Experimental data on collective flow and correlations

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Heavy Ion Meeting 2014-06
20 June 2014

ALICE Results

Extracted from the following talks.

1. “Long-range angular correlations at the LHC with ALICE” by Leonardo Milano

2. “Elliptic flow of identified particles in Pb-Pb collisions at the LHC” by A. Dobrin

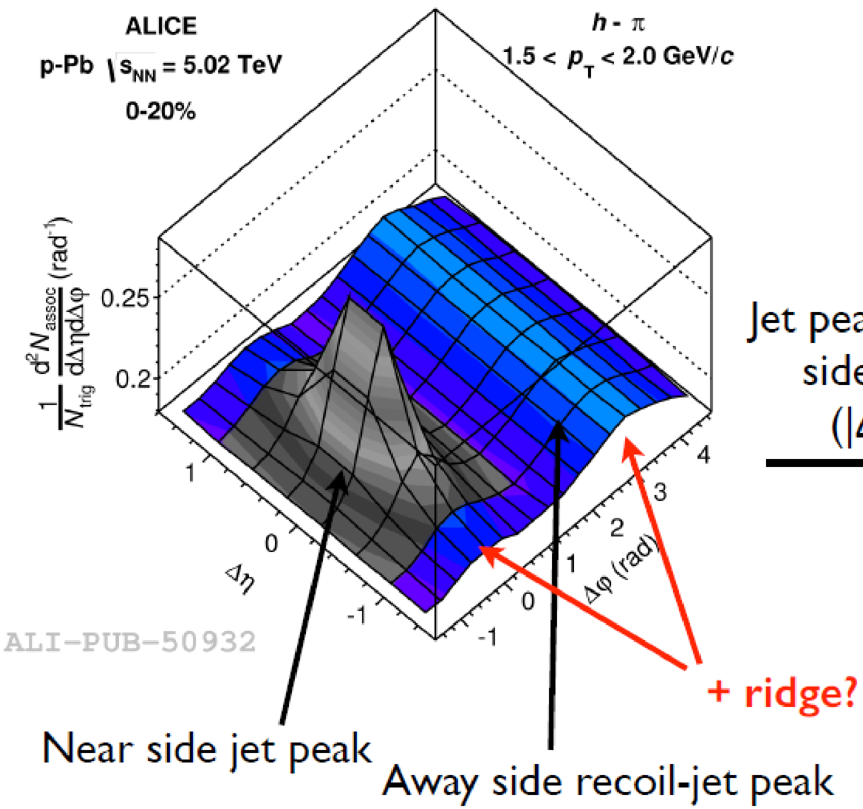
3. “Searchs for azimuthal flow in pp, p-Pb and Pb-Pb collisions” by Anthony Timmins

Associated yield per trigger particle

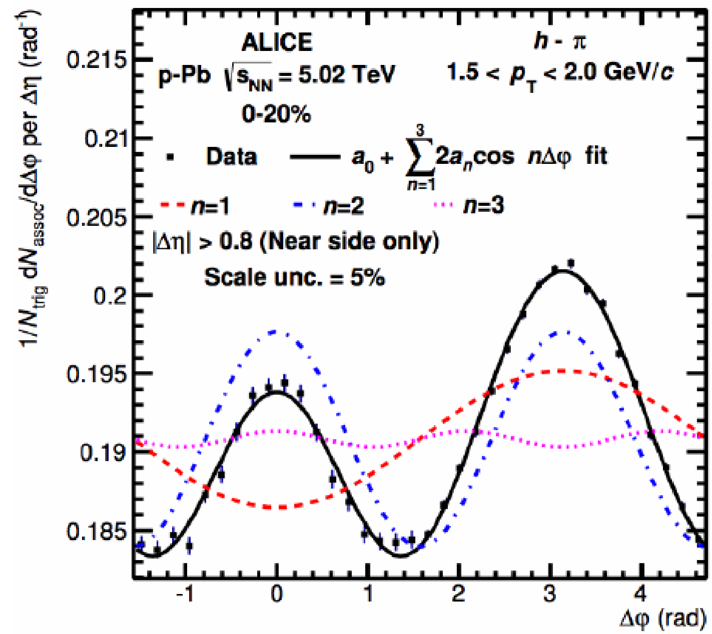
$$\frac{1}{N_{trig}} \frac{d^2 N_{assoc}}{d\Delta\eta \, d\Delta\varphi} = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}$$

$$S(\Delta\eta, \Delta\varphi) = 1/N_{trig} \; d^2 N_{same}/d\Delta\eta \, d\Delta\varphi$$

$$B(\Delta\eta, \Delta\varphi) = \alpha \, d^2 N_{mixed}/d\Delta\eta \, d\Delta\varphi$$



Jet peak in the near side excluded (|Δη|<0.8)



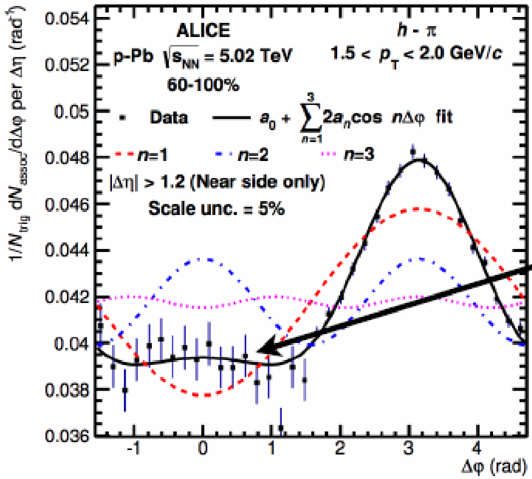
good fit with 3 components:
- first component large due to recoil jet
- a_2 given by jet+ridge
- a_3 much smaller than the other components

How to get rid of the jet contribution?

The subtraction procedure

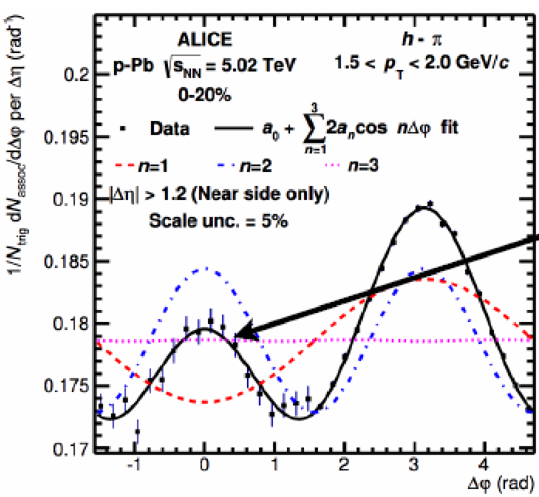
jet contribution reduced assuming:

- Mostly jet contribution (i.e. no significant ridge) in low multiplicity p-Pb events
- No significant medium effect in the energy loss / jet fragmentation



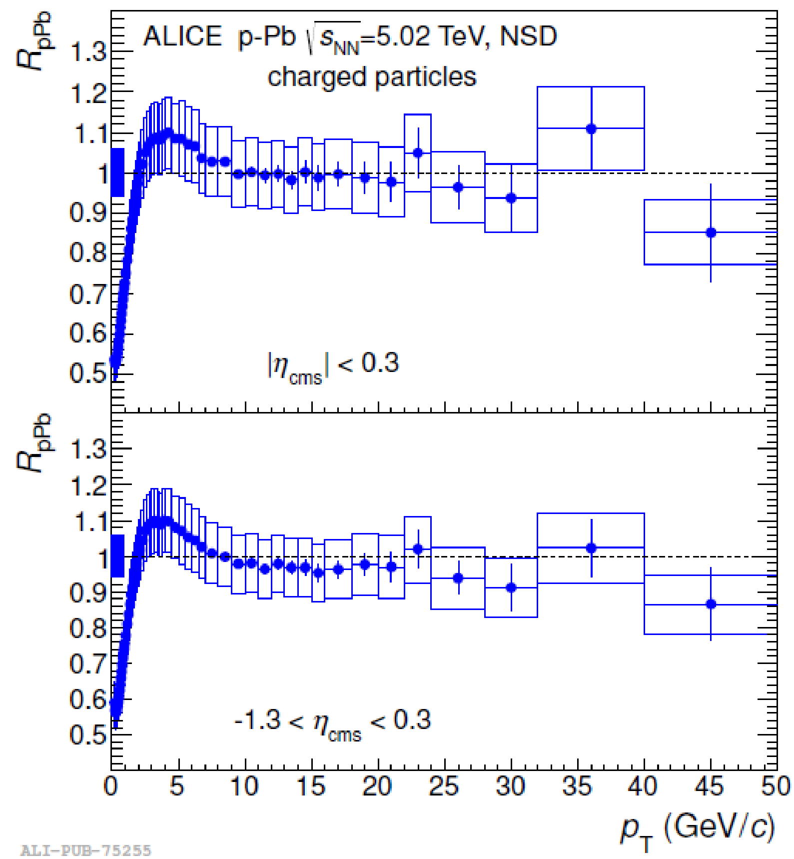
low mult.

No significant ridge in 60-100%



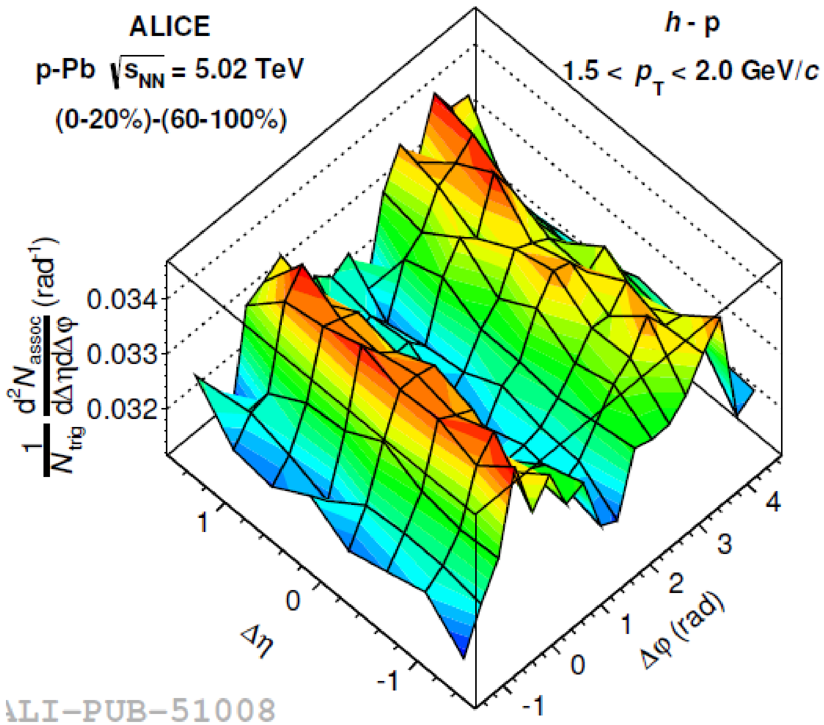
high mult.

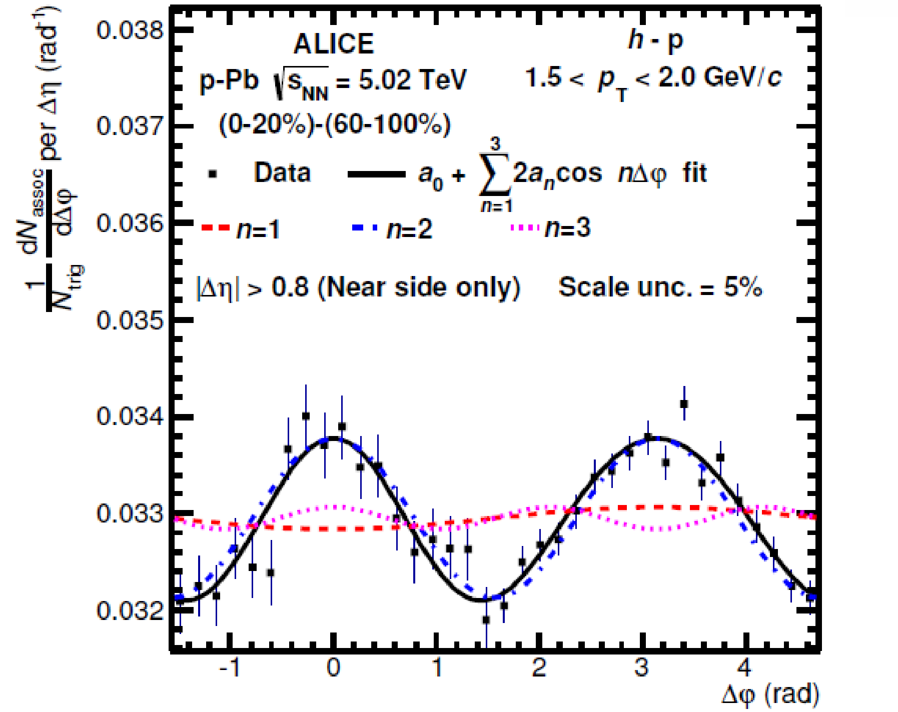
Not the case for 0-20%



ALICE, arXiv:1405.2737 [nucl-ex]

The subtraction procedure





$$V_{n\Delta}\{2\text{PC},\text{sub}\} = a_n/(a_0+b)$$

$$v_n^h\{2\text{PC}\} = \sqrt{V_{n\Delta}^{h-h}}$$

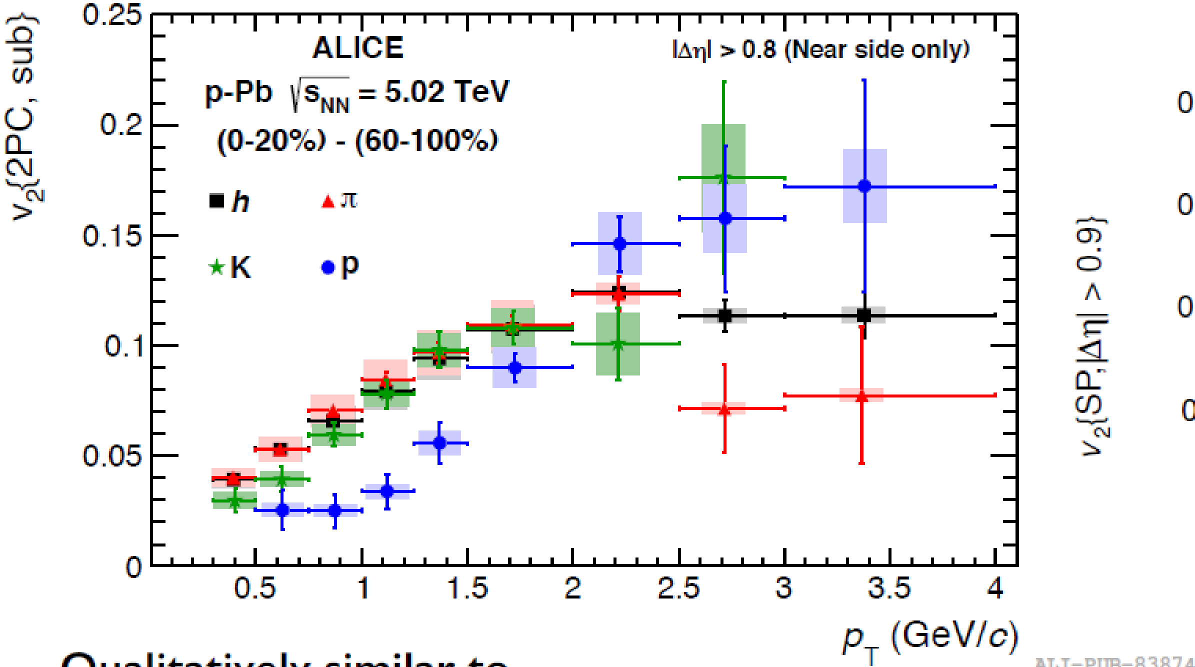
$$v_n^i\{2\text{PC}\} = V_{n\Delta}^{h-i}/\sqrt{V_{n\Delta}^{h-h}}$$

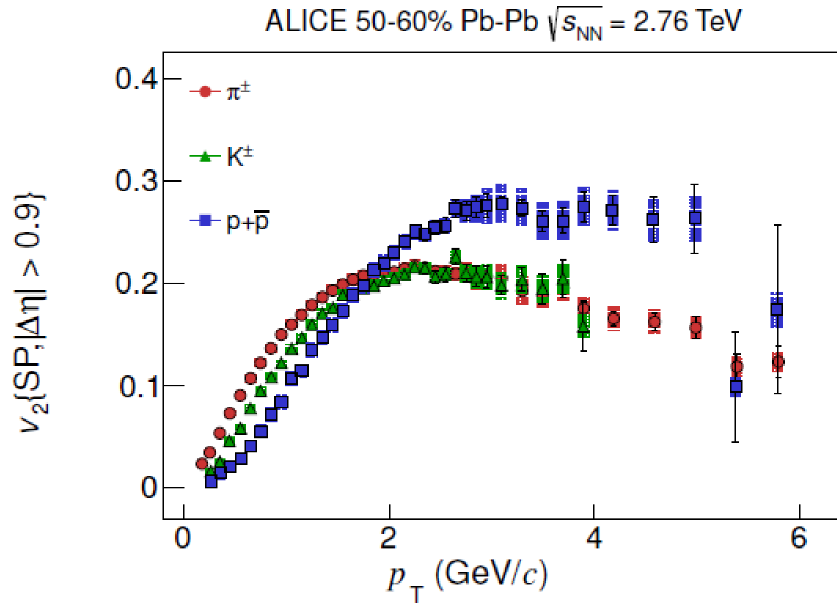
(When each of the particles is correlated with a common plane)

$$v_n\{2\} \equiv \sqrt{c_n\{2\}}$$

*b calculated in 60-100% class

v_2 of π, K, p in high-multiplicity p-Pb

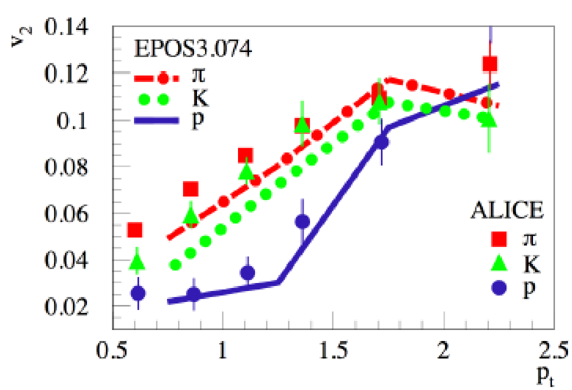




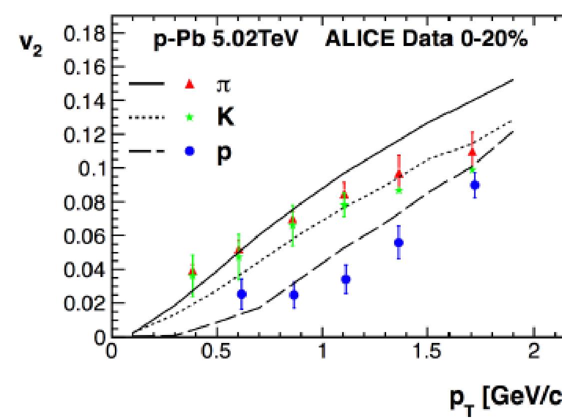
arXiv:1405.4632 [nucl-ex]

Qualitatively similar to Pb-Pb collisions

… and consistent with hydro predictions



K. Werner, M. Bleicher, B. Guiot, I. Karpenko, T. Pierog, arXiv:1307.4379 [nucl-th]



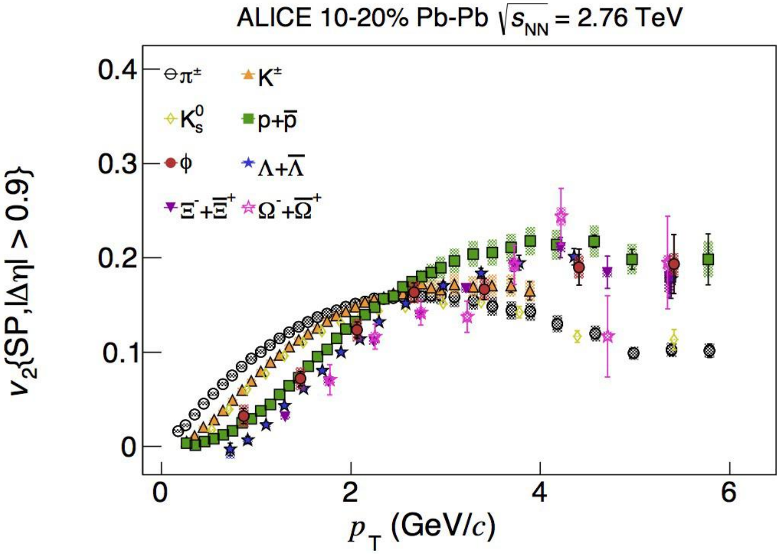
P. Bozek, W. Broniowski, G. Torrieri, Phys. Rev. Lett. 111, 172303 (2013)

Conclusions

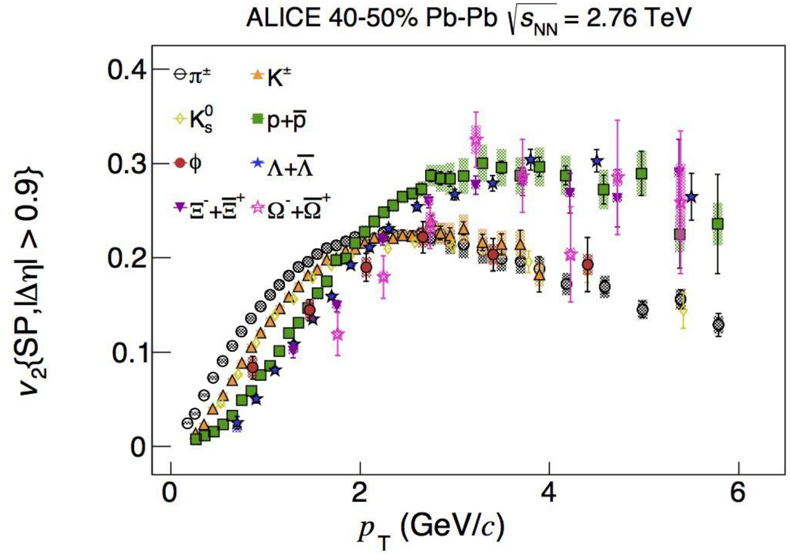
- experimental observations are highly **suggestive** of collective effects in high-multiplicity p-Pb collisions

- **mass ordering** of the second order coefficients of the double ridge

Identified particle v_2



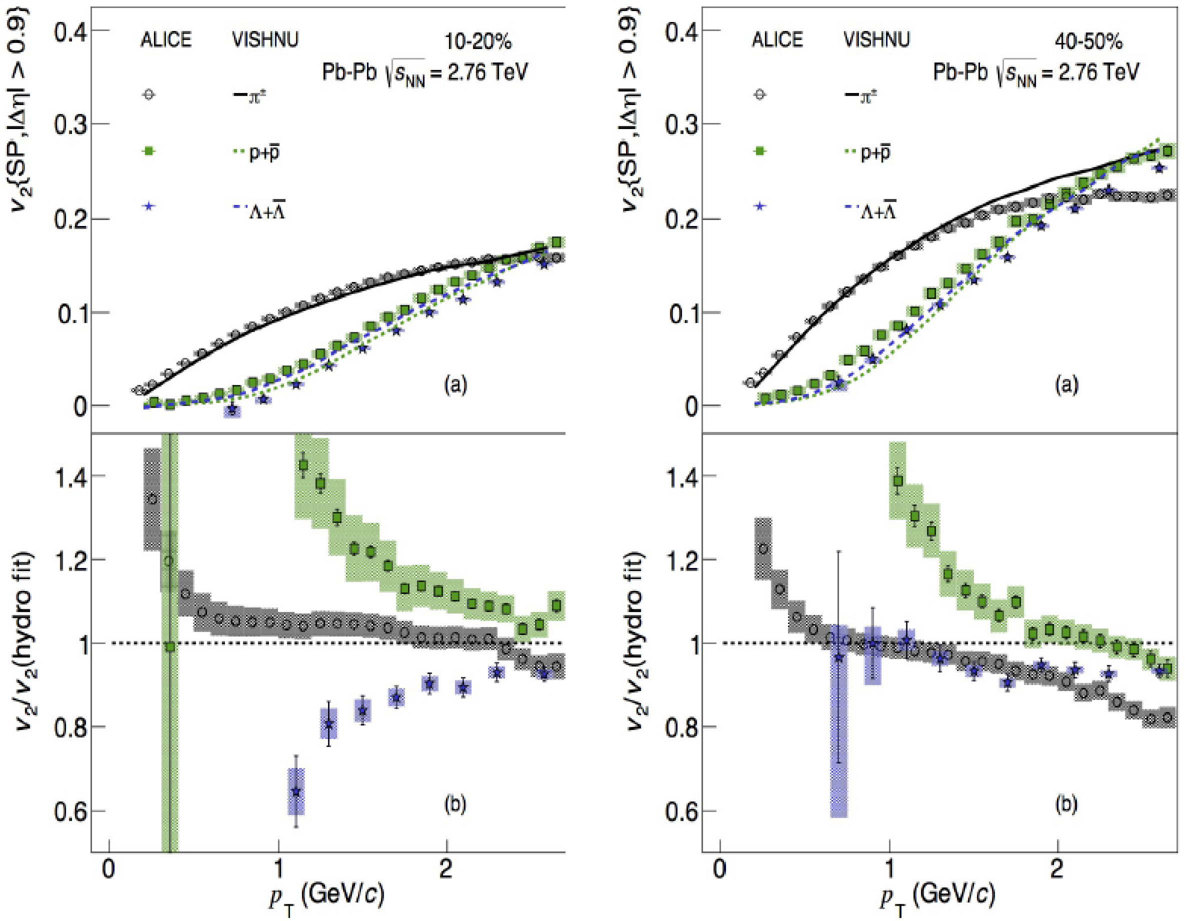
ALI-PUB-82653



ALI-PUB-82660

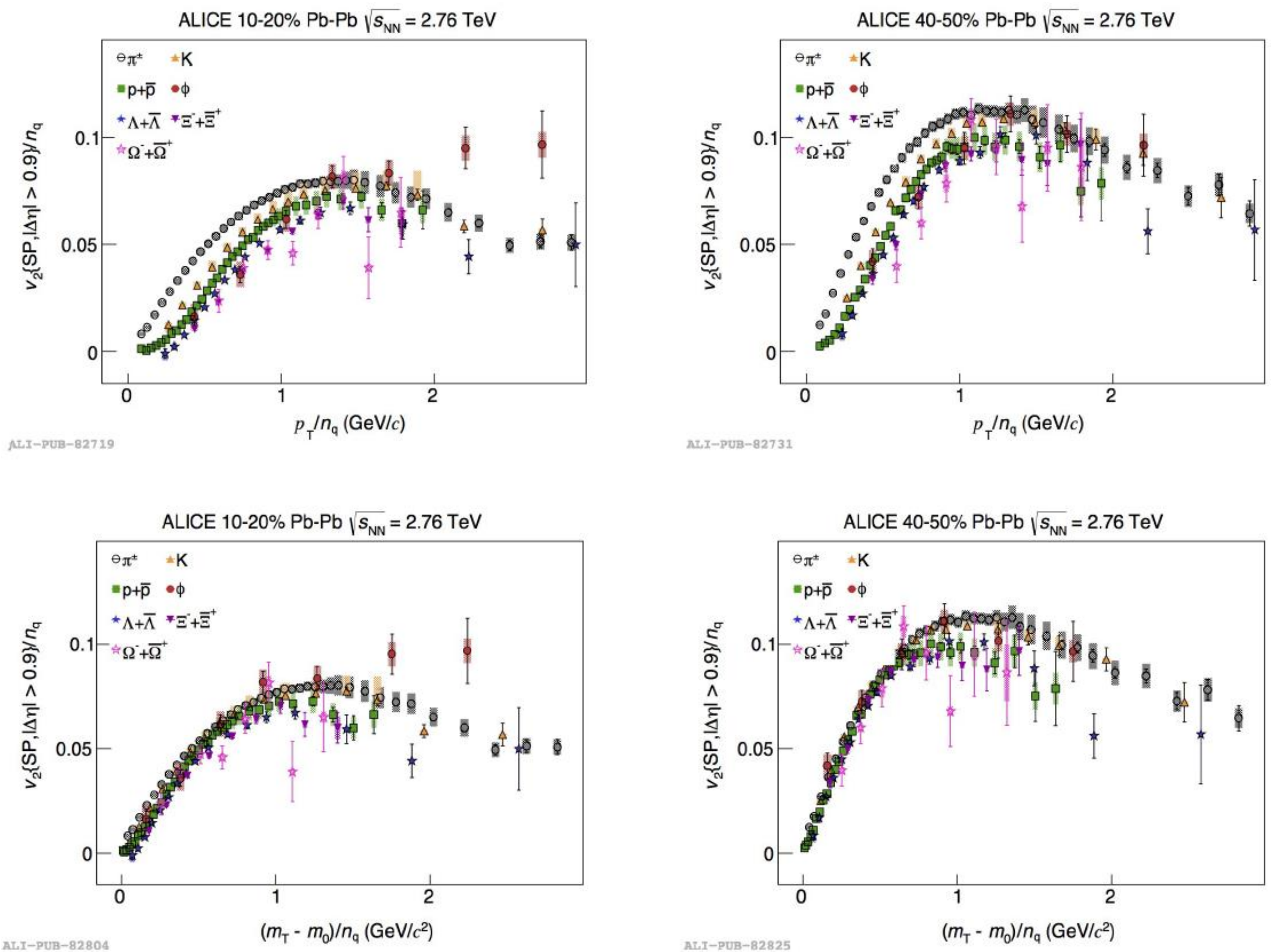
- Small difference between v_2 for $K^{\pm}$ and K_s^0
  - Physics mechanism/detector effect responsible not understood yet
  - v_2 for $K^{\pm}$ and K_s^0 averaged for p_T<4.0 GeV/c in the following slides
- For p_T<2 GeV/c: observe mass ordering indicative of radial flow
- For p_T~2-3.5 GeV/c: crossing between v_2 of p and $\pi^{\pm}$
- For p_T>3 GeV/c: particles tend to group into mesons and baryons
  - v_2 of ϕ follows baryons for central collisions and shift progressively to mesons for peripheral collisions

Comparison with hydrodynamical calculations ($\pi\pm$, p, Λ)

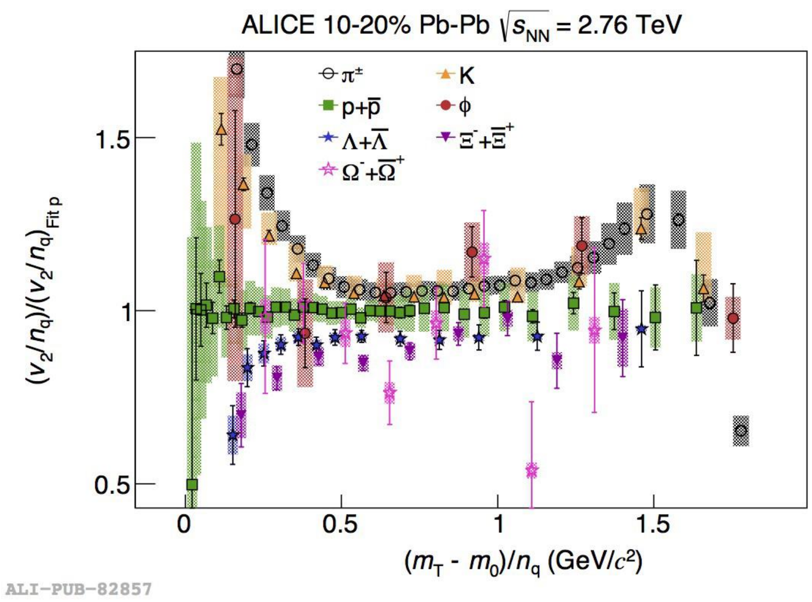


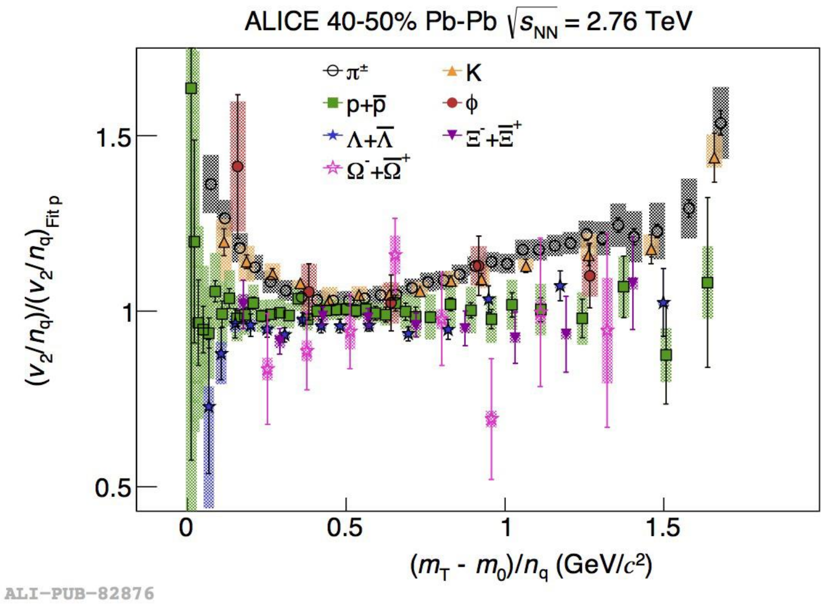
- Hydrodynamical calculations (MC-KLN, η/s=0.16) coupled to a hadronic cascade model (VISHNU) reproduce the main features of v_2 for p_T<2 GeV/c
  - Underestimates the v_2 for $\pi^{\pm}$
  - Underpredicts the v_2 for p
  - Overestimates the v_2 for Λ
    - Mass ordering is broken in the model

p_T/n_q or KE_T/n_q scaling?



KE_T/n_q scaling?



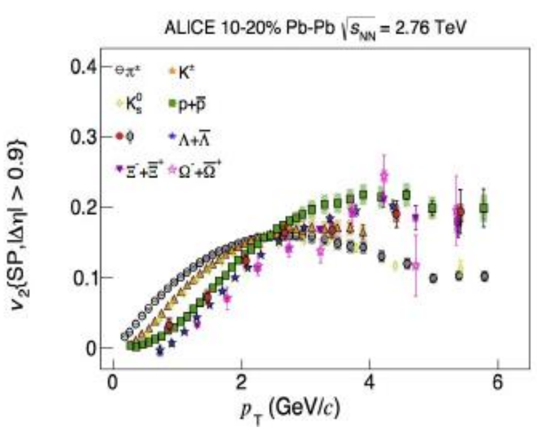


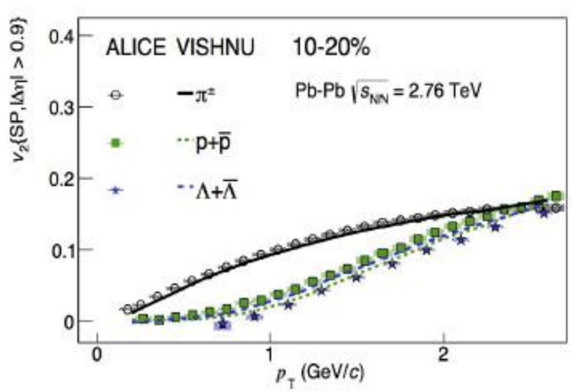
$$KE_T = m_T - m_0 \quad m_T = \sqrt{p_T^2 + m_0^2}$$

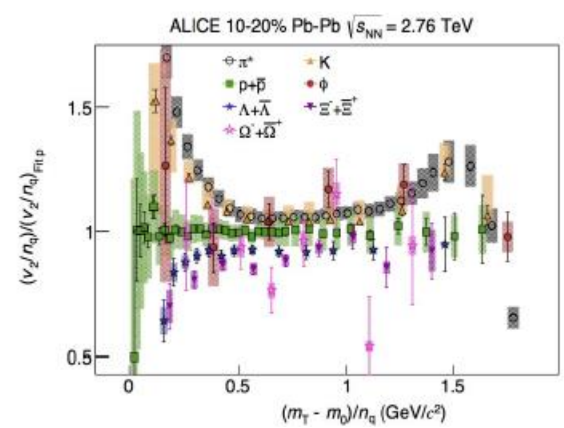
- For KE_T/n_q<0.6-0.8 GeV/c^2: NCQ scaling is broken at the LHC
- For KE_T/n_q>0.8 GeV/c^2: NCQ scaling deviations at the level of ±20%
  - Similar magnitude for all centrality classes

Summary

- v_2 for $\pi^{\pm}$, $K^{\pm}$, p, K_s^0, Λ, ϕ, Ξ, Ω is measured in Pb-Pb collisions using the ALICE detector
  - Observe mass ordering for p_T<2 GeV/*c*
  - Crossing between v_2 of p and π for p_T~2-3.5 GeV/*c*
  - Particles tend to group into mesons and baryons for p_T>3 GeV/*c*
    - v_2 of ϕ follows baryons for central collisions and shift to mesons for peripheral collisions
  - Hydrodynamical calculations (MC-KLN, η/s=0.16) coupled to a hadronic cascade model describe qualitatively the measurements
  - Observe deviations from NCQ scaling at the level of ±20%

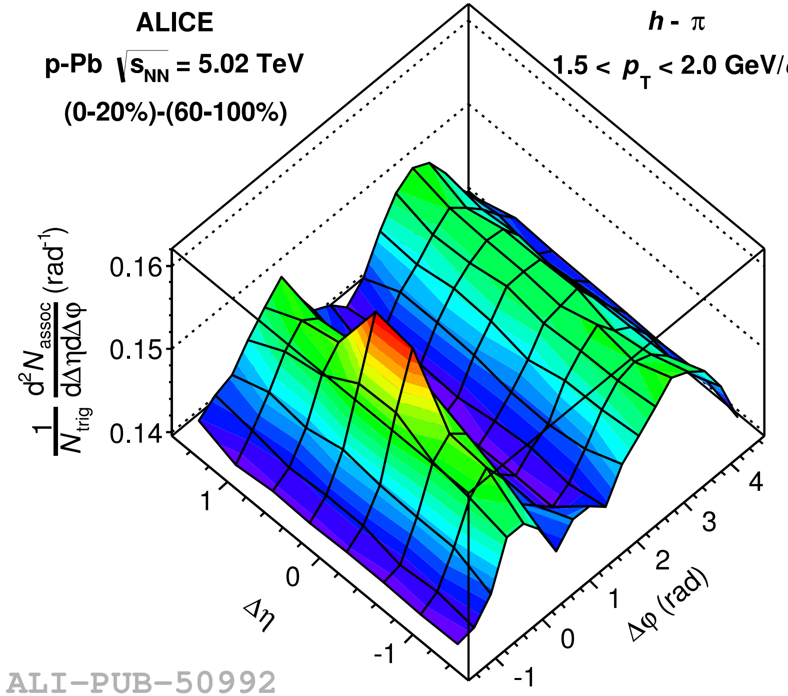


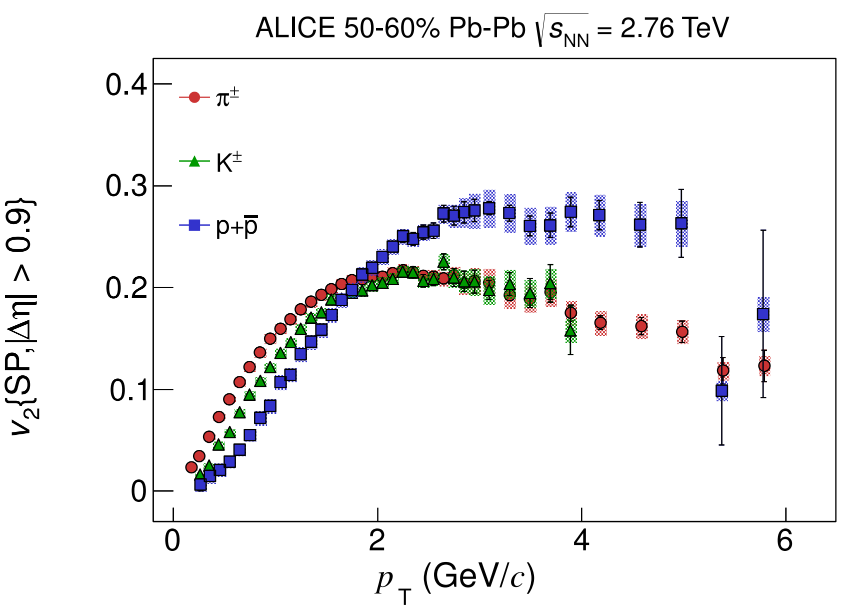




Motivation

- ❑ Double ridge observed in p-Pb collisions
  - ✓ Few or many particle correlations?
- ❑ Flow cumulants sensitive to multi-particle correlations
  - ✓ How do they compare to Pb-Pb at same multiplicity?
- ❑ Mass dependence of v_2 observed in Pb-Pb collisions
  - ✓ Interplay of radial and elliptic flow
  - ✓ What happens in pp and p-Pb collisions?





Phys. Lett. B726 (2014) 164
ALICE PID flow paper just submitted to arivx
p-Pb and Pb-Pb results to be submitted this week

Flow cumulants and coefficients

- ❑ Cumulants formed from v_n moments. Moments from multi-particle correlations (n=flow harmonic, $\langle v_n\rangle^m = \langle m\rangle$).

$$c_n\{2\} = \langle\langle 2\rangle\rangle$$
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$$
$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3$$

$\longrightarrow$

- ❑ Flow coefficients formed from cumulants

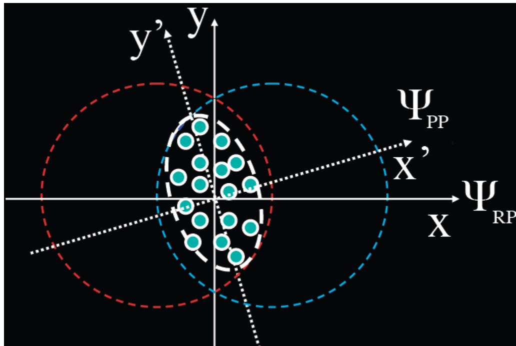
$$v_n\{2\} = \sqrt{c_n\{2\}}$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$
$$v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$$

- ❑ Methods have different sensitivity to flow fluctuations and non-flow

$$v_n\{2\} \cong v_n^2 + \sigma_n^2 + \delta$$
$$v_n\{4\} \cong v_n^2 - \sigma_n^2$$

$v_2\{2\}$ and $v_2\{4\}$ have different sensitivity to flow fluctuations (σ_n) and non-flow (δ)

Plane of symmetry (Ψ_{PP}) fluctuate event-by-event around reaction plane (Ψ_{RP}) => flow fluctuation (σ_n)



- Cumulants:
  - 2- and 4-particle azimuthal correlations for an event:

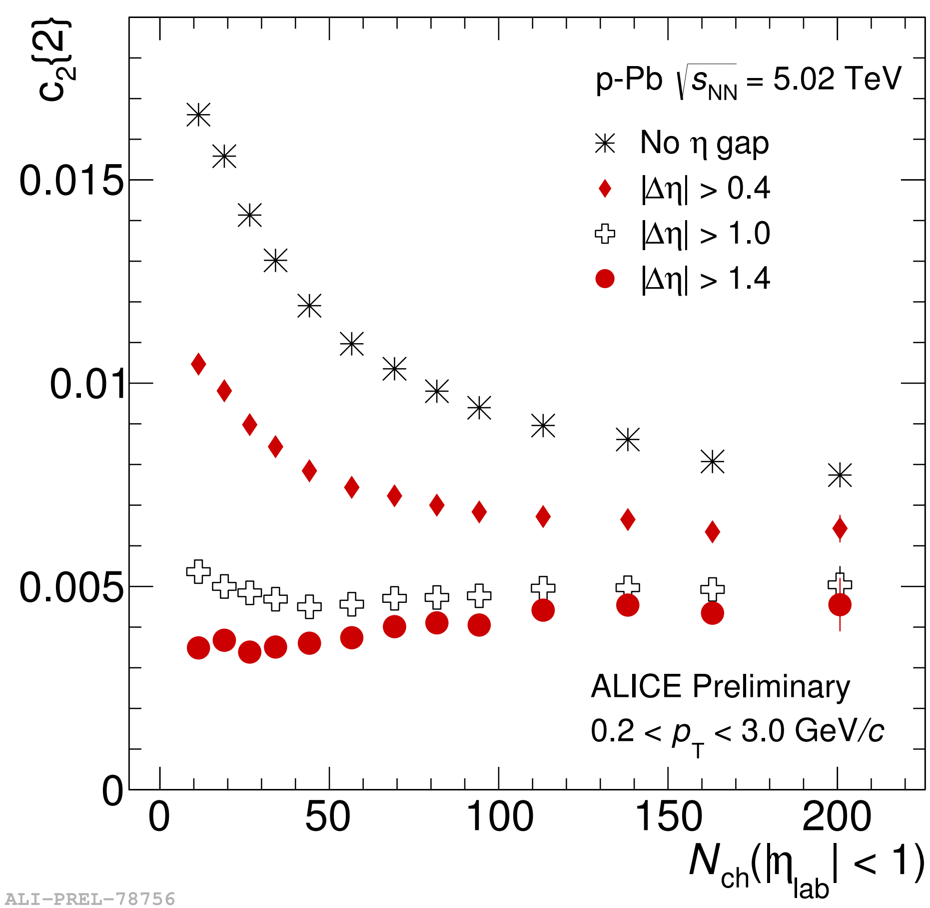
$$\langle 2\rangle \equiv \langle \cos(n(\varphi_i - \varphi_j))\rangle, \varphi_i \neq \varphi_j$$
$$\langle 4\rangle \equiv \langle \cos(n(\varphi_i + \varphi_j - \varphi_k - \varphi_l))\rangle, \varphi_i \neq \varphi_j \neq \varphi_k \neq \varphi_l$$

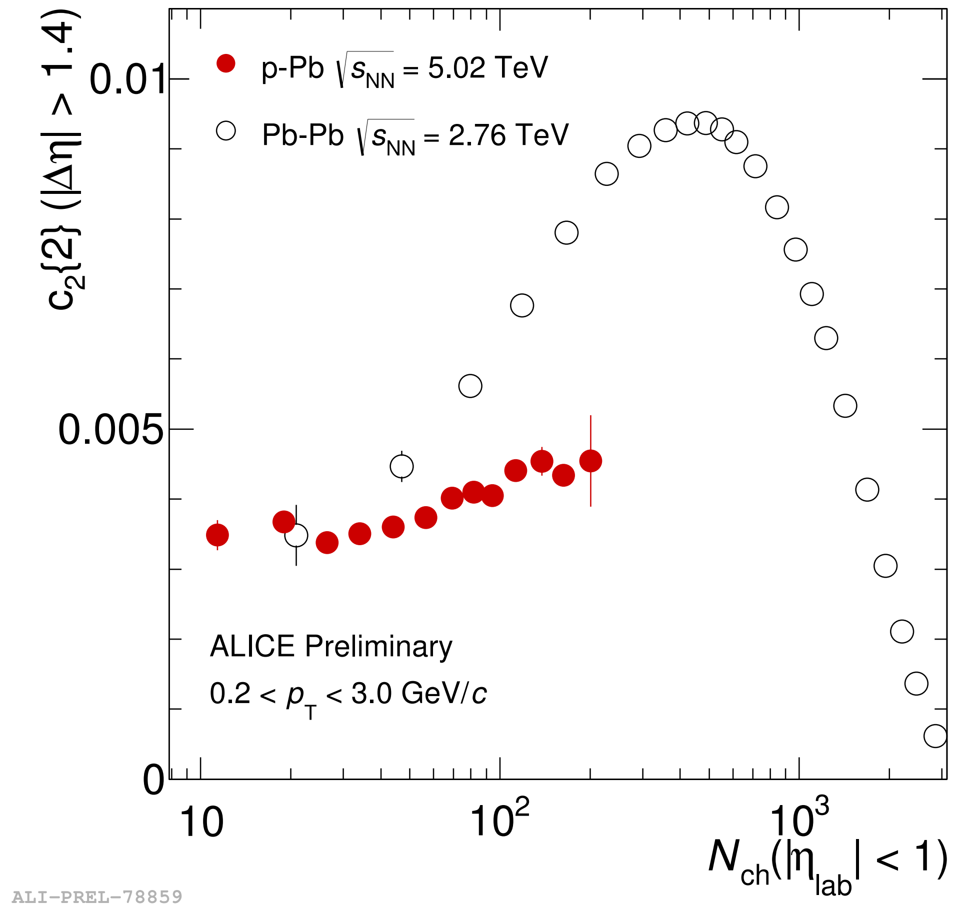
  - Averaging over all events, the 2nd and 4th order cumulants are given:

$$c_2\{n\} = \langle\langle 2\rangle\rangle = v_n^2 + \delta_n$$
$$c_4\{n\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2 = -v_n^4$$

$c_2\{2\}$ in p-Pb and Pb-Pb

$$v_2\{2\} = \sqrt{c_2\{2\}}$$



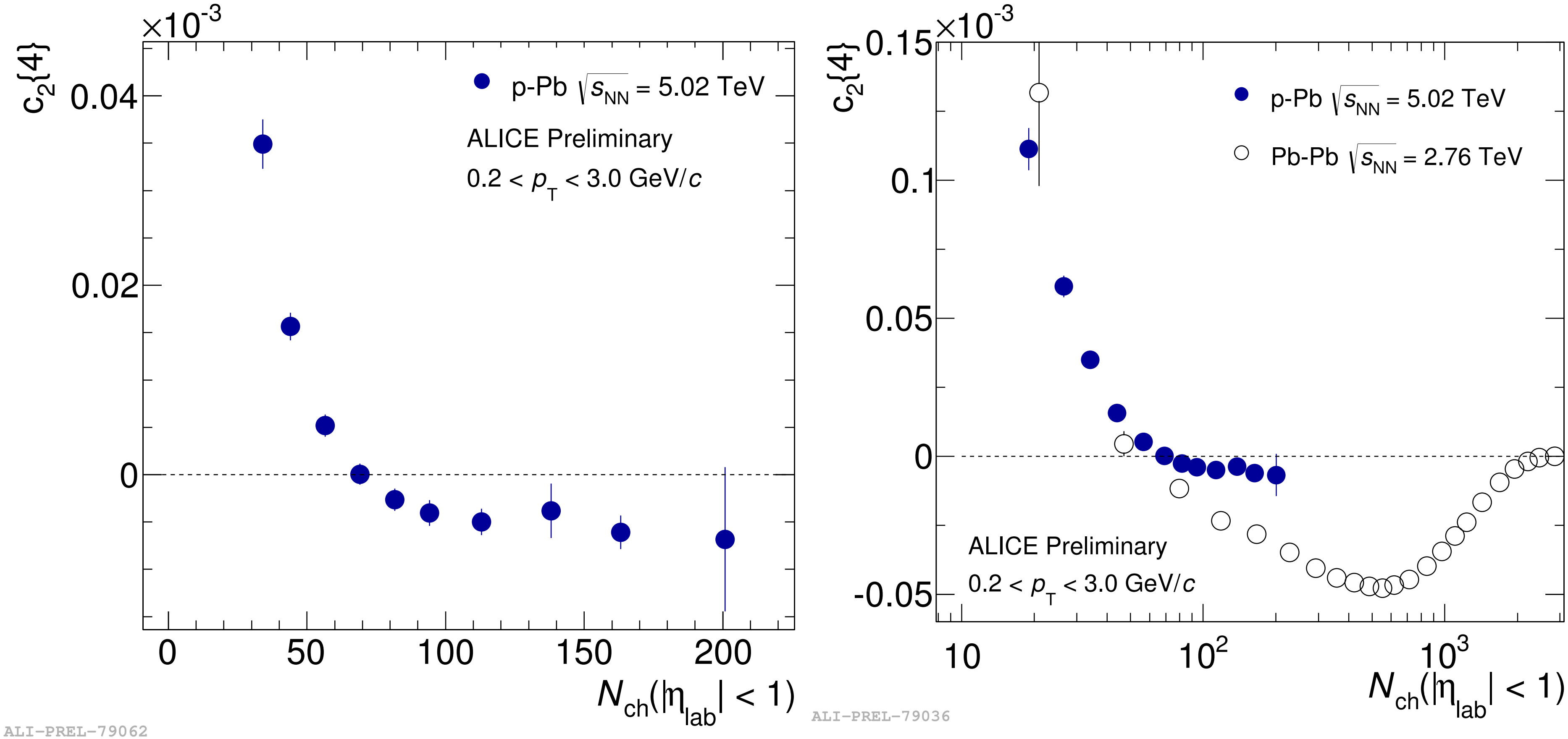


- p-Pb $c_2\{2\}$ rises for large Δη gap. Inconsistent with naïve expectations of non-flow

- Pb-Pb $c_2\{2\}$ values bigger at same $N_{ch.}$
  - ✓ ε_2 (Pb-Pb) $_{RMS}$ driven by geometry & fluctuations.
  - ✓ ε_2 (p-Pb) $_{RMS}$ by just fluctuations?

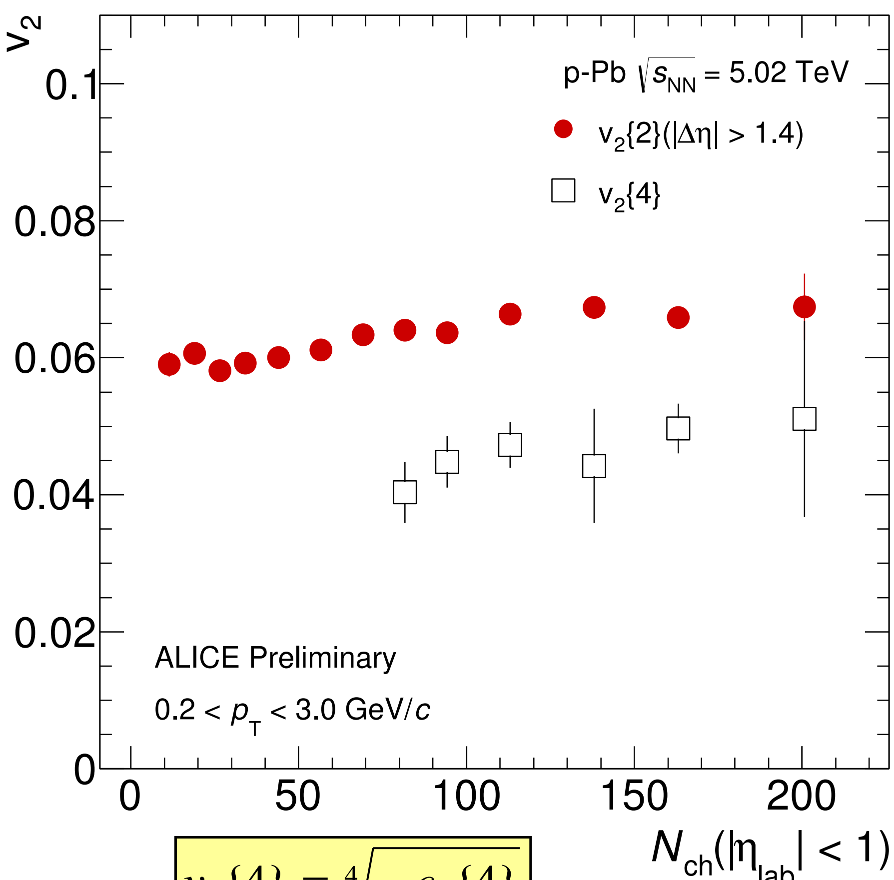
$c_2\{4\}$ in p-Pb and Pb-Pb

$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$



- p-Pb $c_2\{4\}$ switches from pos. to neg. at high $N_{ch.}$ ($v_2\{4\}$ becomes real).
- Pb-Pb $c_2\{4\}$ values more neg. at same N_{ch} after N_{ch} > 100

$v_2\{2\}$ and $v_2\{4\}$ in p-Pb



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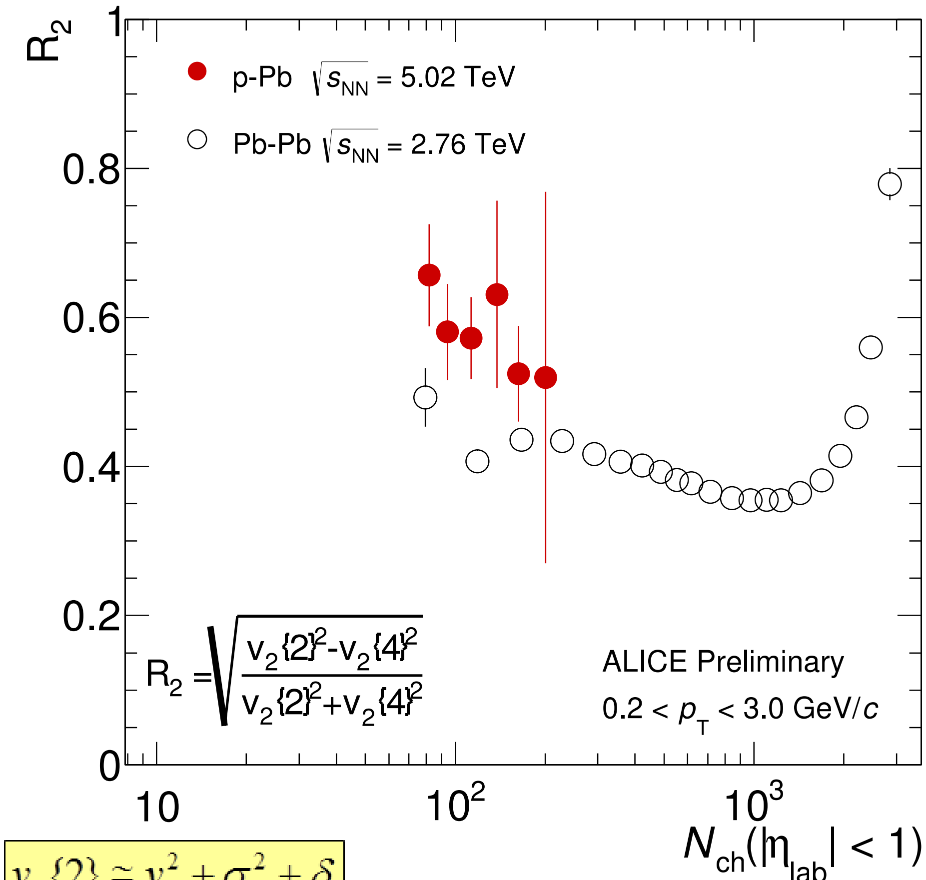
$$v_n\{4\} \equiv \sqrt[4]{-c_n\{4\}}$$

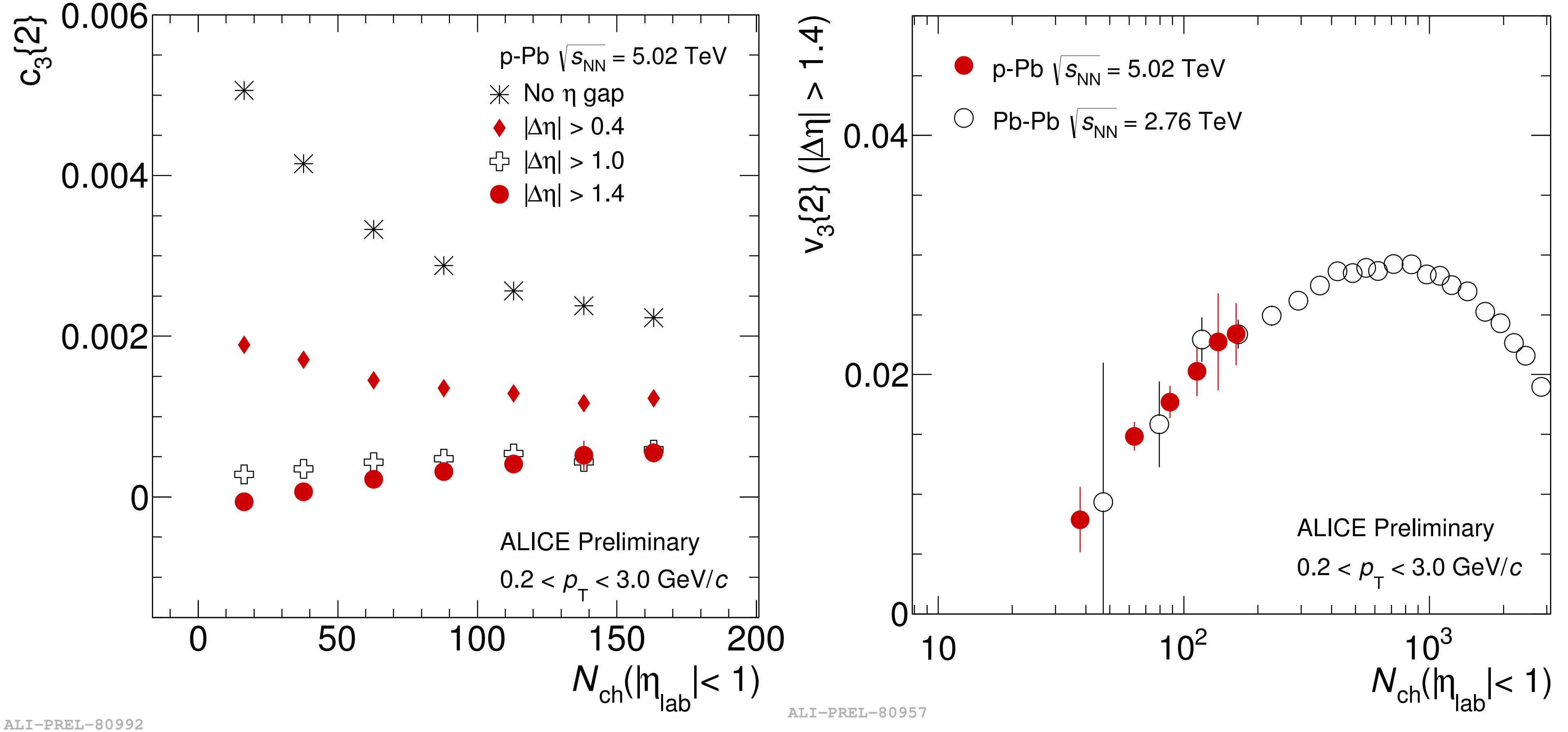


$$v_n\{2\} \cong v_n^2 + \sigma_n^2 + \delta$$

$$v_n\{4\} \cong v_n^2 - \sigma_n^2$$

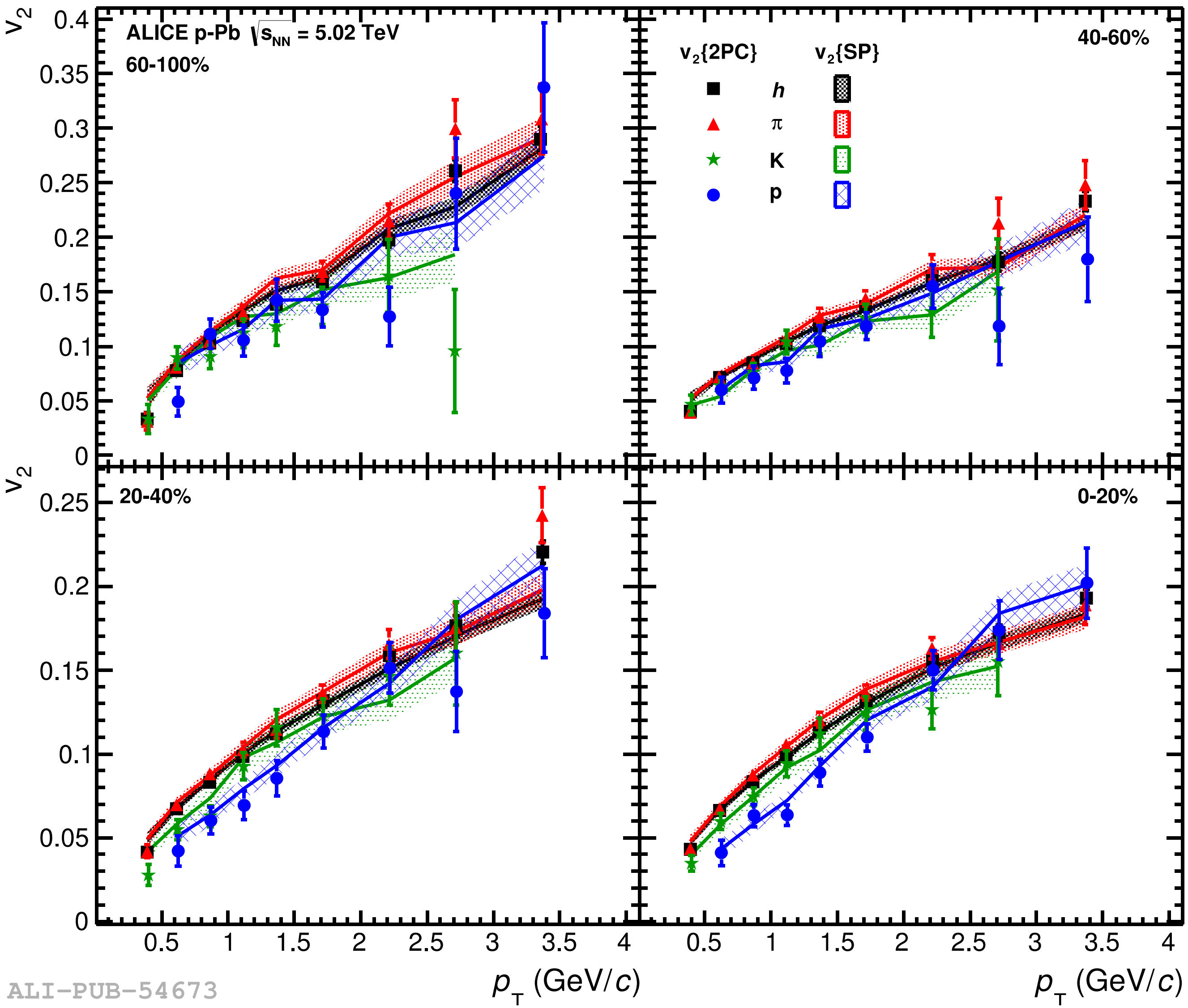
- $v_2\{2\} > v_2\{4\}$ in p-Pb -> Indicative of flow fluctuations? Contributions from non-flow?
- R_2 approximates $\sigma_{v2}/\langle v_2 \rangle$. Fluctuations larger in p-Pb compared to Pb-Pb.

Third harmonic in p-Pb and Pb-Pb collisions



- Large dependence on Δη gap for $c_3\{2\}$. Increases with N_{ch} for large Δη
- $v_3\{2\}$ consistent with Pb-Pb at same N_{ch}
  - ✓ $\varepsilon_3(\text{p-Pb})_{RMS} \sim \varepsilon_3(\text{Pb-Pb})_{RMS}$ and driven by fluctuations?

v_2\{SP\} and v_2\{2PC\} in p-Pb

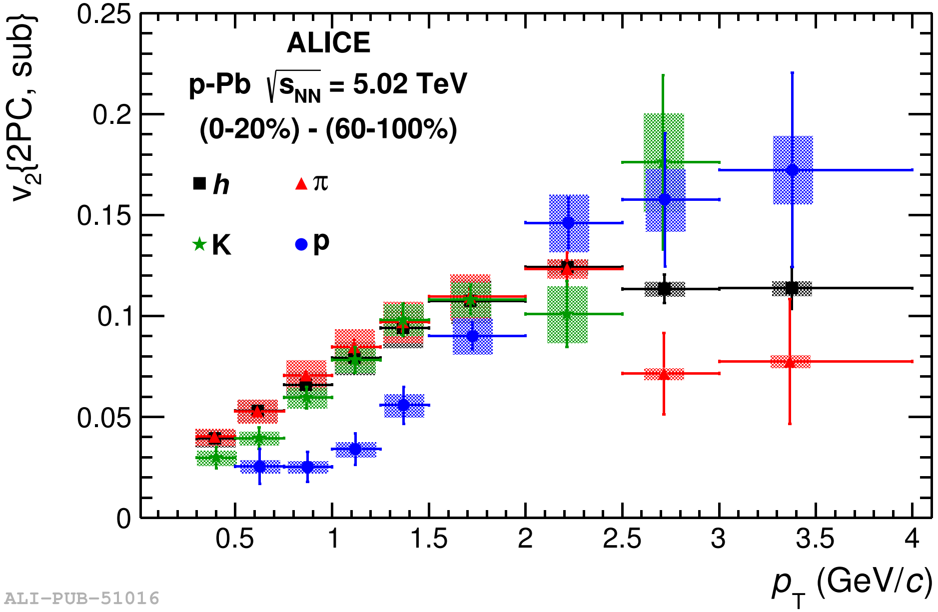


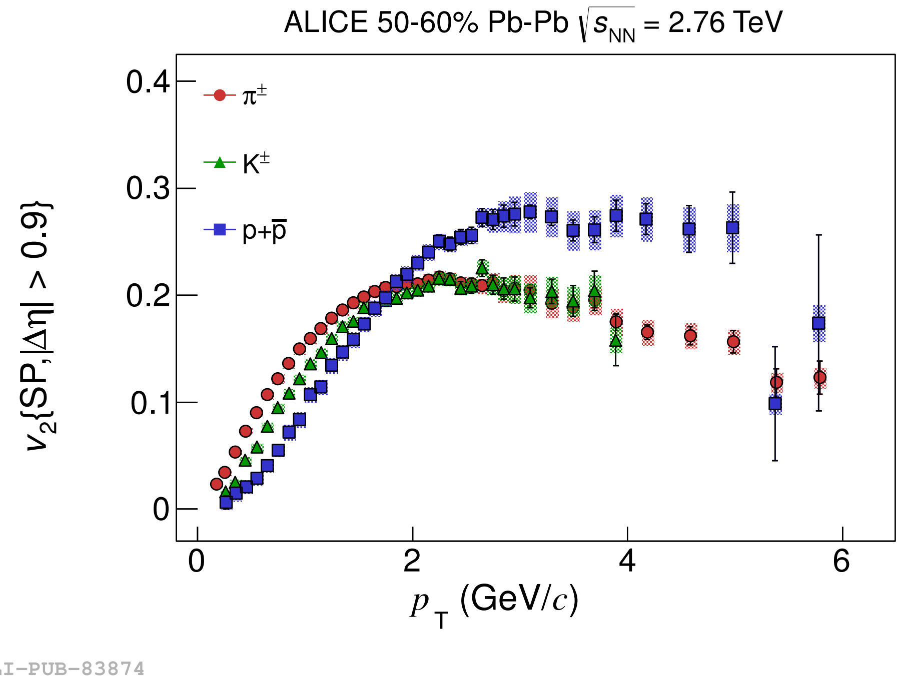
- Both v_2\{SP\} and v_2\{2PC\} equivalent for current p_T selections
- "Centrality" characterized via multiplicity in V0 (Pb side)
- Mass ordering at high multiplicity
  - ✓ Different to pp
  - ✓ $v_2(p) < v_2(K)$
  - ✓ $v_2(\pi) \sim v_2(K)$
  - ✓ Hint of cross over in high mult. classes

2PC = di-hadron correlations

See ALICE talks by Alex Dobrin and Leonardo Milano for more details

v_2\{2PC, sub\} in p-Pb





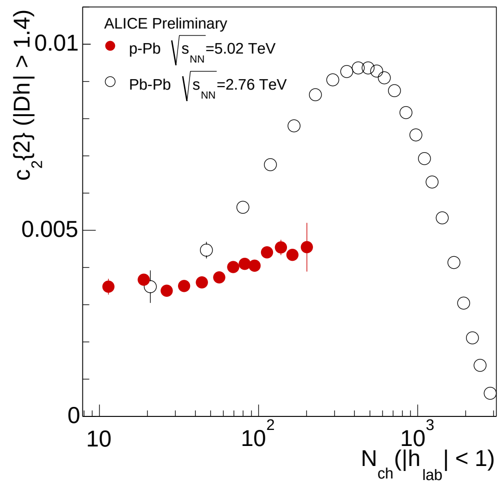
- v_2\{2PC, sub\}: Obtained via central yields – peripheral associated yields
  - ✓ Aims to subtract non-flow
  - ✓ Mass dependence more pronounced.
  - ✓ Cross over of $v_2(\pi)$ & $v_2(p)$
- Qualitatively more similar to Pb-Pb.

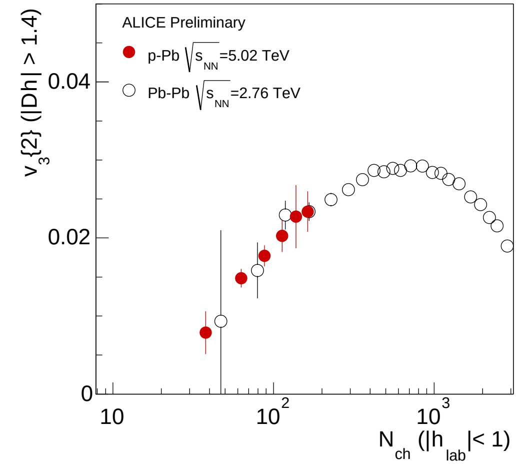
Summary

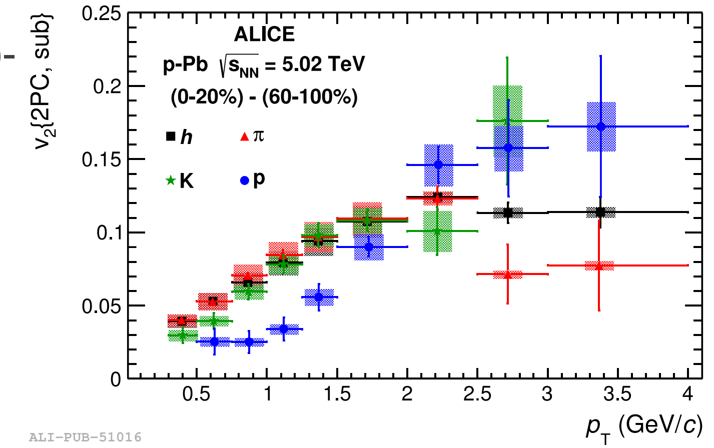
- Experimental observations **highly suggestive of collective** effects in **high mult. p-Pb collisions**

- Integrated $h^{\pm}$ v_n measurements
  - ✓ $c_2\{2\}$ rises in p-Pb with N_{ch} for large $|\Delta\eta|$. Naively inconsistent with non-flow.
  - ✓ $c_2\{4\}$ in p-Pb transitions from pos. to neg. values. $v_2\{4\}$ becomes real.
  - ✓ $c_2\{m\}$ higher in Pb-Pb compared to p-Pb at same $N_{ch.}$
  - ✓ $v_3\{2\}$ in p-Pb and Pb-Pb similar at same $N_{ch.}$

- Differential PID v_2 measurements
  - ✓ Different mass ordering in minbias pp and high mult. p-Pb.
  - ✓ Mass ordering in high mult. p-Pb more pronounced after non-flow subtraction.
  - ✓ Qualitative similar features to Pb-Pb collisions.







CMS Results

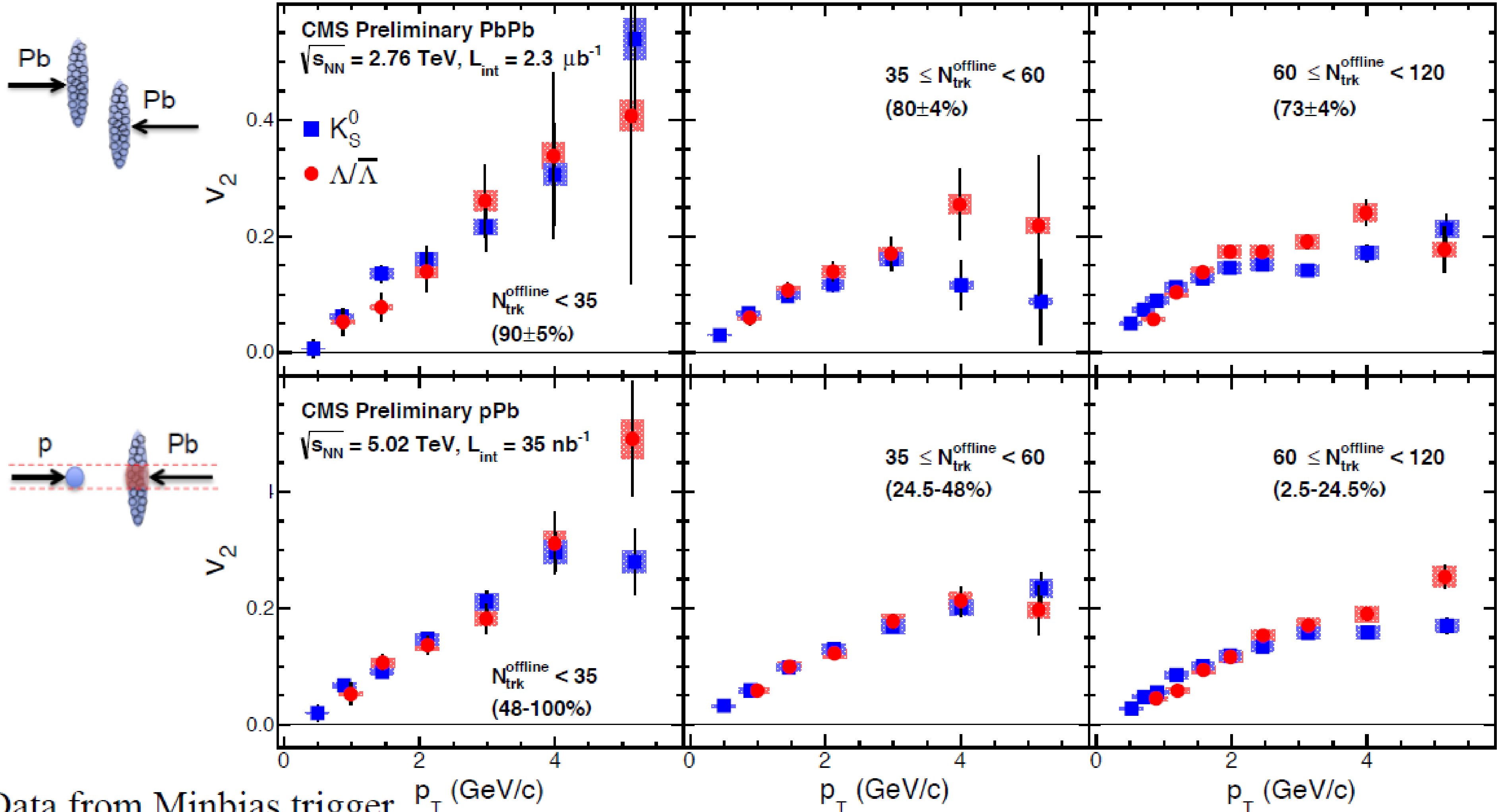
Extracted from the following talks.

1. "Long range two-particle correlations with K_0^S and Λ in pPb and PbPb collisions" by Monika Sharma

2. "Pseudorapidity dependence of long-range two-particle correlations in pPb collision at CMS" by Lingshan Xu

3. "Azimuthal Anisotropy of Charged Particles from Multiparticle Correlations in pPb and PbPb Collisions" by Quan Wang

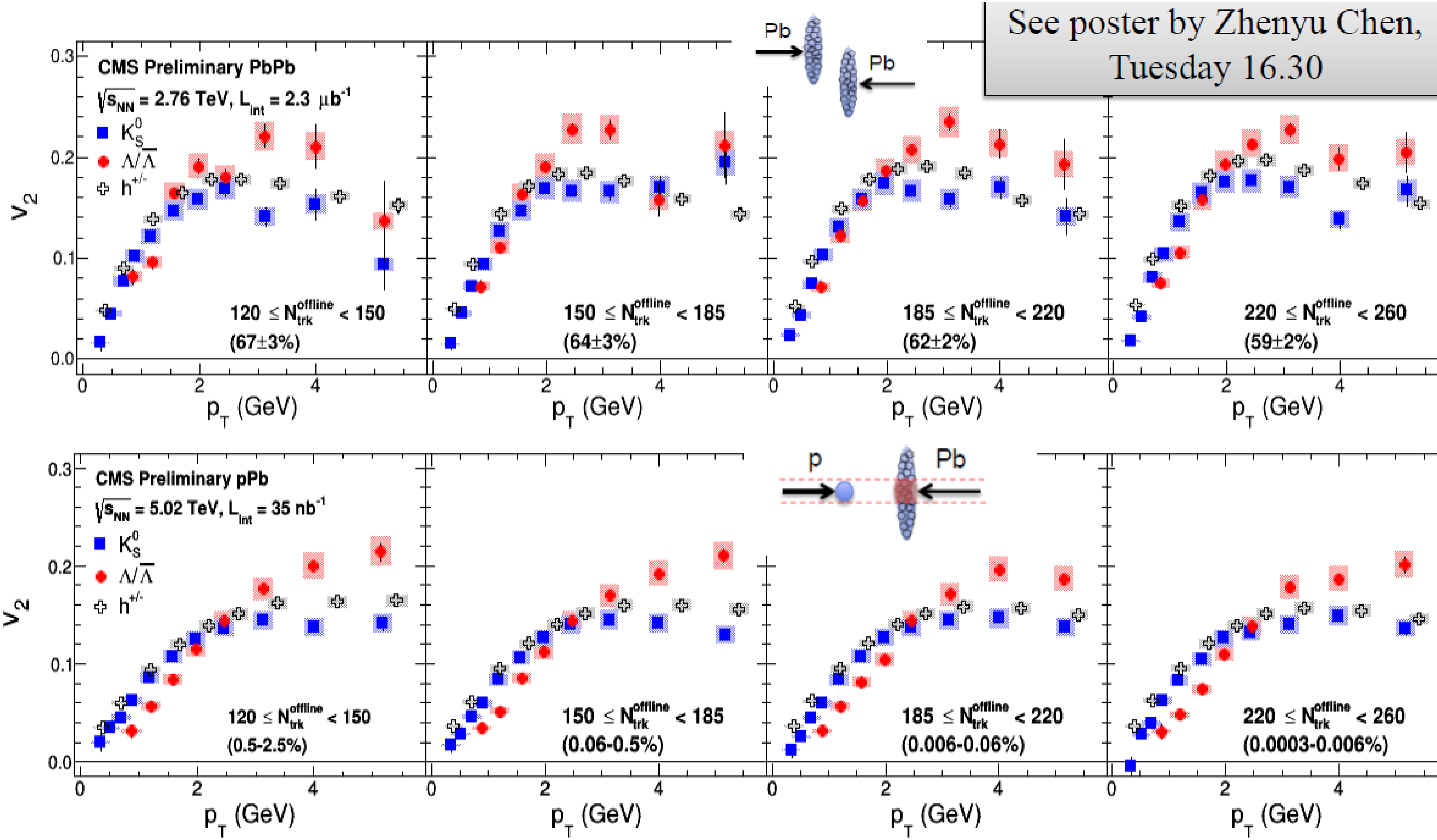
Low multiplicity: pPb and PbPb collisions



Data from Minbias trigger

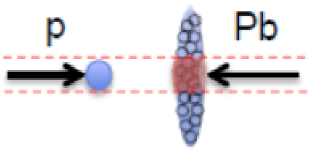
- v_2 patterns almost the same for $K^0{}_S$ and Λ at low multiplicity in both collision systems
- Crossing over observed for p_T around 2 GeV/c for 60 – 120 multiplicity range

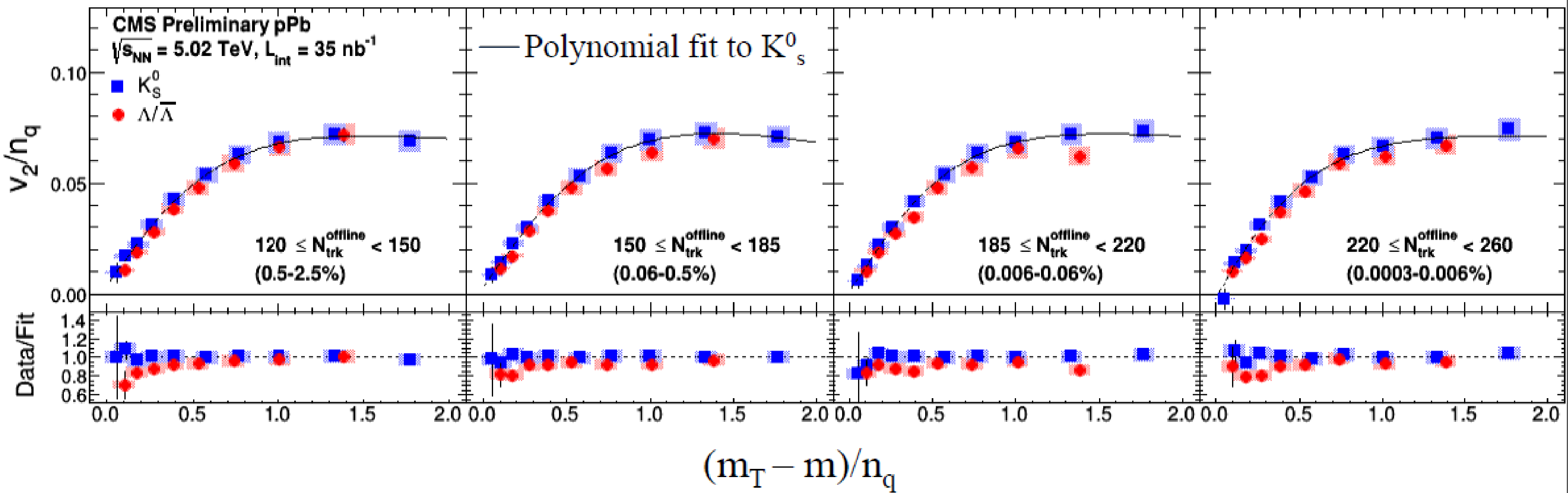
Higher multiplicity class: pPb and PbPb collisions



Mass ordering (below ~2 GeV/c) and cross-over (above ~ 2 GeV/c) observed

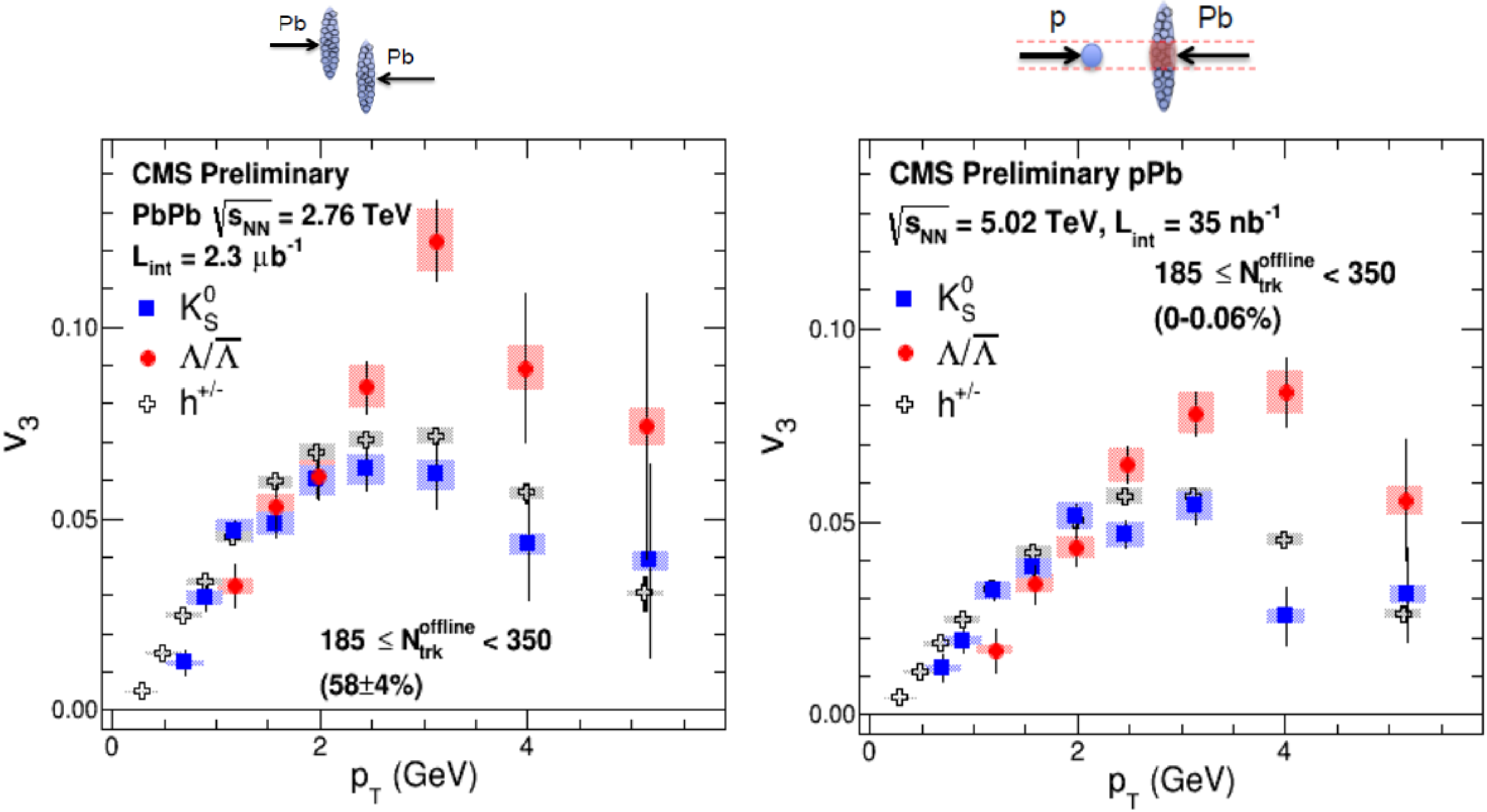
NCQ scaling in high multiplicity pPb collisions





Azimuthal anisotropy develops at the partonic level in pPb collisions?

v_3 in higher multiplicity



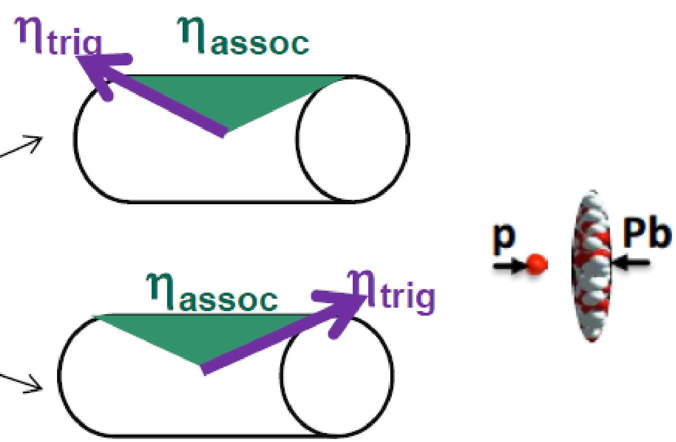
Cross-over (above ~ 2 GeV/c) observed

Conclusions

- Presented the second-order (v_2) and third-order (v_3) anisotropy harmonics of K^0_S and Λ for high-multiplicity in pPb collisions
  - Results were compared to similar multiplicities in PbPb collisions
- Low multiplicity in pPb and PbPb collisions:
  - v_2 patterns are almost the same for K^0_S and Λ
- Higher multiplicity in pPb and PbPb collisions:
  - Mass ordering prominently observed in pPb collisions compared to PbPb collisions
  - Cross-over is seen at p_T around 2 GeV/c
- NCQ scaling observed for v_2 in pPb collisions

Analysis procedure

- Previous analyses integrated over trigger and associate η. Possible $\Delta\eta$ dependence is averaged out.
- Use fixed narrow trigger η range:



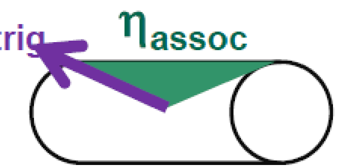
  - ❑ $-2.4 < \eta_{trig} < -2.0$ (Pb-going side)
  - ❑ $2.0 < \eta_{trig} < 2.4$ (p-going side)

  - Two-particle acceptance is 100%; no need to divide by mixed-events.
  - Efficiency corrected for associated particles.
  - Correlation normalized per trigger particle.
  - p_T^{trig} = 0.3-3 GeV/c, p_T^{assoc} = 0.3-3 GeV/c
  - Low-multiplicity: $2 \le N_{trk}^{offline} < 20$. High-multiplicity: $220 \le N_{trk}^{offline} < 260$

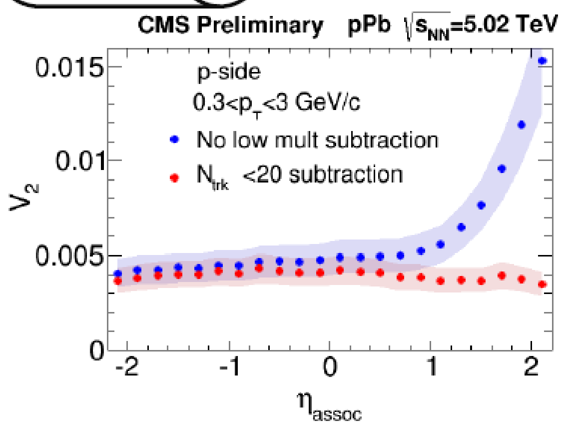
Fourier coefficients V_n from dihadron correlation

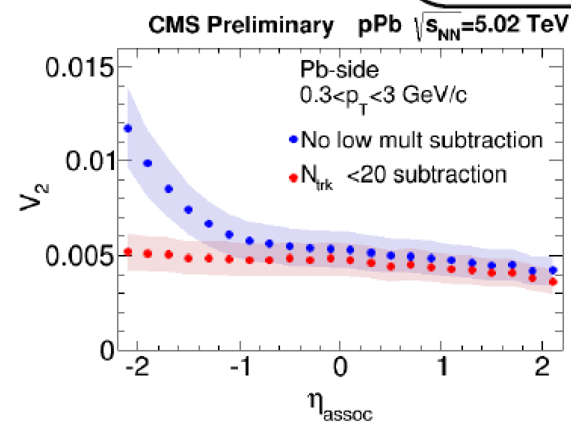
p-going trigger

Pb-going trigger



V_2

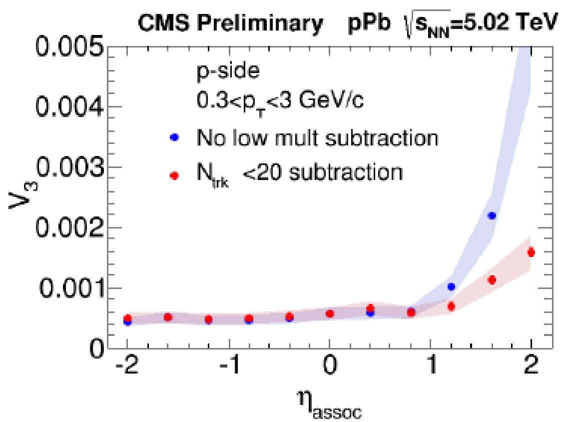


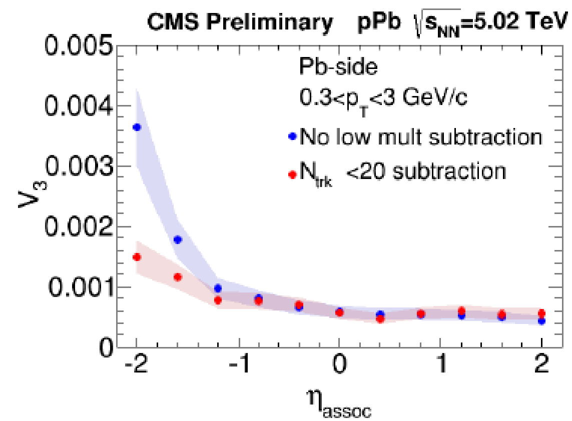


Blue: no jet Subtraction

Red: with jet subtraction

V_3

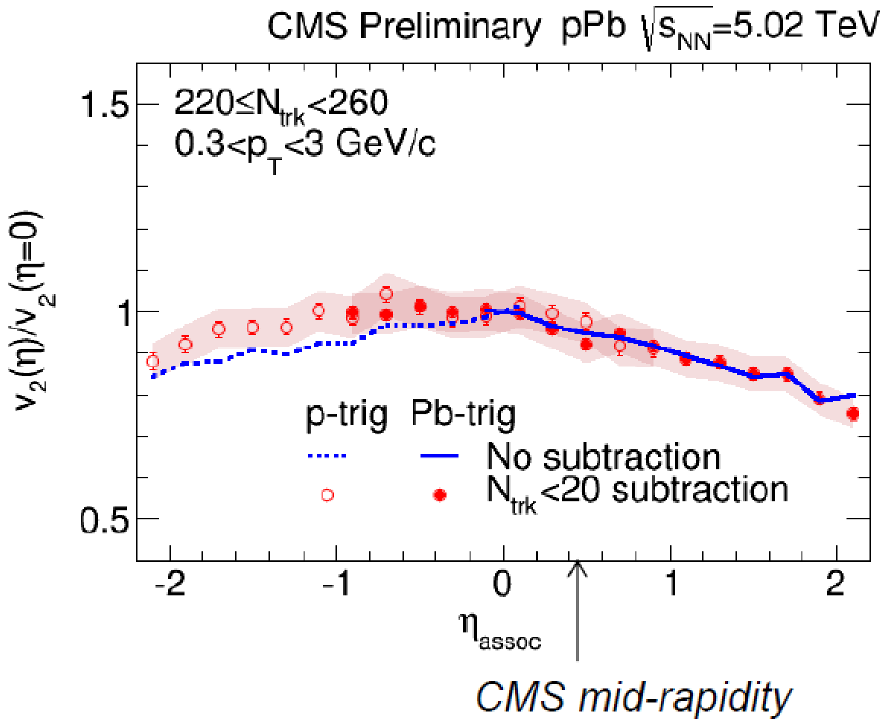




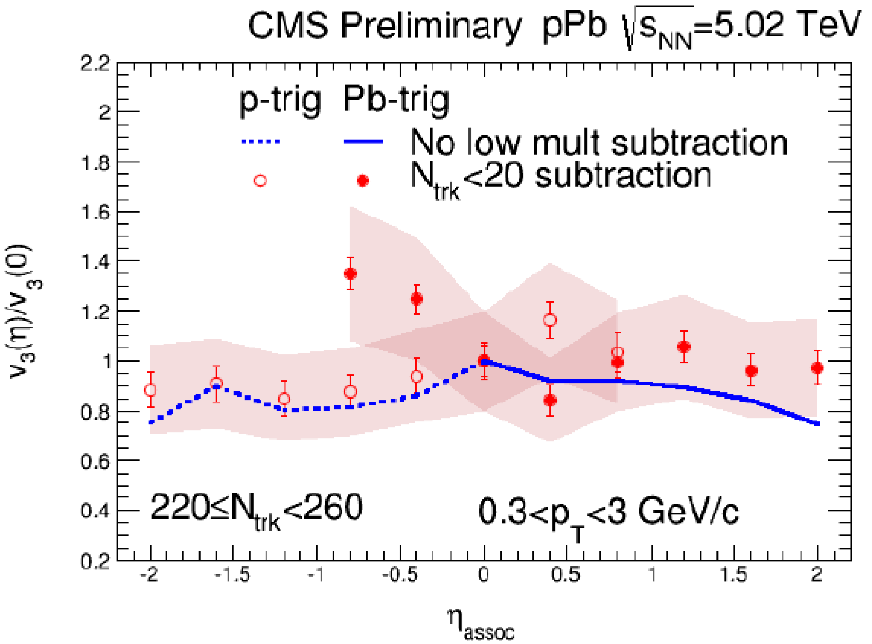
- Jet contribution mostly removed at short range.
- Small difference at long range: away jet contribution is small

Extract $v_n(\eta)/ v_n(0)$ from Fourier coefficient

$v_2(\eta)/ v_2(0)$:



$v_3(\eta)/ v_3(0)$:



- v_2 shape is η dependent !
- v_2 from low-mult. subtraction: asymmetric about mid-rapidity
- With large errors, cannot draw conclusion for v_3

Conclusions

- Two-particle correlations studied in pPb, with trigger particles restricted to fixed, narrow windows, for

  Pb-going side ($-2.4 < \eta_{trig} < -2.0$) and

  p-going side ($2.0 < \eta_{trig} < 2.4$)

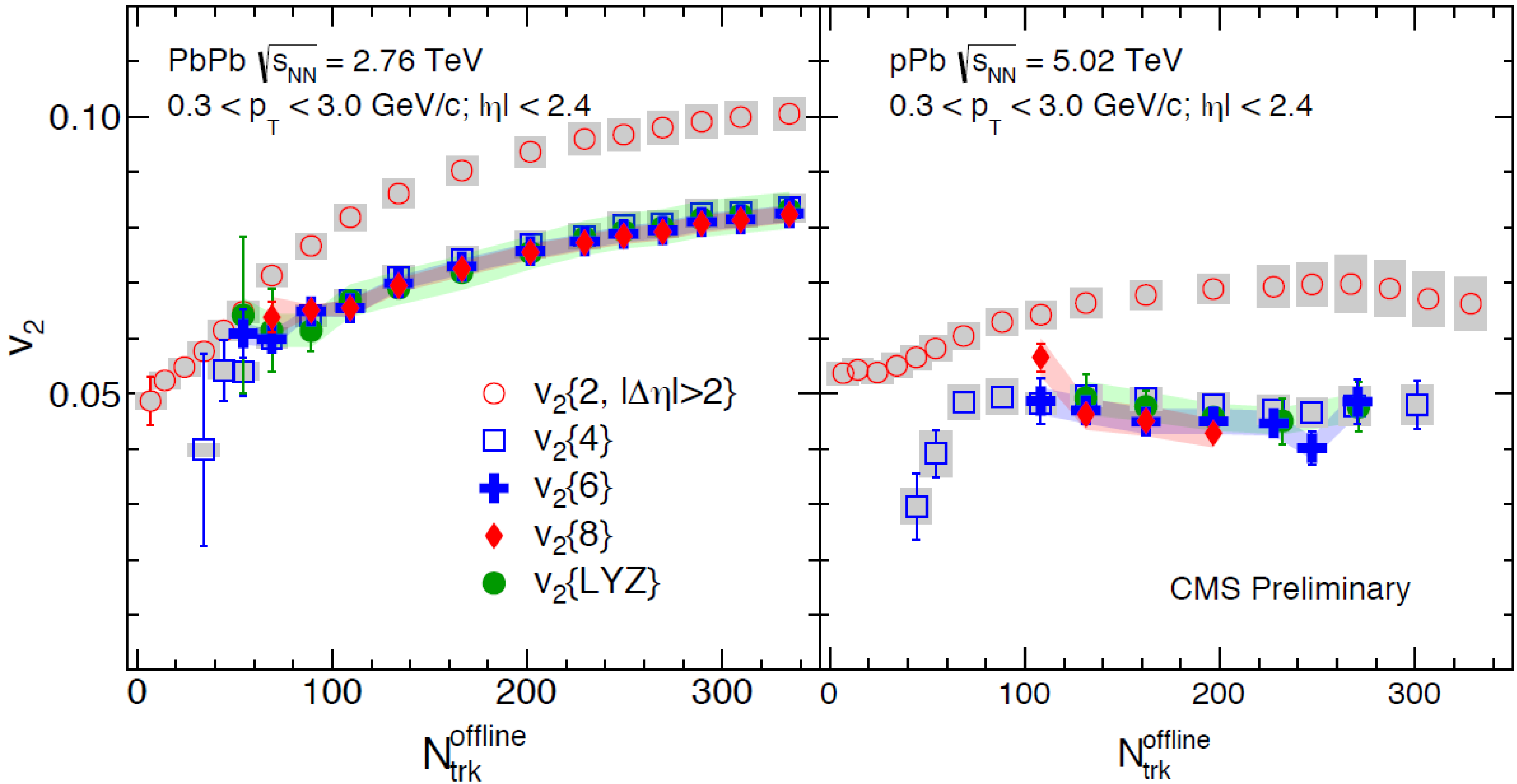
- Near-side jet and ridge decomposed:

  Ridge yield depends on η, and different for Pb-going and p-going triggers.

- Fourier coefficients and self-normalized single-particle harmonics extracted:

  Significant η dependence observed for v_2.

Results – v_2



"Lee-Yang Zeros"
all-particle correlation

- $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ and $v_2\{LYZ\}$ are in good agreement ±10%

Result – Cumulant v_2 ratios

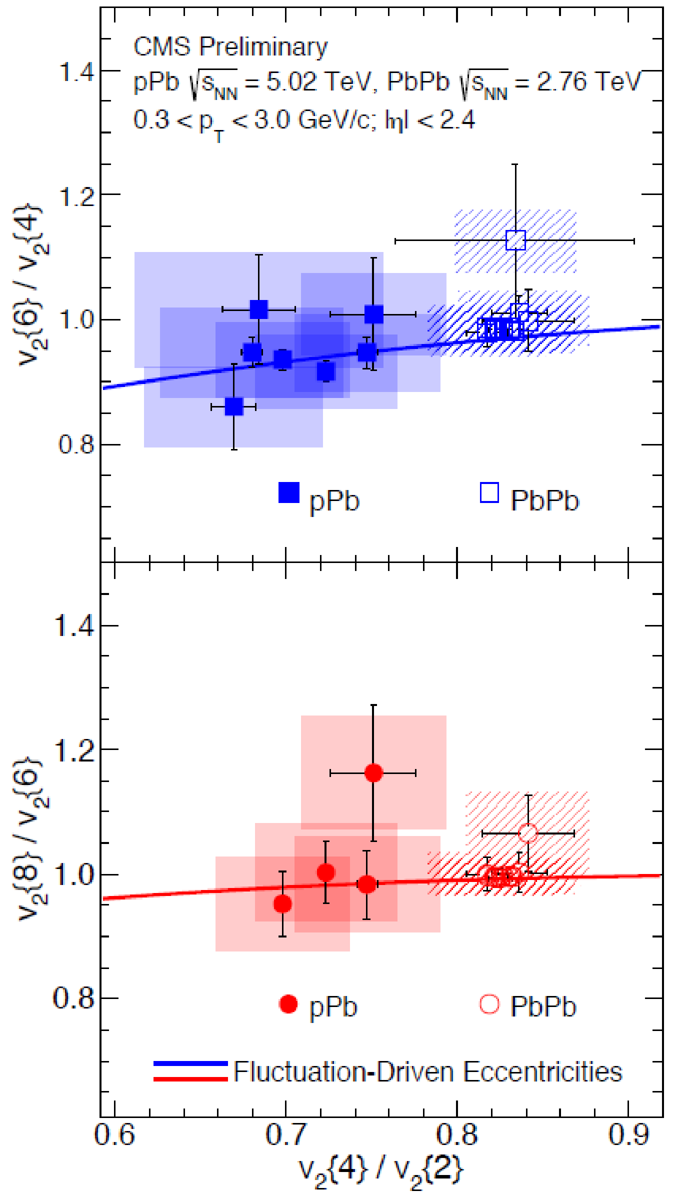
- In hydrodynamic picture
  - arXiv:1311.7325 (Bzdak, Bozek & McLerran)
  - PRL 112 (2014) 082301 (Yan & Ollitrault)

$$\varepsilon_2\{4\} \cong \varepsilon_2\{6\} \cong \varepsilon_2\{8\}$$

$$v_2\{4\} \cong v_2\{6\} \cong v_2\{8\}$$

- Fluctuation-driven initial-state eccentricities

[PRL 112 (2014) 082301 (Yan & Ollitrault)]



Summary

- 6-, 8- and all-particle correlations are measured for the first time in pPb collisions at 5.02 TeV
- A direct comparison is made between pPb and PbPb as a function of multiplicity
- $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ and $v_2\{LYZ\}$ are consistent within 10% in pPb and PbPb, respectively
- Relative ratios of v_2 from cumulant methods are consistent with hydrodynamic predictions within current statistical precision

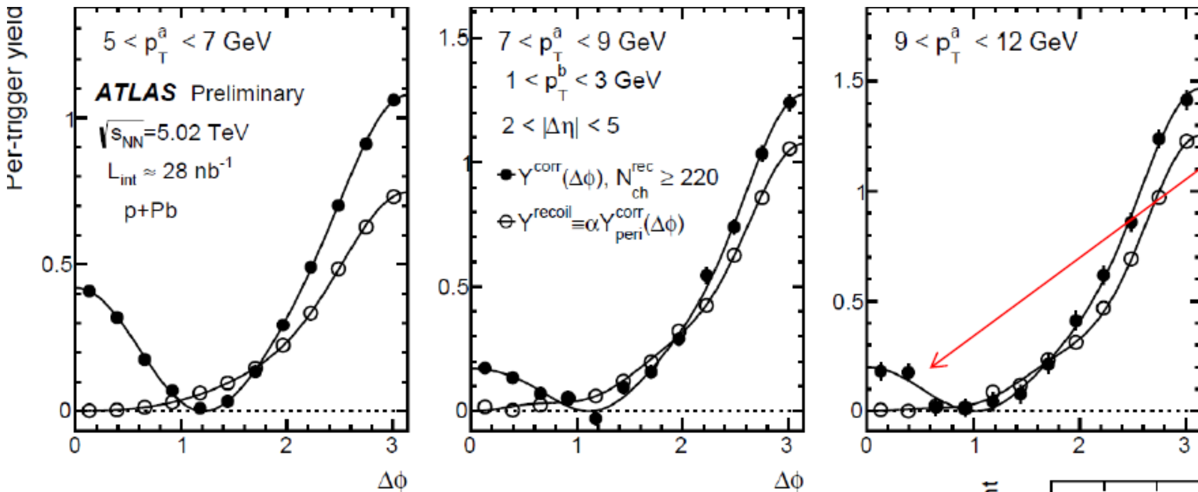
ATLAS Results

Extracted from the following talks.

1. "Measurement of the long-range pseudorapidity correlations and azimuthal harmonics in $\sqrt{s}$=5.02 TeV proton-lead collisions with the ATLAS detector" by Sooraj Radhakrishnan

2. "Flow harmonics in Pb+Pb collisions at energy of $\sqrt{s_{NN}}$ = 2.76 TeV with the ATLAS detector" by Dominik Derendarz

Ridge at higher p_T

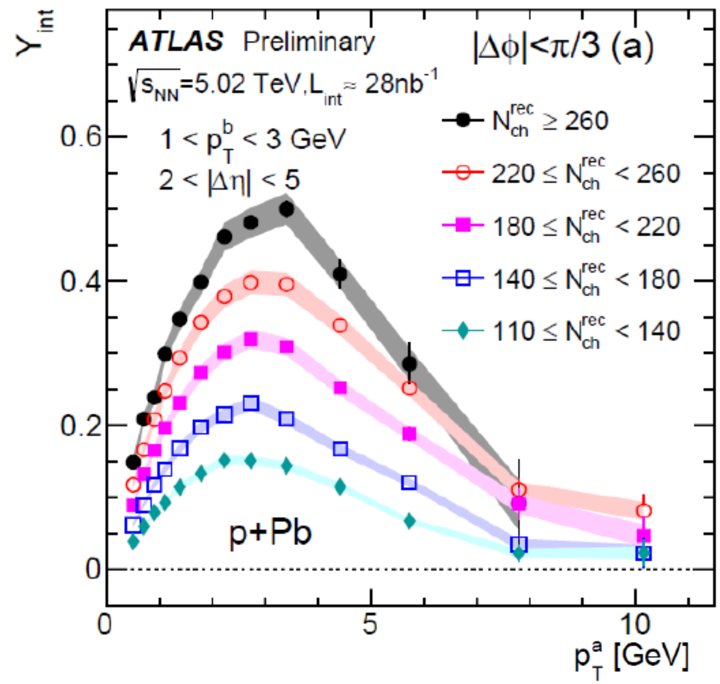


- Near-side ridge visible through the entire p_T range studied.

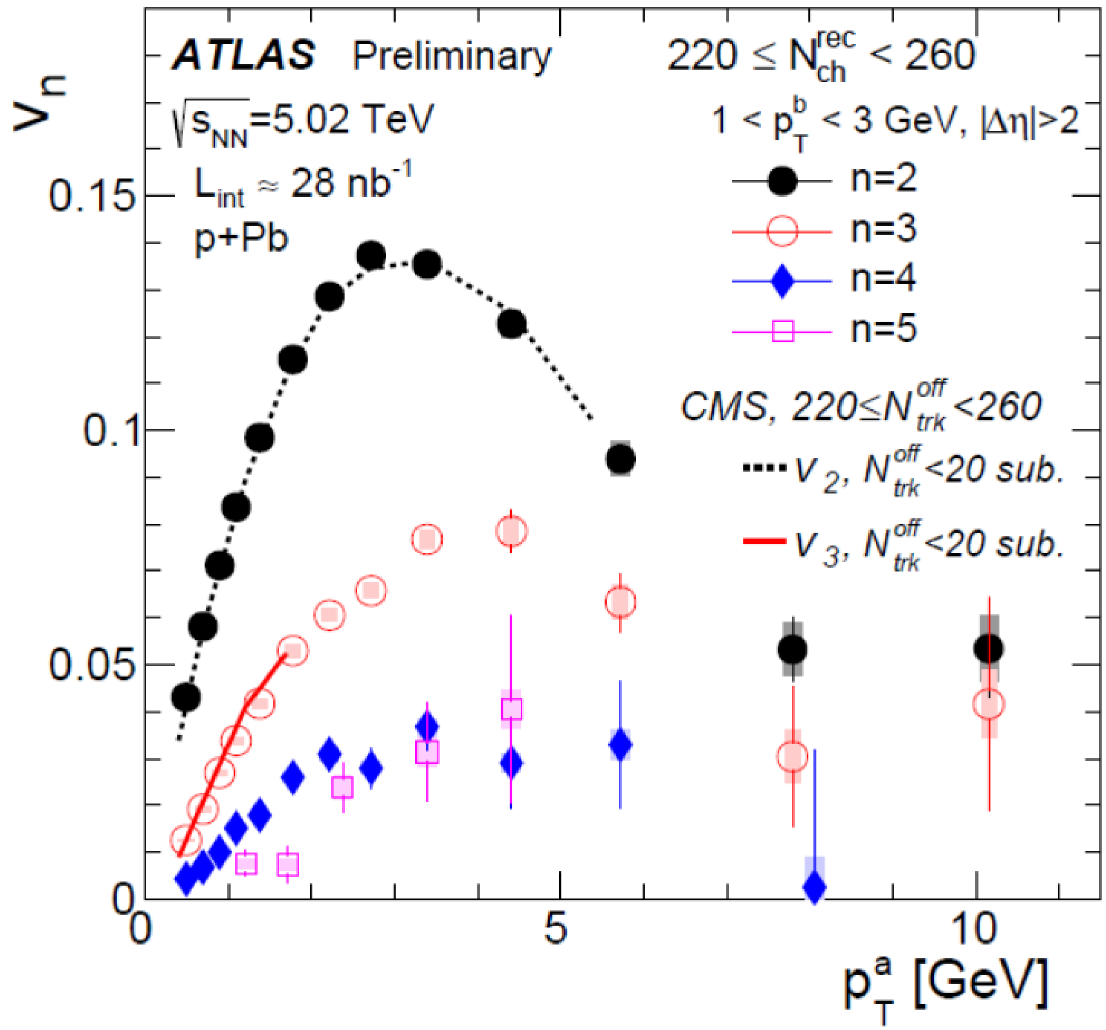
$$Y^{corr}(\Delta\phi) = \frac{\int B(\Delta\phi)d\Delta\phi}{\pi}\left(\frac{S(\Delta\phi)}{B(\Delta\phi)} - b_{ZYAm}\right)$$

- Integrated yield on near-side:
  - increase with p_T
  - reaches maximum ~ 3 -- 4 GeV and then decreases.

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

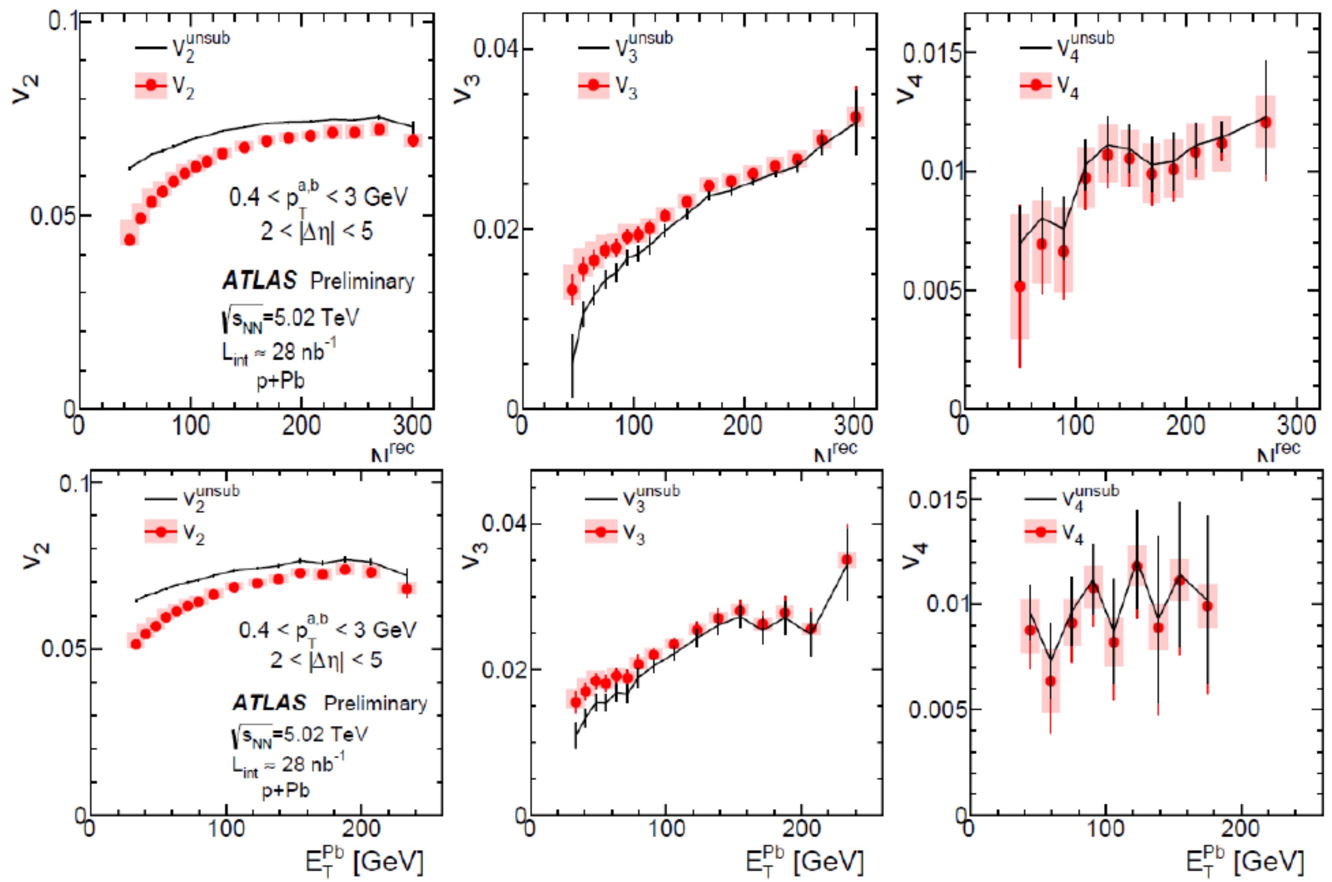


v_n vs p_T for different n



- v_n decrease with increasing n.
- Rise with p_T at low p_T and then decraese.
- Non-zero v_5 in high multiplicity event classes.

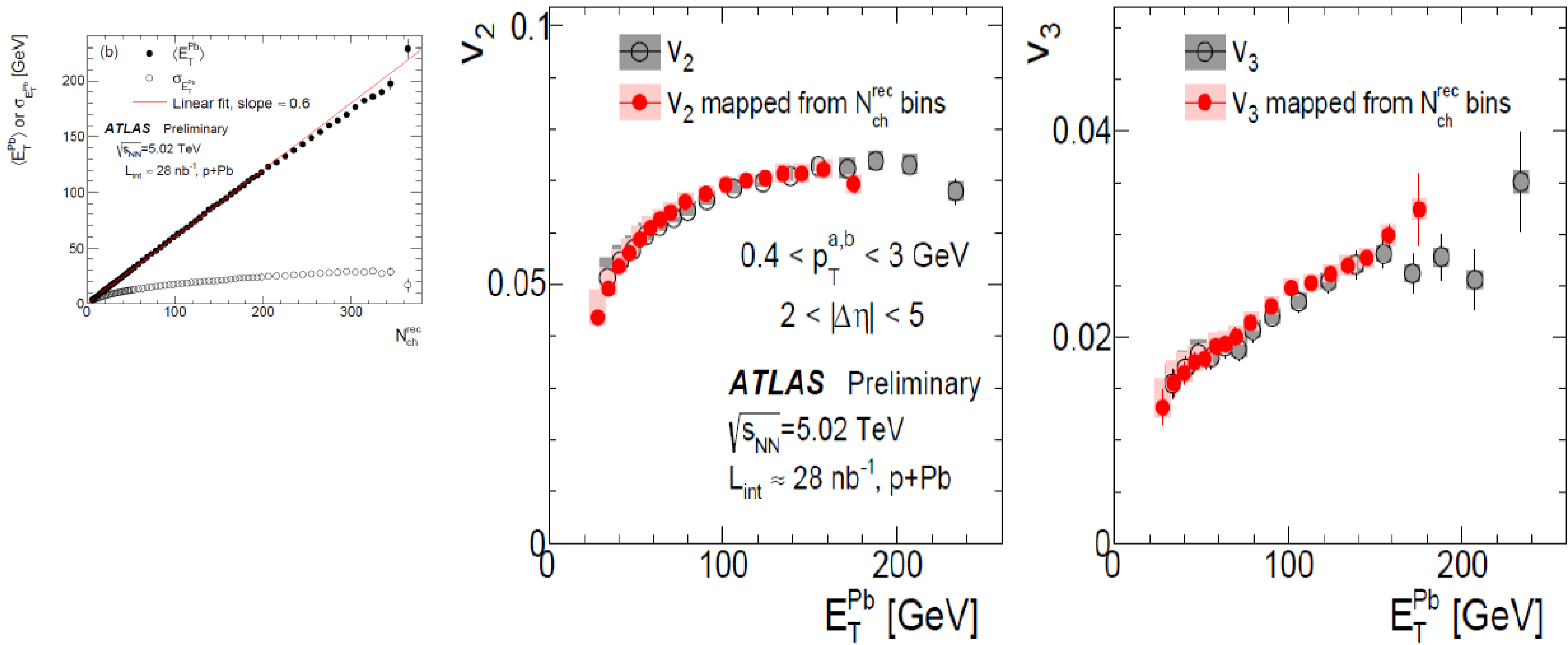
v_n: Event activity dependence



Similar behavior seen for E_T^{Pb} dependence

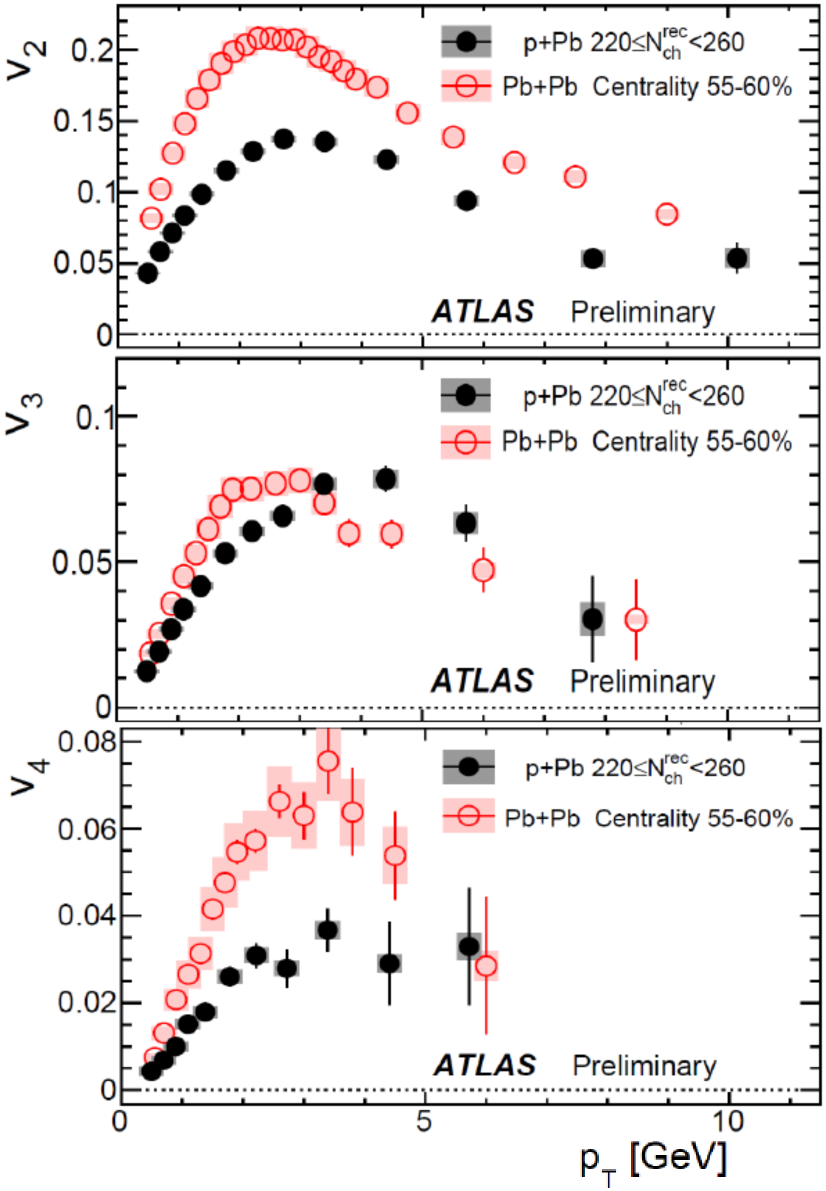
- v_2 show less variation for N_{ch}^{rec}>150, while v_3 continue to increase
- Recoil contribution does not affect the v_n for large N_{ch}^{rec}, but significant deviations see for smaller N_{ch}^{rec}

Mapping N_{ch}^{rec} - dependence to E_T^{Pb} dependence



- The v_n values for N_{ch}^{rec} is plotted at corresponding $<E_T^{Pb}>$ value, using the N_{ch}^{rec} vs E_T^{Pb} correlation data.
- Good consistency suggest that two event-activity definition captures the same azimuthal anisotropy of the long-range correlation.

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 and v_2 are coupled

$v_4 = \sqrt{c_0{}^2 + c_1{}^2 v_2{}^4}$ (see talk by Soumya)

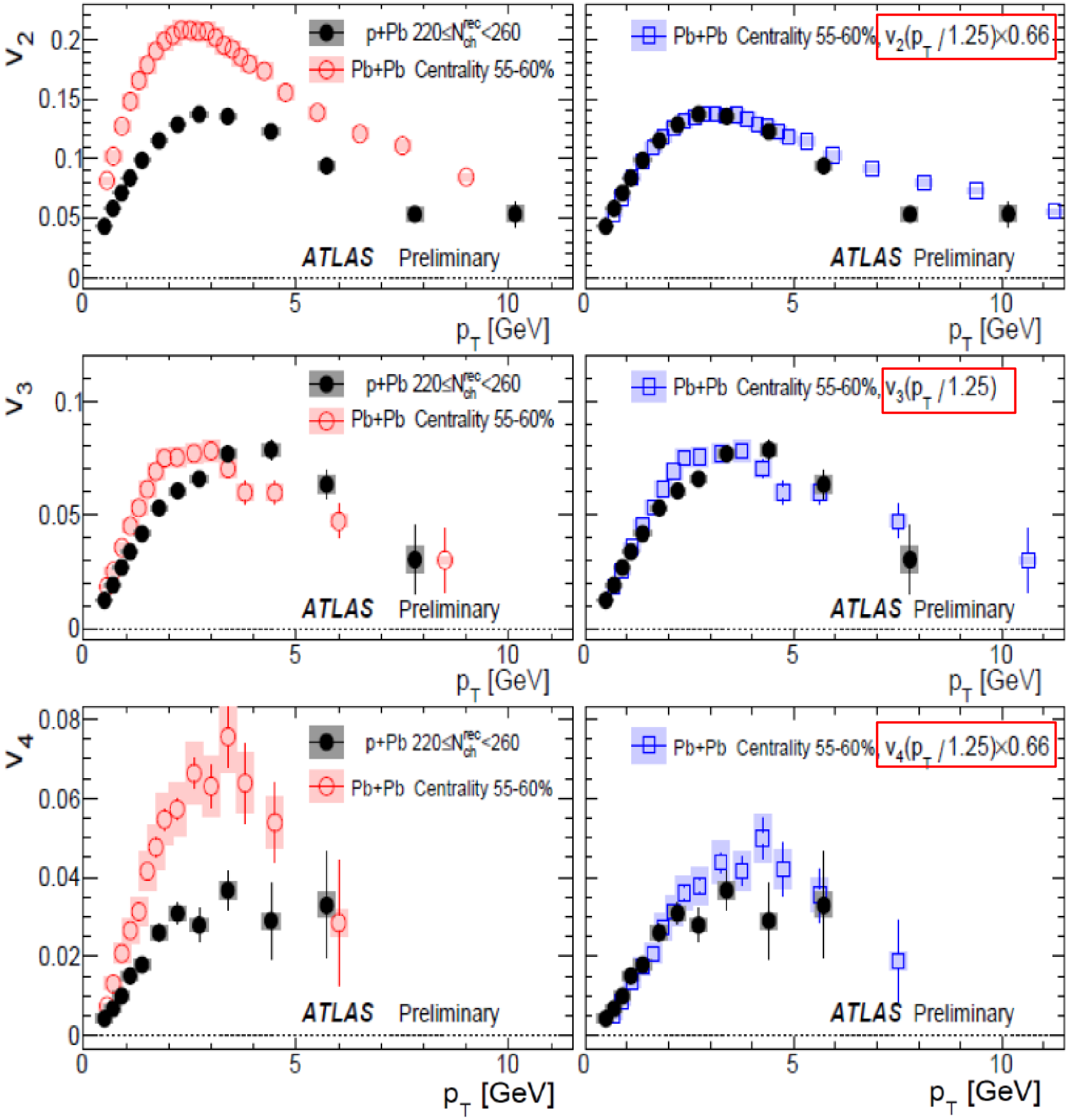
- Compare $v_n(p_T)_{p+Pb}$ with $v_n(p_T/K)_{Pb+Pb}$, *(Teaney et.al arXiv:1312.6770 [nucl-th].)*
  - K=1.25, ratio of <p_T>.

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

They both emerge from a collective response to the geometry dictated by $\frac{l_{mfp}}{L} = f(dN/dy)$

L is the transverse size of the high multiplicity events

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 and similar medium response to initial geometry?

Summary and Conclusions

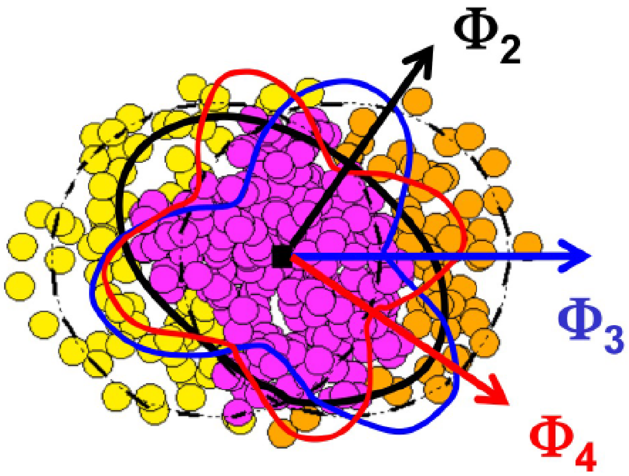
- The long-range correlation in high multiplicity events persists to $p_T \sim$ 12 GeV.

- v_n vs p_T and event-activity.
  - First 5 Fourier harmonics measured
  - The magnitude of v_n decrease with increasing n.
  - v_n found to increase with ${N_{ch}}^{rec}$ and ${E_T}^{Pb}$, but v_2 shows a saturation at higher event activity values.

- Comparison with peripheral Pb+Pb
  - $v_n(p_T)$, n = 1,2,3, are compared between p+Pb and Pb+Pb collisions with similar multiplicity.
  - Similar shape in p_T observed, once a scaling is applied to account for the difference in mean p_T between the two systems.

"Based on an independent cluster model and a simple conformal scaling argument, where the ratio of the mean free path to the system size stays constant at fixed multiplicity, we argue that flow in p+A emerges as a collective response to the fluctuations in the position of clusters, just like in A + A collisions." (arXiv:1312.6770)

Cumulant method



- Higher order harmonics arise due to event-by-event fluctuations in the initial geometry
- Cumulants technique allows for measurement of the v_n fluctuations

- Multi-particle (2k) cumulants are insensitive to lower order correlations (< 2k) – non flow eliminated by construction
- Generating function is used to obtain 2k-particle correlation and cumulants
  (N. Borghini, P. M. Dinh, J. -Y. Ollitrault, arXiv:nucl -ex/0110016)
- Cumulants give estimate of relative fluctuations:

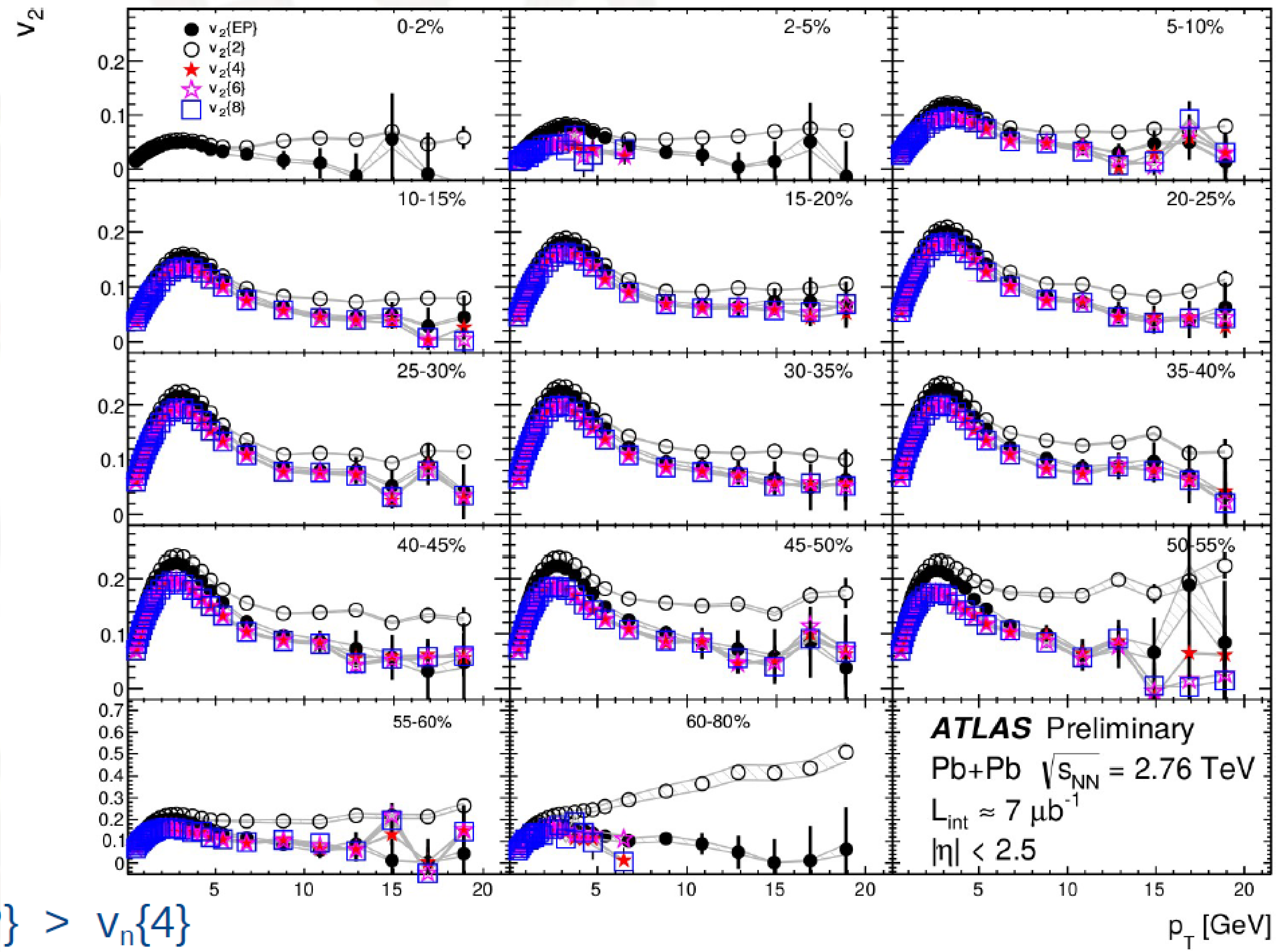
$$F(v_n) = \sqrt{\frac{v_n\{2\}^2 - v_n\{4\}^2}{v_n\{2\}^2 + v_n\{4\}^2}}$$

$$v_n\{2\} \cong v_n^2 + \sigma_n^2 + \delta$$
$$v_n\{4\} \cong v_n^2 - \sigma_n^2$$

- To lower the influence of non-flow effects in estimation of relative fluctuations $v_n\{EP\}$ is used instead of $v_n\{2\}$

Transverse momentum dependence of v_2

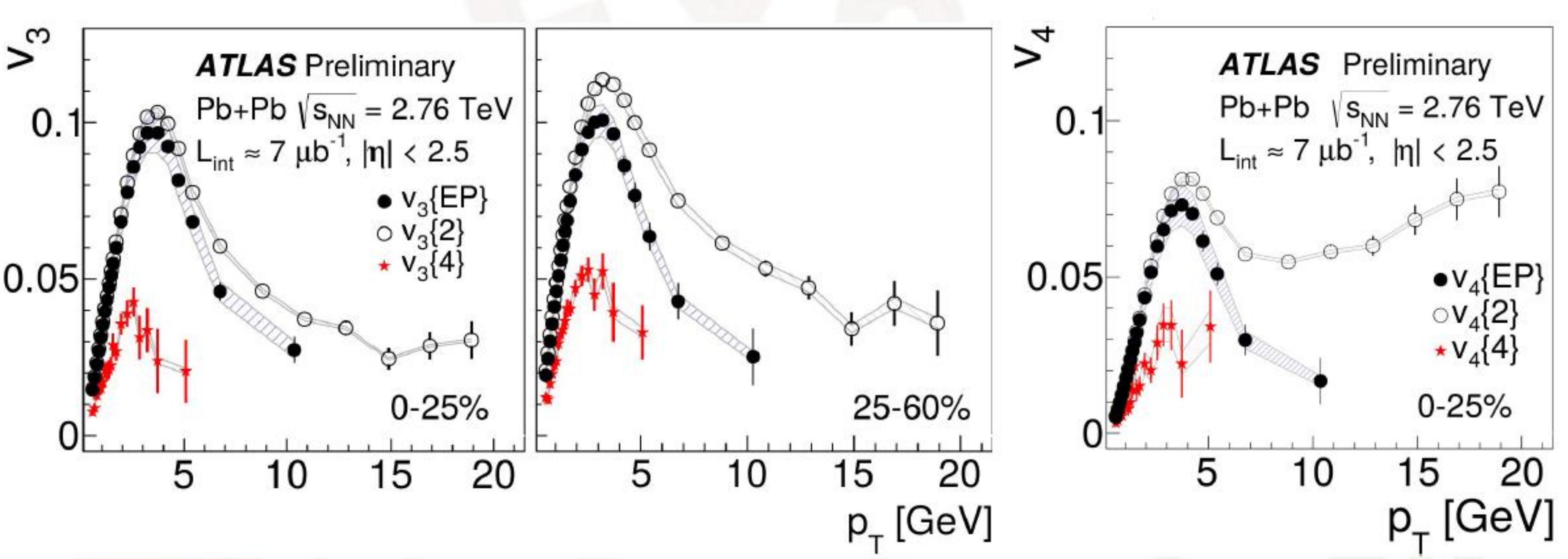
- $v_2\{2\}$ shows a strong flow signal at high p_T (jet-like correlations)
- Strong reduction of v_2 by using more than 2 particle correlations



$v_n\{2\} > v_n\{EP\} > v_n\{4\}$

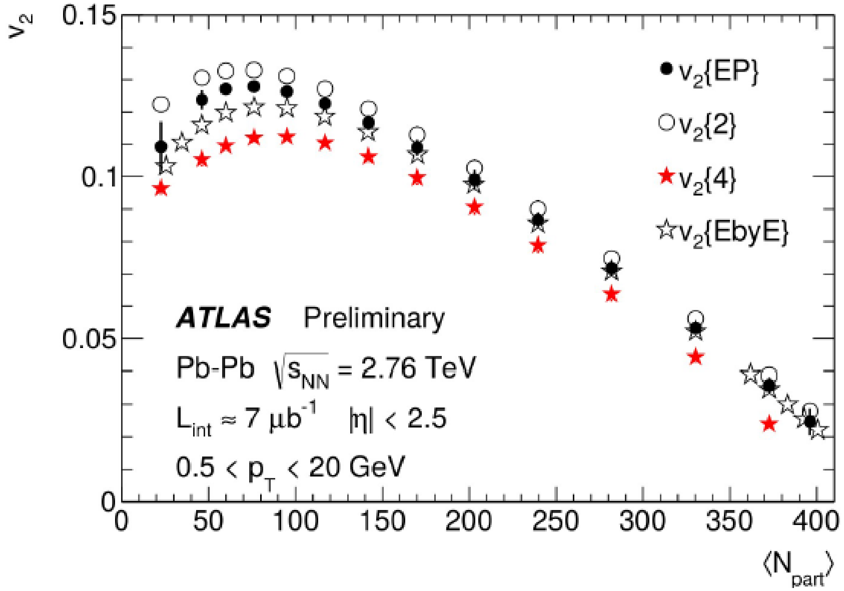
$v_n\{4\} \approx v_n\{6\} \approx v_n\{8\}$

Transverse momentum dependence of v_3 and v_4

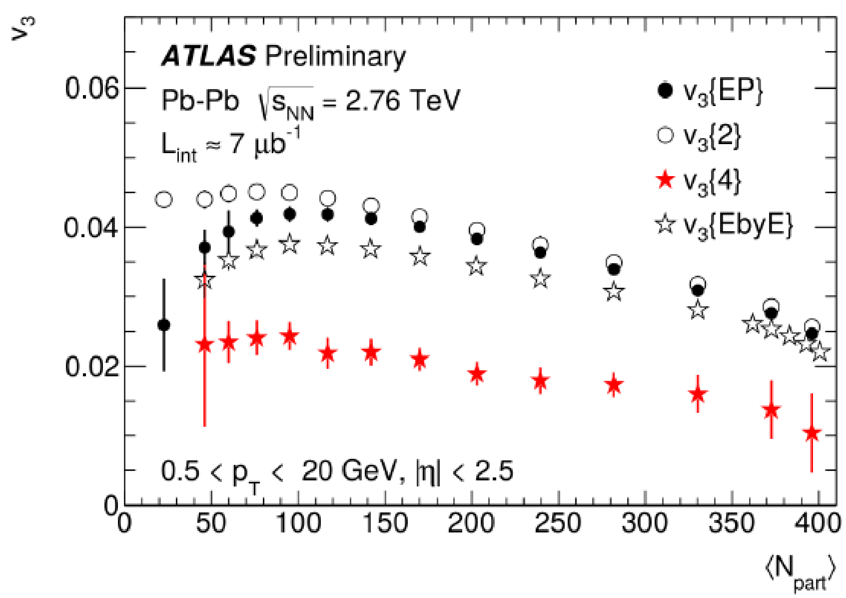


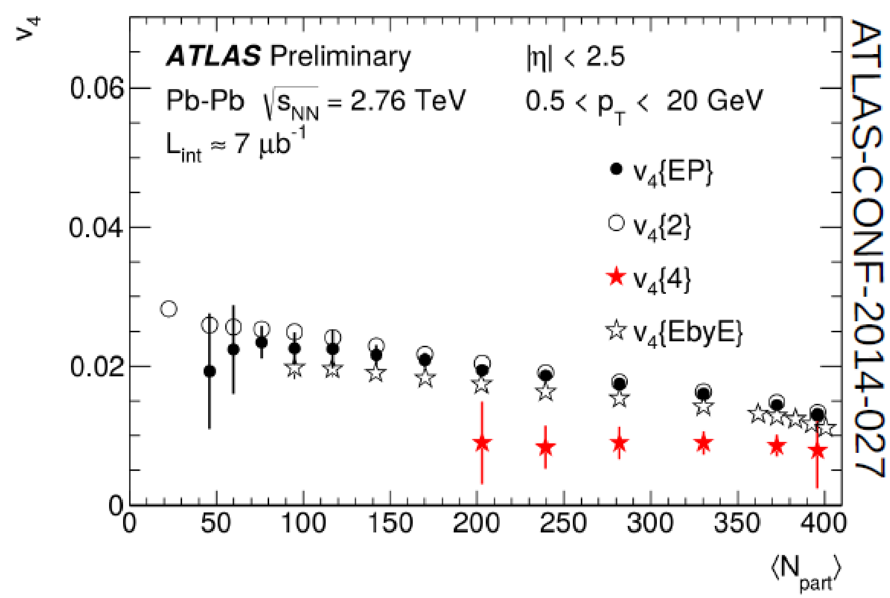
- Significant values of $v_3\{4\}$ and $v_4\{4\}$ calculated
- $v_{3,4}\{4\} < v_{3,4}\{2\}$ - expected from fluctuations and suppression of non-flow effects

Centrality dependence of v_n harmonics

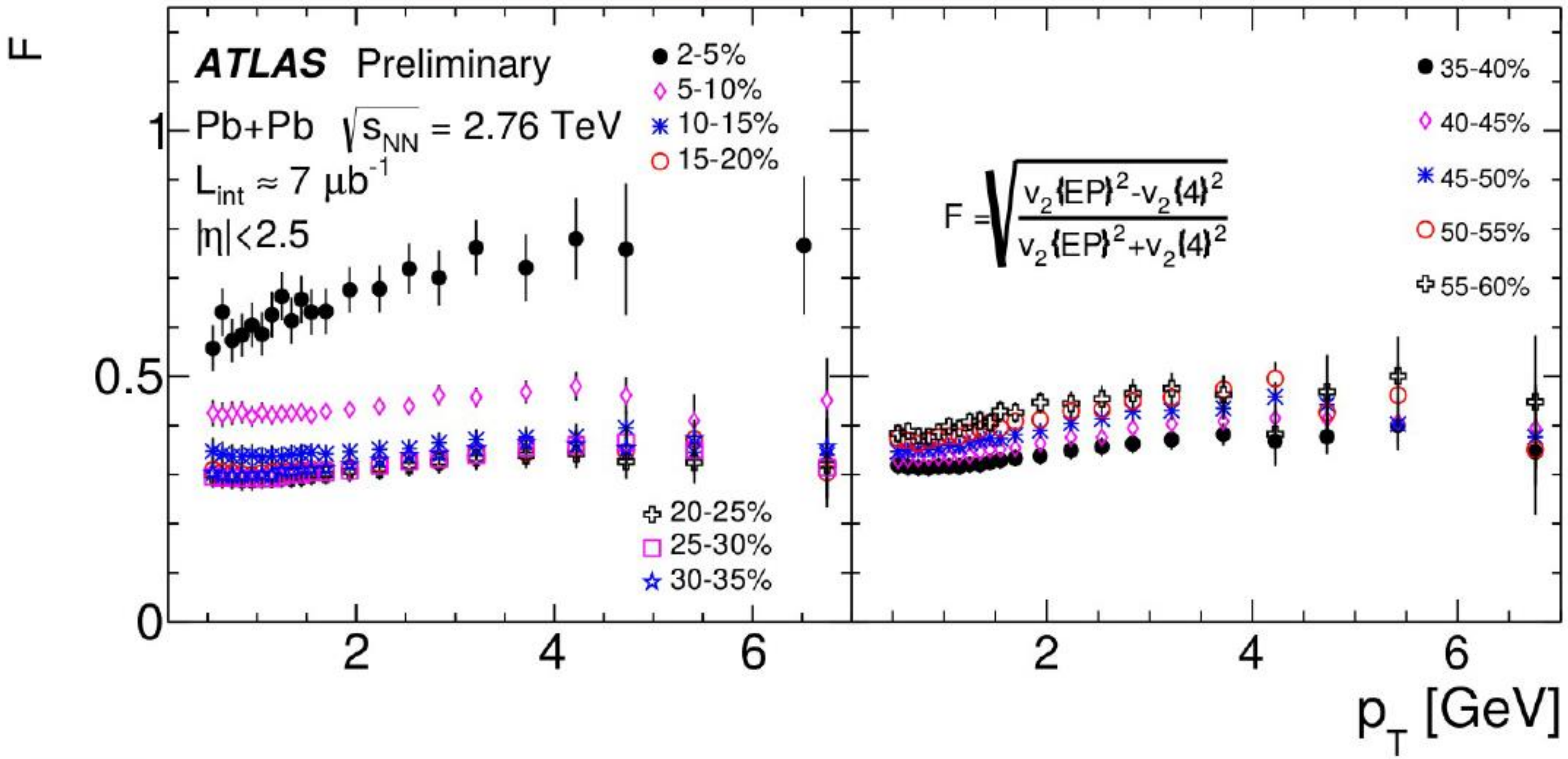


- Comparison of $v_n\{2,4\}$ with $v_n\{EP\}$ and $v_n\{EbyE\}$ (mean of $p(v_n)$ distribution)
- $v_n\{2\}$ > $v_n\{EP\}$ > $v_n\{EbyE\}$ > $v_n\{4\}$
- Difference between $v_n\{2\}$ and $v_n\{4\}$ more pronounced for n = 3,4



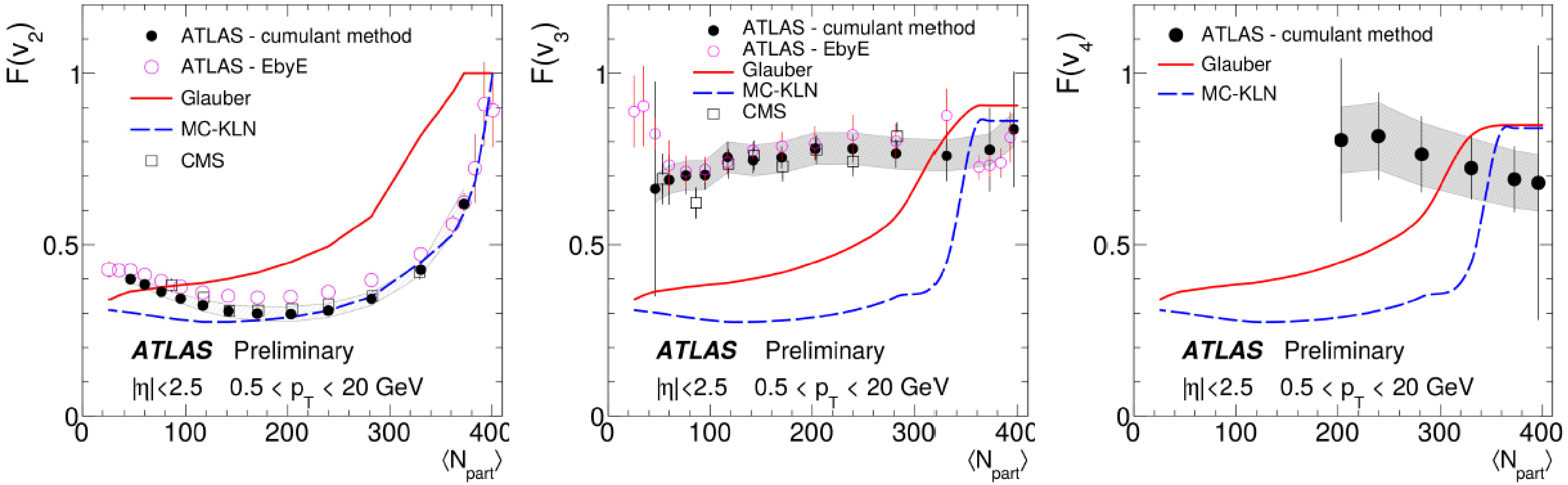


Elliptic flow fluctuations p_T dependence



- Event plane $v_2\{EP\}$ method used instead of $v_2\{2\}$ to lower the contribution of non-flow effects
- Only 2-5% bin shows significant p_T dependence

Fluctuations of v_n <N_{part}> dependence



- Strong dependence of $F(v_2)$ on centrality with a minimum at <N_{part}> ≈ 200
- Large triangular and quadrangular harmonic fluctuations are measured
- Week dependence of $F(v_3)$, $F(v_4)$ on centrality
- Good agreement cumulant results with EbyE calculations
- ATLAS results are consistent with the CMS estimate of v_3 relative fluctuations
- Both models fail to reproduce the relative fluctuations

Conclusions

- Reduction of harmonics observed when calculated with higher order cumulants
  - $v_n\{2\} > v_n\{EP\} > v_2\{EbyE\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
  - $v_3\{2\} \gg v_3\{4\}$
  - $v_4\{2\} \gg v_4\{4\}$

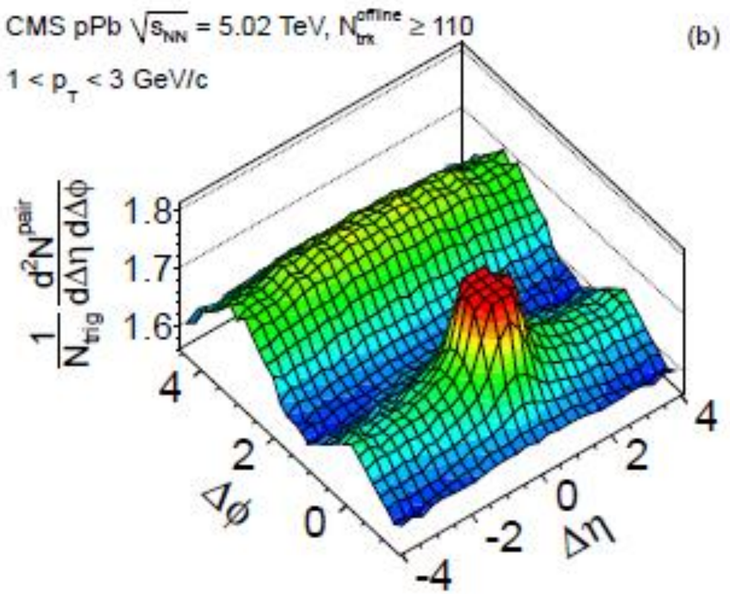
- Relative fluctuations of v_n (for n=2,3,4)
  - Strong centrality dependence for elliptic flow
  - Large values and weak N_{part} dependence of fluctuations for n=3,4 indicate large fluctuation in the shape of the initial geometry
  - Both Glauber and KLN-MC models did not reproduce these fluctuations in the full centrality range

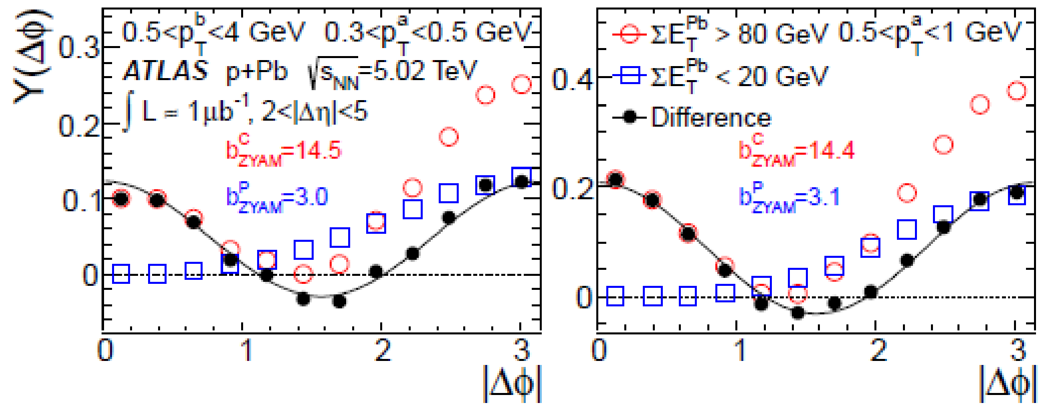
PHENIX Results

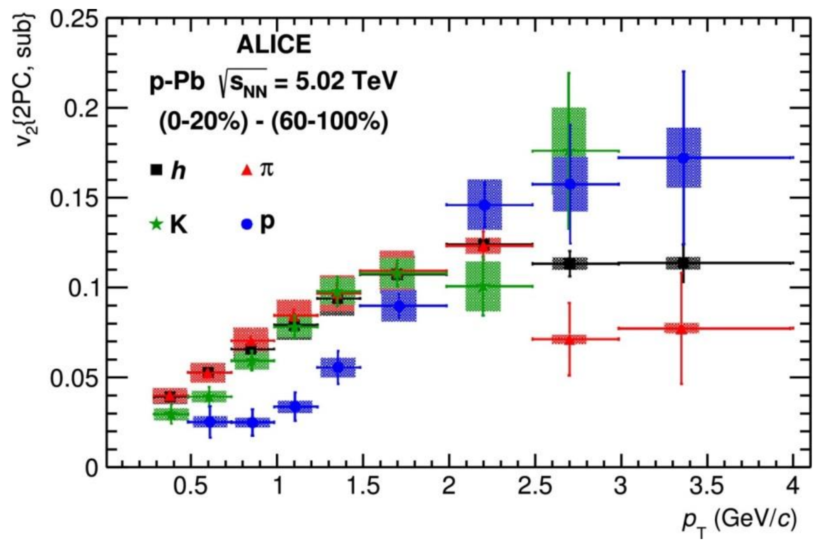
Extracted from the following talks.

1. “Measurements of long-range angular correlation and identified particle v2 in 200 GeV d+Au collisions from PHENIX” by Shengli Huang

“Ridge” and ”v_2” in p+Pb@5.02 TeV



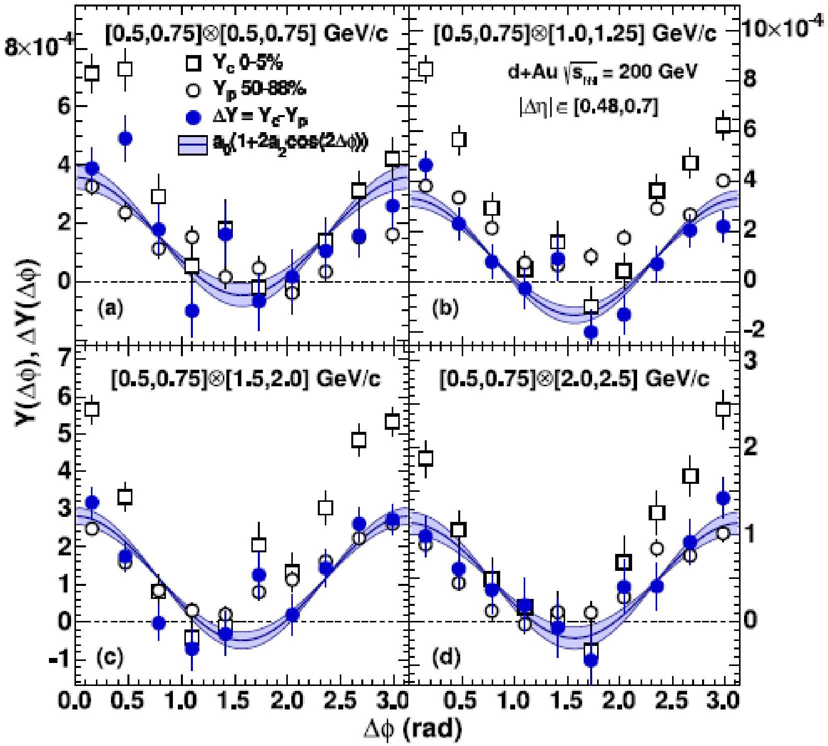


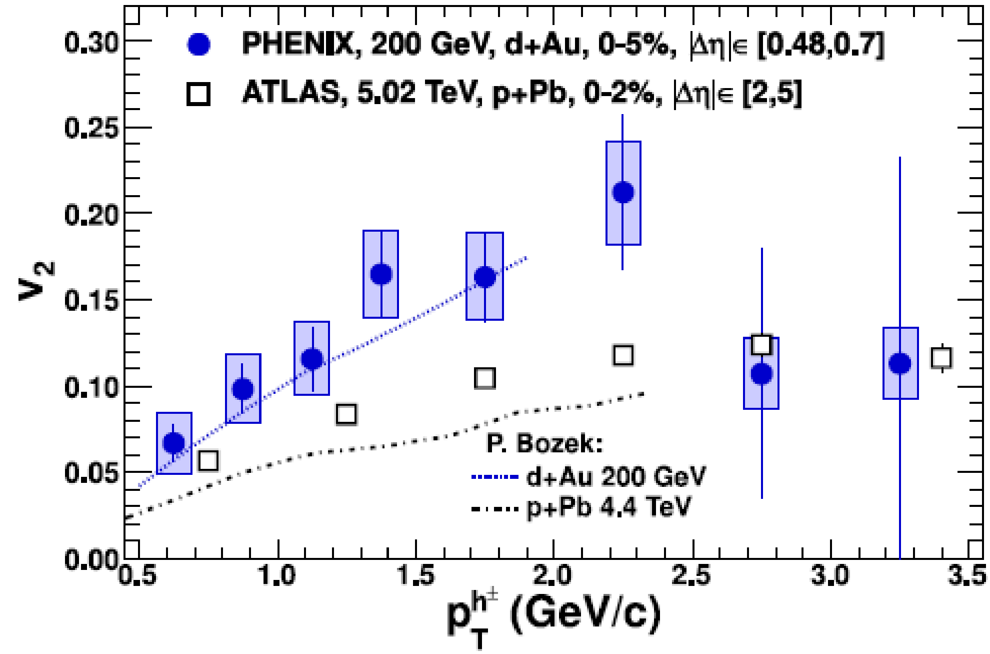


ALICE: Physics Letters B 726 (2013)
ATLAS: Phys. Rev. Lett. 110(2013)
CMS: Phys. Lett. B 7198(2013

- A “ridge” is observed in the central p + Pb@5.02 TeV
- The $\Delta\phi$ distribution shows a $\cos(2\Delta\phi)$ structure
- The identified particle v_2 shows a mass ordering

V_2 in d+Au@ 200 GeV

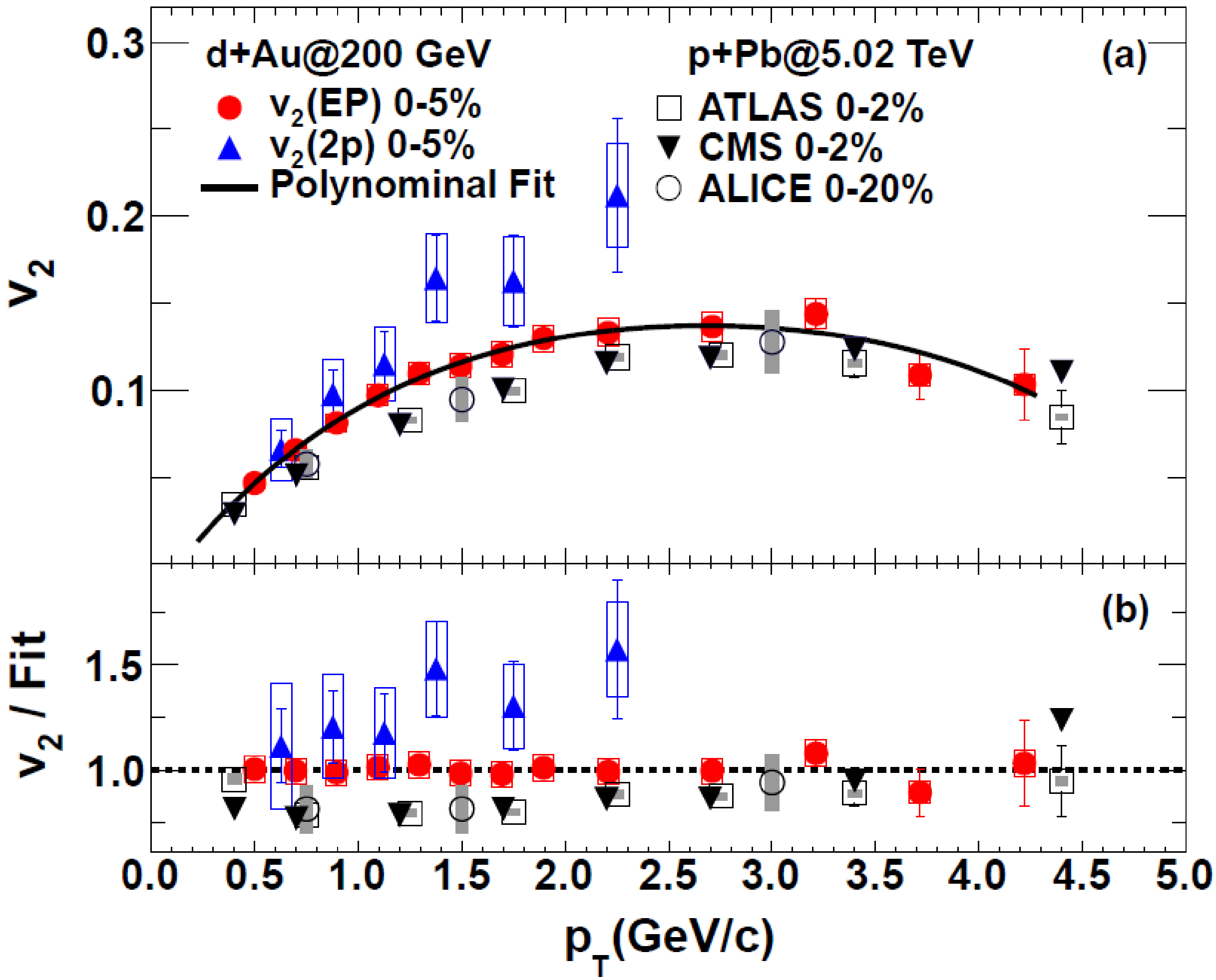




PHENIX: [Phys. Rev. Lett. 111, 212301 (2013)]

- The cos(2Δϕ) structure is also seen in 0-5% d+Au. The cut of |Δη|>0.48 is the limit of our central arm acceptance
- The v_2 in 0-5% d+Au is higher than that in 0-2% p+Pb collisions, which is consistent with hydro calculation
- The measurement with large |Δη| is required!

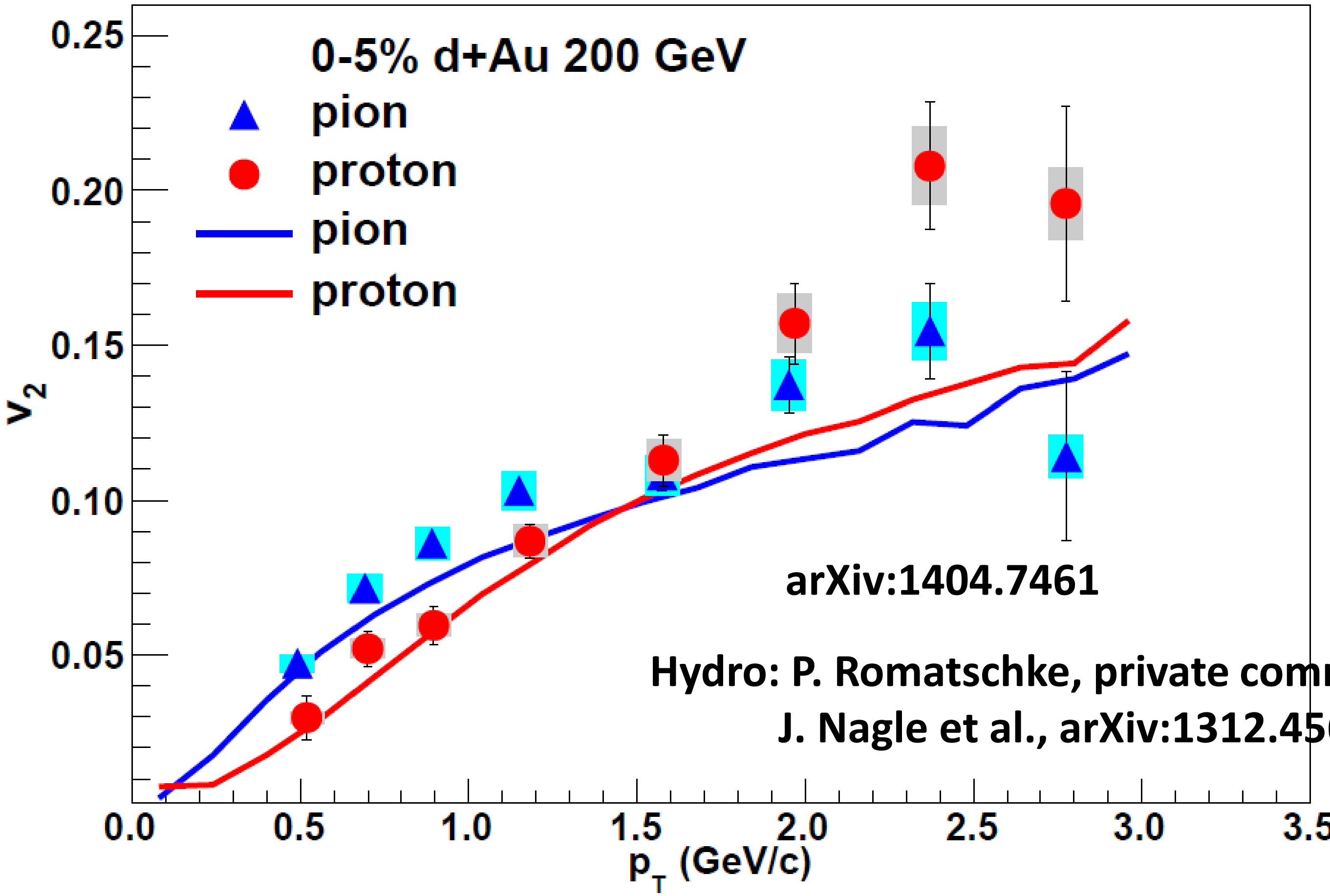
V_2(EP) of charged hadron in 0-5% d+Au



arXiv:1404.7461

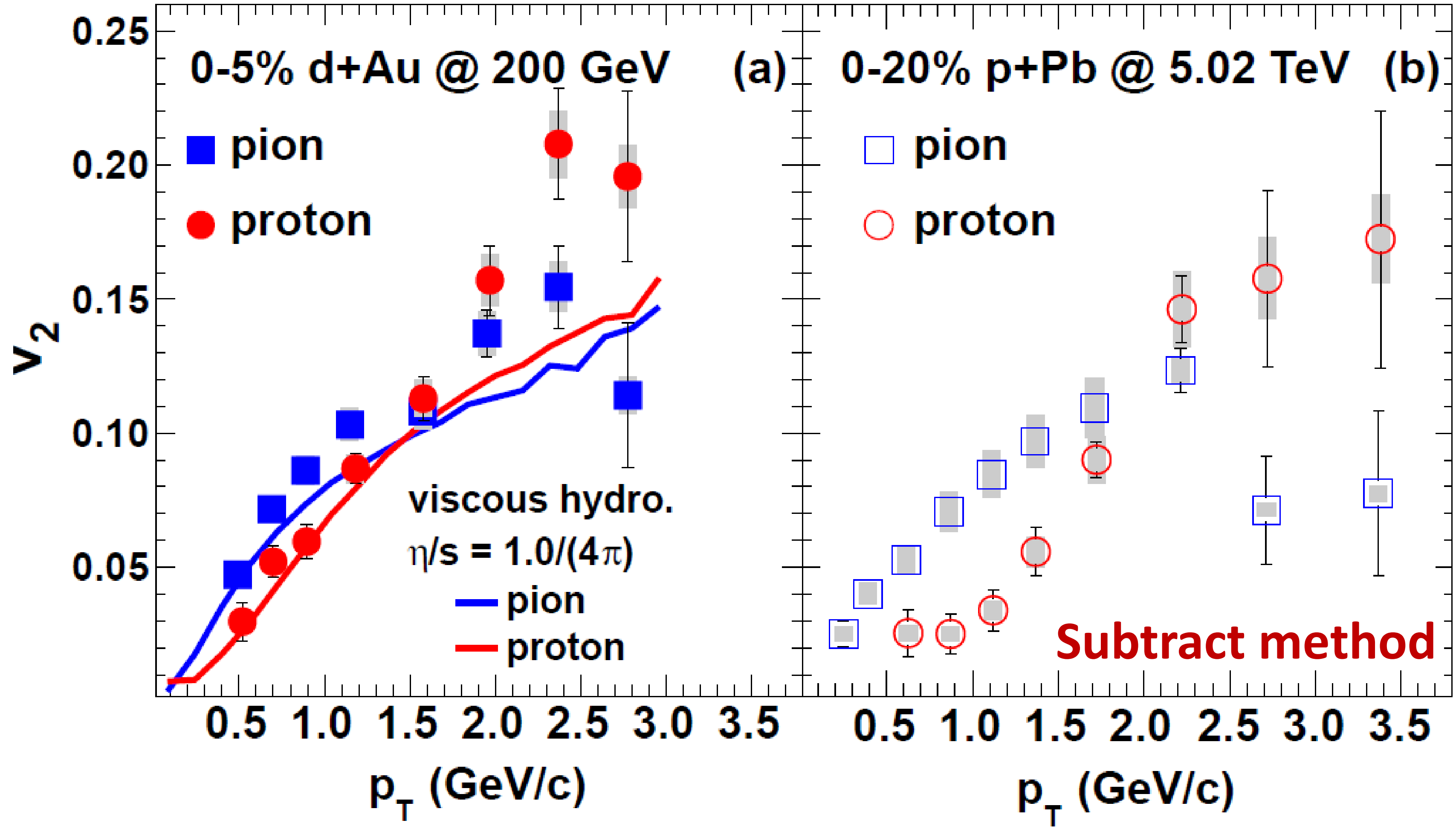
- The charged hadron v_2 measured by the event plane method in central dAu is similar to that in central pPb

Identified particles' v_2 from EP methods



- **Mass ordering is observed in 0-5% d+Au**
- **This ordering can be reproduced in hydro calculation from P. Romatschke et al.**

Weaker radial flow in dAu?



- ❑ The magnitude of mass ordering in p+Pb is larger than that in d+Au
- ❑ Weaker radial flow in d+Au?

Summary

- Is there "ridge" in dAu collisions?

There is "Ridge" in dAu even with $|\Delta\eta|>6.0$

- How about the difference between the v_2 in dAu and pPb?

v_2 in central dAu is similar to that in central pPb, while hydro calculation show a significant difference

- Is there mass ordering for identified particle v_2 in dAu?

The mass ordering is observed in central dAu , while it is smaller comparing with central pPb, it may be due to a weaker radial flow in dAu

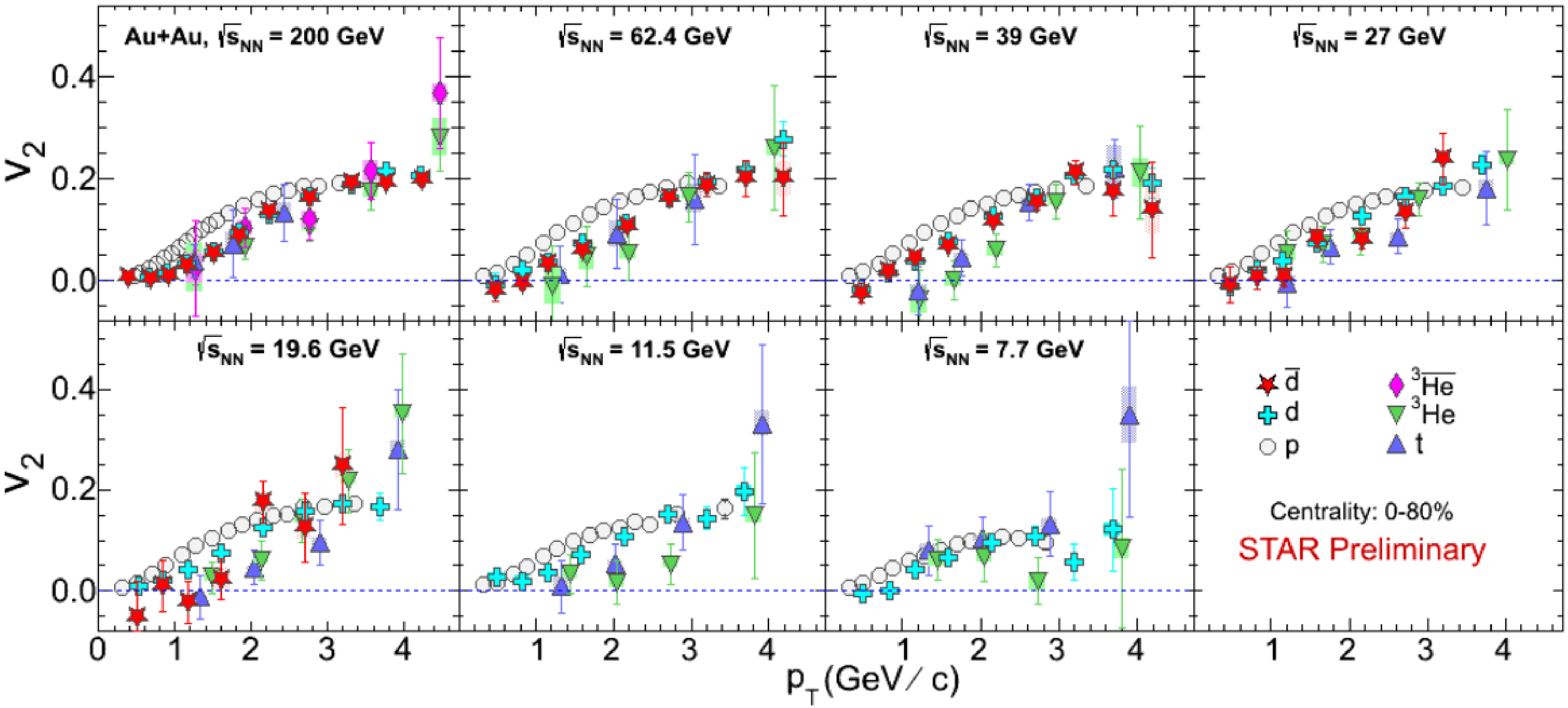
The input from CGC model calculation is expected for the further understanding the physics of "ridge" and "v_2" in small collision system

STAR Results

Extracted from the following talks.

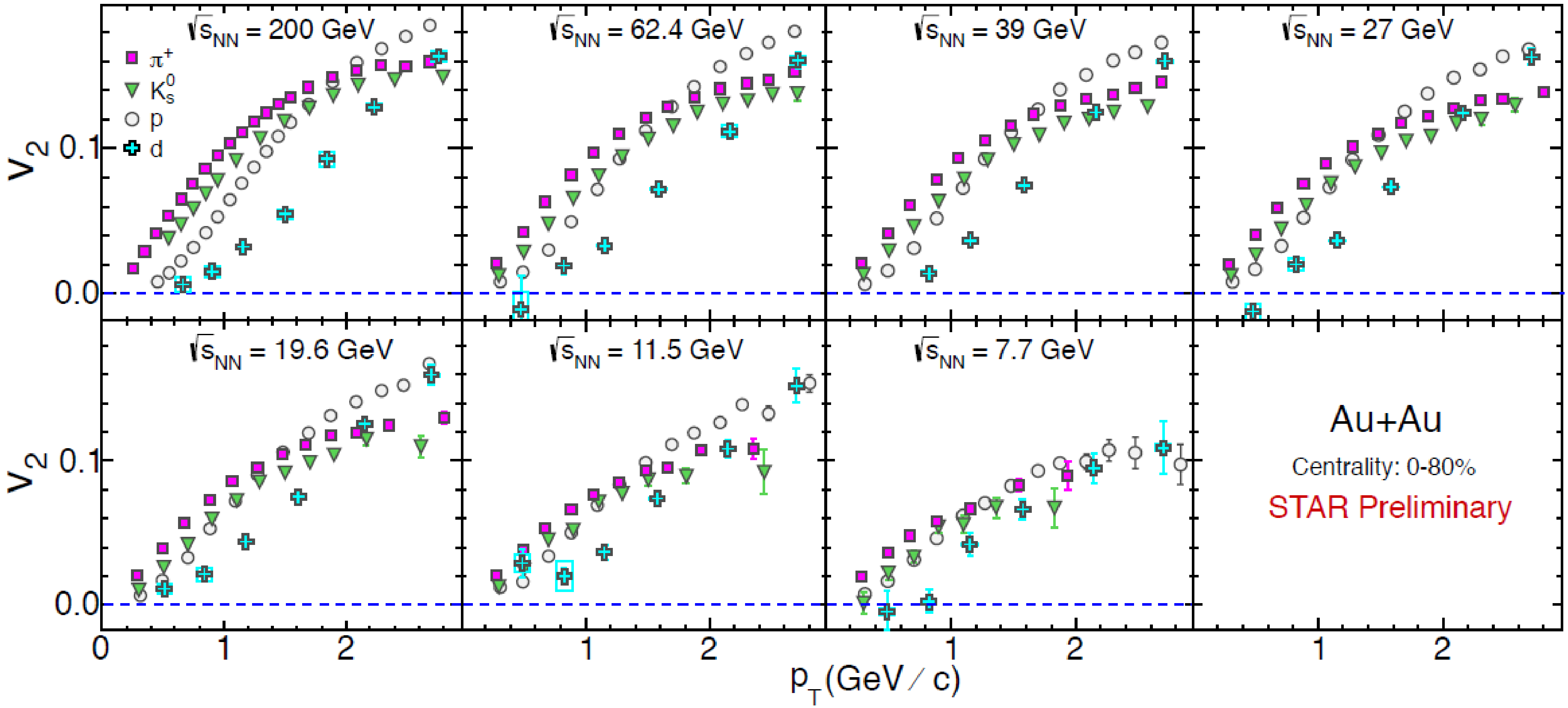
1. “The centrality and energy dependence of the elliptic flow of light nuclei and hadrons in STAR” by Rihan Haque

Measurement of nuclei v_2



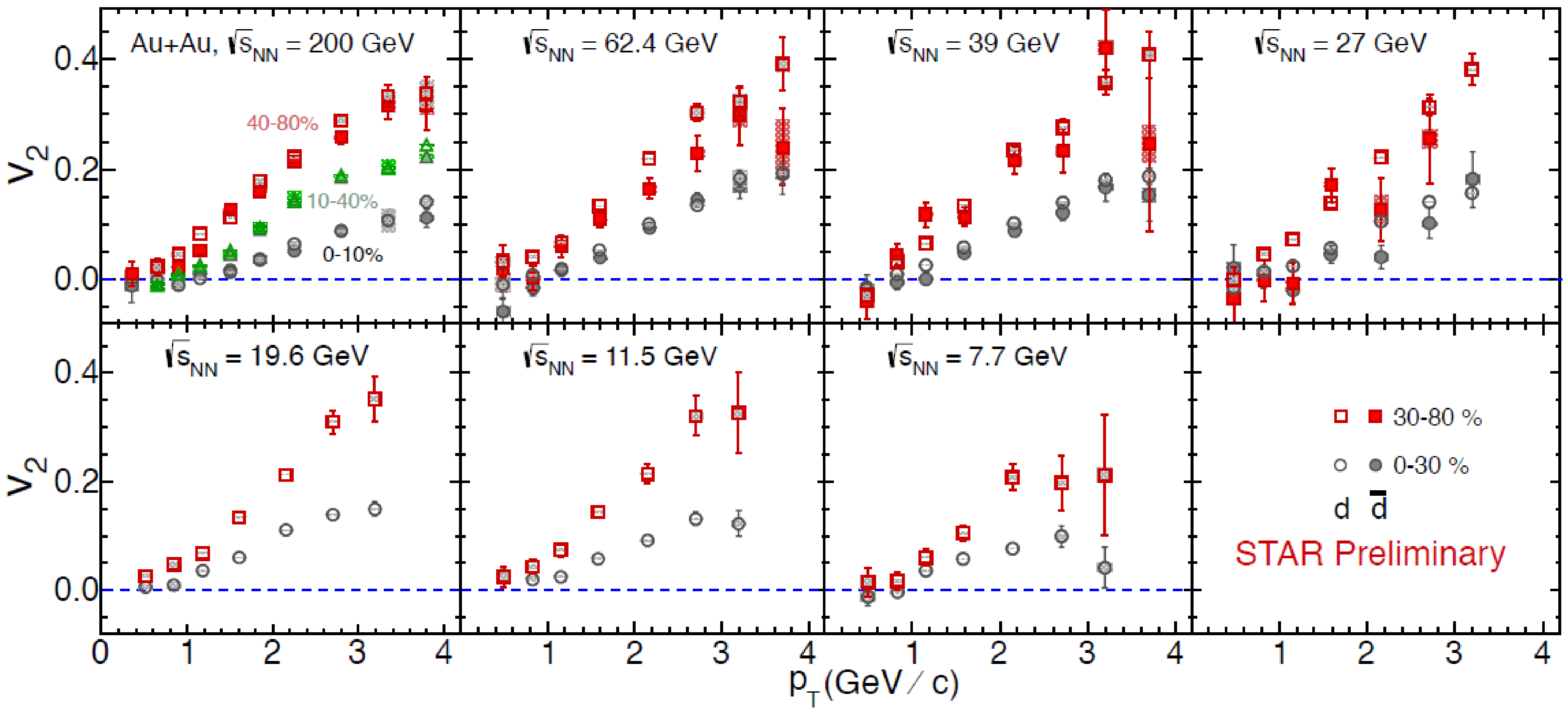
- ✓ Elliptic flow of *d*, *d̄*, *t*, ^{3}He, $^{3}\overline{He}$ measured at mid-rapidity.
- ✓ η sub-eventplane method was used with η-gap = 0.1

Mass ordering of v_2



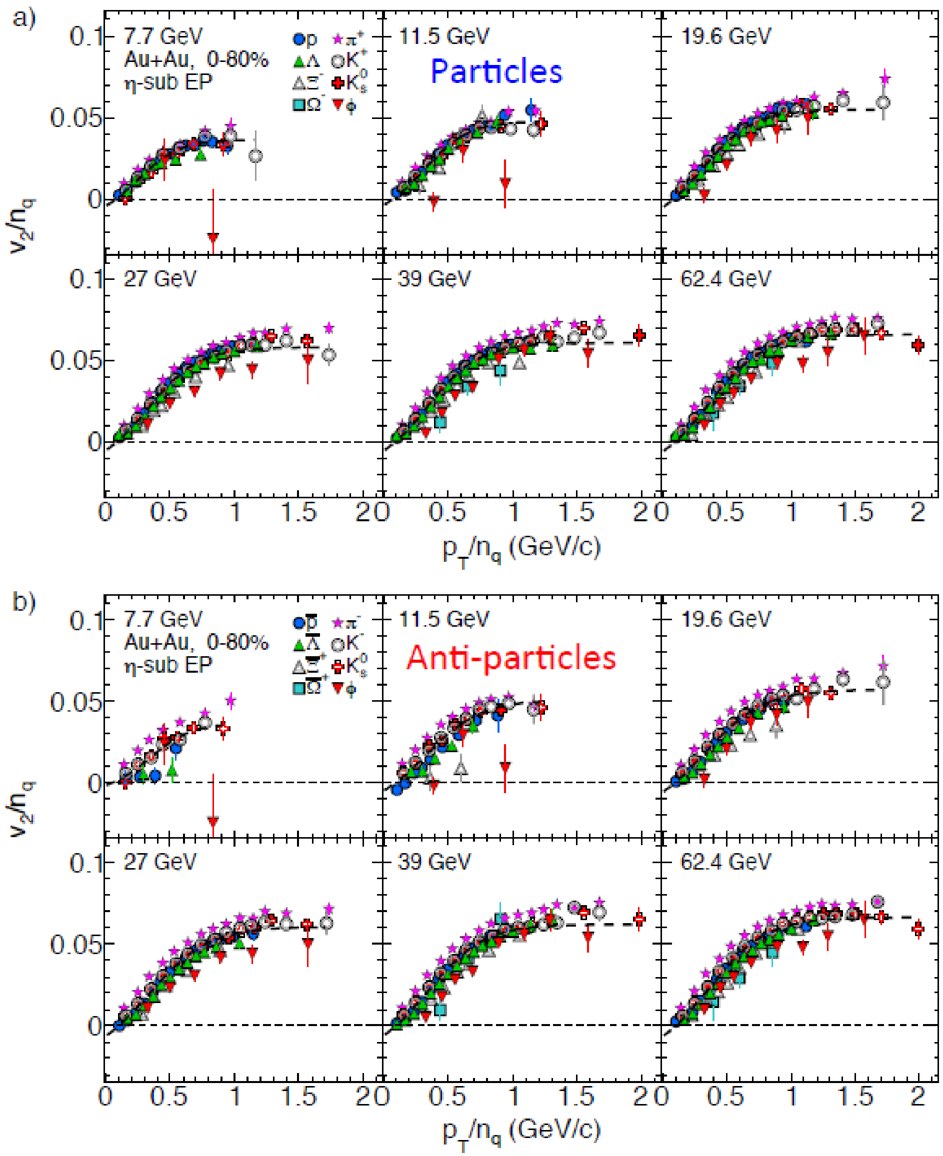
→ *Nuclei v_2 shows mass ordering at low p_T similar to hadrons*

Centrality dependence of nuclei v_2



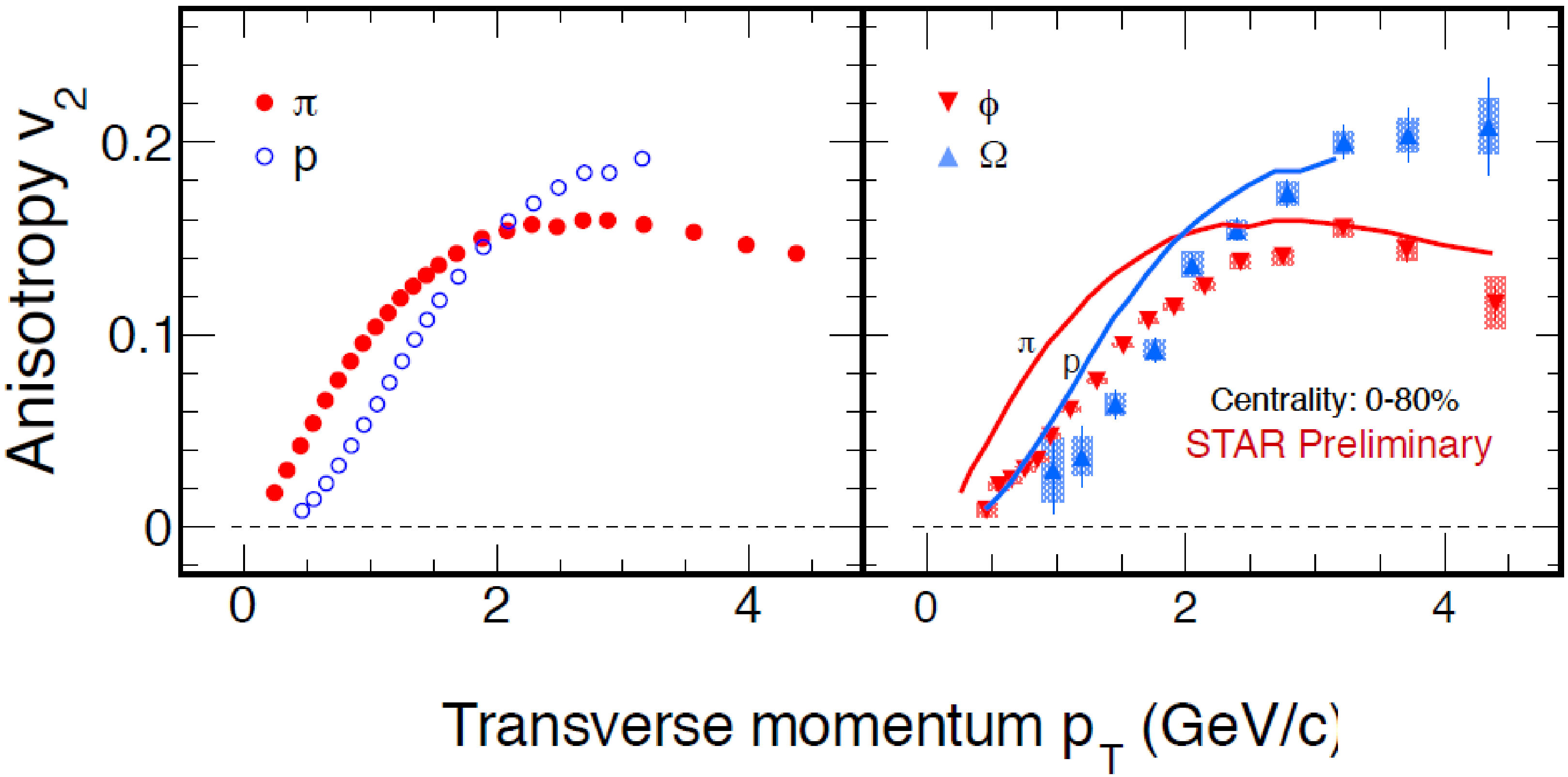
→ *Nuclei v_2 shows centrality dependence for all energies*

NCQ scaling of hadron v_2



- ✓ NCQ scaling observed for particle and anti-particle groups separately for beam energy ≥ 19.6 GeV
- ✓ Scaling holds for 1.5 < p_T < 5.0 GeV/c
- ✓ More statistics is needed for 7.7 and 11.5 GeV/c

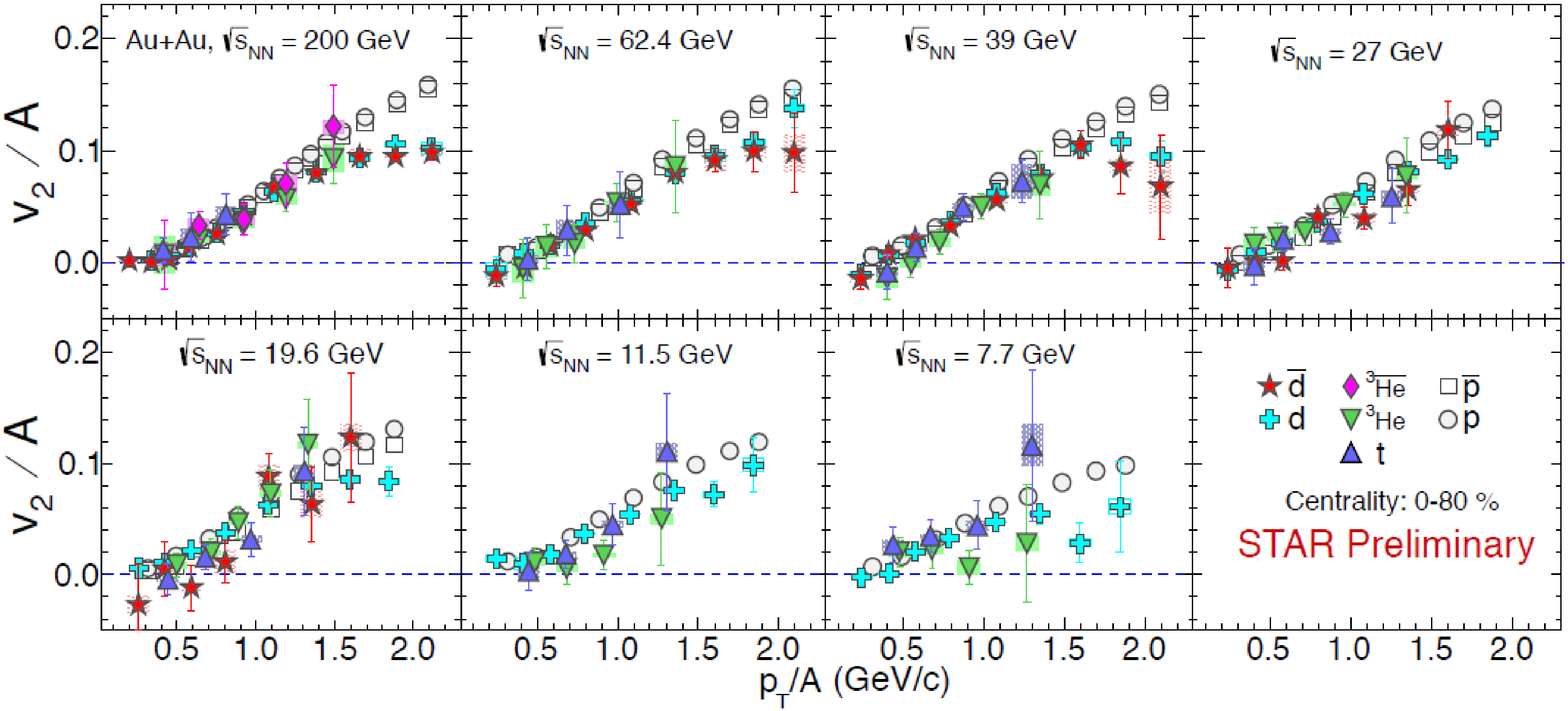
Precision measurement of v_2 of ϕ and Ω



- ✓ Mass ordering observed for p_T < 2.0 GeV/c
- ✓ Baryon – meson splitting for 2.0 < p_T < 5.0 GeV/c

→ *High precision measurement of ϕ and Ω v_2 agree with the previous physics conclusion of partonic collectivity at 200 GeV*

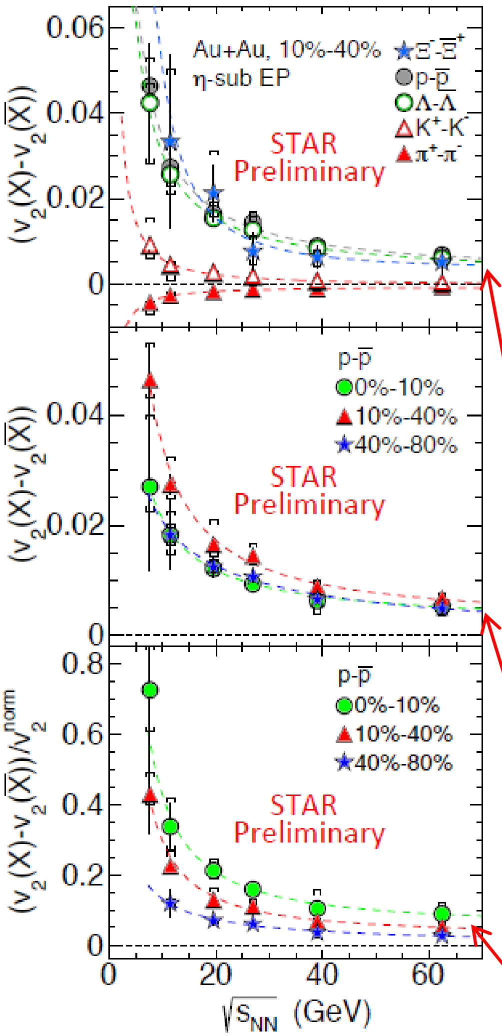
Mass number scaling of v_2



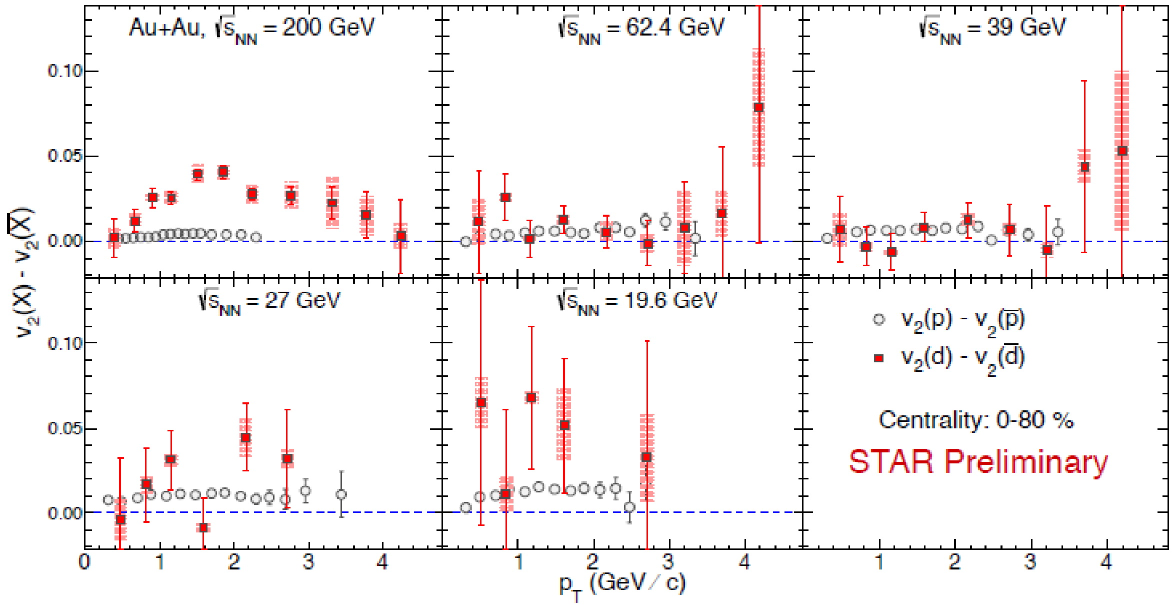
Nuclei v_2 show mass number scaling for p_T /A ~1.5 GeV/c for all beam energies

→ *Support the general idea that nuclei are formed by coalescence of nucleons*

v_2 of particles and anti-particles



v_2^{norm} = v_2 of proton



→ *Nuclei and anti-nuclei v_2 shows a difference at 200 GeV*

→ *Statistical uncertainties large at lower beam energies to make definite conclusions.*

→ *Δv_2 for 10-40% centrality is similar to minimum bias result*

→ *Centrality dependence not observed in Δv_2*

→ *Δv_2 relative to proton v_2 shows a centrality dependence*

Summary

1. Nuclei v_2 versus p_T shows a clear centrality dependence and mass ordering when compared to identified hadrons at all beam energies studied

→ *Mass ordering of v_2 occurs naturally in a hydrodynamic model.*

2. Nuclei v_2 versus p_T shows mass number scaling upto p_T/A = 1.5 GeV/c and the magnitude of nuclei v_2 versus p_T are reproduced by a Coalescence model.

→ *Both these support the physics picture of coalescence of nucleons as the dominant mechanism of nuclei production.*

3. The difference in v_2 of proton and anti-proton is observed to be similar at all collision centralities studied for the BES energies. A centrality dependence appears when this difference is normalized to proton v_2 at the respective beam energies

→ *The results implies hadronic interactions play an important role at lower beam energies.*

"with large Δv_2"

Backups

Fourier coefficients can be extracted from the $\Delta\varphi$ projection of the per-trigger yield by a fit with:

$$\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}N_{\text{assoc}}}{\mathrm{d}\Delta\varphi} = a_0 + 2\,a_1\cos\Delta\varphi + 2\,a_2\cos 2\Delta\varphi + 2\,a_3\cos 3\Delta\varphi. \qquad (2)$$

From the relative modulations $V_{n\Delta}^{h-i}\{2\text{PC}\} = a_n^{h-i}/a_0^{h-i}$, where a_n^{h-i} is the a_n extracted from $h-i$ correlations, the $v_n^i\{2\text{PC}\}$ coefficient of order n for a particle species i (out of h, π, K, p) are then defined as:

$$v_n^h\{2\text{PC}\} = \sqrt{V_{n\Delta}^{h-h}} \qquad\qquad v_n^i\{2\text{PC}\} = V_{n\Delta}^{h-i}/\sqrt{V_{n\Delta}^{h-h}}. \qquad (3)$$

In the case that each of the particles is correlated with a common plane, the $v_n^i\{2\text{PC}\}$ are the Fourier coefficients of the corresponding single-particle angular distributions.

$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$

The flow vector

$$\vec{Q}_n \equiv (|Q_n|\cos(n\Psi_n), |Q_n|\sin(n\Psi_n))$$

$$|Q_n|\cos(n\Psi_n) = \frac{1}{N}\sum_j \cos(n\phi_j)$$

$$|Q_n|\sin(n\Psi_n) = \frac{1}{N}\sum_j \sin(n\phi_j),$$

$$Q_n = |Q_n|e^{in\Psi_n} \equiv \frac{1}{N}\sum_j e^{in\phi_j}$$

The original idea behind the event-plane method is that the direction Ψn of the flow vector in a reference detector provides an estimate of the corresponding angle Φn in the underlying probability distribution. Because a finite sample of particles is used, statistical fluctuations cause Ψn to differ from Φn.

The nonlinear dependence of the resolution on the underlying flow is the origin of the difficulties of the event plane method, which arise when flow fluctuations are considered. A simpler quantity is the projection of the flow vector onto the underlying direction Φn, which directly gives the underlying flow:

$$\left\langle Q_n e^{-in\Phi_n} \right\rangle_{|v_n} = v_n$$

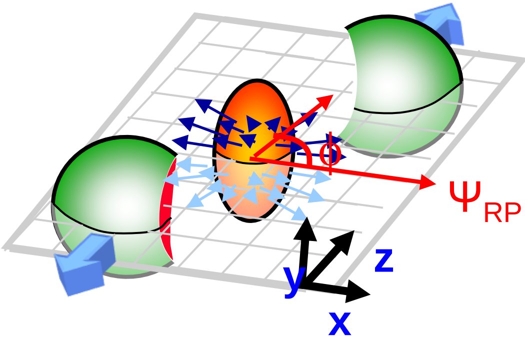
In SP method, use flow vector Q_n to calculate flow v_n

$$v_n = \frac{\langle |Q_n| \cos n(\phi - \Psi_n^{measured}) \rangle}{\bar{Q}_n}$$

where $\bar{Q}_n$ is define as

- $\sqrt{\langle Q_{nA} \cdot Q_{nB} \rangle}$ for 2 sub event
- $\frac{\sqrt{\langle Q_{nA} \cdot Q_{nB} \rangle \langle Q_{nA} \cdot Q_{nC} \rangle}}{\sqrt{\langle Q_{nB} \cdot Q_{nC} for 3 subevent \rangle}}$

Experimental methods



- Event plane (EP) method:

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t\, dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos(n(\varphi-\Psi_{RP}))\right)$$

$$v_n=\langle\cos(n(\varphi_i-\Psi_{RP}))\rangle$$

- Cumulants:
  - 2- and 4-particle azimuthal correlations for an event:

$$\langle 2\rangle\equiv\langle\cos(n(\varphi_i-\varphi_j))\rangle,\ \varphi_i\neq\varphi_j$$

$$\langle 4\rangle\equiv\langle\cos(n(\varphi_i+\varphi_j-\varphi_k-\varphi_l))\rangle,\ \varphi_i\neq\varphi_j\neq\varphi_k\neq\varphi_l$$

  - Averaging over all events, the 2nd and 4th order cumulants are given:

$$c_2\{n\}=\langle\langle 2\rangle\rangle=v_n^2+\delta_n$$

$$c_4\{n\}=\langle\langle 4\rangle\rangle-2\langle\langle 2\rangle\rangle^2=-v_n^4$$

$v_n : reference\_flow$

$\langle\rangle : average\_particles$

$\langle\langle\rangle\rangle : average\_events$

$v_n\{2\}\equiv\sqrt{c_n\{2\}}$

$v_n\{4\}\equiv\sqrt[4]{-c_n\{4\}}$

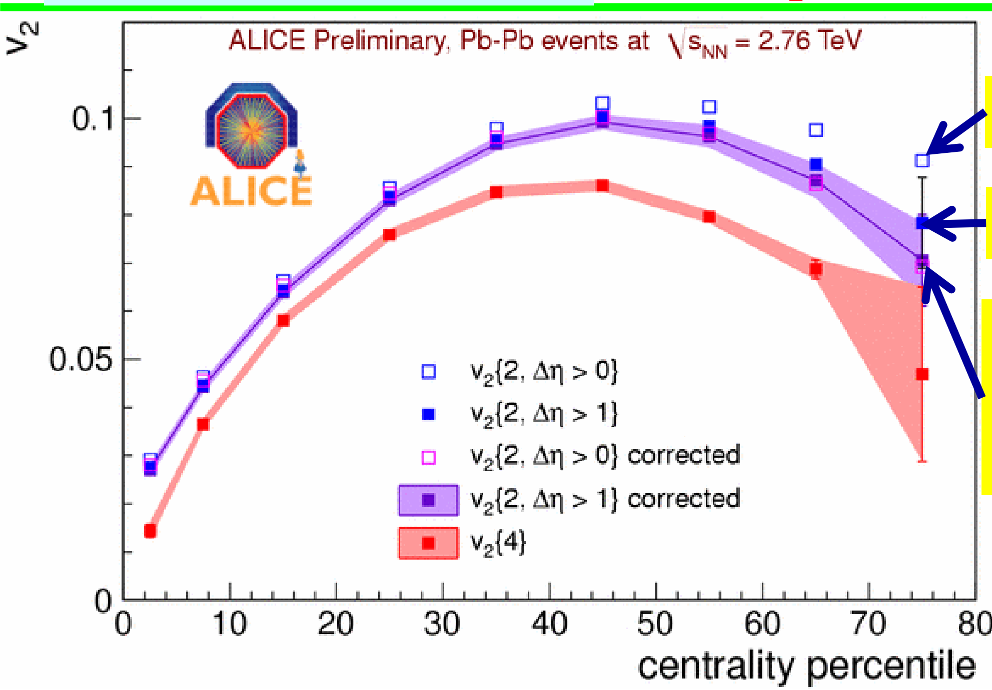
$v_n\{2\}\cong v_n^2+\sigma_n^2+\delta$

$v_n\{4\}\cong v_n^2-\sigma_n^2$

v_2 {2} and v_2{4} have different sensitivity to flow fluctuations (σ_n) and non-flow (δ)

Elliptic Flow v_2

Non-Flow corrections



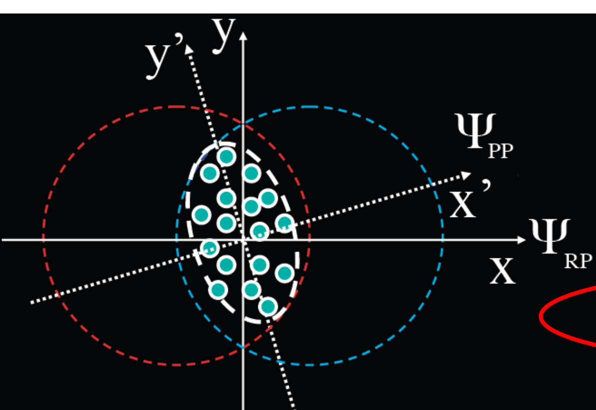
v_2 no eta gap between particles

v_2 $|\eta|>1$ to reduce non-flow such as jets

both v_2 corrected for remaining non-flow using Hijing or scaled pp

With this, we can remove most of non-flow (δ)

Plane of symmetry (Ψ_{PP}) fluctuate event-by-event around reaction plane (Ψ_{RP}) => flow fluctuation (σ_n)



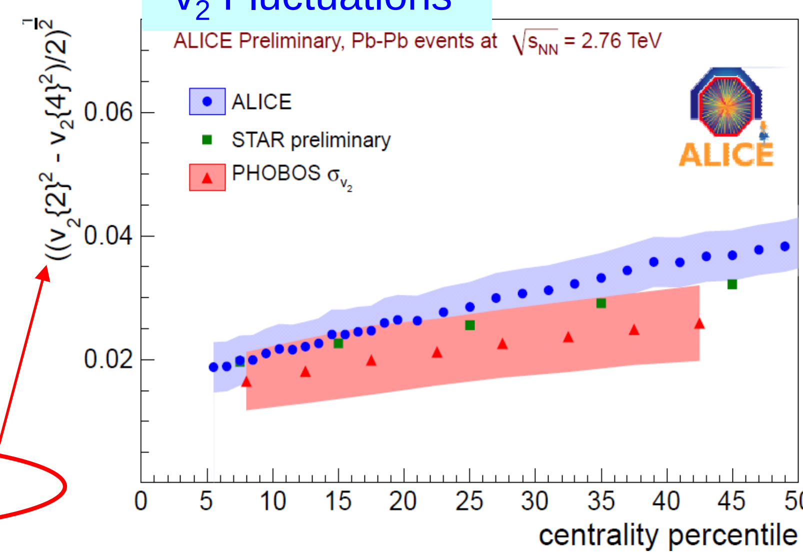
$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2$$

$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$

$$v_n^2\{2\} + v_n^2\{4\} = 2\bar{v}_n^2$$

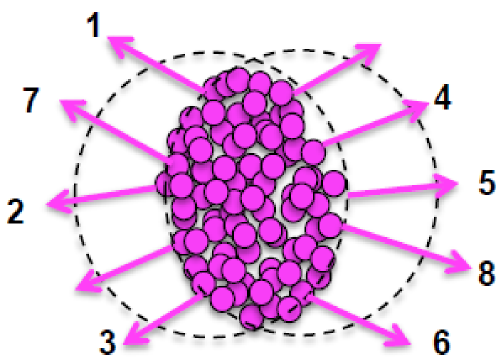
$$v_n^2\{2\} - v_n^2\{4\} = 2\sigma_v^2$$

v_2 Fluctuations



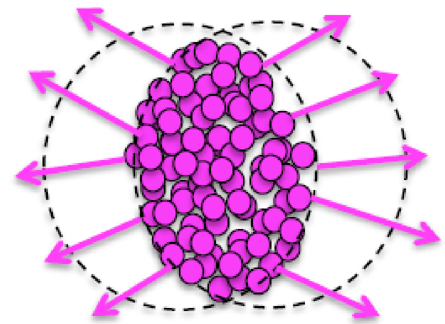
Analysis Techniques

6- and 8-particle cumulant



- Genuine 6- and 8-particle correlations
- Insensitive to non-flow contributions from < 6 and 8 particles

Lee-Yang Zeros



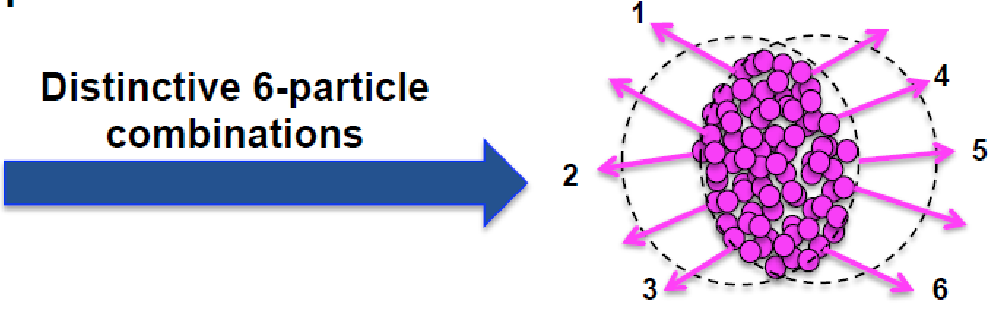
- Genuine all-particle correlation
- Built-in correction for non-uniform distribution

Multiparticle Cumulant

- 6-particle correlator, per event

$$\langle 6 \rangle \equiv \left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)} \right\rangle$$

$$\equiv \frac{1}{P_{M,6}} \sum_{\substack{i \neq j \neq k \\ \neq l \neq m \neq n}}^{M} e^{in(\phi_i+\phi_j+\phi_k-\phi_l-\phi_m-\phi_n)}$$



- 6-particle cumulant, all events

$$c_n\{6\} = \langle\langle 6 \rangle\rangle - 9 \bullet \langle\langle 4 \rangle\rangle \langle\langle 2 \rangle\rangle + 12 \bullet \langle\langle 2 \rangle\rangle^3$$

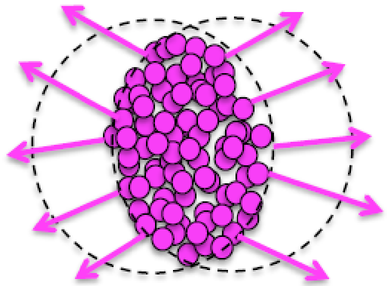
- Q-Cumulant: decompose ➔ flow vector $Q_n \equiv \sum_{i=1}^{M} w_i e^{in\varphi_i}$

- Cumulant v_n ➔ $v_n\{4\} = \sqrt[4]{-c_n\{4\}}, v_n\{6\} = \sqrt[6]{\frac{1}{4} c_n\{6\}}, v_n\{8\} = \sqrt[8]{-\frac{1}{33} c_n\{8\}}$

Lee-Yang Zeros Method

- All-particle correlation, per event

$$g(ir) \equiv \prod_{j=1}^{M} \left[1 + i \cdot r \cdot w_j \cos\left(n(\phi_j - \theta) \right) \right]$$



- Generating function, all events

$$G(ir) = \langle g(ir) \rangle = \frac{1}{N_{evt}} \sum_{events} g(ir)$$

Decompose →

Flow vector:

$$Q_n = (Q_{nx}, Q_{ny})$$

$$Q_{nx} = \sum_{j=1}^{M} w_j \cos(n\phi_j)$$

$$Q_{ny} = \sum_{j=1}^{M} w_j \sin(n\phi_j)$$

- Integrated $v_n\{LYZ\}$

$$V_2\{LYZ\} = \frac{j_{01}}{r_0}$$

j_{01}=2.40483
r_0 is the first zero of |G(ir)|