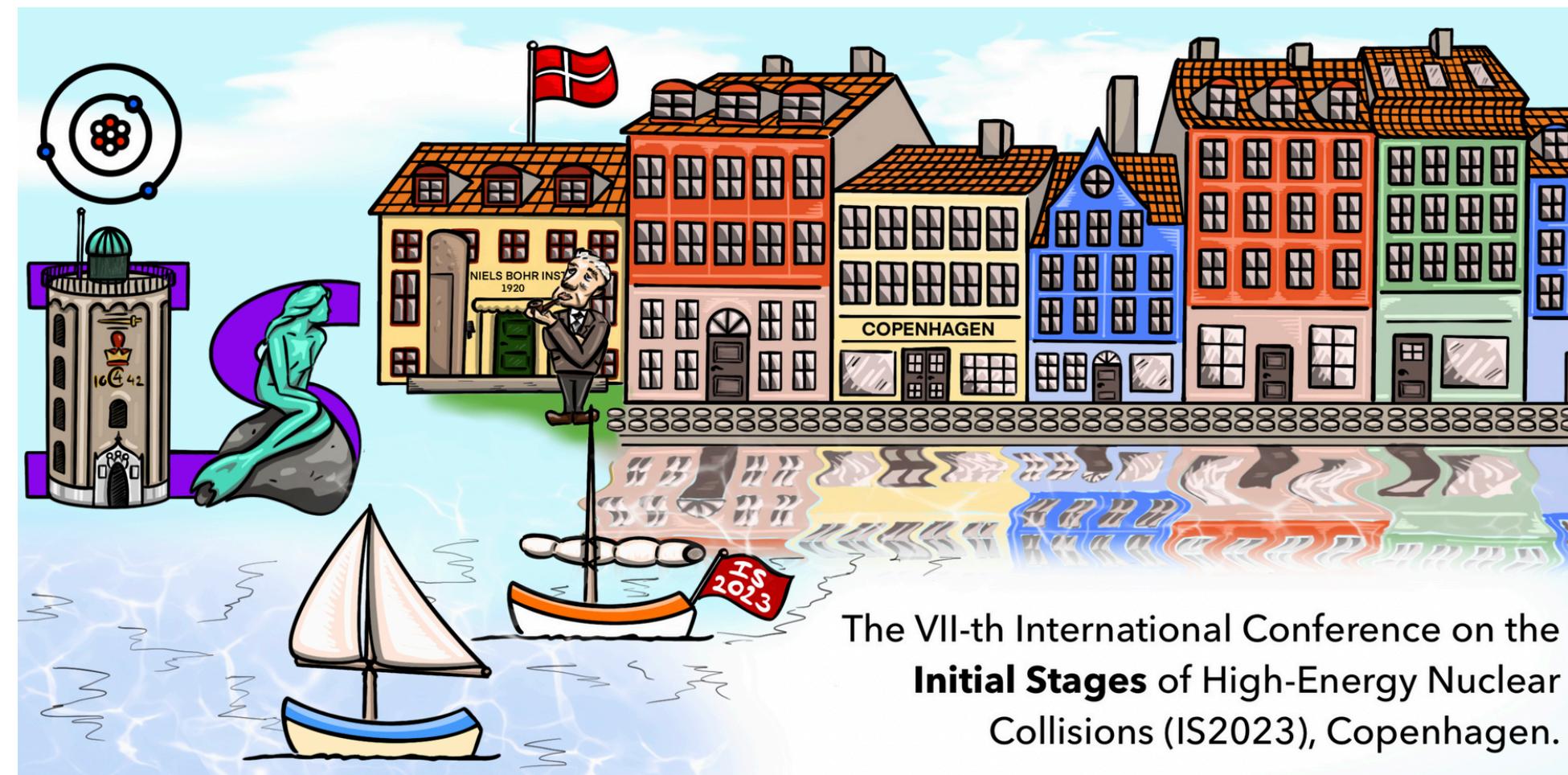


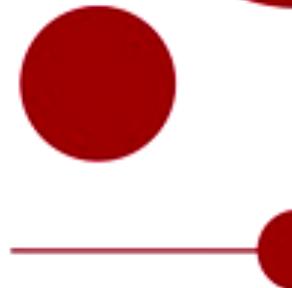
Collective phenomena in small systems (soft probes)

Debojit Sarkar

Niels Bohr Institute
University of Copenhagen
Denmark

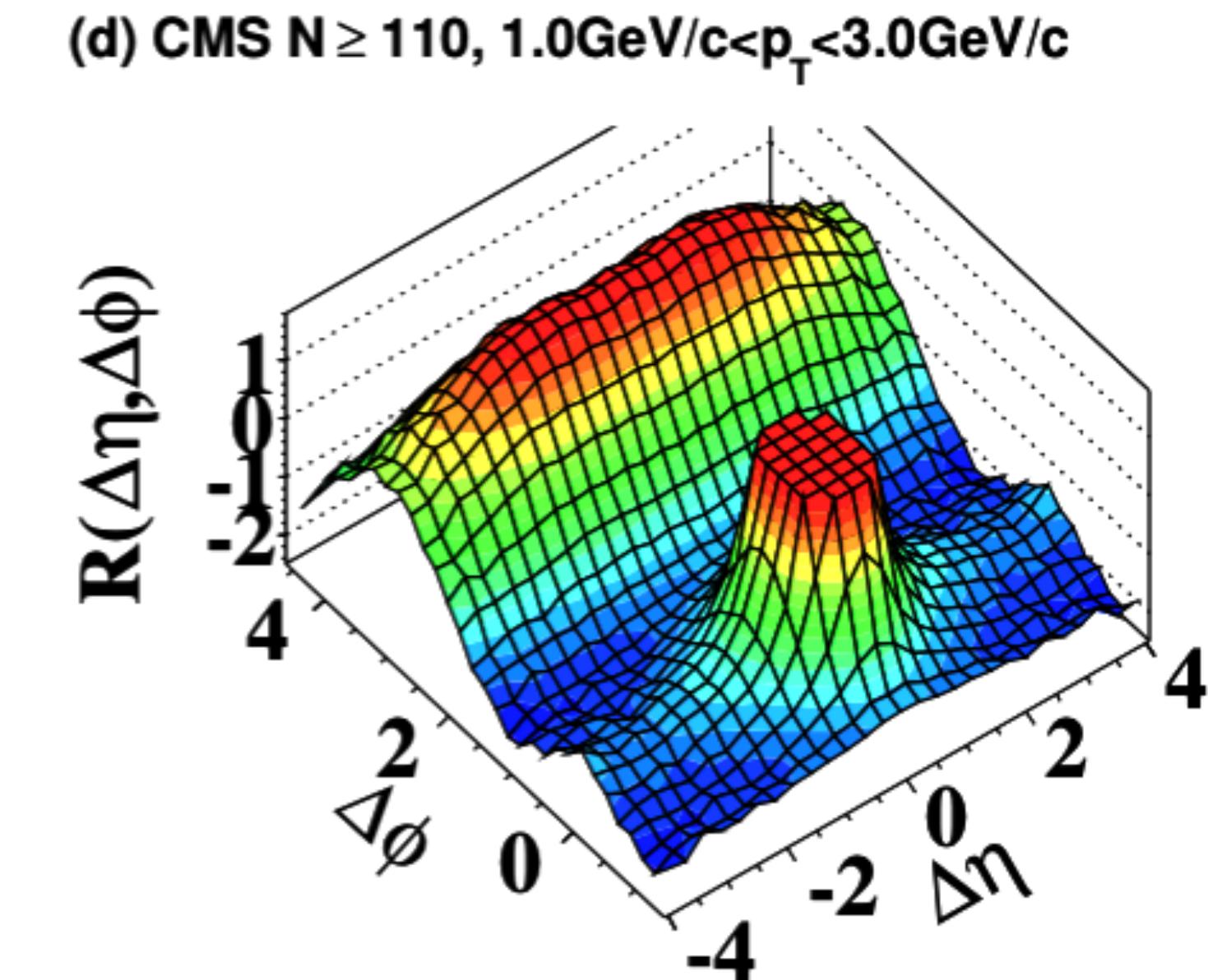
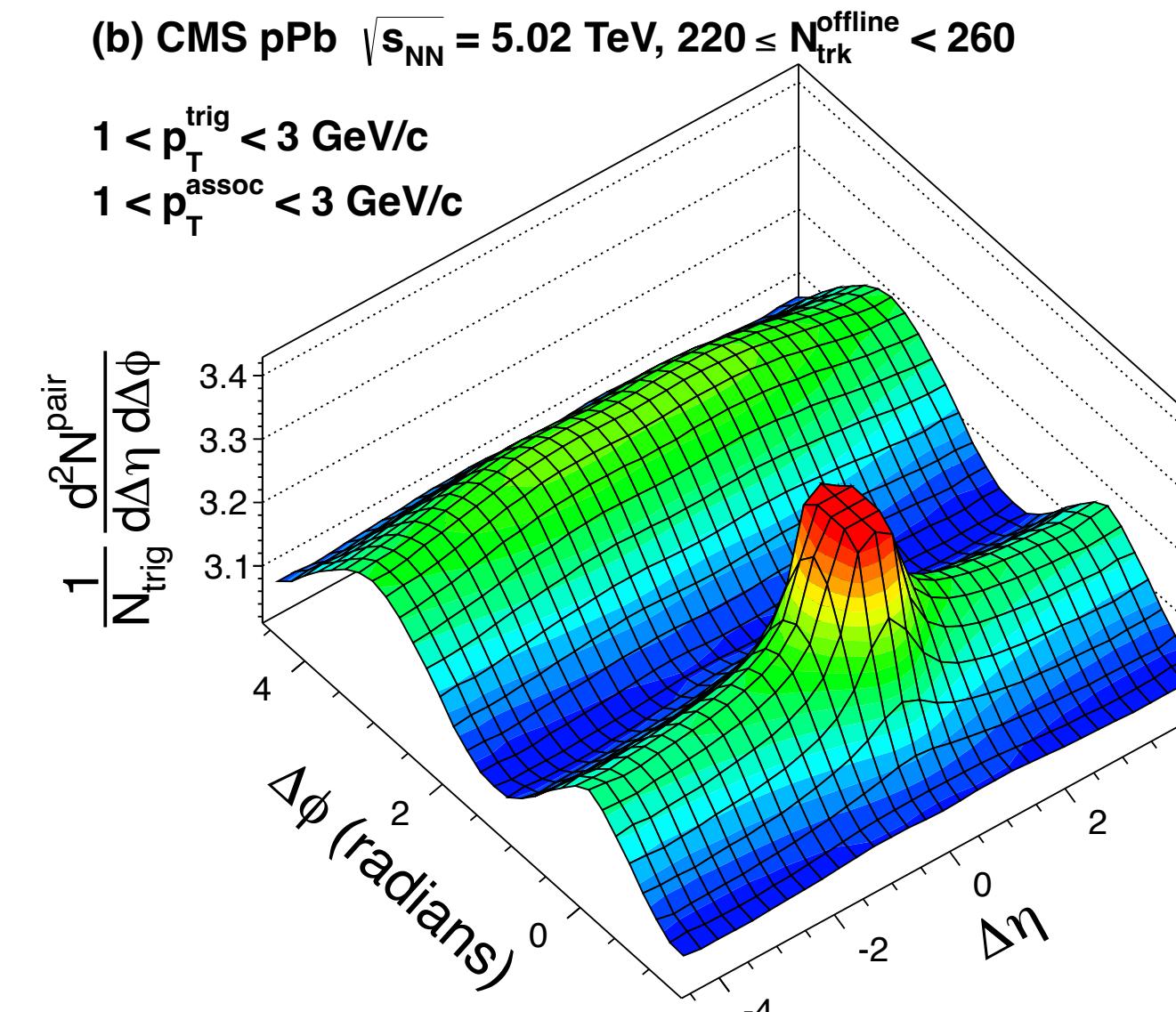
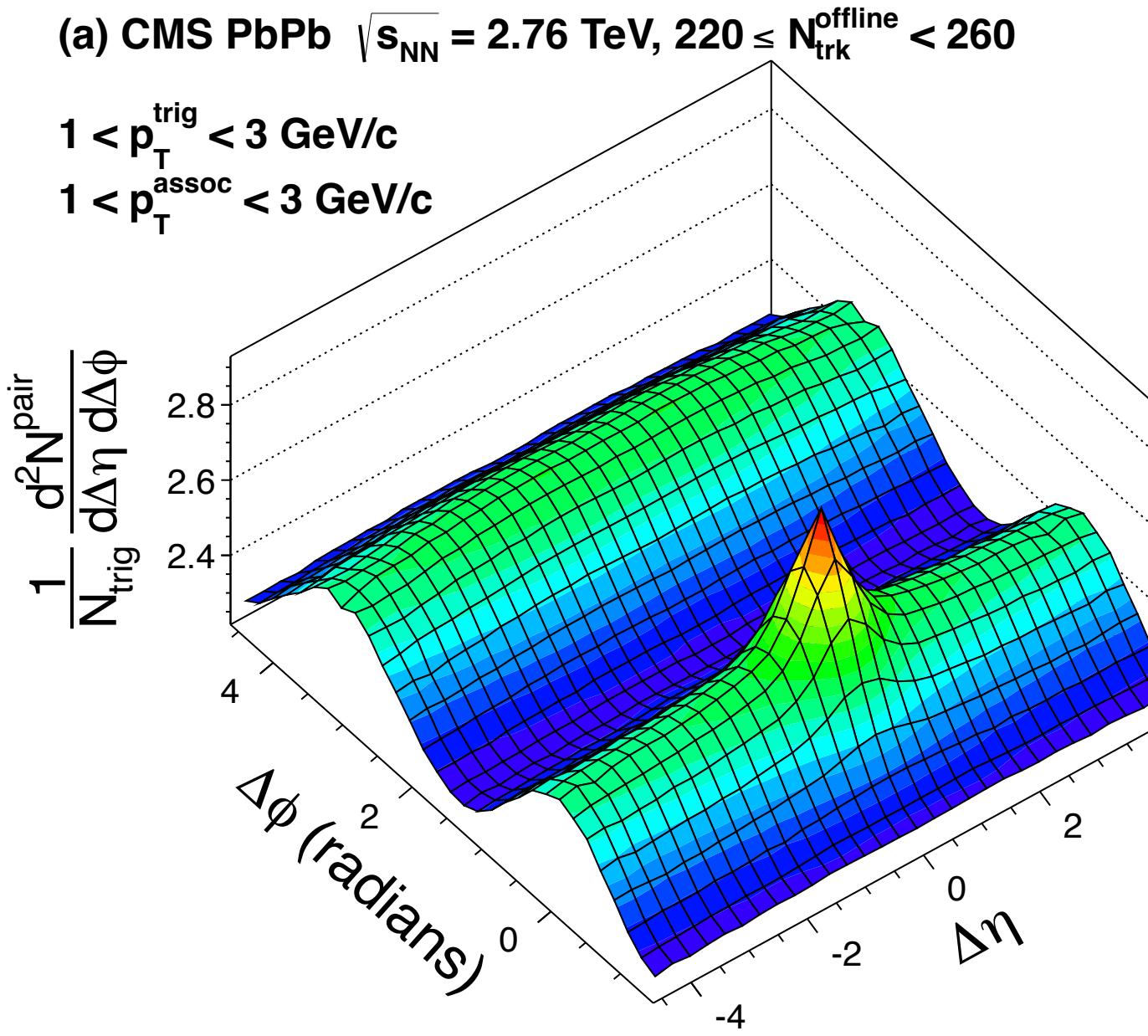


UNIVERSITY OF
COPENHAGEN

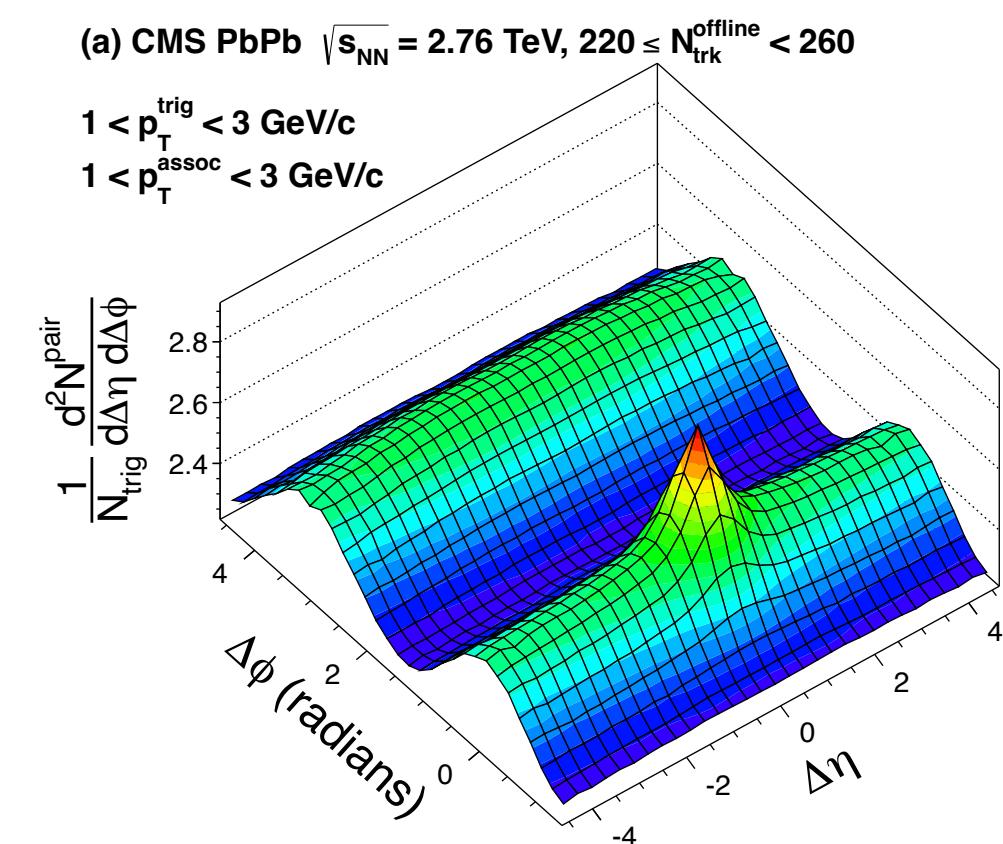
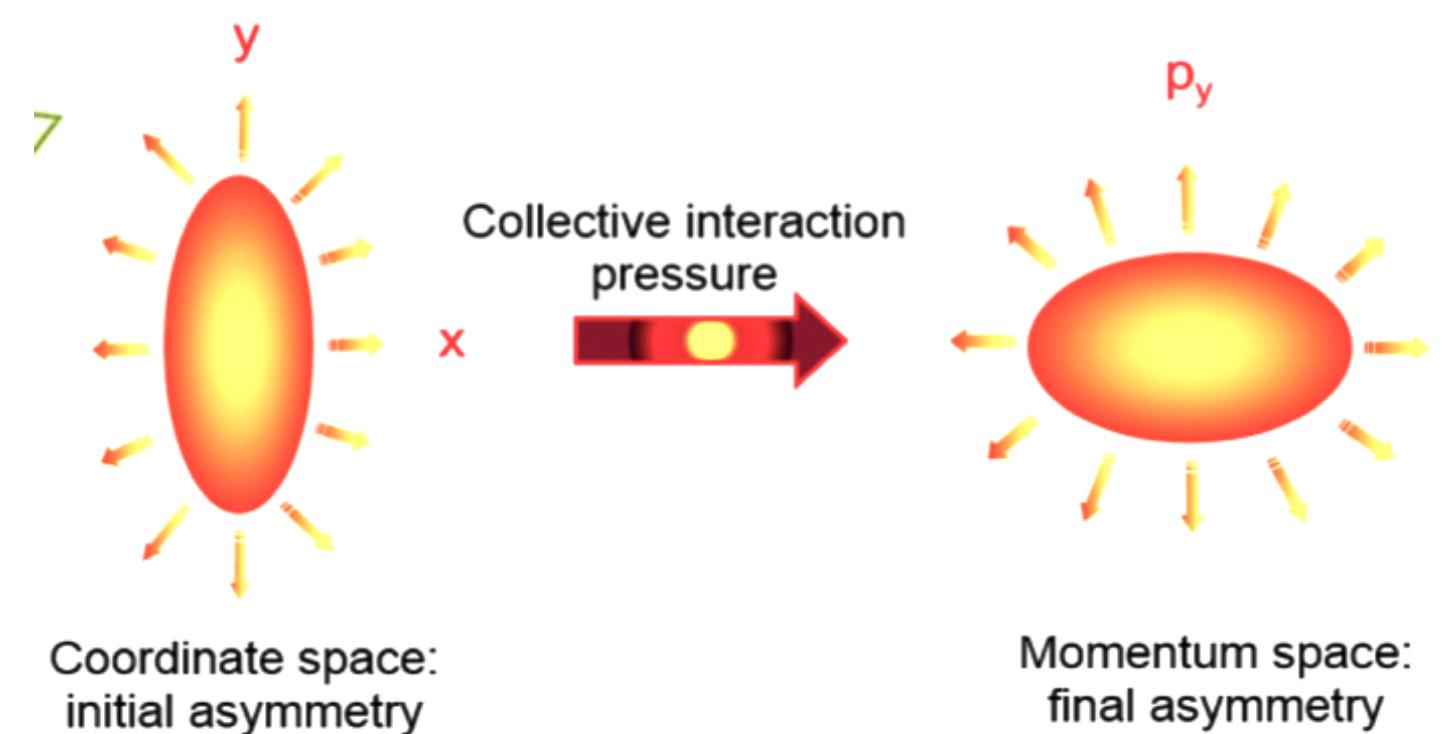
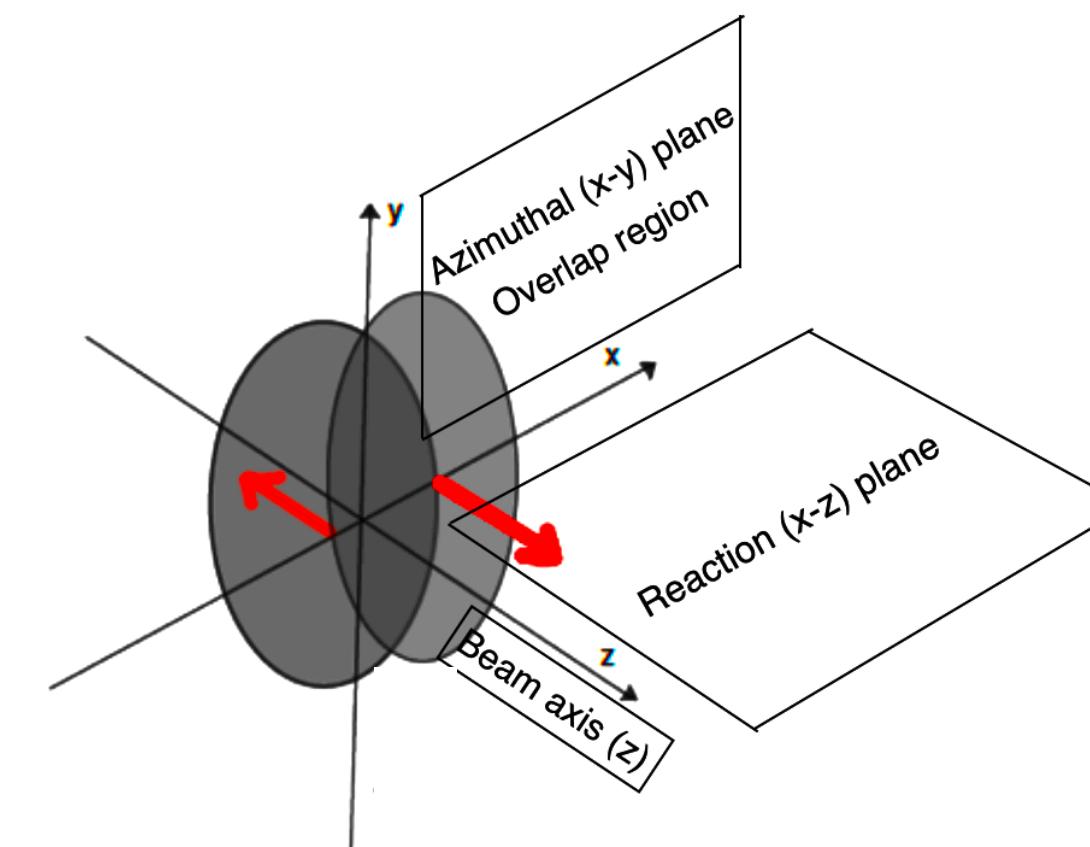




Collectivity in small systems?

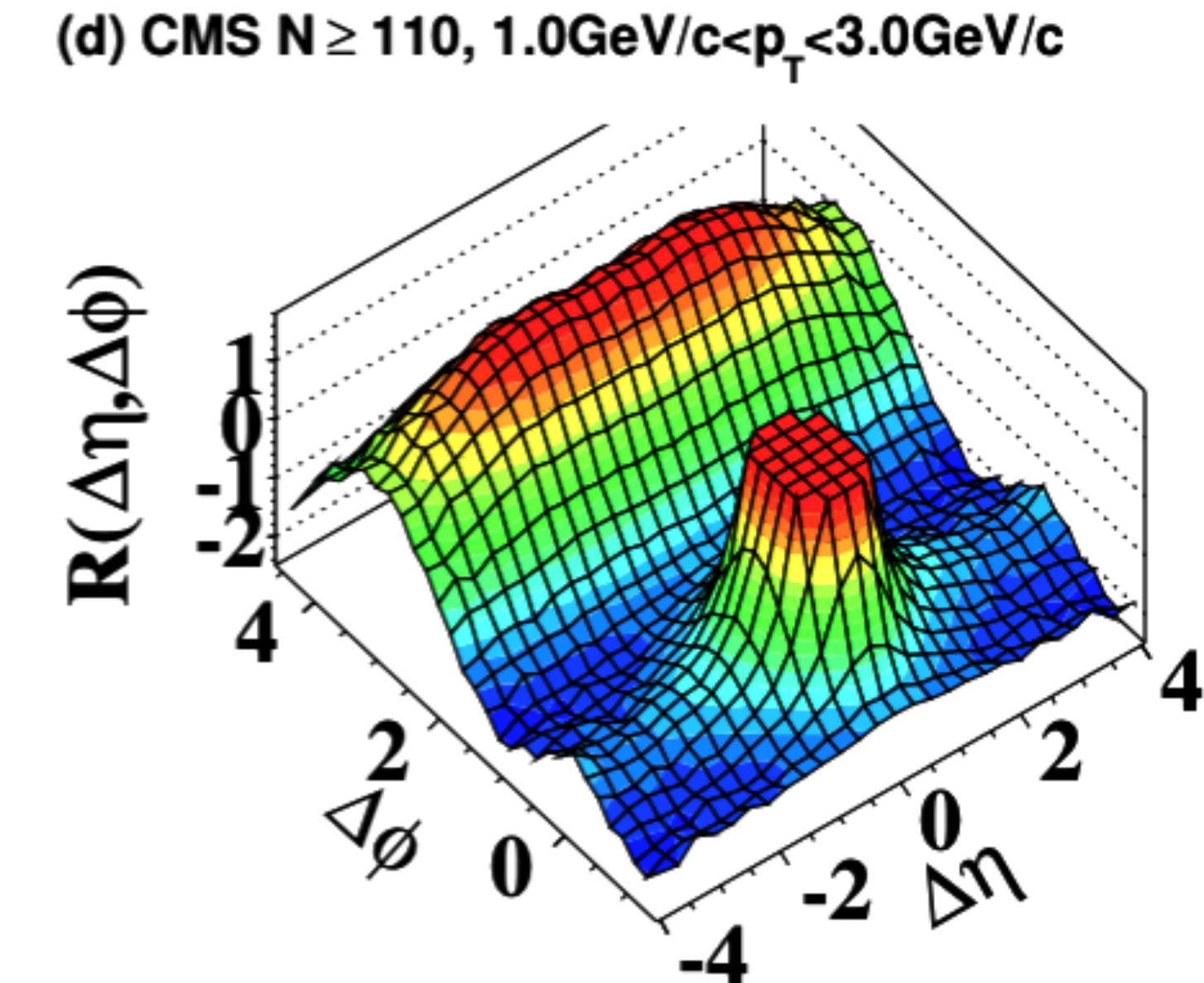
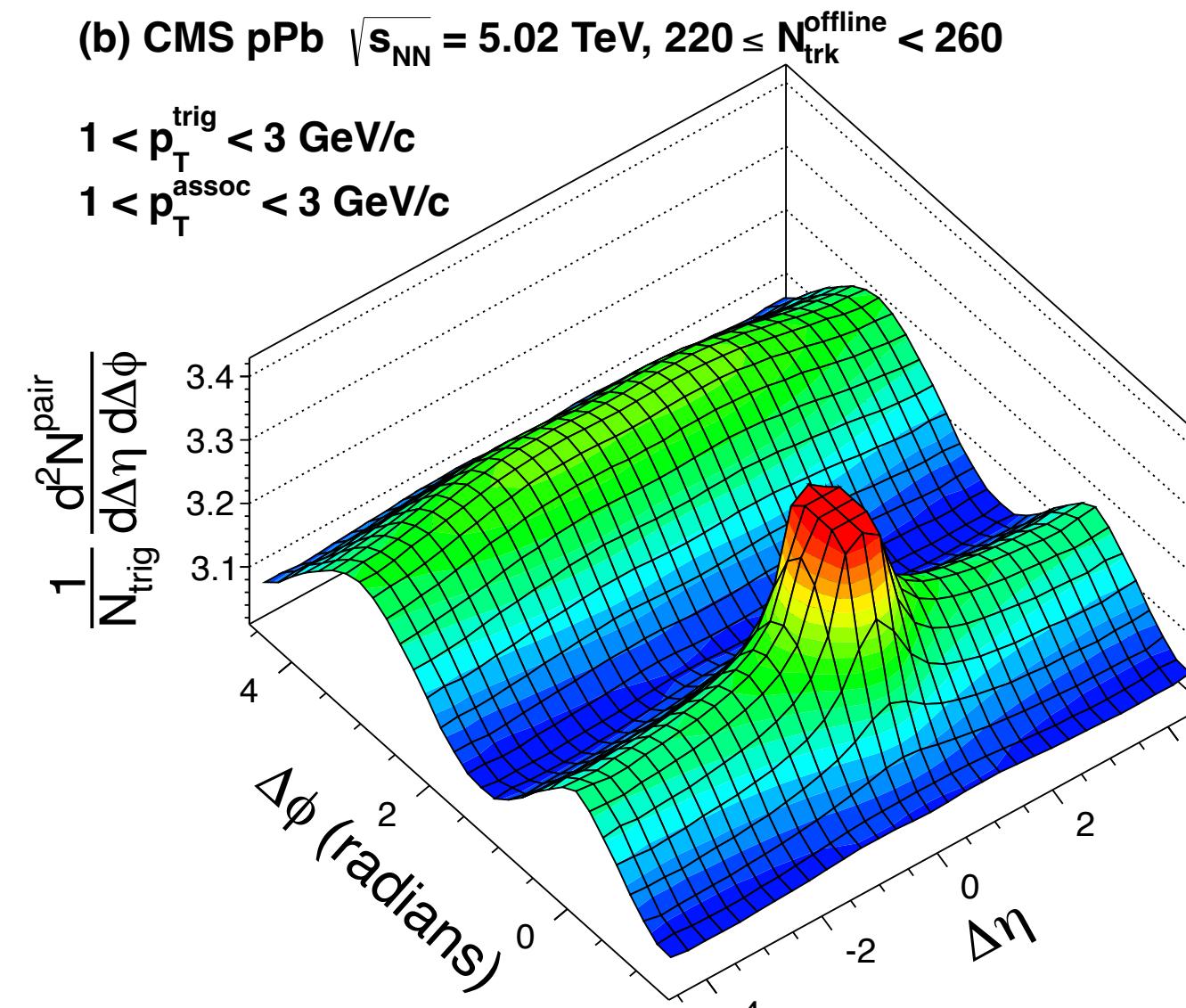
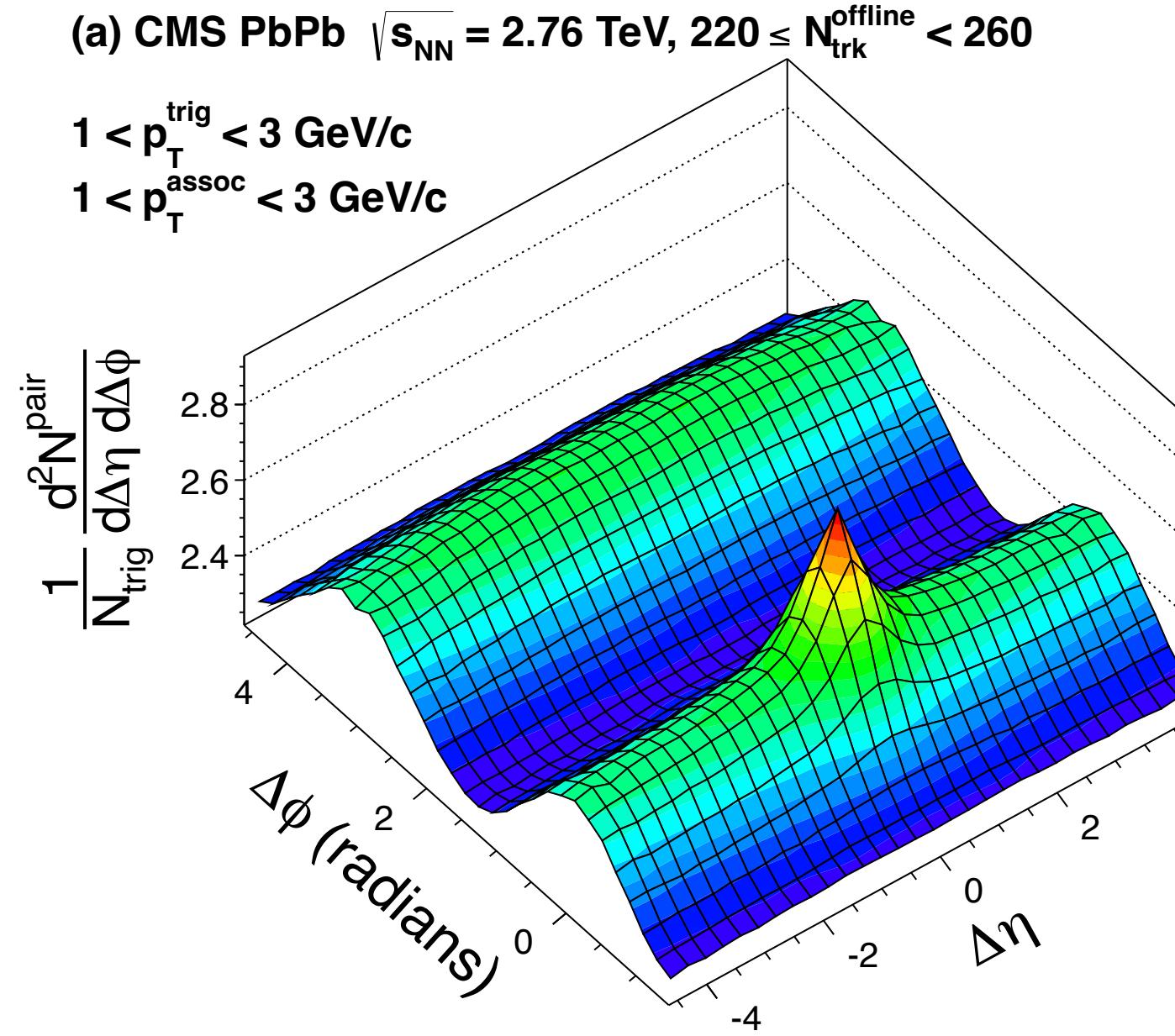


Everything flows (?) - Initial state geometry + Final state interaction (hydro description)





Collectivity in small systems?



Everything flows (?) - Initial state geometry + Final state interaction (hydro description)

Or

Initial State effect(?):

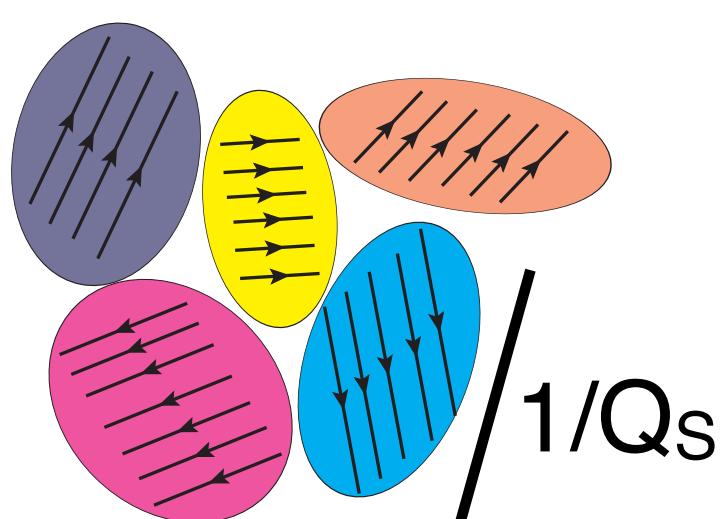
“Glasma flux tube”: Longitudinal extension of color domains with transverse size $\sim 1/Q_s$

Domains are uncorrelated and randomly oriented (in both coordinate space and color space)

Many resolved color domains in the interaction region - reduces the anisotropy

J. L. Nagle, W. A. Zajc; Phys Rev C 99, 054908 (2019)
A Dumitru et al, Phys. Lett. B 697:21-25, 2011

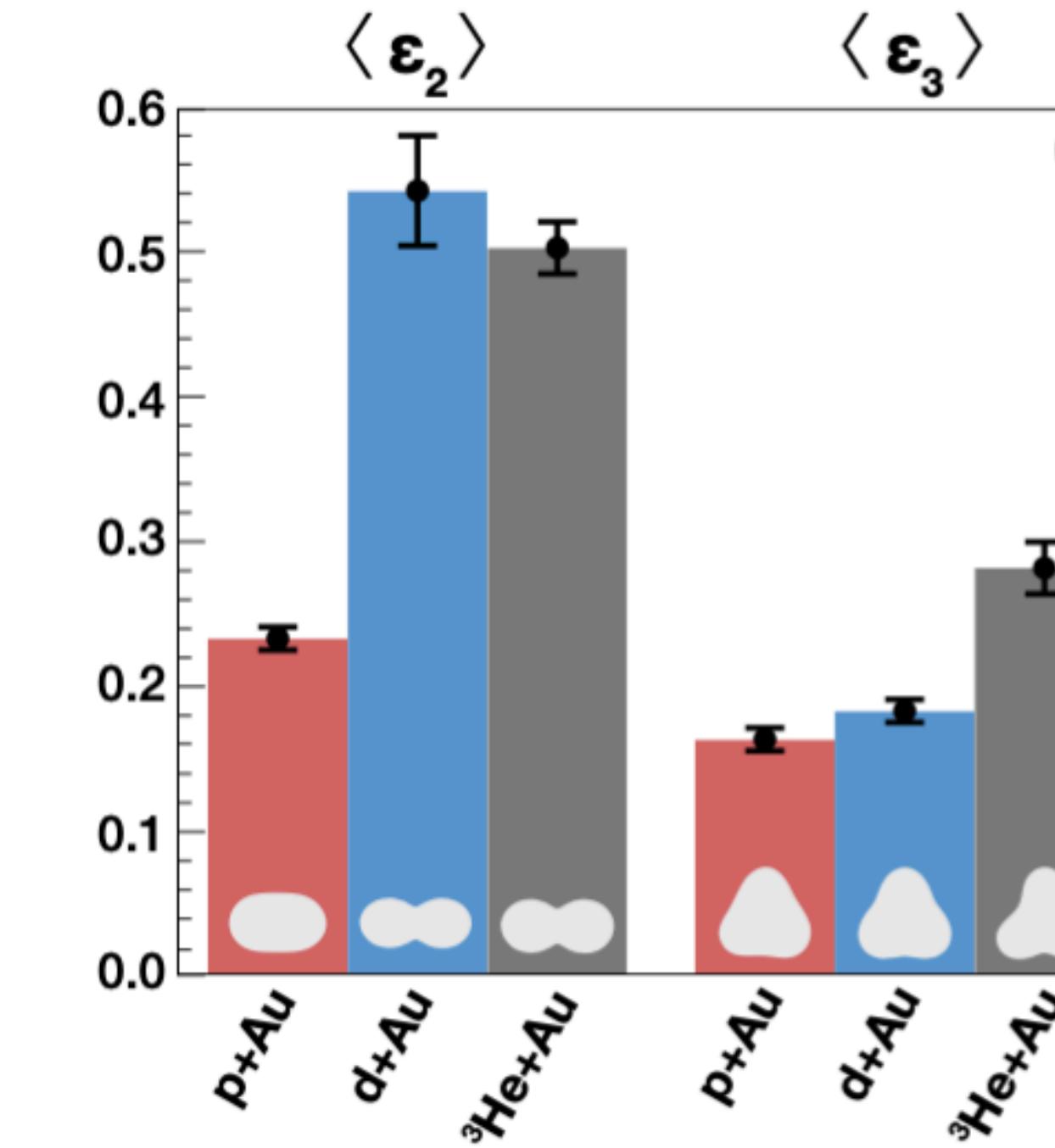
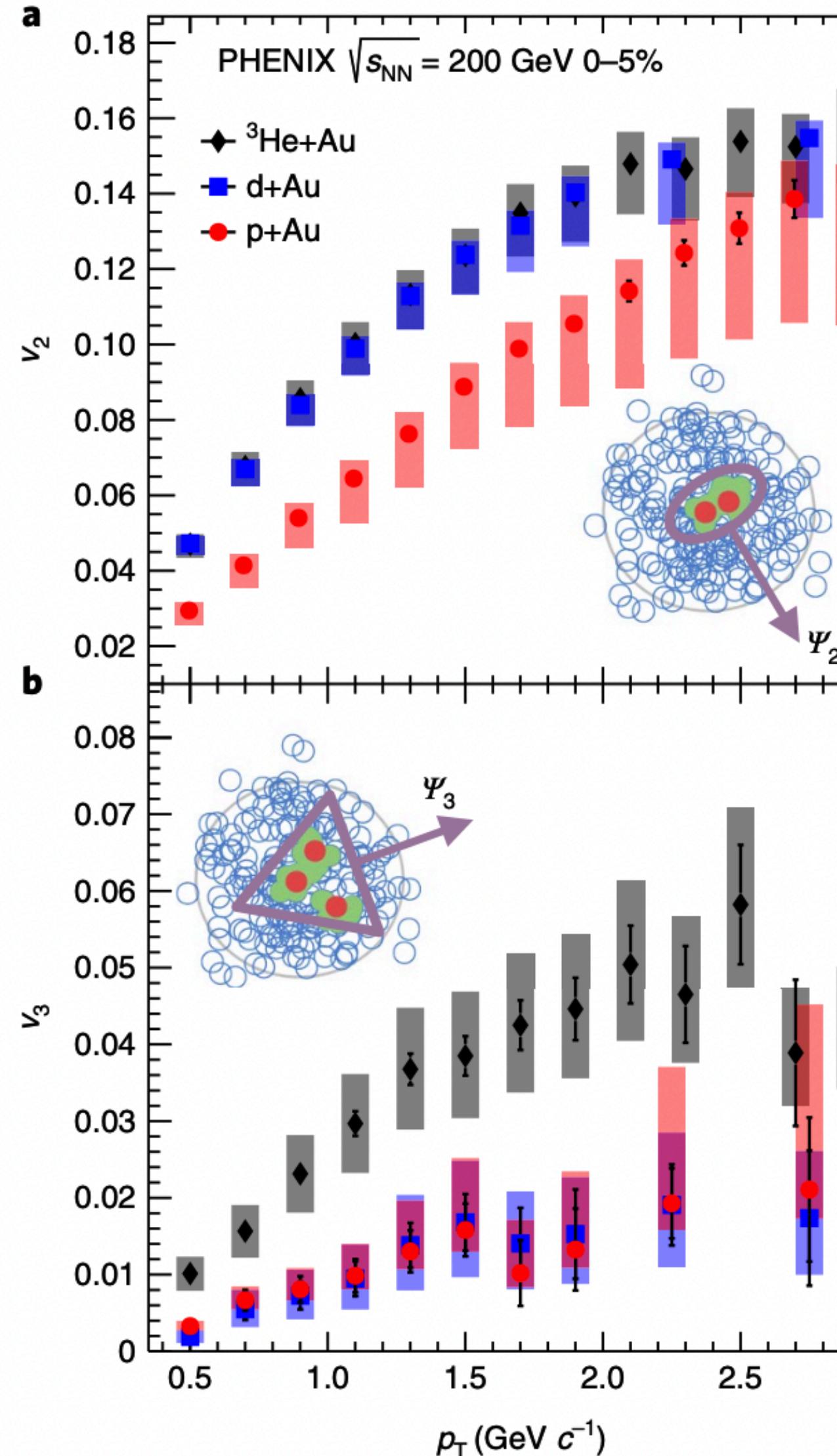
Q_s - saturation momentum scale



T. Lappi et al, JHEP volume 2016: 61 (2016)



Initial Geometry or Initial Momentum anisotropy?



PHENIX, Nature Physics 15, 214-219 (2019)
Consistent with latest results: PHENIX: PRC 107 (2023) 024907

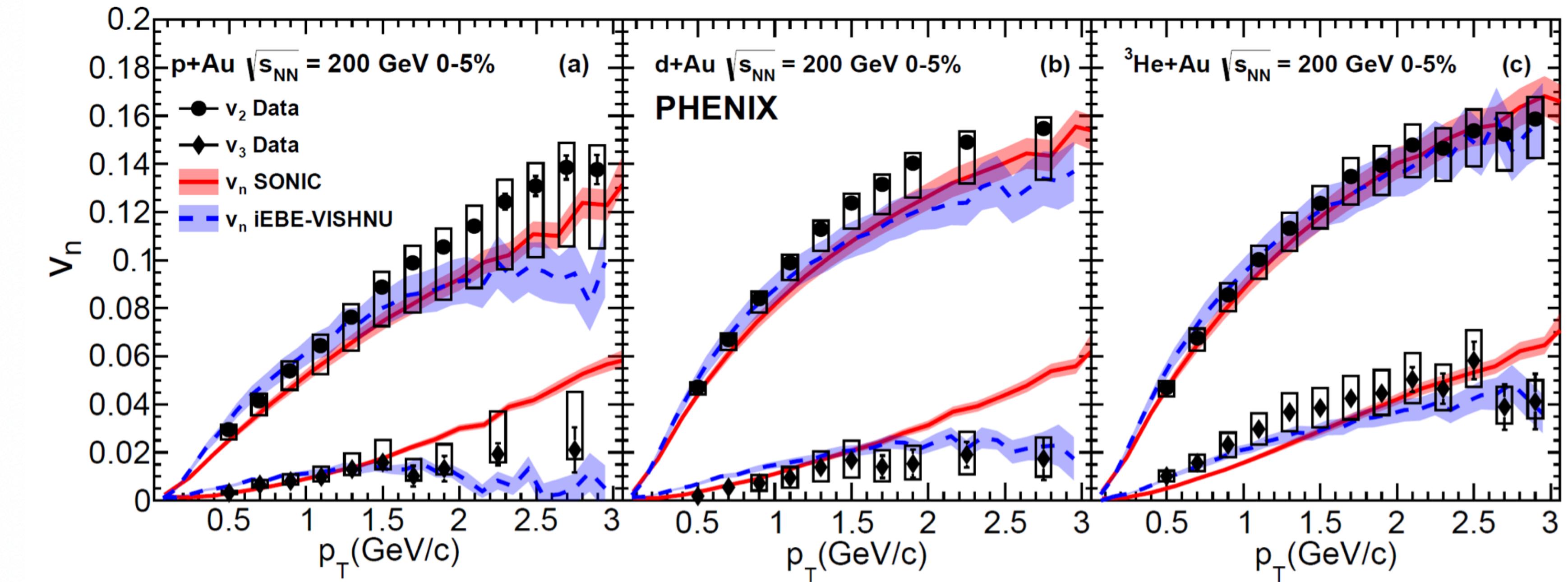
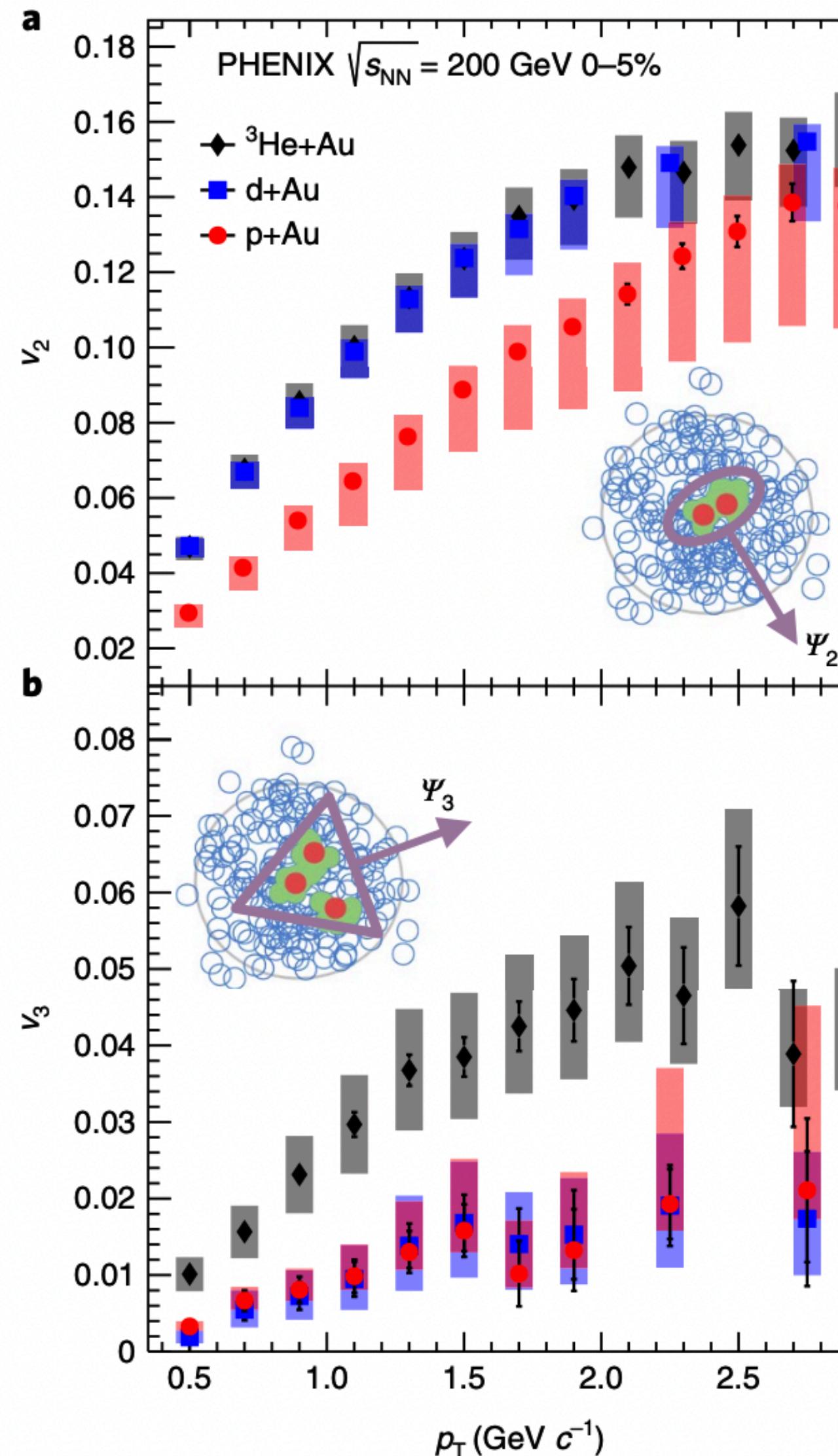
- Hydro prediction ($v_n \propto \epsilon_n$)
- Geometry scan results: consistent with hydro prediction:

$$v_2^{p+\text{Au}} < v_2^{d+\text{Au}} \approx v_2^{{}^3\text{He}+\text{Au}}$$

$$v_3^{p+\text{Au}} \approx v_3^{d+\text{Au}} < v_3^{{}^3\text{He}+\text{Au}}$$



Initial Geometry or Initial Momentum anisotropy?



PHENIX, Nature Physics 15, 214-219 (2019)

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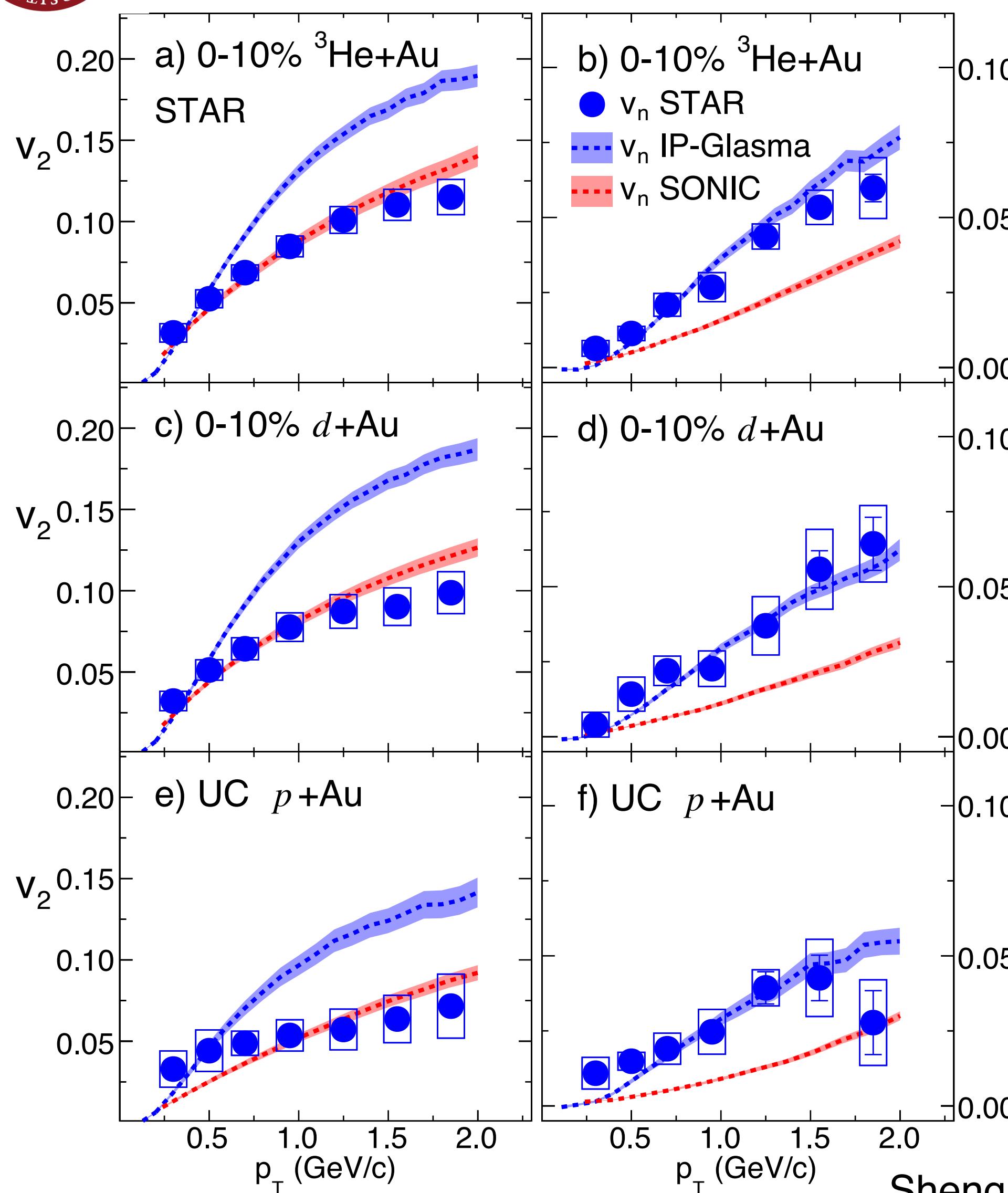
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Possible Initial State effects?

STAR, Phys. Rev. Lett. 130, 242301 (2023)



$$v_2^{\text{p+Au}} < v_2^{\text{d+Au}} \approx v_2^{\text{He+Au}}$$

(Expected hydro ordering)

$$v_3^{\text{p+Au}} \approx v_3^{\text{d+Au}} \approx v_3^{\text{He+Au}}$$

(!!)

- SONIC (nucleonic Glauber)
Describes v_2 — underestimates v_3

- IP-Glasma+MUSIC+URQMD (sub-nucleonic fluctuations + Pre hydro flow): Describes v_3 — overestimates v_2 .

Shengli Huang & ZhenYu Chen

Chun Shen

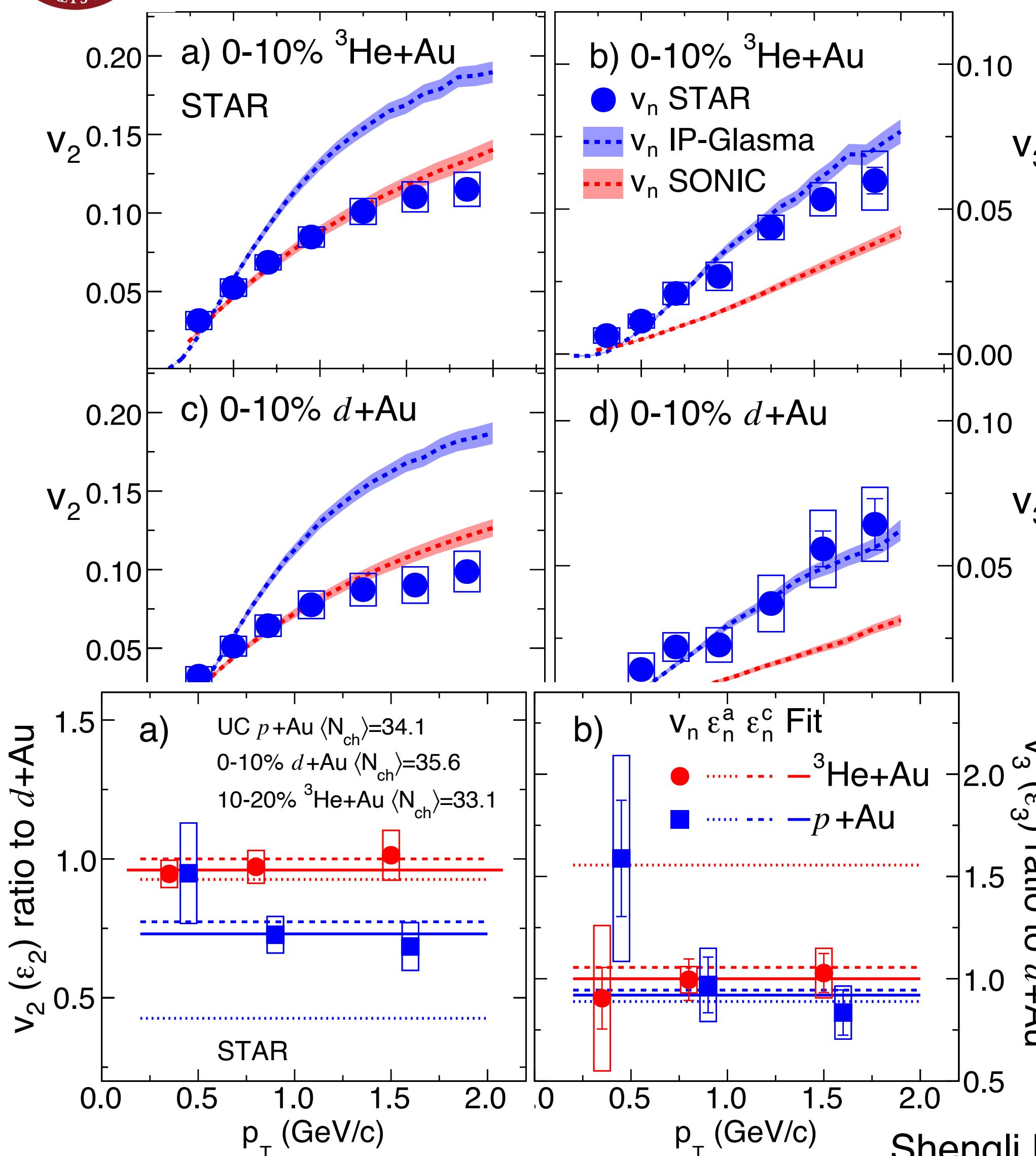
Wed: 14.20

Wed: 12.20



Possible Initial State effects?

STAR, Phys. Rev. Lett. 130, 242301 (2023)



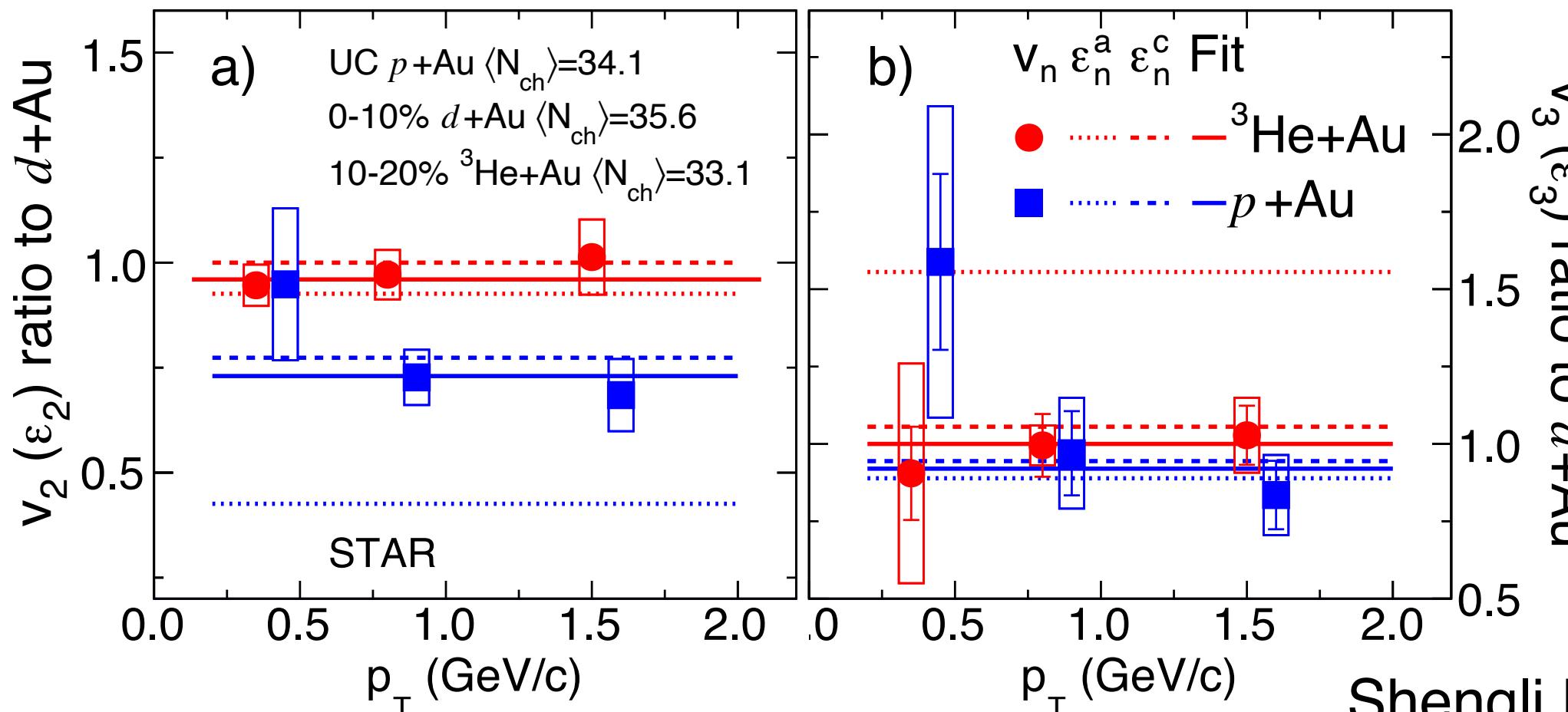
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(!!)

- SONIC (nucleonic Glauber)
Describes v_2 — underestimates v_3

- IP-Glasma+MUSIC+URQMD (sub-nucleonic fluctuations + Pre hydro flow): Describes v_3 — overestimates v_2 .



- Sub-nucleonic fluctuations + Pre hydro flow important for small systems.

- A properly tuned hybrid model (initial state (CGC+?) + final state (hydro)) is the best possible approach?

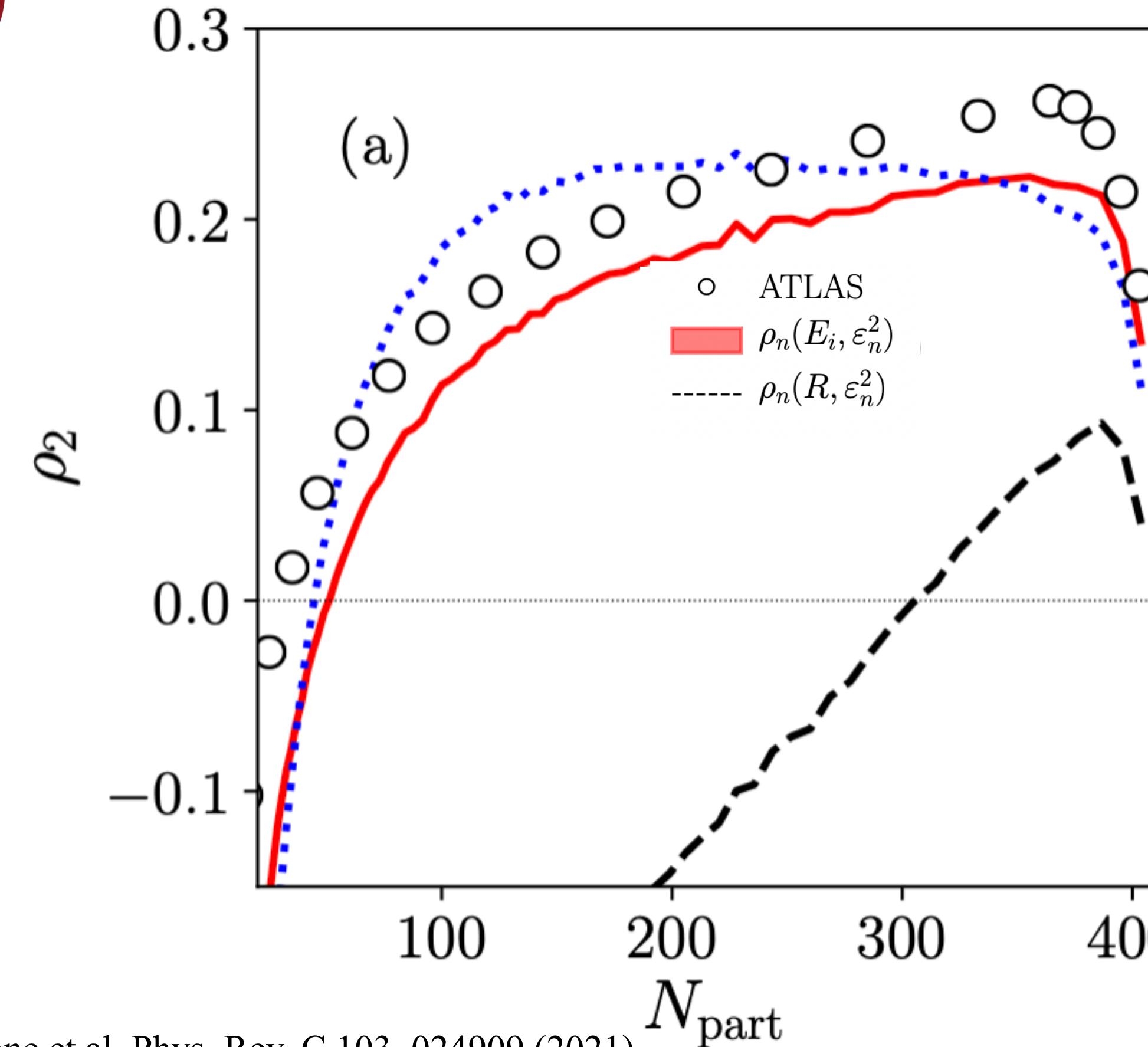
Shengli Huang & ZhenYu Chen

B Schenke, C Shen , P Tribedy; Physics Letters B 803 (2020) 135322

Wed: 14.20



Tracing back “Initial Cause” from “Final Effect”



G. Giacalone et al, Phys. Rev. C 103, 024909 (2021)

Bożek, Phys. Rev. C 93, 044908 (2016)

ATLAS Collaboration, Eur. Phys. J. C 79, 12, 985 (2019)

- Correlation between the initial state effects ($\rho(\epsilon_n^2, E)$) explains the correlation between the final state effects ($\rho(v_n^2, [p_T])$)!
- Important tool to trace back the initial state effects responsible for the observed final state effects.

Initial State	Final State	
ϵ_n	v_n	
Initial State	Final State	
$1/R, E$	$\langle p_T \rangle$	

- Pearson correlation coefficient:

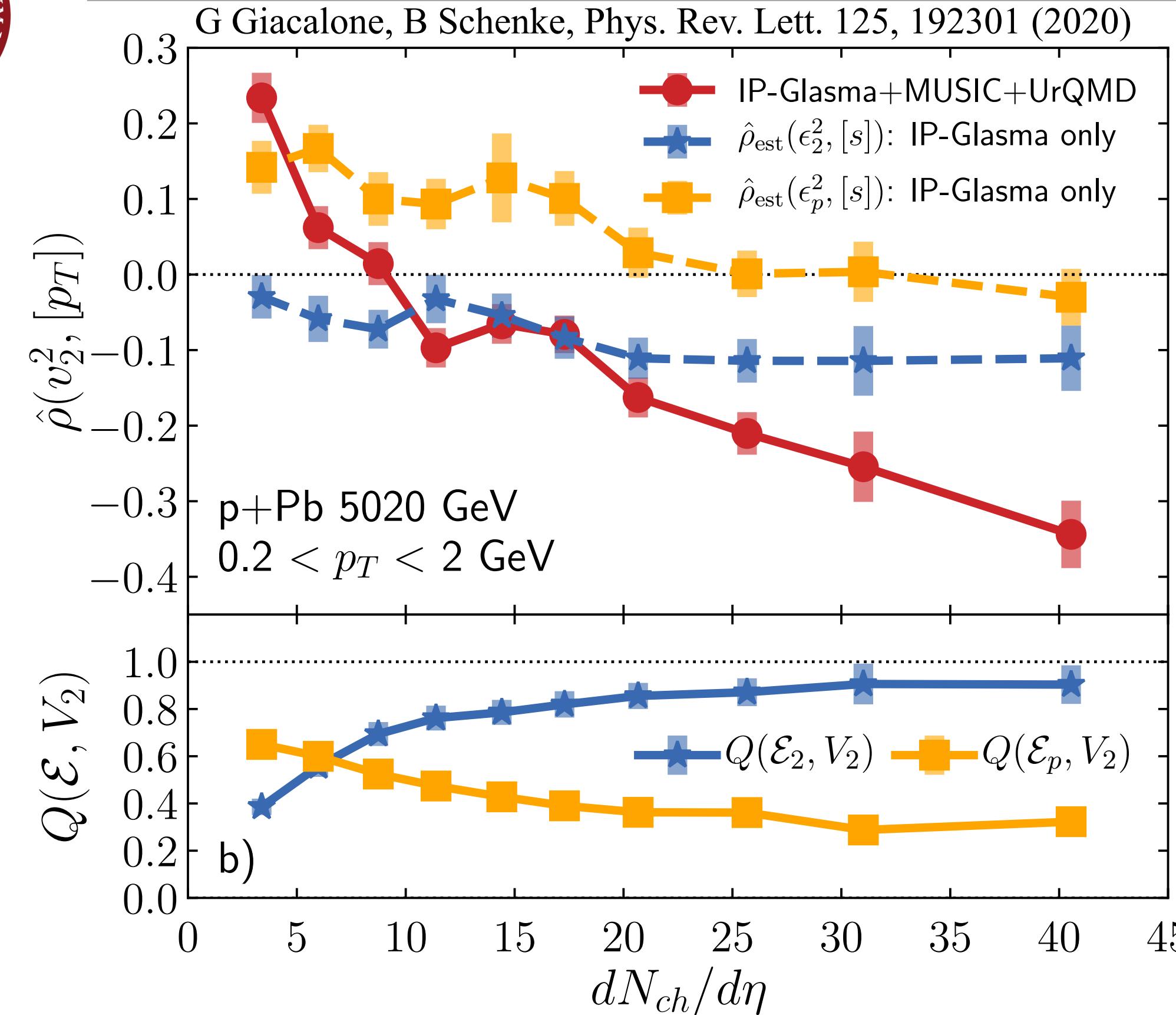
$$\rho(v_n^2, [p_T]) = \frac{\text{cov}(v_n^2, [p_T])}{\sqrt{\text{var}(v_n^2)} \sqrt{\text{var}([p_T])}}$$

- Traces back “initial cause” from “final effect”:

$$\begin{array}{ccc} \text{Final State} & & \text{Initial State} \\ \rho(v_n^2, \langle p_T \rangle) & \approx & \rho(v_n^2, \langle p_T \rangle) \approx \rho(\epsilon_n^2, E) \\ (\text{Data}) & & (\text{Model}) & (\text{Model}) \end{array}$$



Tracing back “Initial Cause” from “Final Effect”

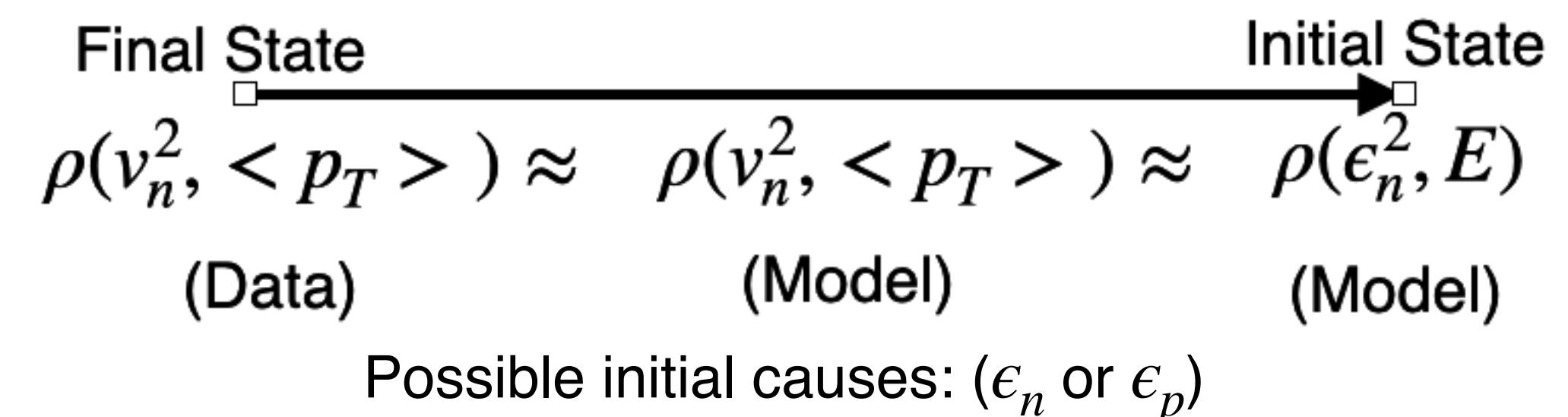


- ρ in small system- different qualitative response to different initial causes(ϵ_n or ϵ_p) - different sign and slope!
- Low multiplicity- initial momentum anisotropy dominates ($\rho(\epsilon_p^2, E/S) \rightarrow$ positive).
- High multiplicity- initial spatial anisotropy +final state interaction dominates ($\rho(\epsilon_n^2, E/S) \rightarrow$ negative).
- Sign change of $\rho(v_n^2, [p_T])$ at $dN_{ch}/d\eta \sim 5-10$ (for p-Pb, d+Au, and p+Au) in data? — experimental evidence of initial state momentum anisotropy?

Pearson correlation coefficient:

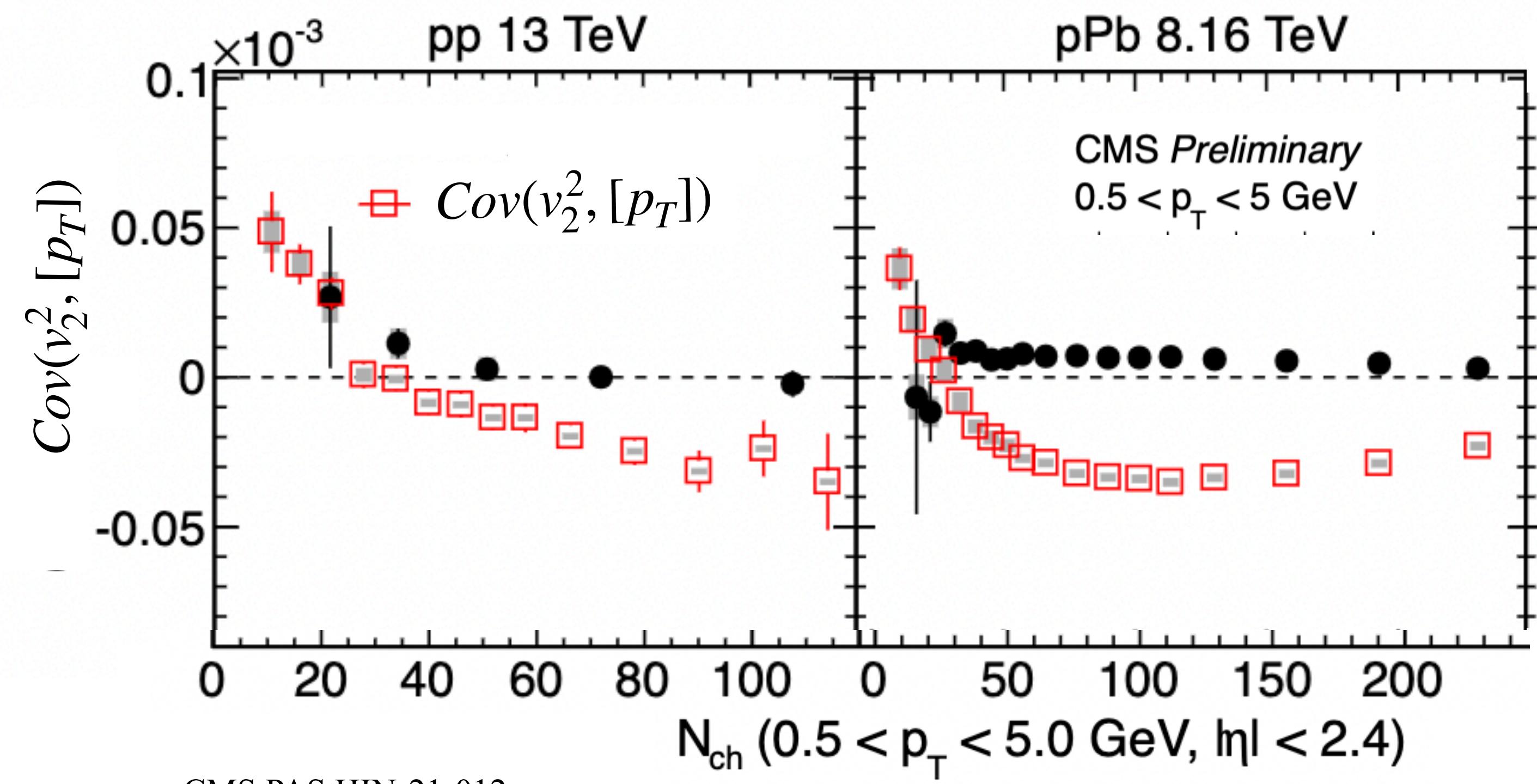
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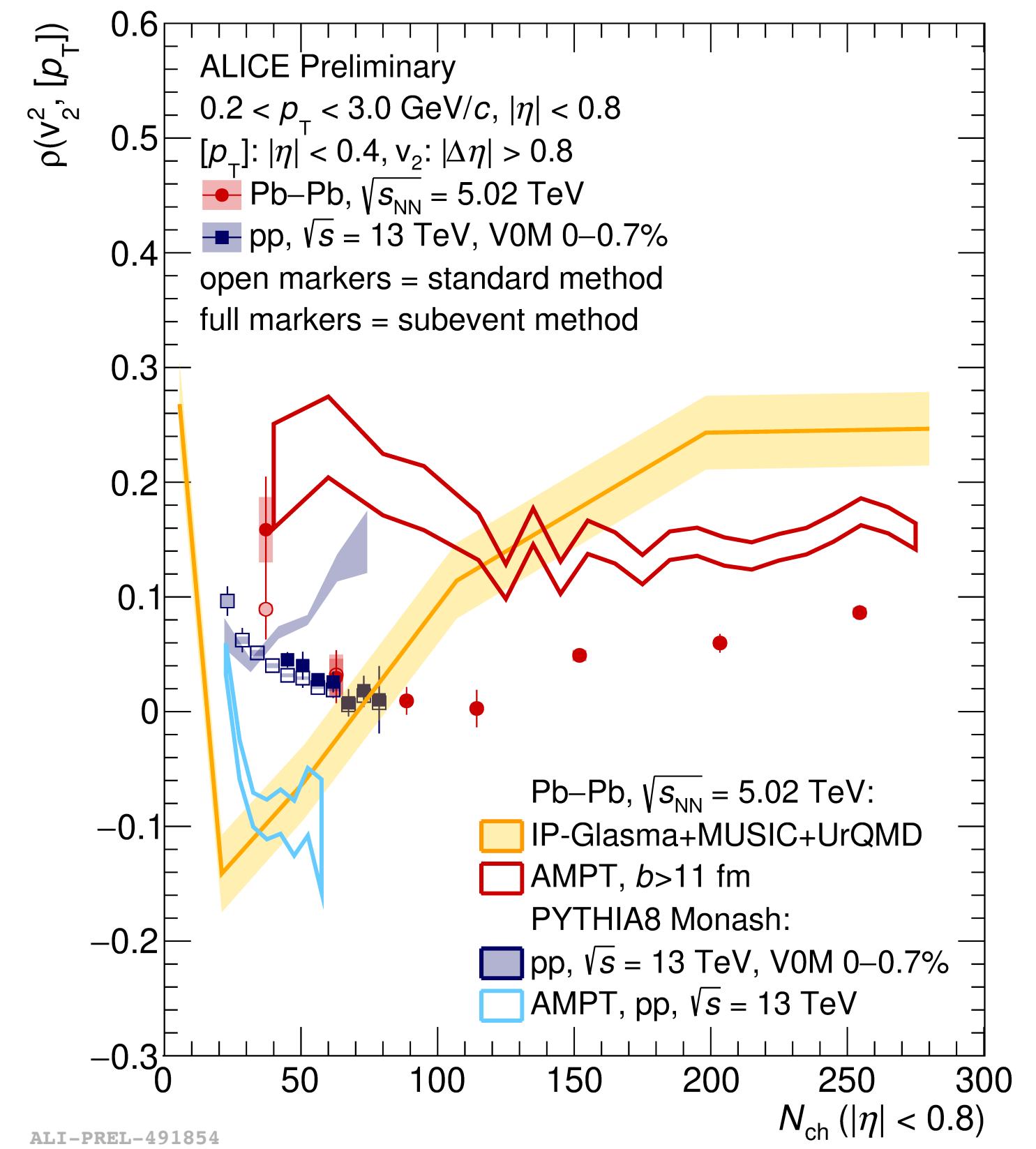




Data shows something like that?

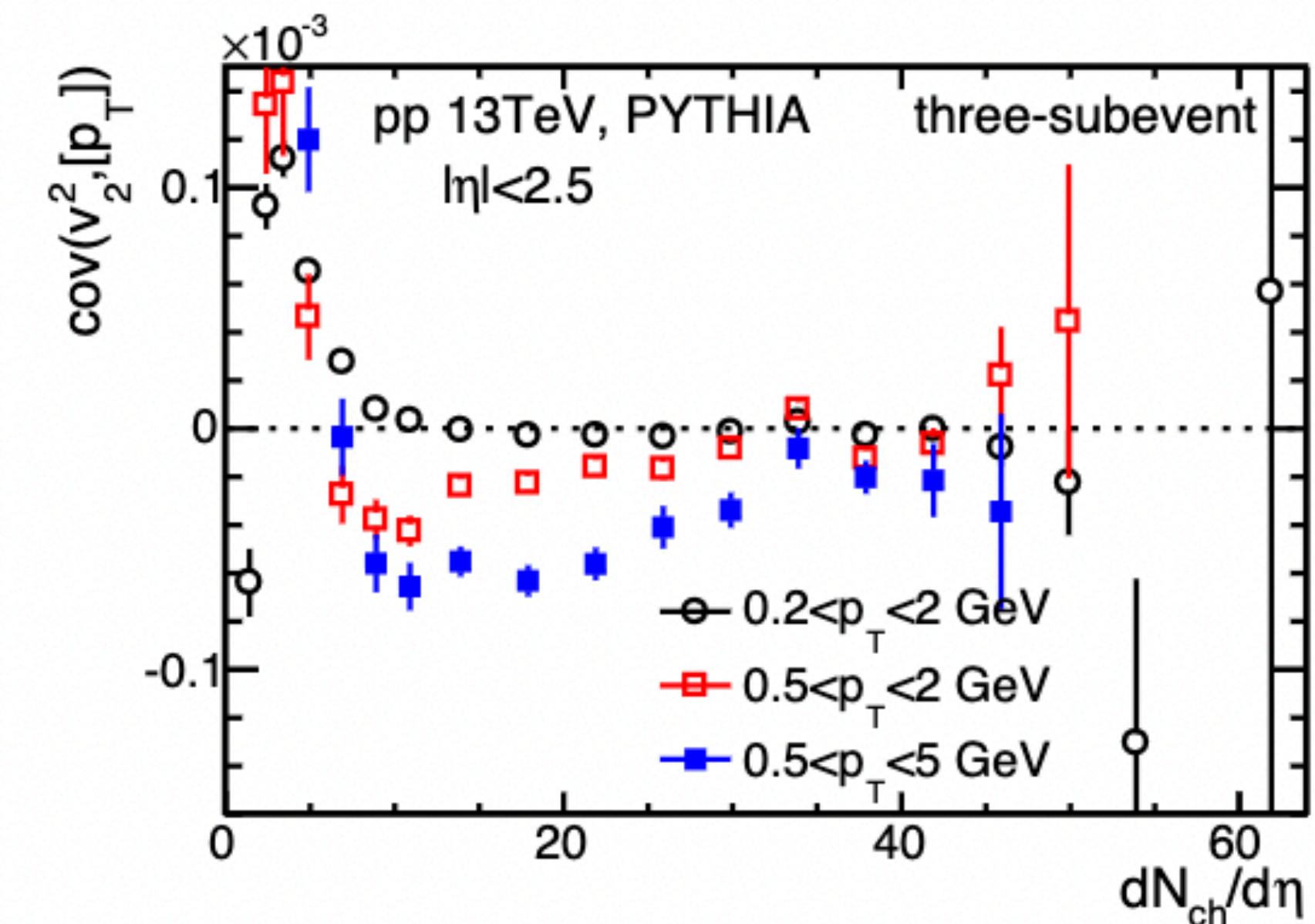
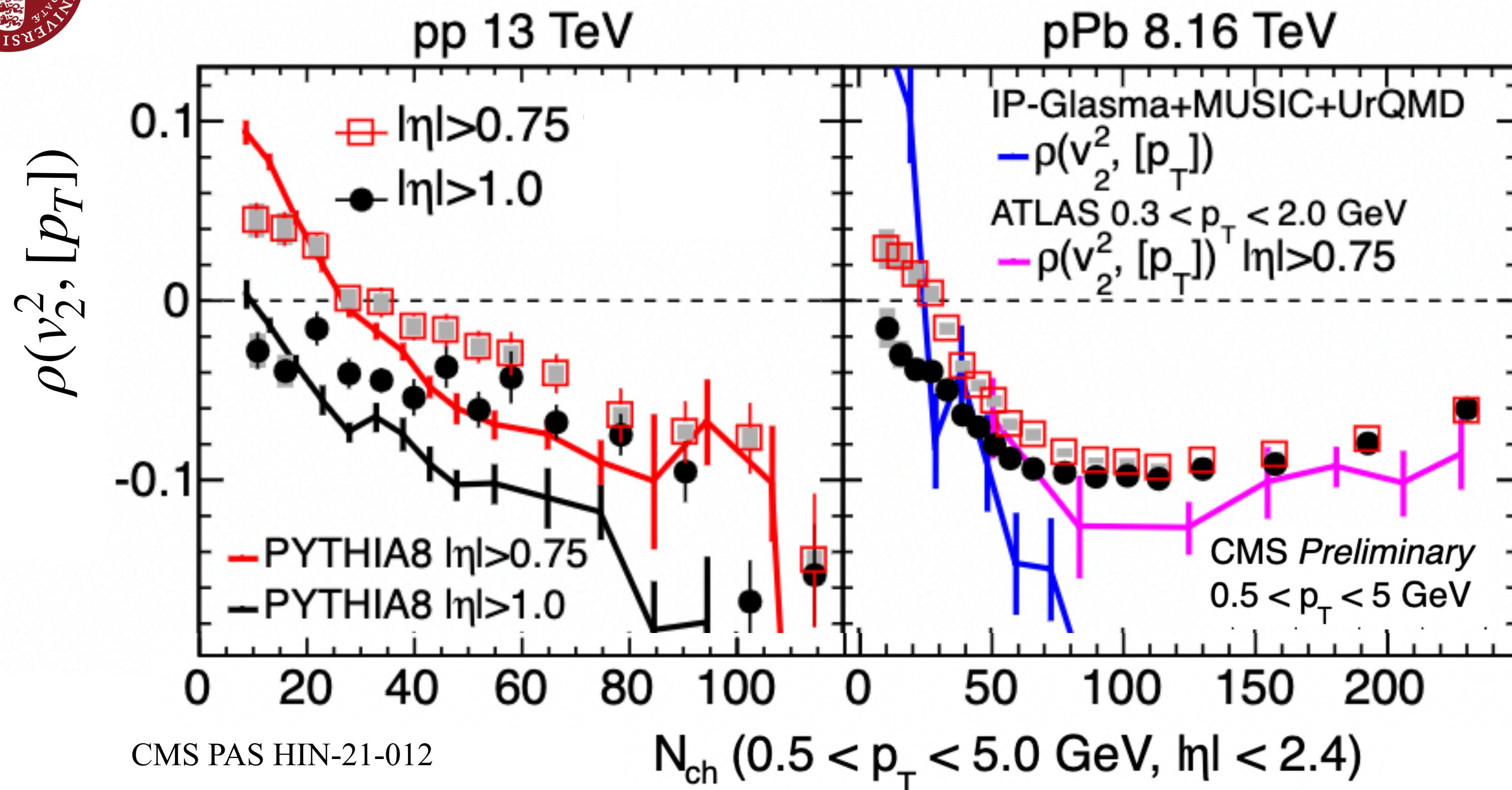


- $\rho(v_2^2, [p_T])$ changes sign with multiplicity in $p\text{-Pb}$ and pp at the LHC (CMS)
- No sign change in ALICE for pp !
- $\rho(v_2^2, [p_T])$ **is sensitive to the kinematic cuts??**



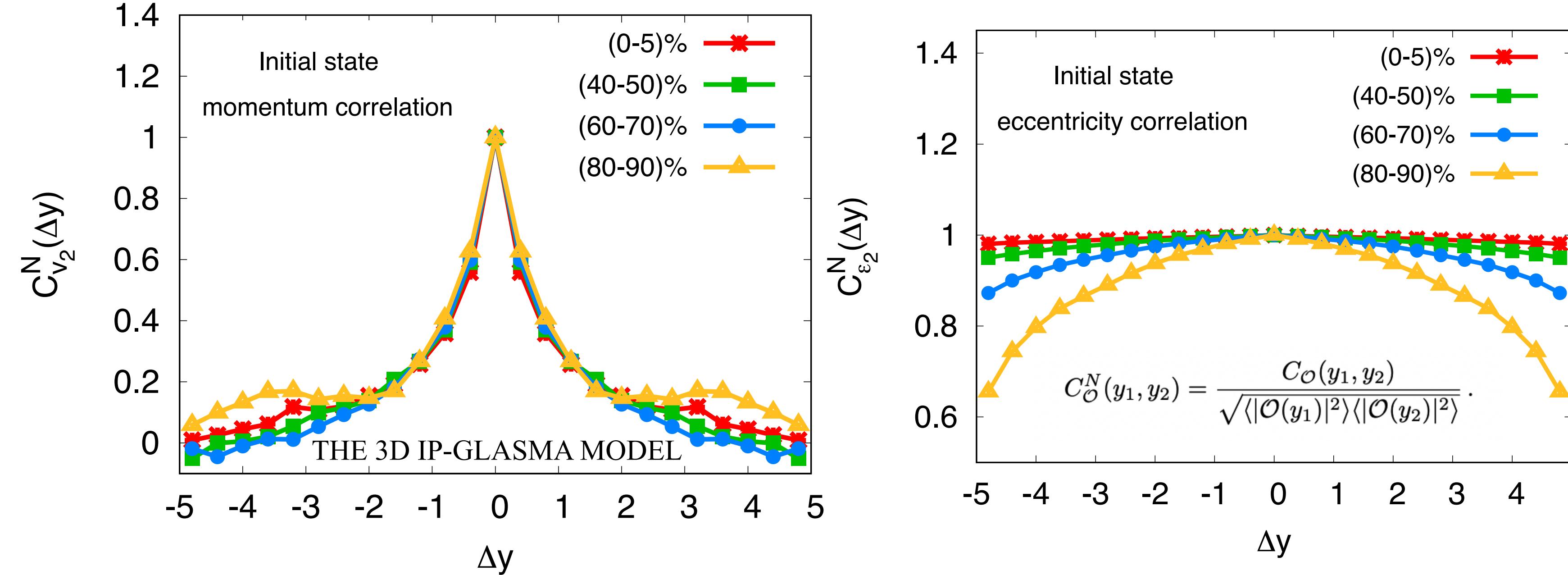


Not really...



Behera, Bhatta, Jia, Zhang, Phys Lett. B 822, 2021, 136702

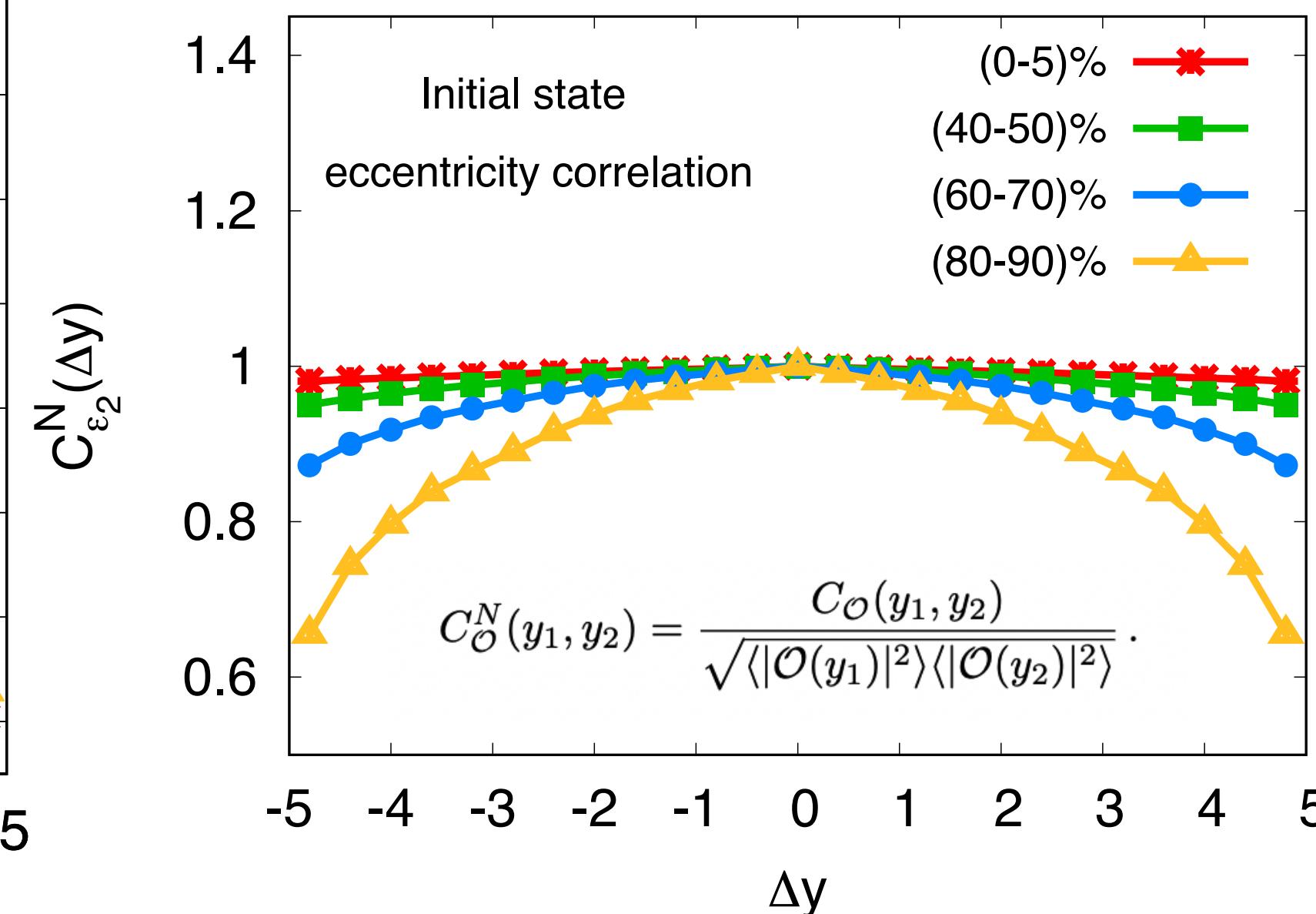
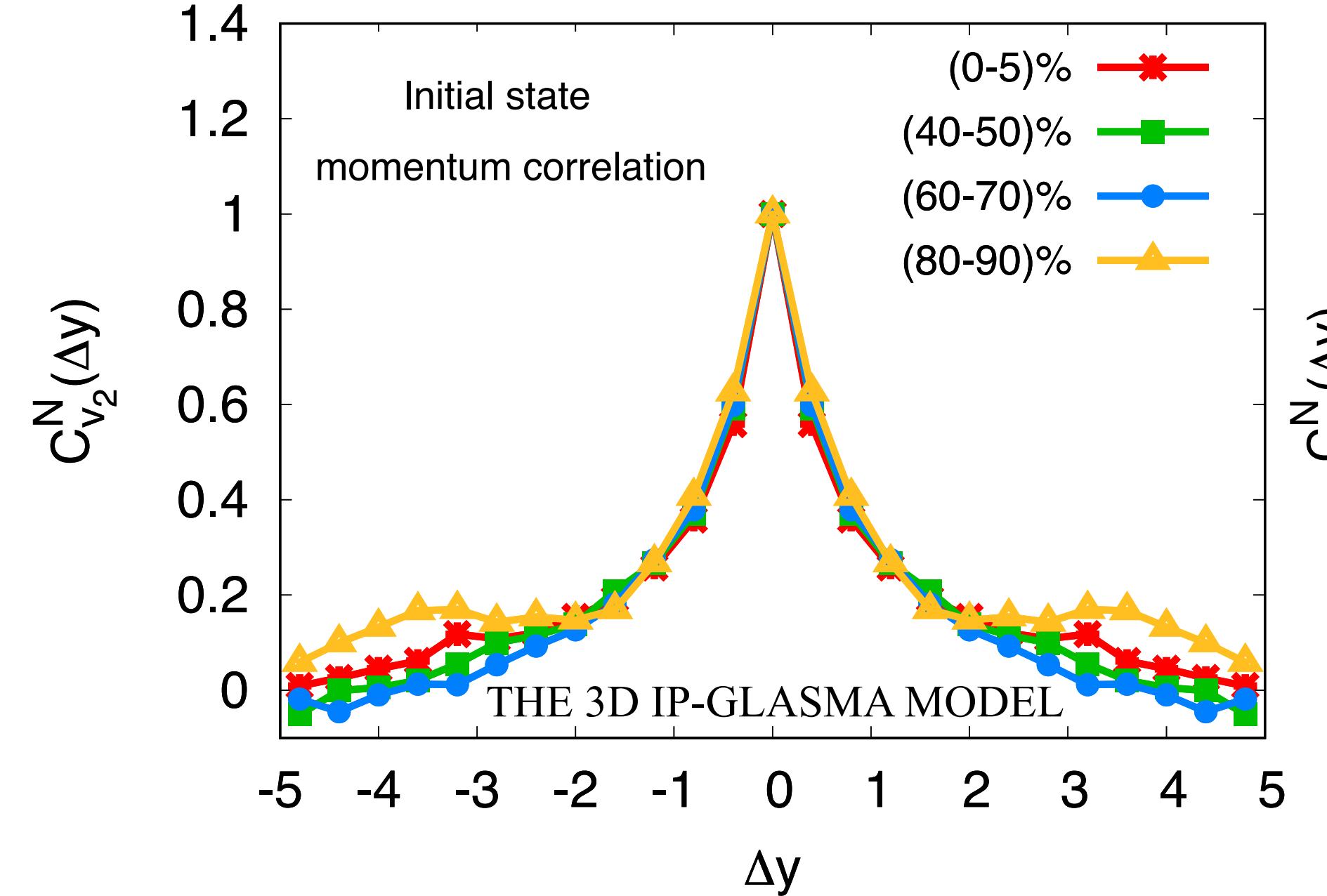
- $\rho(v_2^2, [p_T])$: Sign changes disappear with larger $|\Delta\eta| cut(> 2.0)$! Also, depends on p_T .
- PYTHIA generates similar pattern (similar to the IP-Glasma+MUSIC+UrQMD)! Lim, Nagle, Phys. Rev. C 103, 064906 (2021)
- Sign change in $\rho(v_2^2, [p_T])$ with multiplicity is not unique to the presence of initial momentum anisotropy?
- $\rho(v_2^2, [p_T])$ is sensitive to the kinematic cut...BUT not only for non-flow effects.



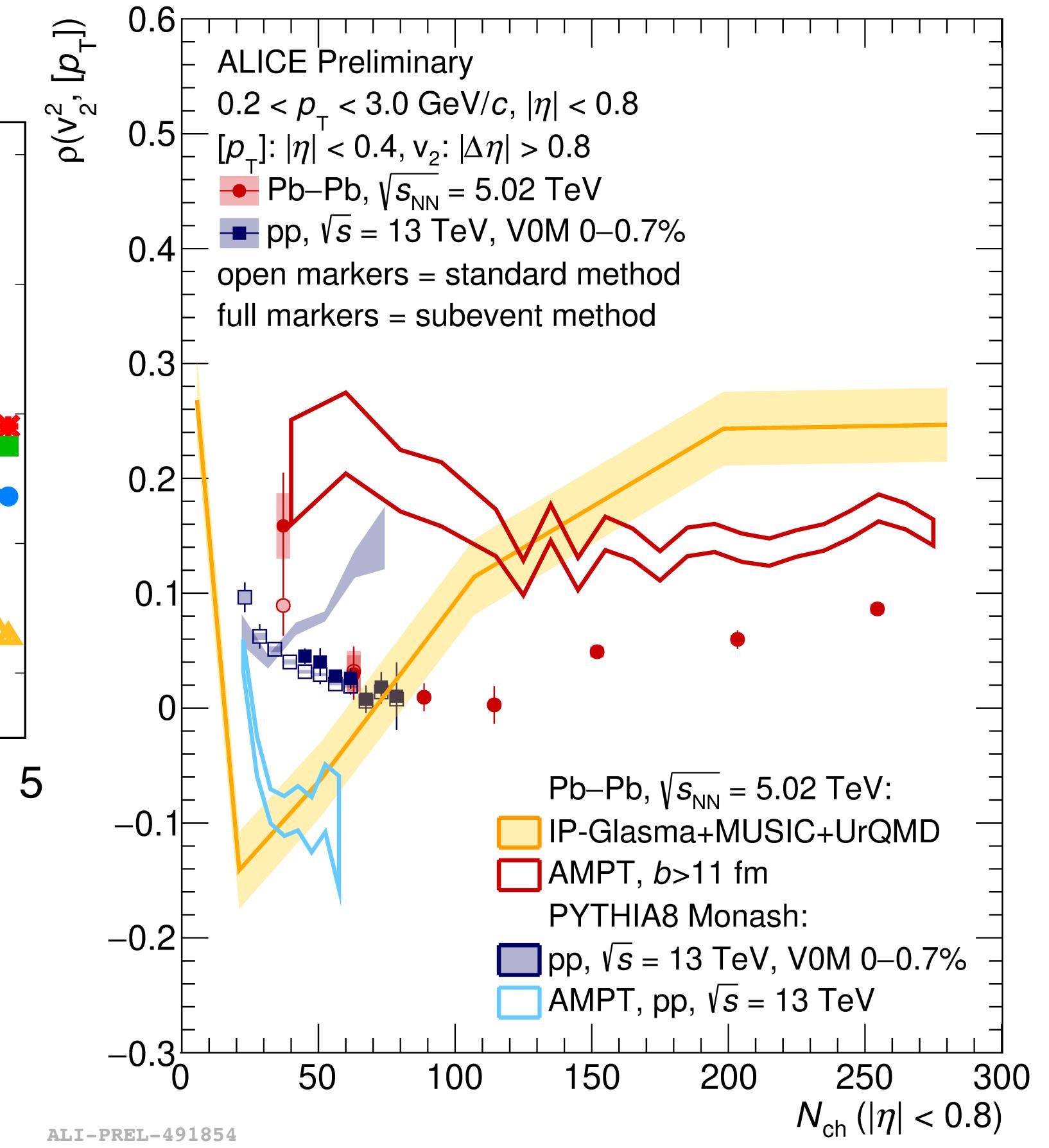
B. Schenke, S. Schlichting, P. Singh; Phys. Rev. D 105, 094023 (2022)

- Event geometry (transverse) – correlated across large rapidity intervals.
- Initial state momentum correlations – relatively short-range!
- $\rho(v_n^2, [p_T])$: constructed from long range correlations to suppress non-flow (jets, resonance etc).

Perhaps looking at a wrong place...



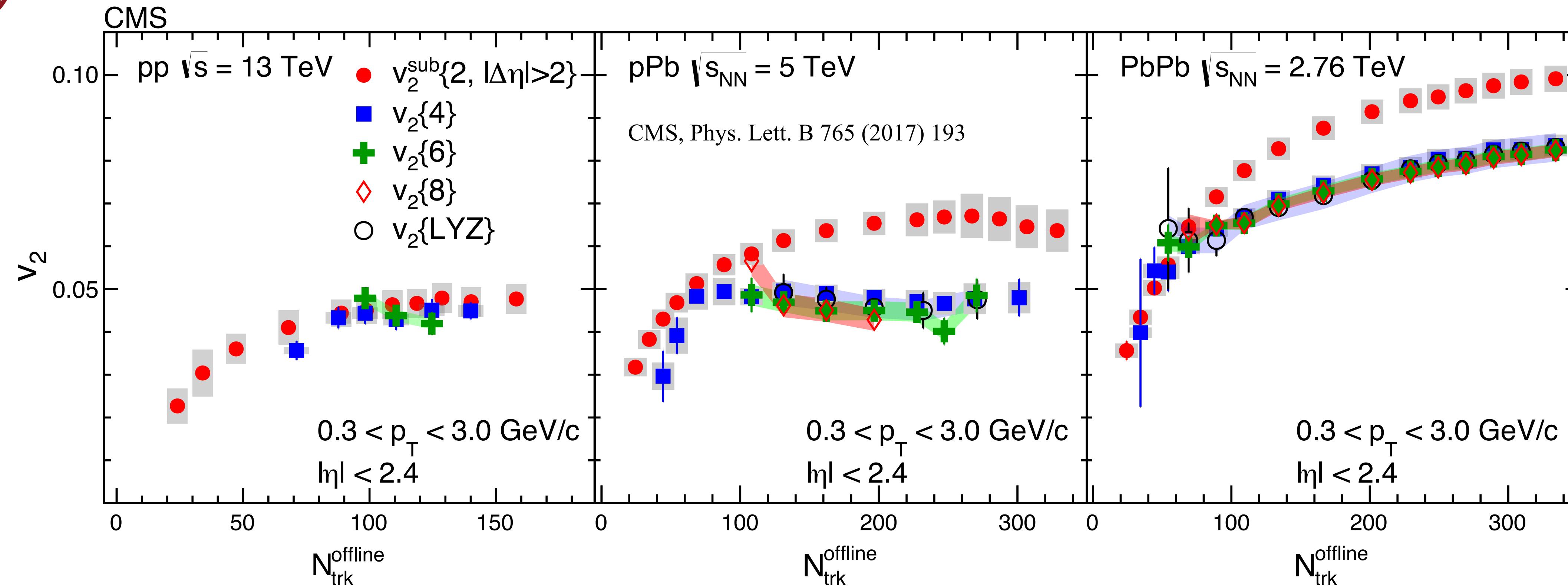
B. Schenke, S. Schlichting, P. Singh; Phys. Rev. D 105, 094023 (2022)



- Event geometry (transverse) – correlated across large rapidity intervals.
- Initial state momentum correlations – relatively short-range!
- $\rho(v_n^2, [p_T])$: constructed from long range correlations to suppress non-flow (jets, resonance etc).
- **Challenge (Exp): Construct short range correlations with effective non-flow suppression?**
- **Challenge (Theory): Is there a better way to probe the initial state momentum anisotropy?**



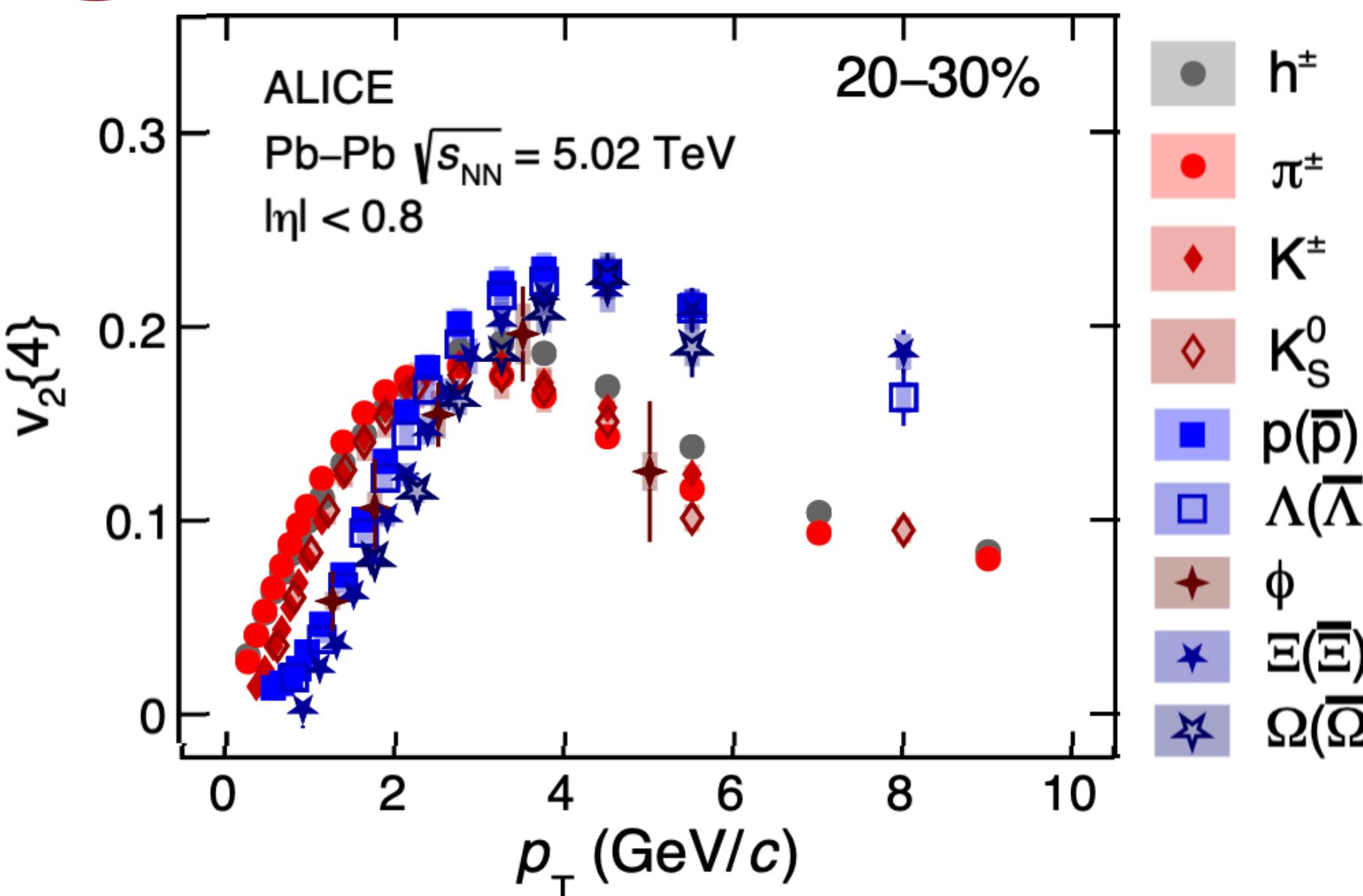
Never mind, Let's turn the tables



- Qualitative similarity between small systems and heavy-ion collisions.
- We can learn about the small systems from identified particle spectra, and flow measurements.
- **Baseline: Heavy-ion Collisions (check the similarity and differences).**



Flow of Identified particles



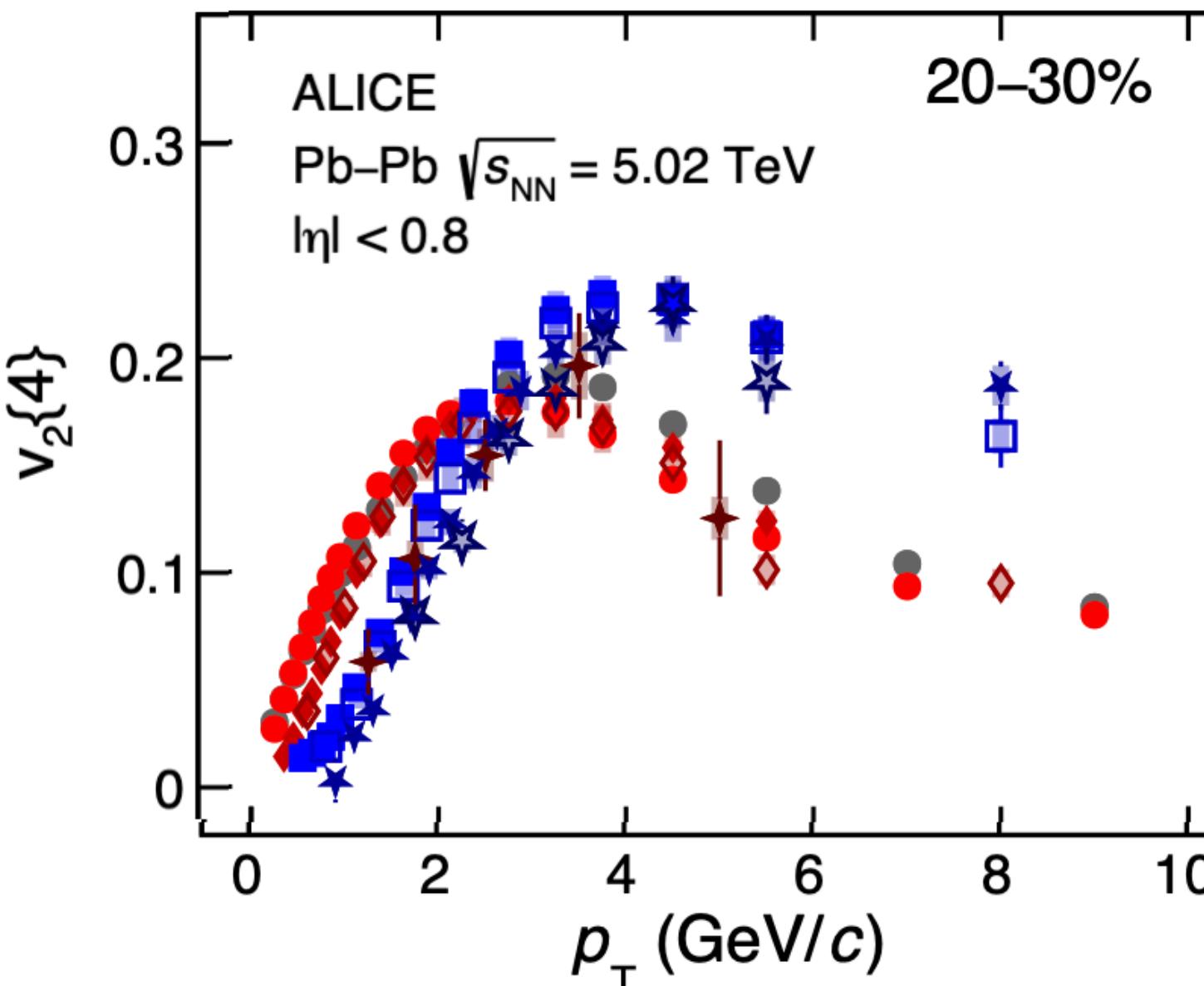
ALICE, JHEP 243 (2023) 243

- low p_T ($p_T \lesssim 3 \text{ GeV}/c$) – Mass ordering – Interplay between radial and elliptic flow, described by hydrodynamics
- Intermediate p_T ($3 < p_T \lesssim 10 \text{ GeV}/c$) – NCQ driven Baryon-meson splitting and grouping – partonic collectivity, hadronization via quark coalescence (ϕ plays an important role)

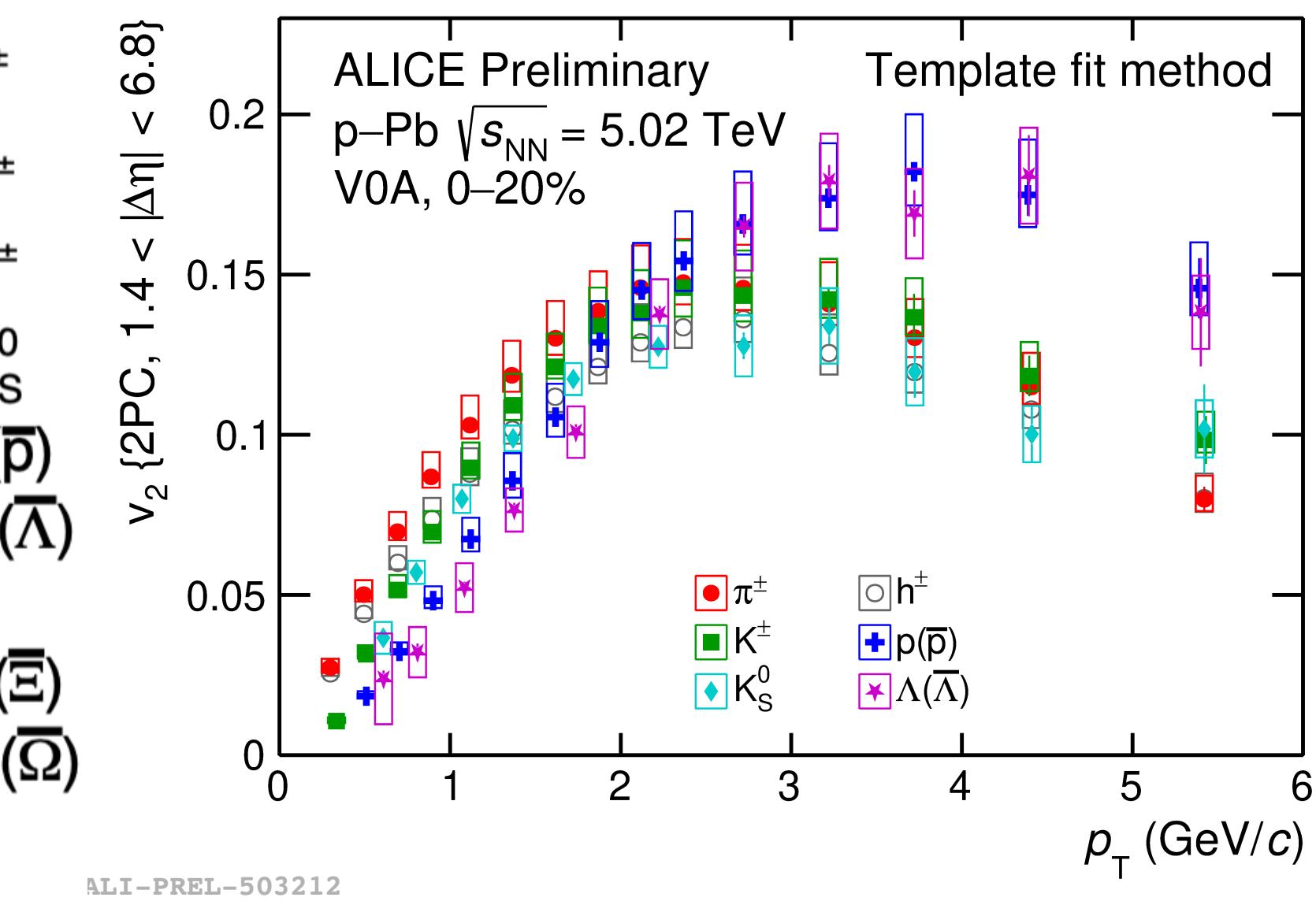
- What about small systems?



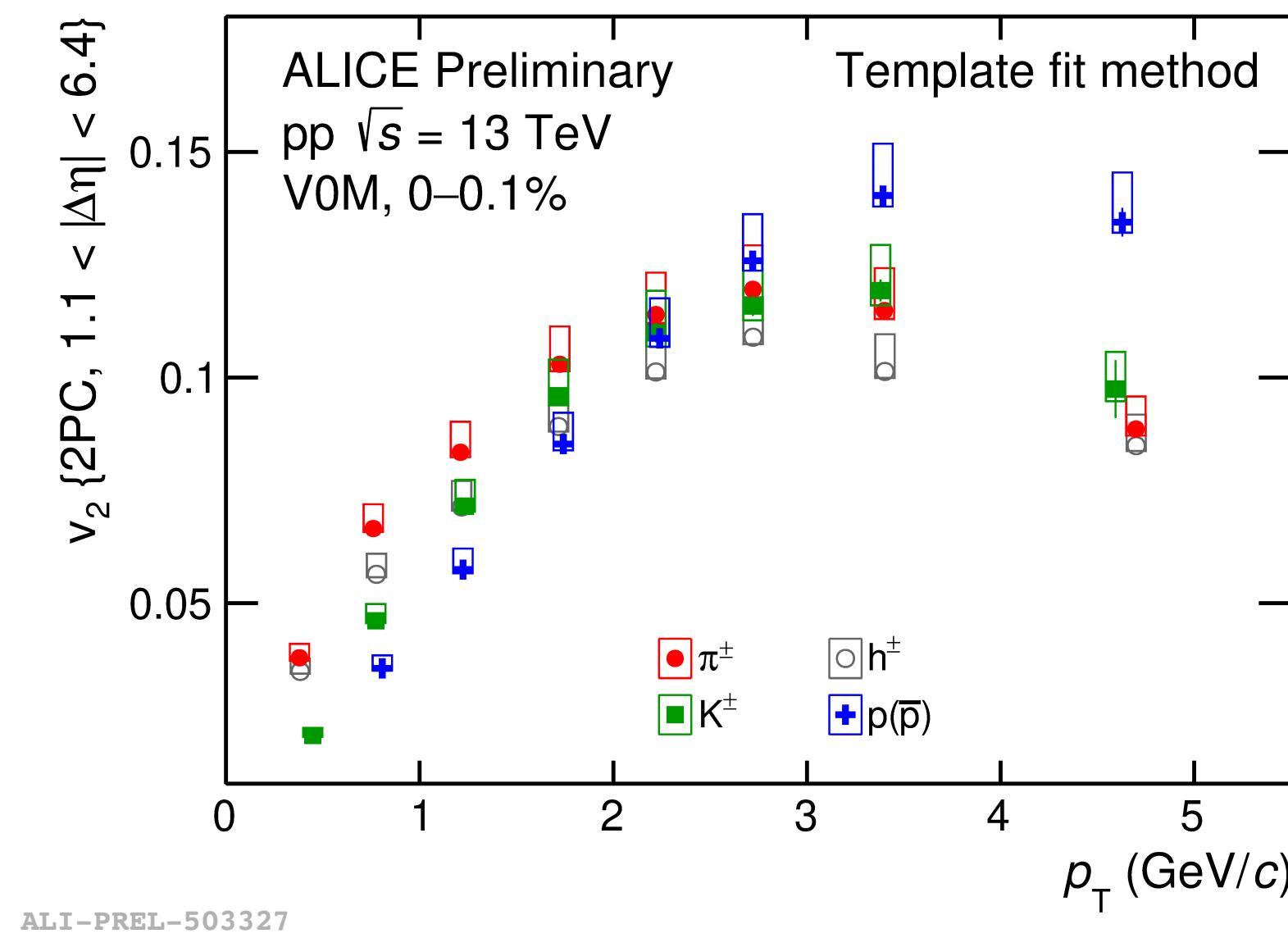
Flow of Identified particles



ALICE, JHEP 243 (2023) 243



ALI-PREL-503212



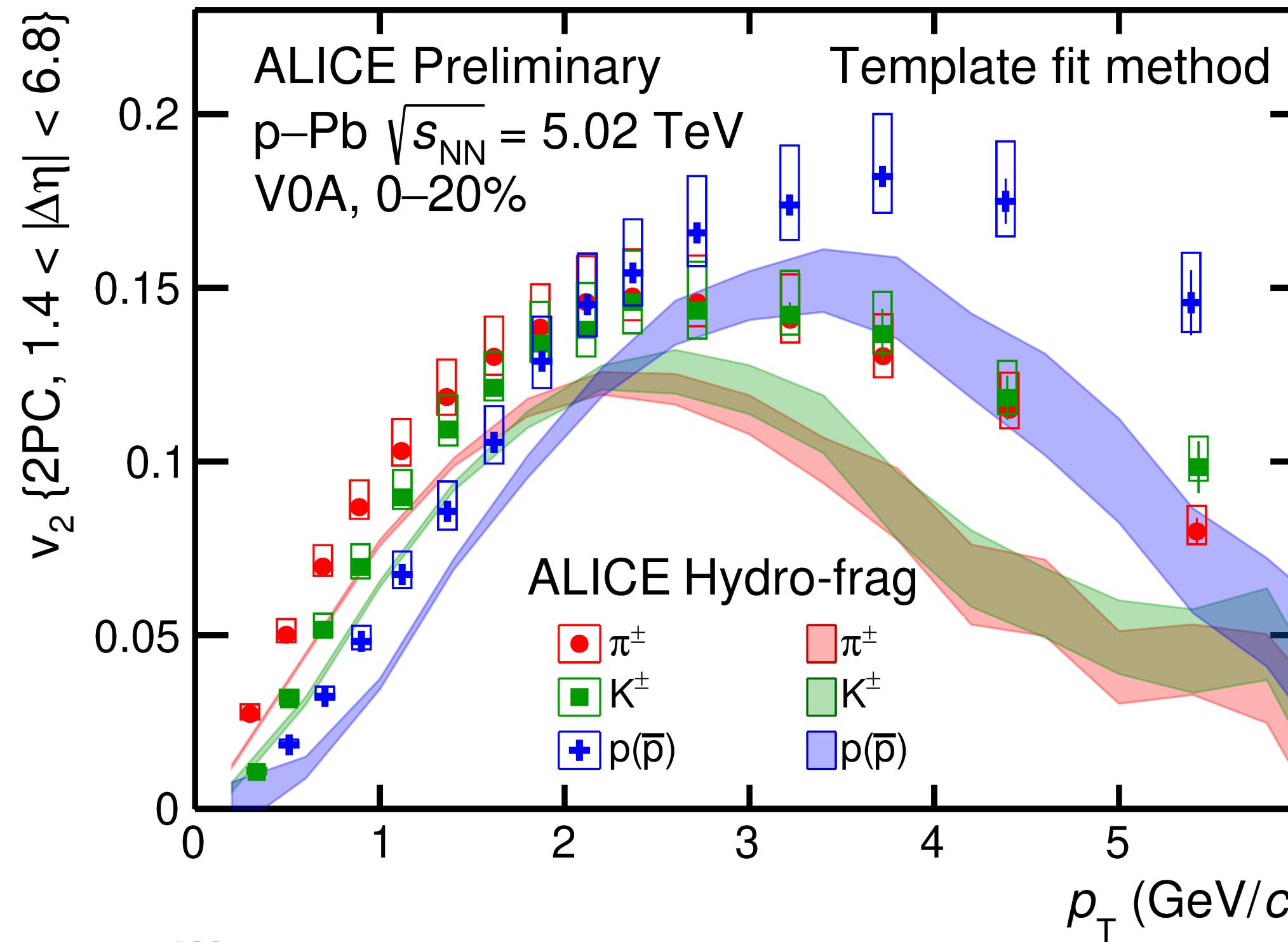
ALI-PREL-503327

Wenya Wu
Wed: 14.00

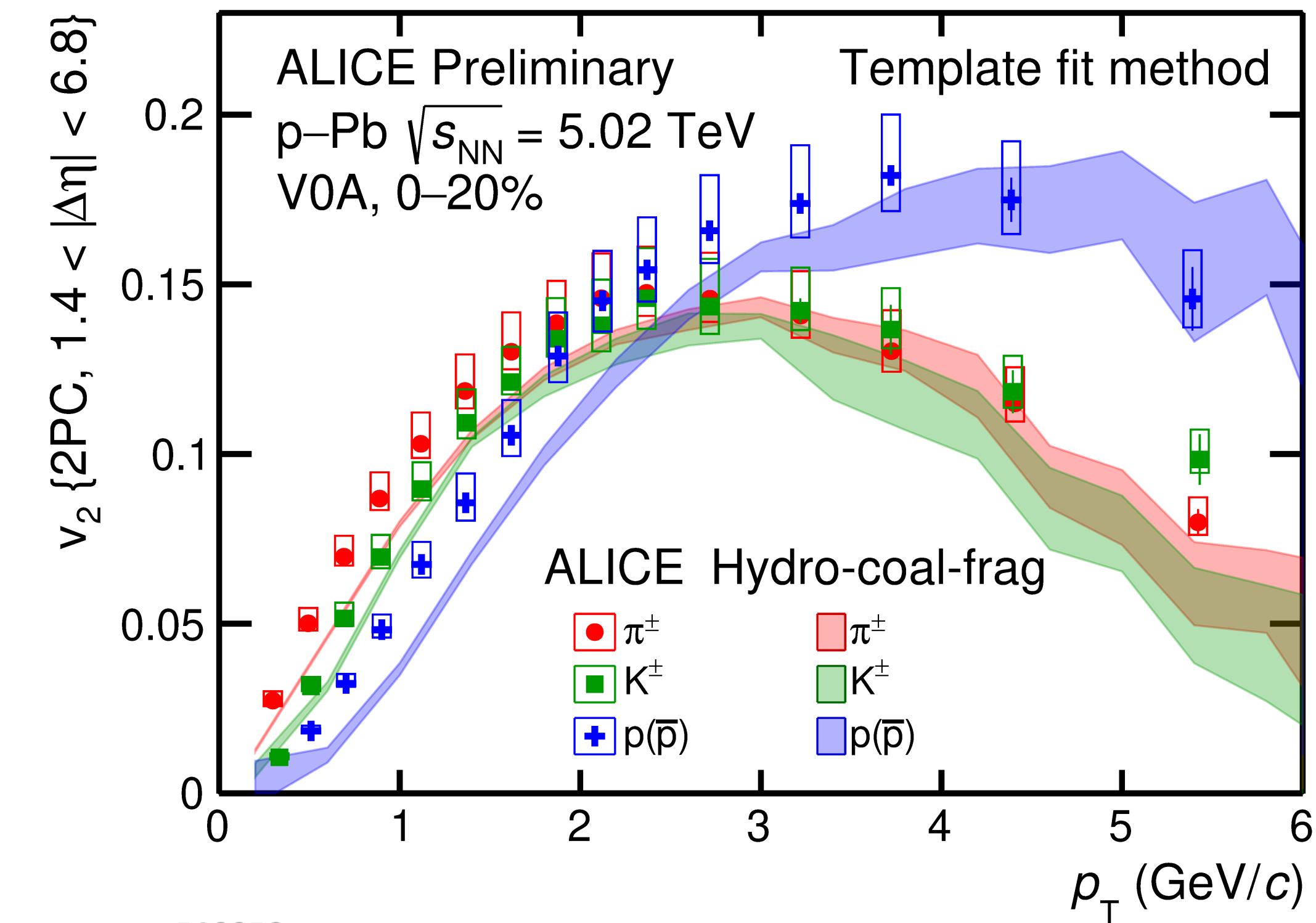
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- Intermediate p_T ($3 < p_T \lesssim 10$ GeV/c) – NCQ driven Baryon-meson splitting and grouping – partonic collectivity, hadronization via quark coalescence (ϕ plays an important role)
- Small systems: Qualitatively similar to the heavy-ion results (ϕ will add more to this picture).
 - Any model comparison?



Partonic flow in high multiplicity p-Pb collisions!



ALI-PREL-503277



ALI-PREL-503272

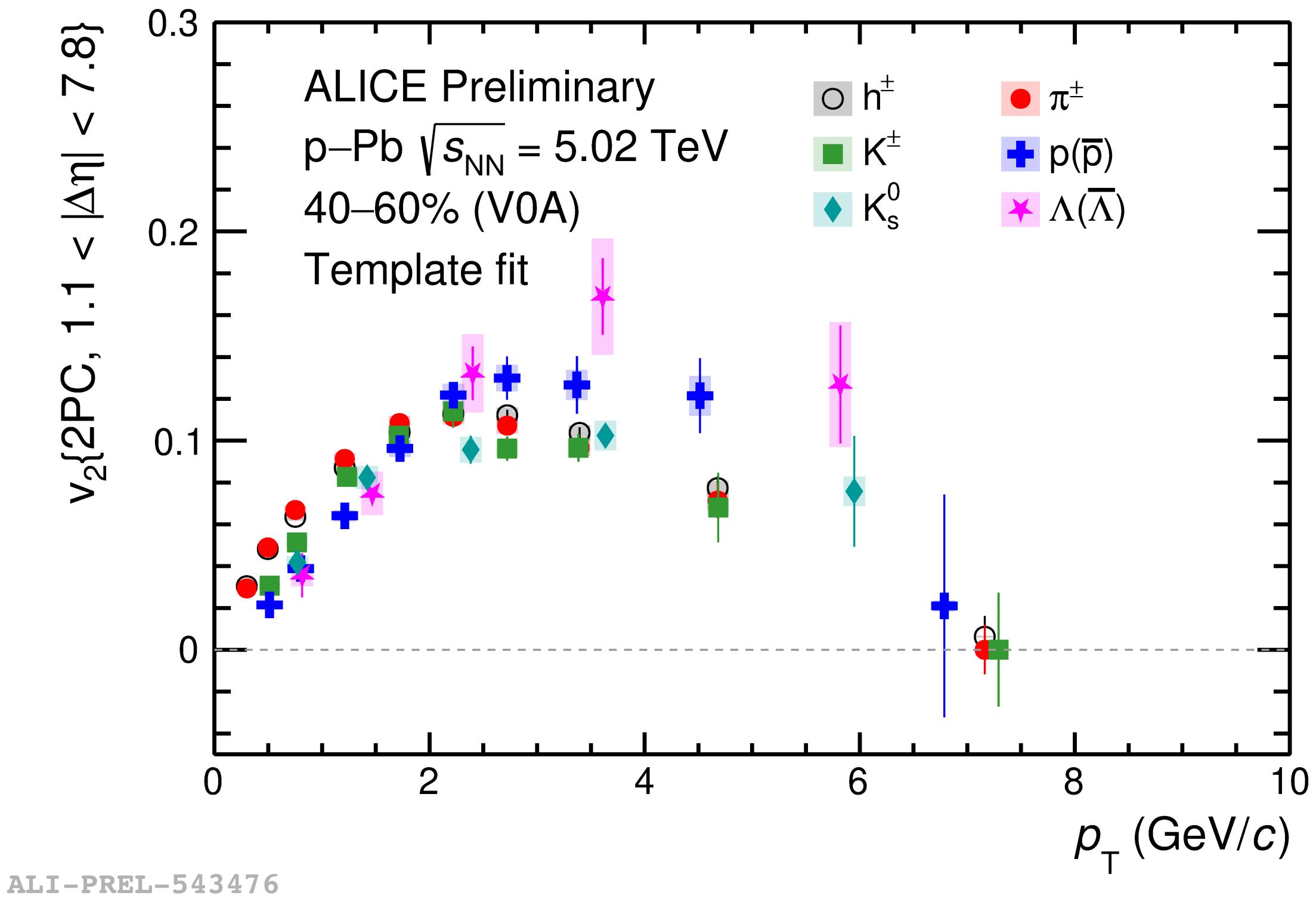
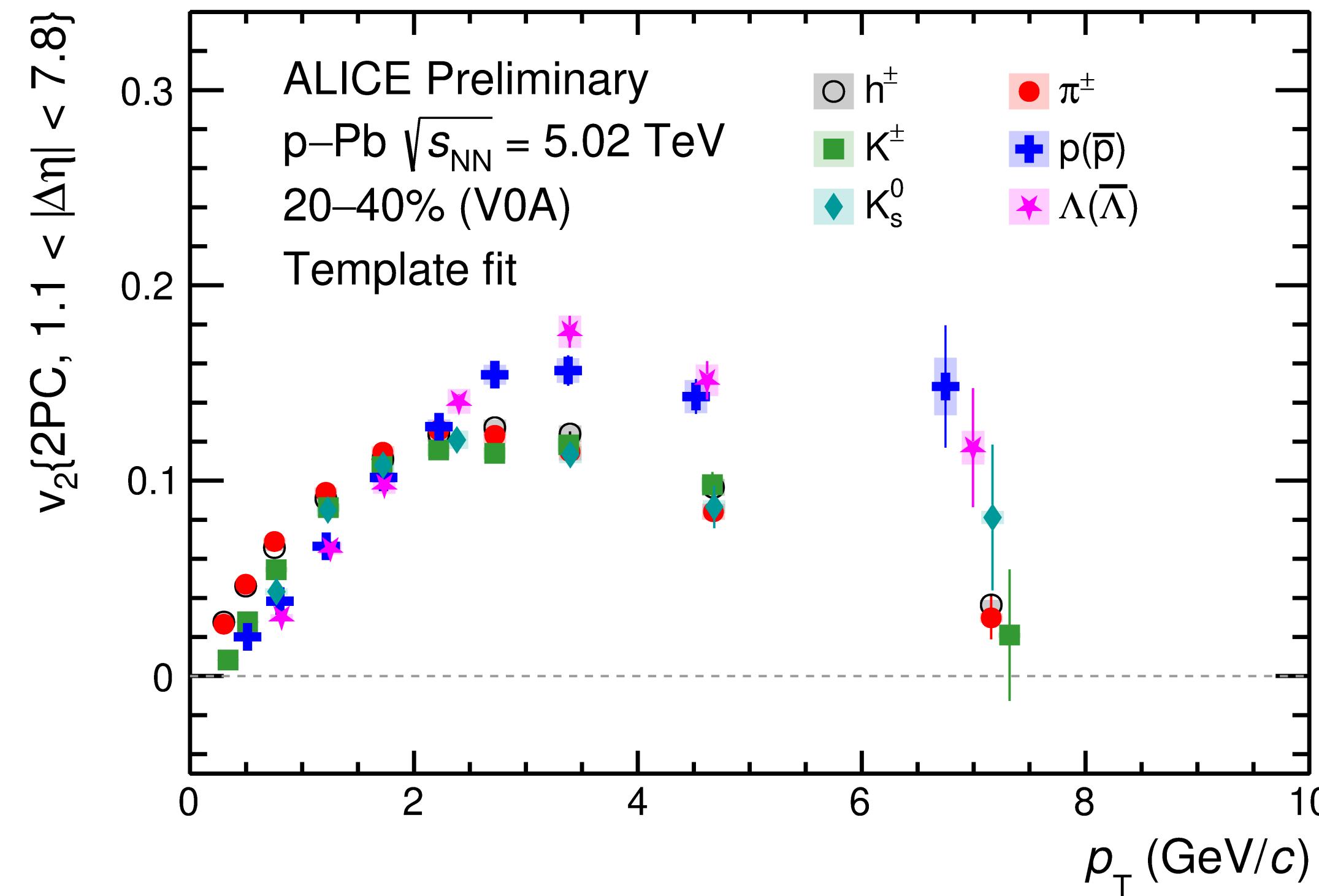
- Small systems: Qualitatively similar to the heavy-ion results (ϕ will add more to this picture).
- For p-Pb: Hydro+Coal+Frag can explain the pattern but not with Hydro+Frag only.
- Partonic collectivity in high multiplicity p-Pb collisions!
 - Need model input for pp

Wenya Wu
Wed: 14.00

Huichao Song
Wed: 15.20



Still flowing?

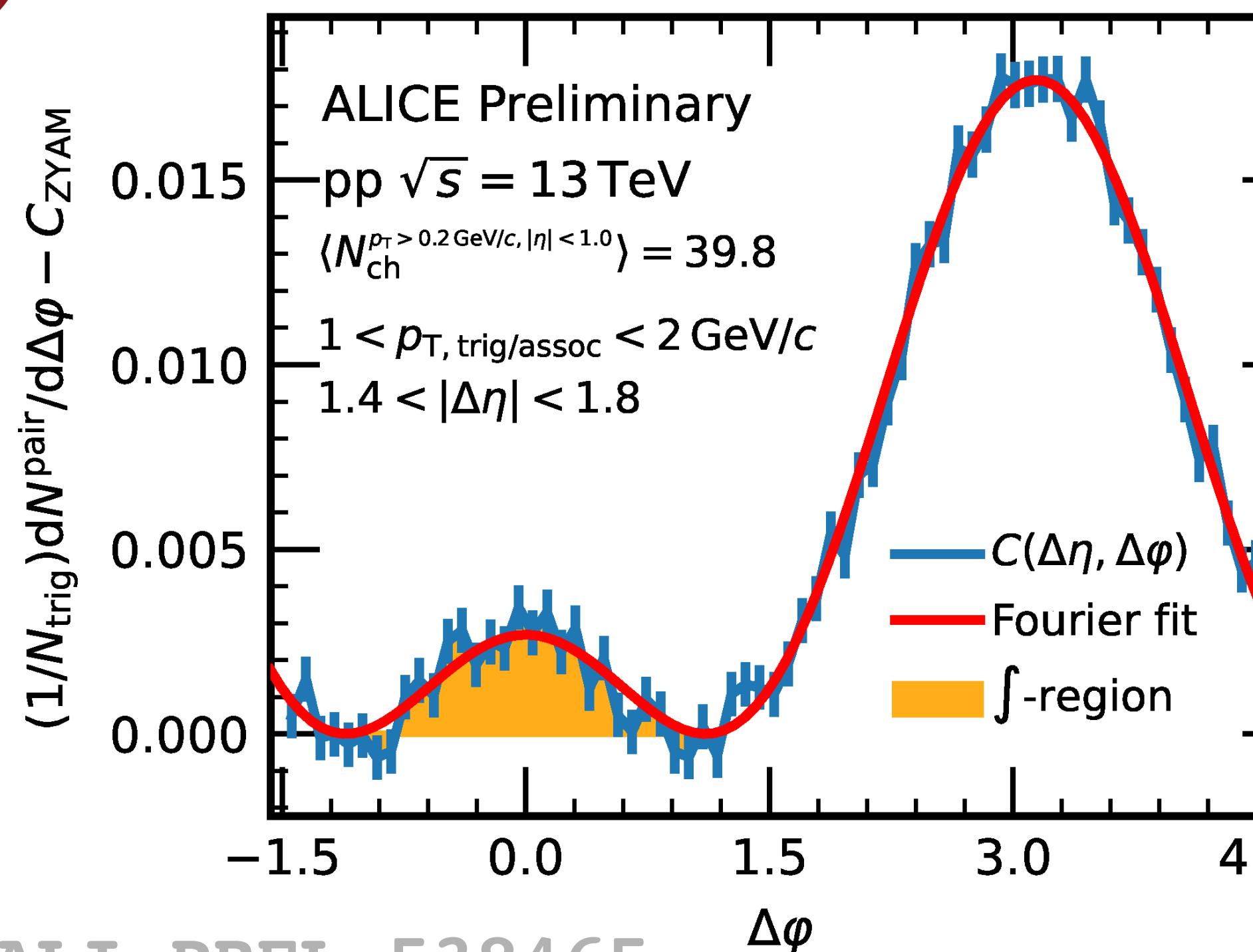


ALI-PREL-543472

- Mass ordering and Baryon-meson splitting and grouping exists upto lower multiplicity classes of p-Pb!
- Need multiplicity evolution results from pp for more insights.
- Can any model(s) explain the small system results over all the multiplicity classes?
- Initial state effects can be probed in low multiplicity classes?
 - **What is the “small” (pA, pp, ee...) and “dilute” (lower multiplicity) limit of onset of collectivity?**

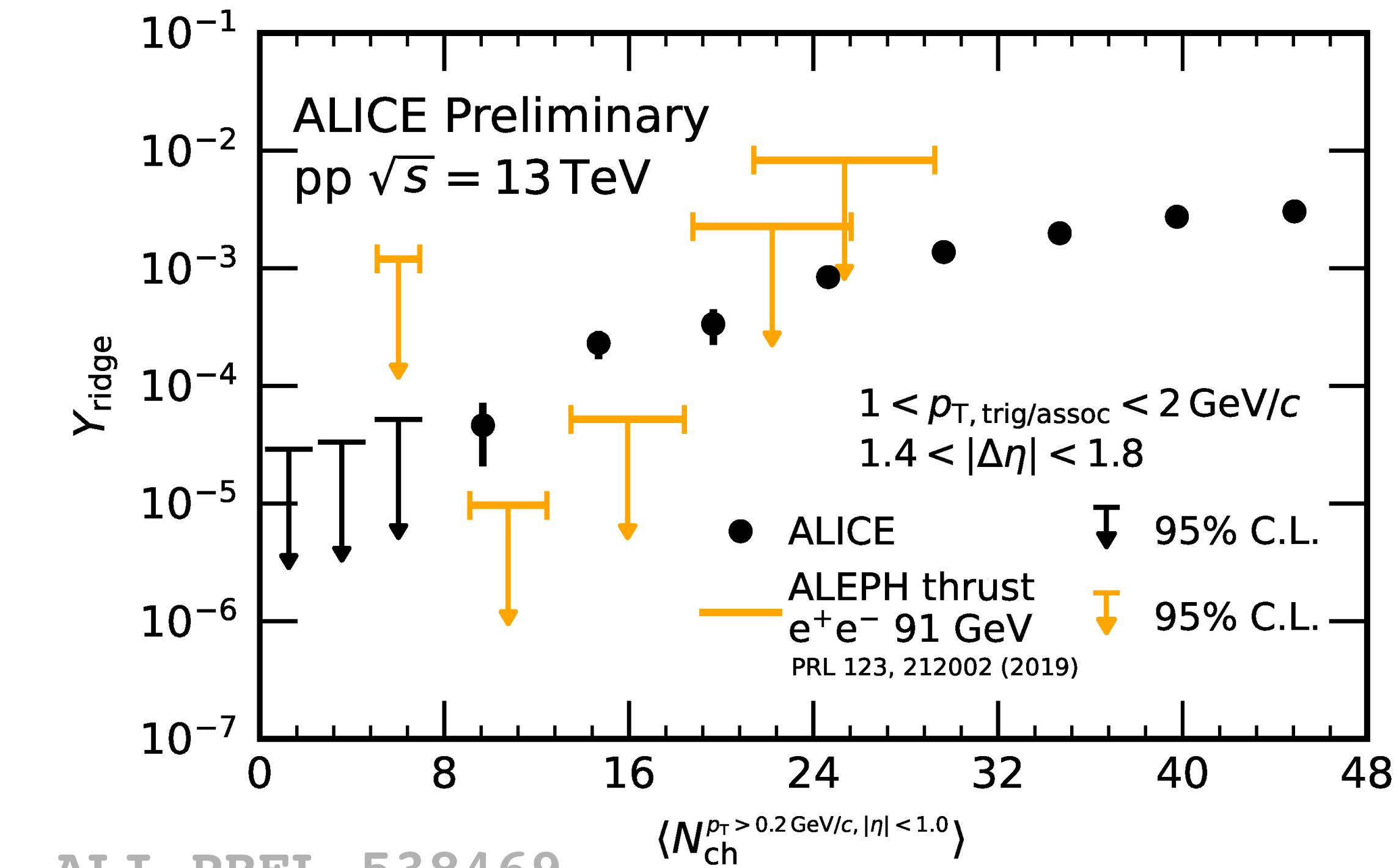


What is the small and dilute limit for collectivity?

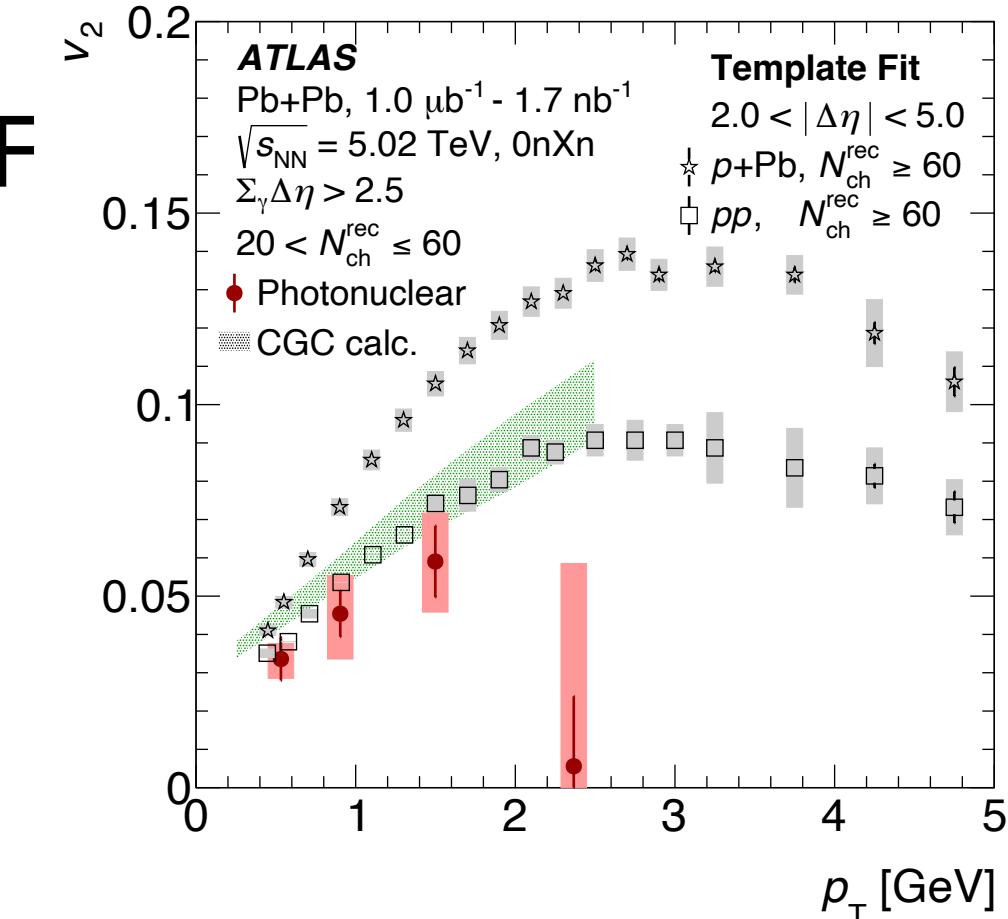


ALI-PREL-538465

- e^+e^- collisions – point-like collision – no uncertainties on initial geometry or PDF description.
- No significant long range correlation in e^+e^- collisions.
- Ridge Yield: $Y_{pp} > Y_{e^+e^-}$ at $\langle N_{\text{ch}} \rangle \sim 15$ with 3sigma.
- Initial state physics (Also look at the UPC)?



ALI-PREL-538469

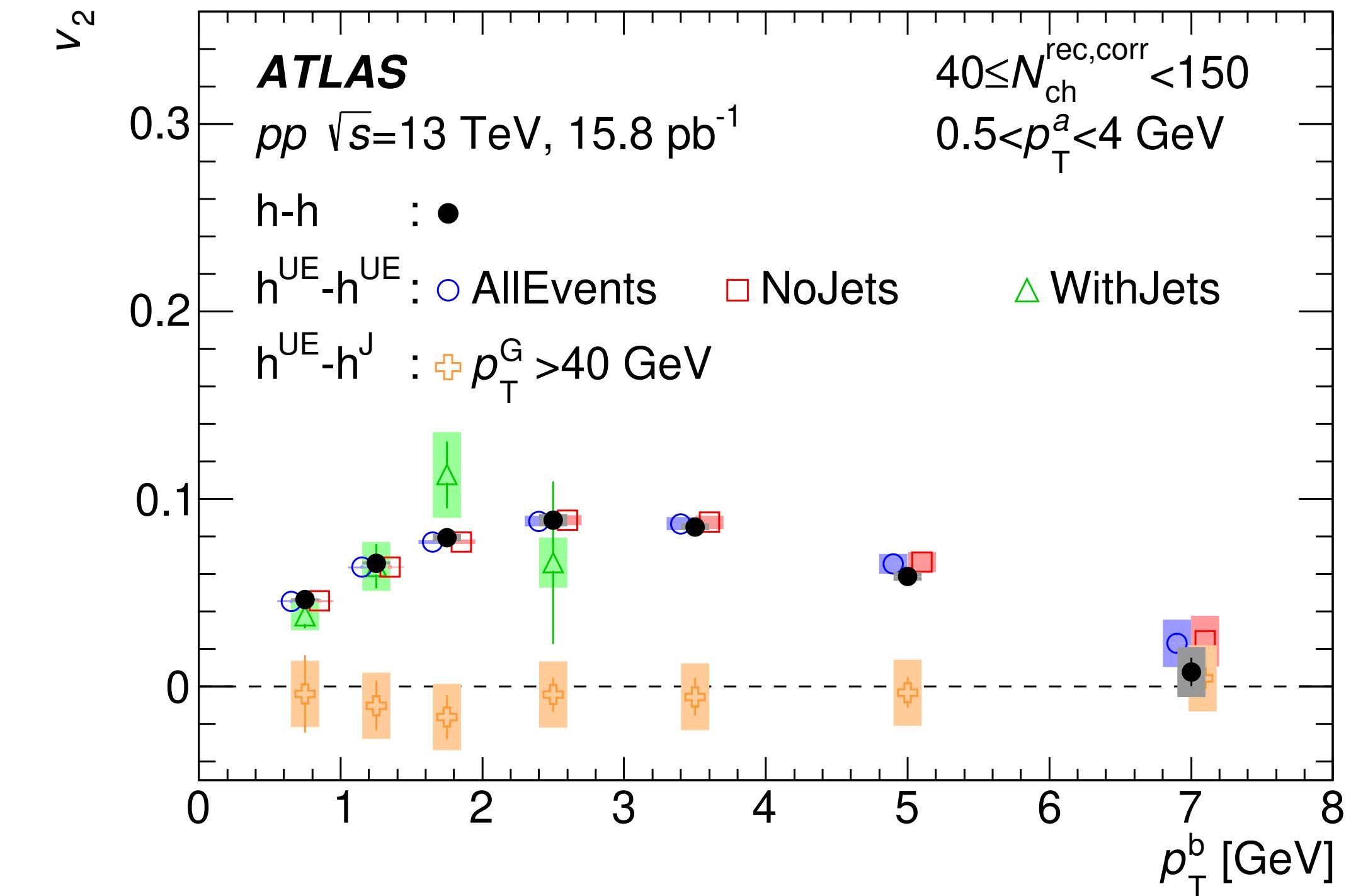
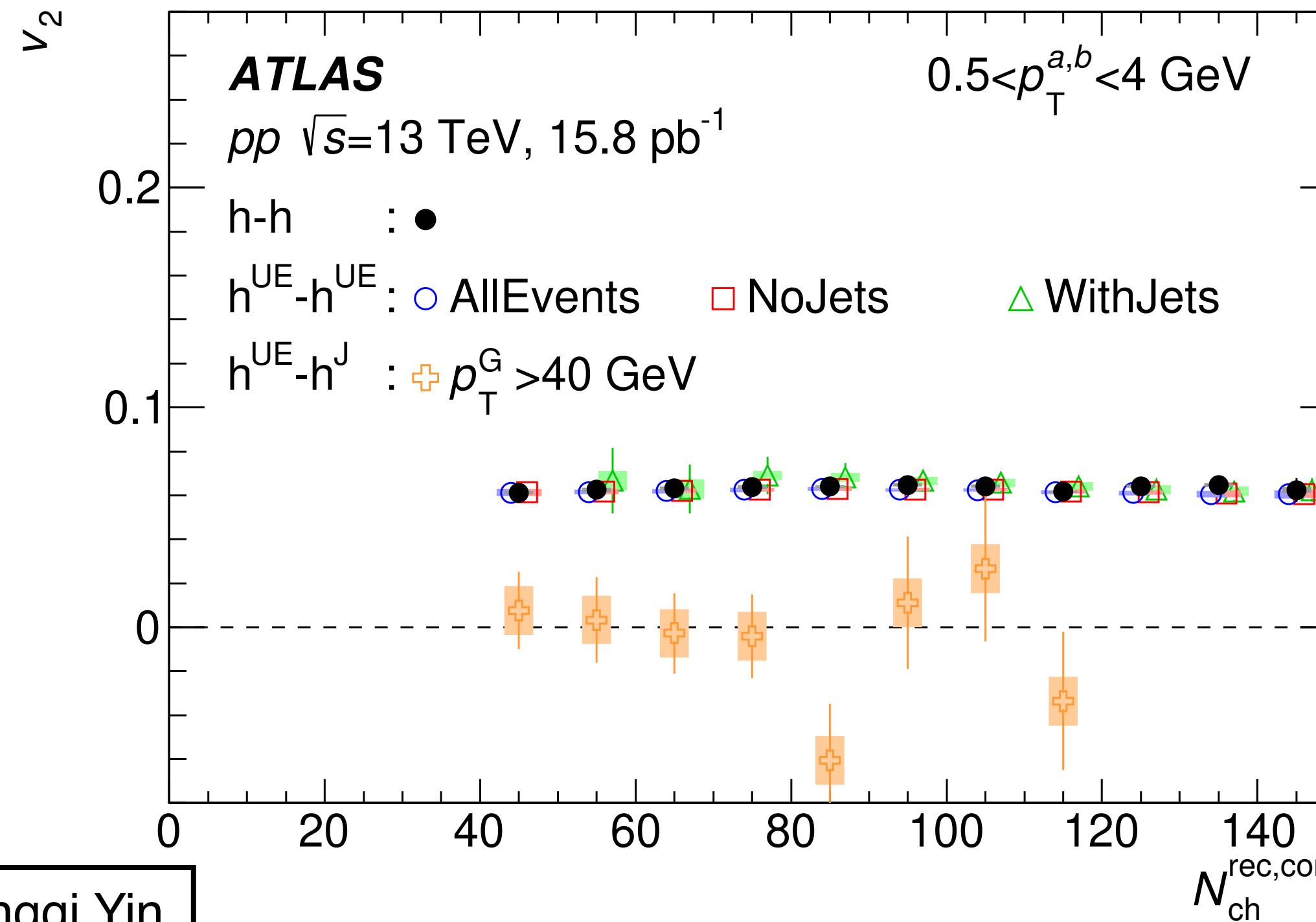


Details on next talk: by Yen-Jie Lee

ATLAS, Phys. Rev. C 104, 014903 (2021)



Hard-soft interplay in small systems (pp)



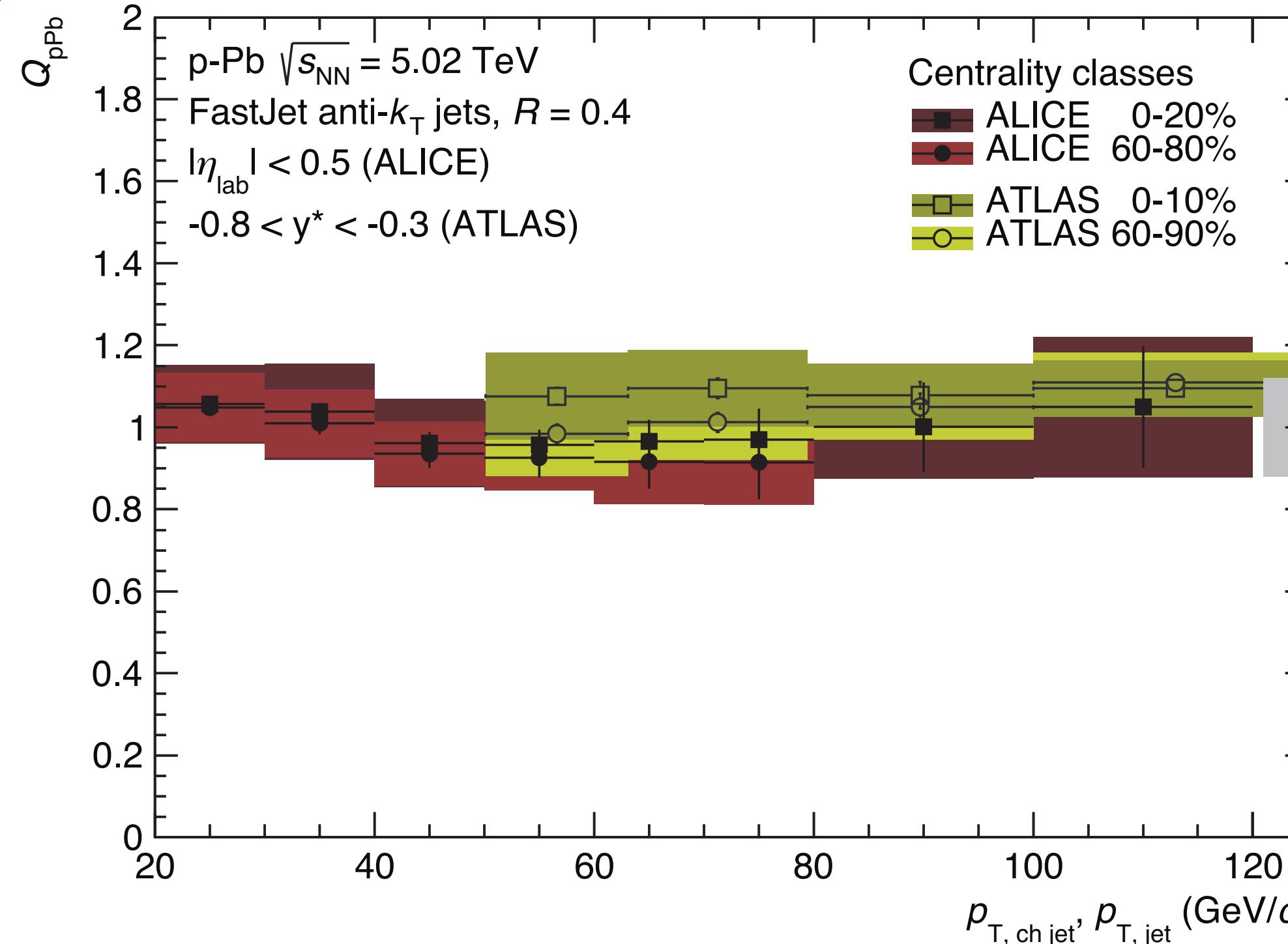
Pengqi Yin
Wed: 16.50

ATLAS, arXiv:2303.17357v1[nucl-ex]

- The v_2 of Underlying Event (UE) is not influenced by the presence or absence of jets with $p_T^G > 15 \text{ GeV}$
- The tracks from jets are not correlated with tracks in UE. v_2 of jet-constituents is consistent with zero
- System size is too small to influence jets? Different scenario compared to p-Pb ?
- Any theoretical model input?



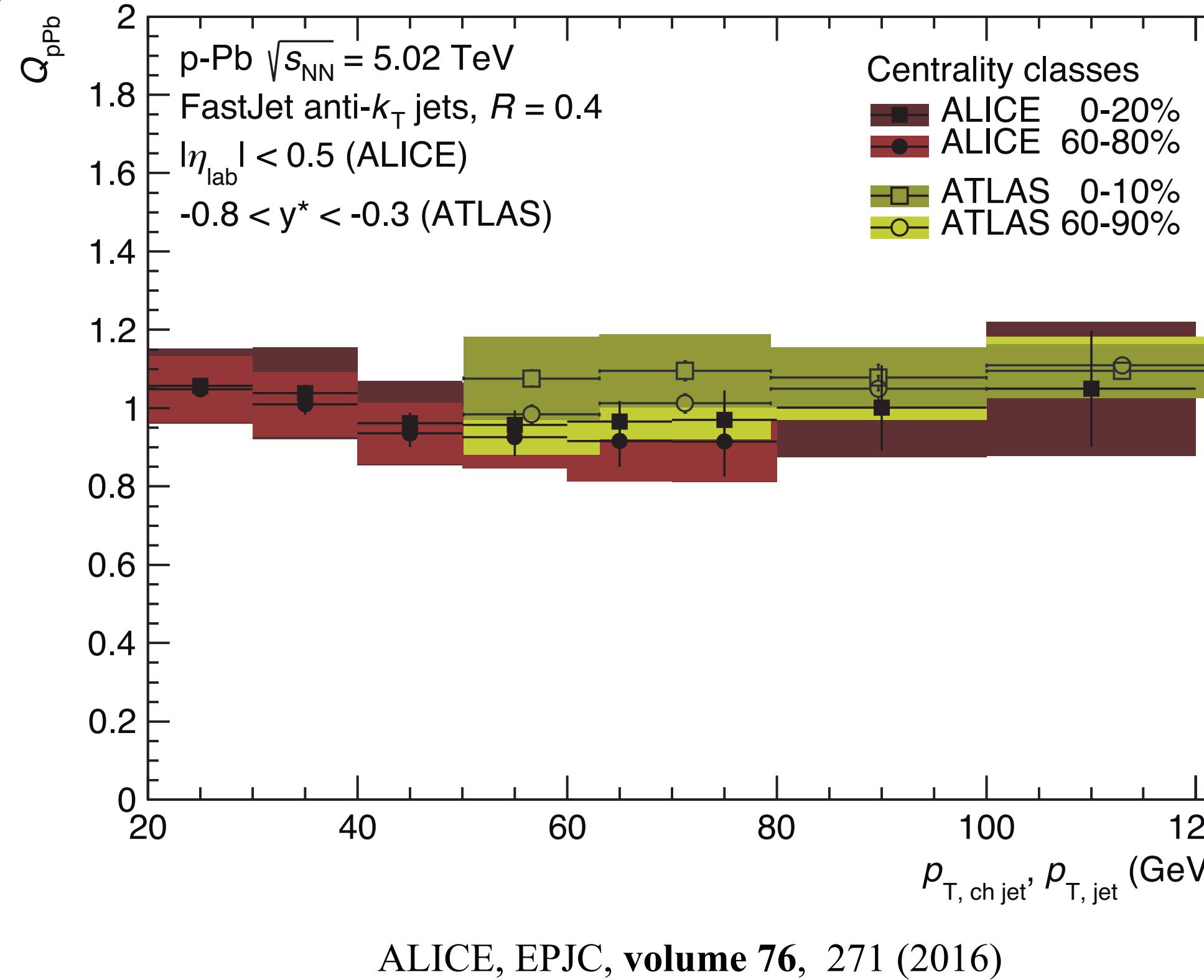
Hard-soft interplay in small systems(pPb)



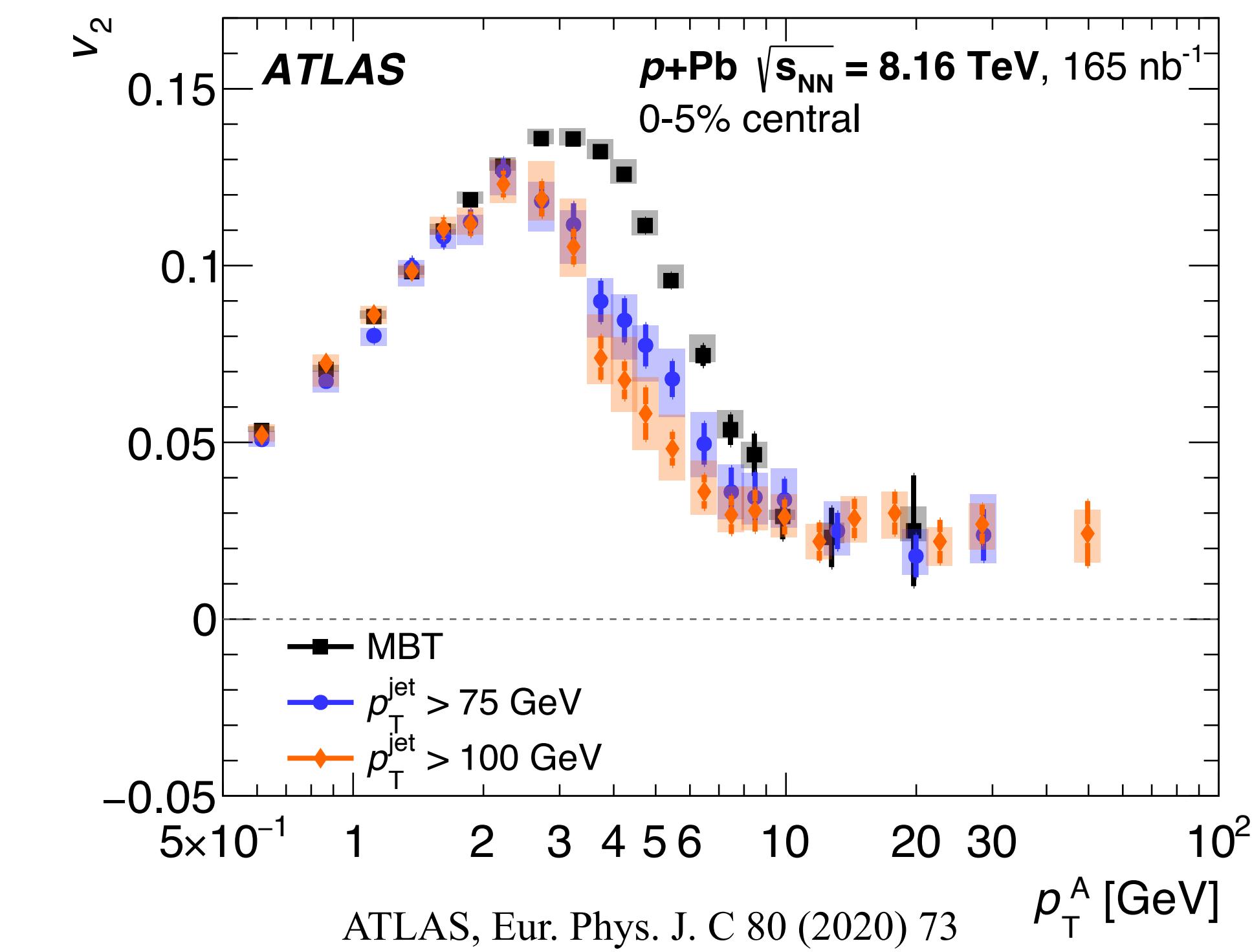
ALICE, EPJC, volume 76, 271 (2016)

- No significant jet-quenching in p-Pb collisions

Hard-soft interplay in small systems(pPb)



ALICE, EPJC, volume 76, 271 (2016)



ATLAS, Eur. Phys. J. C 80 (2020) 73

- No significant jet-quenching in $p\text{-Pb}$ collisions.
- For $p_T < 2 \text{ GeV}$, No modification of v_2 with jet-biasing. Consistent with hydrodynamic estimation.
- For $p_T 2\text{-}9 \text{ GeV}$. Jet biased v_2 is less compared to min-bias.
- Biased event section? Hard-soft interplay??
- Different than pp results. Need proper comparison.



Summary

- Small systems: Indication of partonic collectivity in high multiplicity classes of small systems!
- Need to understand the evolution with multiplicity - need more theoretical input.
- Non-flow subtraction, longitudinal flow decorrelation to be understood in detail for correct interpretation of the experimental results.
- Initial state effects are important (sub-nucleonic fluctuations + pre-flow+ momentum anisotropy + ? + ?). The correct combination is still in making.
- Initial state momentum anisotropy is relatively short range (in rapidity) compared to initial geometry - hard to probe experimentally - any new idea?
- The onset of collectivity is not yet established. High statistics dataset for low multiplicity pp collisions, UPC would be useful.

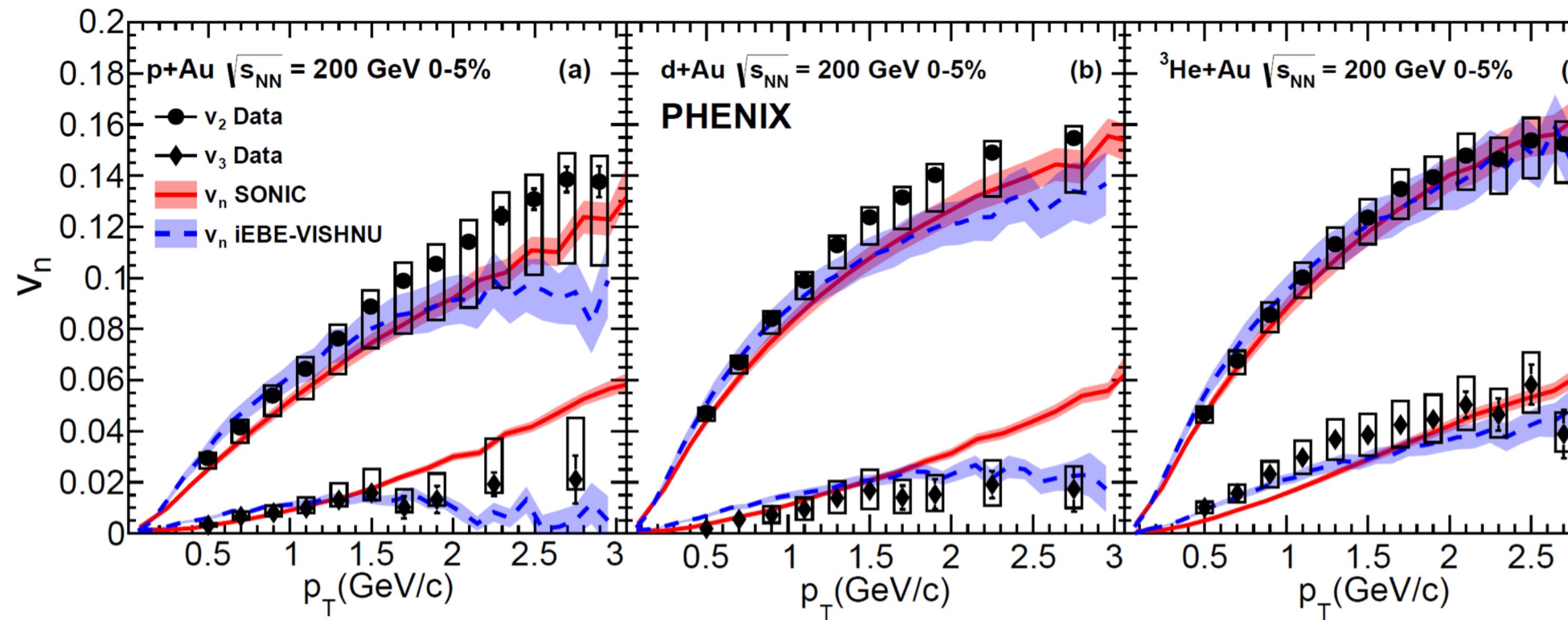
Thank You



Back Up



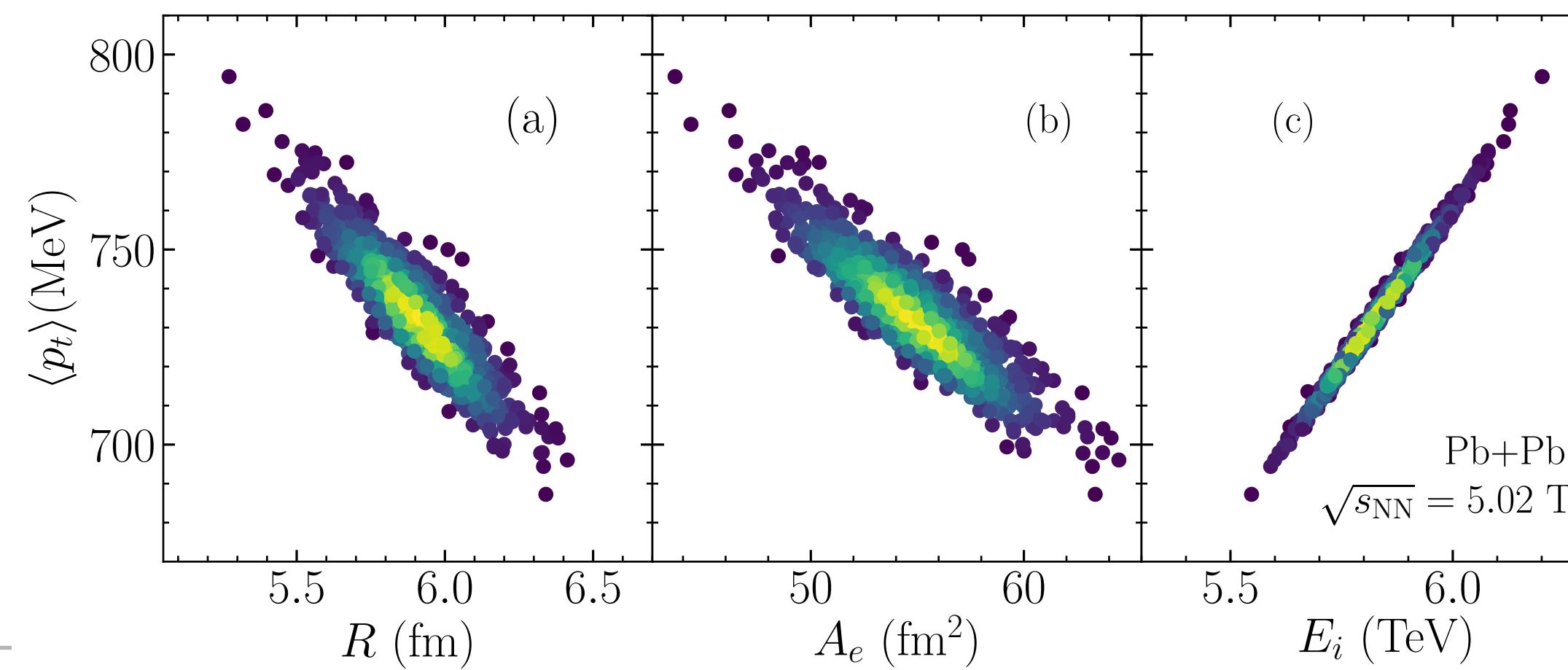
Initial Geometry or Initial Momentum anisotropy?



PHENIX, Nature Physics 15, 214-219 (2019)

Consistent with latest results: PHENIX: PRC 107 (2023) 024907

Geometry scan results: consistent with hydro prediction

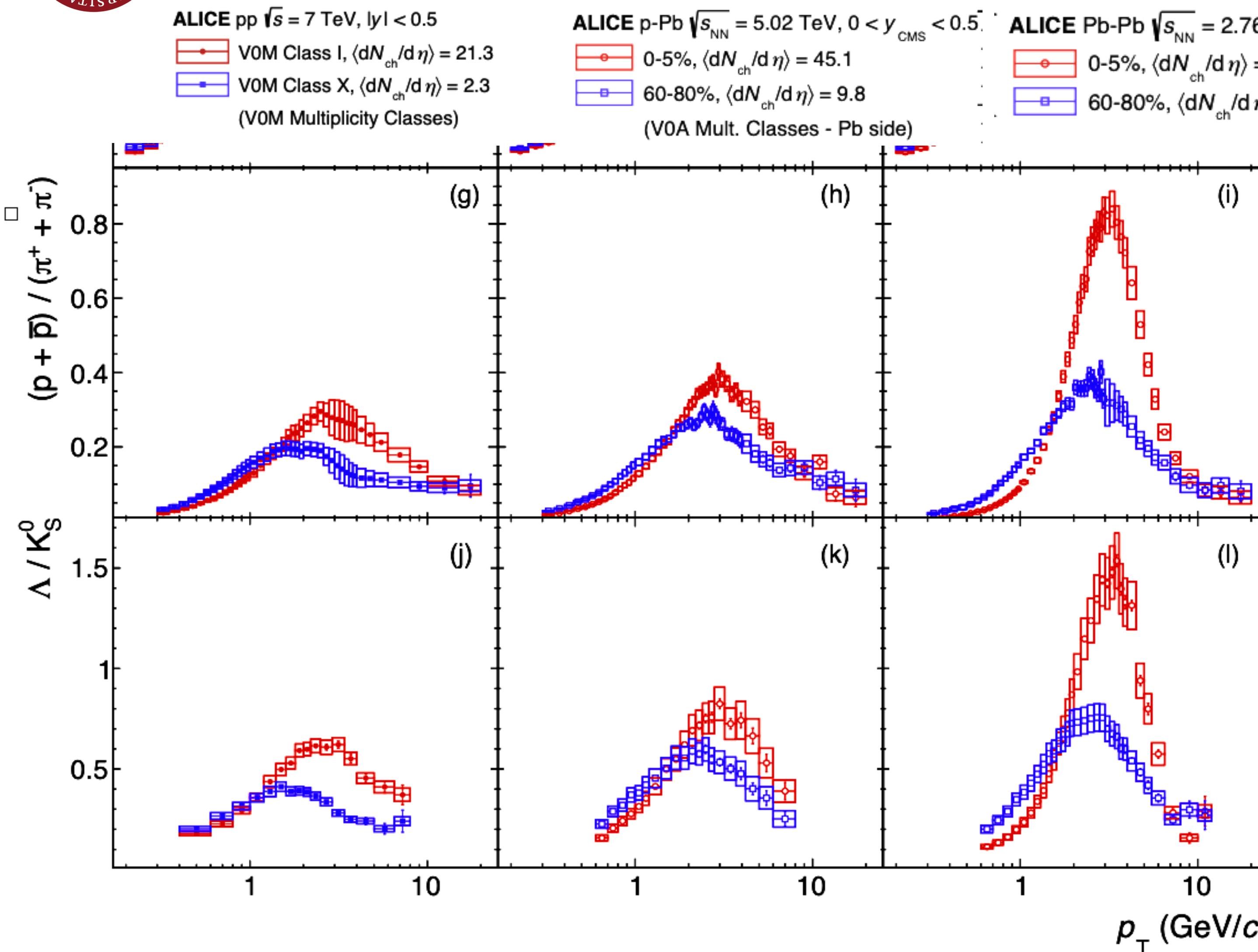


- CGC estimation

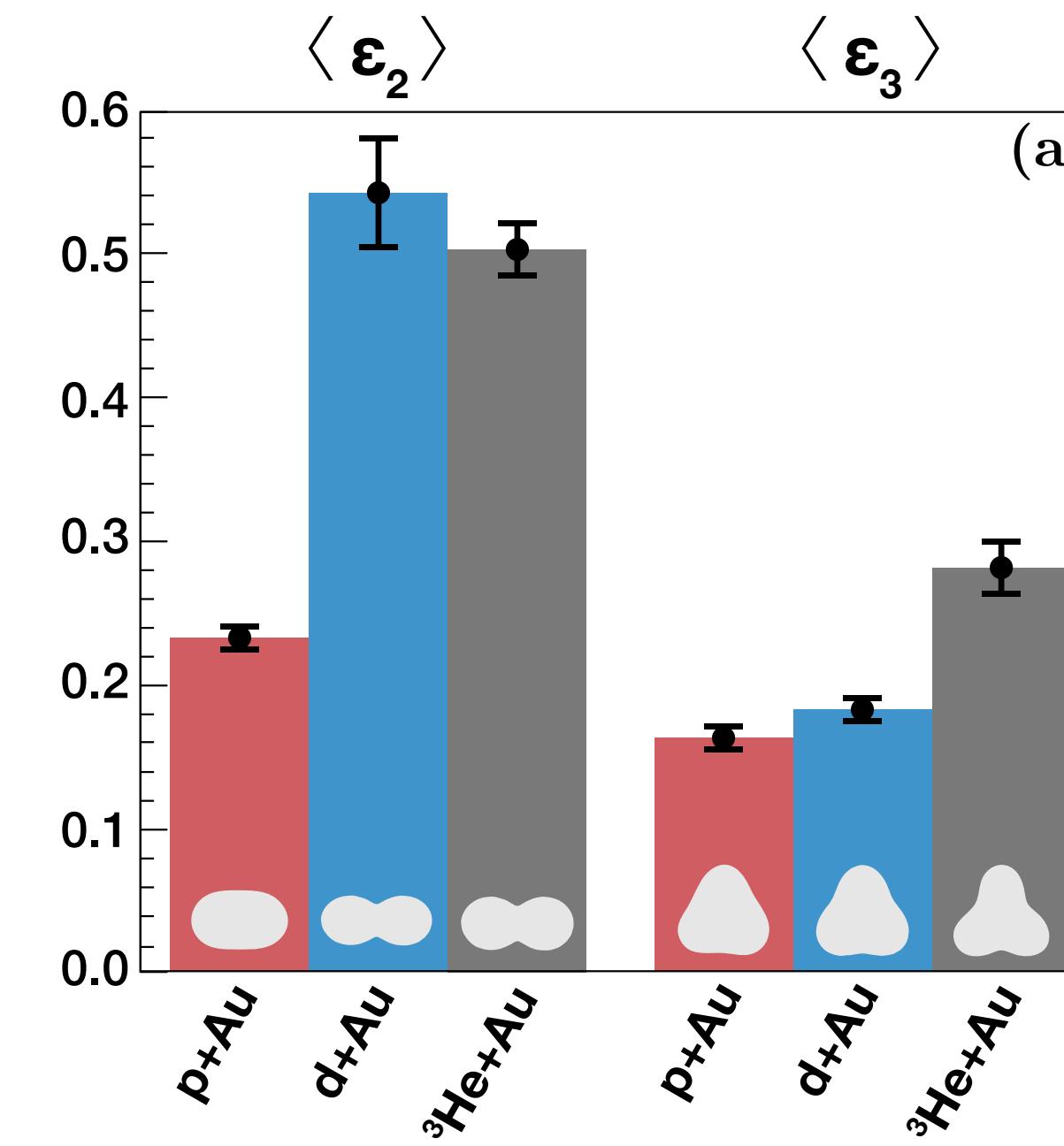
$$v_n^{p+\text{Au}} > v_n^{d+\text{Au}} > v_n^{{}^3\text{He}+\text{Au}}$$



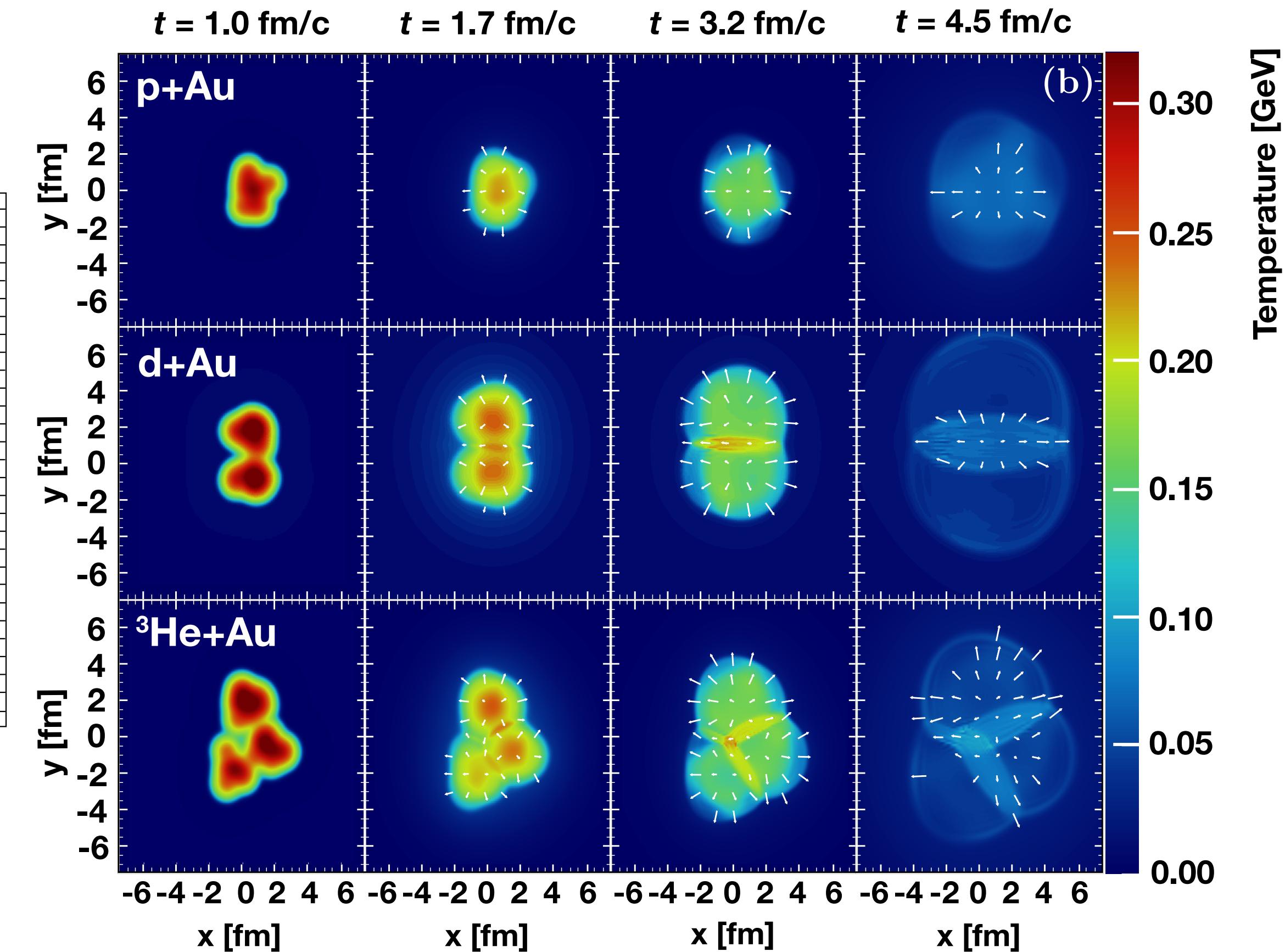
Identified particle results



- Mass dependent hardening of spectra:
Radial flow pushes massive particles more from lower to higher p_T (mass dependent):
Low p_T depletion
Intermediate p_T enhancement
 - pp, p-Pb and Pb-Pb behave in similar way!
- What about the species dependence of the Anisotropic flow?



PHENIX, Nature Physics 15, 214-219 (2019)
J. Nagle *et al.* in PRL 113, 112301(2014)



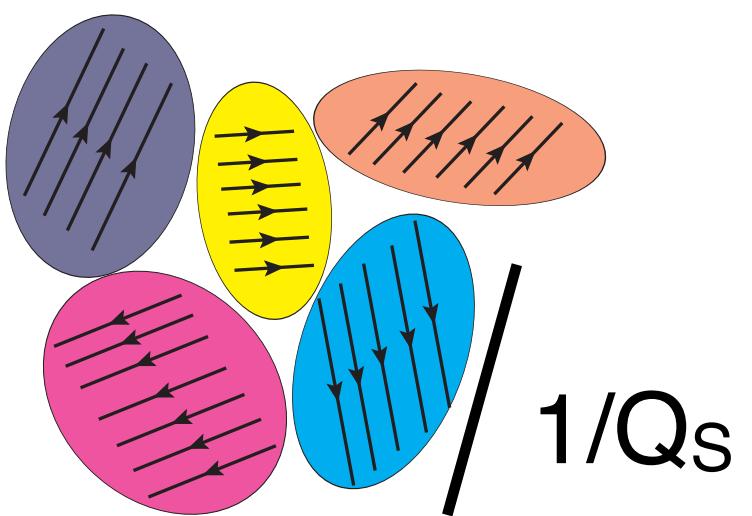
- Hydro prediction ($v_n \propto \epsilon_n$)

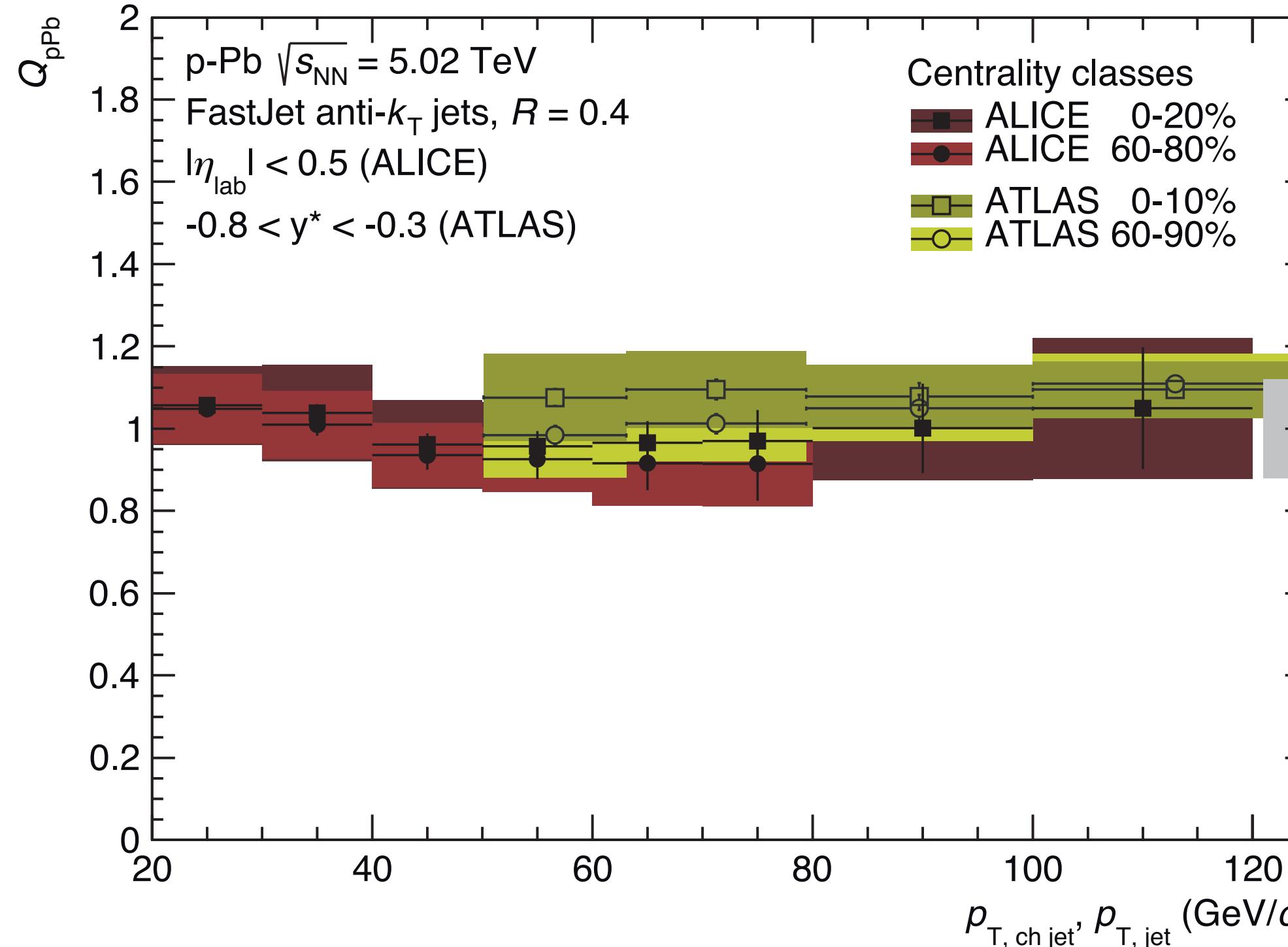
$$v_2^{\text{p+Au}} < v_2^{\text{d+Au}} \leq v_2^{\text{He+Au}}$$

$$v_3^{\text{p+Au}} \leq v_3^{\text{d+Au}} < v_2^{\text{He+Au}}$$

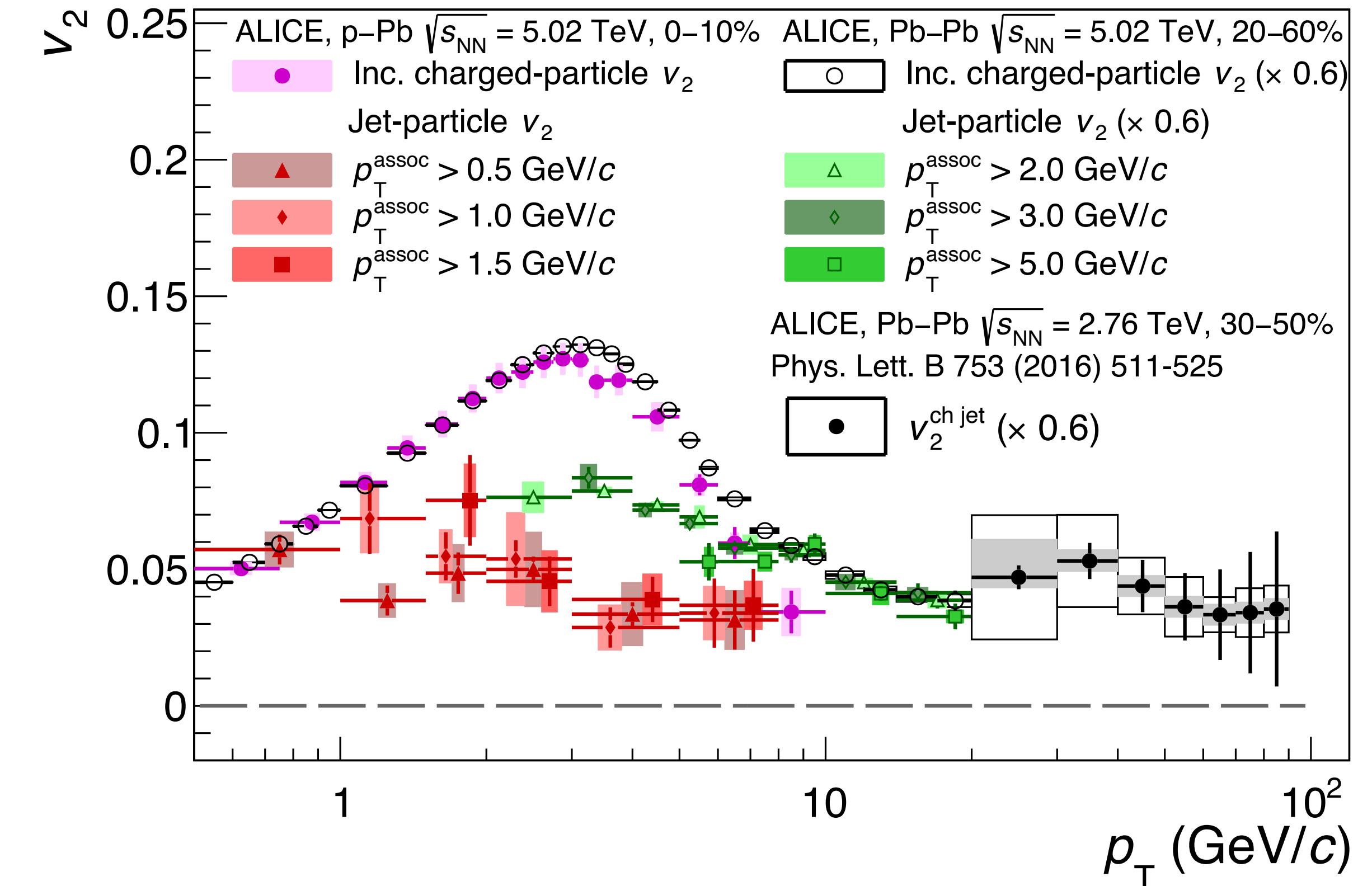
- CGC expectation

$$v_n^{\text{p+Au}} > v_n^{\text{d+Au}} > v_n^{\text{He+Au}}$$

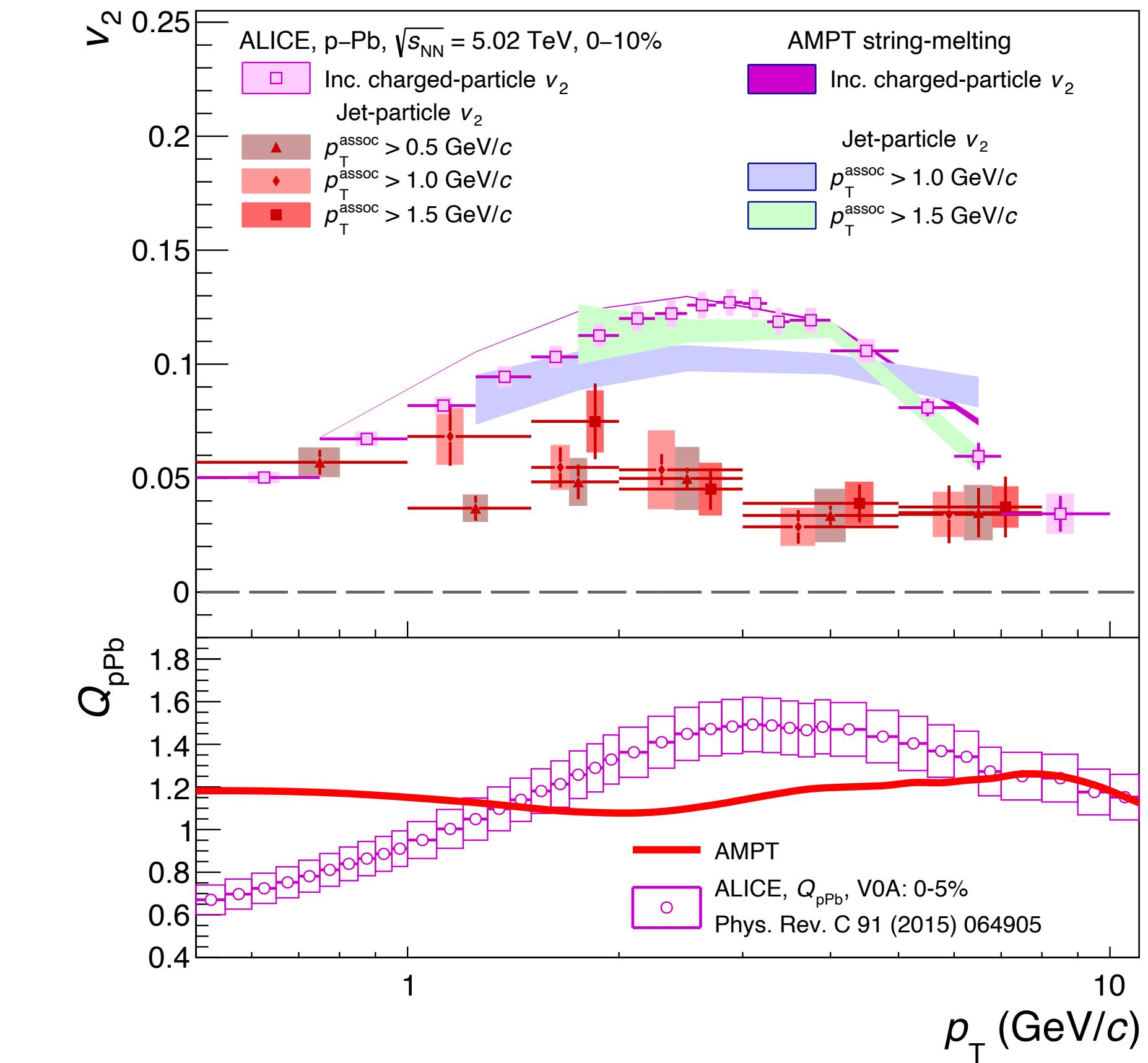
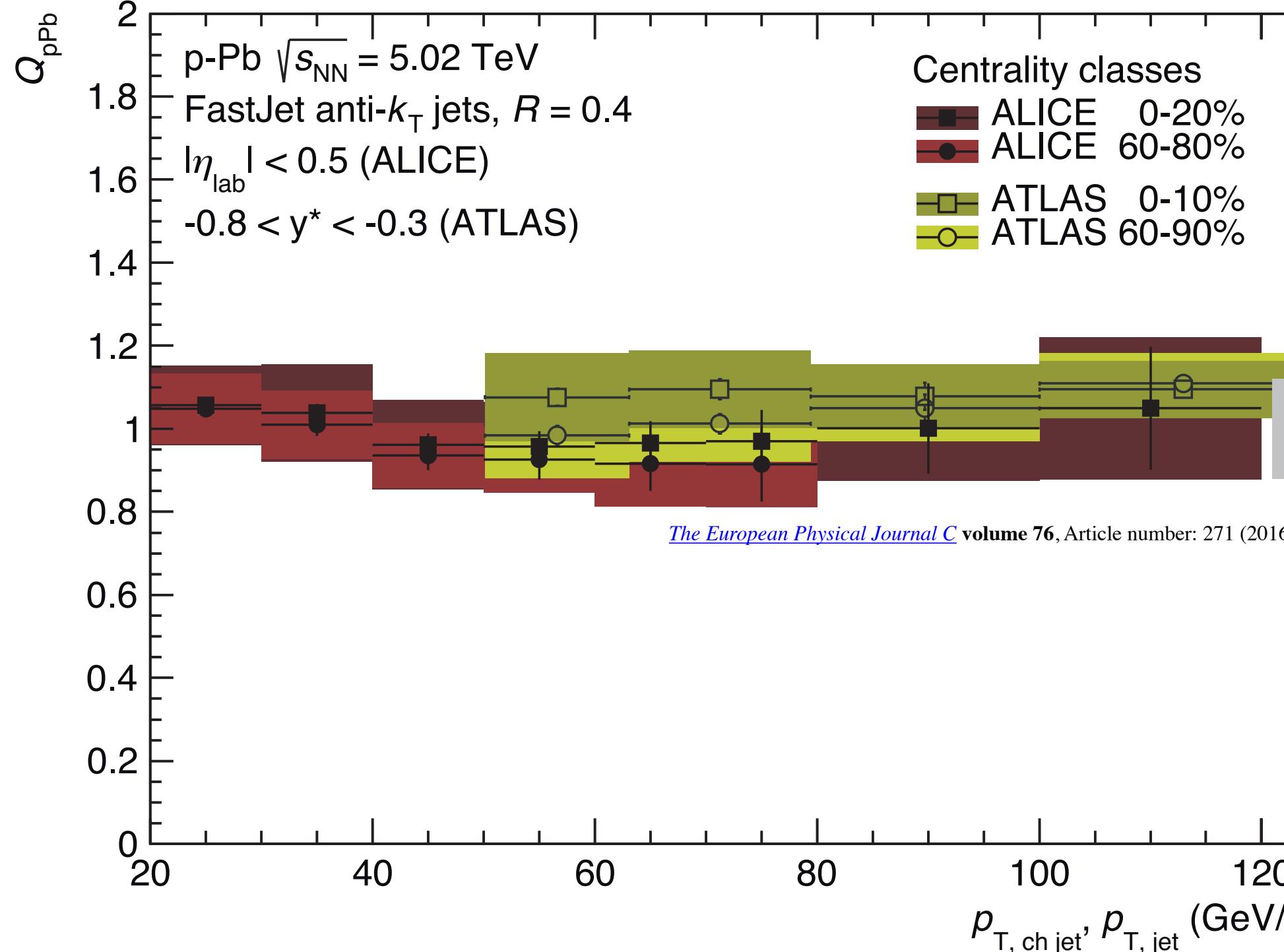




ALICE, EPJC, volume 76, 271 (2016)



- No significant jet-quenching in p-Pb collisions.
- Non-zero jet v_2 in p-Pb collisions!
- Smaller magnitude than inclusive v_2 at intermediate p_T . Converge at high p_T .
- Similar pattern observed in Pb-Pb collisions — path dependent energy loss.
- What is the underlying mechanism in p-Pb? Any model input?



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- Non-zero jet v_2 in p-Pb collisions!
- Smaller magnitude than inclusive v_2 at intermediate pT. Converge at high pT.
- Similar pattern observed in Pb-Pb collisions – path dependent energy loss.
- AMPT generates positive jet v_2 and inclusive v_2 – anisotropic parton escape mechanism responsible for jet v_2 in p-Pb collisions?