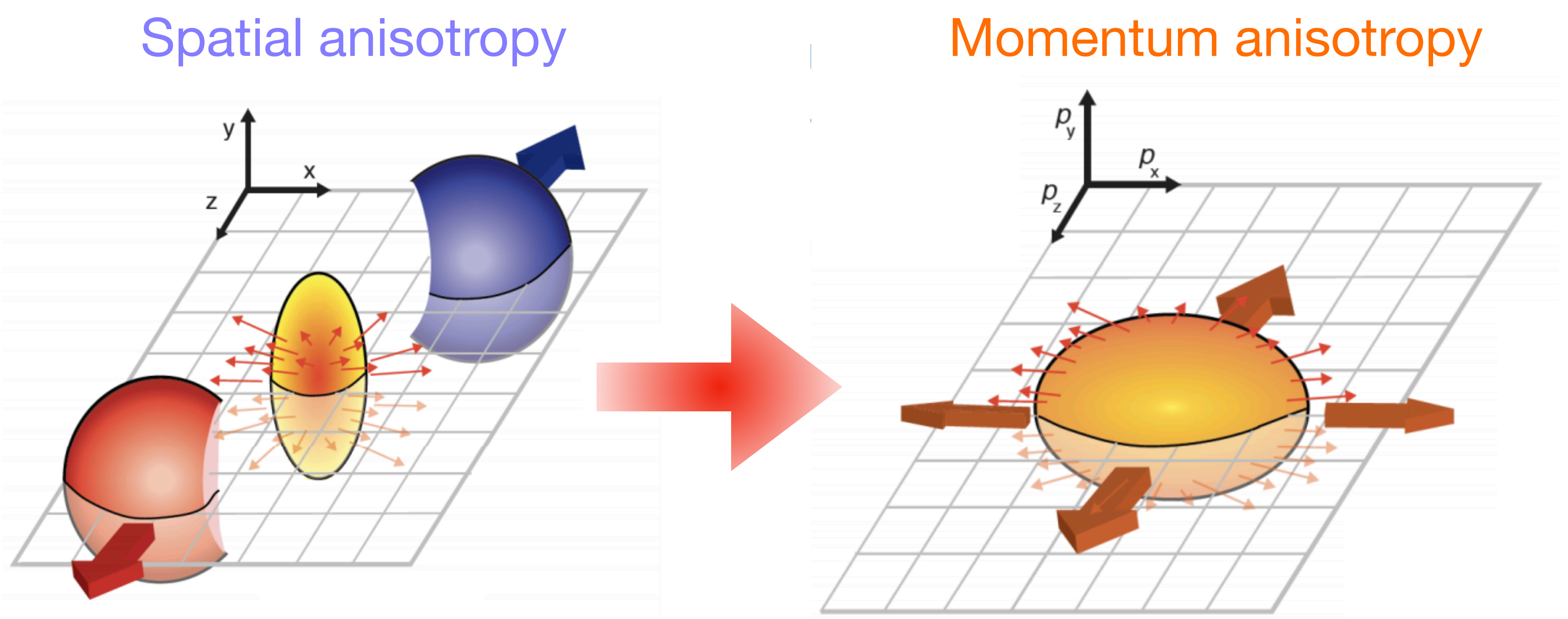
Accessing the initial conditions of Pb—Pb, Xe—Xe and pp collisions with ALICE

Emil Gorm Nielsen for the ALICE collaboration
(Niels Bohr Institute)

THE VELUX FOUNDATIONS
VILLUM FONDEN ✕ VELUX FONDEN

Anisotropic flow

- Overlap between colliding nuclei has specific size and shape
  - Initial state, geometry and its fluctuations
- Initial spatial anisotropy transferred to final state momentum anisotropy
  - Quantified with $v_n = \langle \cos n(\varphi - \Psi_n) \rangle$



J. Schukraft et al, PLB 719 (2013), 394
H. Petersen et al, PRC 88 (2013), 044918
P. Huo et al, PRC 90 (2014), 024910

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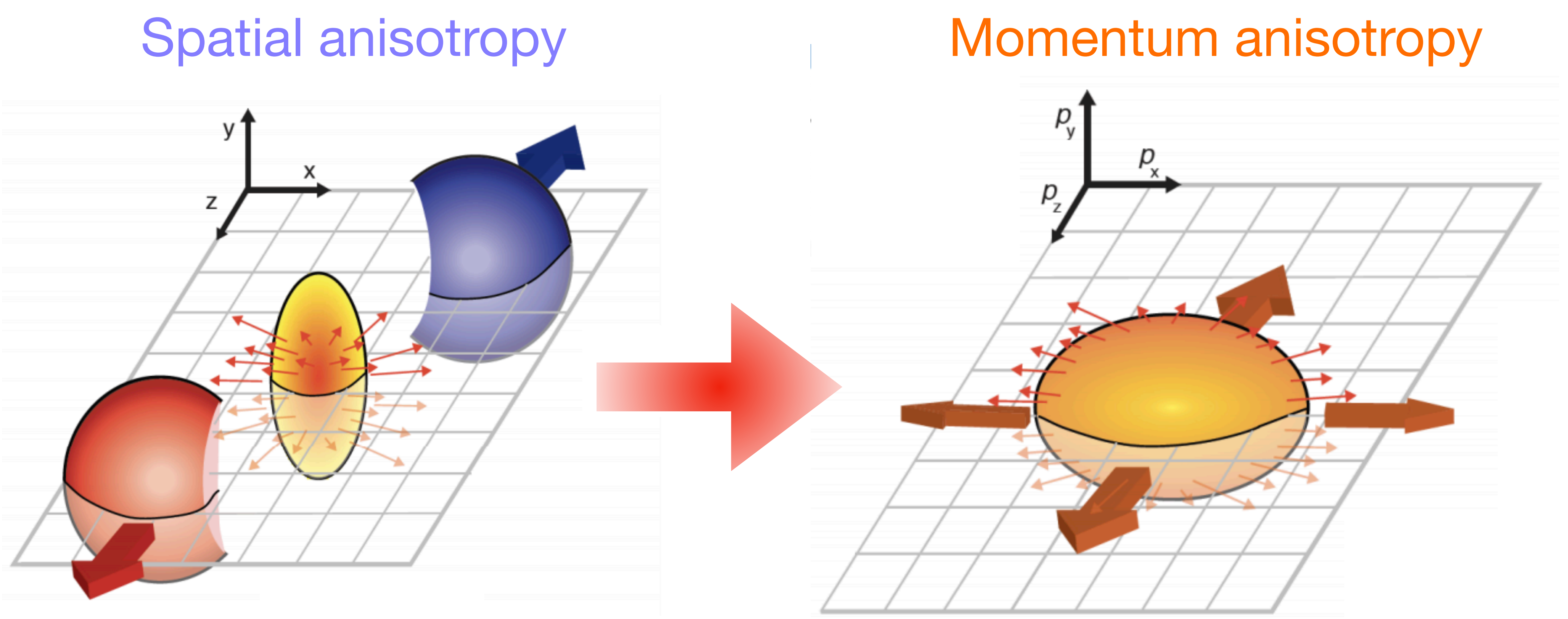


Event-shape engineering

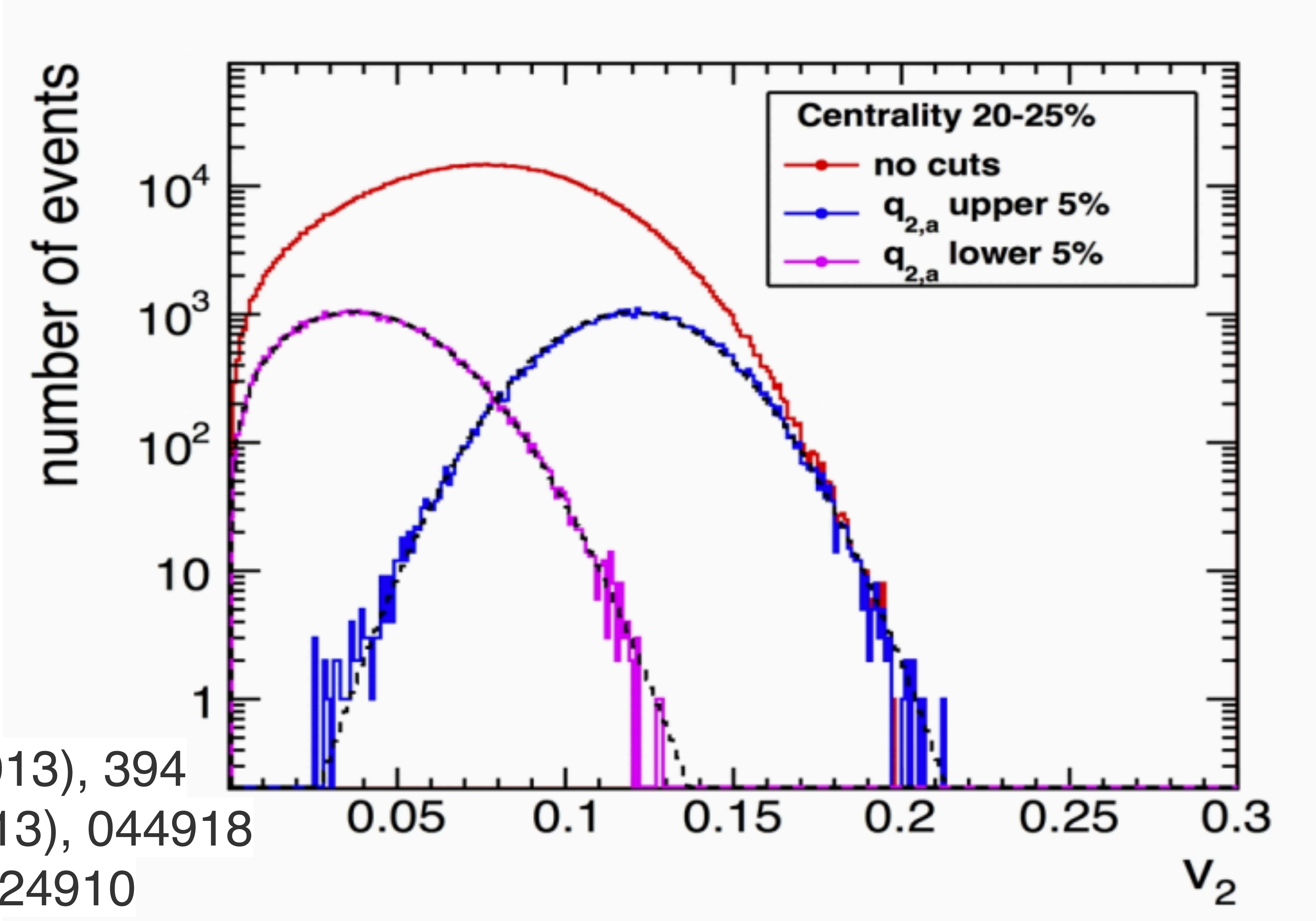
- ❖ Select events with similar centralities, but different shapes based on the event-by-event flow/eccentricity fluctuations

Flow vector

$$Q_{n,x} = \sum_i \cos(n\varphi_i)$$
$$Q_{n,y} = \sum_i \sin(n\varphi_i)$$

q_n distribution

$$Q_n = Q_{n,x}, iQ_{n,y}$$
$$q_n = |Q_n| / \sqrt{M}$$



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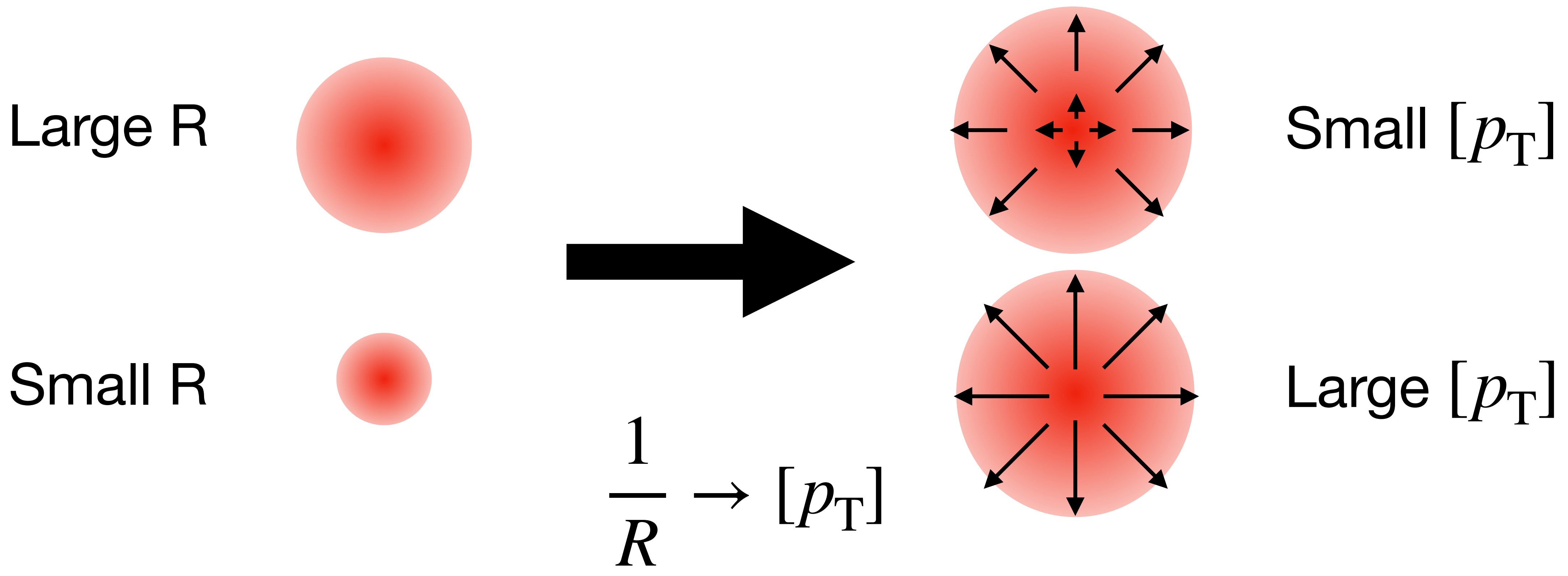
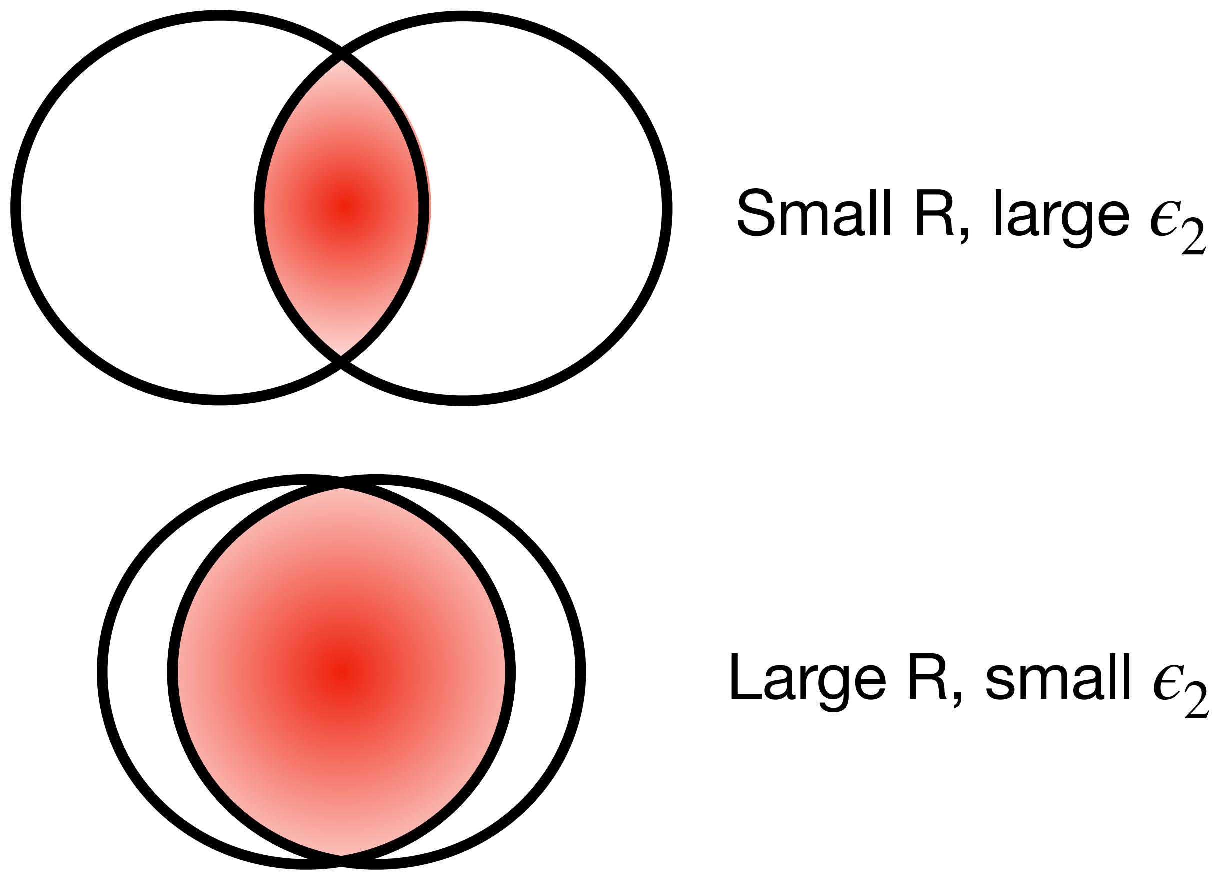
Correlations of mean transverse momentum and flow

- Size of the fireball: radial flow, $[p_T]$
- Shape of the fireball: anisotropic flow
- Current tuned hydrodynamic calculations can describe v_n and $[p_T]$ separately
  - State-of-the-art understanding of initial conditions and transport properties of the QGP

Size: Mean transverse momentum



Size & Shape: v_n-$[p_T]$



$$\langle \epsilon_n^2 \frac{1}{R} \rangle \rightarrow \langle v_n^2 p_T \rangle$$

Initial state   Final state

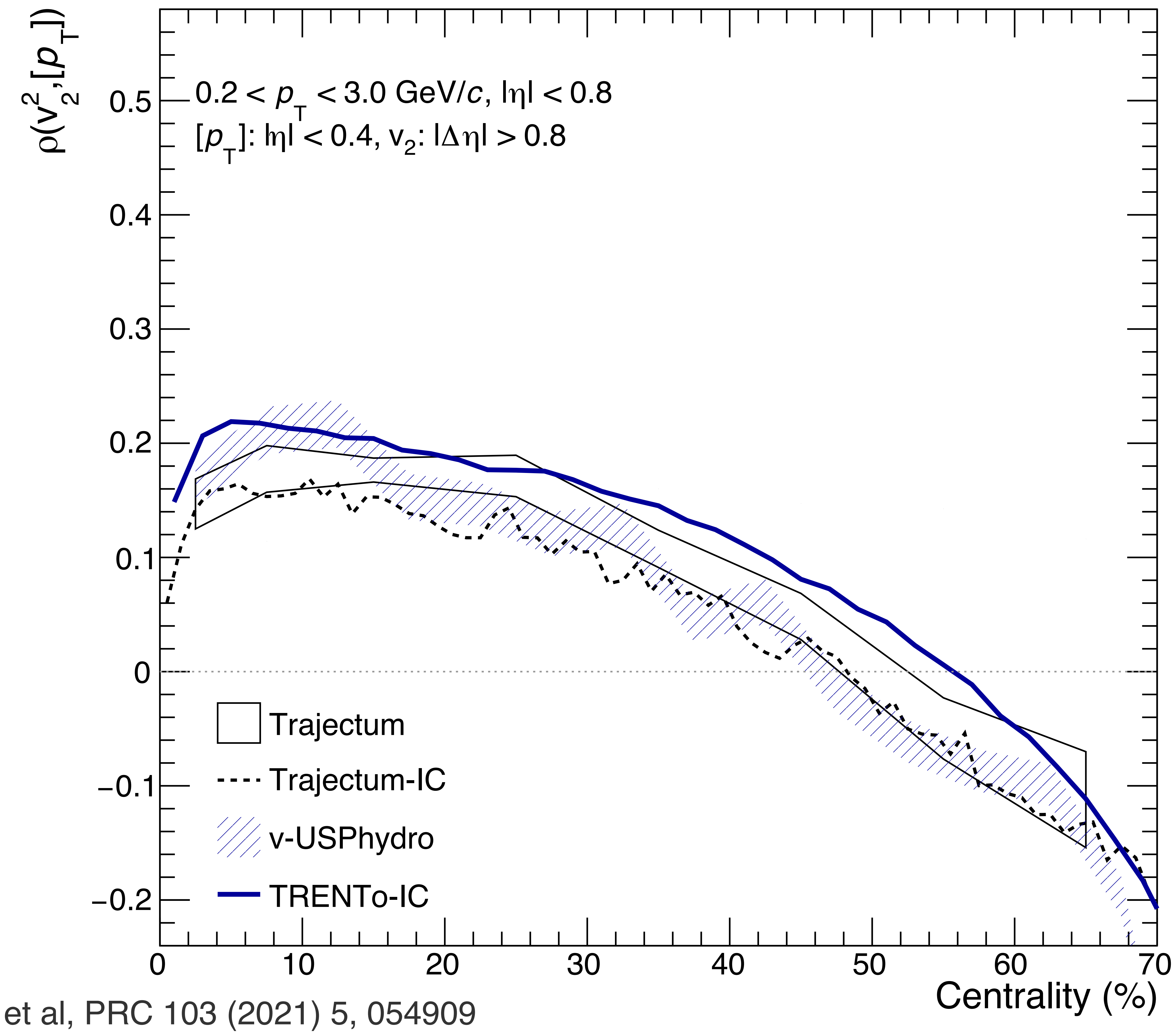
Study with Pearson correlation coefficient:

$$\rho(v_n^2, [p_T]) = \frac{cov(v_n^2, [p_T])}{\sqrt{var(v_n^2)}\sqrt{var([p_T])}}$$

Correlations of mean transverse momentum and flow

Probing the initial state

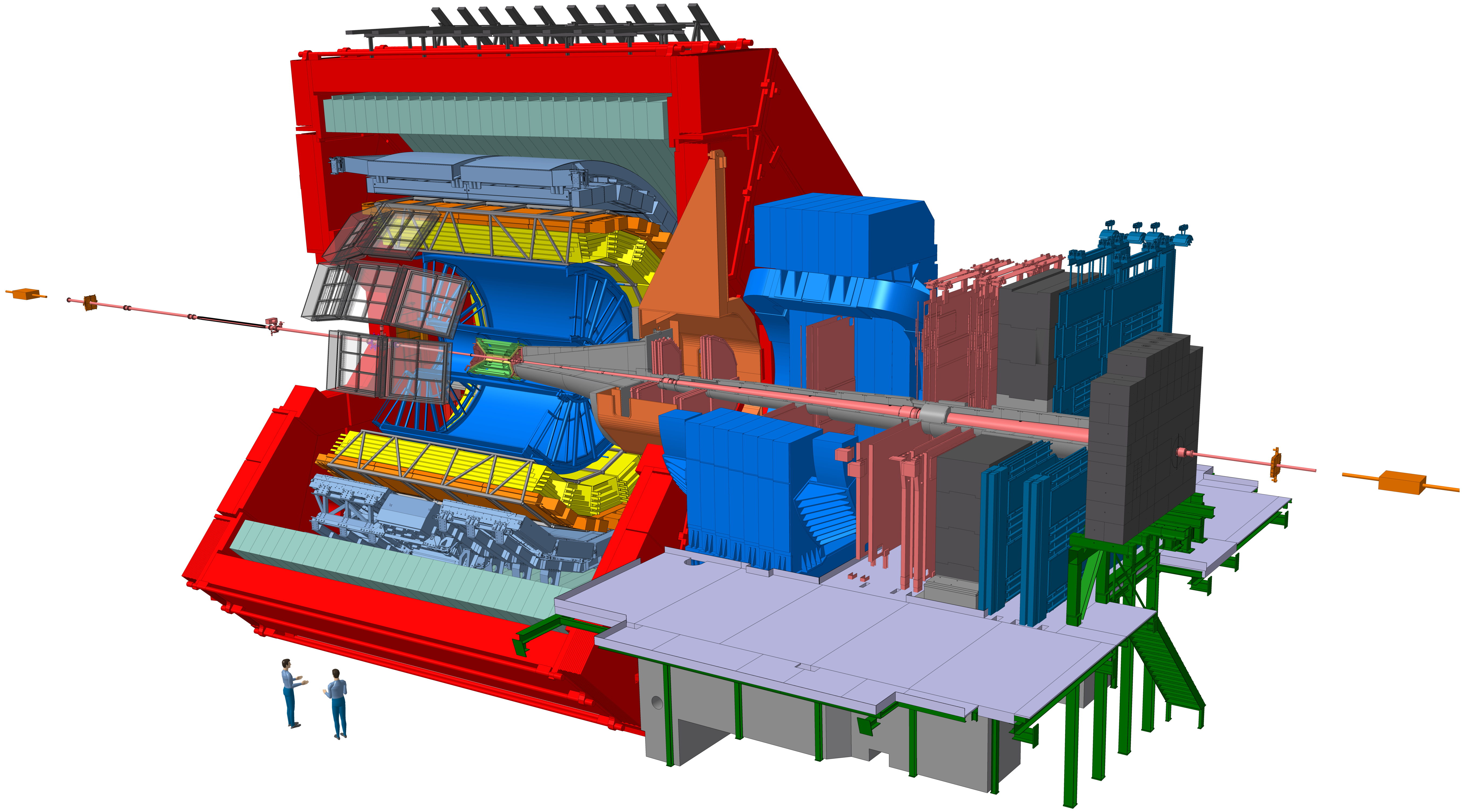
- Agreement between initial state estimations and final state calculations → ρ_n **directly reflects information from the initial state!**
- Low multiplicity region: geometry → initial momentum correlations (CGC?)
- Sensitive to nuclear deformation



G. Nijs et al, PRC 103 (2021) 5, 054909
J. Noronha-Hostler et al, PRC 88 (2013) 4, 044916
J. S. Moreland et al, PRC 92 (2015) 1, 011901

The ALICE experiment

- ❖ Inner tracking system (ITS)
- ❖ Time projection chamber (TPC)
- ❖ Time-of-flight (TOF)
- ❖ V0A($2.8<\eta<5.1$) and V0C($-3.7<\eta<-1.7$)



❖ Track selection

- $|\eta| < 0.8$ (Unidentified)
- $|y| < 0.5$ (Identified)
- $0.4 < p_{\mathrm{T}} < 50$ GeV/c

v_n with ESE

- $0.2 < p_{\mathrm{T}} < 3.0$ GeV/c
- $|\eta| < 0.8$
- $v_2 : |\Delta\eta| > 0.8$
- $[p_{\mathrm{T}}] : |\eta| < 0.4$

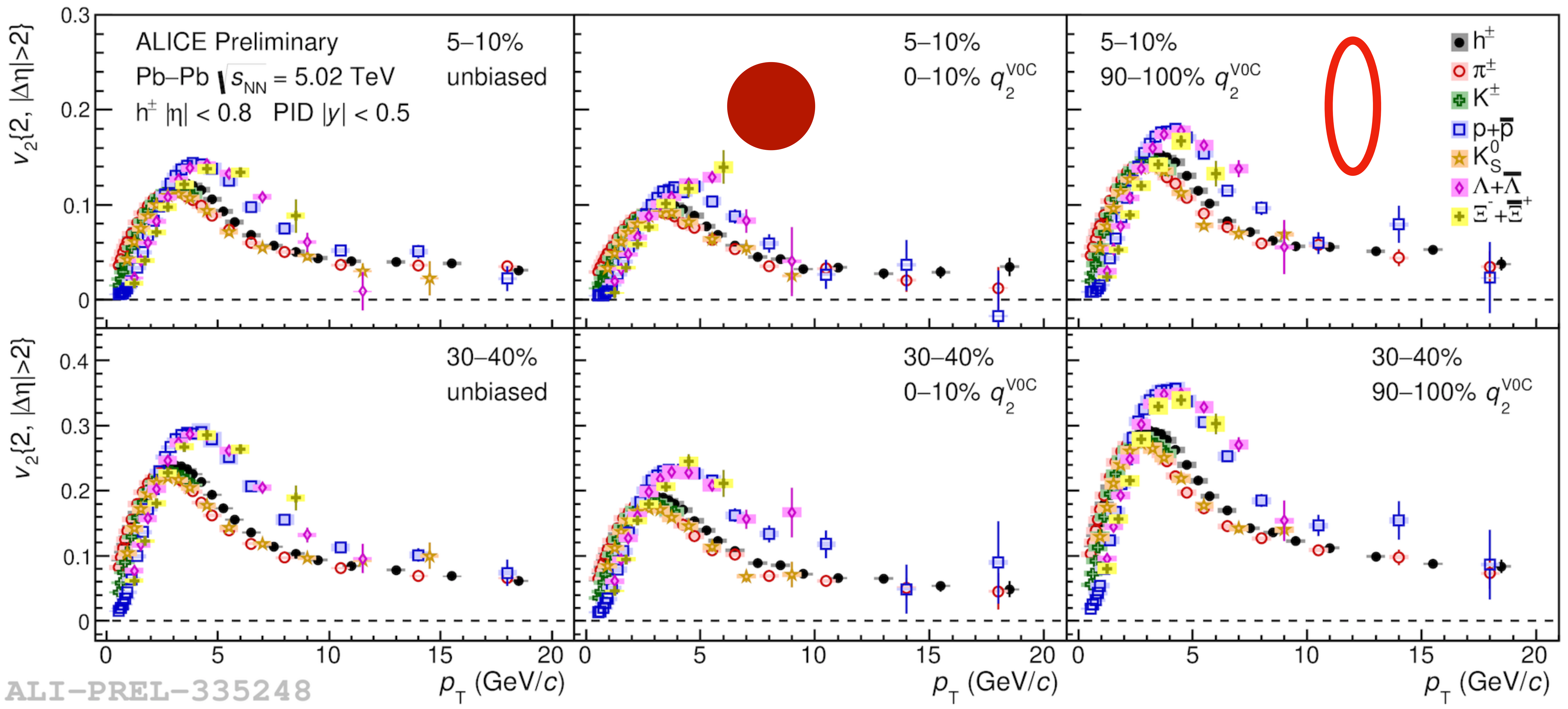
Correlations of $[p_{\mathrm{T}}]$ and v_n

❖ Data:

- Pb$-$Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
- Xe$-$Xe at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV
- pp at $\sqrt{s} = 13$ TeV

Identified particle $v_n(p_T)$ with q_2 selection

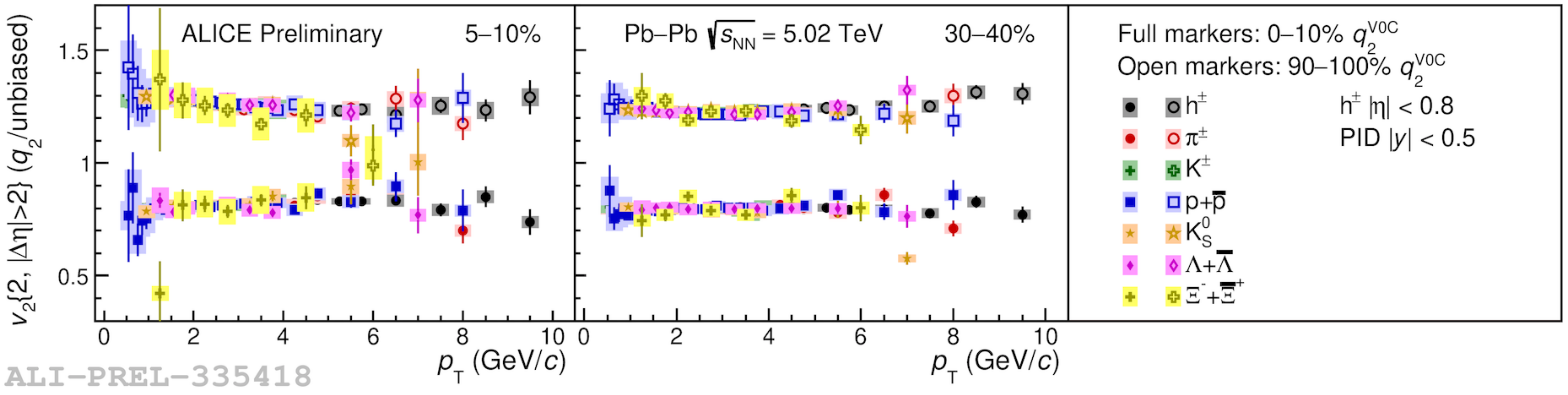
- q_2 selection biases smaller or larger v_2 than average for inclusive and identified particles



Identified particle $v_n(p_T)$ with q_2 selection

- q_2 selection biases smaller or larger v_2 than average for inclusive and identified particles
- v_2 with q_2 selection:
  - $p_T > 3$ GeV$/c$: ratios almost flat - same source of flow fluctuations
  - $p_T < 3$ GeV$/c$:
    - 5-10% centrality: p_T dependence
    - 30-40% centrality: no p_T dependence
- v_3 with q_2 selection
  - v_3 anticorrelated with q_2
  - Flat ratio up to $p_T = 8$ GeV$/c$
- Same values for inclusive and identified particles

v_2 with q_2 selection



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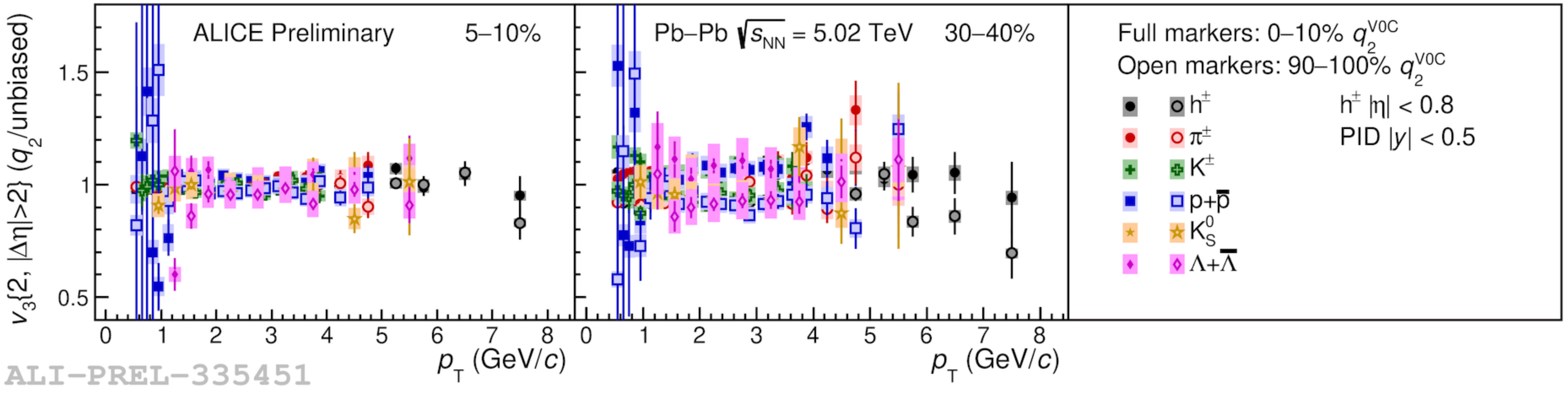
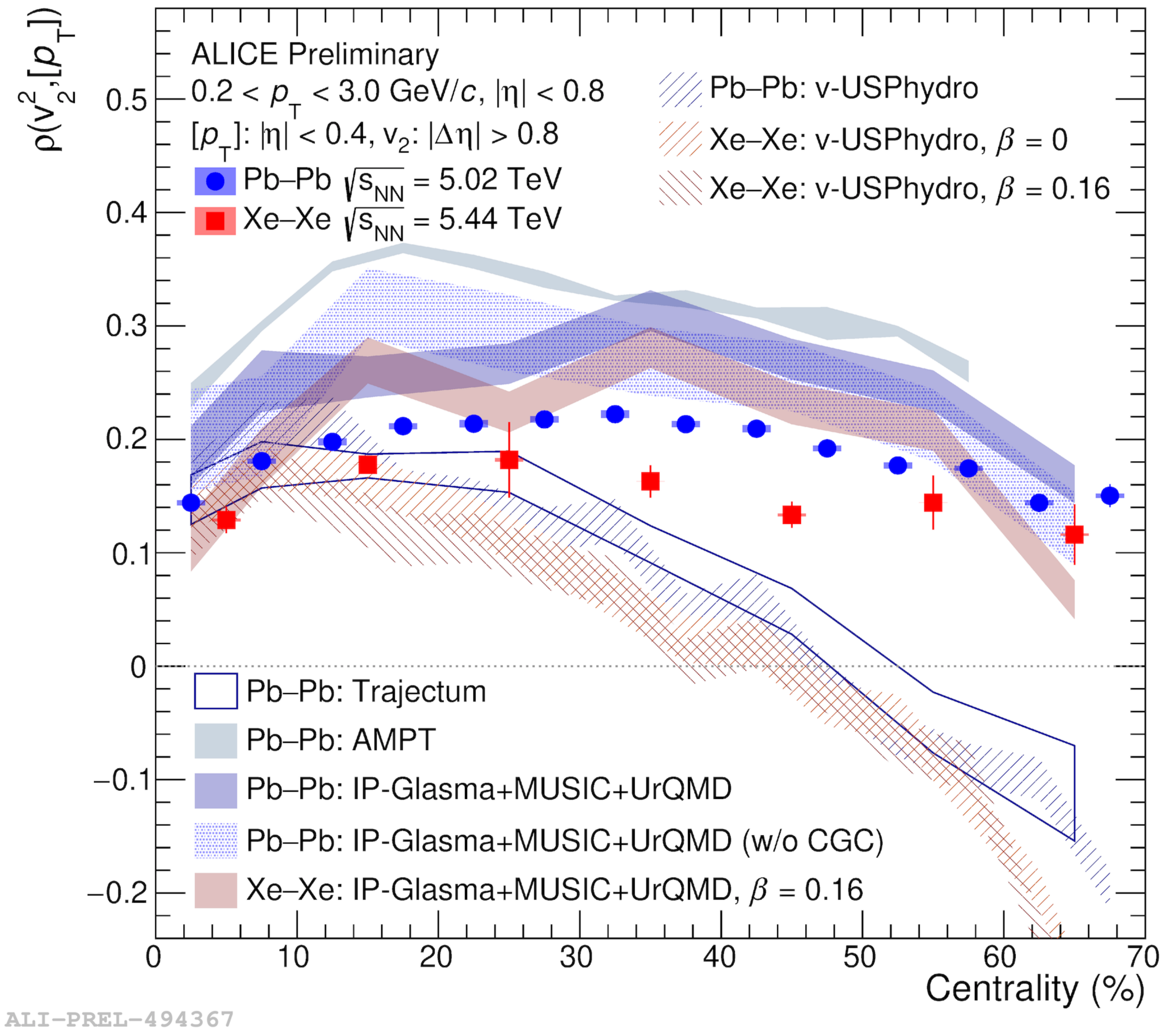


Centrality dependence of $\rho(v_2^2, [p_T])$

- Positive $\rho(v_2^2, [p_T])$ in the presented centrality range - Pb−Pb larger than Xe−Xe
- Comparison to hydro models:
  - IP-Glasma+MUSIC+UrQMD works well for Pb−Pb, overestimates Xe−Xe
  - Comparison of IP-Glasma w/ and w/out CGC rule out CGC effects in the presented centrality→ Must be due to geometry!
  - TRENTo-IC based calculations - strong centrality dependence - negative above 40-50% centrality



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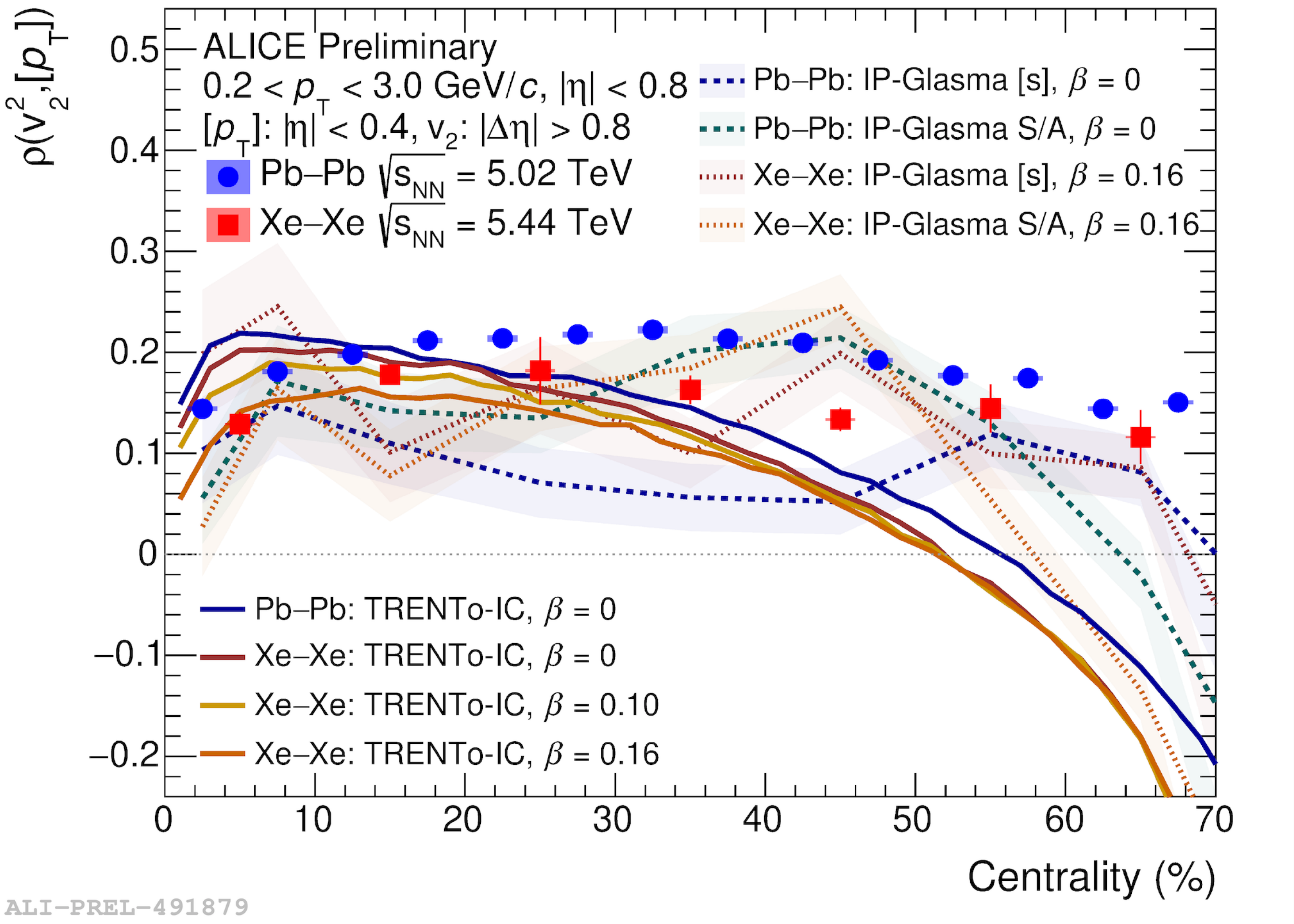
- Comparison to initial state calculations:
  - TRENTo-IC fails to describe ALICE data
  - State-of-the-art Bayesian analysis based on failing initial condition
  - Sensitive to deformation parameter up to 20-30% - previous study only sensitive in 0-10% centrality[1]



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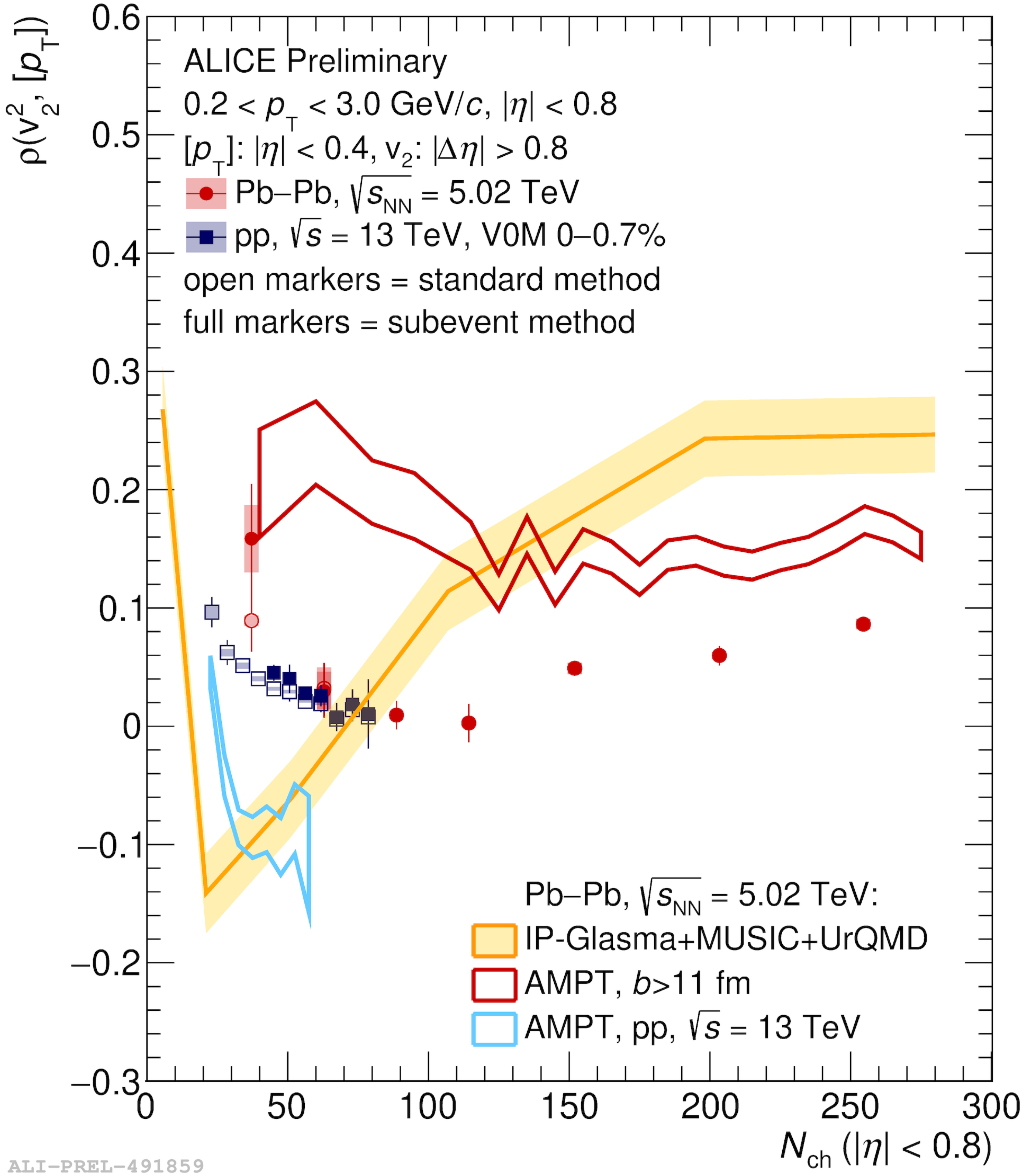
[1] ALICE collaboration, PLB 784 (2018) 82-95

$\rho(v_2^2, [p_T])$ at low multiplicity

- $\rho(v_2^2, [p_T])$ in Pb–Pb:
  - Slope change around N_{ch} of 100
  - IP-Glasma+MUSIC+UrQMD changes slope @ $N_{ch} \sim 20$
- Slope change in both AMPT and IP-Glasma+MUSIC+UrQMD
  $\Rightarrow$ Not unique to CGC?
- No quantitive description of data
- $\rho(v_2^2, [p_T])$ in pp:
  - Decreasing trend with N_{ch}
  - High-multiplicity data consistent with Pb–Pb
  - Underestimated by AMPT



S.H.Lim, J.L. Nagle, arXiv:2103.01348
B. Schenke et al, PRC 102 (2020) 4, 044905

$\rho(v_2^2, [p_\mathrm{T}])$ at low multiplicity

- ❖ $\rho(v_2^2, [p_\mathrm{T}])$ in Pb−Pb:
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  ⇒ Not unique to CGC?
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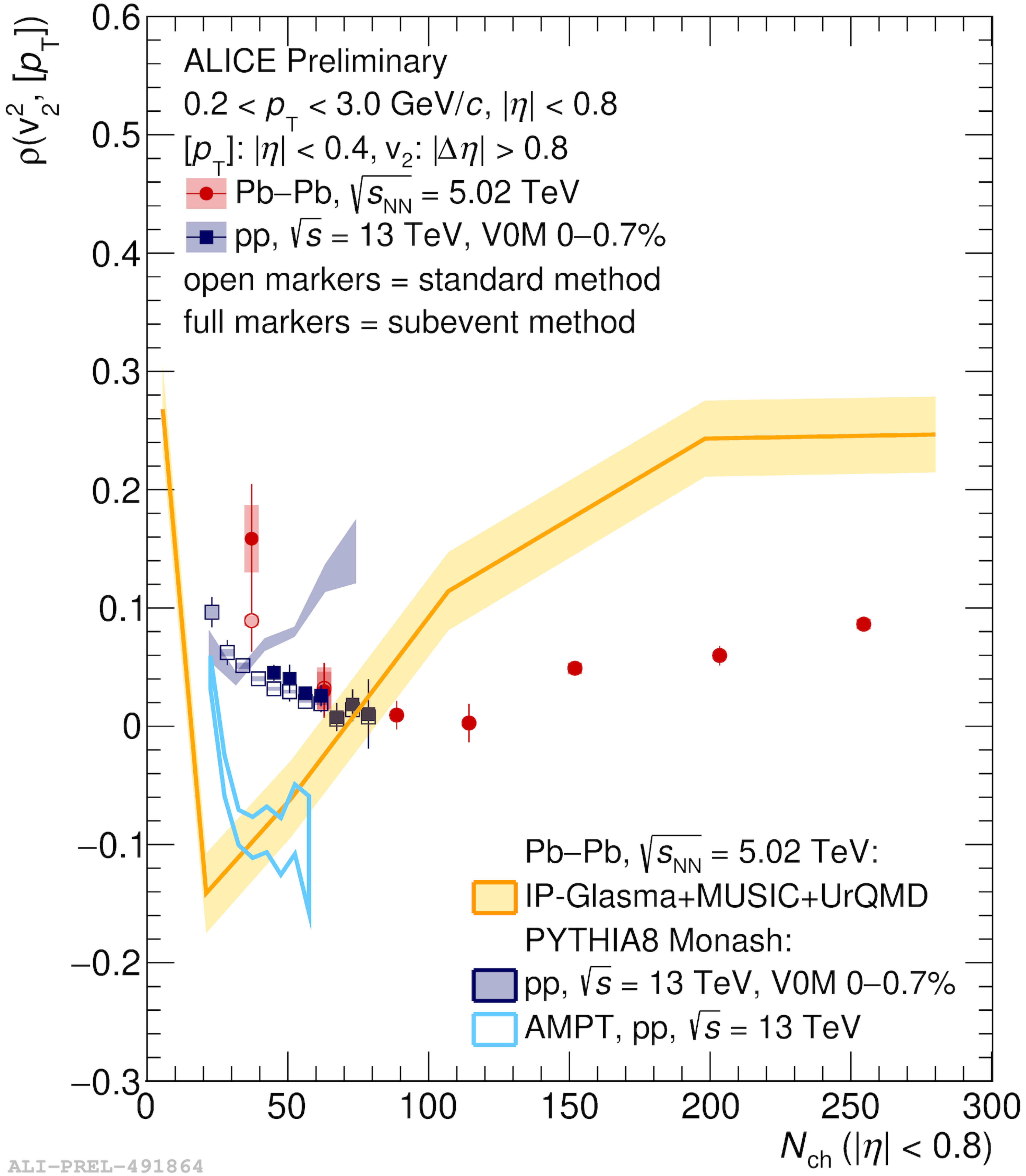
- ❖ $\rho(v_2^2, [p_\mathrm{T}])$ in pp:
  - Decreasing trend with N_ch
  - High-multiplicity data consistent with Pb−Pb
  - Underestimated by AMPT
  - Overestimated by PYTHIA



S.H.Lim, J.L. Nagle, arXiv:2103.01348
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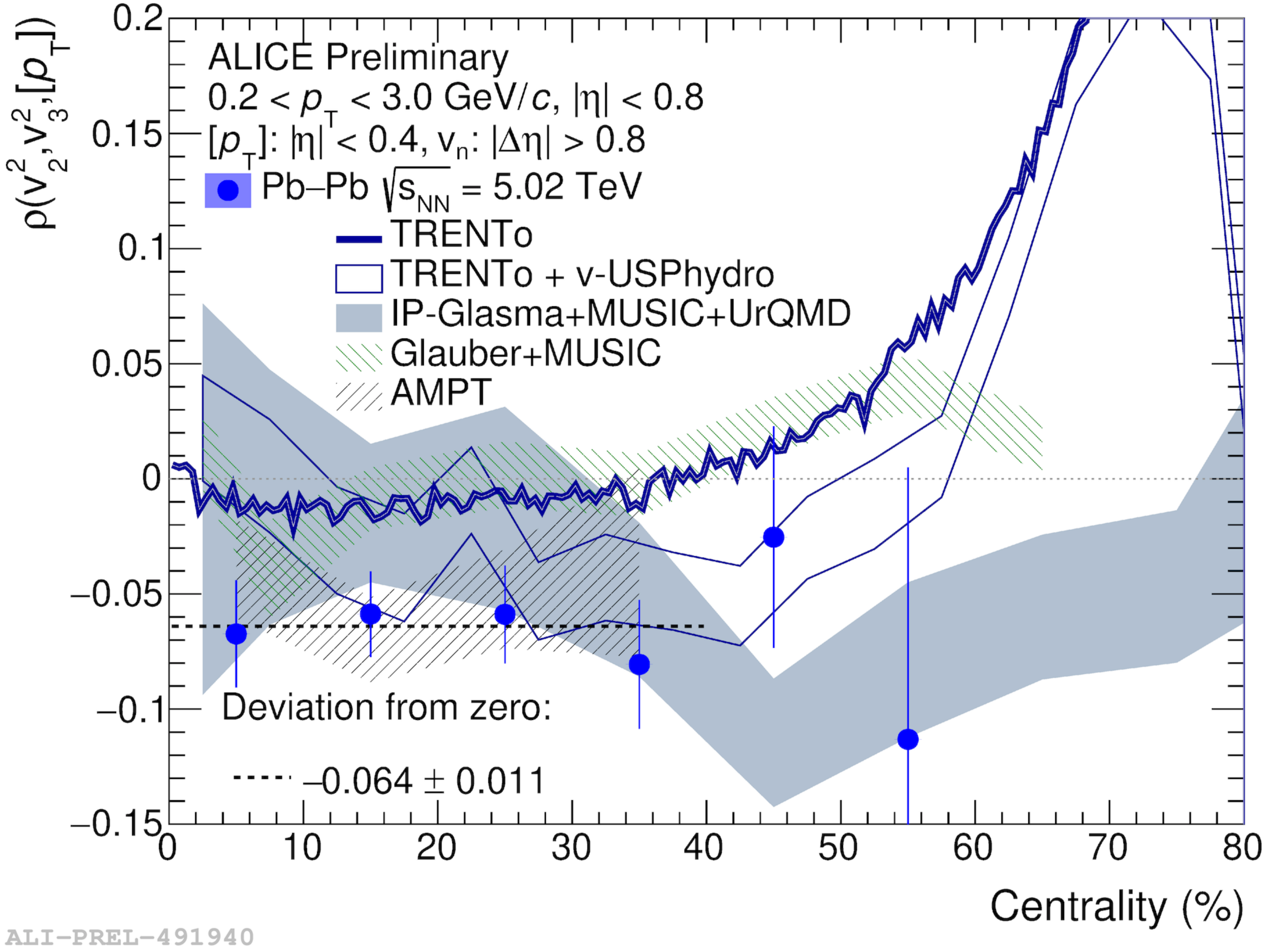
Multiharmonic correlation coefficient

$$\rho(v_2^2, v_3^2, [p_T]) = \frac{\langle v_2^2, v_3^2, [p_T]\rangle - \langle v_2^2\rangle\langle v_3^2, [p_T]\rangle - \langle v_3^2\rangle\langle v_2^2, [p_T]\rangle - \langle [p_T]\rangle\langle v_2^2, v_3^2\rangle + 2\langle [p_T]\rangle\langle v_2^2\rangle\langle v_3^2\rangle}{\sqrt{var(v_2^2)}\sqrt{var(v_3^2)}\sqrt{c_k}}$$

- ❖ Genuine correlation of v_2, v_3 and $[p_T]$
- ❖ **First study in experiment**
  - Non-zero in the presented centrality range
  - $\sim 3\sigma$ effect in 0-40% centrality
  - $\rho(v_2^2, v_3^2, [p_T])$ from IP-Glasma+MUSIC+UrQMD, TRENTo+v-USPhydro and Glauber+MUSIC are very different
  - Models especially differ for centrality above 40-50% where opposite signs are seen.
  - Surprisingly, well described by AMPT



Summary

- Event-shape engineering with q_2 selection biases identified v_2 larger or smaller than average - v_3 less sensitive to q_2 selection

- The **first** measurement of centrality dependence of $\rho(v_2^2, [p_T])$, $\rho(v_3^2, [p_T])$ (in backup material) and $\rho(v_2^2, v_3^2, [p_T])$ in heavy-ion experiments

- For the first time we see completely different behaviours of IP-Glasma and TRENTo (with p=0) models in flow studies

- **All state-of-the-art Bayesian analyses (with TRENTo-IC), which represent our best understanding on the initial conditions and transport coefficients of the QGP, failed or will fail in describing the presented ALICE data**

Summary

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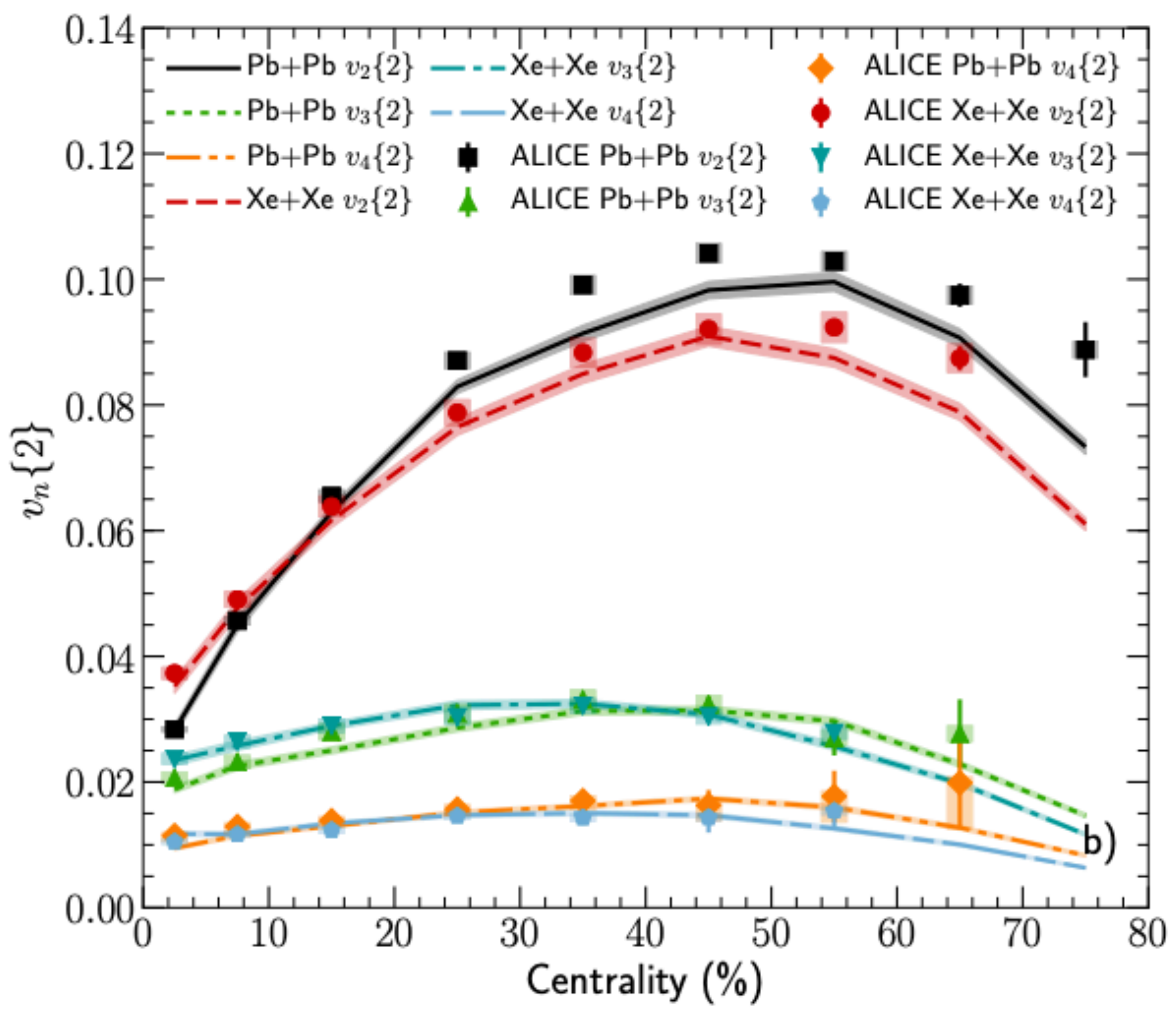
Thank you for your attention!

Backup

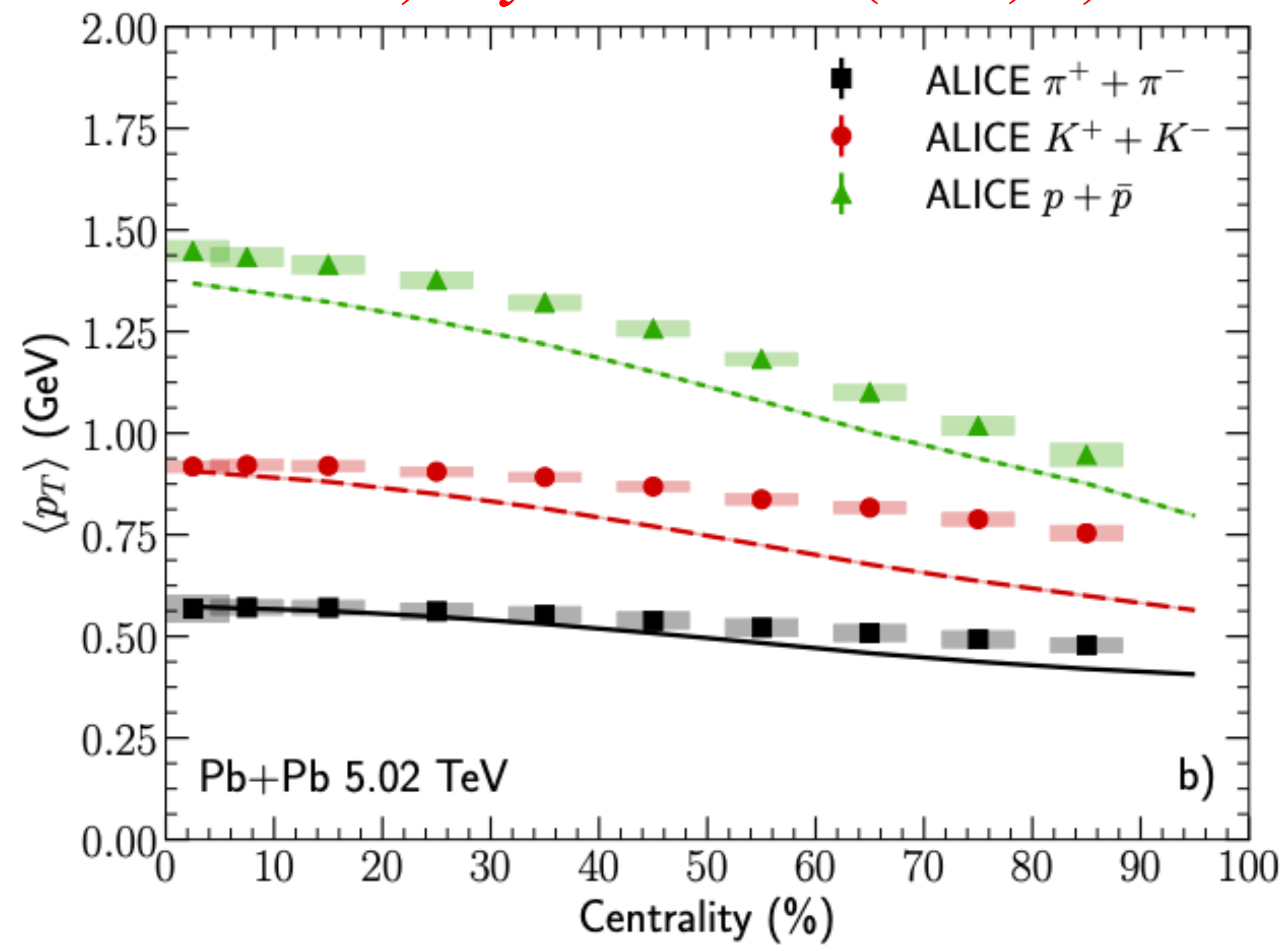
Current understanding of initial state

IP-Glasma

❖ IP-Glasma well describes ALICE data with $\eta/s = 0.12$ and temperature dependent ζ/s up to 0.13 at $T = 160$ MeV

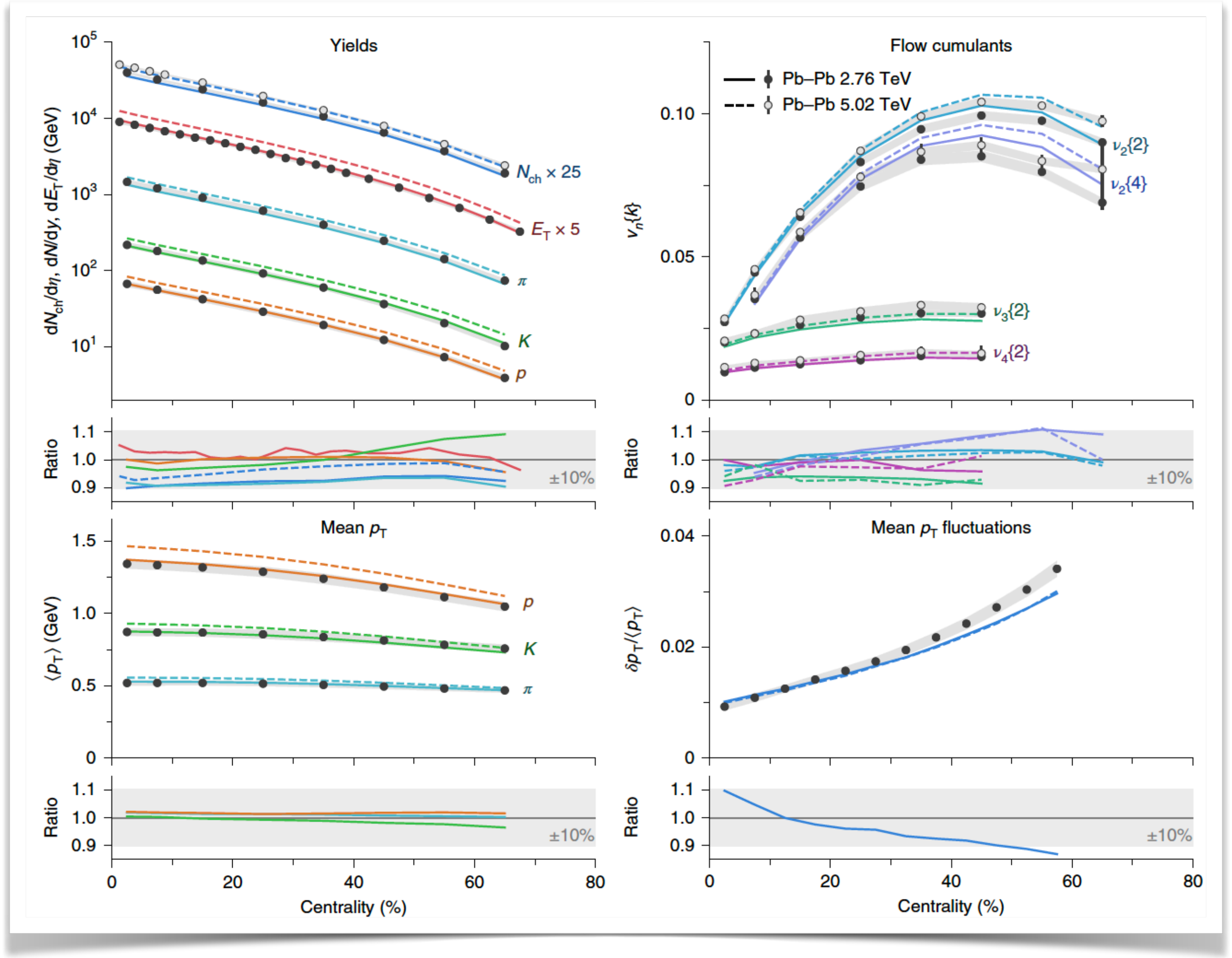


B. Schenke etc, *Phys.Rev.C* 102 (2020) 4, 044905

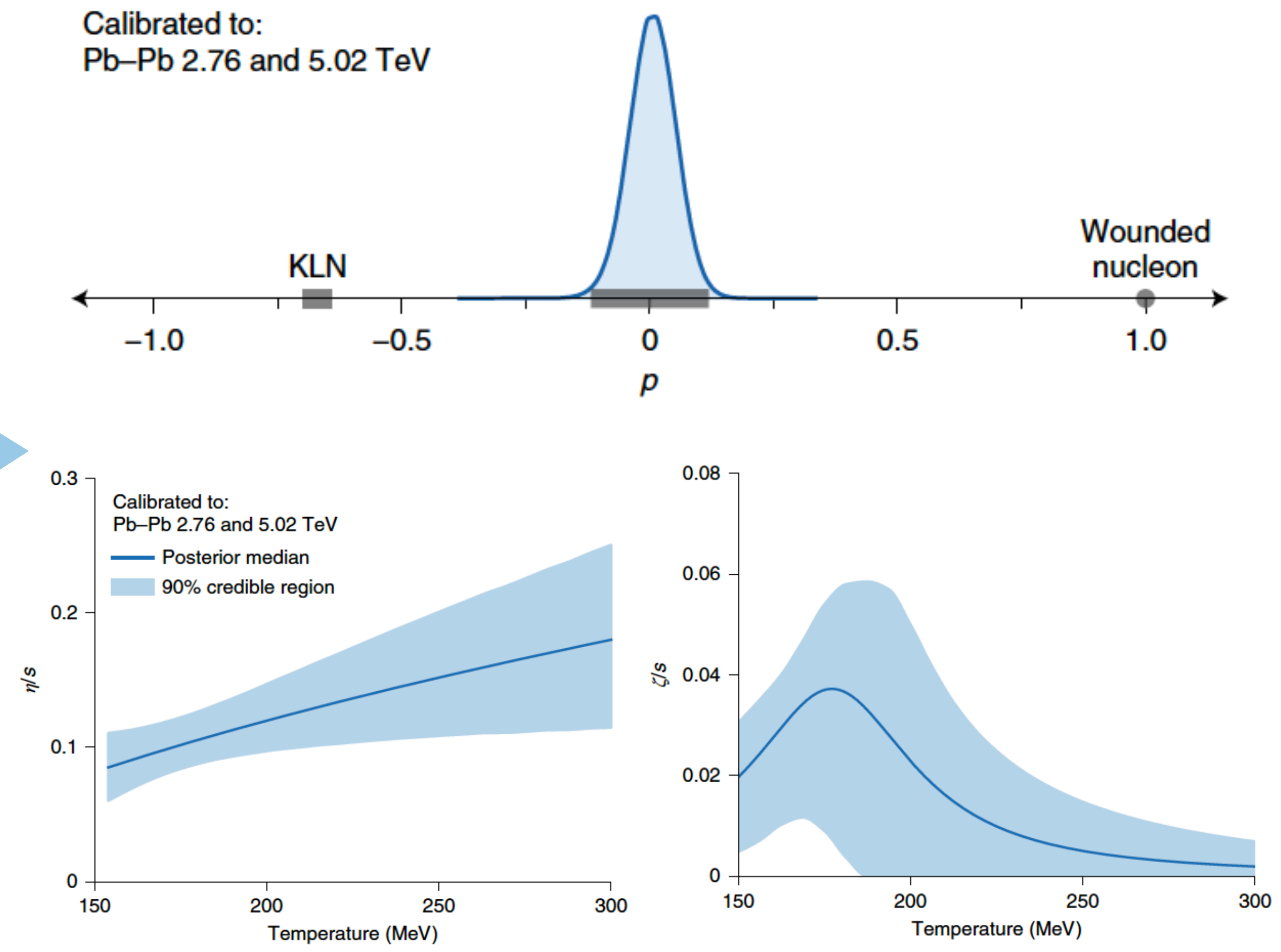


Bayesian analysis (Duke)

❖ Constrain the initial conditions and extract transport coefficients of QGP via <pt> and v_n separately.



J.E. Bernhard etc, Nature Physics,15, 1113 (2019)



Current status of initial state models

❖ “sharp” models: IP-GLASMA and TRENTo 2016

- Nuclecon width ~0.5fm (trento)
- 3 sub-nucleons with size ~0.2fm (IP-Glasma).
- Initial entropy density with Trento
- Only model with realistic pre-equlibrium evolution with longitudinal cooling

[Schenke, Shen, Tribedy 2005.14682]
[Bass, Bernhard, Moreland 1605.03954]

❖ “fat” models: TRENTo 2019 and JETSCAPE

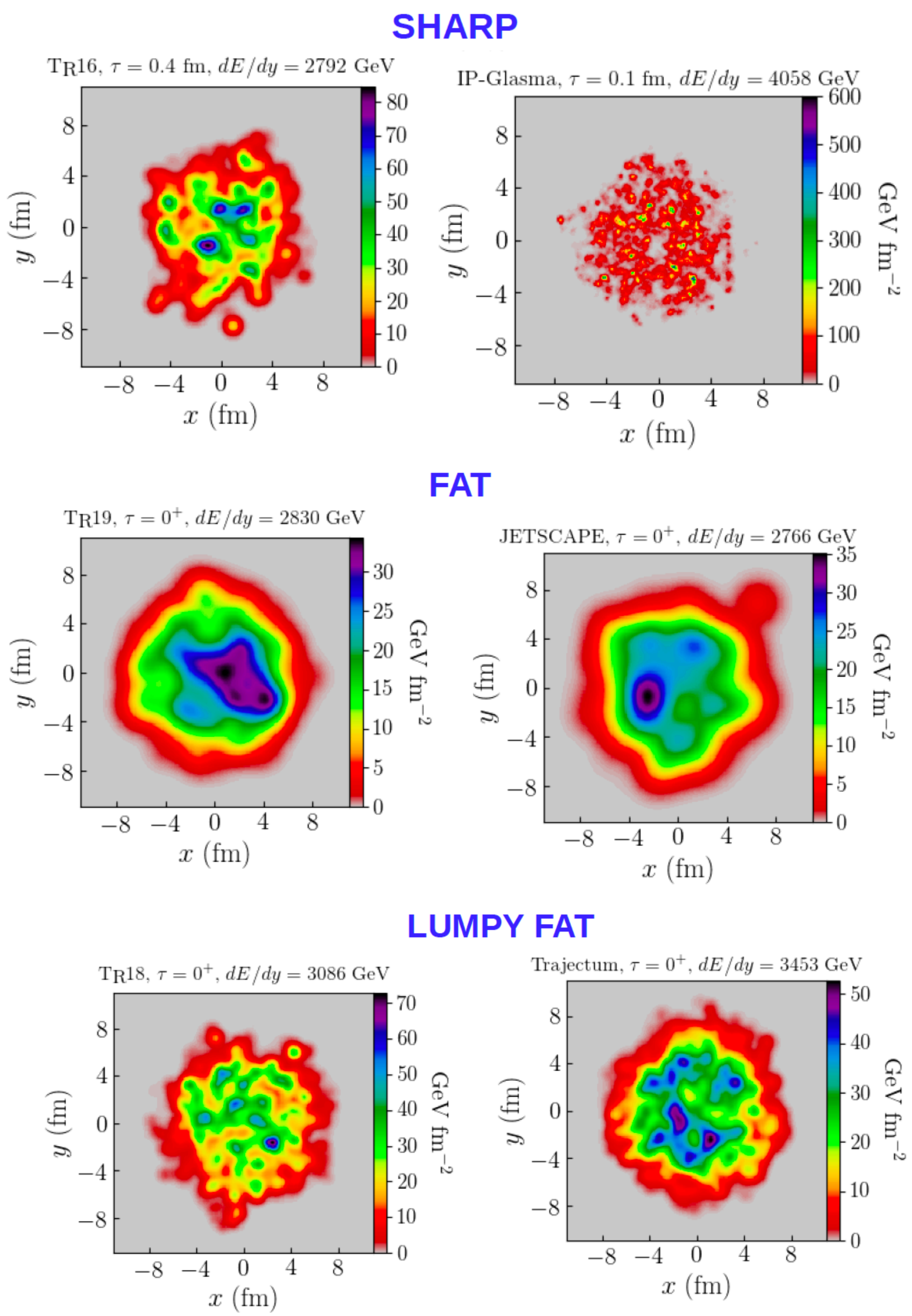
- Trento parametrisation is used for the energy density at tau=0+.
- No substructure, nucleon width is now ~1fm.
- Very smooth profiles

[Bass, Bernhard, Moreland Nature Phys. 15 (2019)]
[JETSCAPE Collaboration 2011.01430, 2010.03928]

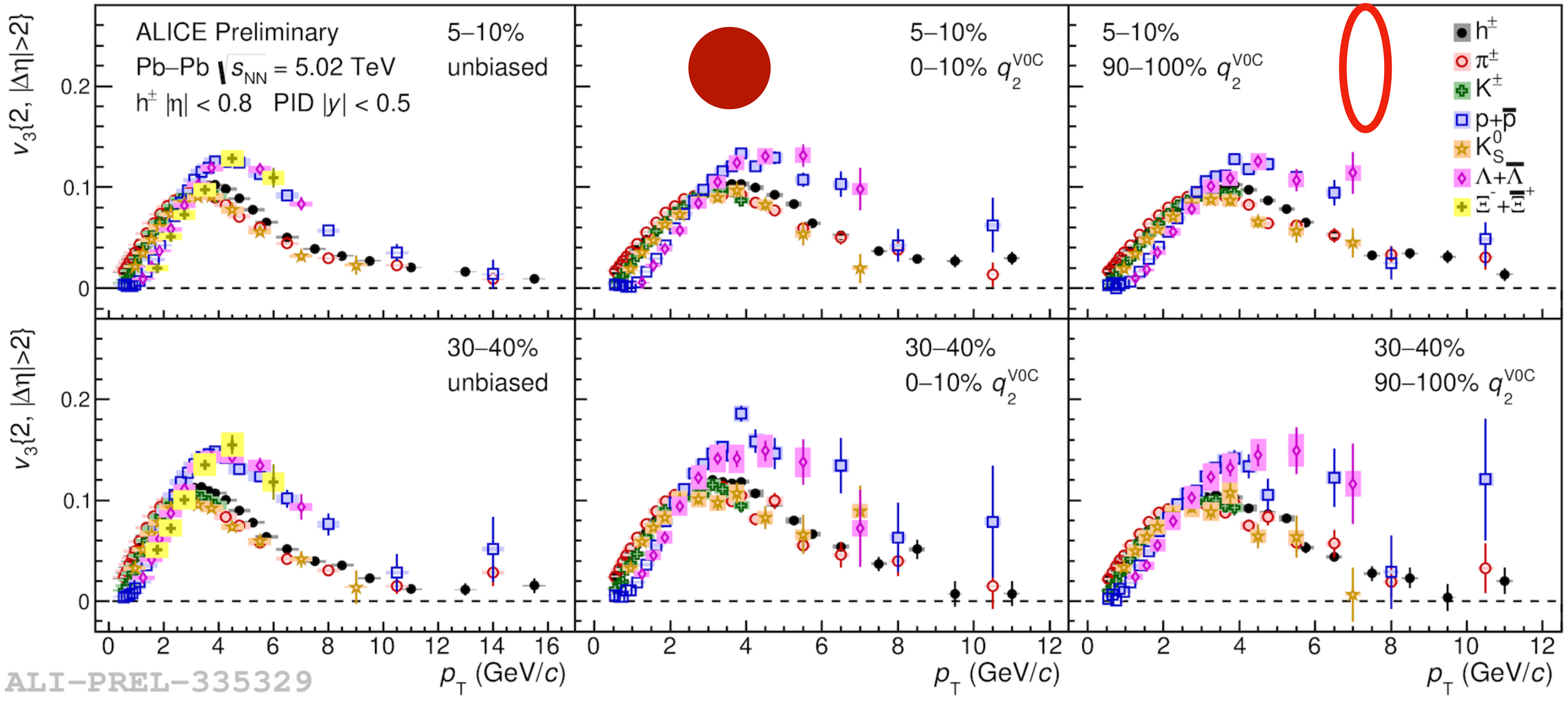
❖ “lumpy fat” models: TRENTo 2018 and Trajectum

- Trento parametrisation is the energy density at tau=0+.
- Substructure is included: 4-6 constituents, nucleon width ~0.5fm
- Profiles with some ‘old school’ lumpiness.

[Bass, Bernhard, Moreland 1808.02106]
[Nijs, van der Schee, Gürsoy, Snellings 2010.15130, 2010.15134]

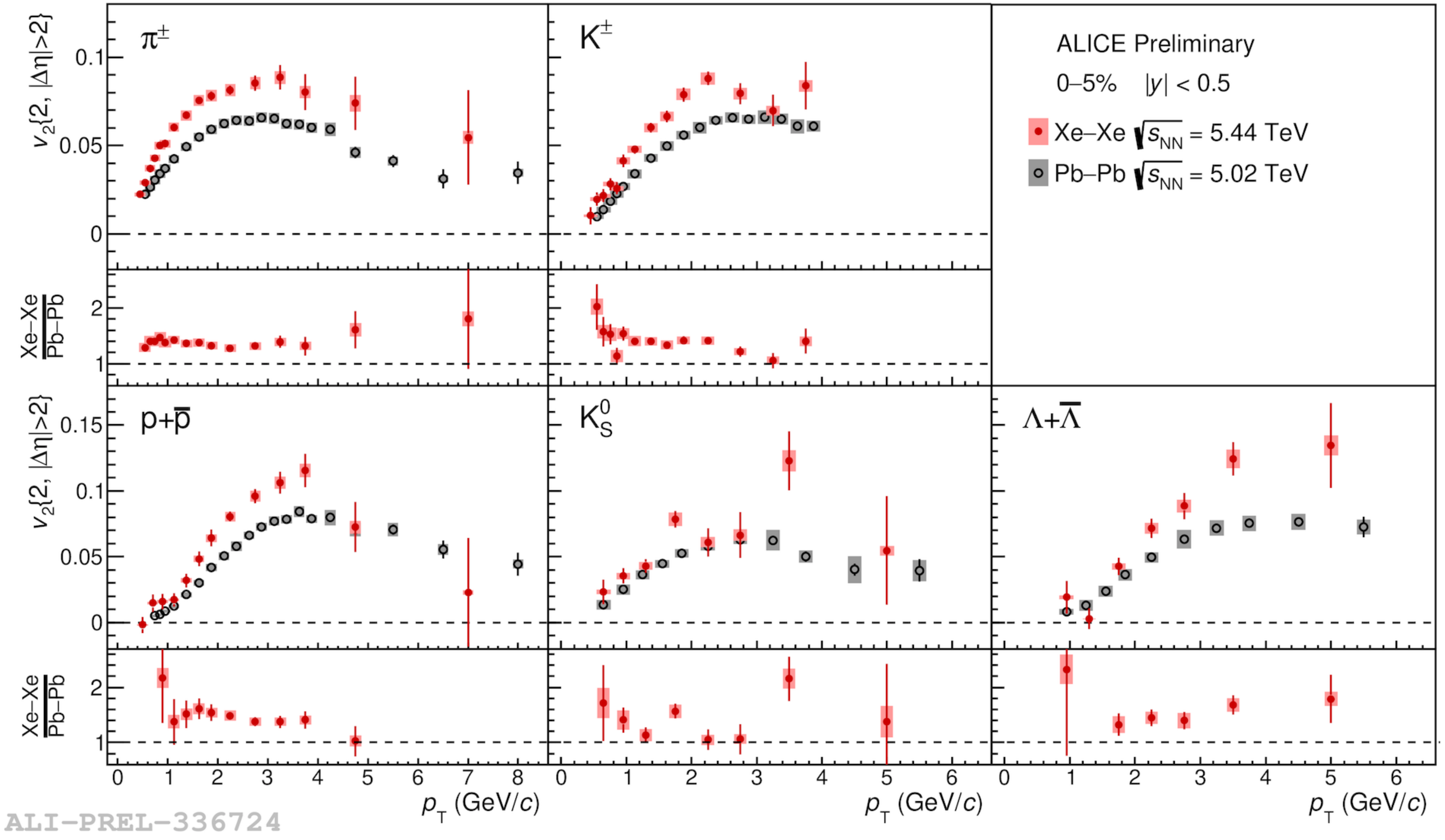


- $p_T < 2$ GeV/c: mass ordering
- $p_T \sim 2-3$ GeV/c: meson-baryon crossing
- $3 < p_T < 10$ GeV/c: particle type dependence $v_3^{\text{baryons}} > v_3^{\text{mesons}}$
- v_3 anti-correlated with q_2
- Flat ratio up to $p_T = 8$ GeV/c
- Same values for inclusive and PID → no dependence on particle species



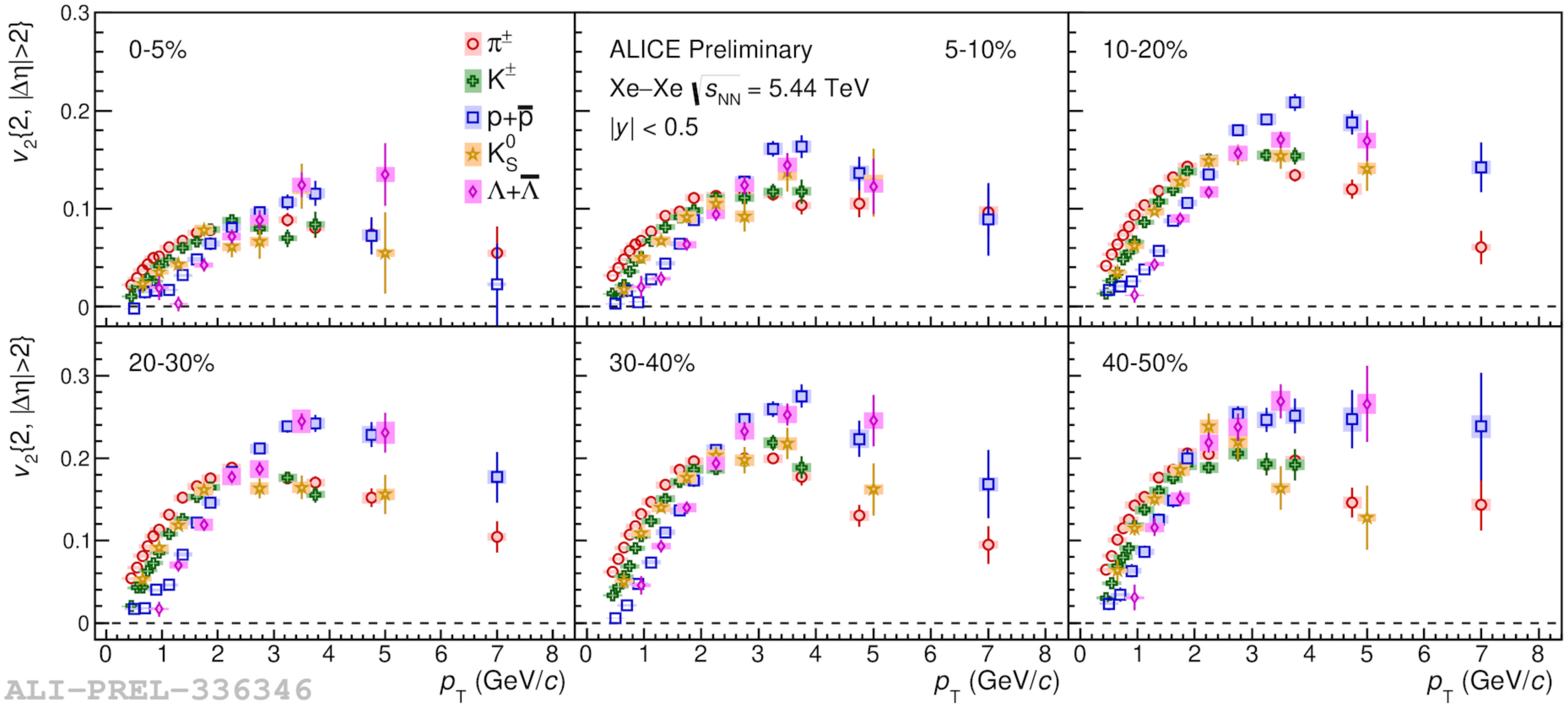
PID $v_2(p_T)$ Xe–Xe vs Pb–Pb: 0-5% centrality

- ❖ Constrain initial geometry and transport coefficients of the QGP
- ❖ $v_2^{Xe} > v_2^{Pb} \rightarrow$ Nuclear deformation of Xe

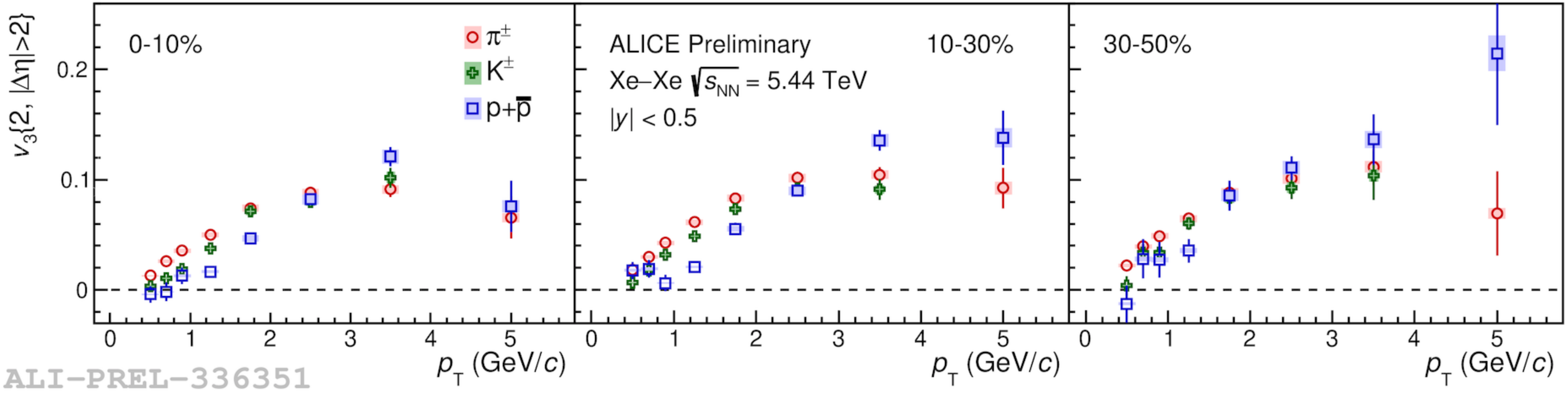


Identified particle $v_2(p_T)$ in Xe–Xe collisions

- No event selection
- $p_T < 2$ GeV/c: mass ordering - interplay between radial flow and initial geometry
- $p_T \sim 2-3$ GeV/c: crossing between mesons and baryons
- $p_T > 3$ GeV/c: grouping according to particle type ($v_2^{\text{baryons}} > v_2^{\text{mesons}}$)



Identified particle $v_3(p_T)$ in Xe−Xe collisions



- ❖ $p_T < 2$ GeV/c: mass ordering
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Centrality dependence of $\rho(v_3^2, [p_T])$

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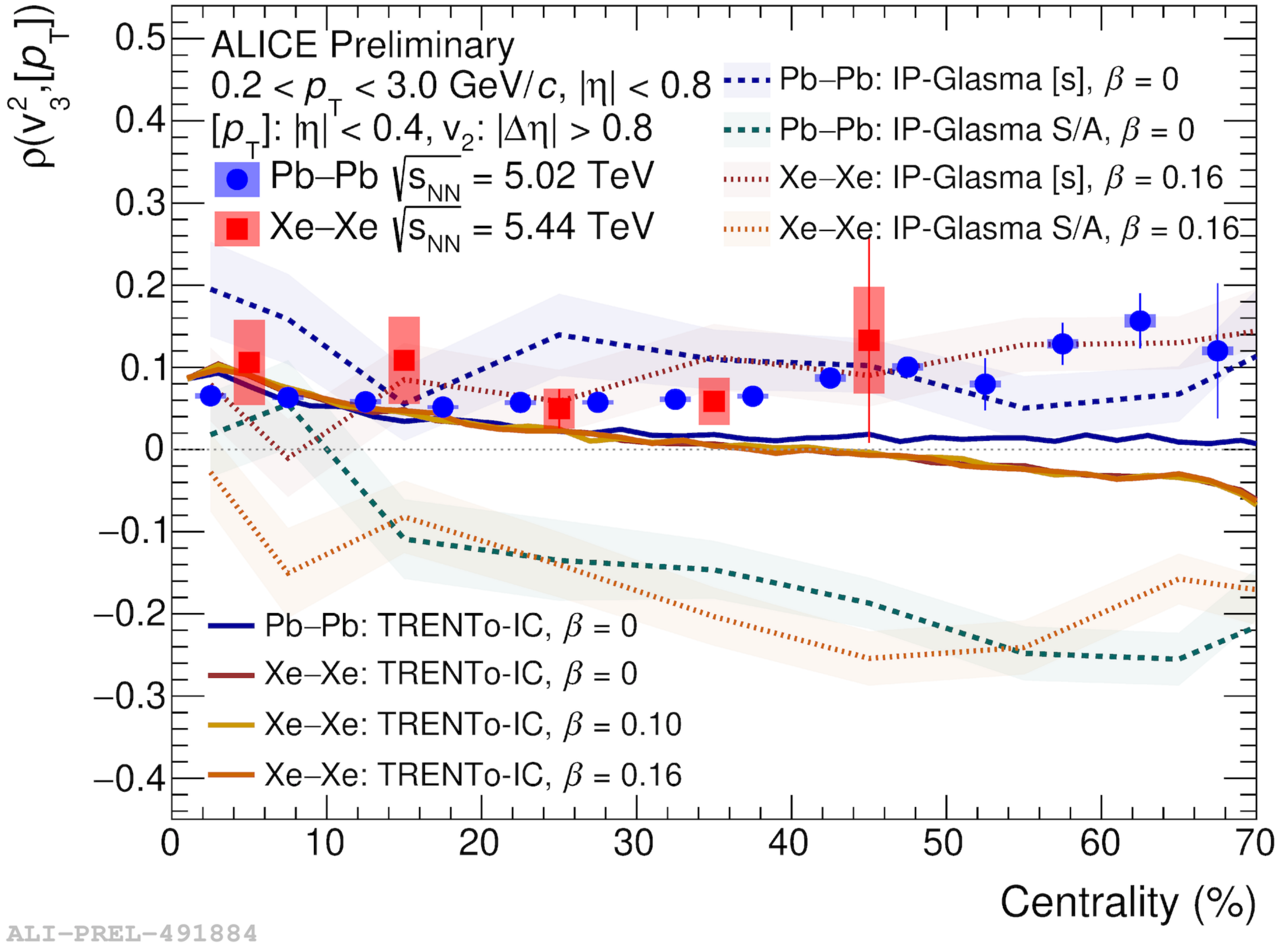
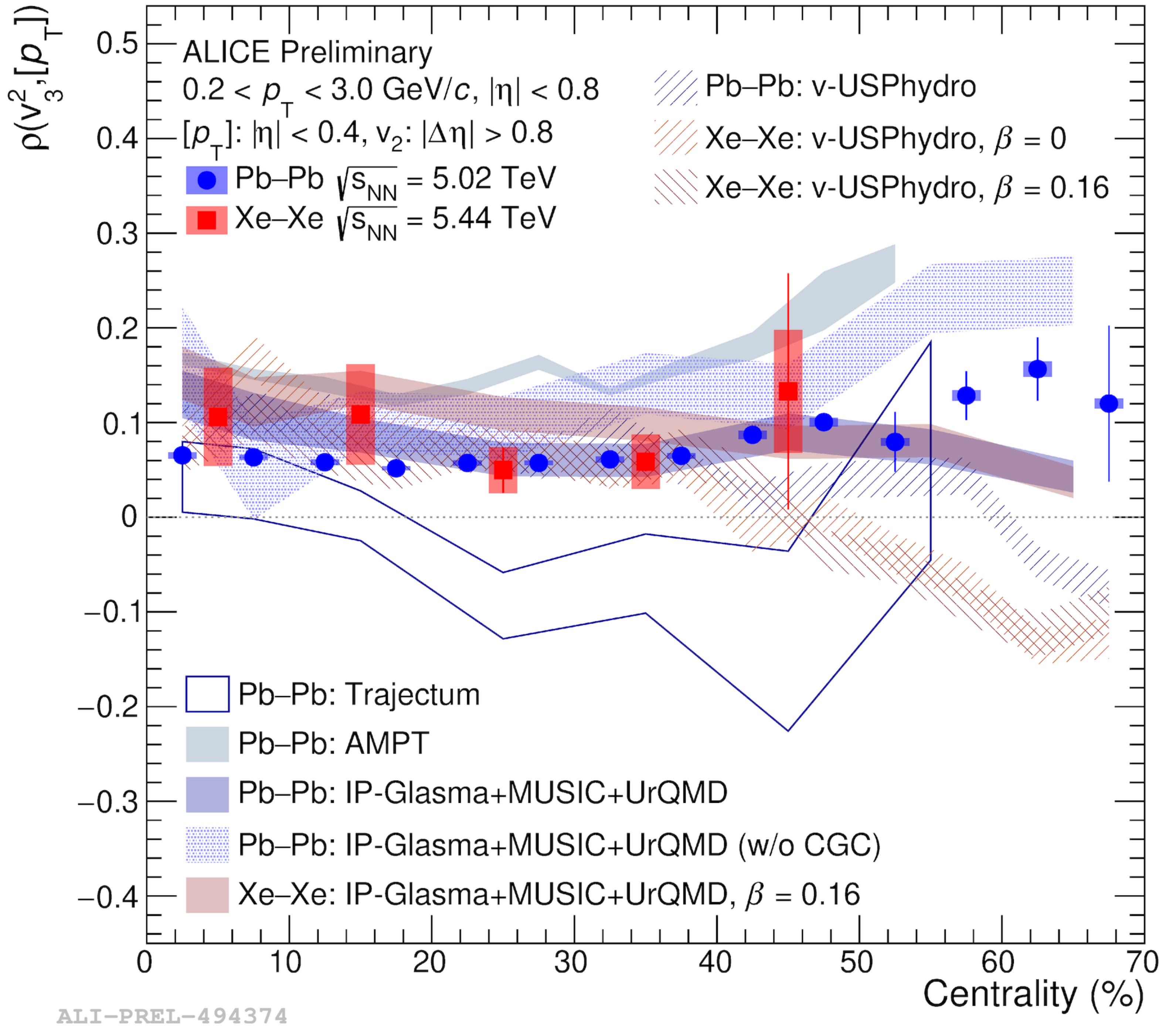
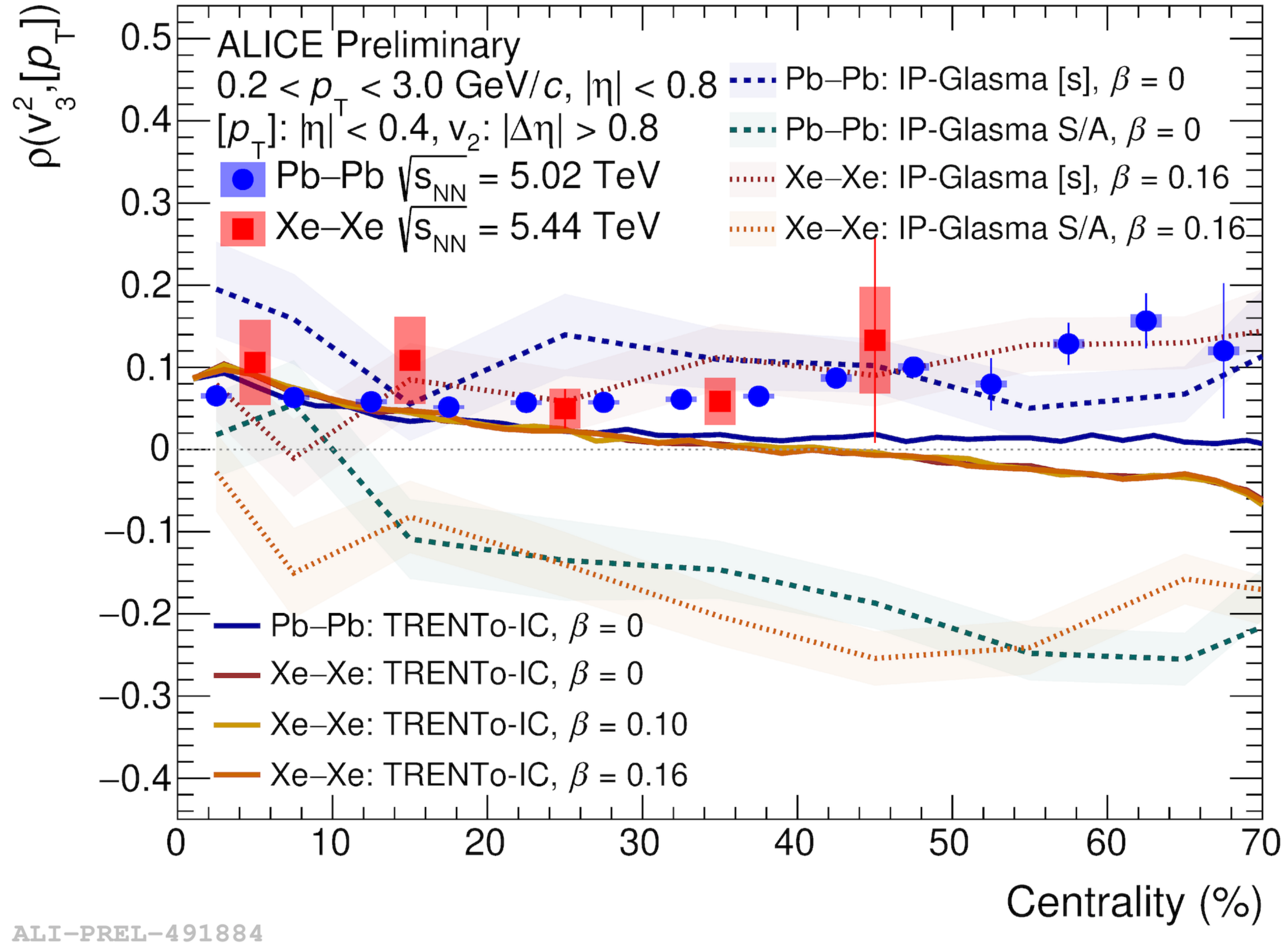


- ❖ ρ_3 comparison to initial state calculations:
  - IP-Glasma with [s] estimator works best
  - Choice of estimator for $[p_T]$ matters

    → S/A has anti-correlation of ϵ_2 and ϵ_3 - leading to negative ρ_3
  - Negative values predicted by TRENTo in non-central collisions - not seen in data
  - ρ_3 not sensitive to deformation parameter β

Centrality dependence of $\rho(v_3^2, [p_T])$





- ❖ ρ_3 Pb−Pb and Xe−Xe results are compatible
- ❖ ρ_3 results are positive and have a modest centrality dependence for the presented centralities
- ❖ Comparison to hydro models:
  - Better described by IP-Glasma
  - TRENTo predicts negative ρ_3 in peripheral collisions which is not seen in data

- ❖ ρ_3 comparison to initial state calculations:
  - IP-Glasma with [s] estimator works best
  - Choice of estimator for $[p_T]$ matters

    → S/A has anti-correlation of ϵ_2 and ϵ_3 - leading to negative ρ_3
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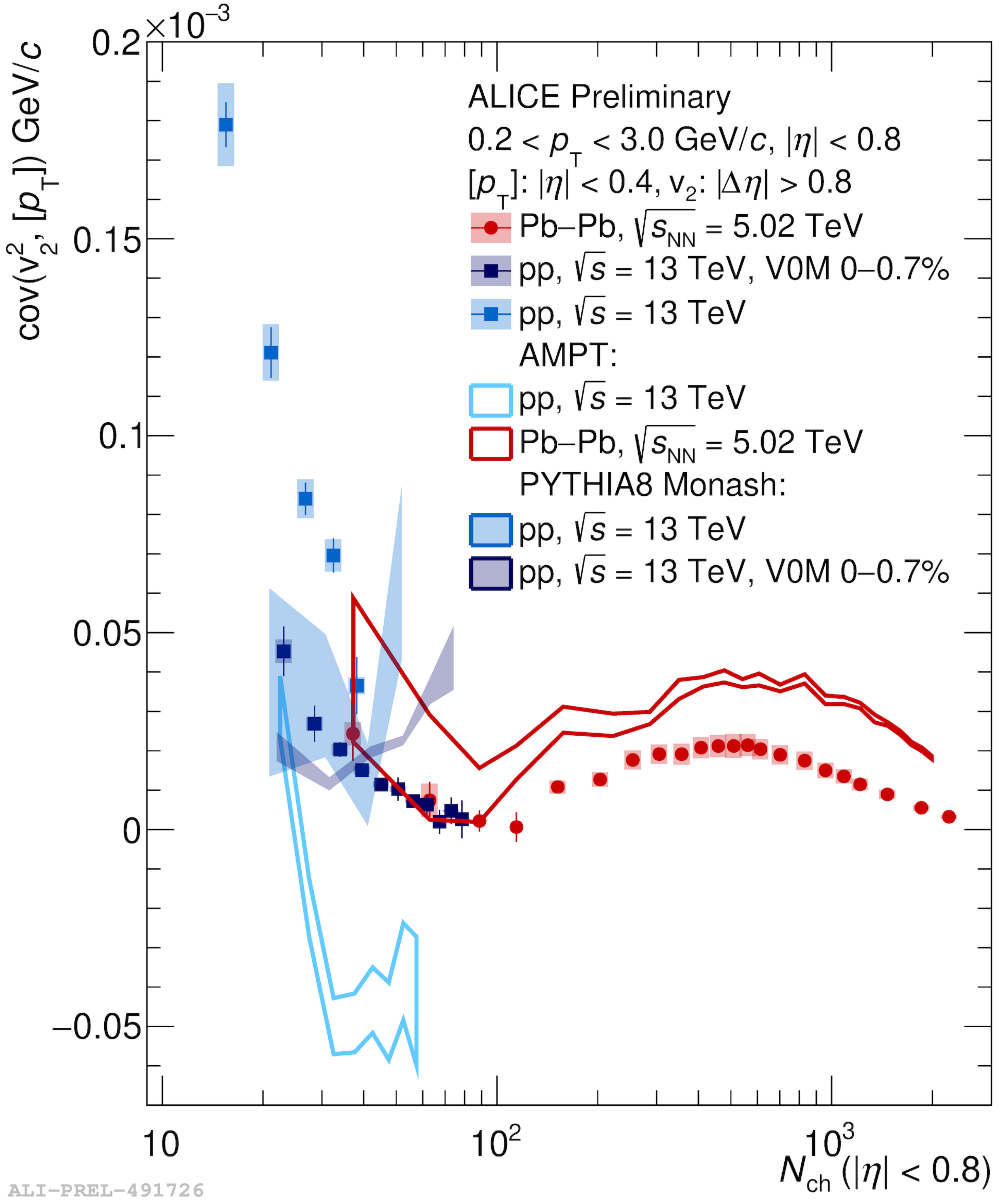
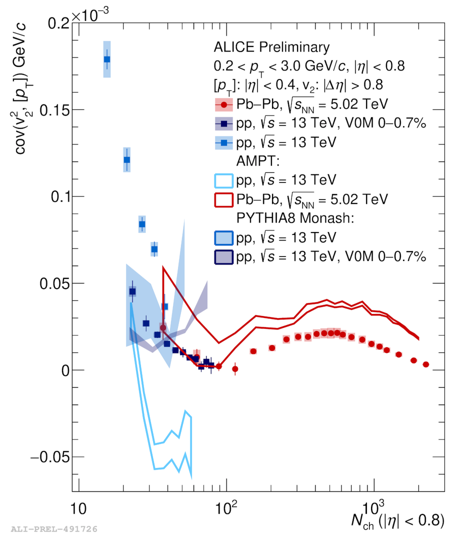
Components of $\rho(v_2^2, [p_T])$

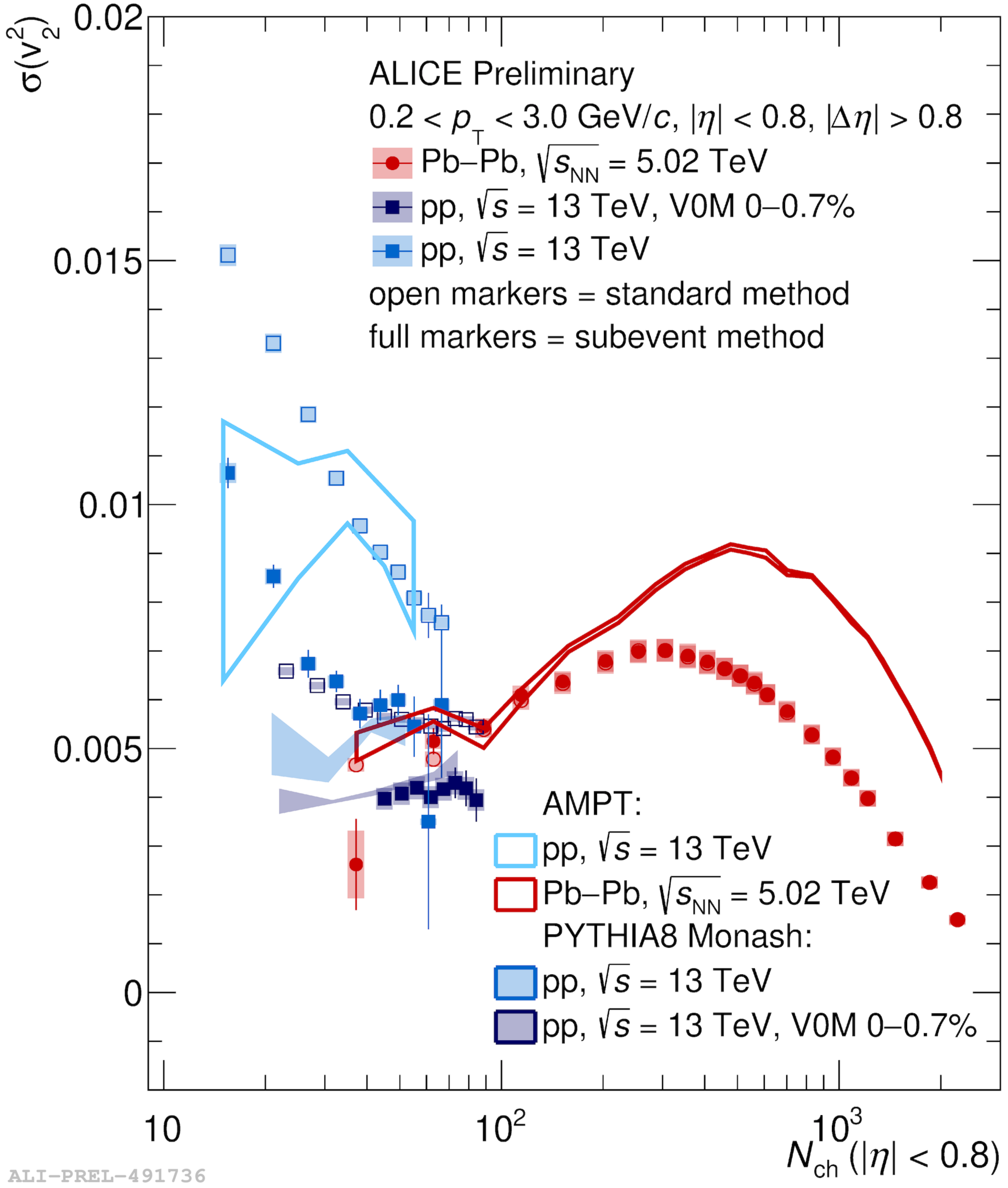
- Covariance of v_n and $[p_T]$



Components of $\rho(v_2^2, [p_\mathrm{T}])$

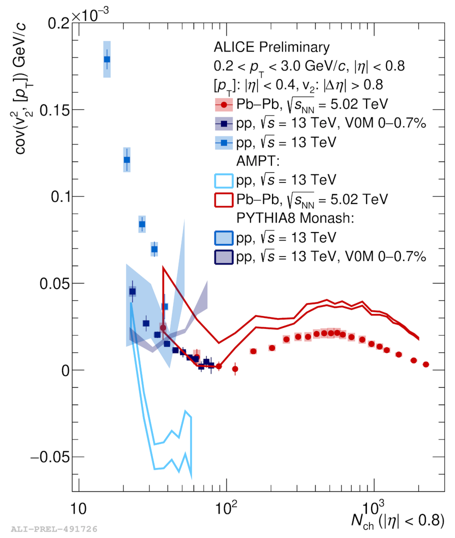
- Covariance of v_n and $[p_\mathrm{T}]$
- v_2 fluctuations

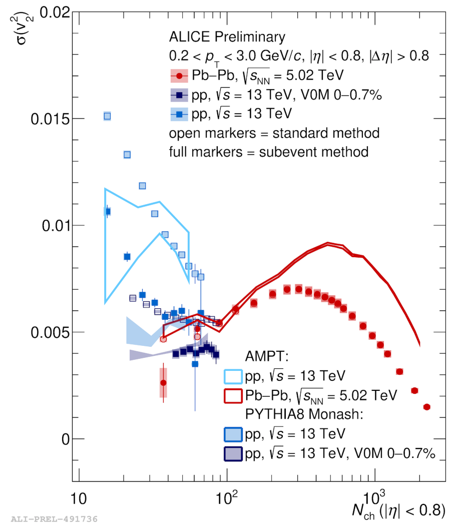


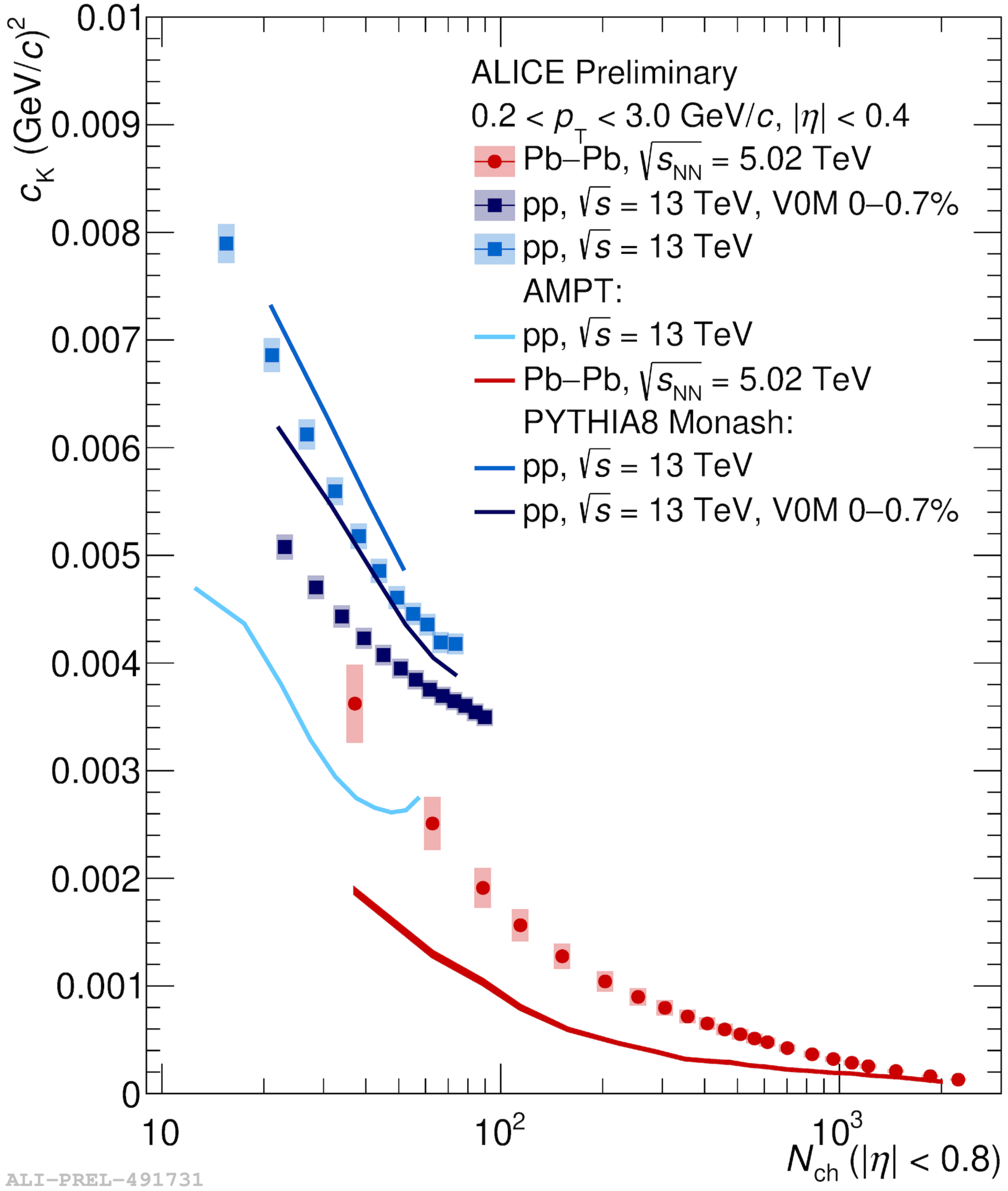


Components of $\rho(v_2^2, [p_T])$

- Covariance of v_n and $[p_T]$
- v_2 fluctuations
- Dynamic fluctuation of $[p_T]$

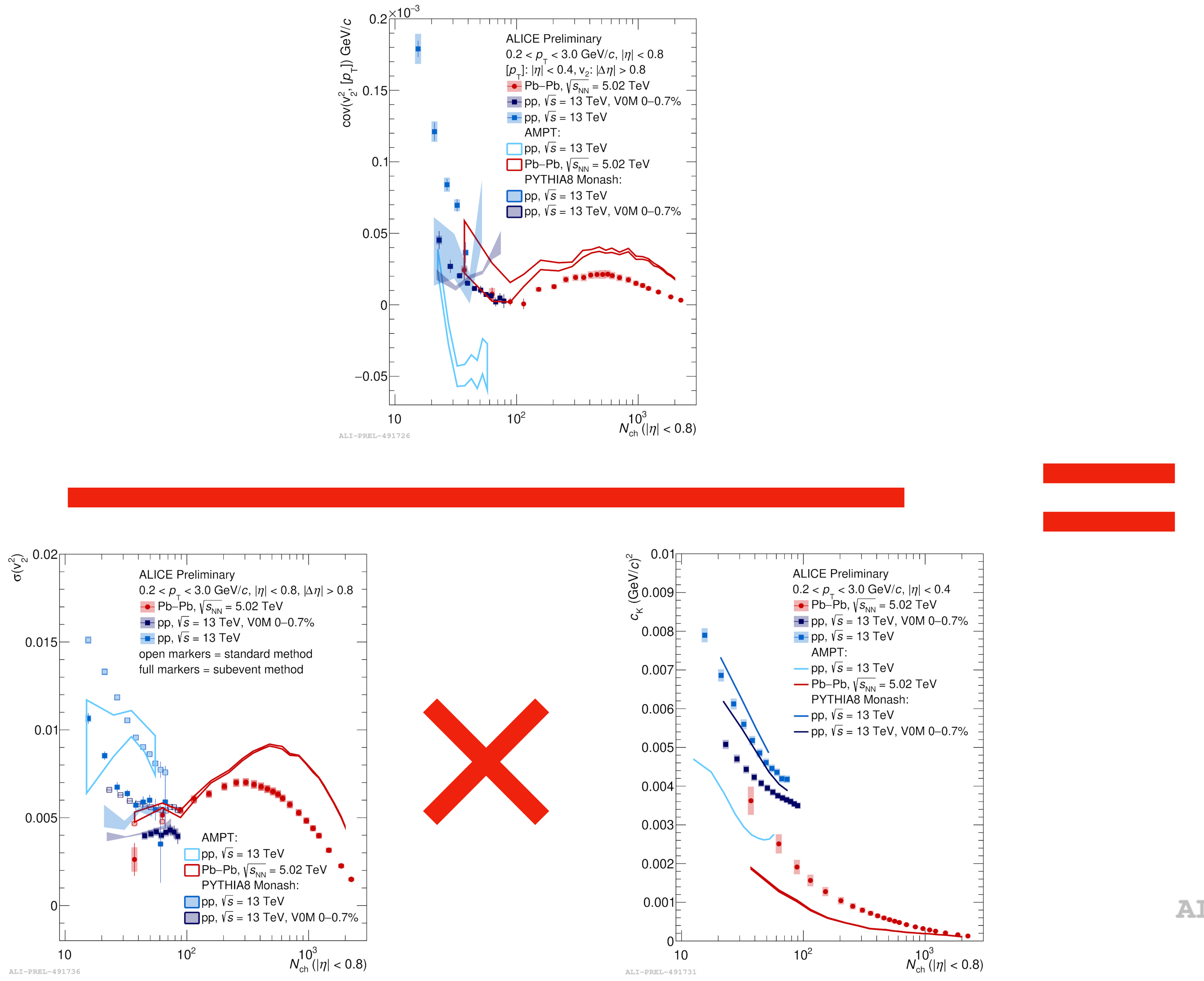


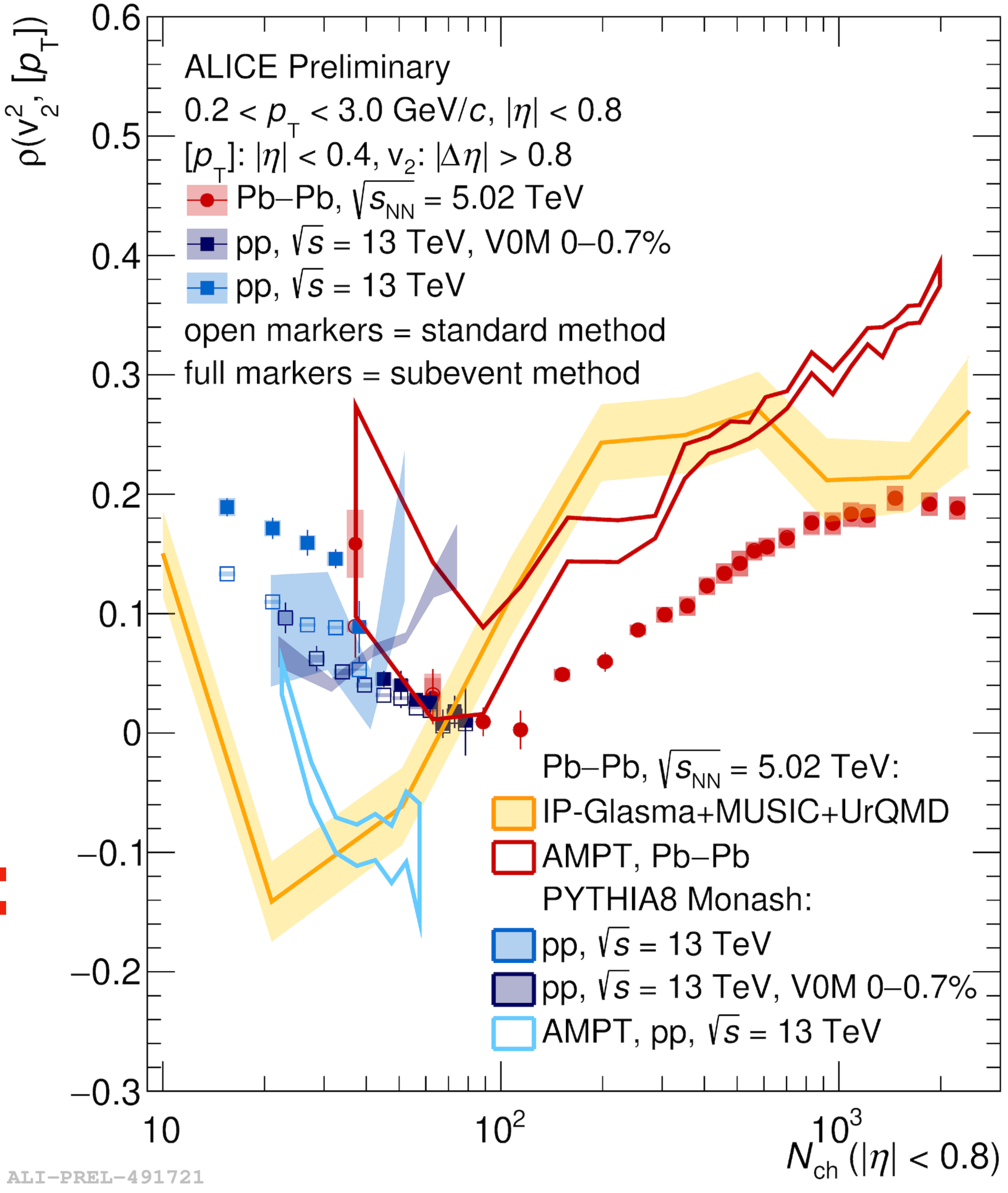




Components of $\rho(v_2^2, [p_T])$

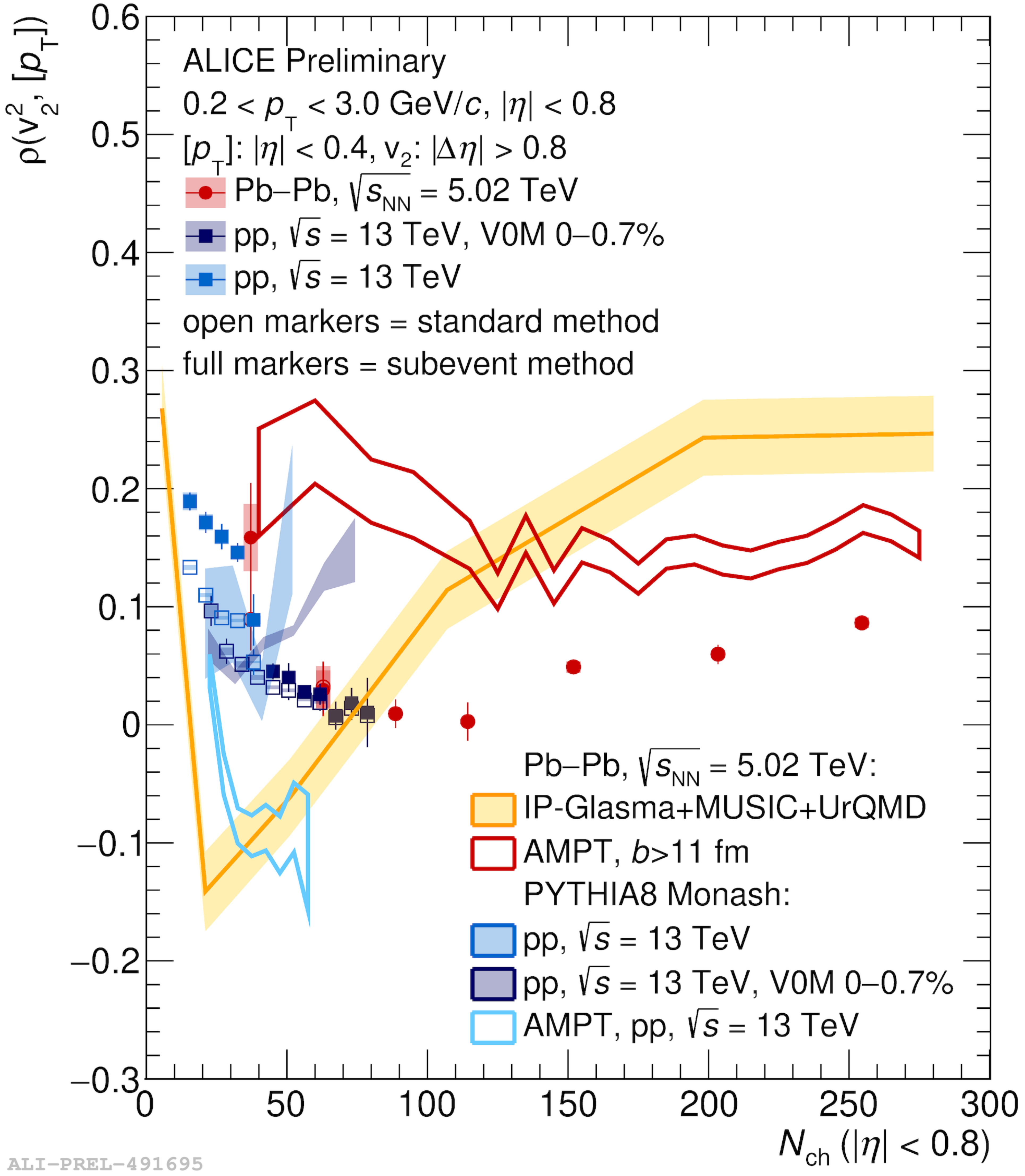
- Covariance of v_n and $[p_T]$
- v_2 fluctuations
- Dynamic fluctuation of $[p_T]$
- $\rho(v_2^2, [p_T])$



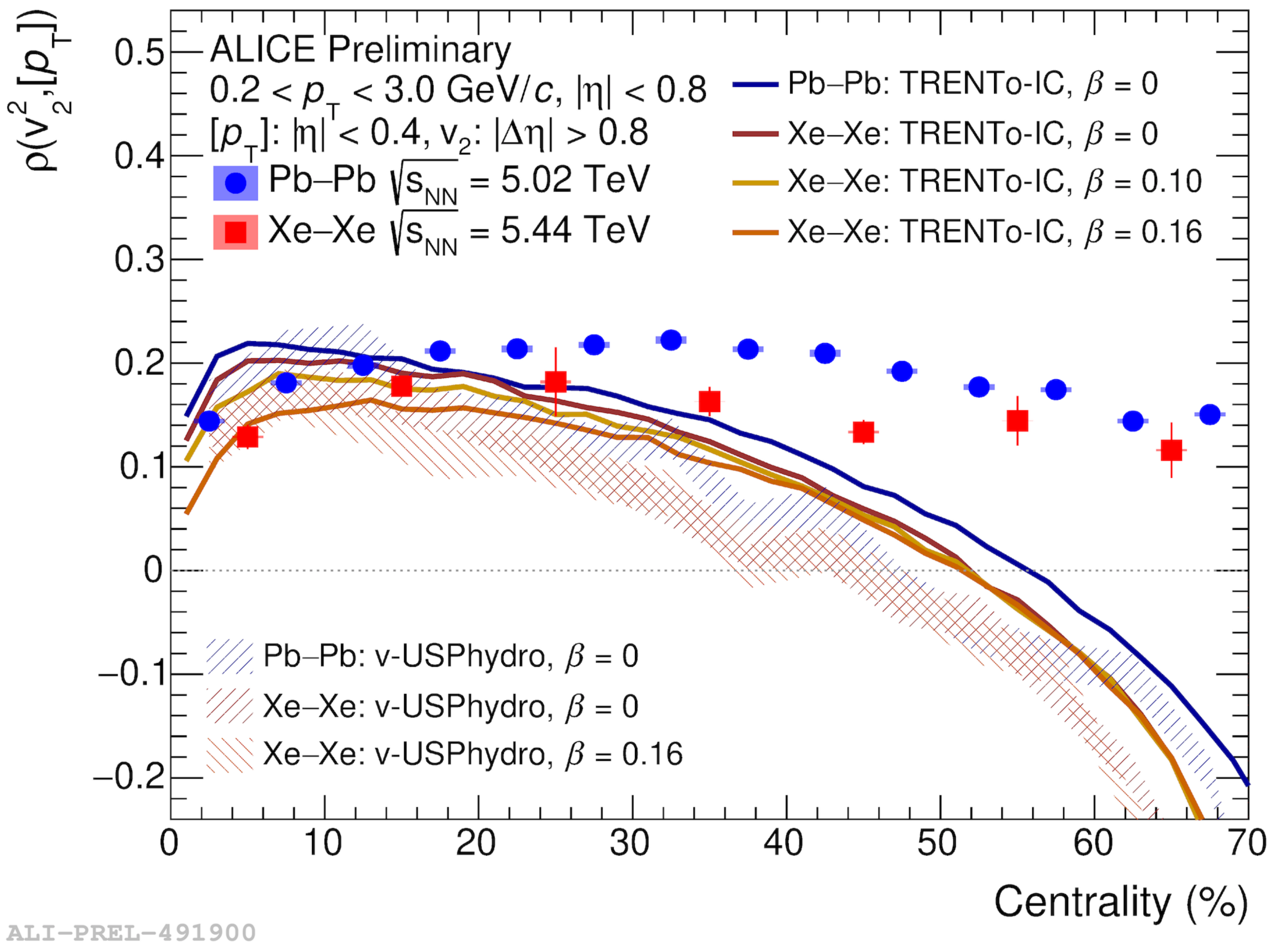


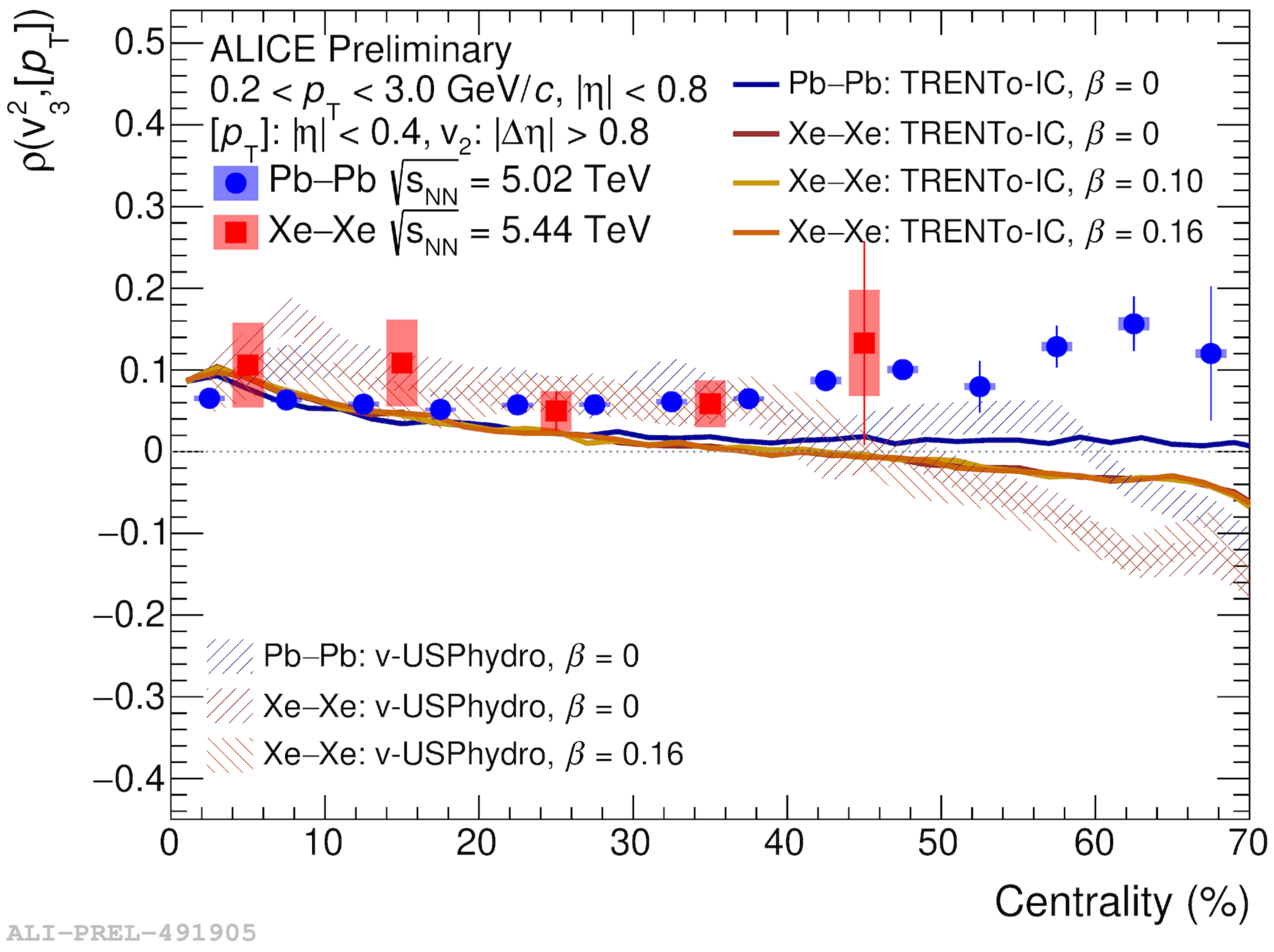
Non-flow in low multiplicity region

- MB measurements significantly higher than HM
- Change of slope may be sensitive to non-flow effects



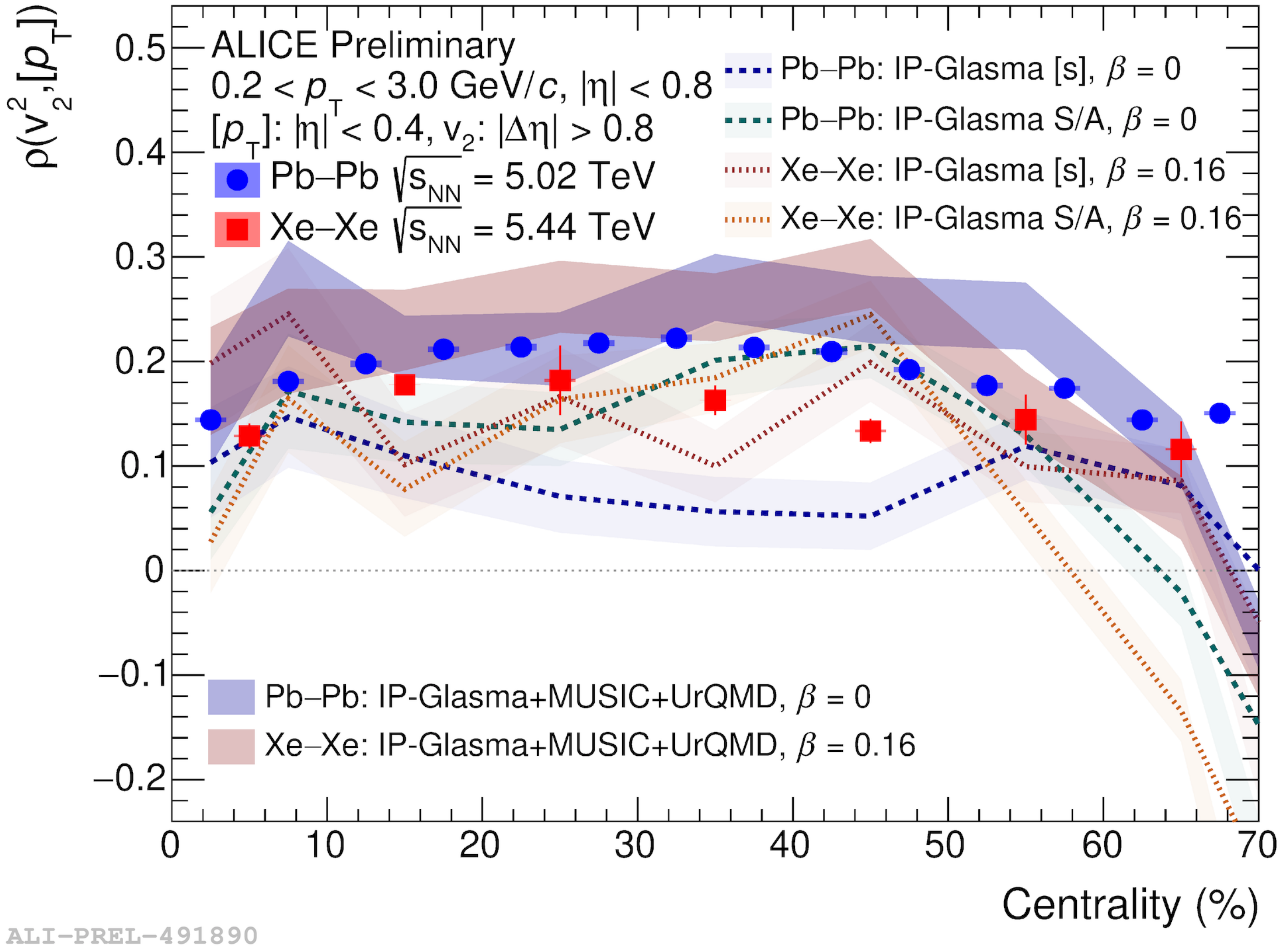
ρ_n initial vs final state: Trento-based models

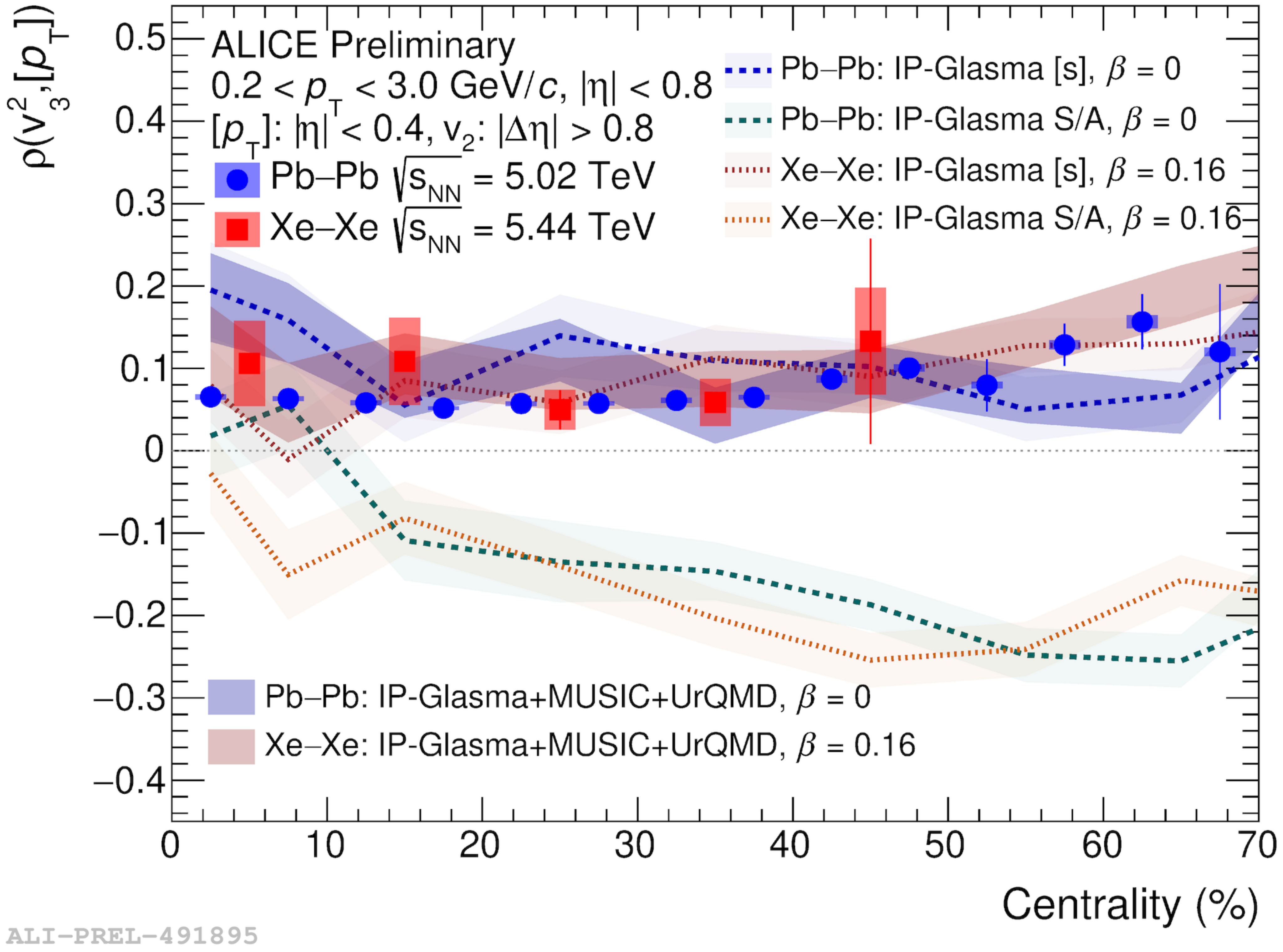




❖ Final and initial state compatible for TRENTo-based models

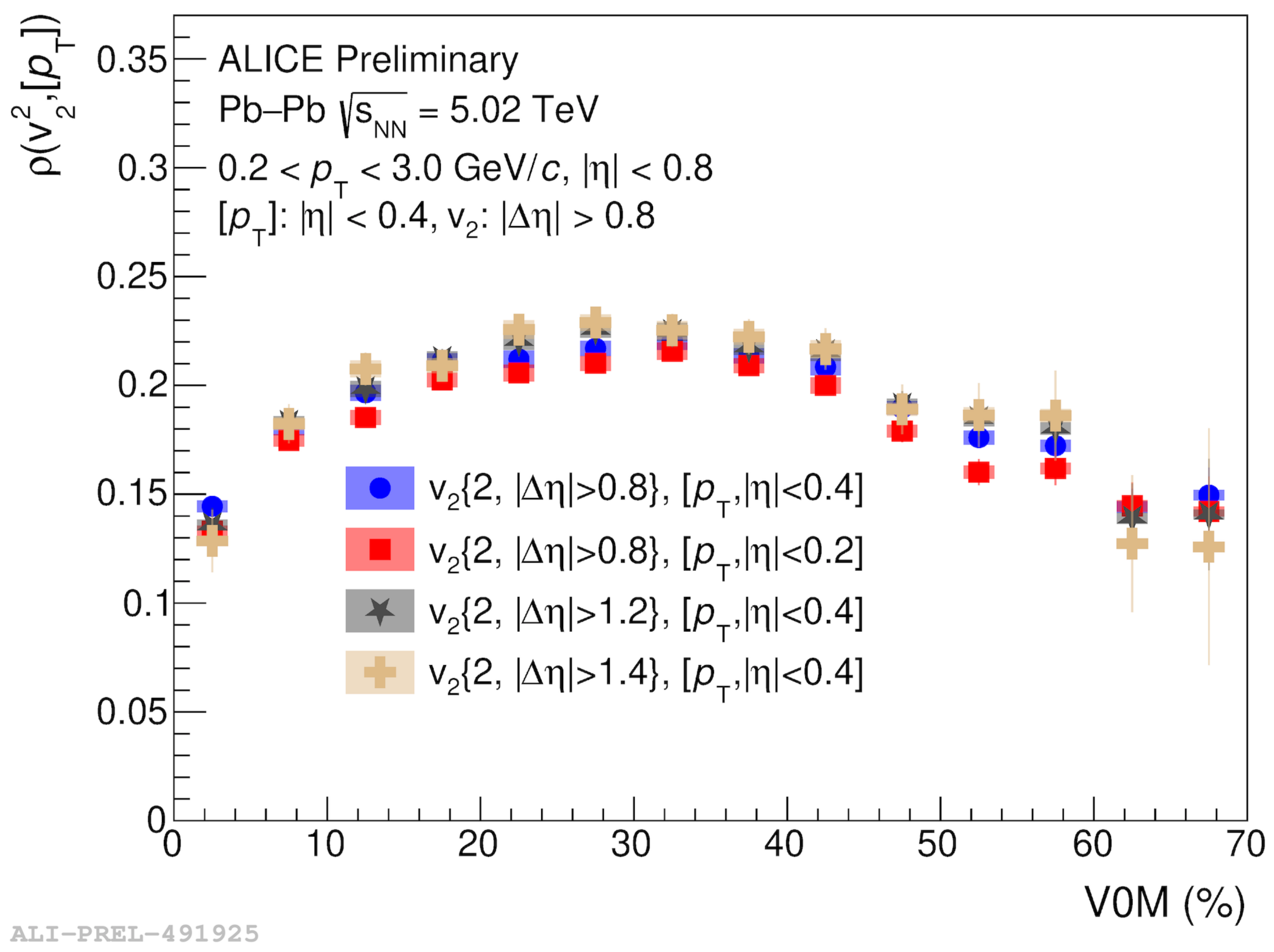
ρ_n initial vs final state: IP-Glasma-based models

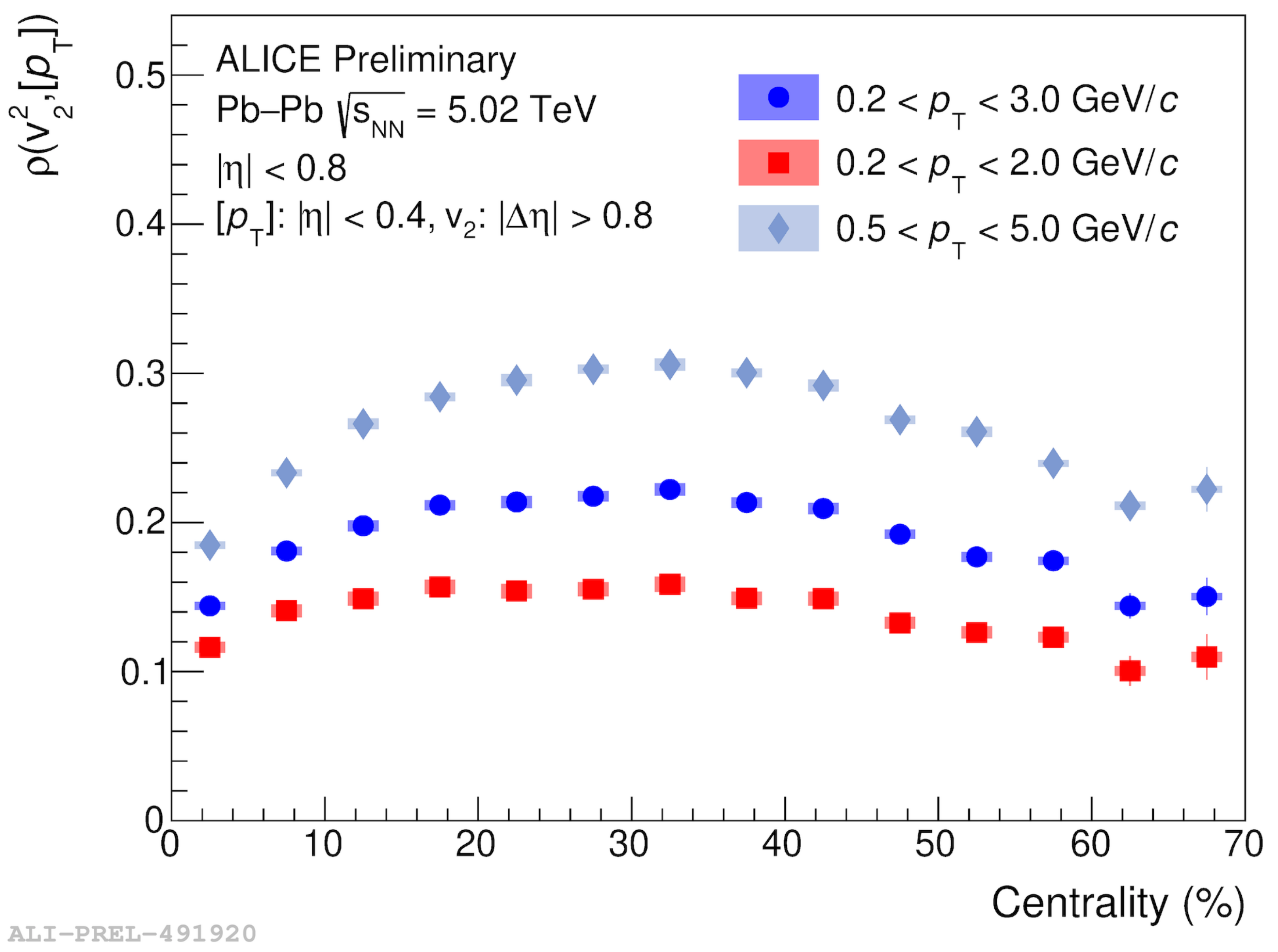


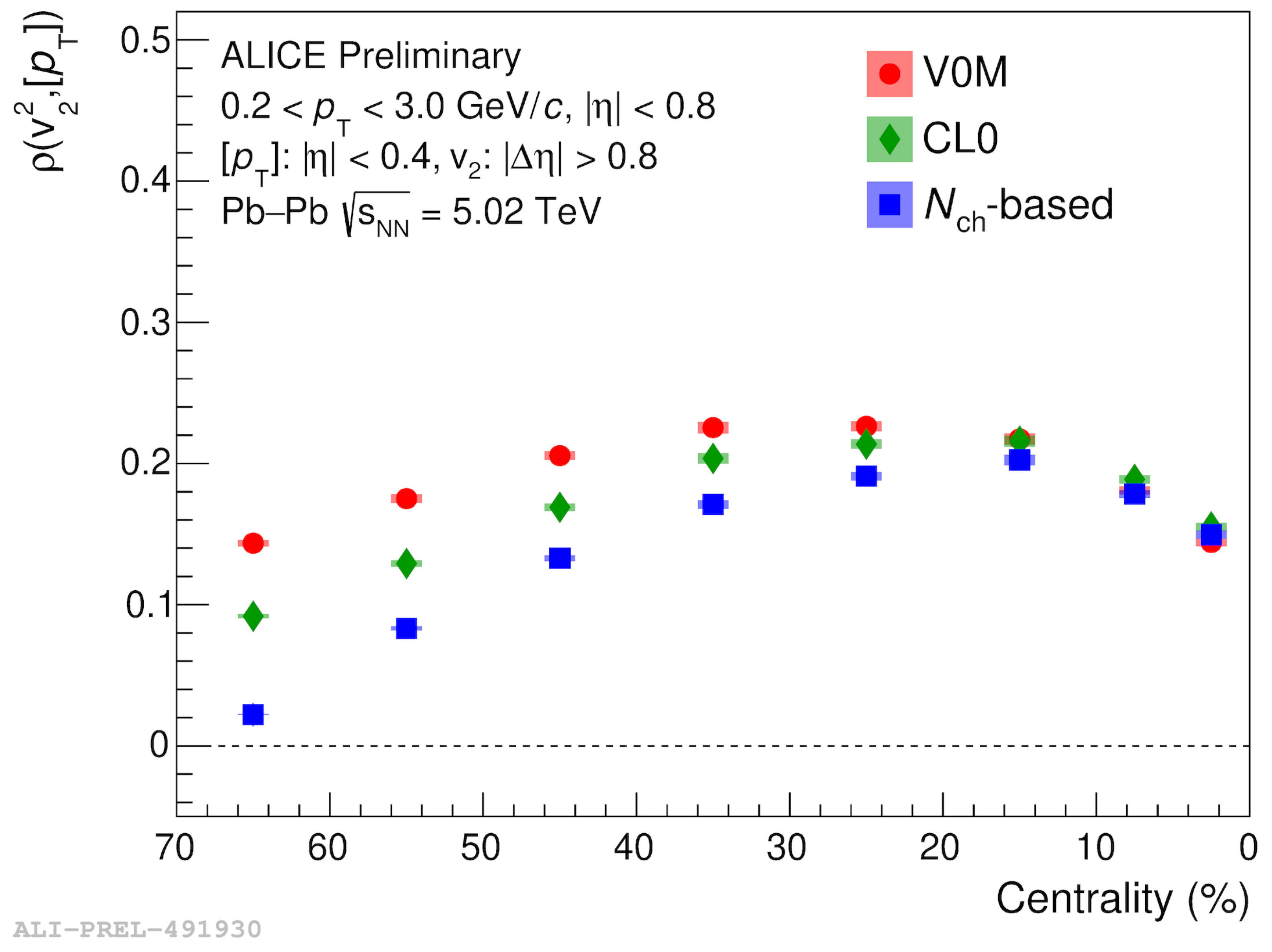


- Final and initial state compatible for IP-Glasma-based models
  - Depends on choice of estimator for $[p_T]$

Kinematic cuts







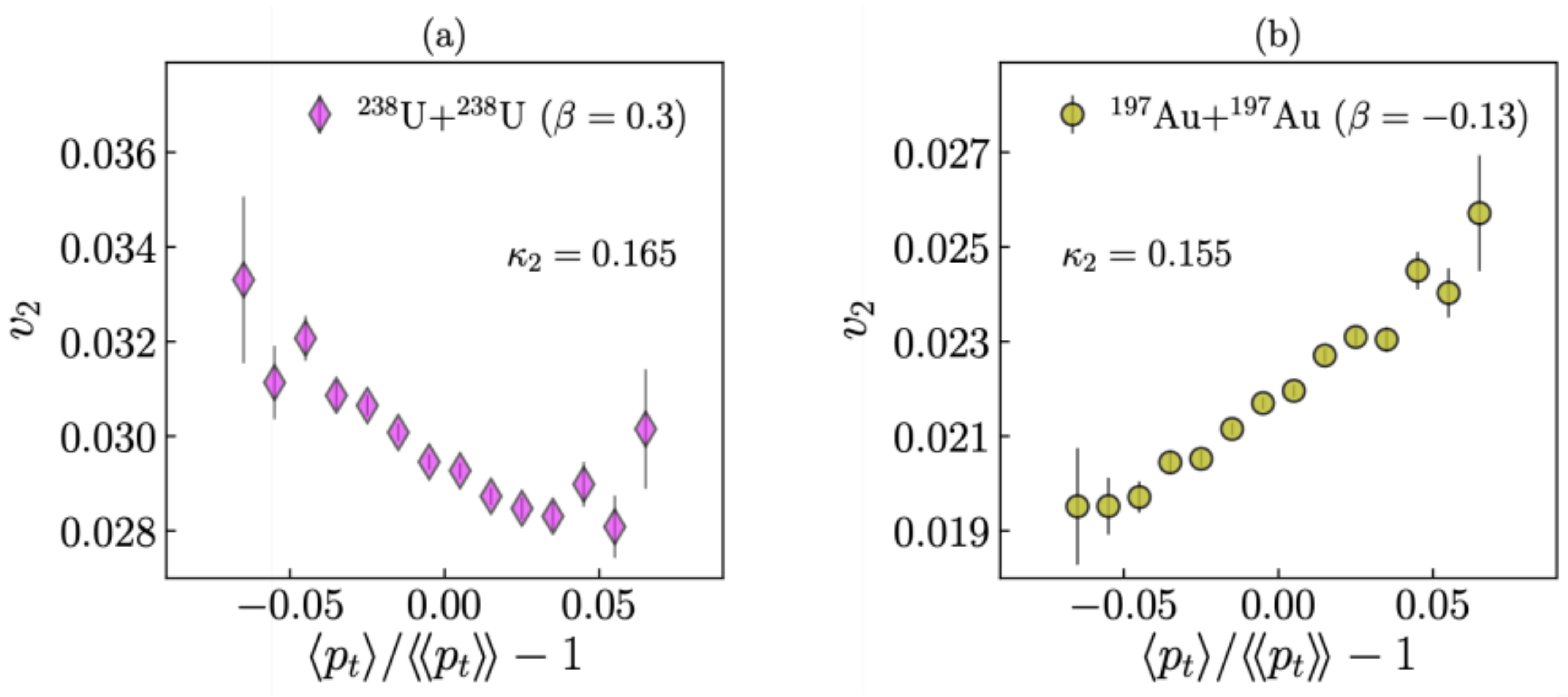
- Left: ρ_2 mostly insensitive to choice of η for the subevents
- Middle: ρ_2 highly sensitive to choice of p_T range
- Right: ρ_2 highly sensitive to choice of centrality estimation

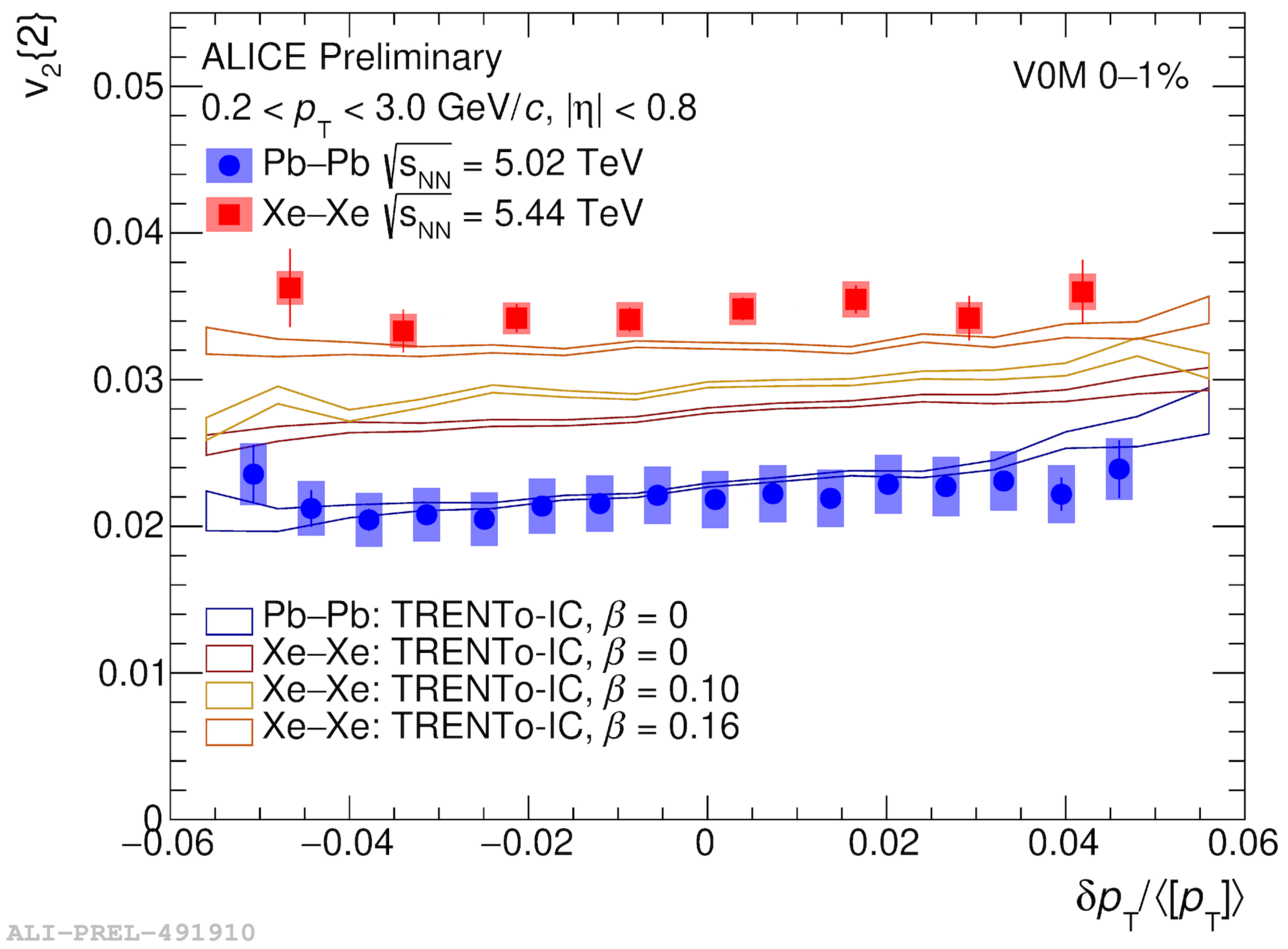
Nuclear deformation

❖ Models:

- Measure v_2 as function of $([p_T] - \langle [p_T] \rangle)/(\langle [p_T] \rangle$ in most central collisions
- Pb−Pb: No deformation ⇒ no correlation
- Xe−Xe: v_2 larger in events with smaller $[p_T]$

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





❖ ALICE

- Pb−Pb and Xe−Xe significantly different
- No significant slope observed
- Xe−Xe best described with $\beta = 0.16$