An overview of the ATLAS experiment results on azimuthal anisotropy in high energy nuclear collisions

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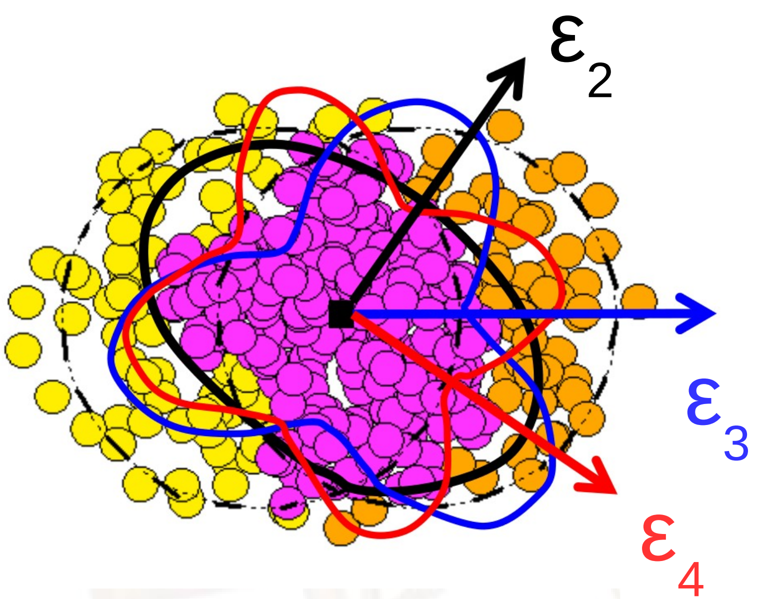
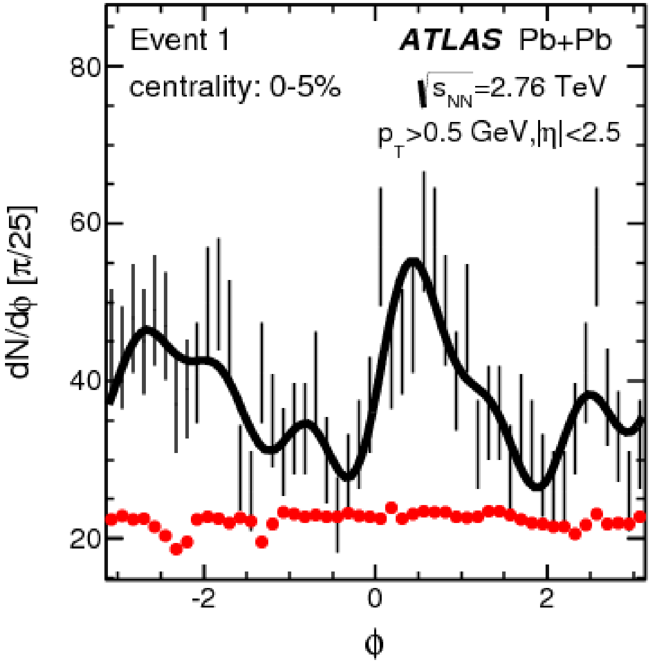
Motivation

- Study the strongly coupled quark gluon plasma
- Study the collective response of the plasma to (fluctuating) initial conditions



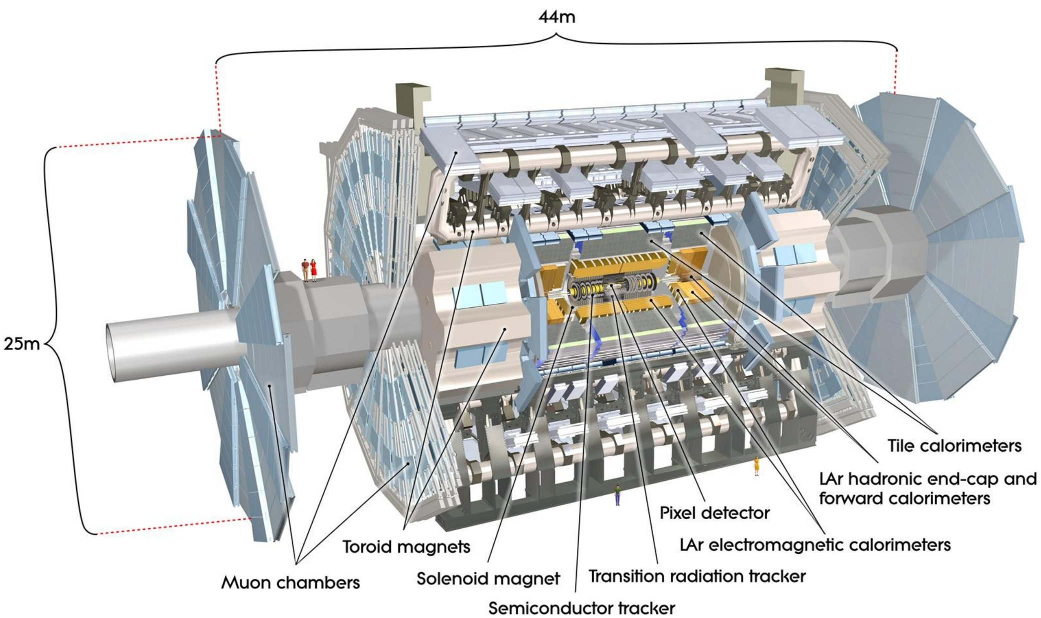


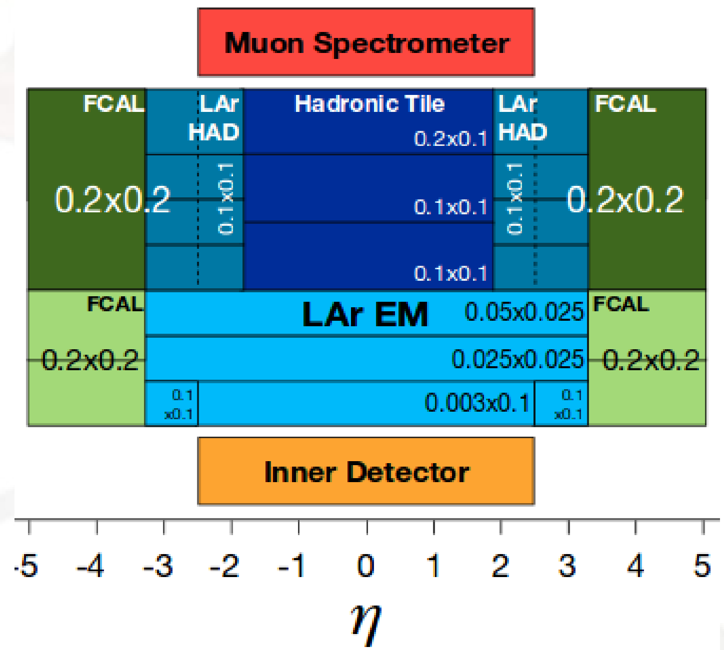
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

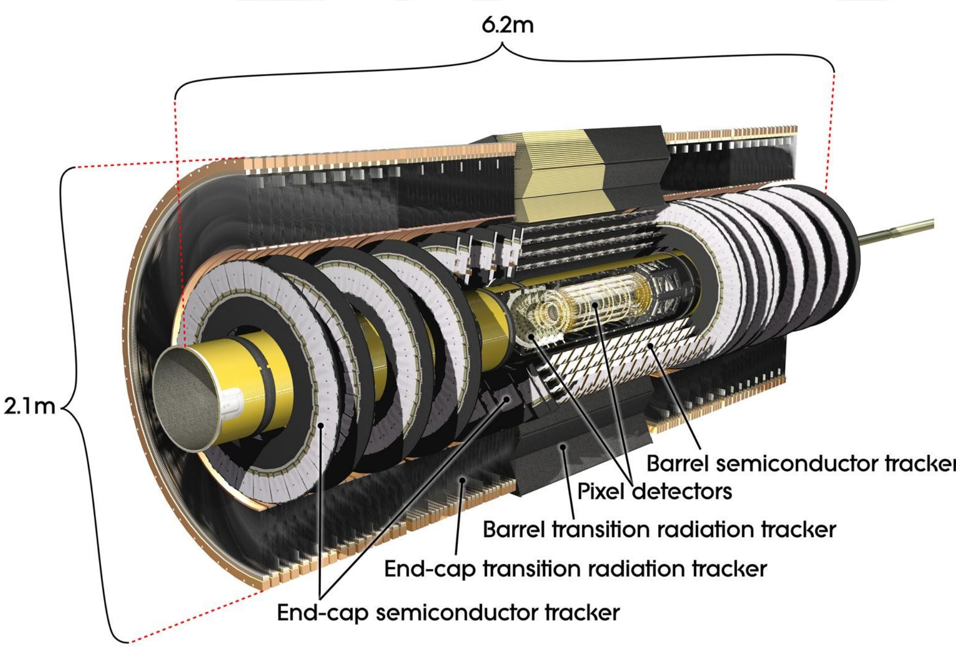
$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$$

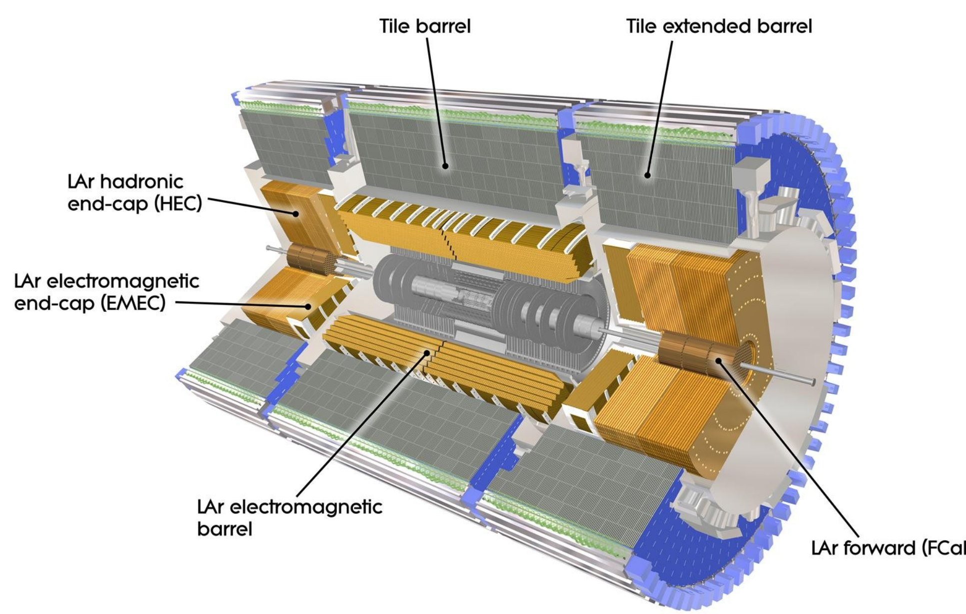
$$\frac{dN}{d\varphi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n\left(\varphi - \Phi_n\right)\right)\right]$$

The ATLAS detector

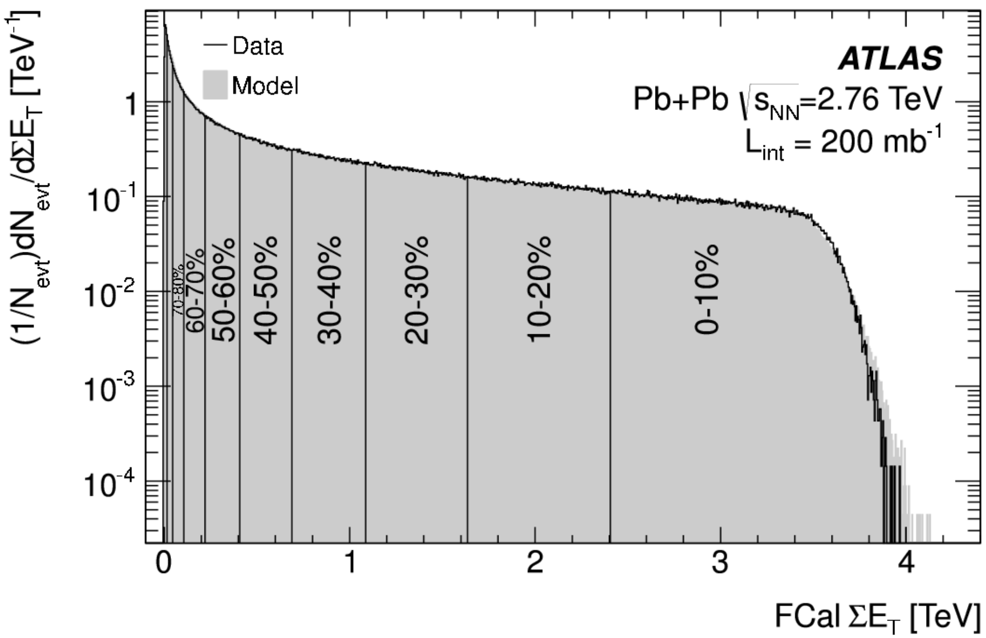


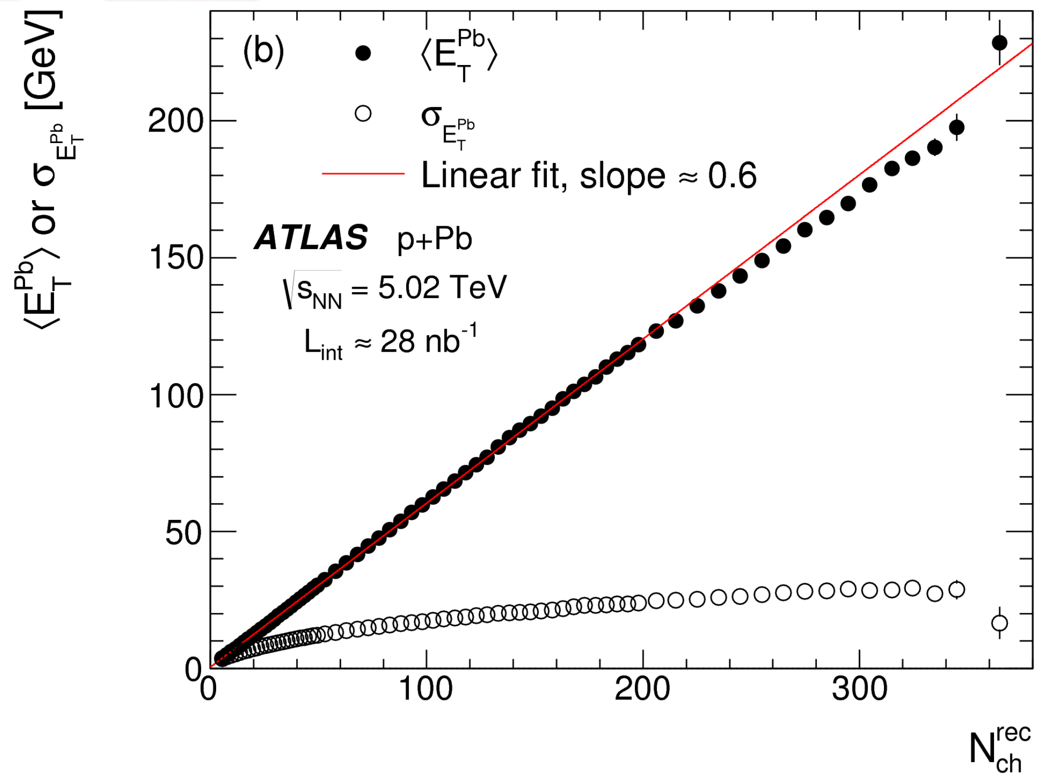






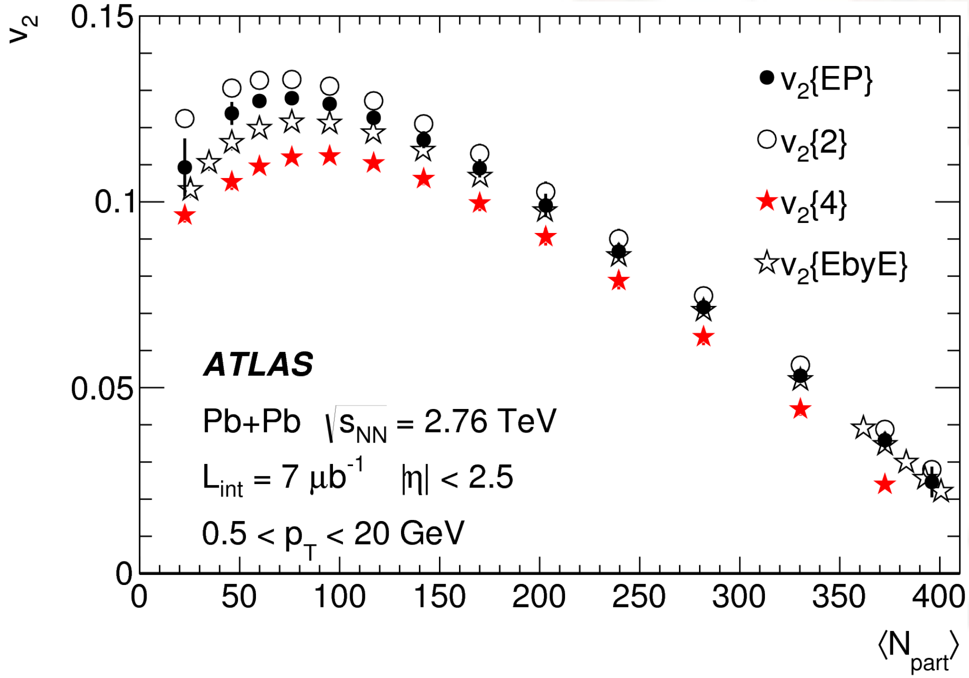
Centrality in Pb+Pb and p+Pb





- Measured with the forward calorimeter(s)
  In p+Pb, on Pb-going side only – good correlation with N_{ch}
- For Pb+Pb usual Glauber MC for geometry

Flow harmonics vn from different methods



- Comparison of $v_n\{2,4\}$ with $v_n\{EP\}$ and $v_n\{EbyE\}$ (mean of $p(v_n)$ distribution)
- $v_n\{2\}$ > $v_n\{EP\}$ > $v_n\{EbyE\}$ > $v_n\{4\}$
- Difference between $v_n\{2\}$ and $v_n\{4\}$ more pronounced for n = 3,4

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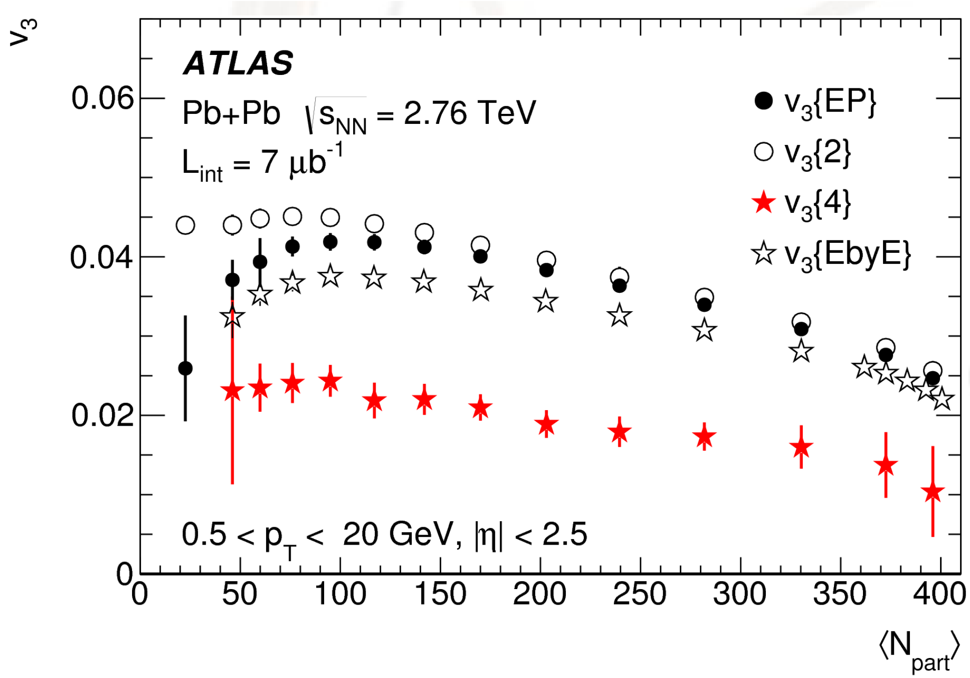

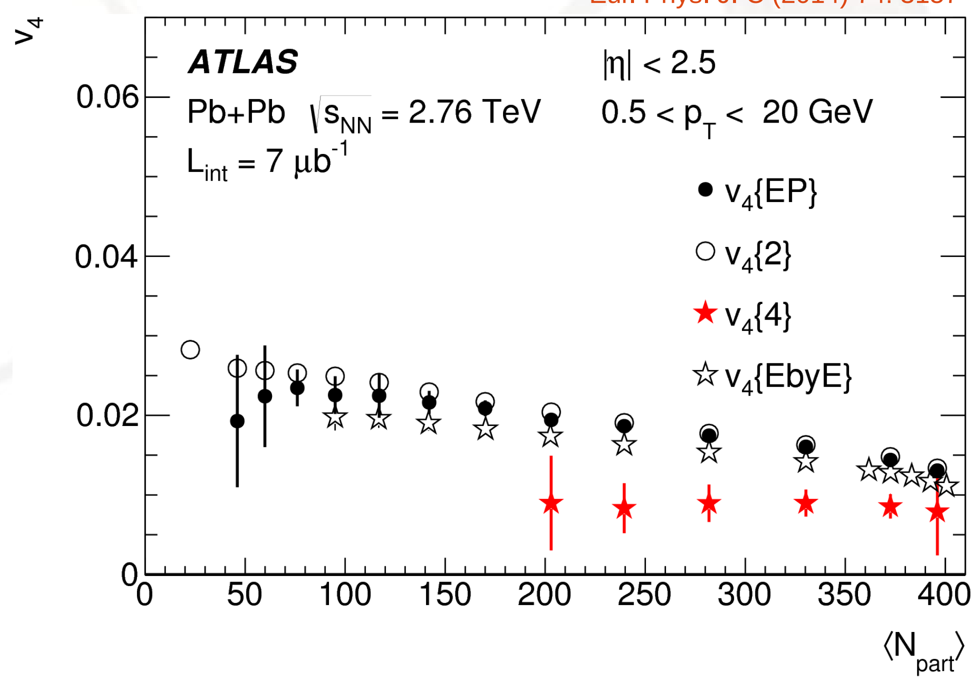

Flow harmonics vn from different methods

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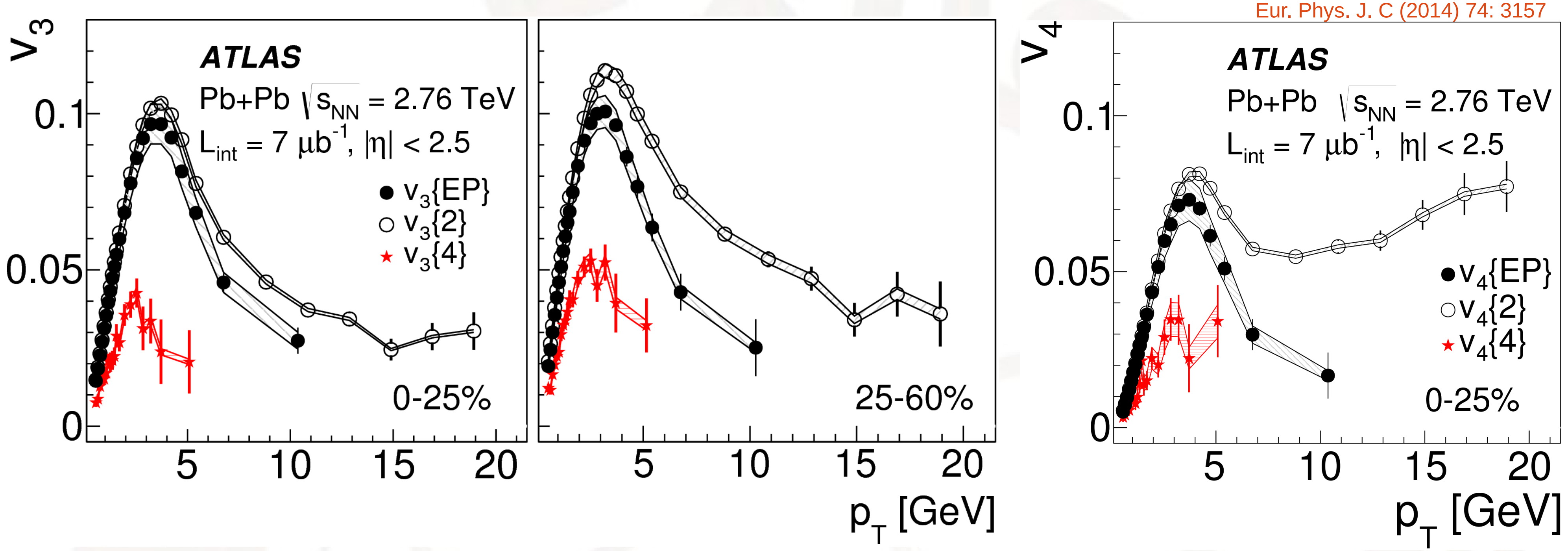
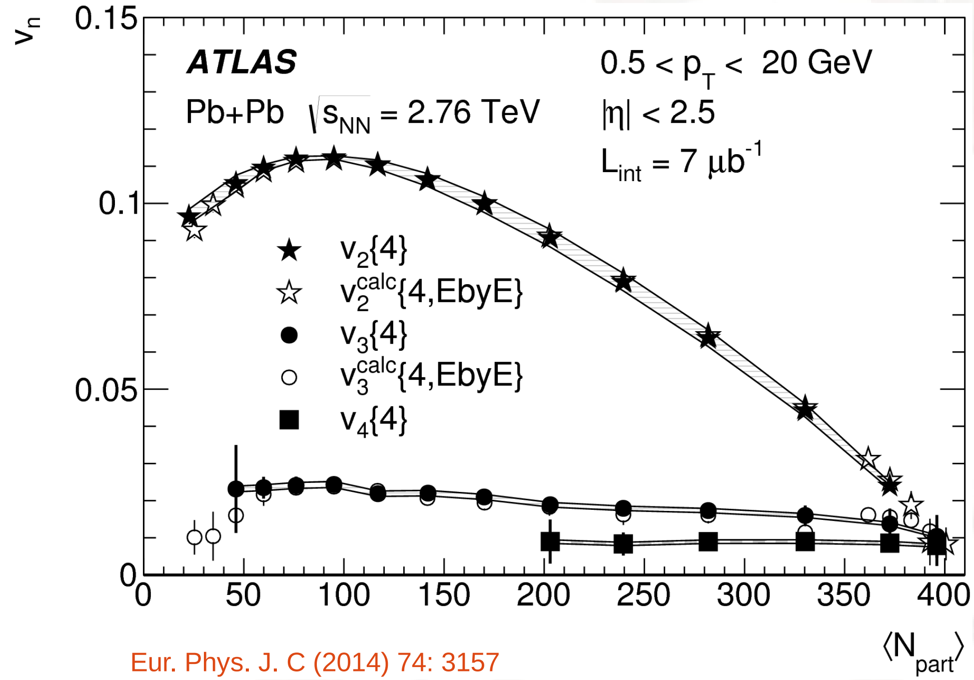


- Significant values of $v_3\{4\}$ and $v_4\{4\}$ calculated
- Strong reduction of v_n by using more than 2 particle correlation
- $v_{3,4}\{4\} < v_{3,4}\{2\}$ - expected from fluctuations and suppression of non-flow effects

Cumulants vs event-by-event v_n



- Cumulants of $p(v_n)$ distributions ($v_n^{calc}\{EbyE\}$) are in excellent agreement with directly measured cumulants
- Residual differences between $v_n\{4\}$, $v_n\{6\}$ an $v_n\{8\}$ – reproduced by EbyE cumulants

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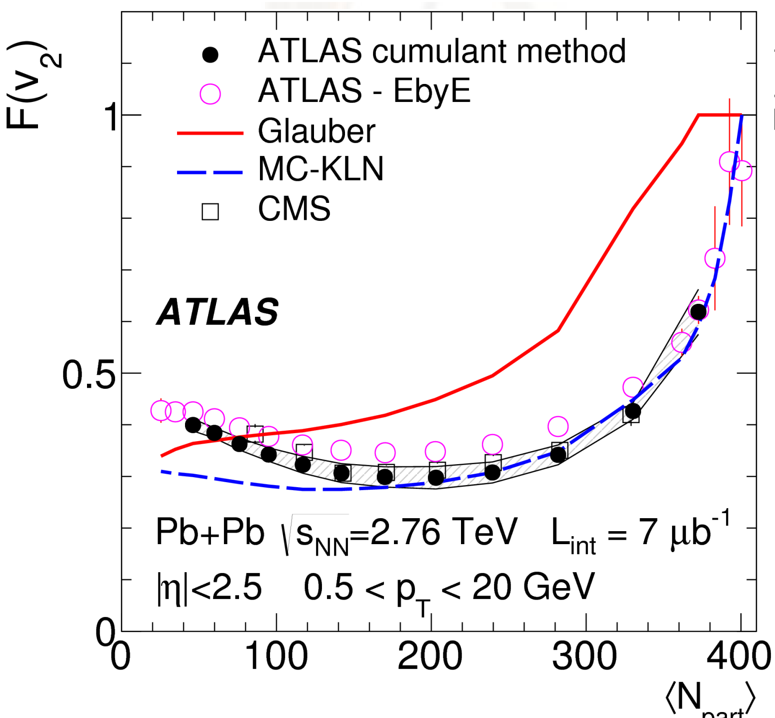
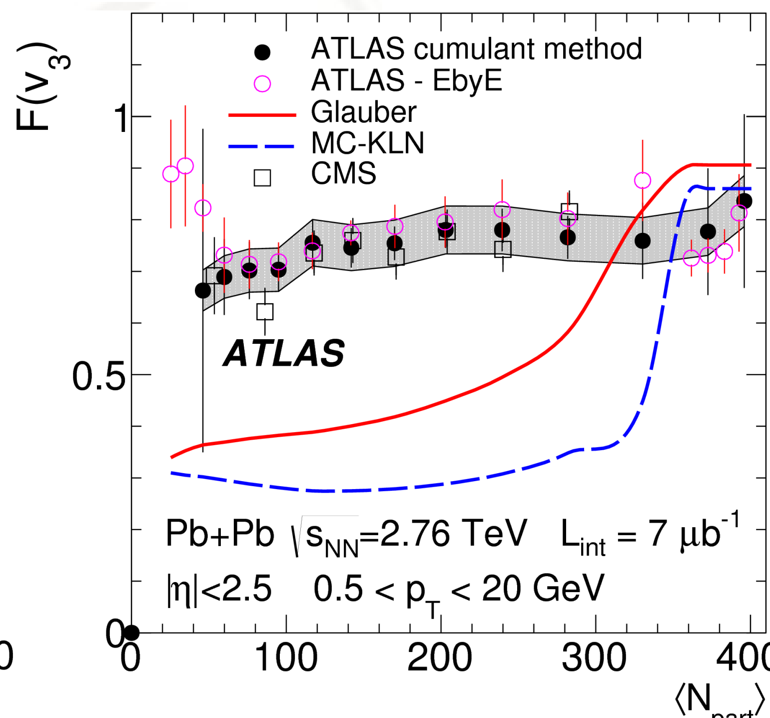




$$F(v_n) = \sqrt{\frac{v_n\{2\}^2 - v_n\{4\}^2}{v_n\{2\}^2 + v_n\{4\}^2}}$$

$$F(v_n) = \sqrt{\frac{v_n\{EP\}^2 - v_n\{4\}^2}{v_n\{EP\}^2 + v_n\{4\}^2}}$$

Event plane correlations

- Measure event plane angles, Φn , event-by-event using ATLAS calorimeter (also with ID tracks in midrapidity)

- Evaluate: $\langle \cos(c_1 \Phi_1 + 2c_2 \Phi_2 + \ldots + l c_l \Phi_l) \rangle$

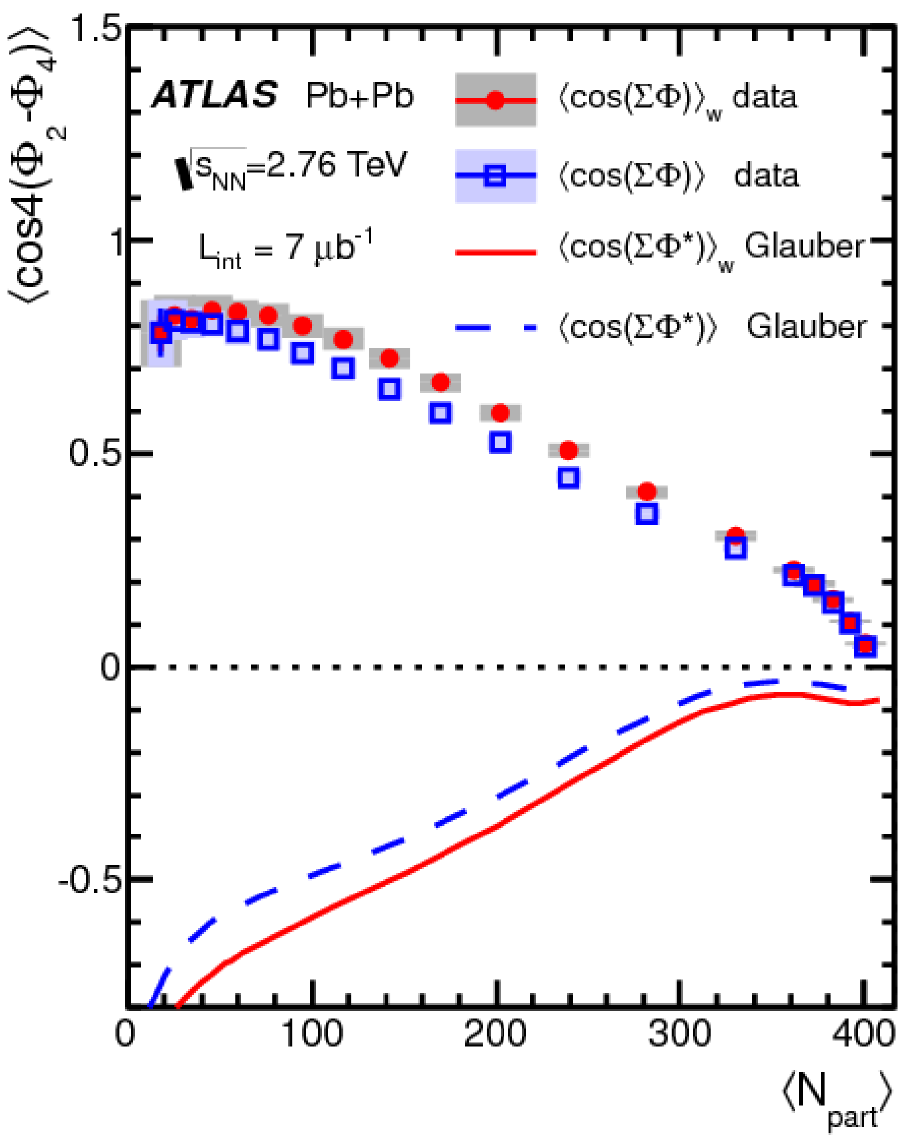
  with $c_1 + 2c_2 + \ldots + lc_l = 0$

- Measurement performed with two methods; standard event plane and scalar product (EP weighted by the magnitude of the event q-vector)

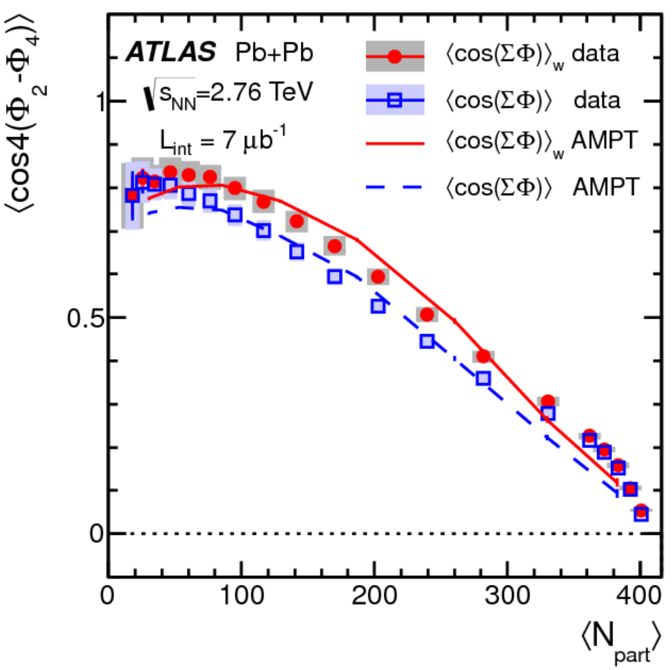
- Flow response is linear for v_2 and v_3 i.e. $v_n \propto \varepsilon_n ; \Phi_n \approx \Psi_n$

  and higher-order flow arises from EP correlations

Event plane correlations

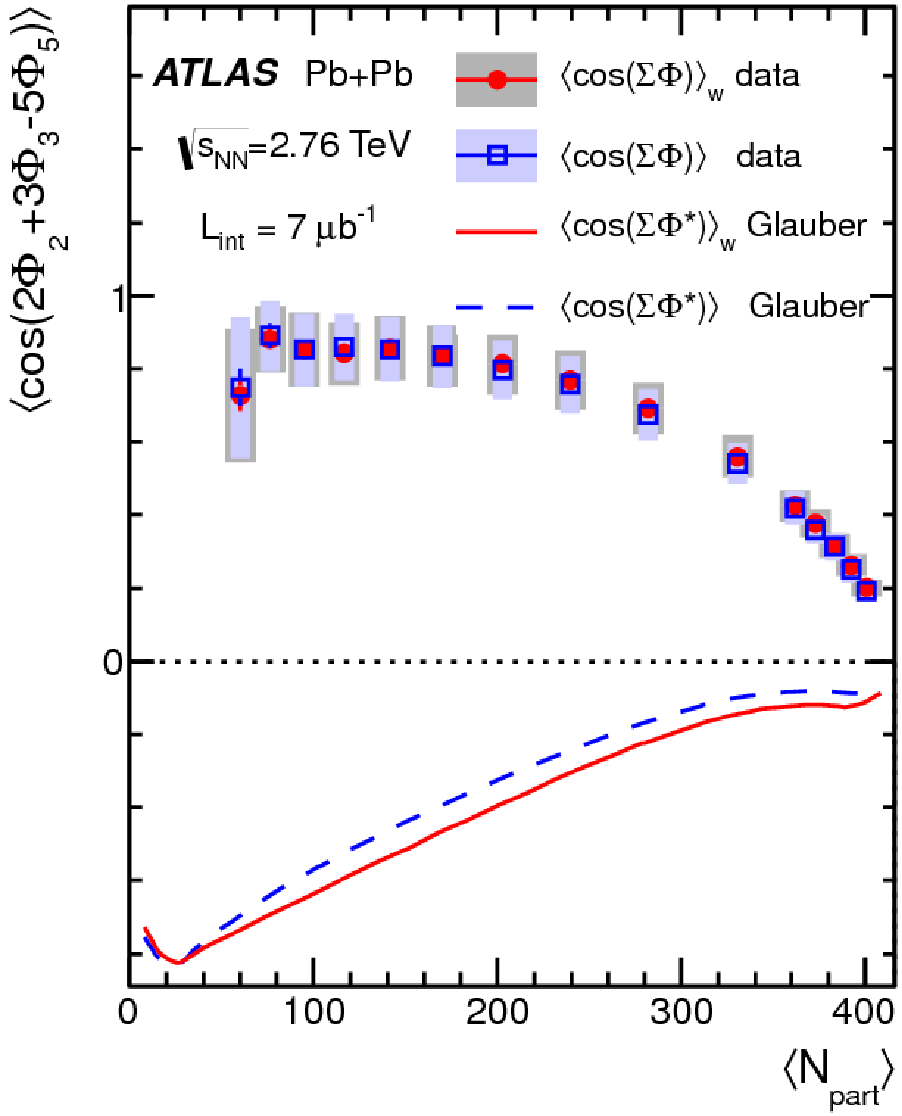


Phys. Rev. C 90, 024905 (2014)



- Results for all 2, 3-plane correlations agree poorly with Glauber, well with AMPT

Event plane correlations



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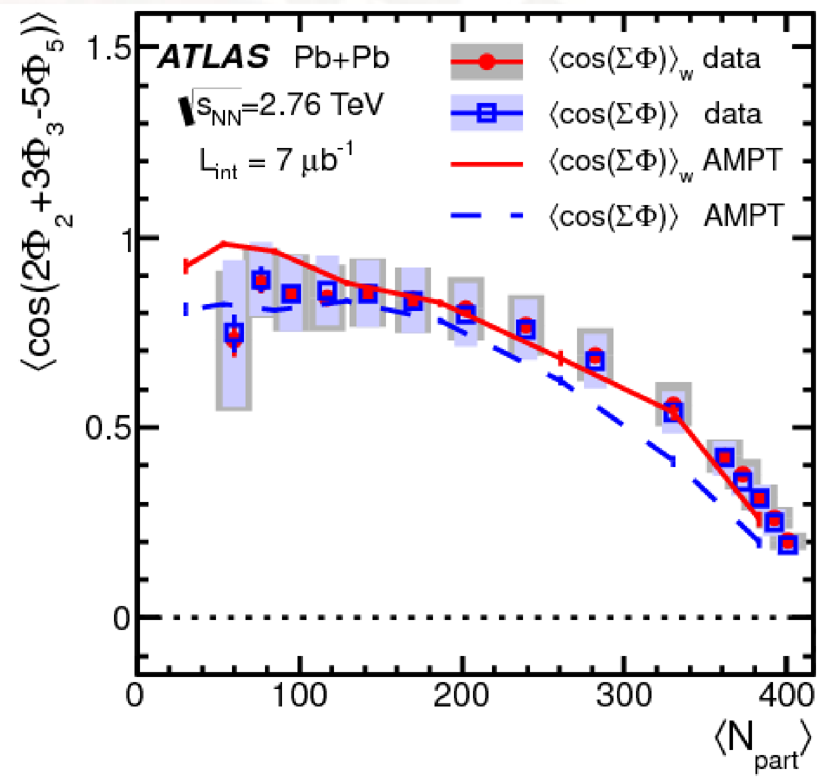

- Results for all 2, 3-plane correlations agree poorly with Glauber, well with AMPT

Event shape selection

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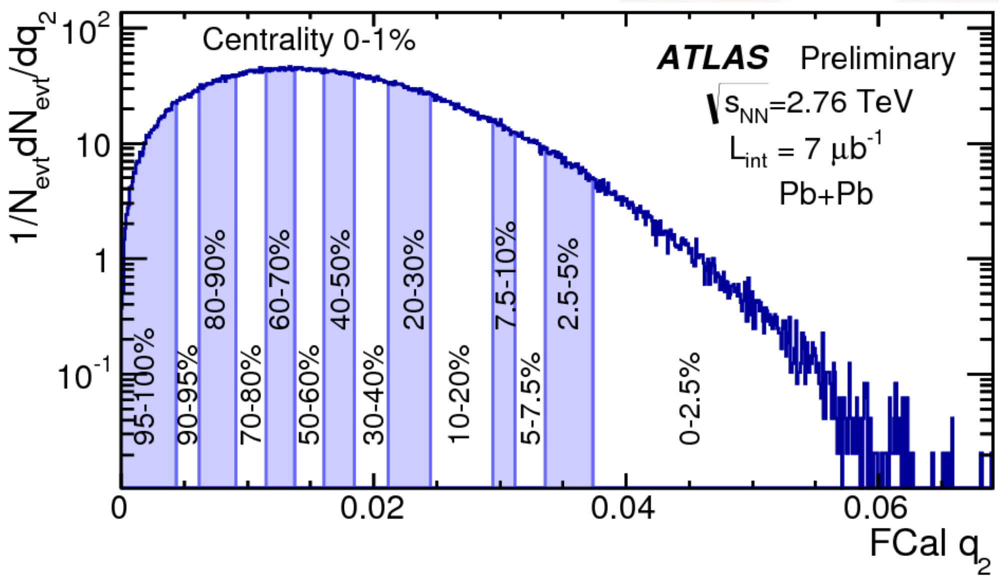
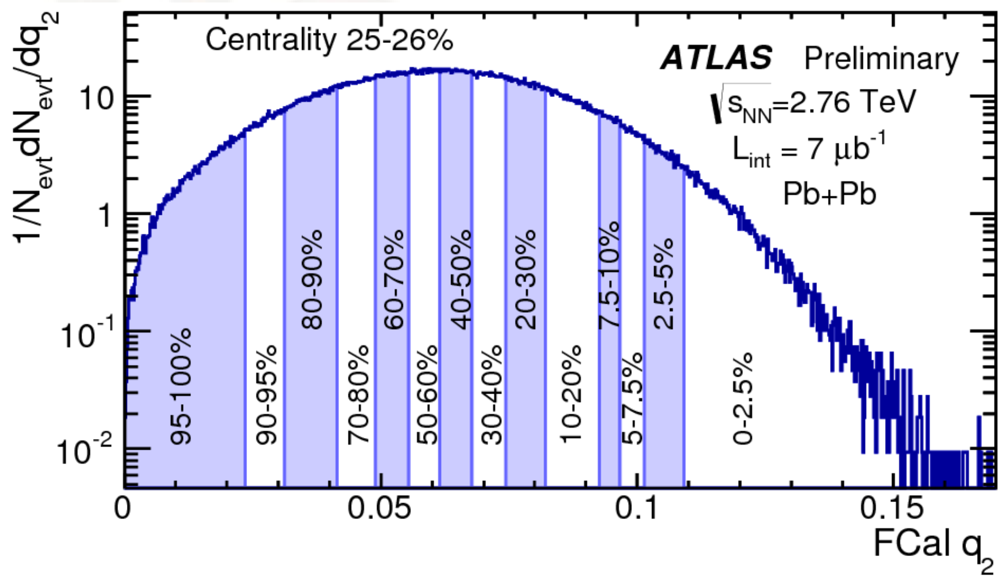
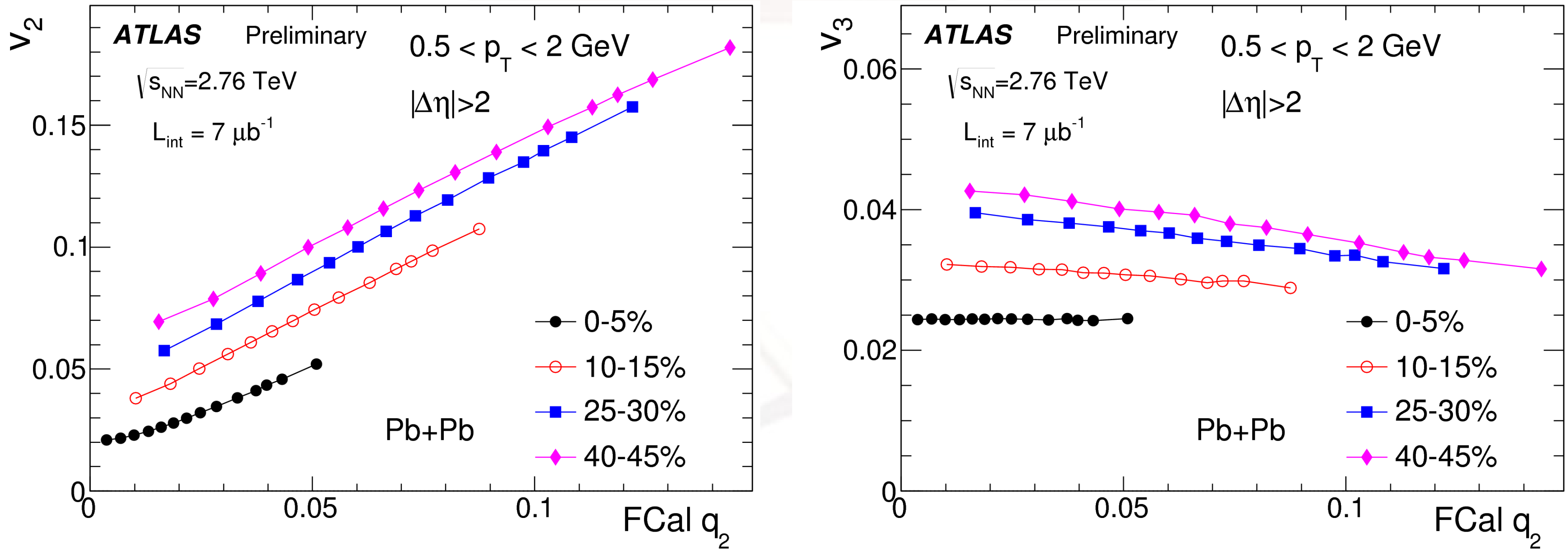




- Fix initial geometry via centrality, select events according to elliptic flow vector magnitude (q_2 – measured in FCal)
- Study two-particle correlations in $|\eta|< 2.5$

Event shape selection

ATLAS-CONF-2014-022



- Change in ellipticity by a factor of 3
- Triangular flow almost independent on the q_2 selection

Event shape selection

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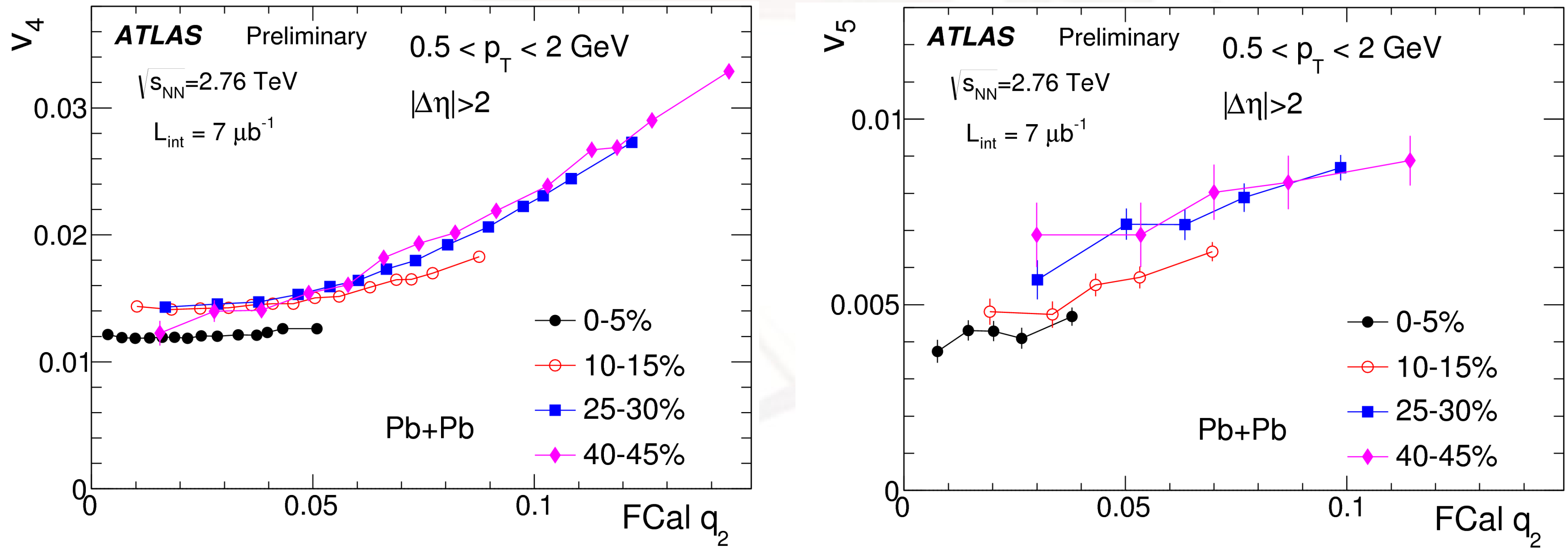

- Clear nonlinear dependence of v_4

v_n-v_2 correlation: q_2 bins

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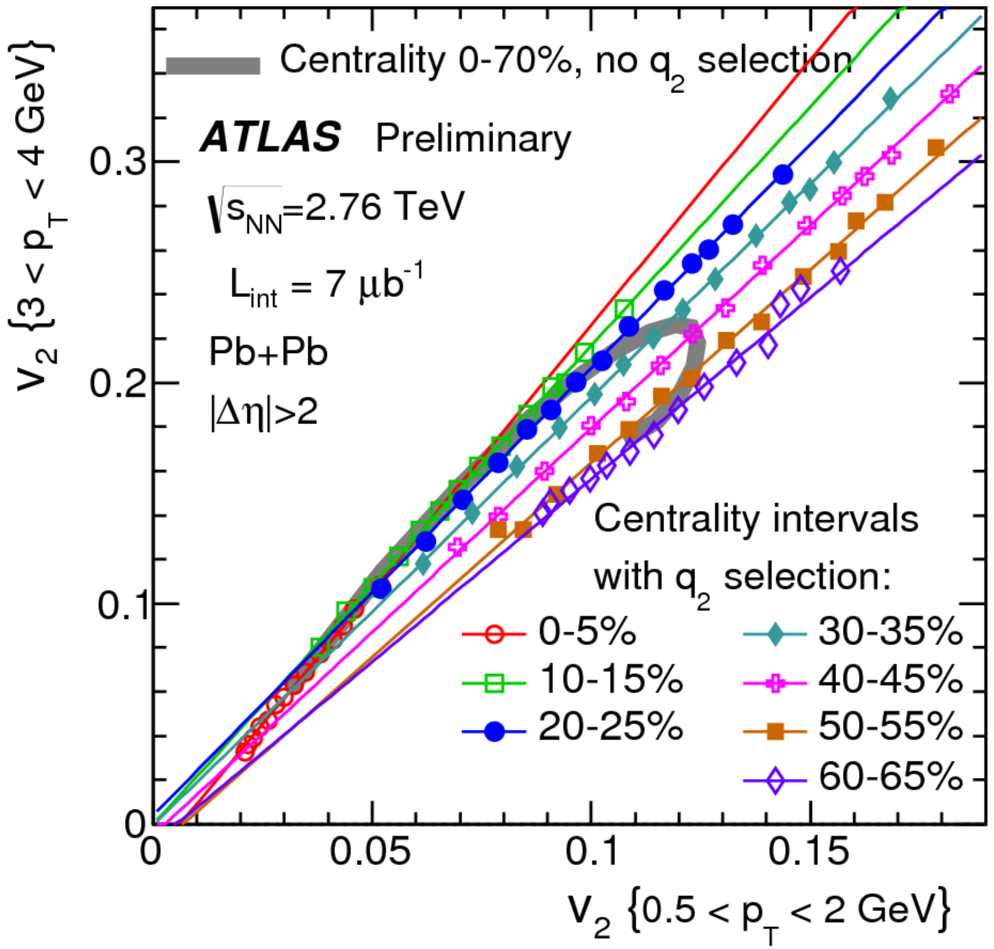

- Linear correlation for forward selected v_2
- Viscous damping controlled by the system size not shape

- Correlation between v_2 in different p_T ranges
- For higher orders v_n-v_2 correlation in the same p_T windows

v_n-v_2 correlation: q_2 bins

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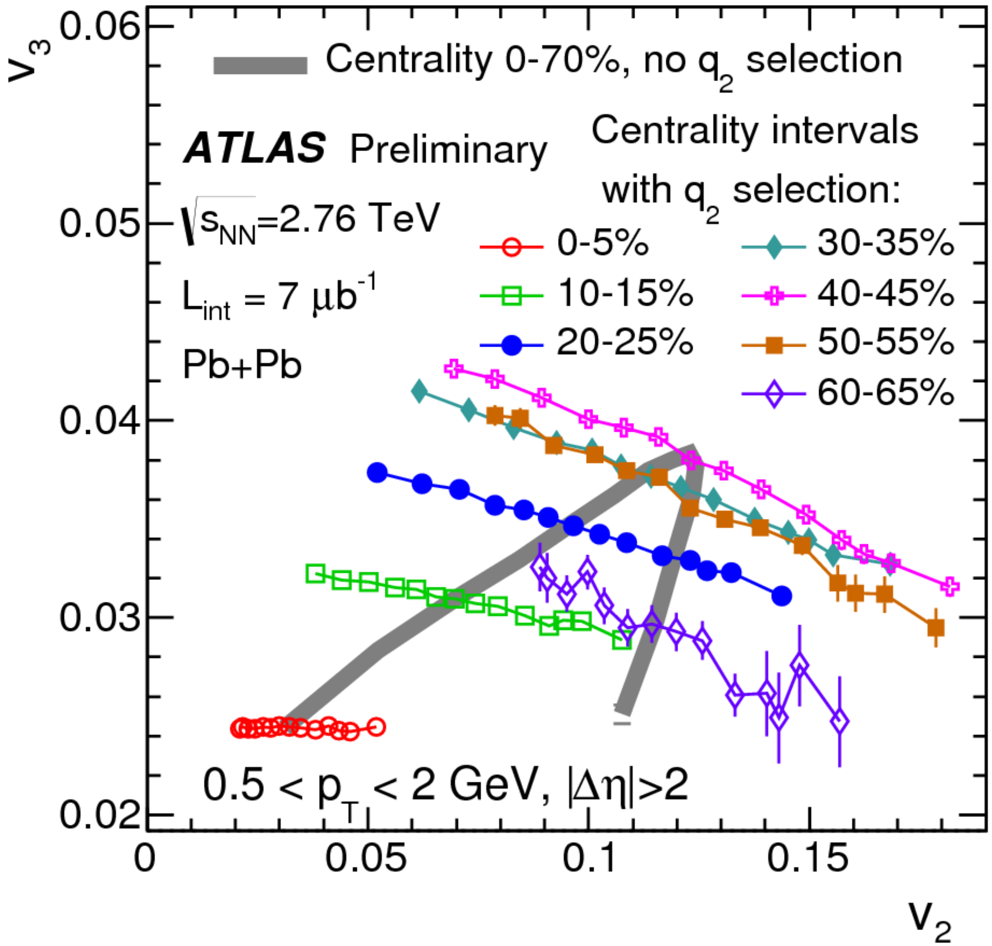

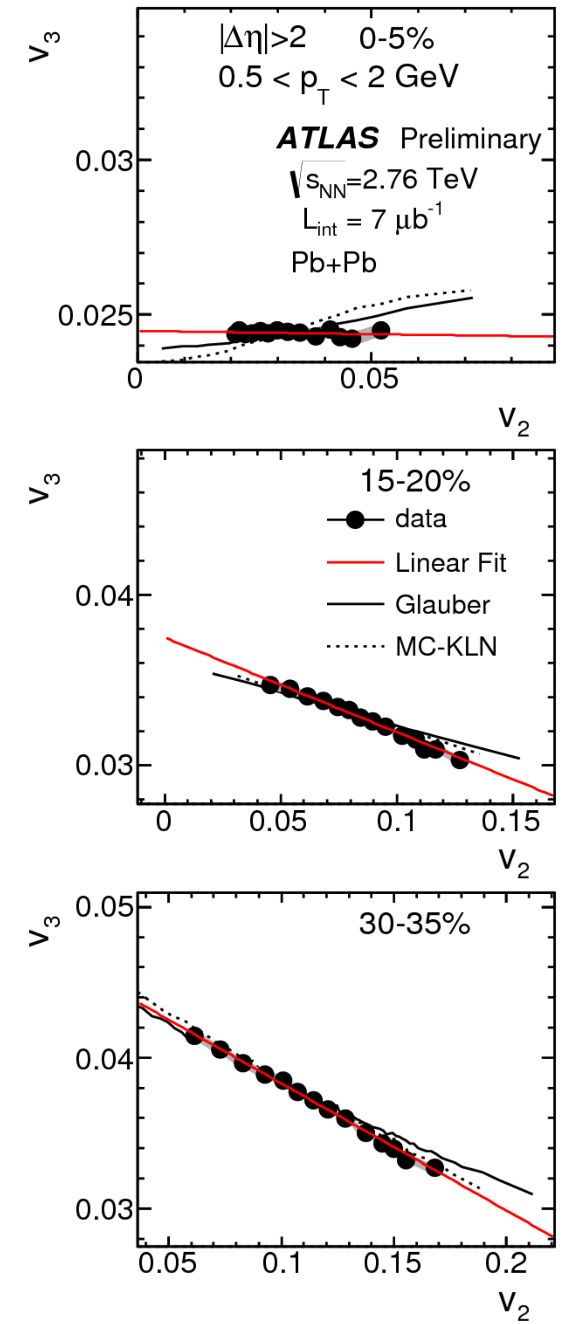

- Anti-correlation between v_2 and v_3 at fixed centrality
- Compare correlations to ε_3-ε_2 correlations calculated in Glauber & CGC models
- Good agreement in most centralities but some deviation in (0-5)% central events

v_n-v_2 correlation: q_2 bins

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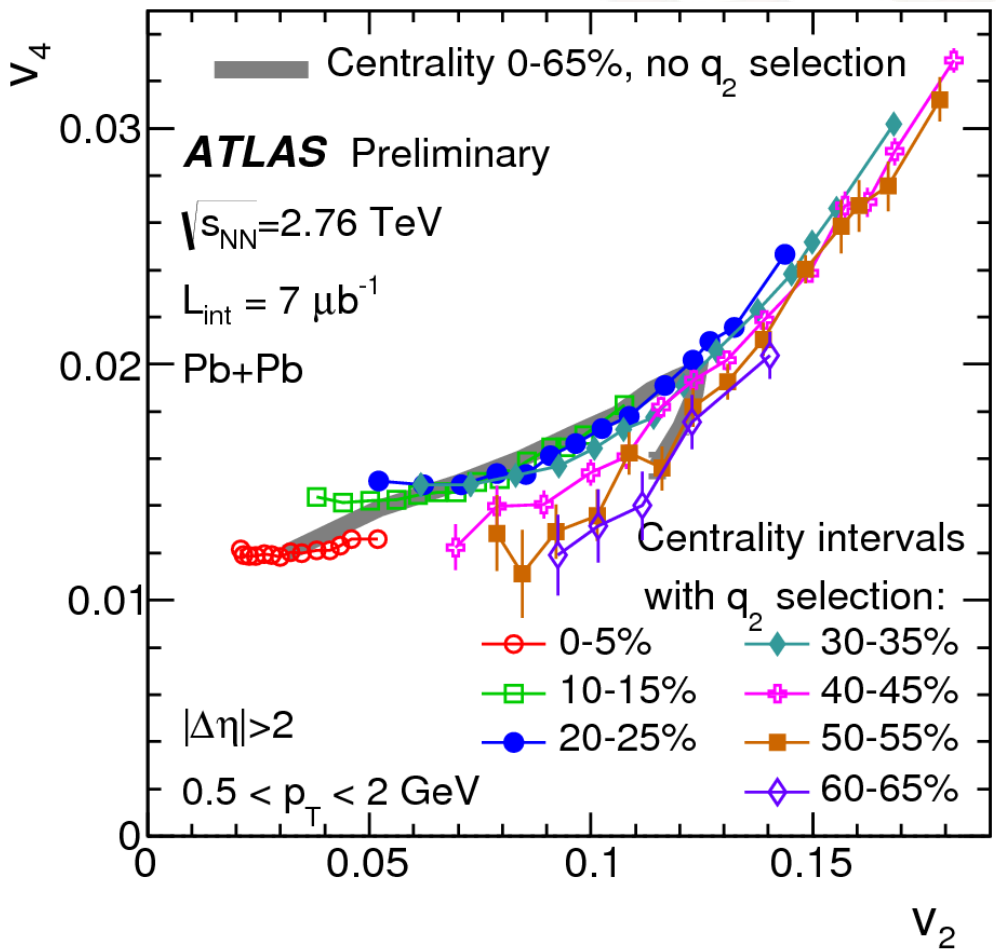
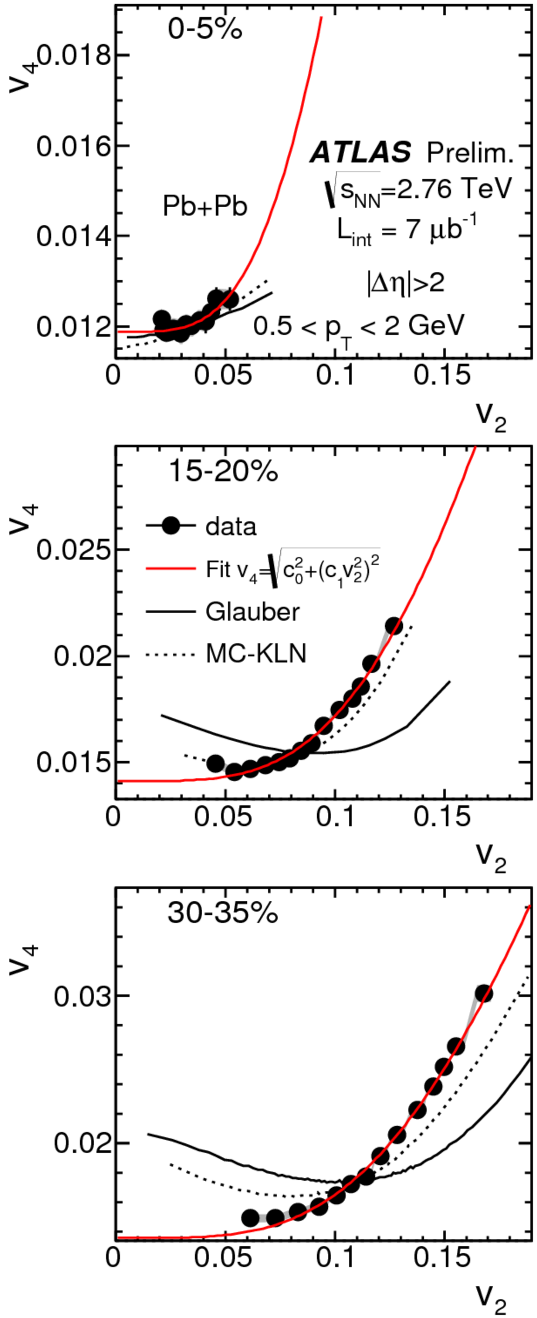


Fit to:

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



- Clear non-linear correlations seen in v_4-v_2 case: upward bending of v_4 at large v_2
- Parameterize v_4 into two components, one that is correlated to v_2 and one that is independent

Linear and nonlinear components

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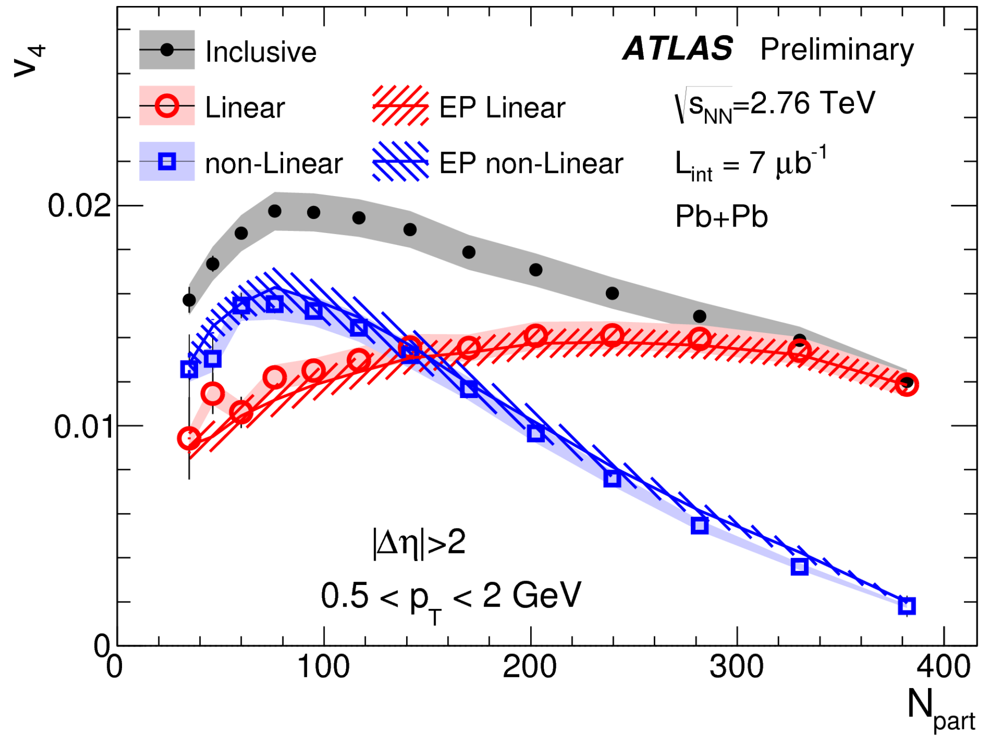
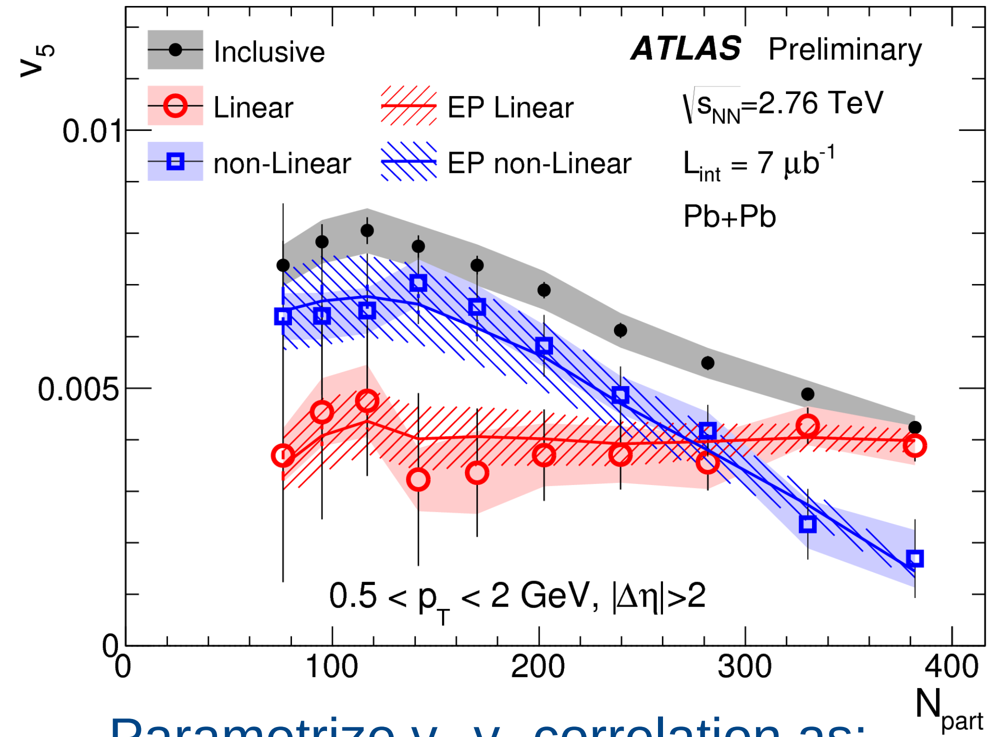




Parametrize v_5-v_2 correlation as:

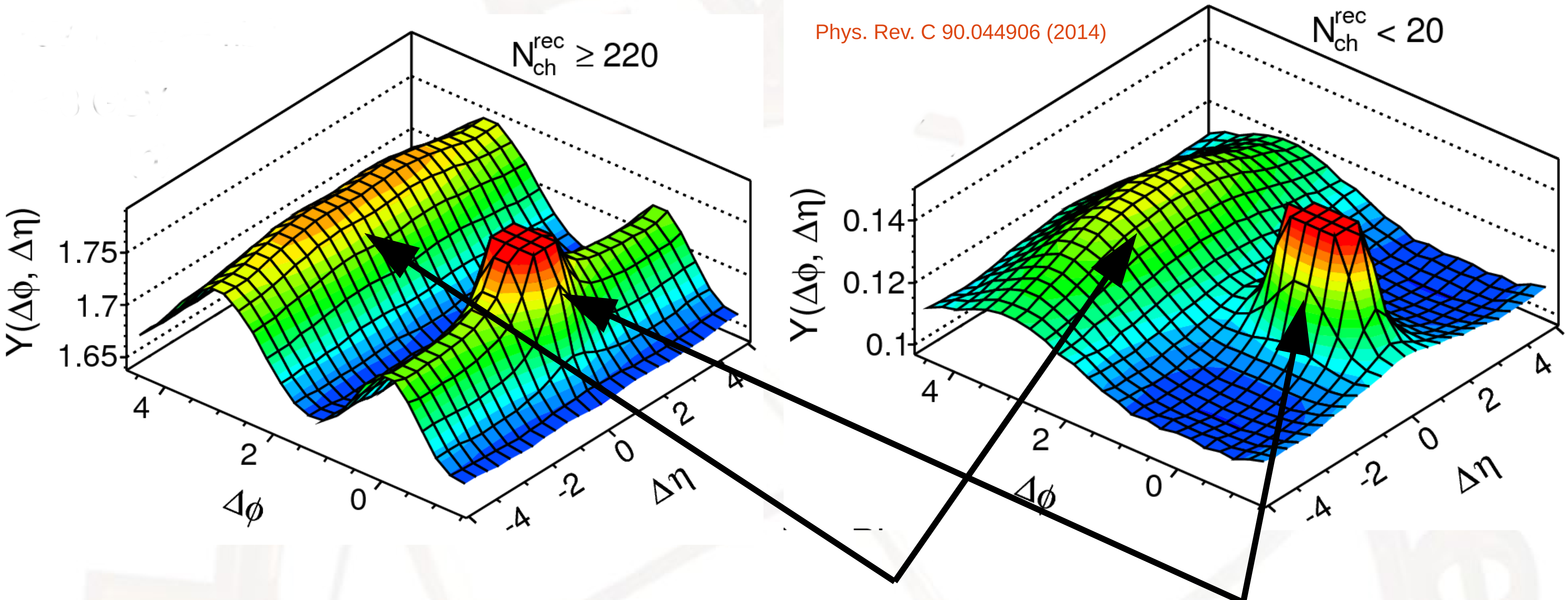
$$v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2}$$

- Linear and non-linear components vs centrality
- Compared to the event plane correlation result:

$$v_4^{NL} = v_4 \langle \cos 4(\Phi_2 - \Phi_4) \rangle \qquad v_5^{NL} = v_5 \langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$$

$$v_4^{L} = \sqrt{v_4^2 - (v_4^{NL})^2} \qquad v_5^{L} = \sqrt{v_5^2 - (v_5^{NL})^2}$$

Two-particle correlation – recoil subtraction



$$Y(\Delta\phi,\Delta\eta) = Y_{Ridge}(\Delta\phi,\Delta\eta) + Y_A(\Delta\phi,\Delta\eta) + Y_N(\Delta\phi,\Delta\eta)$$

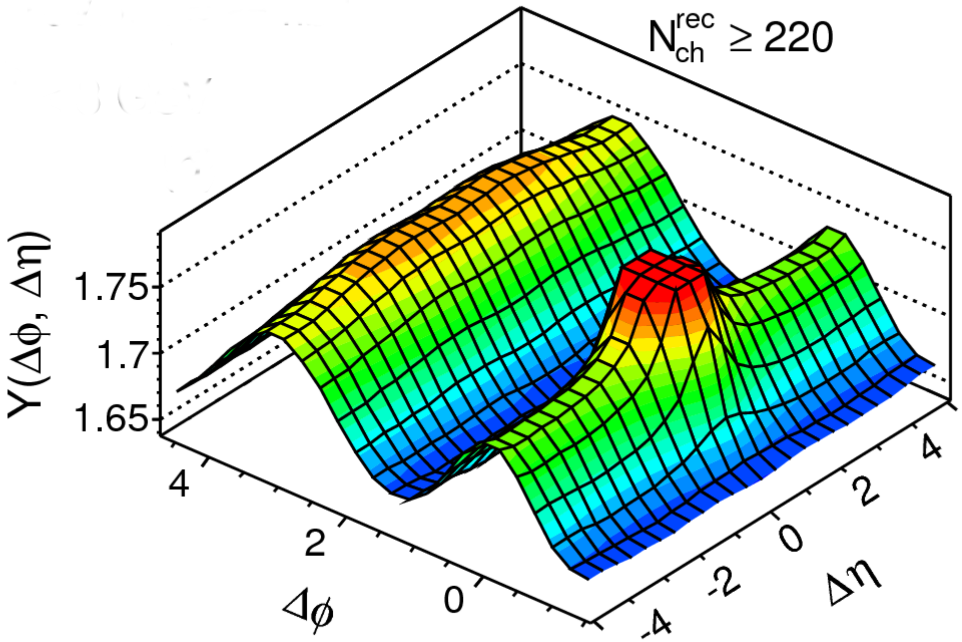
Signal of interest

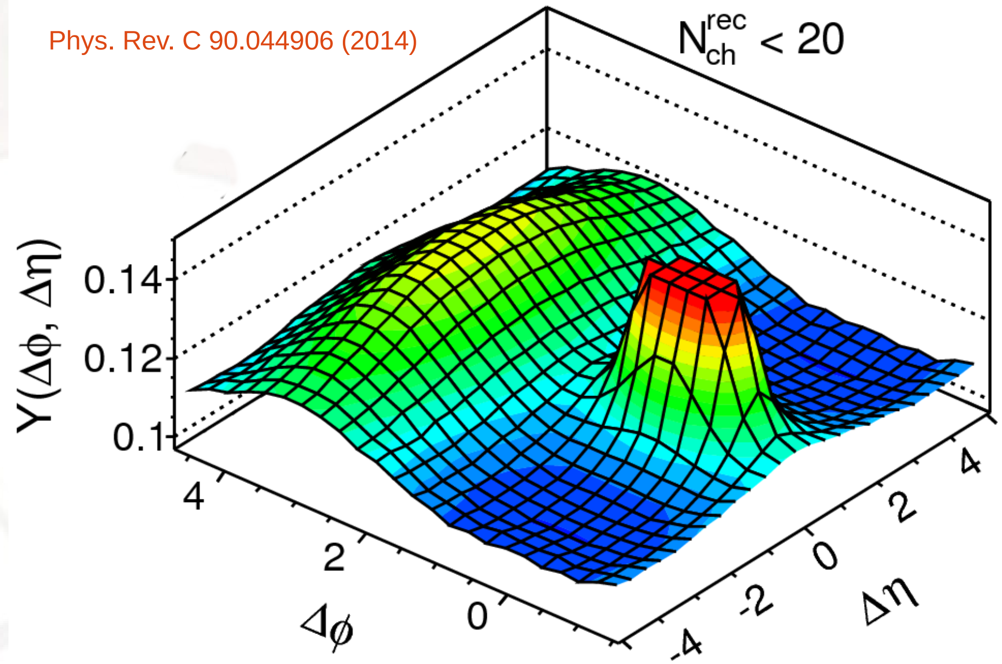
Away side recoil

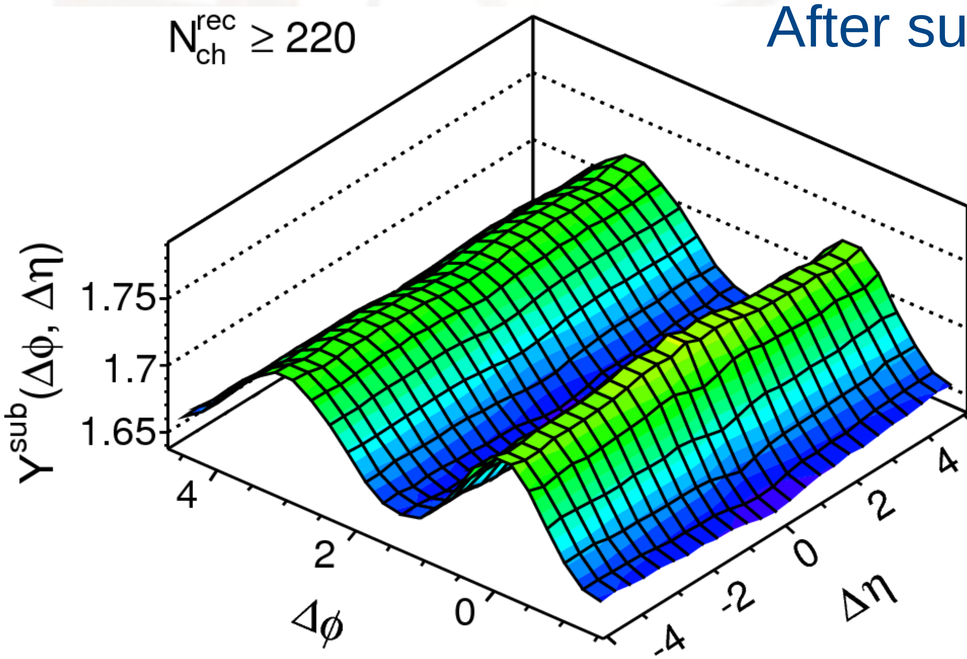
Near-side jet peak

- Jet peak & recoil in central collisions are estimated from the peripheral collisions and subtracted

Two-particle correlation – recoil subtraction







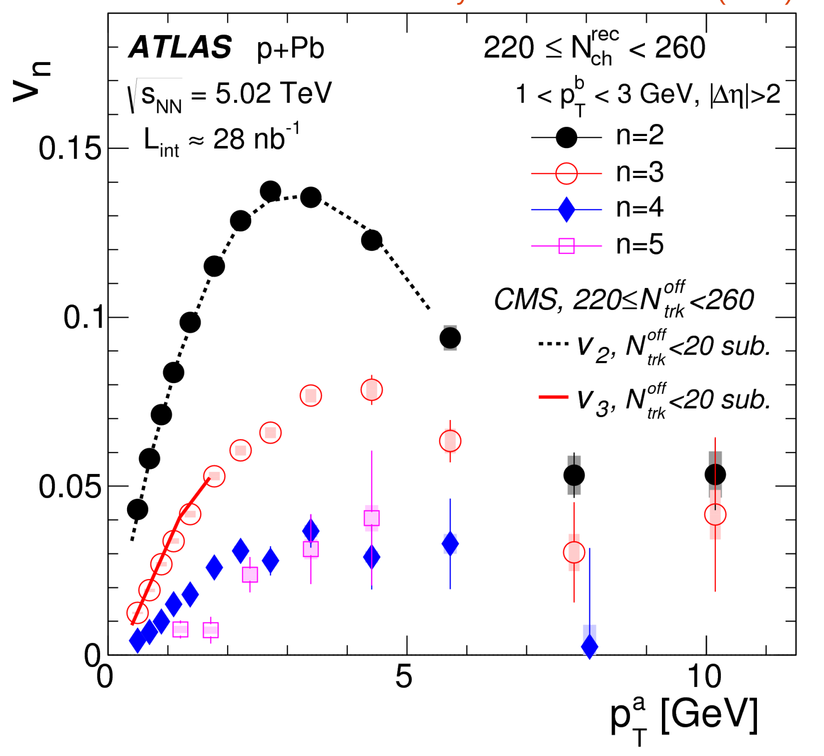
After subtraction

- Use minimum-bias + high-multiplicity trigger data for analysis

p+Pb 2-particle $v_n(p_T)$

- Significant signal for n = 2,3,4 and 5
- v_2, v_3 out to 10 GeV, remain 3-5%, small jet modifications?

Phys. Rev. C 90.044906 (2014)



p+Pb 2-particle $v_n(p_T)$

- Significant signal for n = 2,3,4 and 5
- v_2, v_3 out to 10 GeV, remain 3-5%, small jet modifications?
- v_2 show less variation for N_{ch}>150, while v_3 continue to increase

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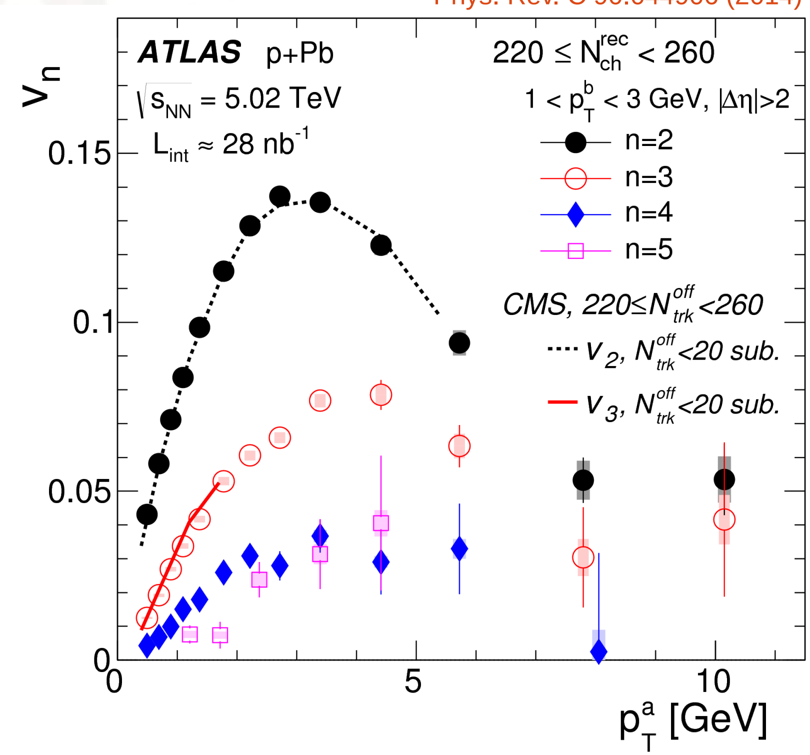
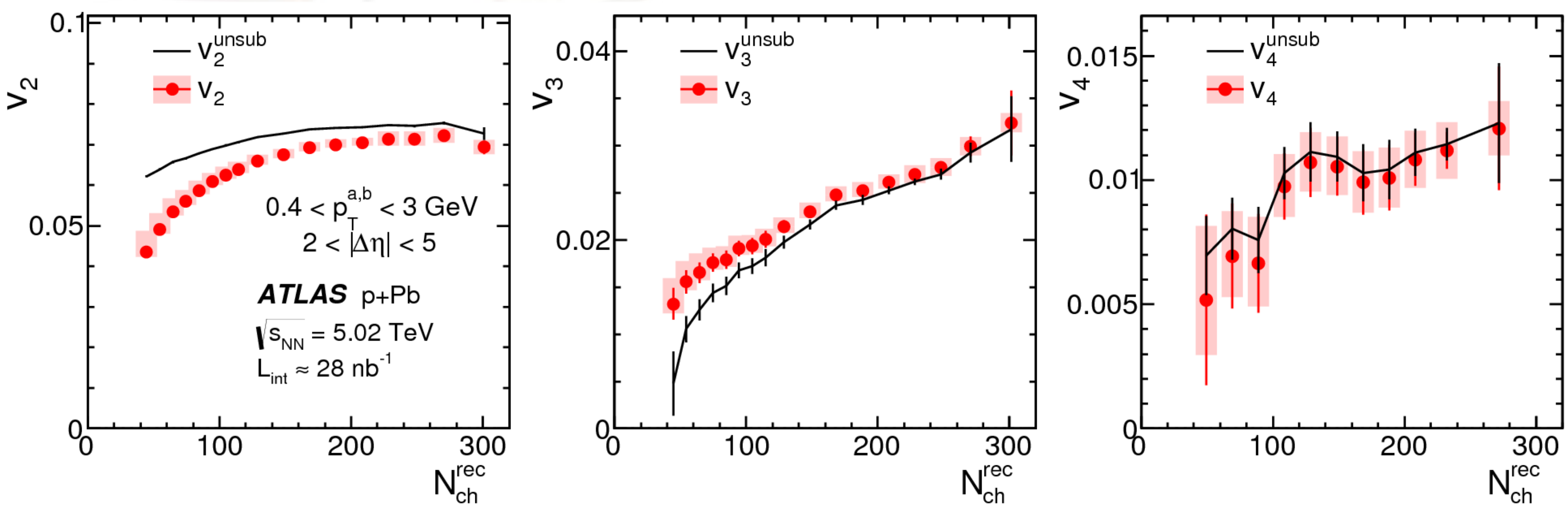
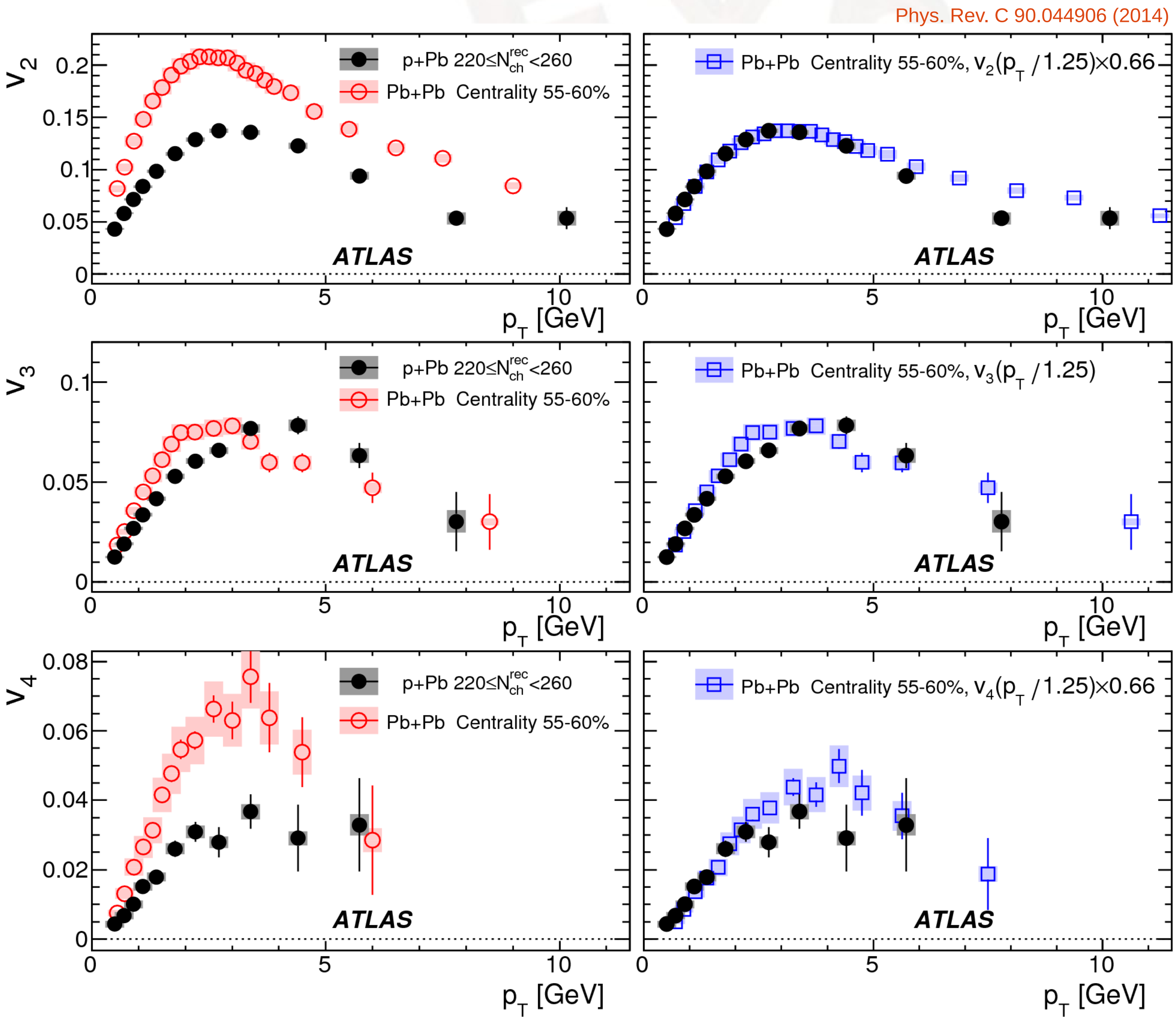


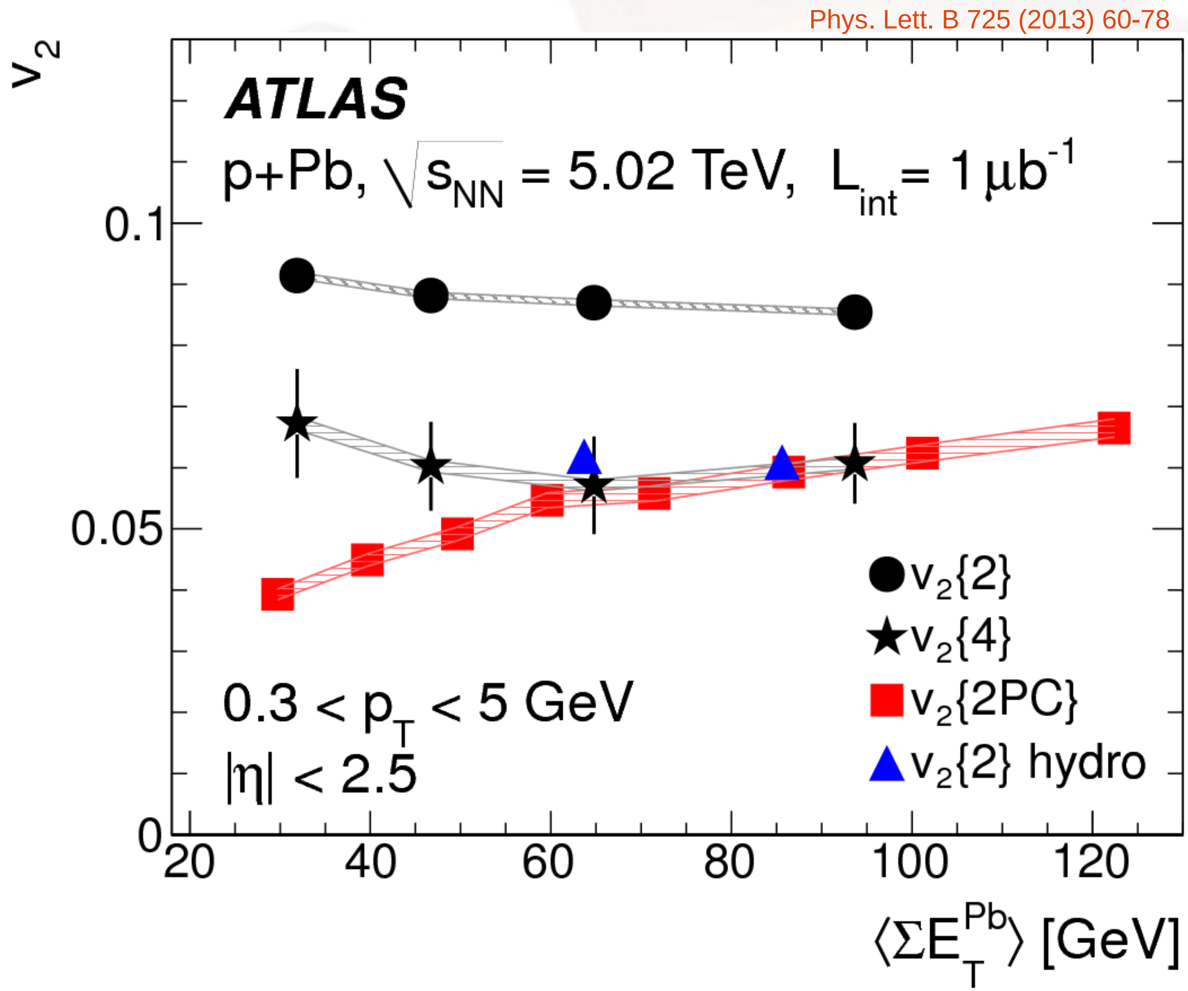


Comparison of p+Pb and Pb+Pb v_n



- Right panels adjust p+Pb p_T scale by 4/5 to account for difference in $<p_T>$
- Pb+Pb v_2 and v_4 multiplied by 0.66 to match p+Pb

Cumulant v_2 in p+Pb



- Clear sign of significant flow-like 4-particle correlations in high multiplicity (here high ΣE_T^{Pb}) p+Pb collisions

Summary

- High precision measurements on azimuthal anisotropy in Pb+Pb and p+Pb collisions were performed by ATLAS
- Very good consistency between cumulant and previous event-by-event flow measurements
- Φ_n and v_n correlations show non-linear flow effects
- Collective flow in p+Pb - long range azimuthal correlations (ridge) observed in p+Pb, confirmed with cumulants
- v_n compared between p+Pb and Pb+Pb collisions with matching multiplicity - similar shape observed, once a scaling is applied to account for the difference in mean p_T