Collective phenomena in small systems (soft probes)

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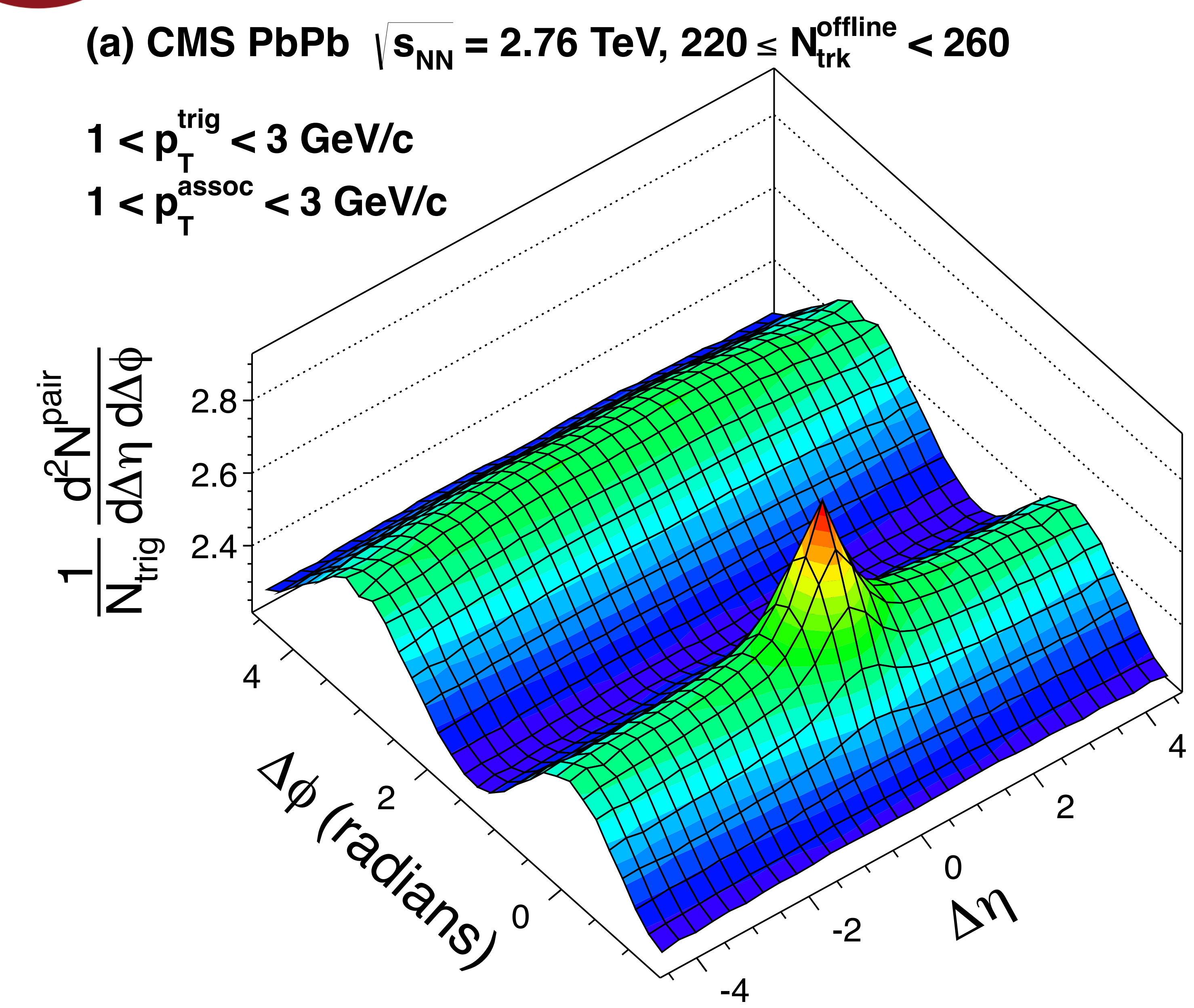
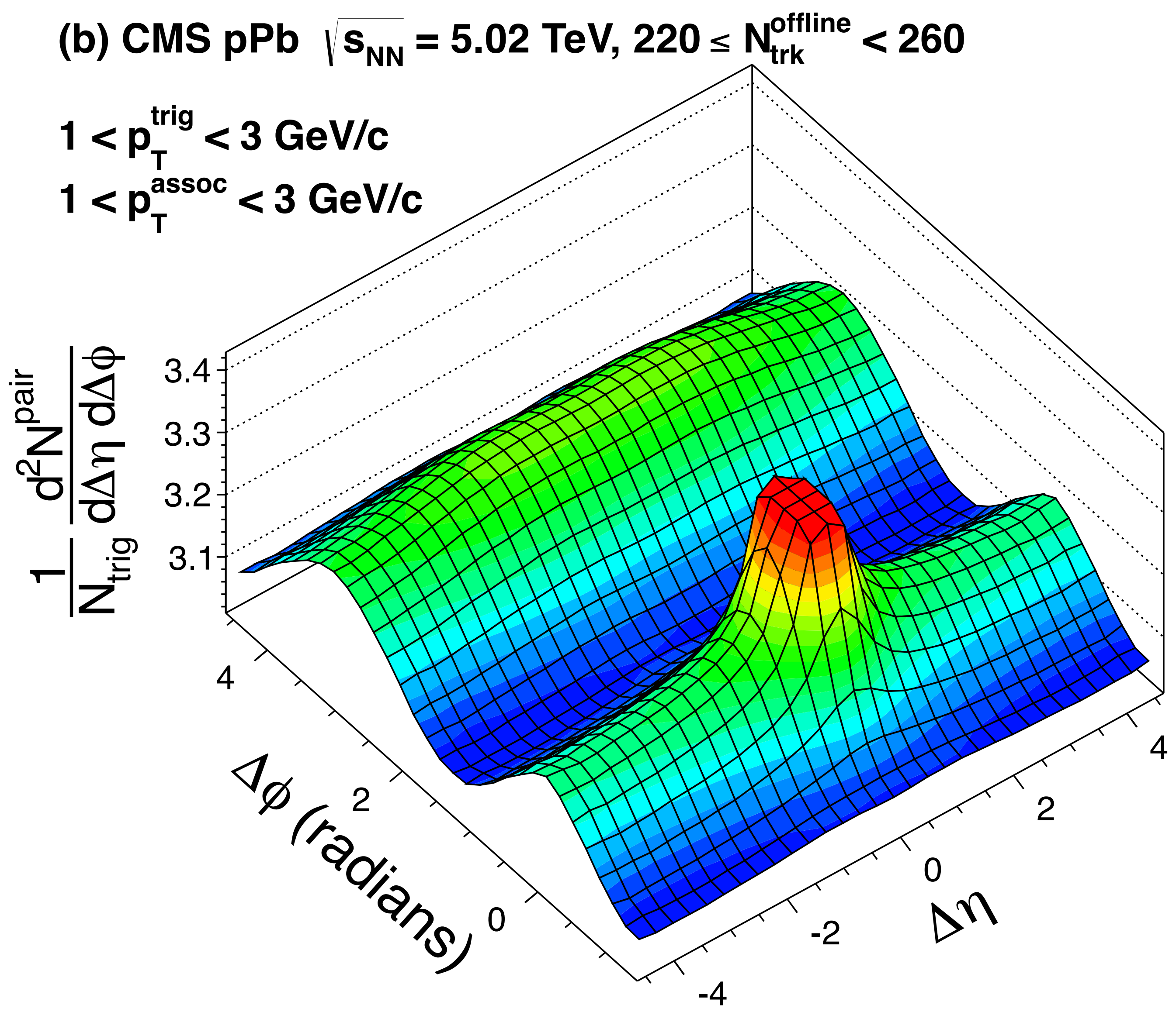
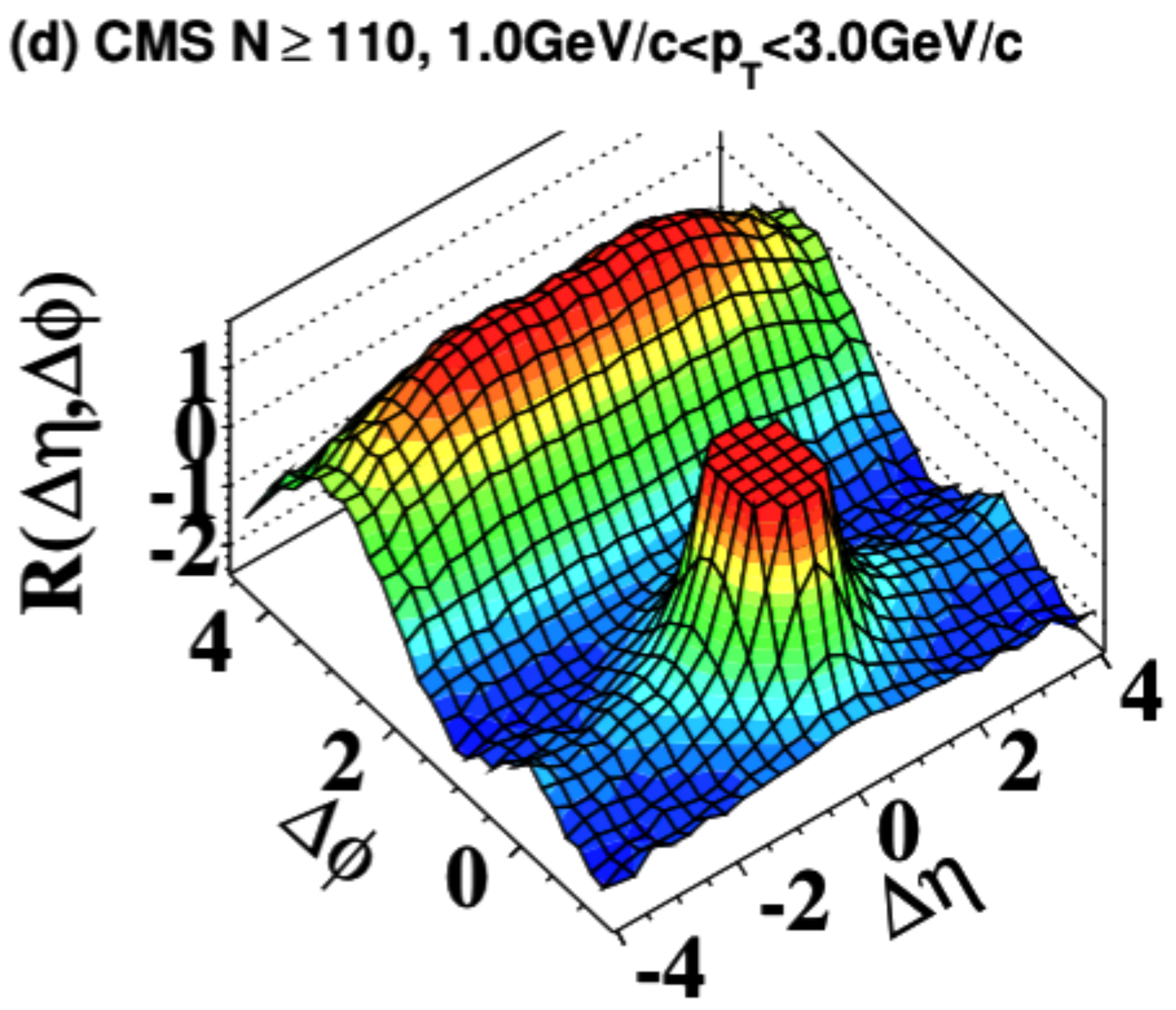
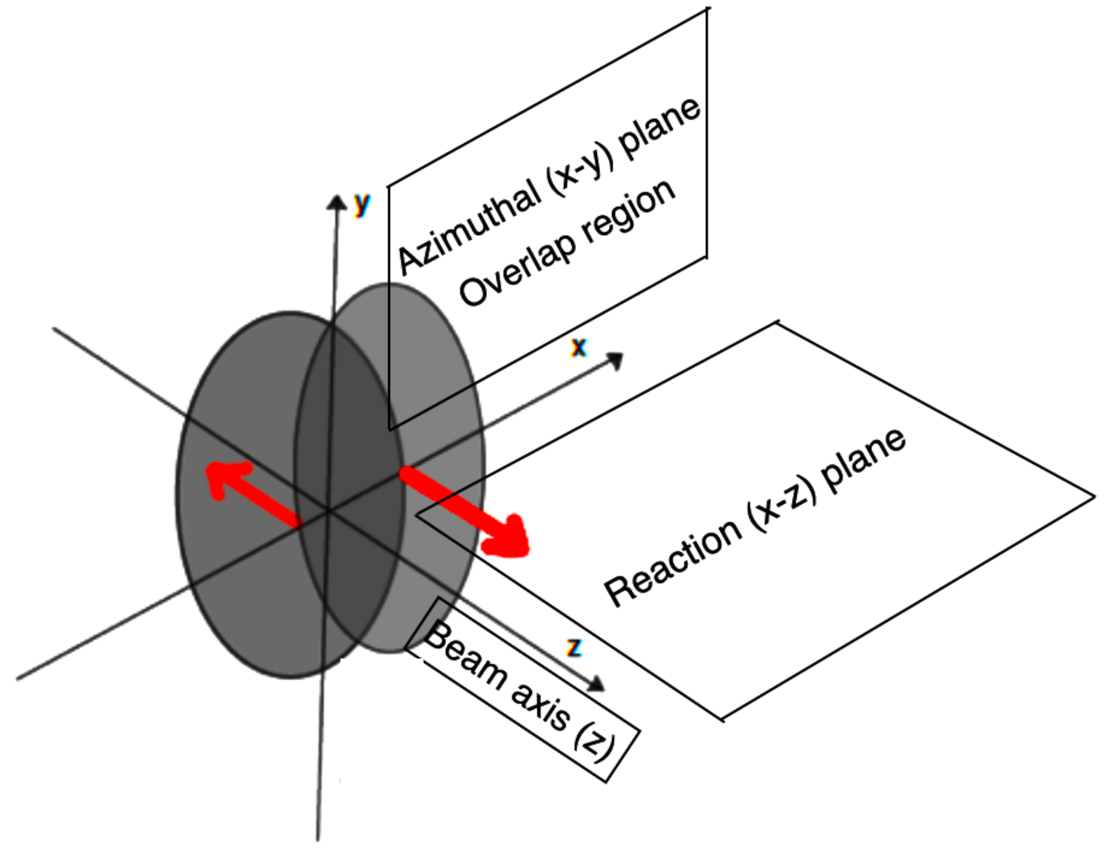
Collectivity in small systems?

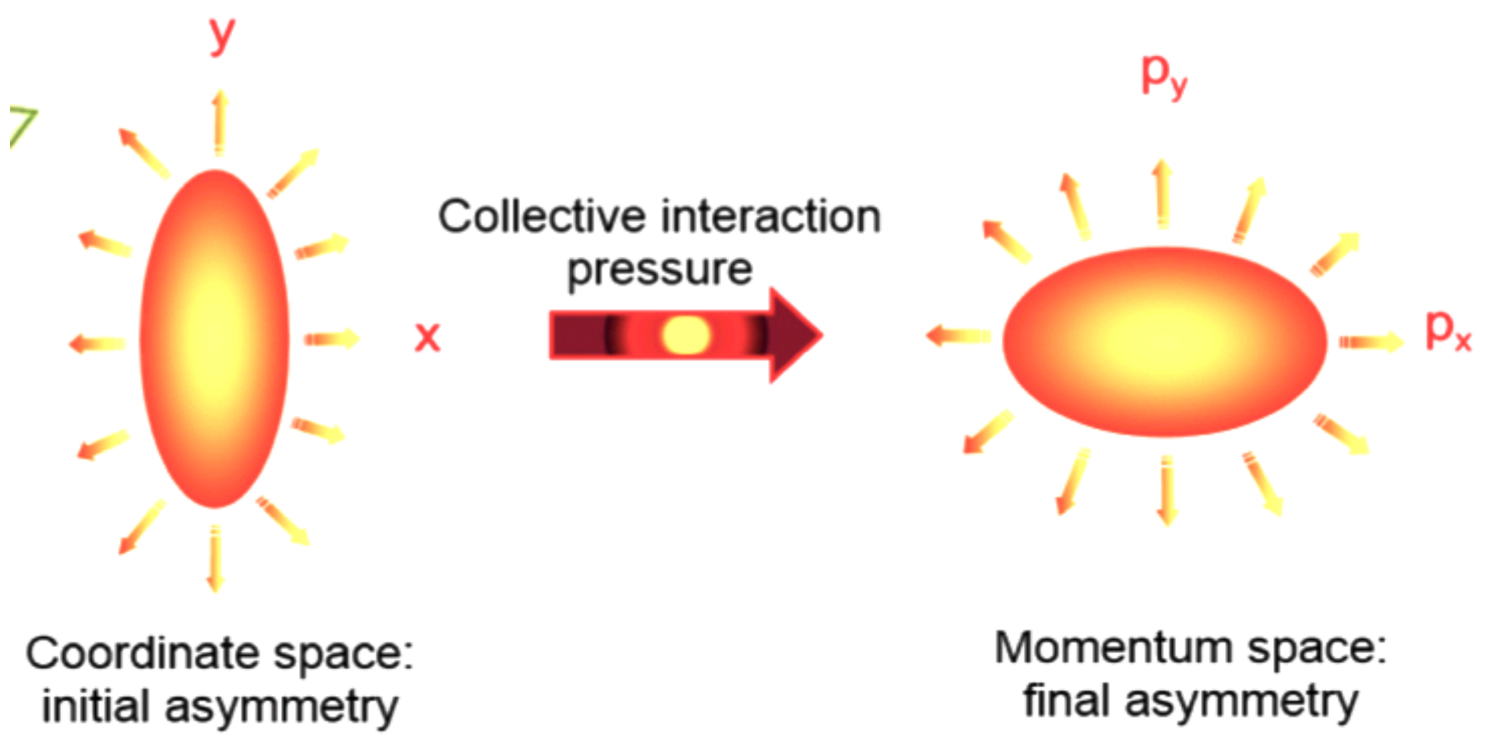


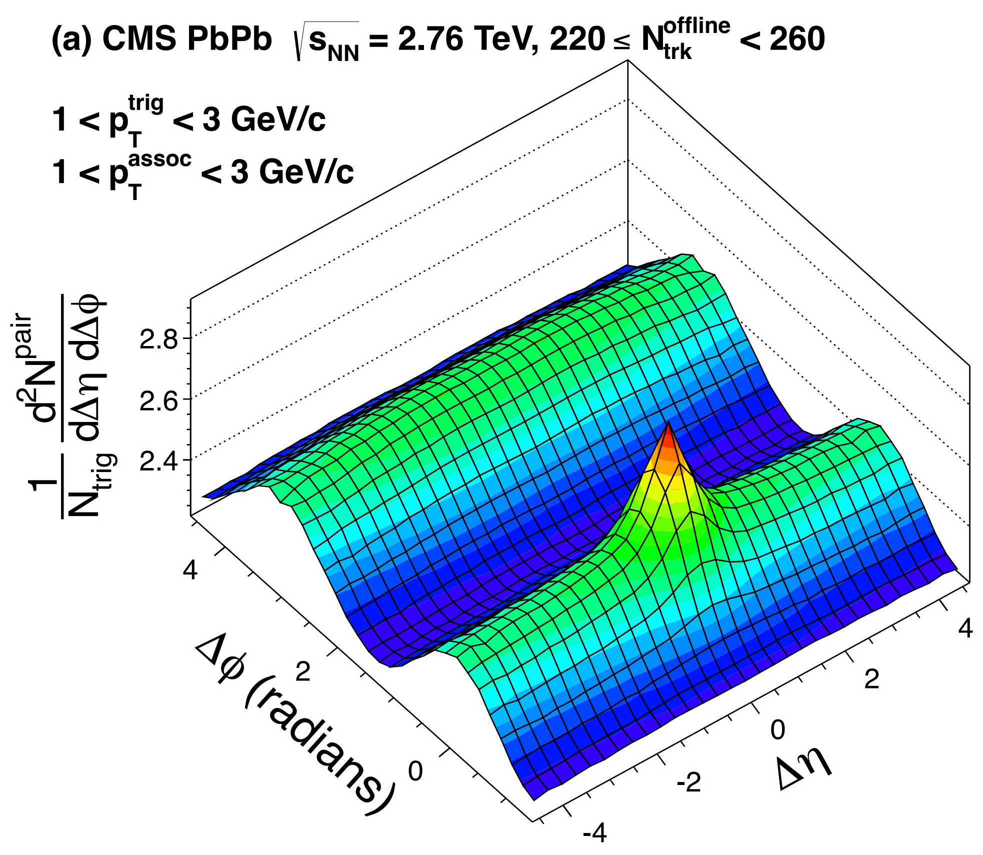




Everything flows (?) - Initial state geometry + Final state interaction (hydro description)







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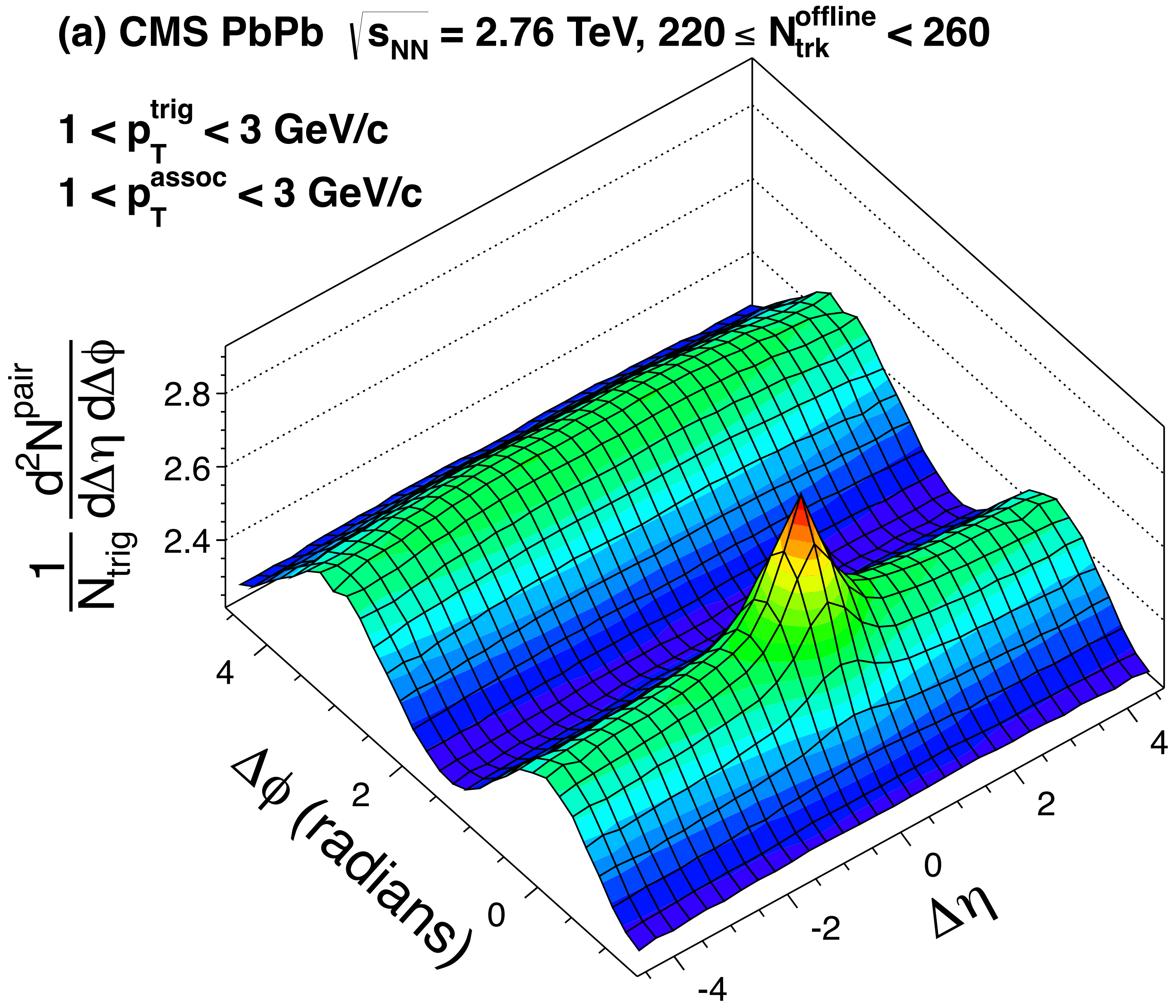
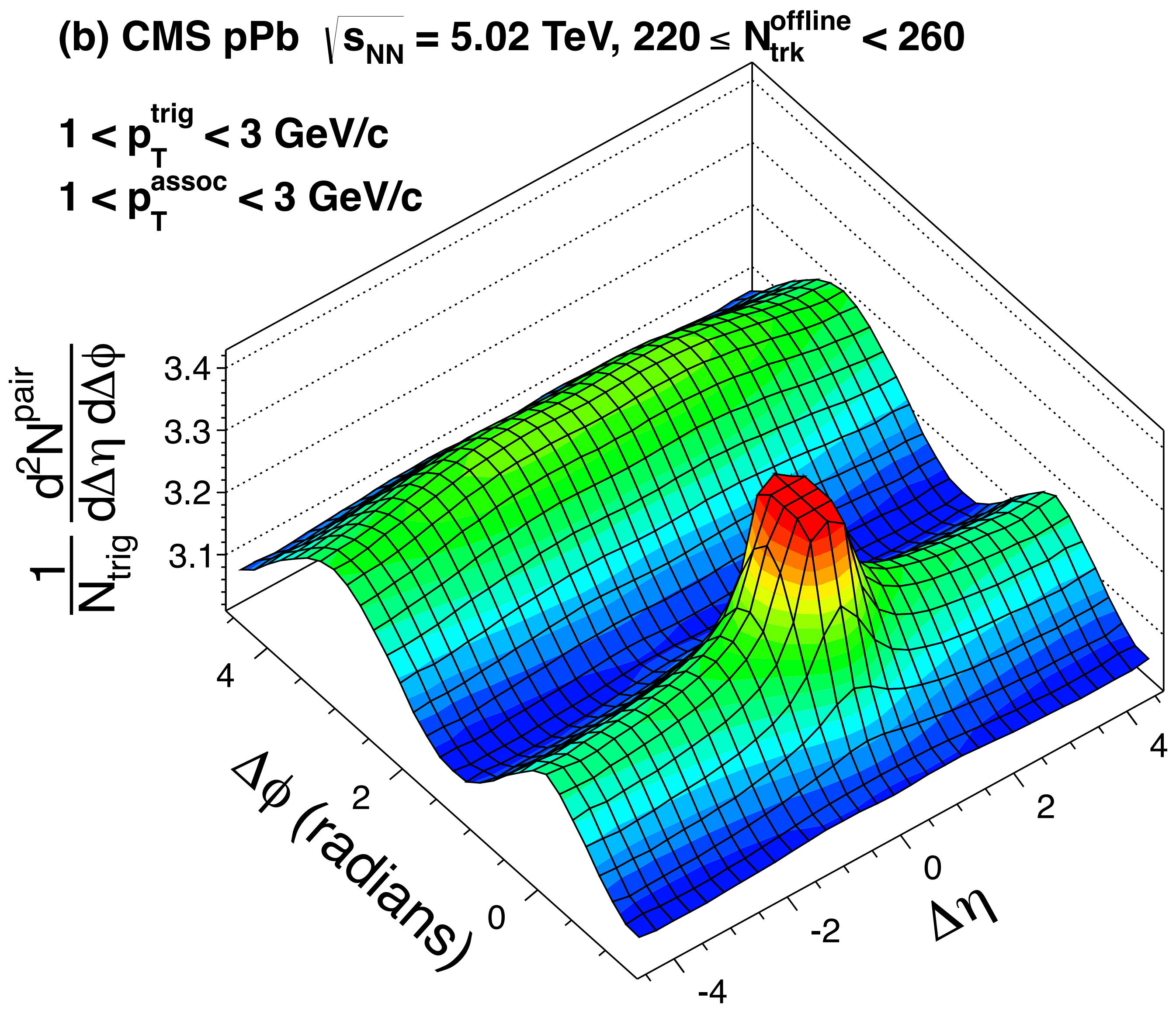
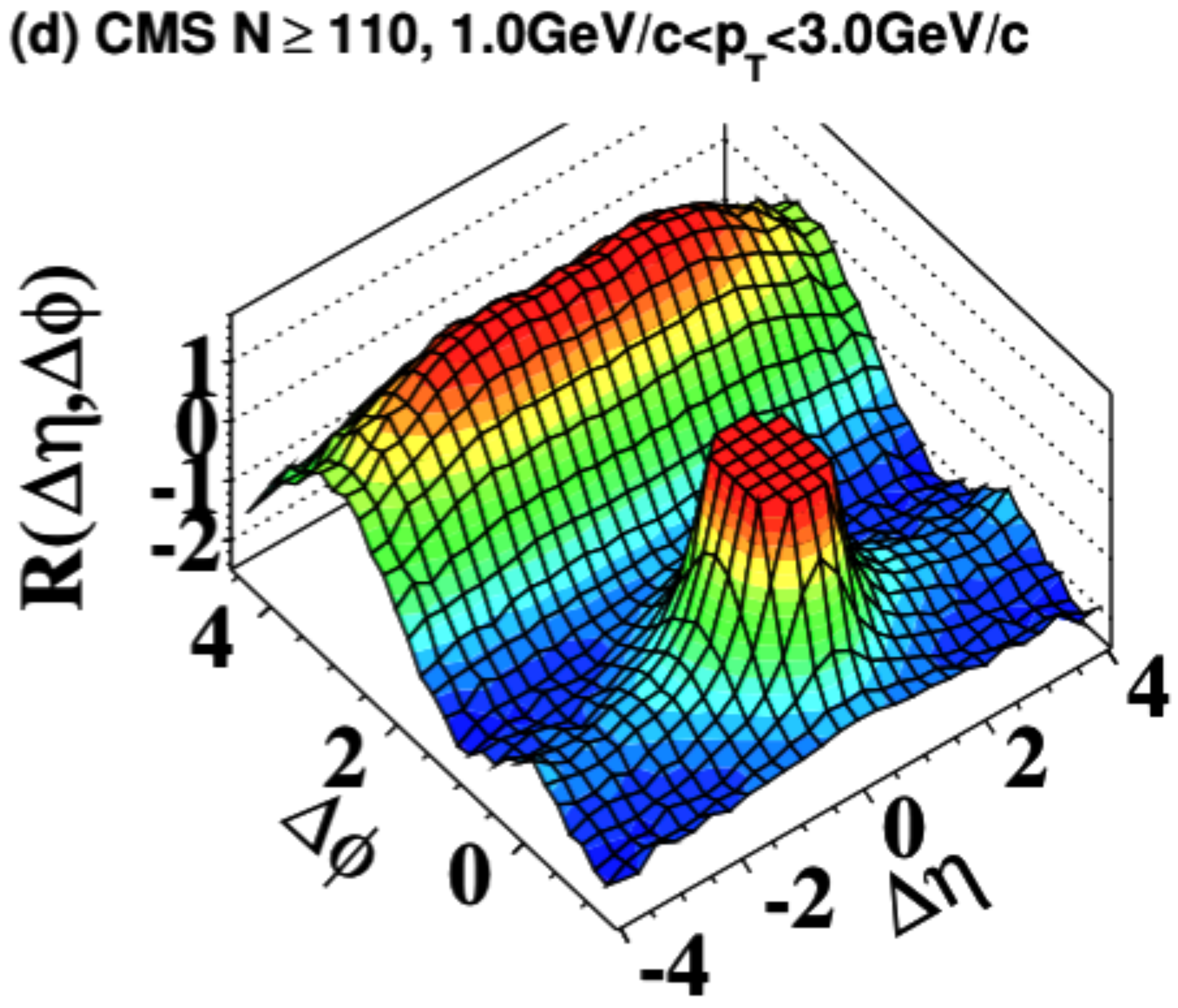






Everything flows (?) - Initial state geometry + Final state interaction (hydro description)

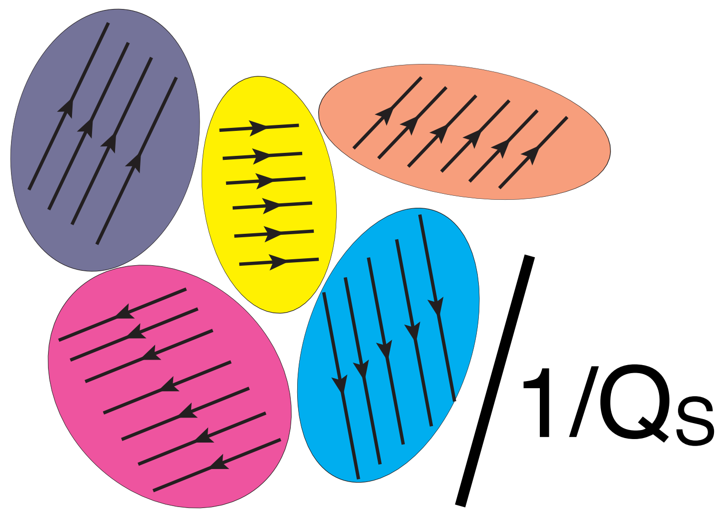
J. L. Nagle, W. A. Zajc; Phys Rev C **99**, 054908 (2019)

A Dumitru et al, Phys. Lett. B 697:21-25,2011

Or

Initial State effect(?):

Q_S - saturation momentum scale



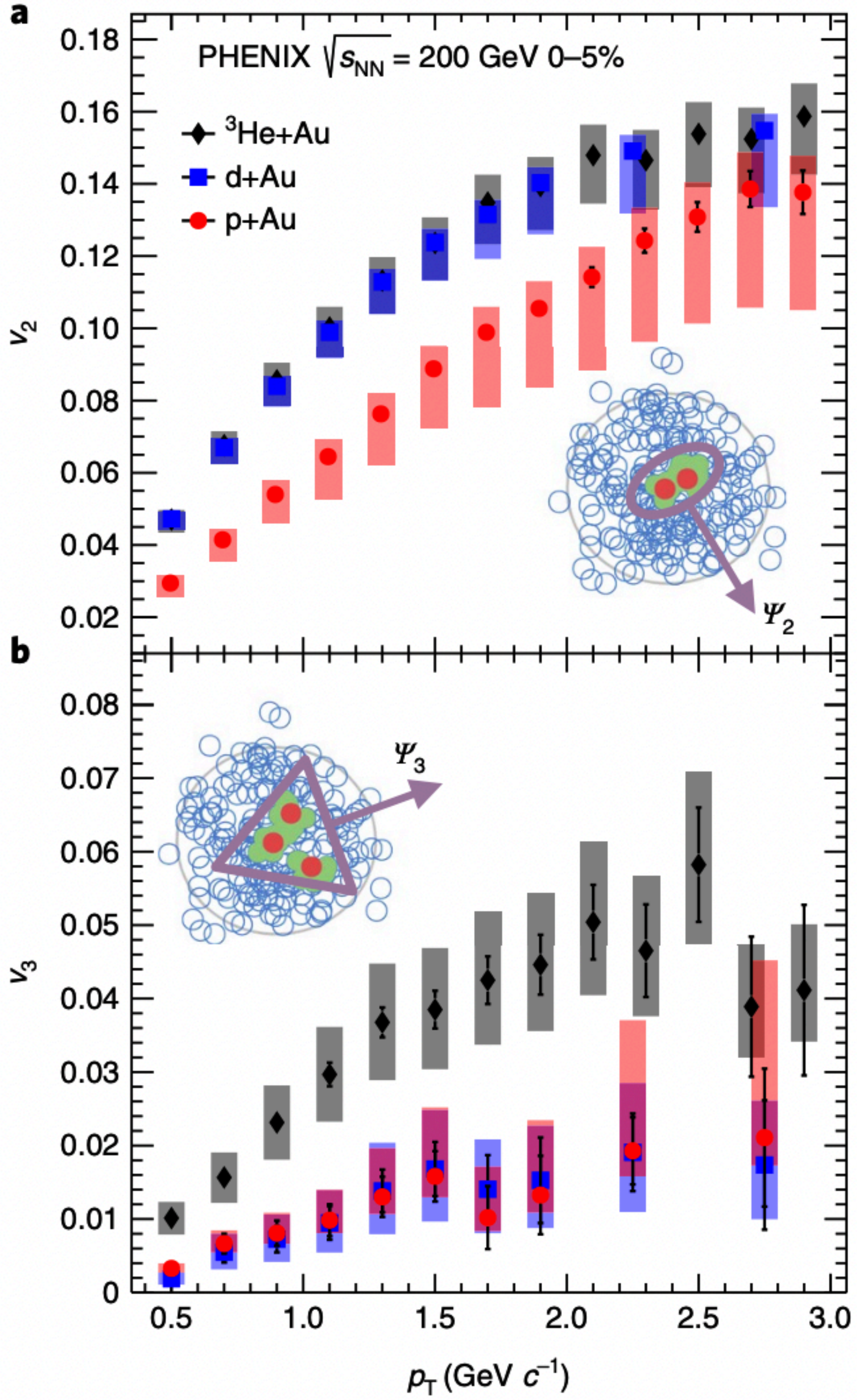
"Glasma flux tube": Longitudinal extension of color domains with transerse size ~ $1/Q_S$

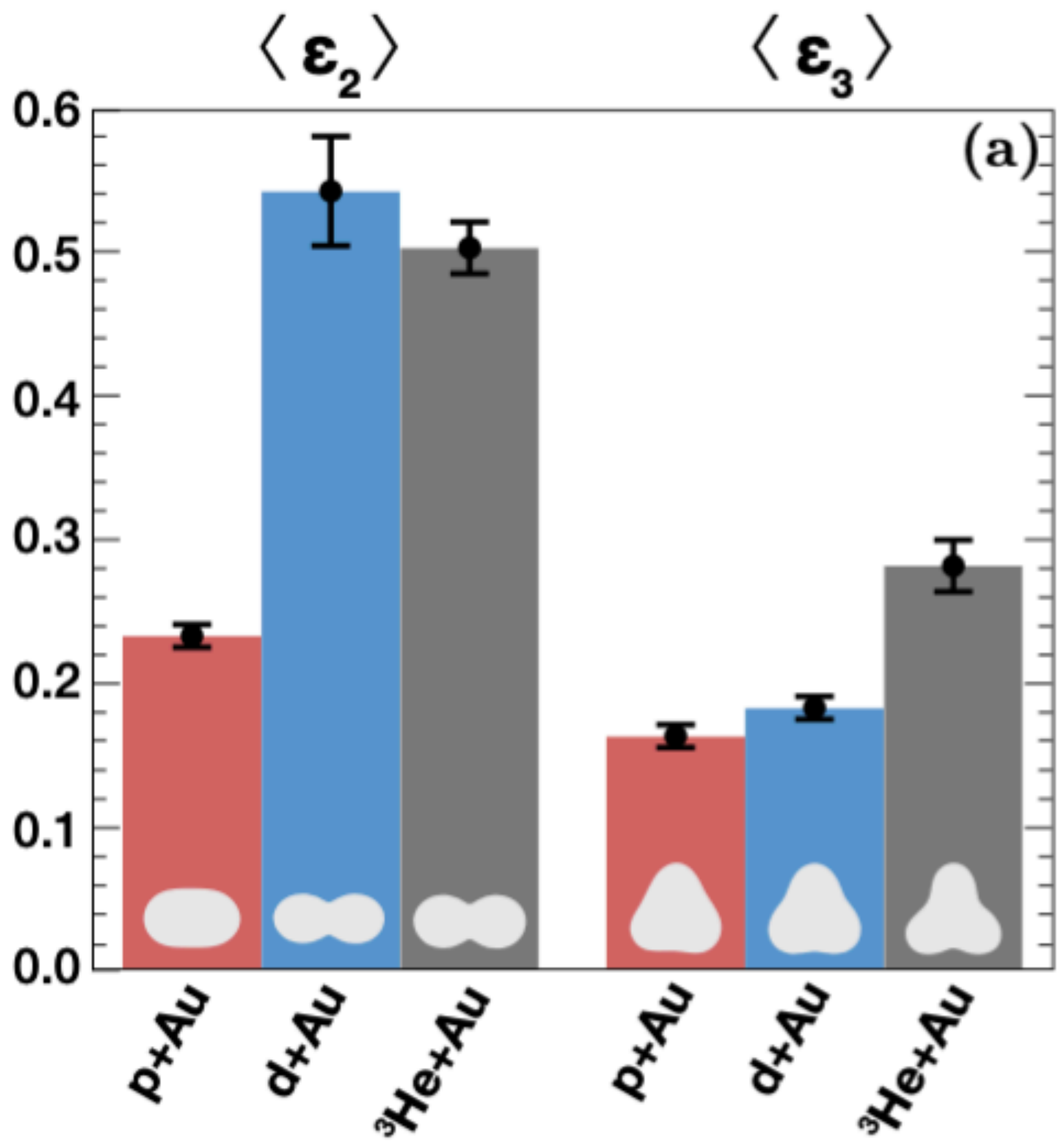
Domains are uncorrelated and randomly oriented (in both coordinate space and color space)

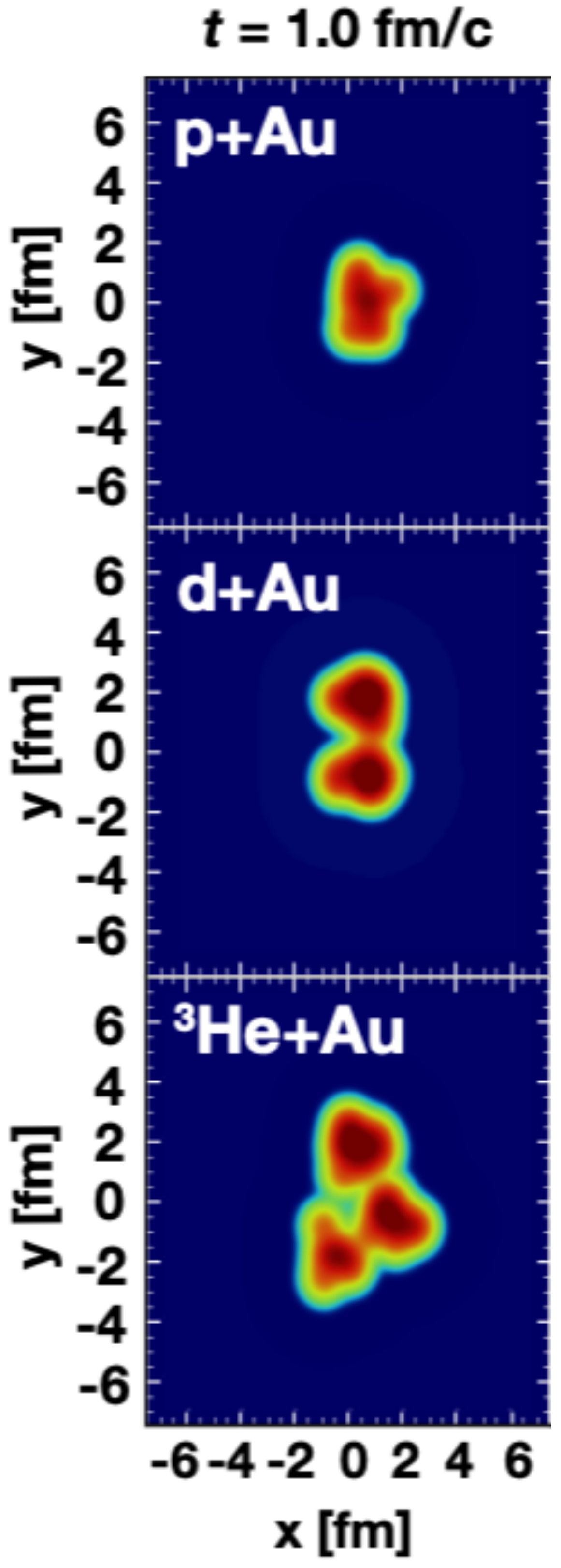
Many resolved color domains in the interaction region - reduces the anisotropy

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 (initial nucleonic geometry + Final state interactions):

$$v_n \propto \epsilon_n$$

- Geometry scan results (PHENIX): consistent with hydro prediction:

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

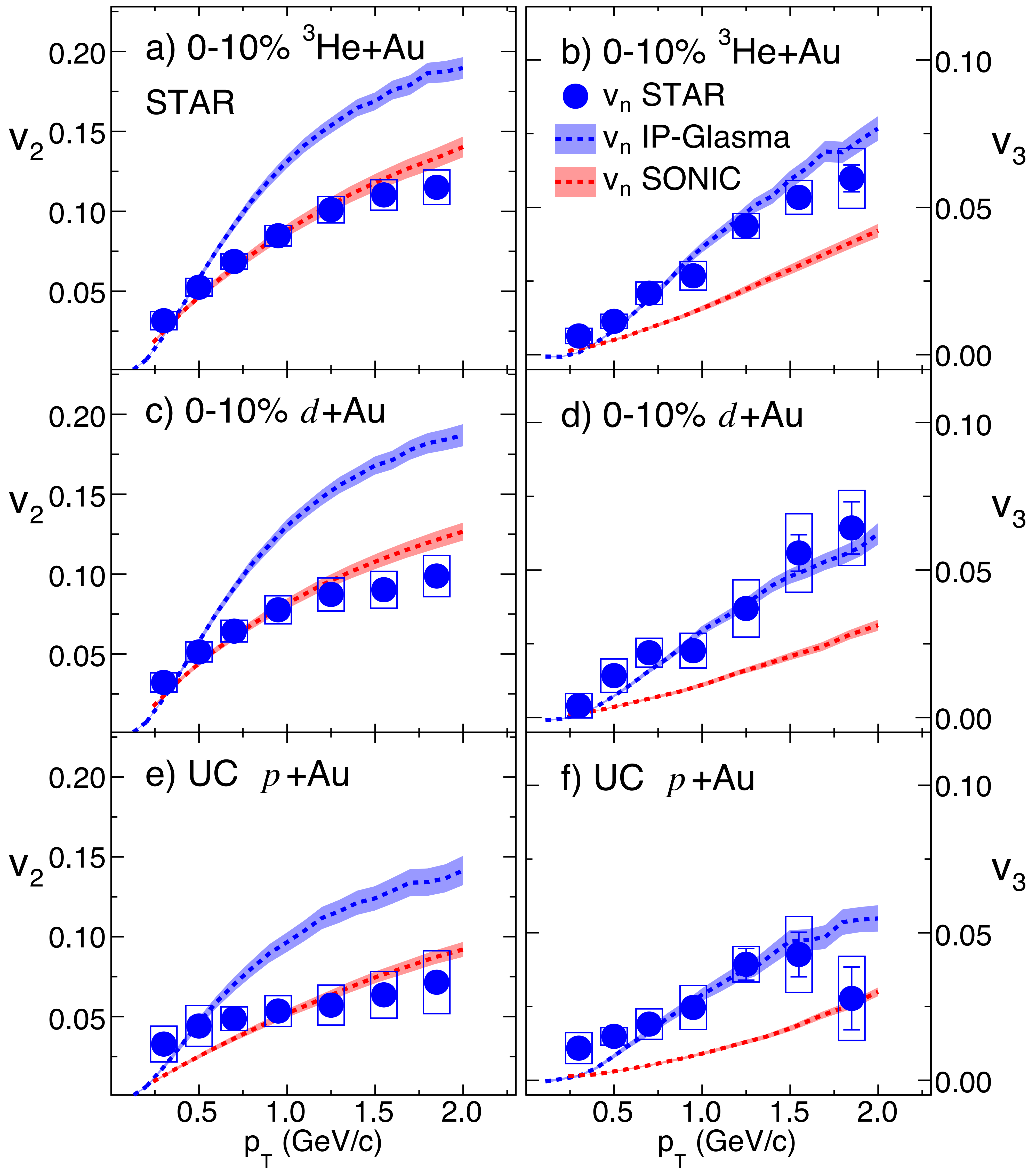
$$v_3^{\mathrm{p+Au}} \approx v_3^{\mathrm{d+Au}} < v_3^{^3He+Au}$$

- CGC expectation:

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

Or both?

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



STAR measurement adds more to this scenario:

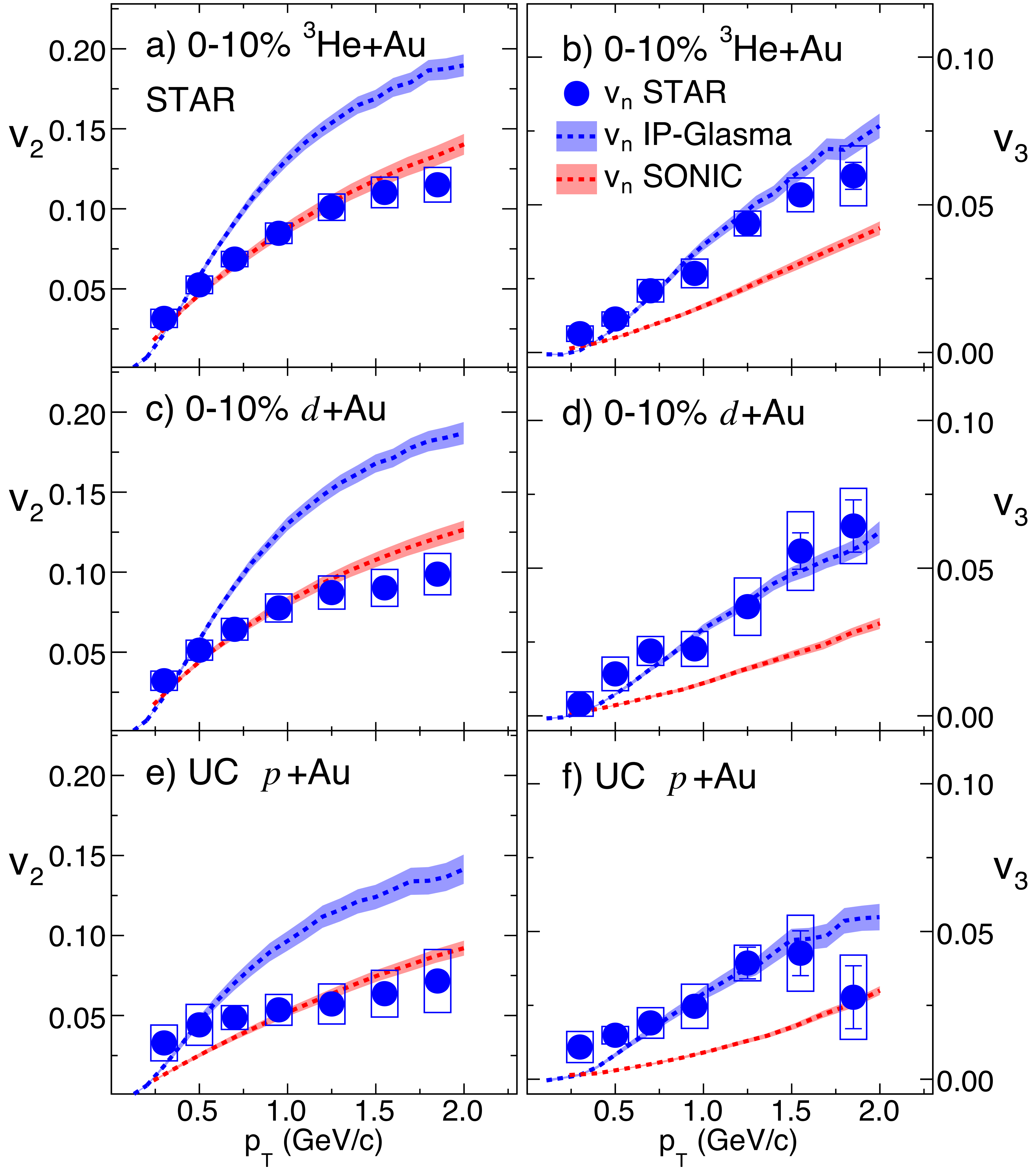
$$v_2^{p+Au} < v_2^{d+Au} \approx v_2^{^3He+Au} \text{ (Expected hydro ordering)}$$

$$v_3^{p+Au} \approx v_3^{d+Au} \approx v_3^{^3He+Au} \quad \text{(!!)}$$

- $v_3(p_T)$ is system independent! Simple Hydro description missing something?

Maybe both…

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



STAR measurement adds more to this scenario:

$$v_2^{\mathrm{p+Au}} < v_2^{\mathrm{d+Au}} \approx v_2^{{}^3He+Au} \text{ (Expected hydro ordering)}$$

$$v_3^{\mathrm{p+Au}} \approx v_3^{\mathrm{d+Au}} \approx v_3^{{}^3He+Au} \text{ (!!)}$$

- $v_3(p_T)$ is system independent! Simple Hydro description missing something?
- Posible missing factors:

  sub-nucleonic fluctuations (initial geometry)

  \+

  initial momentum anistropy (CGC)

  \+

  hydrodynamic gradient-expansion corrections

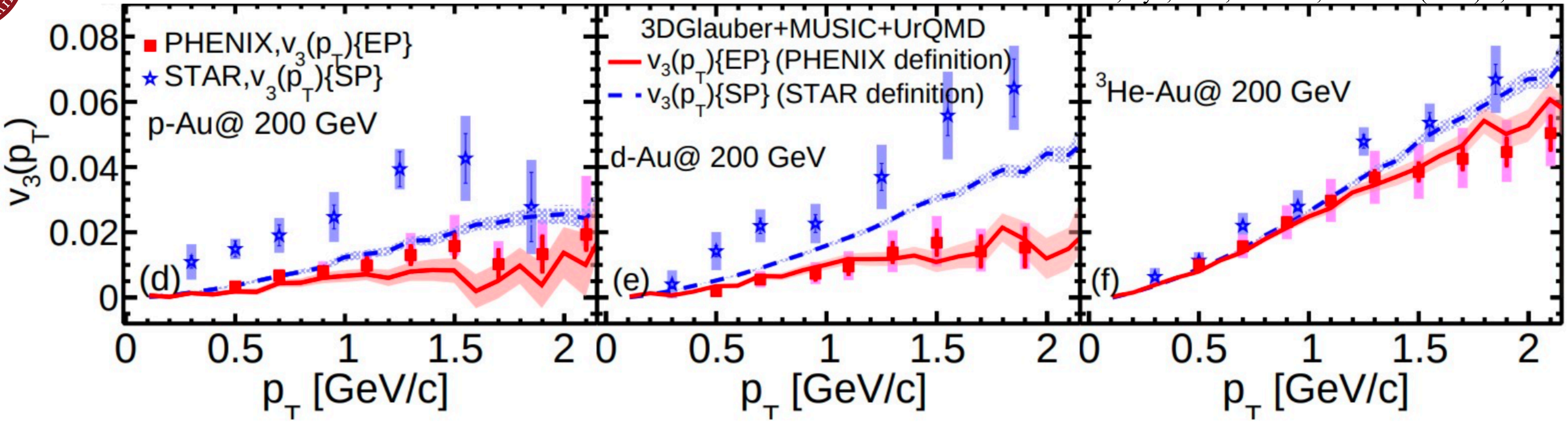
  \+

  ??
- IP-Glasma+MUSIC+URQMD: describes system independent v_3!

What else (for discrepancy between STAR and PHENIX v_3)?

Longitudinal flow decorrelations

Zhao, Ryu, Shen, Schenke, PRC **107** (2023) 1, 014904



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

- PHENIX: particles from mid and backward/forward rapidities.
- STAR : particles from mid rapidity only. STAR, Phys. Rev. Lett. 130, 242301 (2023)

Longitudinal flow decorrelations

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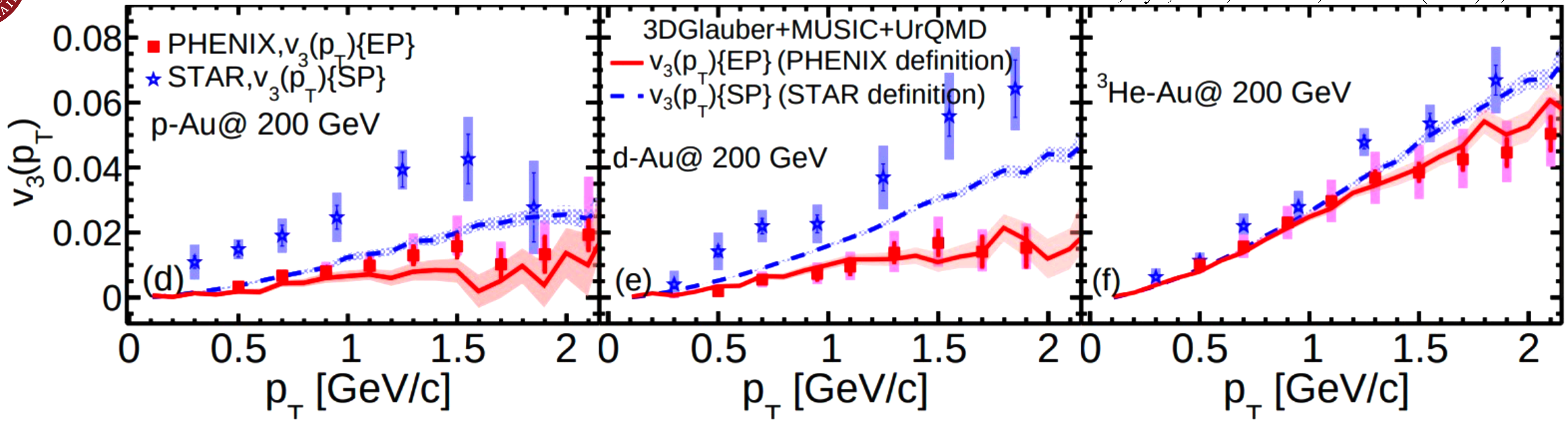
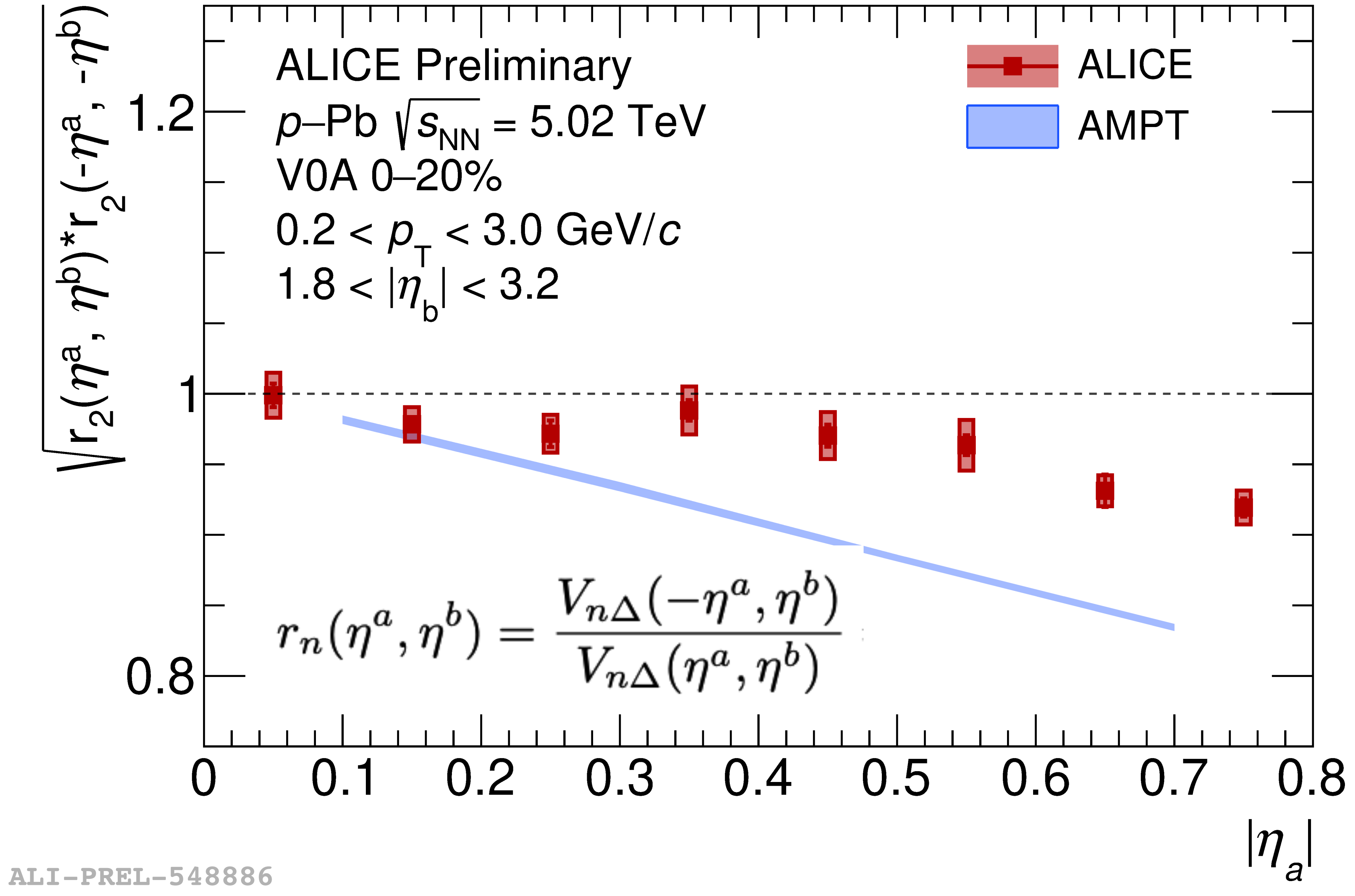




$$r_n(\eta^a,\eta^b) = \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$$

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

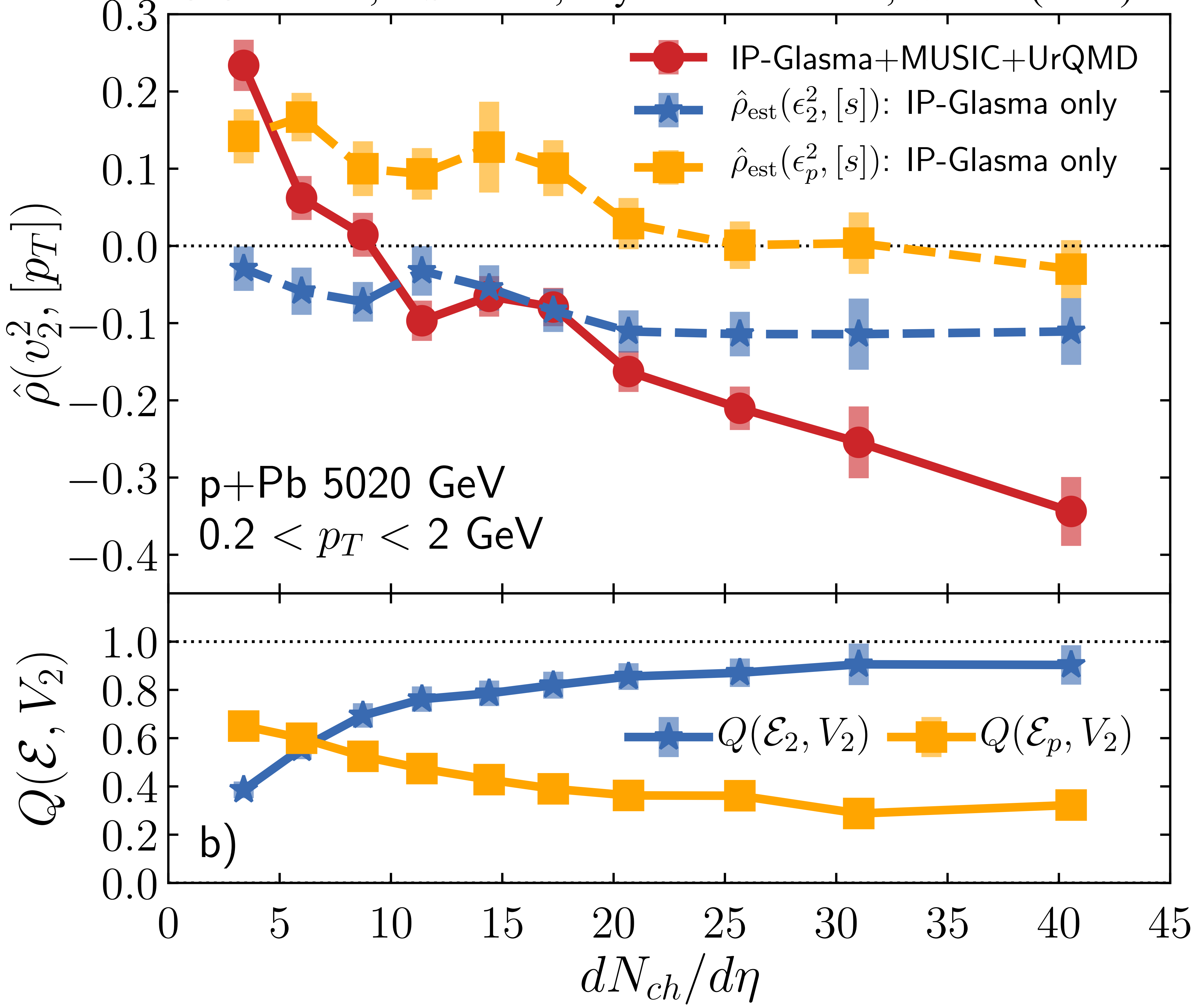
- PHENIX: particles from mid and backward/forward rapidities.
- STAR : particles from mid rapidity only. STAR, Phys. Rev. Lett. 130, 242301 (2023)
- Longitudinal flow decorrelation experimentally observed.
- Proper 3-D modelling (geometry, momentum anisotropy,…) crucial for explaining v_2, v_3 in small systems .

Zhao, Ryu, Shen, Schenke, PRC **107** (2023) 1, 014904

How to trace back initial conditions from final state observables?

Tracing back “Initial Cause” from “Final Effect”

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



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

Bożek, Phys. Rev. C 93, 044908 (2016)

Pearson correlation coefficient:

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

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

Final State → Initial State

$$\rho(v_n^2, <p_T>) \approx \rho(v_n^2, <p_T>) \approx \rho(\epsilon_{n/p}^2, E)$$

(Data) (Model) (Model)

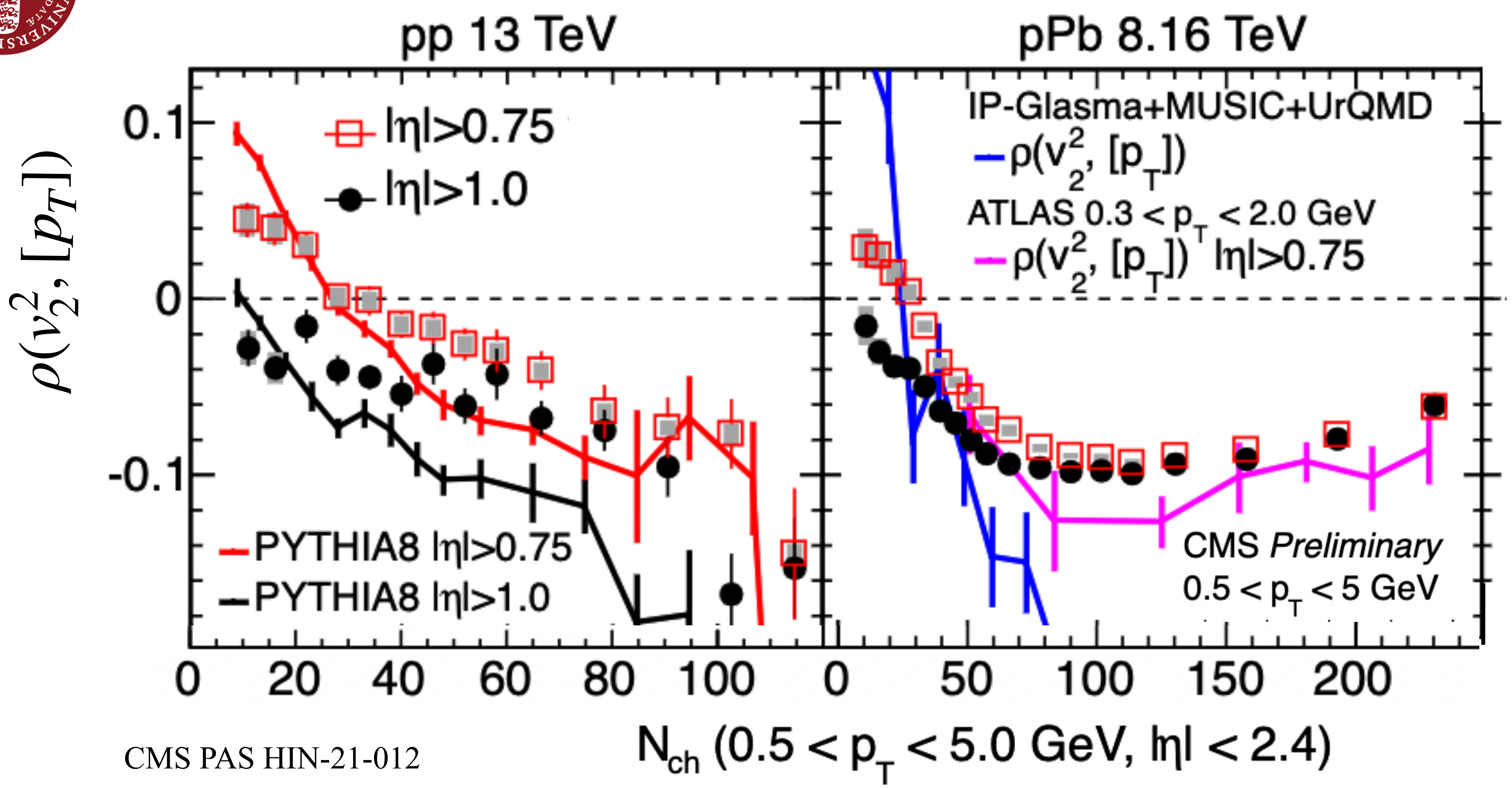
Possible initial causes: (ϵ_n or ϵ_p)

$\epsilon_n =$ Initial geometry (eccentricity)

$\epsilon_p =$ Initial momentum anisotropy

- ρ in small system- different qualitative response to different initial causes(ϵ_n or ϵ_p) - different sign and slope!
- 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?

Data shows something like that?



CMS PAS HIN-21-012

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

- $\rho(v_2^2, [p_T])$: Sign changes disappear with larger $|\Delta\eta|cut(>2.0)$! Also, depends on p$_T$.

Lim, Nagle, Phys. Rev. C 103, 064906 (2021)

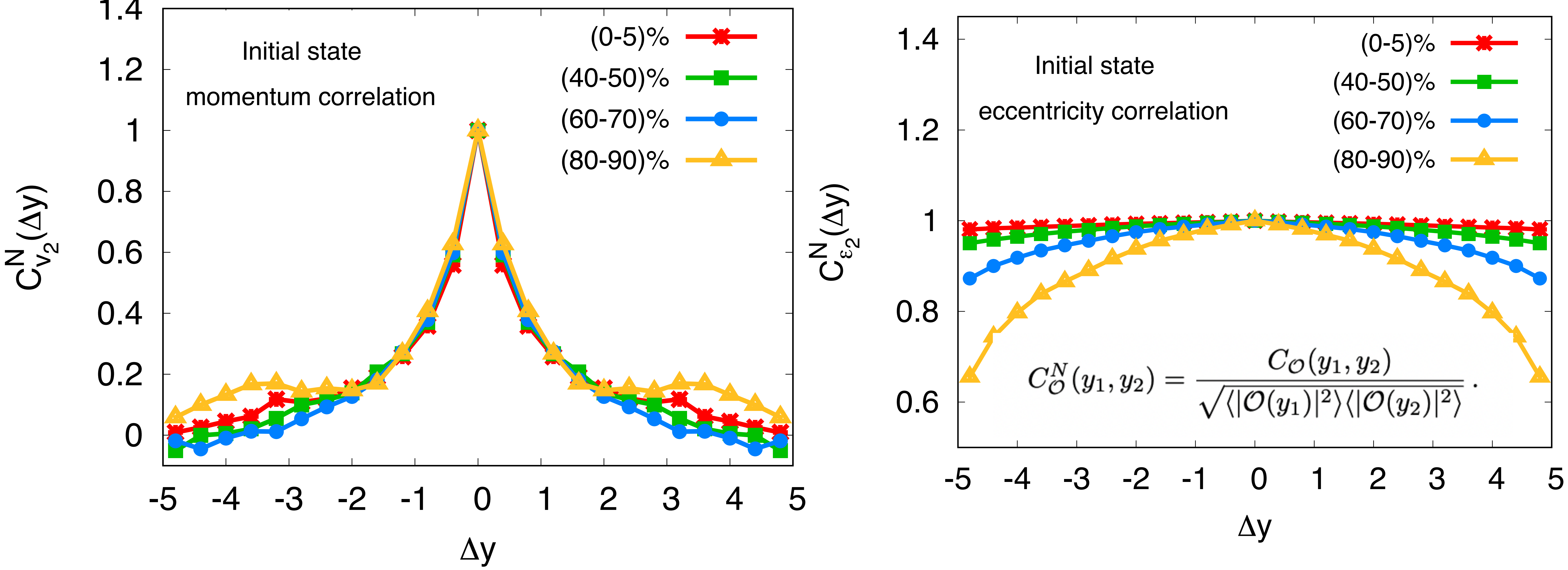
- PYTHIA generates similar pattern (similar to the IP-Glasma+MUSIC+UrQMD)!

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

- Sign change in $\rho(v_2^2, [p_T])$ - NOT unique to the presence of initial momentum anisotropy.
- $\rho(v_2^2, [p_T])$ **is sensitive to the kinematic cuts…BUT not only for non-flow effects.**

Perhaps looking at a wrong place…

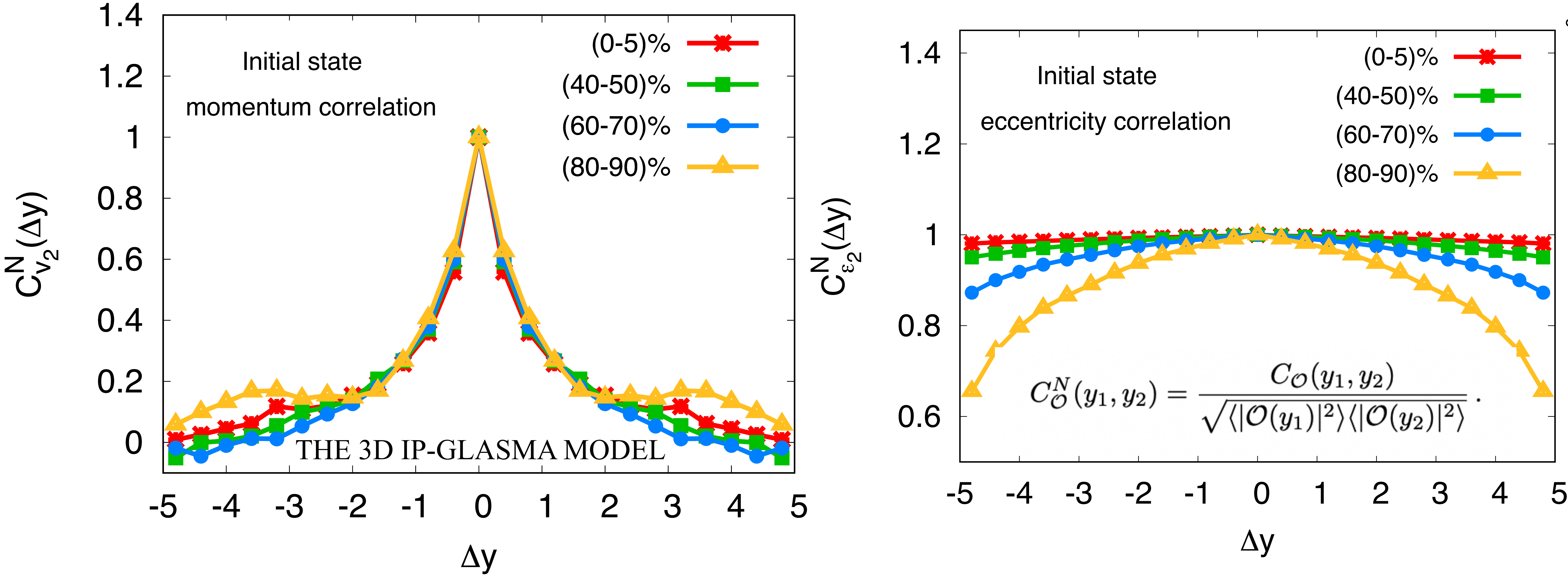
THE 3D IP-GLASMA MODEL



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…



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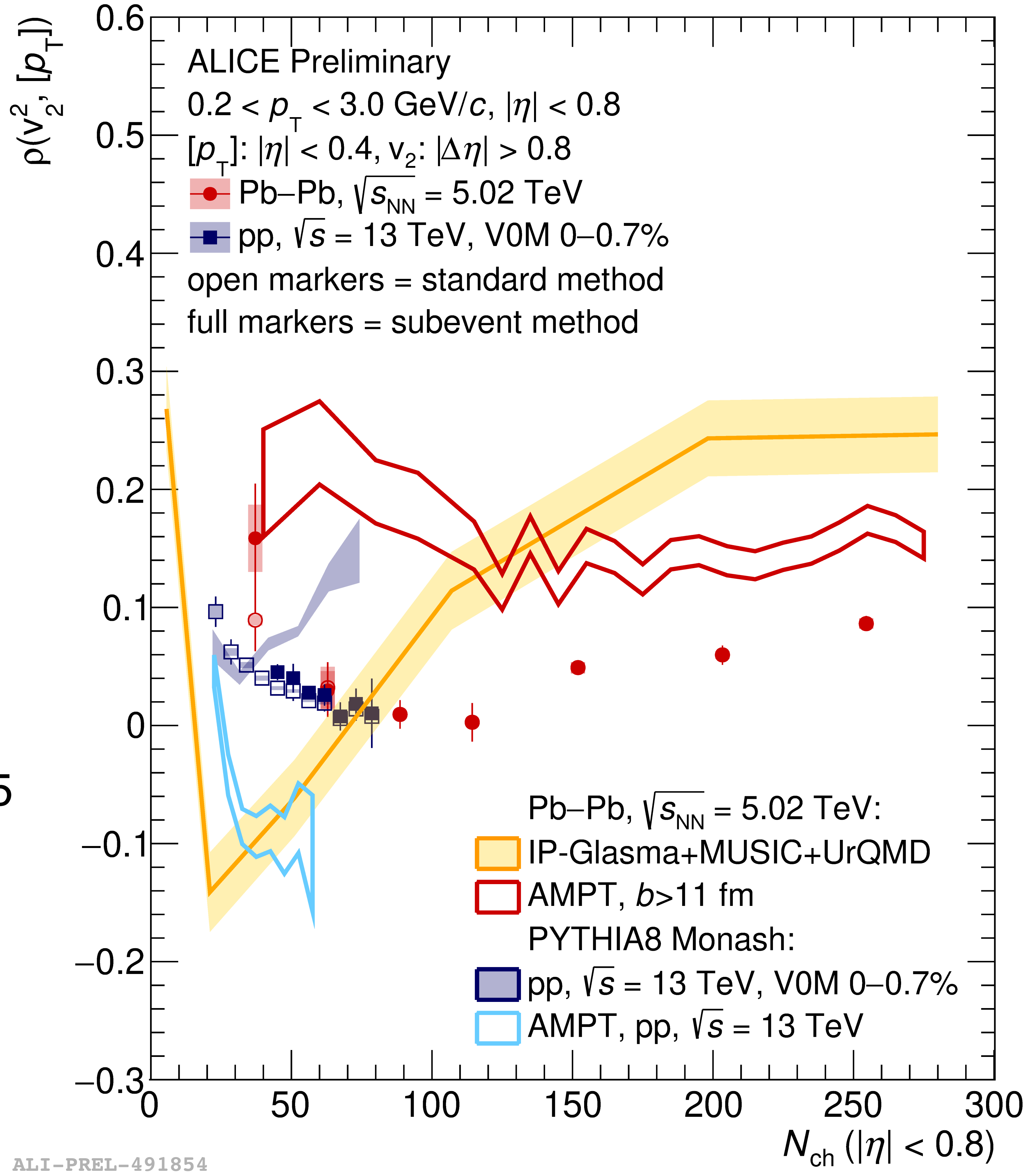
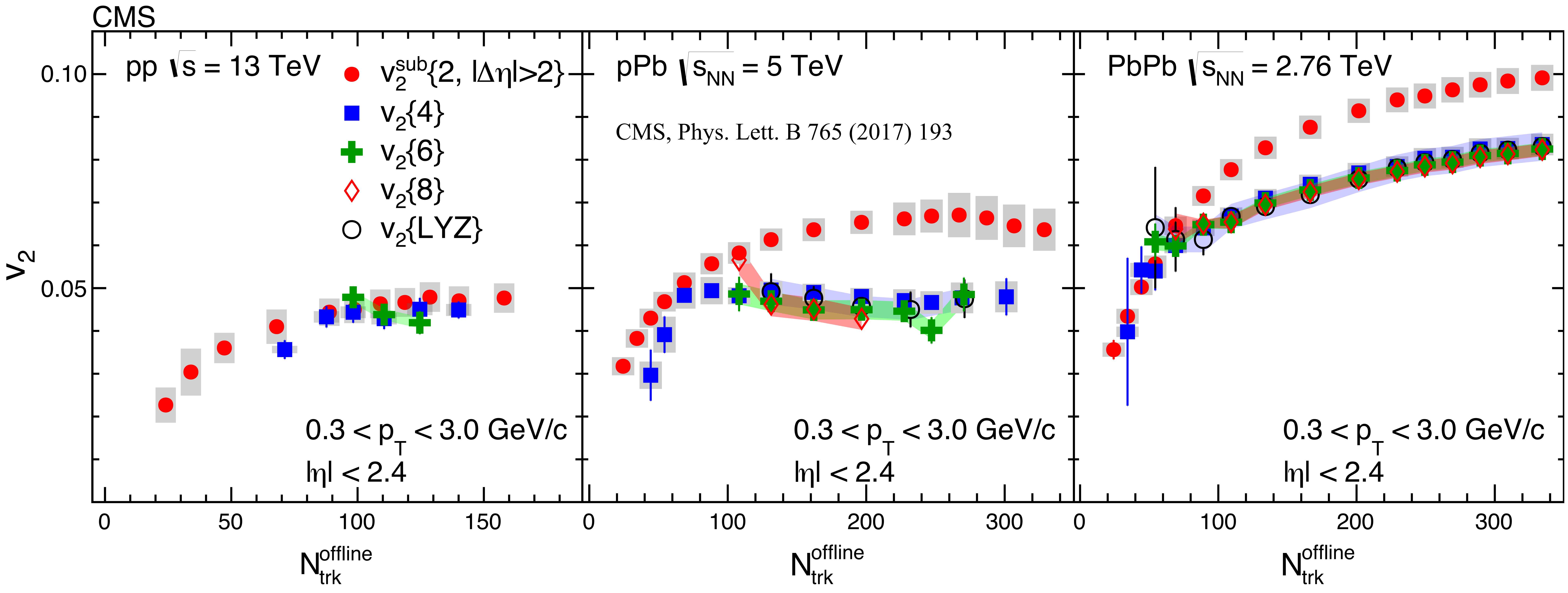


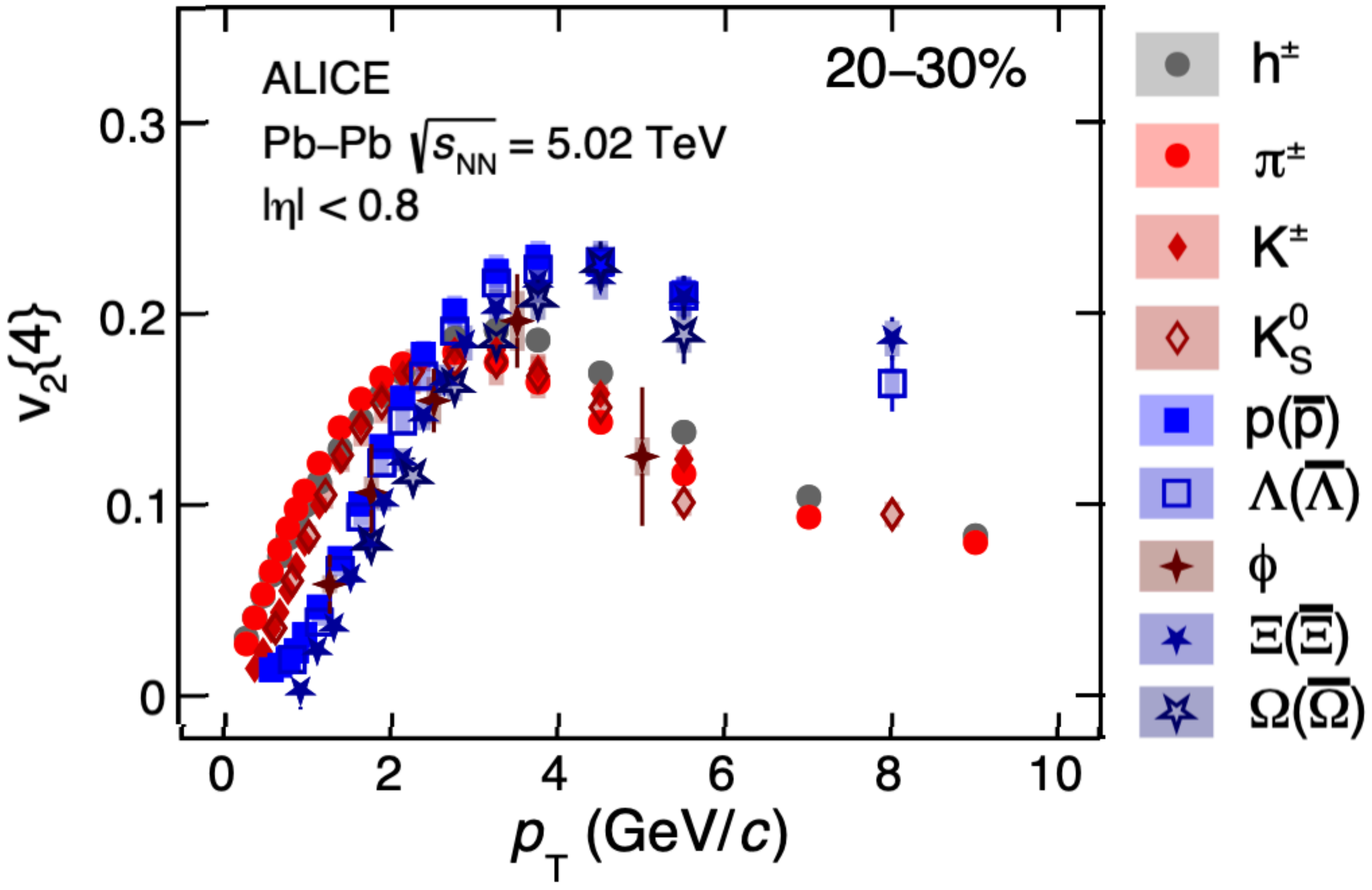
- Event geometry (transverse) — correlated across large rapidity intervals.
- Initial state momentum correlations — relatively short-range!
- $\rho(v_n^2, [p_T])$: constructed from long range correlations to suppress non-flow (jets, resonance etc).
- **Challenge (Exp): Construct short range correlations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

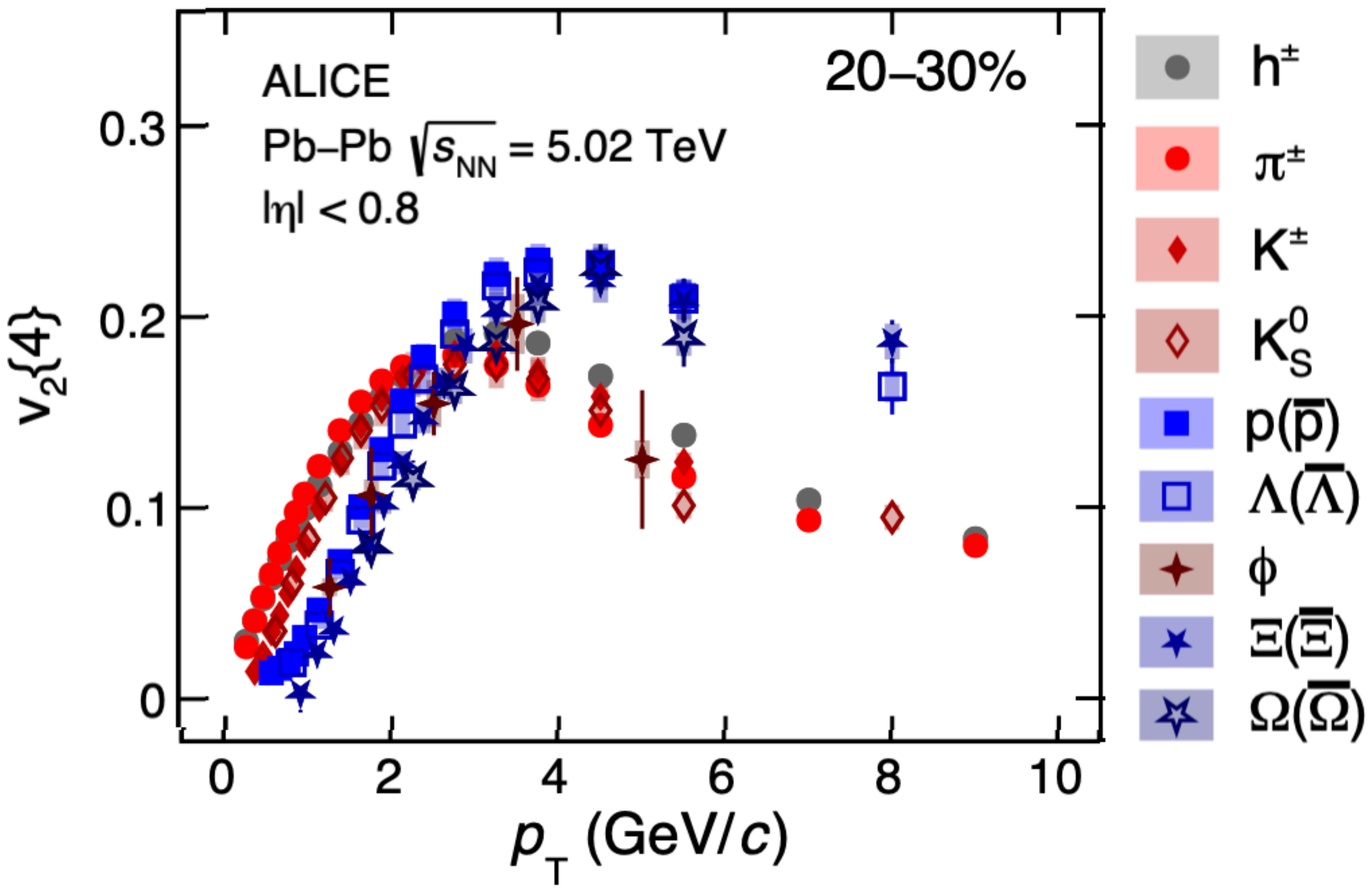


ALICE, JHEP 243 (2023) 243

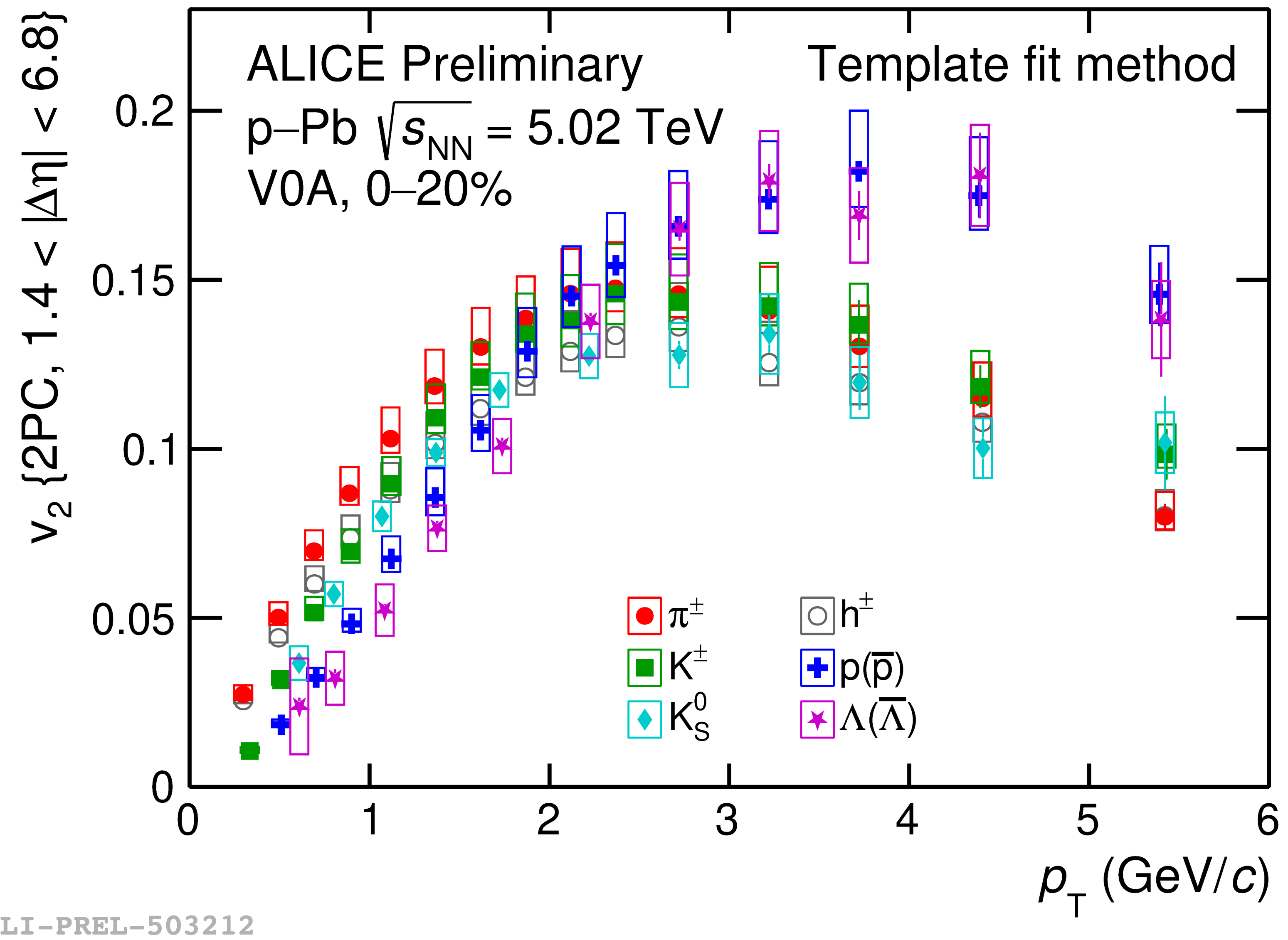
- low pT ($p_{\mathrm{T}} \lesssim 3\ \mathrm{GeV}/c$) — Mass ordering — described by hydrodynamics.
- Intermediate pT ($3 < p_{\mathrm{T}} \lesssim 10\ \mathrm{GeV}/c$) — NCQ driven Baryon-meson splitting and grouping — partonic collectivity, hadronization via quark coalescence (ϕ plays an important role)

- **What about small systems?**

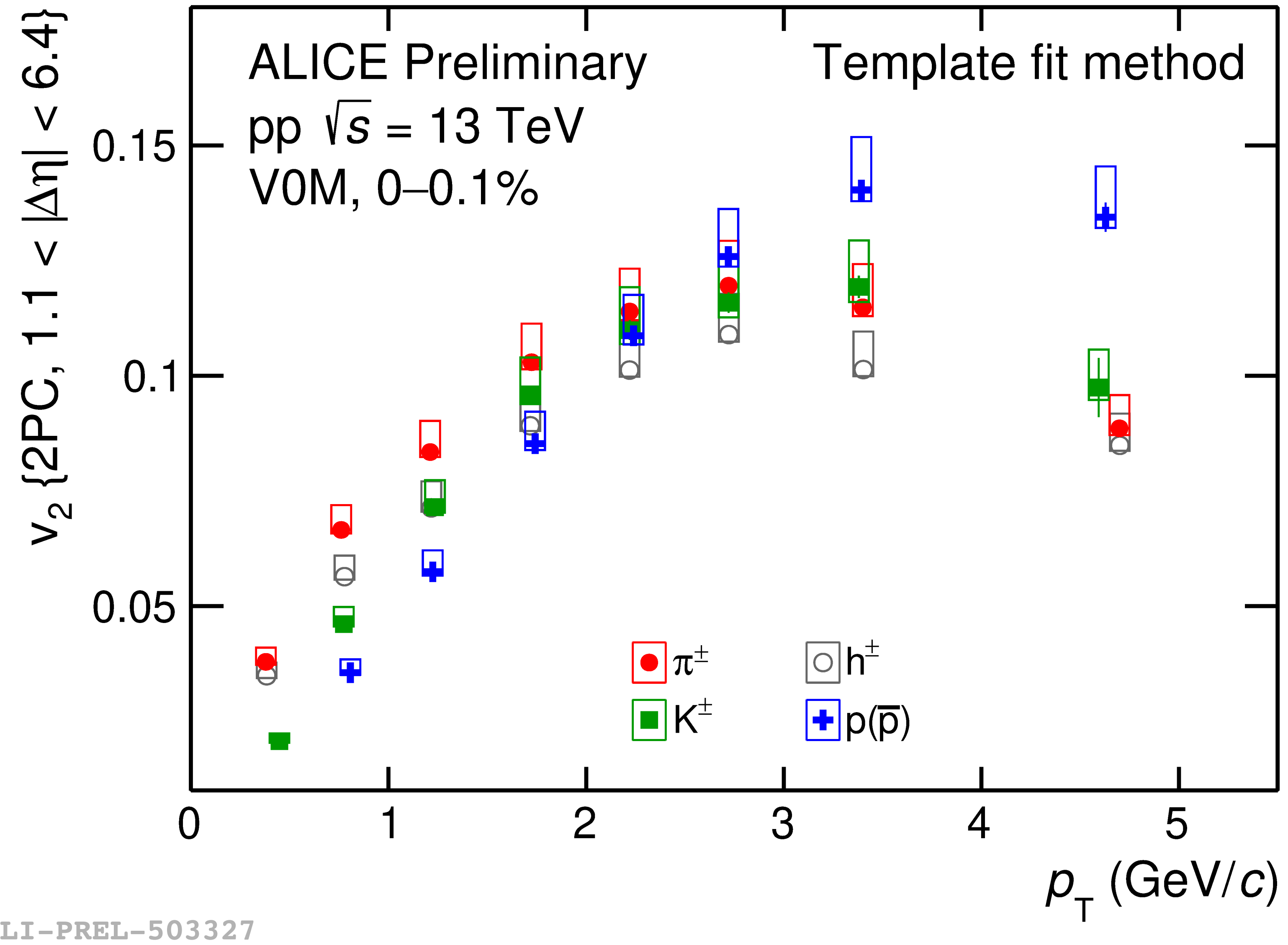
Flow of Identified particles



ALICE, JHEP 243 (2023) 243



ALI-PREL-503212

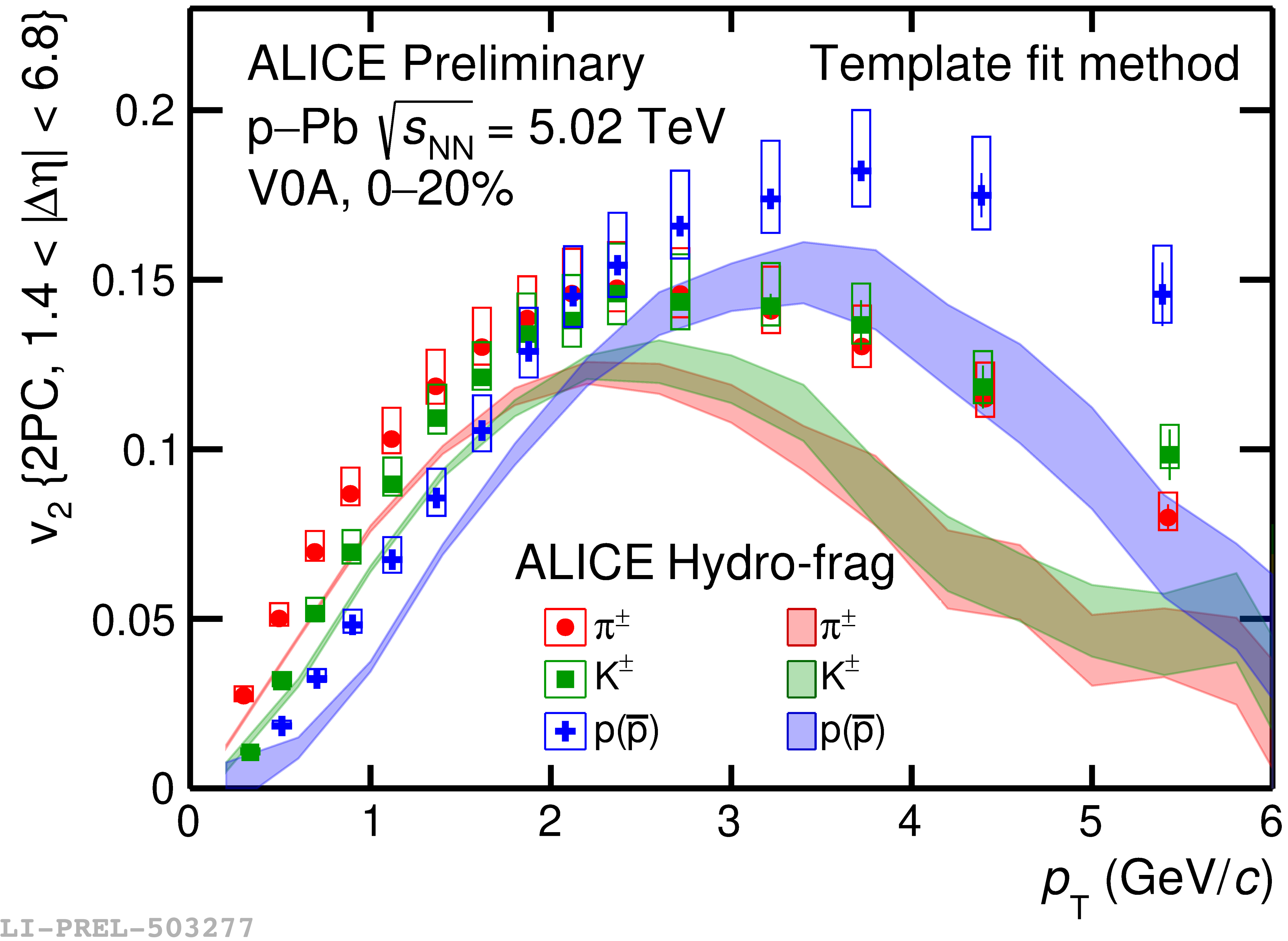


ALI-PREL-503327

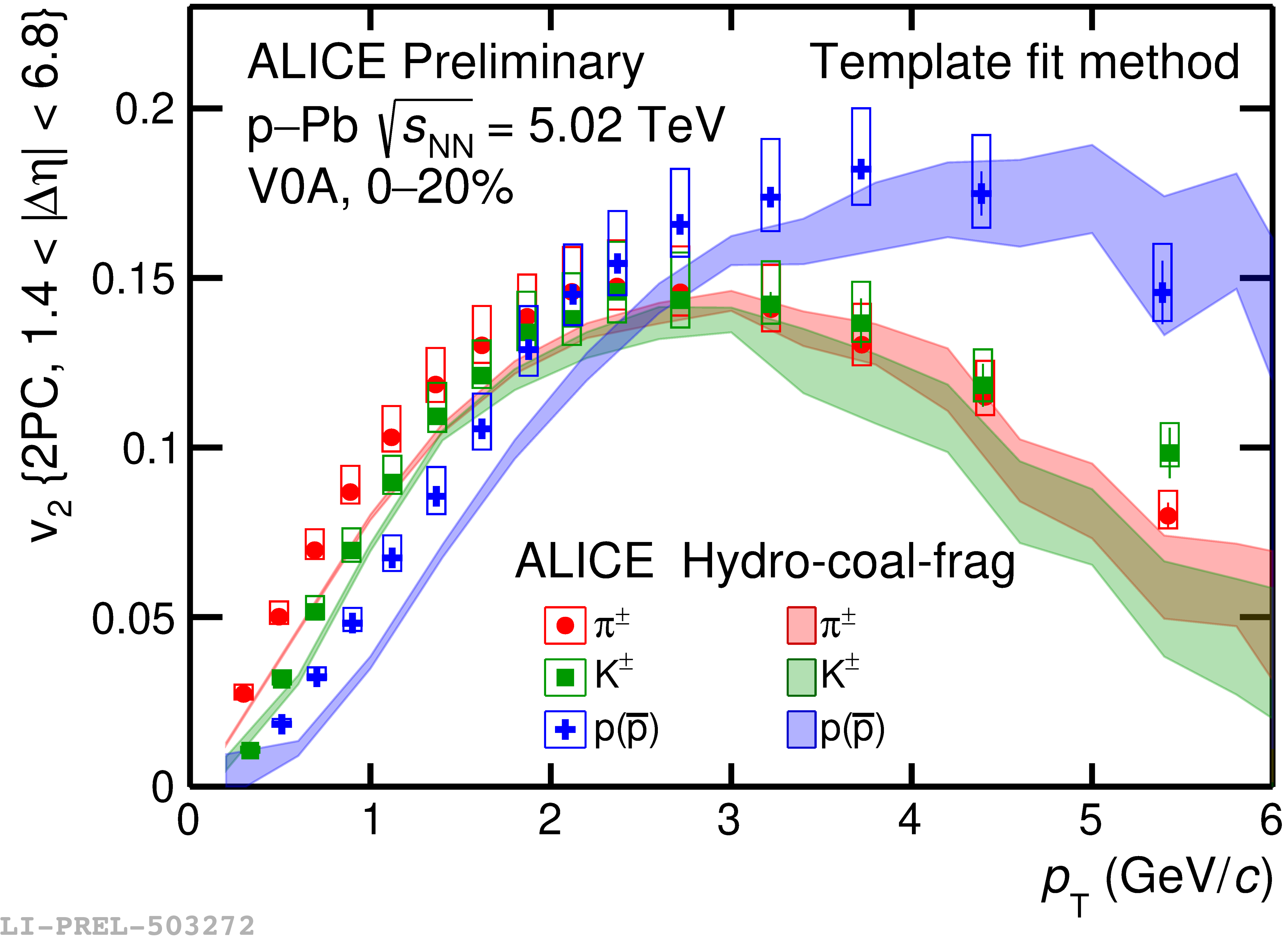
- low pT ($p_T \lesssim 3$ GeV/c) — Mass ordering — described by hydrodynamics.
- Intermediate pT ($3 < p_T \lesssim 10$ GeV/c) — NCQ driven Baryon-meson splitting and grouping — partonic collectivity, hadronization via quark coalescence (ϕ plays an important role).
- Small systems: Qualitatively similar 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

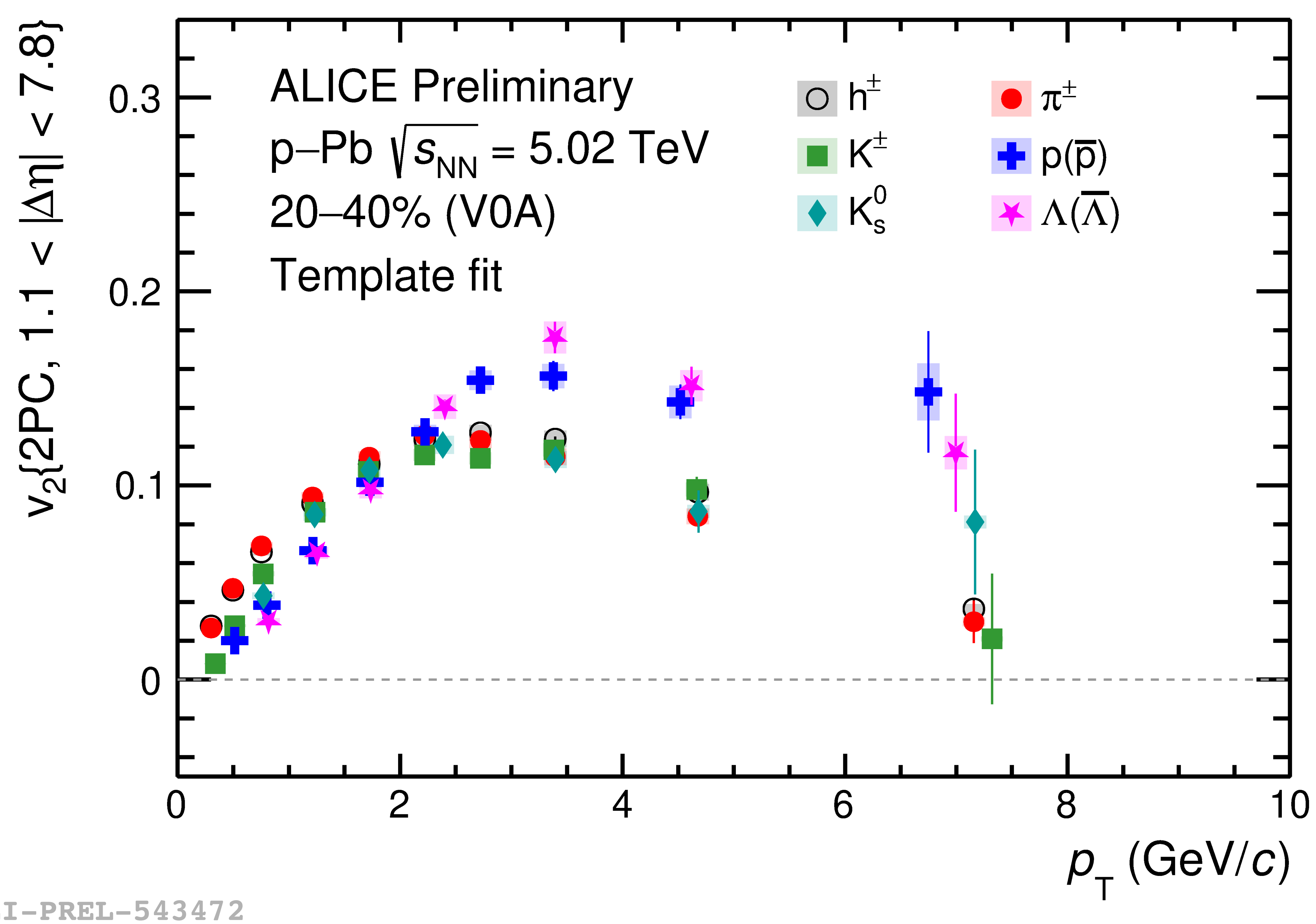


ALI-PREL-503272

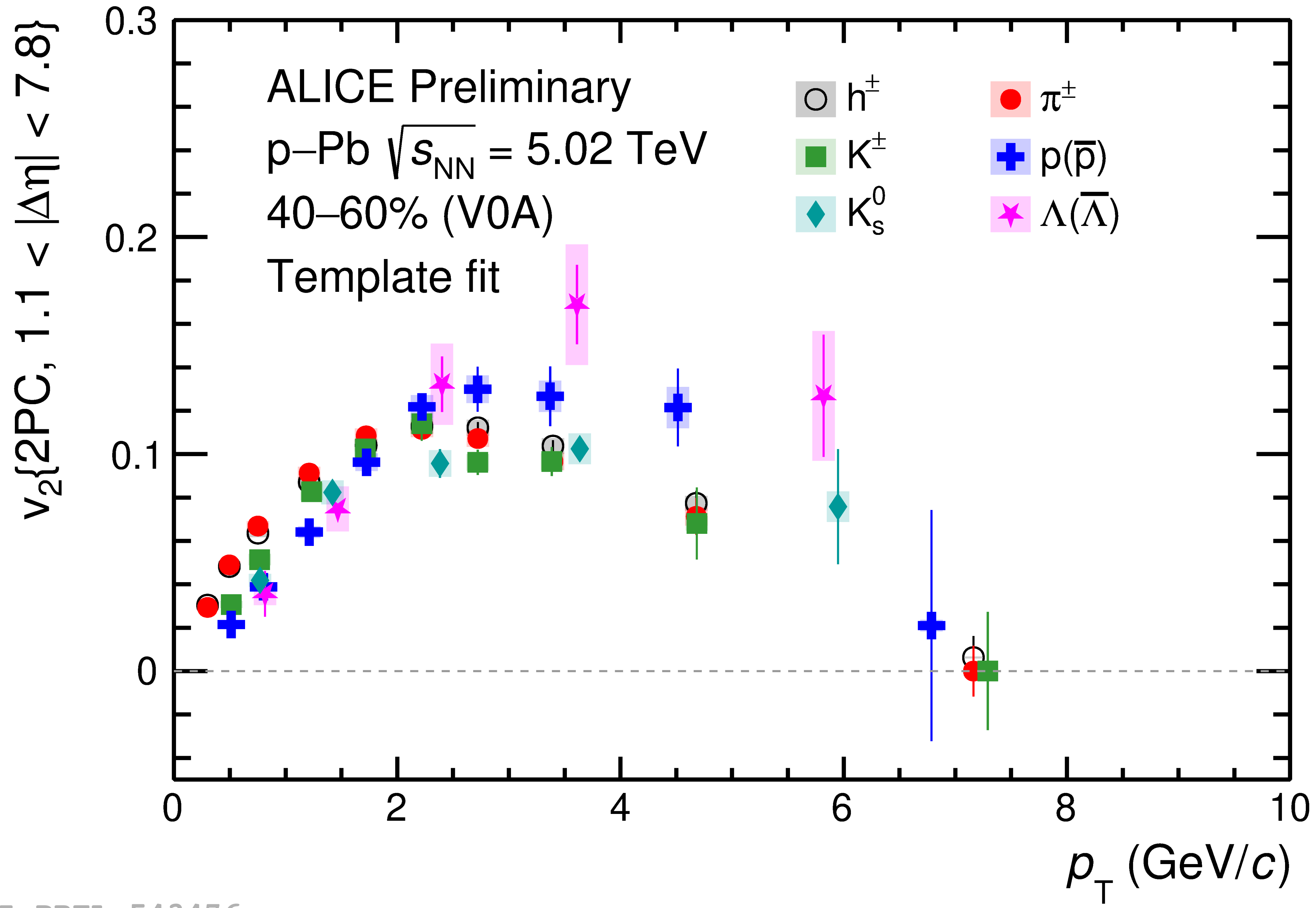
- Small systems: Qualitatively similar to the heavy-ion results.
- For p-Pb: Hydro+Coal+Frag can explain the results but not with Hydro+Frag only.
- Partonic collectivity in high multiplicity p-Pb collisions!

- **Need model input for pp**

Still flowing?



ALI-PREL-543472

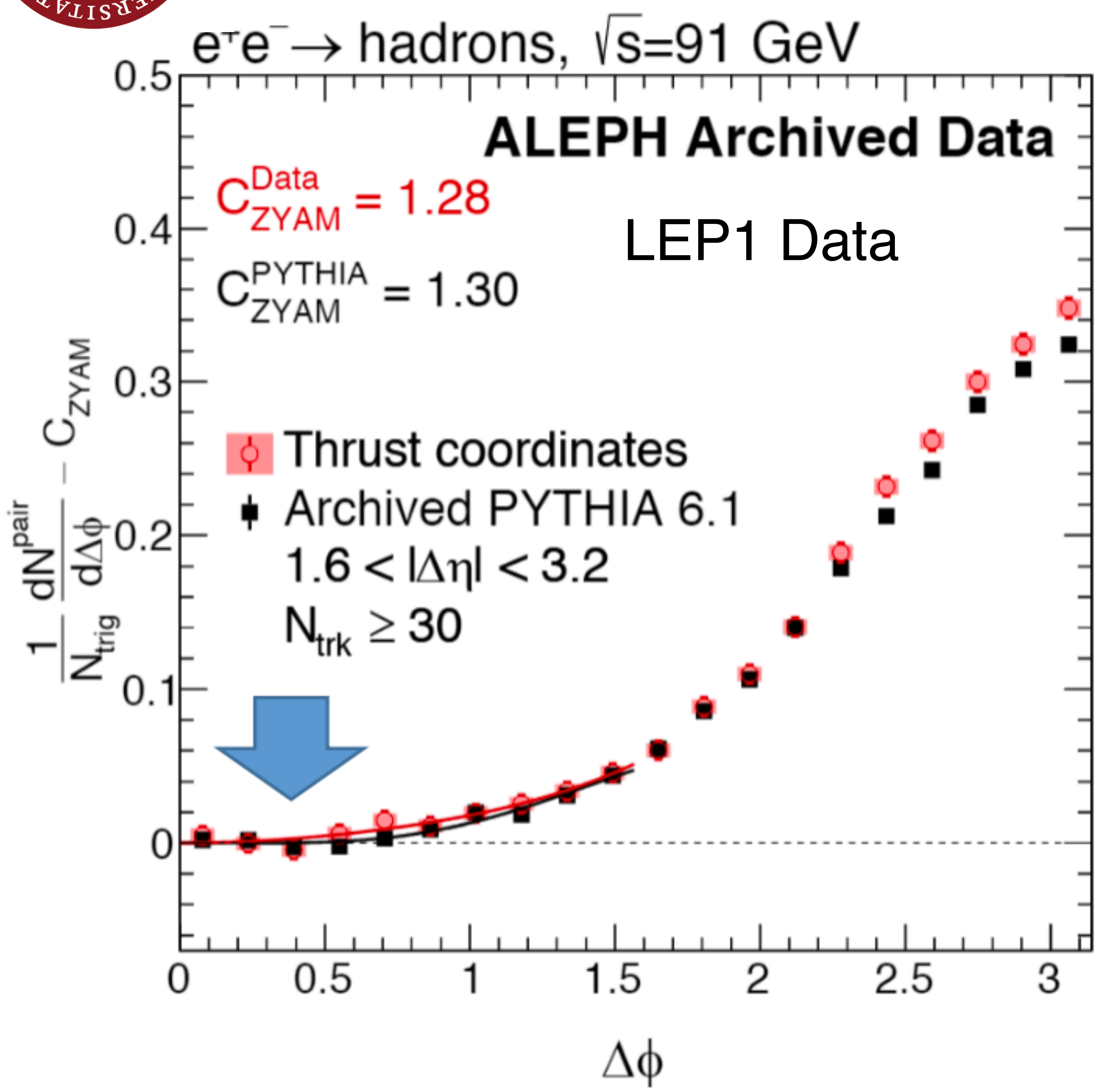


ALI-PREL-543476

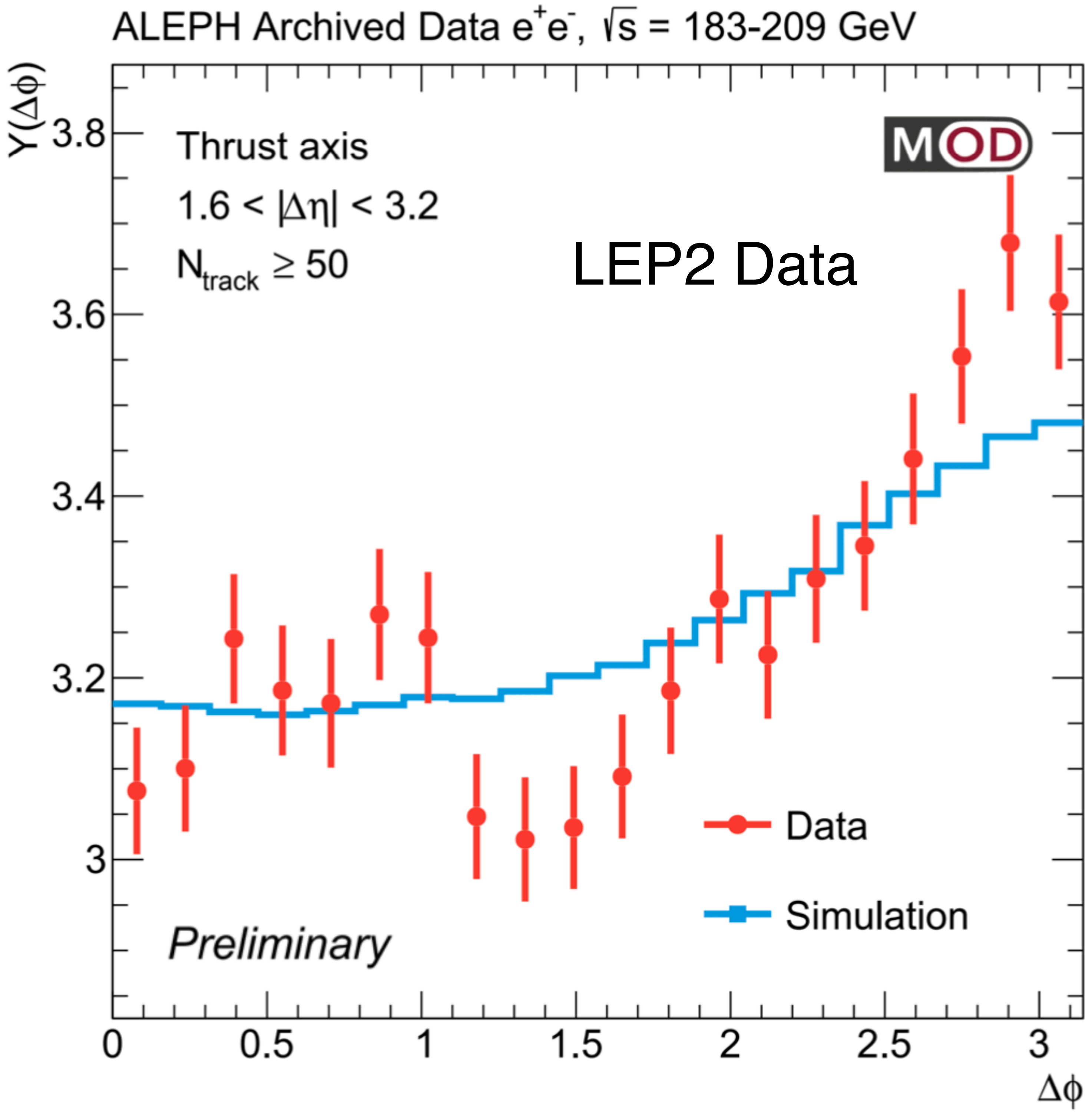
- Mass ordering and Baryon-meson splitting and grouping exists upto lower multiplicity classes of p-Pb!
- Can any model(s) explain the small system results over all the multiplicity classes?
- Initial state effects can be probed in low multiplicity classes?

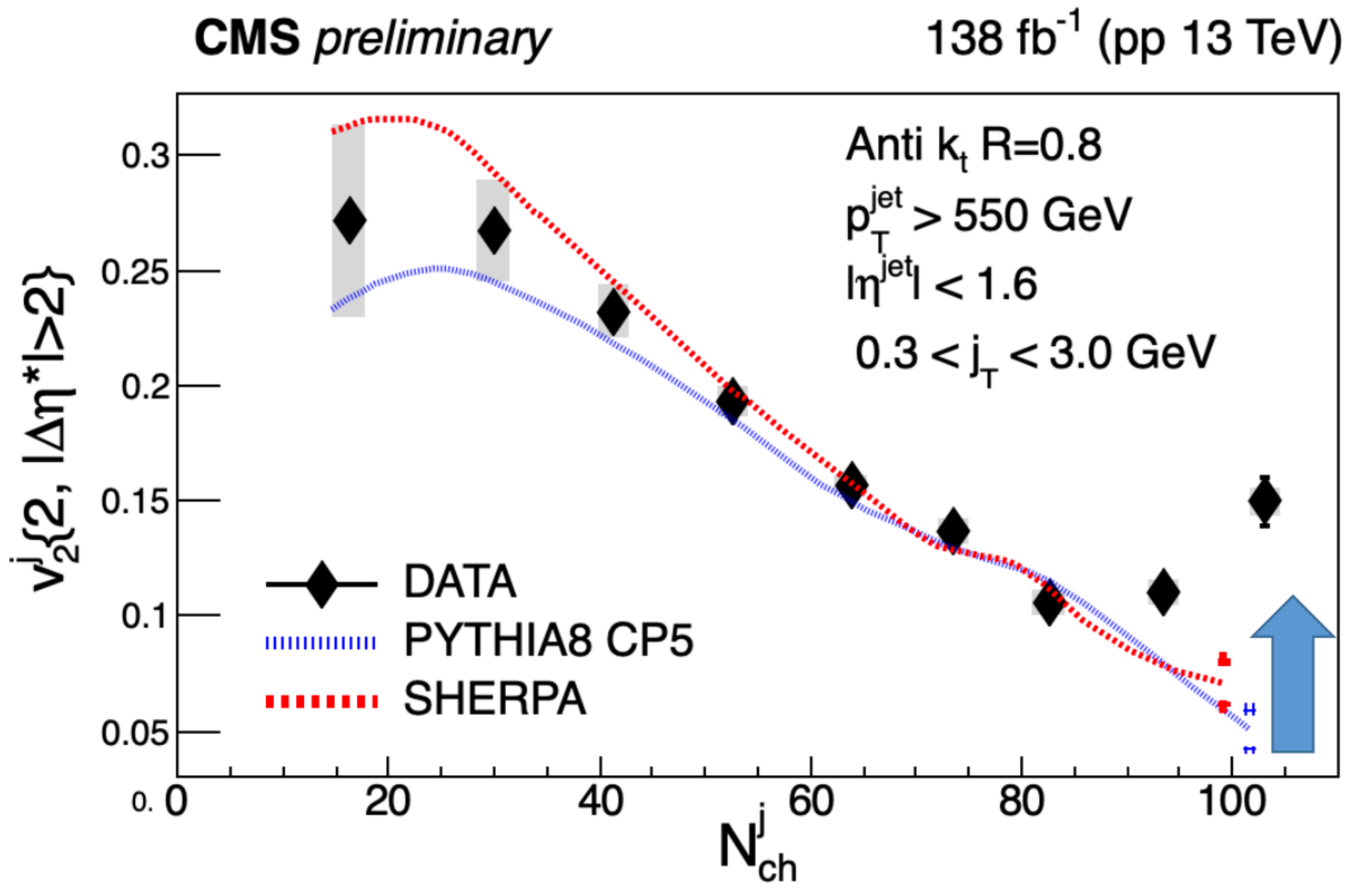
  - **What is the “small” (pA, pp, ee…) and “dilute” (lower multiplicity) limit of onset of collectivity?**

What is the small and dilute limit for collectivity?



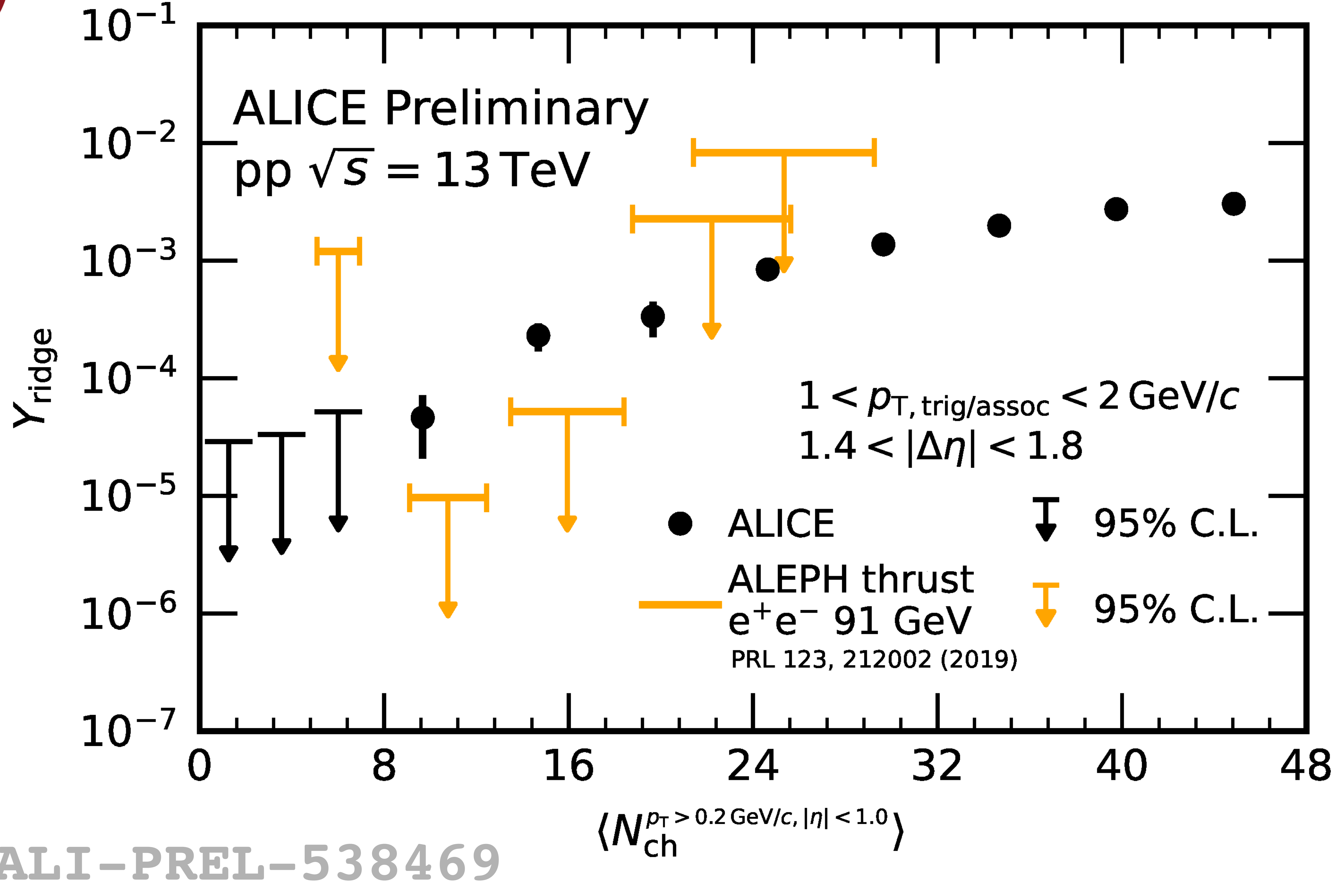
ALEPH archived data PRL 123, 212002 (2019)

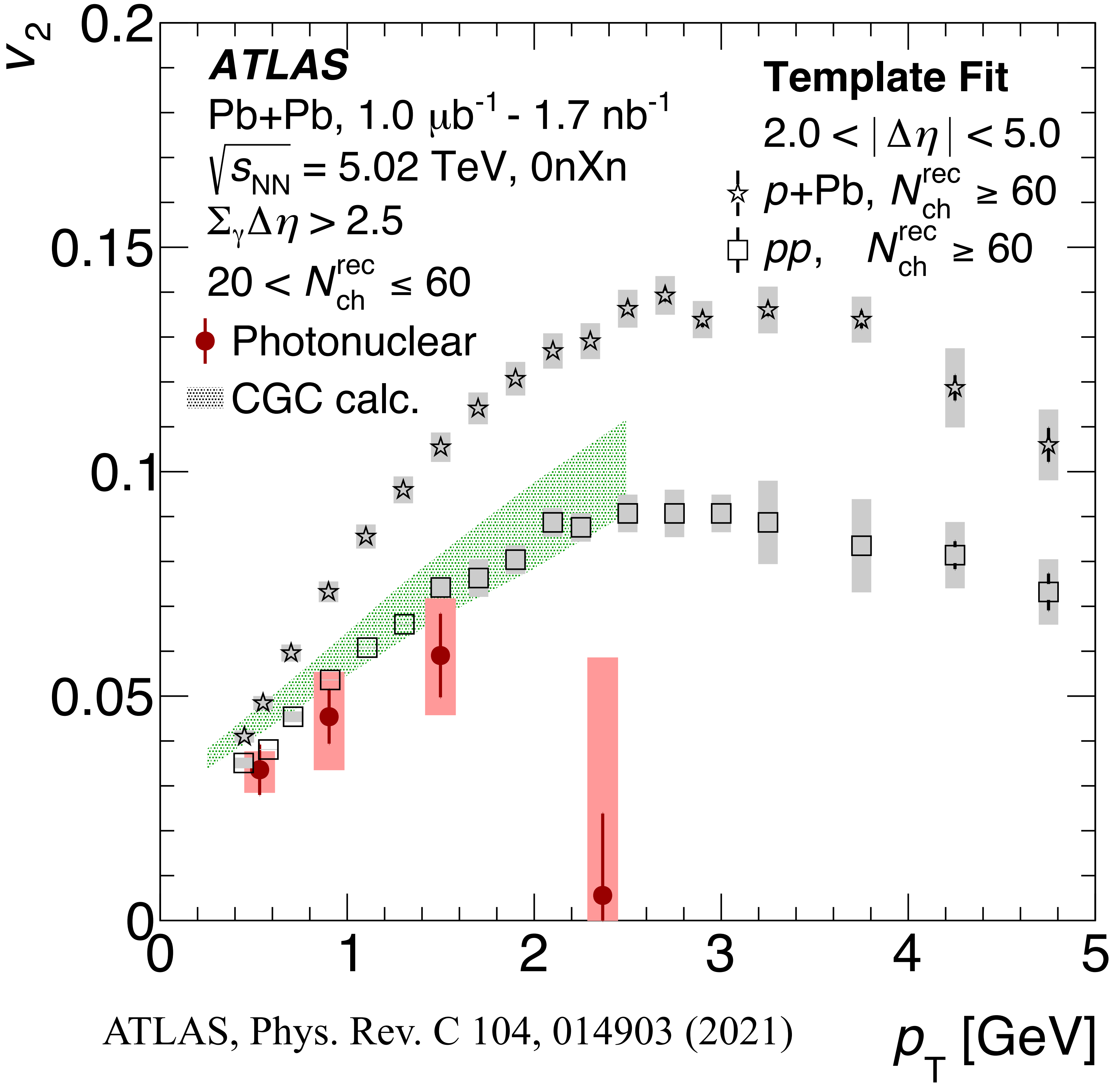




- e^+e^- collisions— point-like collision — no uncertainties on initial geometry or PDF description, no Multi-Parton Interactions (MPI).
- No significant long range correlation in e^+e^- —> $q\overline{q}$ process. New baseline for collectivity?
- Ridge in high multiplicity e^+e^- collisions (e^+e^- —> W^+W^- —> $q\overline{q}q\overline{q}$ process)!
- A single high multiplicity jet can generate a ridge-like structure. QCD ridge? What about ridge from MPI?

What is the small and dilute limit for collectivity?





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

- Ridge Yield: $Y^{pp} > Y^{e^+e^-}$ at <Nch> ~15 with ~3sigma.
- Photonuclear Collisions with PbPb UPC at the LHC: Finite v_2! A good probe to study initial state conditions.
- MPI can generate ridge structures even in low multiplicity.
- Interplay between the “Multiplicity" and “MPI” on ridge in small and dilute systems to be explored…

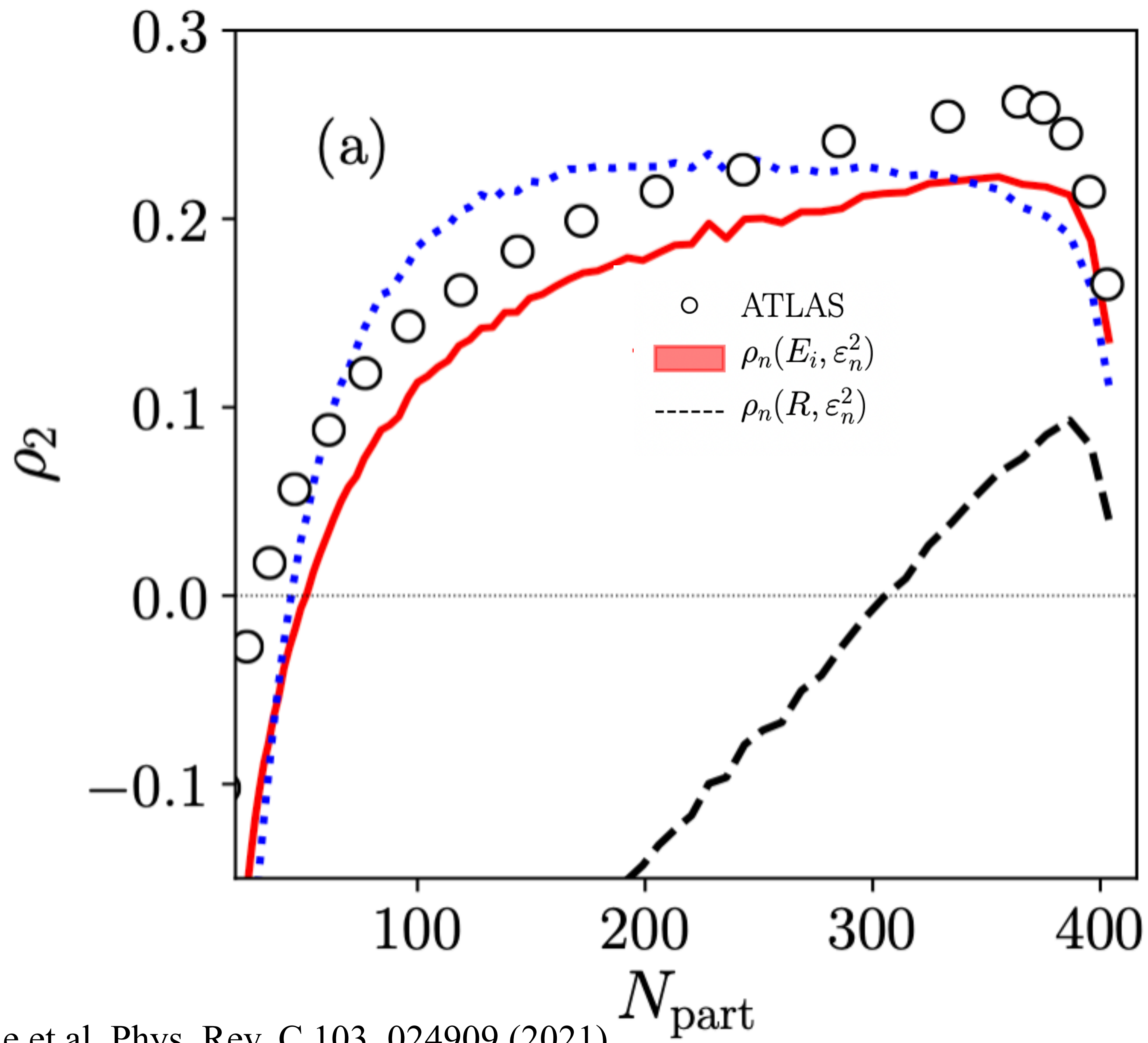
Summary

- Small systems: Partonic collectivity in high multiplicity classes of small systems! Similar pattern in lower multiplicity classes! Same origin?
- Initial state effects are important (sub-nucleonic fluctuations + momentum anisotropy + ? + ?). The perfect combination (?) is still in making.
- What is the small and dilute limit of collectivity?
- Ongoing analyses of pPb, pp, ep, γPb, e^+e^-… collisions — to determine the role of system size, multiplicity, MPI, initial and final state effects on collectivity.
- Non-flow subtraction, longitudinal flow decorrelation to be understood in detail for correct interpretation of the experimental results.
- The new high statistics dataset at the LHC for low multiplicity pp collisions, UPC would be useful.

Thank You

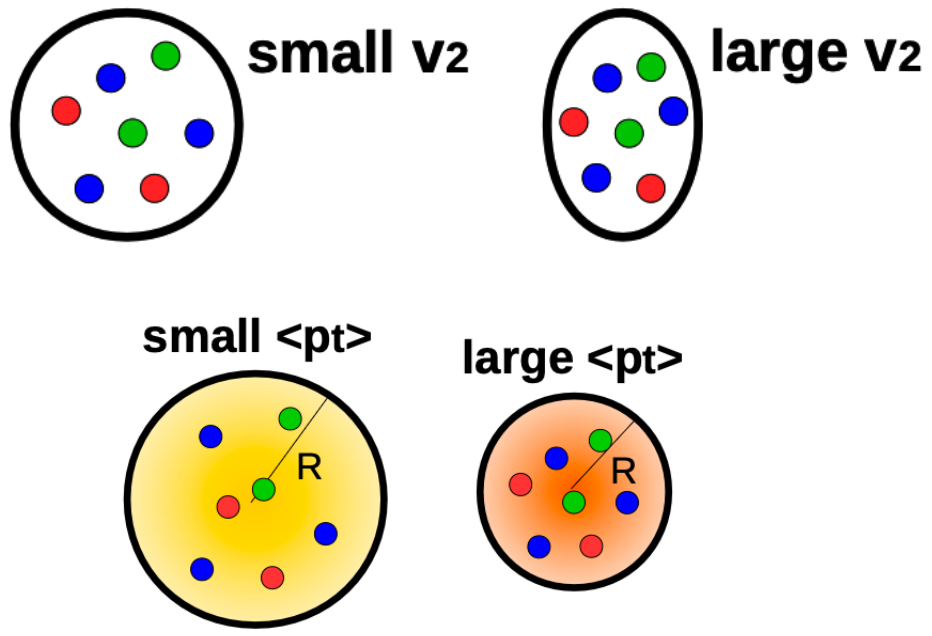
Back Up

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)

Initial State	Final State
ϵ_n	v_n
Initial State	Final State
$1/R\ , E$	$< p_T >$



- Pearson correlation coefficient:

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

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

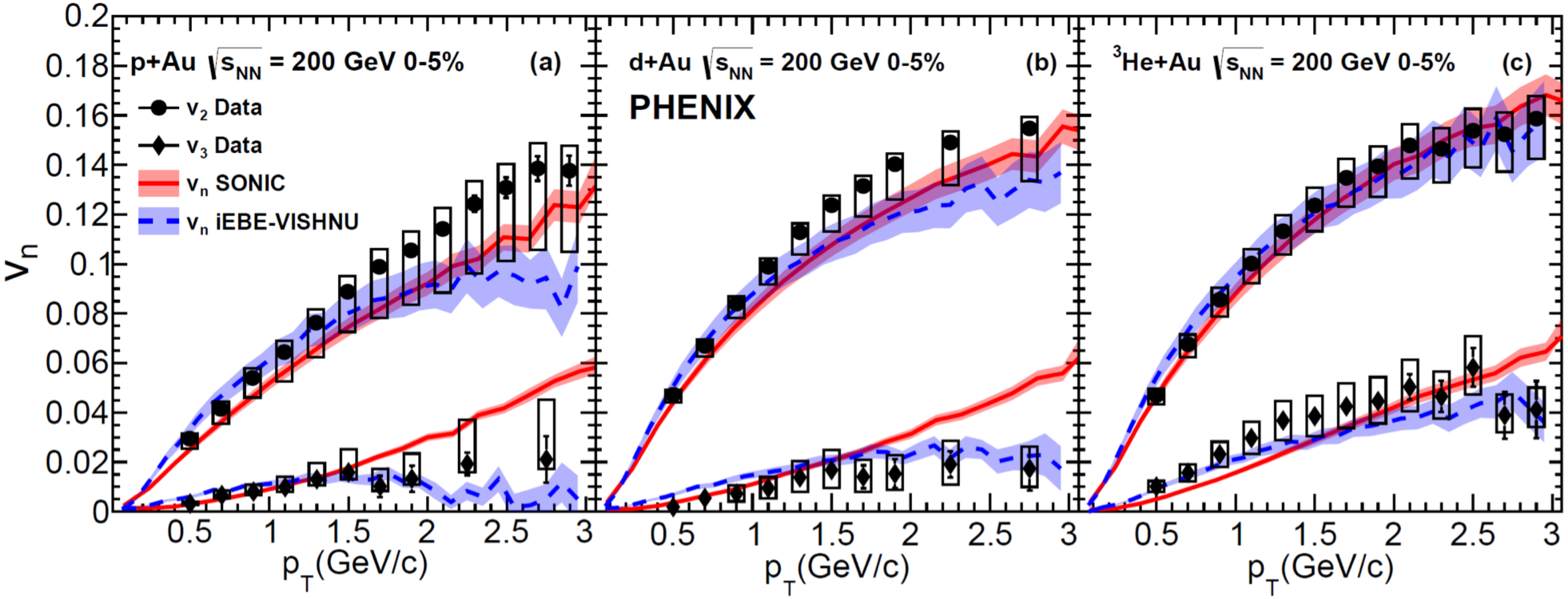
Final State $\longrightarrow$ Initial State

$\rho(v_n^2, < p_T >) \approx$	$\rho(v_n^2, < p_T >) \approx$	$\rho(\epsilon_{n/p}^2, E)$
(Data)	(Model)	(Model)

- 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 Geometry or Initial Momentum anisotropy?



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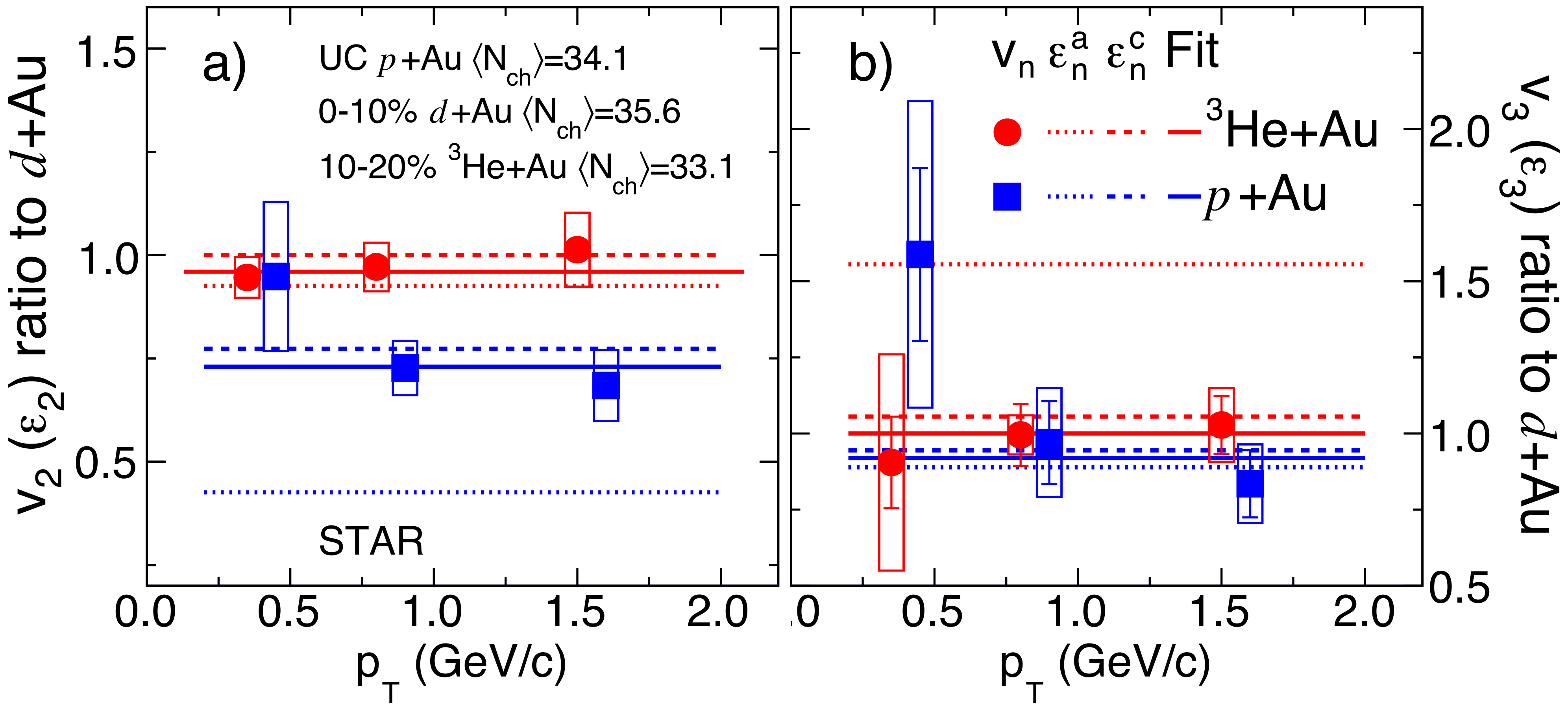
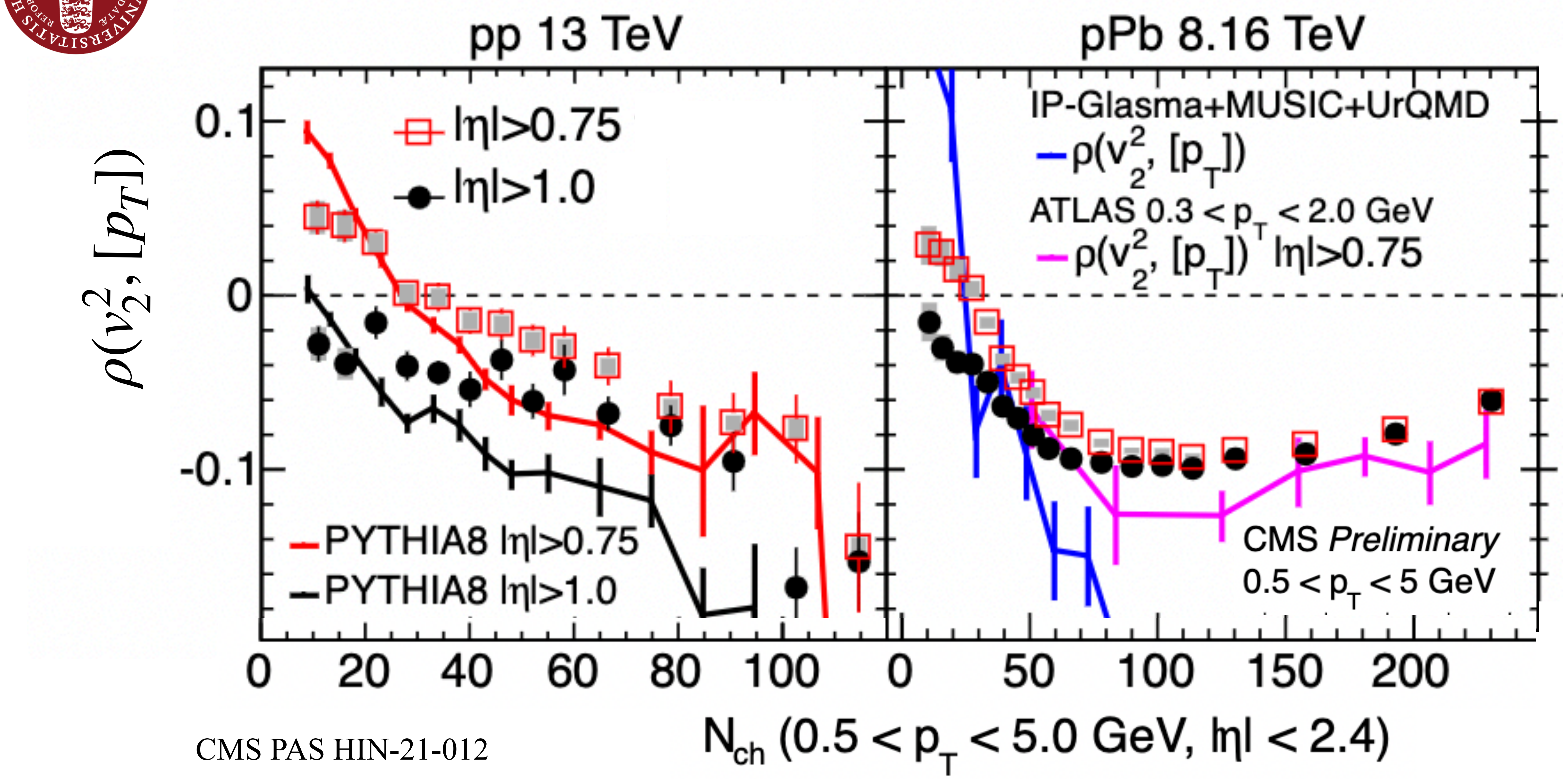


STAR, Phys. Rev. Lett. 130, 242301 (2023)

Not really…



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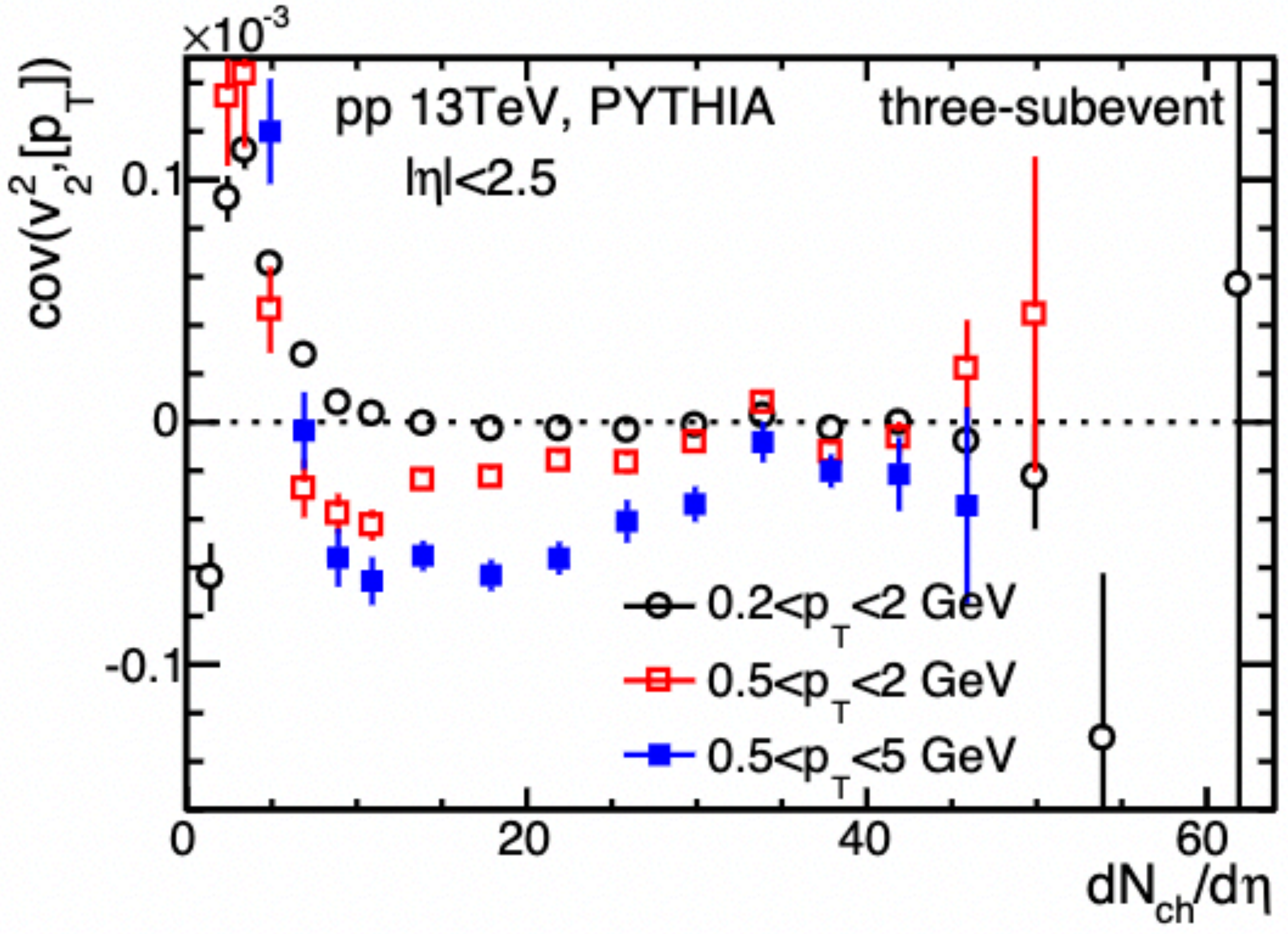
ATLAS Collaboration, Eur. Phys. J. C 79,. 12, 985 (2019)

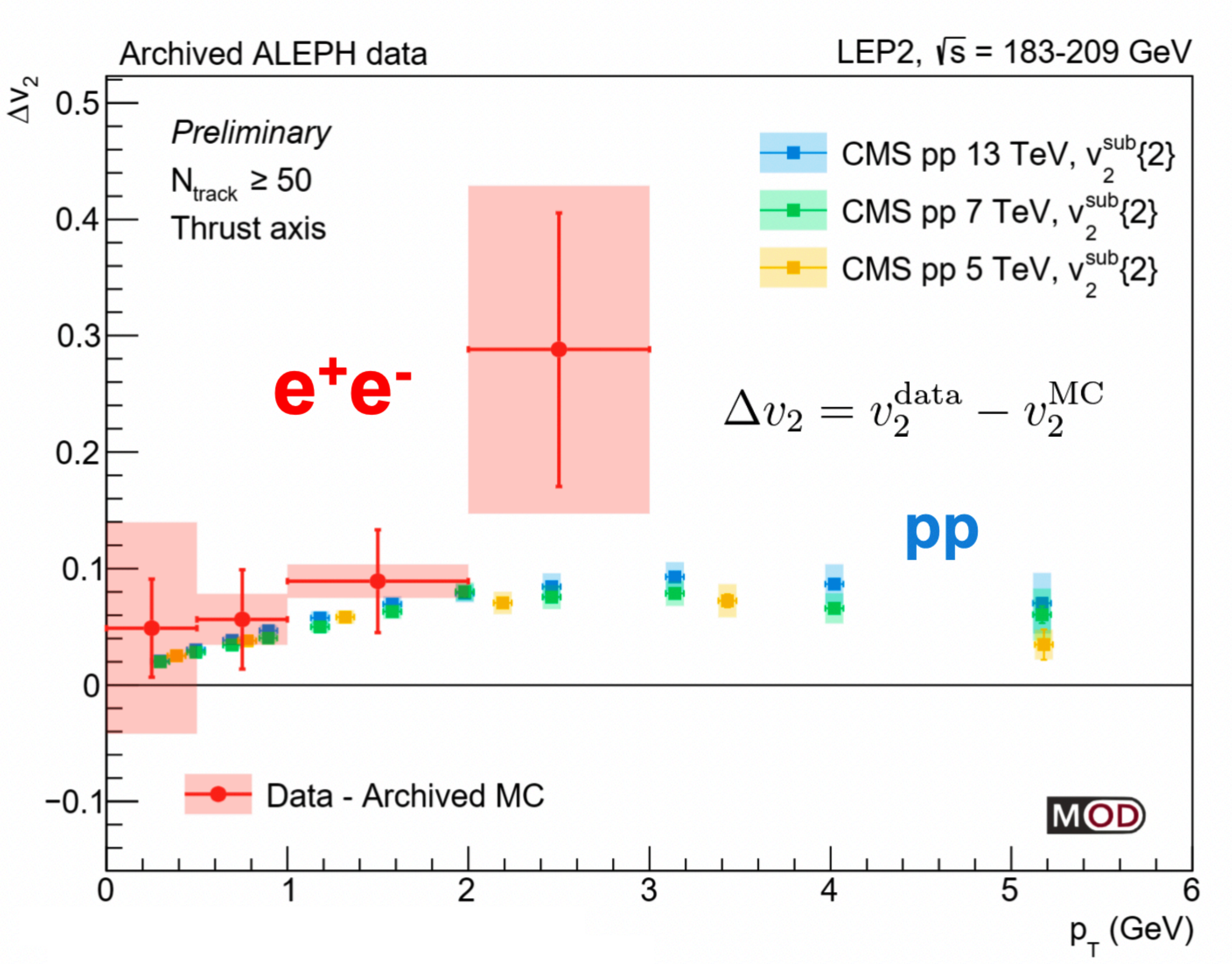


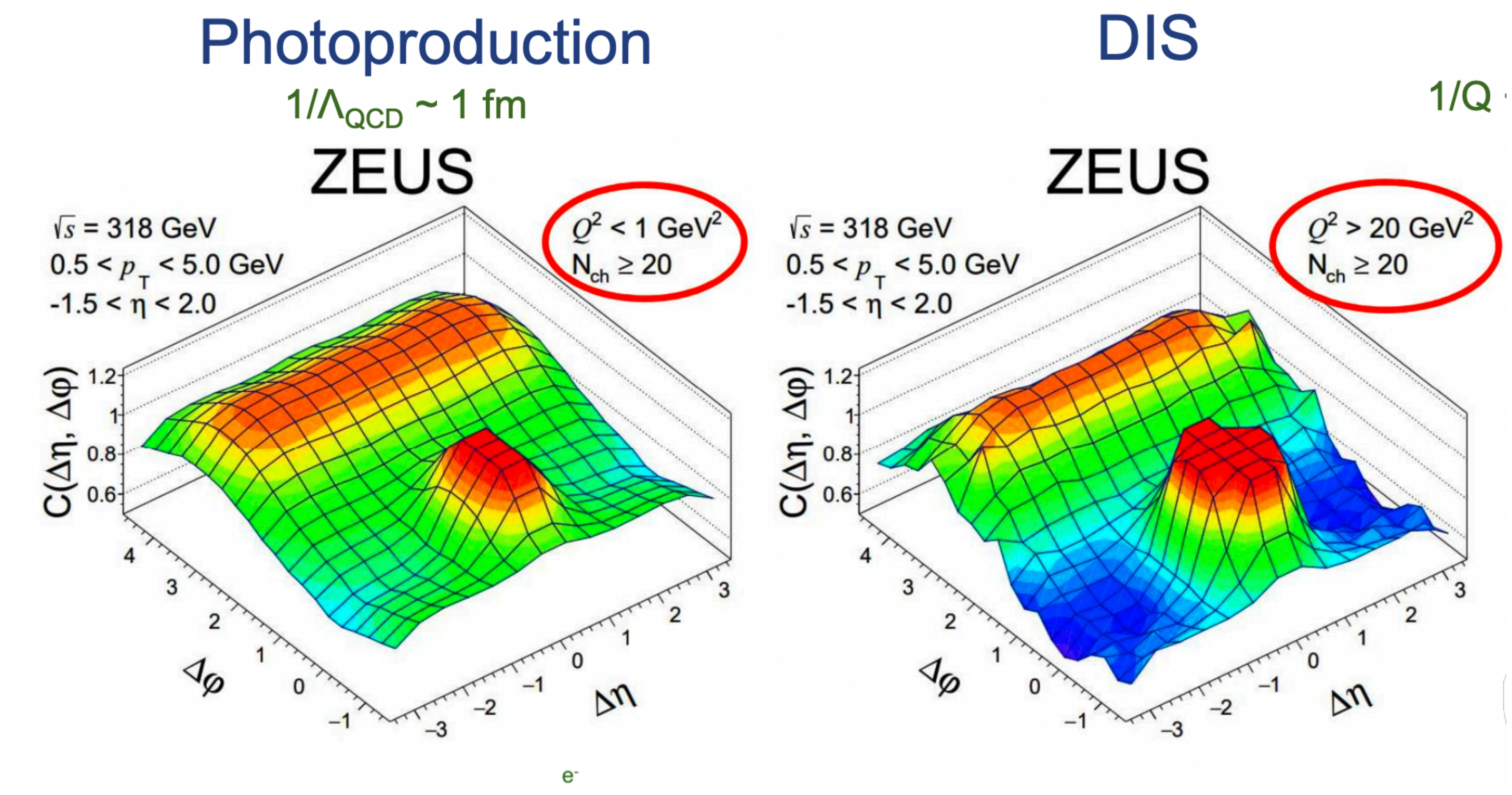
Behera, Bhatta, Jia, Zhang, Phys Lett. B 822, 2021, 136702

- $\rho(v_2^2, [p_T])$: Sign changes disappear with larger $|\Delta\eta| cut(>2.0)$! Also, depends on p_T.

Lim, Nagle, Phys. Rev. C 103, 064906 (2021)

- PYTHIA generates similar pattern (similar to the IP-Glasma+MUSIC+UrQMD)!
- Sign change in $\rho(v_2^2, [p_T])$ - NOT unique to the presence of initial momentum anisotropy.
- $\rho(v_2^2, [p_T])$ **is sensitive to the kinematic cuts…BUT not only for non-flow effects.**

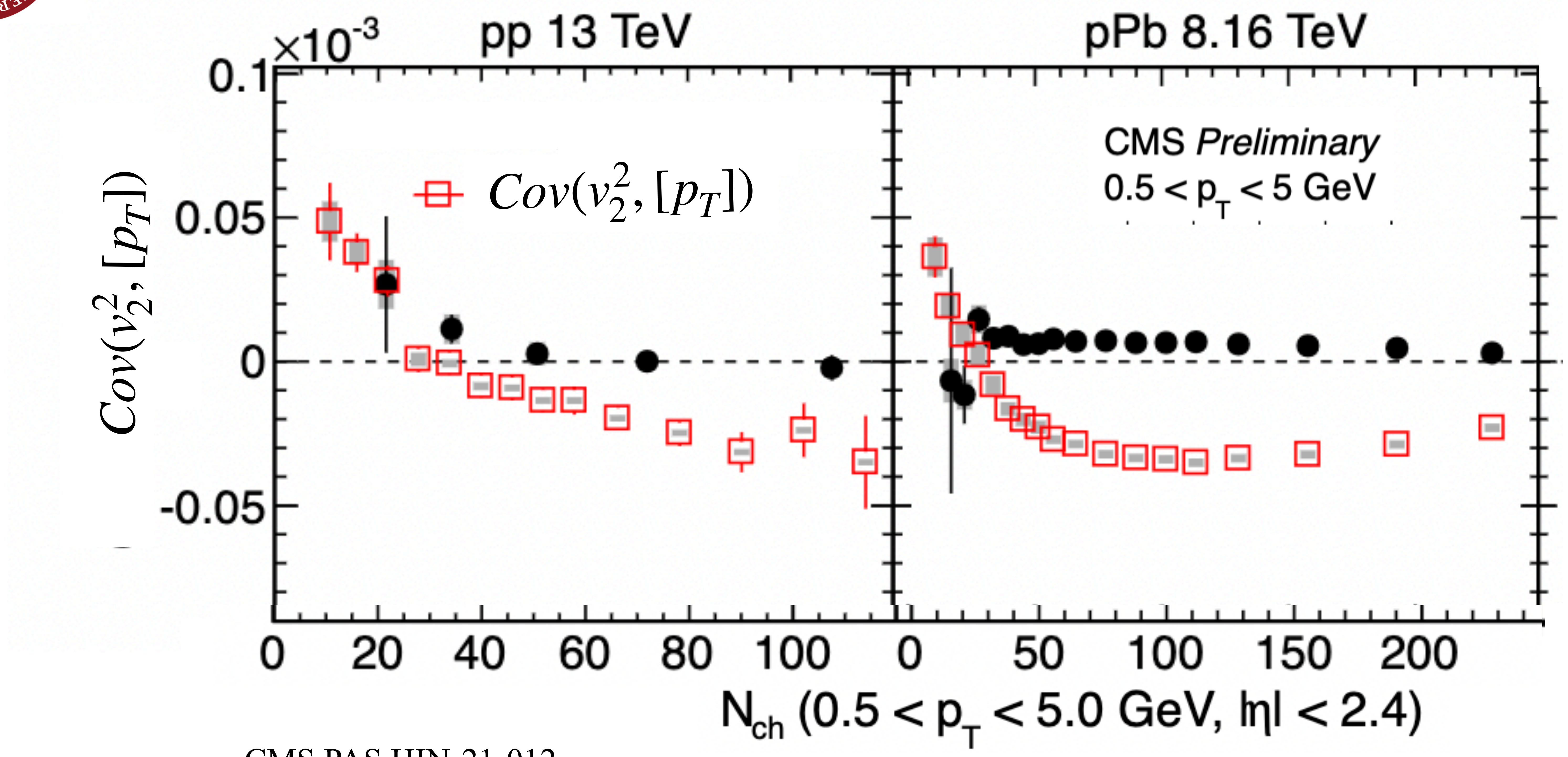




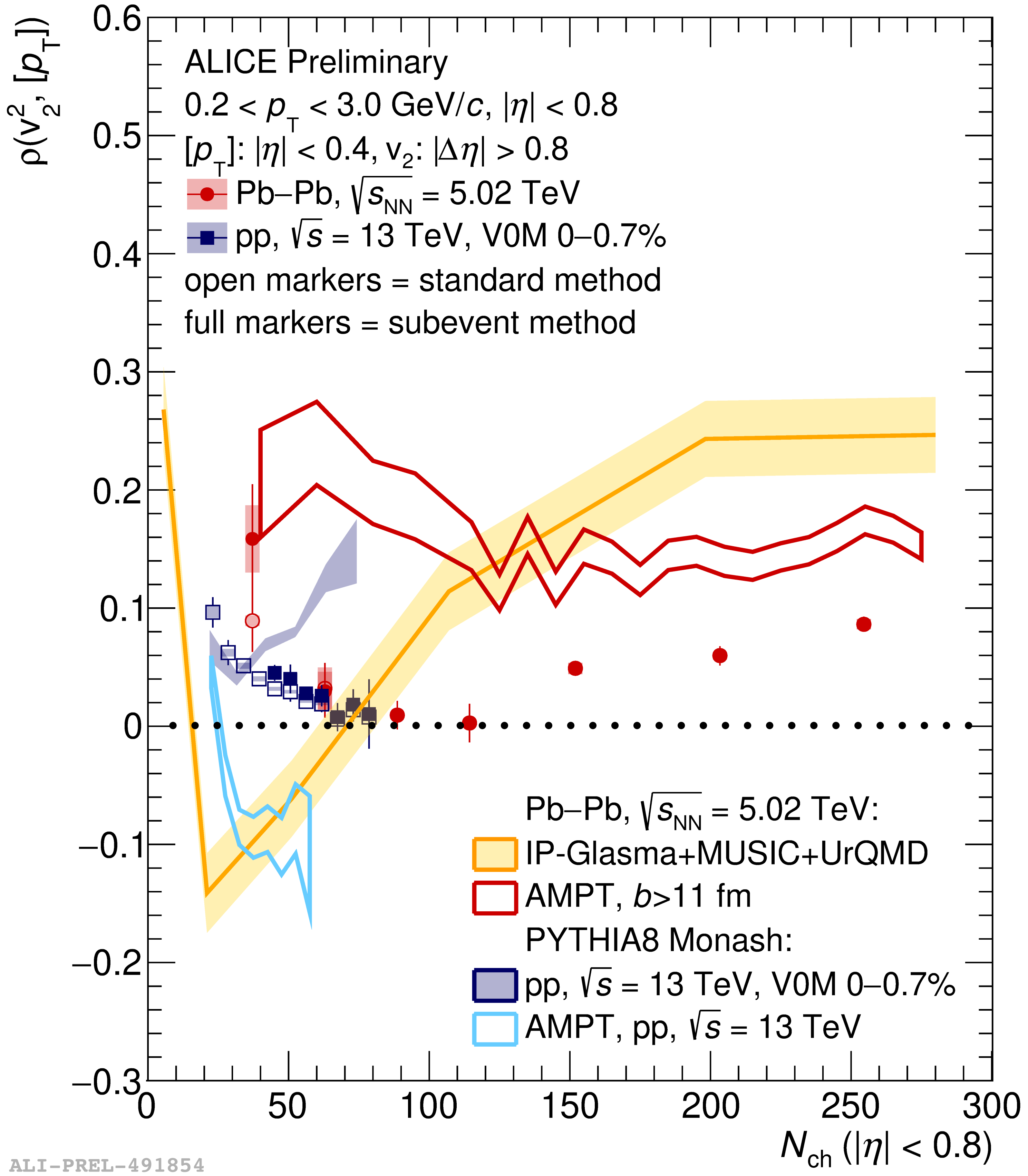
ZEUS DIS JHEP 04 (2020) 070
ZEUS Photoproduction JHEP 12 (2021) 102

- Plots from: https://indico.cern.ch/event/1043736/contributions/5441955/

Data shows something like that?



CMS PAS HIN-21-012



ALI-PREL-491854

- $\rho(v_2^2,[p_T])$ changes sign with multiplicity in p-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??**