Fluctuations and correlations of flow in heavy-ion collisions measured by ALICE

Initial stages 2021

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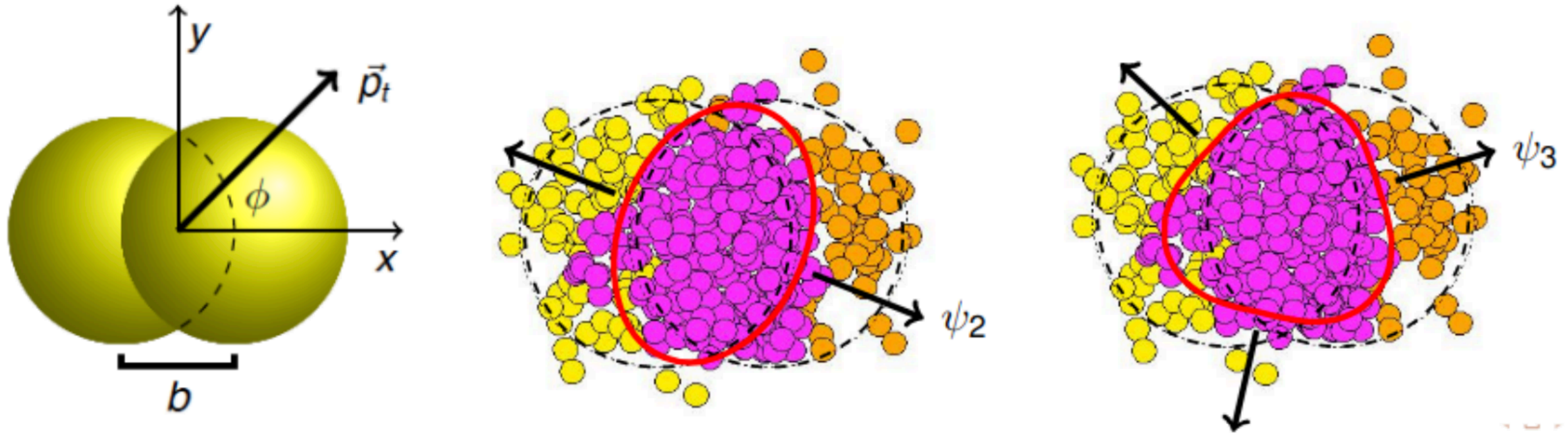
THE VELUX FOUNDATIONS
VILLUM FONDEN VELUX FONDEN

Probe QGP with anisotropic flow

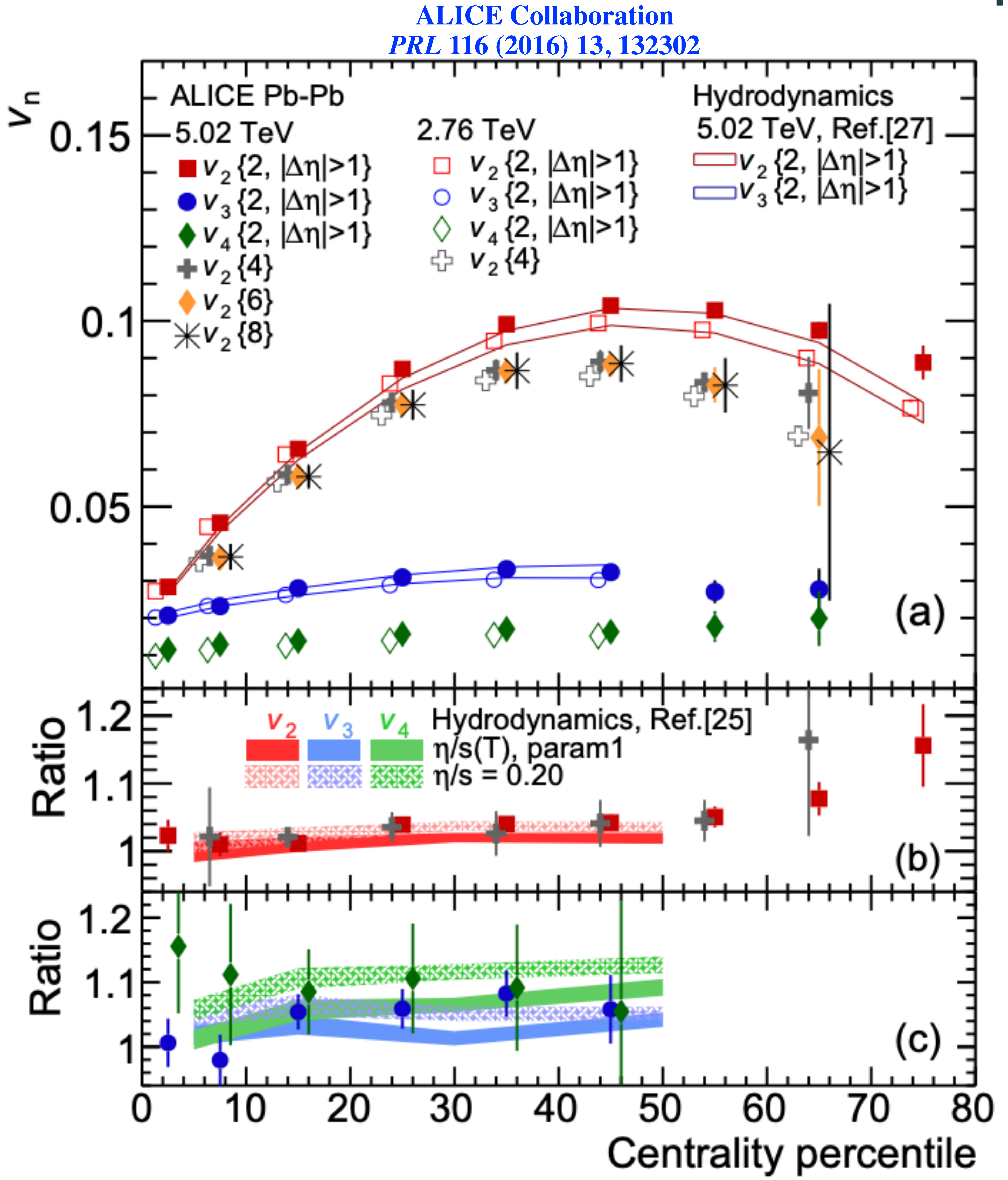
- QGP created in heavy-ion collisions can be probed via **anisotropic flow**

- Initial spatial anisotropy is transferred via large pressure gradients to final state momentum anisotropy

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} V_n e^{in\varphi}$$



- Comparing data with theoretical models allow for extraction of QGP properties



p_T-dependent flow vector fluctuations

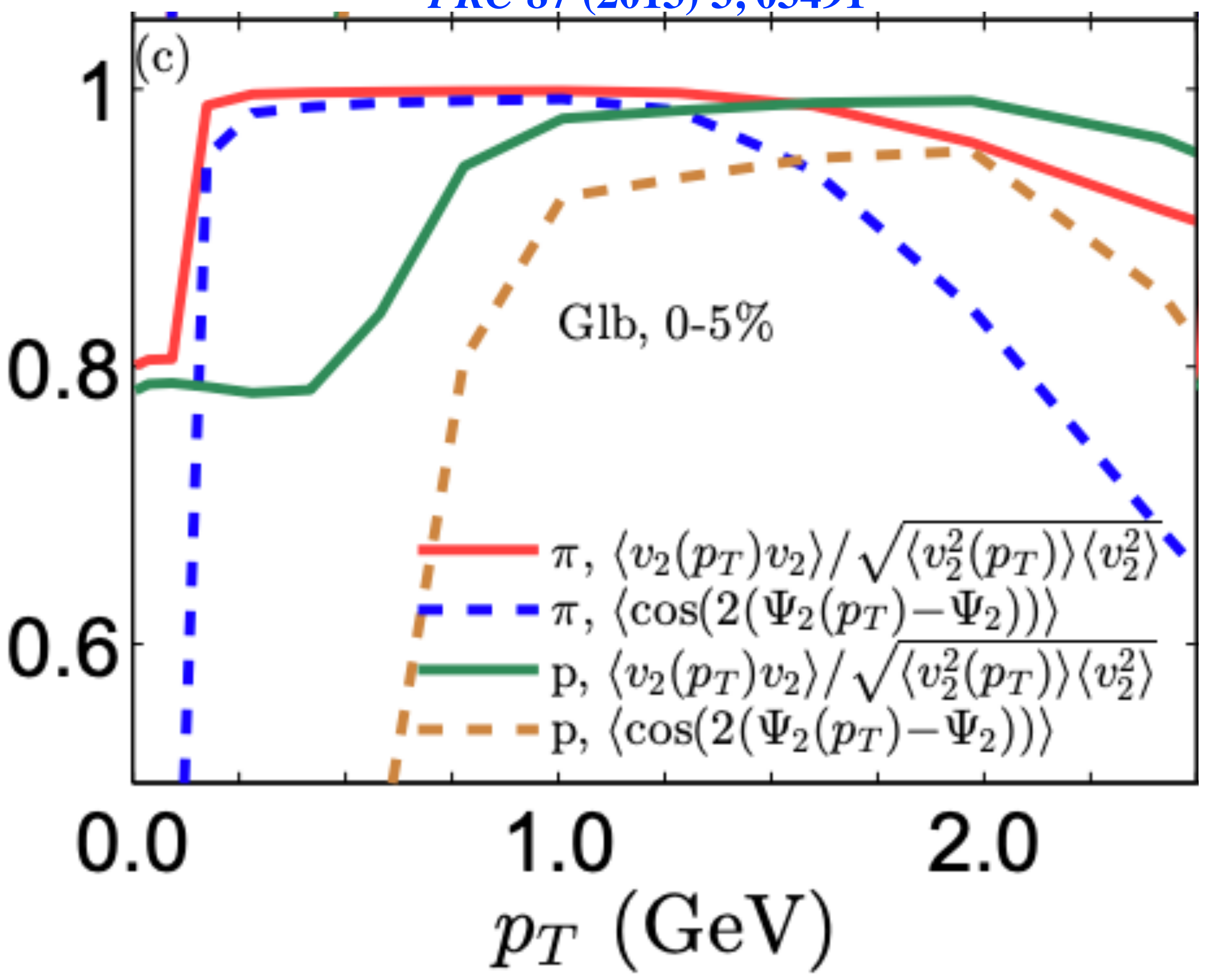
- Flow vector may fluctuate with p_T

$$\vec{V}_n = v_n e^{in\Psi_n}$$

- v_n : Anisotropic flow
- Ψ_n : Flow symmetry plane angle

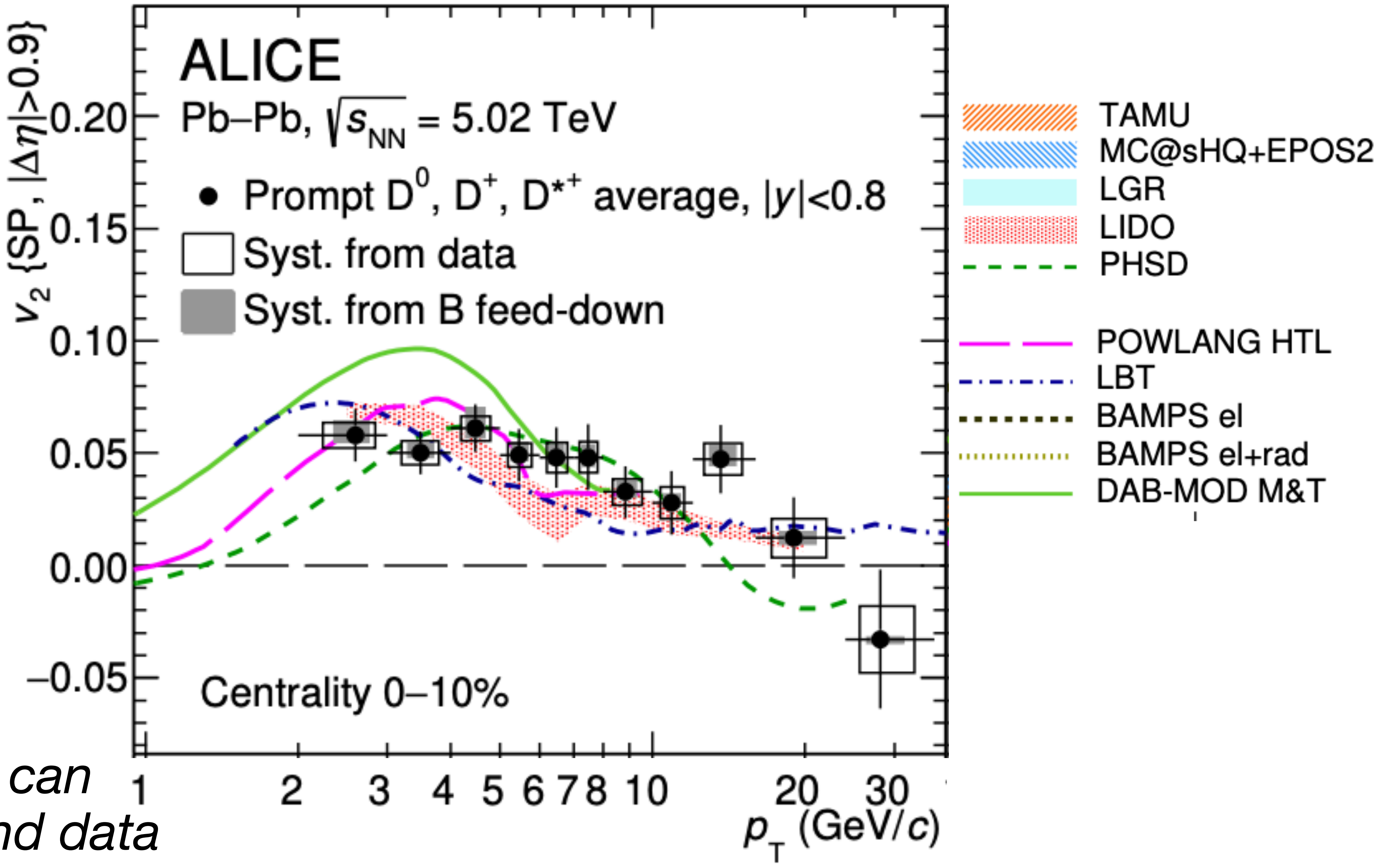
Both v_n and Ψ_n may fluctuate with p_T!

U. Heinz et al.
PRC 87 (2013) 3, 03491



- Hydro model predicted additional flow angle and flow magnitude fluctuations
- Cannot be disentangled with current observables based on **2-particle correlations**
- Non-hydro models does not have these fluctuations
- Quantifying additional fluctuations is necessary for correctly estimating QGP properties with high p_T flow measurements

ALICE, arXiv: 2005.11131



Example where additional fluctuations can lead to discrepancy between model and data

Probing flow vector fluctuations with $v_n\{2\}/v_n[2]$

Observable to probe flow vector fluctuations

$$\frac{v_n\{2\}}{v_n[2]} = \frac{\langle v_n(p_T^a)\ v_n \cos n[\Psi_n(p_T^a) - \Psi_n]\rangle}{\sqrt{\langle v_n^2(p_T^a)\rangle}\sqrt{\langle v_n^2\rangle}}$$

→ Flow angle fluctuations

→ Flow magnitude fluctuations

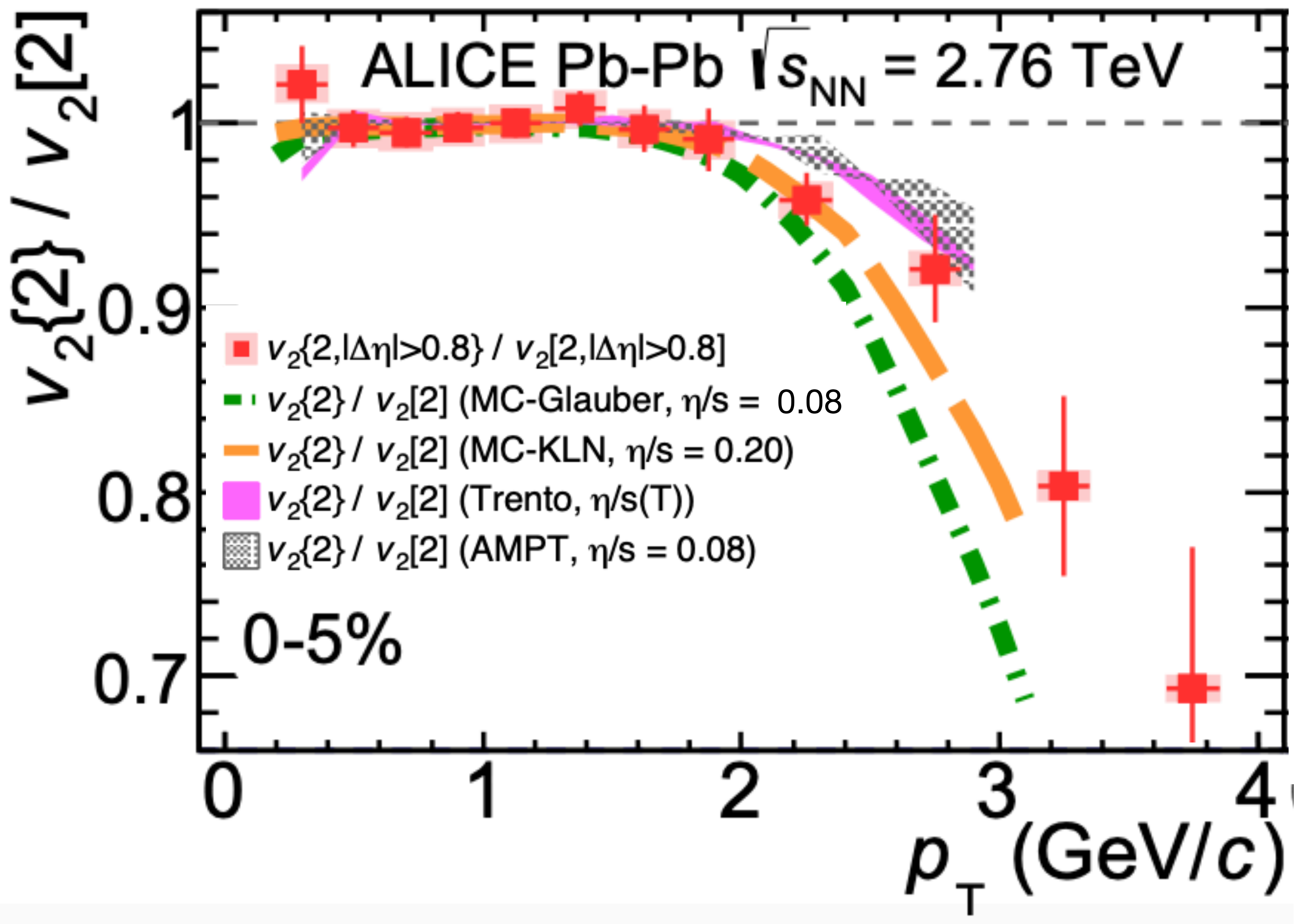
Standard 2-particle correlation

$$v_n\{2\} = \frac{\langle v_n(p_T)\ v_n \cos n[\Psi_n(p_T) - \Psi_n]\rangle}{\sqrt{\langle v_n^2\rangle}}$$

$$v_n[2] = \sqrt{\langle v_n^2(p_T^a)\rangle}$$

ALICE Collaboration
JHEP 09 (2017) 032

Run 1



- $v_n\{2\}$ has contribution from flow angle and assumes factorisation of $\langle v_n(p_T)\ v_n\rangle = \sqrt{\langle v_n^2(p_T)\rangle}\sqrt{\langle v_n^2\rangle}$
- If $v_2\{2\}/v_2[2] < 1$, it indicates presence of flow vector fluctuations
- ***How can we disentangle the two contributions and quantify each of them?***

Separating flow angle and flow magnitude fluctuations

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- New observable to measure **flow angle fluctuations**:

$$F(\Psi_n^a, \Psi_n) = \frac{\langle\langle \cos[n(\varphi_1^a + \varphi_2^a - \varphi_3 - \varphi_4)] \rangle\rangle}{\langle\langle \cos[n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4)] \rangle\rangle}$$

$$= \frac{\langle v_n^2(p_T^a)\ v_n^2 \cos 2n[\Psi_n(p_T^a) - \Psi_n] \rangle}{\langle v_n^2(p_T^a) v_n^2 \rangle}$$

$$\approx \langle \cos 2n[\Psi_n(p_T^a) - \Psi_n)] \rangle$$

$F(\Psi_n^a, \Psi_n) < 1$ indicates p_T-dependent **flow angle fluctuations**

- New observable to measure **flow magnitude fluctuations**

$$\frac{\langle\langle \cos n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4) \rangle\rangle}{\langle\langle \cos n(\varphi_1^a - \varphi_3^a) \rangle\rangle \langle\langle \cos n(\varphi_2 - \varphi_4) \rangle\rangle} = \frac{\langle v_n^2(p_T^a)\ v_n^2 \rangle}{\langle v_n^2(p_T^a) \rangle \langle v_n^2 \rangle}$$

- p_T-integrated baseline: $\langle v_n^4 \rangle / \langle v_n^2 \rangle^2$

Deviations from baseline indicate the presence of p_T-dependent **flow magnitude fluctuations**

Comparing with $v_n\{2\}/v_n[2]$

Flow vector fluctuations

Flow magnitude fluctuations

Flow angle fluctuations

- $$\frac{v_n\{2\}}{v_n[2]} = \frac{\langle v_n(p_T^a)\, v_n \cos n[\Psi_n(p_T^a) - \Psi_n]\rangle}{\sqrt{\langle v_n^2(p_T^a)\rangle}\sqrt{\langle v_n^2\rangle}}$$

Twice the angle

- $$F(\Psi_n^a, \Psi_n) = \langle \cos 2n[\Psi_n(p_T^a) - \Psi_n]\rangle$$

2nd moments of v_n

- $$\frac{\langle v_n^2(p_T^a)\, v_n^2\rangle}{\langle v_n^2(p_T^a)\rangle\langle v_n^2\rangle}$$

- Enable comparison with flow vector fluctuations from $v_n\{2\}/v_n[2]$

$$\sqrt{\frac{F(\Psi_n^a, \Psi_n)+1}{2}} = \sqrt{\langle \cos^2 n[\Psi_n(p_T^a) - \Psi_n]\rangle}$$

$$\geq \langle \cos n[\Psi_n(p_T^a) - \Psi_n]\rangle$$

- Provides upper limit on the flow angle fluctuations (lower limit is $v_n\{2\}/v_n[2]$)

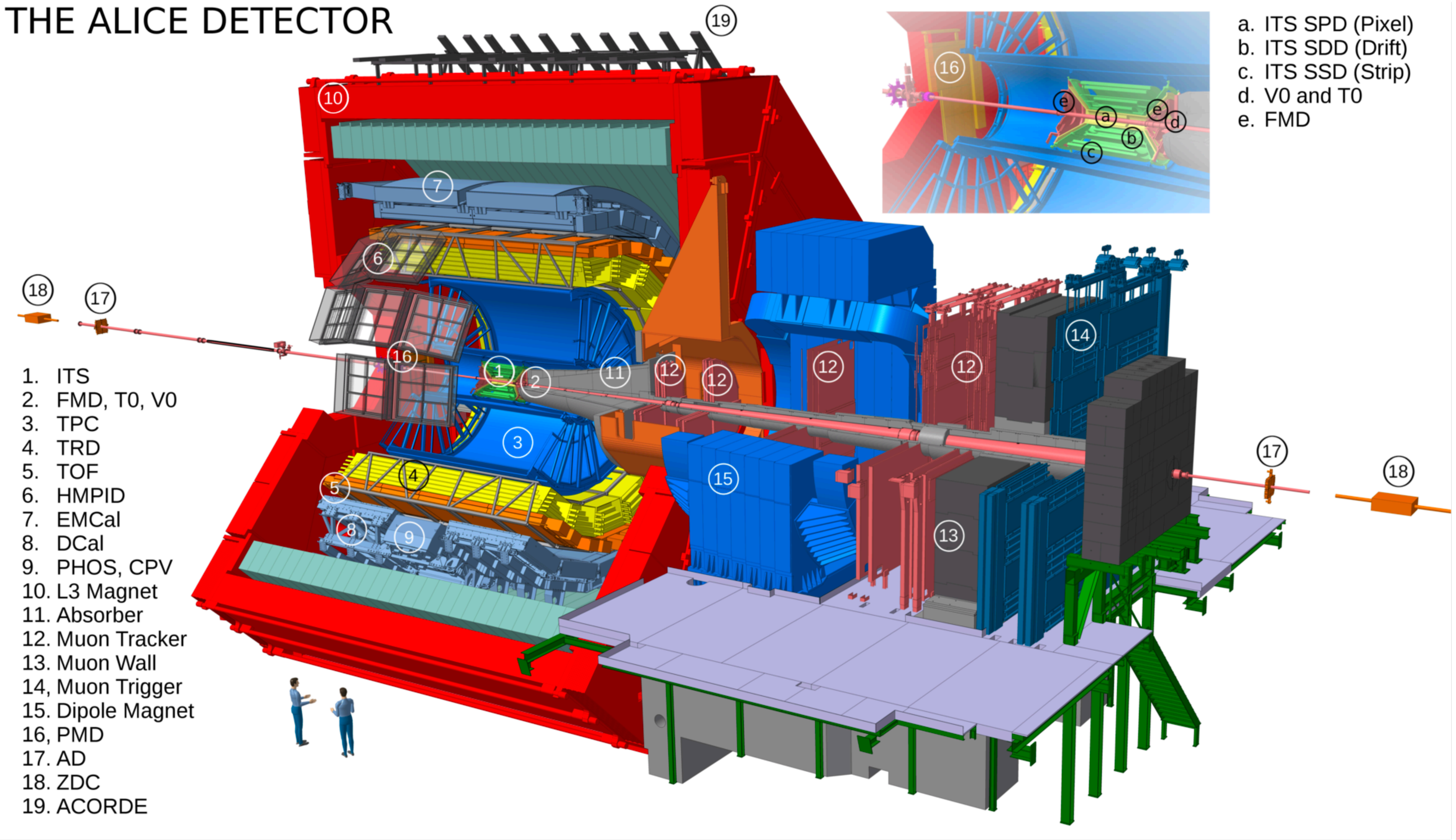
- How can we probe 1st moment flow magnitude fluctuations?

$$F(v_n^a, v_n) \equiv \frac{v_n\{2\}/v_n[2]}{\sqrt{\frac{F(\Psi_n^a, \Psi_n)+1}{2}}} \leq \frac{\langle v_n(p_T^a) v_n\rangle}{\sqrt{\langle v_n^2(p_T^a)\rangle}\sqrt{\langle v_n^2\rangle}}$$

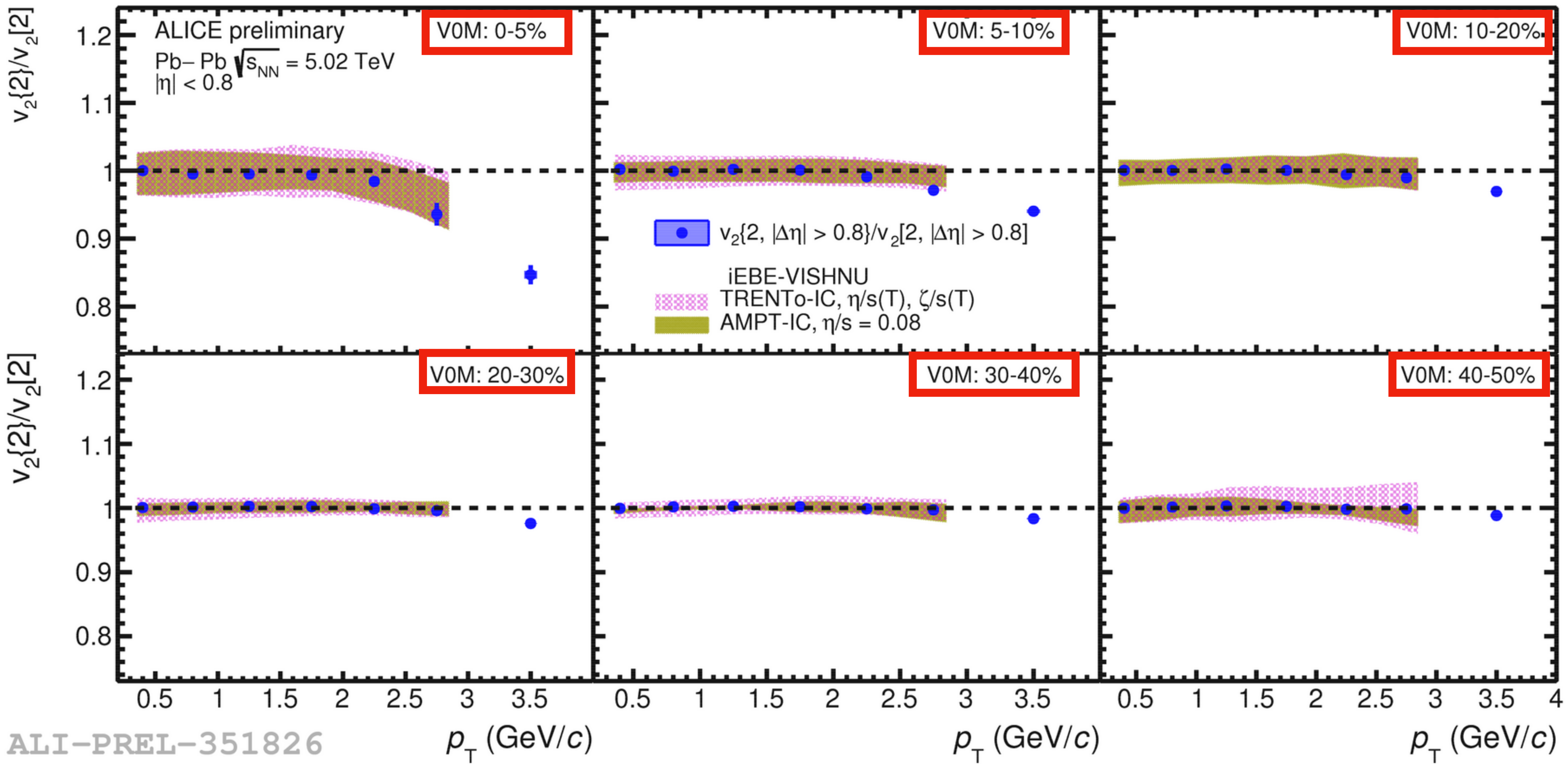
- Provides lower limit on flow magnitude fluctuations (upper limit is unity)

The ALICE experiment

- Dedicated heavy-ion experiment at the LHC
- Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV
- Data from 2015 Run 2 data taking period
- ITS and TPC detectors provide tracking information
- V0M for centrality estimation



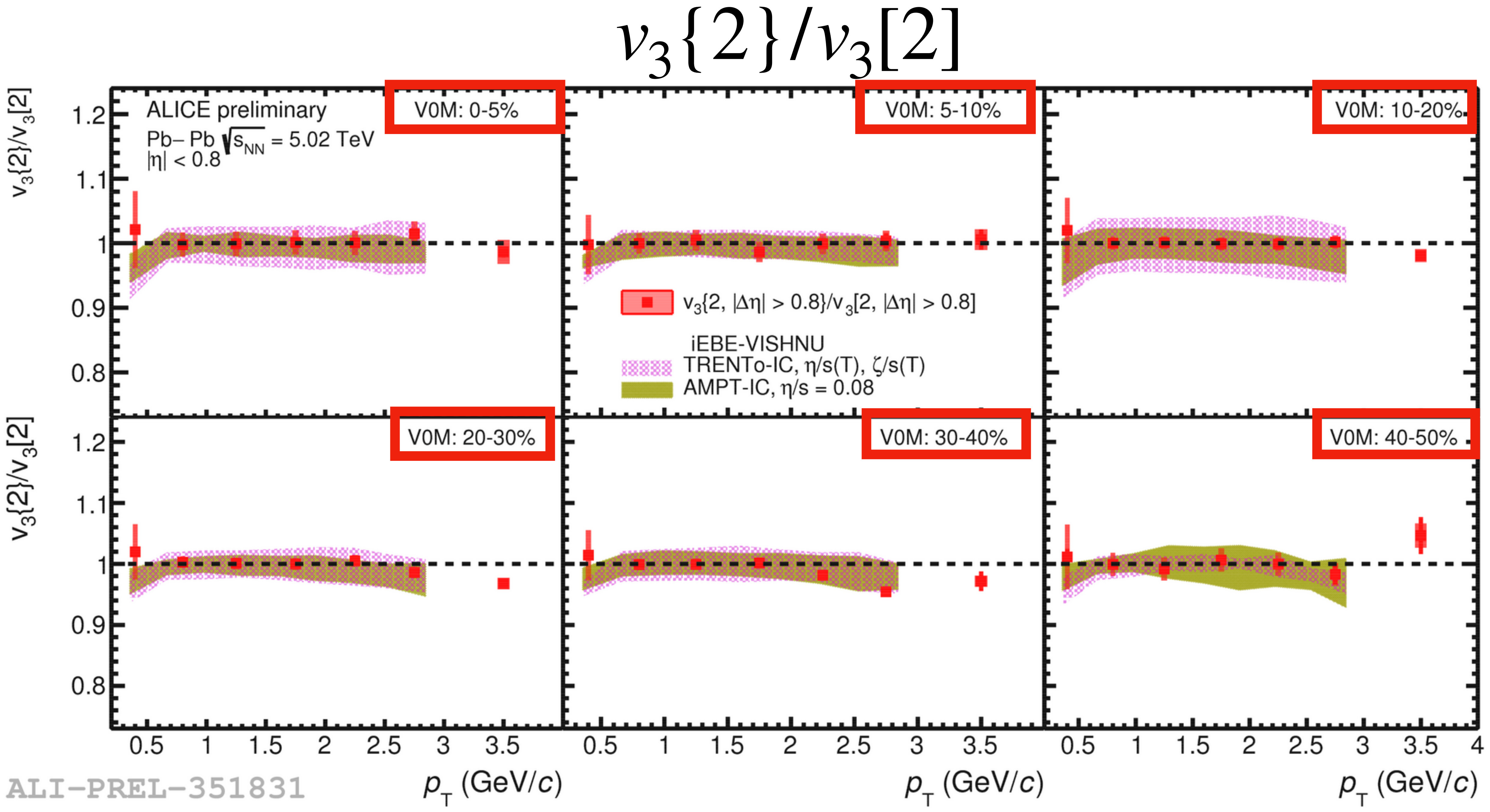
p_T-dependent flow vector fluctuations: V_2

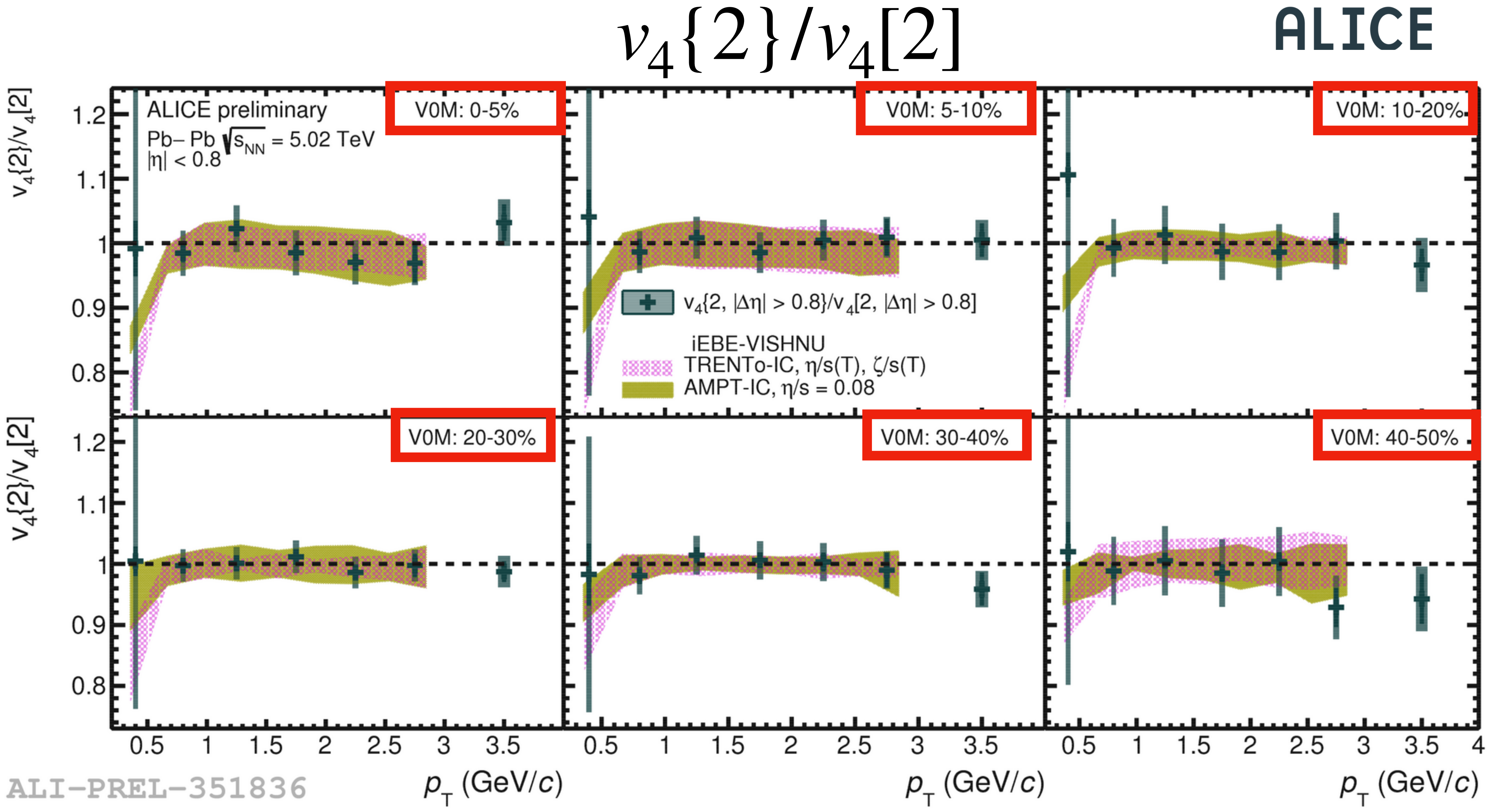


Preliminary model calculations
Statistical errors are expected to decrease

- Deviations from unity of $v_2\{2\}/v_2[2]$ in central collisions → p_T-dependent V_2 flow vector fluctuations
- Deviations are largest at the edge of hydro p_T range
- High precision Run 2 measurements allow for improved constraints on future model comparisons

p_T-dependent flow vector fluctuations: V_3 and V_4





- $v_3\{2\}/v_3[2]$ and $v_4\{2\}/v_4[2]$ consistent with unity
- No indication of p_T-dependent V_3 or V_4 fluctuations
- Hydro models consistent with unity
- High precision Run 2 measurements allow for improved constraints on future model comparisons

Flow angle and magnitude fluctuations

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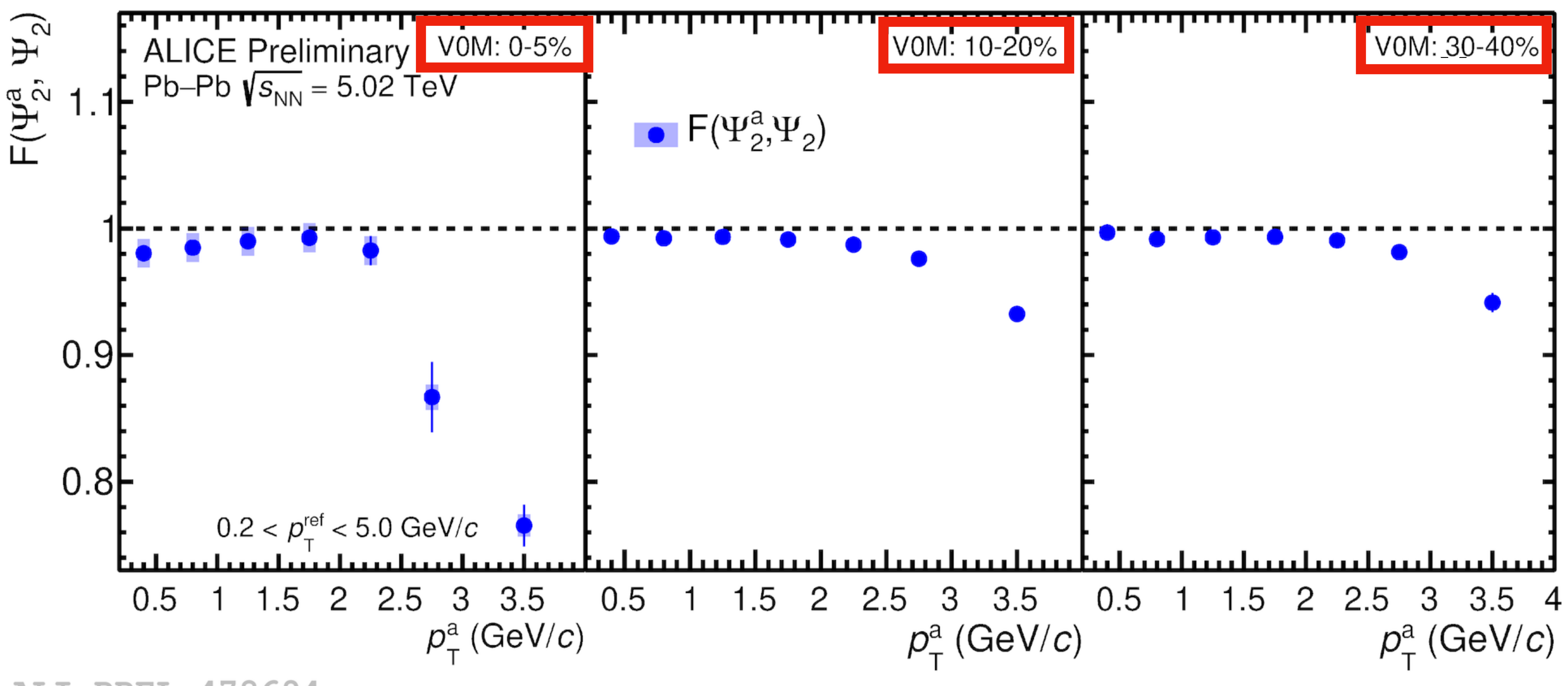
Flow angle fluctuations

$$F(\Psi_2^a, \Psi_2) = \langle \cos 2n[\Psi_2(p_T^a) - \Psi_2] \rangle$$

Flow magnitude fluctuations

$$\langle v_n^2(p_T^a) v_n^2 \rangle / \langle v_n^2(p_T^a) \rangle \langle v_n^2 \rangle$$

NEW



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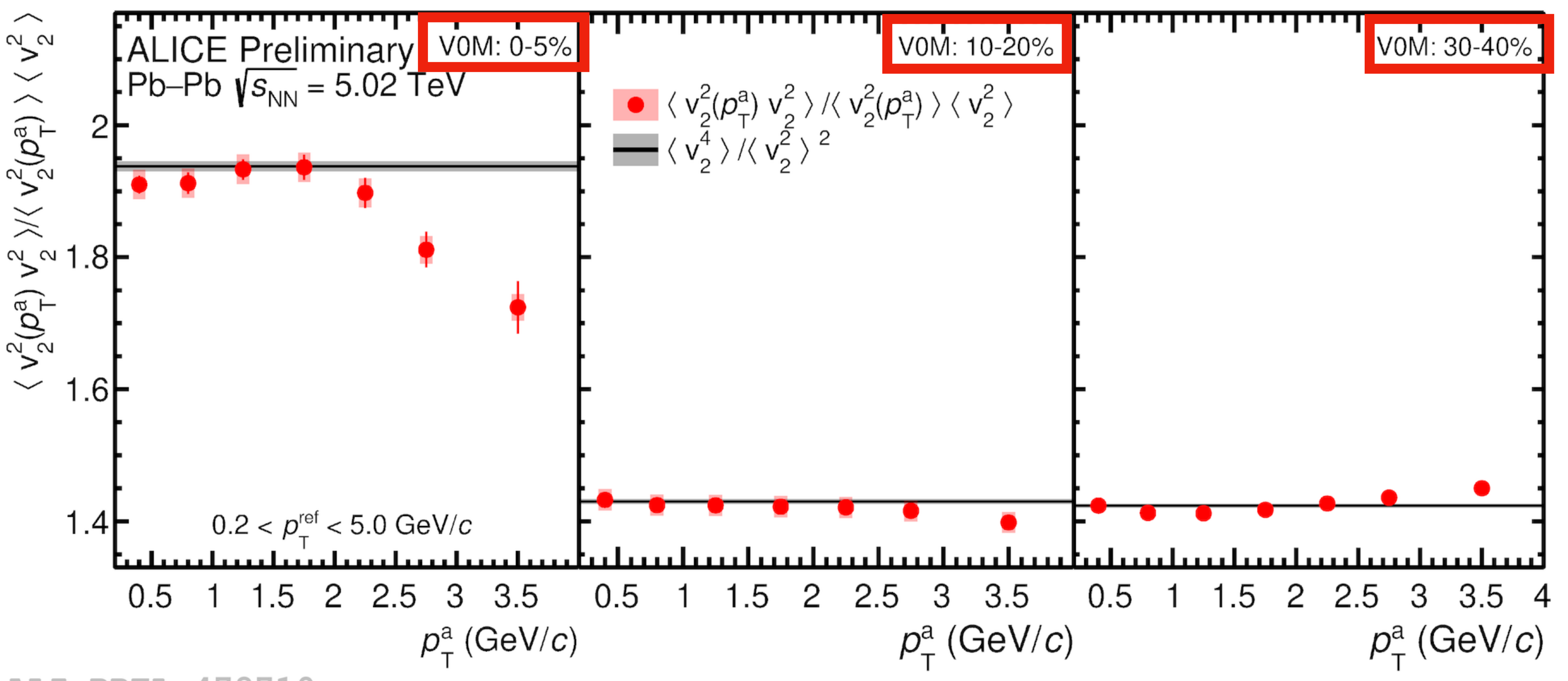


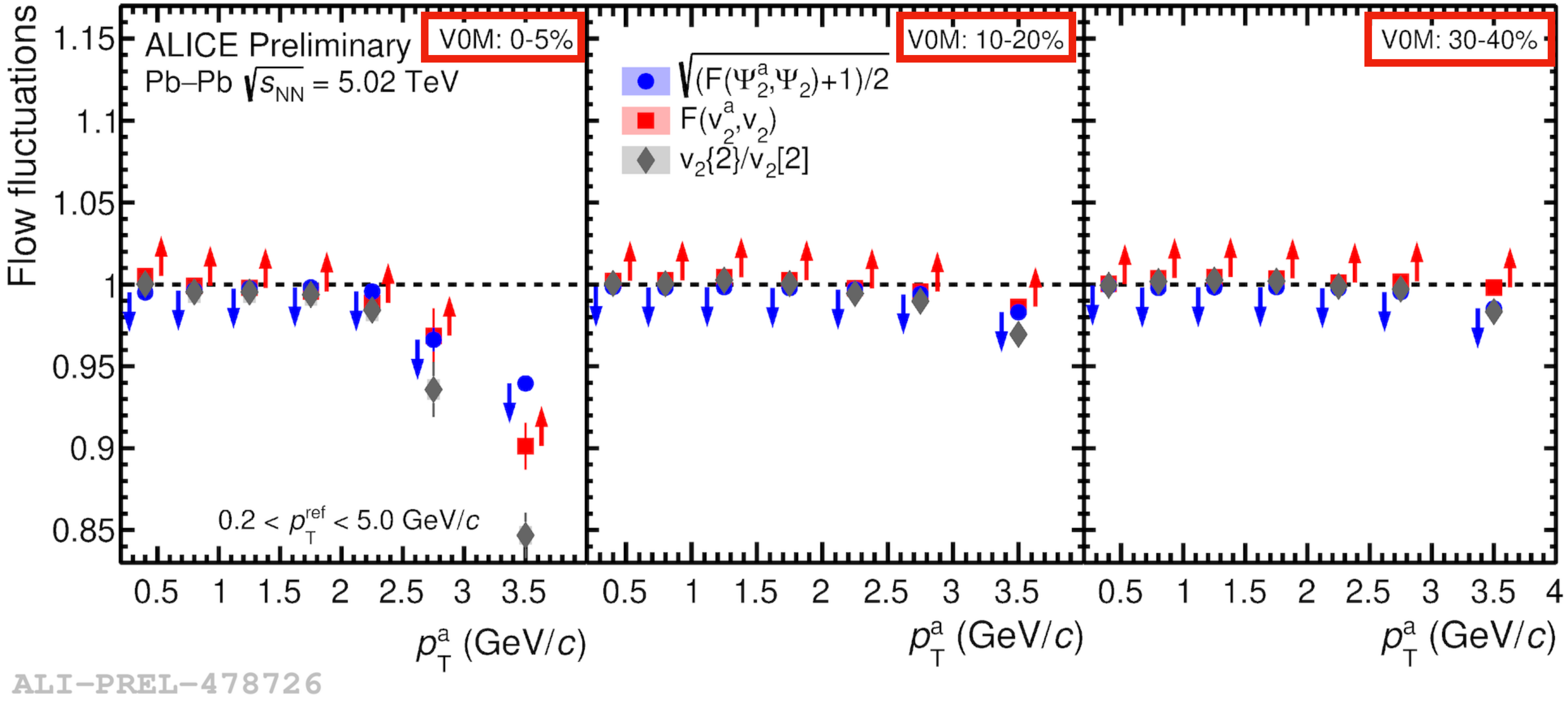
- Deviation from unity → p_T-dependent flow angle fluctuations
- $> 5\sigma$ significance in most centralities

- Deviation from $\langle v_n^4 \rangle / \langle v_n^2 \rangle^2$ → p_T-dependent flow magnitude fluctuations
- $\sim 5\sigma$ significance in most central collisions

Discovery of both flow angle and flow magnitude fluctuations in most central collisions!

$v_n\{2\}/v_n[2]$, flow angle and flow magnitude

NEW



- Only possible to extract limits of flow angle and flow magnitude fluctuations in 2-particle correlation
- Effects most significant in central collisions

Limits on fluctuations from 2-pc

Flow angle upper limit:

$$\sqrt{\frac{F(\Psi_2^a,\Psi_2)+1}{2}} \geq \langle \cos n[\Psi_2(p_T^a)-\Psi_2] \rangle$$

Flow angle lower limit:

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

Flow magnitude upper limit:

Unity

Flow magnitude lower limit:

$$F(v_2^a, v_2) \leq \frac{\langle v_n(p_T^a) v_n \rangle}{\sqrt{\langle v_n^2(p_T^a)\rangle}\sqrt{\langle v_n^2\rangle}}$$

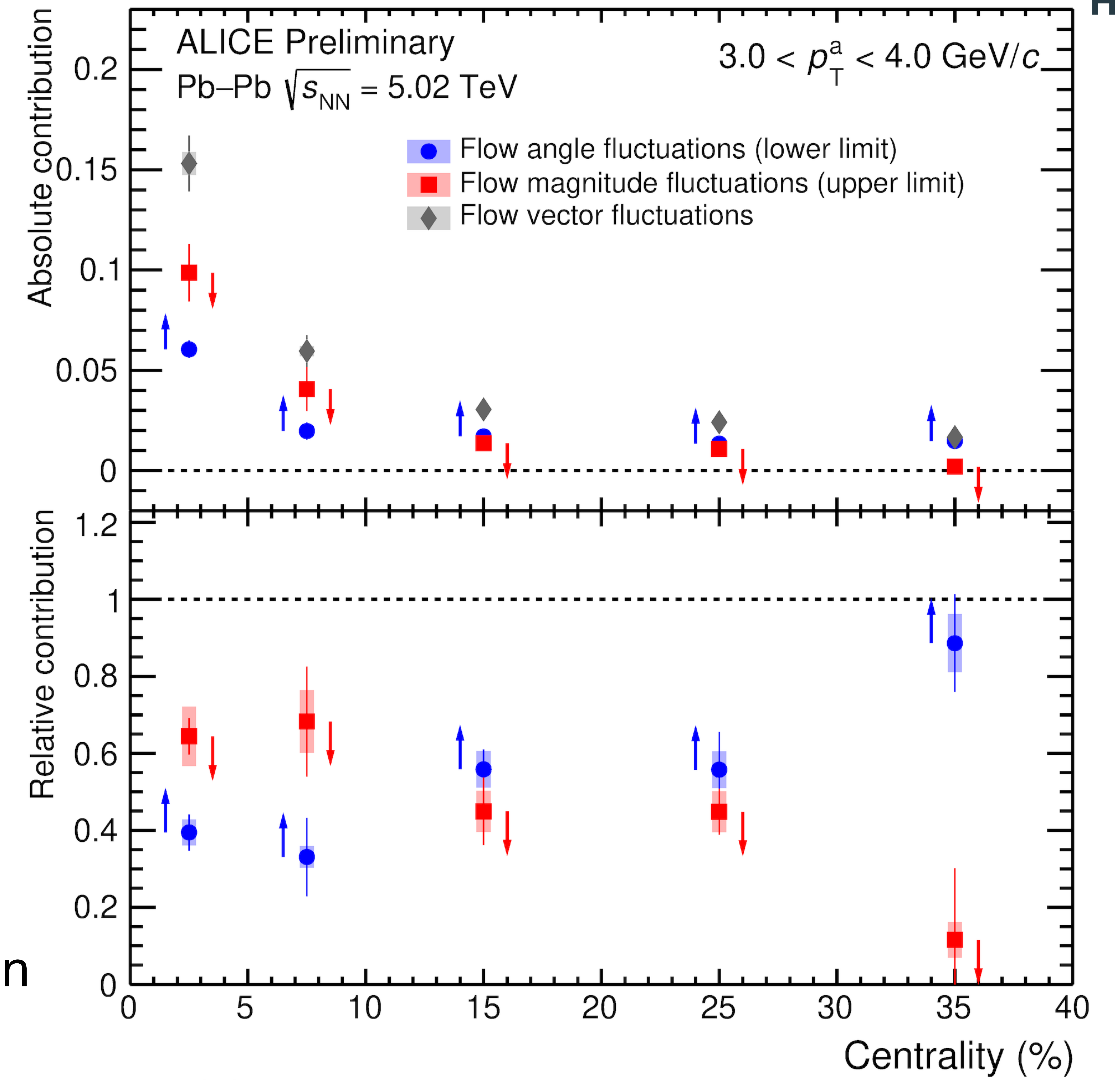
$v_n\{2\}/v_n[2]$, flow angle and flow magnitude

- Significant flow angle and flow magnitude fluctuations observed in central collisions
- Flow angle fluctuations significant in most centralities
- Flow magnitude fluctuations only significant in most central collisions

New flow picture

- Flow angle fluctuations not included in many theoretical models for high p_T calculations
- Future flow modelling should include flow angle fluctuations for more accurate extraction of QGP properties

NEW

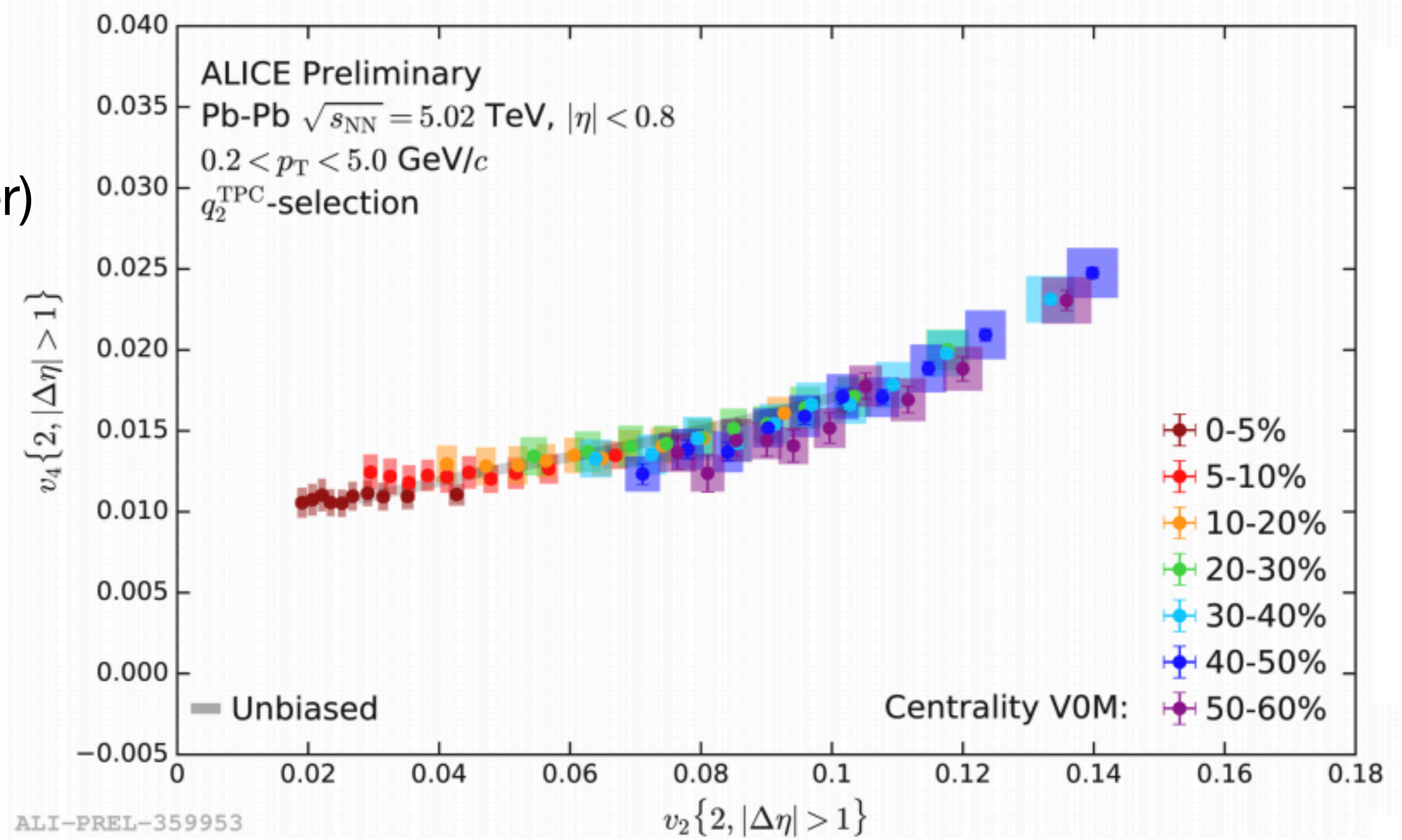


ALI-PREL-478734

Flow with event-shape-engineering

Correlations of flow

- Event-shape-engineering (ESE) allows for selection of initial geometry
- Select high (low) ϵ_n resulting in higher (lower) values of flow
- Probe correlations between different order harmonics with ESE
- Positive correlation between v_2 and v_4



See back-up for more information

Flow with event-shape-engineering

Linear and non-linear flow modes

- Extract linear and non-linear flow modes with fit $v_4 = \sqrt{c_0^2 + (c_1 v_2^2)^2}$

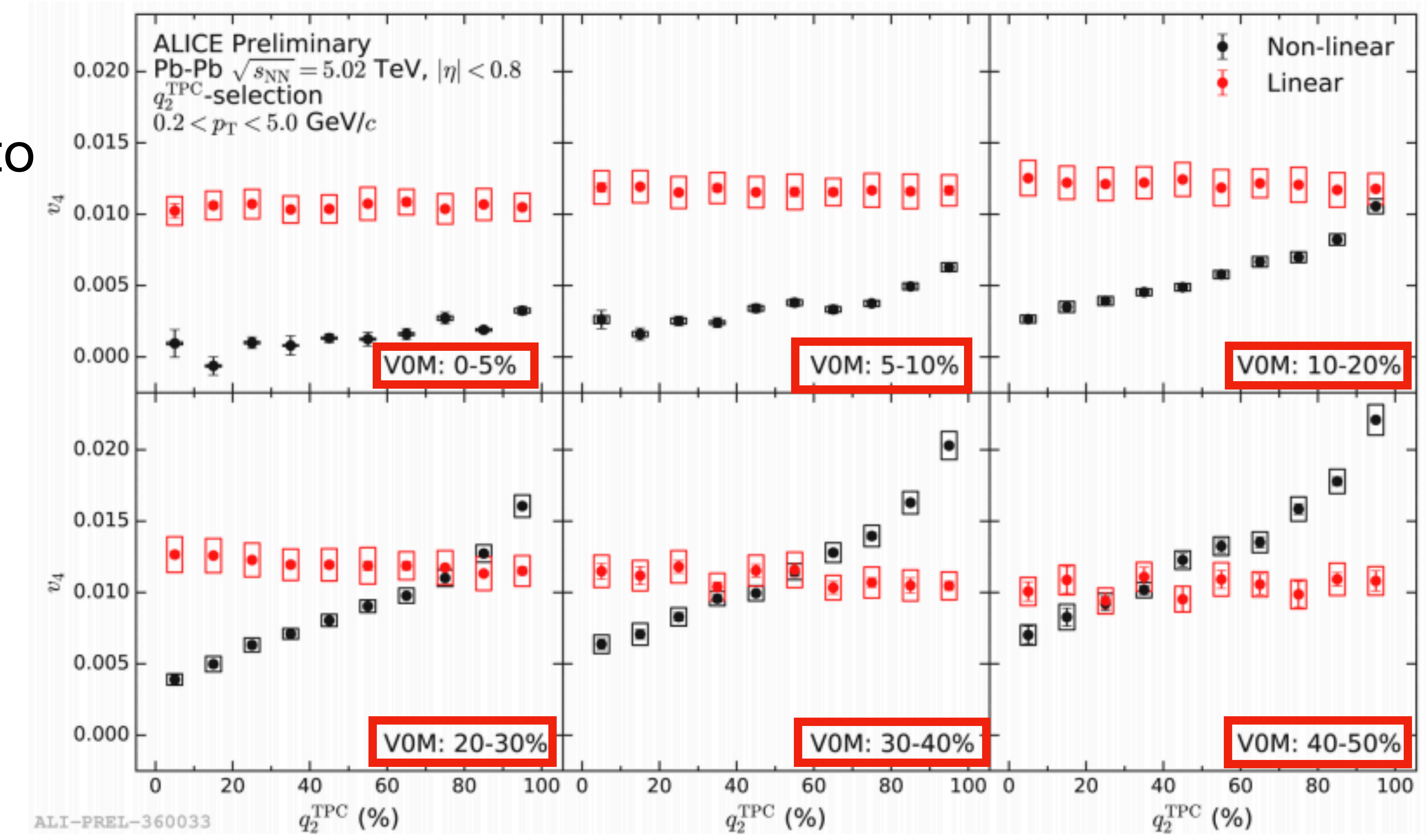
- So how does v_4^{L} and v_4^{NL} couple to q_2 and to each other?

$$v_4 = v_4^{\mathrm{L}} + v_4^{\mathrm{NL}}$$

$$\Downarrow \qquad \Downarrow \qquad \Downarrow$$

$$\epsilon_4 \qquad \epsilon_4' \overset{?}{\Leftrightarrow} \epsilon_2$$

- Non-linear increase in v_4^{NL} while v_4^{L} is unaffected $\rightarrow$ v_4^{NL} and v_4^{L} must be entirely uncorrelated



See back-up for more information

Summary

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- New **precision** measurements of $v_n\{2\}/v_n[2]$ show $\boldsymbol{p_{\mathrm{T}}}$**-dependent** $\boldsymbol{V_2}$ **fluctuations**
    - No indication of V_3 or V_4 fluctuations
- Novel observables allow for *disentanglement* of flow angle and flow magnitude fluctuations
    - First time measured separately. Discovery of **both** effects in most central collisions
    - These discoveries give a new flow picture! Can quantify both the flow angle and flow magnitude fluctuations and give limits on their contribution to the 2-particle correlation flow vector fluctuations
    - Crucial examinations on the theoretical models, it will significantly improve the overall understanding of the initial fluctuations and also the dynamical expansion of the QGP
- Event-shape-engineering provides a useful tool to study correlation between different order flow harmonics and to extract linear and non-linear flow modes of v_4

Thank you for your attention!

Event-shape-engineering

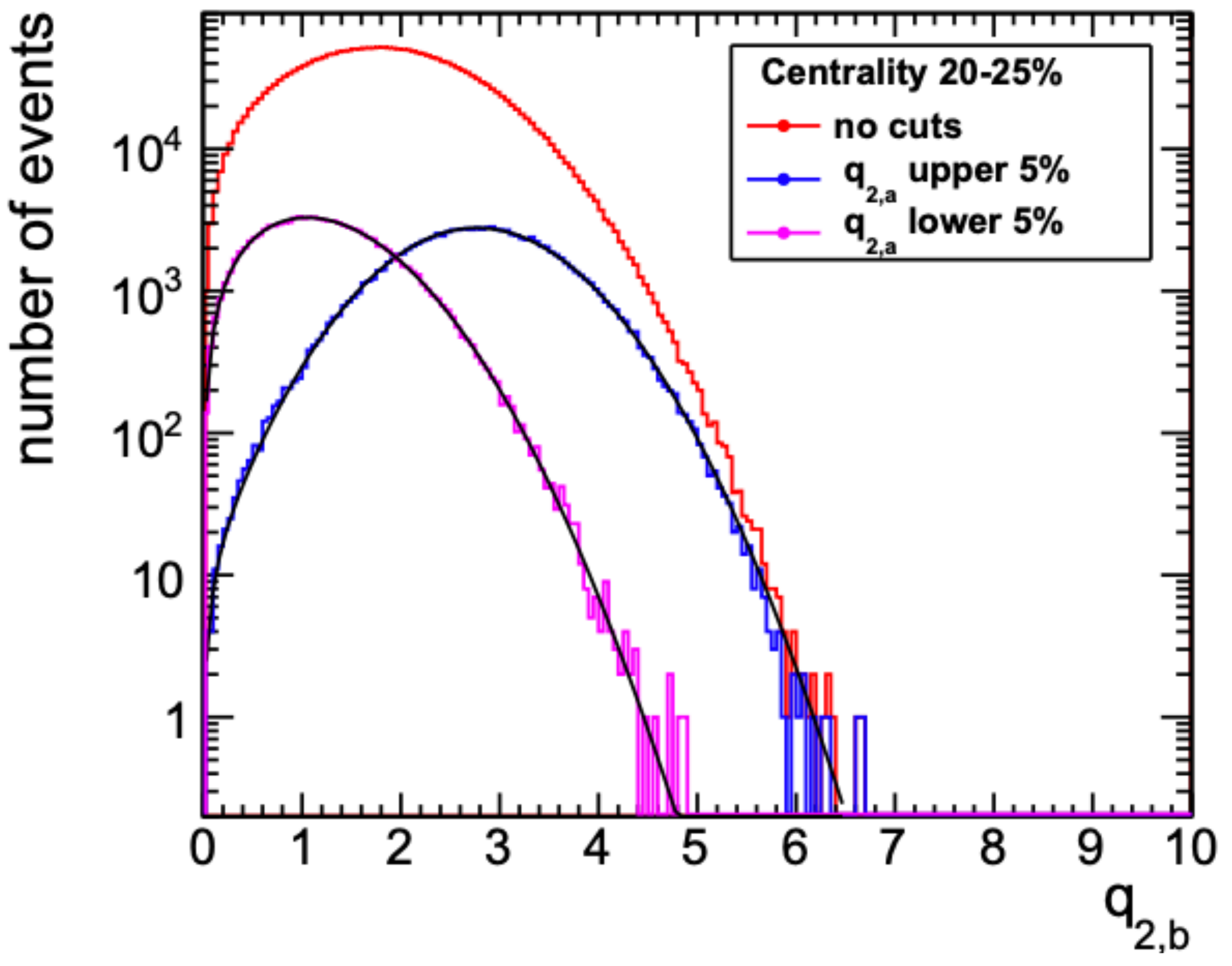
- Event-shape-engineering (ESE) allows for selection of initial geometry
- Select high (low) ϵ_n resulting in higher (lower) values of flow

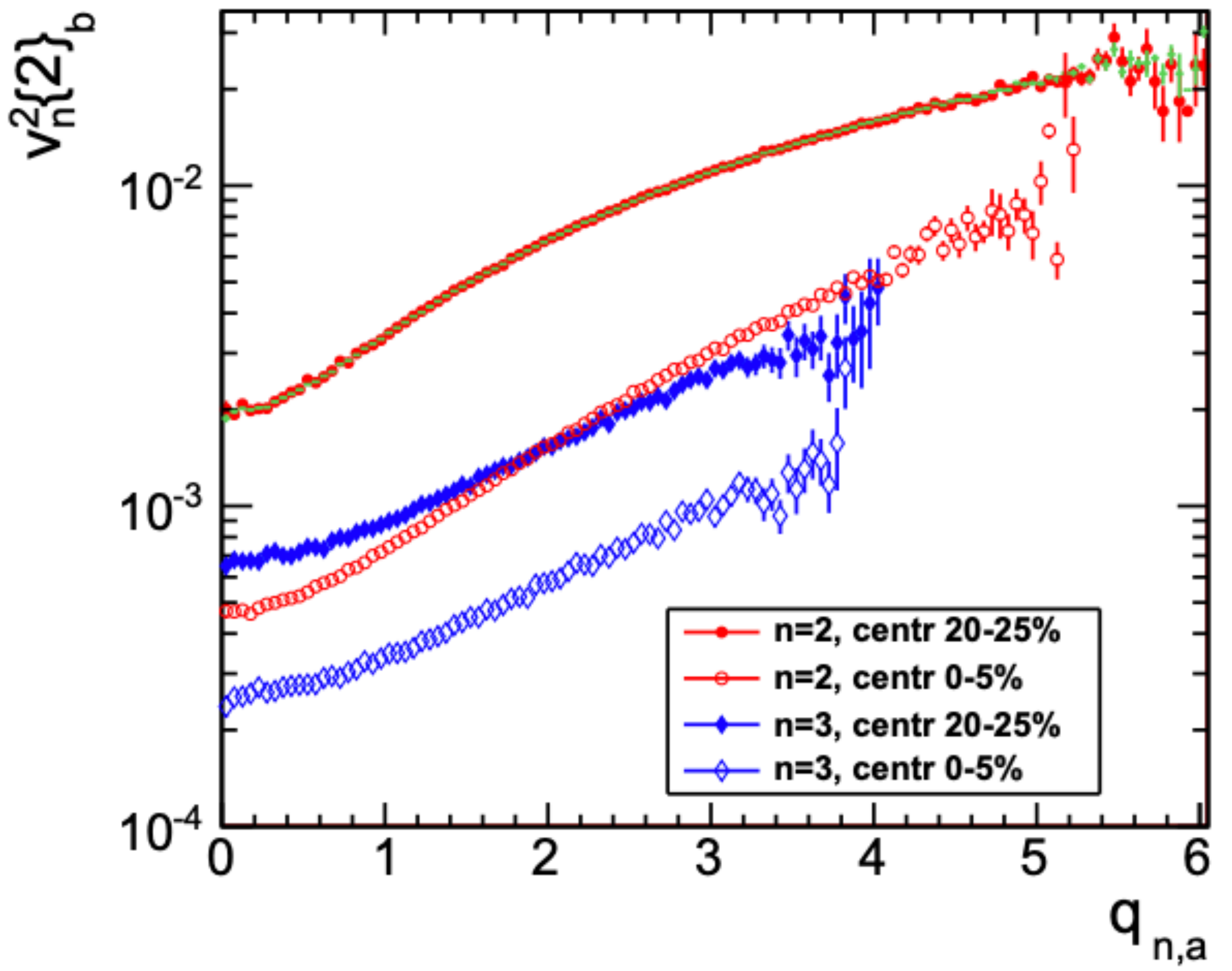
$$q_n = \frac{|Q_n|}{\sqrt{M}}$$

- The reduced Q-vector q_n can be constructed in different detectors to avoid self-correlations

Select $q_n \rightarrow$ change eccentricity

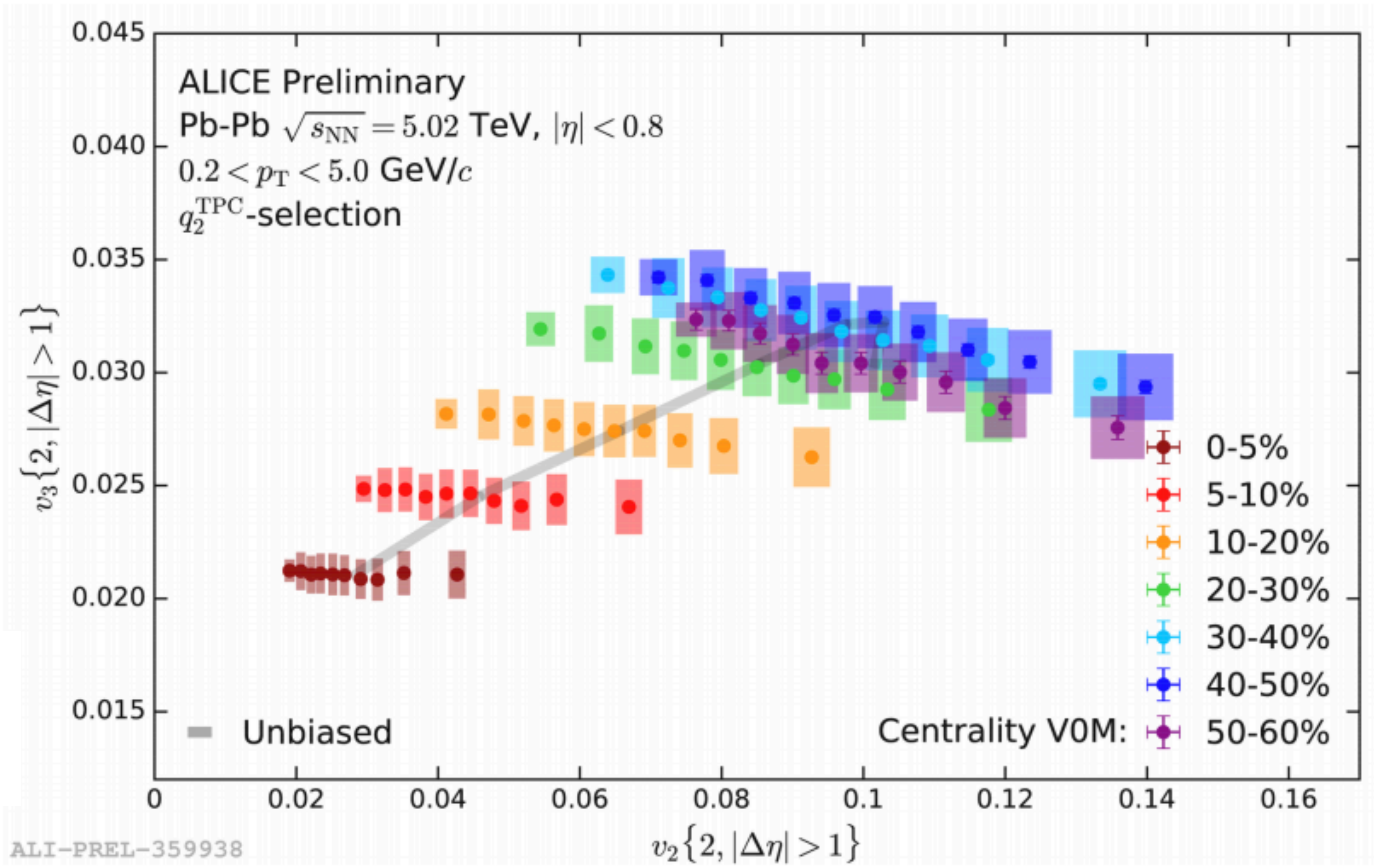
Phys.Lett.B 719 (2013) 394-398

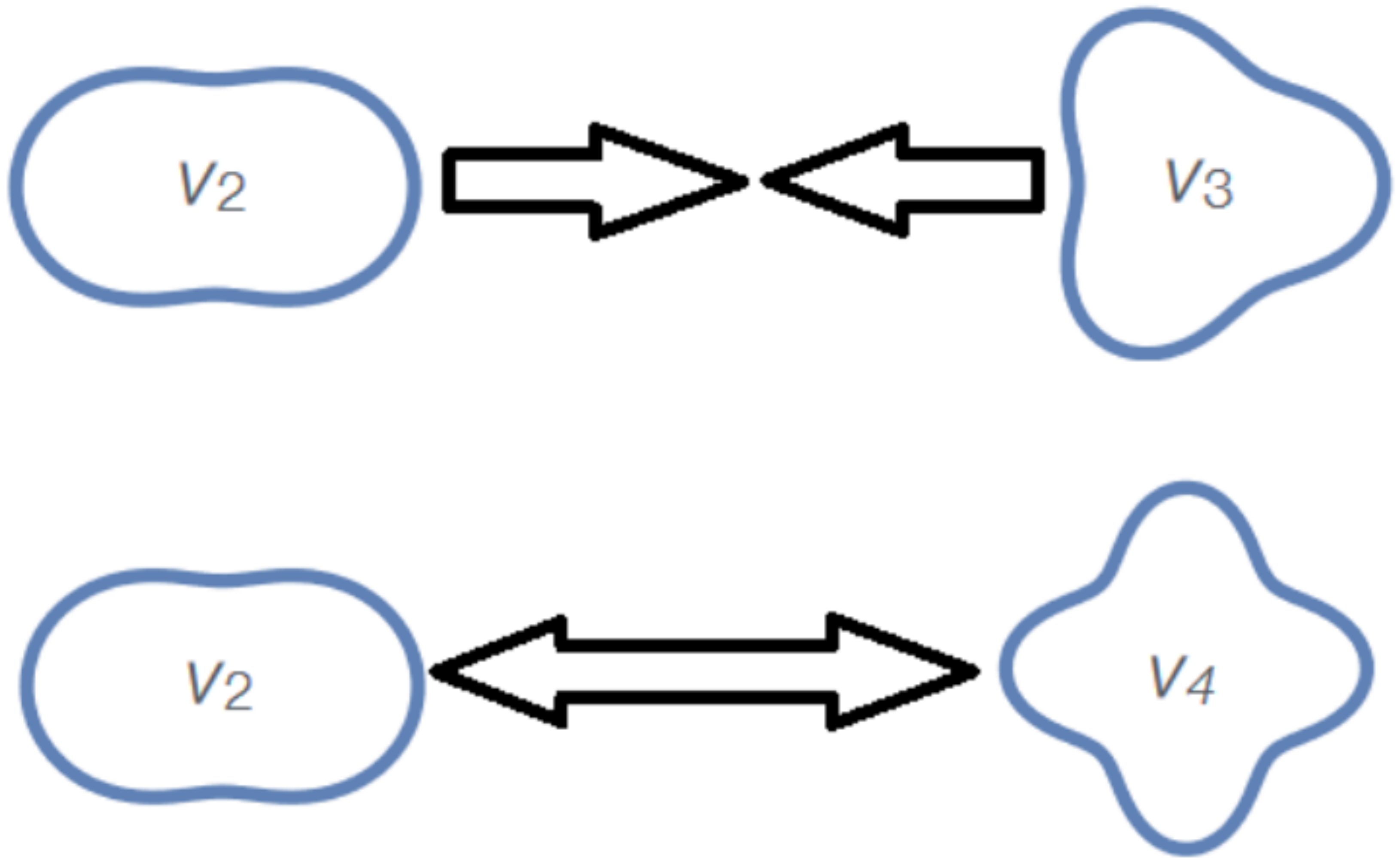


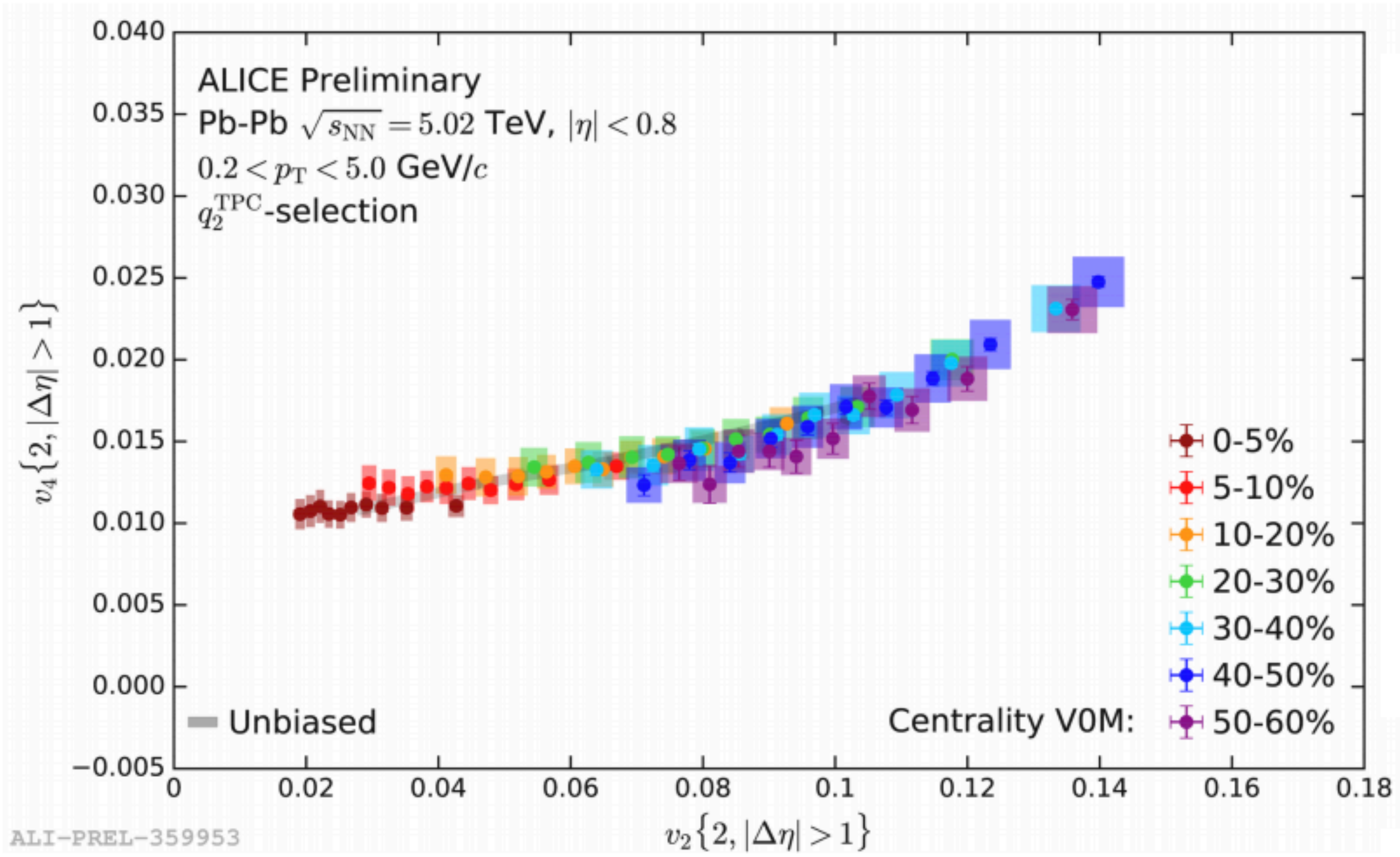


Correlations of flow

- Correlations between different order harmonics with ESE
- Negative correlation between v_2 and v_3, and positive correlation between v_2 and v_4





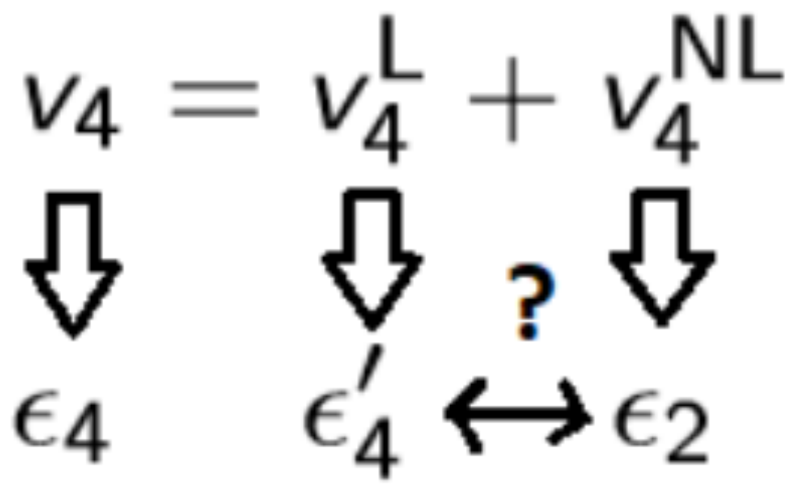


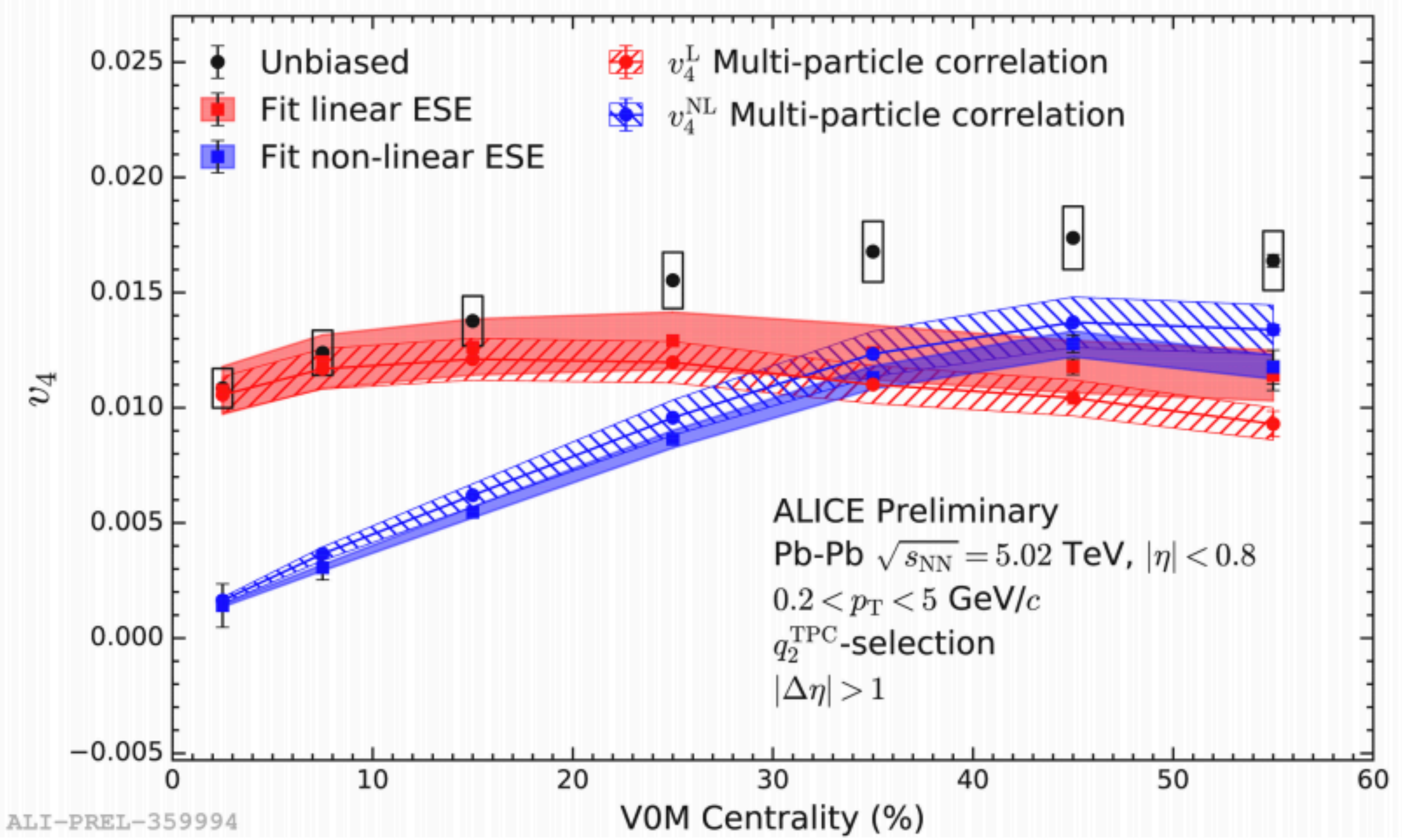
Linear and non-linear flow modes

- Extract linear and non-linear contributions from v_2-v_4 correlation with fit:

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

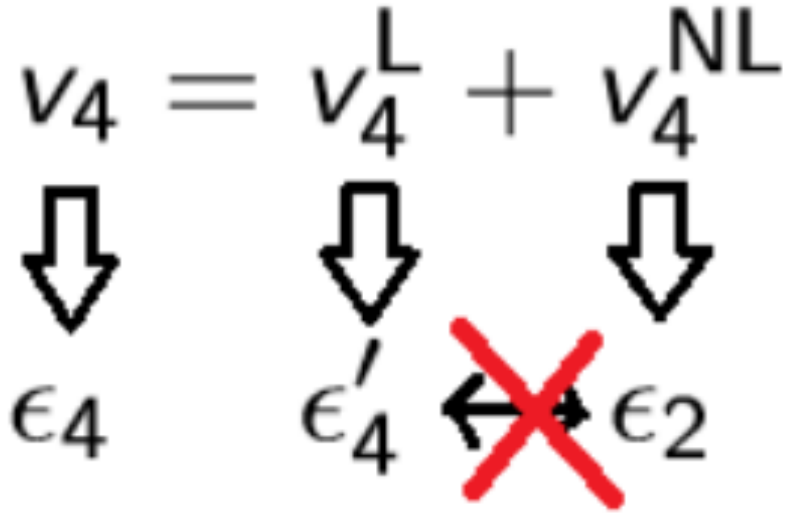
- Good agreement between fit and multi-particle correlation
- So how does v_4^{L} and v_4^{NL} couple to q_2 and to each other?

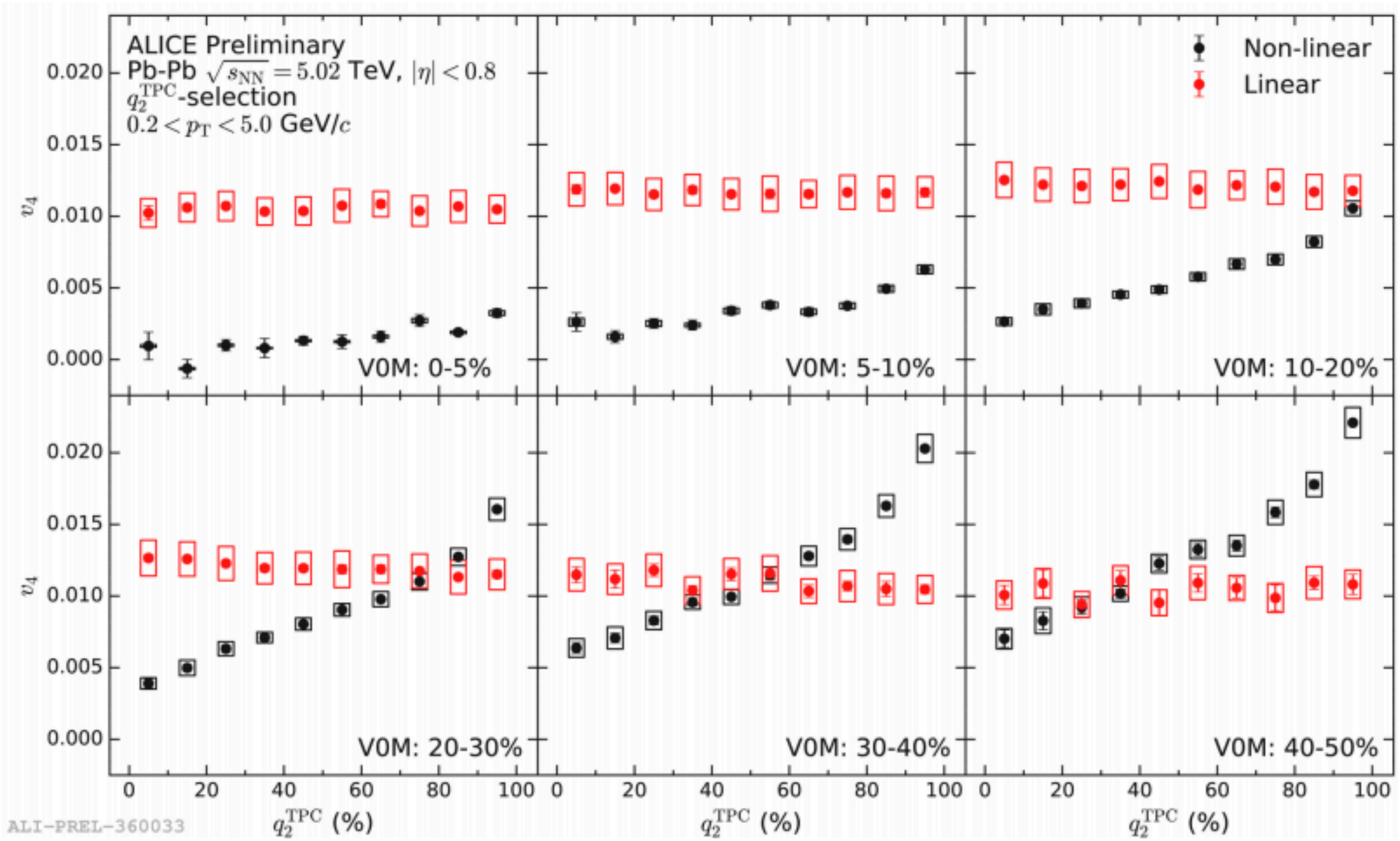




Linear and non-linear flow modes

- v_4^{L} and v_4^{NL} as function of q_2 percentiles
- Non-linear increase in v_4^{NL} while v_4^{L} is unaffected → v_4^{NL} and v_4^{L} must be entirely uncorrelated
- This conclusion was reached in a previous study, albeit with stronger assumptions
  Phys.Lett.B **773 (2017) 68-80**





Particle selection

- Particles are selected from different subevents to separate flow angle and flow magnitude fluctuations

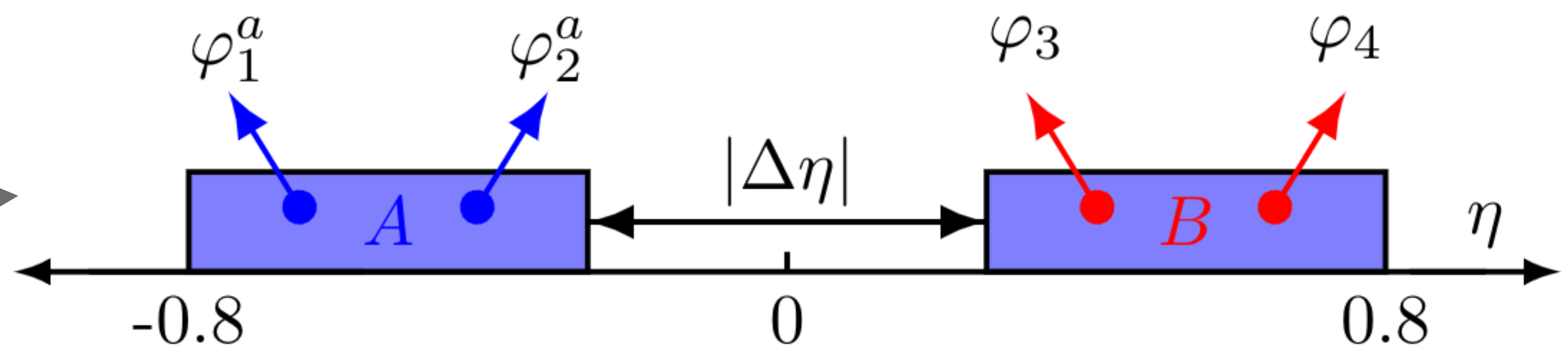
Flow angle fluctuations:

$$F(\Psi_n^a, \Psi_n) = \frac{\langle\langle \cos[n(\varphi_1^a + \varphi_2^a - \varphi_3 - \varphi_4)] \rangle\rangle}{\langle\langle \cos[n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4)] \rangle\rangle}$$

Flow magnitude fluctuations:

$$\frac{\langle v_n^2(p_T^a)\ v_n^2 \rangle}{\langle v_n^2(p_T^a) \rangle \langle v_n^2 \rangle} = \frac{\langle\langle \cos n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4) \rangle\rangle}{\langle\langle \cos n(\varphi_1^a - \varphi_3^a) \rangle\rangle \langle\langle \cos n(\varphi_2 - \varphi_4) \rangle\rangle}$$

POI from same subevent:



POI from different subevents: