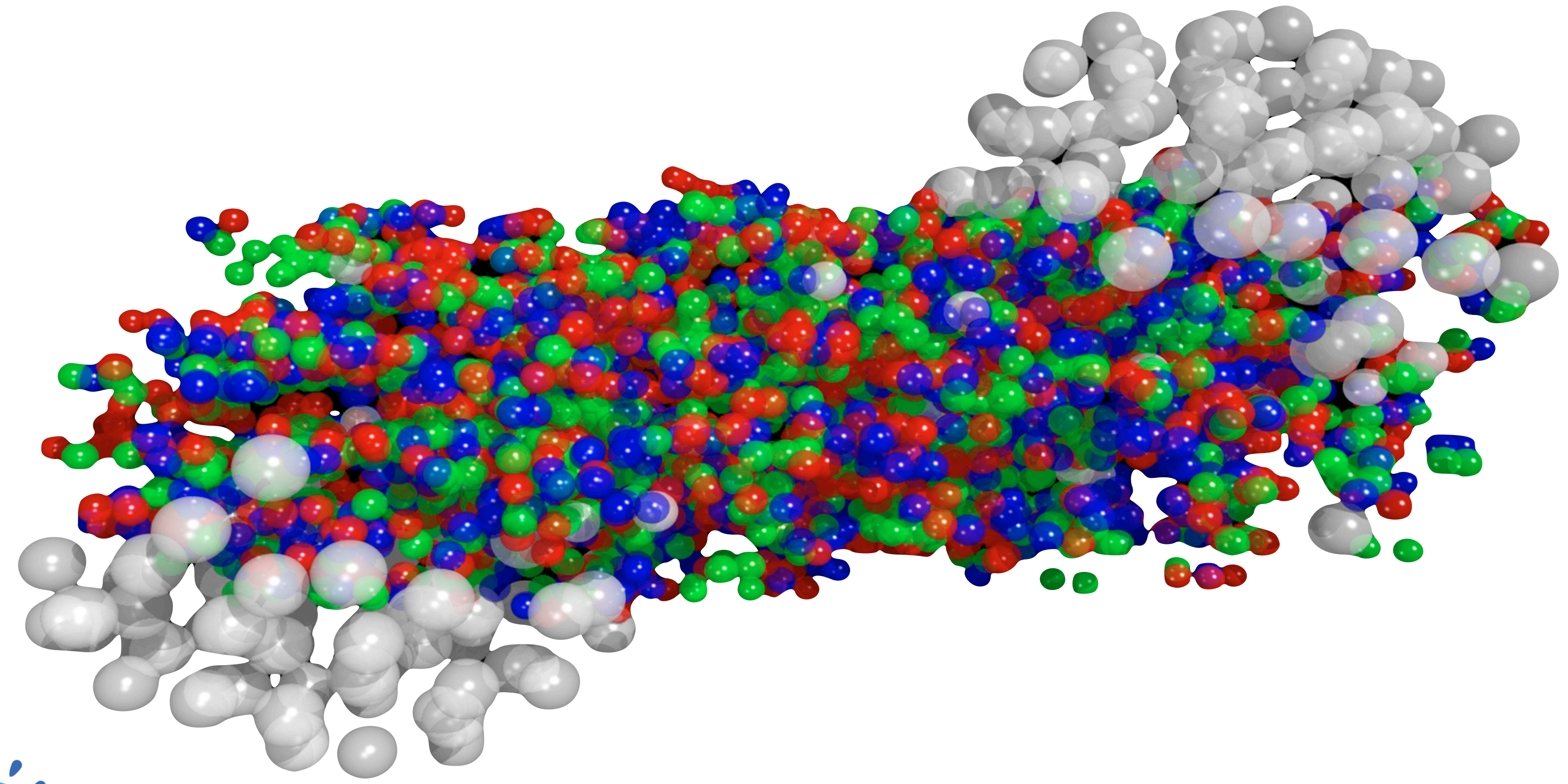
Insights into the initial conditions and evolution of hadronic collisions with flow observables

Strangeness in Quark Matter, Busan, Republic of Korea
Vytautas Vislavicius, Lund University, Sweden
June 16th, 2022

SQM 2022

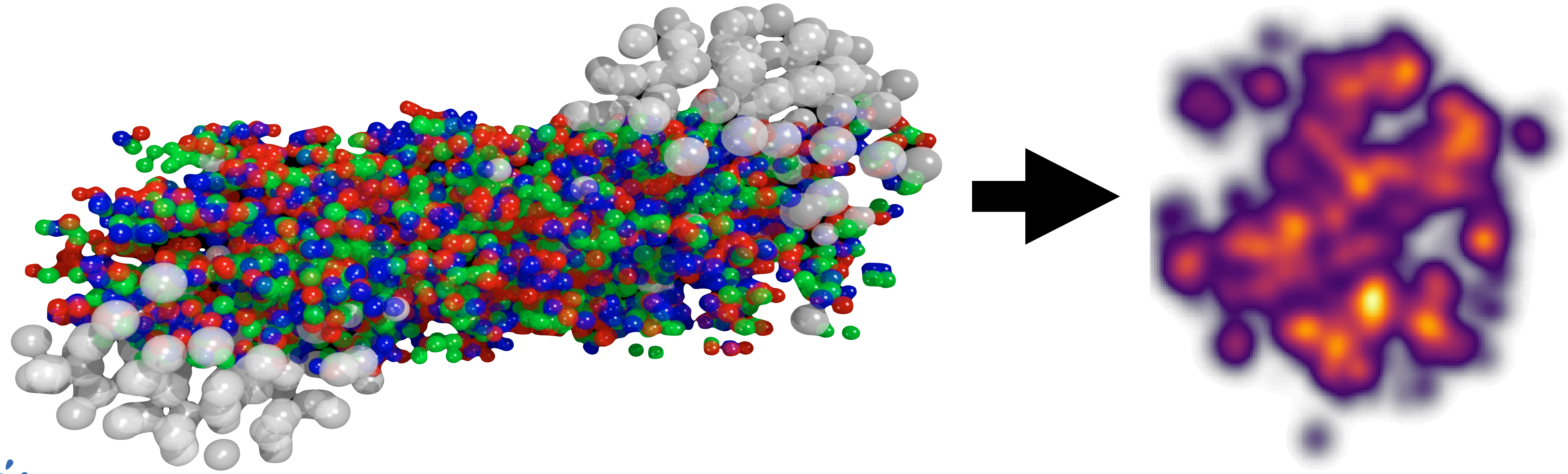
LUND UNIVERSITY

From collisions to measurements



From collisions to measurements

- Overlap between colliding nuclei:
  ⇛ Initial state, geometry & its fluctuations

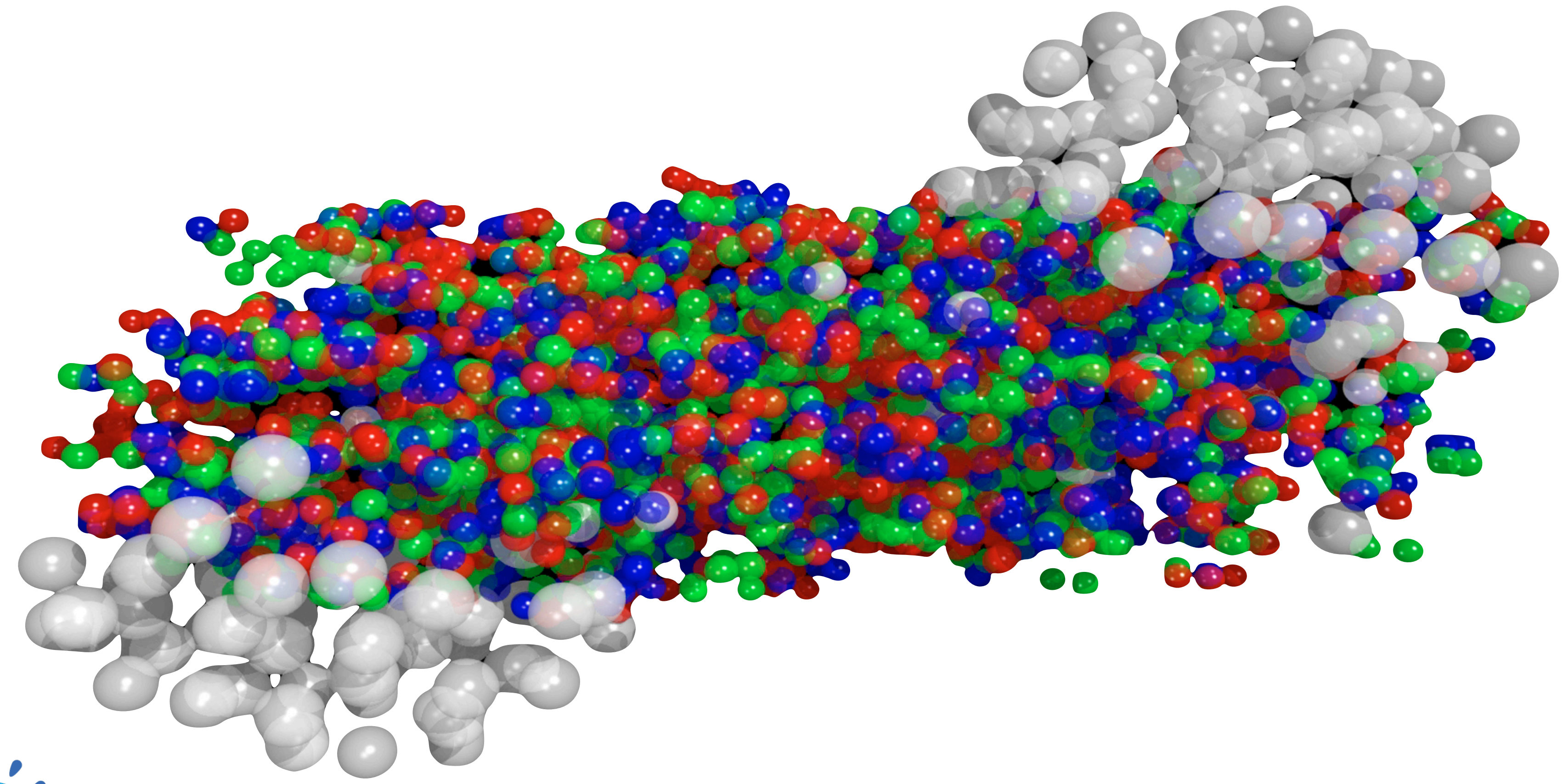


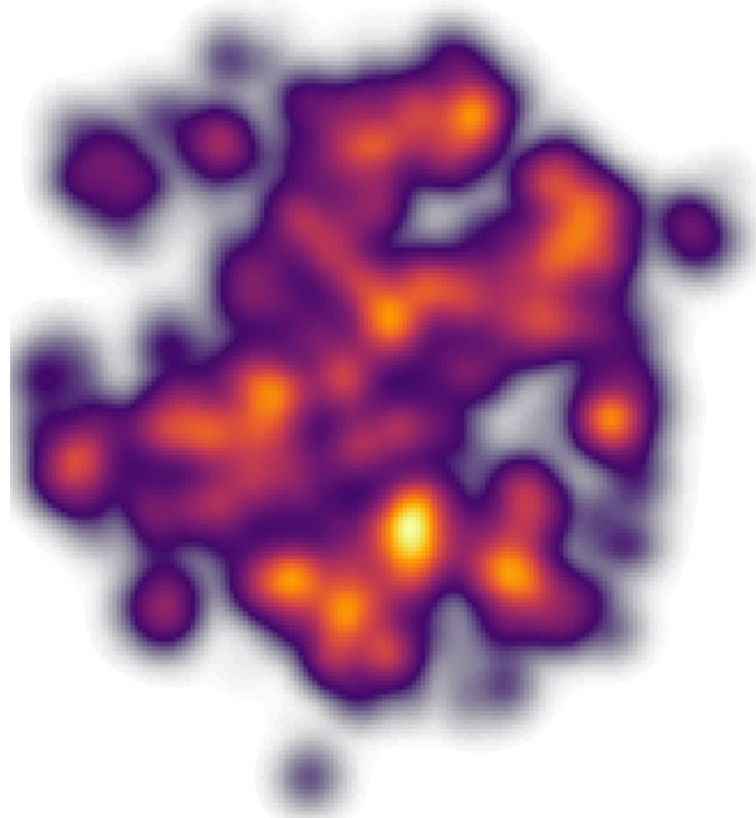
Jonah Bernhard, Scott Moreland and Steffen Bass, Nature Phys. 15 (2019) 11, 1113-1117

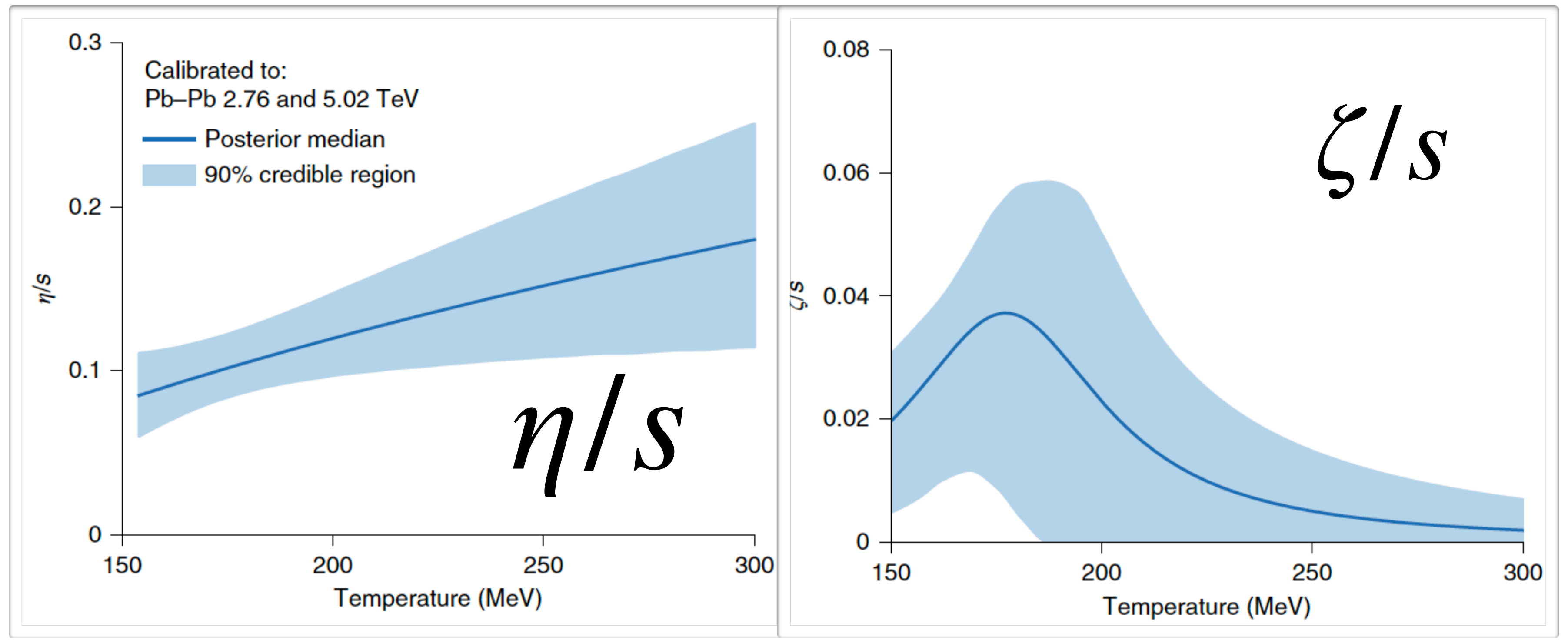
From collisions to measurements

- Overlap between colliding nuclei:
  ⇛ Initial state, geometry & its fluctuations

- Hydrodynamic expansion of QGP:
  ⇛ Radial and anisotropic flow, sensitive to initial state and properties of QGP





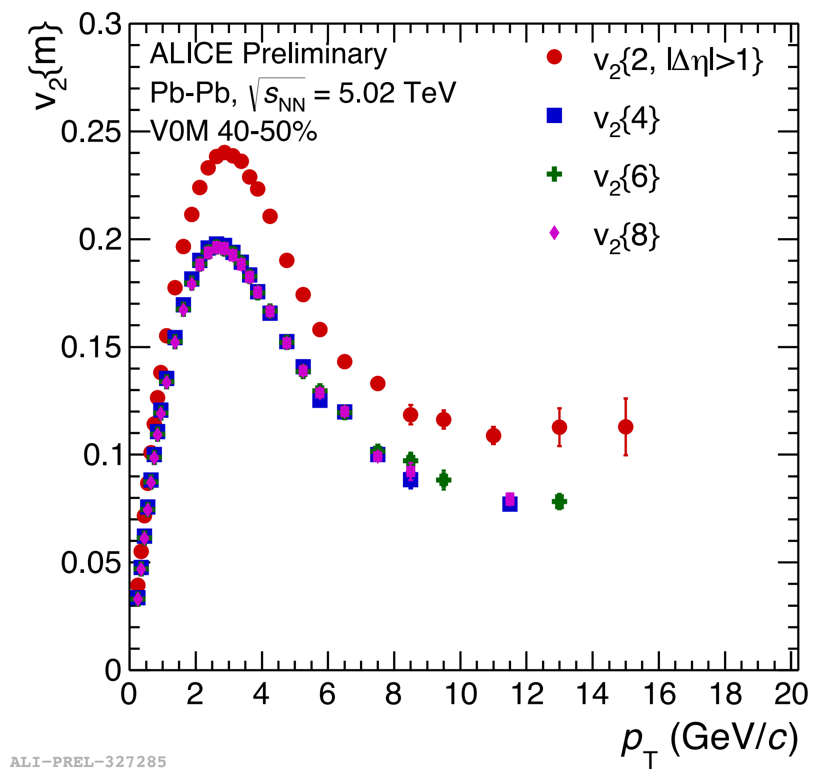


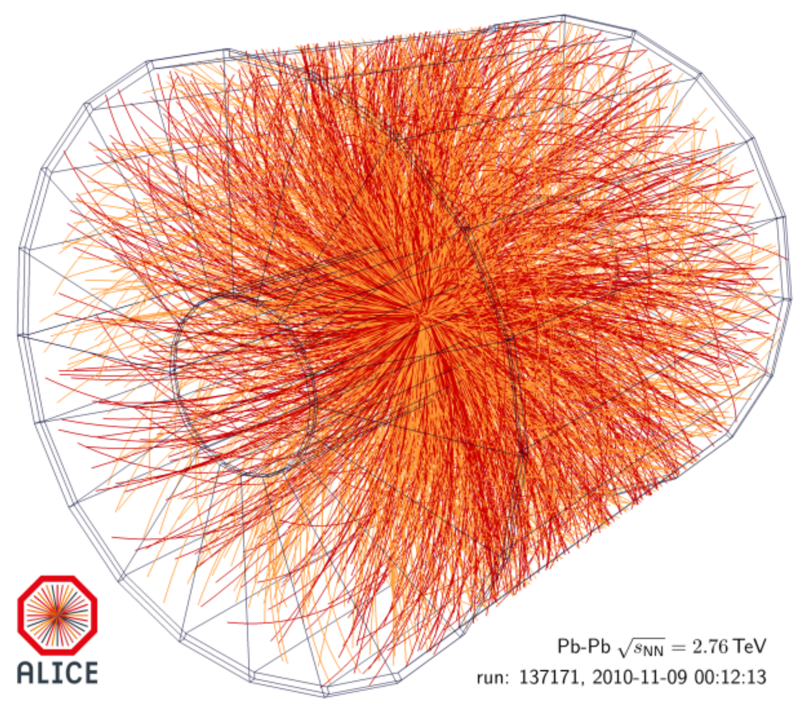
Jonah Bernhard, Scott Moreland and Steffen Bass, Nature Phys. 15 (2019) 11, 1113-1117

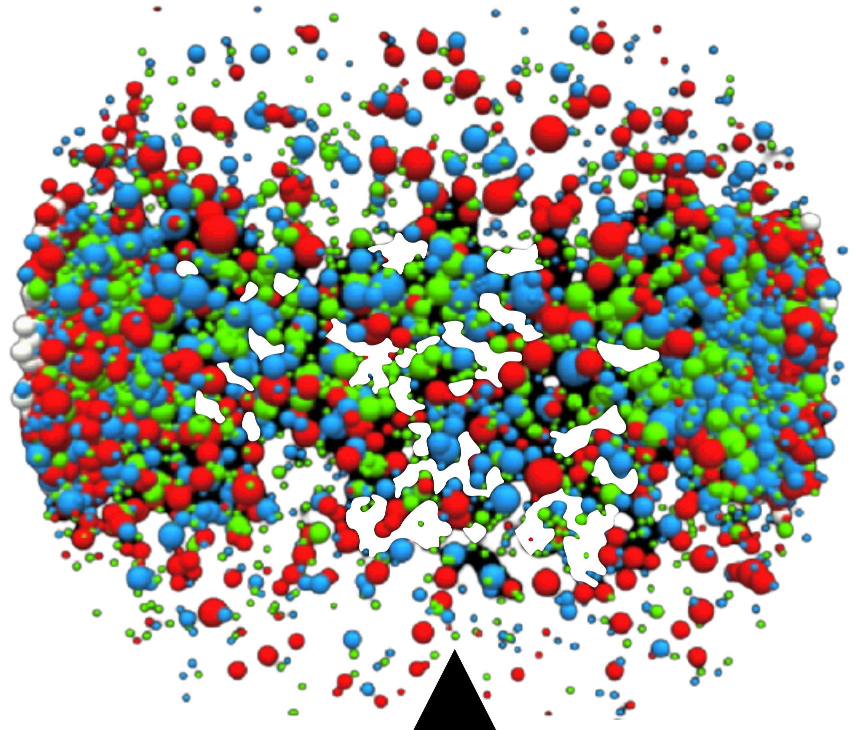
From collisions to measurements

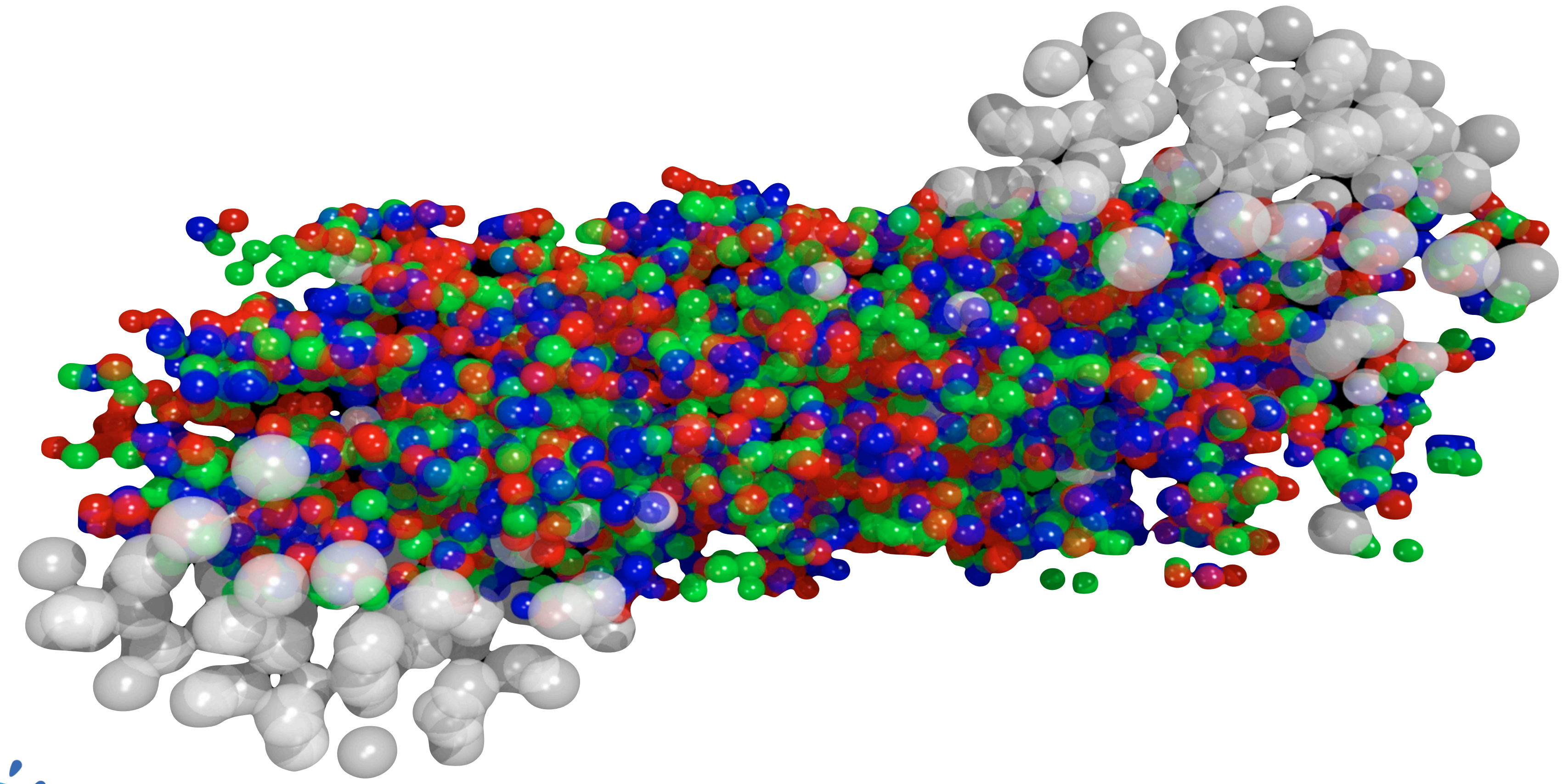
- Overlap between colliding nuclei:
  ⇛ Initial state, geometry & its fluctuations

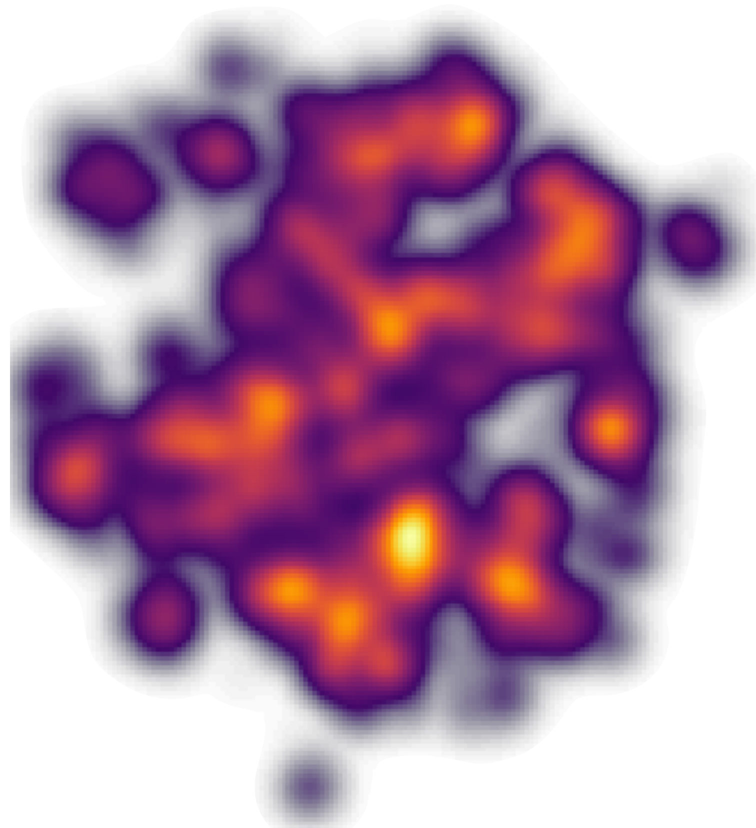
- Hydrodynamic expansion of QGP:
  ⇛ Radial and anisotropic flow, sensitive to initial state and properties of QGP

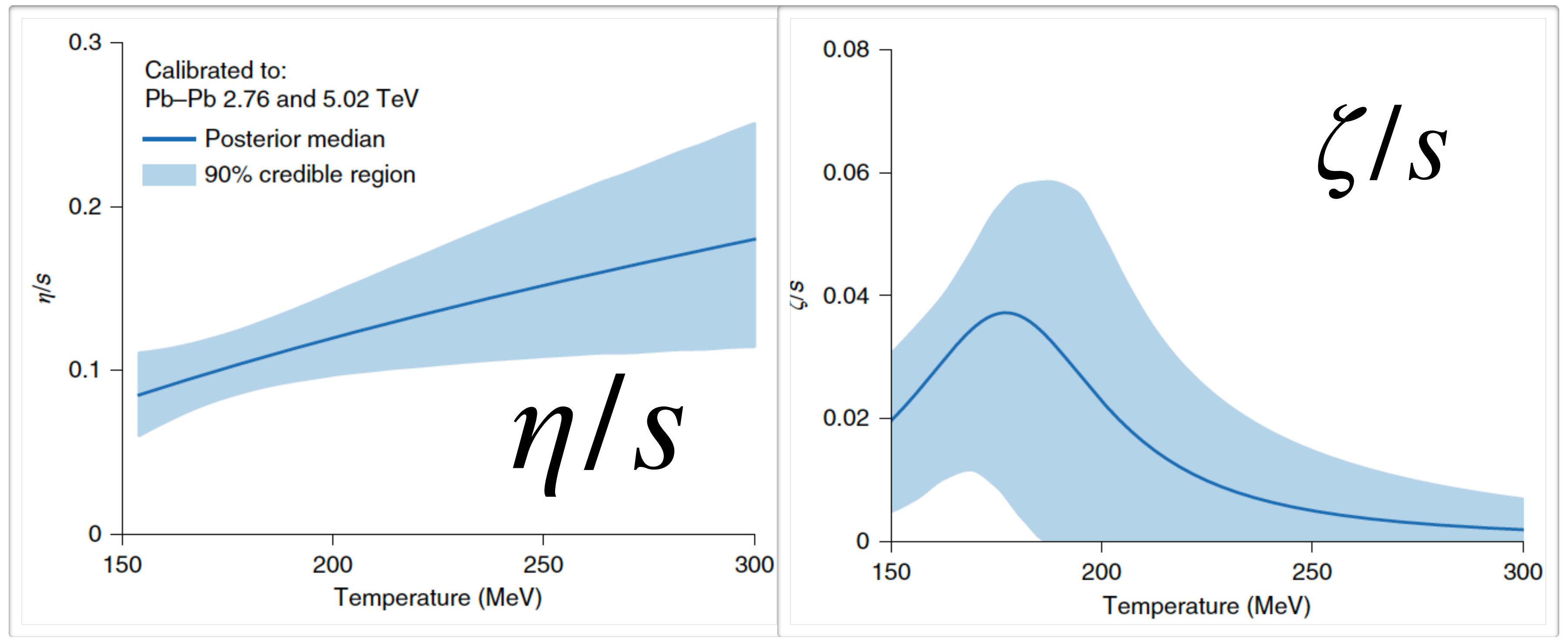










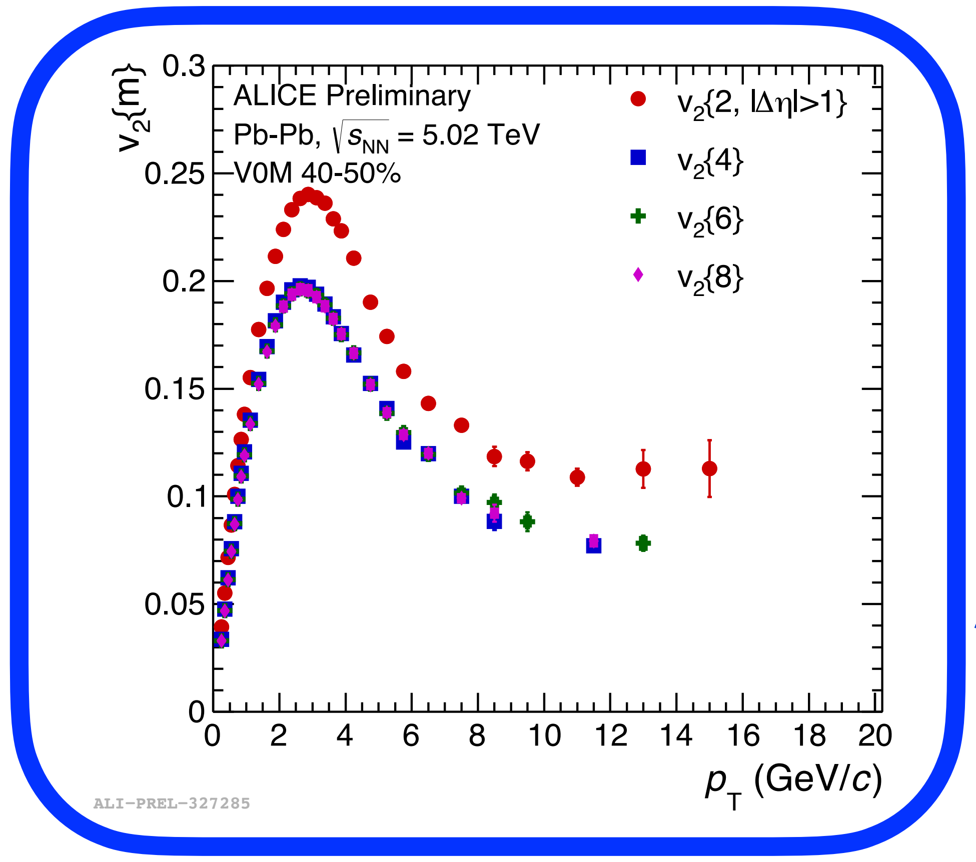


Jonah Bernhard, Scott Moreland and Steffen Bass, Nature Phys. 15 (2019) 11, 1113-1117

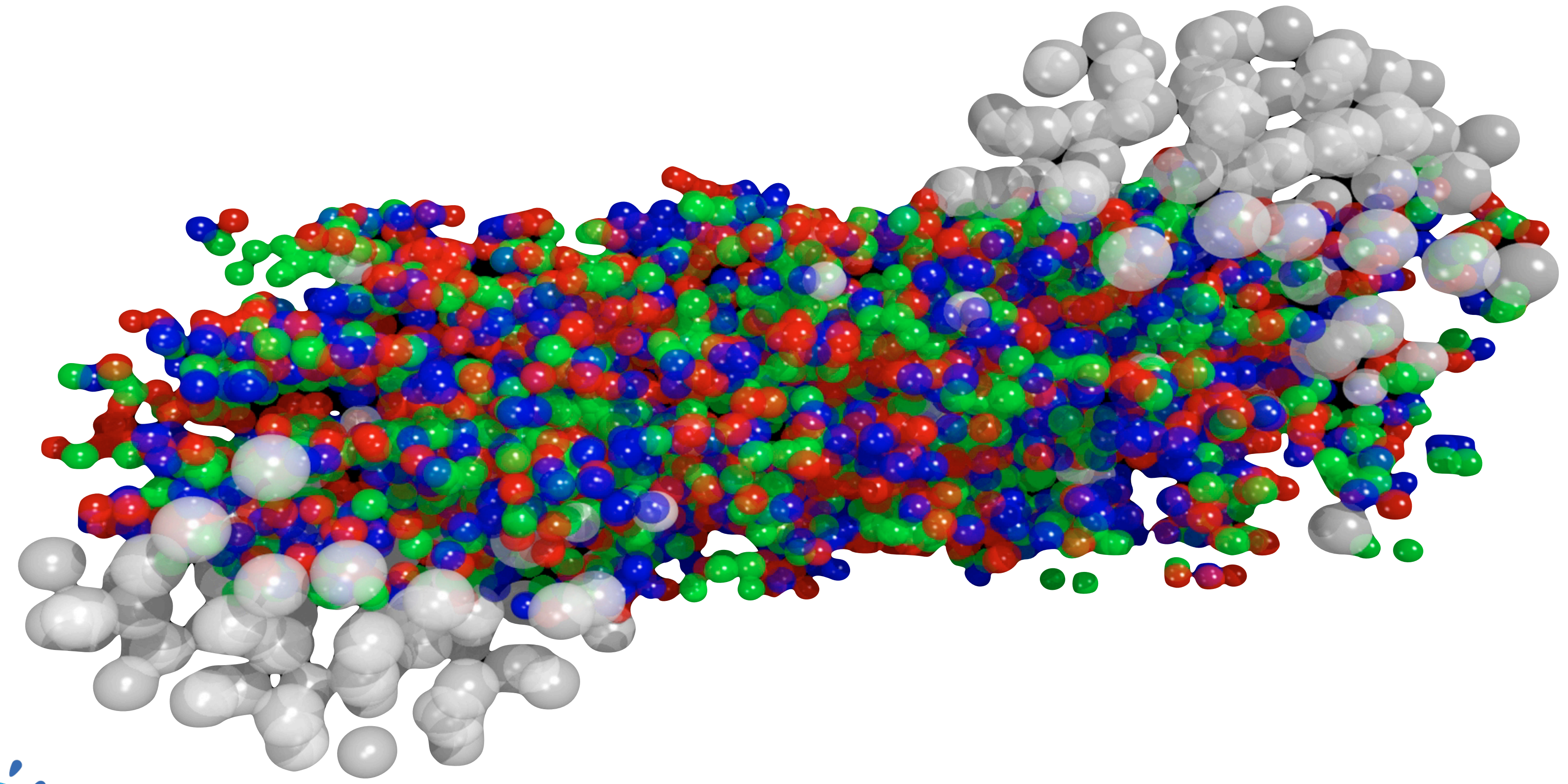
From collisions to measurements

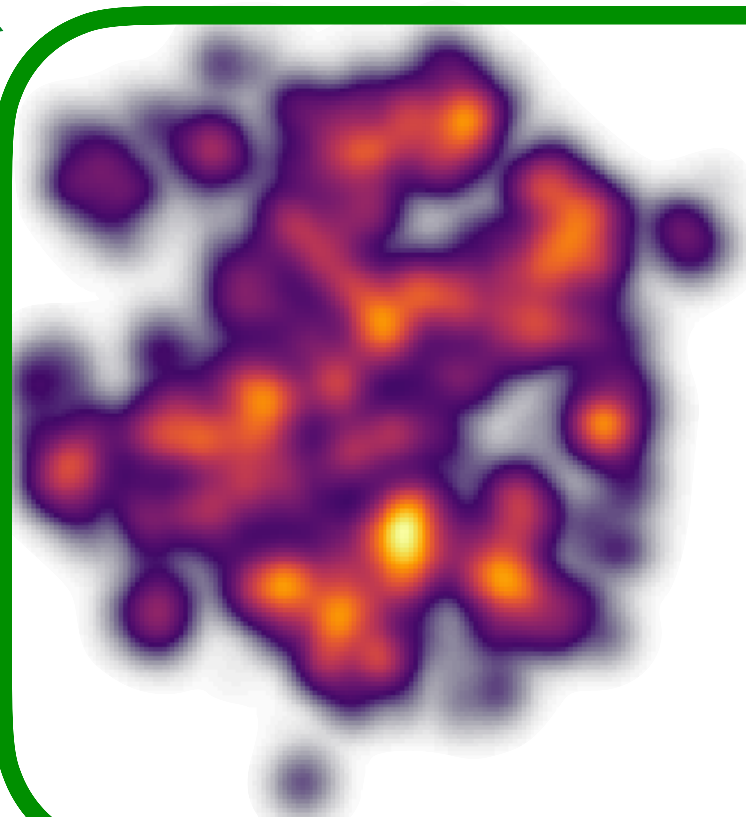
- Overlap between colliding nuclei:
  ⇛ Initial state, geometry & its fluctuations

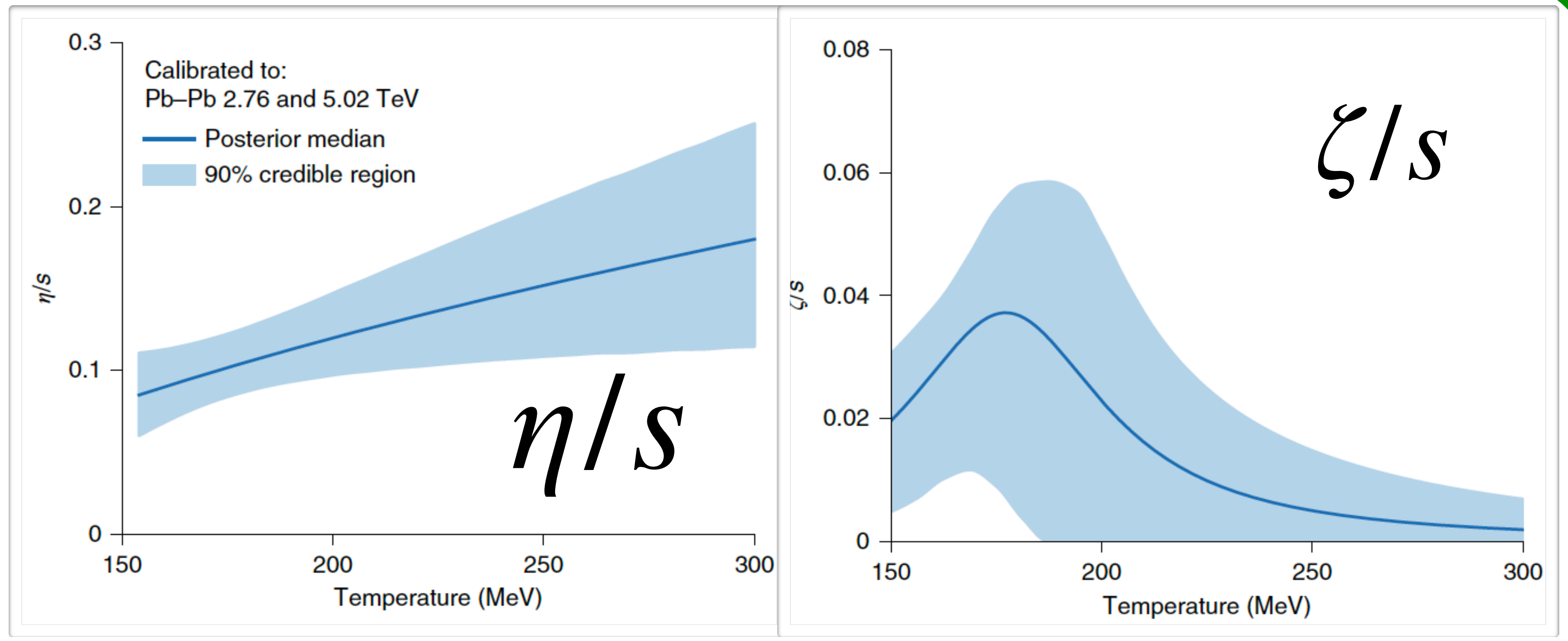
- Hydrodynamic expansion of QGP:
  ⇛ Radial and anisotropic flow, sensitive to initial state and properties of QGP



What can we learn about the initial state and properties of QGP from the measurements of radial and anisotropic flow?



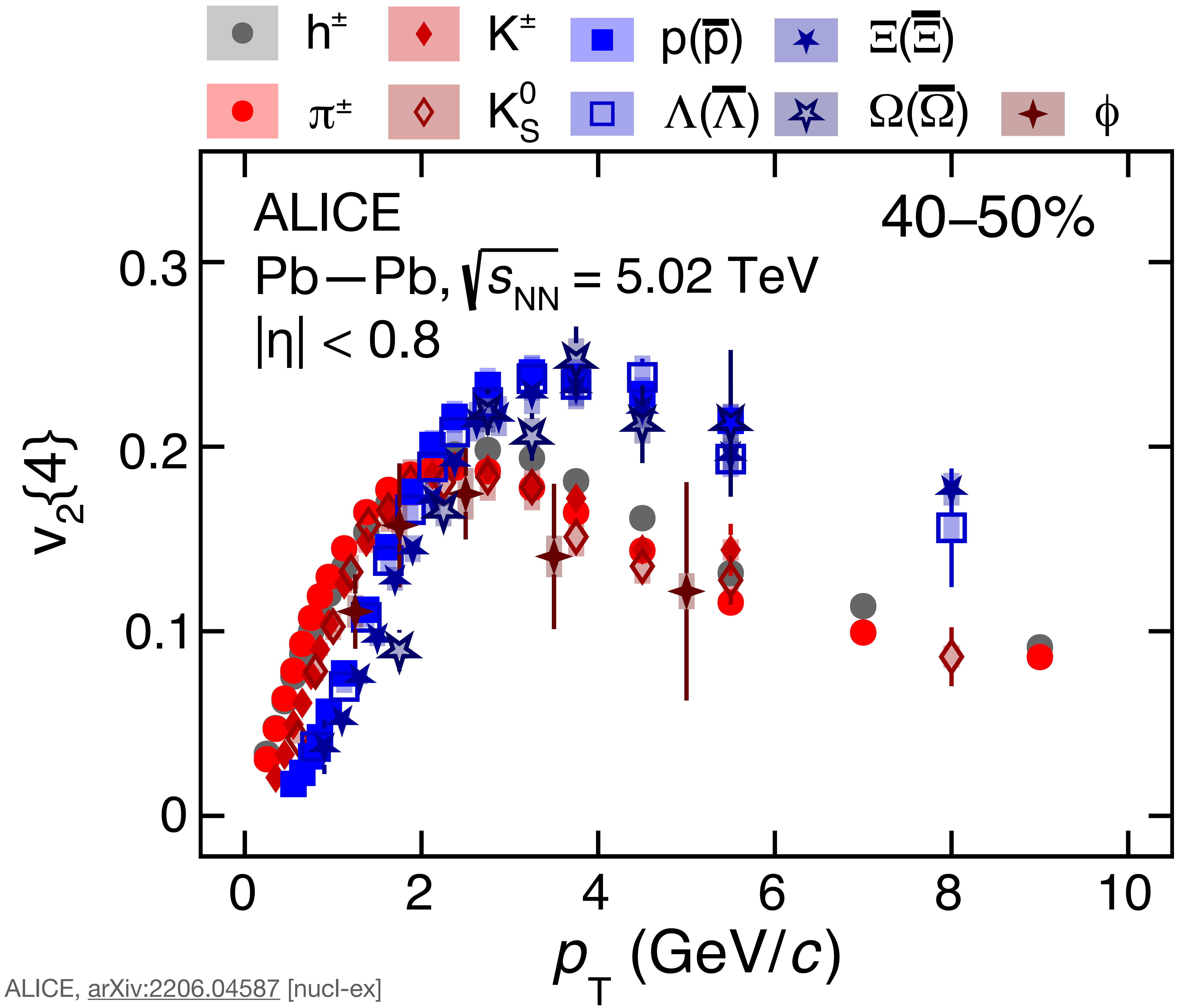




Jonah Bernhard, Scott Moreland and Steffen Bass, Nature Phys. 15 (2019) 11, 1113-1117

v_2 of baryons and mesons in Pb—Pb

- Measurements of v_2:
  ⇛ Baryon/meson ordering and crossing



ALICE, arXiv:2206.04587 [nucl-ex]

v_2 of baryons and mesons in Pb—Pb

comparison to hydro model

- Measurements of v_2:

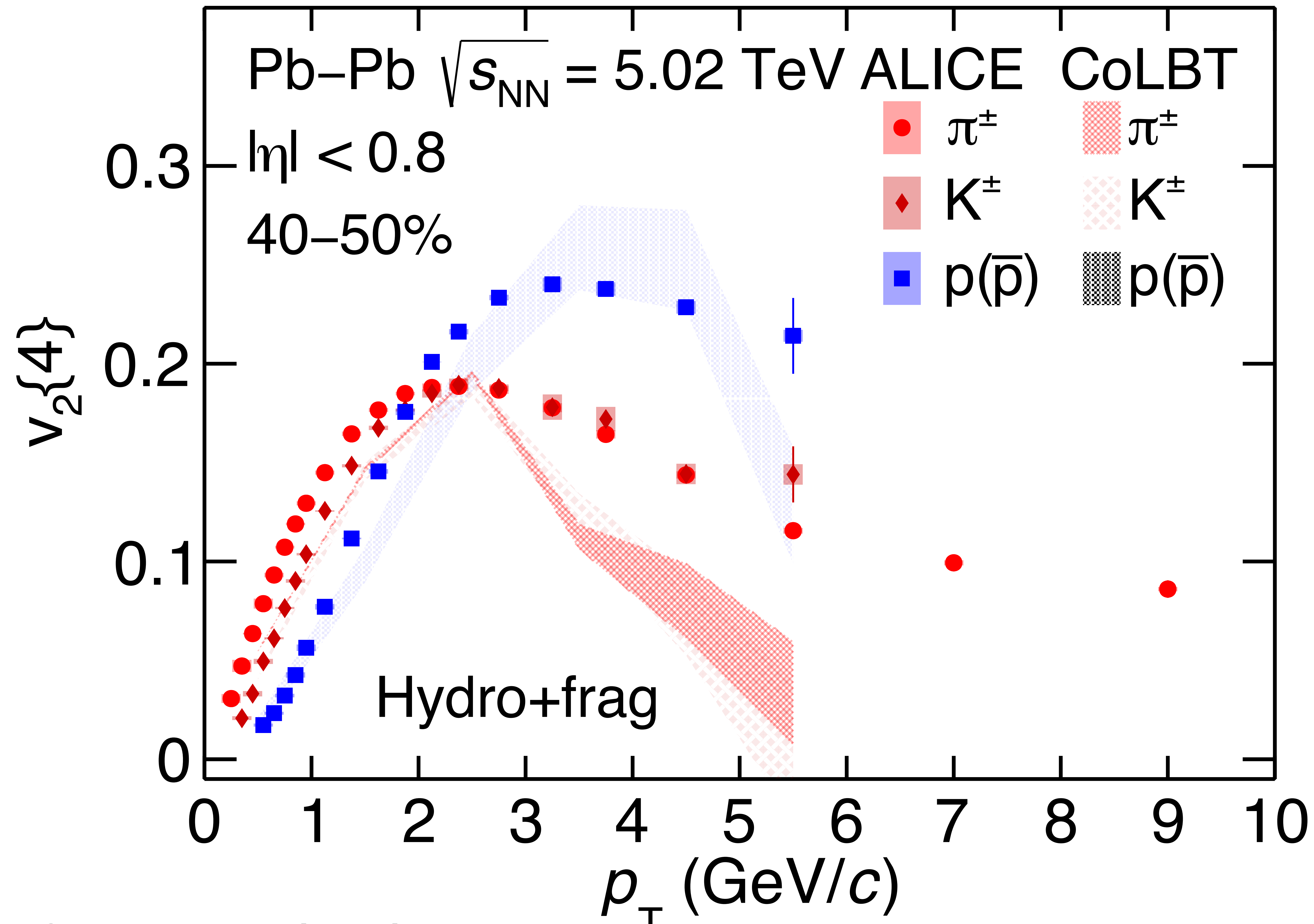
  ⇛ Baryon/meson ordering and crossing

- Hydro + fragmentation:

  ✗ Underestimates the data in most cases

  ✓ Baryon/meson crossing predicted

  ⇛ Arises from species-dependent p_T cut, where fragmentation dominates over hydro

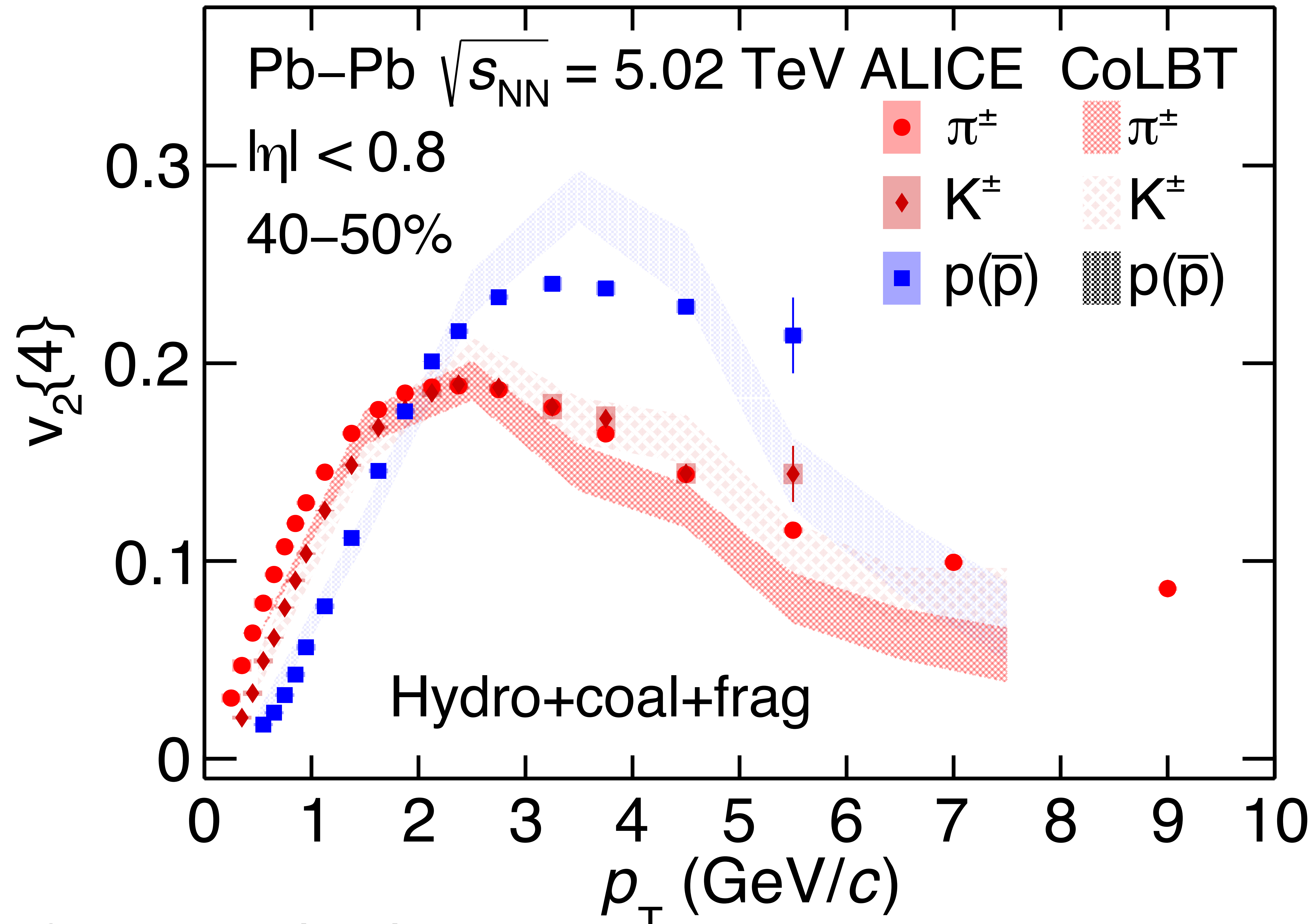


ALICE, arXiv:2206.04587 [nucl-ex]

v_2 of baryons and mesons in Pb—Pb

comparison to hydro model

- Measurements of v_2:
  ⇛ Baryon/meson ordering and crossing
- Hydro + fragmentation:
  ✗ Underestimates the data in most cases
  ✓ Baryon/meson crossing predicted
  ⇛ Arises from species-dependent p_T cut, where fragmentation dominates over hydro
- Hydro + coalescence + fragmentation:
  ✓ Significantly better description of data
- But crossing is not unique to coalescence!



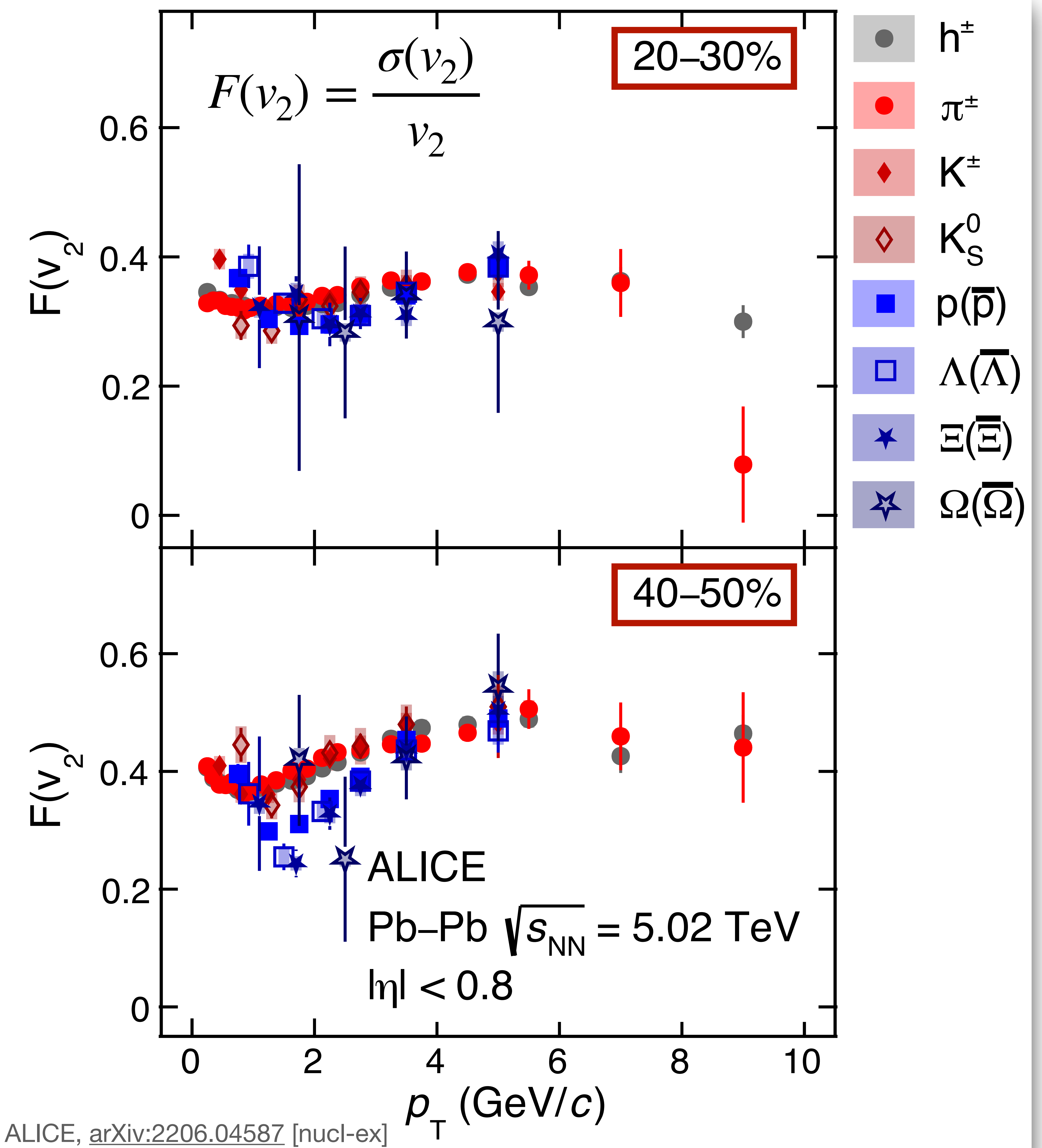
ALICE, arXiv:2206.04587 [nucl-ex]

v_2 fluctuations of baryons and mesons

in Pb—Pb collisions

- Emerging p_T dependence from central to peripheral collisions

- Baryon/meson grouping in semi-central collisions
  - ⇛ Different from that observed for v_2
  - ⇛ Could point to a different origin of this observation



ALICE, arXiv:2206.04587 [nucl-ex]

v_2 fluctuations: skewness and kurtosis

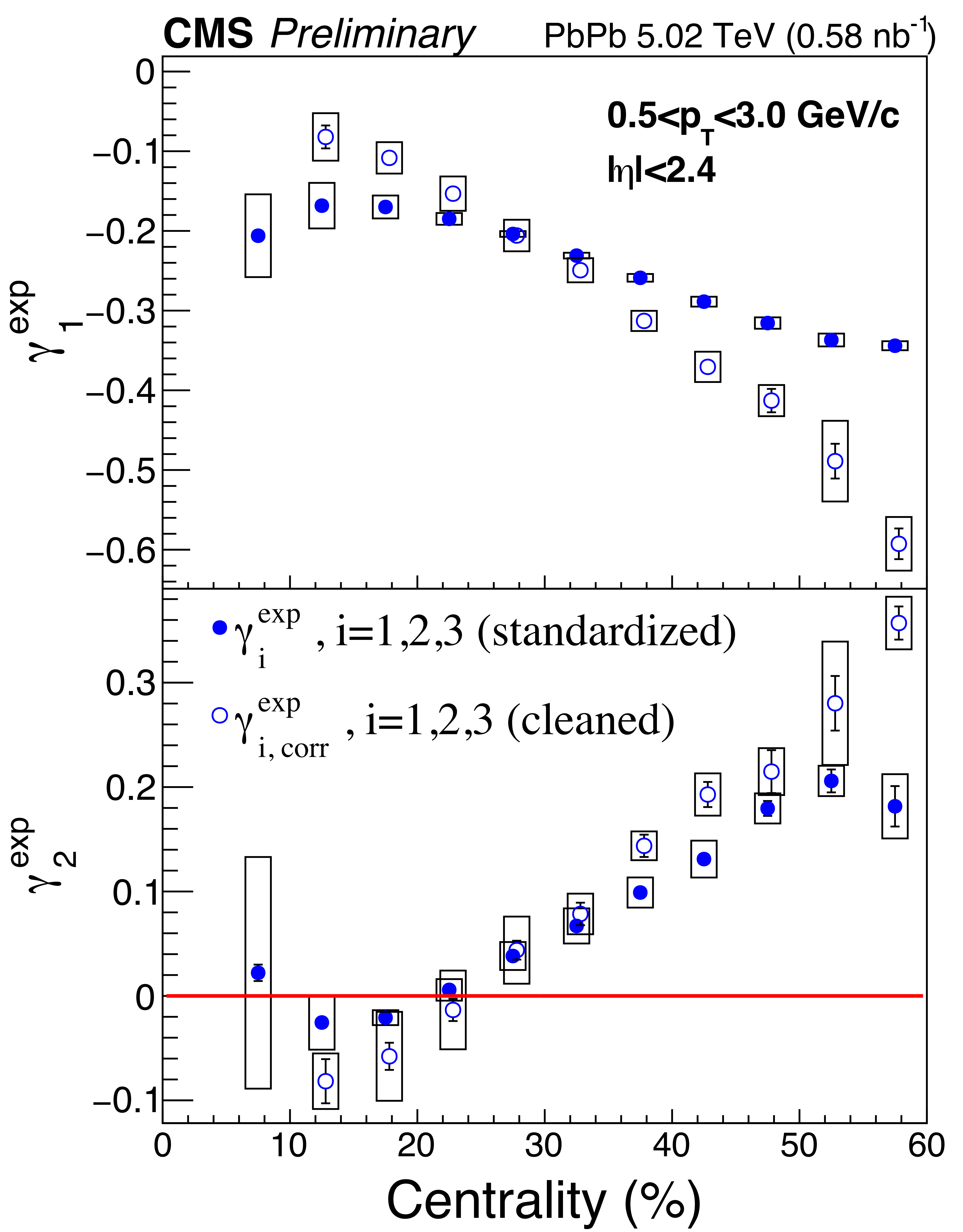
in Pb—Pb collisions

Measure v_2 with multiparticle cumulants:

⇛ Sensitive to underlying v_2 probability density function (PDF) and thus initial geometry

- Skewness (γ_1) decreasing with centrality, PDF becoming less symmetric
- Kurtosis (γ_2) increasing with centrality, tails become "fatter"

Do γ_1, γ_2 probe initial geometry exclusively?



CMS, CMS-PAS-HIN-21-010

v_2 fluctuations: skewness and kurtosis

in Pb—Pb collisions

Measure v_2 with multiparticle cumulants:

⇛ Sensitive to underlying v_2 probability density function (PDF) and thus initial geometry

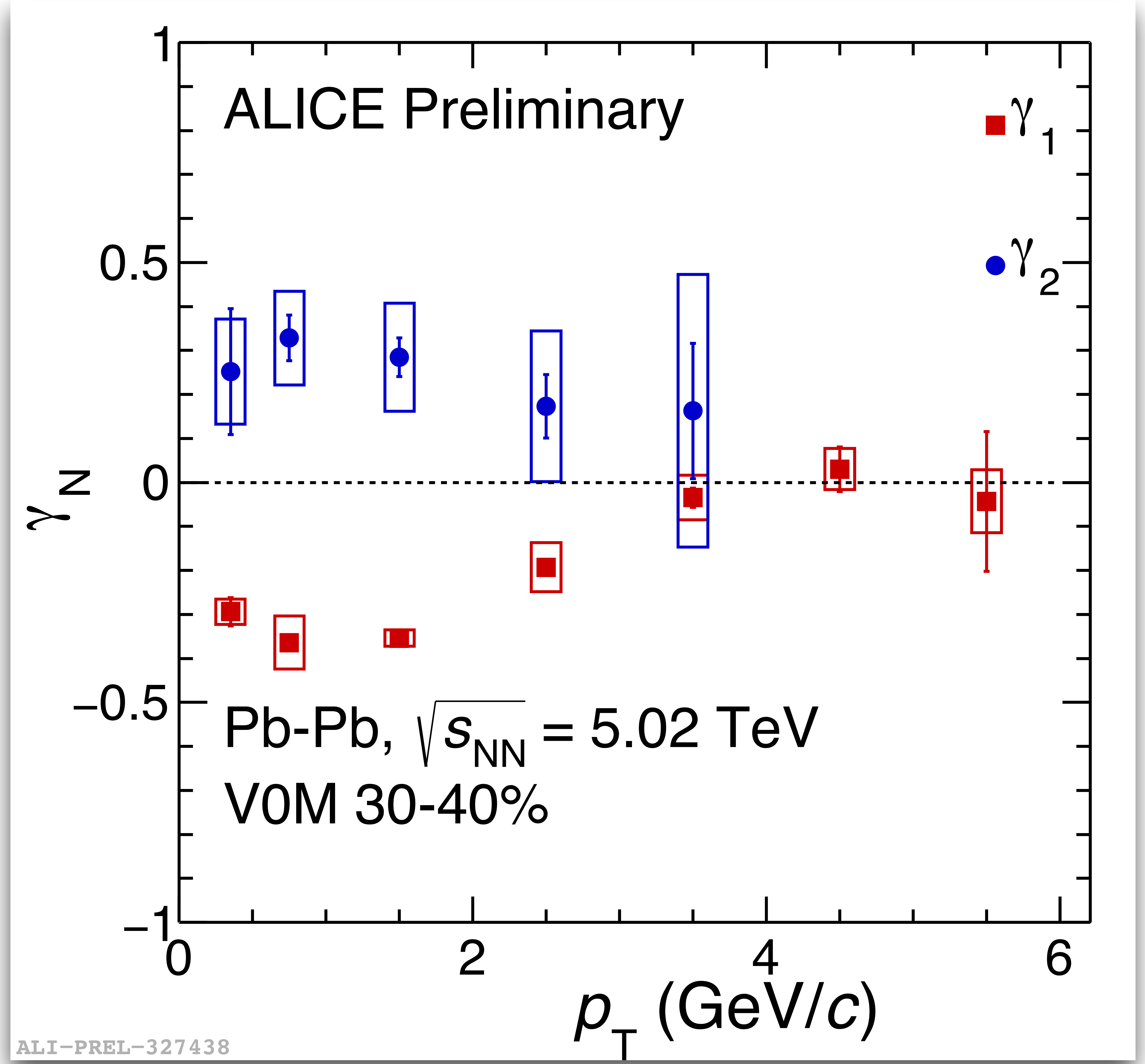
- Skewness (γ_1) decreasing with centrality, PDF becoming less symmetric
- Kurtosis (γ_2) increasing with centrality, tails become "fatter"

Do γ_1, γ_2 probe initial geometry exclusively?

Not necessarily!

- Both γ_1 and γ_2 show evolution with p_T

⇛ Suggests that v_2 PDF is modified by the evolution of QGP



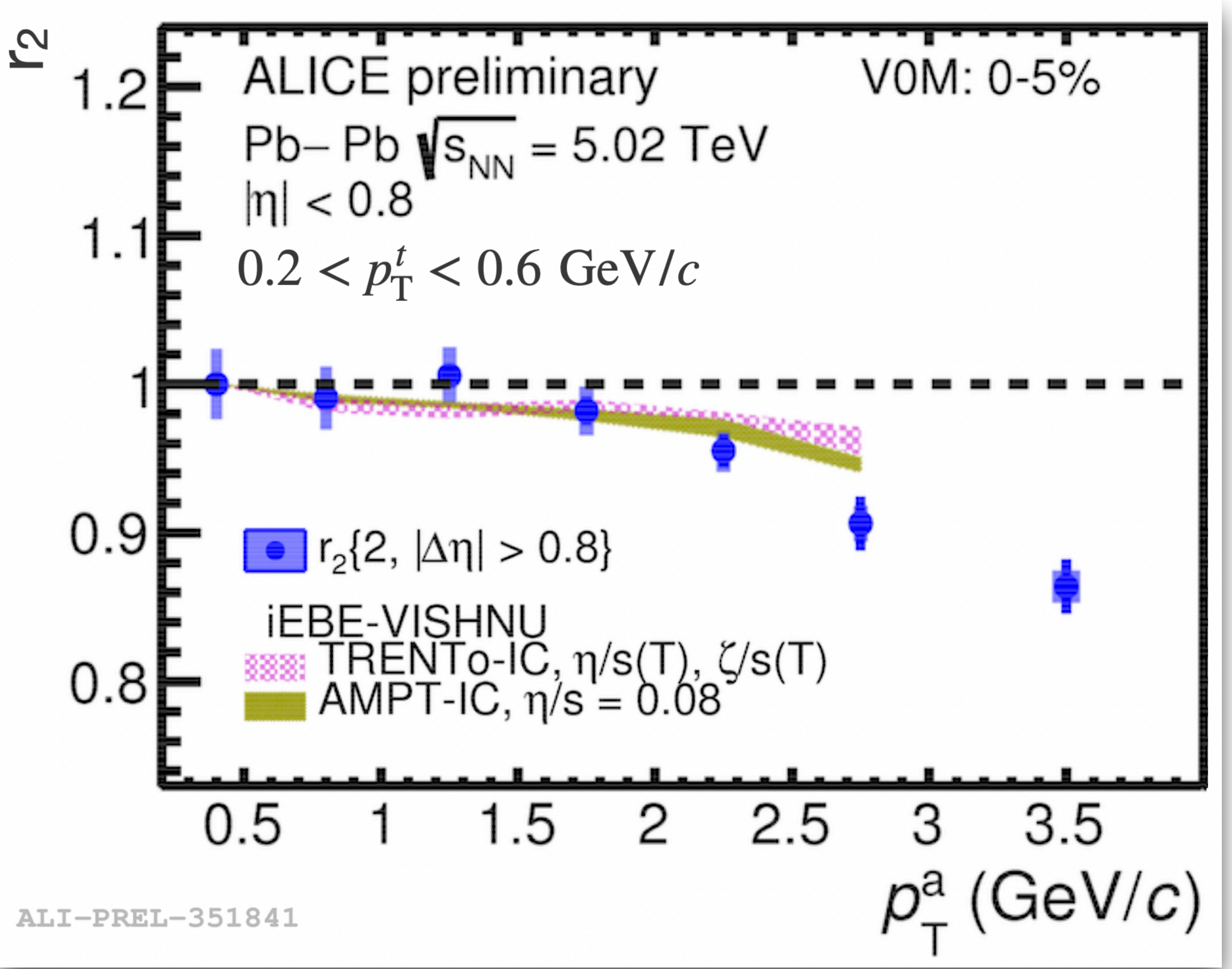
Flow vector fluctuations in Pb—Pb

Flow factorisation ratio (**t**rigger and **a**ssociated) $r_n = \frac{\langle v_n^a v_n^t \cos[n(\Psi_n^a - \Psi_n^t)]\rangle}{\sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}}$

Flow vector fluctuations in Pb—Pb

Flow factorisation ratio (**t**rigger and **a**ssociated) $r_n = \dfrac{\langle v_n^a v_n^t \cos[n(\Psi_n^a - \Psi_n^t)]\rangle}{\sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}}$

Largest fluctuations in central Pb—Pb collisions at high $p_T \Rrightarrow$ large event-by-event fluctuations in the initial state



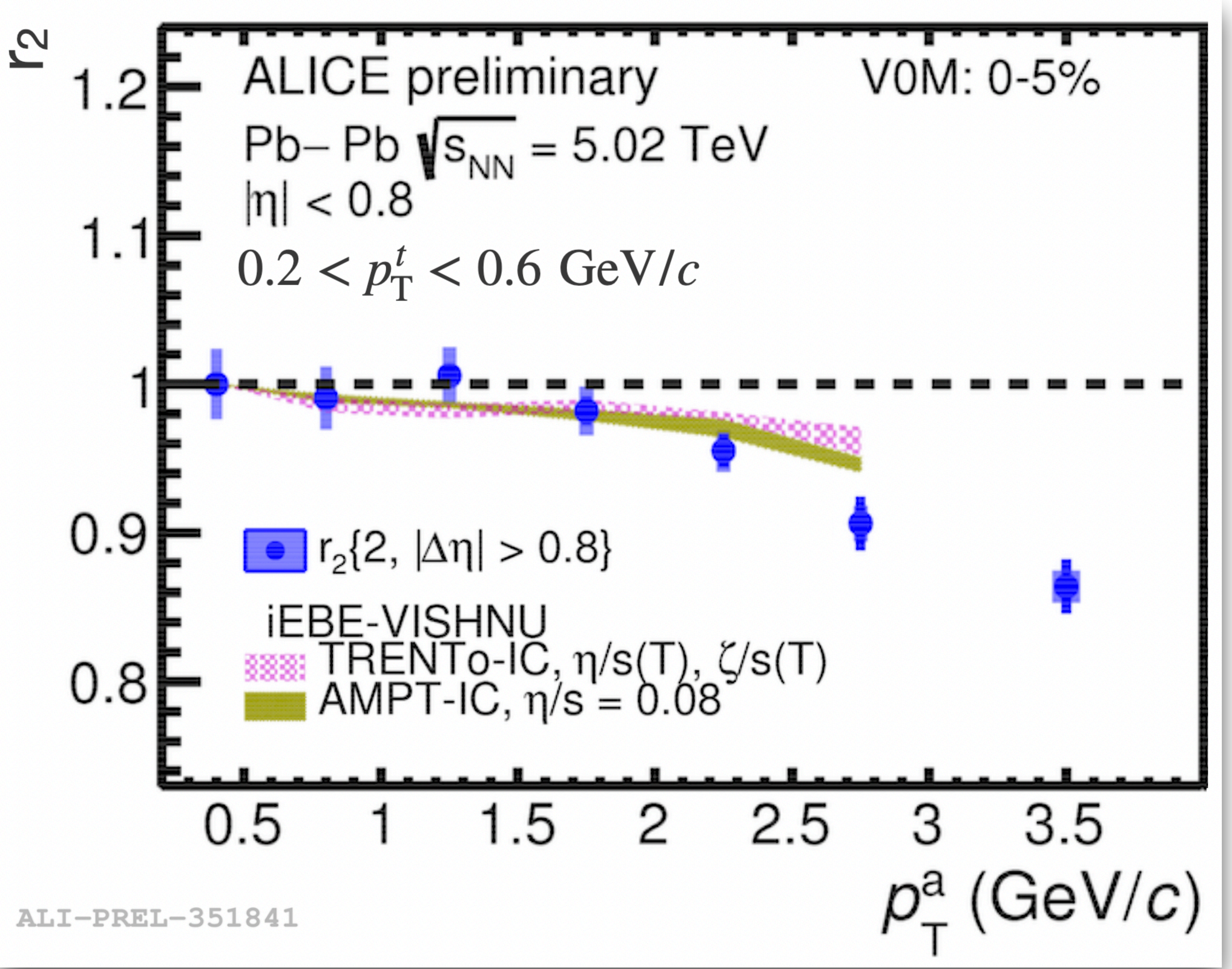
Flow vector fluctuations in Pb—Pb

Flow factorisation ratio (**t**rigger and **a**ssociated) $r_n = \frac{\langle v_n^a v_n^t \cos[n(\Psi_n^a - \Psi_n^t)]\rangle}{\sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}}$

Largest fluctuations in central Pb—Pb collisions at high $p_T \Rrightarrow$ large event-by-event fluctuations in the initial state

Deviations from $r_n = 1$ can be due to:

- *Flow angle fluctuations,*
  $\langle \cos\left[n\left(\Psi_n^a - \Psi_n^t\right)\right]\rangle \neq 1$
- *Flow magnitude fluctuations,*
  $\langle v_n^a v_n^t\rangle \neq \sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}$
- Cannot be measured directly, but upper/lower limits can be estimated



Flow vector fluctuations in Pb—Pb

Flow factorisation ratio (**t**rigger and **a**ssociated) $r_n = \frac{\langle v_n^a v_n^t \cos[n(\Psi_n^a - \Psi_n^t)]\rangle}{\sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}}$

Largest fluctuations in central Pb—Pb collisions at high $p_T \Rightarrow$ large event-by-event fluctuations in the initial state

Deviations from $r_n = 1$ can be due to:

- *Flow angle fluctuations,*

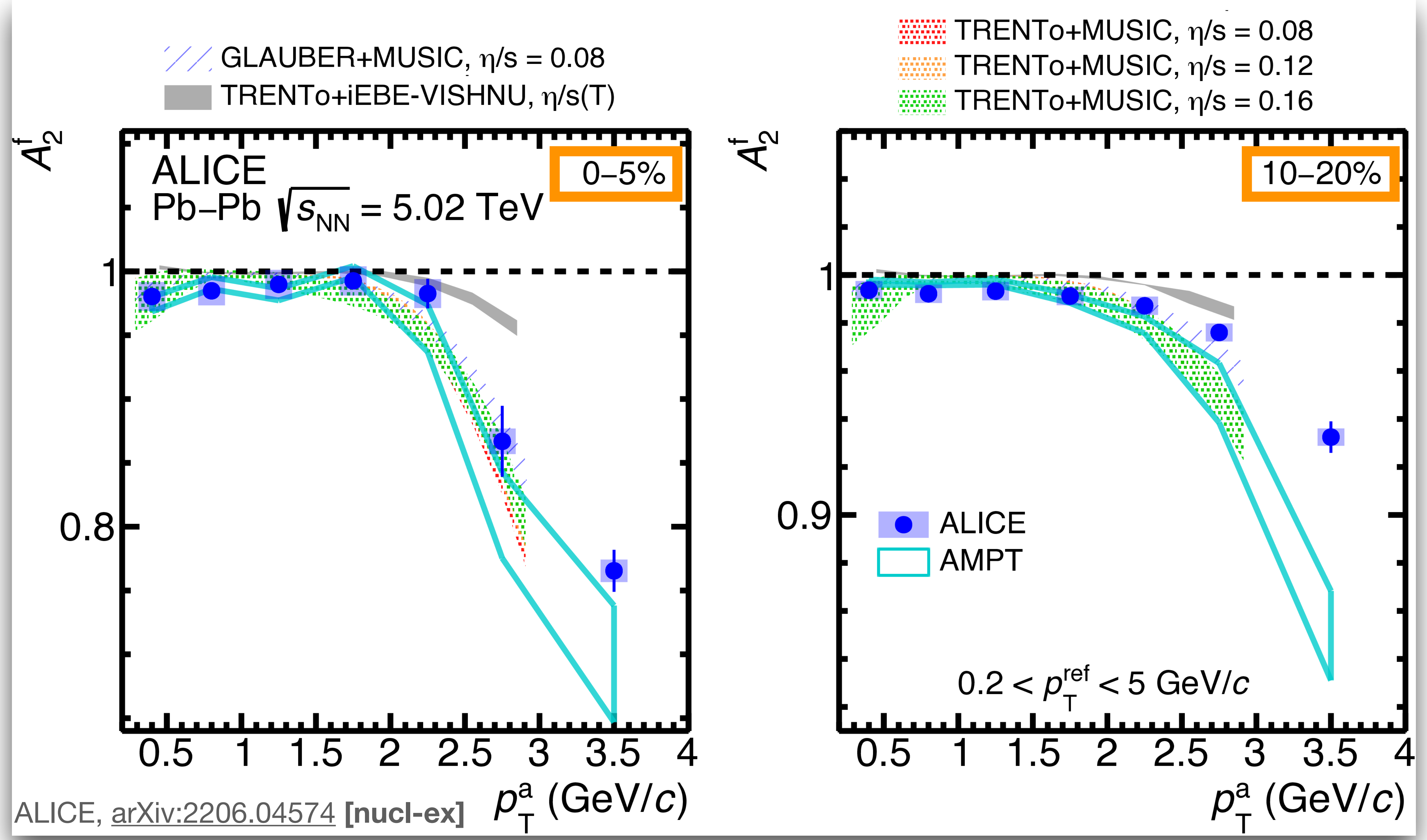
$$\langle \cos\left[n\left(\Psi_n^a - \Psi_n^t\right)\right]\rangle \neq 1$$

- *Flow magnitude fluctuations,*

$$\langle v_n^a v_n^t\rangle \neq \sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}$$

- Cannot be measured directly, but upper/lower limits can be estimated

Flow angle fluctuations



ALICE, arXiv:2206.04574 **[nucl-ex]**

- Sensitive to fluctuations in initial state, little sensitivity to η/s

Flow vector fluctuations in Pb—Pb

Flow factorisation ratio $r_n = \frac{\langle v_n^a v_n^t \cos[n(\Psi_n^a - \Psi_n^t)]\rangle}{\sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}}$
(**t**rigger and **a**ssociated)

Largest fluctuations in central Pb—Pb collisions at high $p_T \Rightarrow$ large event-by-event fluctuations in the initial state

Deviations from $r_n = 1$ can be due to:

- *Flow angle fluctuations,*

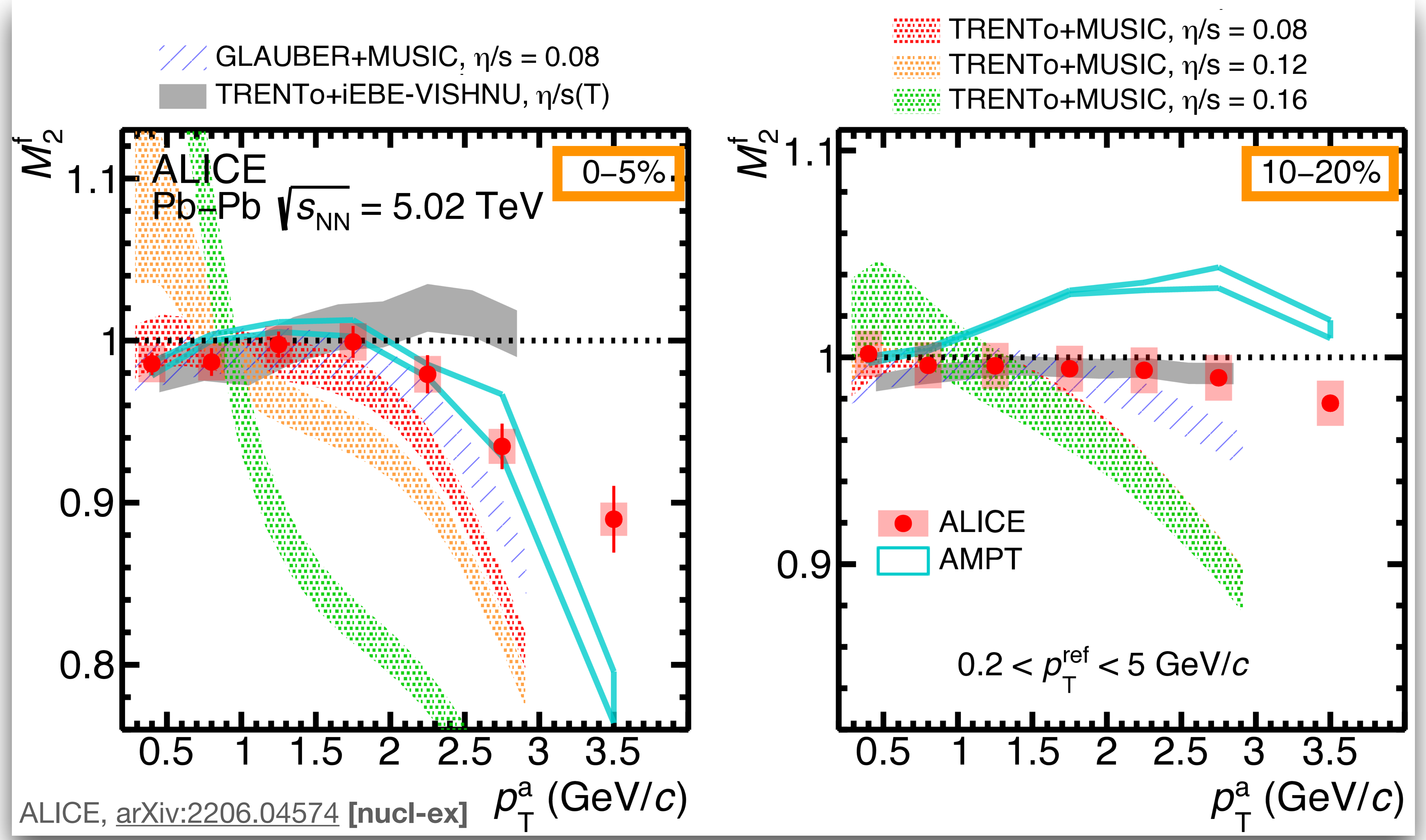
  $$\langle \cos\left[n\left(\Psi_n^a - \Psi_n^t\right)\right]\rangle \neq 1$$

- *Flow magnitude fluctuations,*

  $$\langle v_n^a v_n^t\rangle \neq \sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}$$

- Cannot be measured directly, but upper/lower limits can be estimated

Flow magnitude fluctuations



- Sensitive to fluctuations in initial state, little sensitivity to η/s
- Strong sensitivity to shear viscosity, but only in the most central collisions

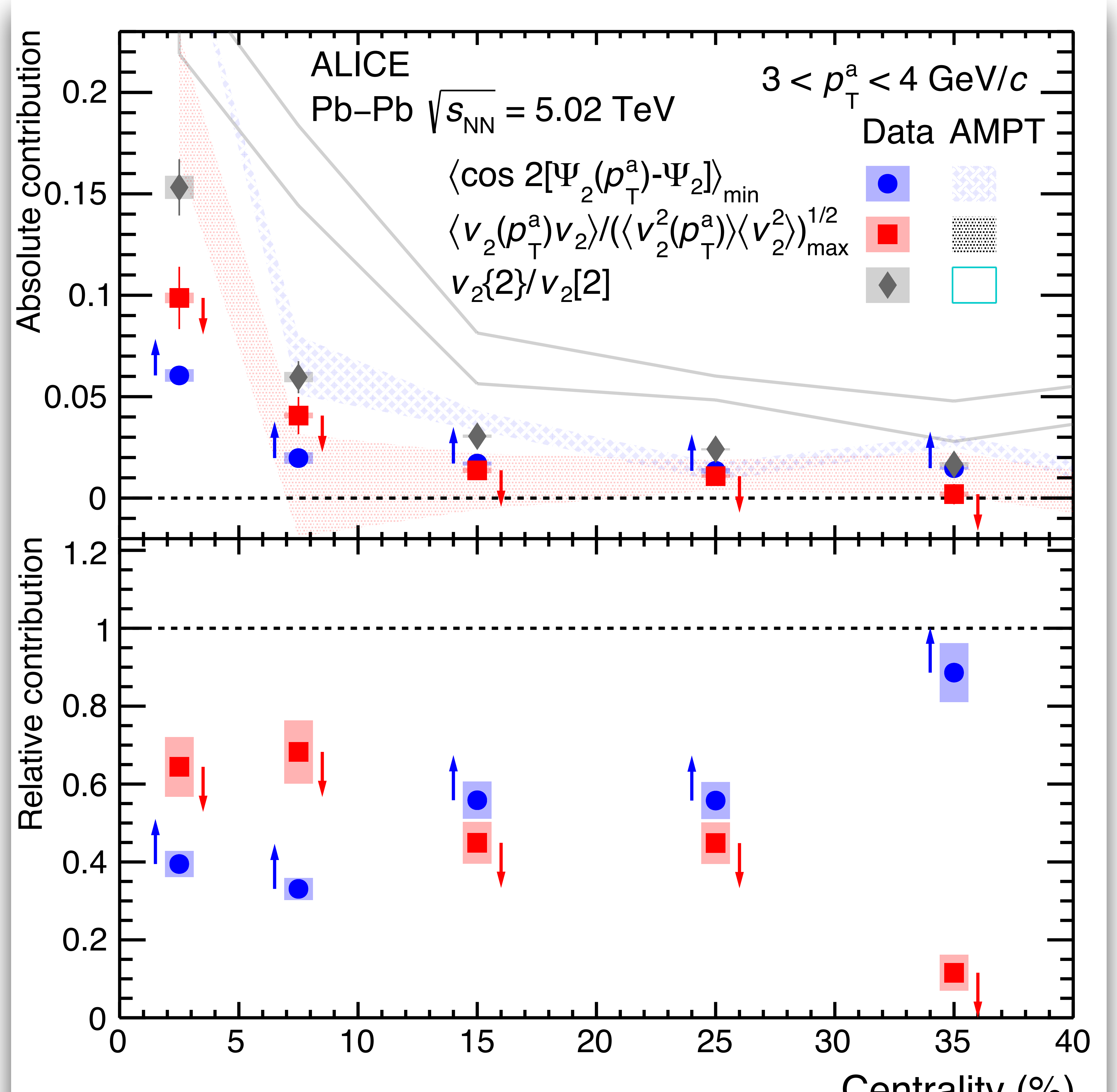
Flow vector fluctuation limits in Pb—Pb

Flow factorisation ratio
(**t**rigger and **a**ssociated)

Largest fluctuations in central Pb—Pb collisions at high $p_T \Rrightarrow$ large event-by-event fluctuations in the initial state

- At least 40% of fluctuations in central collisions originate from flow angle fluctuations
- Above 30% centrality, flow magnitude fluctuations are suppressed

First measurement separating flow angle and magnitude fluctuations ⇛ Challenges the assumption of a common symmetry plane



ALICE, arXiv:2206.04574 **[nucl-ex]**

Correlation between $[p_{\mathrm{T}}]$ and v_2

- Shape of the fireball: anisotropic flow, $\varepsilon_n \rightarrow v_n$
- Size of the fireball: radial flow, $[p_{\mathrm{T}}]$, $1/R \rightarrow [p_{\mathrm{T}}]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between v_n and $[p_{\mathrm{T}}]$

⇛ Study with Pearson correlation coefficient:

$$\rho_n\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_T]\right)}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{\mathrm{var}\left([p_T]\right)}}$$

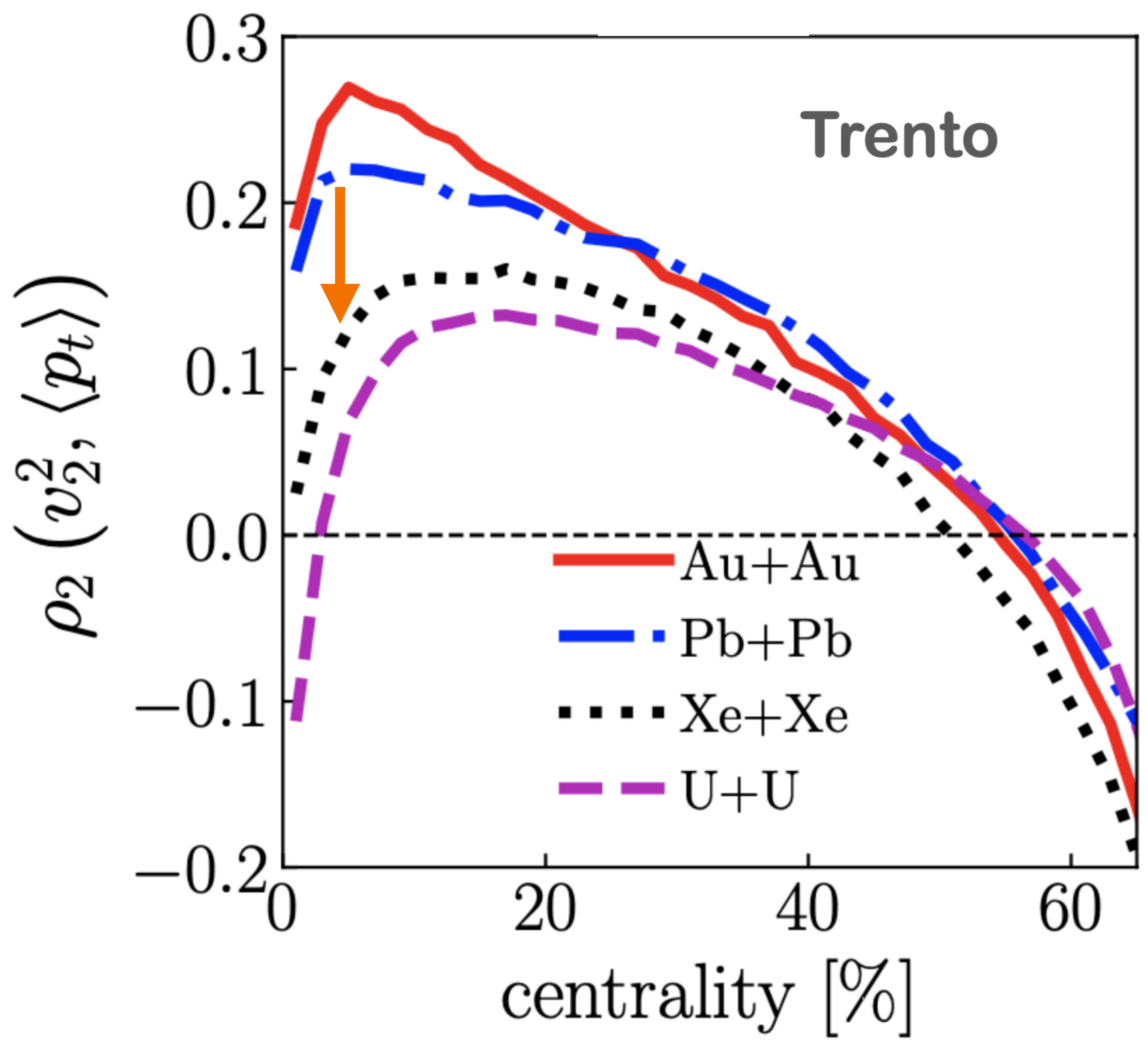
Correlation between $[p_{\mathrm{T}}]$ and v_2
and deformation of nuclei

- Shape of the fireball: anisotropic flow, $\varepsilon_n \to v_n$
- Size of the fireball: radial flow, $[p_{\mathrm{T}}]$, $1/R \to [p_{\mathrm{T}}]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between v_n and $[p_{\mathrm{T}}]$

⇛ Study with Pearson correlation coefficient:

$$\rho_n\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_T]\right)}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{\mathrm{var}\left([p_T]\right)}}$$

⇛ ρ_2 is significantly smaller in central collisions of deformed Xe nuclei (deformation parameter $\beta_2 \approx 0.16$) compared to spherical Pb ($\beta_2 \approx 0$)



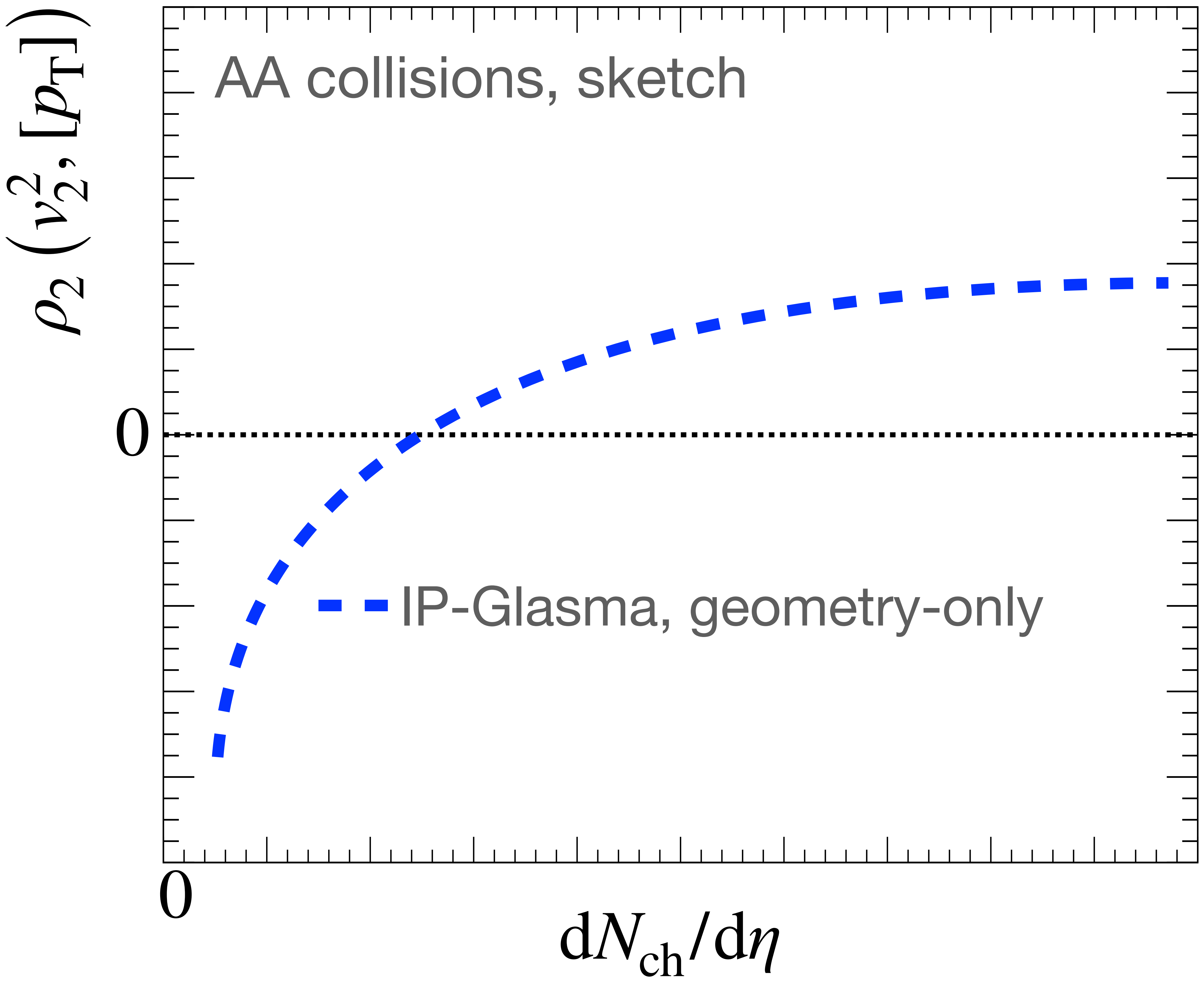
G. Giacalone, Phys. Rev. C 102, 024901 (2020)

Correlation between $[p_{\mathrm{T}}]$ and v_2
at low multiplicity

- Shape of the fireball: anisotropic flow, $\varepsilon_n \to v_n$
- Size of the fireball: radial flow, $[p_{\mathrm{T}}]$, $1/R \to [p_{\mathrm{T}}]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between v_n and $[p_{\mathrm{T}}]$

⇛ Study with Pearson correlation coefficient:

$$\rho_n\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_T]\right)}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{\mathrm{var}\left([p_T]\right)}}$$

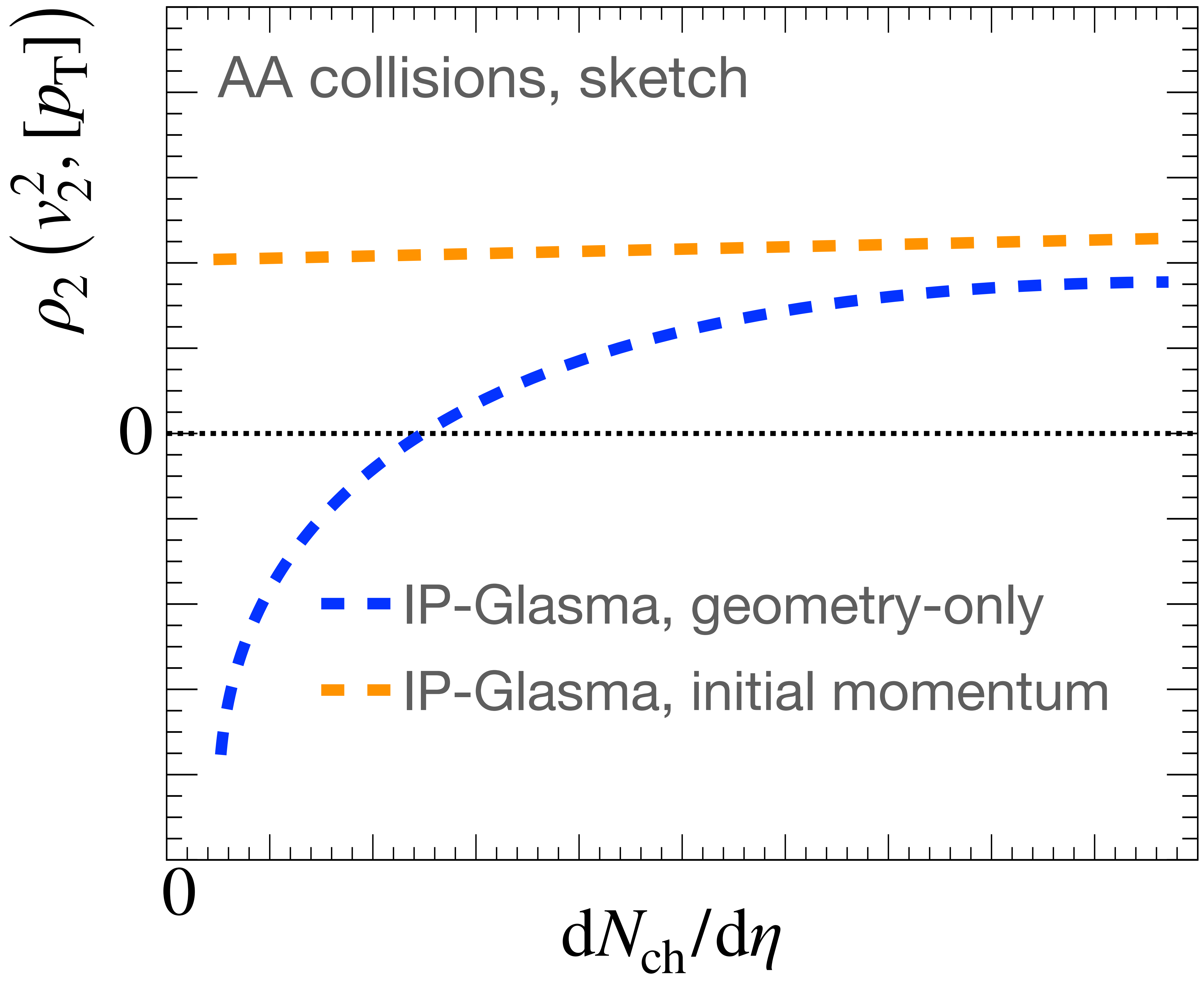


Correlation between $[p_\mathrm{T}]$ and v_2 at low multiplicity

- Shape of the fireball: anisotropic flow, $\varepsilon_n \to v_n$
- Size of the fireball: radial flow, $[p_\mathrm{T}]$, $1/R \to [p_\mathrm{T}]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between v_n and $[p_\mathrm{T}]$

⇛ Study with Pearson correlation coefficient:

$$\rho_n\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_T]\right)}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{\mathrm{var}\left([p_T]\right)}}$$

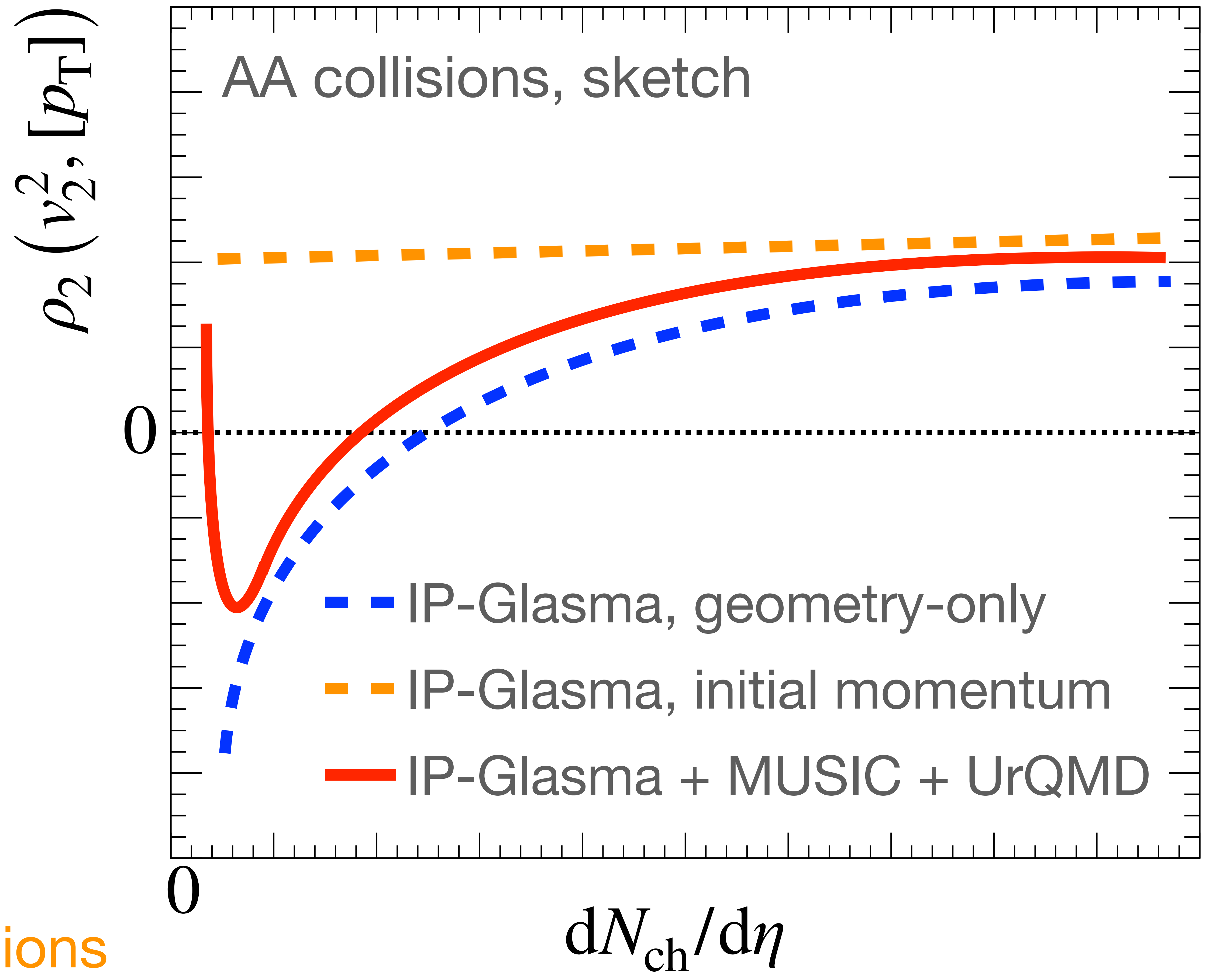


Correlation between $[p_T]$ and v_2 at low multiplicity

- Shape of the fireball: anisotropic flow, $\varepsilon_n \to v_n$
- Size of the fireball: radial flow, $[p_T]$, $1/R \to [p_T]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between v_n and $[p_T]$

⇛ Study with Pearson correlation coefficient:

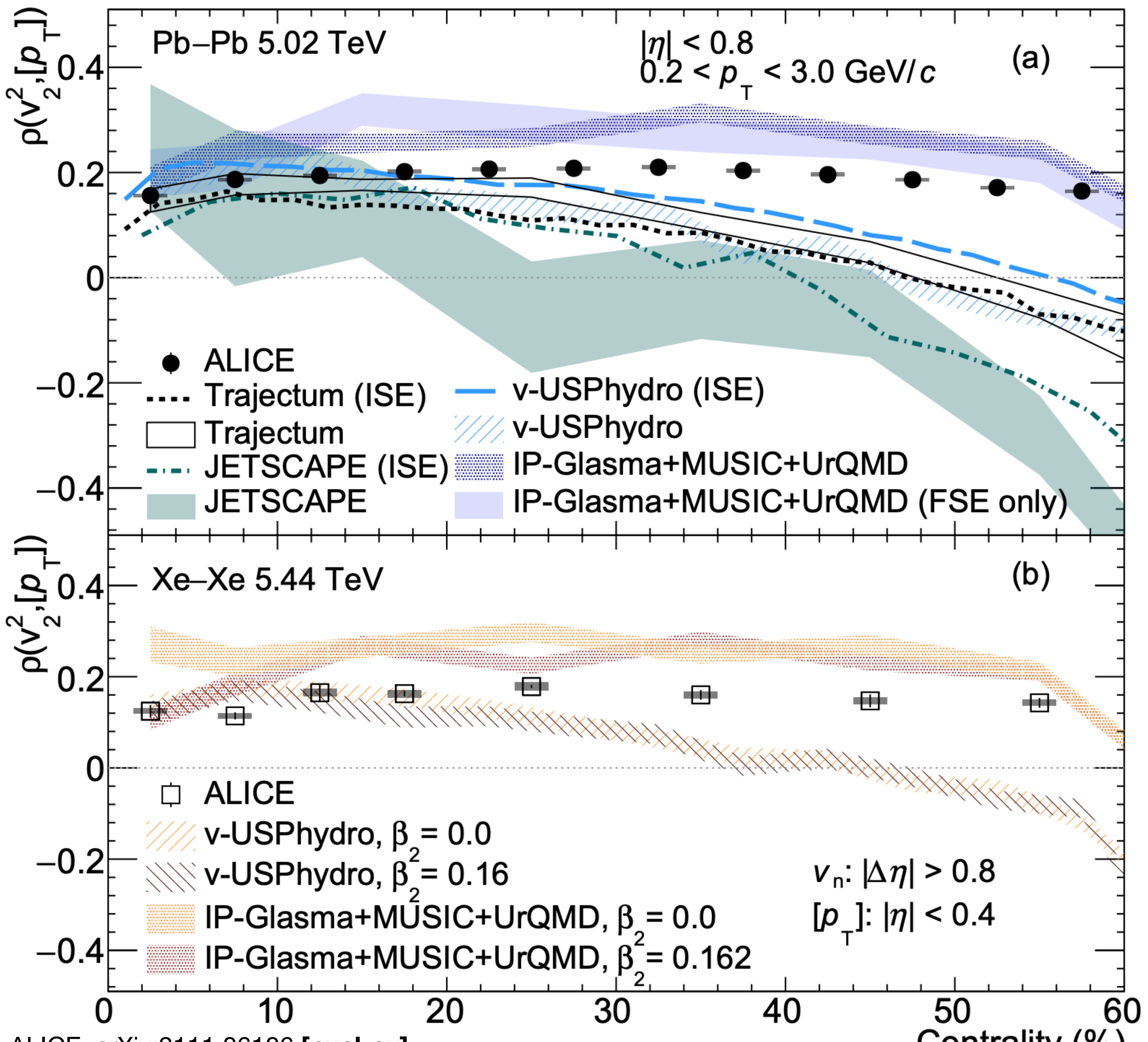
$$\rho_n\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_T]\right)}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{\mathrm{var}\left([p_T]\right)}}$$



Low multiplicity: geometry → initial momentum correlations
⇒ Change of slope sign → presence of CGC?

Correlation between $[p_T]$ and v_2 in Pb—Pb and Xe—Xe collisions

- ρ_2 slightly larger in Pb—Pb compared to Xe—Xe
- Comparison to models:
  - — Below 20% centrality, all models provide a decent description
  - — More peripheral → best described by models with IP-Glasma
- Xe—Xe:
  - — β_2 = 0.162 gives better description in most central collisions, similar to β_2 = 0 in more peripheral



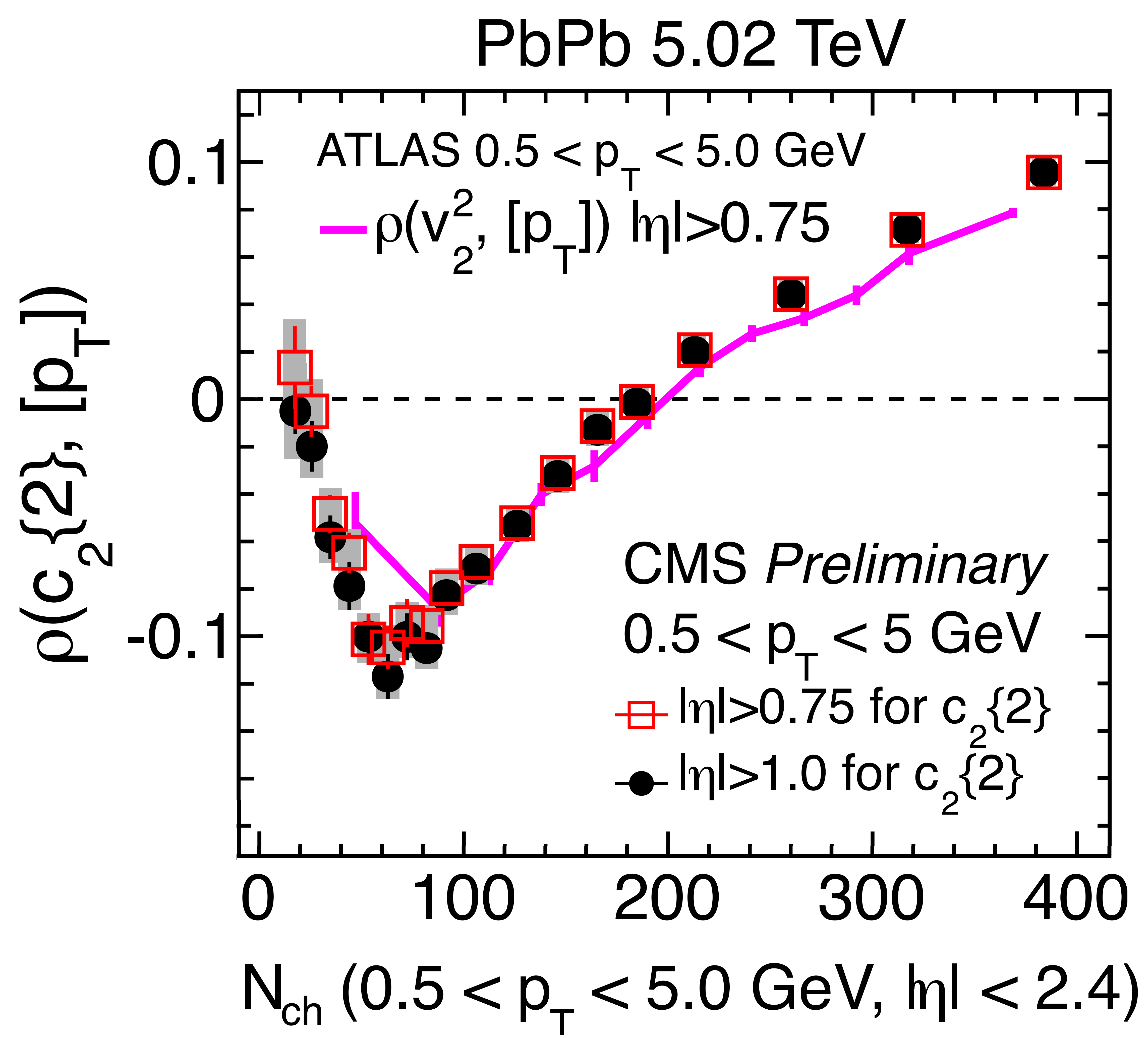
ALICE, arXiv:2111.06106 [nucl-ex]

Correlation between $[p_T]$ and v_2

in Pb—Pb at low multiplicity

$\rho(v_2^2, [p_T])$ in Pb—Pb:

- Decreasing + increasing trend at low multiplicity



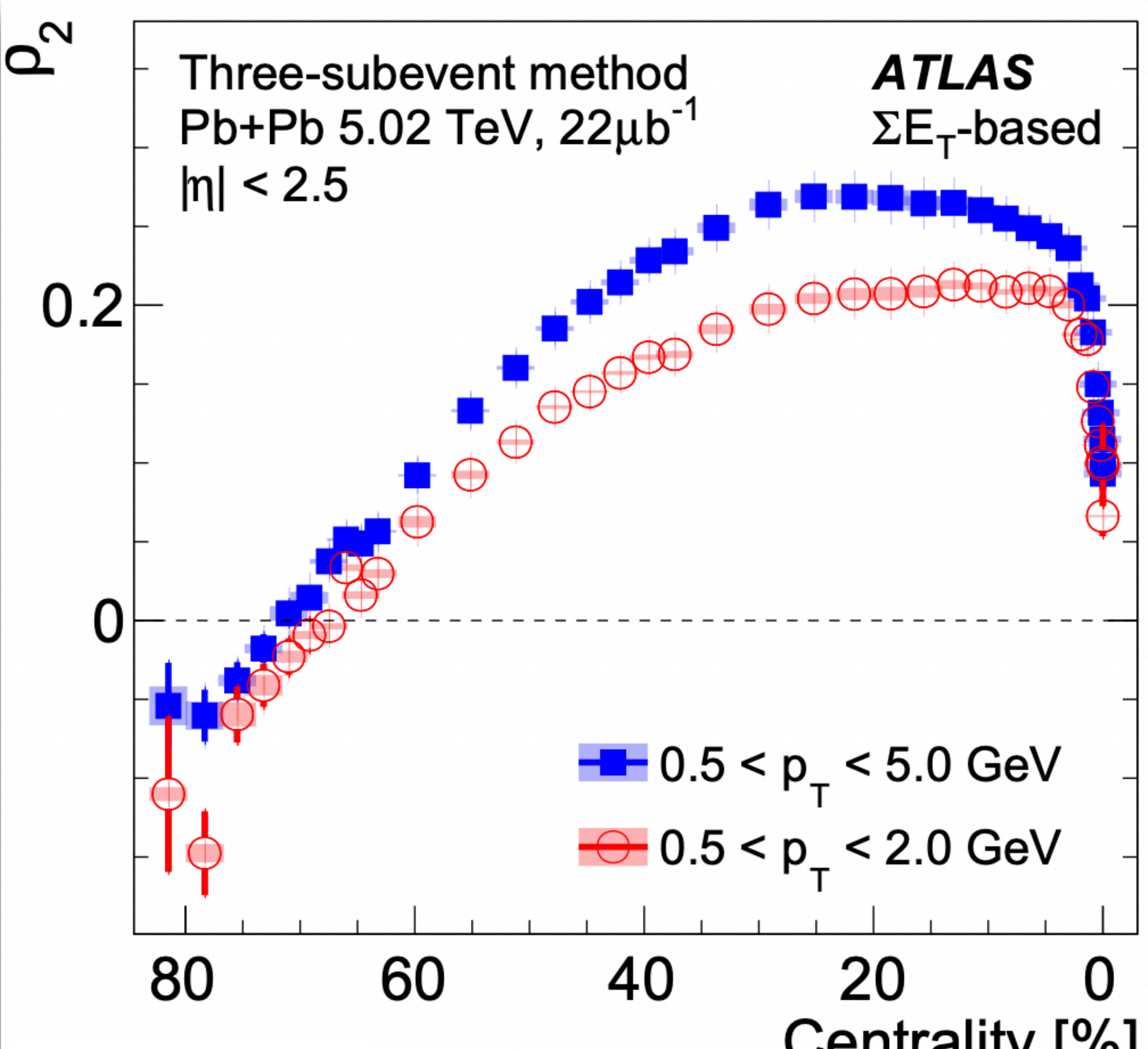
CMS, CMS-PAS-HIN-21-012

ATLAS, Eur. Phys. J. C 79 (2019) 985

Correlation between $[p_T]$ and v_2
in Pb—Pb at low multiplicity

$\rho(v_2^2, [p_T])$ in Pb—Pb:

- Decreasing + increasing trend at low multiplicity
- Sensitive to p_T interval…



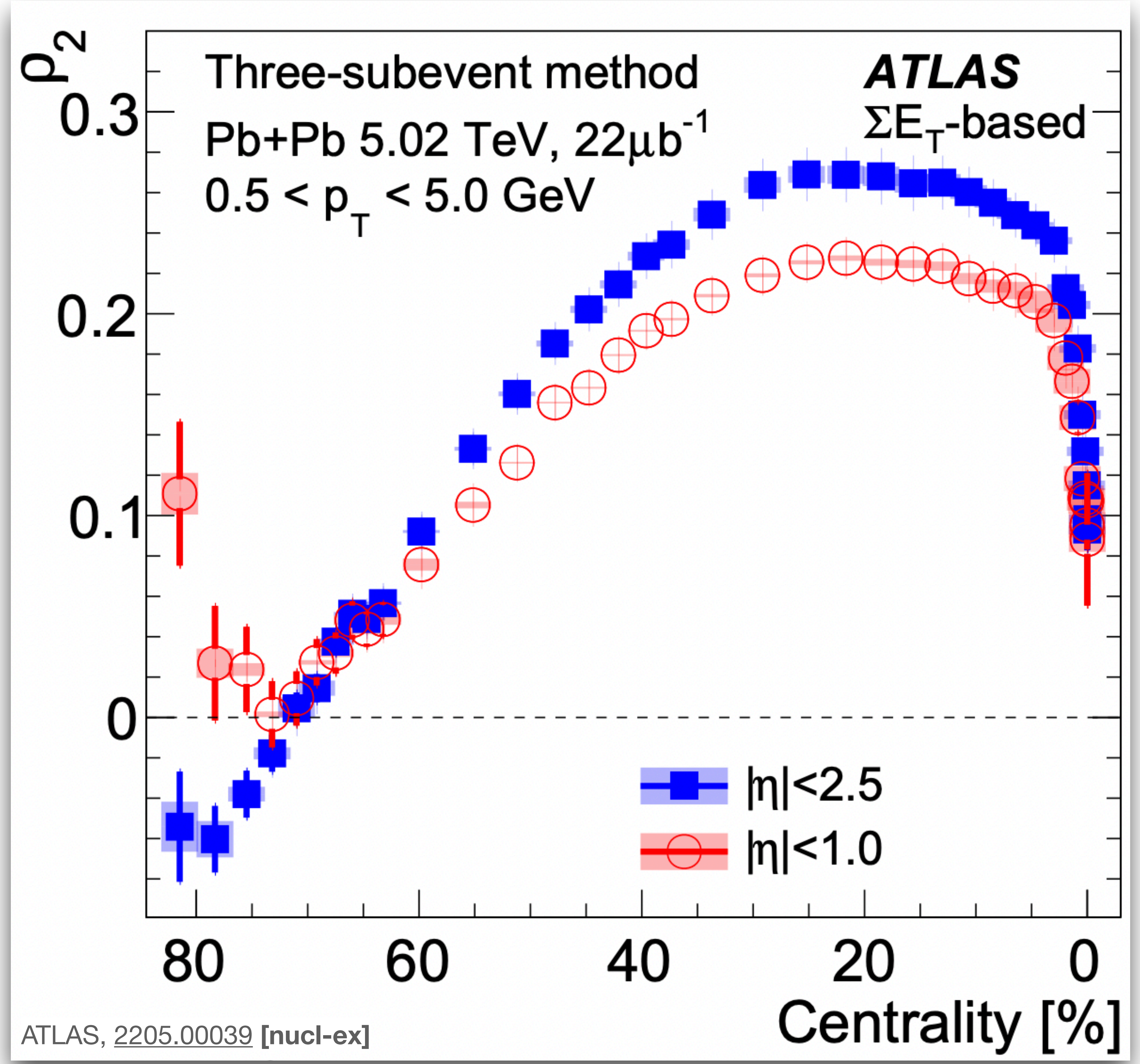
ATLAS, 2205.00039 **[nucl-ex]**

Correlation between $[p_T]$ and v_2

in Pb—Pb at low multiplicity

$\rho(v_2^2, [p_T])$ in Pb—Pb:

- Decreasing + increasing trend at low multiplicity
- Sensitive to p_T interval…
- and pseudorapidity range…

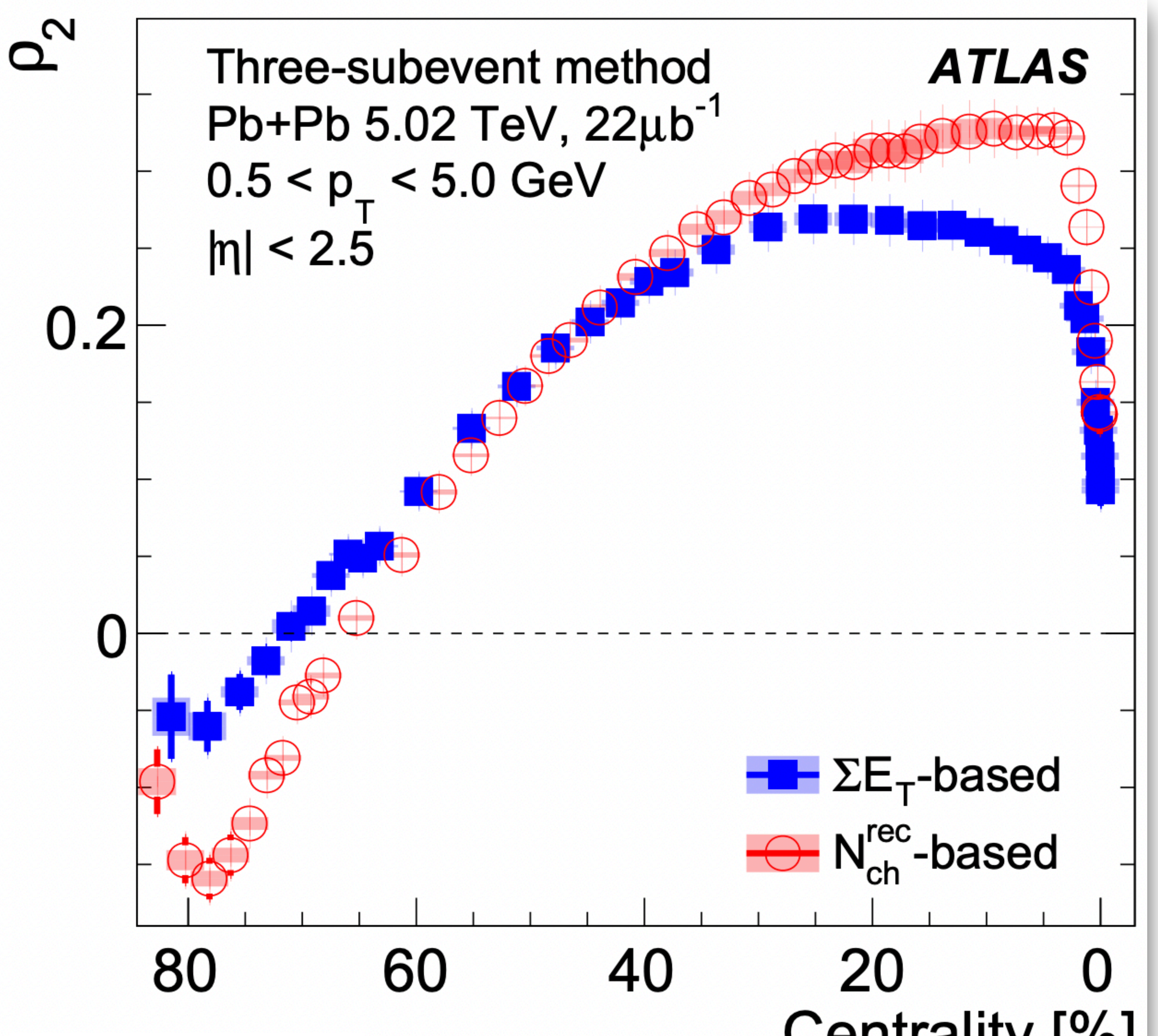


Correlation between $[p_T]$ and v_2

in Pb—Pb at low multiplicity

$\rho(v_2^2, [p_T])$ in Pb—Pb:

- Decreasing + increasing trend at low multiplicity
- Sensitive to p_T interval…
- and pseudorapidity range…
- and even the multiplicity estimator



ATLAS, 2205.00039 **[nucl-ex]**

Correlation between $[p_T]$ and v_2

comparison to models

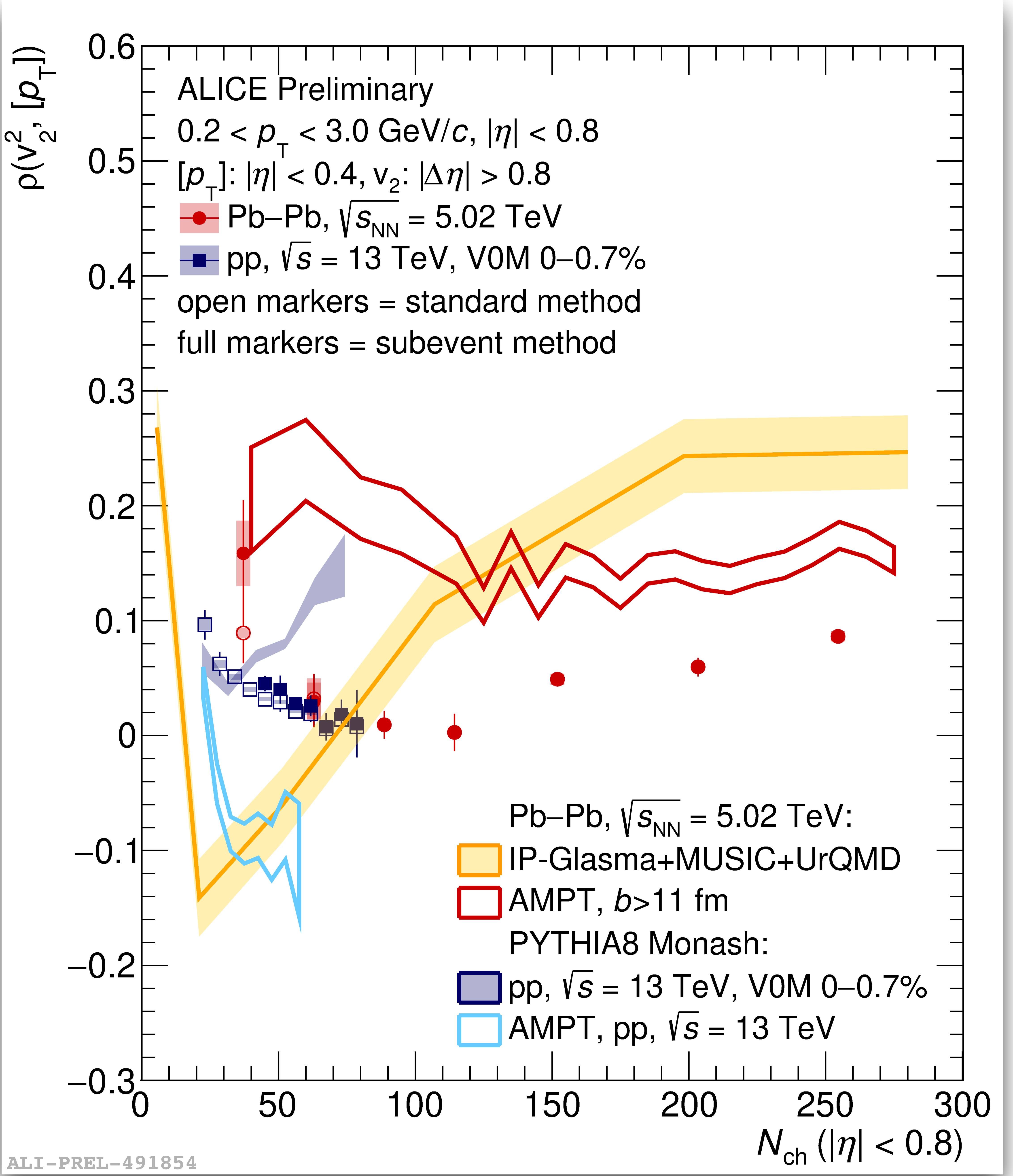
$\rho(v_2^2, [p_T])$ in Pb—Pb:

- IP-glasma+MUSIC+UrQMD:
  - Slope change around 20 charged tracks, significantly lower than in data
- AMPT:
  - Change of slope also observed, although at significantly higher N_{ch}

⇛ Slope change not exclusive to IP-Glasma

$\rho(v_2^2, [p_T])$ in pp:

- Consistent with Pb—Pb at similar N_{ch}
- Underestimated by AMPT, overestimated by PYTHIA



Summary

- Relative flow fluctuations: emerging p_T dependence in peripheral collisions
- Higher moments of v_2 PDF: evolution with centrality and p_T suggests sensitivity to initial geometry and transport properties of QGP

- First ever measurement separating flow angle and flow magnitude fluctuations
  ⇛ Dominated by flow angle fluctuations
  ⇛ Challenges the assumption of a single event-averaged symmetry plane

- Correlations between $[p_T]$ and v_2:
  ⇛ Highly sensitive to kinematic cuts and multiplicity estimator
  ⇛ Data better described by models with IP-Glasma in initial conditions
  ⇛ Observed decreasing trend at small N_{ch} in Pb—Pb collisions
  ⇛ Change of slope at low N_{ch} sensitive to interplay between initial conditions and geometry

Backup

From collisions to measurement

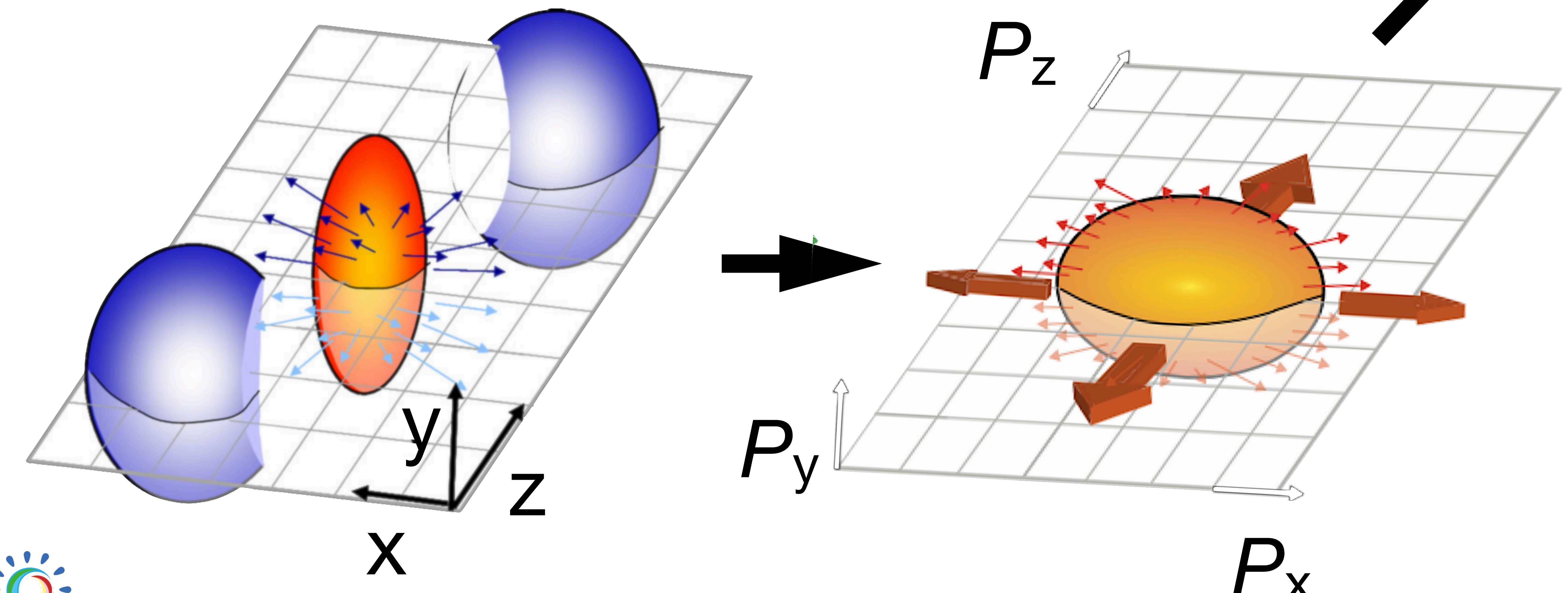
- Overlap between colliding nuclei:
  ⇛ Initial state, geometry & its fluctuations

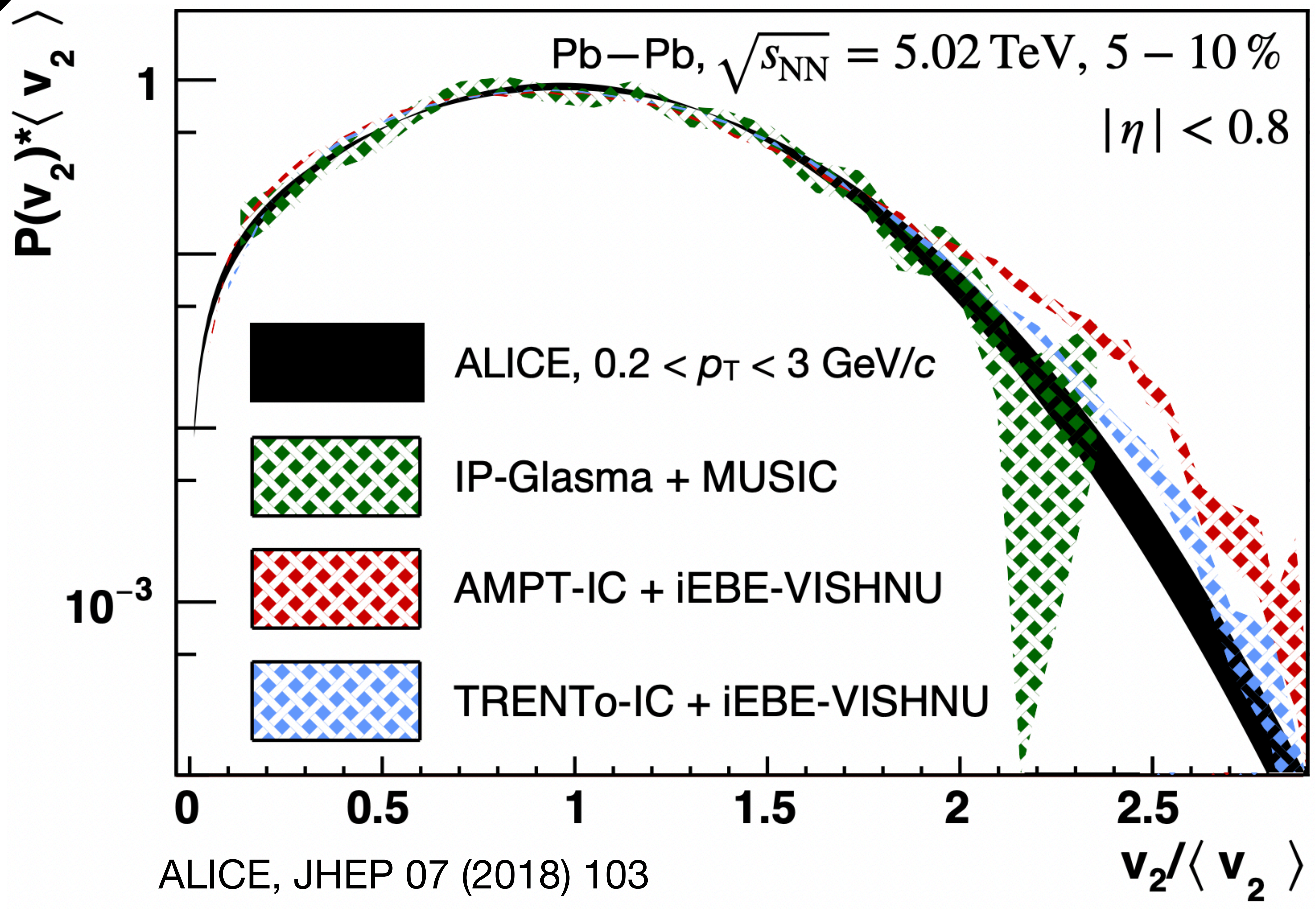
- Hydrodynamic expansion of QGP:
  ⇛ Radial and anisotropic flow, sensitive to initial state and properties of QGP

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n\left(\varphi - \Psi_n\right)$$

⇛ (Non-)Gaussian probability density function of v_n sensitive to initial state eccentricity ε_n

⇛ v_n fluctuations measured w.r.t. averaged Ψ_n

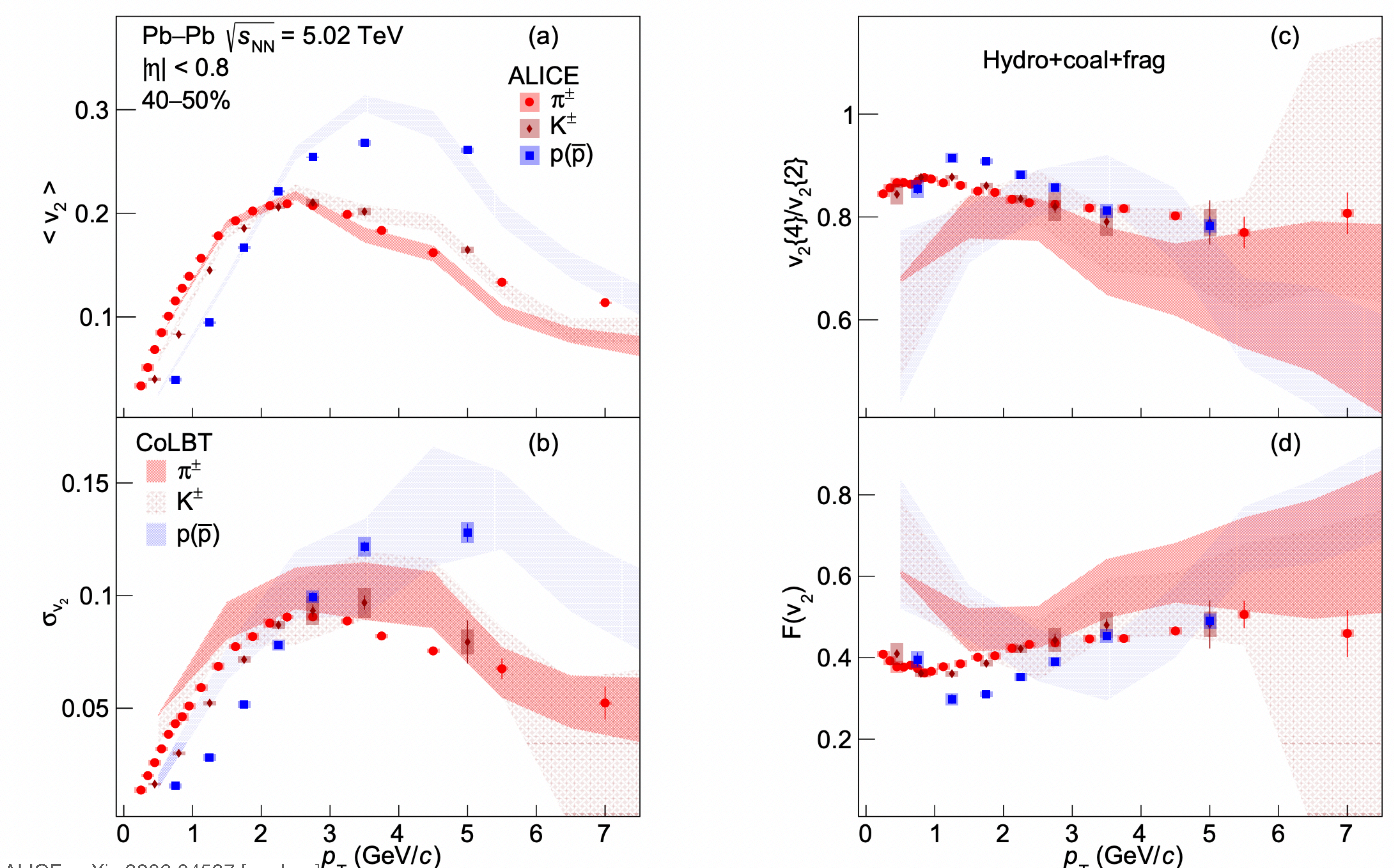




ALICE, JHEP 07 (2018) 103

v_2 fluctuations and v_2 ratios

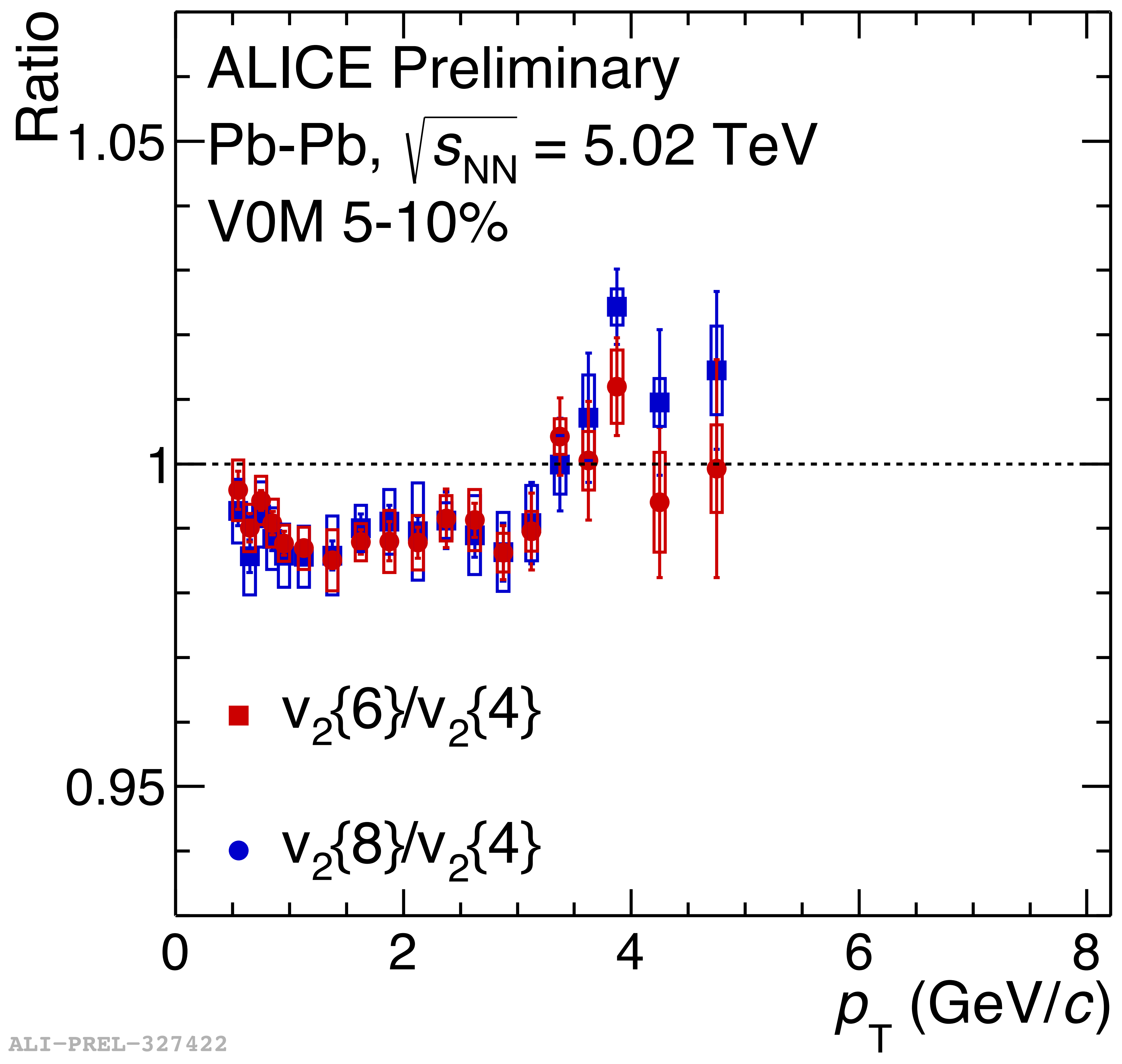
in Pb—Pb collisions

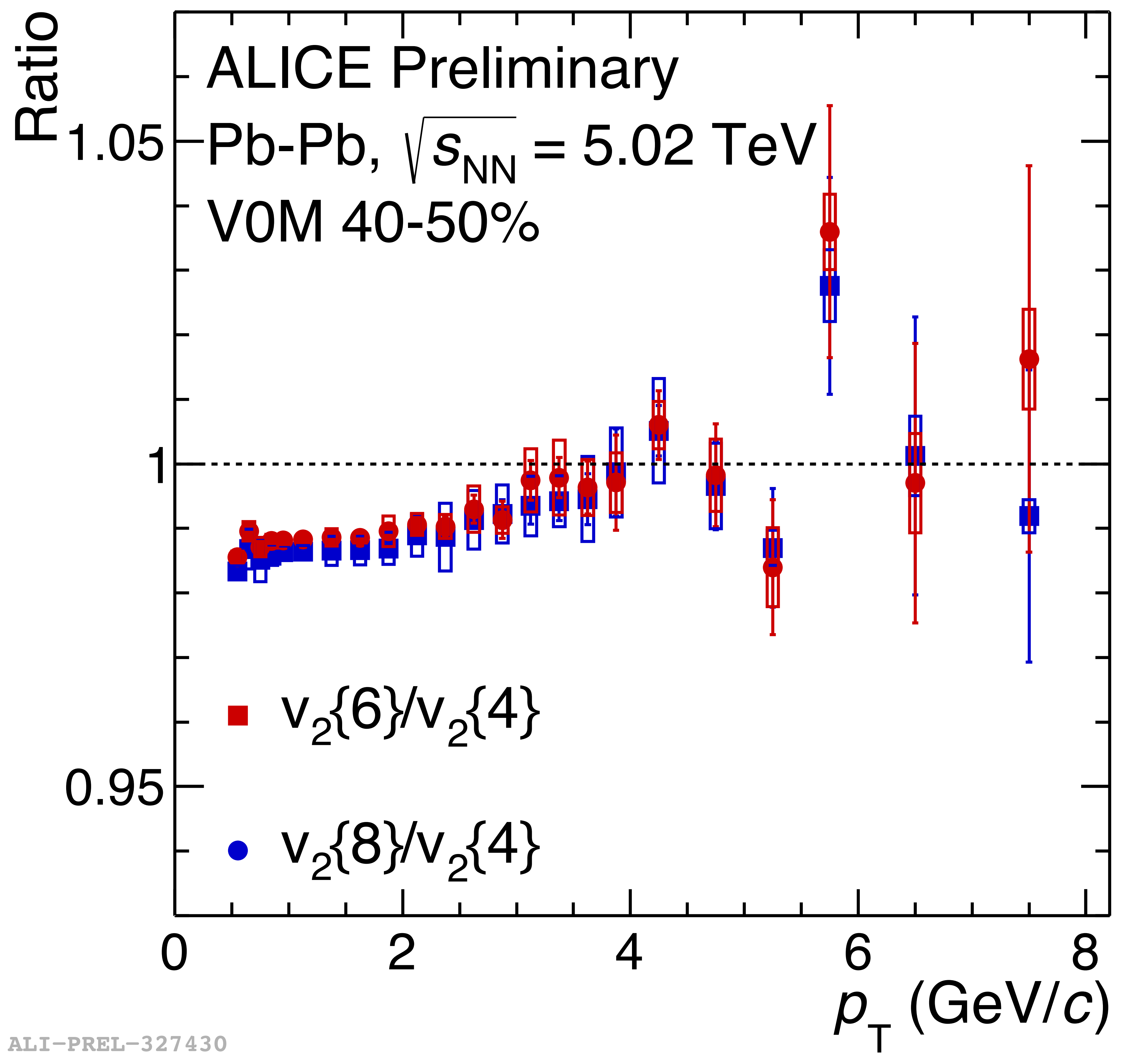


ALICE, arXiv:2206.04587 [nucl-ex]

v_2 fluctuations and v_2 ratios

in Pb—Pb collisions





Flow vector fluctuations in Pb—Pb

Define flow factorisation as $r_n = \dfrac{V_{n\Delta}(p_T^a, p_T^t)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) \cdot V_{n\Delta}(p_T^t, p_T^t)}} = \dfrac{\langle v_n^a v_n^t \cos[n(\Psi_n^a - \Psi_n^t)]\rangle}{\sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}}$

Deviations from $r_n = 1$ can be due to:

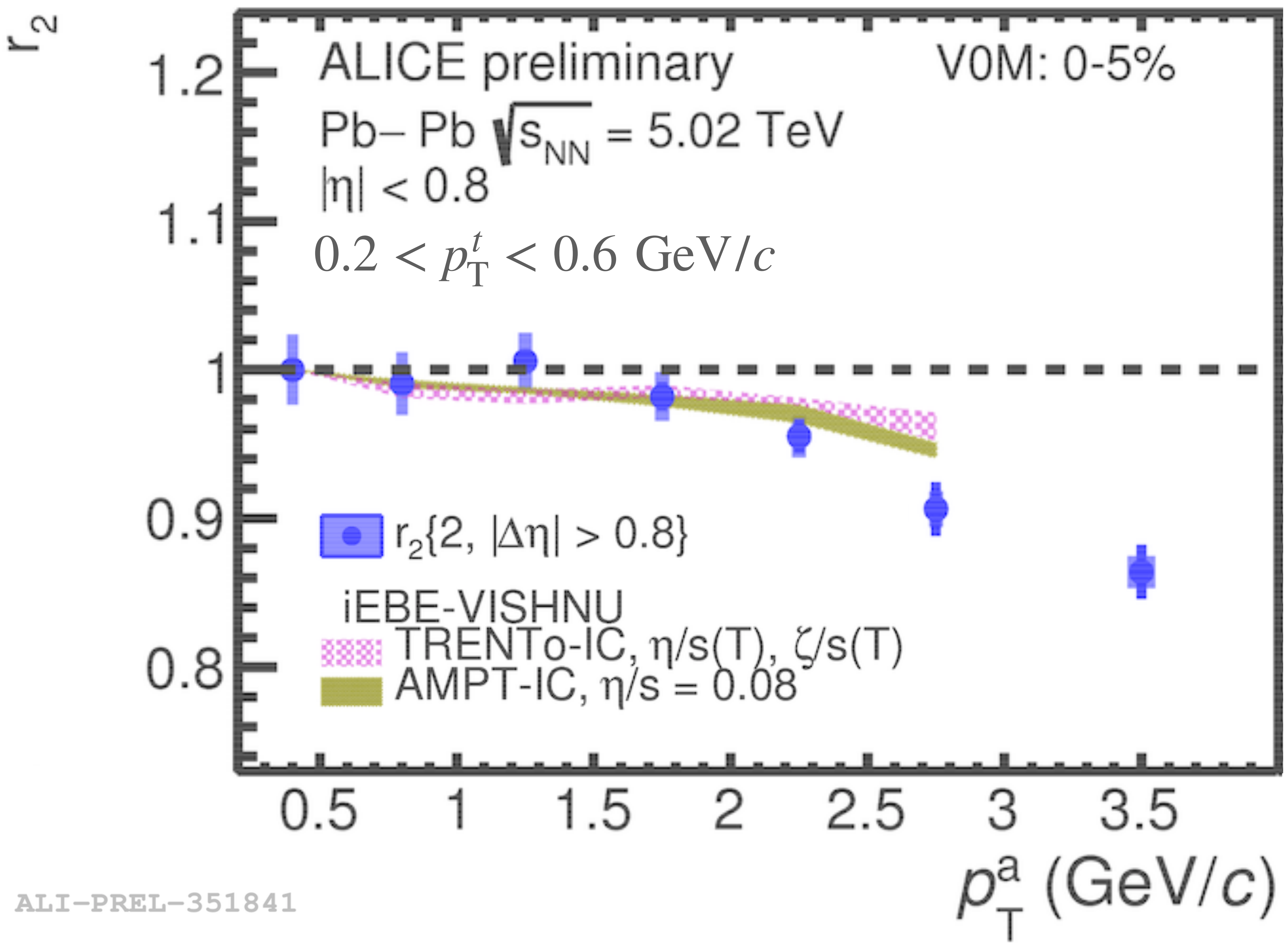
- *Flow magnitude fluctuations,*

  $\langle v_n^a v_n^t \rangle \neq \sqrt{\langle v_n^{a,2}\rangle\langle v_n^{t,2}\rangle}$

- *Flow angle fluctuations,*

  $\langle \cos\left[n\left(\Psi_n^a - \Psi_n^t\right)\right]\rangle \neq 1$

- Cannot measure directly, but *can* measure upper/lower limits!



Correlation between $[p_\mathrm{T}]$ and v_2

- Shape of the fireball: anisotropic flow, $\varepsilon_n \rightarrow v_n$
- Size of the fireball: radial flow, $[p_\mathrm{T}]$, $1/R \rightarrow [p_\mathrm{T}]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between v_n and $[p_\mathrm{T}]$

Study with Pearson correlation coefficient:

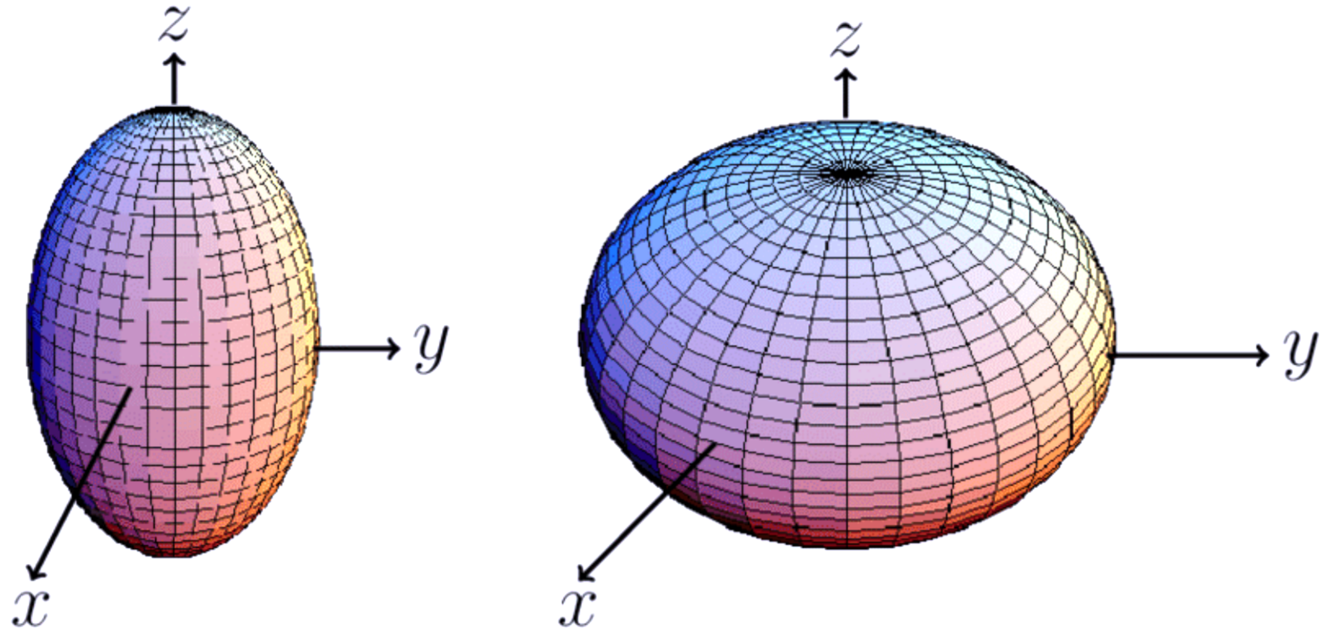
$$\rho_n\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_T]\right)}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{\mathrm{var}\left([p_T]\right)}}$$

For deformed nuclei

Significantly smaller ρ_2 in central Xe—Xe, compared to Pb—Pb

⇒ Deformation β reduces ρ_2

$$D_{WS}(r) = \frac{D_0}{1 + e^{\left(r - R_0\left(1+\beta Y_{20}\right)\right)/a}}$$

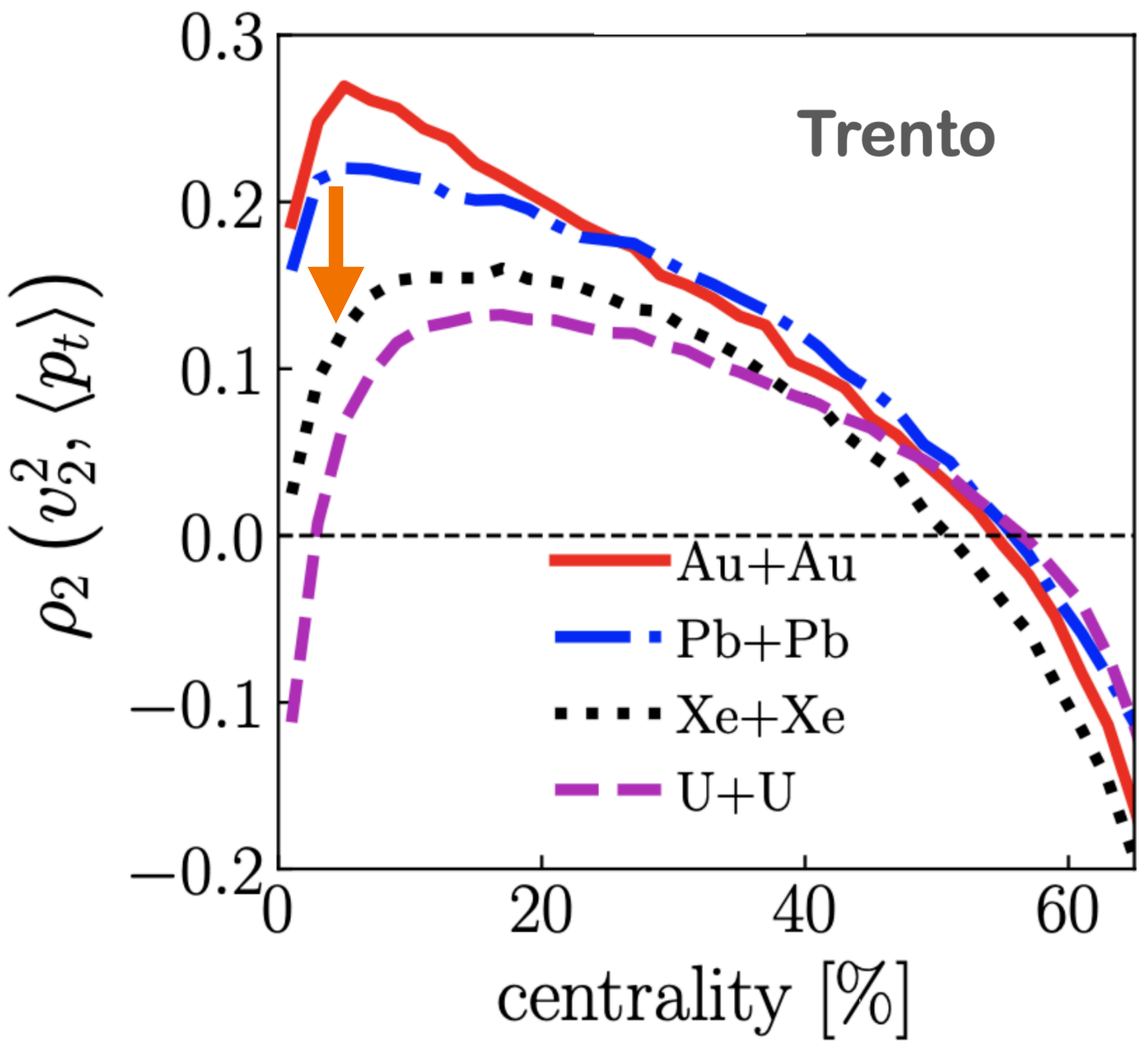


$\beta > 0$ $\beta < 0$

Pb—Pb: $\beta \approx 0$

Xe—Xe: $\beta \approx 0.16$

G. Giacalone, Phys. Rev. C 102, 024901 (2020)



Correlation between $[p_T]$ and v_2

- Shape of the fireball: anisotropic flow, $\varepsilon_n \rightarrow v_n$
- Size of the fireball: radial flow, $[p_T]$, $1/R \rightarrow [p_T]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between v_n and $[p_T]$

Study with Pearson correlation coefficient:

$$\rho_n\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_T]\right)}{\sqrt{\mathrm{var}\,(v_n^2)}\sqrt{\mathrm{var}\left([p_T]\right)}}$$

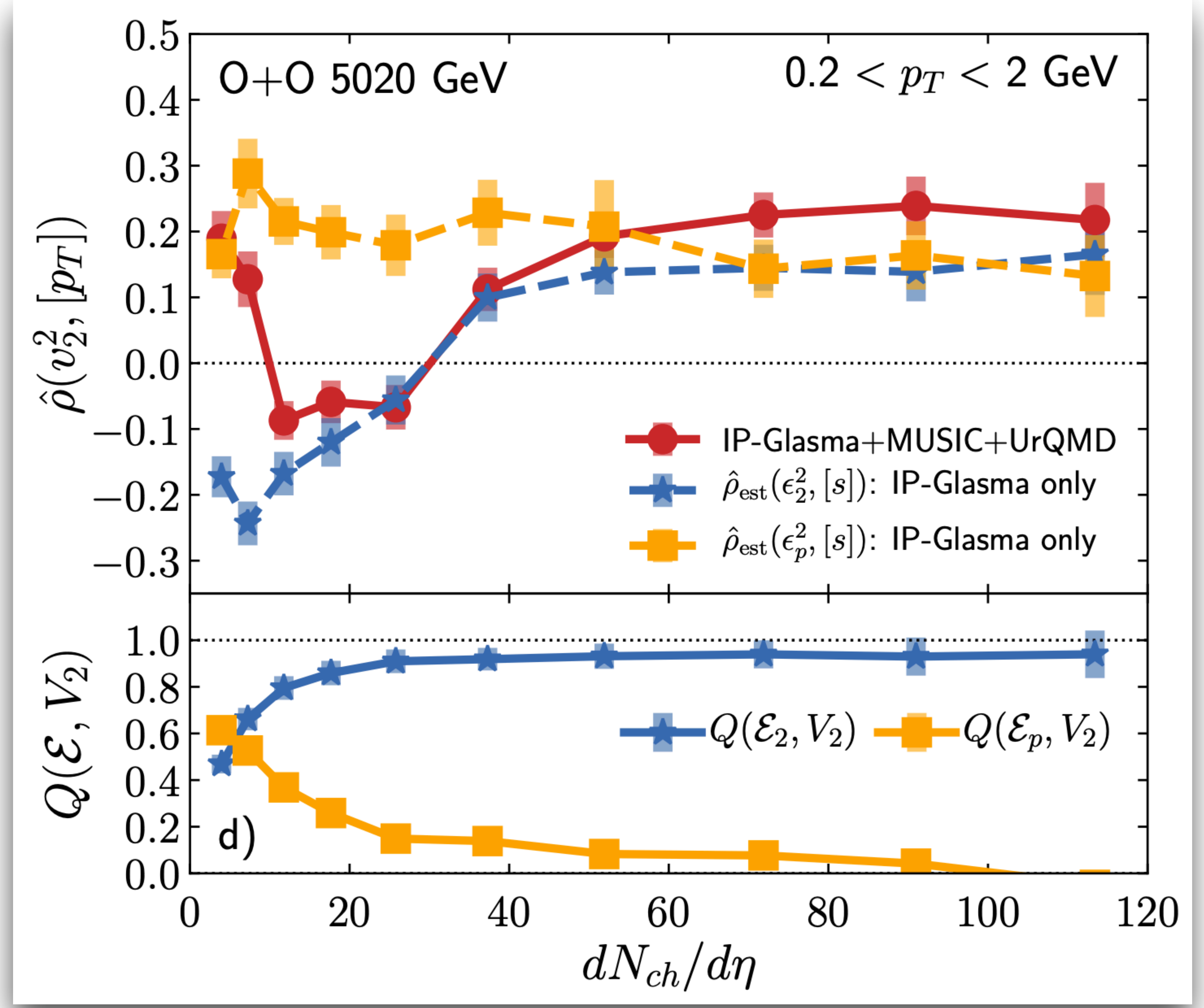
For deformed nuclei

Significantly smaller ρ_2 in central Xe—Xe, compared to Pb—Pb

⇒ Deformation β reduces ρ_2

Probing the initial state

- Low multiplicity: geometry → initial momentum correlations
  ⇒ Change of slope sign → presence of CGC?



G. Giacalone, Phys. Rev. Lett. 125, 192301 (2020)