Insights into the evolution of hadronic collisions with flow observables

NBI Heavy-ion Seminar, Copenhagen

Vytautas Vislavicius, Lund University, Sweden

February 9th, 2023

LUND UNIVERSITY

Where (and when) are we?

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~11:20, Thursday, 9th February, 2023
Aud. A., NBI, Copenhagen, DK

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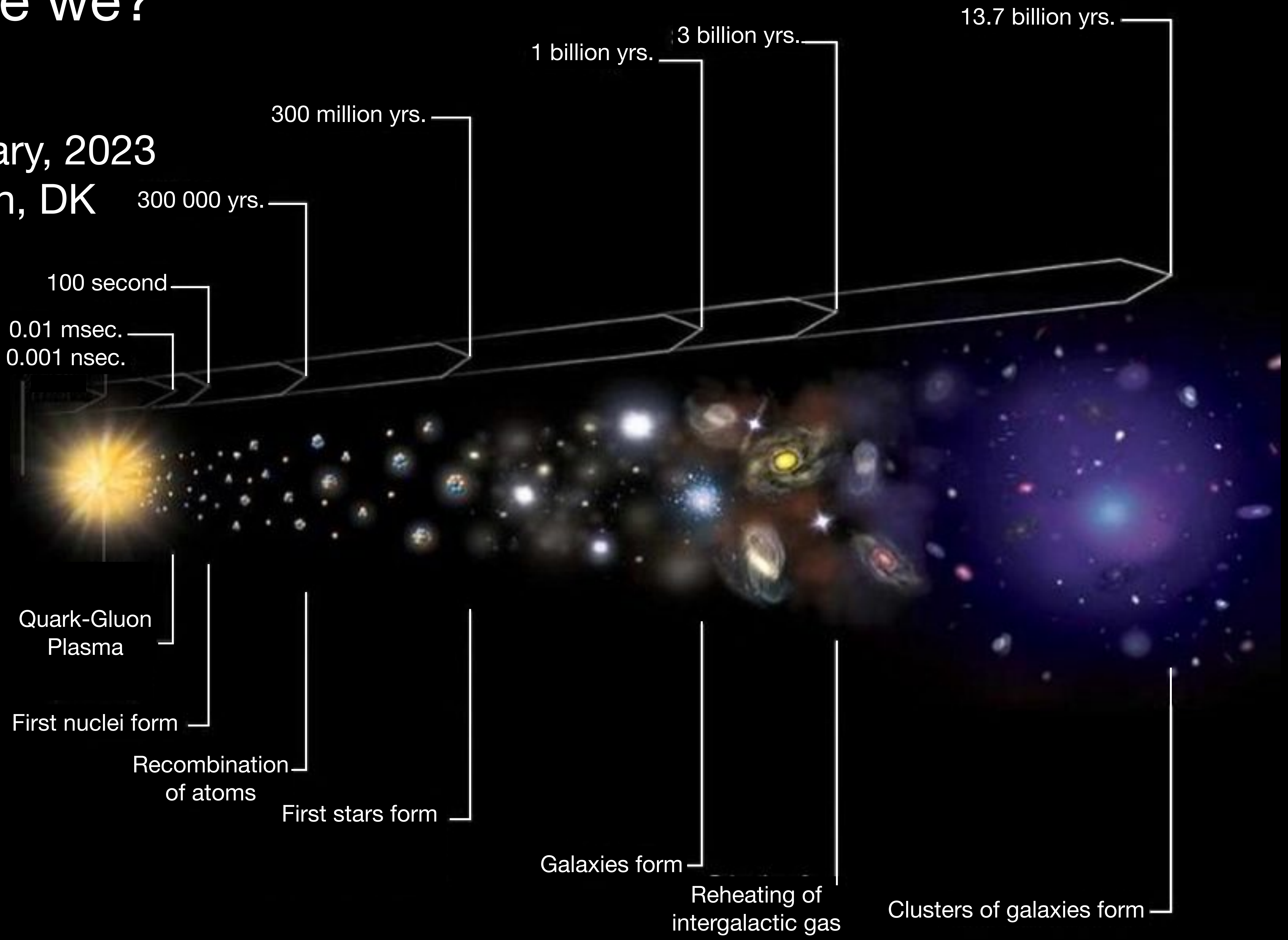

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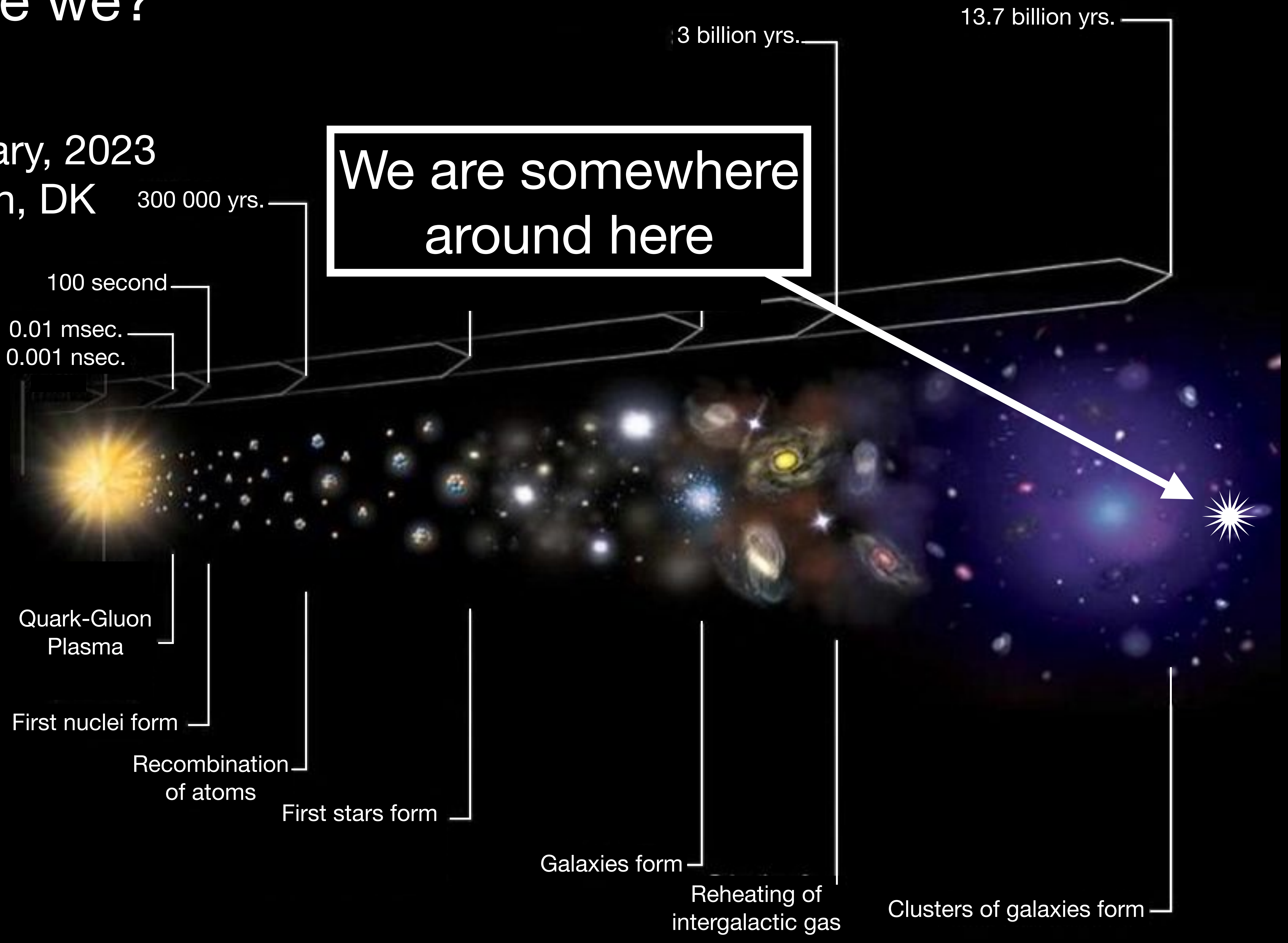
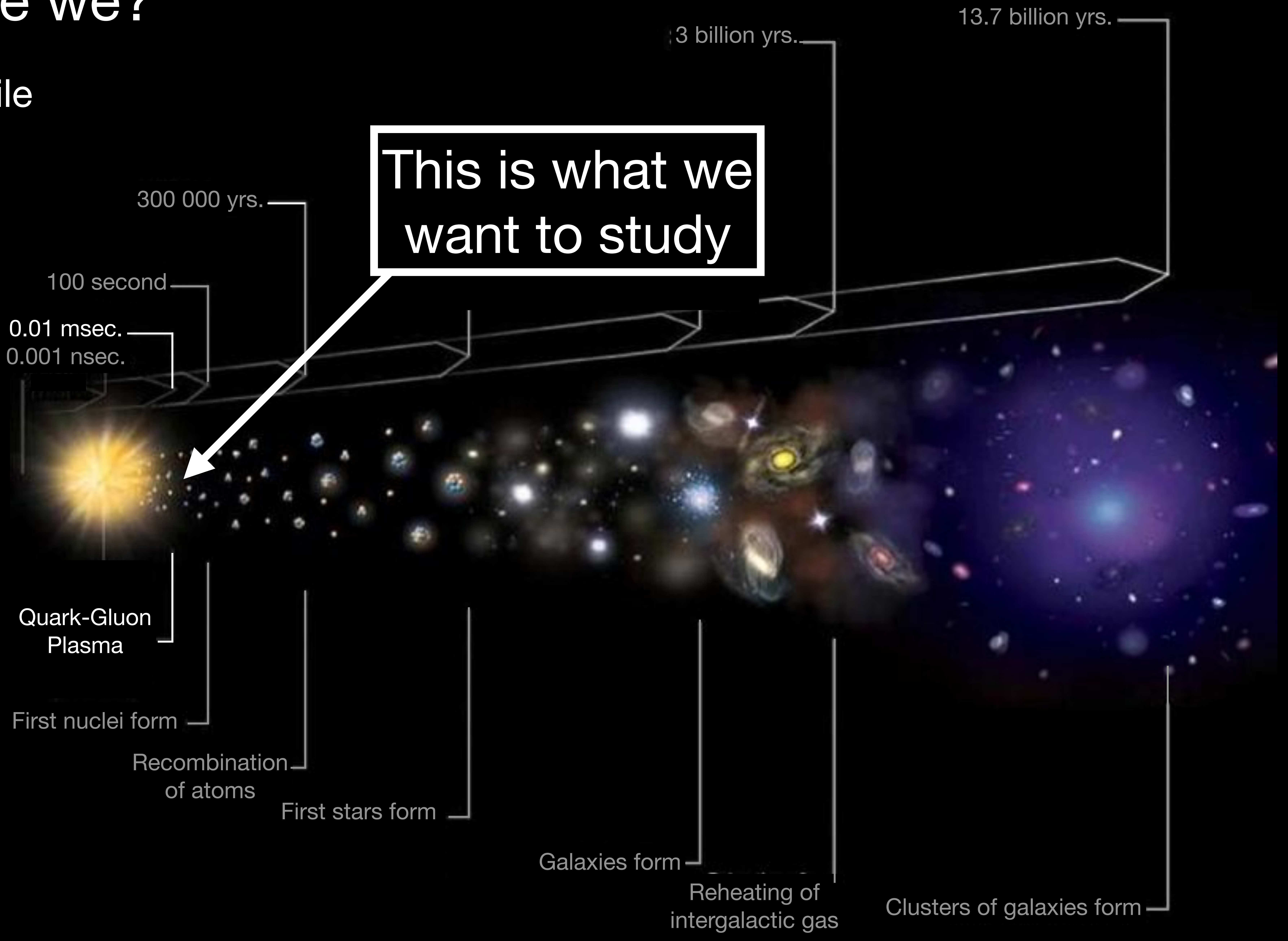


Where (and when) are we?

- Interested in extremely volatile processes that happened 13+ billion years ago



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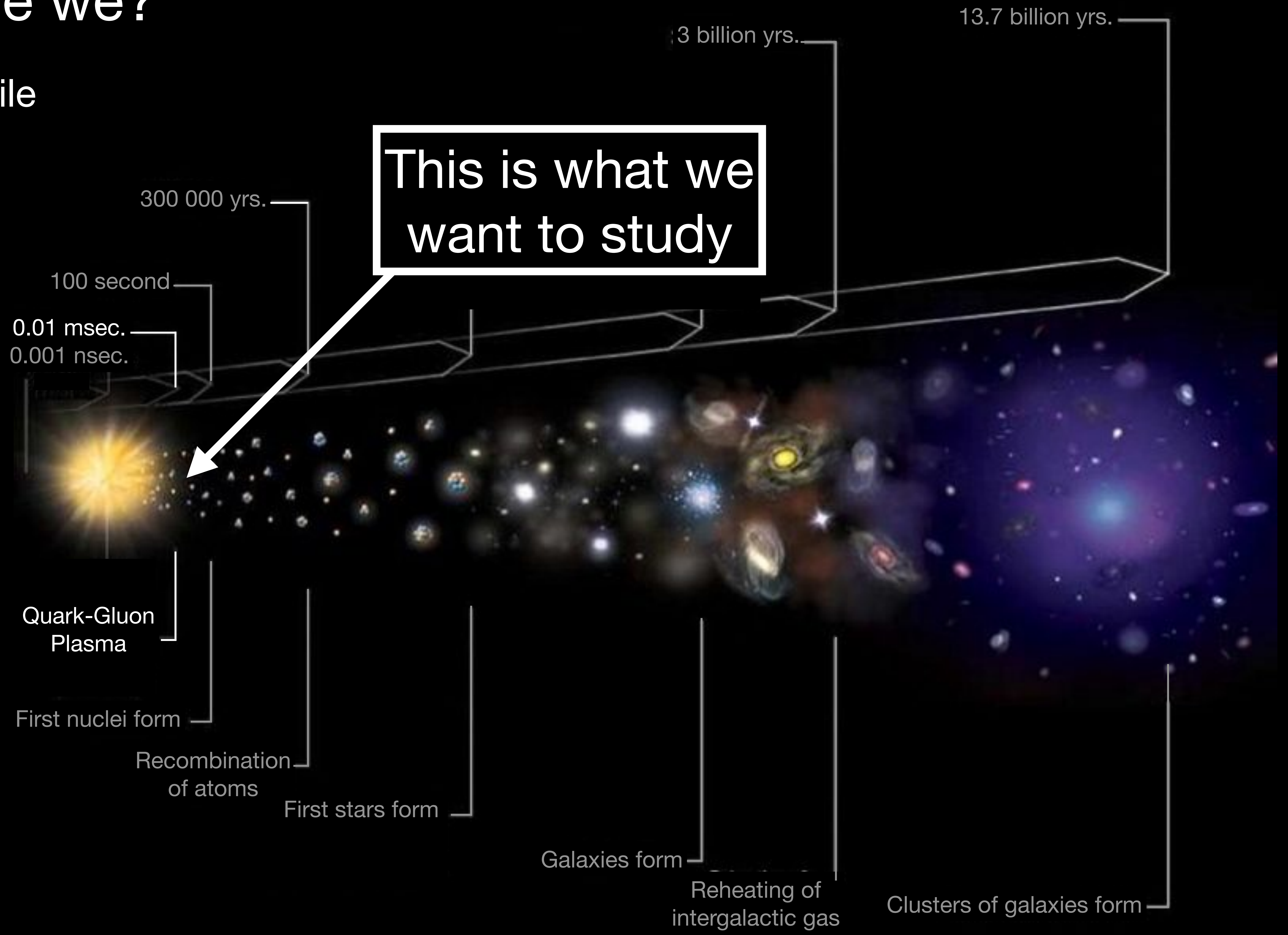
- Don't have means, knowledge, or resources to make new Big Bang(s)



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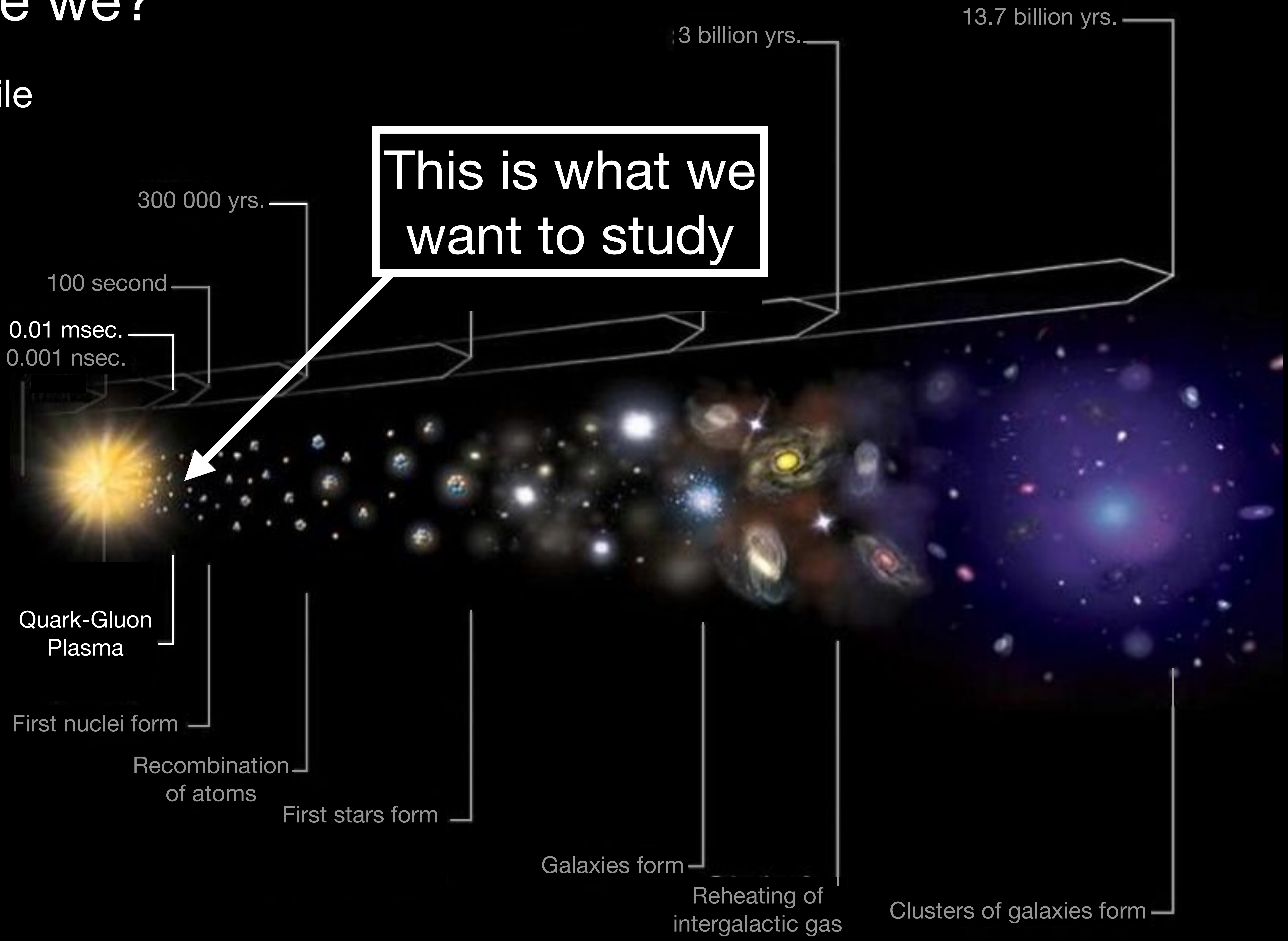

Where (and when) are we?

- Interested in extremely volatile processes that happened 13+ billion years ago
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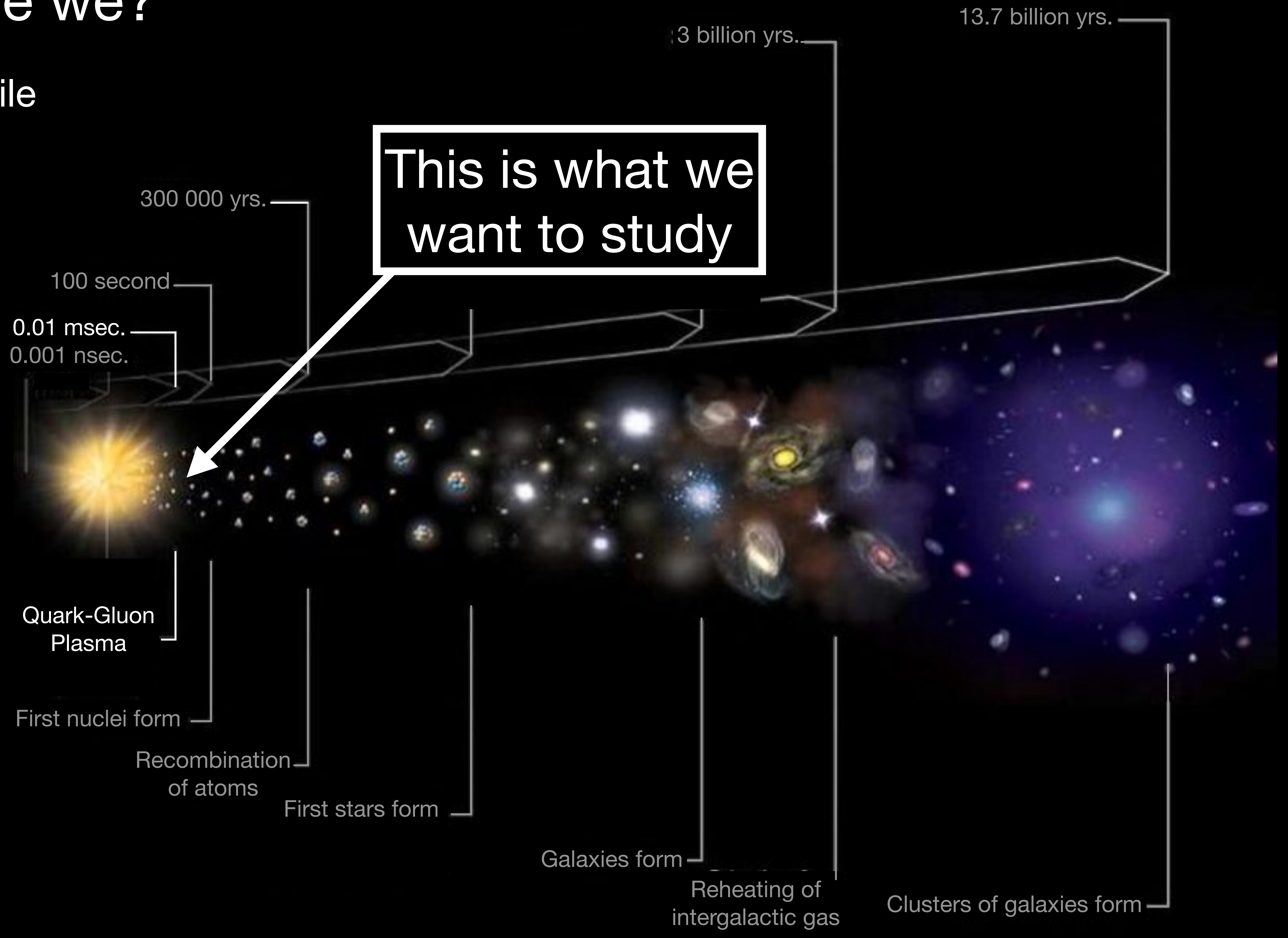
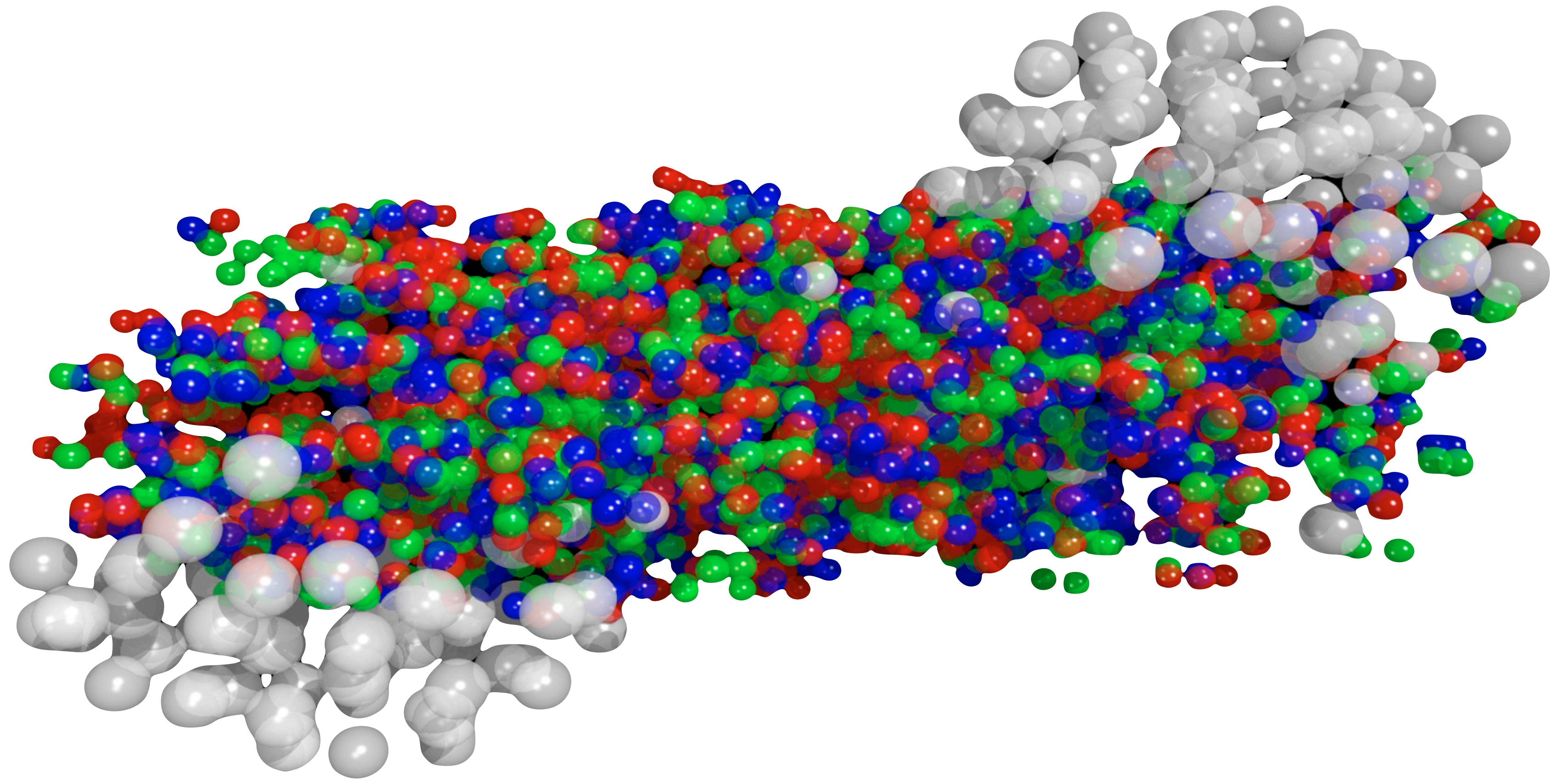
- …
- But we can produce small droplets of QGP by smashing heavy ions* at relativistic energies



From collisions to measurements



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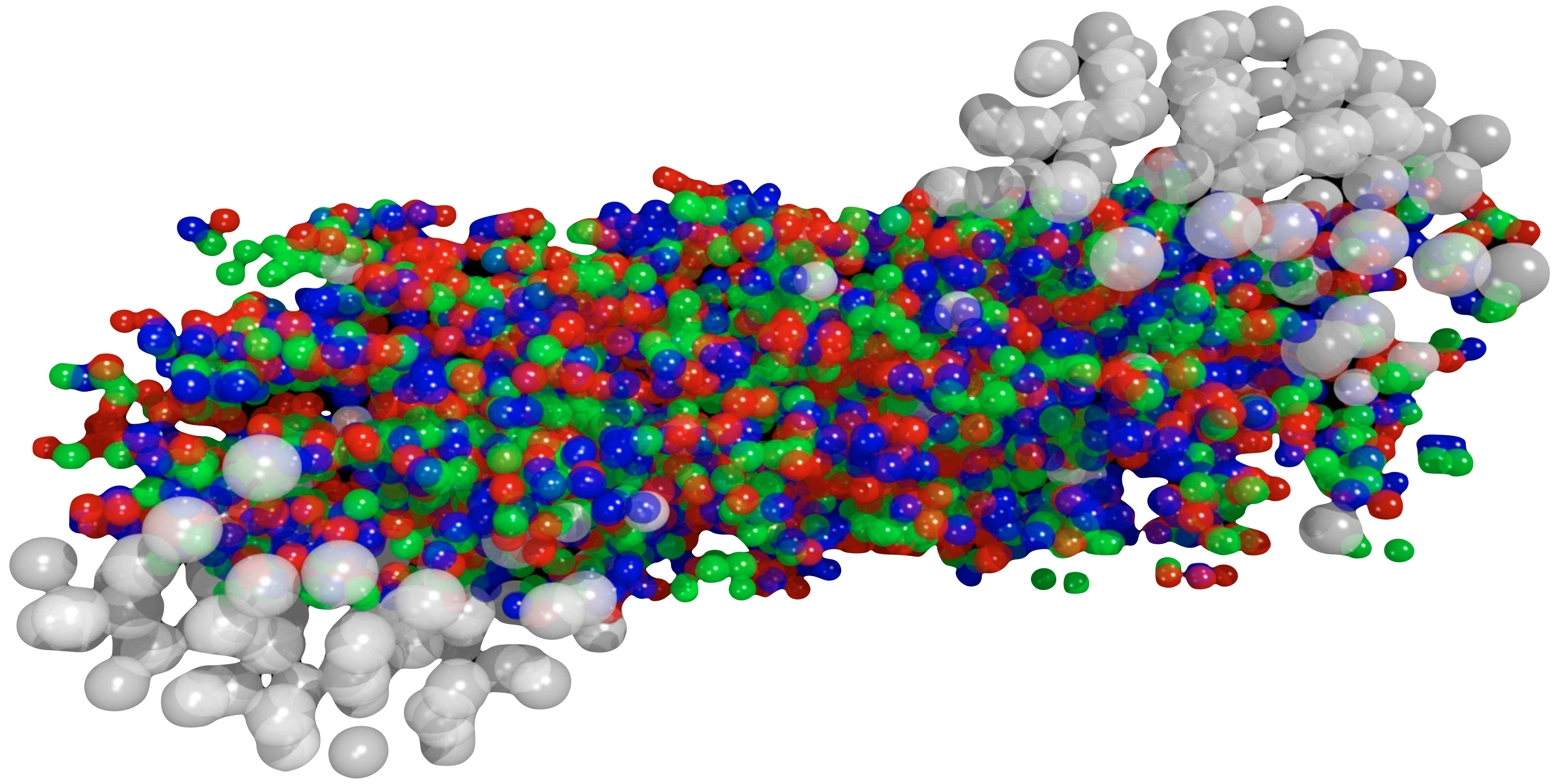
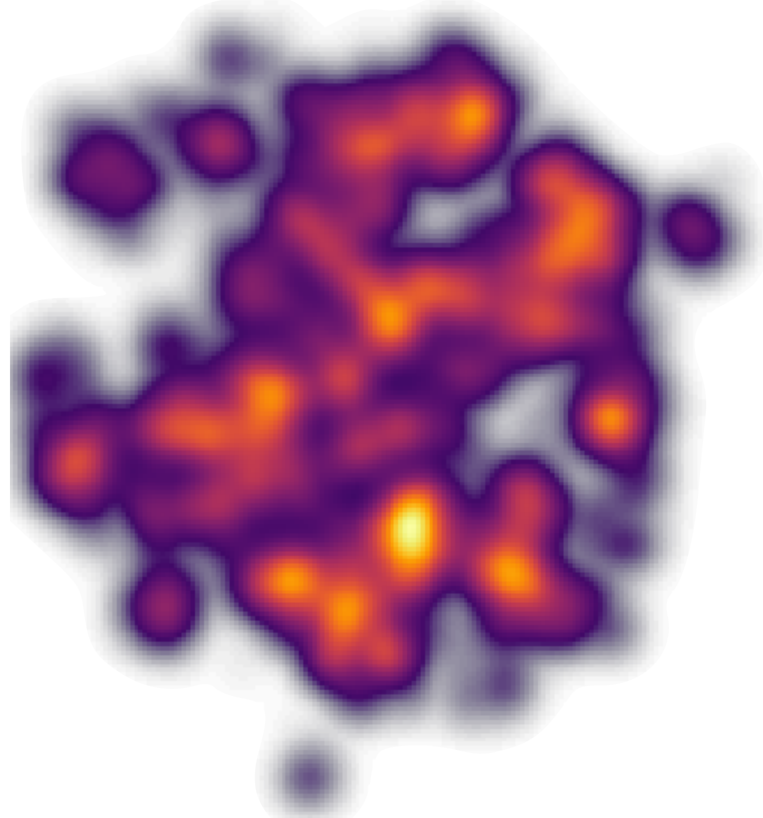
- Overlap between colliding nuclei:
  ⇛ Initial state, geometry & its fluctuations





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

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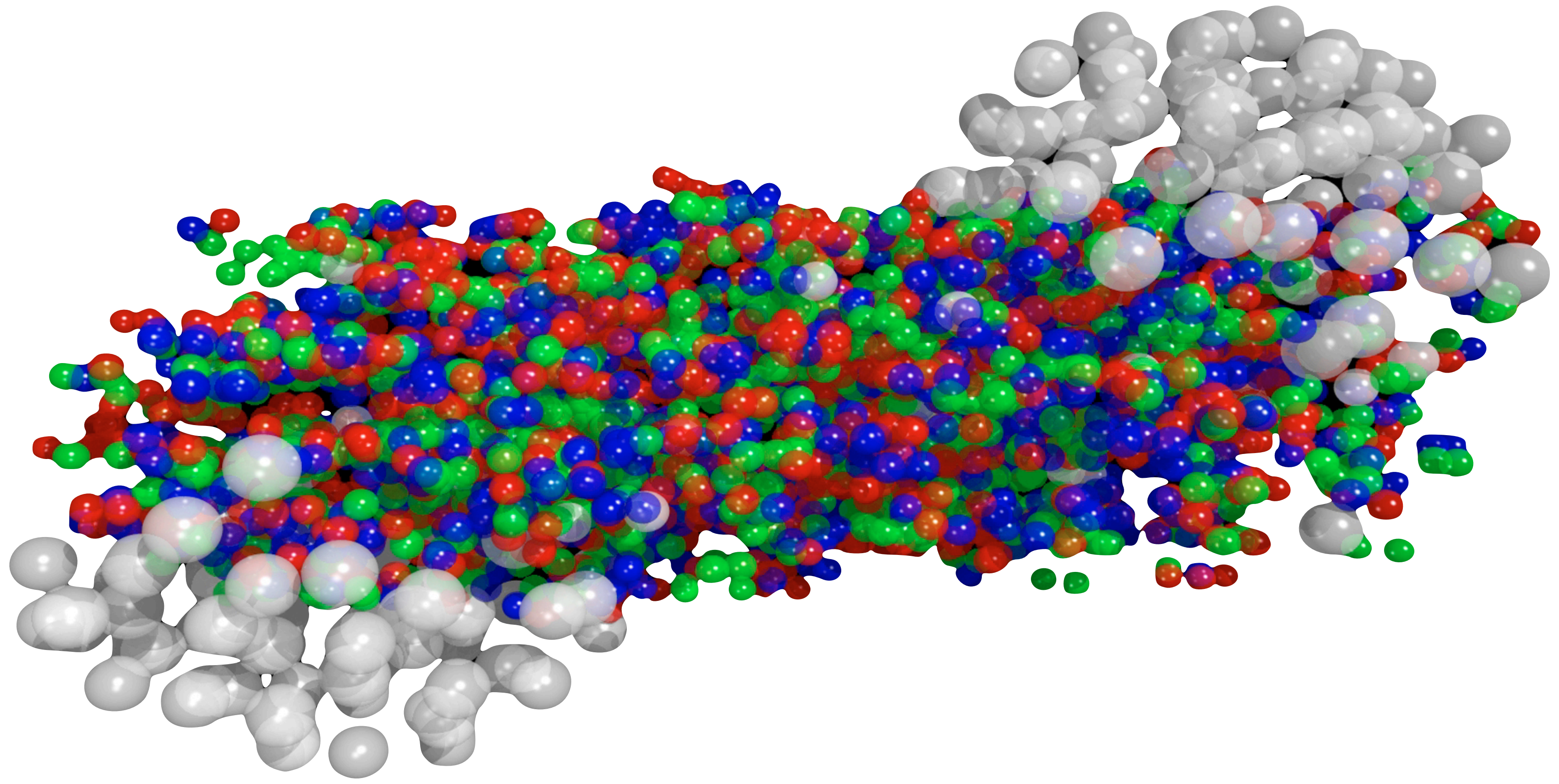
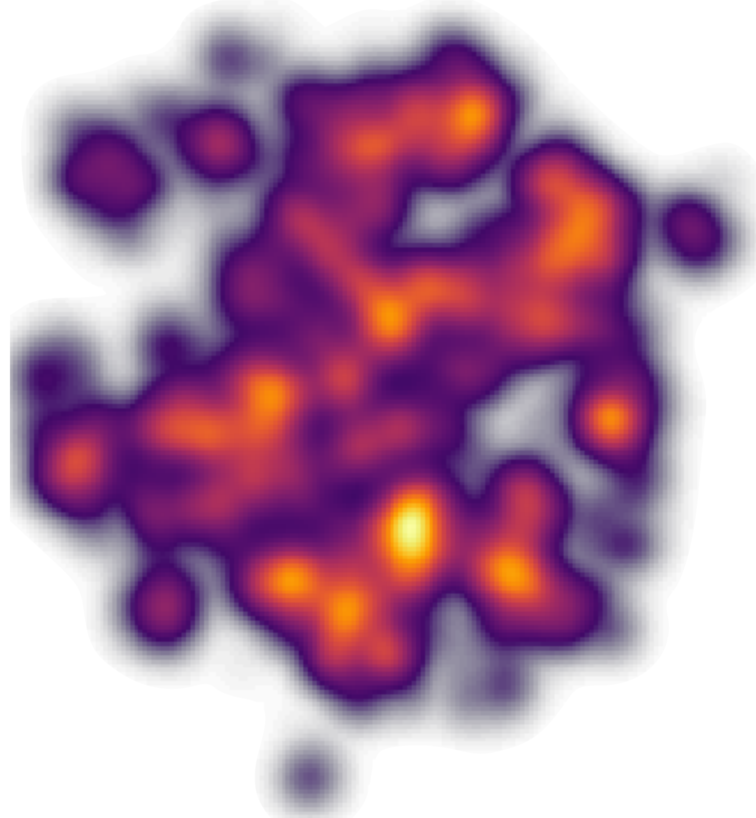
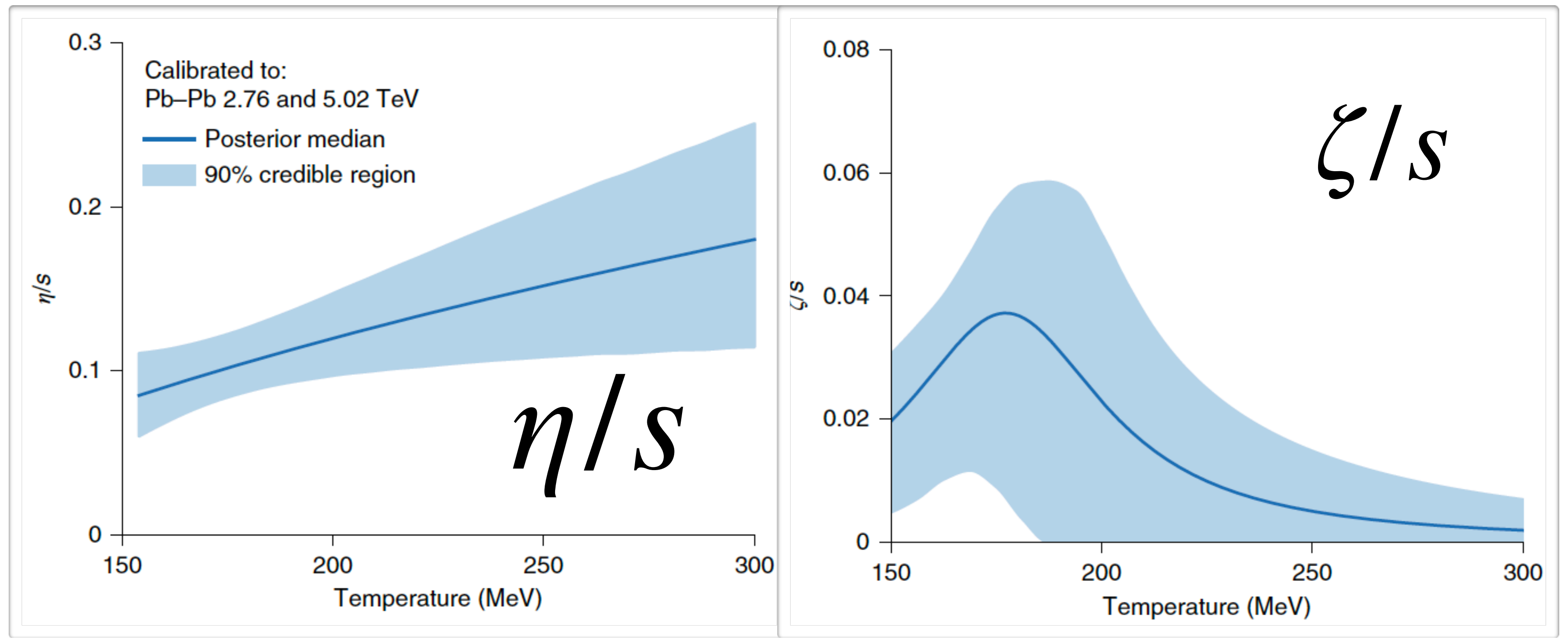
- Hydrodynamic expansion of QGP:
  ⇛ Radial and anisotropic flow, sensitive to initial state and properties of QGP







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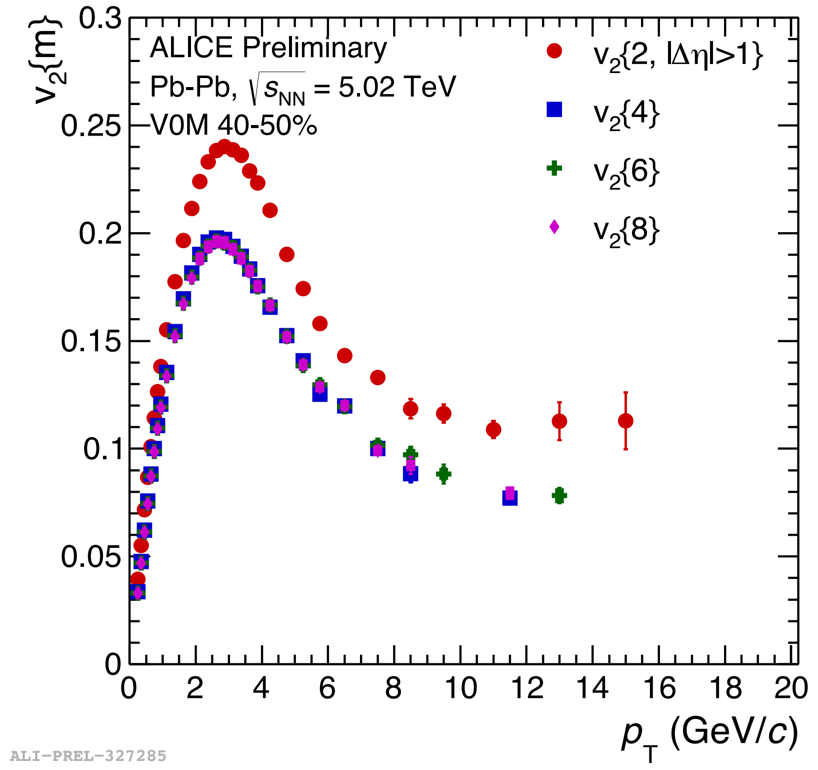

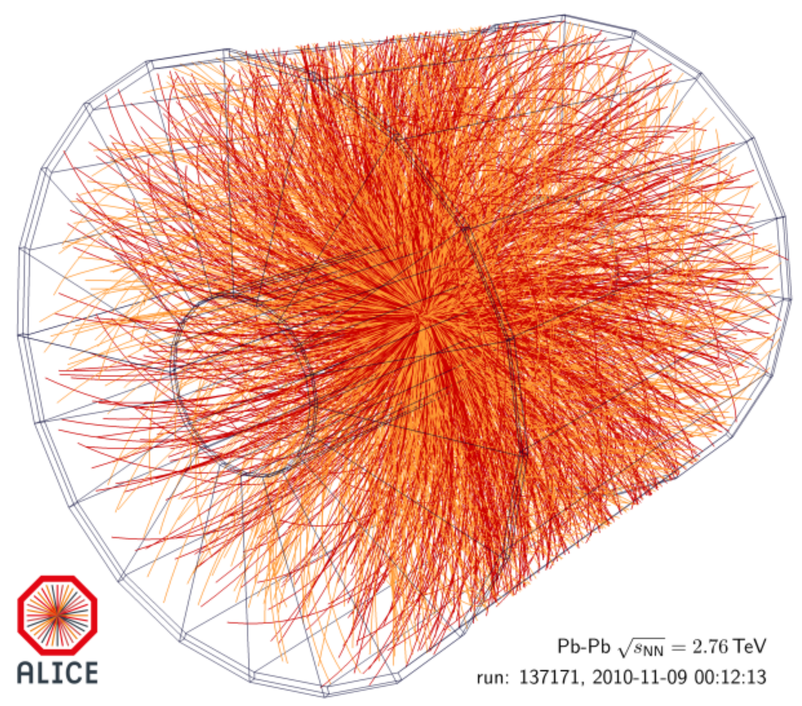

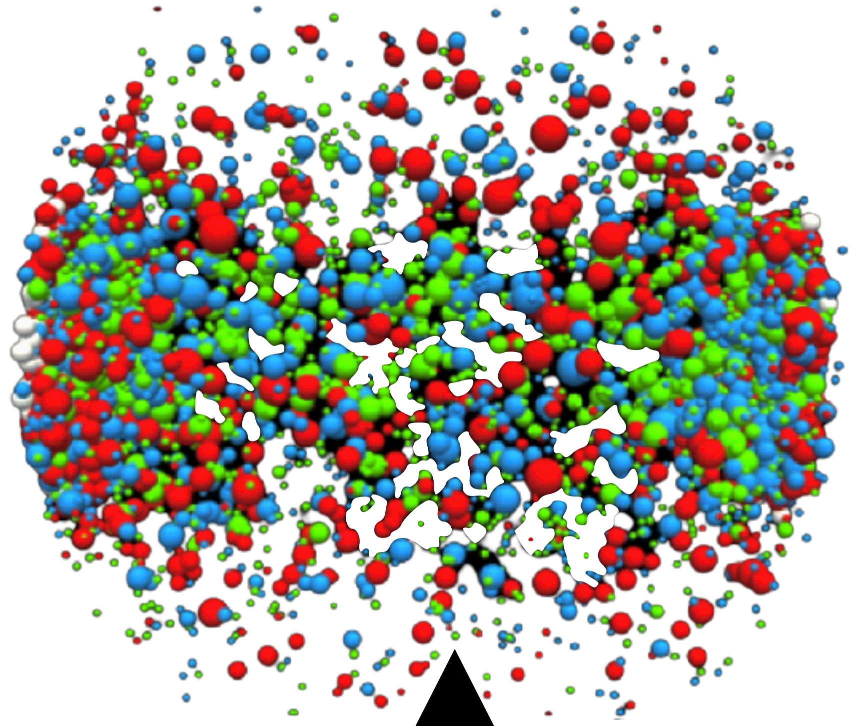

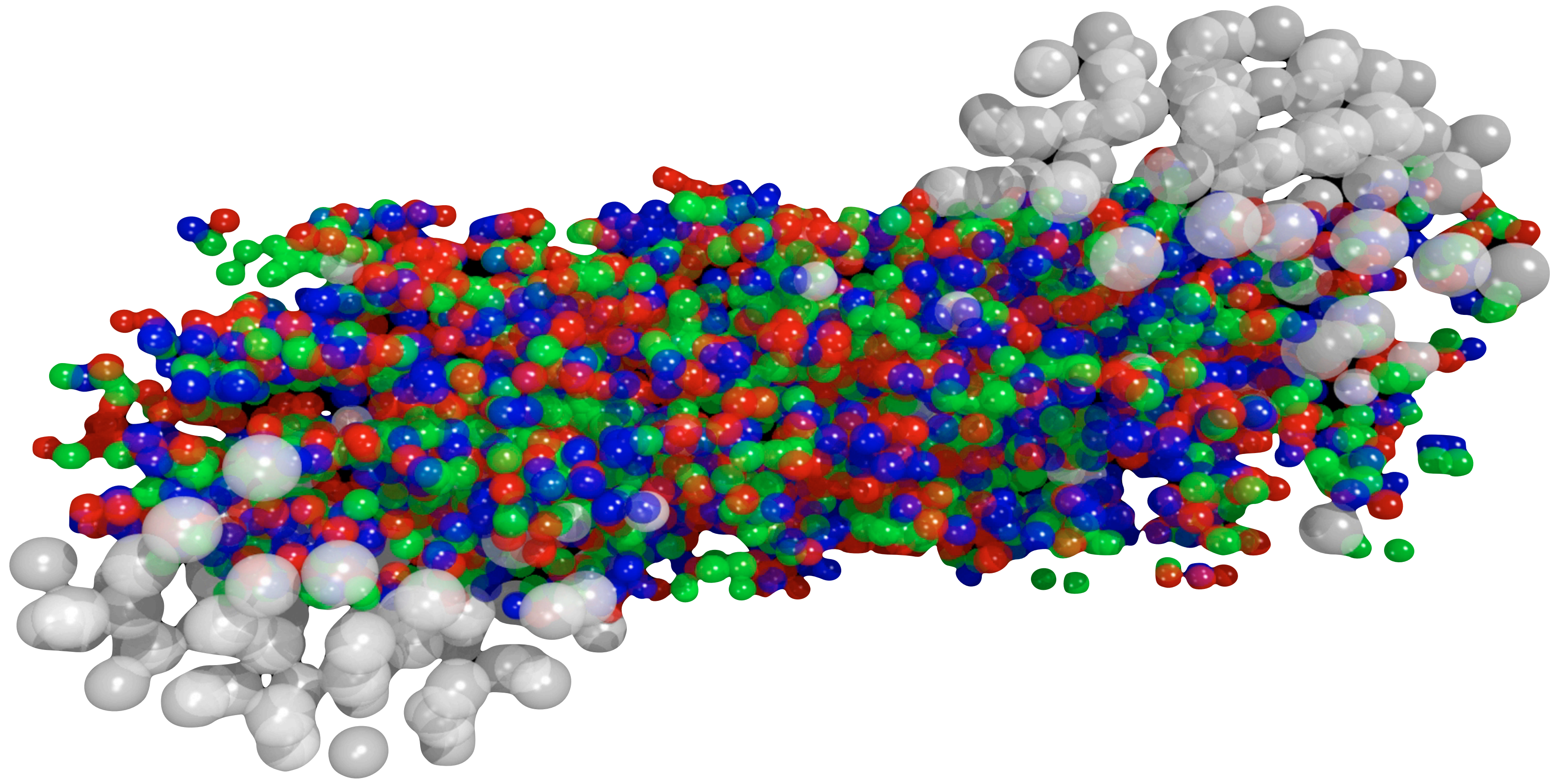

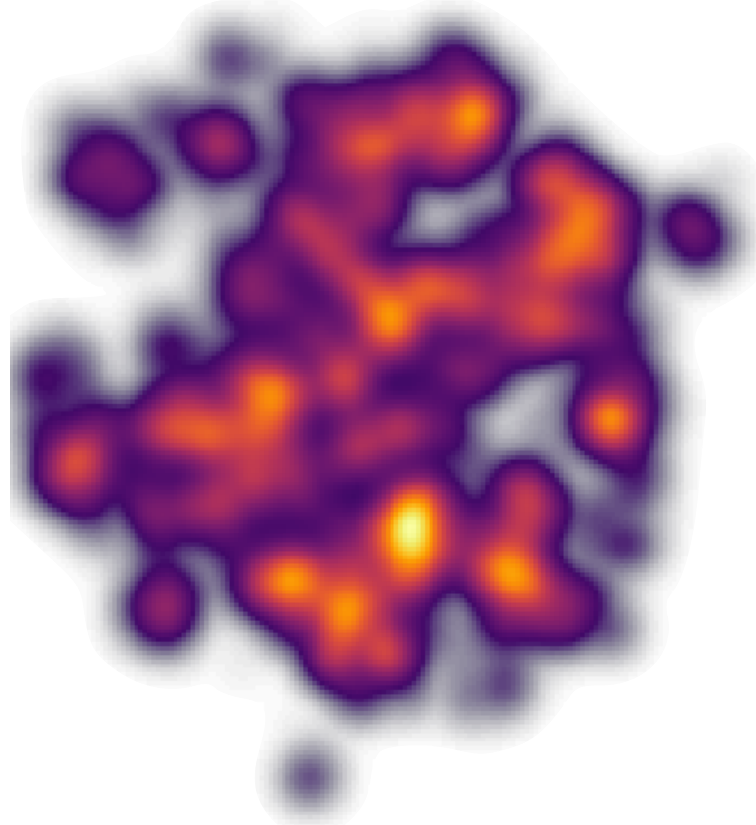

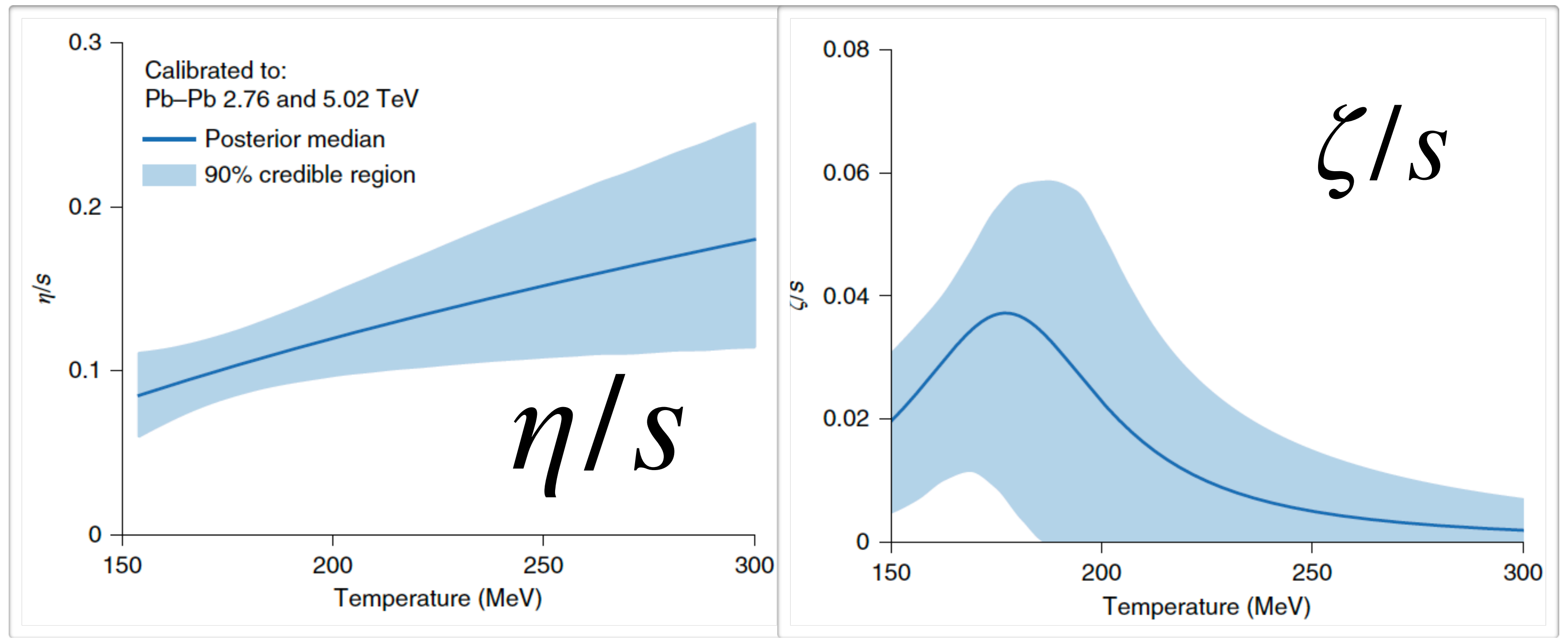

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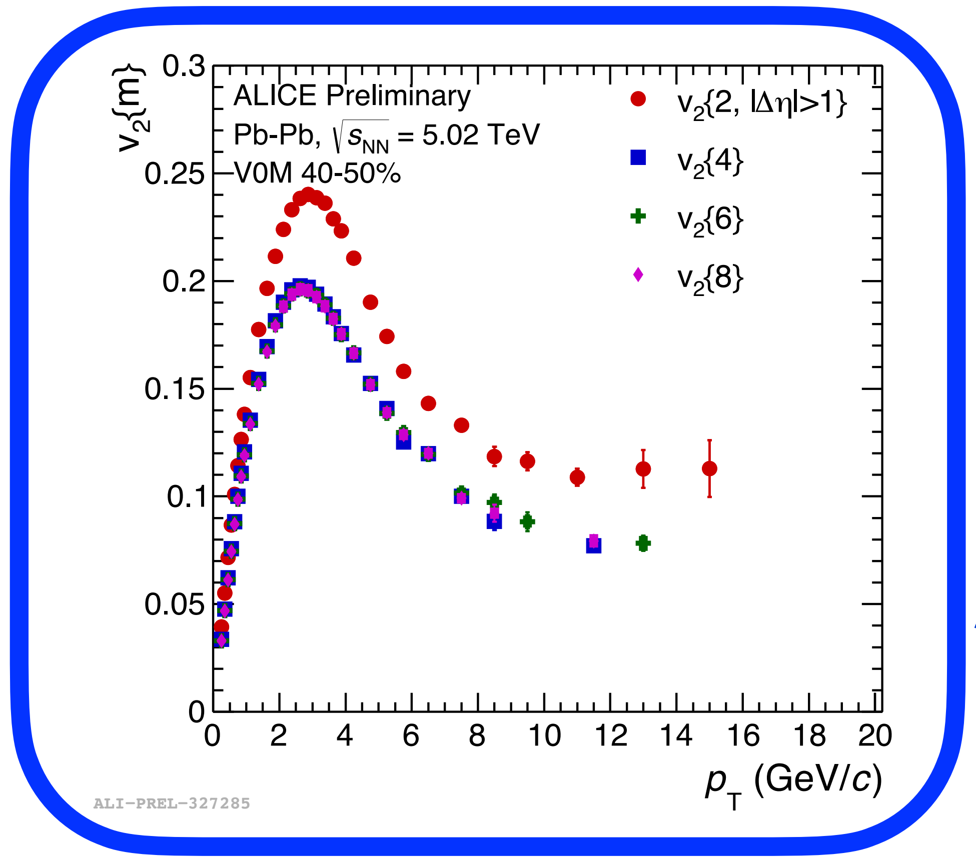
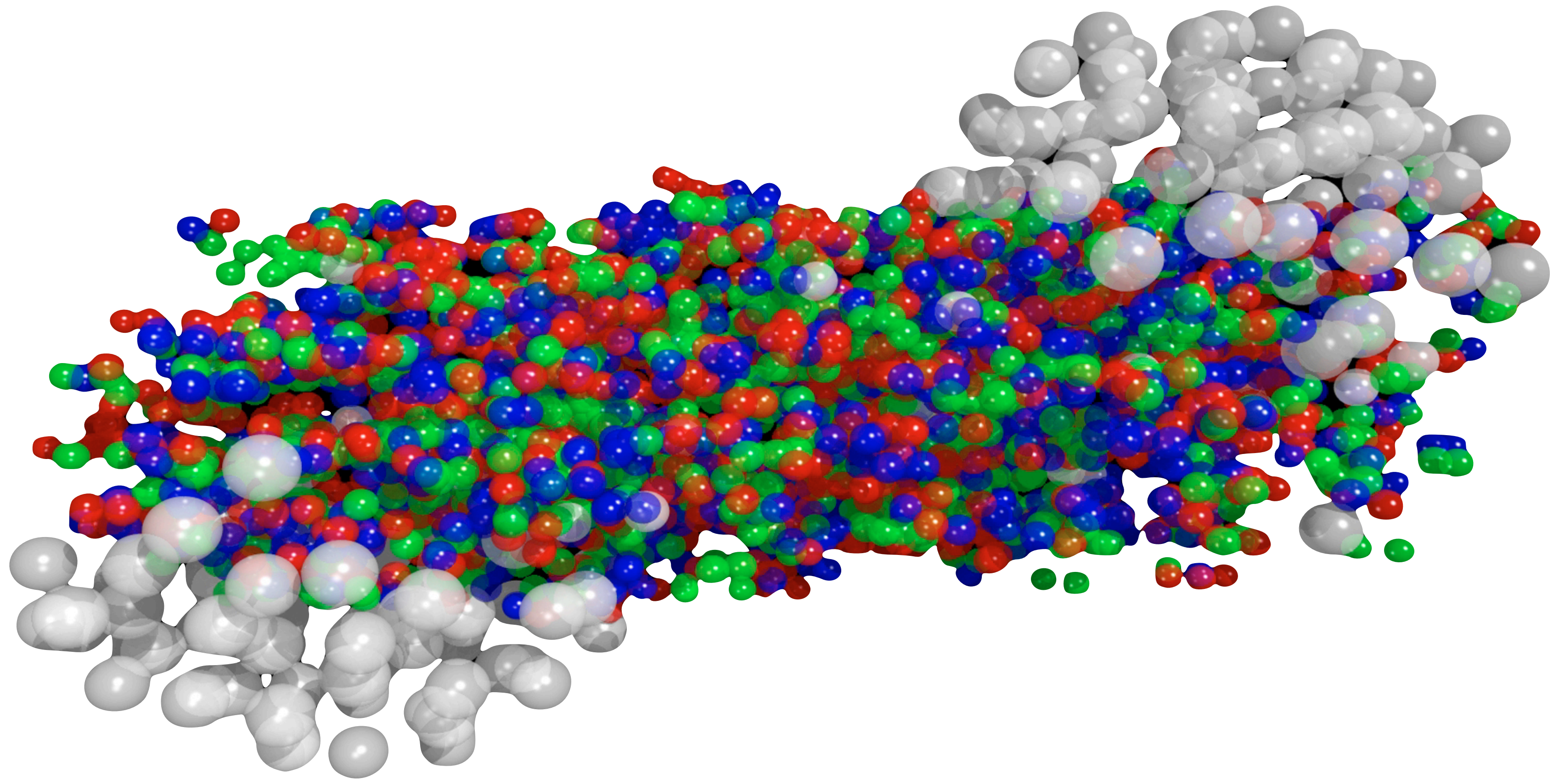
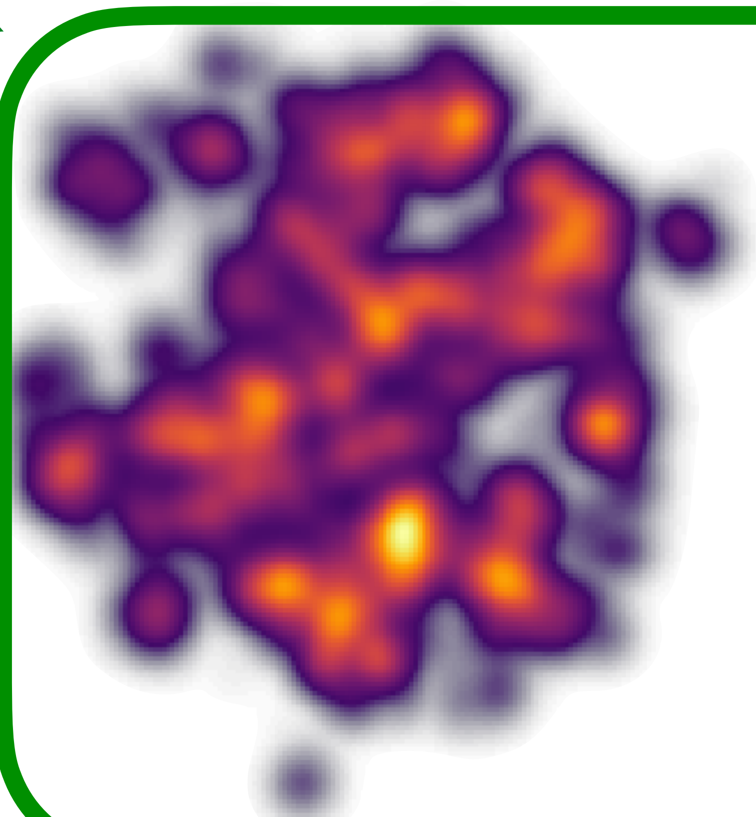
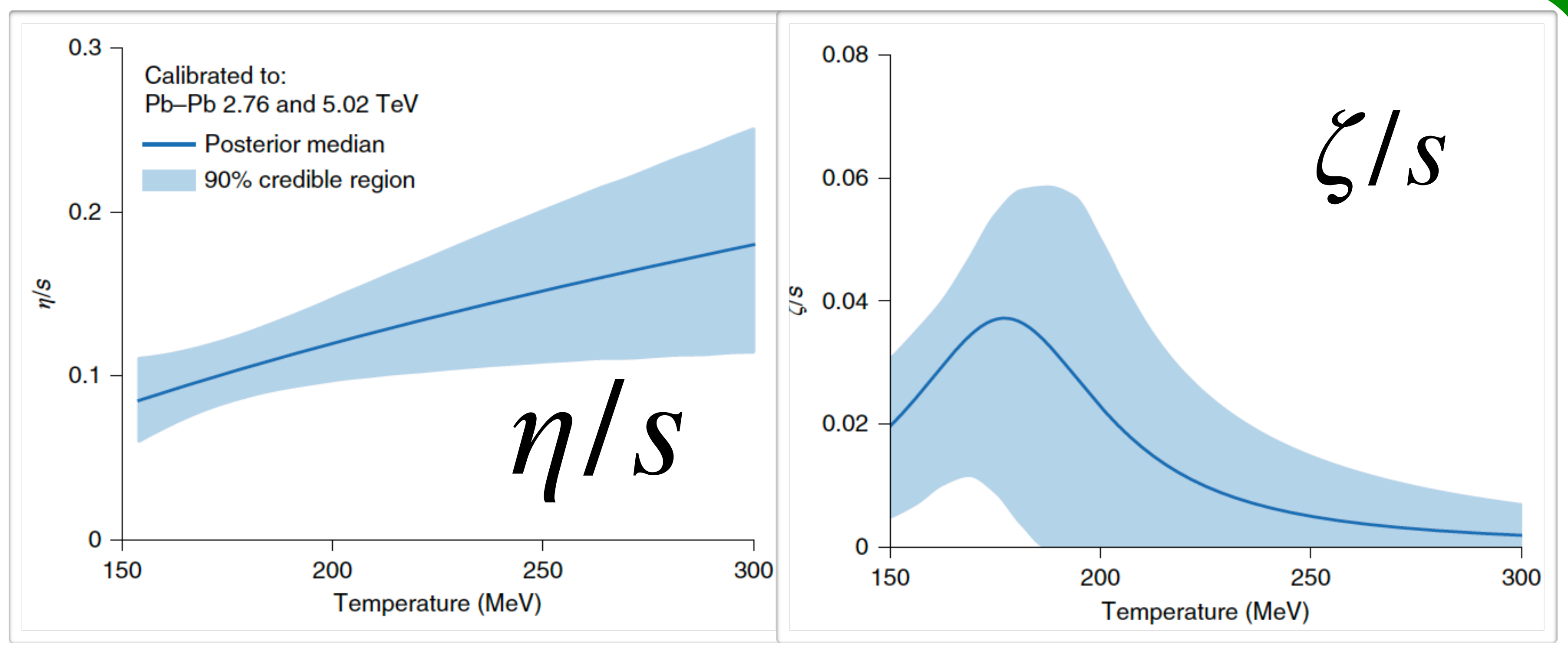
What can we learn about the initial state and properties of QGP from the measurements of radial and anisotropic flow?









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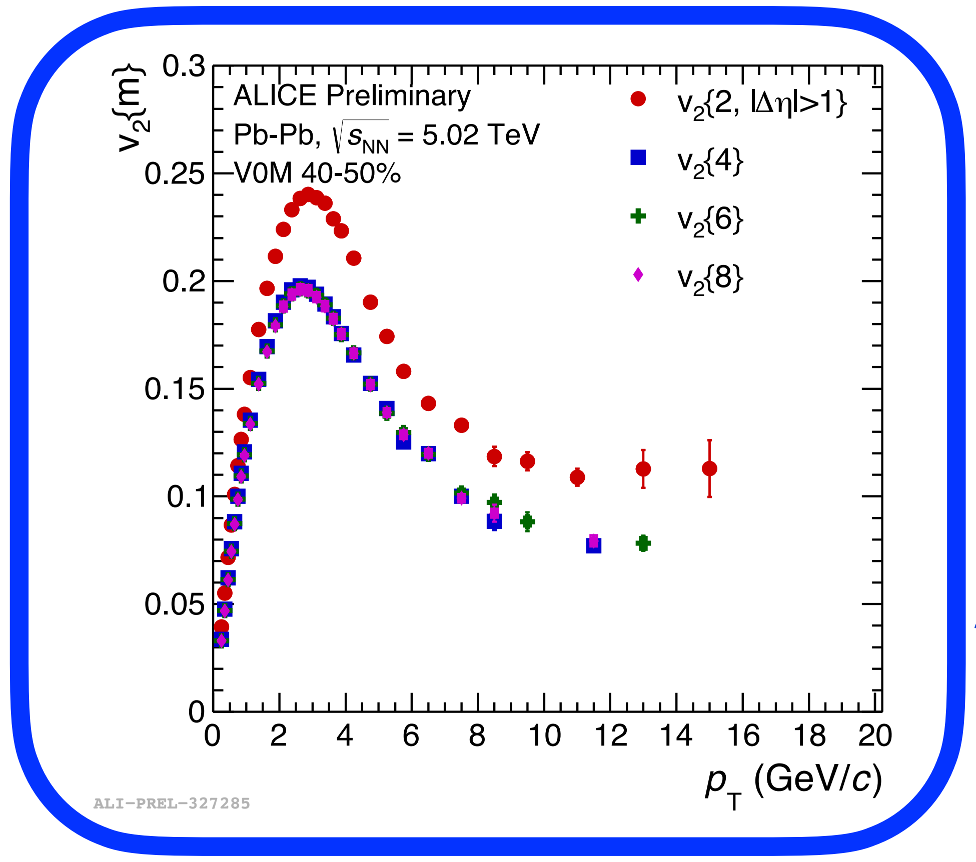
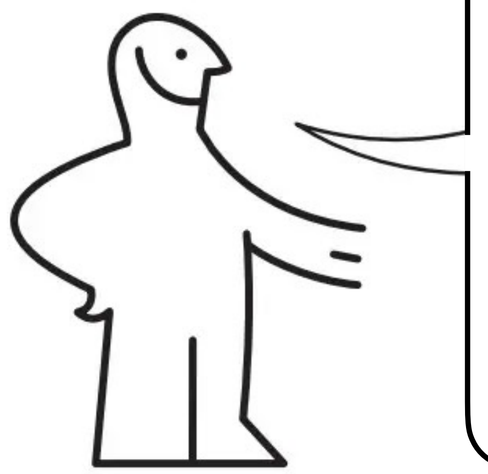
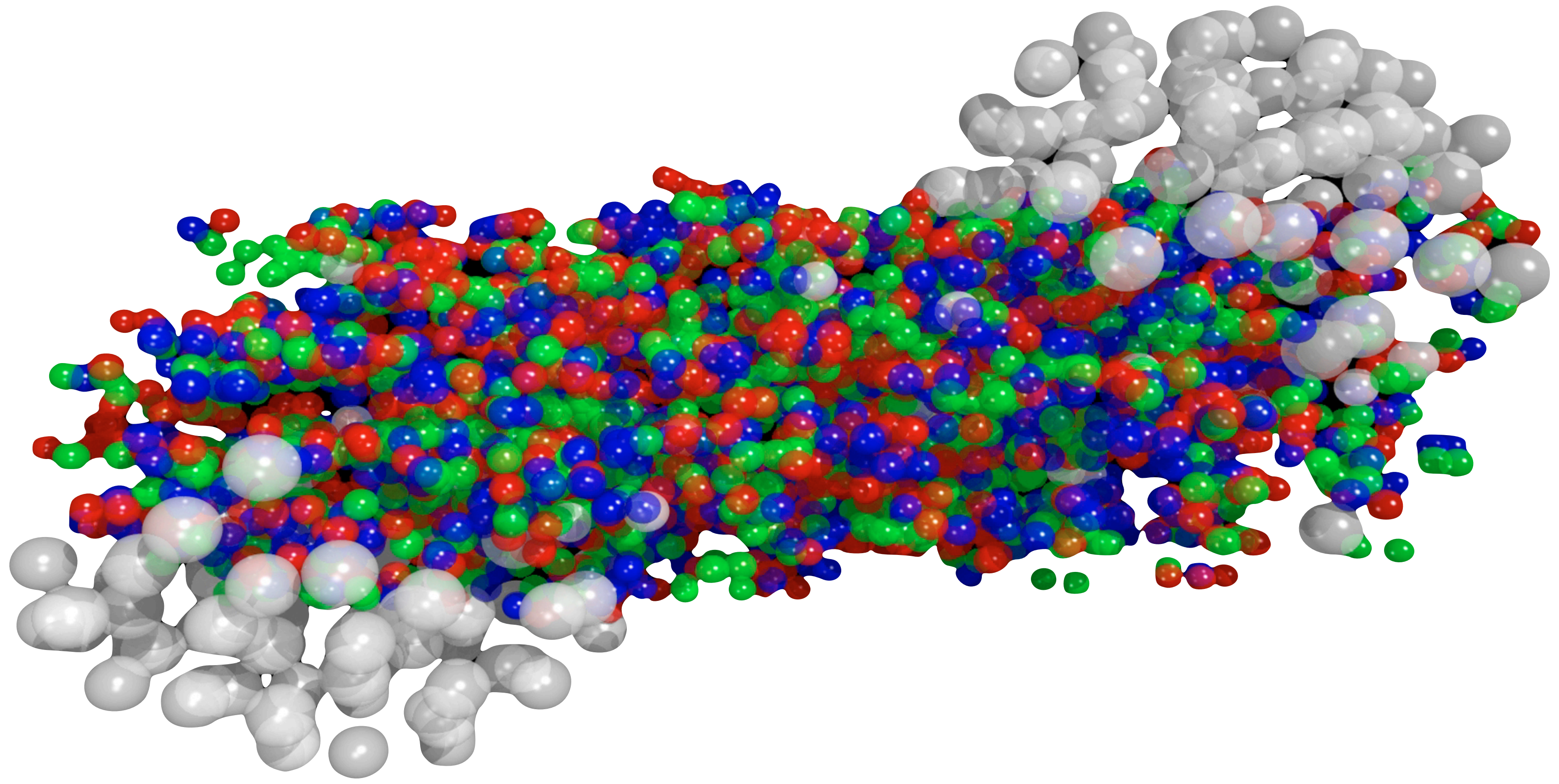
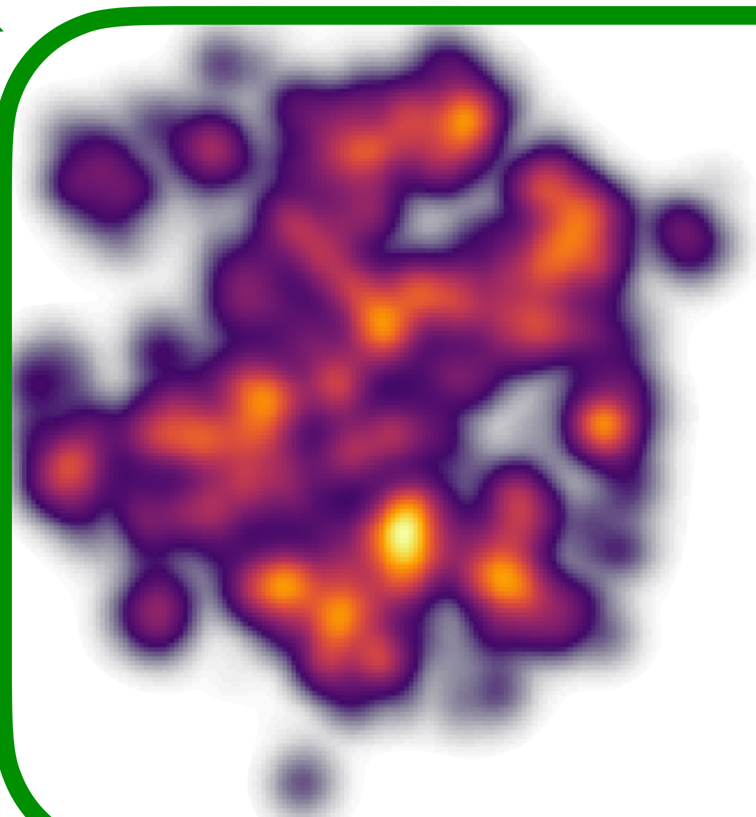
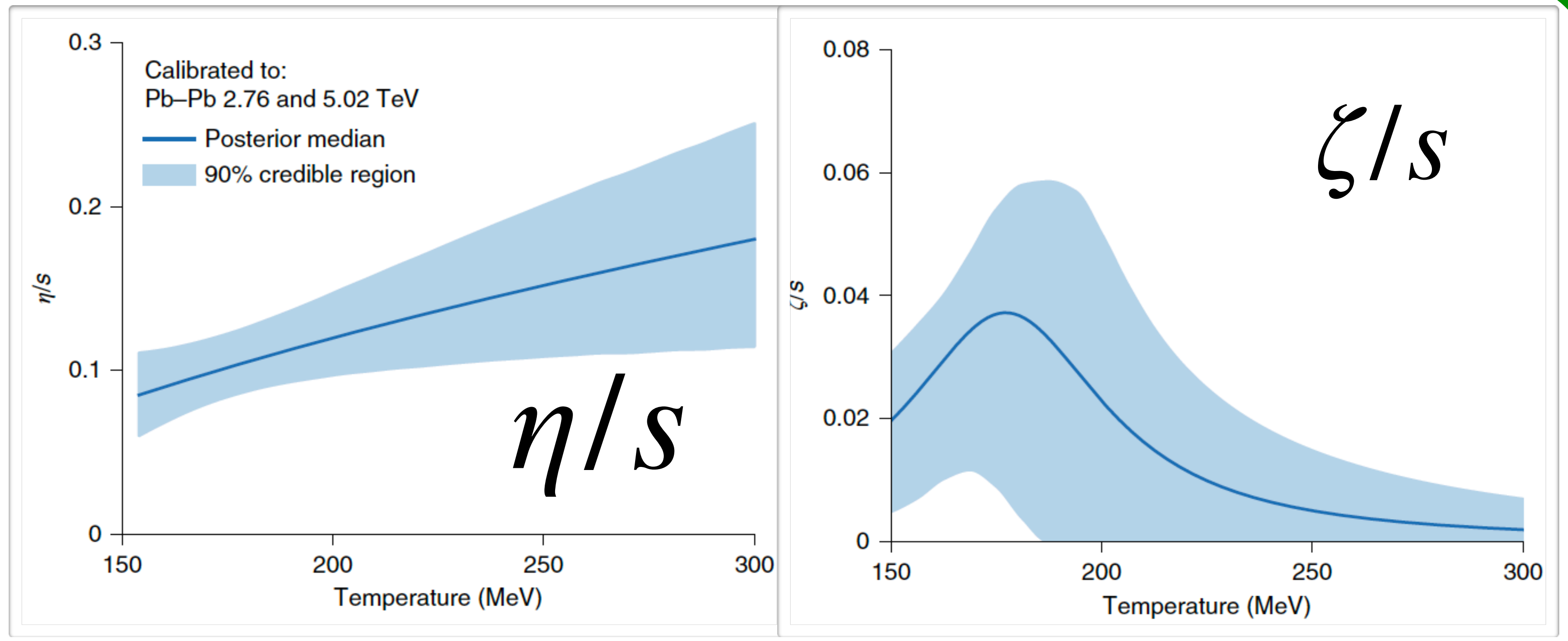




- Radial flow: boost of particles in radial direction by the expanding QGP
- Anisotropic flow: azimuthal asymmetries in particle production, eg elliptic flow v_2







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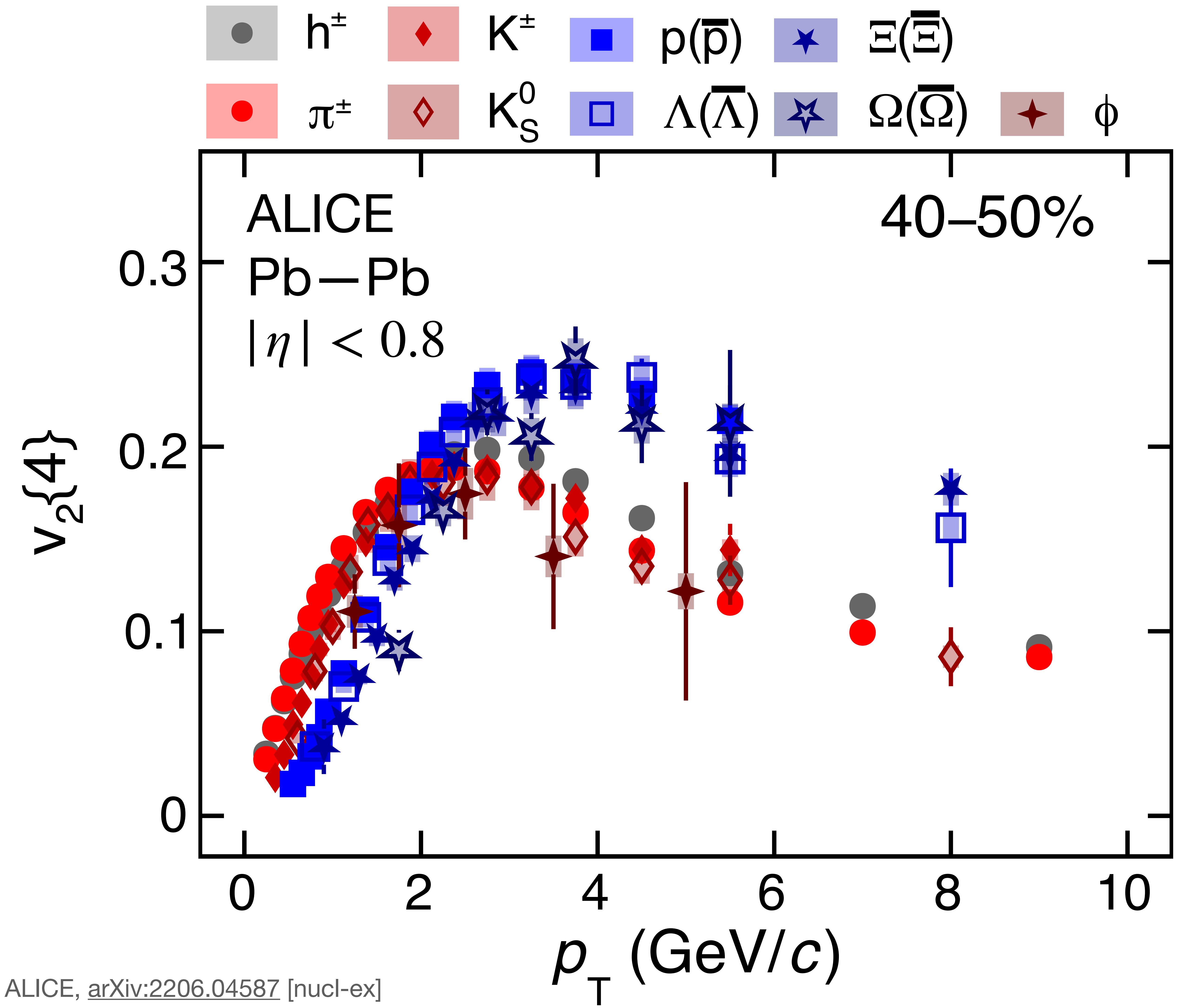
v_2 of baryons and mesons in Pb—Pb

- Low p_T:
  - Inverse mass ordering ⇛ expected from hydrodynamics



ALICE, arXiv:2206.04587 [nucl-ex]

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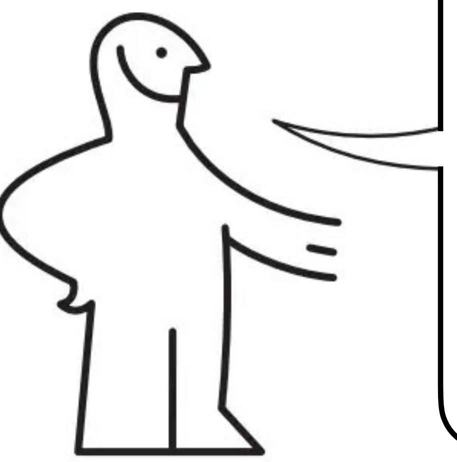
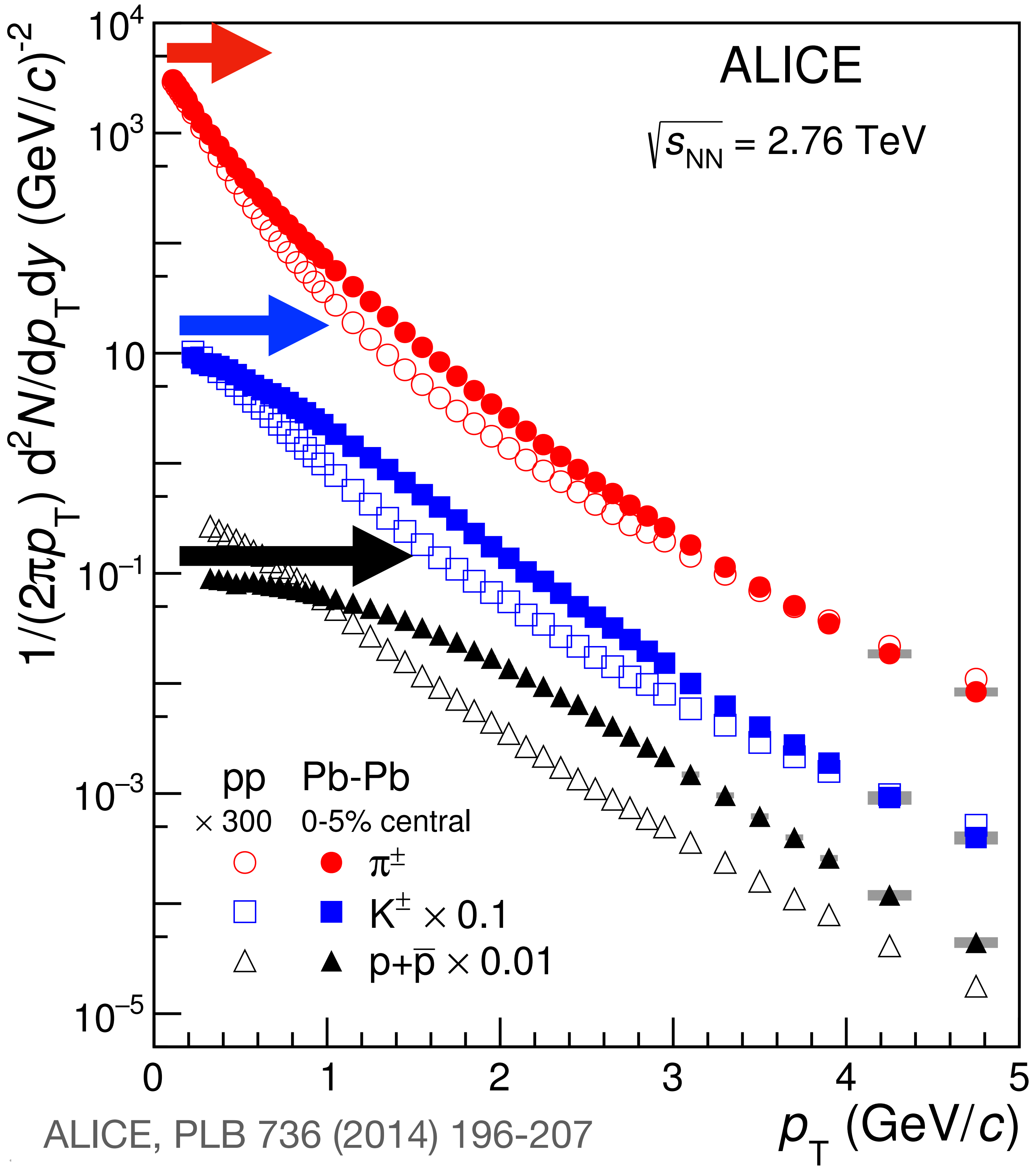
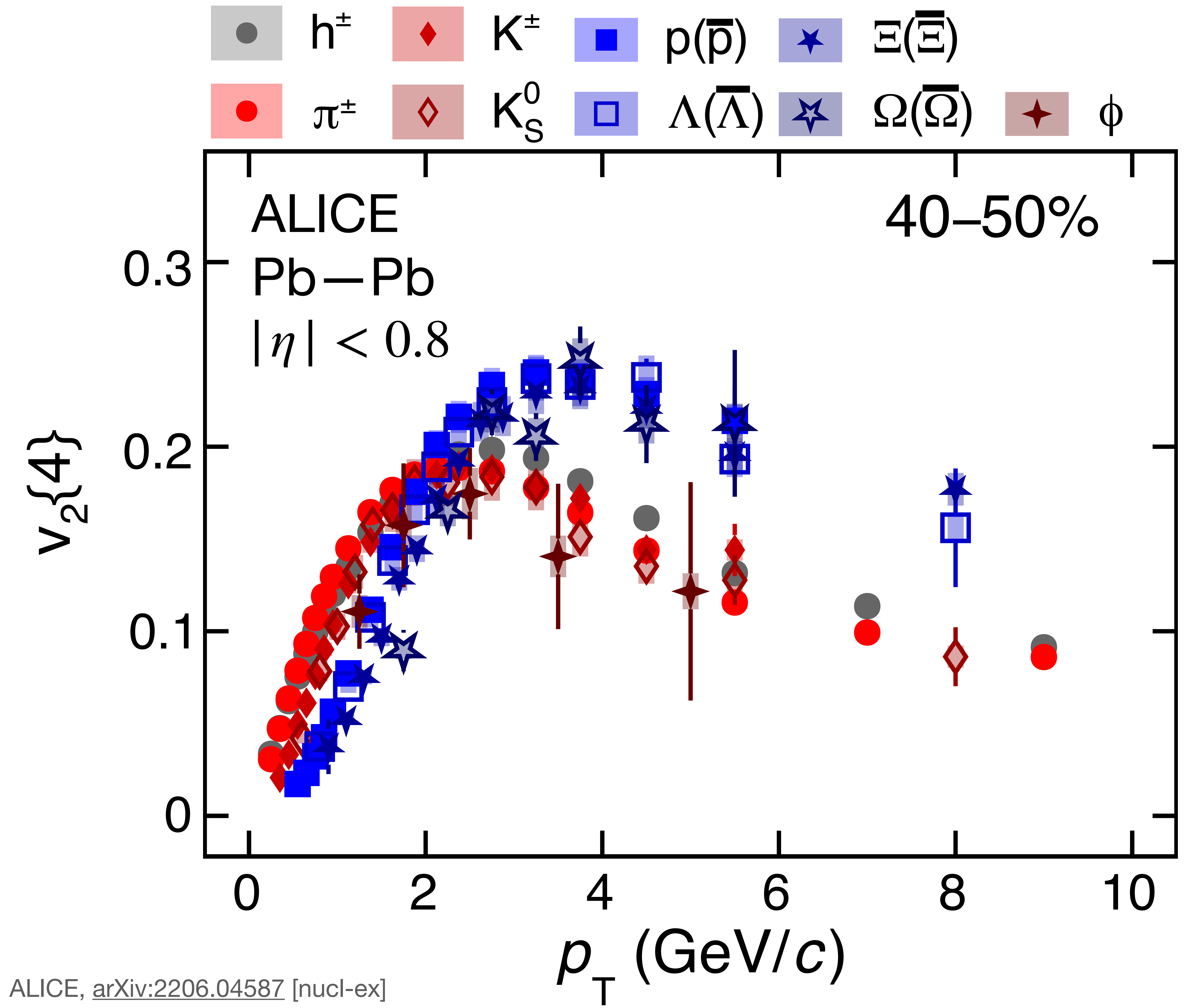


- Mass ordering at low p_T: radial flow



ALICE, PLB 736 (2014) 196-207



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v_2 of baryons and mesons in Pb—Pb

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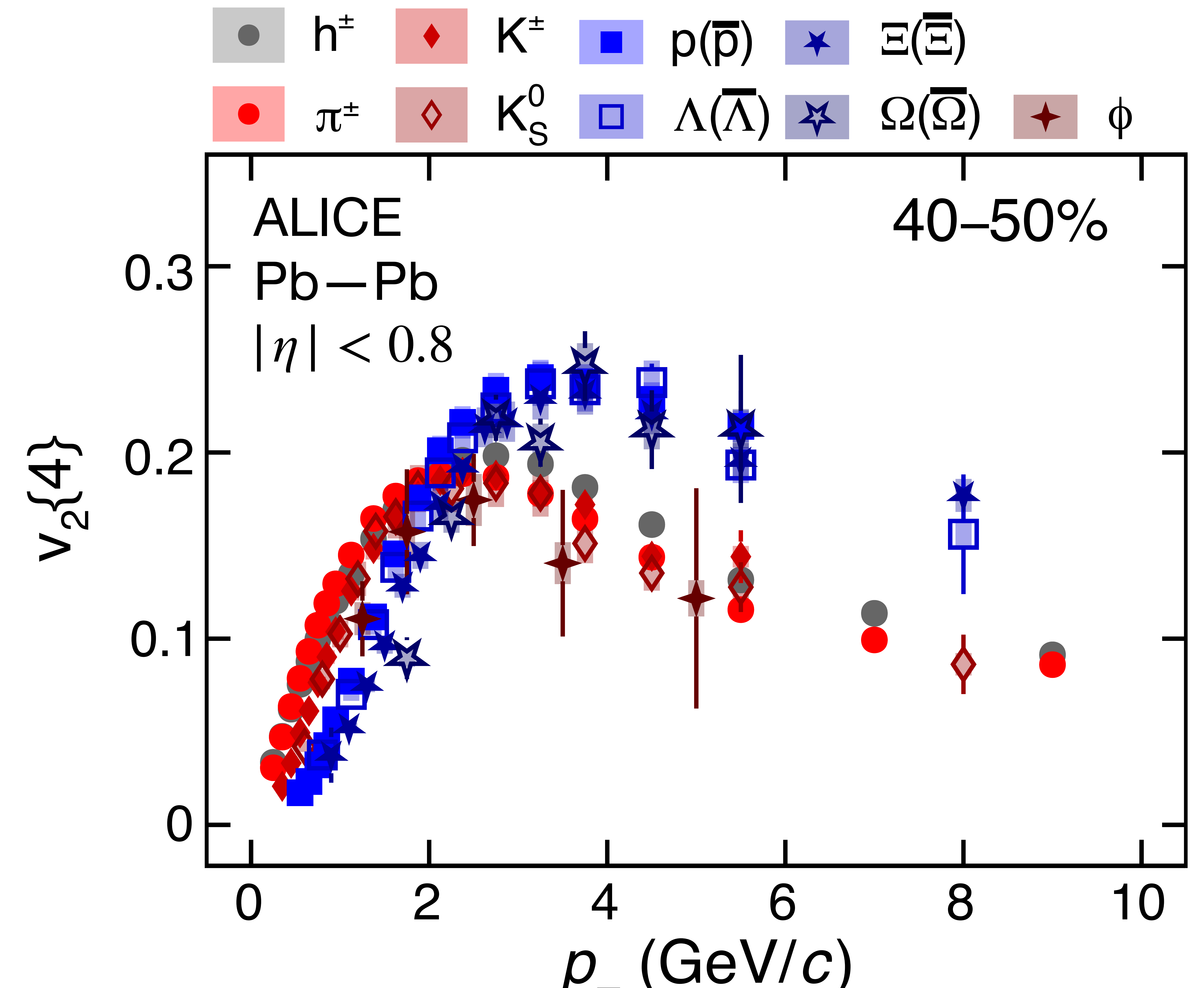
- Intermediate p_T:
  — Crossing point ⇛ radial flow and/or coalescence?



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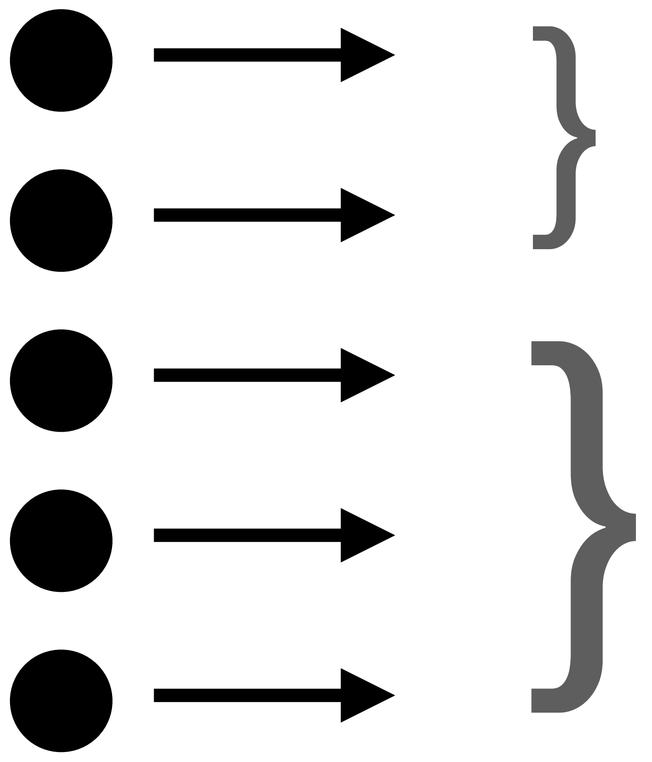
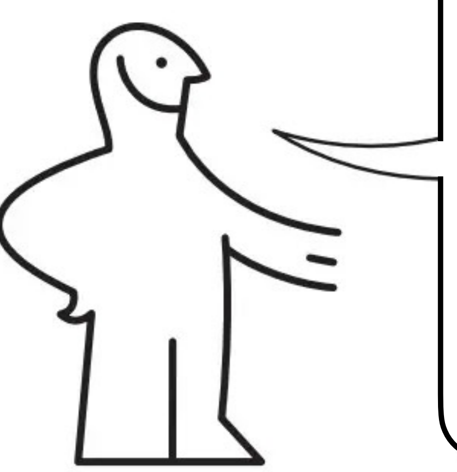
- Partonic coalescence:

p_T ~ 1 GeV/c



Meson, ~ 2 GeV/c

Baryon, ~ 3 GeV/c



Disclaimer: this is a very naive sketch

v_2 of baryons and mesons in Pb—Pb

- Low p_T:
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- Intermediate p_T:
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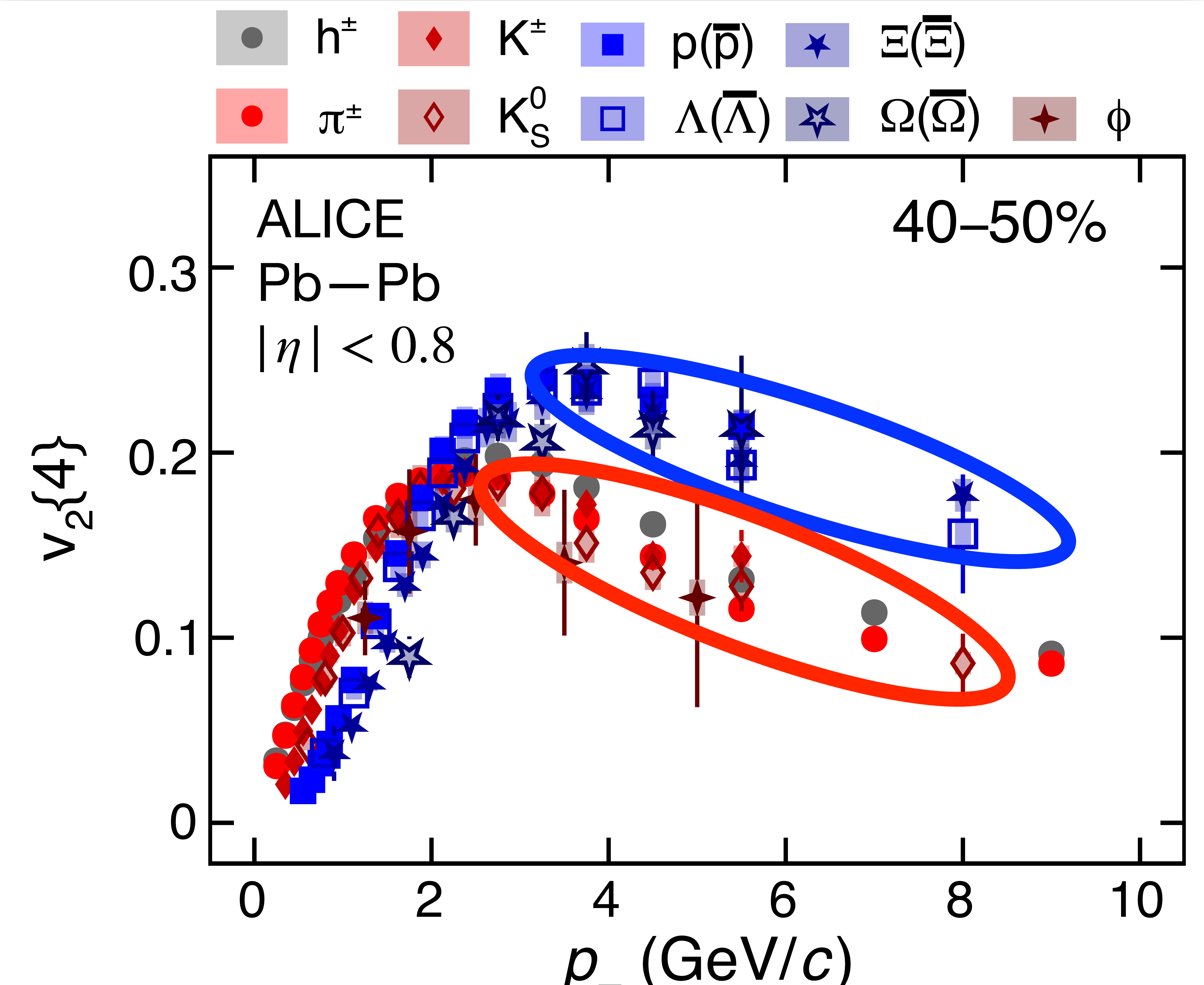
  - — Baryon/meson grouping ⇛ coalescence?
- ✳ High p_T: jet quenching [1]

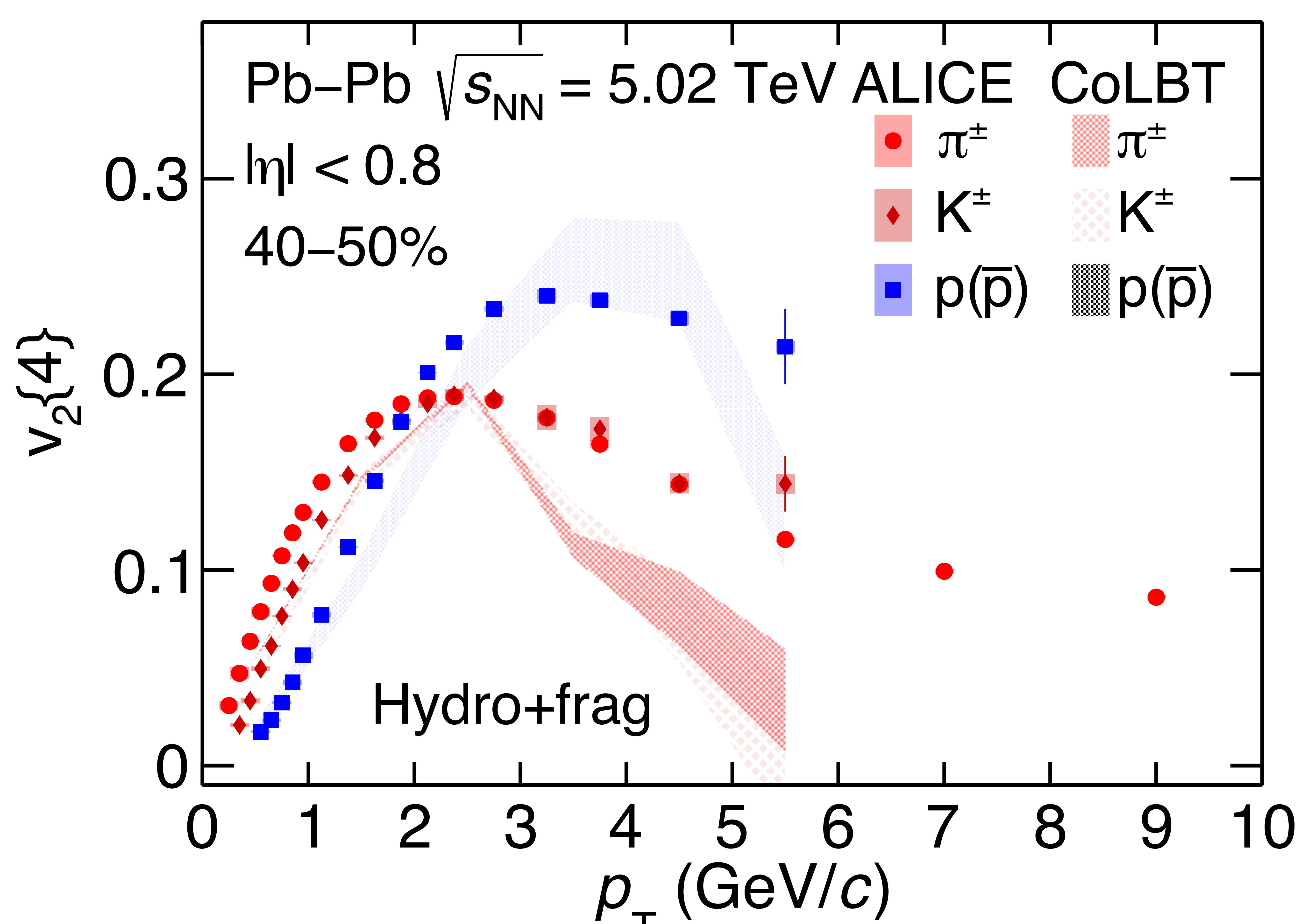


ALICE, arXiv:2206.04587 [nucl-ex]

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



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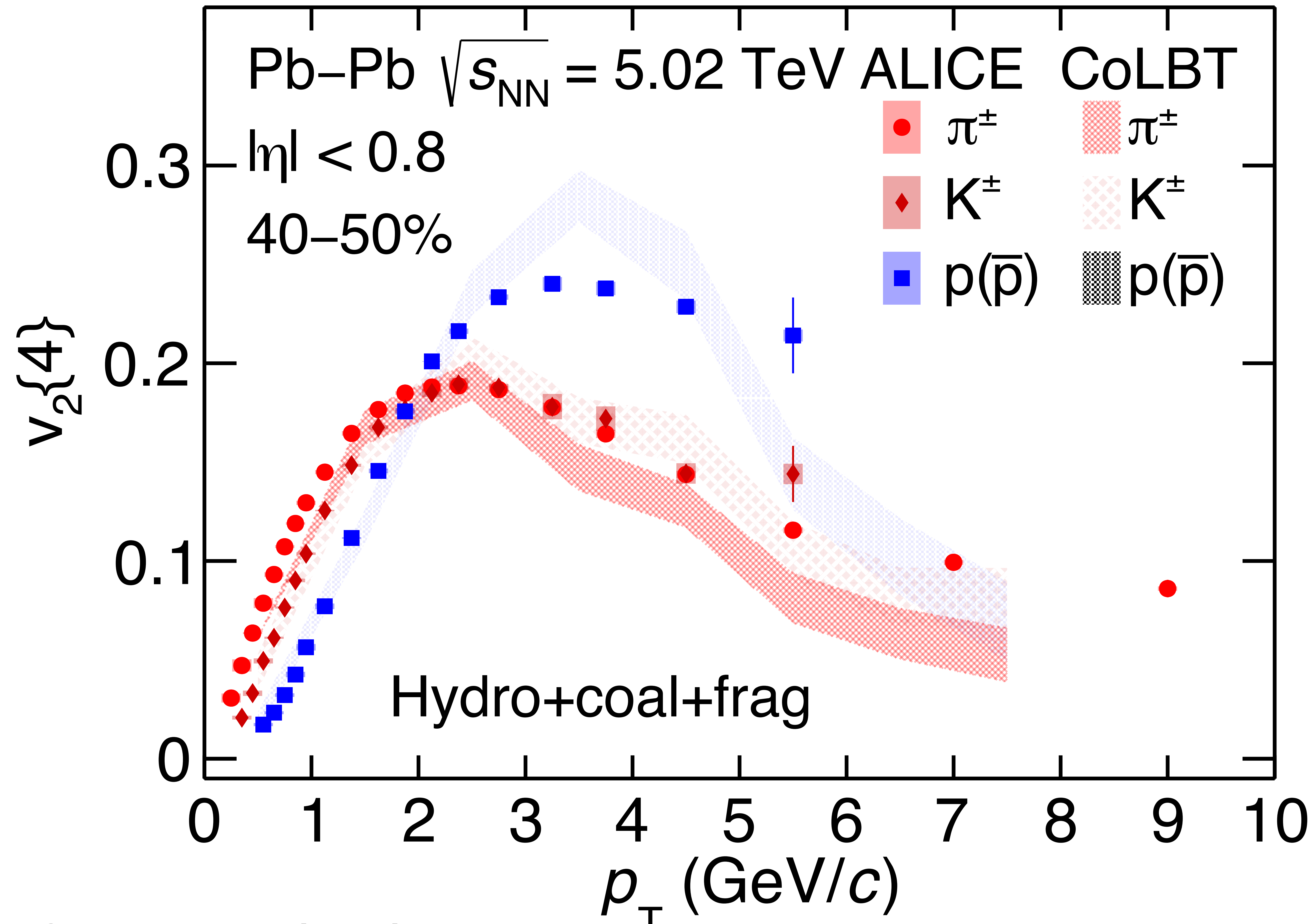
- Hydro + coalescence + fragmentation:

  ✓ Significantly better description of data

- But crossing is not unique to coalescence!



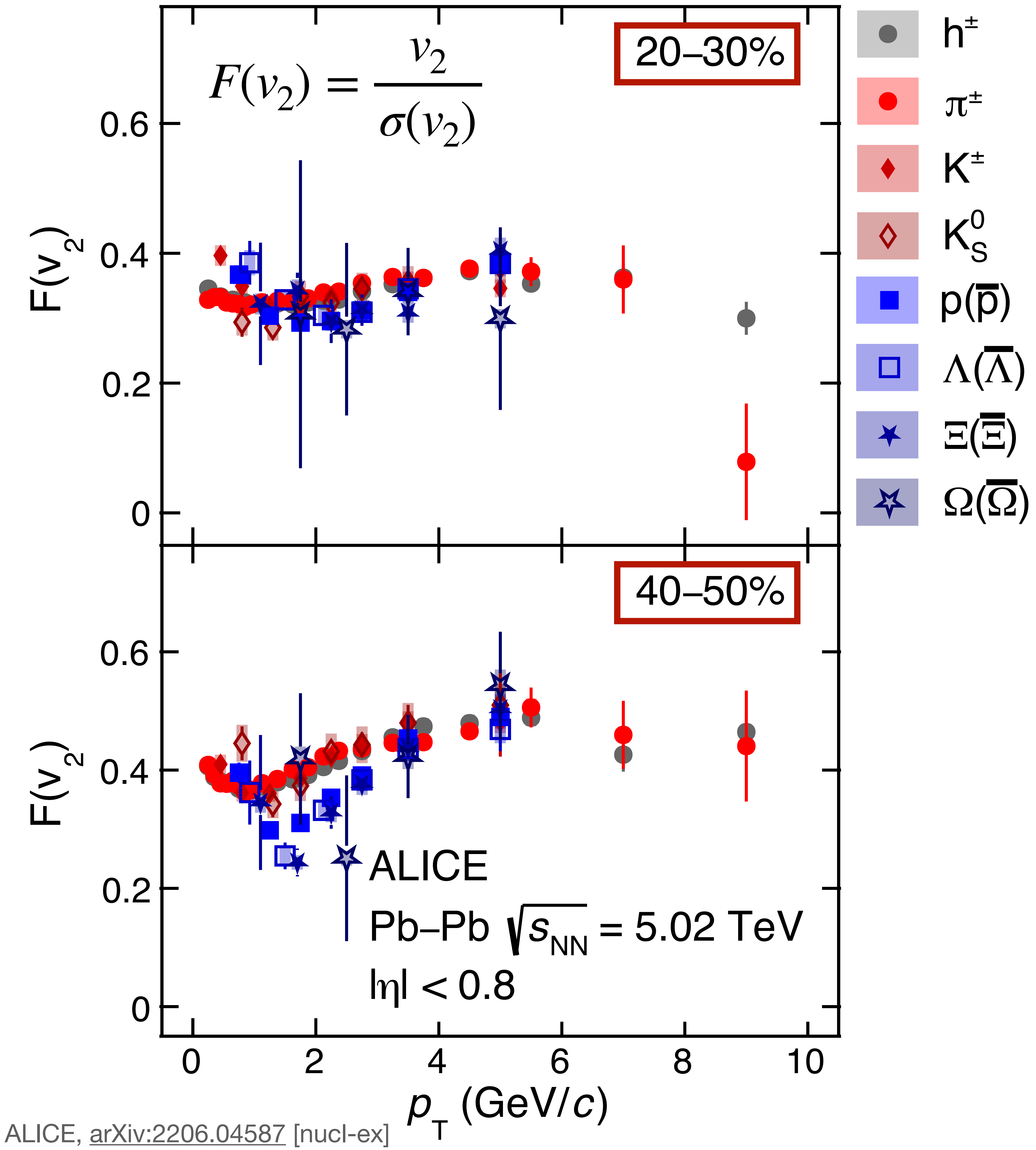
ALICE, arXiv:2206.04587 [nucl-ex]

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

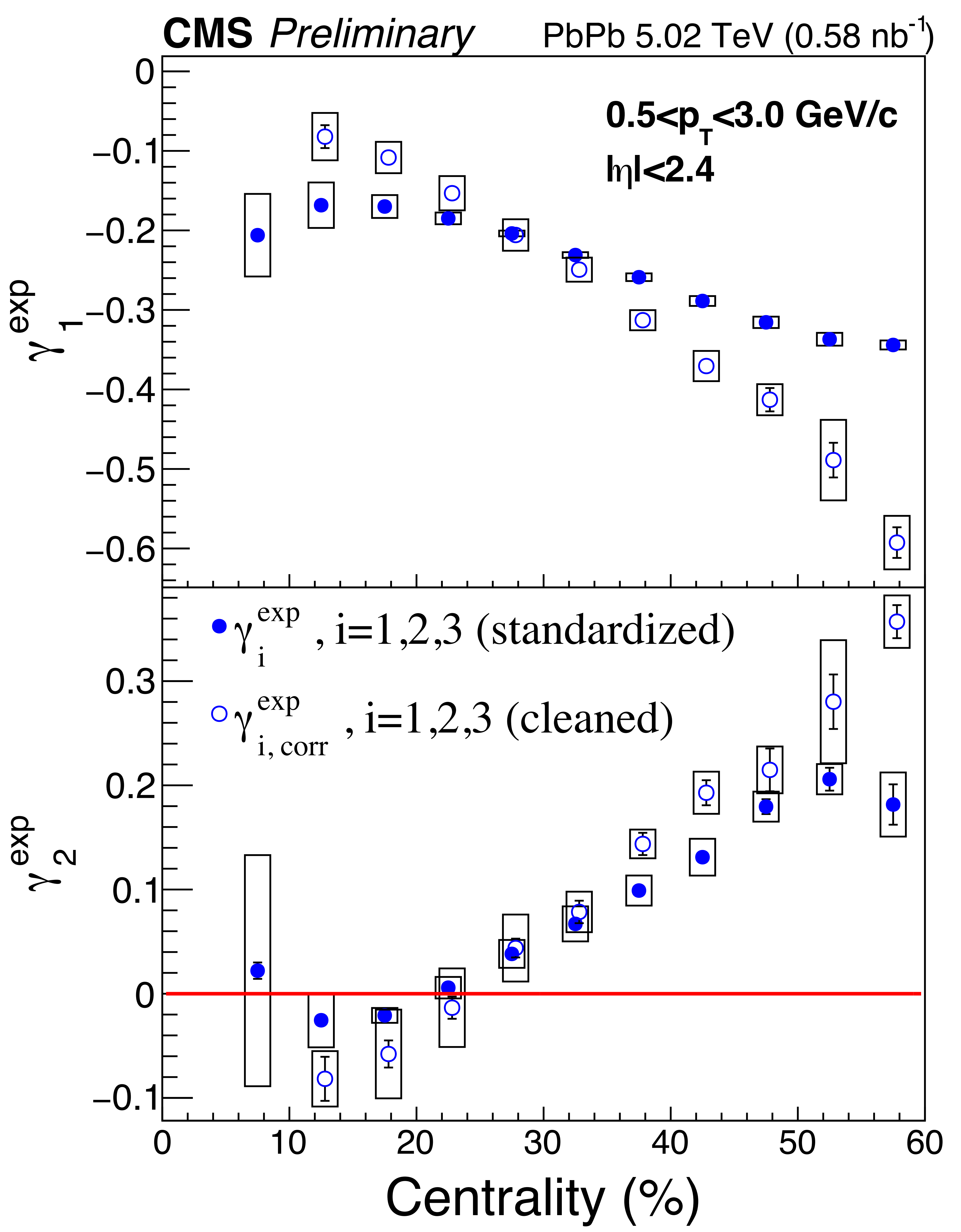
in Pb—Pb collisions

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

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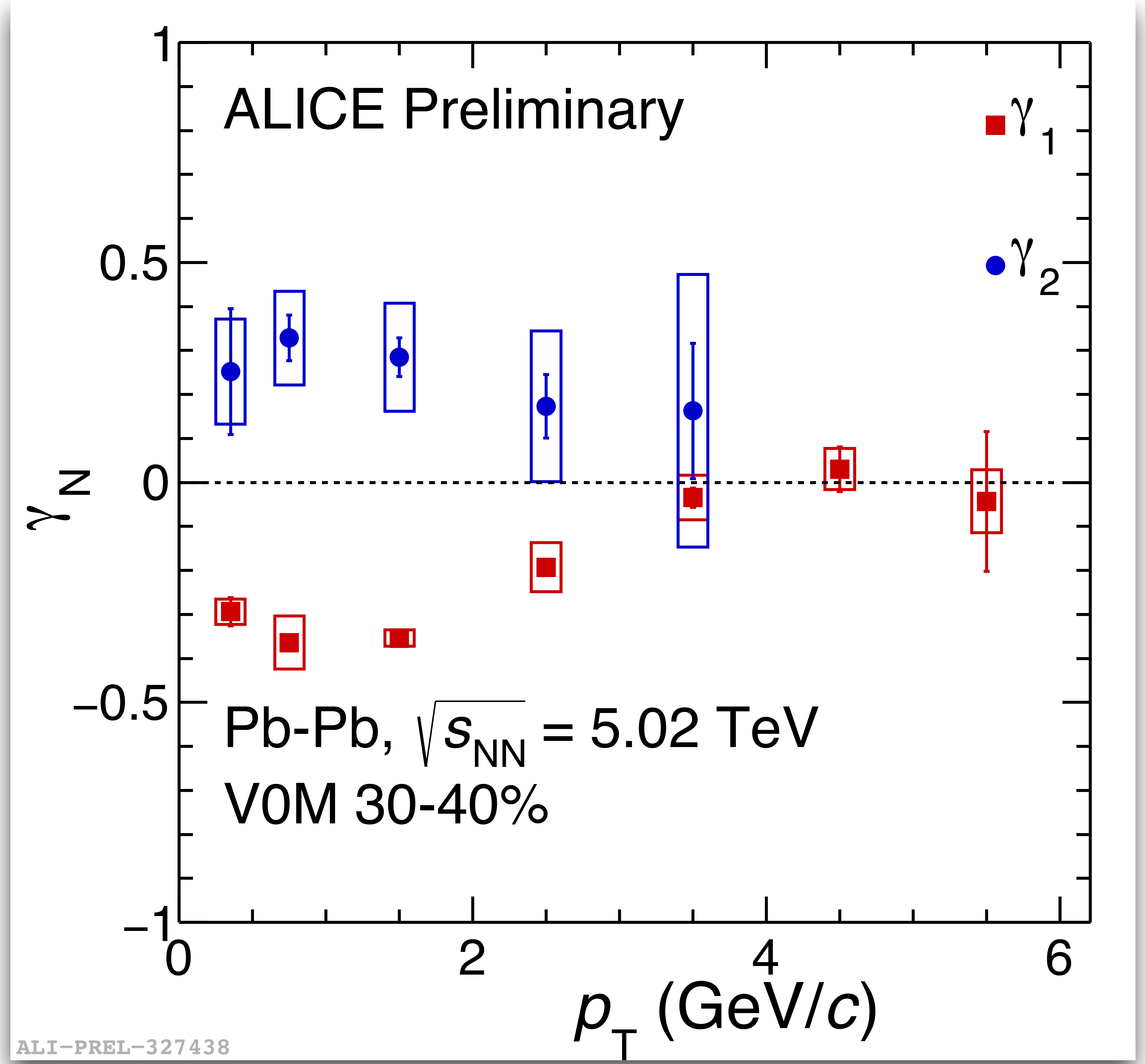
Do γ_1, γ_2 probe initial geometry exclusively?

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



Is QGP produced exclusively in heavy-ion collisions?

"Standard" paradigm:

- QGP in heavy-ion collisions
- Cold nuclear matter in proton-ion collisions
- Reference in pp

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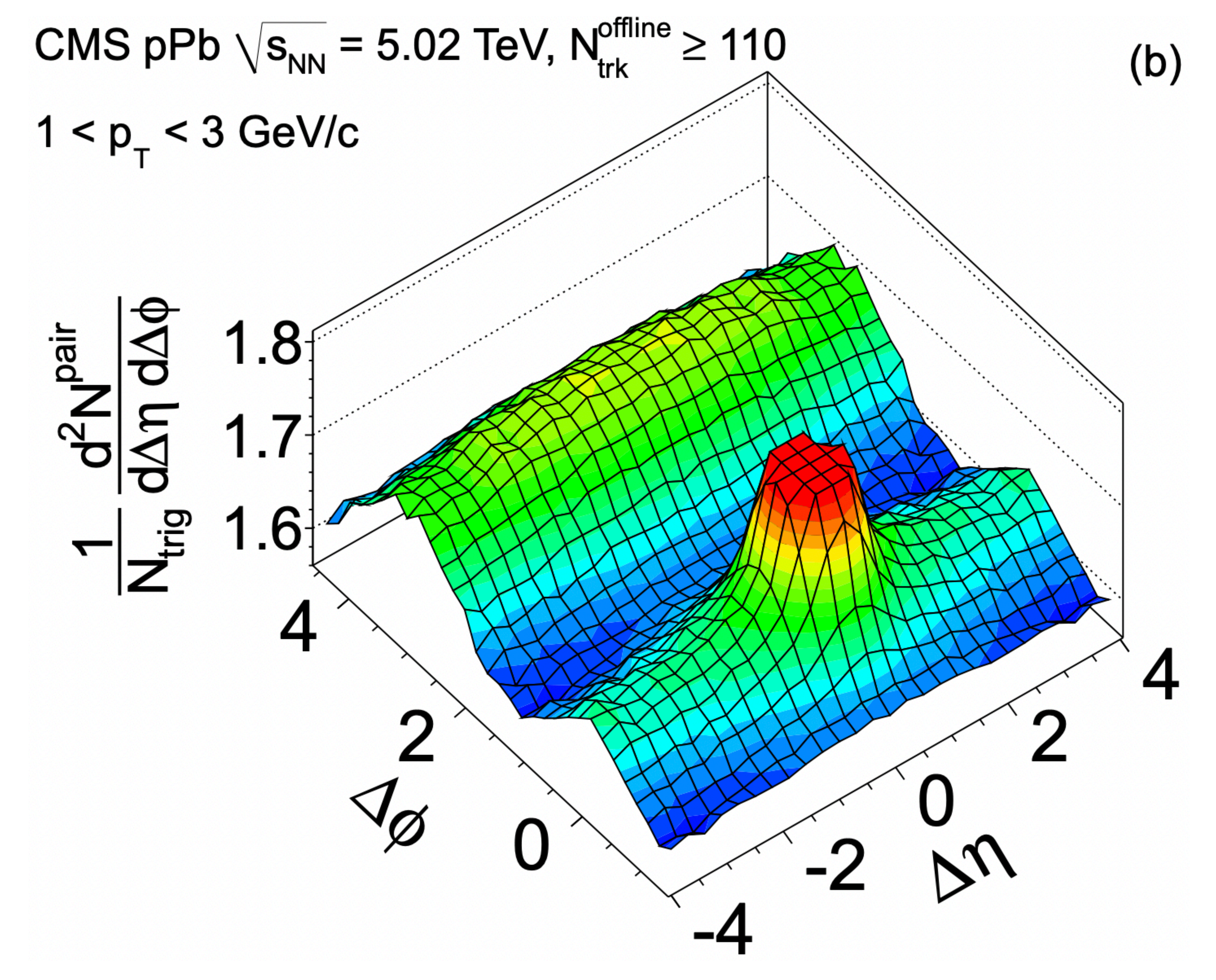
Pandora’s box since 2013:

- Near-side ridge in p-Pb, reminiscent of QGP



CMS, Phys. Lett. B 718 (2013) 795

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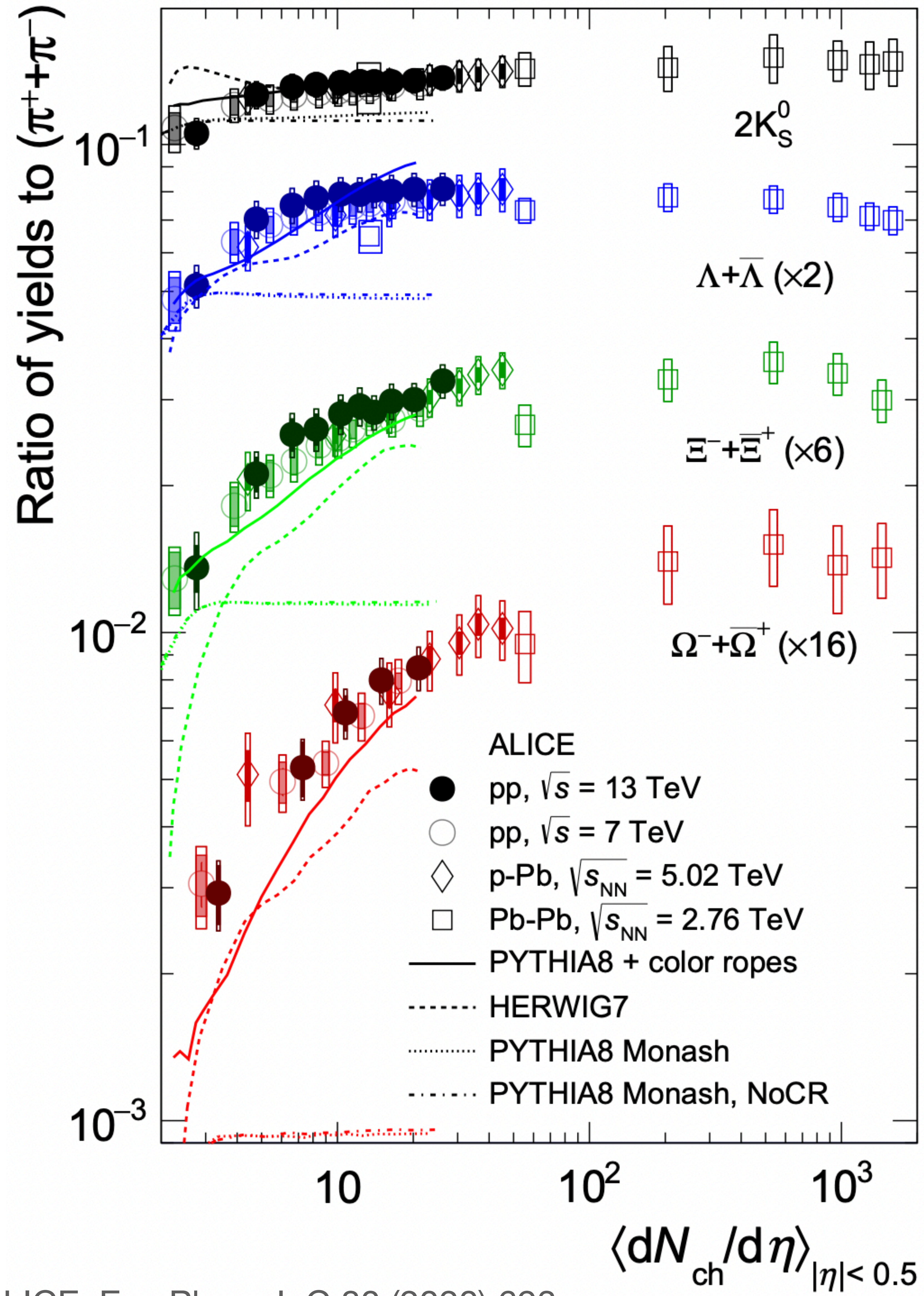

ALICE, Eur. Phys. J. C 80 (2020) 693

Is QGP produced exclusively in heavy-ion collisions?

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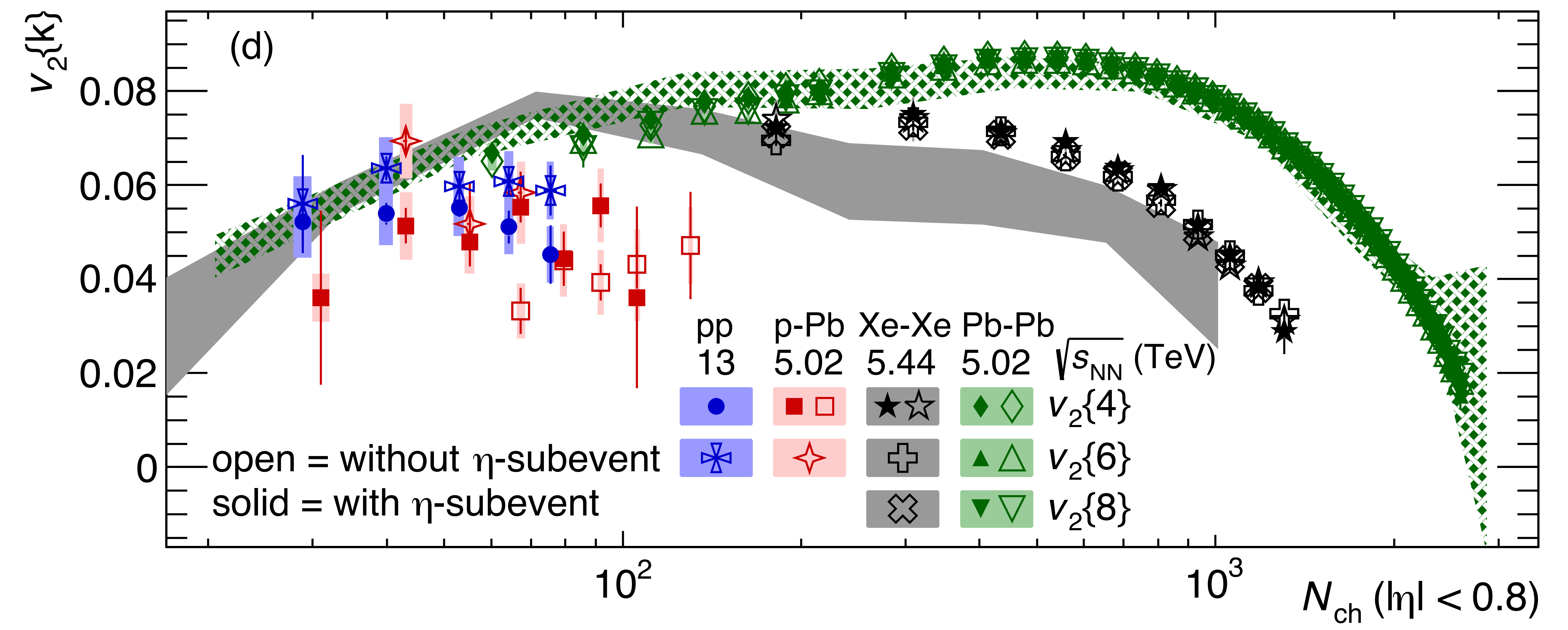
Is v_2 measured in pp and p—Pb collisions QGP-like?
Study it in p_T-differential way

Pandora's box since 2013:

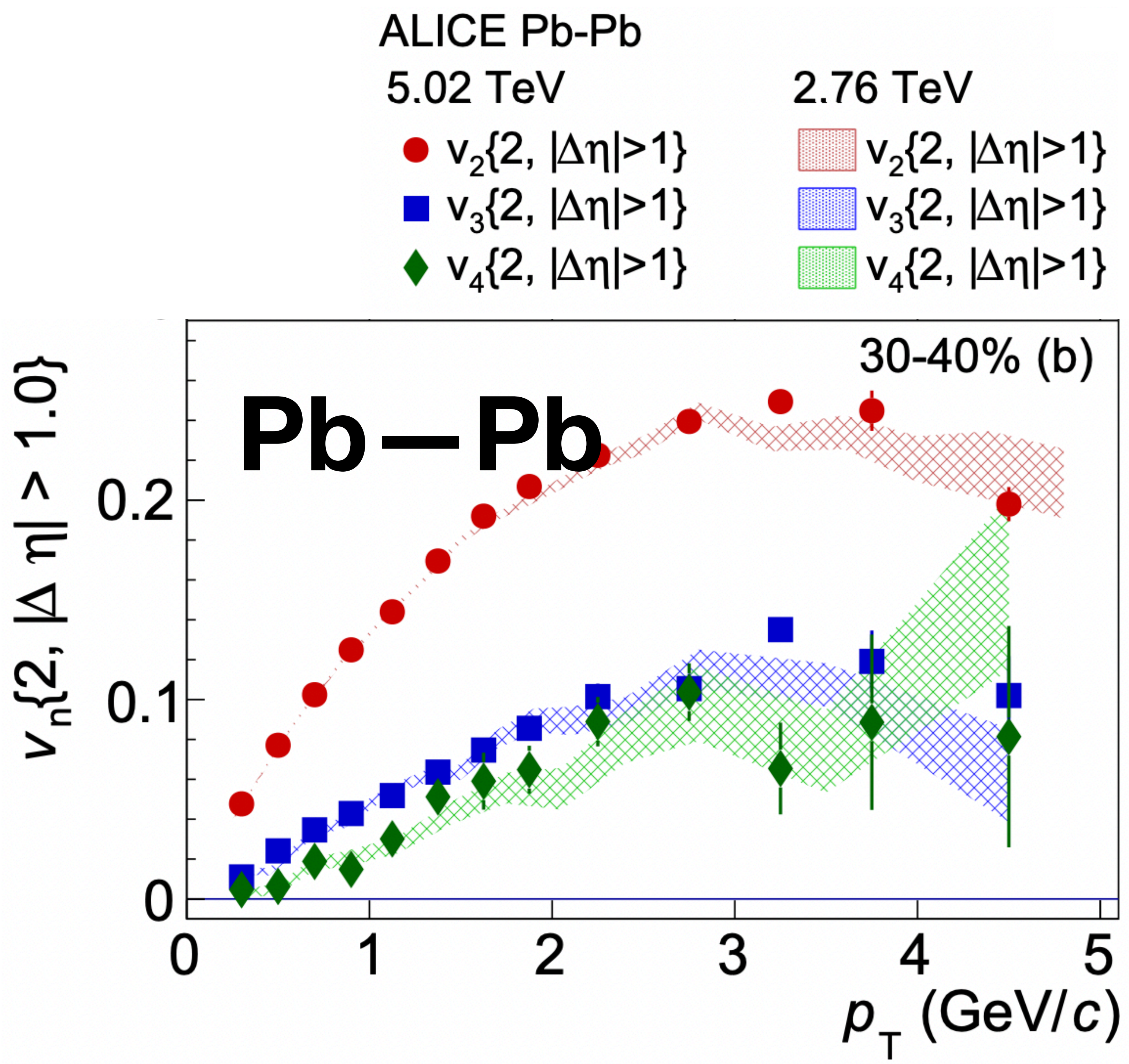
- Near-side ridge in p-Pb, reminiscent of QGP
- Particle production mechanism in pp and p—Pb similar to that in Pb—Pb
- Non-zero v_2 coefficients

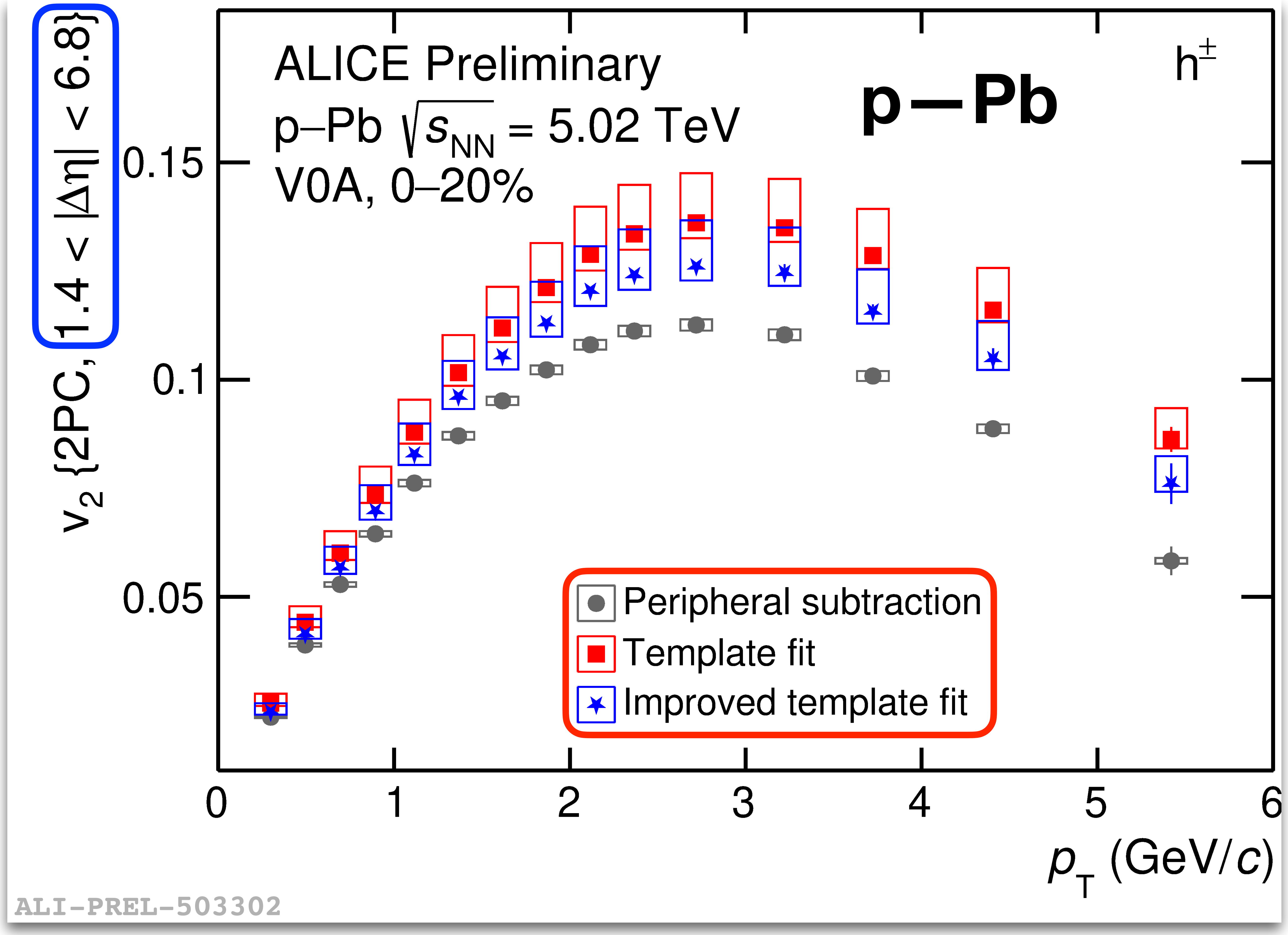


ALICE, Phys. Rev. Lett. 123, 142301 (2019)

Anisotropic flow in p—Pb collisions
for charged hadrons

- Small systems dominated by non-flow
  Suppress by:
  - Large |Δη| gap
  - Subtraction of low multiplicity collisions
- Qualitatively similar trends in Pb—Pb and p—Pb

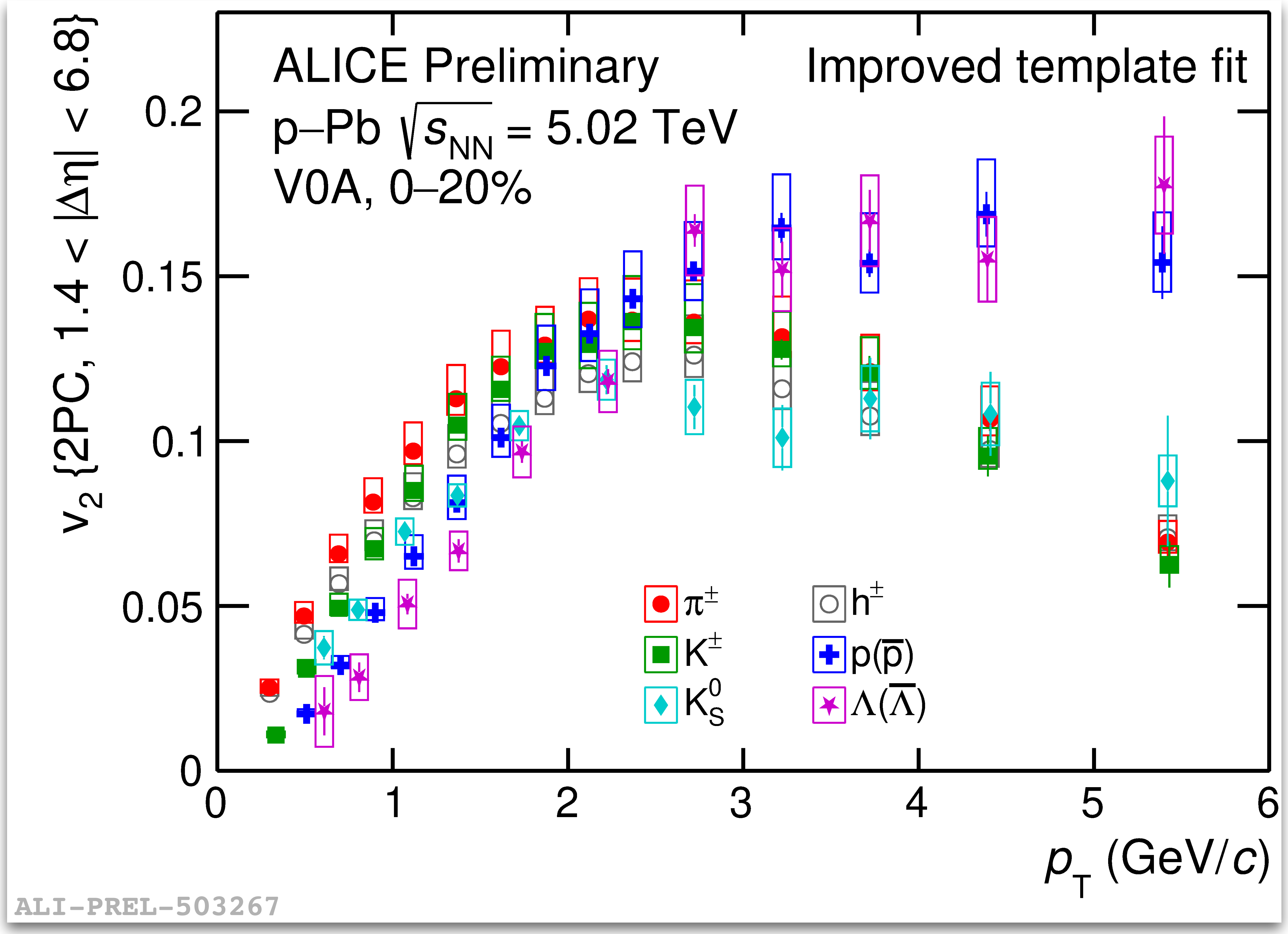




Anisotropic flow in p—Pb collisions

for identified particles

- p_T-differential measurements of v_2 in p—Pb collisions for identified particles:
  - Inverse mass ordering at low p_T
  - Baryon/meson grouping at intermediate p_T with 3σ



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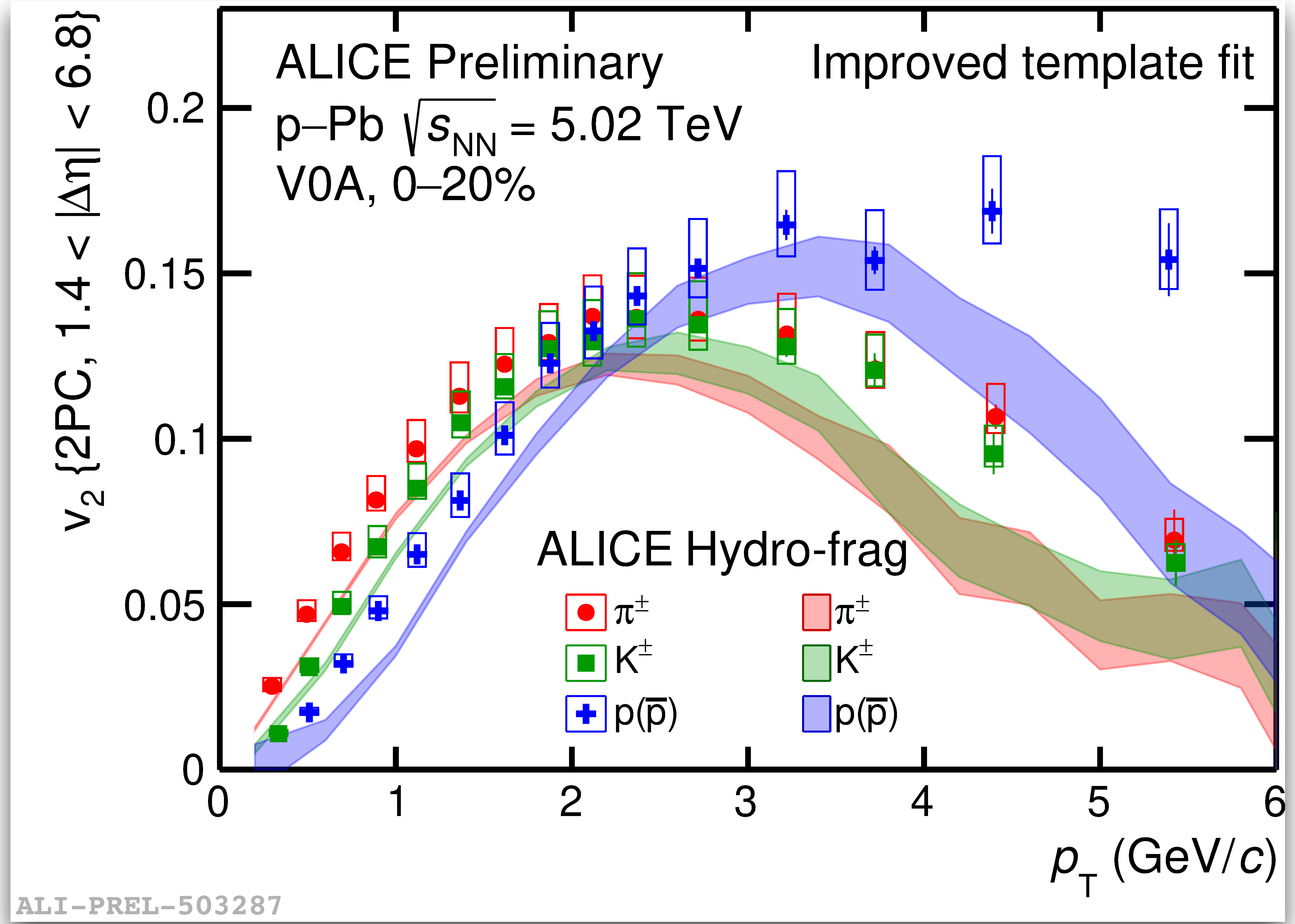

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- Comparison to models:
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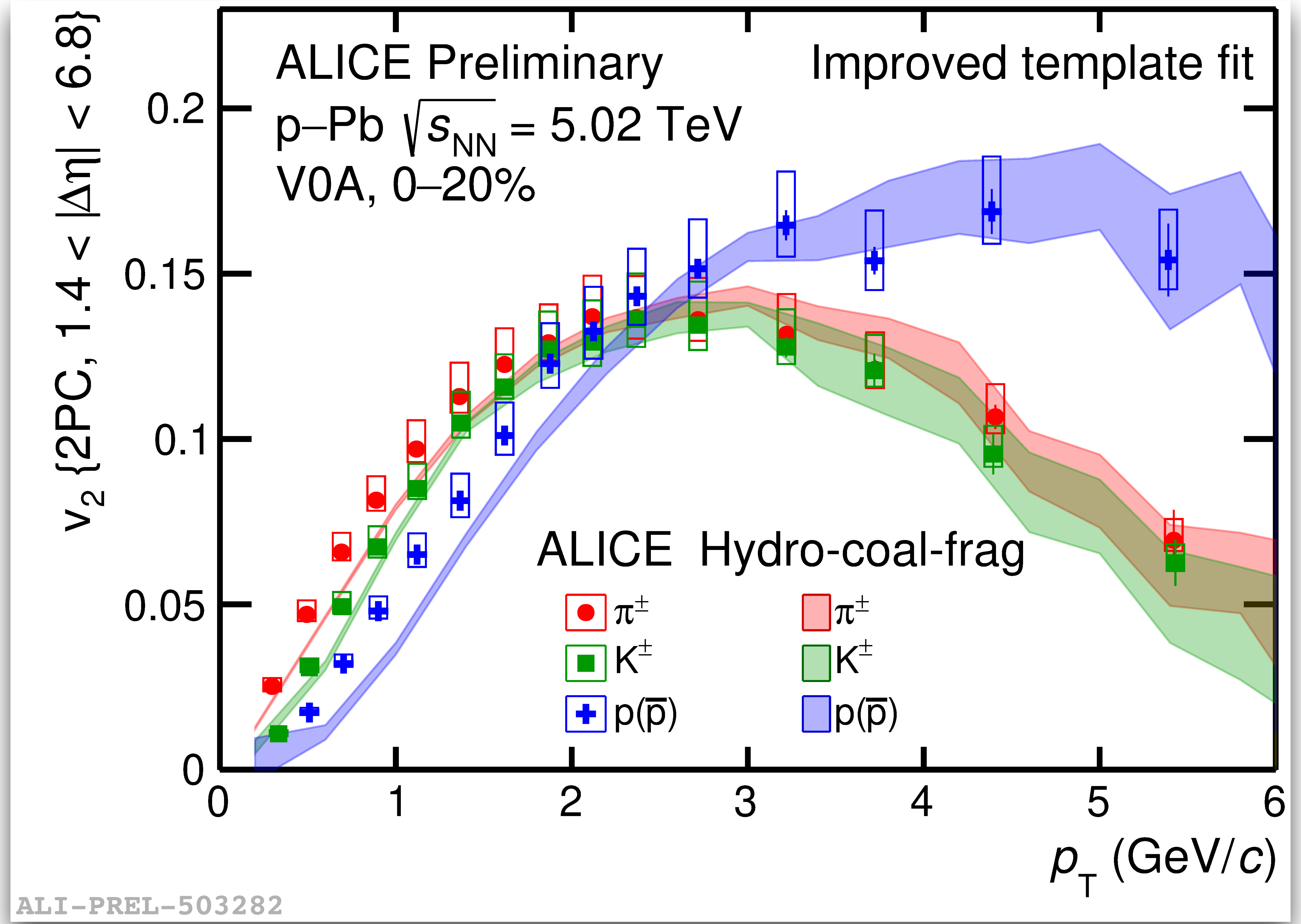
  - — Hydro + coalescence + fragmentation: good description of data at intermediate p_T

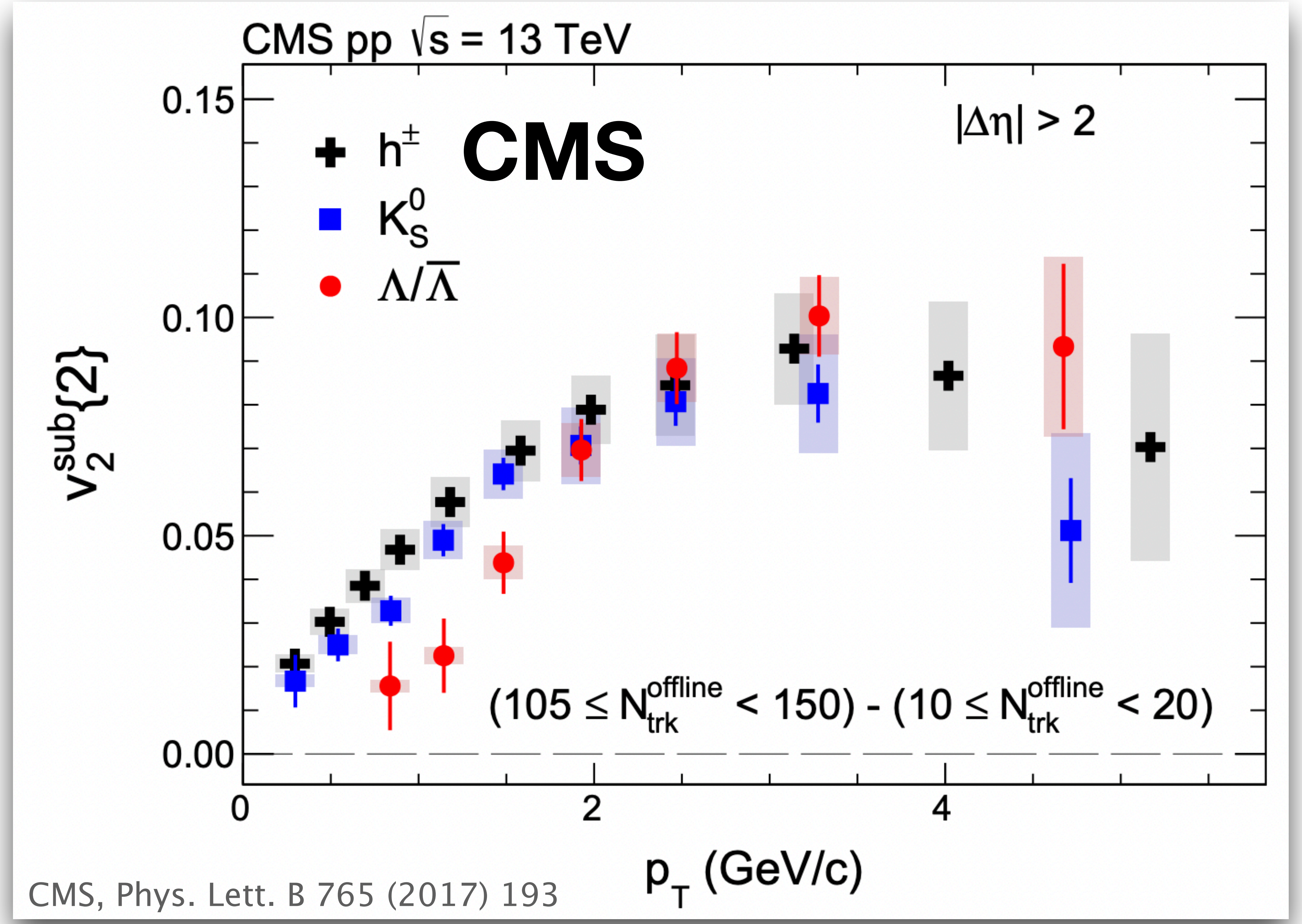
⇛ Presence of partonic collectivity in p—Pb

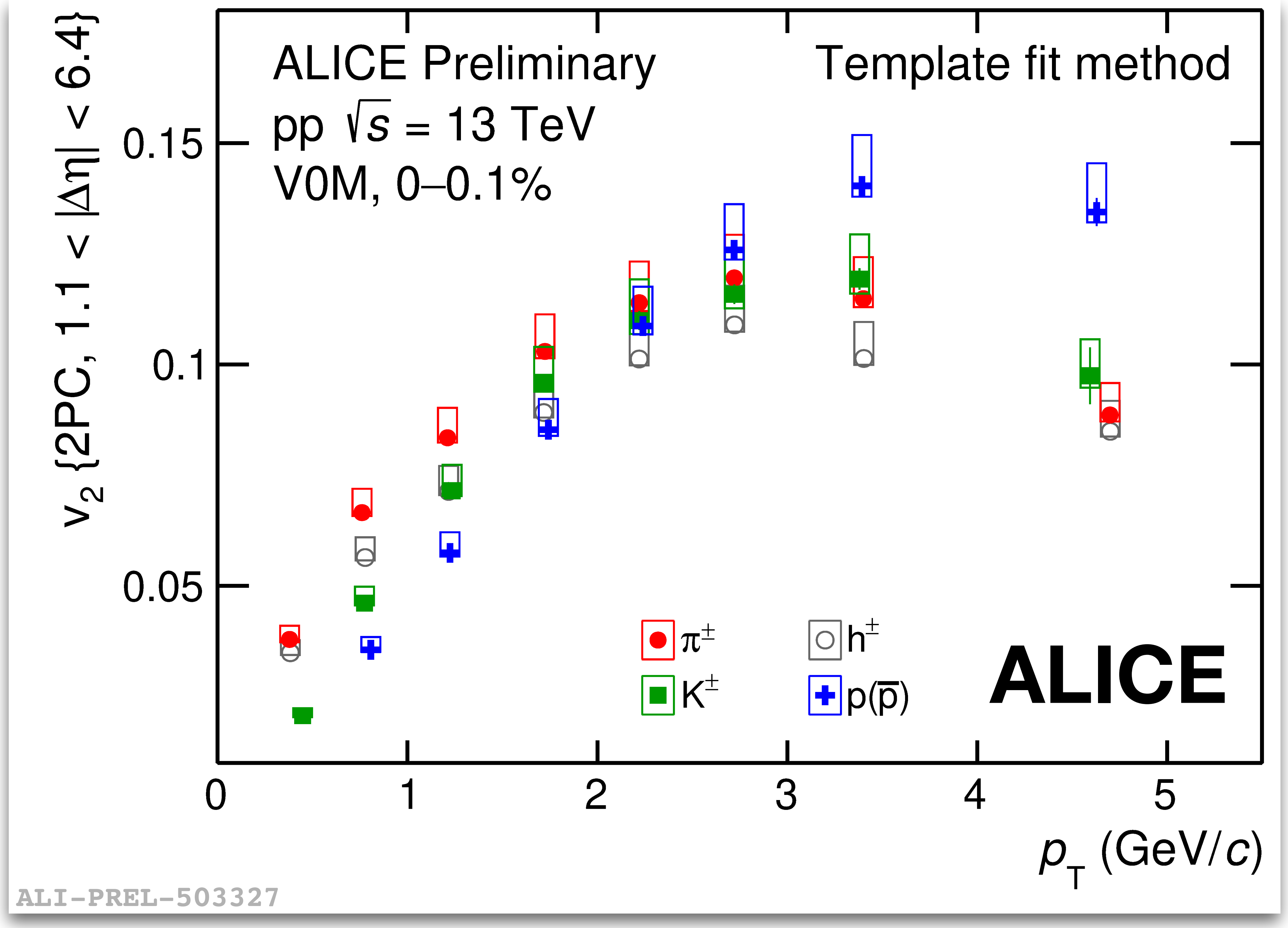


Anisotropic flow in pp collisions
for identified particles

- Inverse mass ordering at low p_T
- Clear separation (> 3σ) between protons and π/K at intermediate p_T!

Hydrodynamics—like trends observed in pp and p—Pb. Are they of the same origin?
⇛ Need to study the initial state





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

- 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
and deformation of nuclei

- 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
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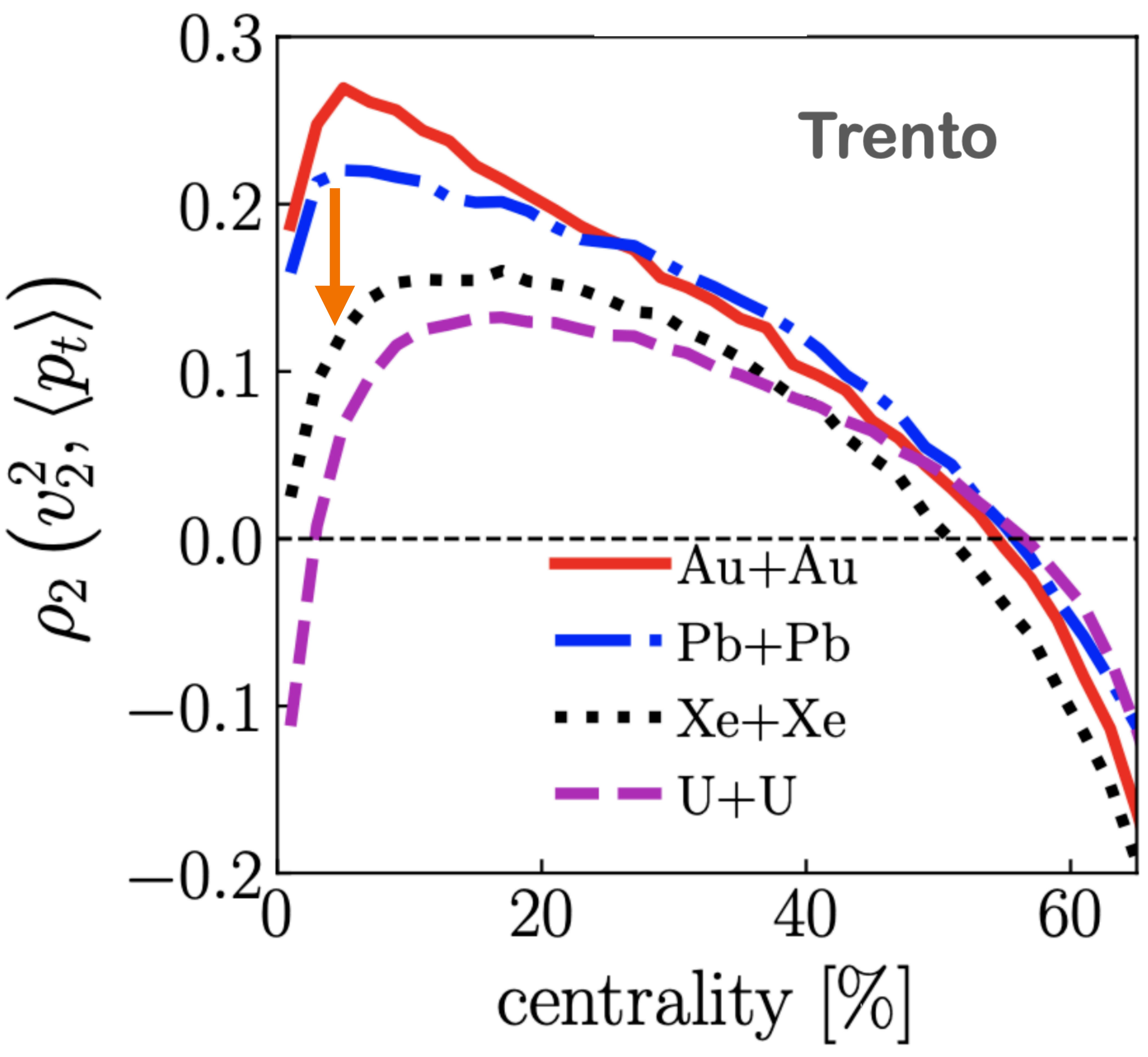
⇛ Study with Pearson correlation coefficient:

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

⇛ 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

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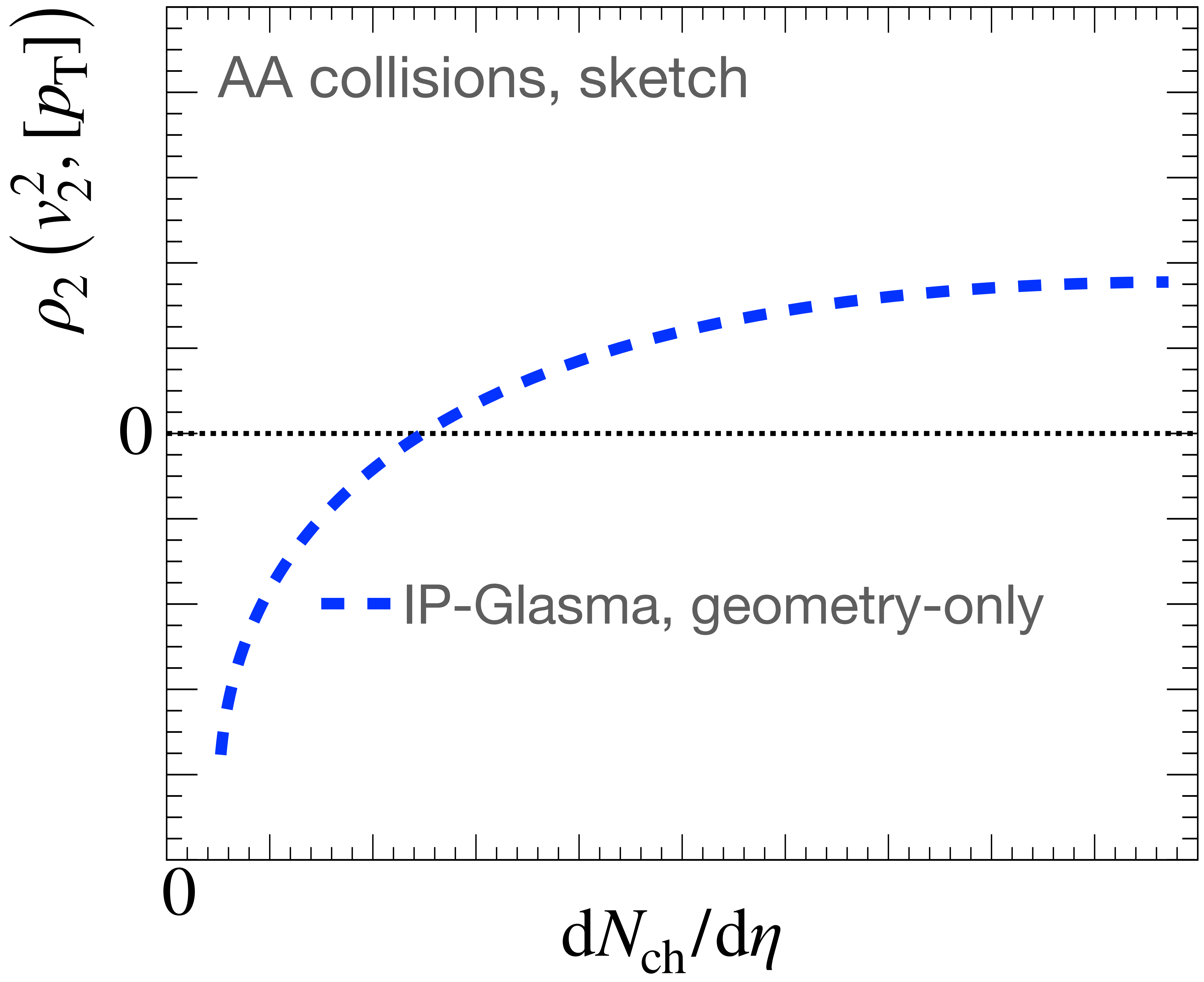

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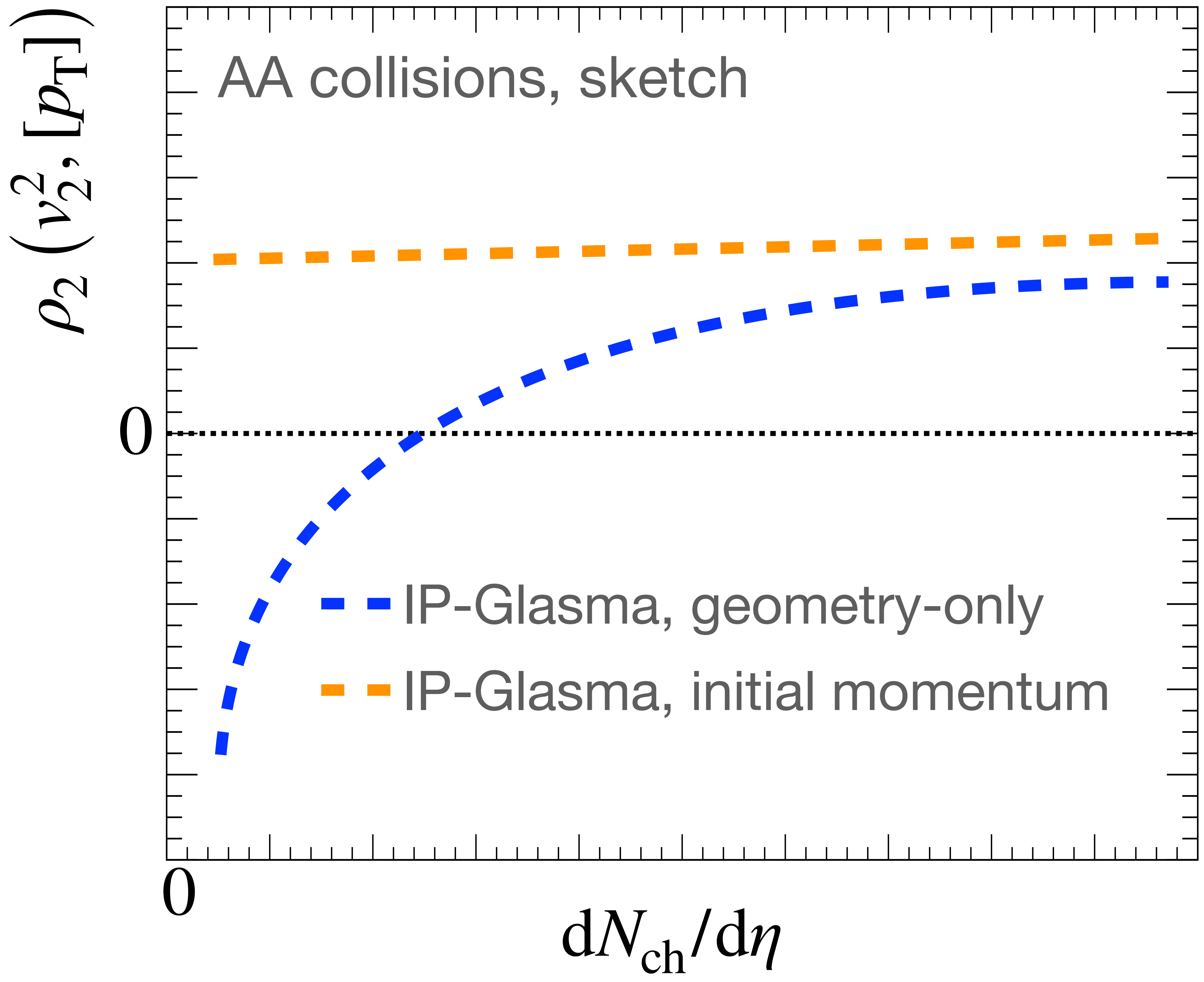

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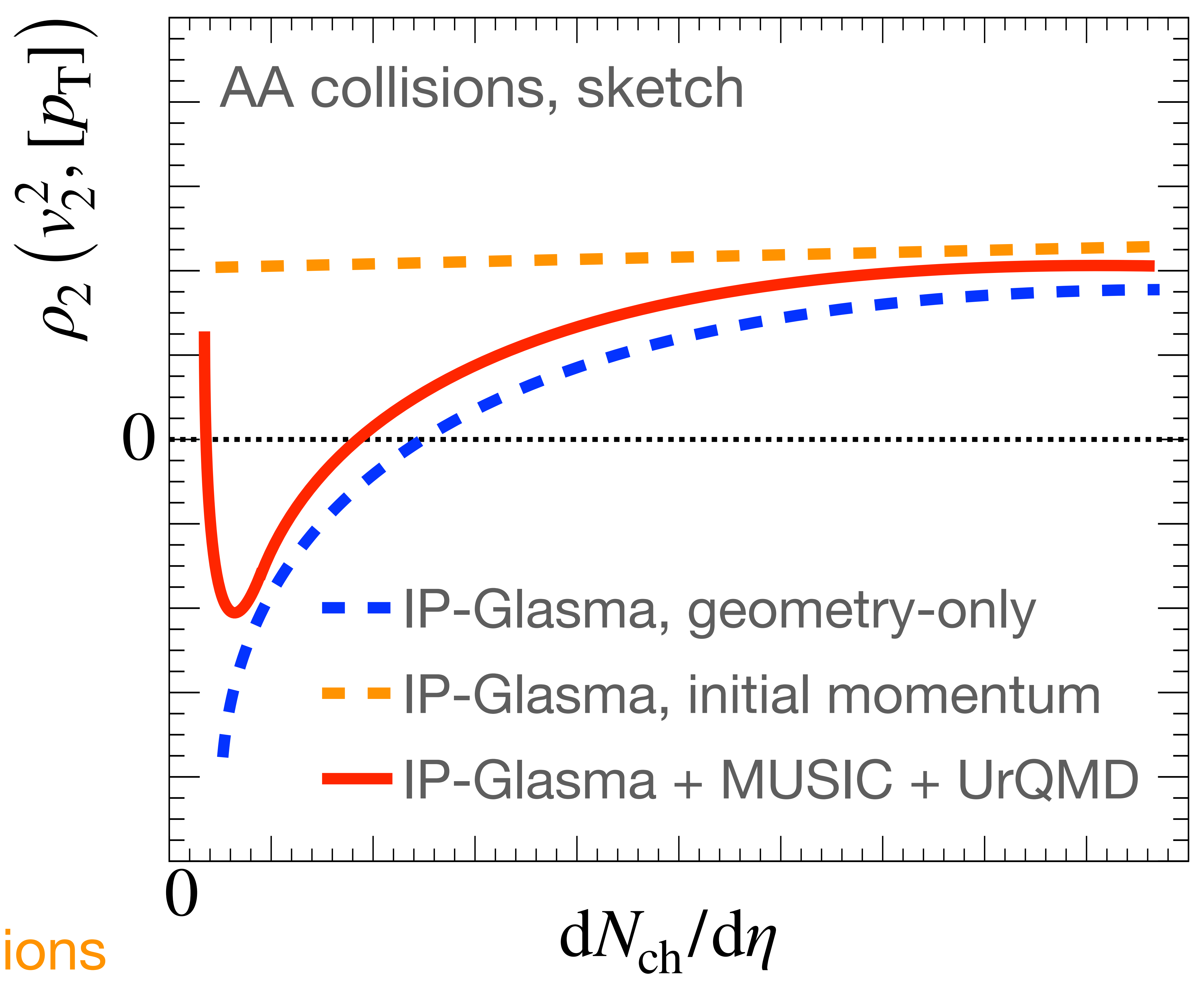


Low multiplicity: geometry → initial momentum correlations

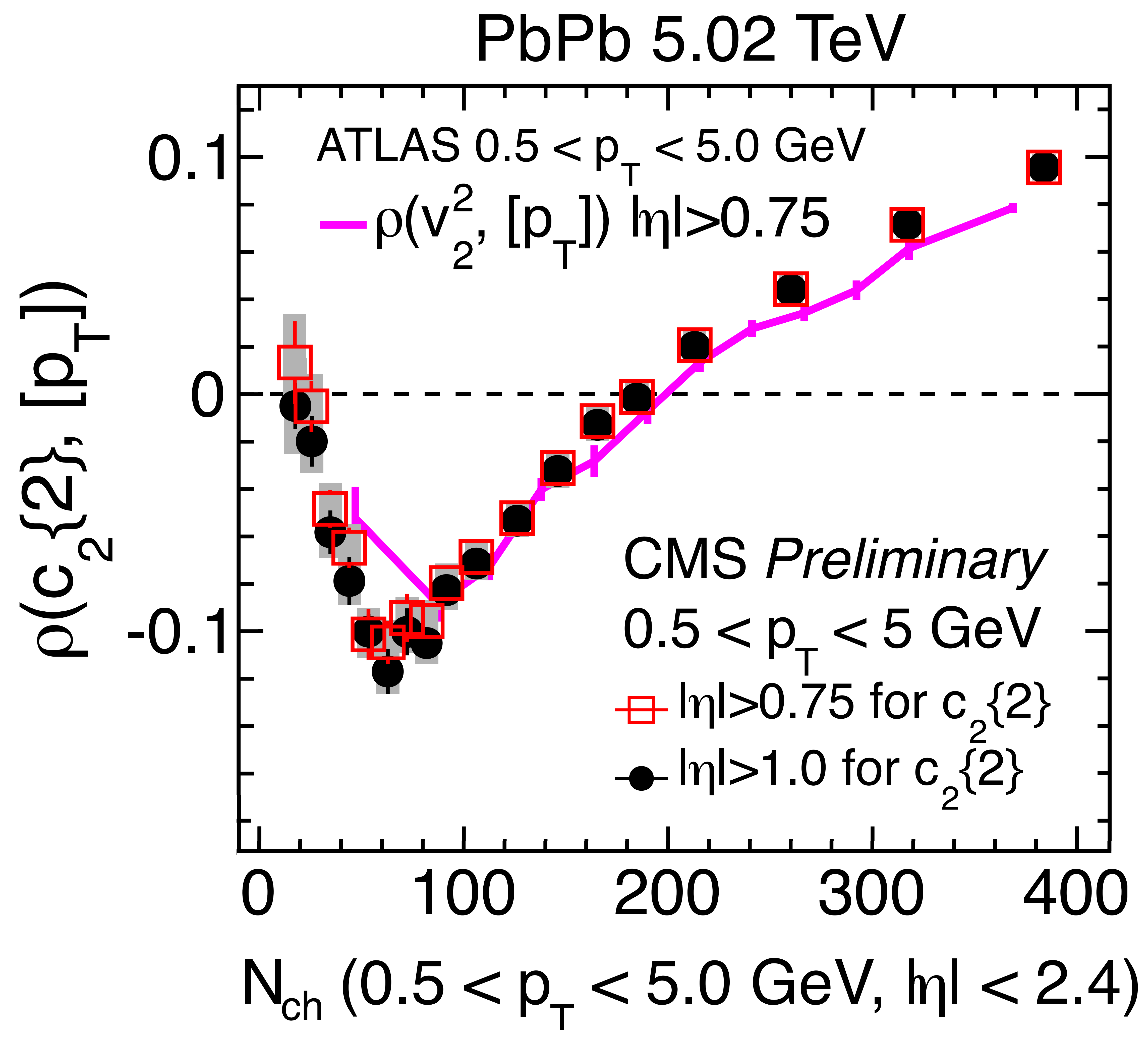
⇒ Change of slope sign → presence of CGC?

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

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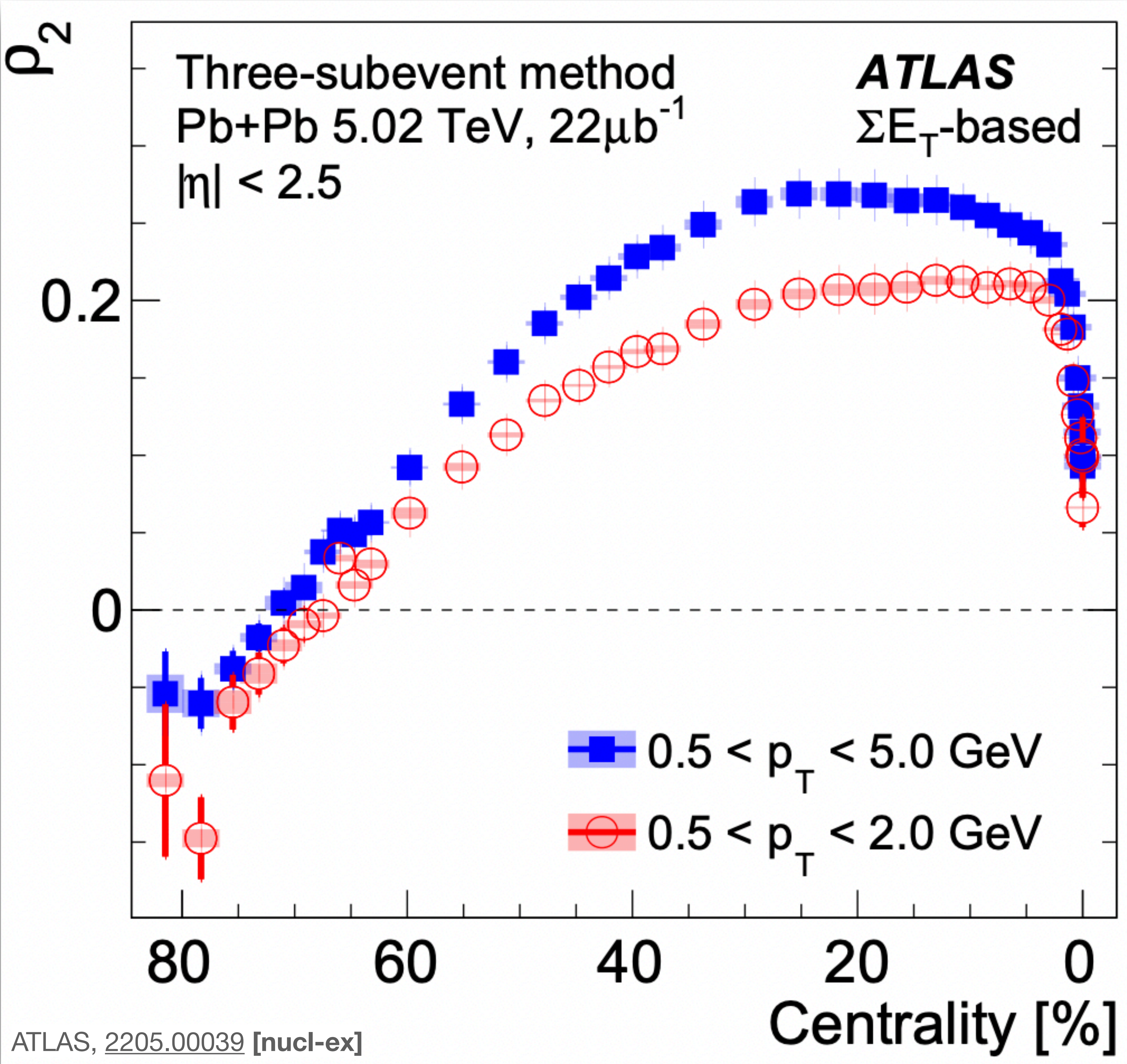
$\rho(v_2^2, [p_T])$ in Pb—Pb:

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



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

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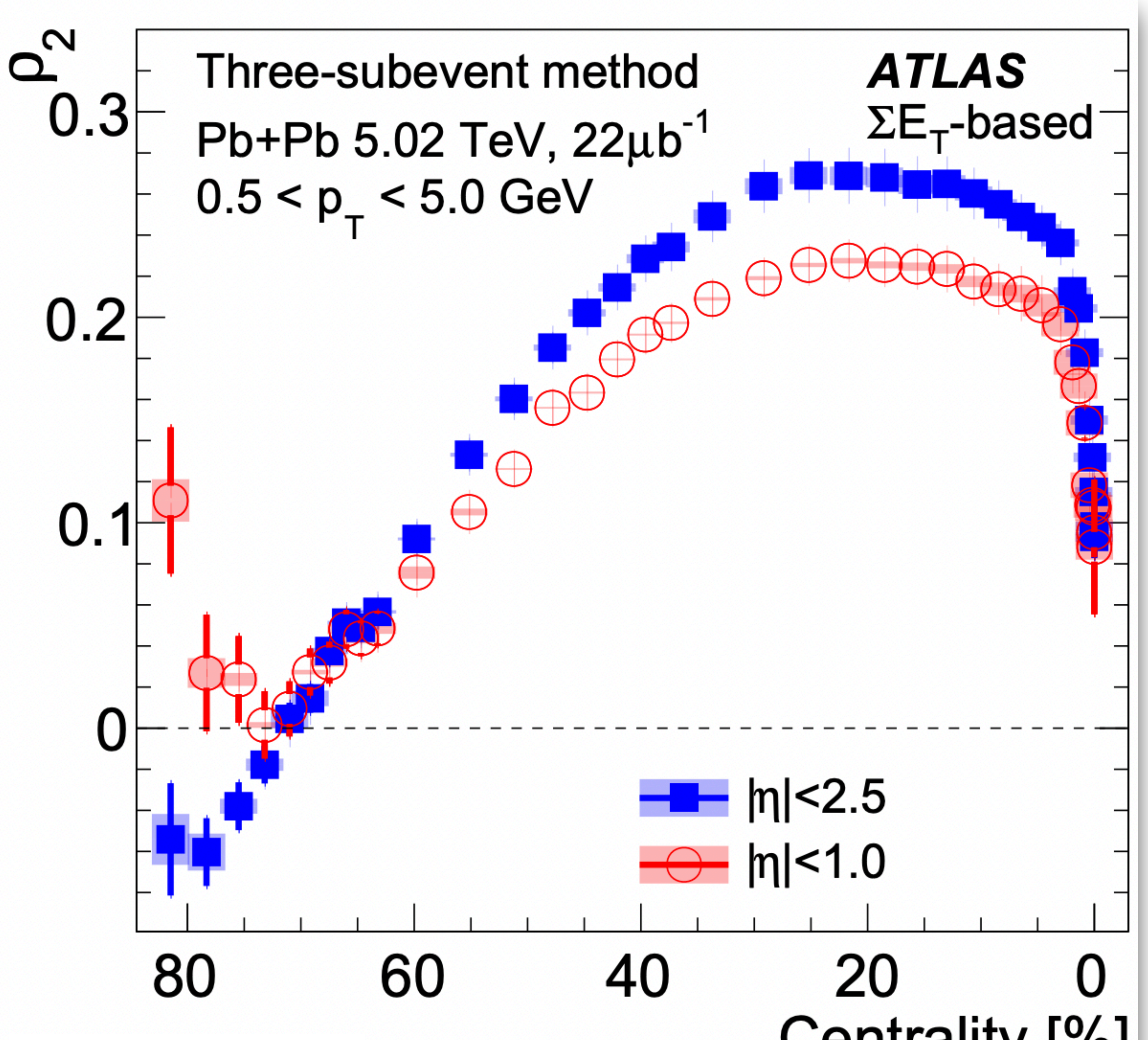
- Sensitive to p_T interval…
- and pseudorapidity range…



ATLAS, 2205.00039 [nucl-ex]

Correlation between $[p_T]$ and v_2
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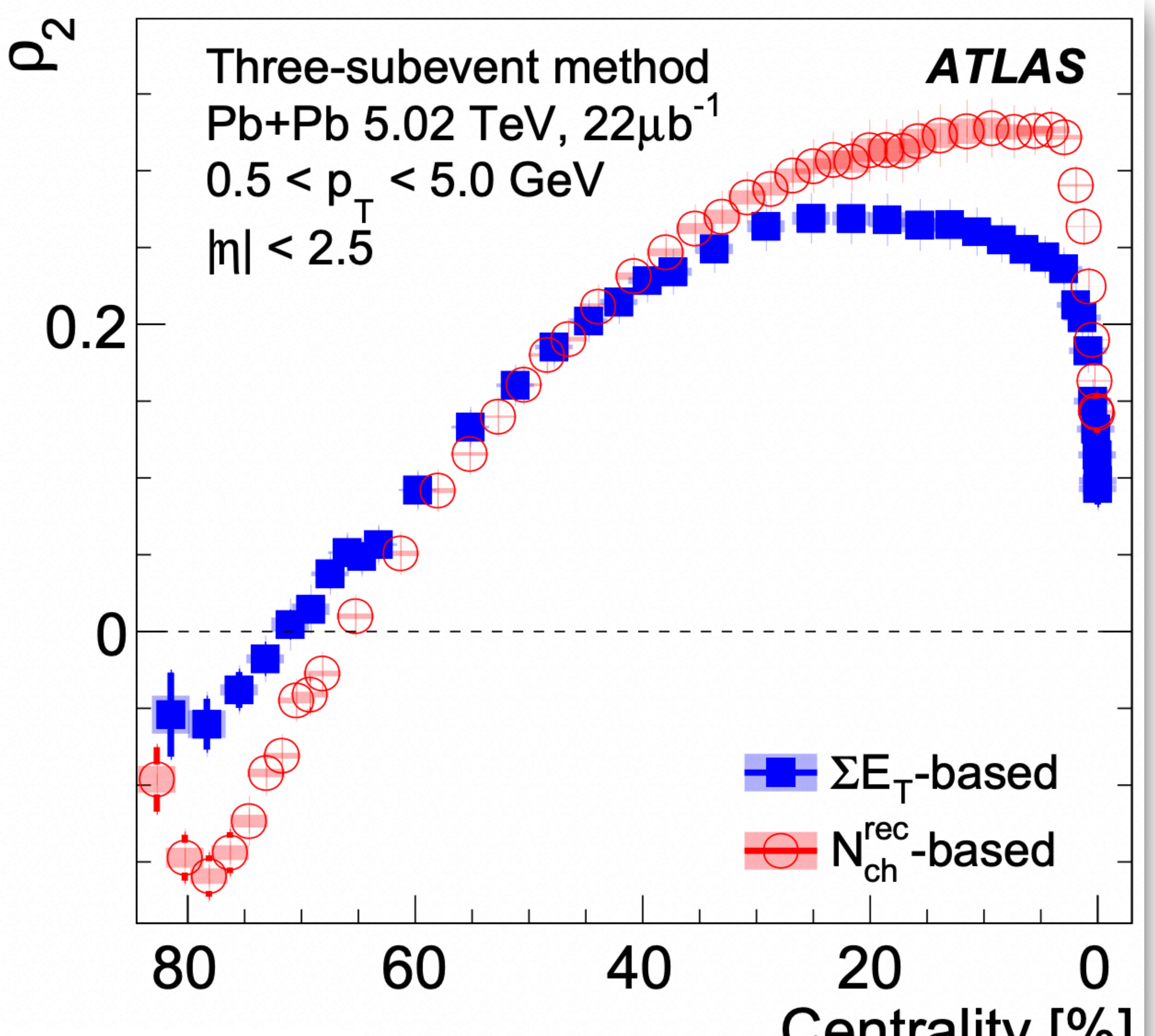
$\rho(v_2^2, [p_T])$ in Pb—Pb:

- 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:

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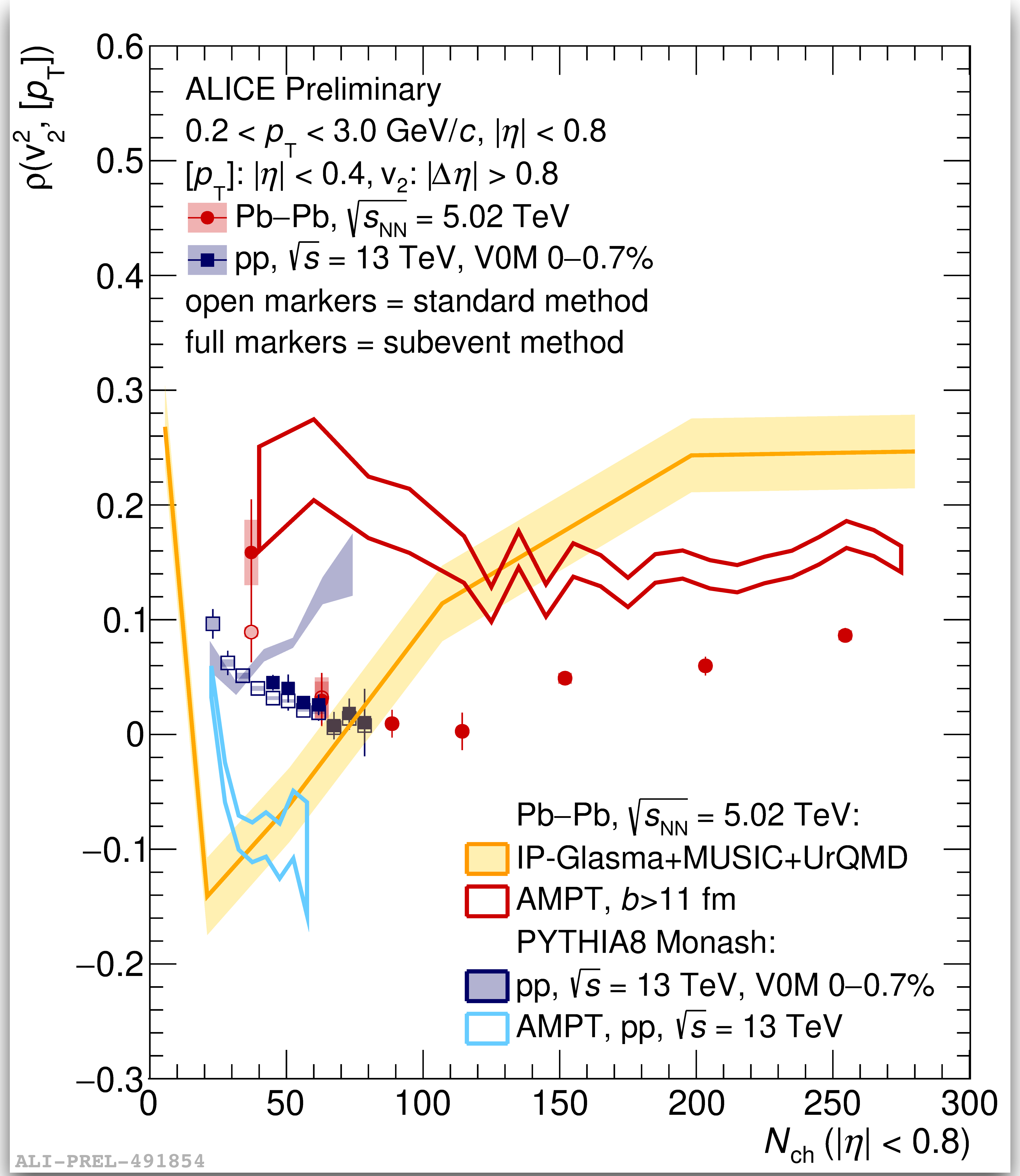
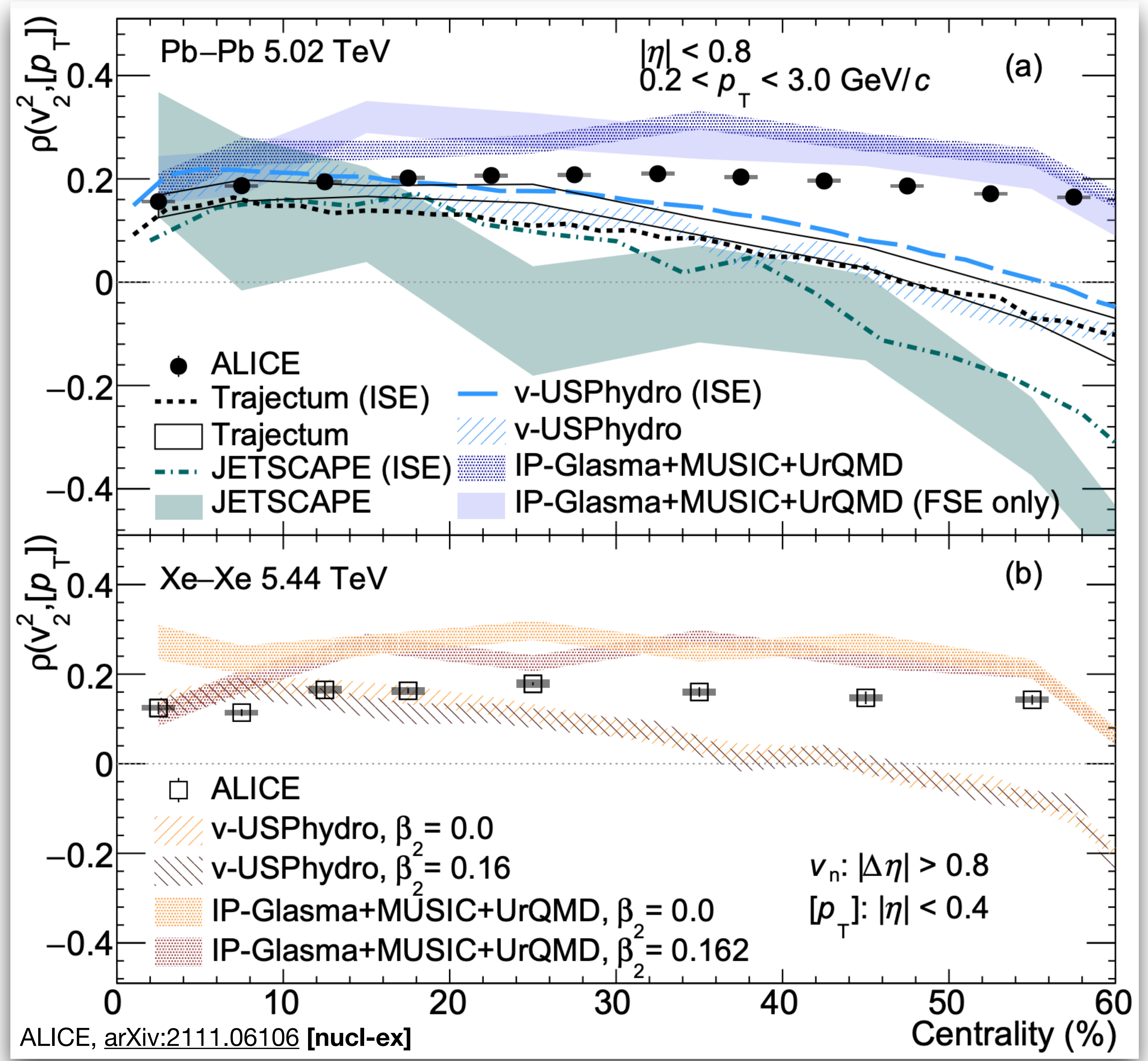


Correlation between $[p_T]$ and v_2 in Pb—Pb and Xe—Xe collisions

- 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:
  - — $\beta_2 = 0.162$ gives better description in most central collisions, similar to $\beta_2 = 0$ in more peripheral



Summary

- p_T-differential v_2 of identified hadrons in pp and p—Pb collisions show remarkable similarities to Pb—Pb collisions
  ⇛ Suggests dynamical evolution similar to that in Pb—Pb

- 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

- 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} not unique to models with IP-Glasma

Backup

From collisions to measurement

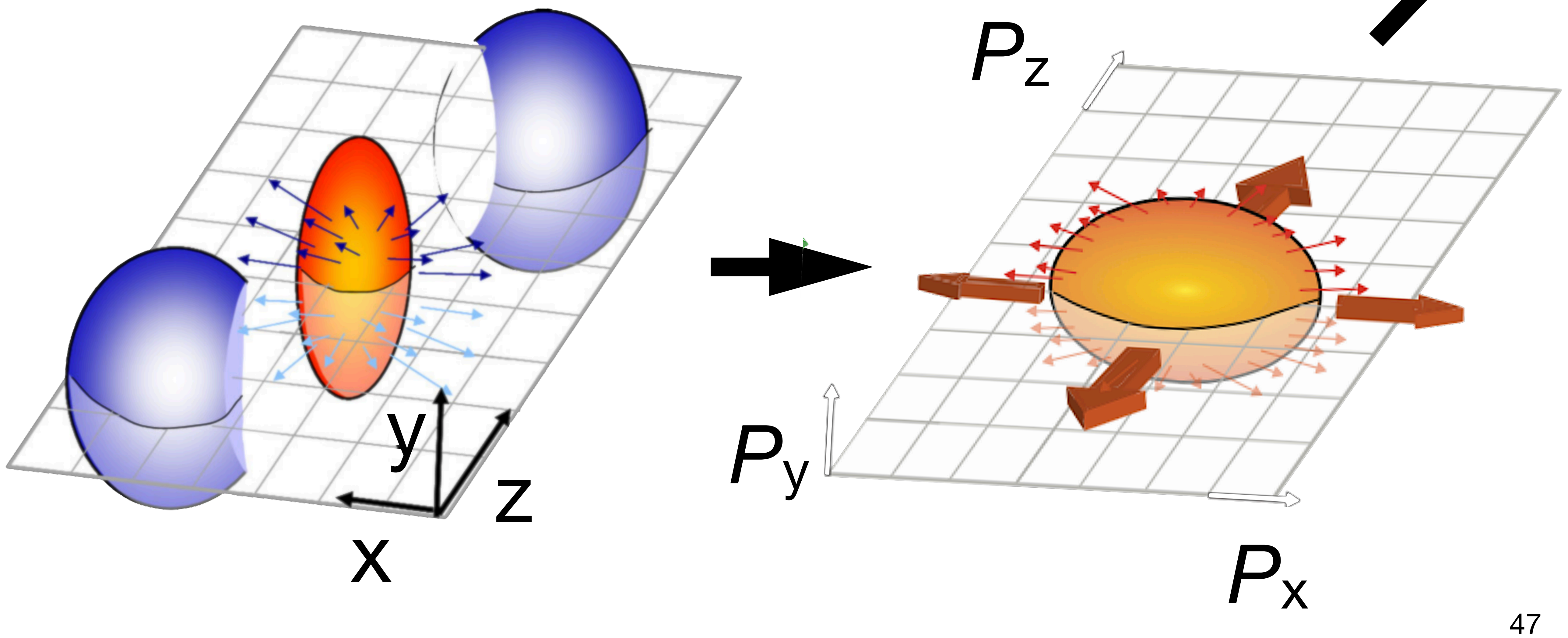
- Overlap between colliding nuclei:
  ⇛ Initial state, geometry & its fluctuations

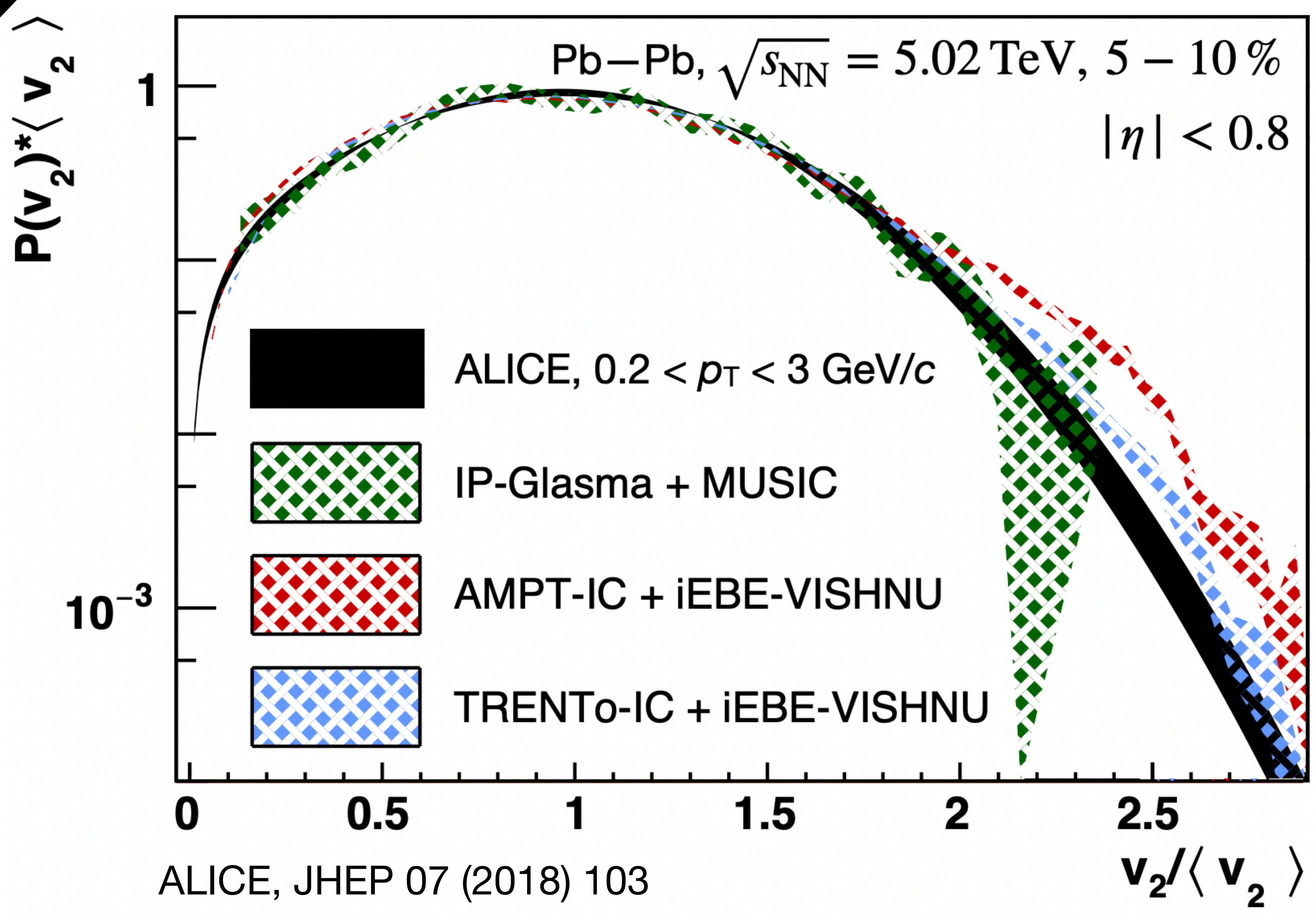
- Hydrodynamic expansion of QGP:
  ⇛ Radial and anisotropic flow, sensitive to initial state and properties of QGP

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

⇛ (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

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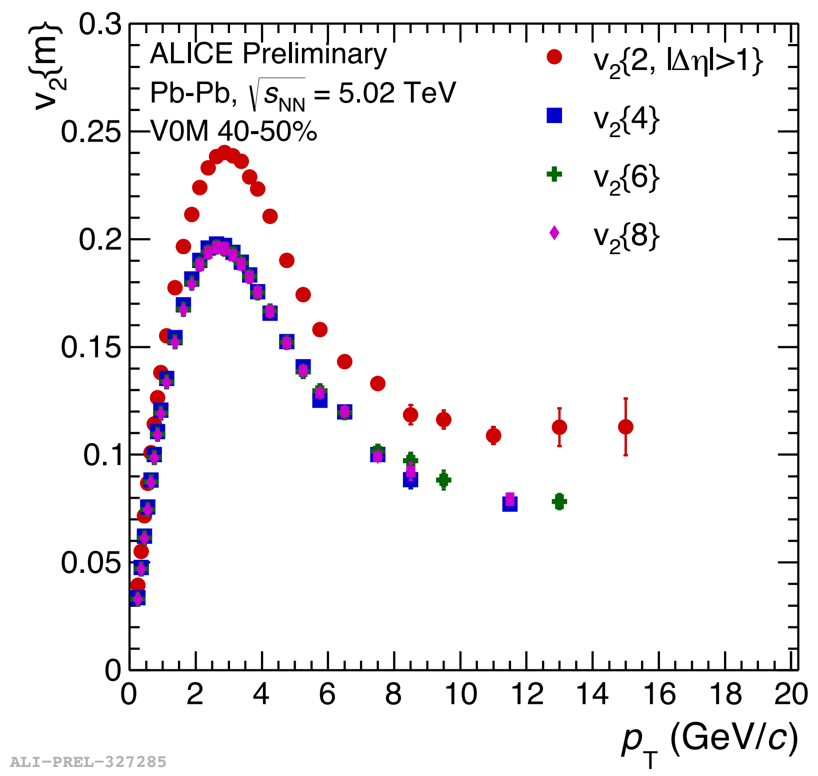

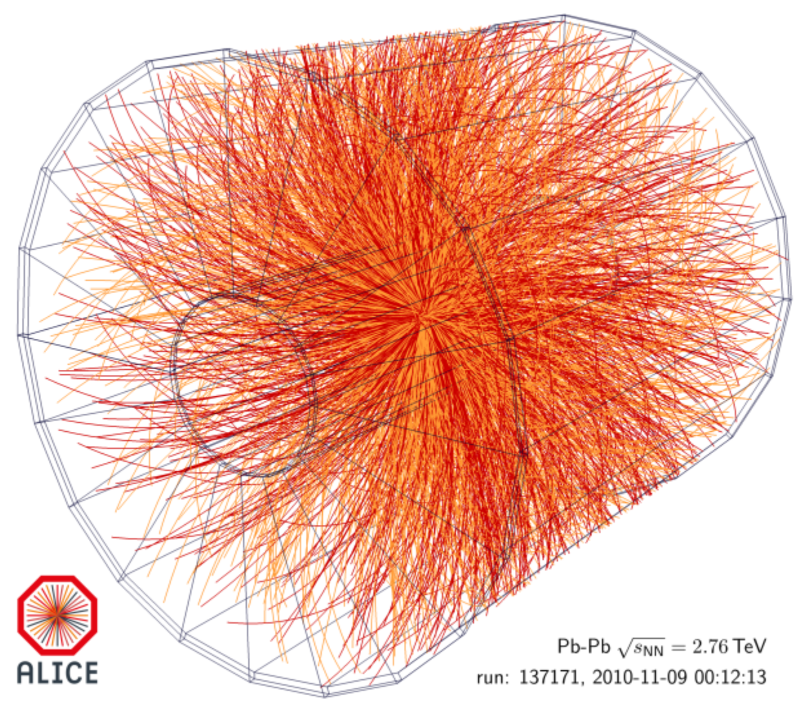

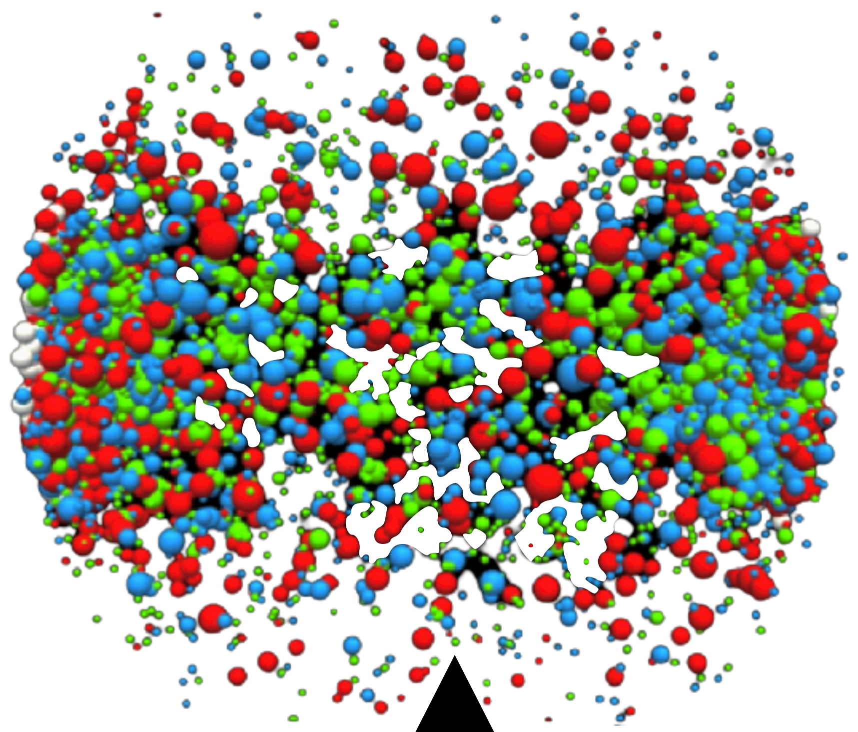

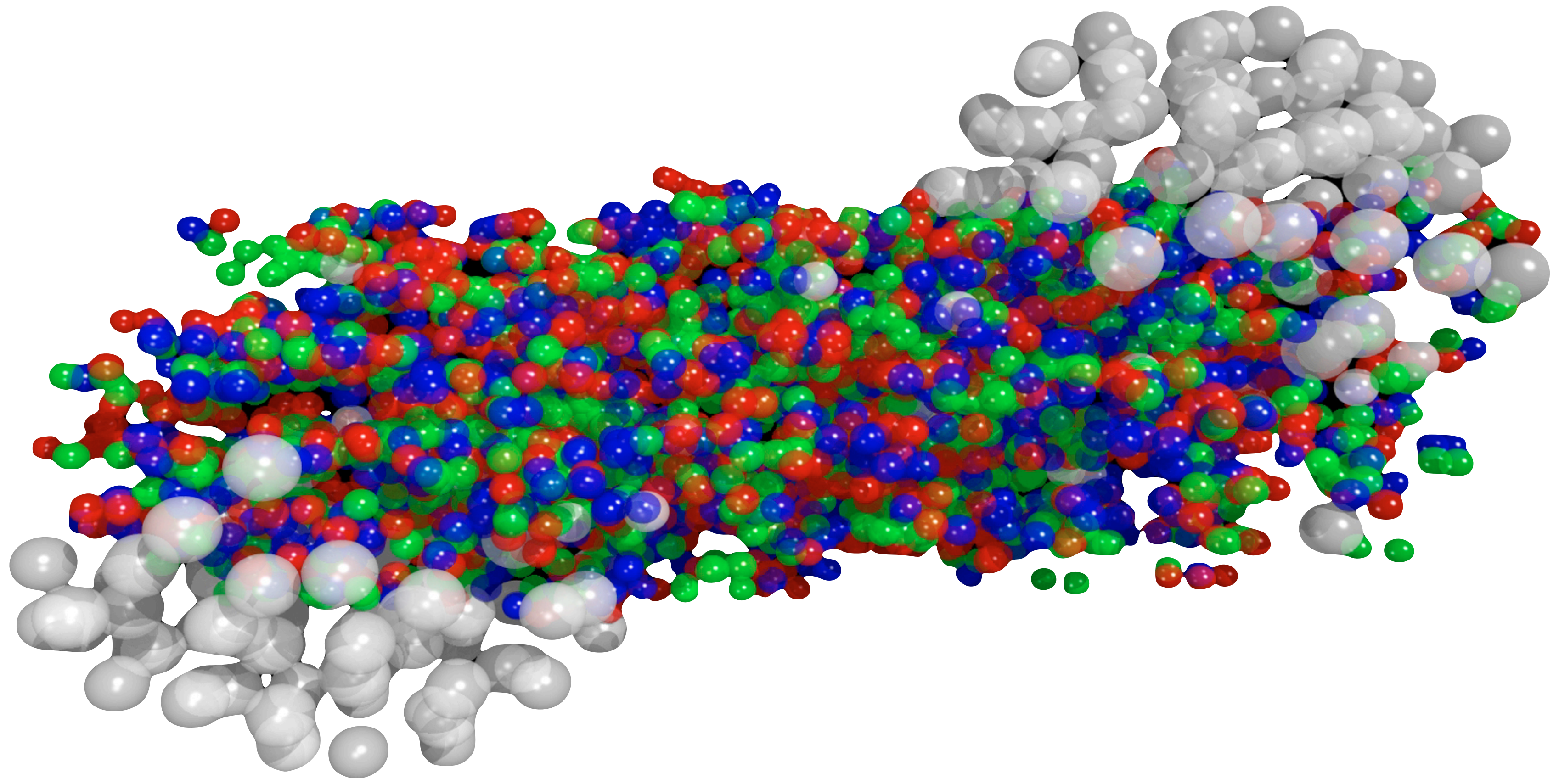

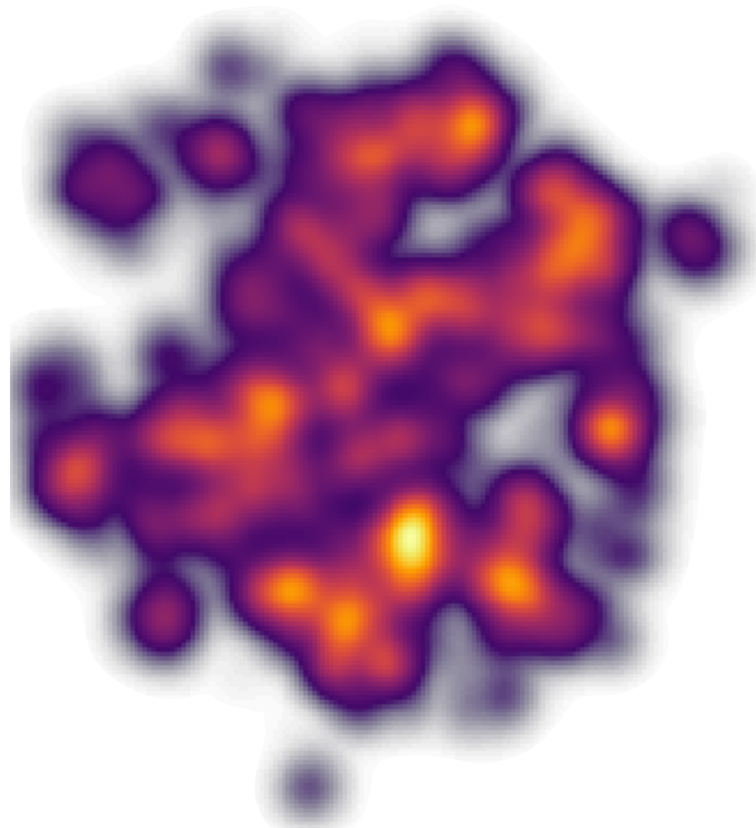

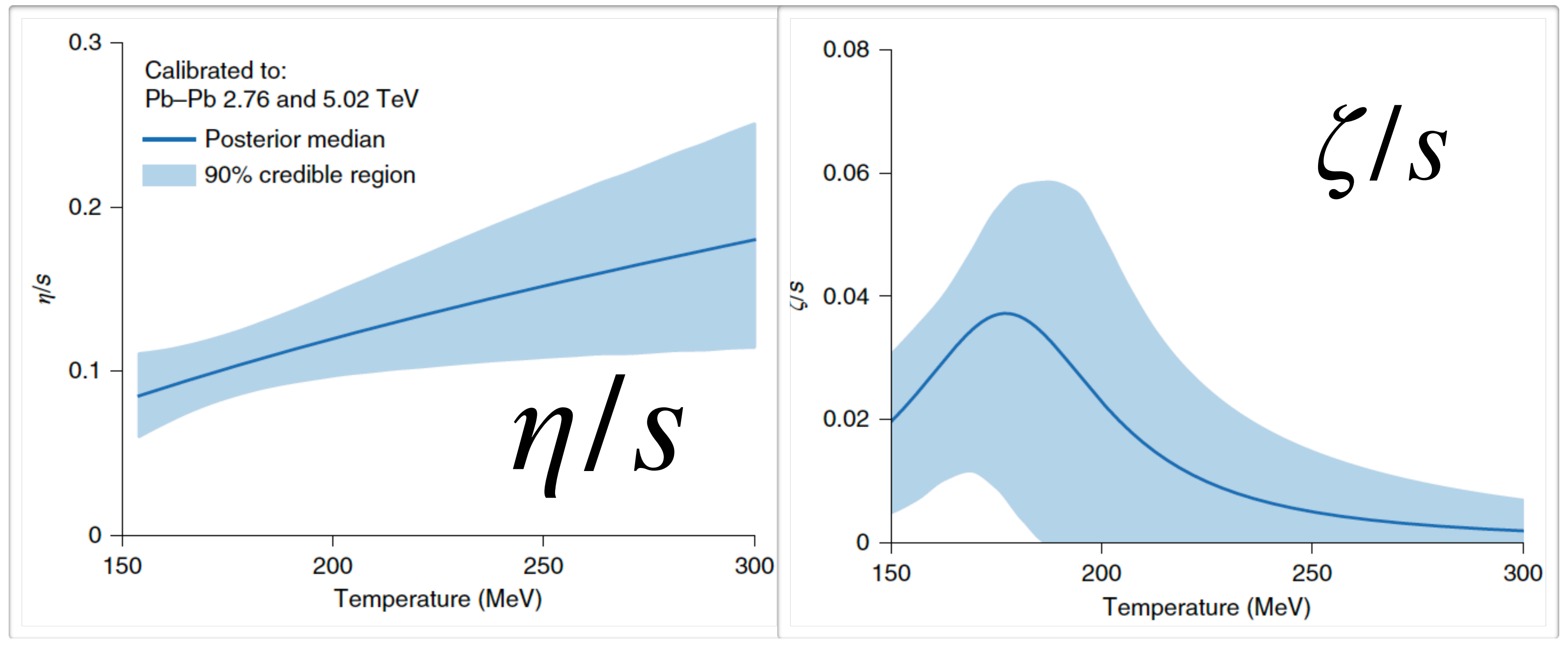

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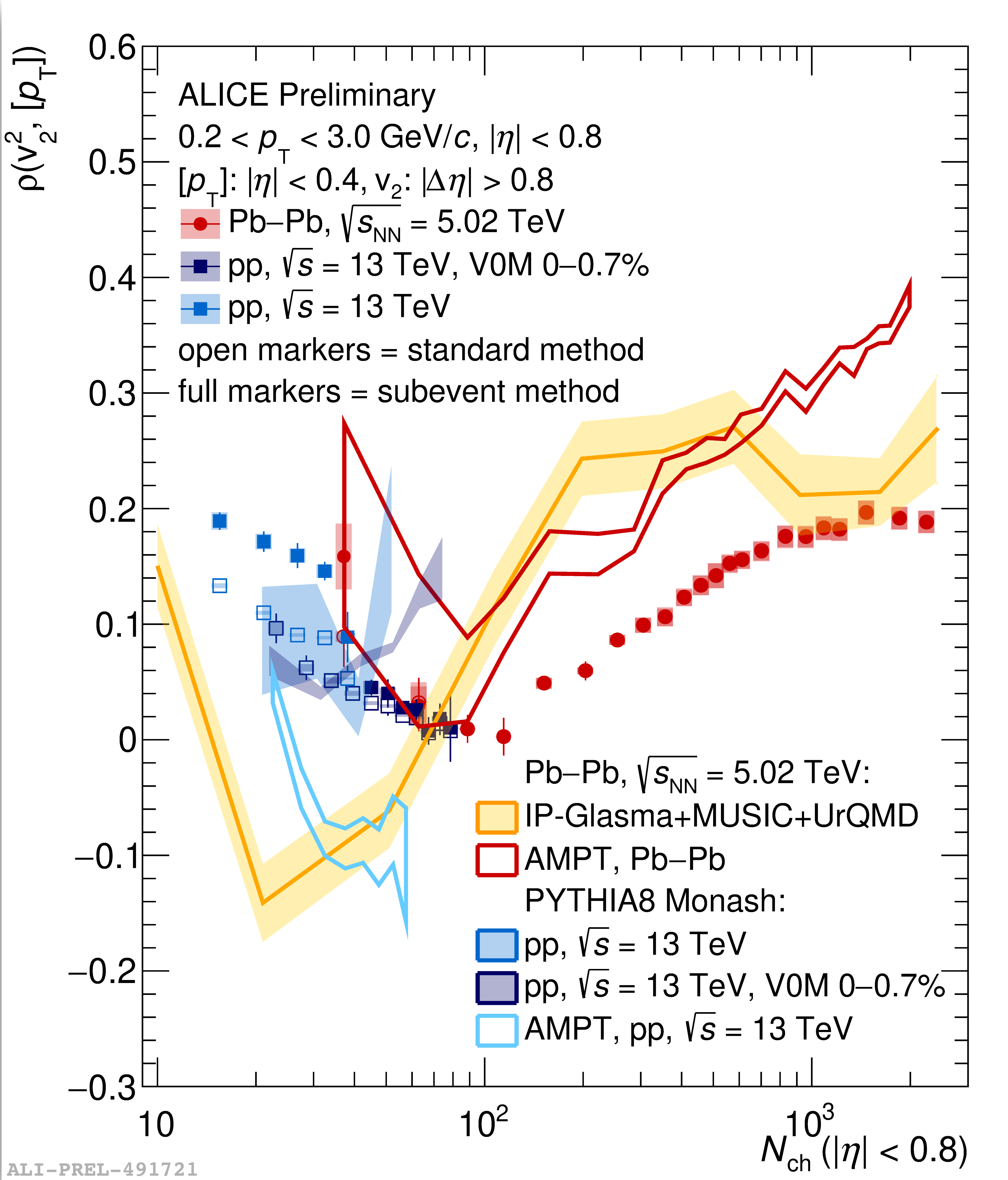

Flow vector fluctuations in Pb—Pb

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

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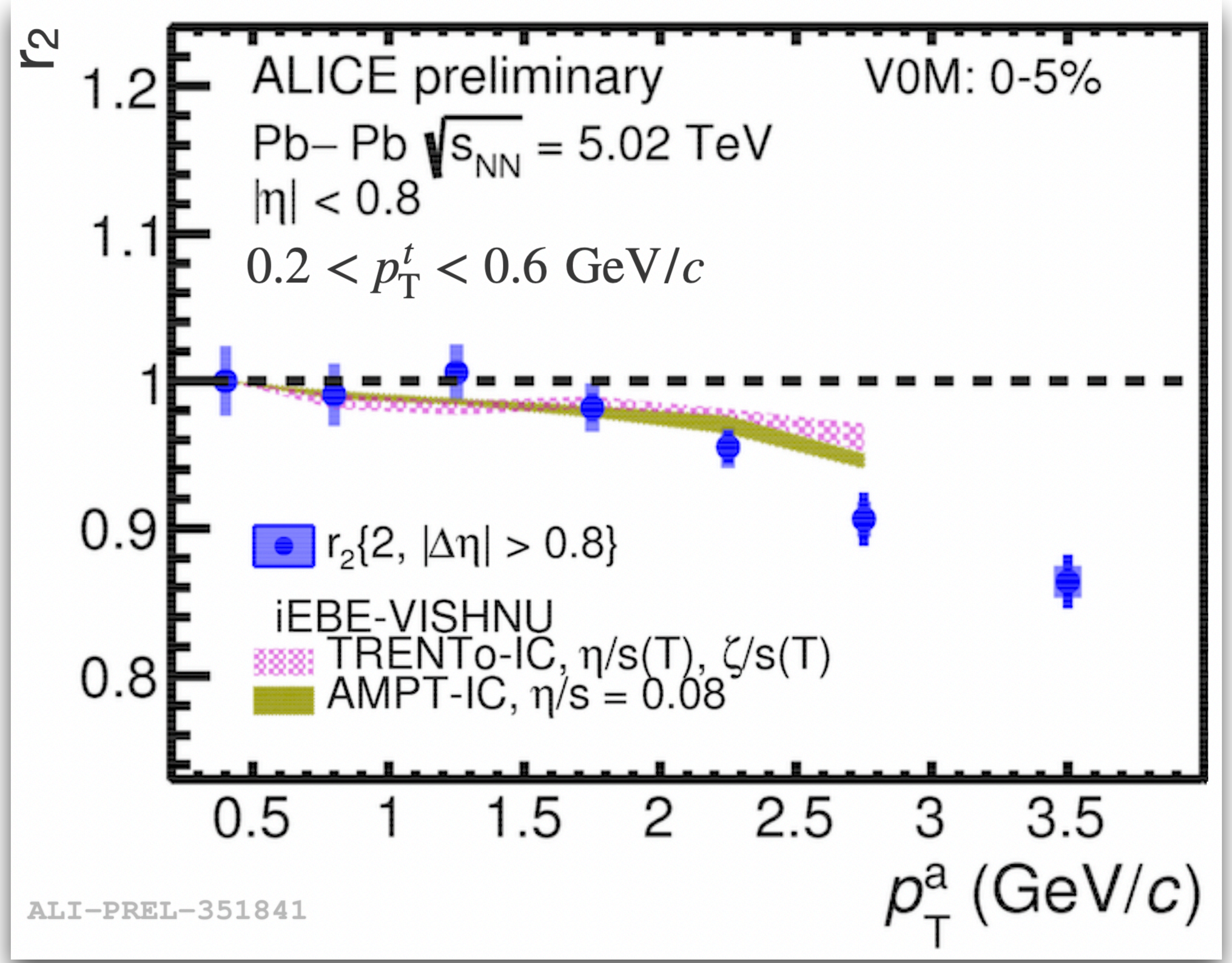
Largest fluctuations in central Pb—Pb collisions at high $p_T \Rightarrow$ large event-by-event fluctuations in the initial state



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

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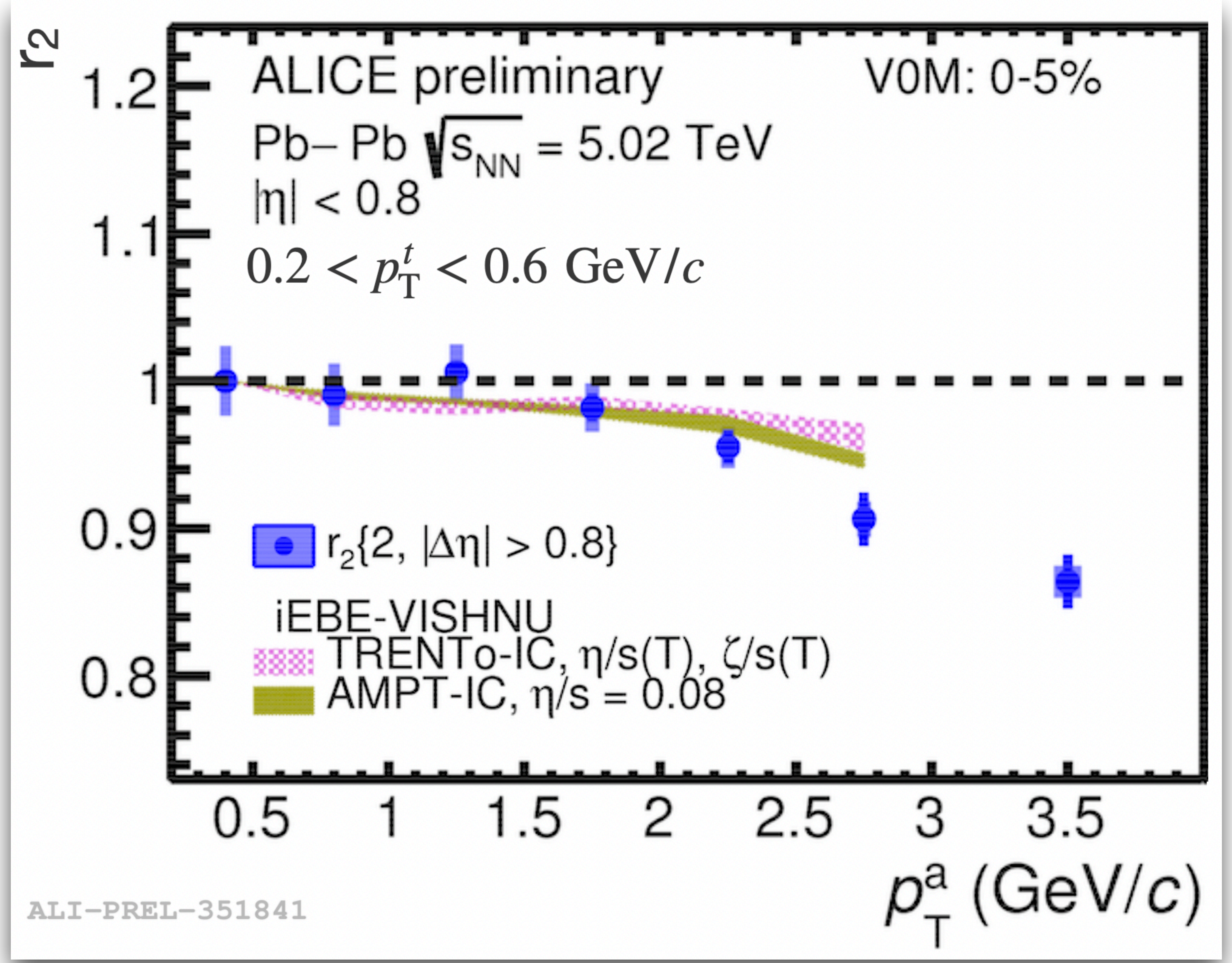
- Cannot be measured directly, but upper/lower limits can be estimated



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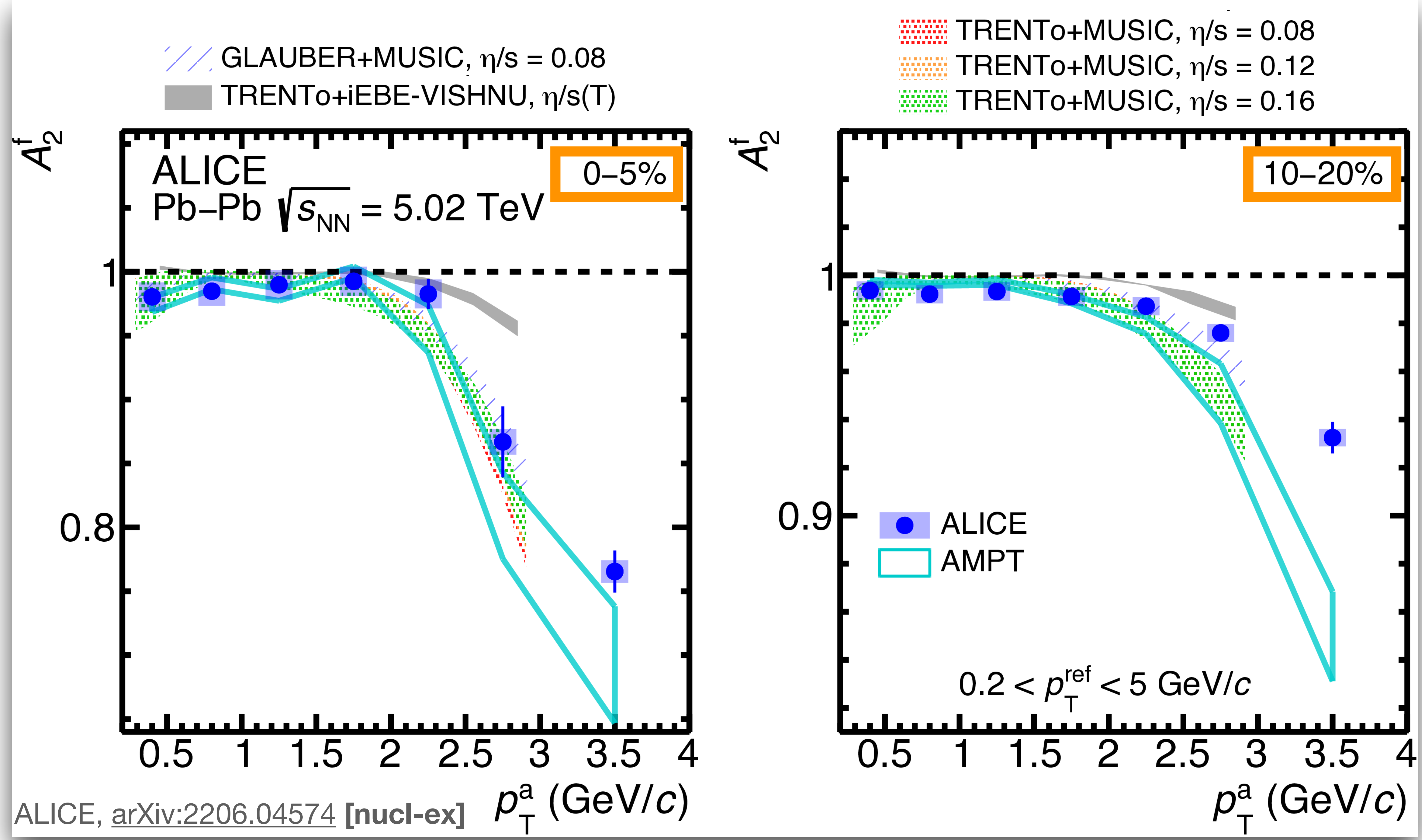

- Sensitive to fluctuations in initial state, little sensitivity to η/s

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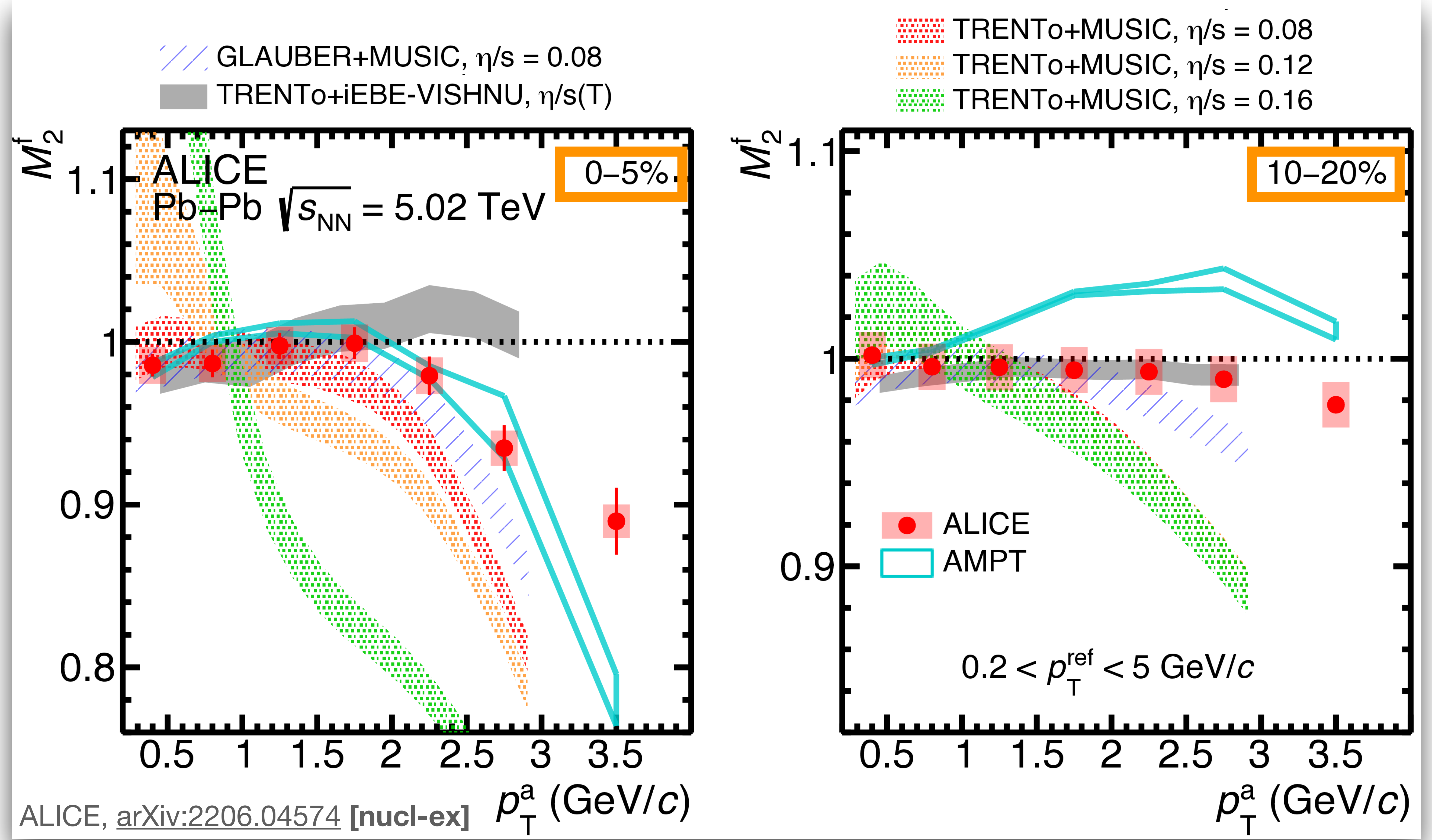

- Sensitive to fluctuations in initial state, little sensitivity to η/s
- Strong sensitivity to shear viscosity, but only in the most central collisions

Flow vector fluctuation limits in Pb—Pb

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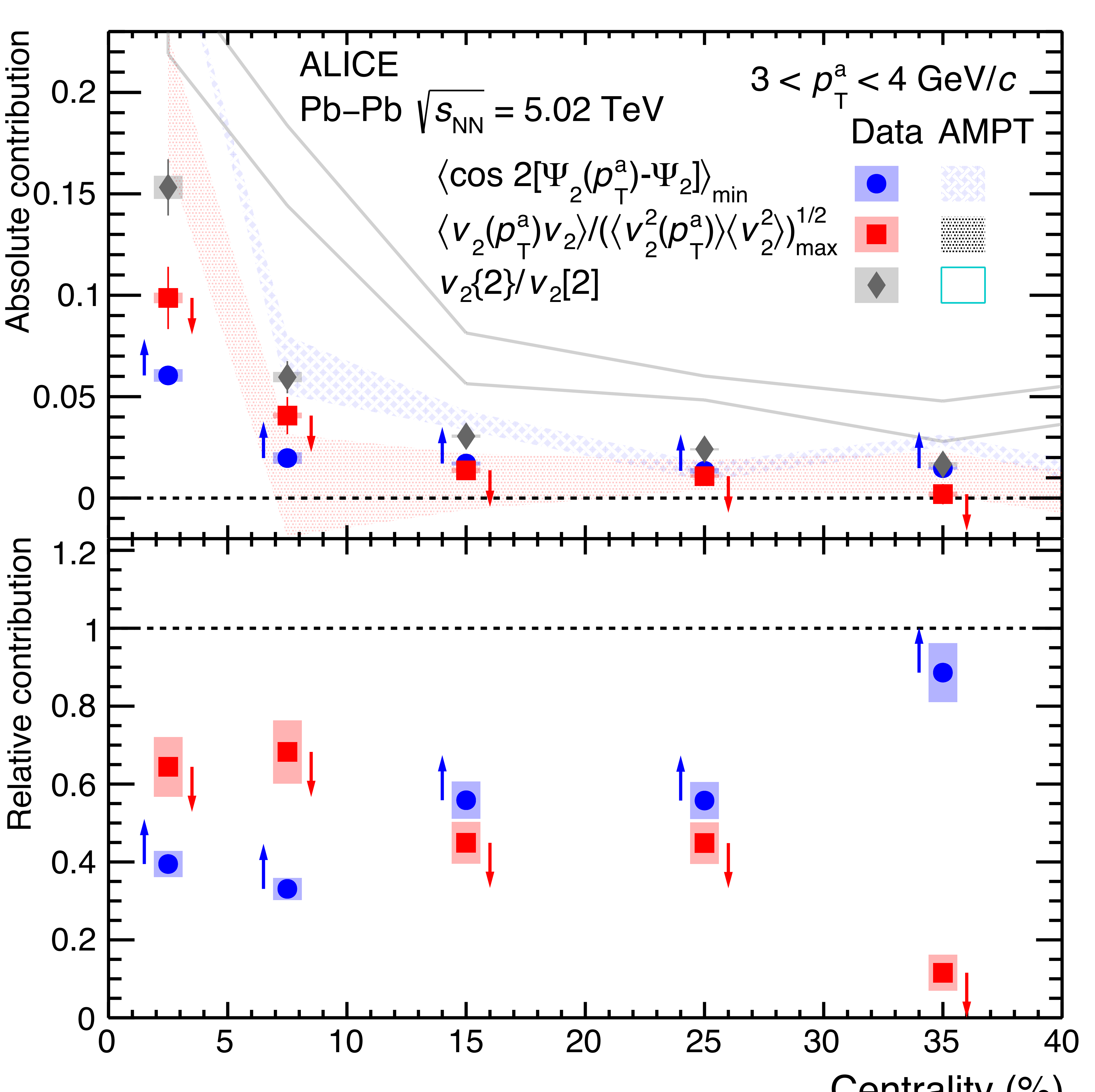
Largest fluctuations in central Pb—Pb collisions at high $p_T \Rightarrow$ large event-by-event fluctuations in the initial state

- 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]

Flow vector fluctuations in Pb—Pb

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

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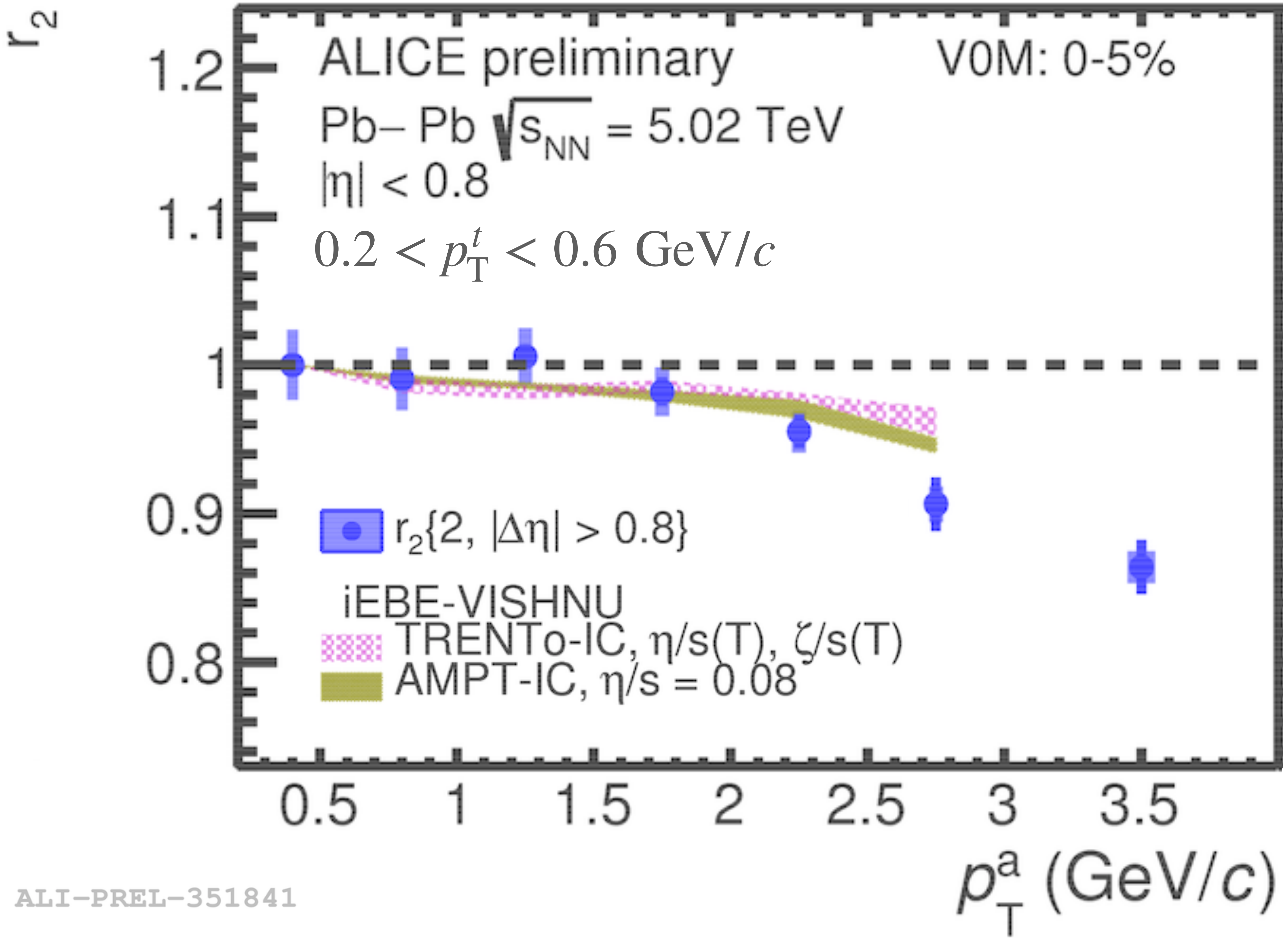

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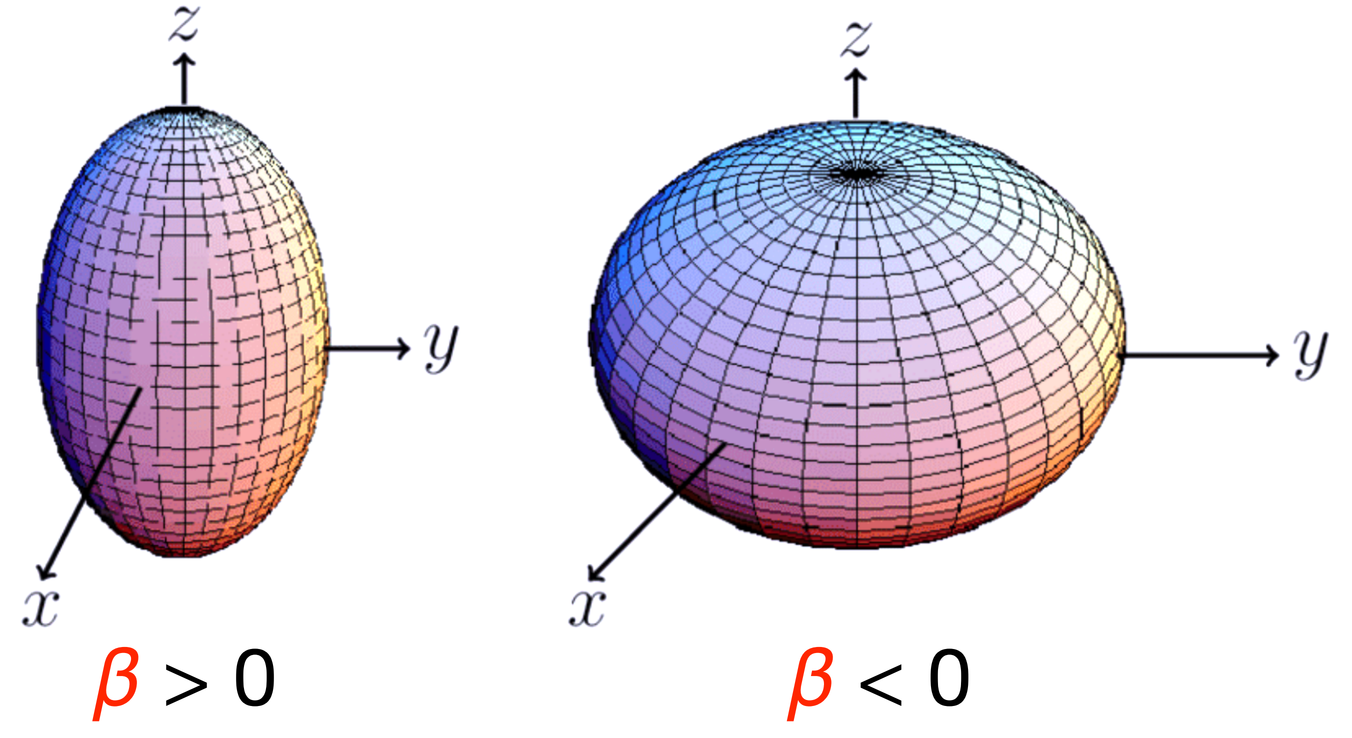
For deformed nuclei

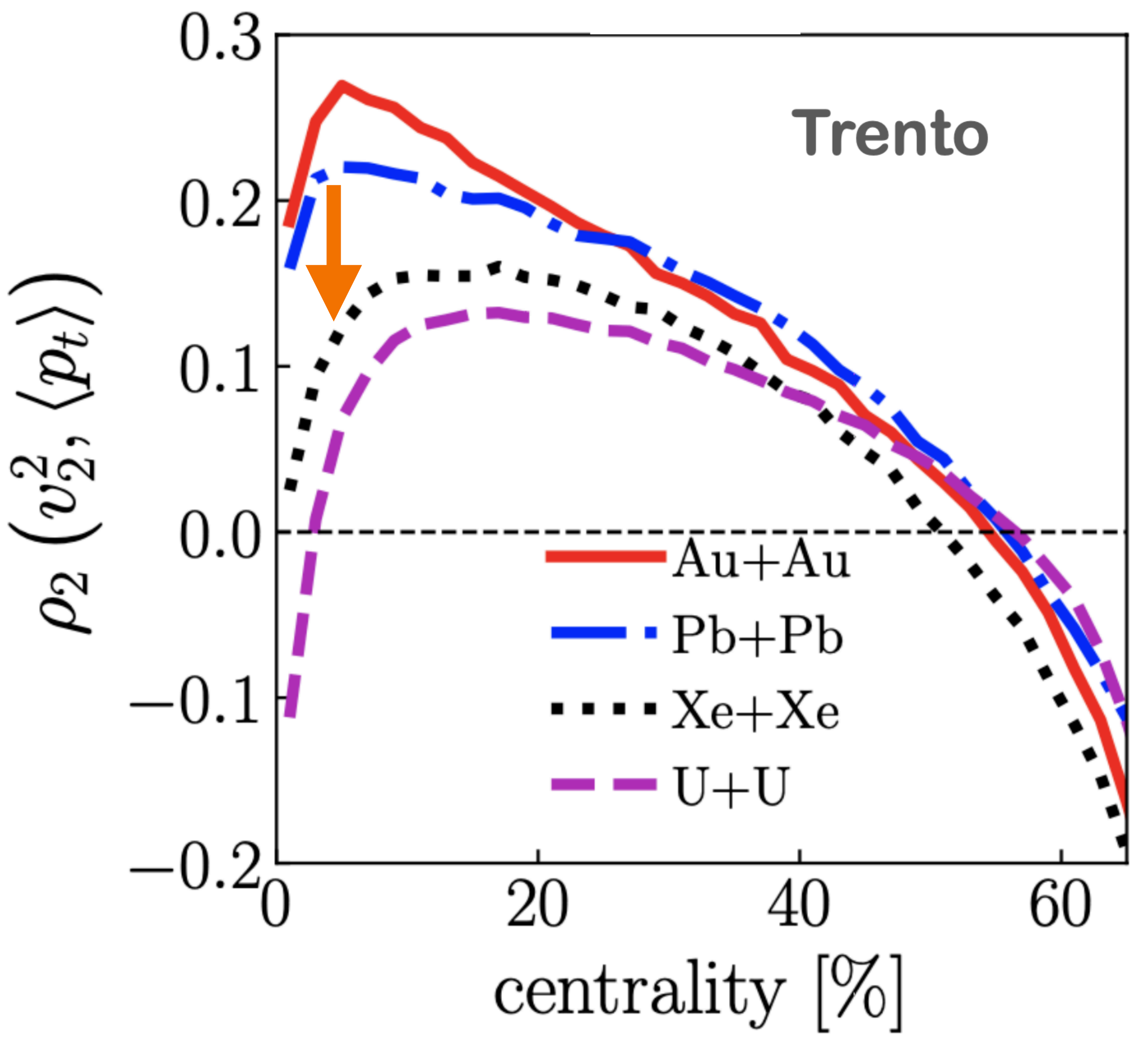
Significantly smaller ρ_2 in central Xe—Xe, compared to Pb—Pb

⇒ Deformation β reduces ρ_2

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



Pb—Pb: $\beta \approx 0$
Xe—Xe: $\beta \approx 0.16$



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

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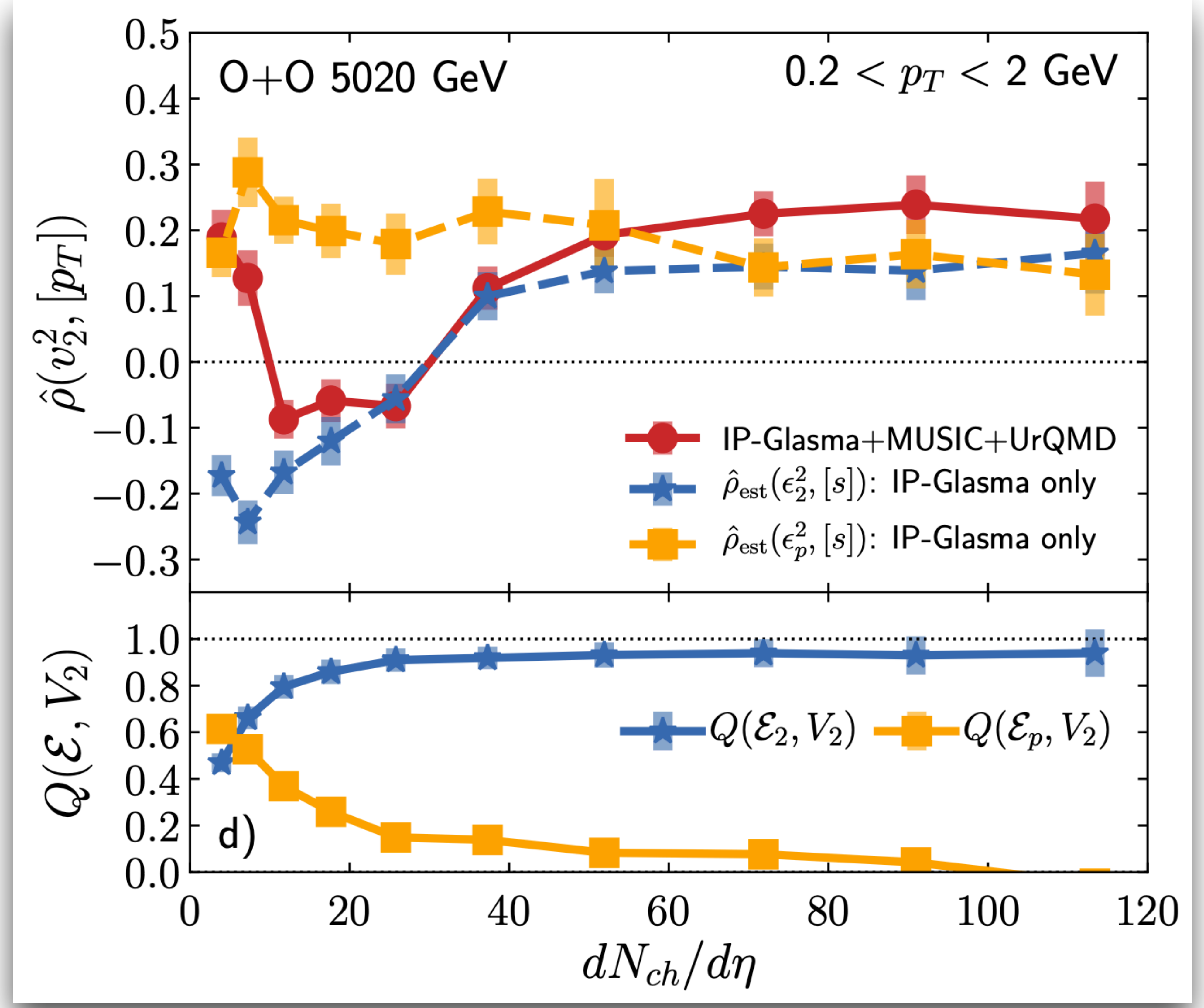

G. Giacalone, Phys. Rev. Lett. 125, 192301 (2020)

Probing the initial state

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