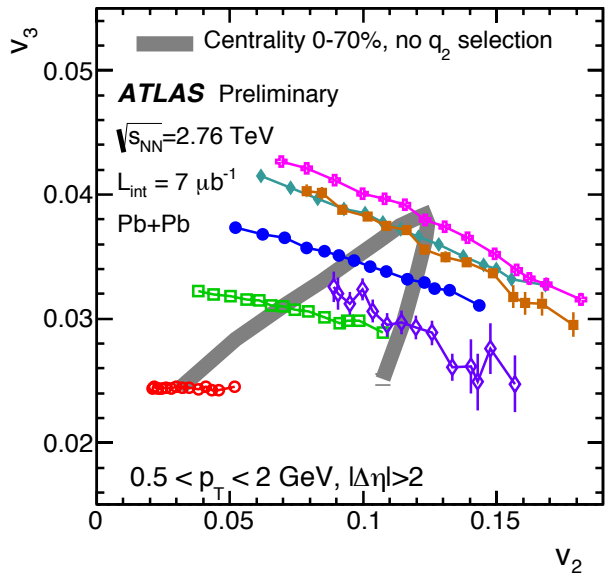
Probe $p(v_n,v_2)$

v_2 (higher p_T)



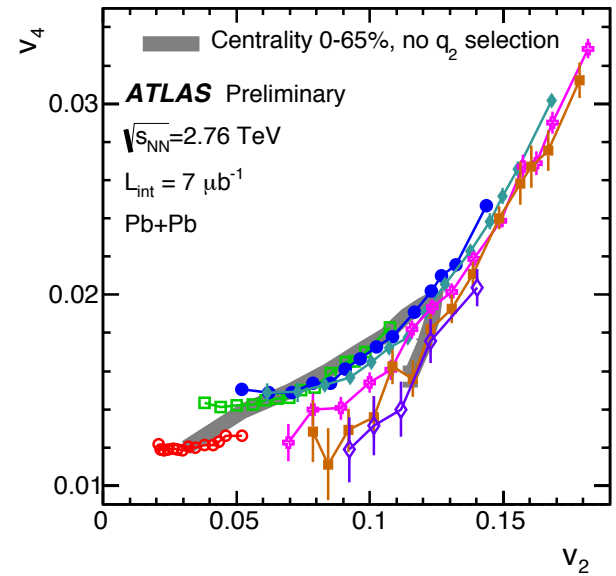
Linear correlation within a given centrality→viscous damping controlled by system size, not shape

v_3



Clear anti-correlation,

v_4



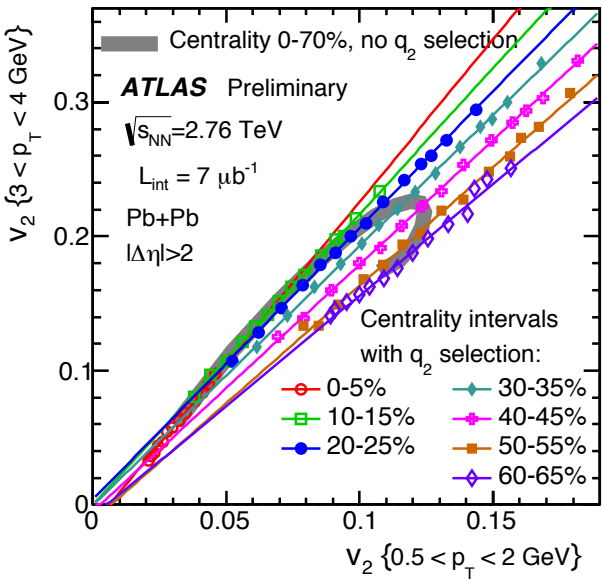
quadratic rise from non-linear coupling to v_2^2

v_n-v_2 correlations: within fixed centrality

- Fix system size and vary the ellipticitiy!
- Overlay ε_3-ε_2 and ε_4-ε_2 correlations, rescaled

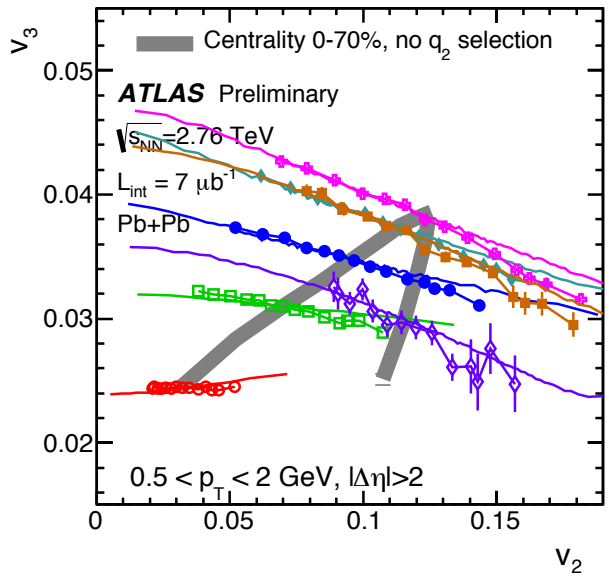
Probe $p(v_n,v_2)$

v_2 (higher p_T)



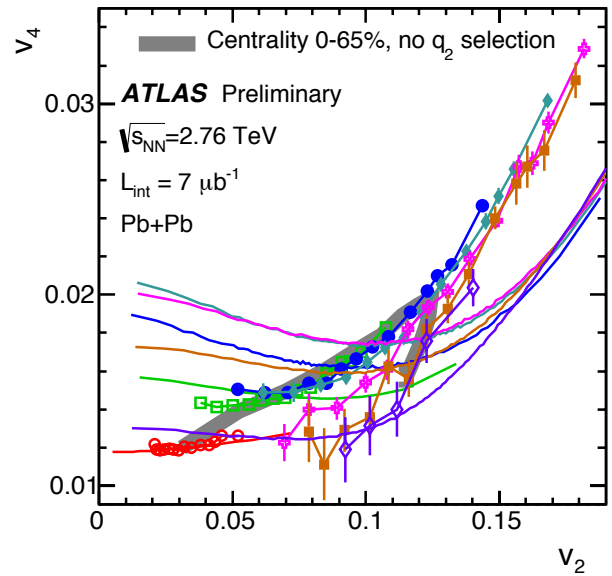
Linear correlation within a given centrality→viscous damping controlled by system size, not shape

v_3



Clear anti-correlation, mostly initial geometry effect!!

v_4

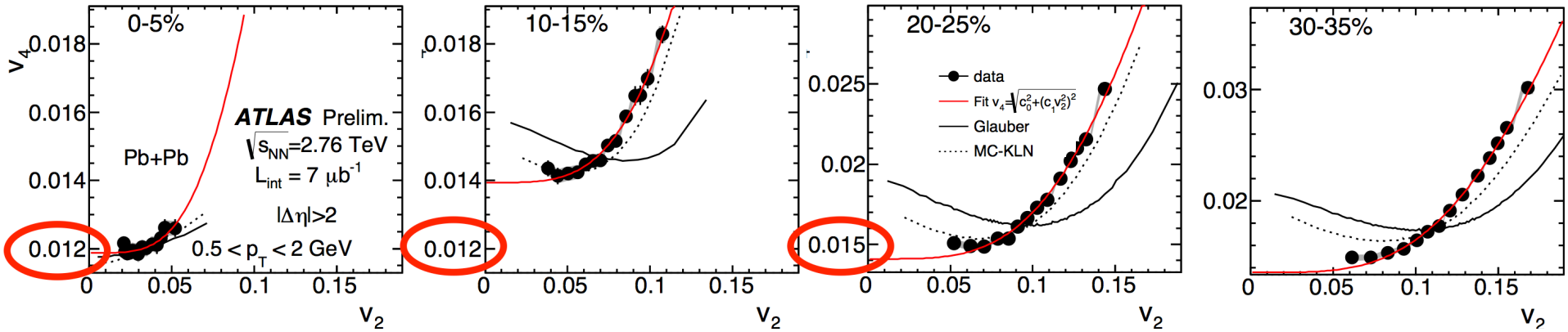


quadratic rise from non-linear coupling to v_2^2 initial geometry does not work!!

Initial geometry describe v_3-v_2 but fails v_4-v_2 correlation

linear (ε_4) and non-linear (v_2^2) component of v_4

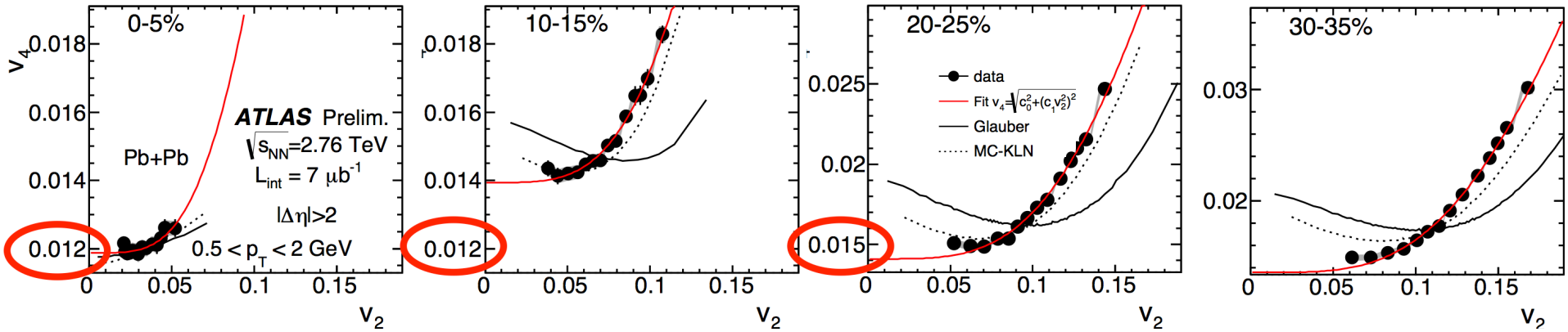
- v_4-v_2 correlation for fixed centrality bin $v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^*} + c_1 \left(v_2 e^{i2\Phi_2} \right)^2 \Rightarrow$ Fit by $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$



- Fit $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$ to separate linear (ε_4) and non-linear (v_2^2) component

linear (ε_4) and non-linear (v_2^2) component of v_4

- v_4-v_2 correlation for fixed centrality bin $v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^*} + c_1 \left(v_2 e^{i2\Phi_2} \right)^2 \Rightarrow$ Fit by $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$



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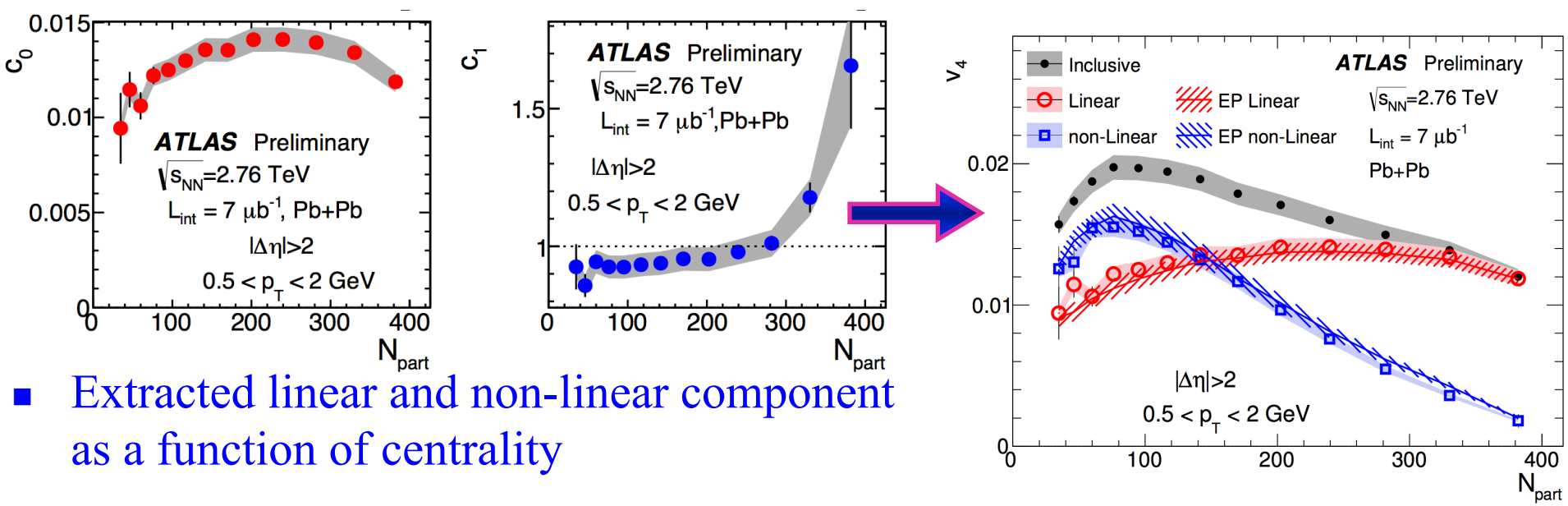
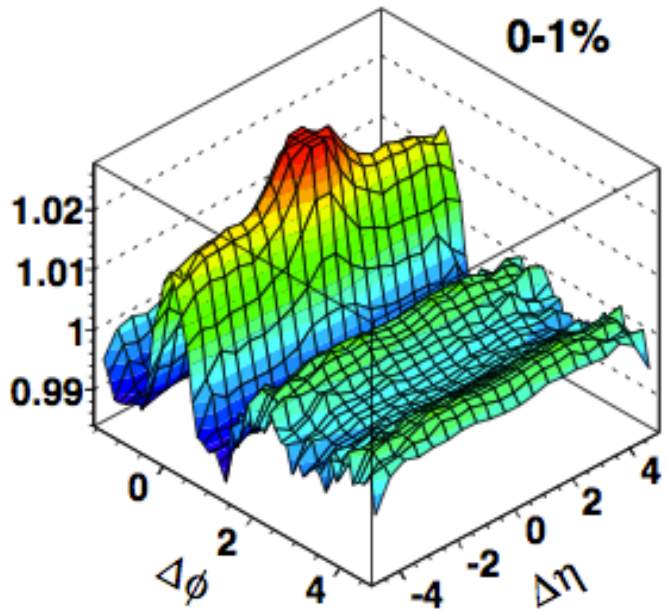
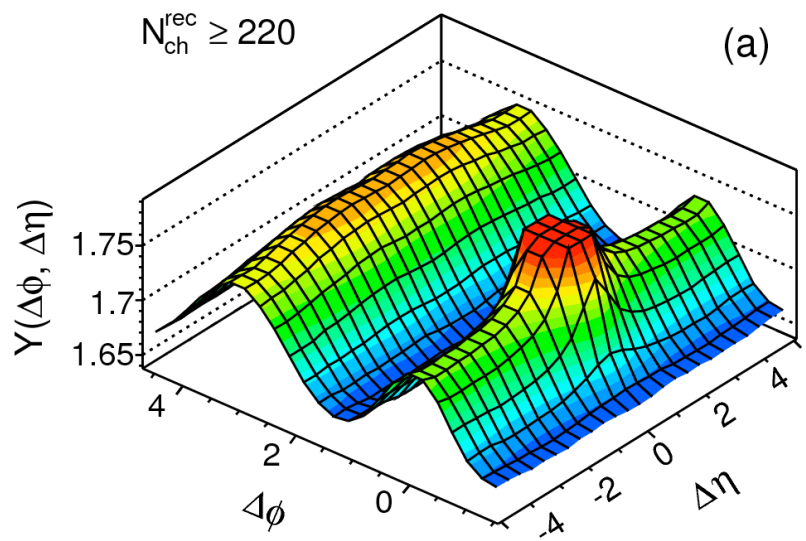


- Extracted linear and non-linear component as a function of centrality

Ridges in Pb-Pb and p+Pb



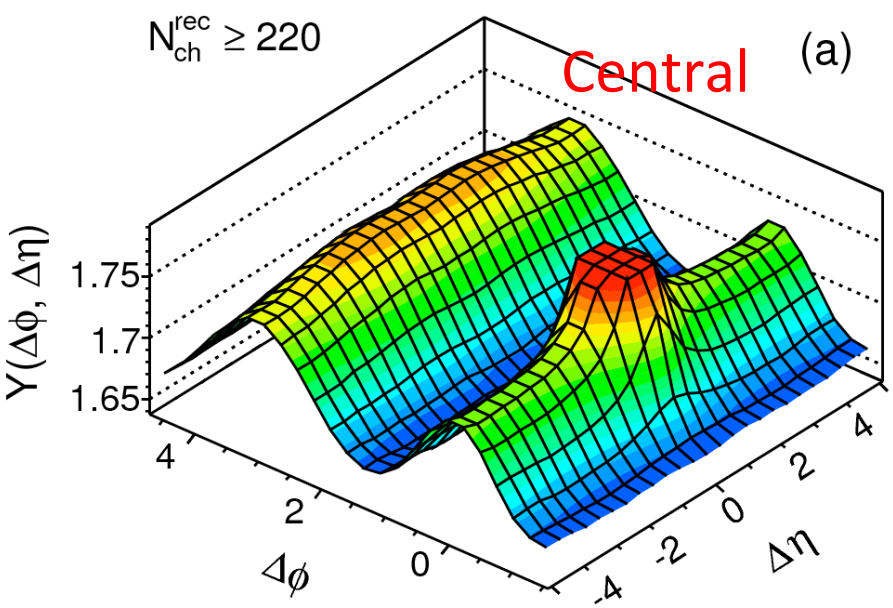
Pb+Pb ridge

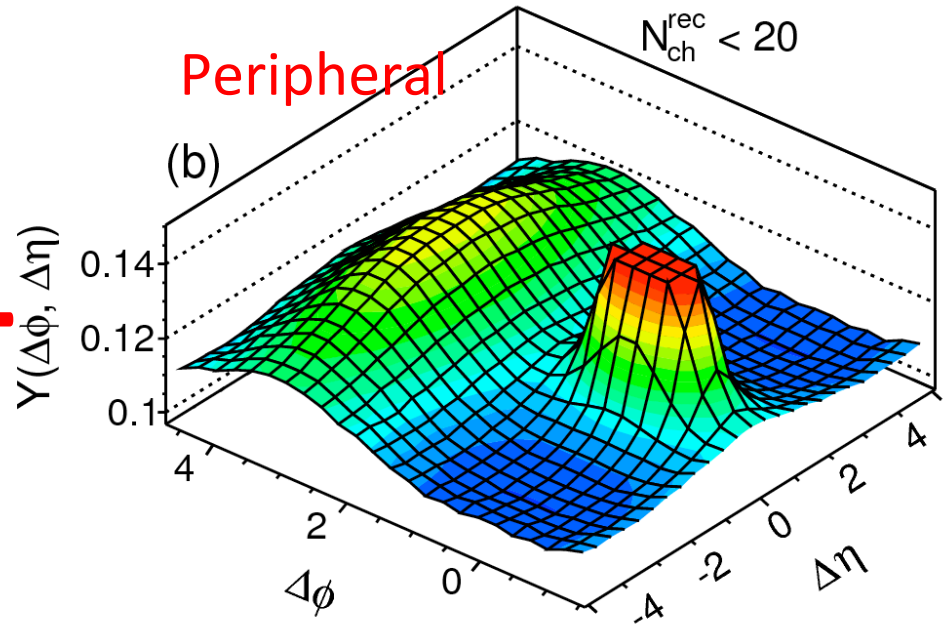


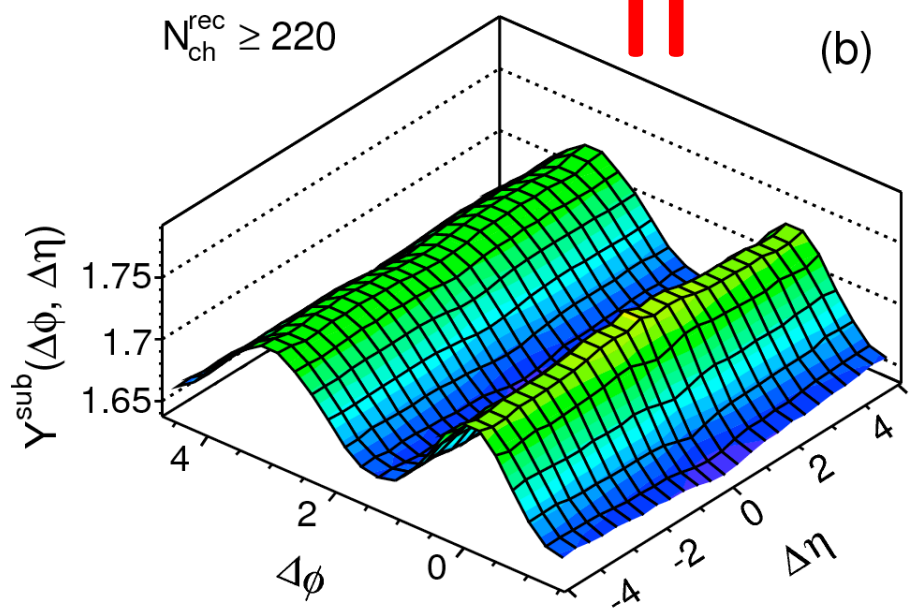
p+Pb ridge

- Two-particle correlations show long range correlation structure along $\Delta\eta$ at $\Delta\phi=0$.
- Is there an effective mechanism that rules them all? Is it initial state effect, final state effect or both?
  - Final state effect may not imply hydro
- Is there an away-side ridge in pp and pPb?
- What is its detailed p_T, η, and centrality dependence?

Peripheral subtraction



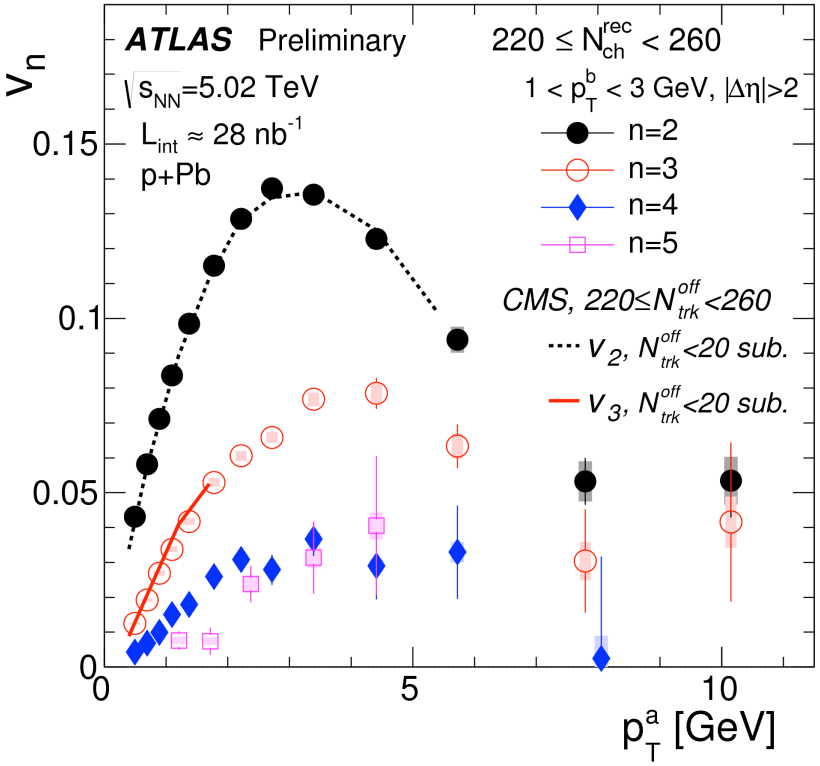




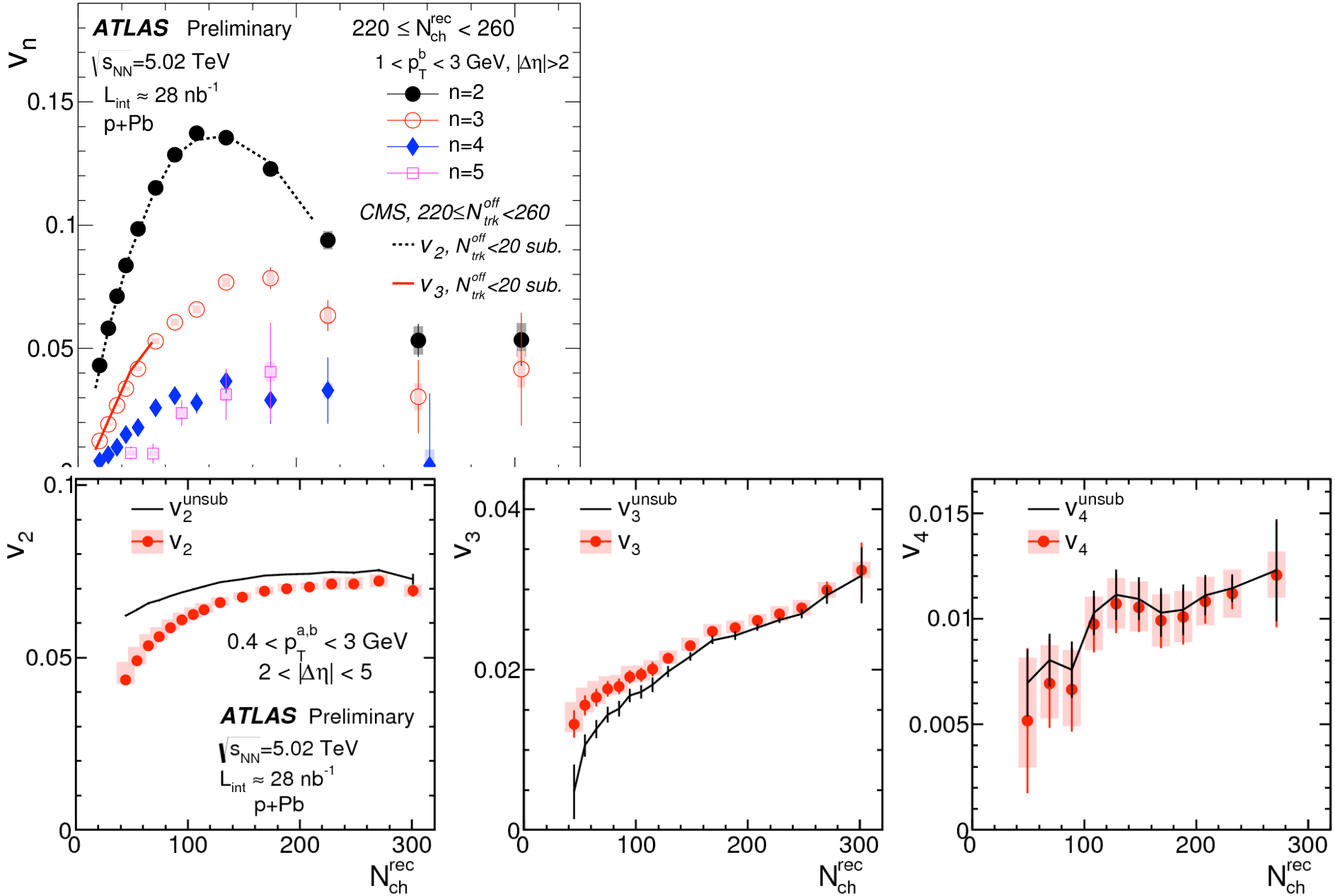
- Estimate contribution of jet & recoil correlations using low multiplicity events
- Subtract from correlations in high-multiplicity events to obtain "true" long-range correlations

Central - Peripheral=True correlation

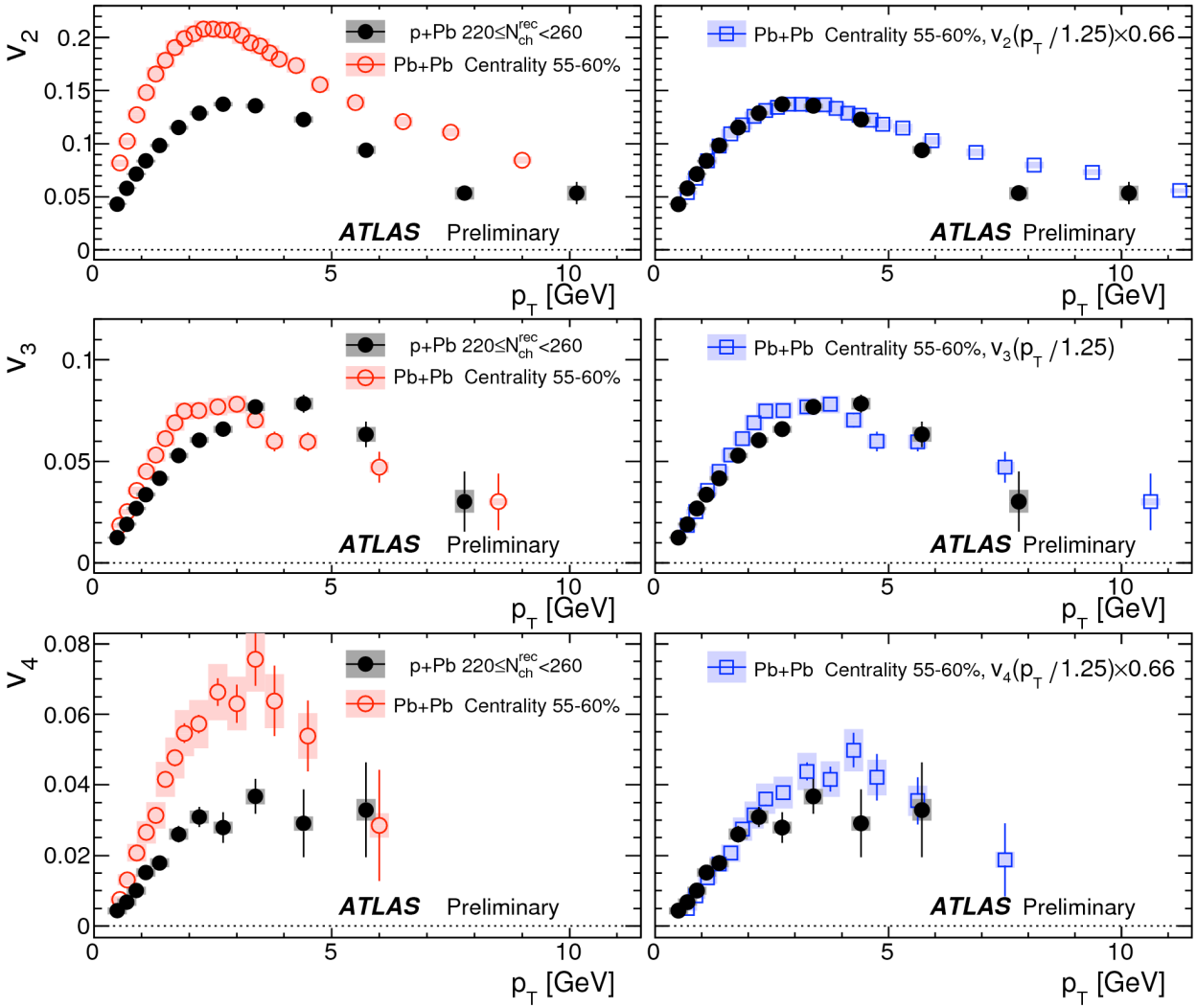
p+Pb v_n


ATLAS Preliminary
√sNN=5.02 TeV
Lint ≈ 28 nb-1
p+Pb
220 ≤ Nrec ch < 260
1 < pb T < 3 GeV, |Δη|>2
n=2
n=3
n=4
n=5
CMS, 220≤Noff trk<260
v2, Noff trk<20 sub.
v3, Noff trk<20 sub.
vn
pa T [GeV]
0
0.05
0.1
0.15
5
10

p+Pb v_n


ATLAS Preliminary
$\sqrt{s_{NN}}$=5.02 TeV
$L_{int} \approx 28\ nb^{-1}$
p+Pb
$220 \le N_{ch}^{rec} < 260$
$1 < p_T^b < 3$ GeV, $|\Delta\eta|>2$
n=2
n=3
n=4
n=5
CMS, $220 \le N_{trk}^{off} < 260$
v_2, $N_{trk}^{off}<20$ sub.
v_3, $N_{trk}^{off}<20$ sub.
v_n
v_2^{unsub}
v_2
$0.4 < p_T^{a,b} < 3$ GeV
$2 < |\Delta\eta| < 5$
ATLAS Preliminary
$\sqrt{s_{NN}}$=5.02 TeV
$L_{int} \approx 28\ nb^{-1}$
p+Pb
v_3^{unsub}
v_3
v_4^{unsub}
v_4
N_{ch}^{rec}

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

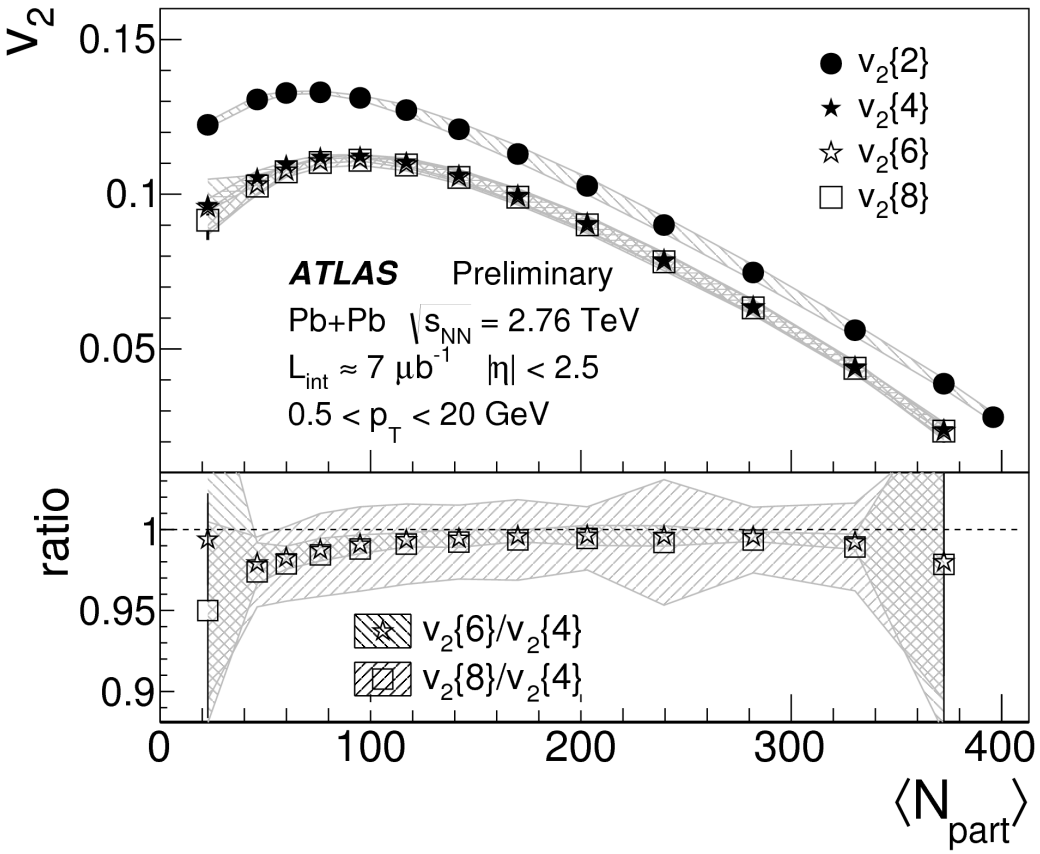
Good agreement between p+Pb and Pb+Pb when including p_T and v_2, v_4 rescaling

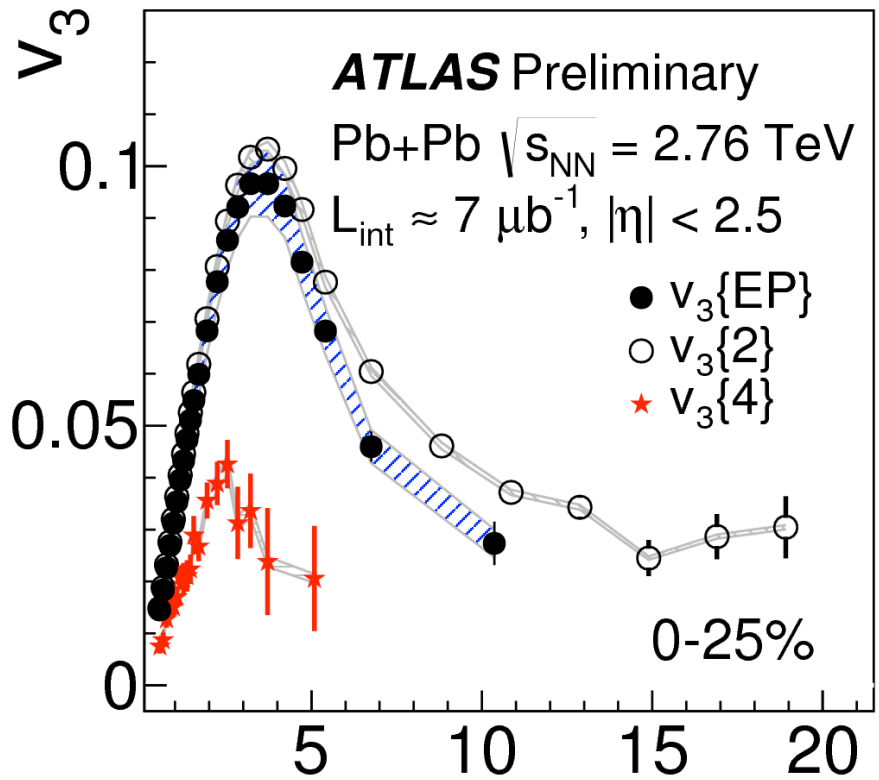
Summary

- ATLAS has measured collective phenomena in Pb+Pb collisions
  - Two-particle correlations, Event-plane & Cumulants
- Unique ATLAS measurements
  - Event-by-Event probability distribution of v_2-v_4
  - v_m-v_2 correlations
  - Event-Plane correlations
- Direct understanding of fluctuations in initial geometry & nature of hydrodynamic response to the fluctuations

- Measured long-range correlations in p+Pb events
  - Estimated and removed jet and recoil contributions using peripheral events
  - Extracted v_1-v_5 using two-particle correlations
  - Harmonics qualitatively similar to those in Pb+Pb correlations

Cumulant measurements



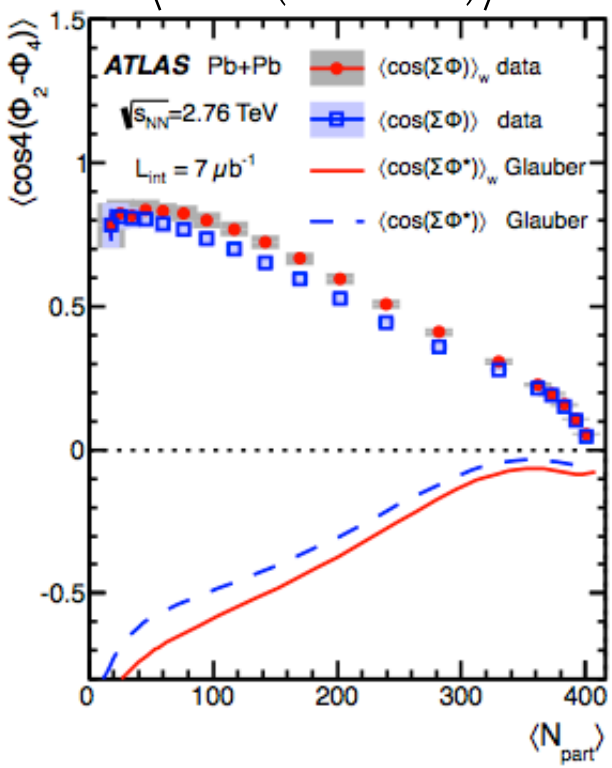


Measured v_2 using 2,4,6 & 8-particle cumulants

Measured v_3, v_4 using 2 & 4-particle cumulants

Correlation between Φ_2 and Φ_4

$$\left\langle \cos 4\left(\Phi_2 - \Phi_4\right)\right\rangle$$



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

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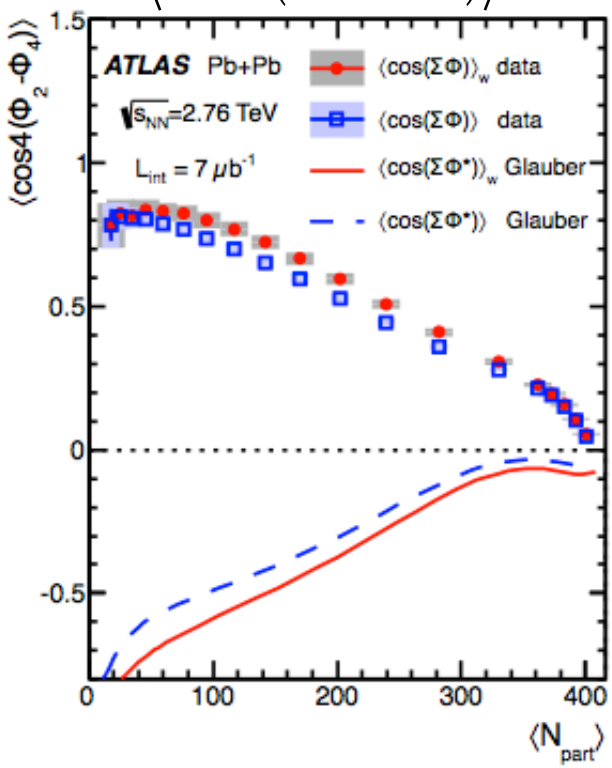

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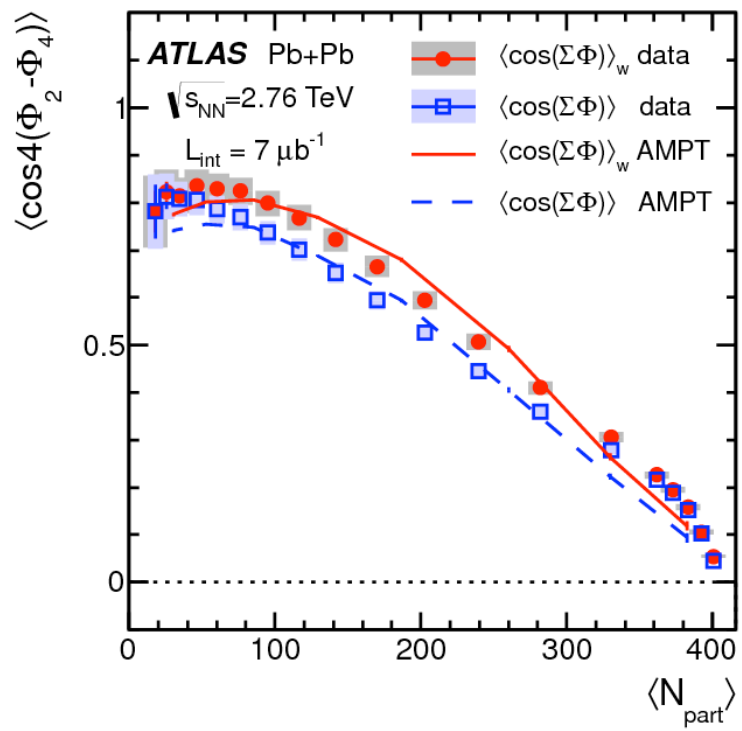
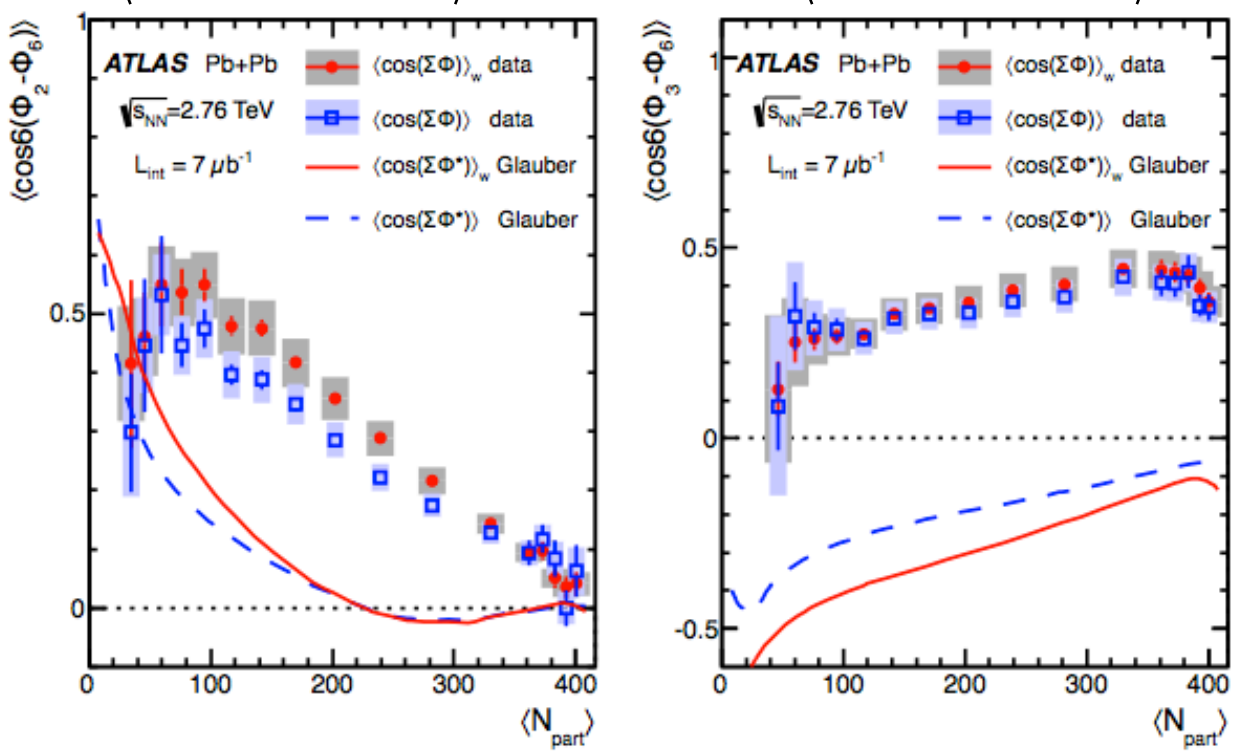


- Results expressed as function of N_{part}.
- Very different from correlations in initial state (Glauber)
- What happens if we include final-state-interactions?
- Correlations well reproduced in AMPT model
  - AMPT results from **arXiv:1307.0980** (Bhalerao et. al.)
- Conclusion: large fraction of v_4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

Correlation of Φ_2 or Φ_3 with Φ_6

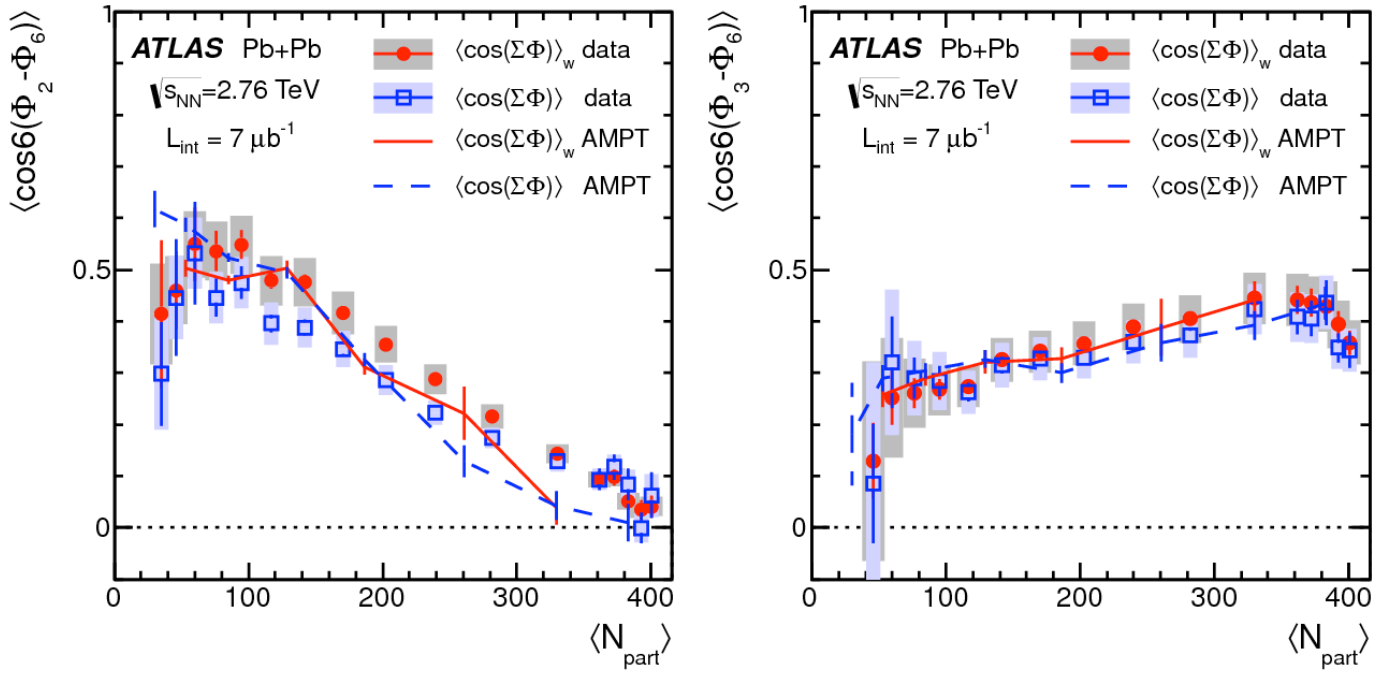
$\langle \cos 6(\Phi_2 - \Phi_6) \rangle$ $\langle \cos 6(\Phi_3 - \Phi_6) \rangle$



- 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 ?

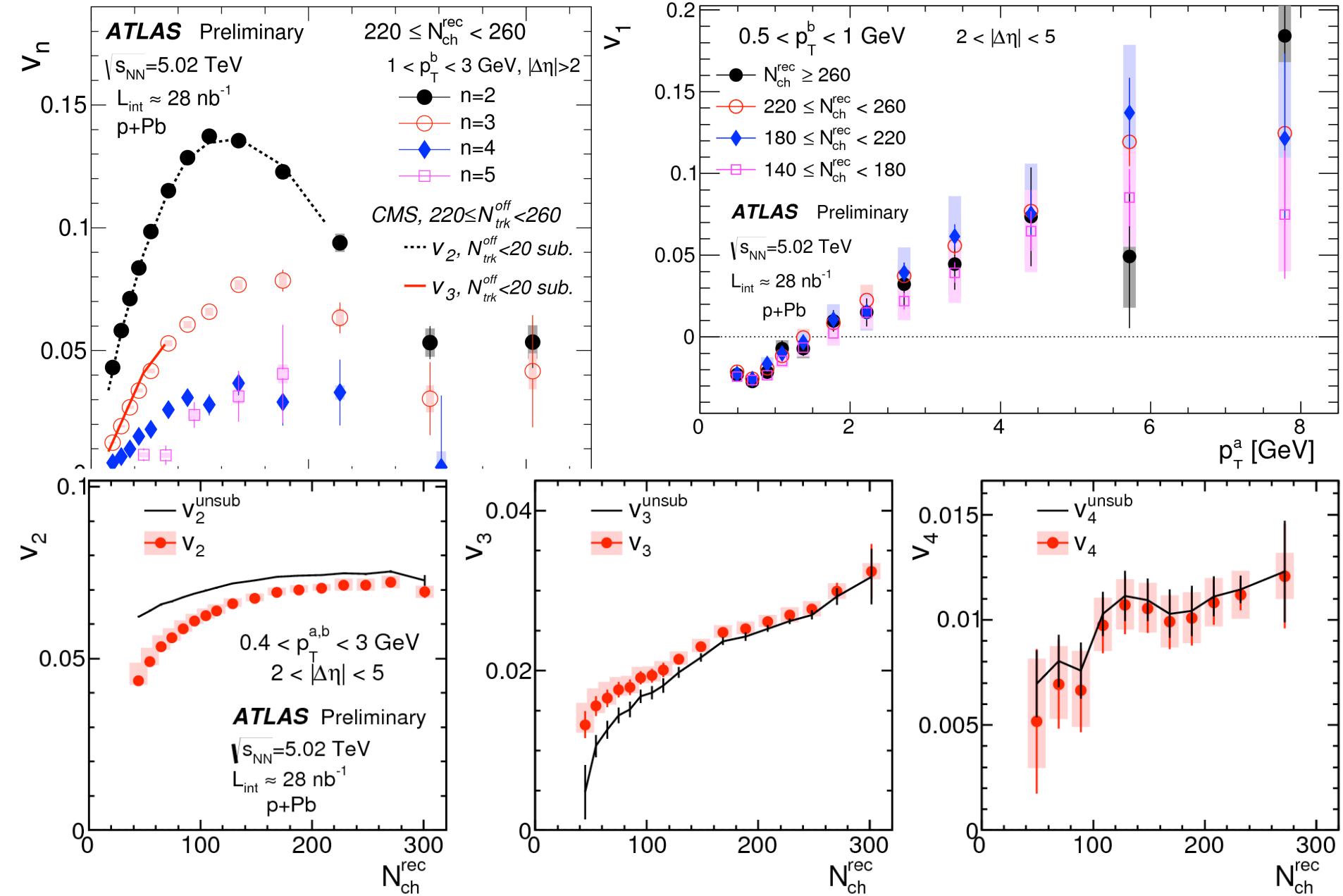
Correlation of Φ_2 or Φ_3 with Φ_6

$$\left\langle \cos 6\left(\Phi_2 - \Phi_6\right)\right\rangle \qquad \left\langle \cos 6\left(\Phi_3 - \Phi_6\right)\right\rangle$$

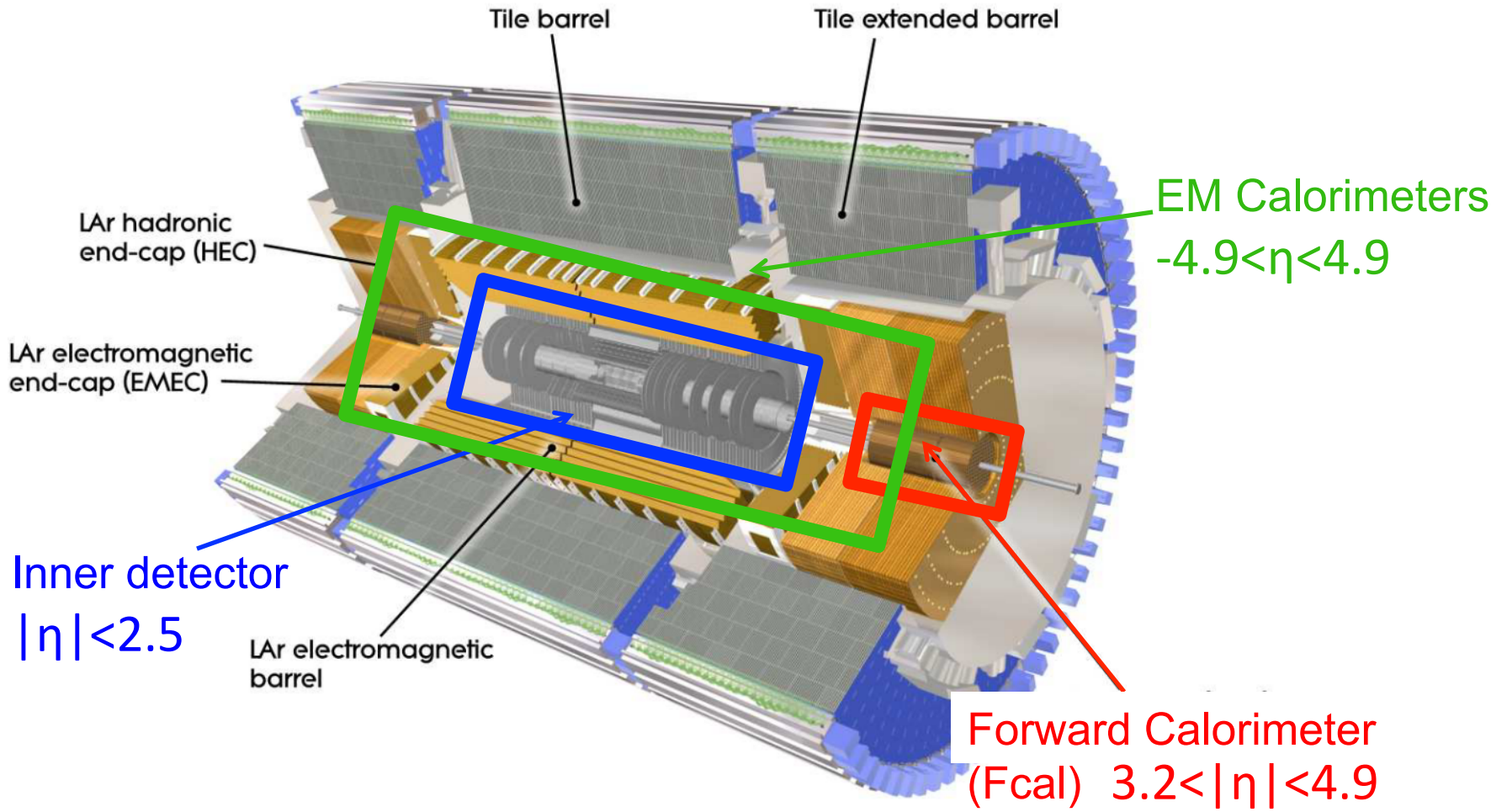


- Final state interactions reproduce the correlations
- Conclusion: large contribution to v_6 from $(\varepsilon_2)^3$ & $(\varepsilon_3)^2$ during hydrodynamic expansion !!!

p+Pb v_n


ATLAS Preliminary
$\sqrt{s_{NN}}$=5.02 TeV
$L_{int} \approx 28$ nb^{-1}
p+Pb
$220 \le N_{ch}^{rec} < 260$
$1 < p_T^b < 3$ GeV, $|\Delta\eta|>2$
n=2
n=3
n=4
n=5
CMS, $220 \le N_{trk}^{off} < 260$
v_2, $N_{trk}^{off}<20$ sub.
v_3, $N_{trk}^{off}<20$ sub.
v_n
$0.5 < p_T^b < 1$ GeV
$2 < |\Delta\eta| < 5$
$N_{ch}^{rec} \ge 260$
$220 \le N_{ch}^{rec} < 260$
$180 \le N_{ch}^{rec} < 220$
$140 \le N_{ch}^{rec} < 180$
v_1
p_T^a [GeV]
v_2^{unsub}
v_2
$0.4 < p_T^{a,b} < 3$ GeV
$2 < |\Delta\eta| < 5$
v_3^{unsub}
v_3
v_4^{unsub}
v_4
N_{ch}^{rec}

ATLAS Detector



- Tracking coverage : |η|<2.5
- FCal coverage : 3.2<|η|<4.9 (used to determine Event Planes)
- For event-plane correlations use entire EM calorimeters (-4.9 <η< 4.9)