Probing p_{T}-dependent flow vector fluctuations with ALICE

5th international conference on particle physics and astrophysics

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October 7th

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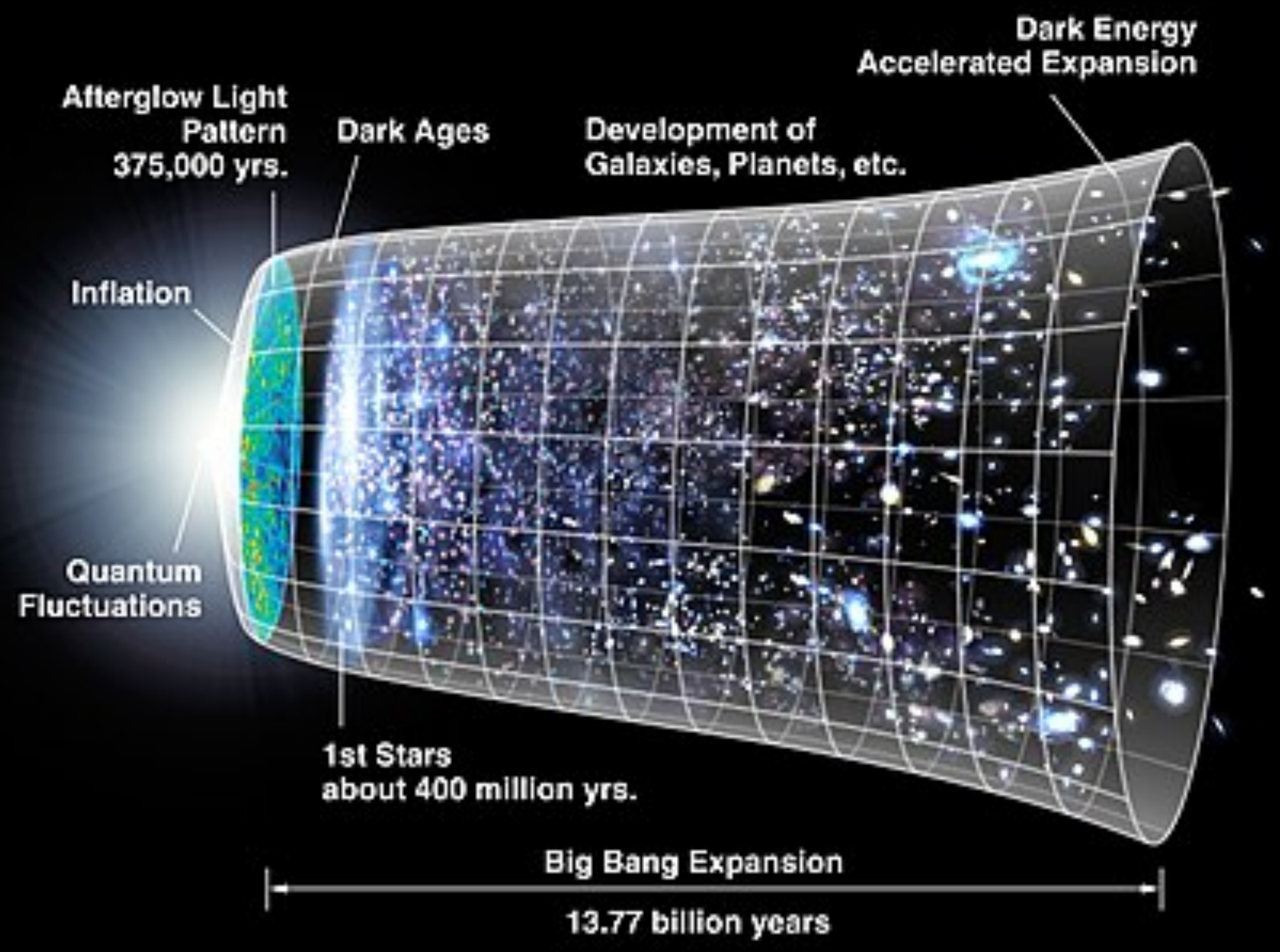
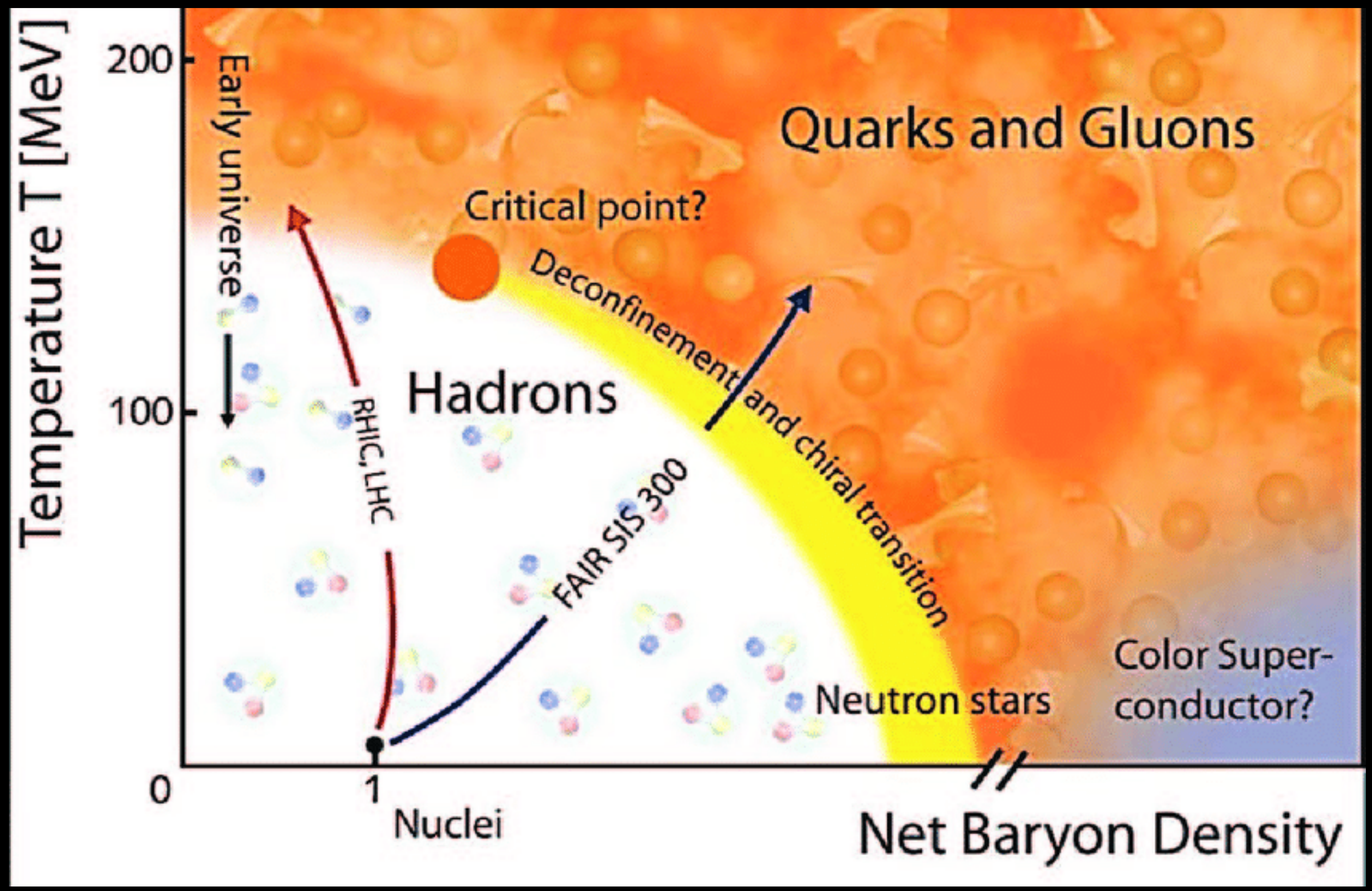
THE VELUX FOUNDATIONS
VILLUM FONDEN VELUX FONDEN

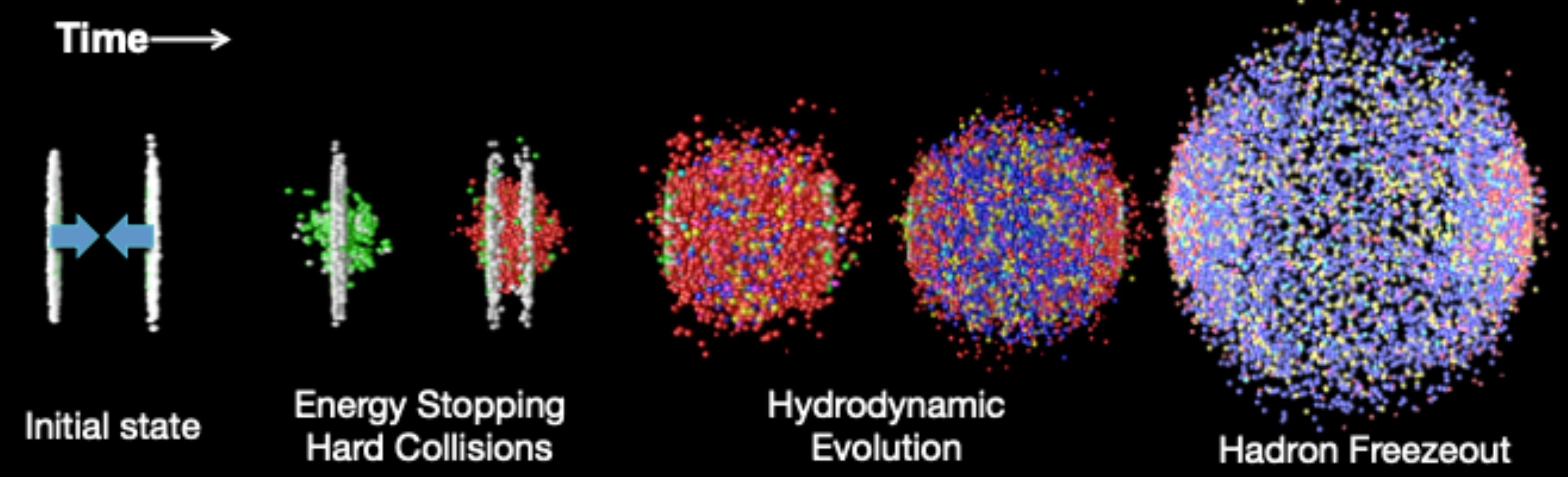
Quark-Gluon Plasma

- Early universe dominated by hot, dense matter
- Deconfined state of quarks and gluons → Quark-gluon plasma (QGP)
- QGP is recreated in experiments with heavy-ion collisions ("little bangs")
- Experiments at the LHC probe high-temperature/low baryon chemical potential region

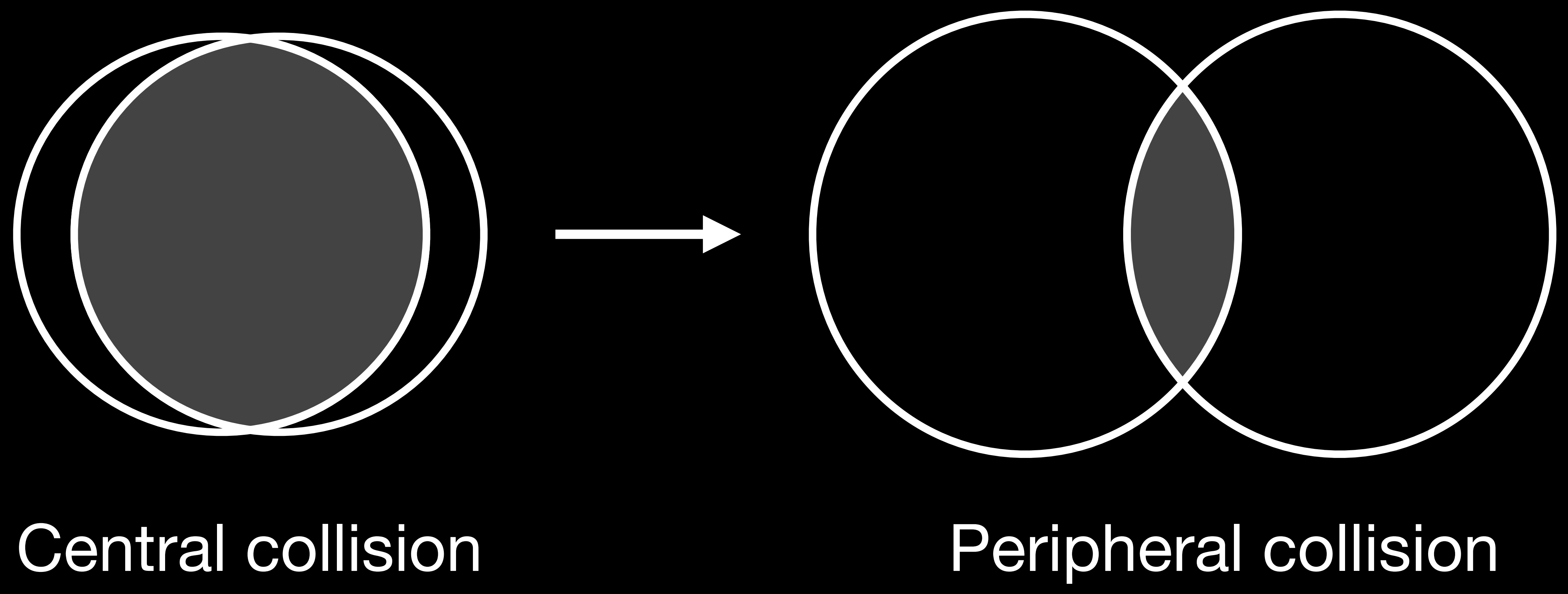




Heavy-ion collisions



- After thermalization time $\tau \sim 1$ fm/c → System described by hydrodynamics
- Experiments seek to determine initial conditions (IC) and the QGP properties
  - Shear viscosity η/s and bulk viscosity ζ/s
- Hydrodynamic models can constrain IC and η/s, ζ/s
- Strong interactions transfer initial geometric anisotropy into final state momentum-space azimuthal anisotropy
  - Anisotropic flow, an observable sensitive to IC, η/s, ζ/s



Anisotropic flow

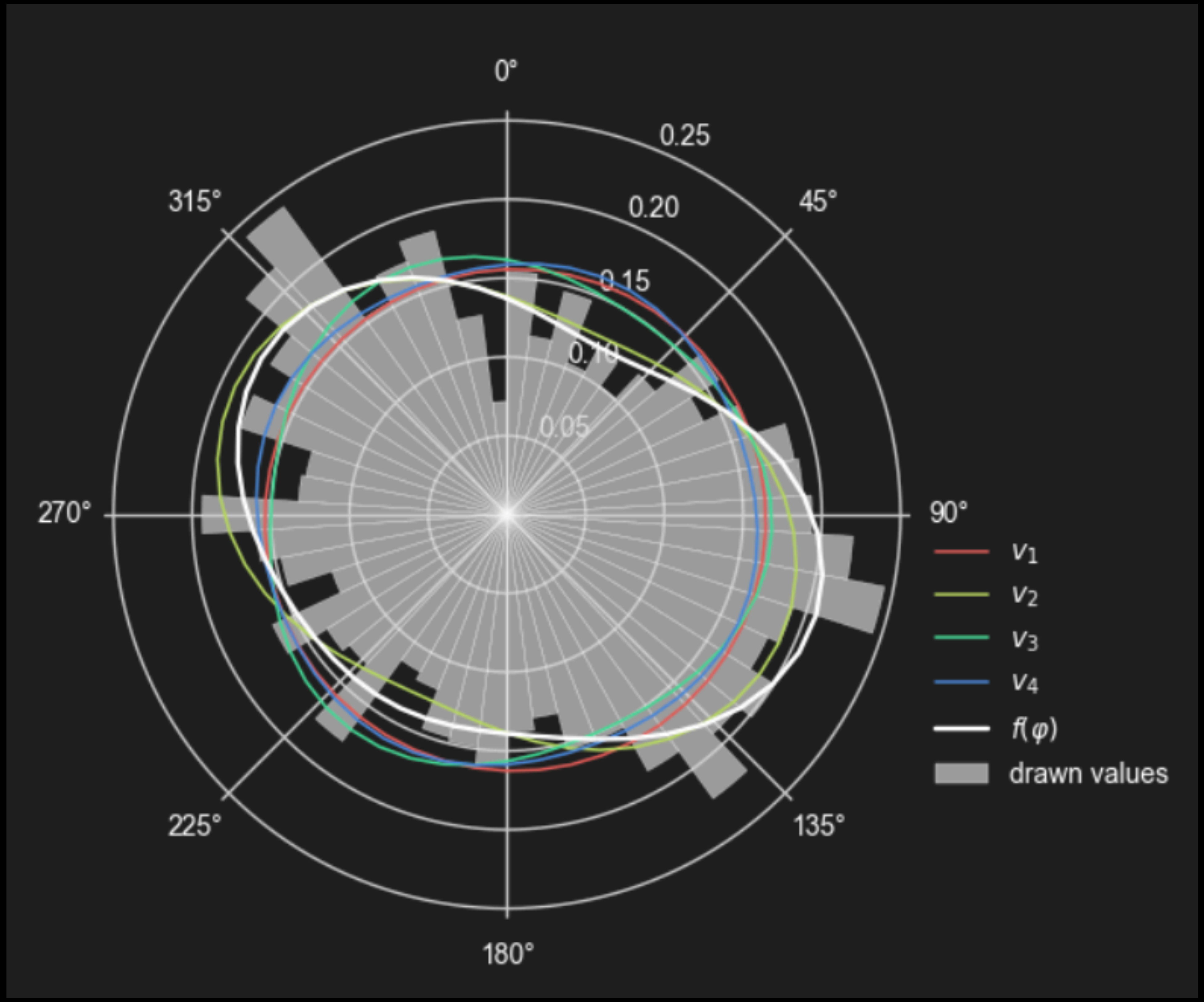
- Fourier expansion of azimuthal distribution of emitted particles:

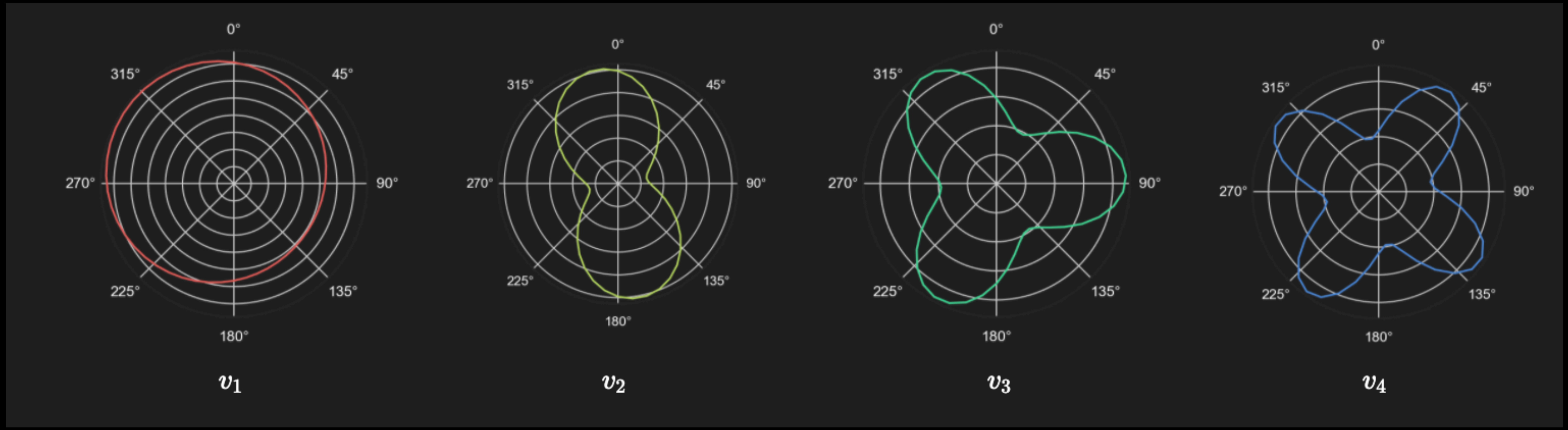
$$\frac{dN}{d\varphi} \propto f(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} V_n e^{in\varphi}\right]$$

- Complex flow vector $V_n = v_n e^{in\Psi_n}$
- with magnitude:

$$v_n = \langle \cos n[\varphi - \Psi_n] \rangle$$

- and flow angle Ψ_n





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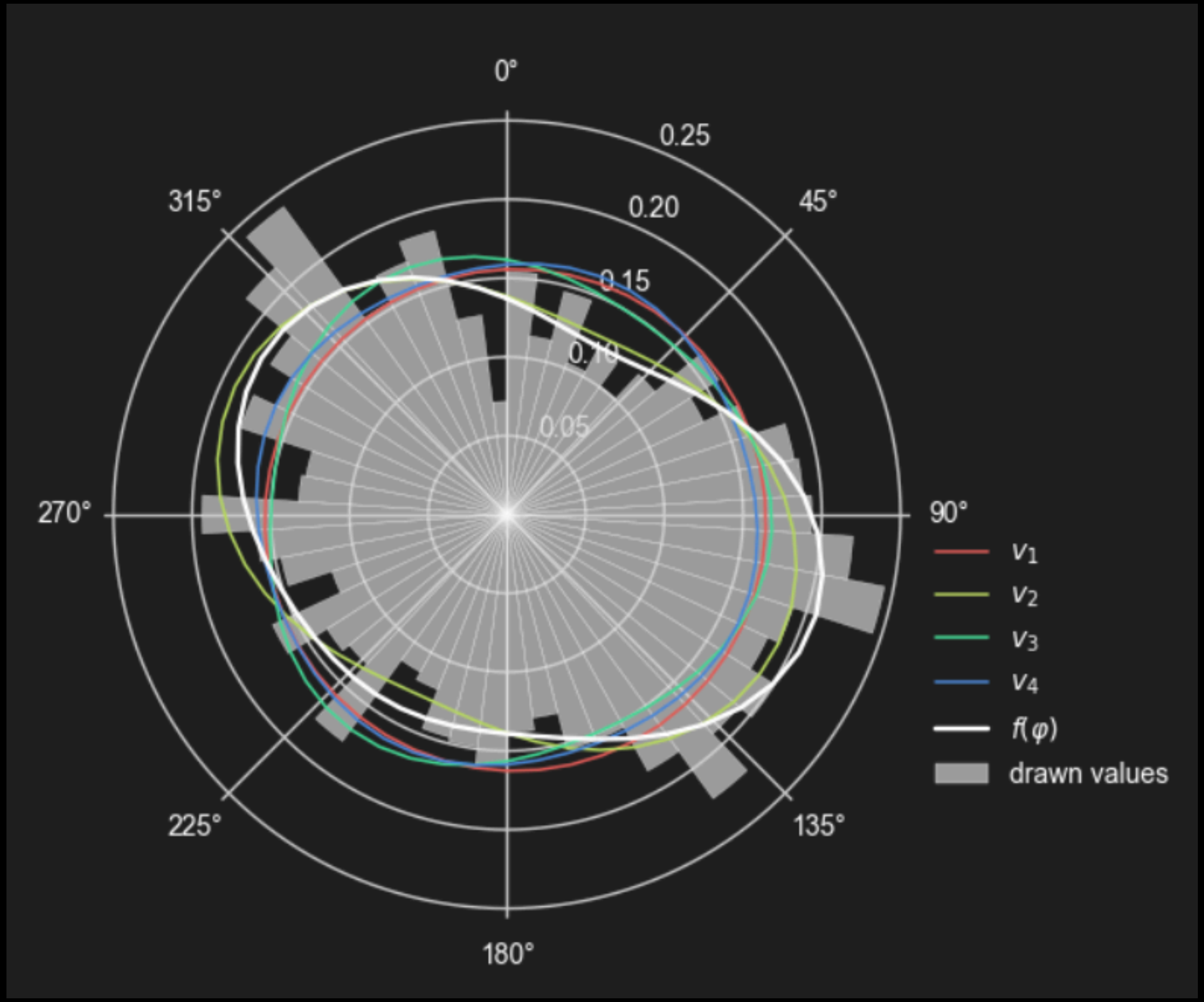

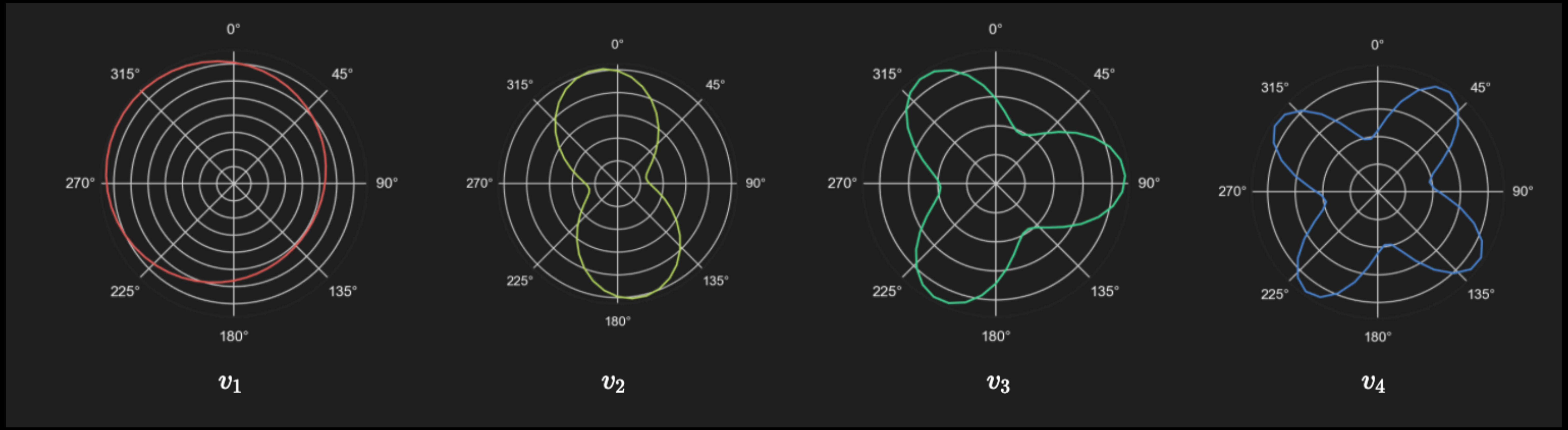

Flow vector fluctuations

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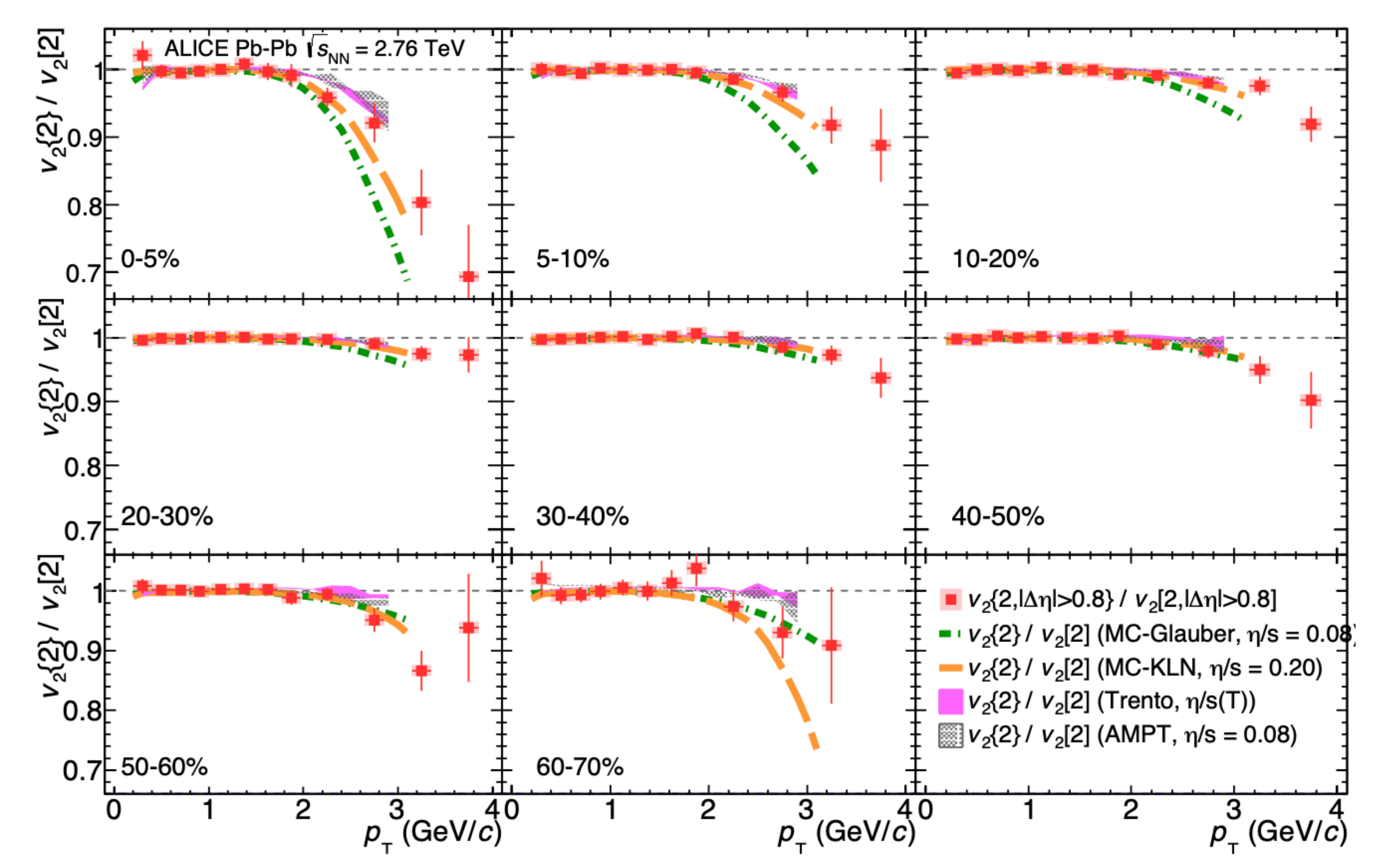
- Flow vector fluctuates from collision to collision
- Measured with:

$$\frac{v_n\{2\}}{v_2[2]} = \frac{\langle v_n(p_T)\, v_n \cos n[\Psi_n(p_T) - \Psi_n]\rangle}{\sqrt{\langle v_n(p_T)^2\rangle}\sqrt{\langle v_n^2\rangle}}$$

- $v_n(p_T) \neq v_n$ and $\Psi_n(p_T) \neq \Psi_n$, then $v_n\{2\}/v_n[2] < 1$



- New precision measurements of flow vector fluctuations → Better constraints on initial conditions and QGP properties

Flow vector fluctuations

JHEP 09 (2017) 032

- Another way to measure flow vector fluctuations is with factorization ratio r_n:

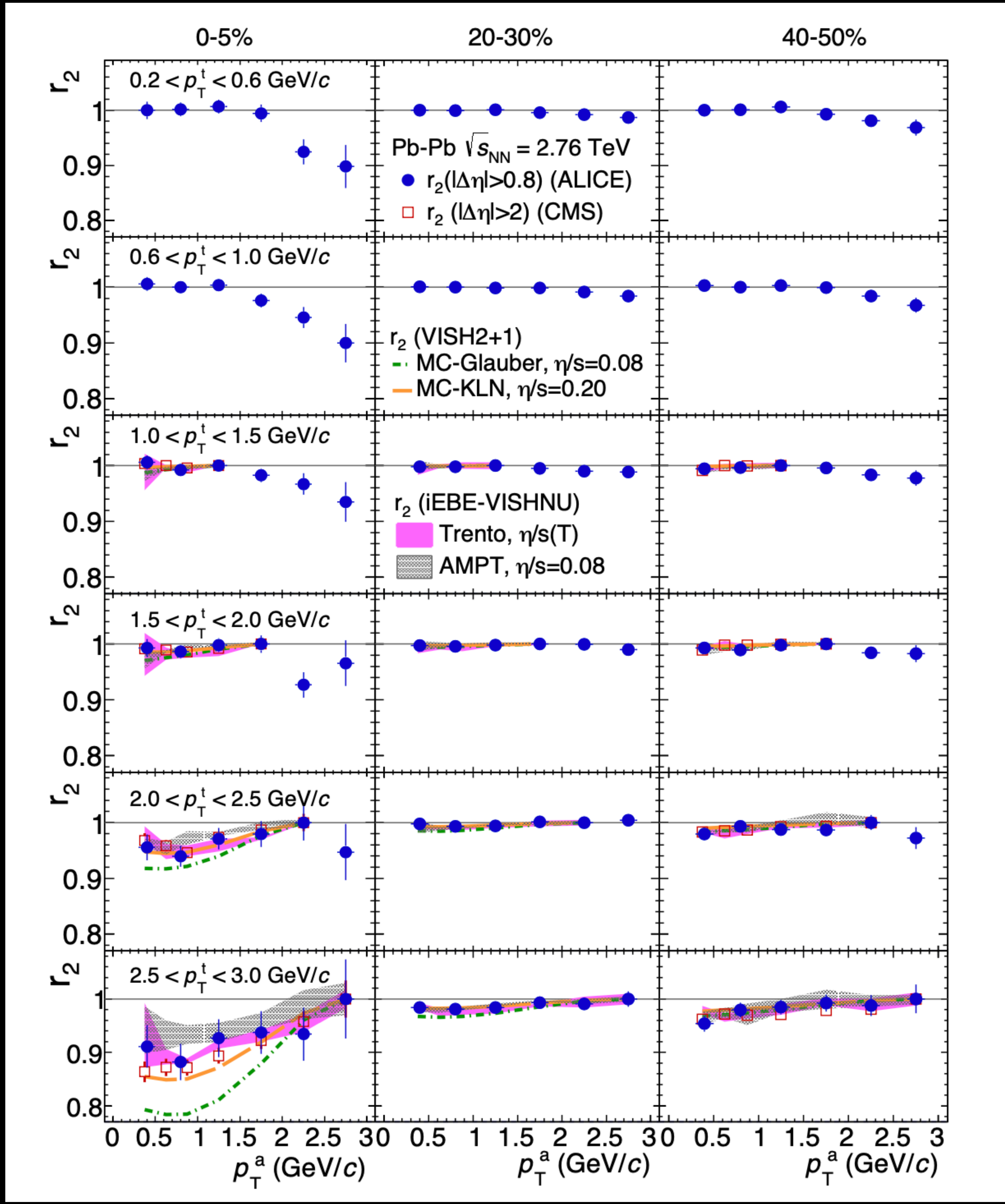
$$r_n = \frac{V_{n\Delta}(p_T^a, p_T^t)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)V_{n\Delta}(p_T^t, p_T^t)}}$$

- Chooses particles from different narrow p_T bins

- Tests factorization

$$V_{n\Delta}(p_T^a, p_T^t) \overset{?}{=} v_n(p_T^a) \times v_n(p_T^t)$$

- $r_n < 1$ indicates flow vector fluctuations



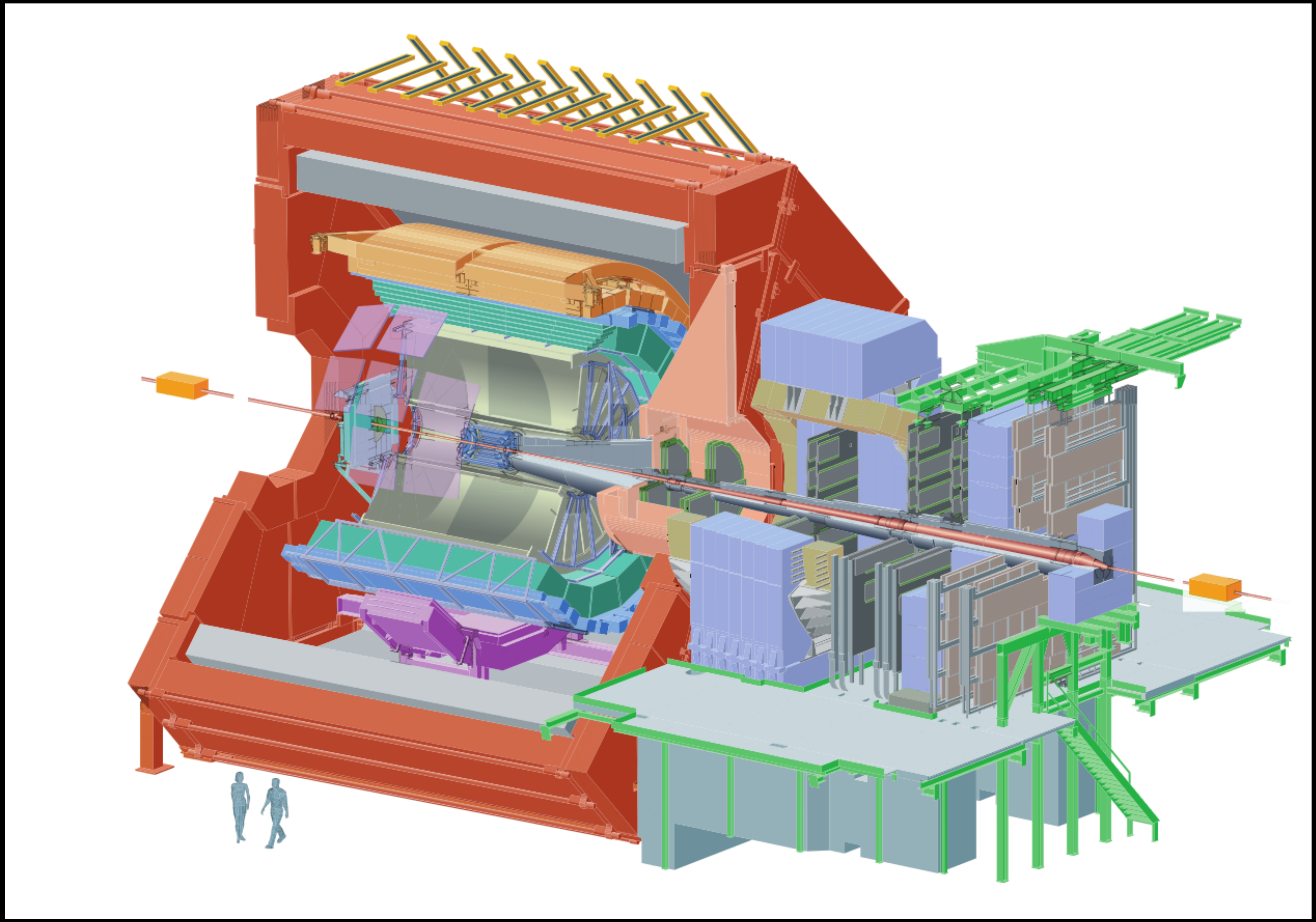
- New precision measurements of flow vector fluctuations → Better constraints on initial conditions and QGP properties

The ALICE detector

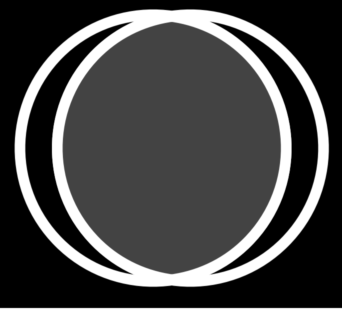
- General-purpose heavy-ion experiment
- Designed to study physics of strongly interacting matter
- Capable of dealing with very large particle multiplicities
- Particle selection:

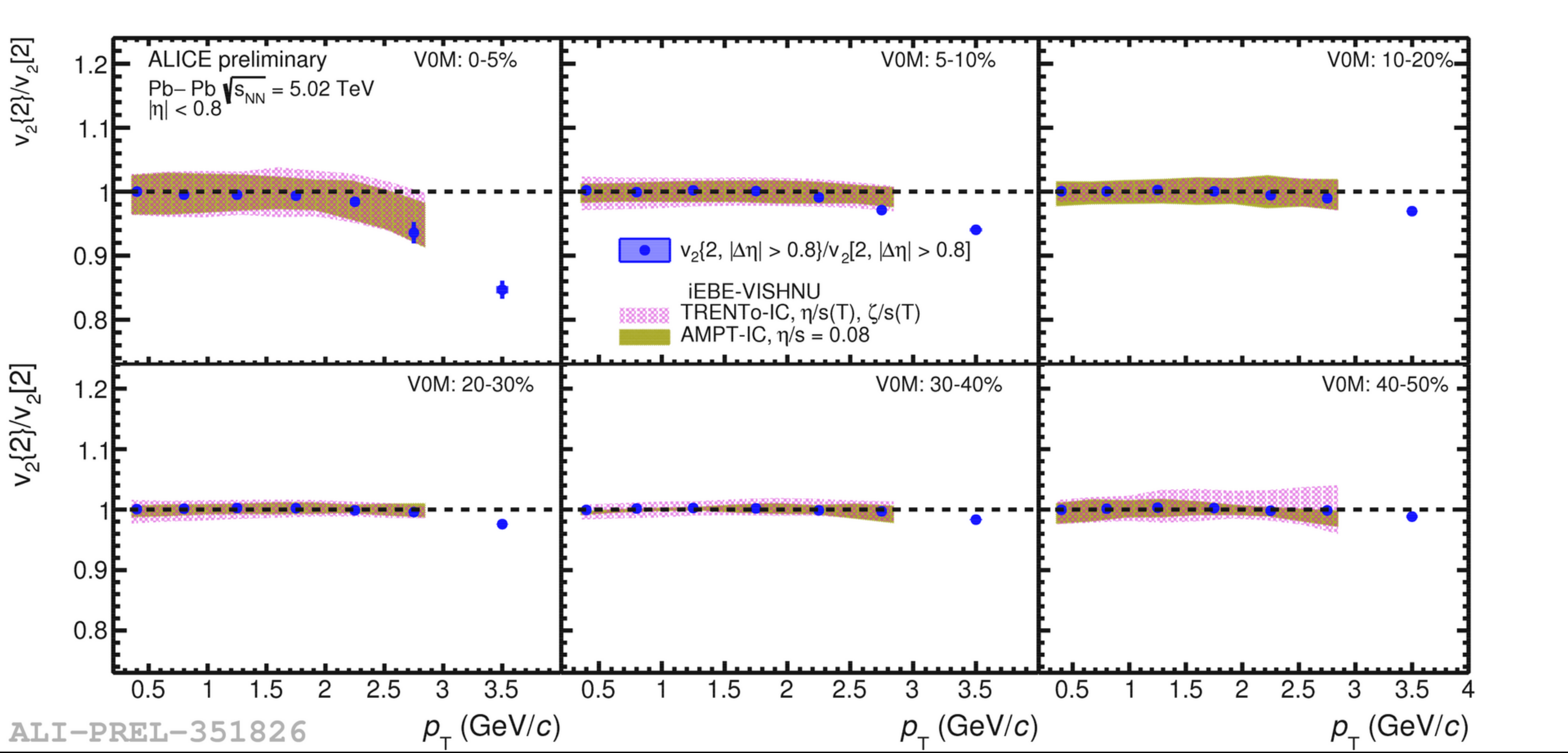
$$0.2 < p_{\mathrm{T}} < 5.0 \text{ GeV}/c$$

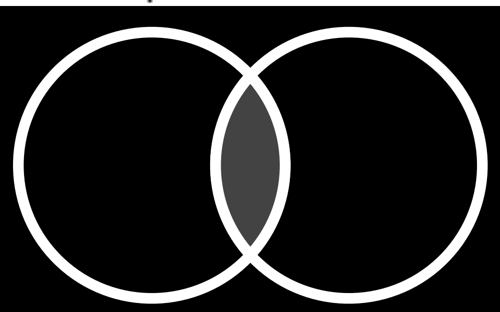
$$|\eta| < 0.8$$



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




ALICE preliminary
Pb– Pb $\sqrt{s_{NN}}$ = 5.02 TeV
$|\eta| < 0.8$
V0M: 0-5%
V0M: 5-10%
V0M: 10-20%
V0M: 20-30%
V0M: 30-40%
V0M: 40-50%
$v_2\{2, |\Delta\eta| > 0.8\}/v_2[2, |\Delta\eta| > 0.8]$
iEBE-VISHNU
TRENTo-IC, $\eta/s(T)$, $\zeta/s(T)$
AMPT-IC, $\eta/s = 0.08$
$v_2\{2\}/v_2[2]$
p_T (GeV/c)
ALI-PREL-351826



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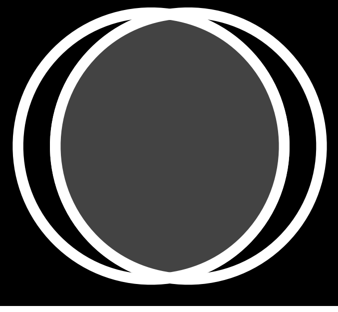
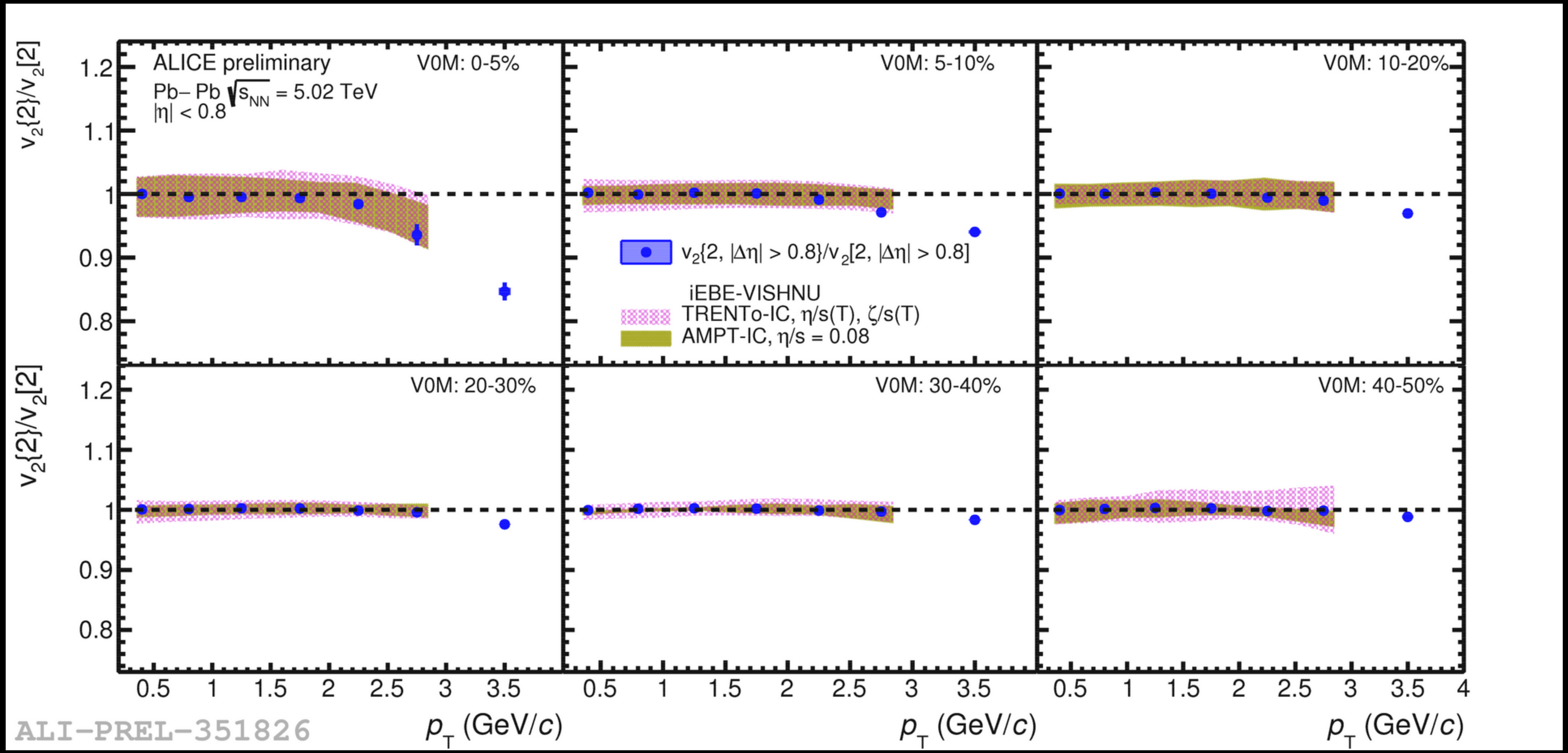
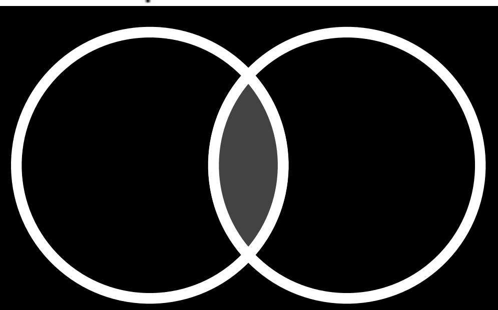
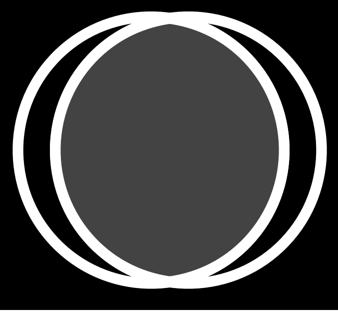




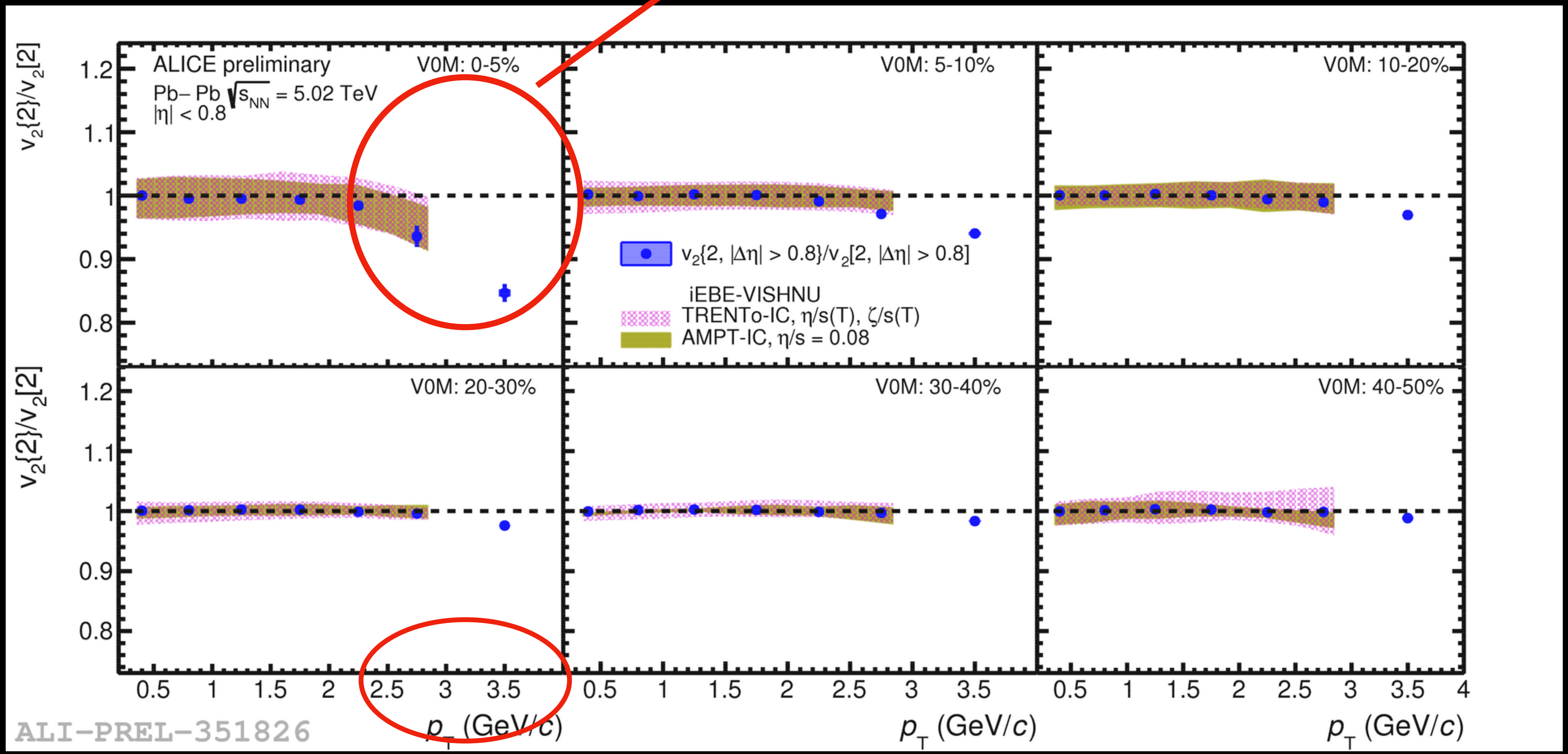
- Deviation of $v_2\{2\}/v_2[2]$ from unity in central collisions



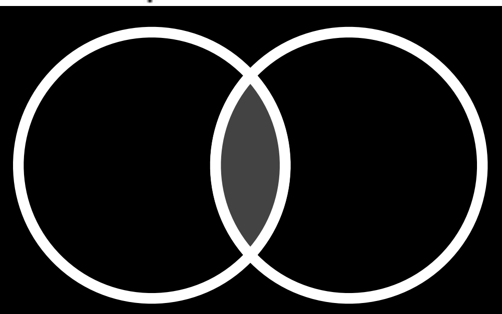
$v_n\{2\}/v_n[2]$



High p_{T}

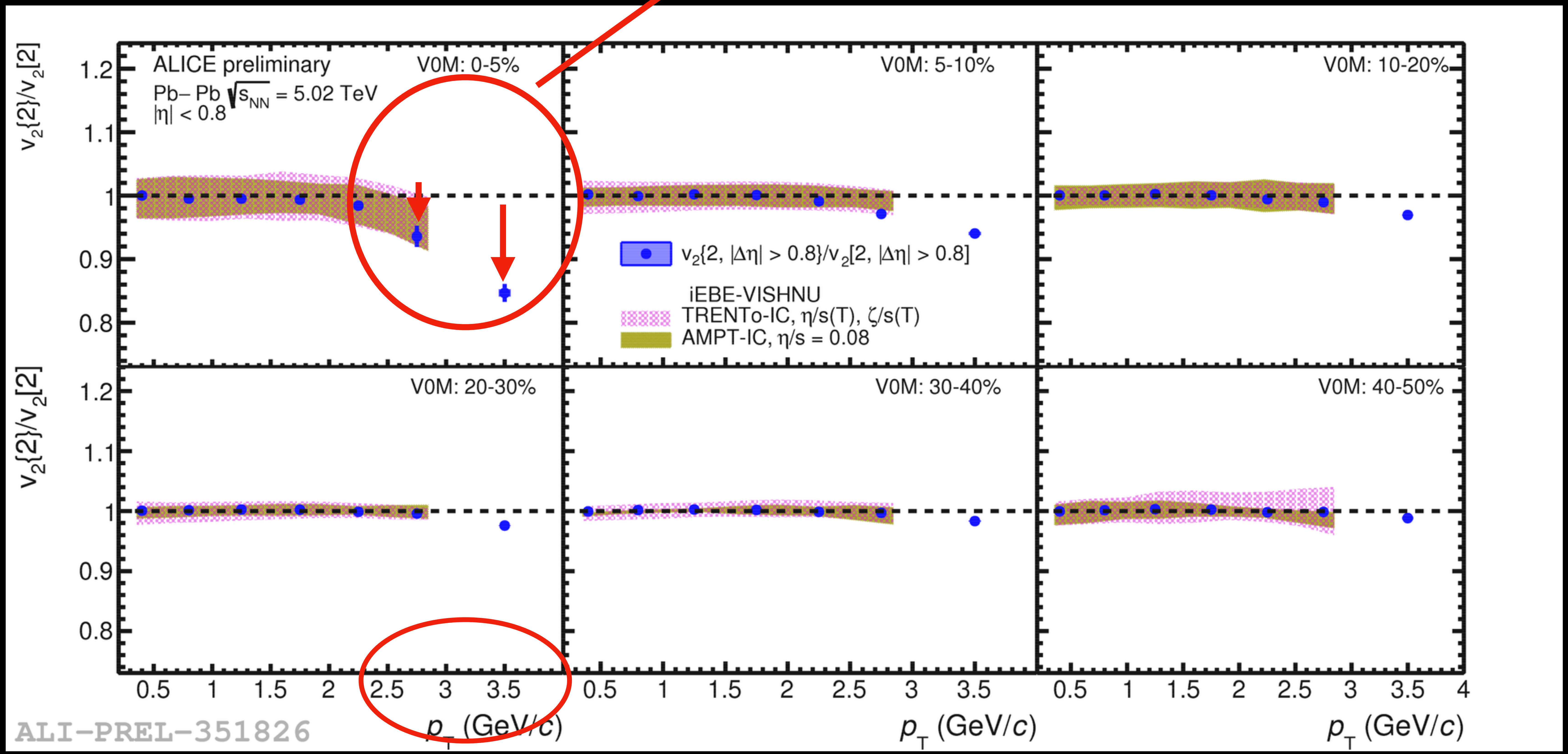


- Deviation of $v_2\{2\}/v_2[2]$ from unity in central collisions
- Deviations increase with p_{T}



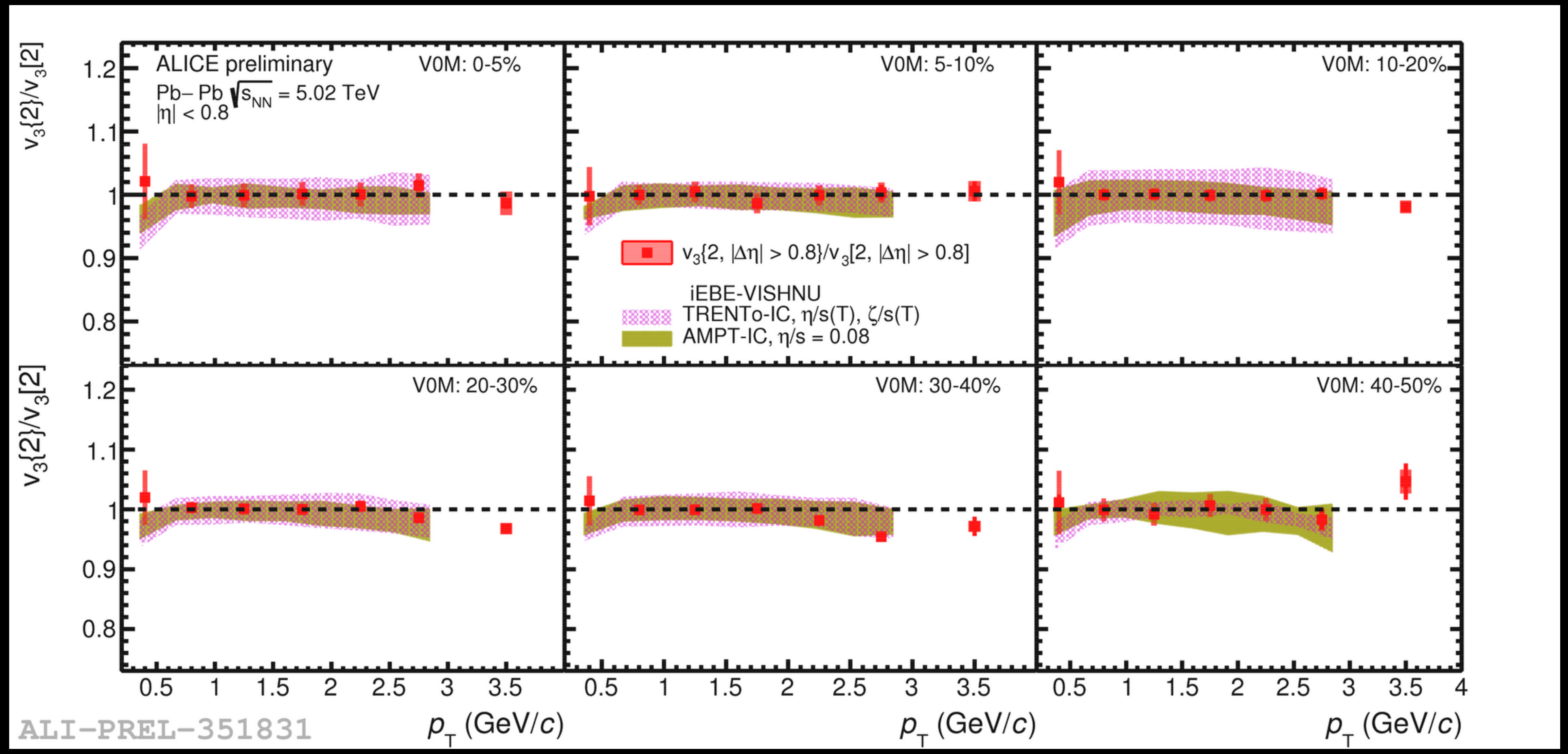
$v_n\{2\}/v_n[2]$

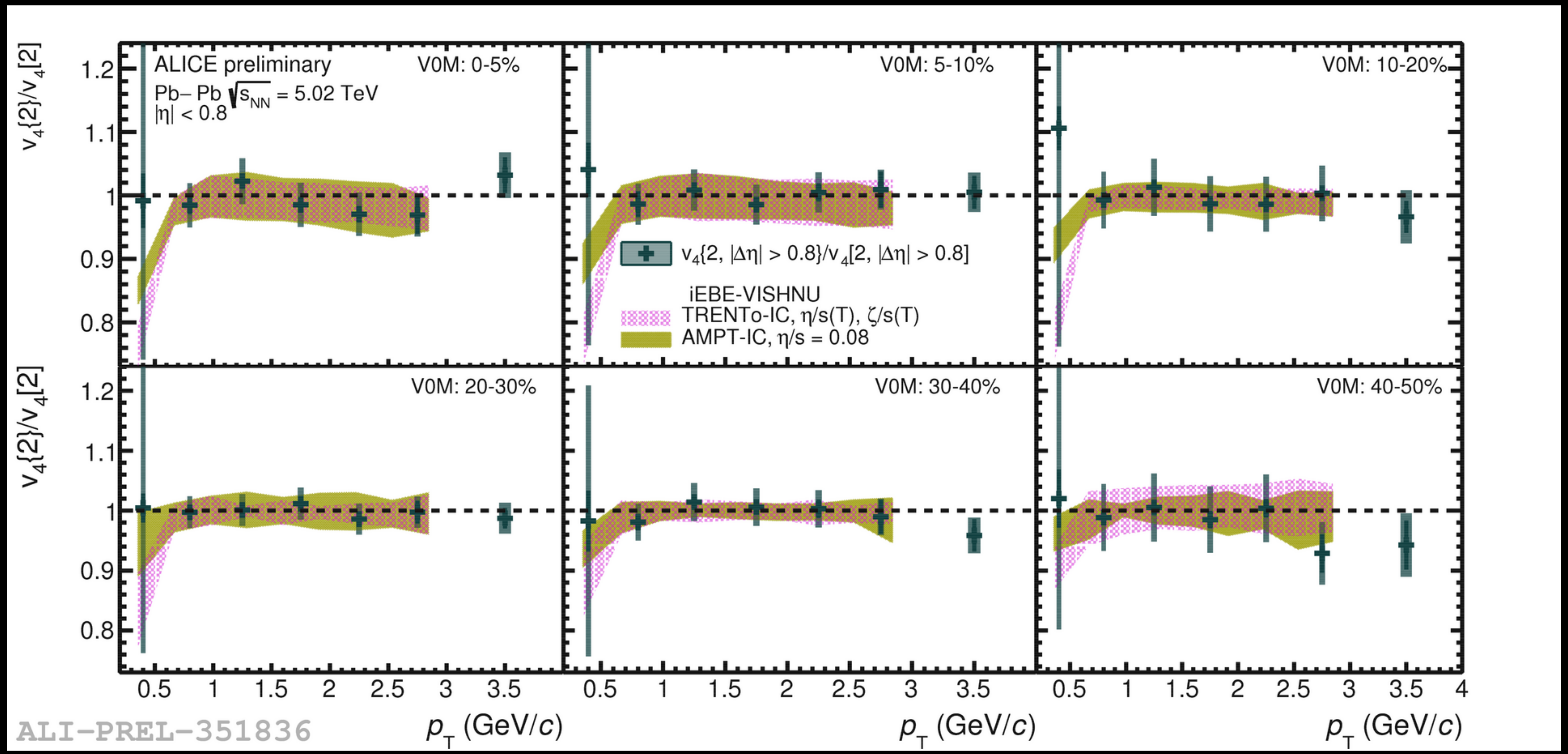
High p_{T}



- Deviation of $v_2\{2\}/v_2[2]$ from unity in central collisions
- Deviations increase with p_{T}
- p_{T}-dependent V_2 fluctuations

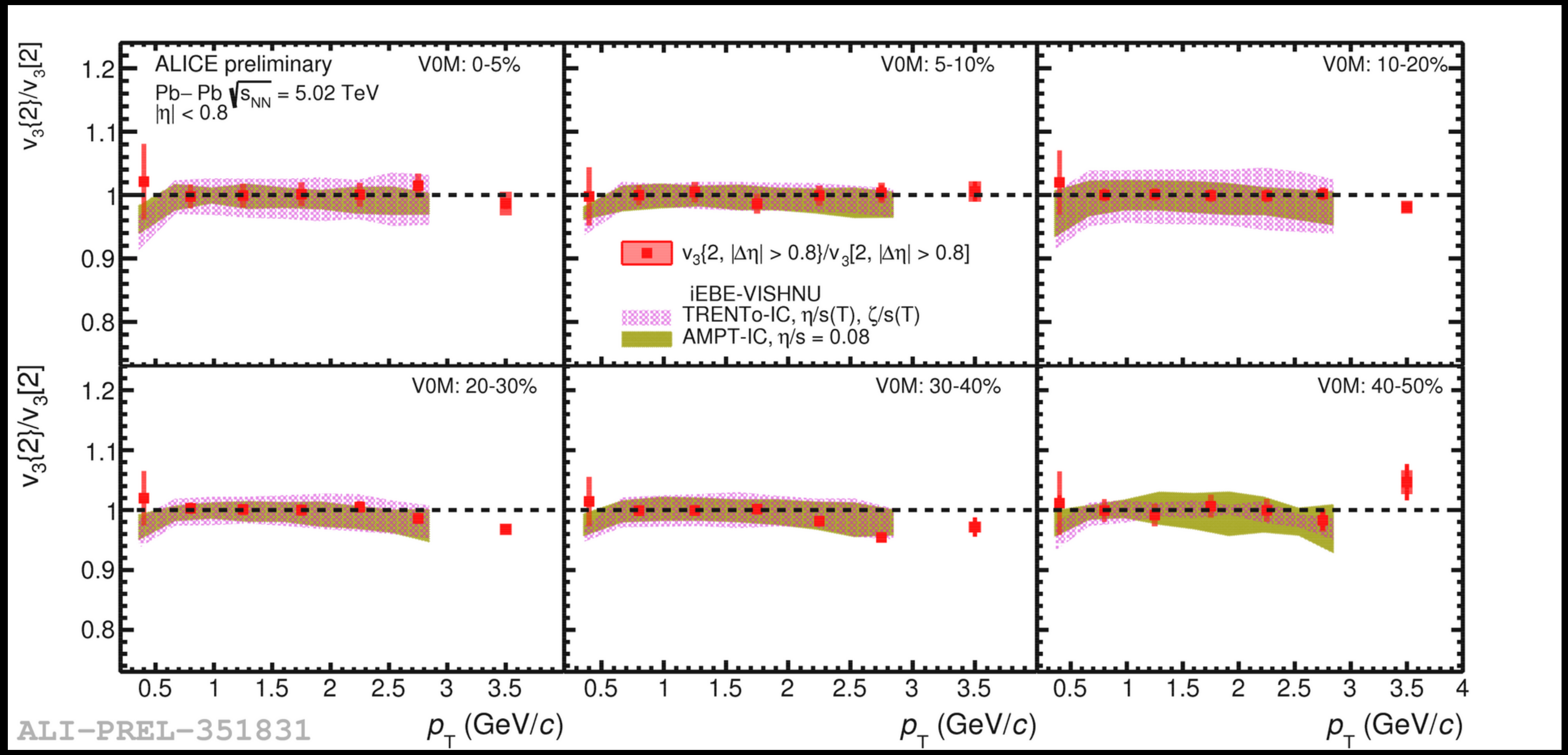
$v_n\{2\}/v_n[2]$

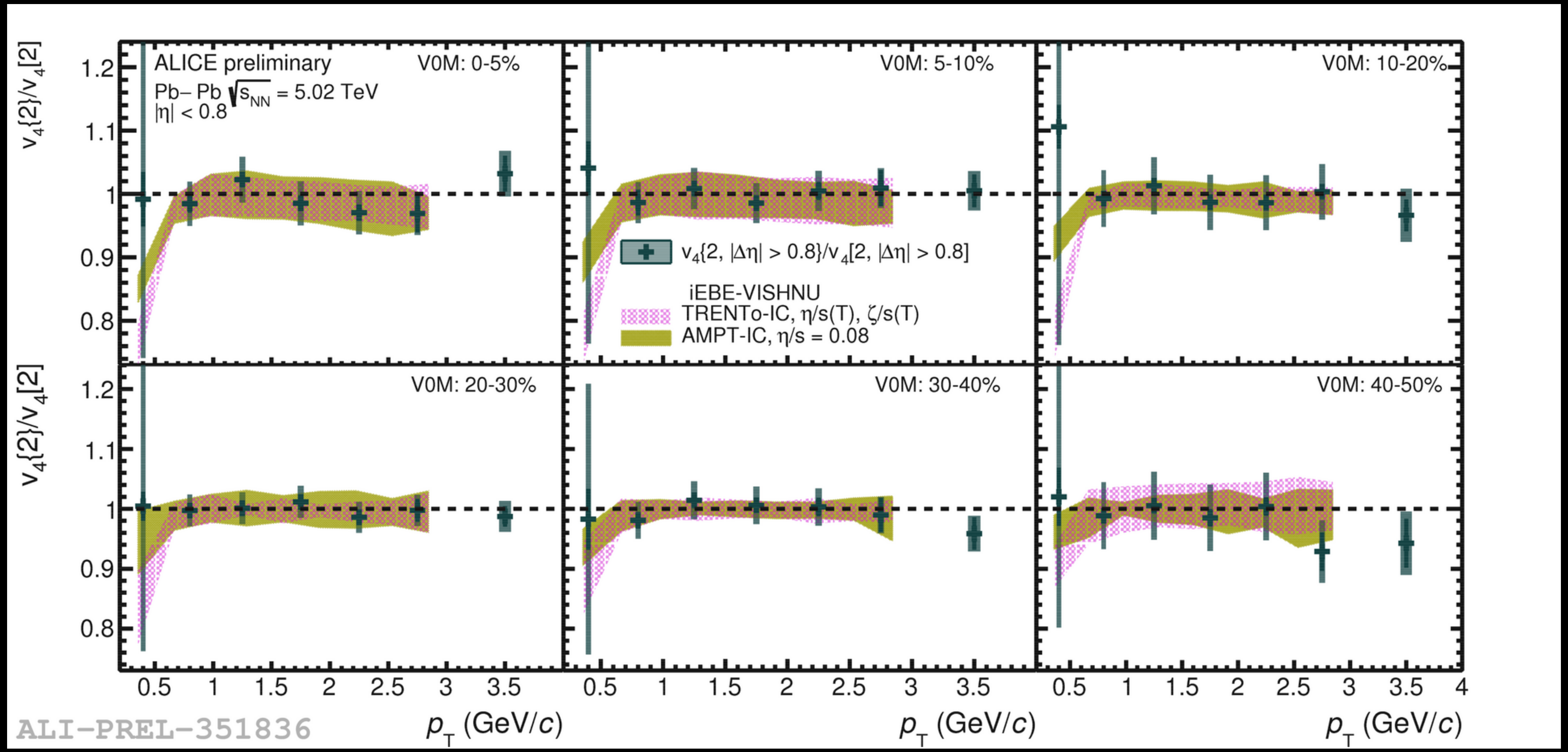




- Deviation of $v_2\{2\}/v_2[2]$ from unity in central collisions
- Deviations increase with p_T
- p_T-dependent V_2 fluctuations
- Higher order harmonics $(n > 2)$

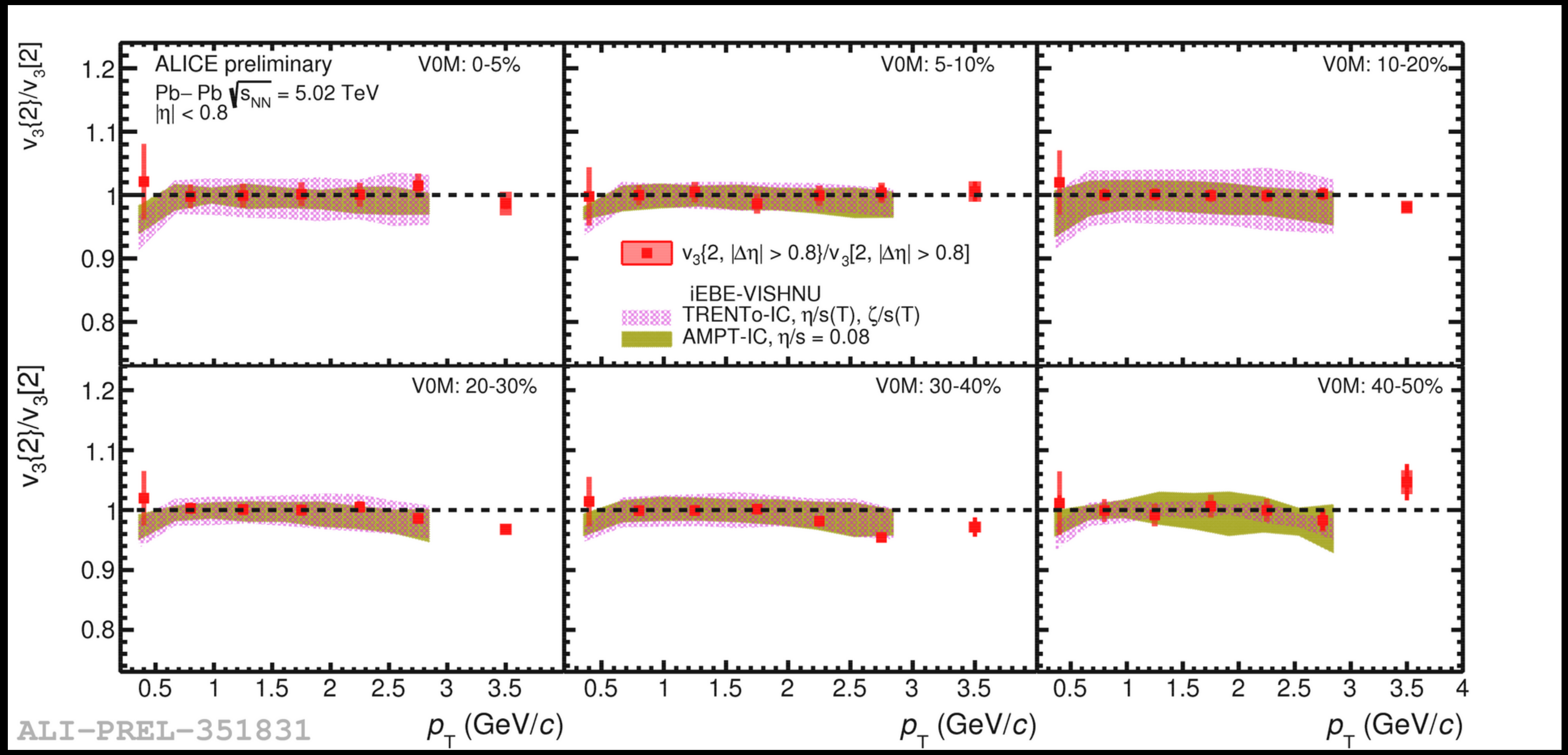
$v_n\{2\}/v_n[2]$

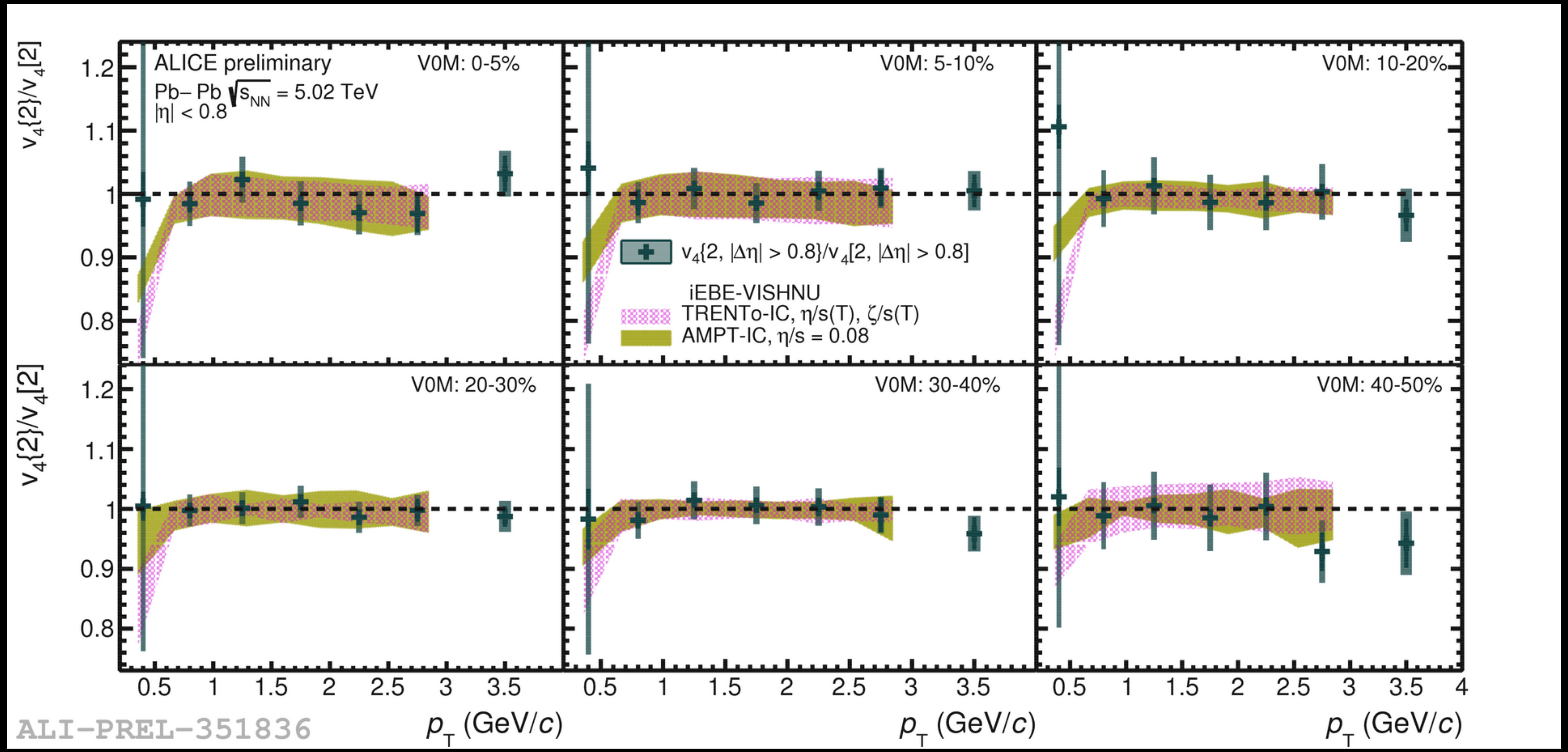




- Deviation of $v_2\{2\}/v_2[2]$ from unity in central collisions
- Deviations increase with p_T
- p_T-dependent V_2 fluctuations
- Higher order harmonics $(n > 2)$
- $v_3\{2\}/v_3[2]$ and $v_4\{2\}/v_4[2]$ consistent with unity

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

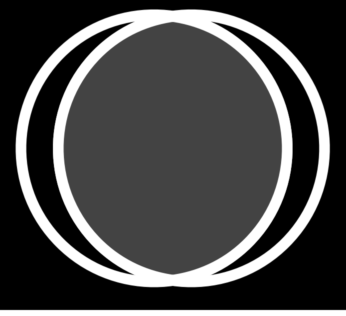


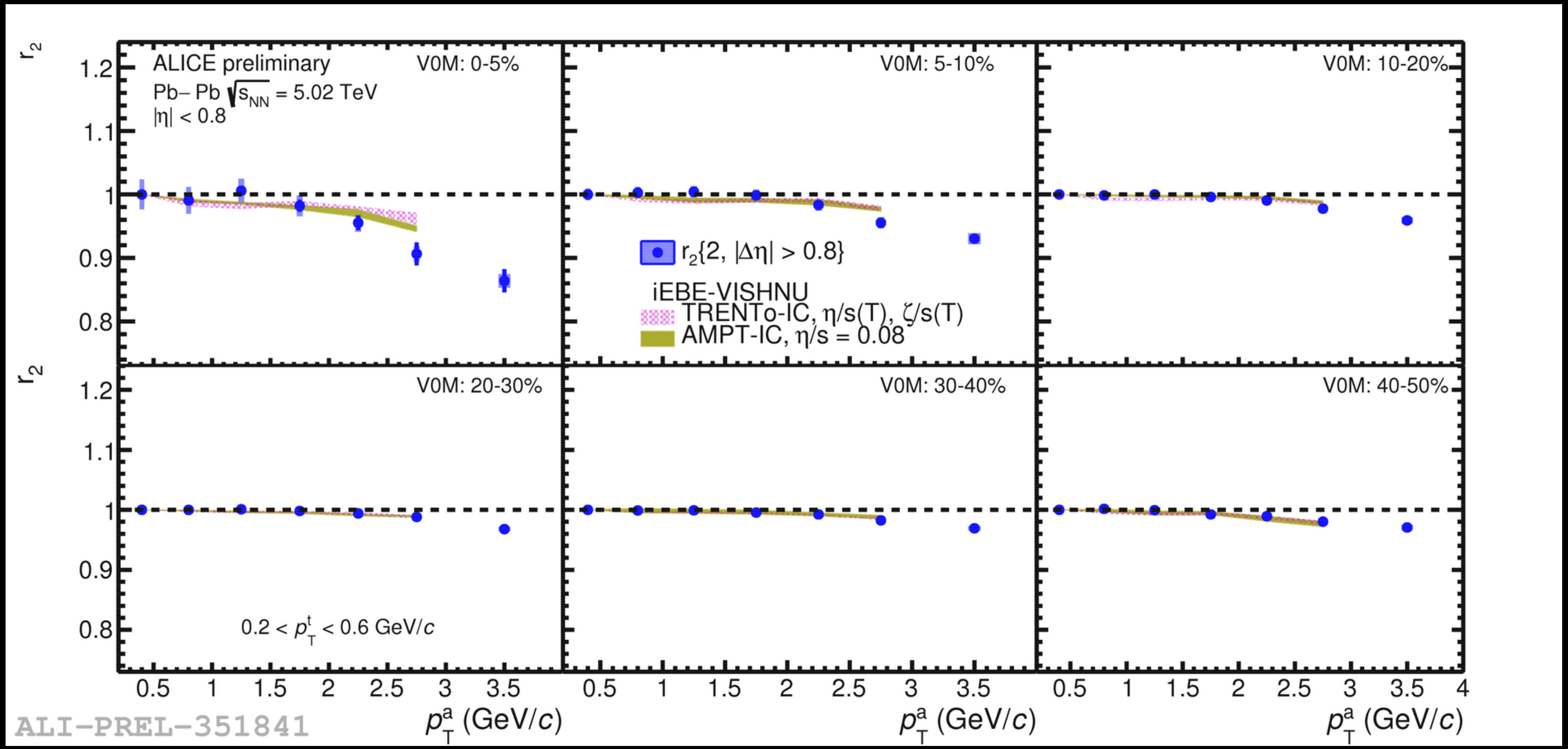


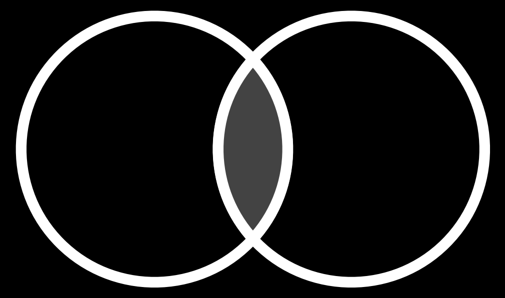
- Deviation of $v_2\{2\}/v_2[2]$ from unity in central collisions
- Deviations increase with p_{T}
- p_{T}-dependent V_2 fluctuations
- Higher order harmonics $(n > 2)$
- $v_3\{2\}/v_3[2]$ and $v_4\{2\}/v_4[2]$ consistent with unity
- Suggests V_3 and V_4 does not fluctuate with p_{T}

Factorization ratio r_n

- Deviation of r_2 from unity observed
  → Factorization is broken







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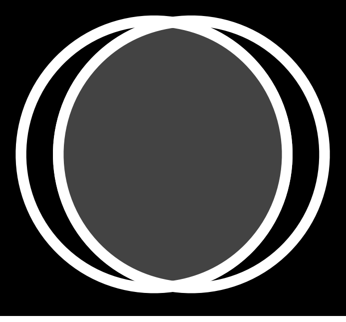
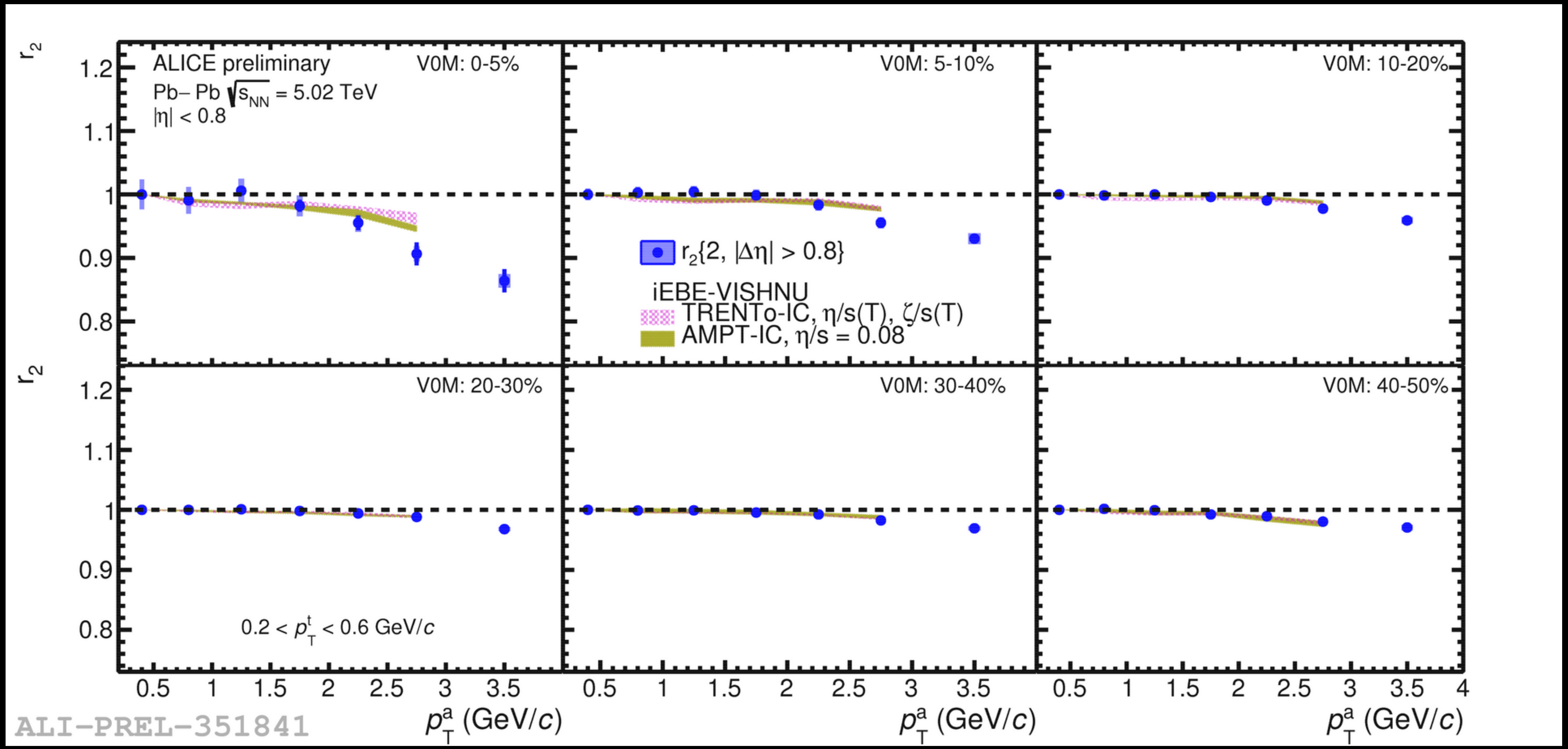
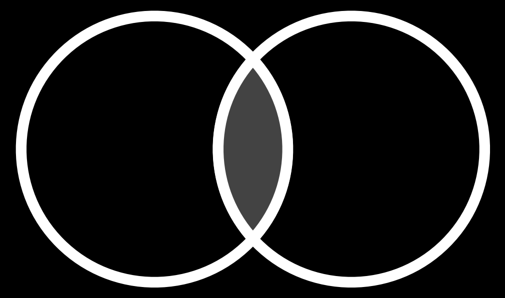


- Deviation of r_2 from unity observed
  $\rightarrow$ Factorization is broken

- Deviation increases as difference $|p_{\mathrm{T}}^{a} - p_{\mathrm{T}}^{t}|$ increases





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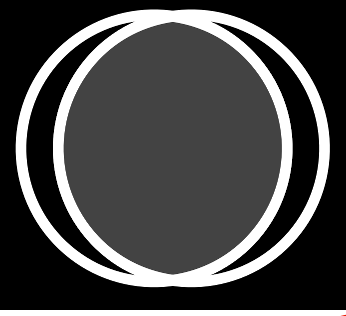
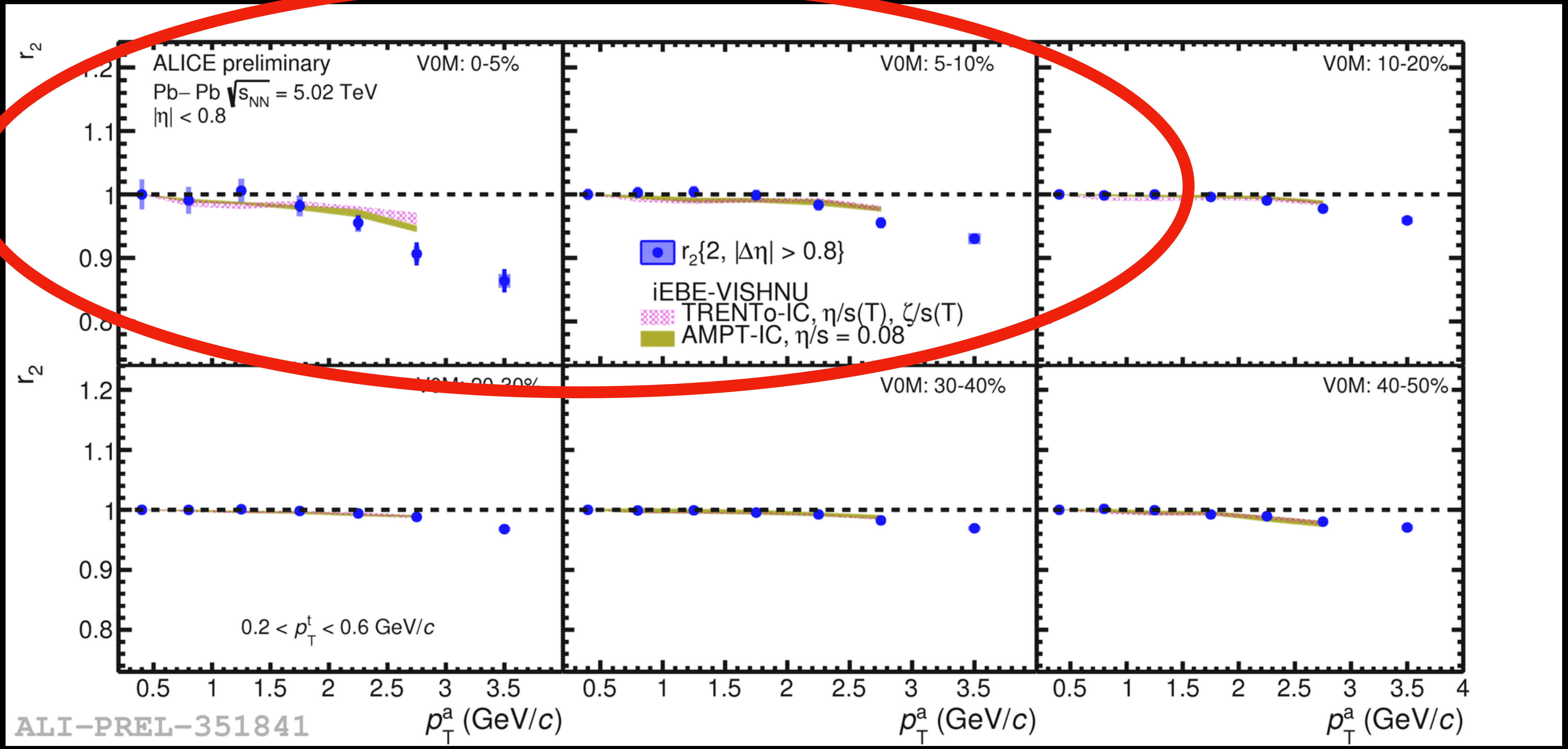
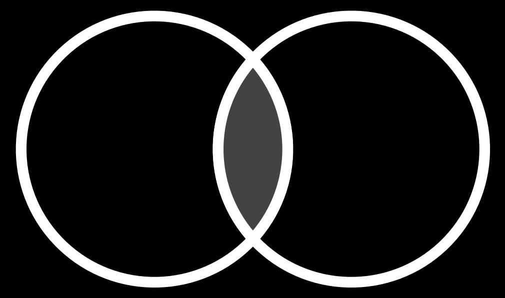




- Deviation increases as difference $|p_T^a - p_T^t|$ increases

- Strongest breakdown of factorization in central collisions



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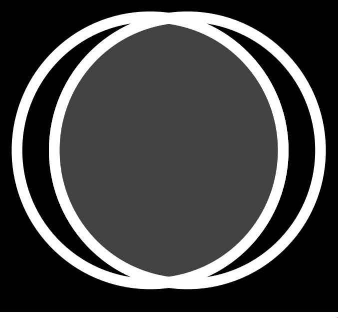
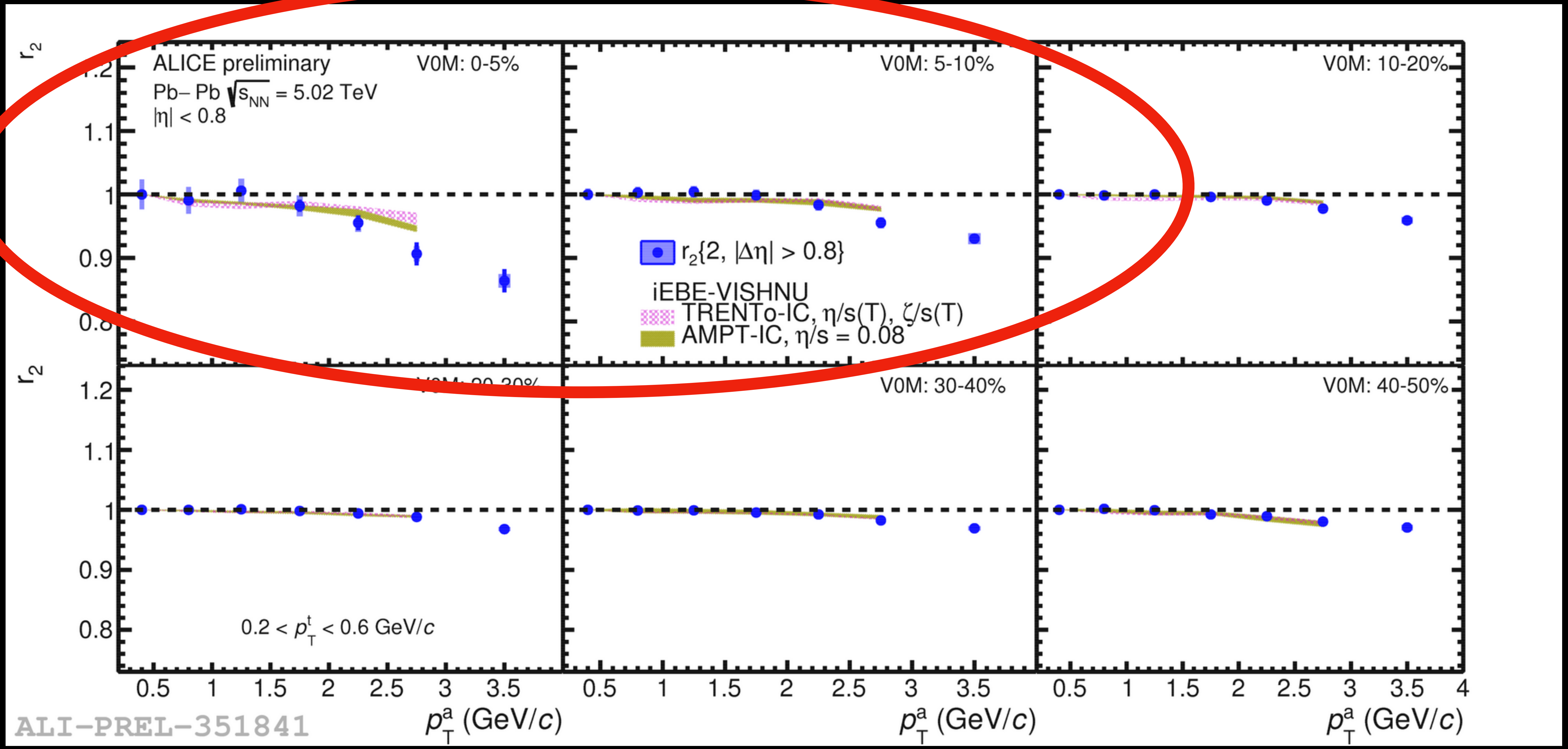
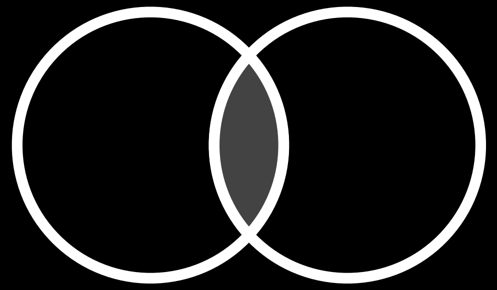


- Deviation of r_2 from unity observed $\rightarrow$ Factorization is broken
- Deviation increases as difference $|p_{\mathrm{T}}^{a} - p_{\mathrm{T}}^{t}|$ increases
- Strongest breakdown of factorization in central collisions
- Also predicted by hydrodynamic calculations





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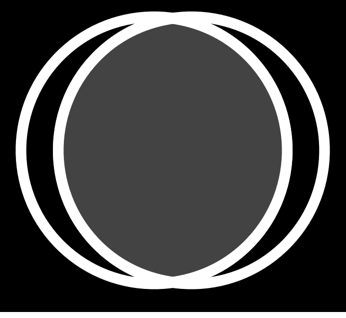


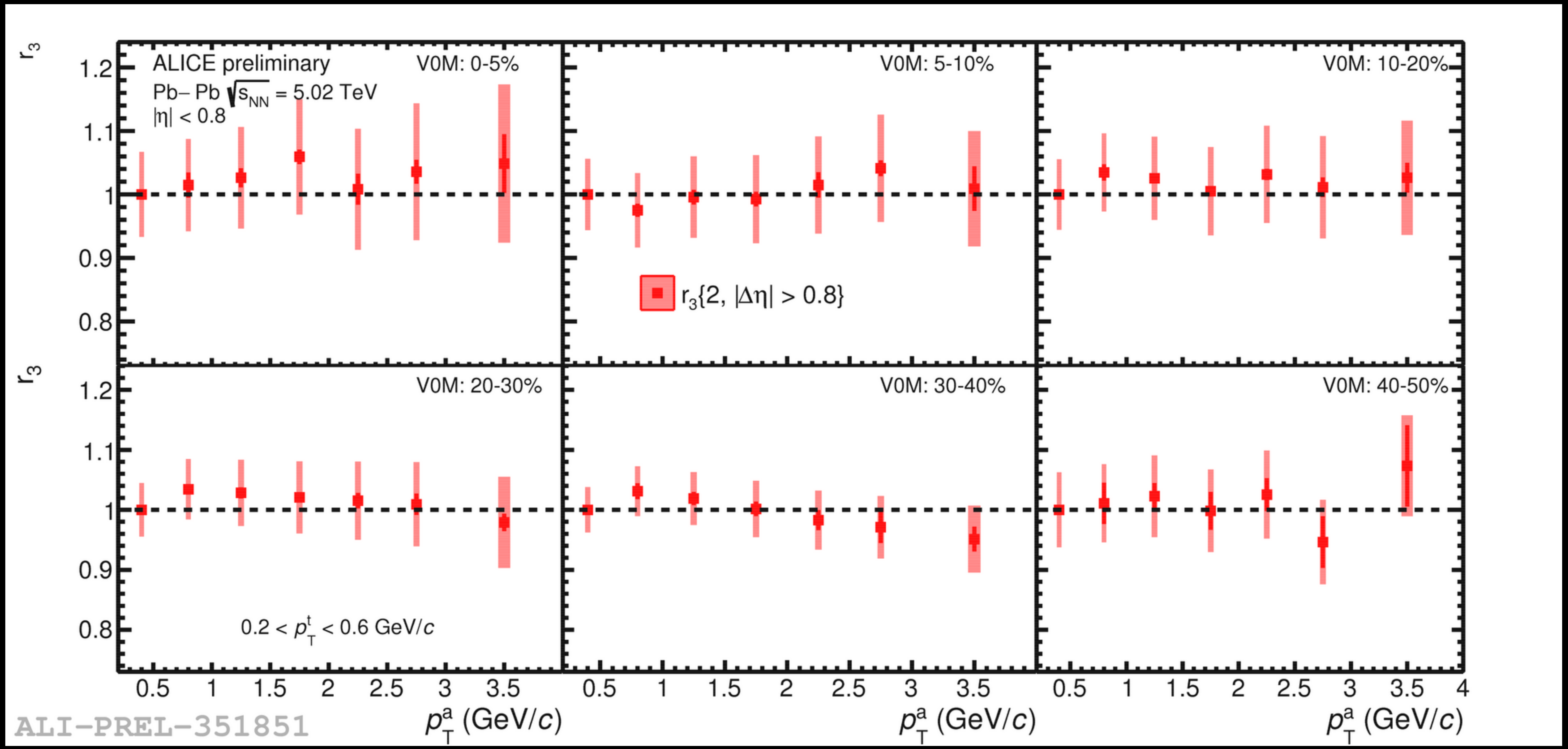
- Deviation of r_2 from unity observed
  $\rightarrow$ Factorization is broken

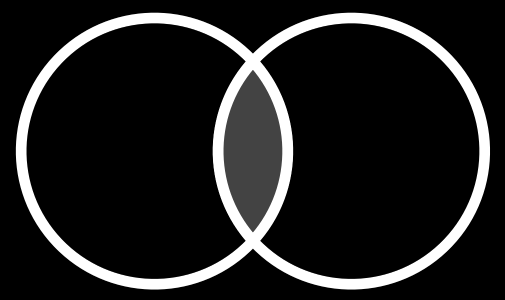
- Deviation increases as difference $|p_{\mathrm{T}}^{a} - p_{\mathrm{T}}^{t}|$ increases

- Strongest breakdown of factorization in central collisions

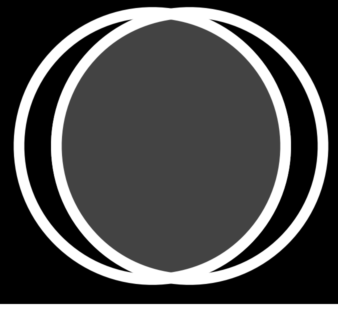
- Also predicted by hydrodynamic calculations

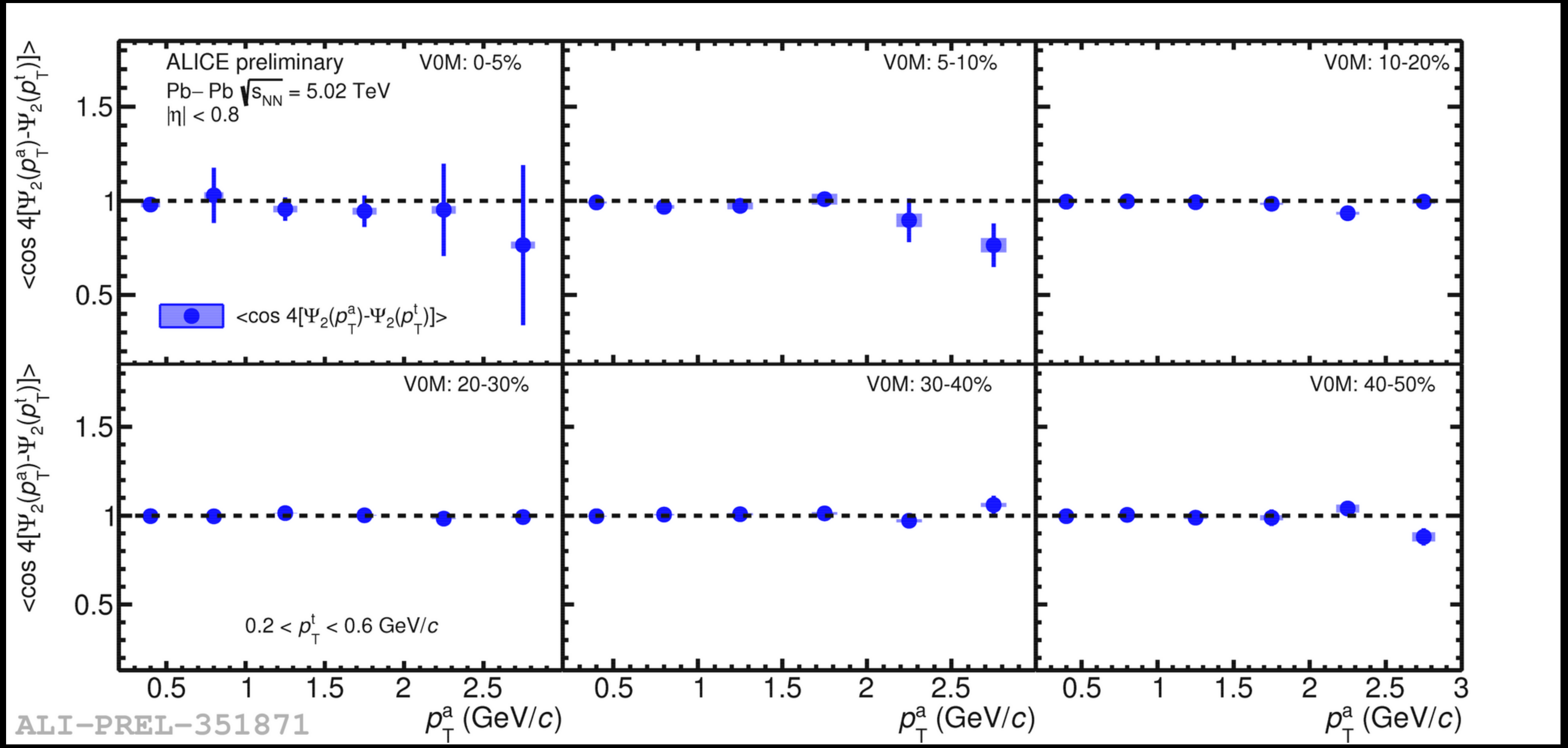
- Factorization of V_3 not broken, or at least within few percent

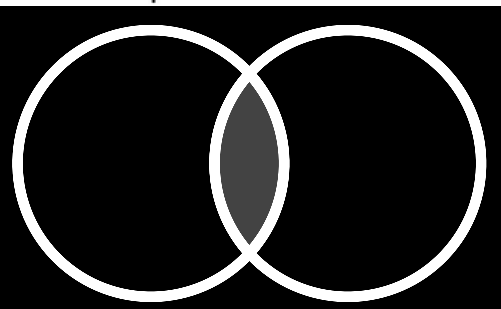




$C(\Psi_2^a, \Psi_2^t)$

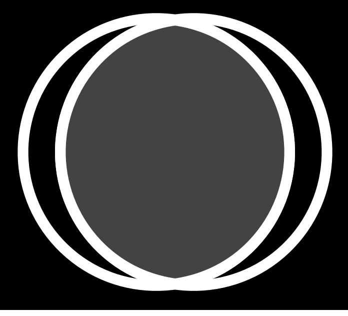


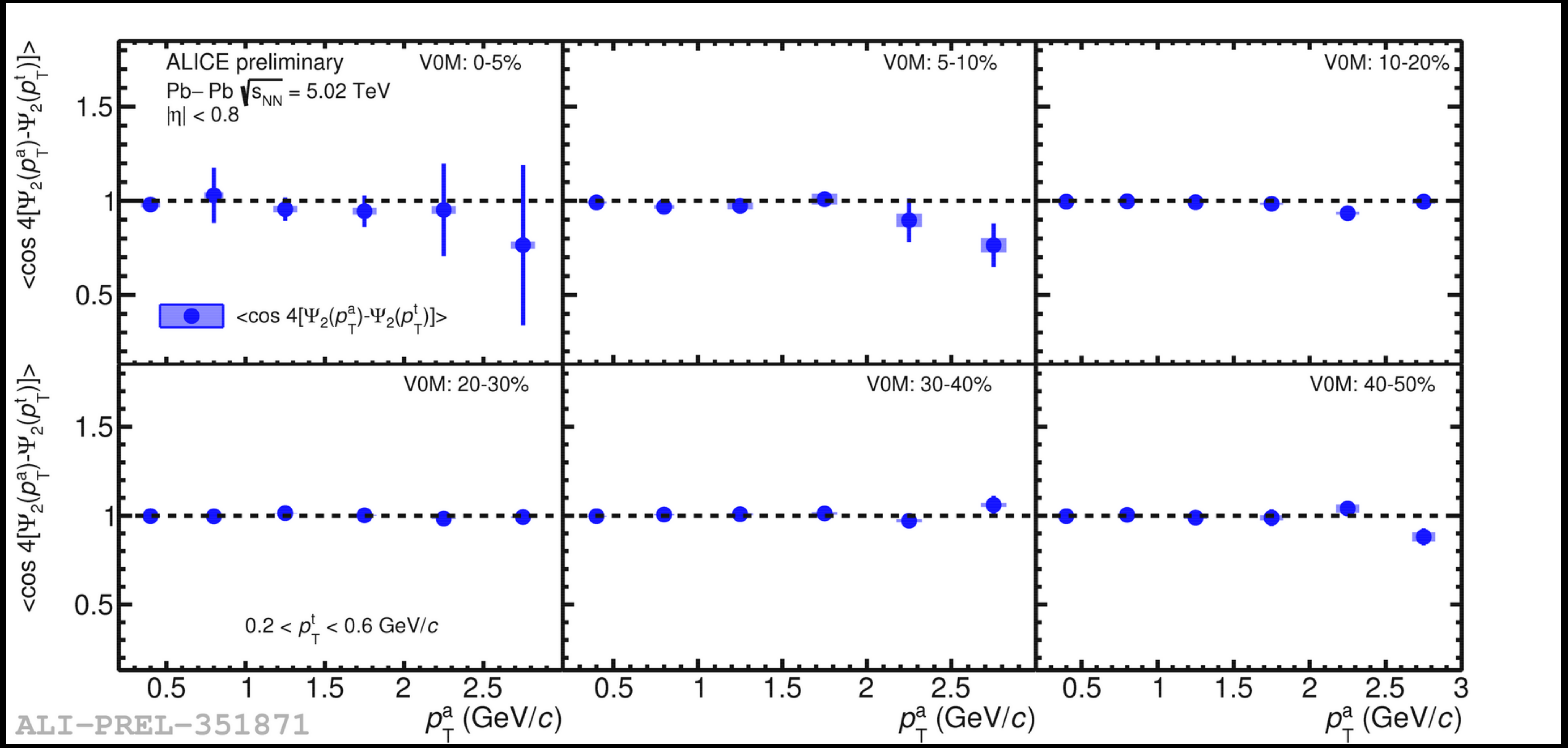


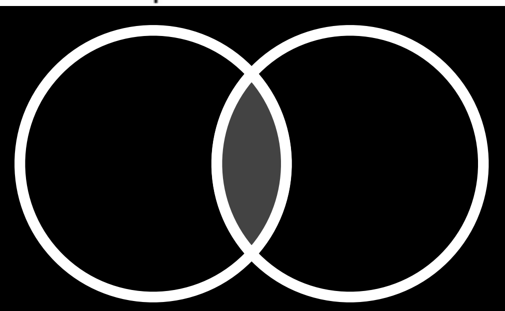


$C(\Psi_2^a, \Psi_2^t)$

- Newly proposed observable:



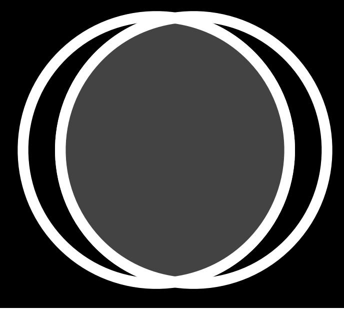


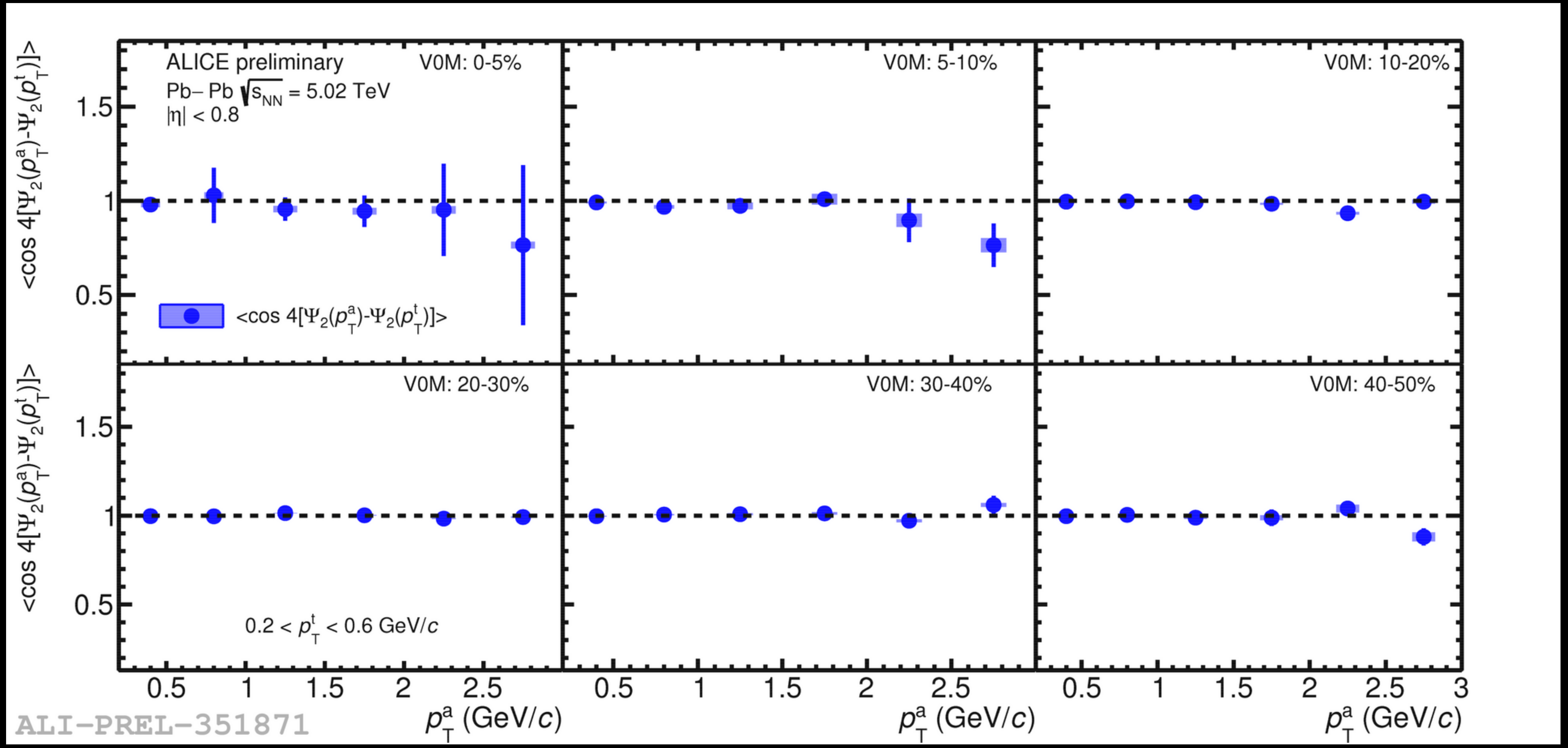


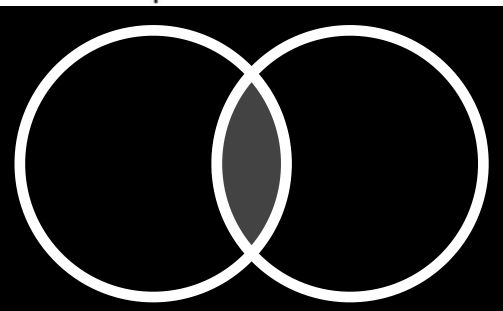
$C(\Psi_2^a, \Psi_2^t)$

- Newly proposed observable:

$$C(\Psi_n^a, \Psi_n^t) \approx \langle \cos 2n[\Psi_n(p_\mathrm{T}^a) - \Psi_n(p_\mathrm{T}^t)] \rangle$$





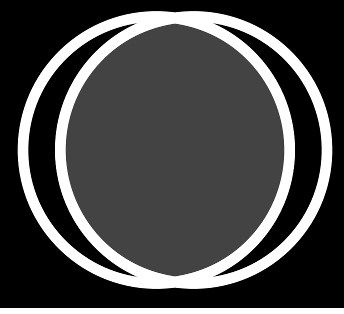


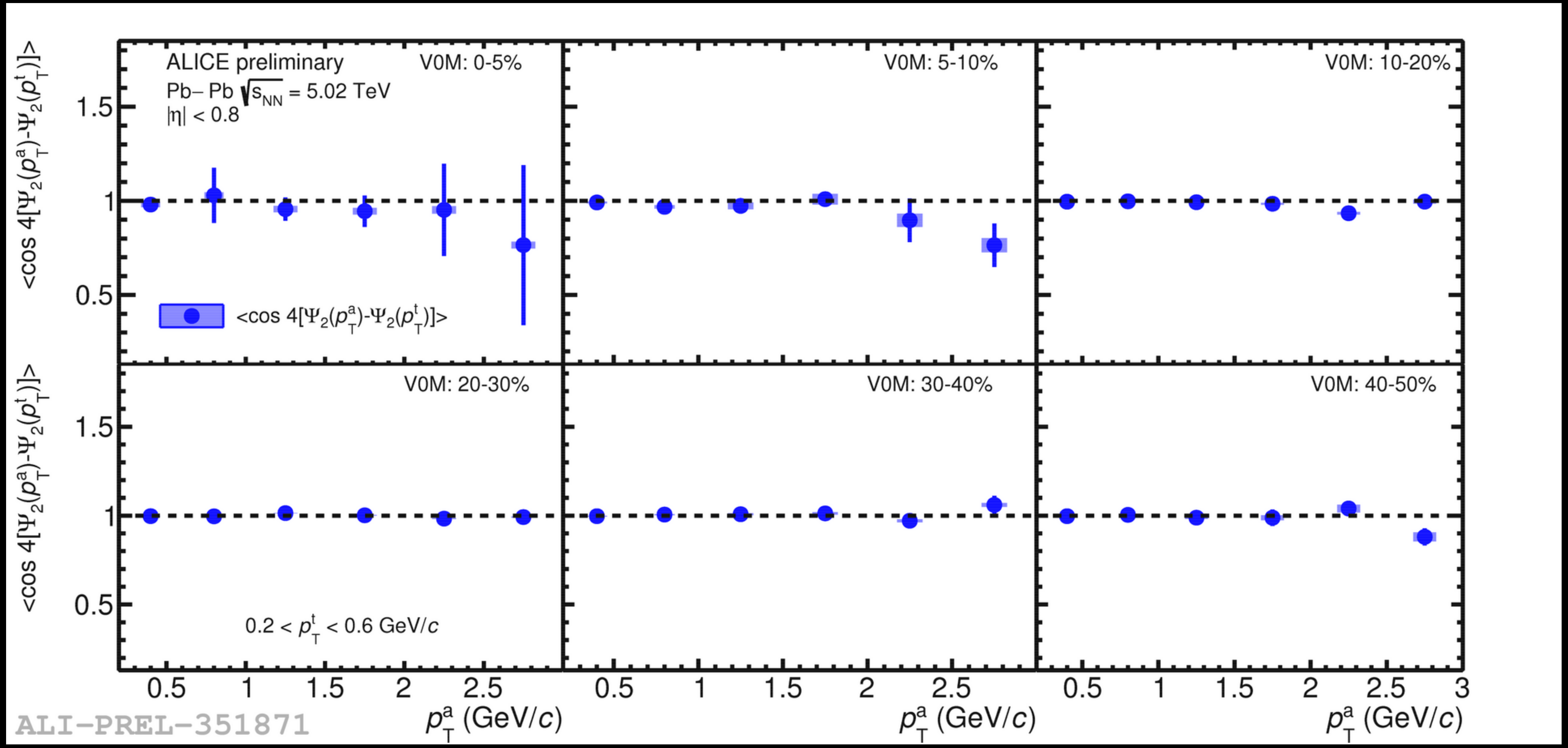
$C(\Psi_2^a, \Psi_2^t)$

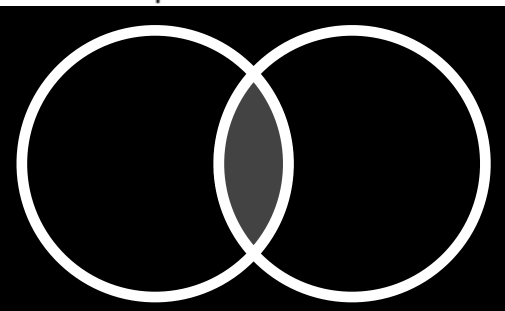
Does not depend on v_n

- Newly proposed observable:

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







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Does not depend on v_n

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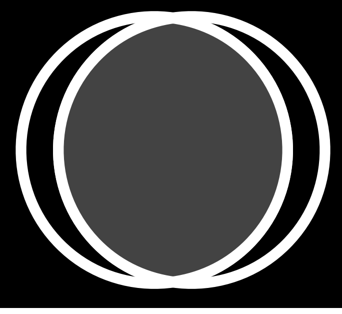
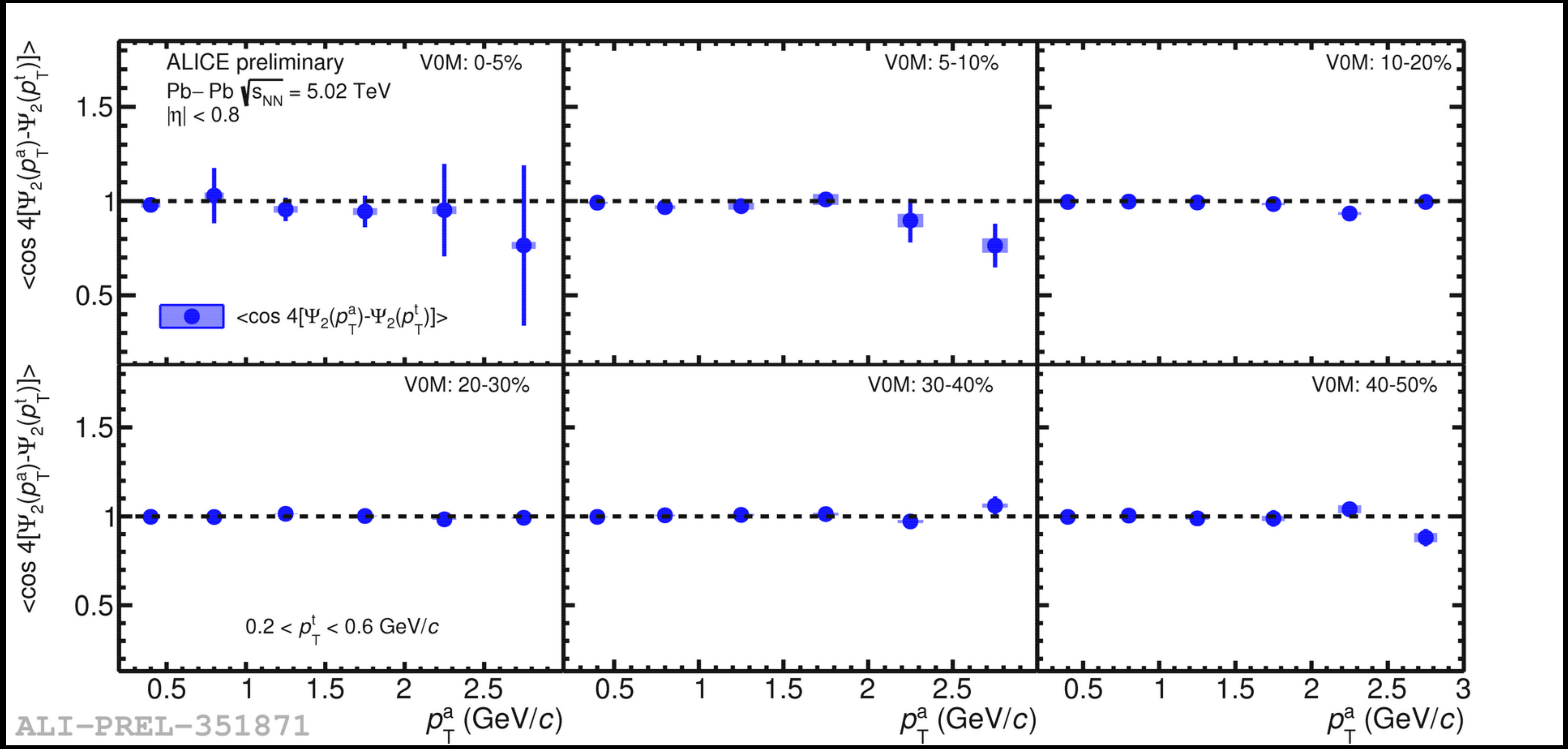
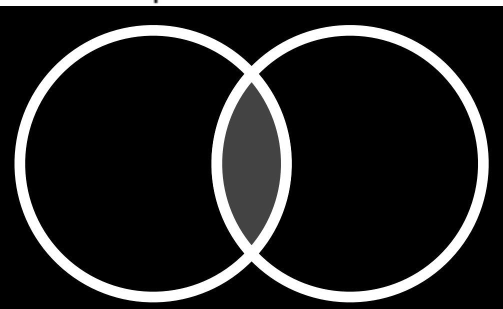




- If $C(\Psi_n^a, \Psi_n^t) < 1$, indication of flow angle fluctuation



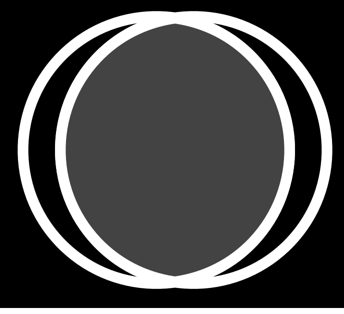
$C(\Psi_2^a, \Psi_2^t)$

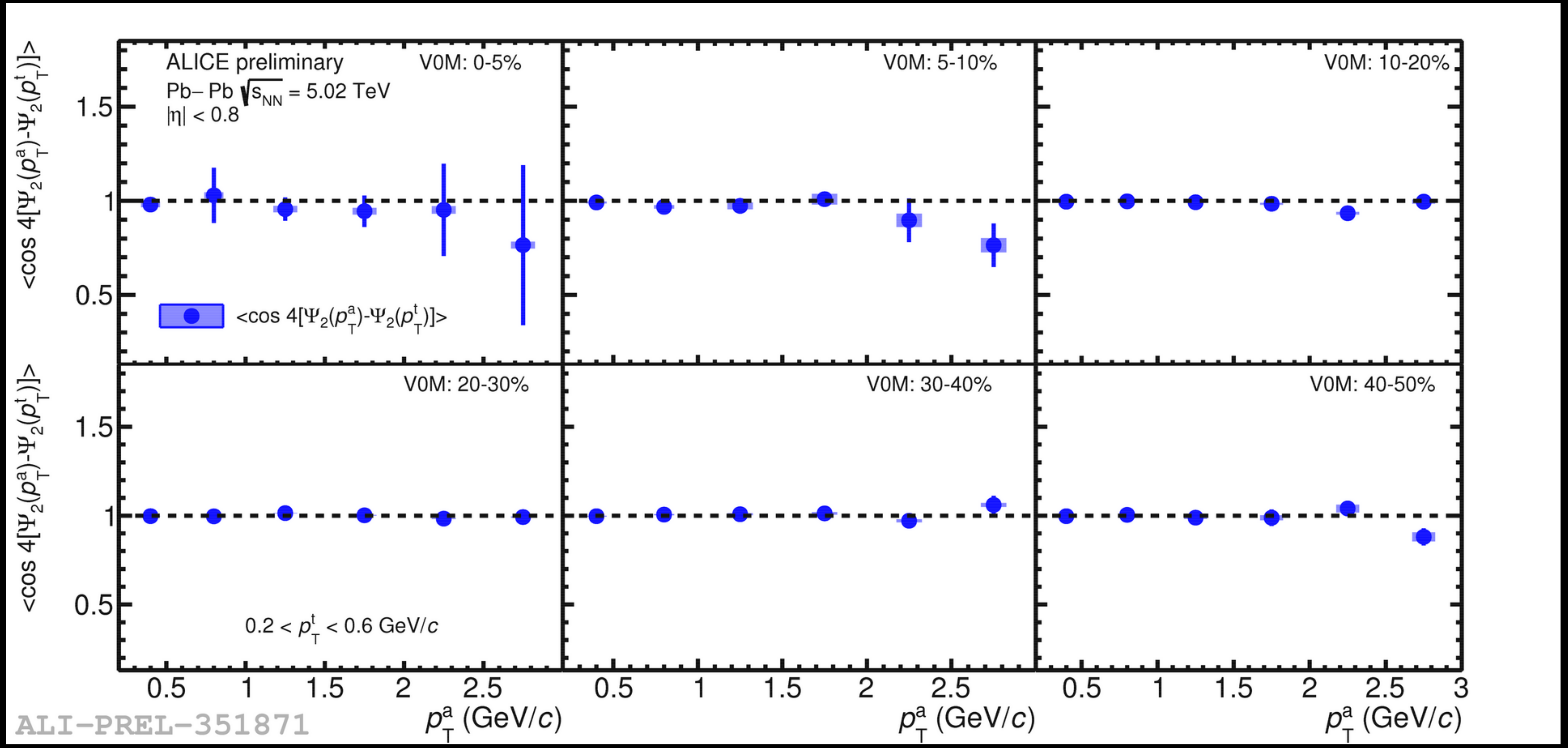
Does not depend on v_n

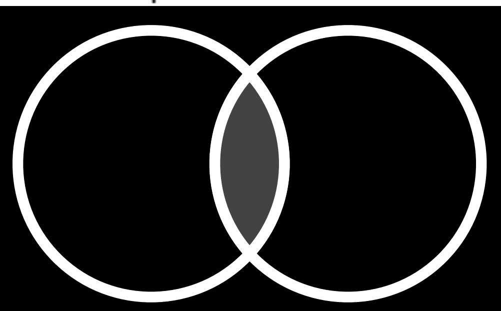
- Newly proposed observable:

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

- If $C(\Psi_n^a, \Psi_n^t) < 1$, indication of flow angle fluctuation
- No deviation from unity within uncertainties







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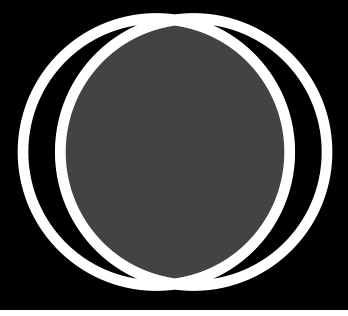
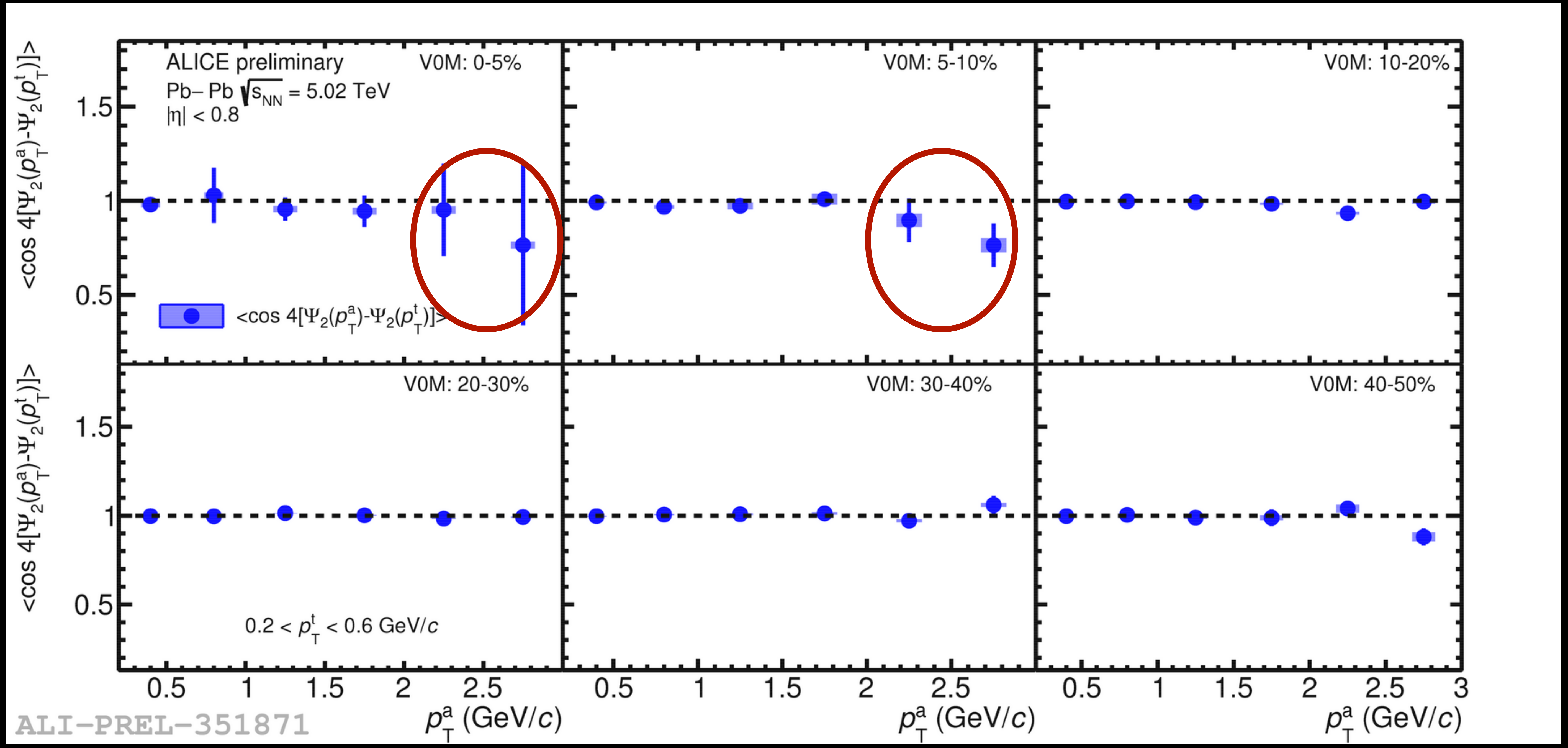
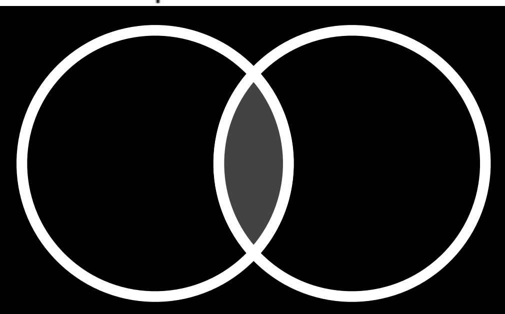




- If $C(\Psi_n^a, \Psi_n^t) < 1$, indication of flow angle fluctuation
- No deviation from unity within uncertainties
    - Hint of $C(\Psi_n^a, \Psi_n^t) < 1$ in central collisions

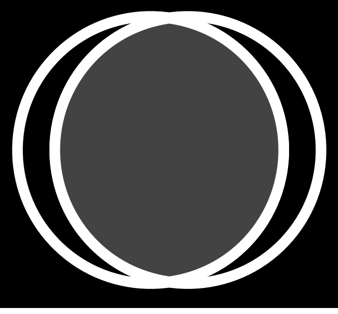


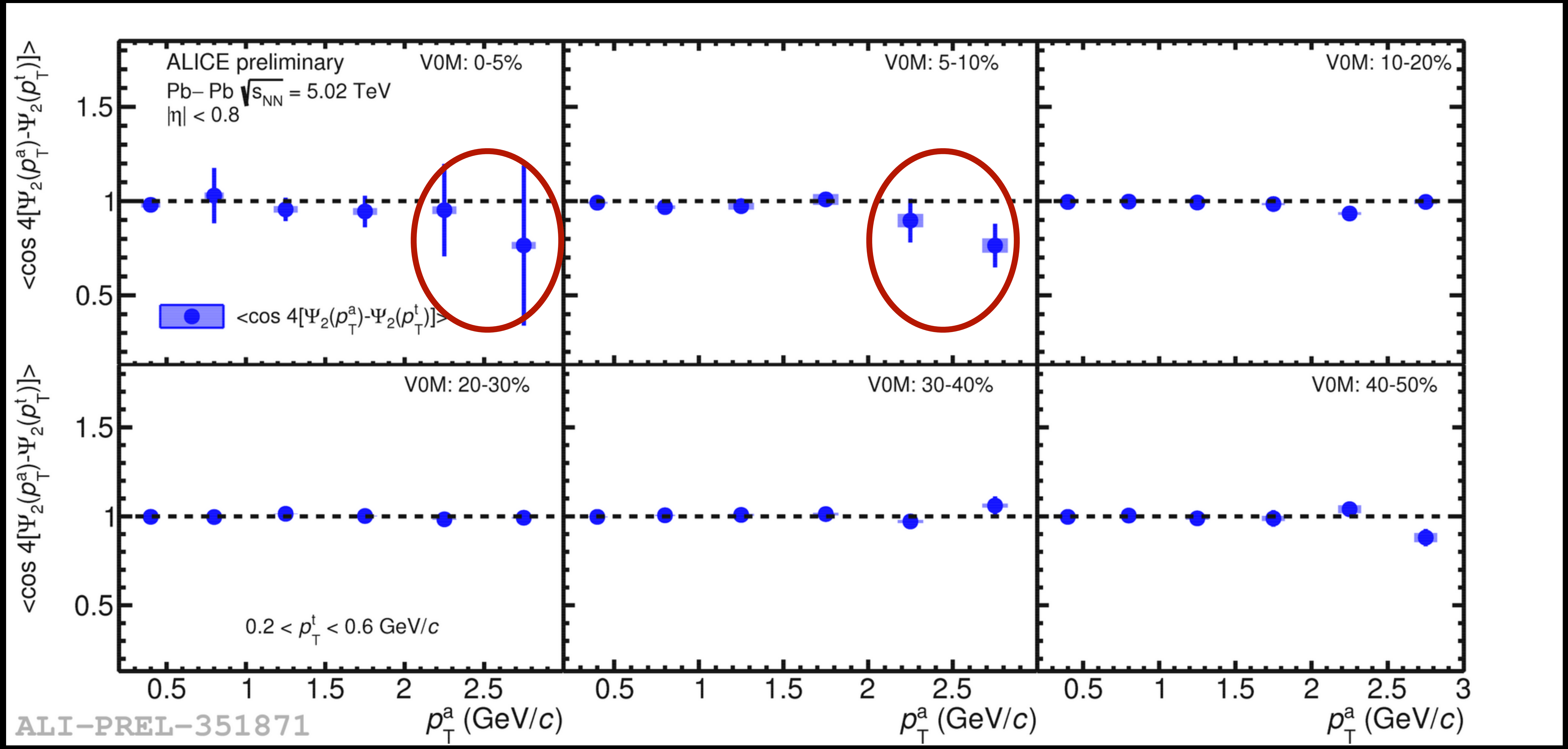
$C(\Psi_2^a, \Psi_2^t)$

Does not depend on v_n

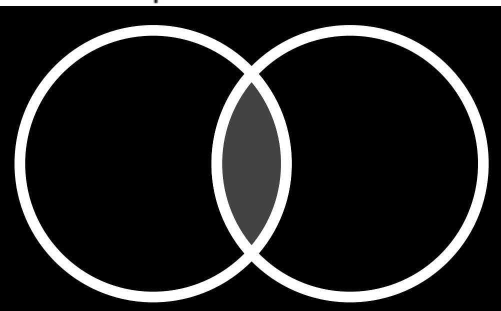
- Newly proposed observable:

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





- If $C(\Psi_n^a, \Psi_n^t) < 1$, indication of flow angle fluctuation
- No deviation from unity within uncertainties
  - Hint of $C(\Psi_n^a, \Psi_n^t) < 1$ in central collisions
- Suggests that flow angle does not significantly fluctuate in peripheral collisions



Correlations of flow

- Symmetric cumulant

$$NSC(n,m) = \frac{\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle}{\langle v_n^2\rangle\langle v_m^2\rangle}$$

- Probes correlation between v_n and v_m

- Differential study might bring better sensitivity to IC and QGP properties

$$NSC(n,m_{p_\mathrm{T}}) = \frac{\langle v_n^2\ v_m(p_\mathrm{T})^2\rangle - \langle v_n^2\rangle\langle v_m(p_\mathrm{T})^2\rangle}{\langle v_n^2\rangle\langle v_m(p_\mathrm{T})^2\rangle}$$

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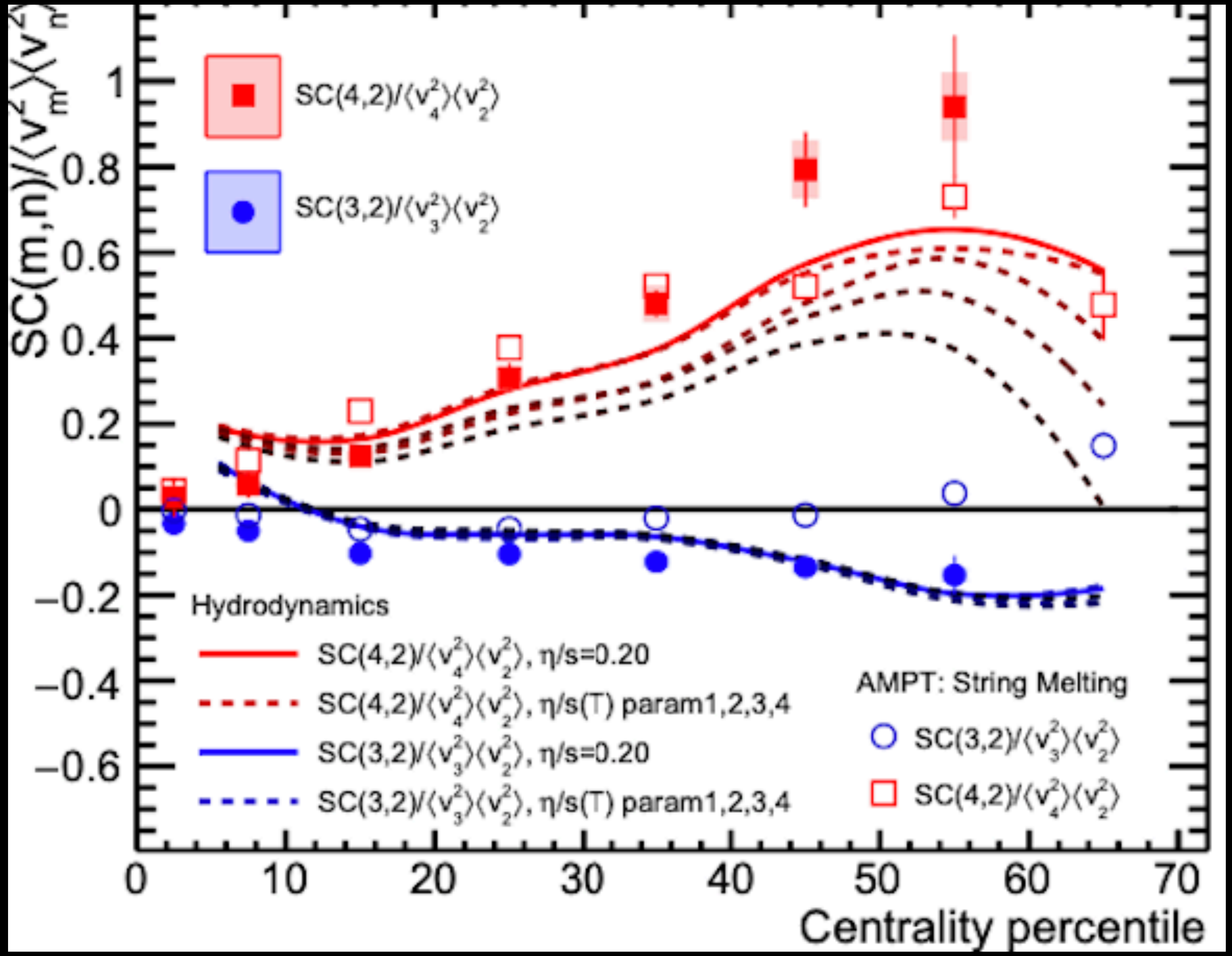
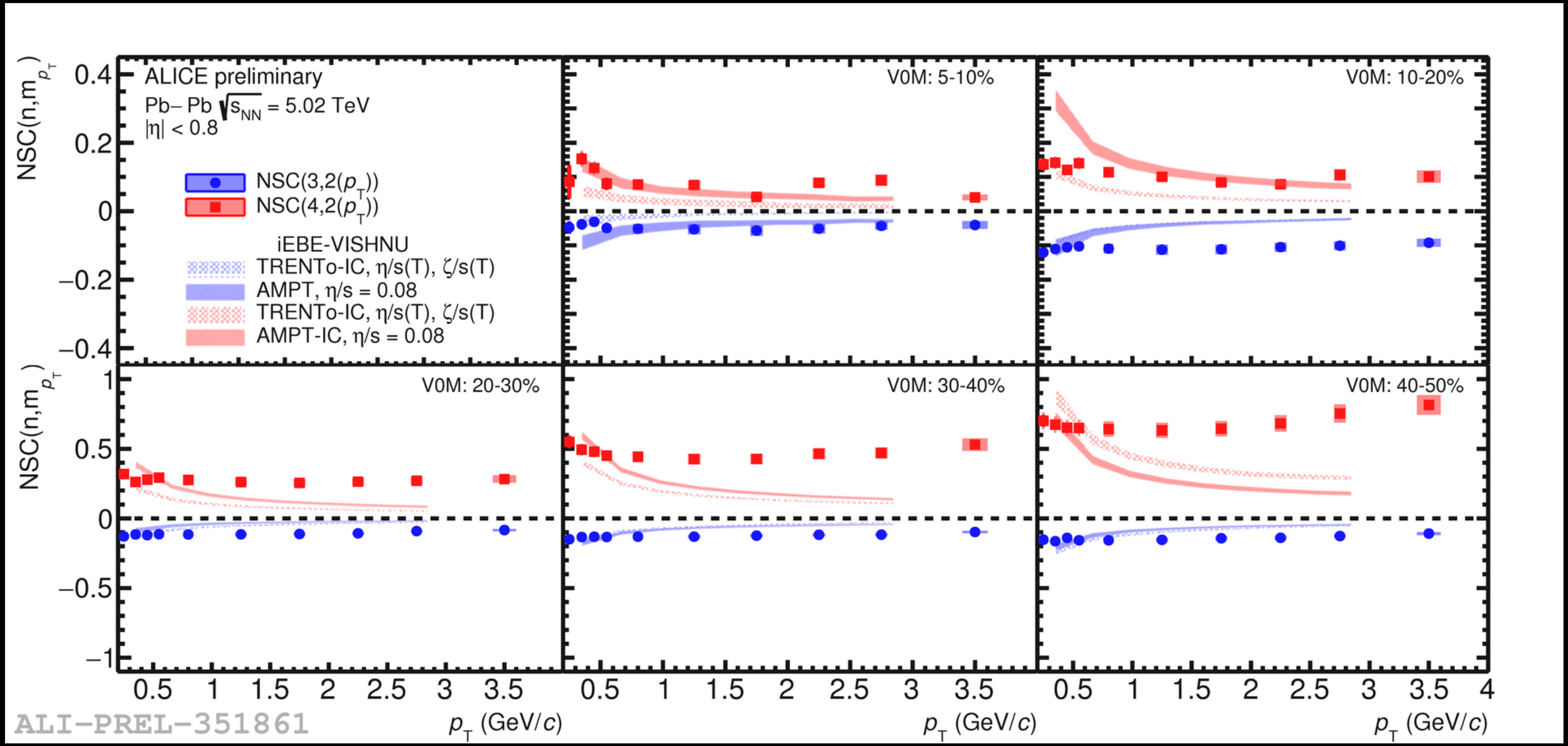
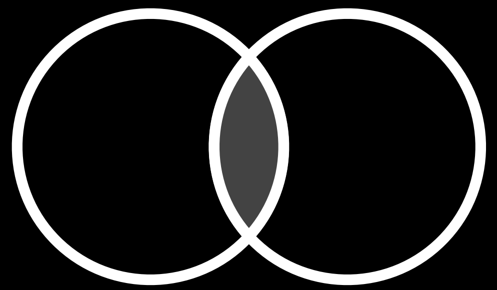


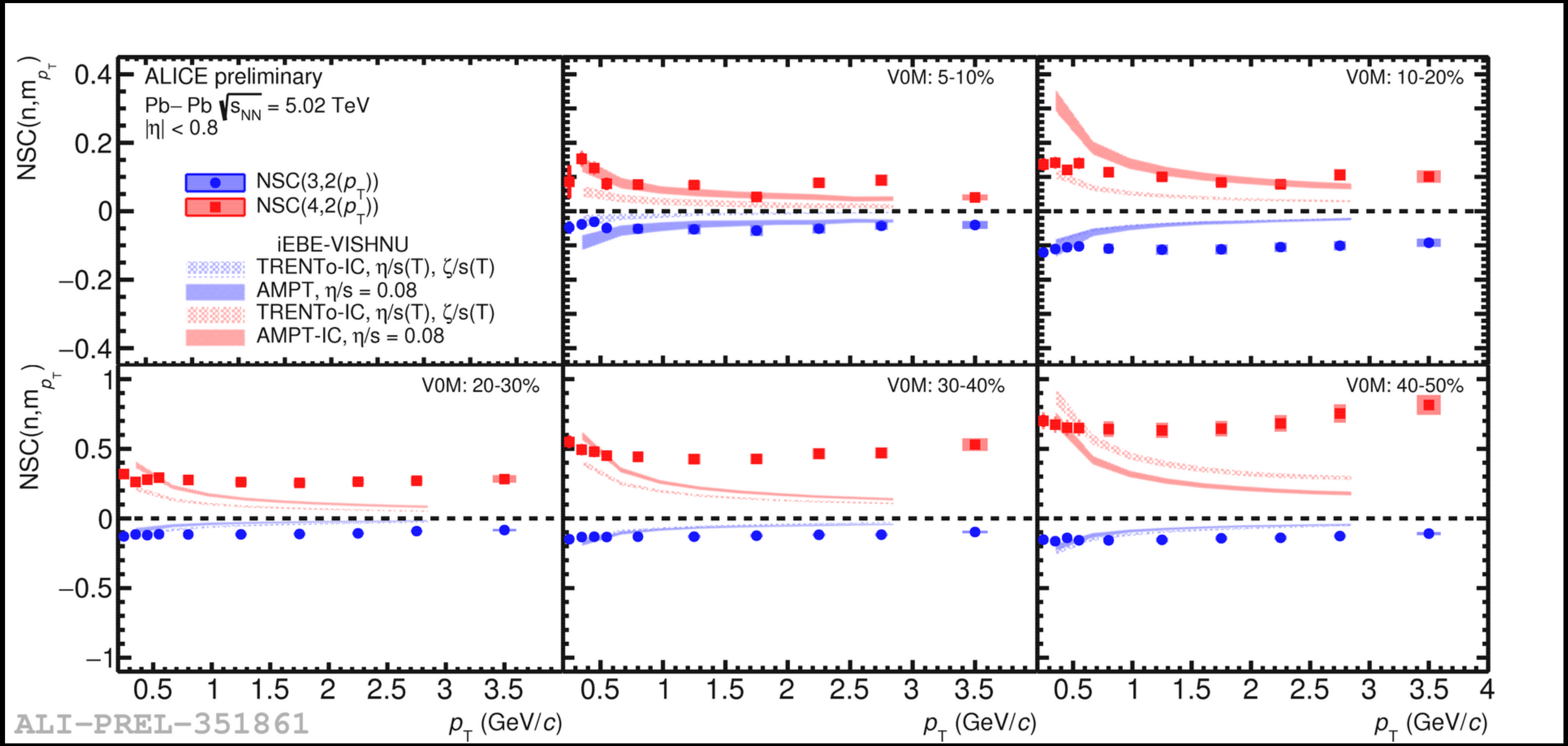
$NSC(n, m_{p_T})$



ALICE preliminary
Pb– Pb $\sqrt{s_{NN}}$ = 5.02 TeV
$|\eta|$ < 0.8
NSC(3,2(p_T))
NSC(4,2(p_T))
iEBE-VISHNU
TRENTo-IC, η/s(T), ζ/s(T)
AMPT, η/s = 0.08
TRENTo-IC, η/s(T), ζ/s(T)
AMPT-IC, η/s = 0.08
V0M: 5-10%
V0M: 10-20%
V0M: 20-30%
V0M: 30-40%
V0M: 40-50%
NSC(n,m$_{p_T}$)
p_T (GeV/c)
ALI-PREL-351861

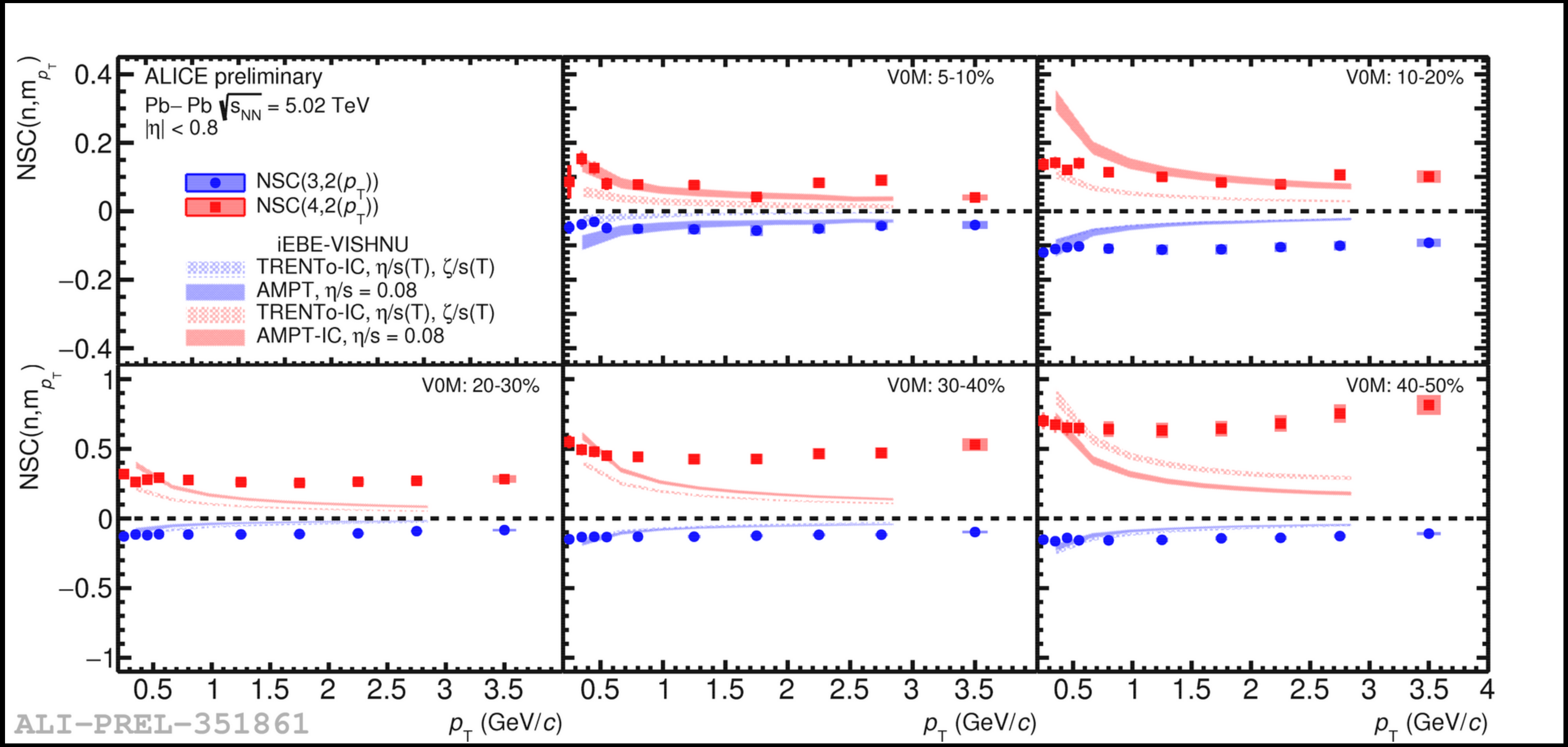


$NSC(n, m_{p_T})$



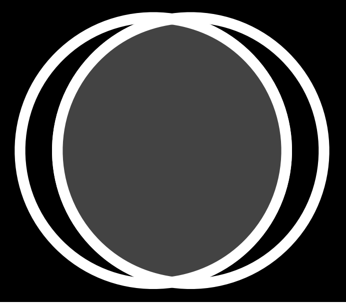
- $NSC(3,2_{p_T})$ and $NSC(4,2_{p_T})$ mostly constant with p_T

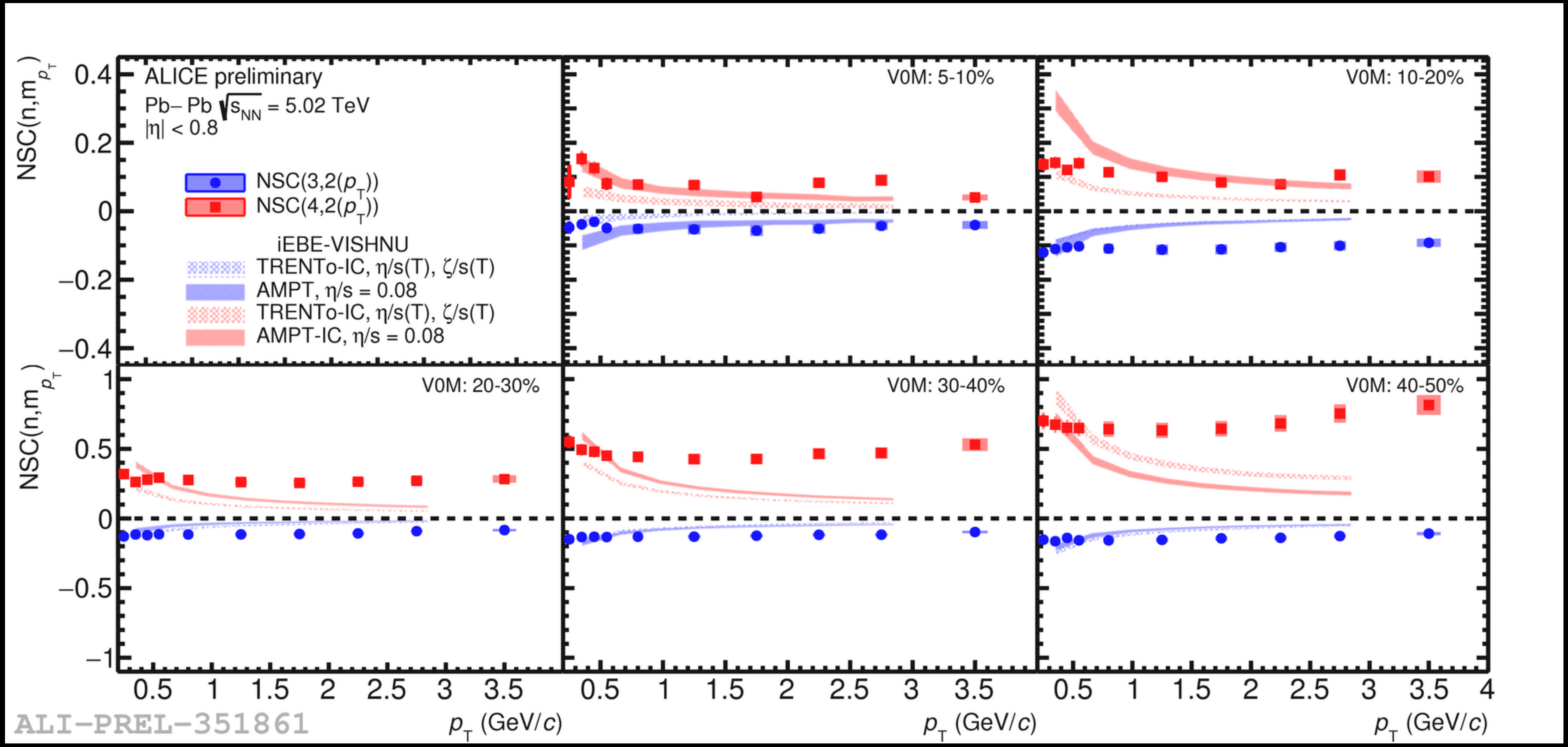
$NSC(n, m_{p_T})$



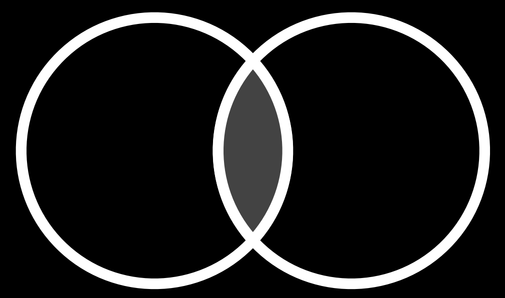
- $NSC(3,2_{p_T})$ and $NSC(4,2_{p_T})$ mostly constant with p_T
- v_4 and v_2 correlated

$NSC(n, m_{p_T})$

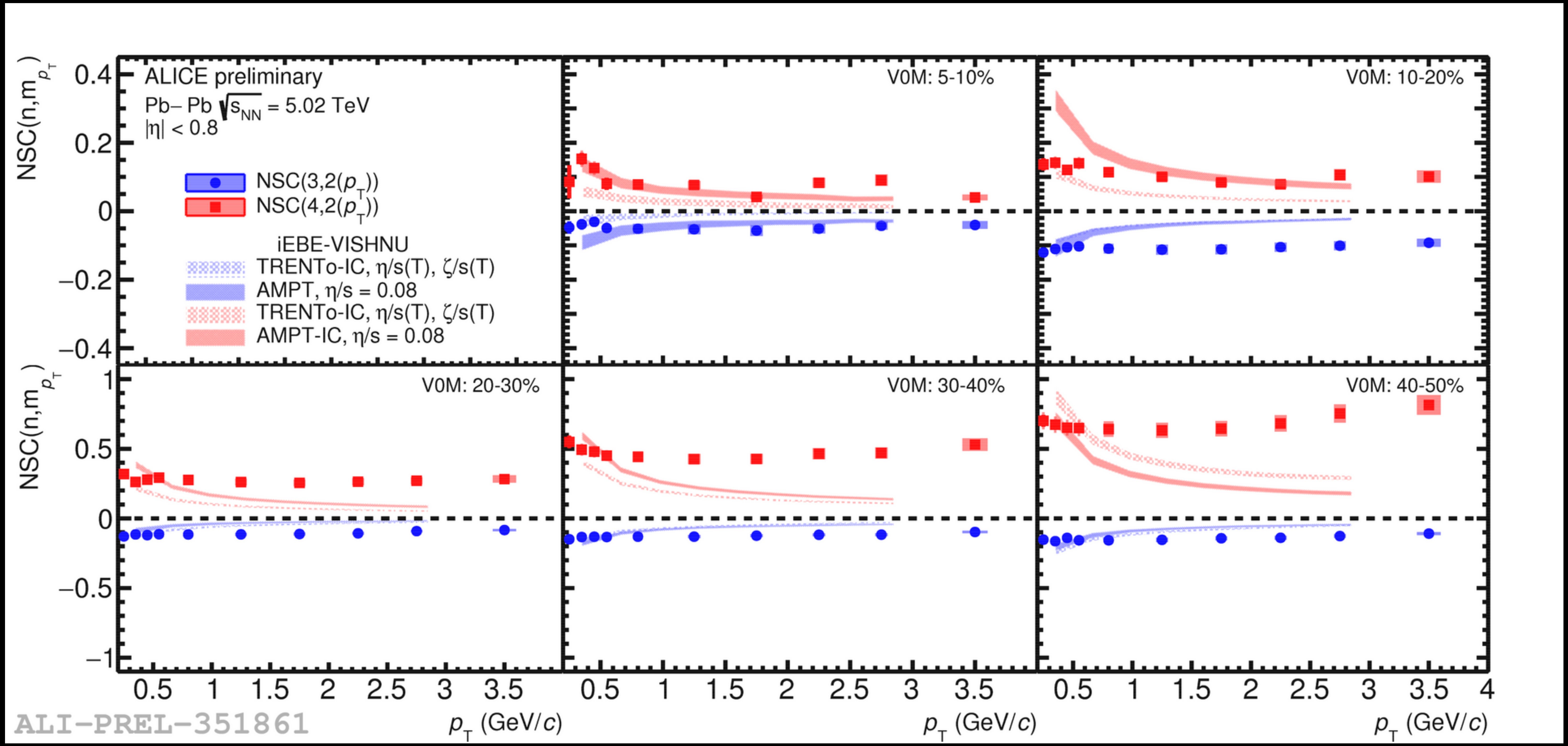




- $NSC(3,2_{p_T})$ and $NSC(4,2_{p_T})$ mostly constant with p_T
- v_4 and v_2 correlated
- v_3 and v_2 anti-correlated

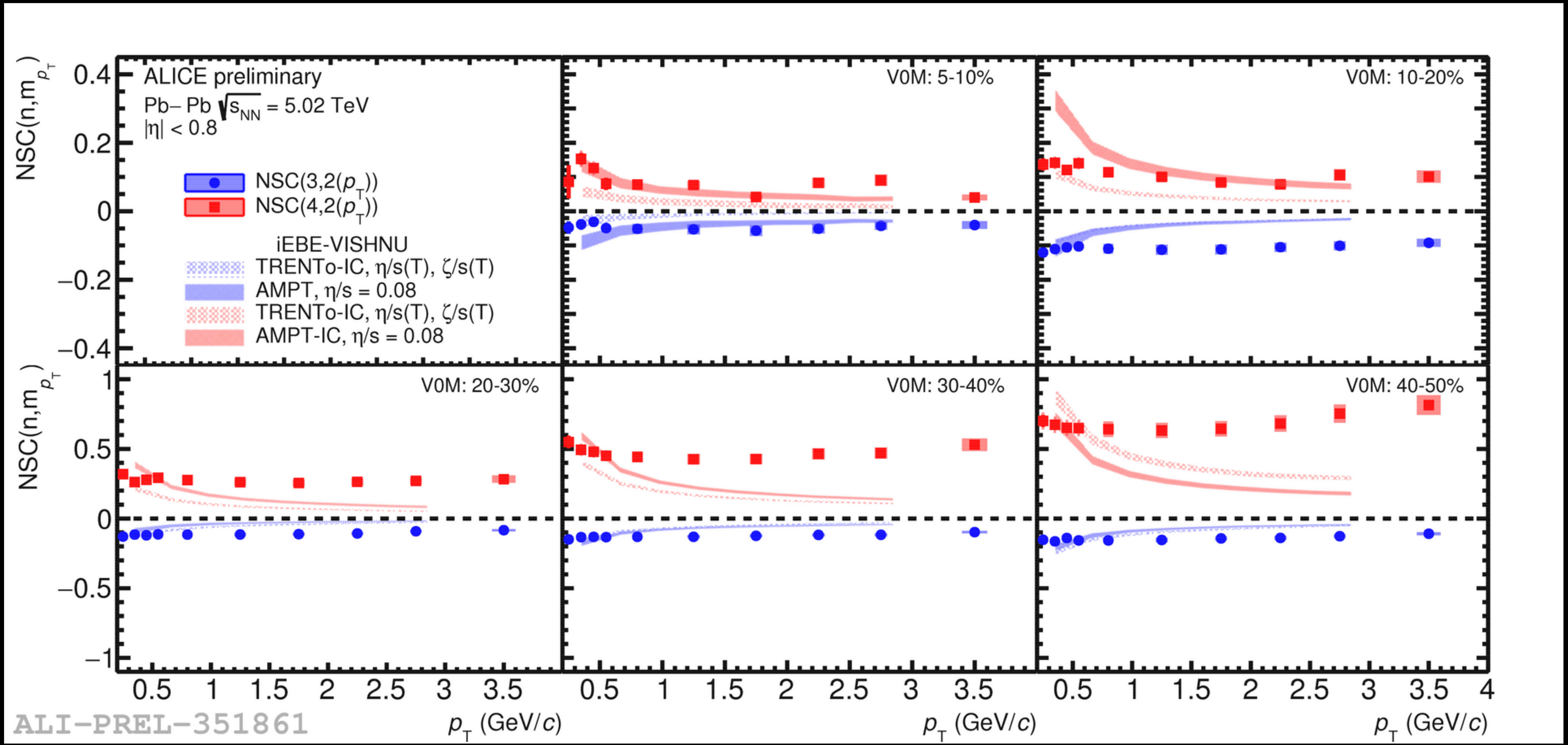


$NSC(n, m_{p_T})$



- $NSC(3,2_{p_T})$ and $NSC(4,2_{p_T})$ mostly constant with p_T
- v_4 and v_2 correlated
- v_3 and v_2 anti-correlated
- Strength of the correlation not p_T-dependent

$NSC(n, m_{p_\mathrm{T}})$



- $NSC(3,2_{p_\mathrm{T}})$ and $NSC(4,2_{p_\mathrm{T}})$ mostly constant with p_T
- v_4 and v_2 correlated
- v_3 and v_2 anti-correlated
- Strength of the correlation not p_T-dependent
- Hydro caculations mostly underestimate $NSC(n, m_{p_\mathrm{T}})$

Summary

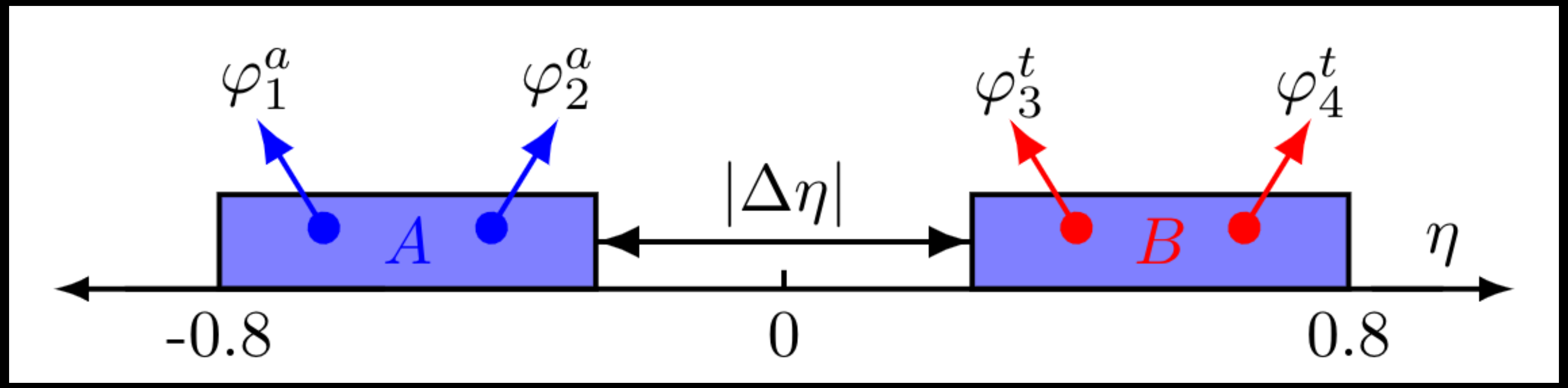
- Precision measurements show p_{T}-dependent V_2 fluctuations
- No indication of V_3 and V_4 fluctuations, if they exist they are within few percent
- Flow angle fluctuations not significant with the available statistics
- Differential study of symmetric cumulants show p_{T}-independent $NSC(3,2_{p_{\mathrm{T}}})$ and $NSC(4,2_{p_{\mathrm{T}}})$
- These results will further advance our understanding of flow and constrain hydrodynamic models

Thank you for your attention!

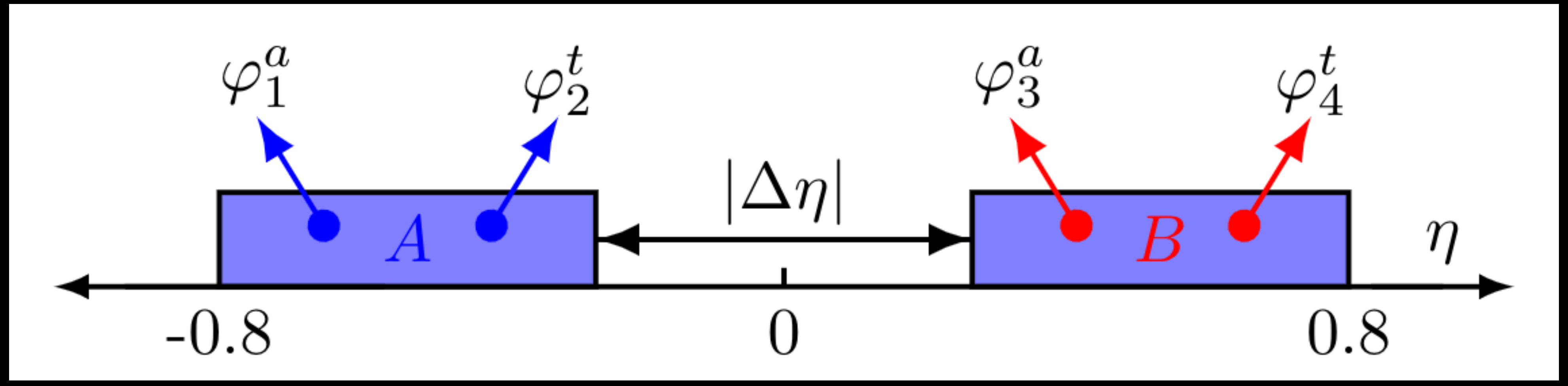
$C(\Psi_n^a, \Psi_n^t)$

- Two particles from p_{T}^a and two from p_{T}^t

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



$$= \frac{\langle v_n(p_{\mathrm{T}}^a)^2 \; v_n(p_{\mathrm{T}}^t)^2 \;\; \cos 2n[\Psi_n(p_{\mathrm{T}}^a) - \Psi_n(p_{\mathrm{T}}^t)]\rangle}{\langle v_n(p_{\mathrm{T}}^a)^2 \; v_n(p_{\mathrm{T}}^t)^2\rangle}$$



- Assuming non-flow is the same:

$$C(\Psi_n^a, \Psi_n^t) \approx \langle \cos 2n[\Psi_n(p_{\mathrm{T}}^a) - \Psi_n(p_{\mathrm{T}}^t)]\rangle$$

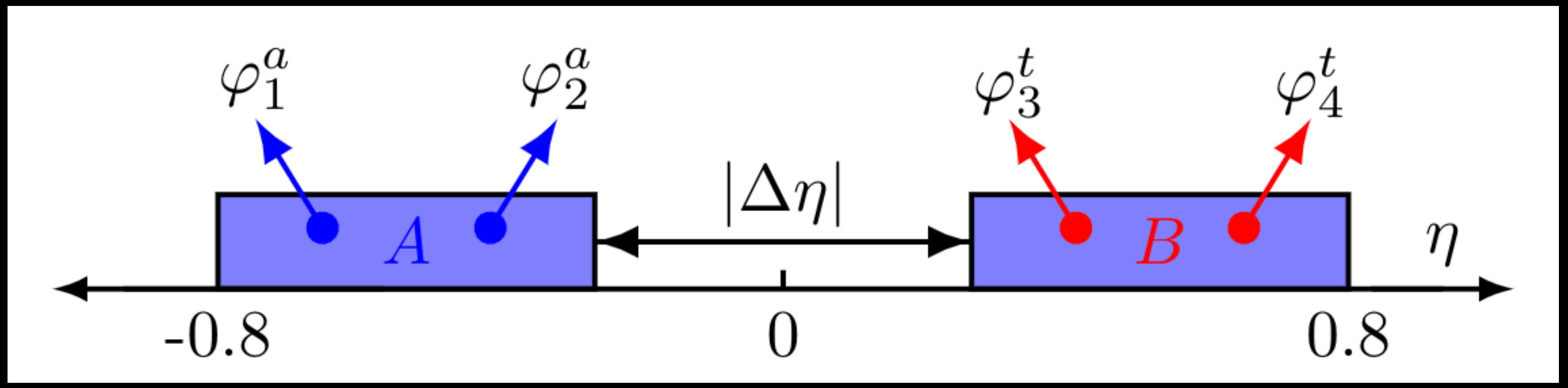
- $C(\Psi_n^a, \Psi_n^t) < 1$

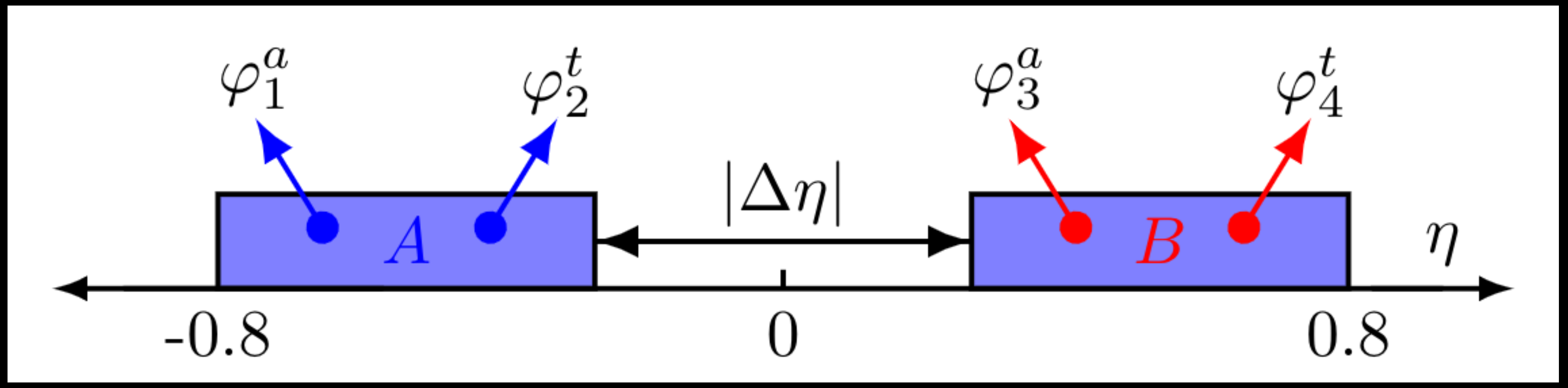
$C(\Psi_n^a, \Psi_n^t)$

- Two particles from p_{T}^a and two from p_{T}^t

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

$$= \frac{\langle v_n(p_{\mathrm{T}}^a)^2 \; v_n(p_{\mathrm{T}}^t)^2 \; \cos 2n[\Psi_n(p_{\mathrm{T}}^a) - \Psi_n(p_{\mathrm{T}}^t)] \rangle}{\langle v_n(p_{\mathrm{T}}^a)^2 \; v_n(p_{\mathrm{T}}^t)^2 \rangle}$$





- Assuming non-flow is the same:

$$C(\Psi_n^a, \Psi_n^t) \approx \langle \cos 2n[\Psi_n(p_{\mathrm{T}}^a) - \Psi_n(p_{\mathrm{T}}^t)] \rangle$$

- $C(\Psi_n^a, \Psi_n^t) < 1$

Decorrelation of flow angle at p_{T}^a and p_{T}^t