HOT QUARKS '14

Sept. 21-28

Las Negras – Cabo de Gata Natural Park, Andalucia, Spain

Soft probes of p+Pb and Pb+Pb collisions in the ATLAS experiment at the LHC

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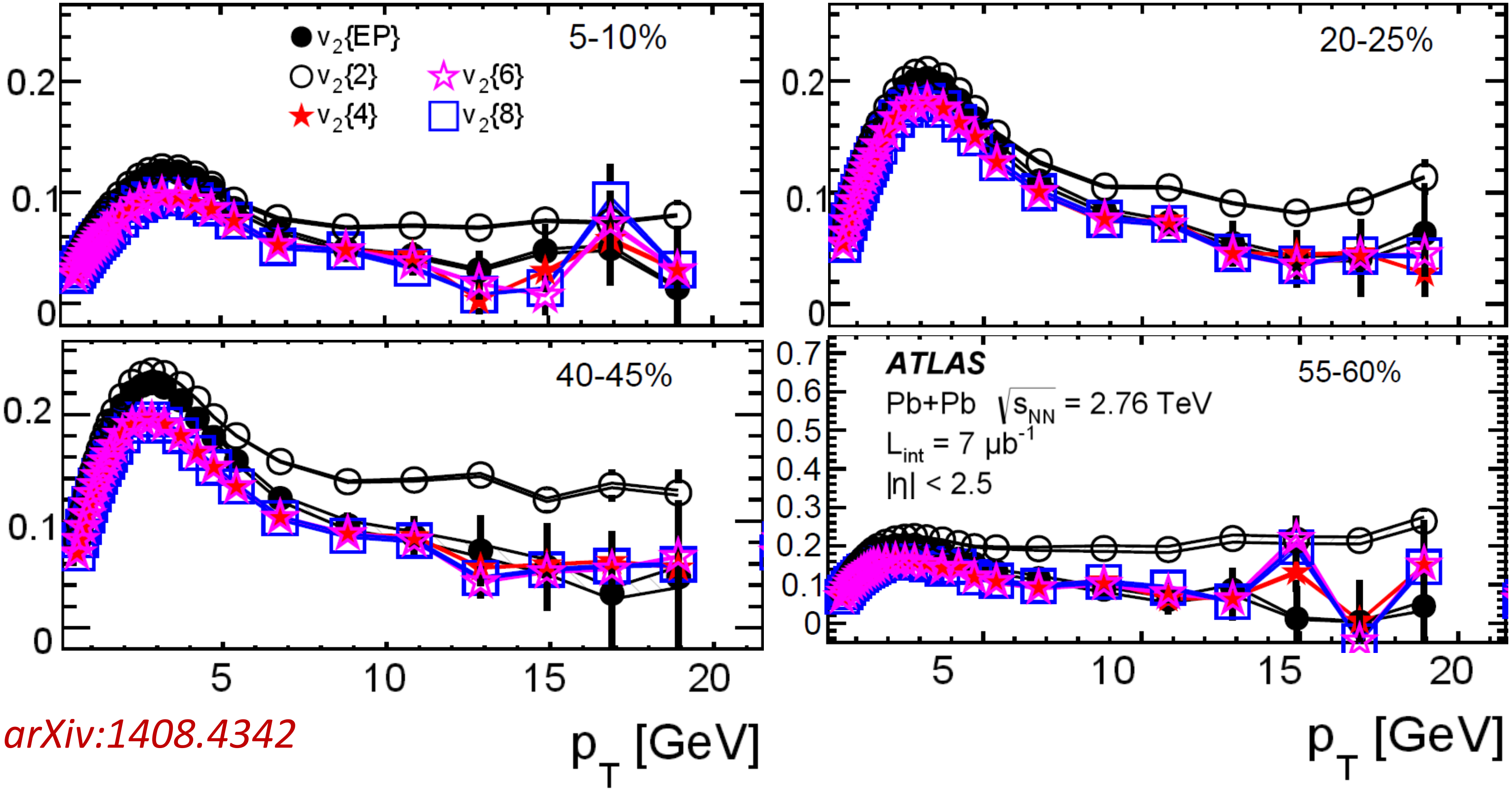
Soft probes in p+Pb and Pb+Pb collisions

- Collective flow in Pb+Pb:
  - Flow fluctuations, flow correlations, event-by-event measurements ..
  - More tools to constrain initial conditions and medium response (viscosity, equation of state, ..)

- ‘Flow’/Ridge in p+Pb:
  - Long range correlations in p+Pb: Flow in small systems?.
  - Measurement of Fourier harmonics associated with ridge to high p_T (~10 GeV)
  - First and higher order harmonics
  - Comparison of flow harmonics in p+Pb and Pb+Pb. Common origin?

Flow, correlations and fluctuations in Pb+Pb

Flow harmonics from multi-particle cumulants



arXiv:1408.4342

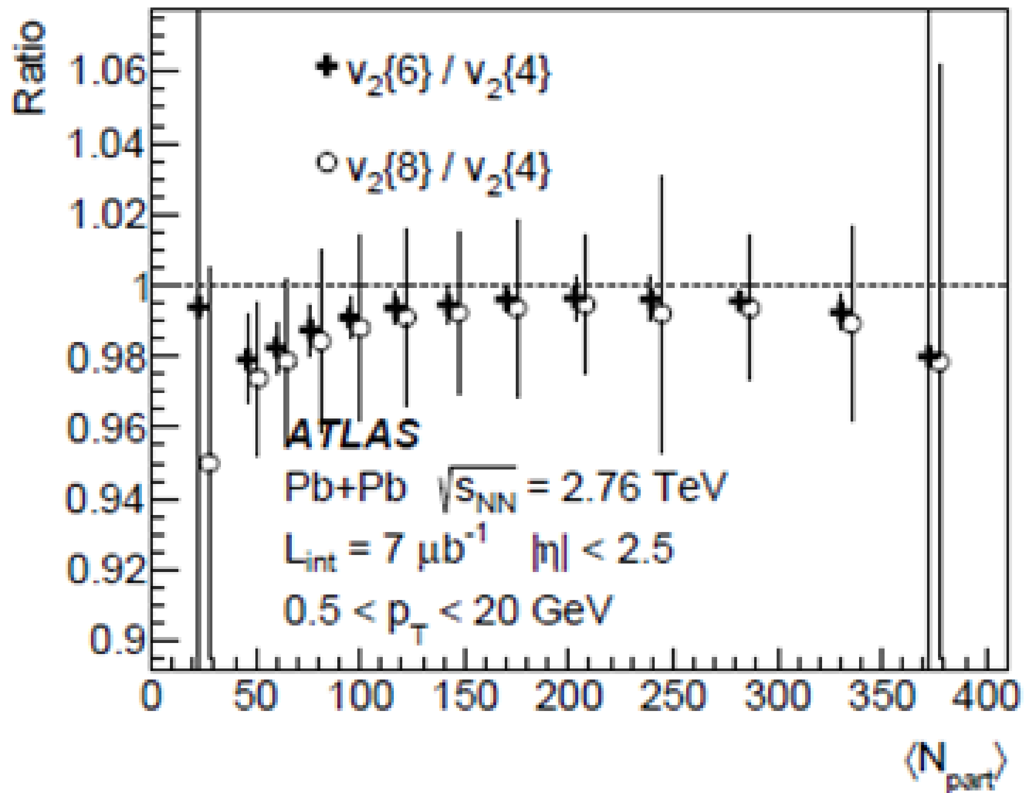
- If flow fluctuations are Gaussian,

$$p(\vec{v}_n) = \frac{1}{2\pi\delta_{v_n}{}^2} e^{-\{(\overrightarrow{\vec{v}_n - \vec{v}_n{}^{RP}})^2 / 2\delta_{v_n}{}^2\}}$$

$$v_n\{4\} = v_n\{6\} = v_n\{8\} = v_n{}^{RP}$$

- Also non-flow contributions are suppressed in v_n from higher order cumulants

Flow harmonics from multi-particle cumulants



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Ratio of higher order cumulants close to1

- If flow fluctuations are Gaussian,

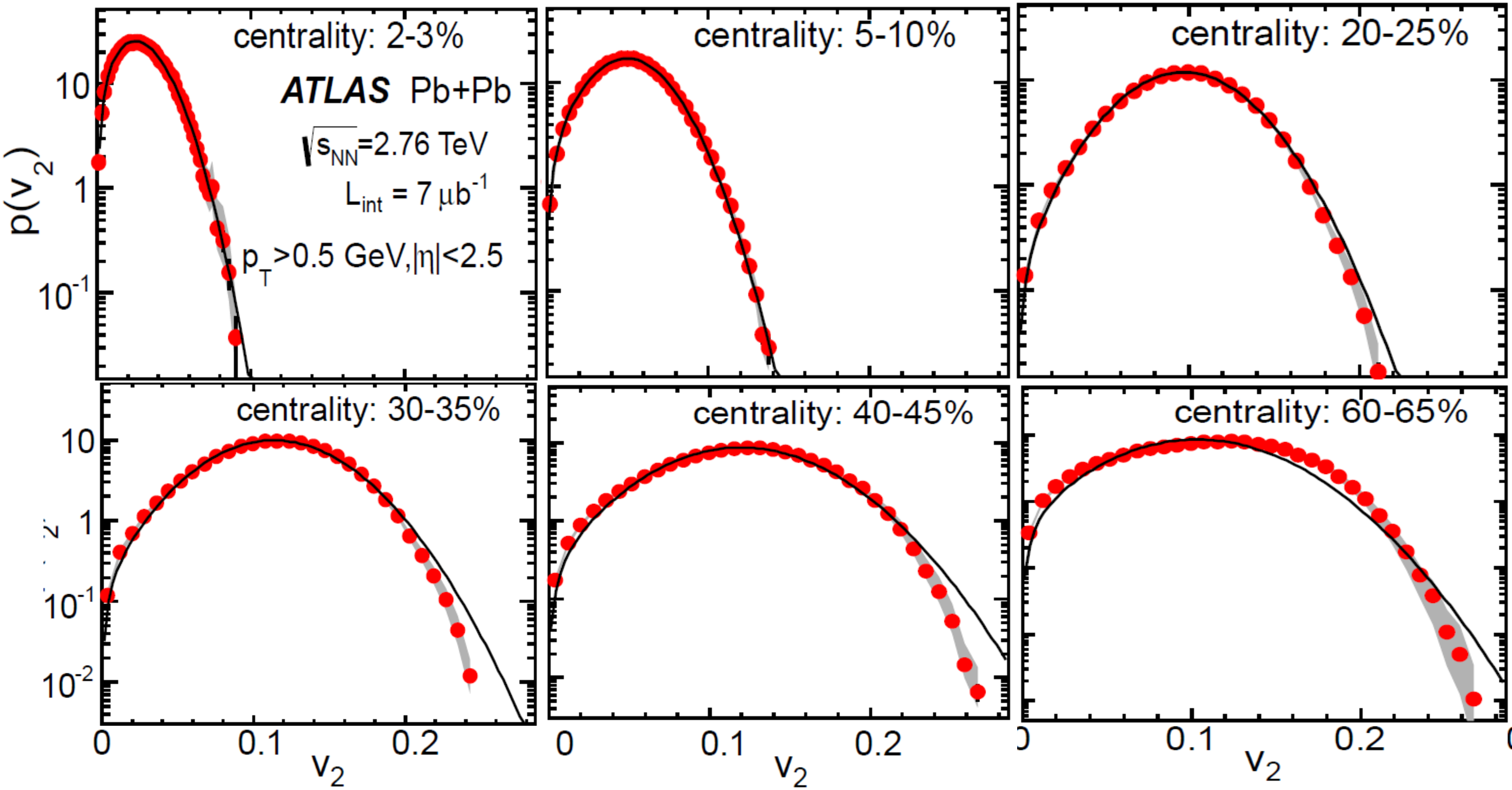
$$p(\vec{v}_n) = \frac{1}{2\pi\delta_{v_n}^{\;2}} e^{-\{(\overrightarrow{\vec{v}_n - \vec{v}_n}^{RP})^2/2\delta_{v_n}^{\;2}\}}$$

$$v_n\{4\} = v_n\{6\} = v_n\{8\} = v_n^{RP}$$

- Also non-flow contributions are suppressed in v_n from higher order cumulants

Event by event flow and flow fluctuations

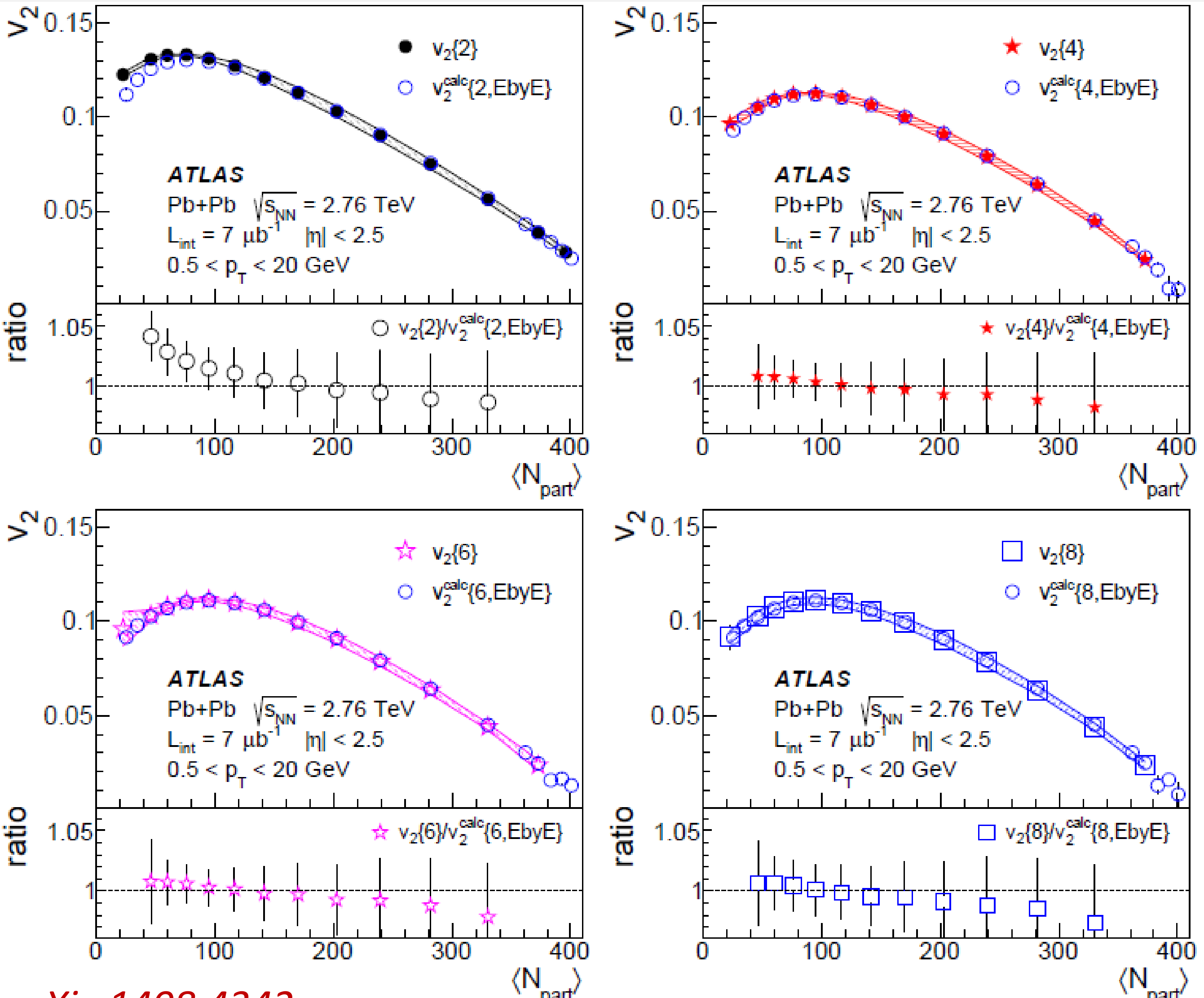
- $v_n\{2k\}$ can also be calculated from P(v_n) from EbE flow measurements



JHEP11(2013)183

Comparison of EbyE and cumulant results

- $v_n\{2k\}$ can also be calculated from P(v_n) from EbE flow measurements

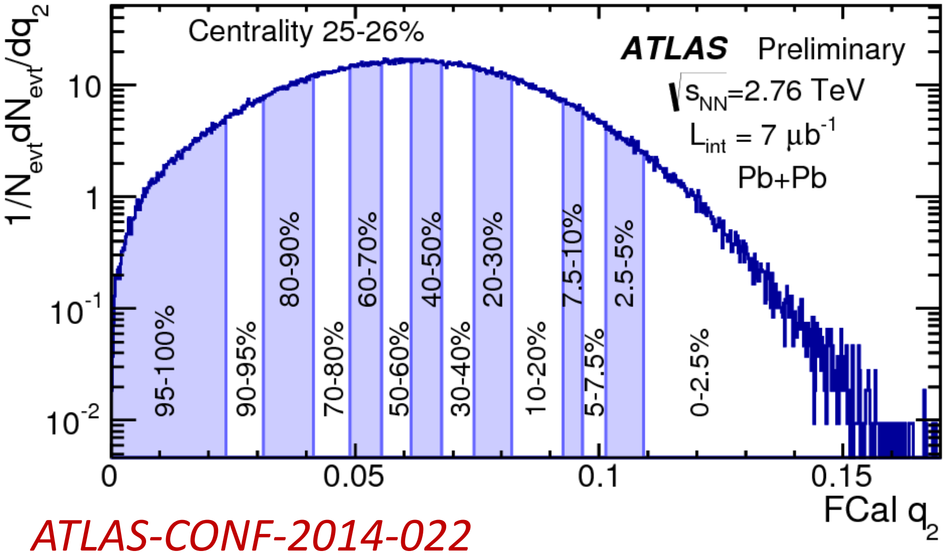


- Good consistency between the two set of measurements.

arXiv:1408.4342

Flow correlations – Event shape selection

- Can measure correlations between v_n by selecting on event-shape



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- For each centrality select on v_2 in the FCal (3.2 < |η| < 4.9)

Flow correlations – Event shape selection

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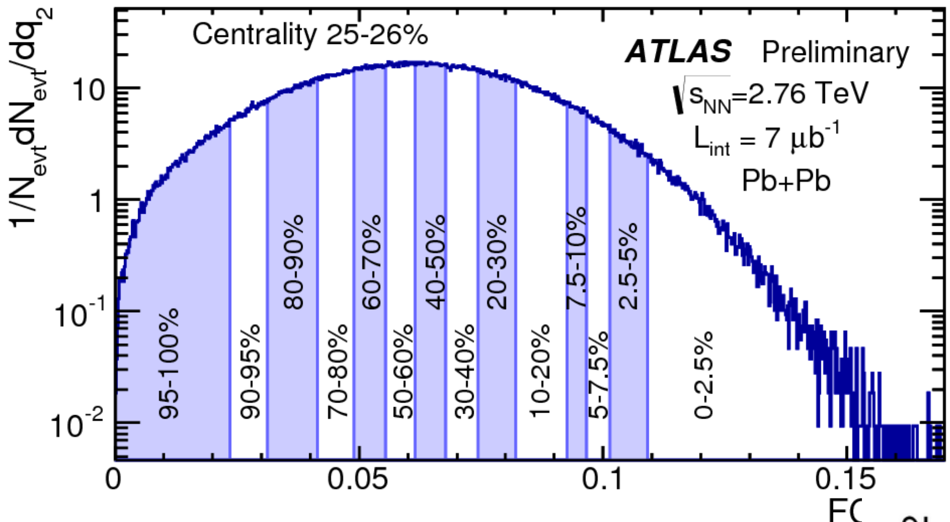

- For each centrality select on $|\vec{Q}|$ in the FCal (3.2 < |η| < 4.9)
- Control on event-shape: v_2 in ID (|η| < 2.5) varies by ~ a factor of 3.

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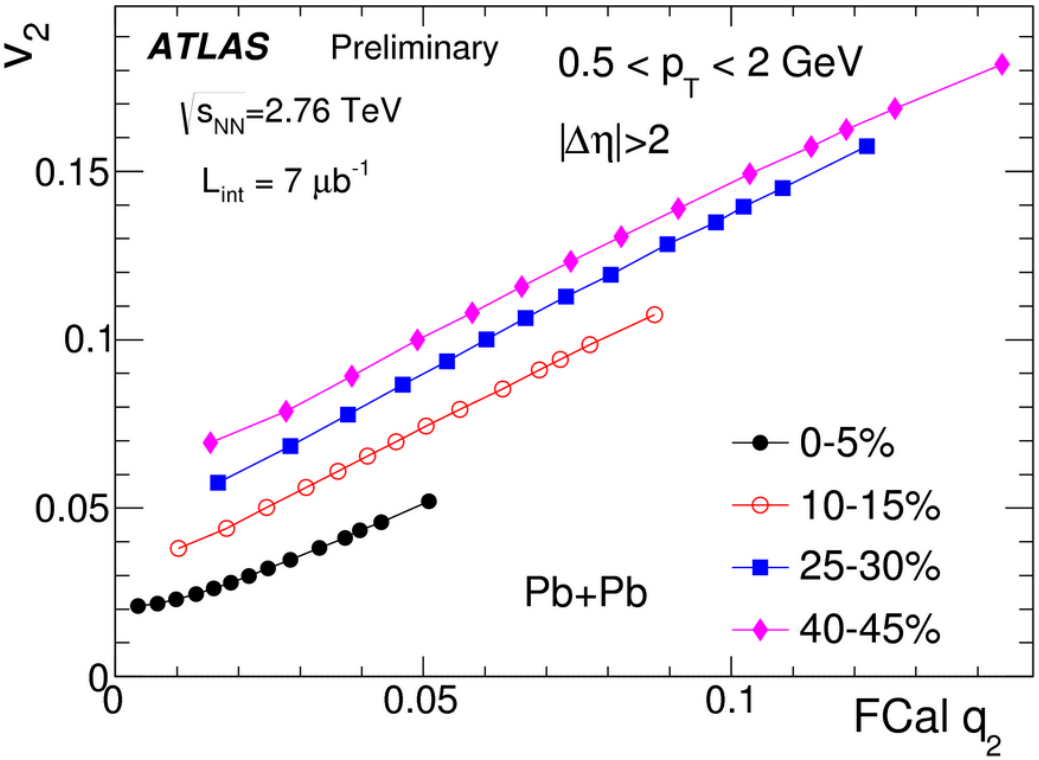
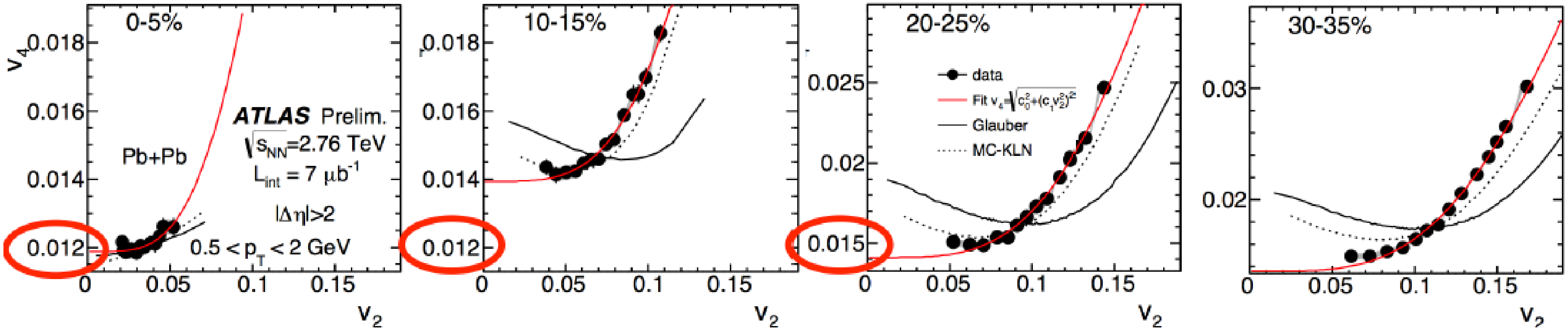


- Measure v_n in ID (|η| < 2.5) for each class using 2PC.
- Study correlations between v_n -> insensitive to selection bias from statistical smearing

Linear and non-linear contributions, v_4

- Non-linear response: $v_4 e^{i4\varphi_4} = c_0 e^{i4\varphi_4^*} + c_1(v_2\, e^{i2\varphi_2})^2$



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

Linear and non-linear contributions, v_4

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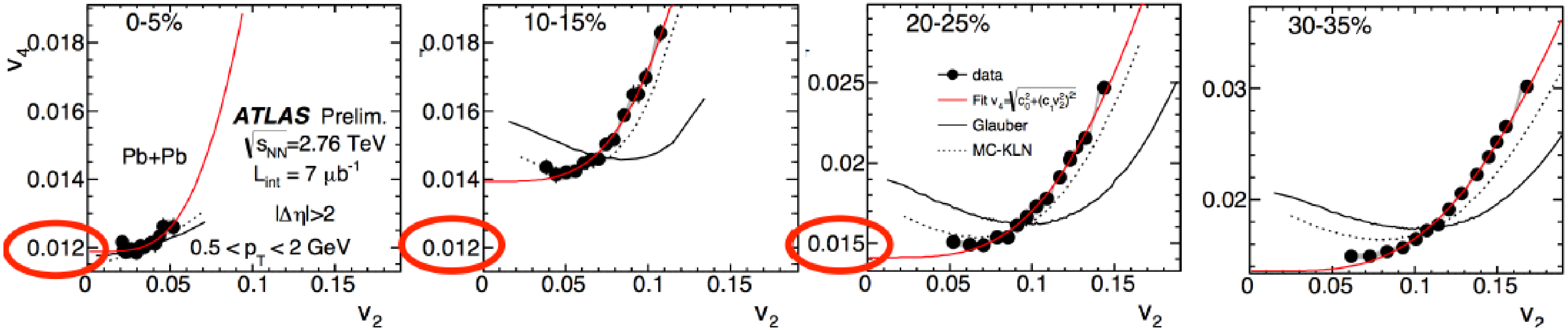

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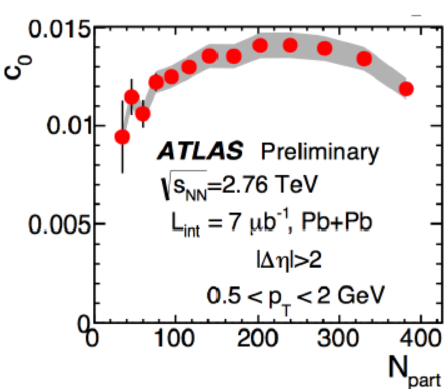

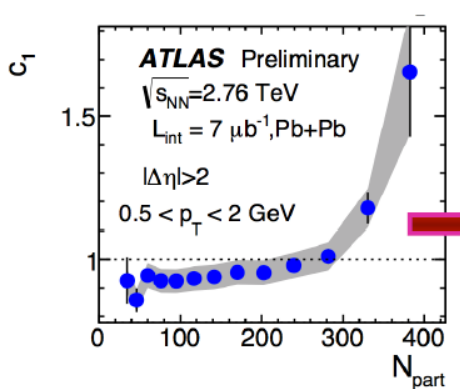

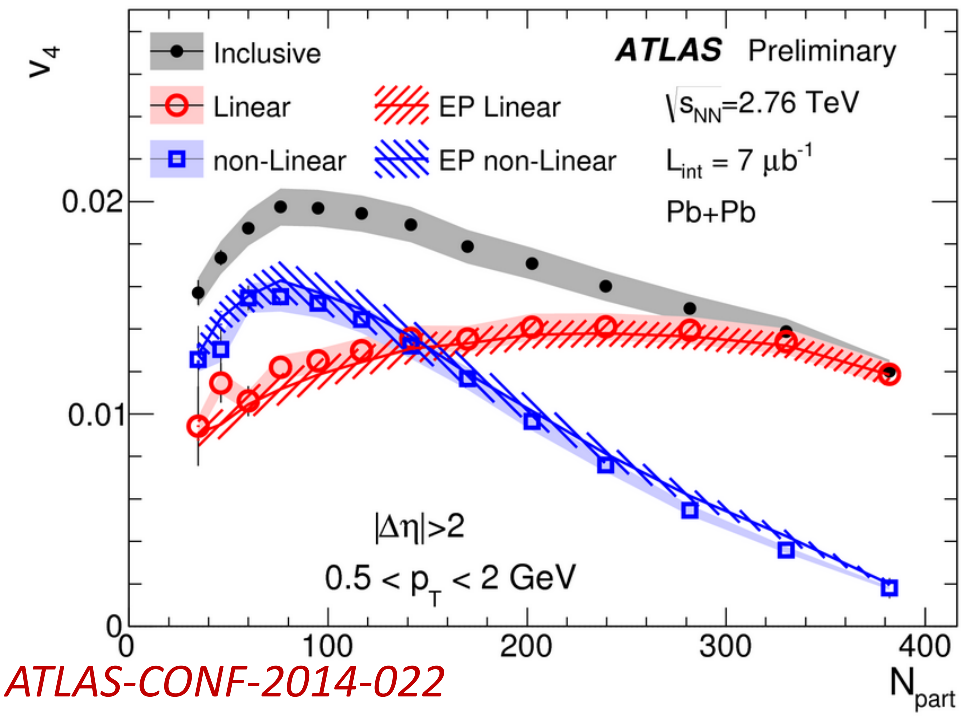

- Linear component dominates in central classes, non-linear in peripheral

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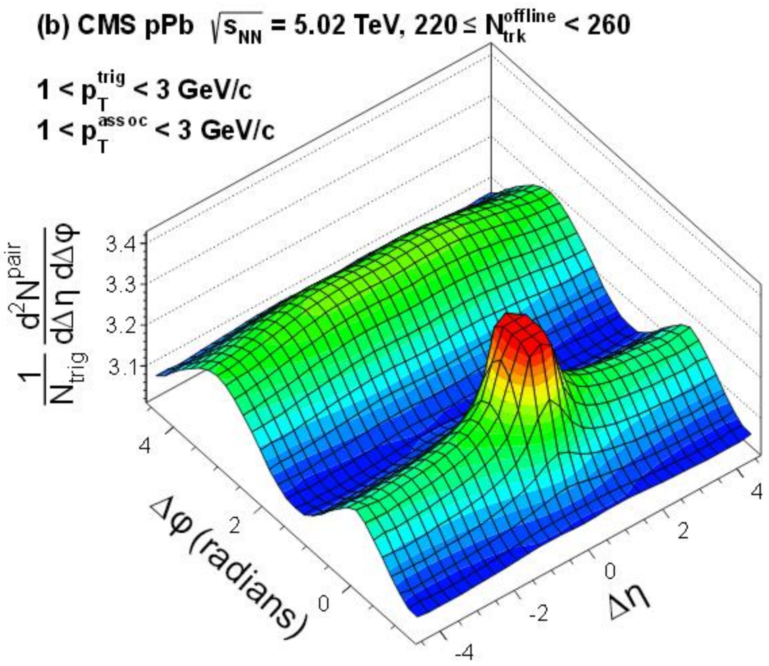
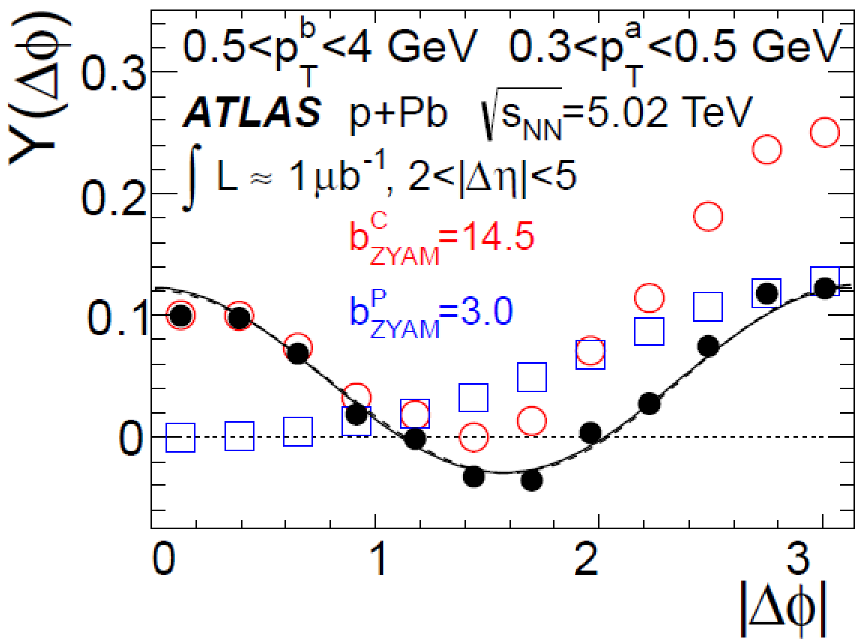
Ridge in p+Pb

More results and details in *arXiv:1409.1792*

Ridge in p+Pb collisions



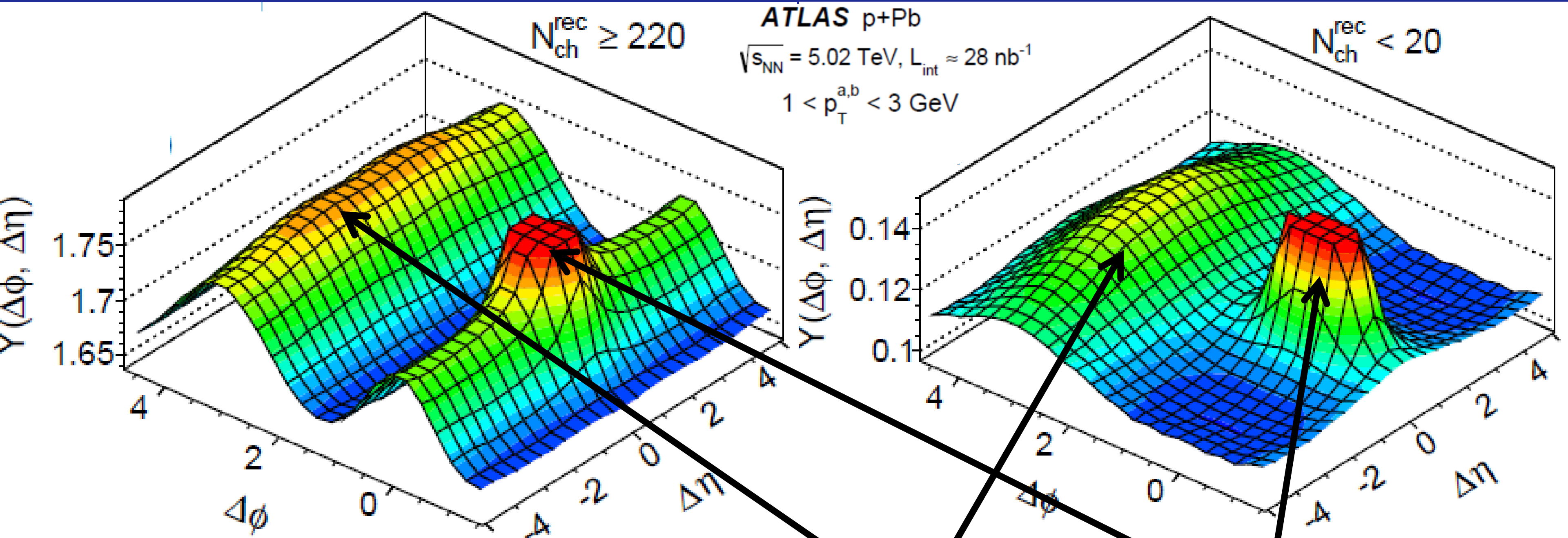
Phys. Lett. B 724



PhysRevLett.110.182302

- Long-range correlations ('ridge') observed in high multiplicity p+Pb collisions.
- Ridge present on both near and away sides.
- Arising from final state interactions or initial state correlations?

2PC Analysis – recoil subtraction

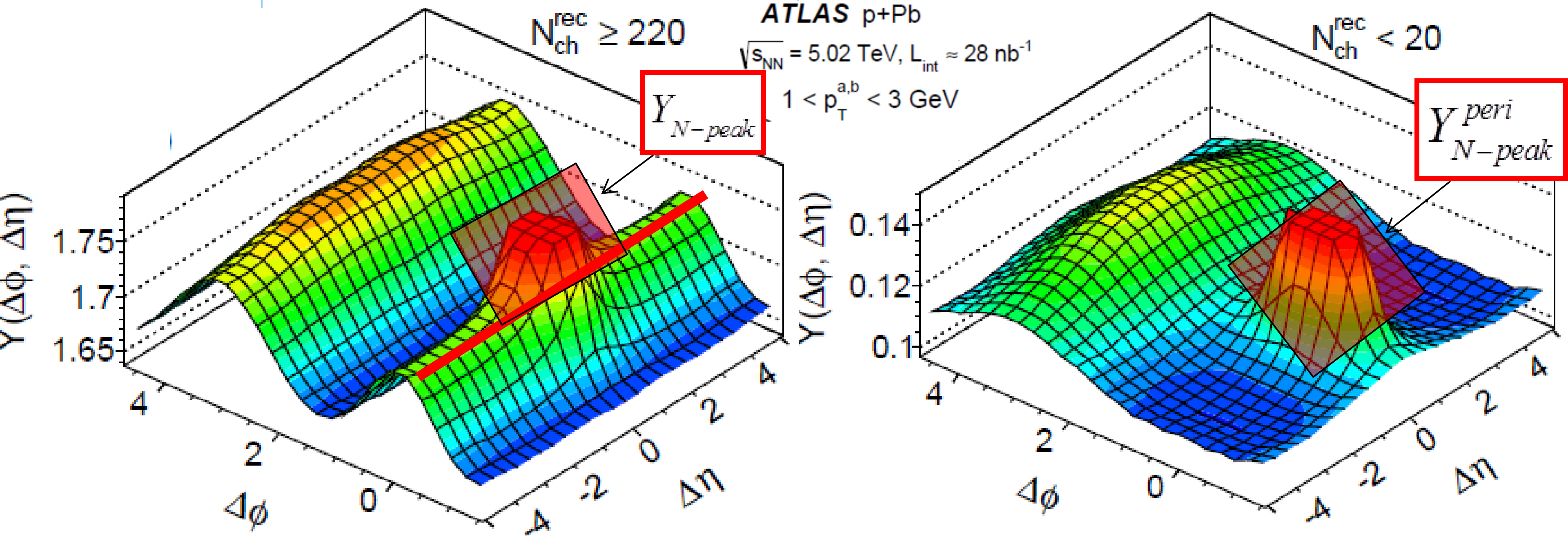


$$Y(\Delta\phi,\Delta\eta) = Y_{Ridge}(\Delta\phi) + Y_A(\Delta\phi,\Delta\eta) + Y_N(\Delta\phi,\Delta\eta)$$

Signal of interest — Away-side recoil — Near-side jet peak

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

2PC Analysis – recoil subtraction



$$Y^{\rm corr}(\Delta\phi,\Delta\eta) = \frac{\int B(\Delta\phi,\Delta\eta)d\Delta\phi d\Delta\eta}{\pi\eta_\Delta^{\rm max}}\left(\frac{S(\Delta\phi,\Delta\eta)}{B(\Delta\phi,\Delta\eta)} - b_{\rm ZYAM}\right)$$

per-trigger yield in 2D

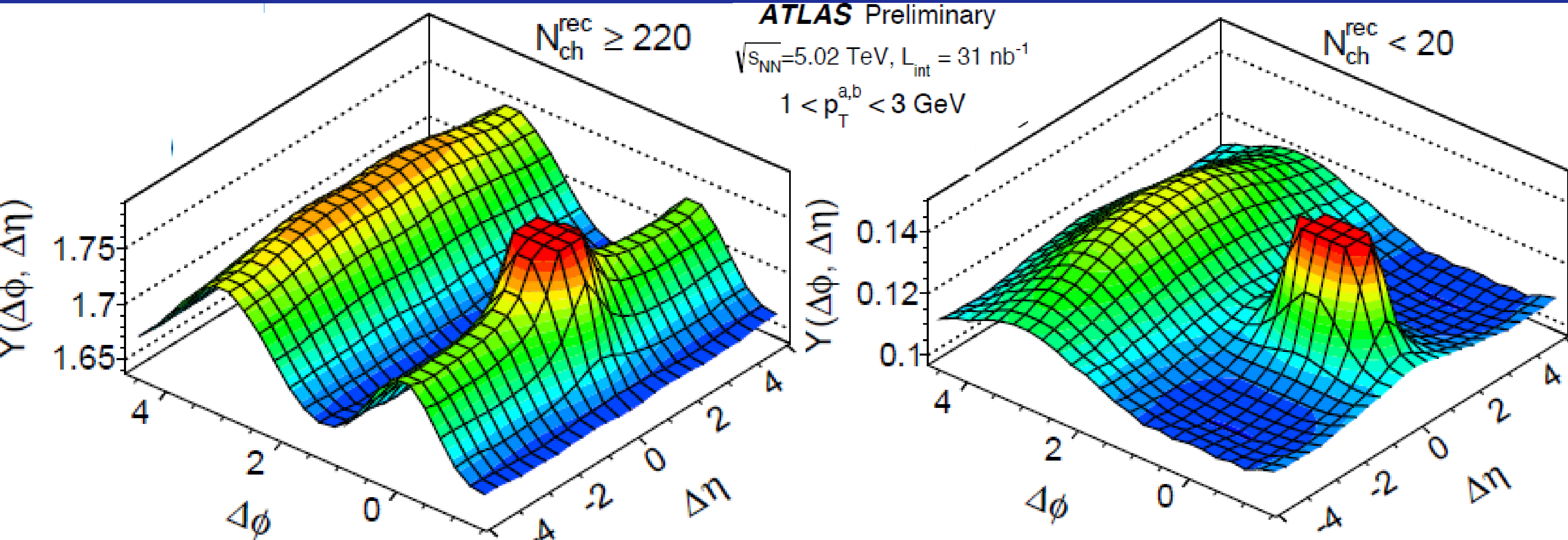
combinatorial background b_{ZYAM}

$$Y^{\rm sub}(\Delta\phi,\Delta\eta) = Y(\Delta\phi,\Delta\eta) - \alpha Y^{\rm corr}_{\rm peri}(\Delta\phi,\Delta\eta)$$

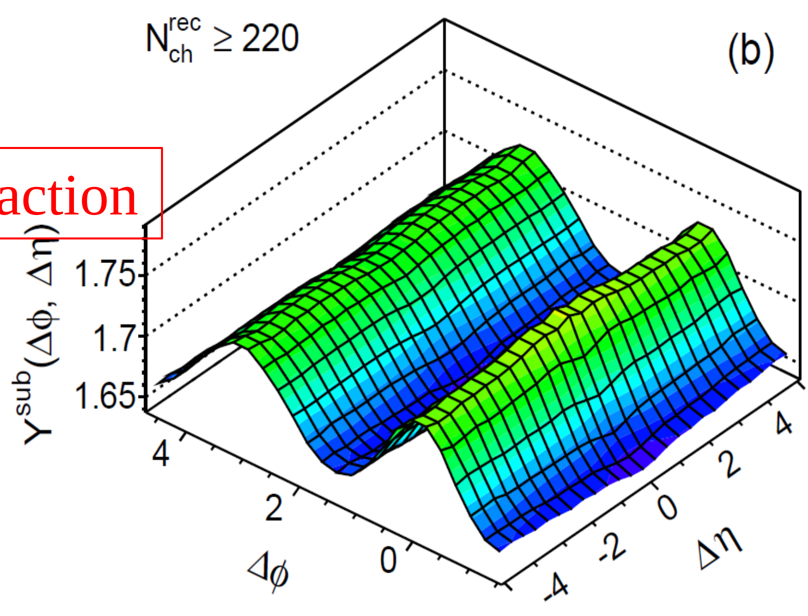
α is chosen such that $\alpha Y_{N-peak}^{peri} = Y_{N-peak}$

$$Y^{\rm N-Peak} = \int_{|\Delta\eta|<1} Y(\Delta\eta)d\Delta\eta - \frac{1}{3}\int_{2<|\Delta\eta|<5} Y(\Delta\eta)d\Delta\eta$$

2PC Analysis – recoil subtraction



Before subtraction

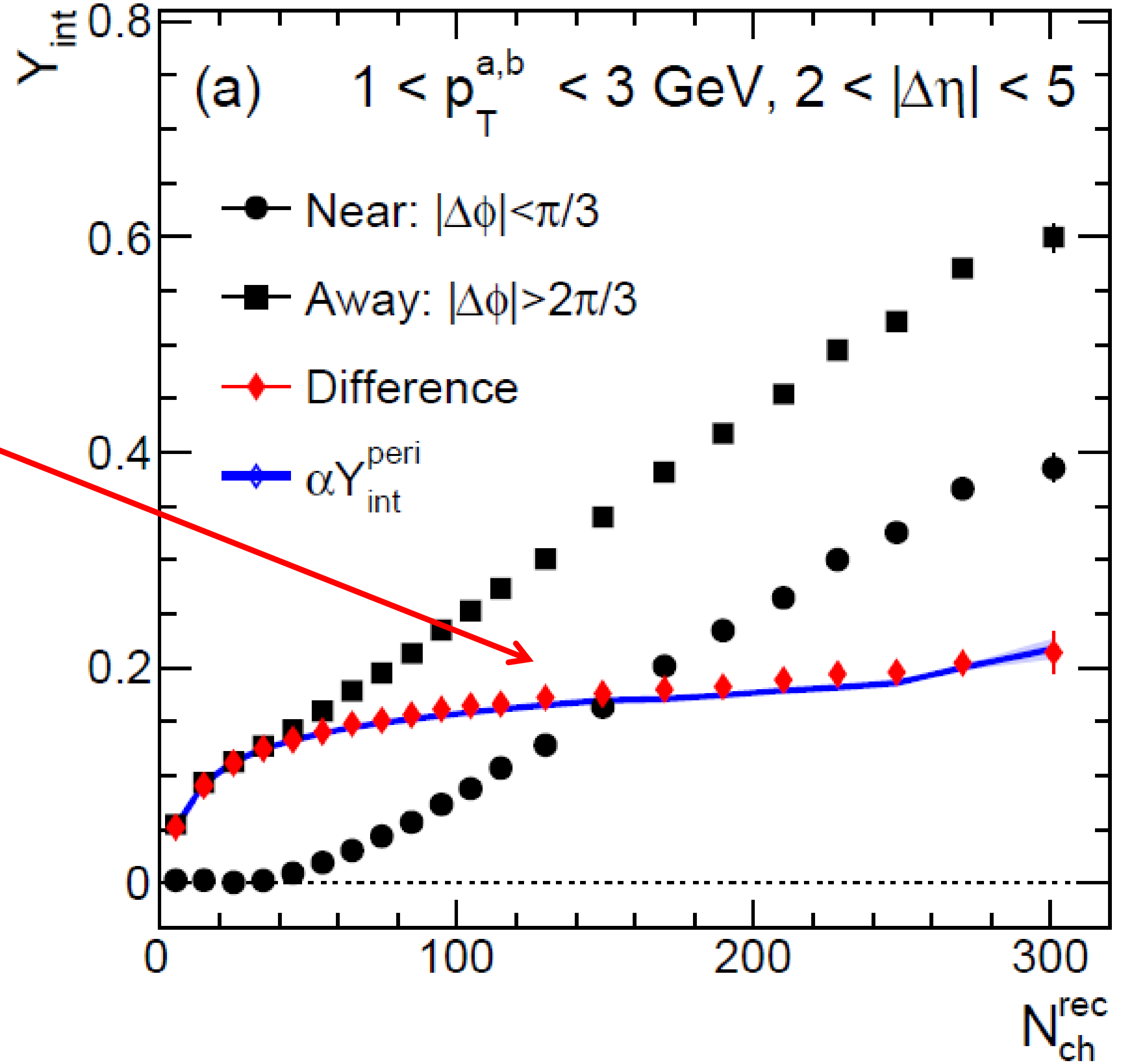


After subtraction

$$Y^{\text{sub}}(\Delta\phi,\Delta\eta) = Y(\Delta\phi,\Delta\eta) - \alpha Y^{\text{corr}}_{\text{peri}}(\Delta\phi,\Delta\eta)$$

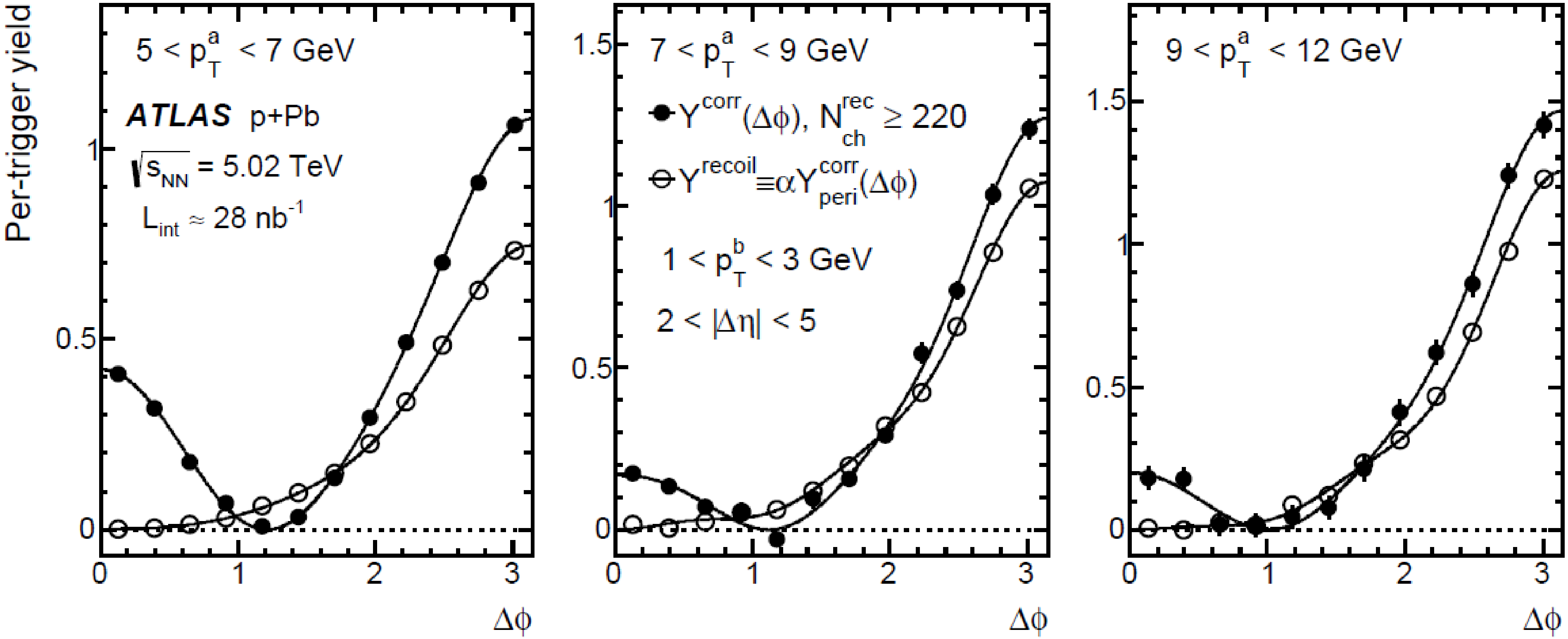
Away side – Near side

- 2^{nd} 3^{rd} and 4^{th} order harmonics cancel in the difference.
  - Yield from recoil matches the yield difference for $1 < {p_T}^b < 3$ GeV
  - Holds irrespective of ${p_T}^a$
- At other ${p_T}^b$, differences are seen
  - consistent with a long range v_1.



$$Y_{int} = \int_a^b Y^{corr}(\Delta\phi)\, d\Delta\phi$$

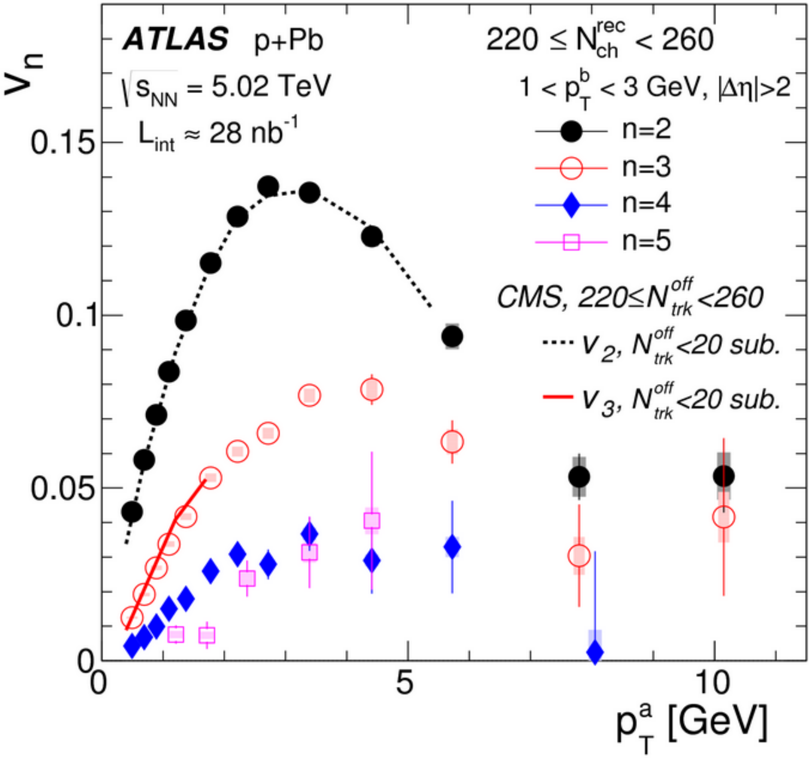
Ridge at higher p_T



$$Y^{corr}(\Delta\phi) = \frac{\int B(\Delta\phi)d\Delta\phi}{\pi}\left(\frac{S(\Delta\phi)}{B(\Delta\phi)} - b_{ZYAm}\right)$$

- Near-side ridge visible through the entire p_T range studied.
- Origin of high- p_T ridge?

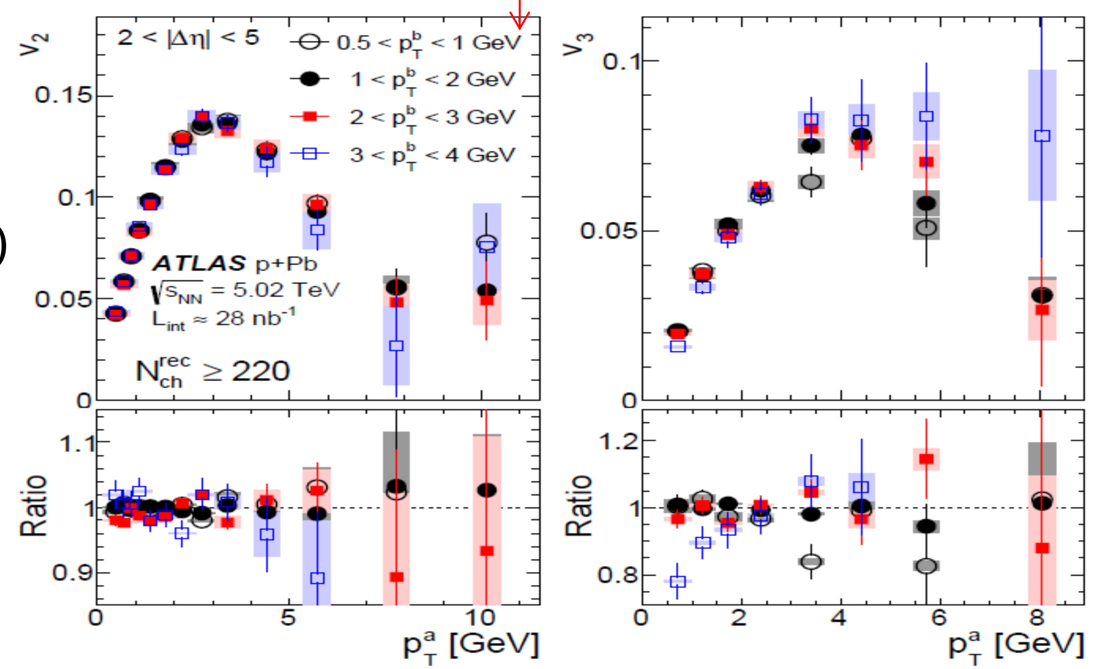
Fourier harmonics



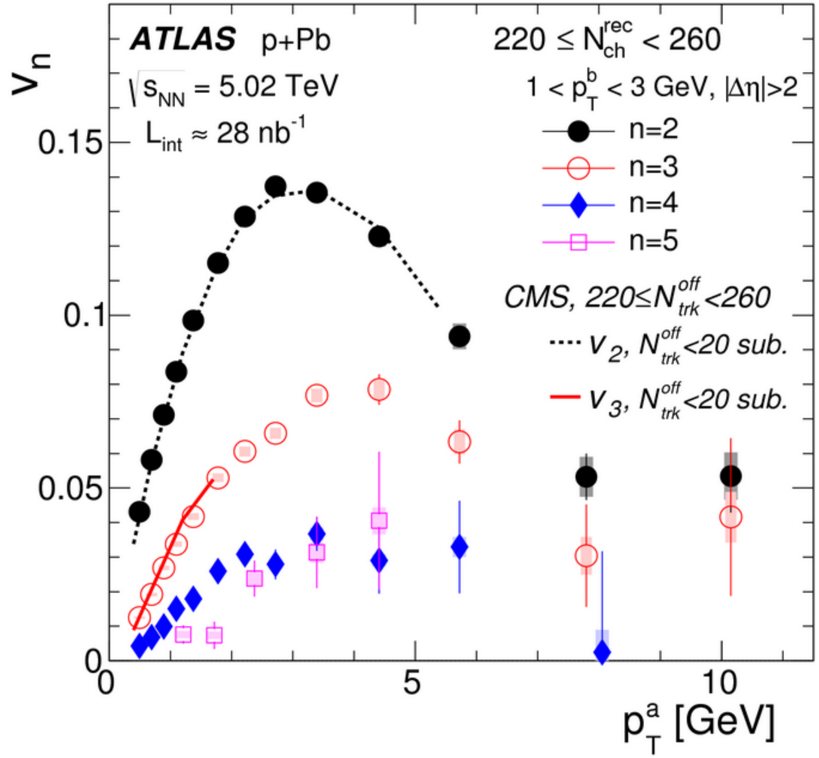
- Non-zero v_2, v_3 at high p_T (~10 GeV).
- v_n decrease with increasing n.
- Rise with p_T at low p_T and then decraese.
- Factorizes within a few percent for $p_T{}^b < 4$ GeV.

$$Y^{sub}(\Delta\phi) \sim 1 + \sum_n 2v_{n,n}\cos(n\Delta\phi)$$

$$v_n(p_T{}^a) = \frac{v_{n,n}(p_T{}^a, p_T{}^b)}{\sqrt{v_{n,n}(p_T{}^b, p_T{}^b)}}$$

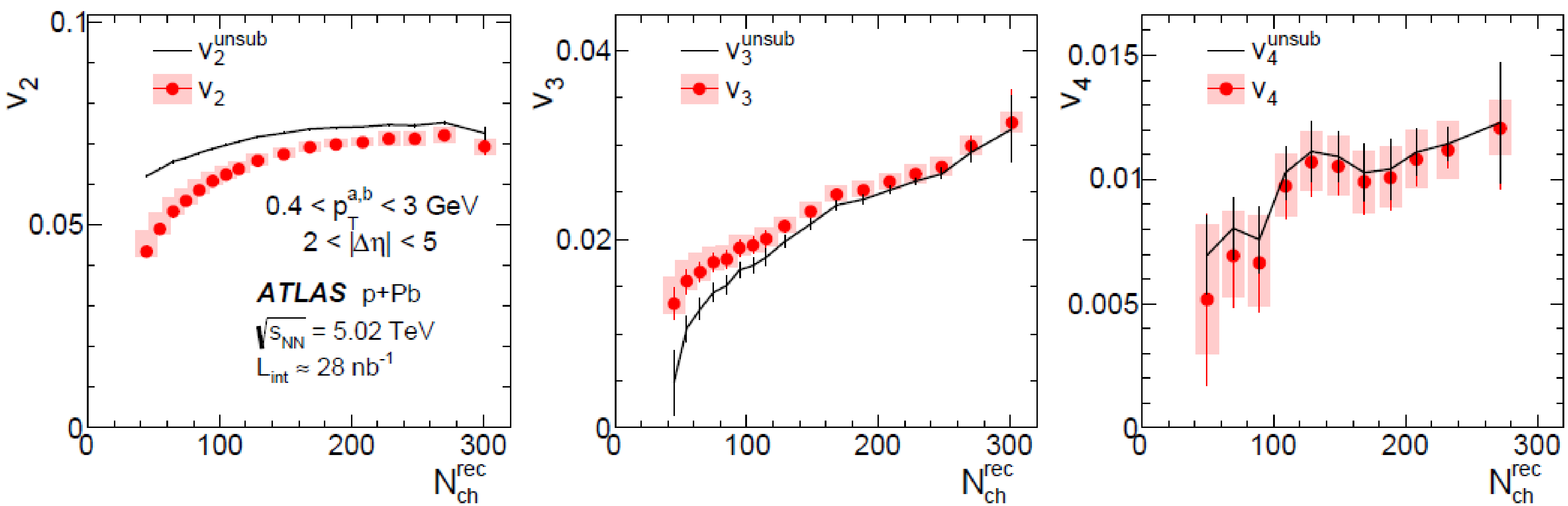


Fourier harmonics

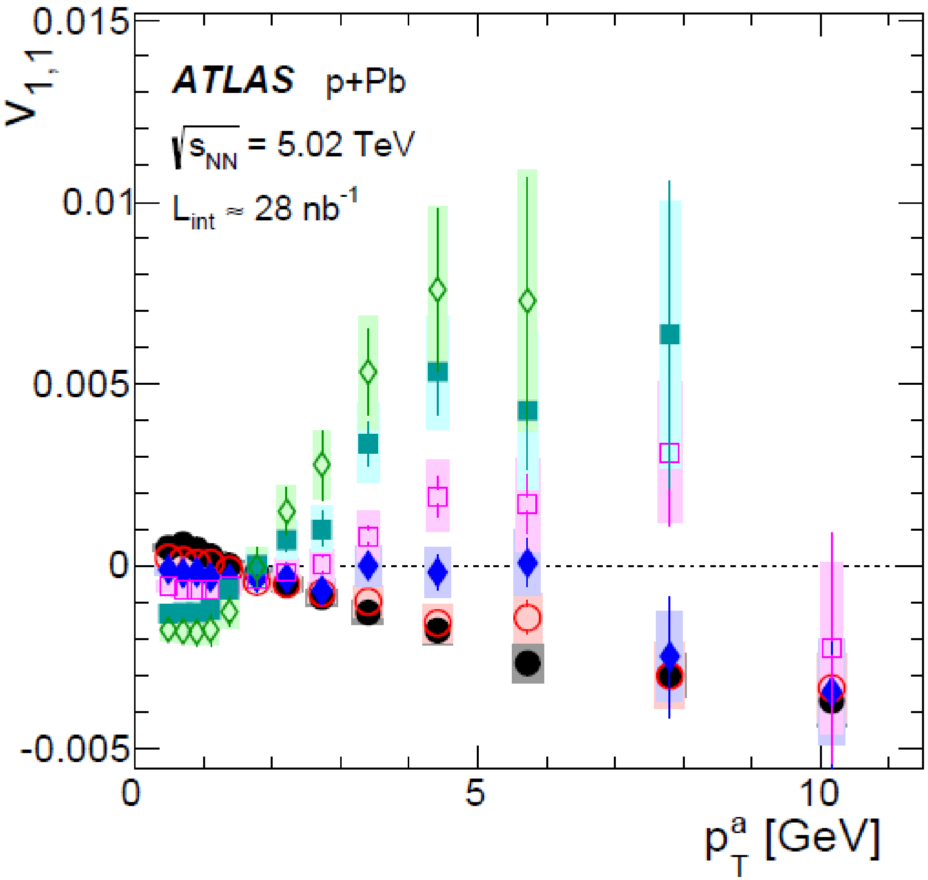


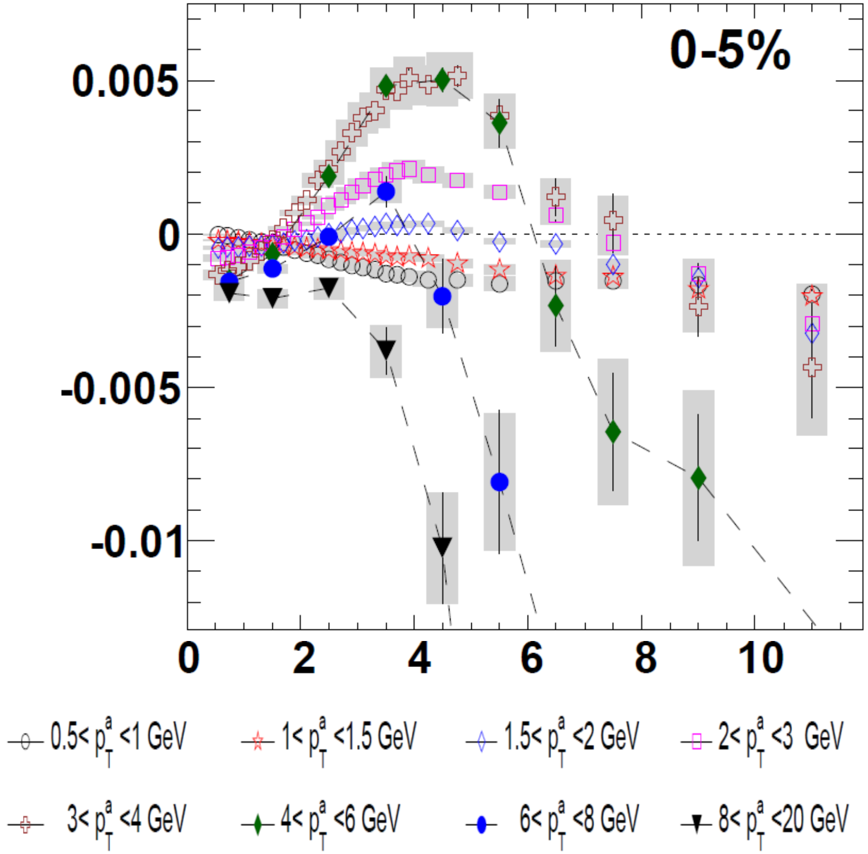
- Non-zero v_2, v_3 at high p_T (~10 GeV).
- v_n decrease with increasing n.
- Rise with p_T at low p_T and then decraese.

- Less variation in integrated v_2 for N_{ch}^{rec} >150, v_3 continues to increase.



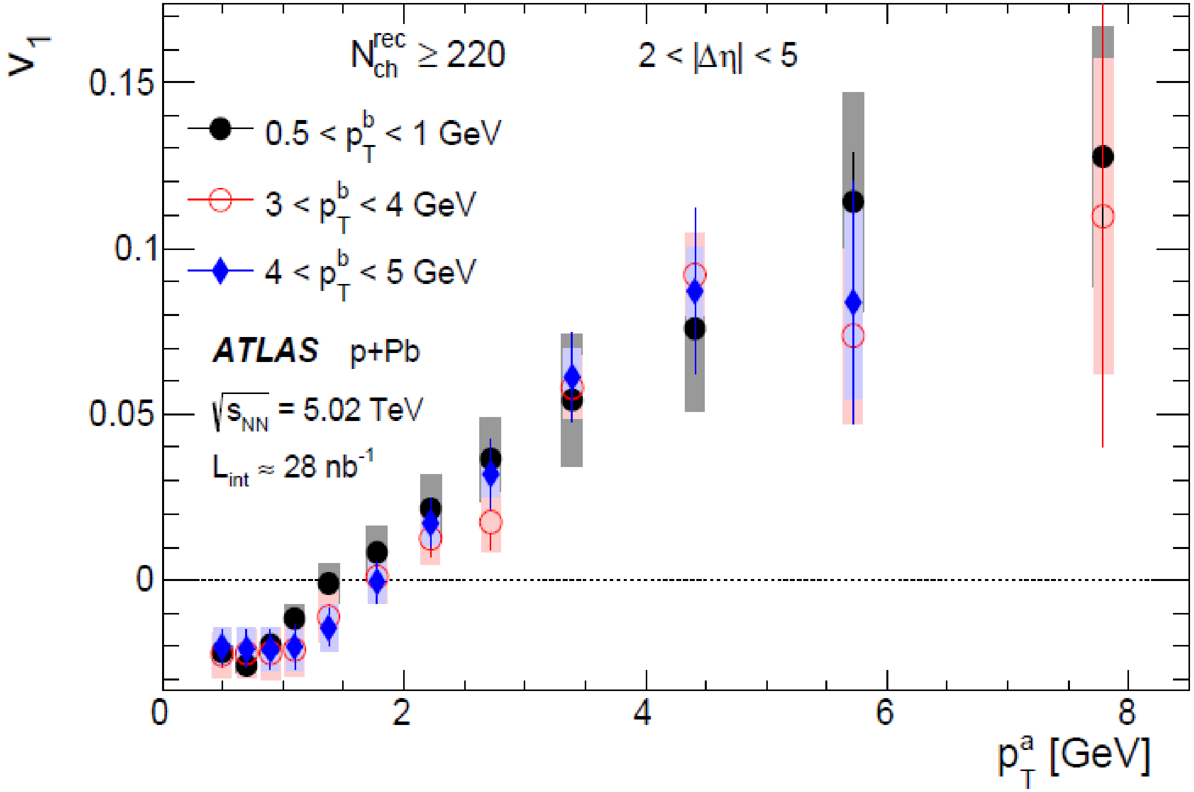
$v_{1,1}$ - First order harmonic in p+Pb





- After recoil subtraction, ${p_T}^{a,b}$ dependence of v_{11} similar to that seen in Pb+Pb collisions
  - In Pb+Pb, attributed to long-range v_1 from density fluctuations which is −ve at low p_T and +ve at higher p_T.

Dipolar flow in p + Pb



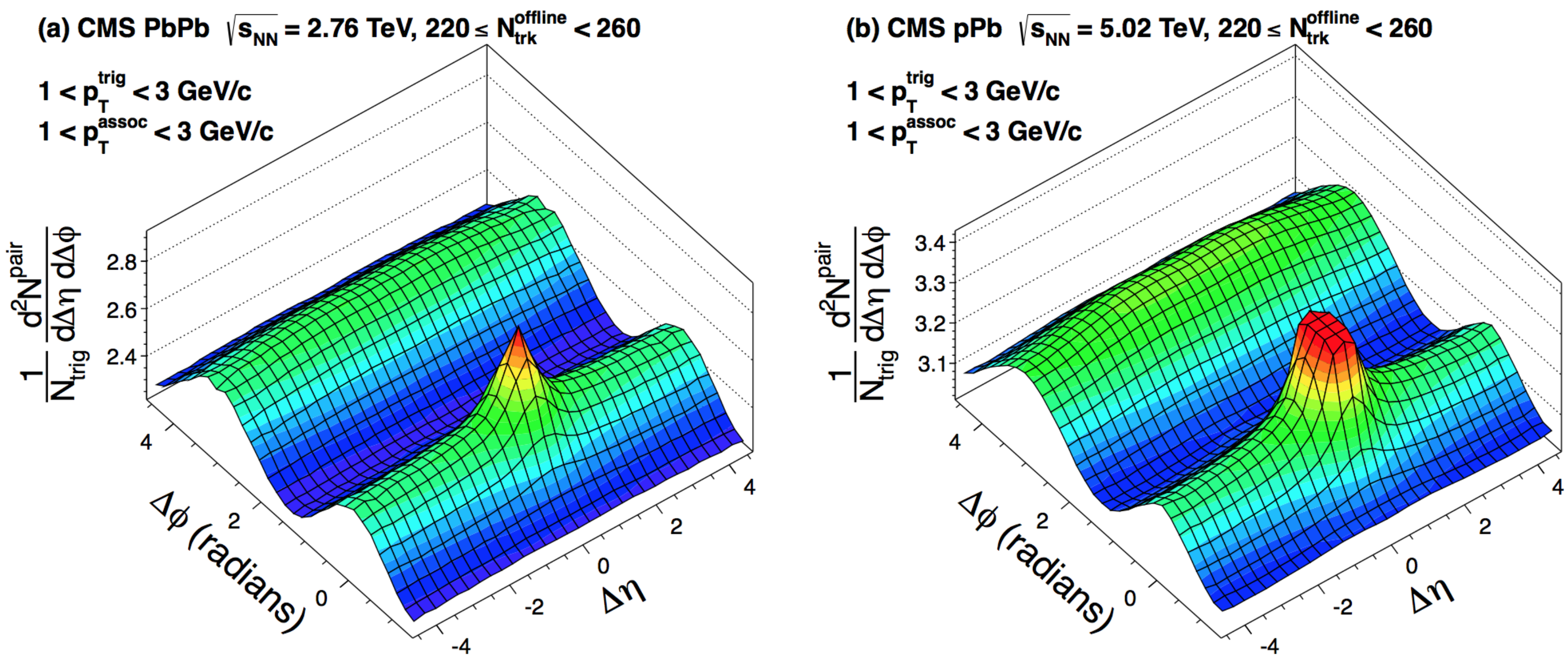
- Employ similar factorization as other harmonics, but account for sign change
- $v_{1,1}$ can be factorized as

$$v_1(p_T) \equiv \frac{v_{1,1}(p_T, p_T^{ref})}{v_1(p_T^{ref})}$$

$$v_1(p_T^{ref}) = \text{sign}(p_T - p_T^0)\sqrt{\left|v_{1,1}(p_T^{ref}, p_T^{ref})\right|} \qquad p_T^0 = 1.5 \text{ GeV}$$

- Good agreement for different ${p_T}^{ref}$, suggesting a single particle modulation.

Comparison of with peripheral Pb+Pb.



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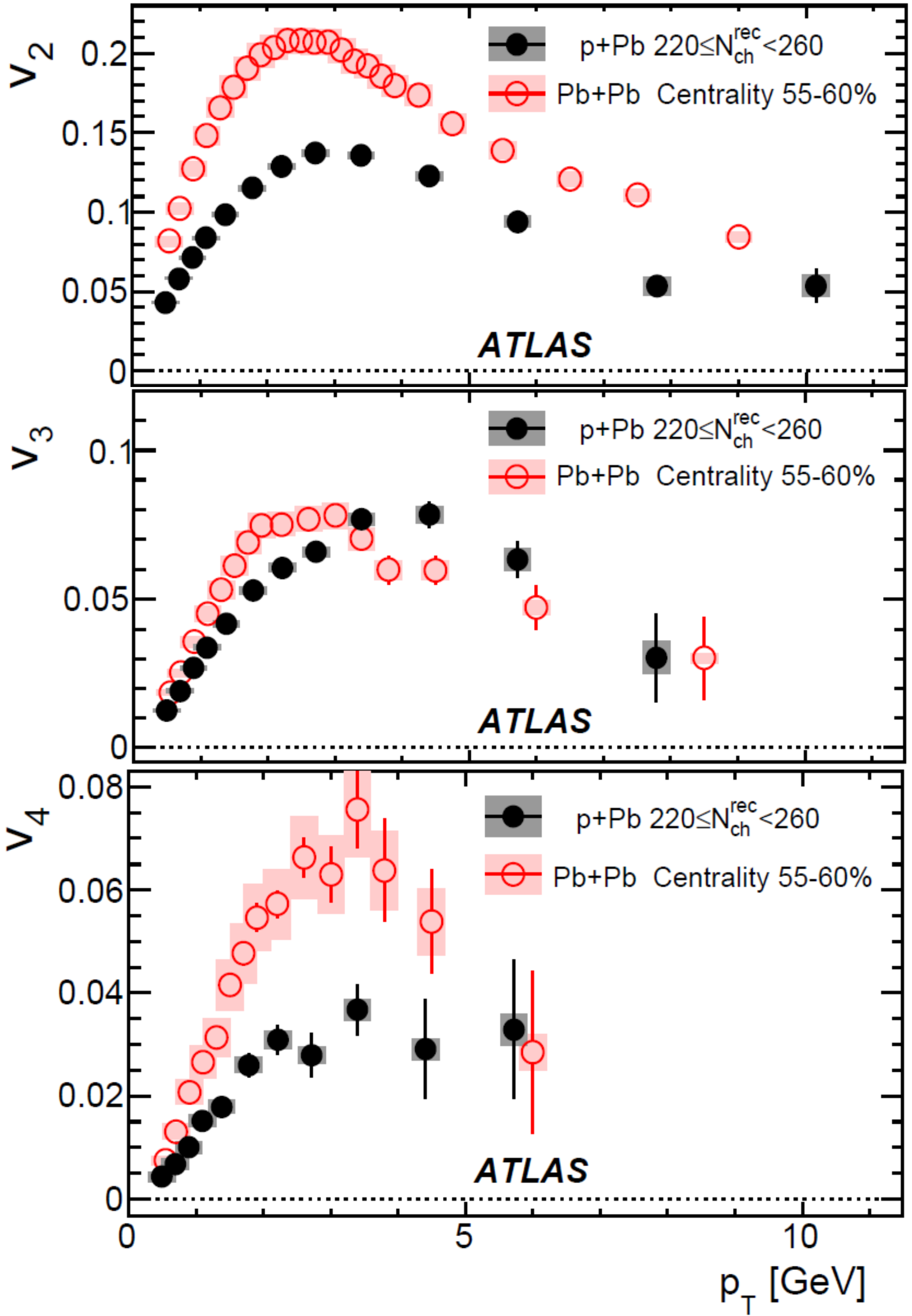
- Peripheral Pb+Pb collisions have comparable multiplicity as ultra central p+Pb collisions.
- Larger jet contribution in p+Pb than Pb+Pb in events with similar multiplicity.

Comparison of v_n in p+Pb and peripheral Pb+Pb.

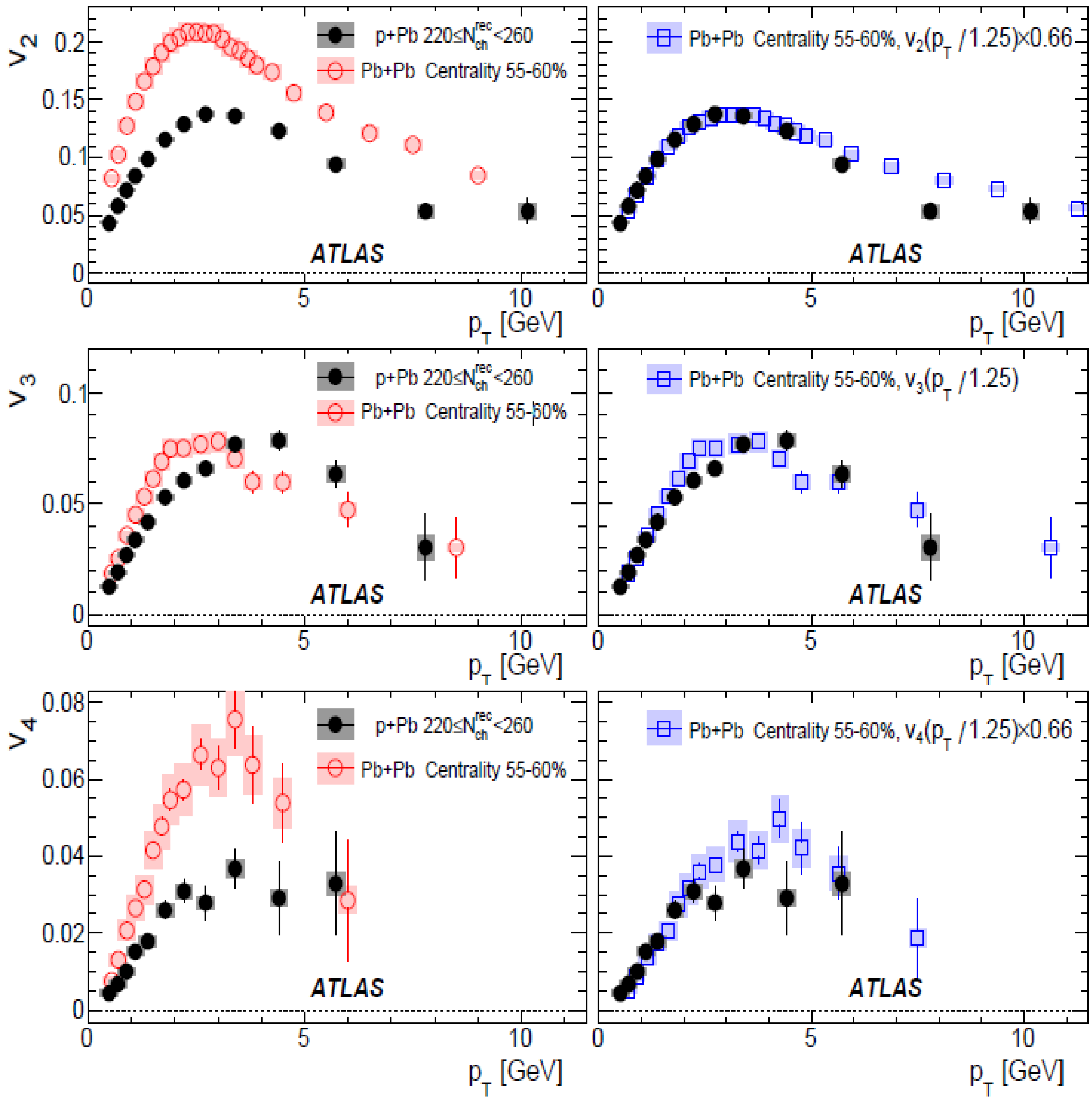


- Significantly larger v_2 and v_4 in Pb+Pb, but comparable magnitudes for v_3
  - Large elliptic geometry from overlap in PbPb
  - v_4 gets contribution from v_2

- Compare $v_n\,(p_T)_{p+Pb}$ with $v_n\,(p_T/K)_{Pb+Pb}$, *(Teaney et.al)*
  - K=1.25, ratio of <p_T>.

- p+Pb: <N_{ch}> ± σ = 259 ± 13
- Pb+Pb: <N_{ch}> ± σ = 241 ± 43

v_n scaling between the p+Pb and Pb+Pb systems.



- v_2 values, after scaling the p_T axis, differ only by a scale factor between the two systems.
- Suggests a similar origin for v_2 in the two systems?

Summary and Conclusions

- Flow and fluctuations in Pb+Pb
  - *Consistent results from cumulant and EbE measurements.*
  - *Correlations of v_2 with higher order v_n → Event shape selection*
  - *Linear and non-linear components separated for v_4 and v_5*

- Ridge in p+Pb
  - *Non-zero near-side ridge and v_n at higher p_T (~10 GeV)*
  - *v_1 in p+Pb : changes sign around 1.5 GeV, reaches 0.1 for $p_T > 4$*
  - *Similar p_T dependence as v_n from peripheral Pb+Pb, after scaling the p_T axis for Pb+Pb by mean p_T:*
    - *Suggests a similar origin for v_2 in the two systems?*