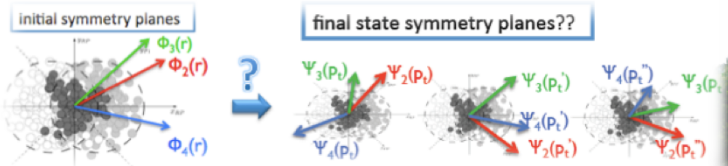
XXIV QUARK MATTER
DARMSTADT 2014

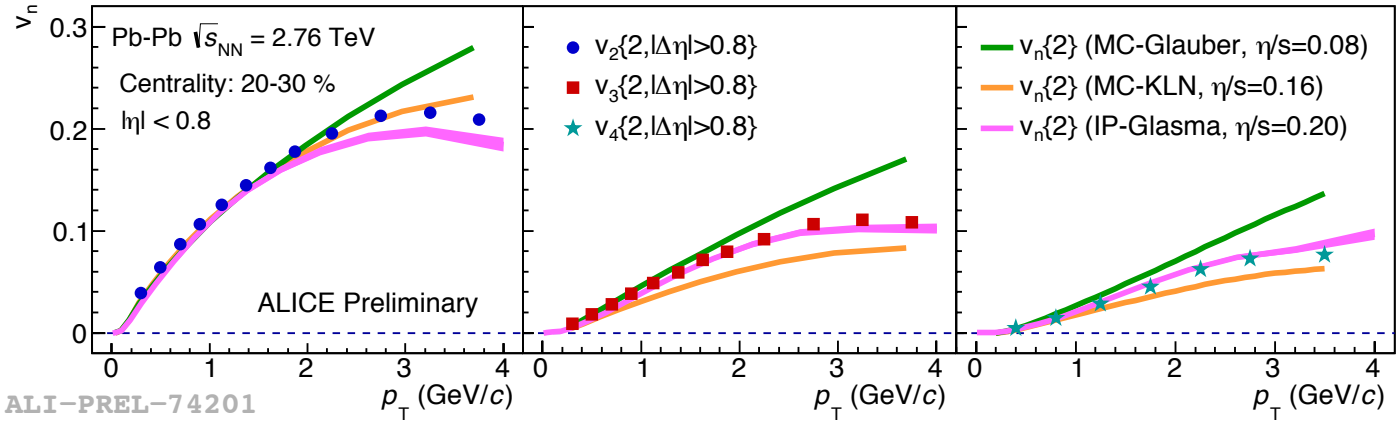


Searches for p_T dependent fluctuations of flow angle and magnitude in Pb-Pb and p-Pb collisions

You Zhou
Nikhef & Universiteit Utrecht
(On behalf of the ALICE Collaboration)

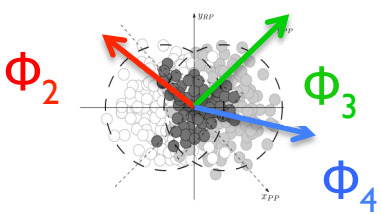
Motivation

- Traditionally *Flow* analyses look for correlations w.r.t common symmetry planes over a large range in p_T.

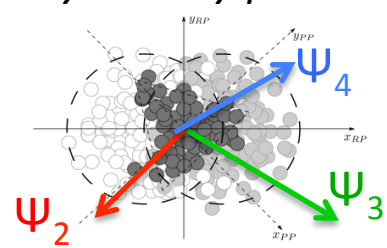


- Constraints on the initial state and η/s.

Initial symmetry planes

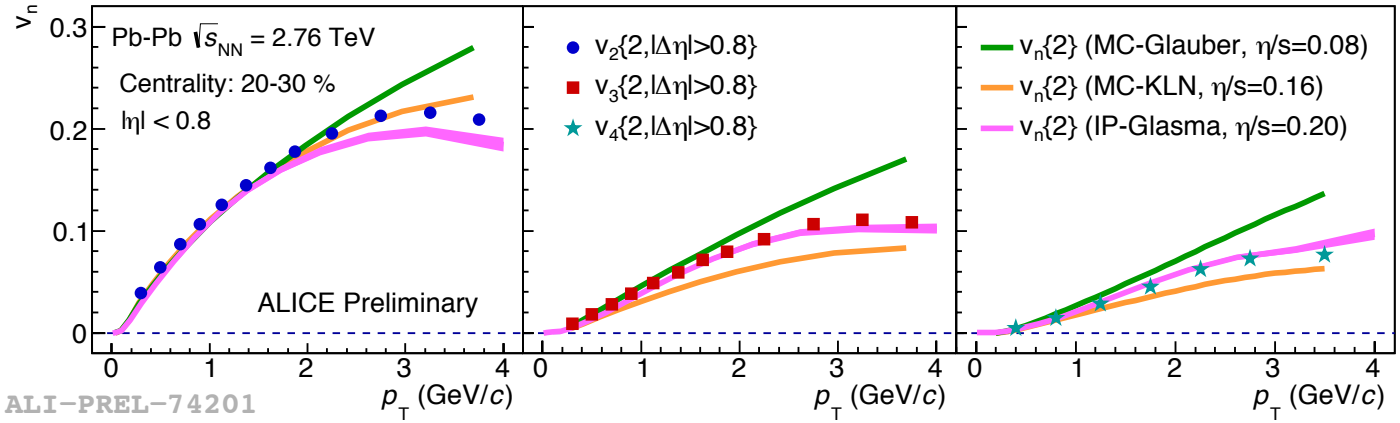


Final symmetry planes ??



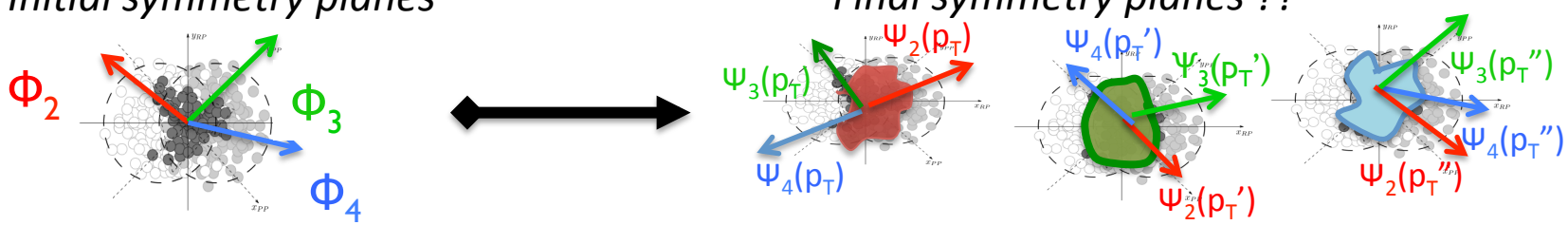
Motivation

- Traditionally *Flow* analyses look for correlations w.r.t common symmetry planes over a large range in p_T.



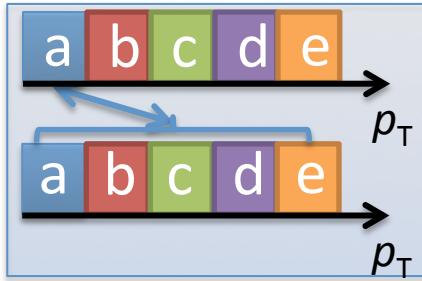
- However, recent hydrodynamic simulations show p_T dependent flow angle and magnitude fluctuations
  - Further constraints on the initial state and η/s.

Initial symmetry planes *Final symmetry planes ??*

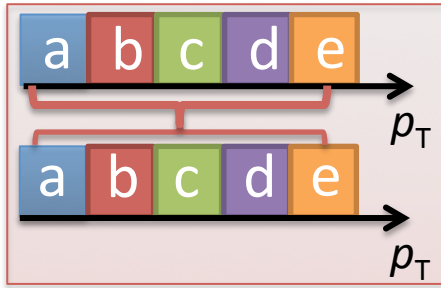


- 2 particle correlations probe these predicted effects in experiments.

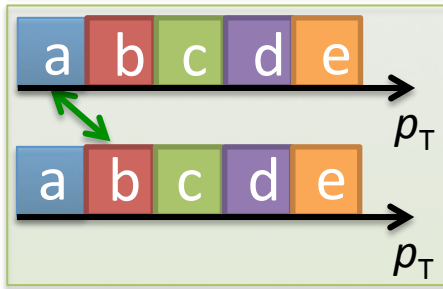
2 Particle Correlations



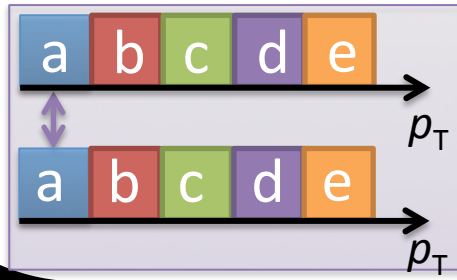
- Type < a, All >
  One particle from p_T^a, the other from entire p_T
  - $d_n\{2\}$



- Type < All, All >
  Two particles from entire p_T
  - $c_n\{2\}$



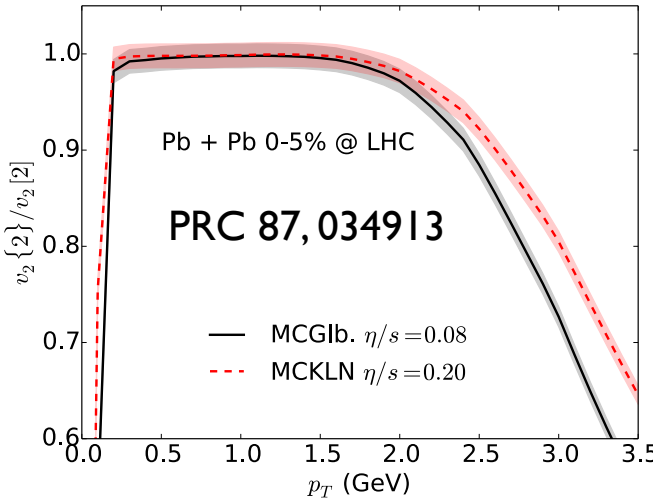
- Type < a, b >
  One particle from p_T^a, the other from p_T^b
  - $V_{n\Delta}(p_T^a, p_T^b)$

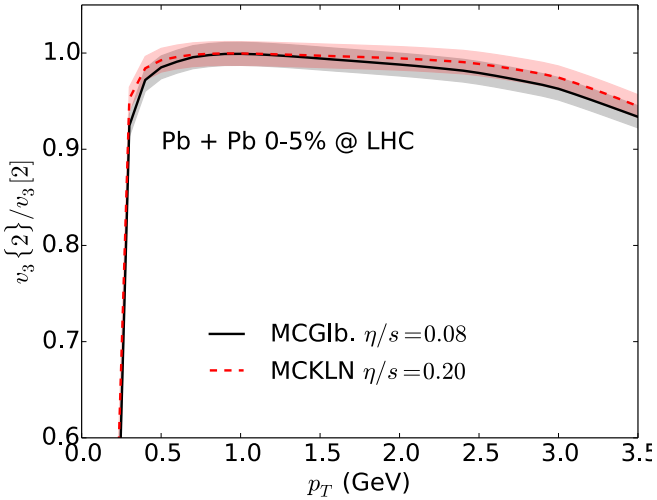


- Type < a, a >
  Two particles from p_T^a
  - $v_n[2]$
  - $V_{n\Delta}(p_T^a, p_T^a) = v_n[2]^2$

$v_n\{2\}$ and $v_n[2]$

- $v_n\{2\} = d_n\{2\}/c_n\{2\}^{1/2}$
  - < a, All > for $d_n\{2\}$ and < All, All > for $c_n\{2\}$
  - Contributions from possible p_T dependent flow angle and magnitude fluctuations, in addition from non-flow
- $v_n[2]$:
  - < a, a >
  - Contributions from non-flow
- Ratio of $v_n\{2\}/v_n[2]$: < a, All > ➡ <All, All> & < a, a >





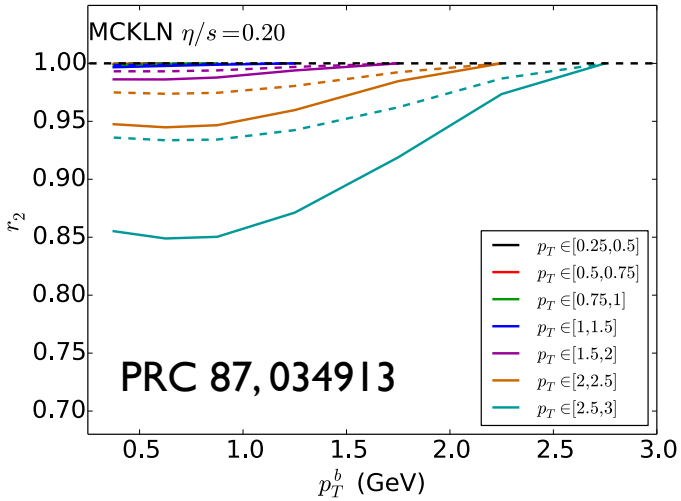
- Hydrodynamic calculations: $v_n\{2\}/v_2[2] < 1$ => p_T dependent flow angle and magnitude fluctuations.

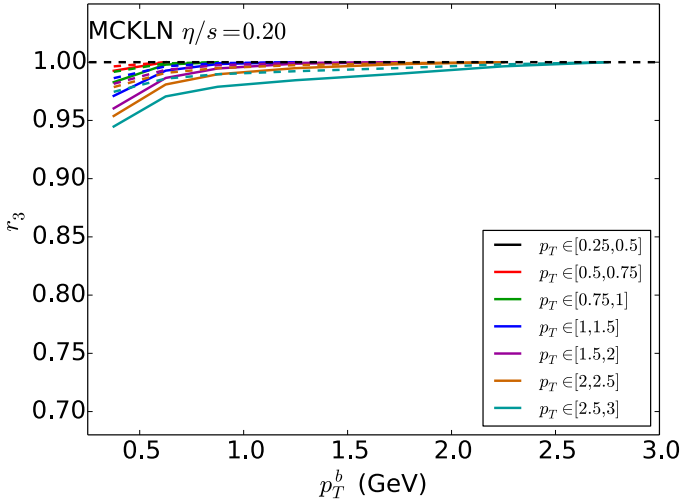
Factorization ratio r_n

- r_n : PRC 87, 031901(R)

$$r_n = \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) \cdot V_{n\Delta}(p_T^b, p_T^b)}}$$

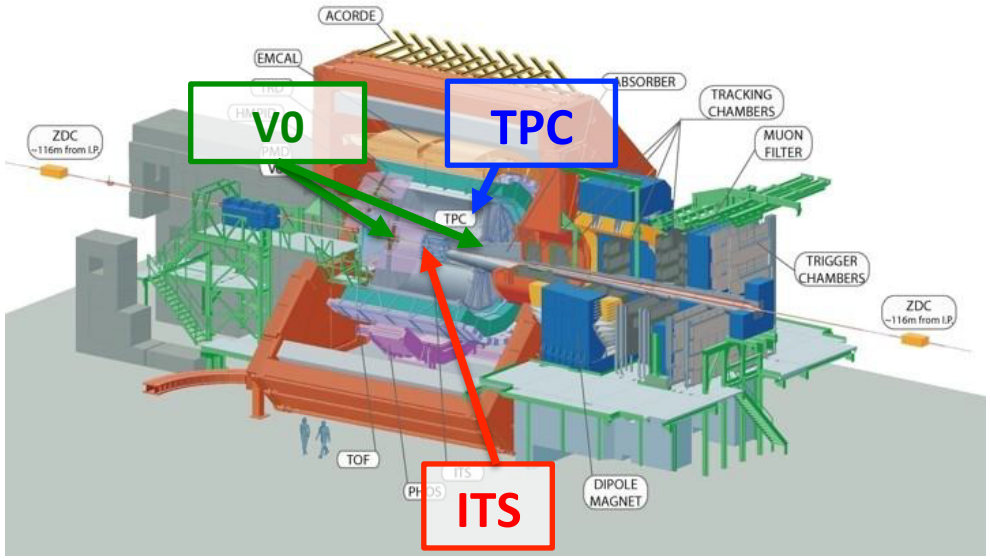
  - r_n probes < a, b > ➡ < a, a > & < b, b >
  - r_n < 1, Factorization broken





- r_n < 1 observed in hydrodynamic calculations
  - indication of p_T dependent fluctuations of flow angle and magnitude.

Analysis Details



❖ Detectors used:

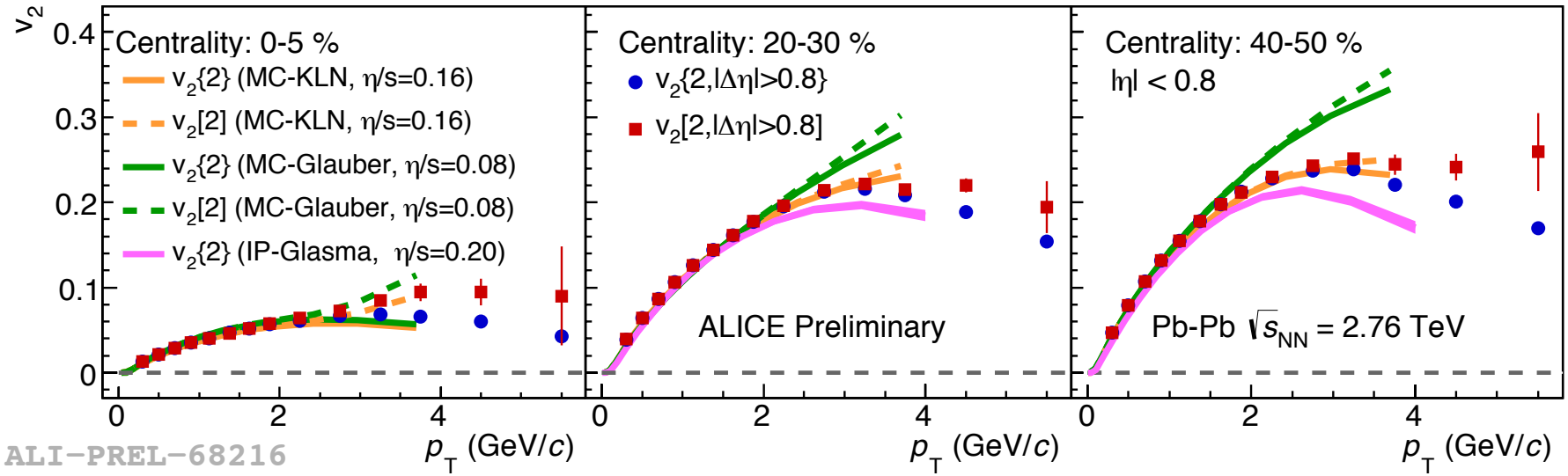
- Inner Tracking System (trigger, tracking and vertexing)
- Time Projection Chamber (tracking, centrality determination)
- V0 detectors
  $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$
  (trigger, centrality determination)

❖ Data sample:

- Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
  - ~ 12 M events analyzed
- p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
  - ~ 96 M events analyzed
- Tracks used:
  - $-0.8 < \eta < 0.8$
  - $0.2 < p_T < 6.0$ GeV/c

v_2

MC-Glauber & MC-KLN: PRC 87, 034913 **IP-Glasma: PRL 110, 012302**



- $v_2\{2\}$ and $v_2[2]$
  - MC-KLN works better for both $v_2[2]$ and $v_2\{2\}$ up to higher p_T.

$v_2\{\ \}$ / $v_2[\ ]$

MC-Glauber & MC-KLN: PRC 87, 034913

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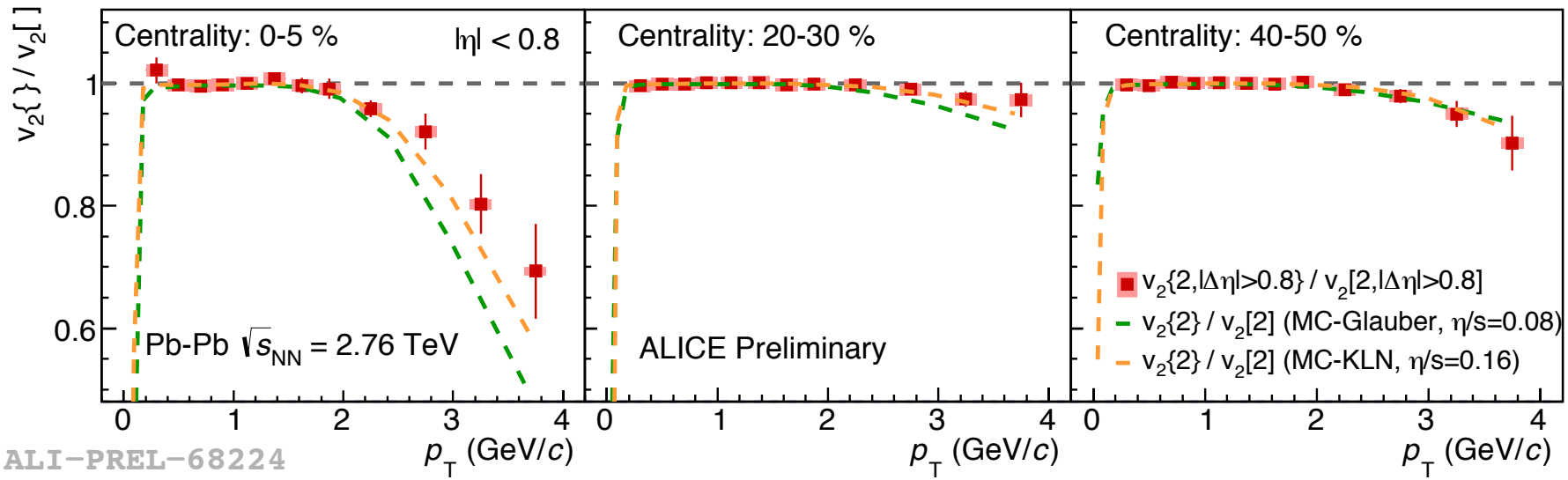
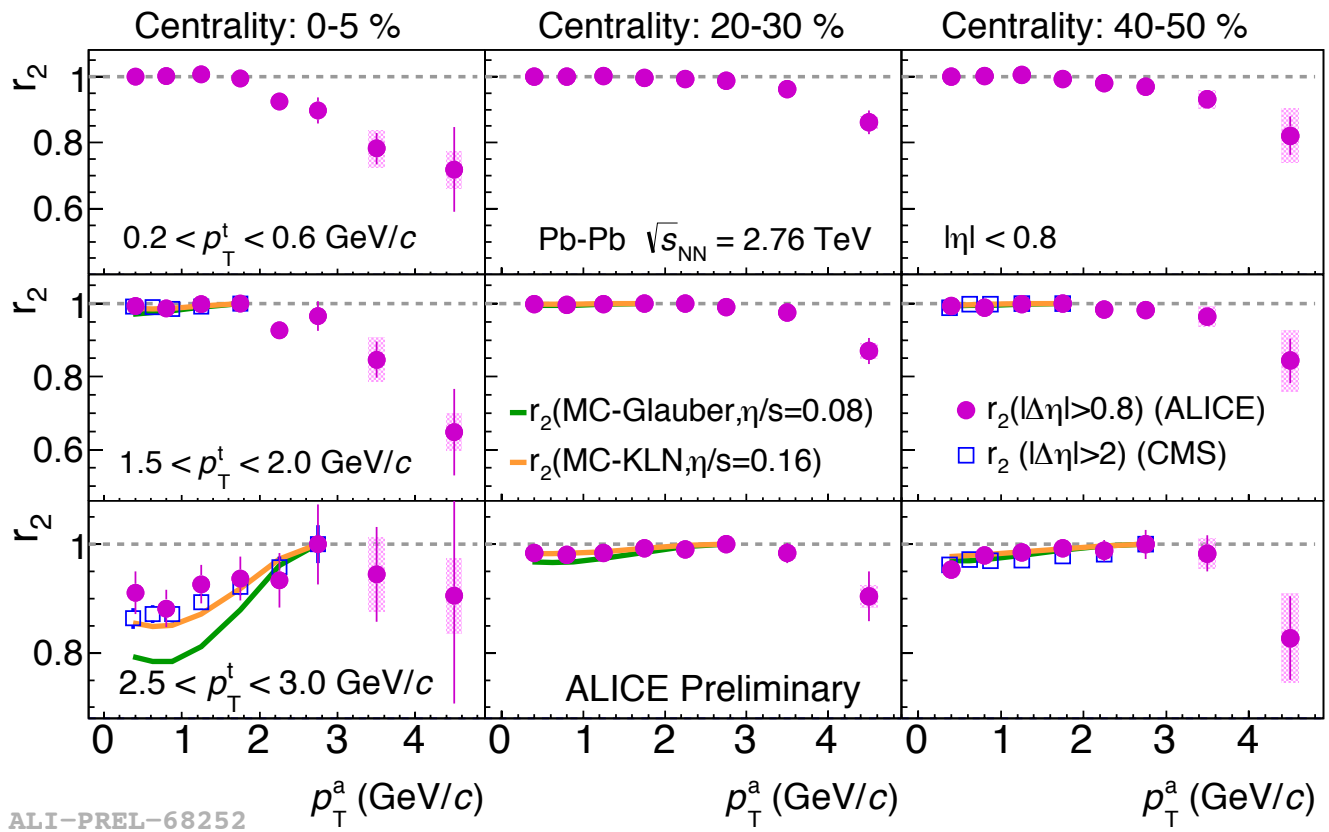


- $v_2\{2\}$ / $v_2[2]$
  - Significant deviation for p_T >2 GeV/c in most central collisions.
- Hydrodynamic calculations (no non-flow) already overestimate the deviation of $v_2\{2\}/v_2[2]$ in most central collisions
  - Calculations with MC-KLN describe the data better than MC-Glauber.

Centrality dependence of r_2



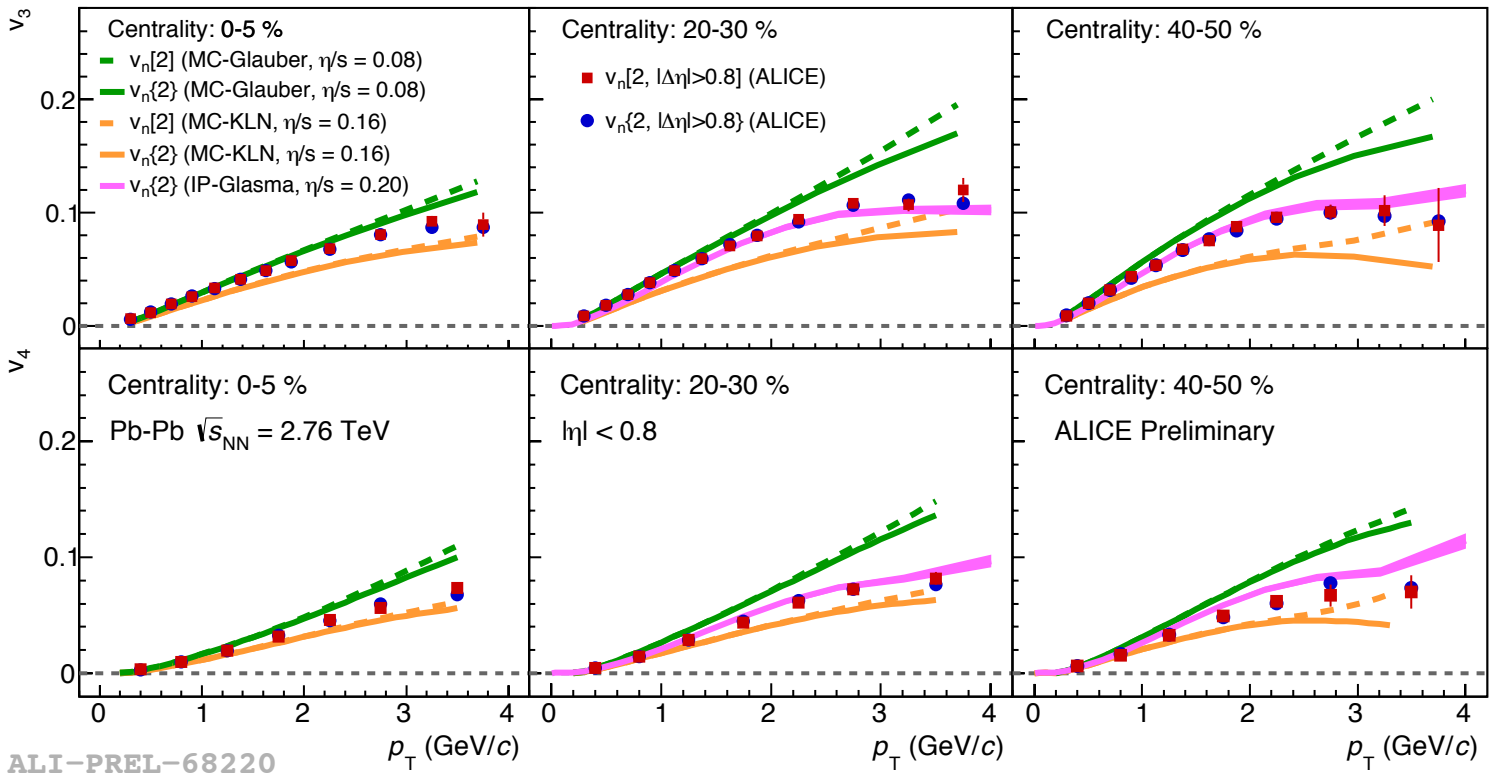
MC-Glauber & MC-KLN:
PRC 87, 034913

CMS,
JHEP 02, 088

- Breakdown of factorization more pronounced in central collisions.
- Hydrodynamic calculations also show that the factorization is broken.
- CMS $r_2(|\Delta\eta|>2.0)$ quantitatively agrees with our measurements
  - Additional η dependent fluctuations of flow angle (Ψ_2) and/or magnitude (v_2) are not observed or non-flow is similar between $|\Delta\eta| > 0.8$ and 2.0.

v_3 and v_4

MC-Glauber & MC-KLN: PRC 87, 034913 **IP-Glasma: PRL 110, 012302**



- No clear difference of $v_3\{2\}$ compared to $v_3[2]$ and $v_4\{2\}$ compared to $v_4[2]$ up to $p_T \sim 4$ GeV/c.
- Hydrodynamic calculations:
  - with IP-Glasma agree $v_n\{2\}$ very well, interesting to test if it can reproduce $v_n[2]$.
  - with MC-KLN or MC-Glauber do not describe the p_T dependence of v_3 or v_4.

$v_n\{\ \}/v_n[\ ]$

MC-Glauber & MC-KLN: PRC 87, 034913

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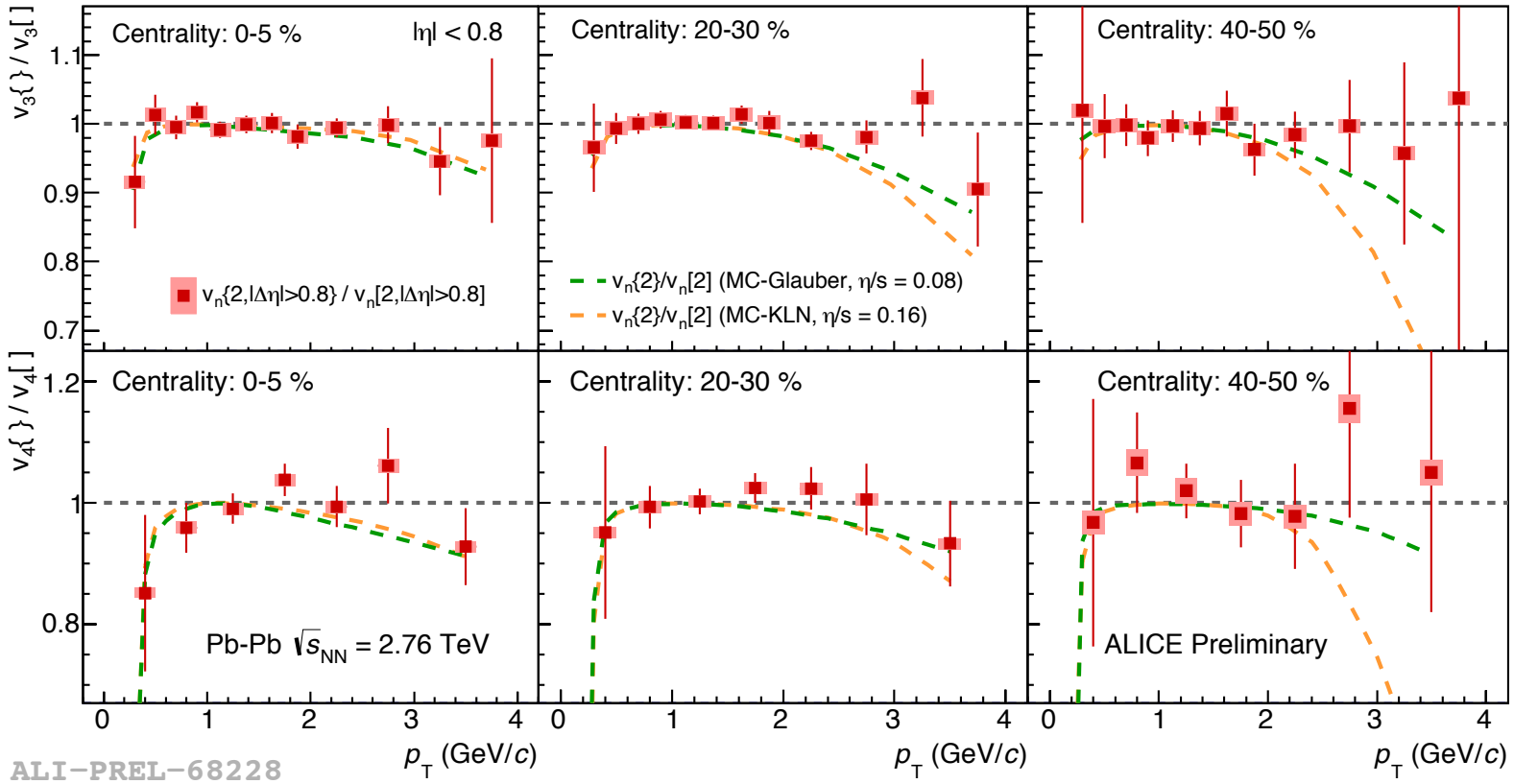
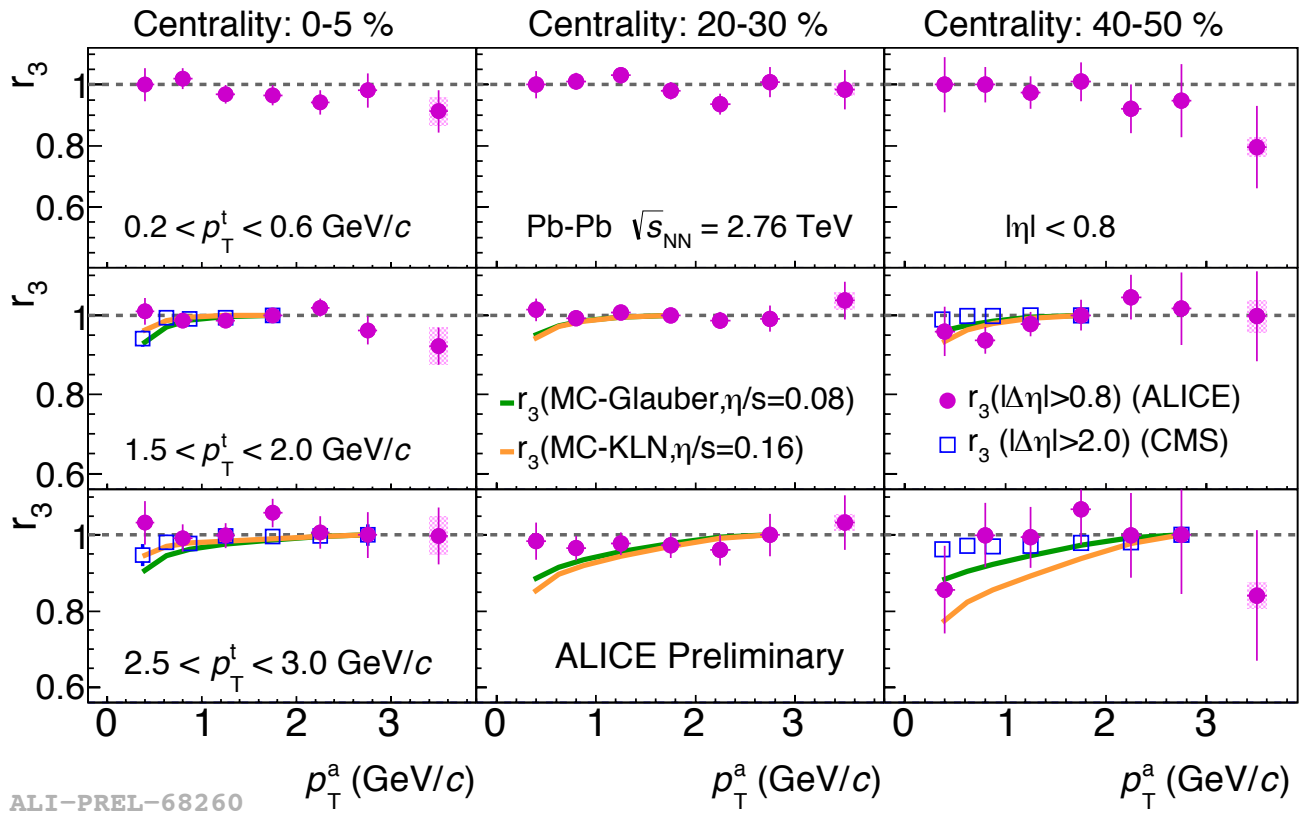


- In data no clear indication of p_T dependent fluctuations of flow angle (Ψ_3, Ψ_4) and magnitude (v_3, v_4).
- These effects seem more pronounced in hydrodynamic calculations.

Centrality dependence of r_3



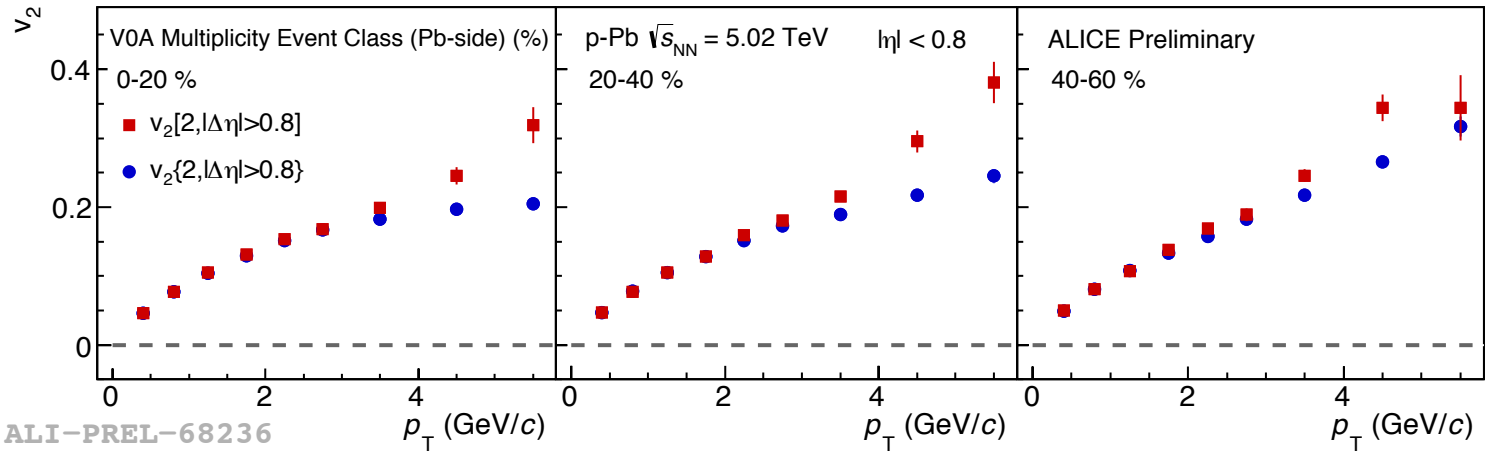
MC-Glauber & MC-KLN:
PRC 87, 034913

CMS,
JHEP 02, 088

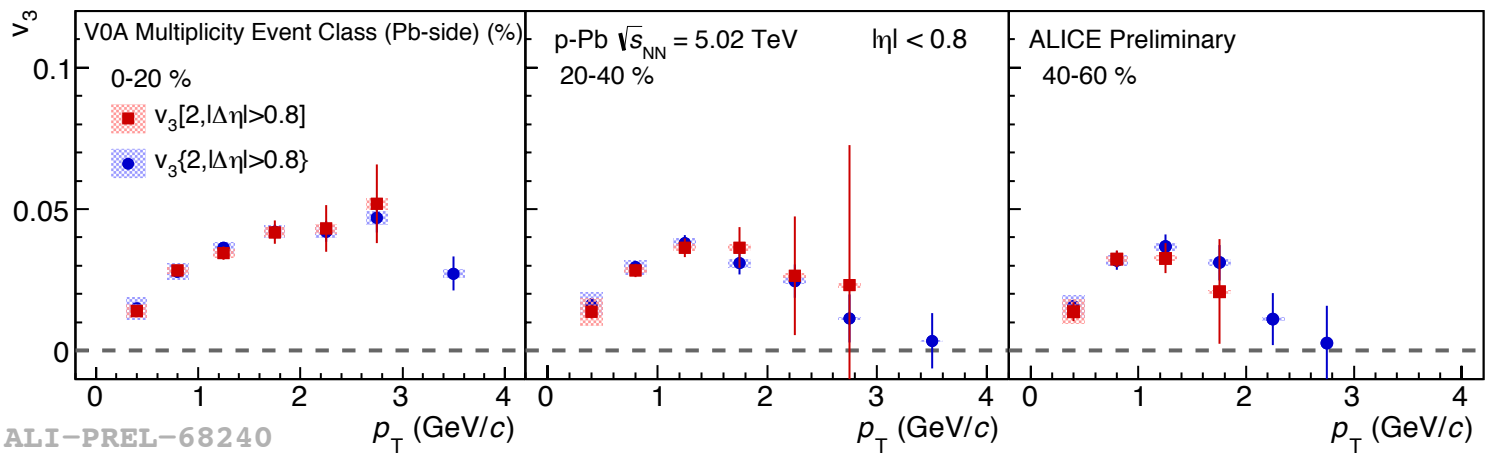
- r_3 consistent with 1 up to $|p_T^t - p_T^a| \sim 3$ GeV/c.
- Good agreement between ALICE and CMS measurements.
  - No clear contribution from additional η dependent fluctuations of flow angle (Ψ_3) and magnitude (v_3) or non-flow.
- Hydrodynamic calculations seem to overestimate the effect.

v_2 and v_3 in p-Pb

✧ *Flow in p-Pb? See talks: L. Milano (Tuesday, 14:40)*



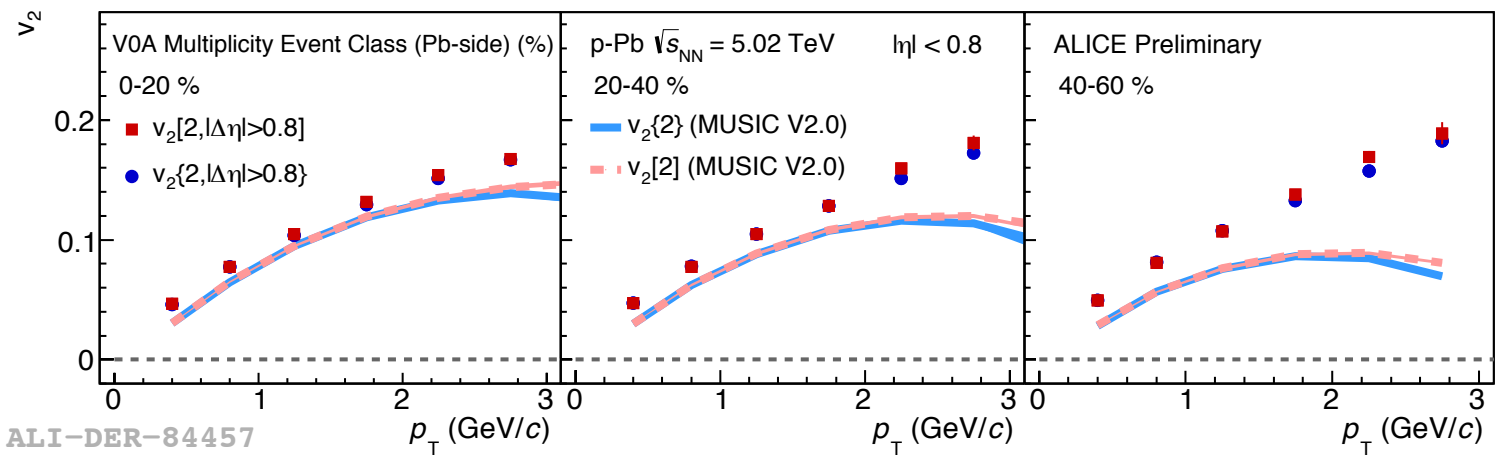
- $v_2[2]$ and $v_2\{2\}$ deviate at p_T~ 3 GeV/c for presented multiplicity classes.



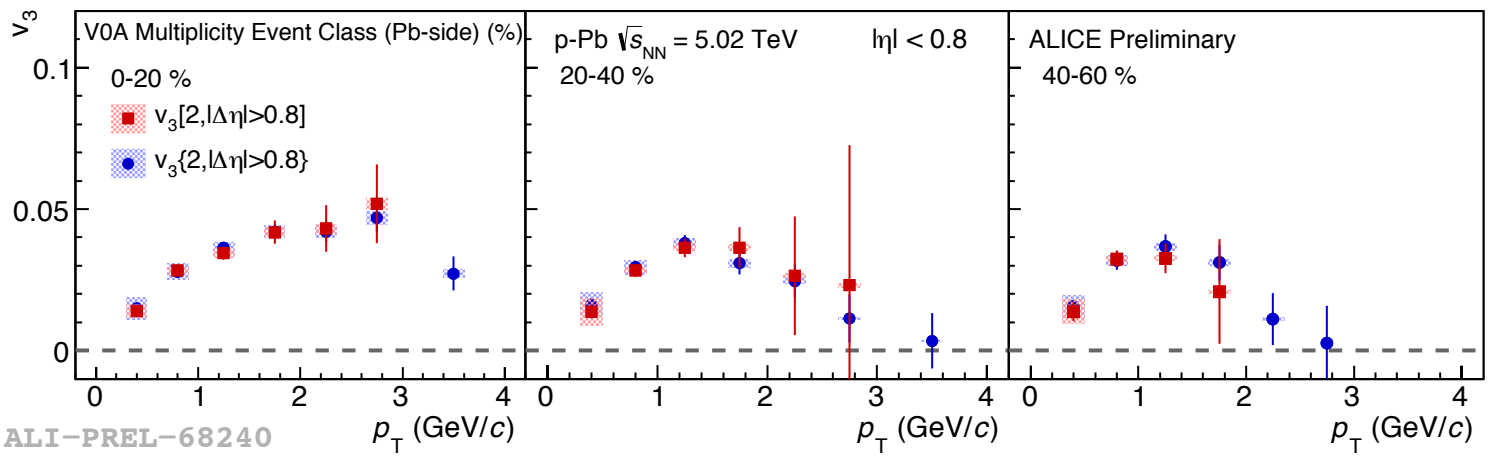
- No clear difference between $v_3[2]$ and $v_3\{2\}$ for the presented p_T range.

v_2 and v_3 in p-Pb

MUSIC: arXiv:1405.3976

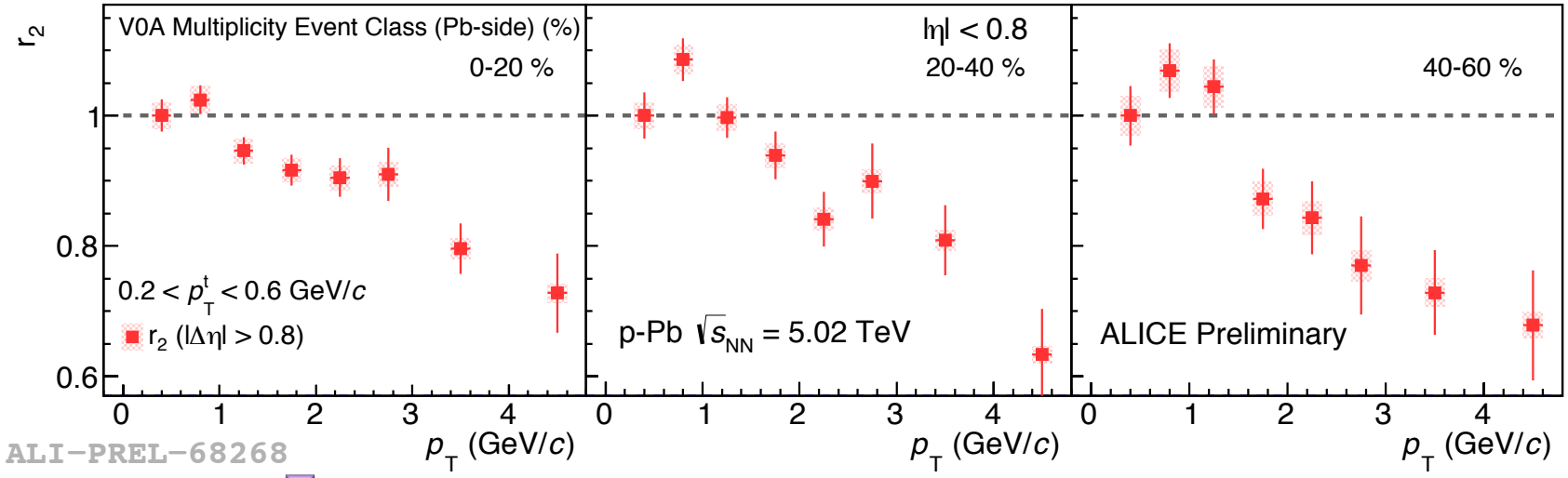


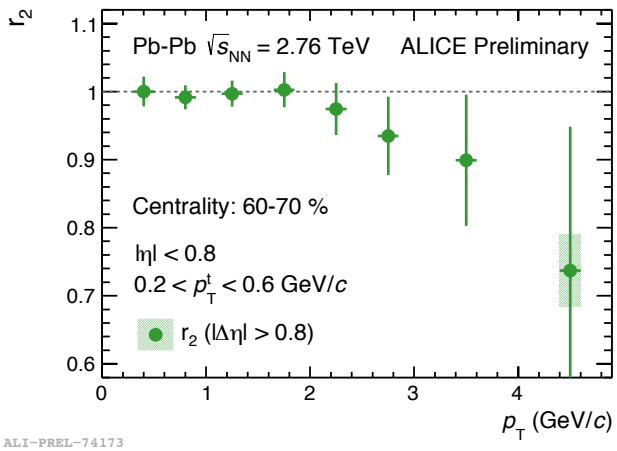
- Hydrodynamic calculations works better in central than peripheral p-Pb collisions.



- No clear difference between $v_3[2]$ and $v_3\{2\}$ for the presented p_T range.

r_2 in p-Pb and Pb-Pb





- Factorization is always significantly broken in p-Pb collisions (in case there is no non-flow subtraction).
- Factorization is valid for a wider p_T range in peripheral Pb-Pb collisions.

Summary

- We presented $v_n\{2\}$, $v_n[2]$, ratio of $v_n\{2\}/v_n[2]$ and r_n in Pb-Pb collisions.

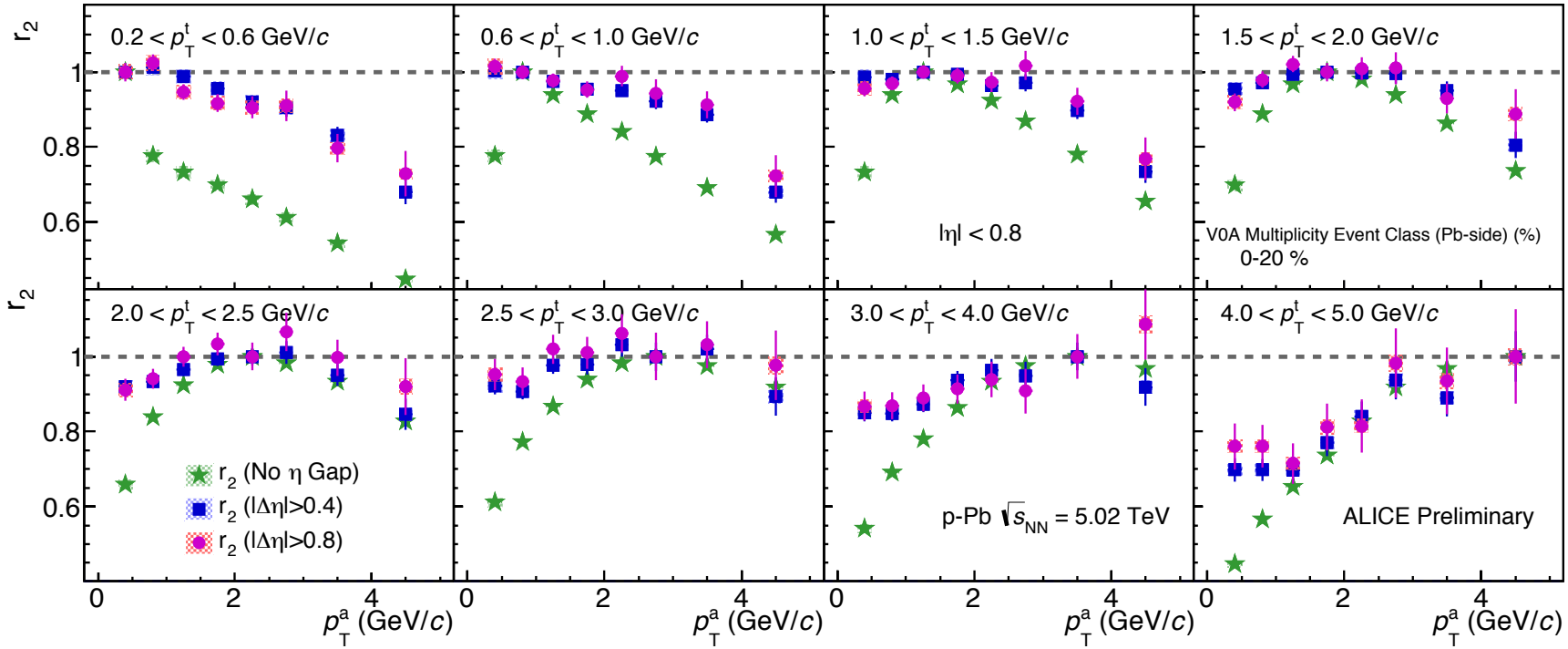
  - We observed indications of p_T dependent flow angle (Ψ_2) and magnitude (v_2) fluctuations, however non-flow contributions are not fully excluded.
  - The p_T dependent fluctuations of the flow angle and magnitude seem to be smaller than what hydrodynamic predictions.

- Factorization is more strongly broken in p-Pb collisions
  - Different from peripheral Pb-Pb collisions.
  - Further study on non-flow are necessary.

Thanks for your attention!

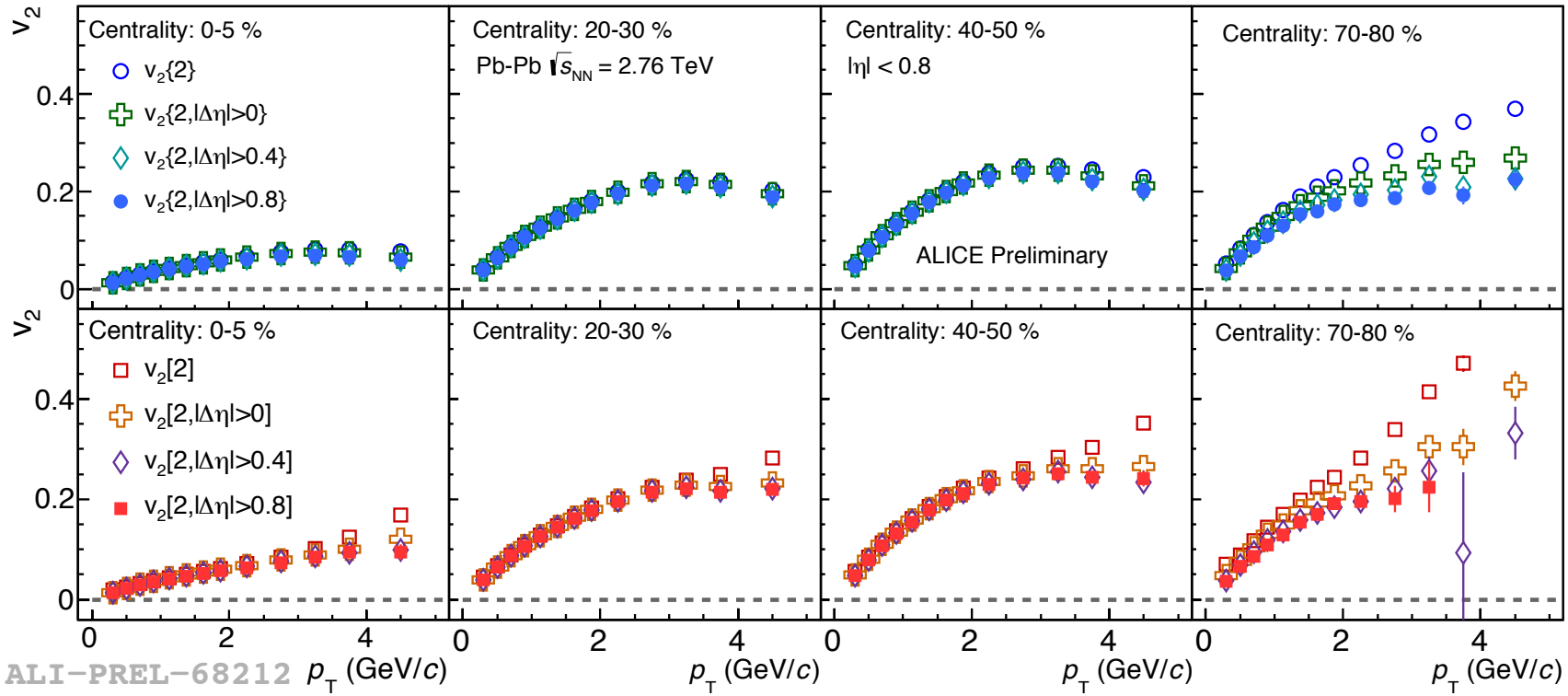
Backup

r_2 in p-Pb



- Without η gap, r_2 deviates from unity for entire p_T range
- With η gap
  - Consistent results for |Δη|>0.4 and |Δη|>0.8.
  - Factorization is broken as $|p_T^t - p_T^a|$ increase.

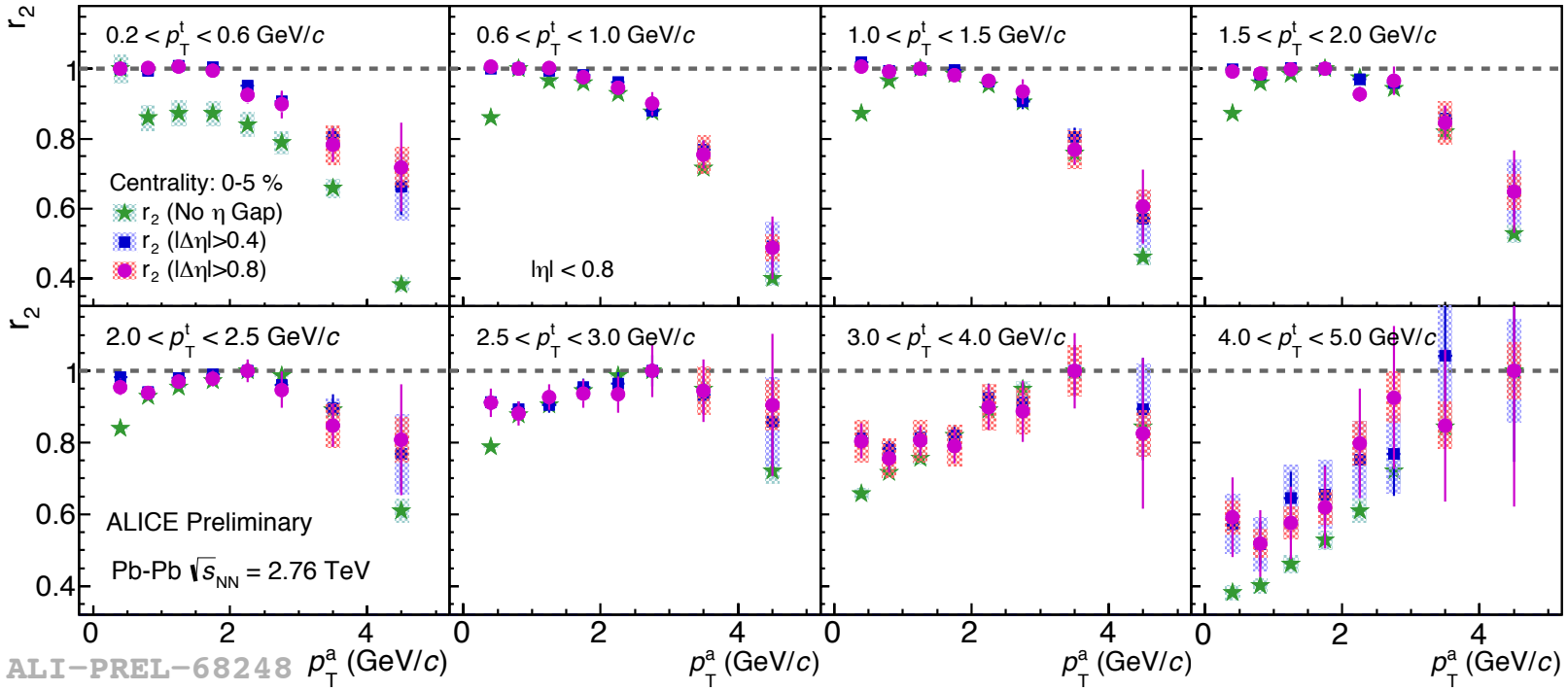
Δη dependence of v_2 in Pb-Pb



- $v_2\{2\}$ and $v_2[2]$
  - decrease when the Δη increase;
  - The short range correlations (non-flow) are expected to be suppressed when applying Δη gap.

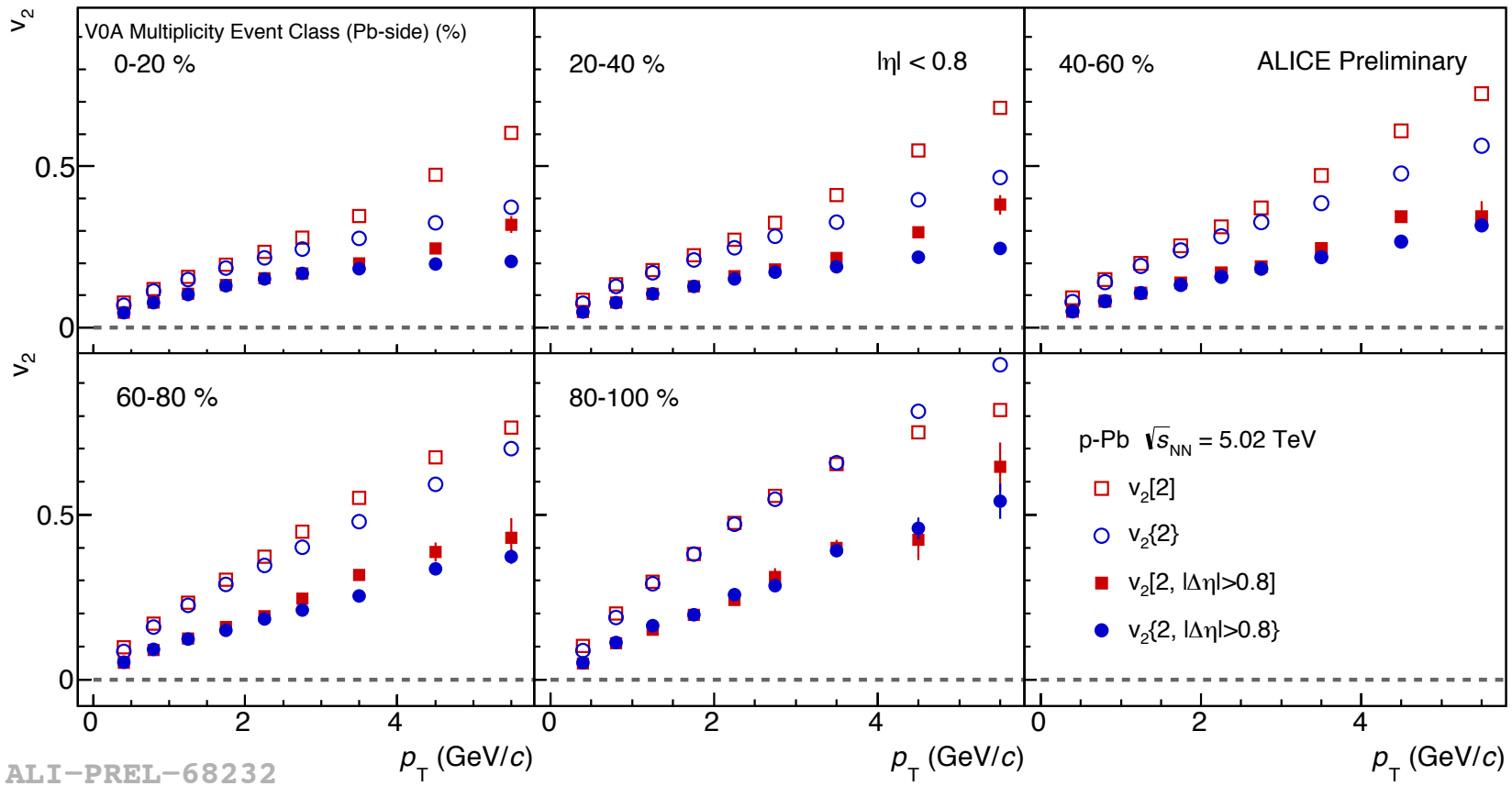
Δη dependence of r_2 in Pb-Pb

< a, b > ➡ < a, a > & < b, b >



- Without η gap, r_2 deviates from unity
- With η gap
  - Consistent results for |Δη|>0.4 and |Δη|>0.8, non-flow effects are suppressed
  - The factorization is valid when $p_T^a \sim p_T^t$ and broken stronger as $|p_T^t - p_T^a|$ increase
    - Can be explained by p_T dependent flow magnitude fluctuations, as well as by non-flow probably.

Δη dependence of v_2 in p-Pb



- $v_2\{2\}$ and $v_2[2]$
  - decrease when the Δη increase;
  - The short range correlations (non-flow) are expected to be suppressed when applying Δη gap.

$V_{n\Delta}$ via *Q*-cumulant method

- $V_{n\Delta}$ is a product of Q_n^a and Q_n^{b*} scaled by corresponding multiplicities in certain p_T bin in each sub-event.

$$V_{n\Delta}(p_T^a, p_T^b) = \langle V_n^a V_n^{b*} \rangle = \langle v_n^a v_n^b \cdot e^{in(\Psi_n^a - \Psi_n^b)} \rangle$$

$$V_{n\Delta}(p_T^a, p_T^b) = \langle \frac{Q_n^a \cdot Q_n^{b*}}{M_a M_b} \rangle$$

$$Q_n = \sum_{i=1}^{N} e^{in\phi_i}$$: Flow-vector

Q_n^a and Q_n^b from p_T^a and p_T^b

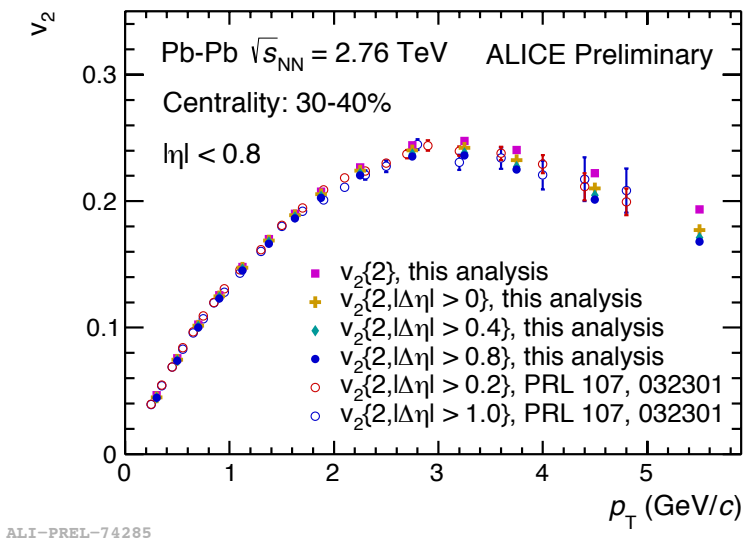
$$V_{n\Delta}(p_T^a, p_T^{a'}) = \langle \frac{Q_n^a \cdot Q_n^{a'*}}{M_a M_a'} \rangle$$

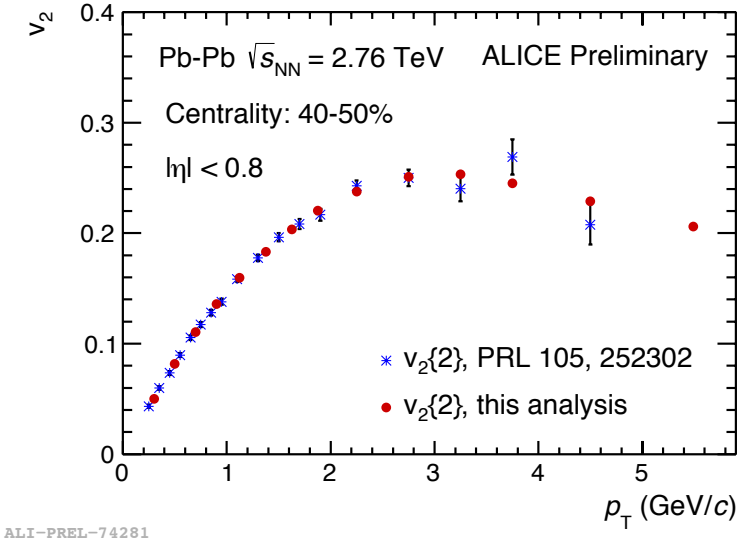
$$V_{n\Delta}(p_T^b, p_T^{b'}) = \langle \frac{Q_n^b \cdot Q_n^{b'*}}{M_b M_b'} \rangle$$

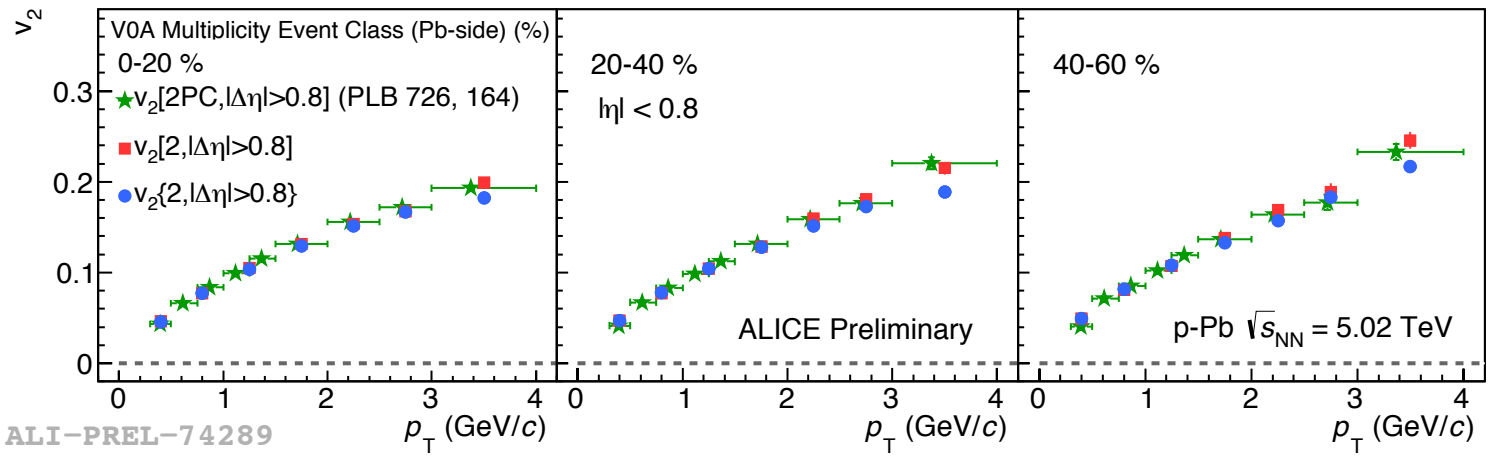
Here Q_n^a and $Q_n^{a'}$ (Q_n^b and $Q_n^{b'}$) from same p_T range but different sub-events.

- If the main goal of using two-particle correlation is to obtain $V_{n\Delta}$, using modified *Q*-Cumulant method is a direct and efficient way.

Comparison to published results

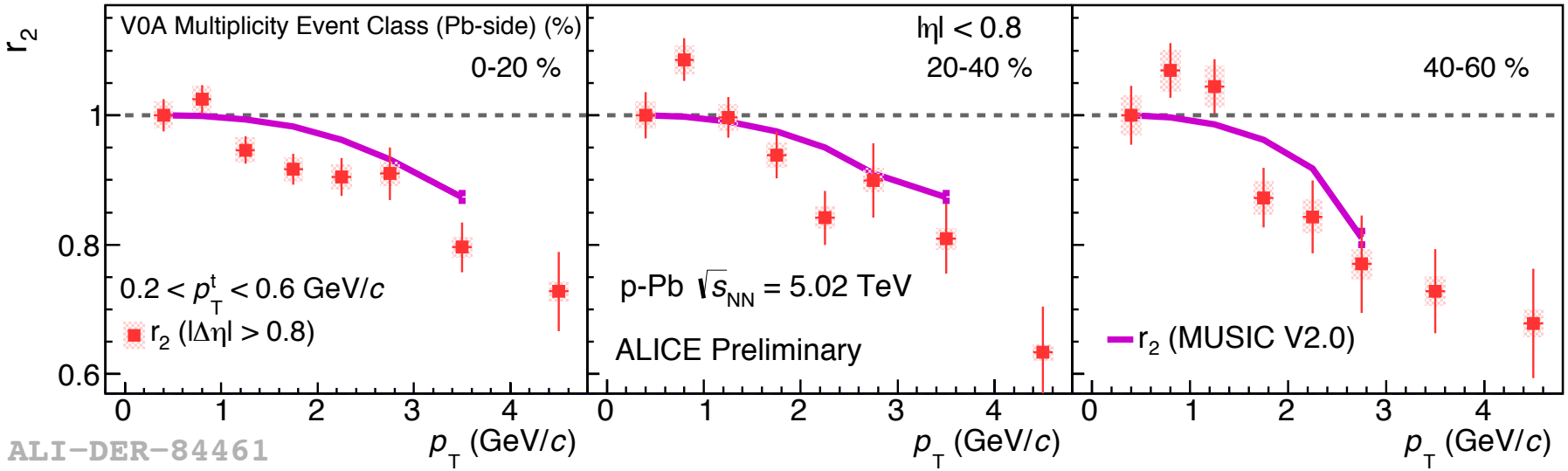






r_2 in p-Pb and Pb-Pb

MUSIC: arXiv:1405.3976



- The definition of "centrality" might be different in ALICE and hydrodynamic calculations (MUSIC).