Flow measurements from large to small systems
What data tell us

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QCD Challenges from pp to AA collisions

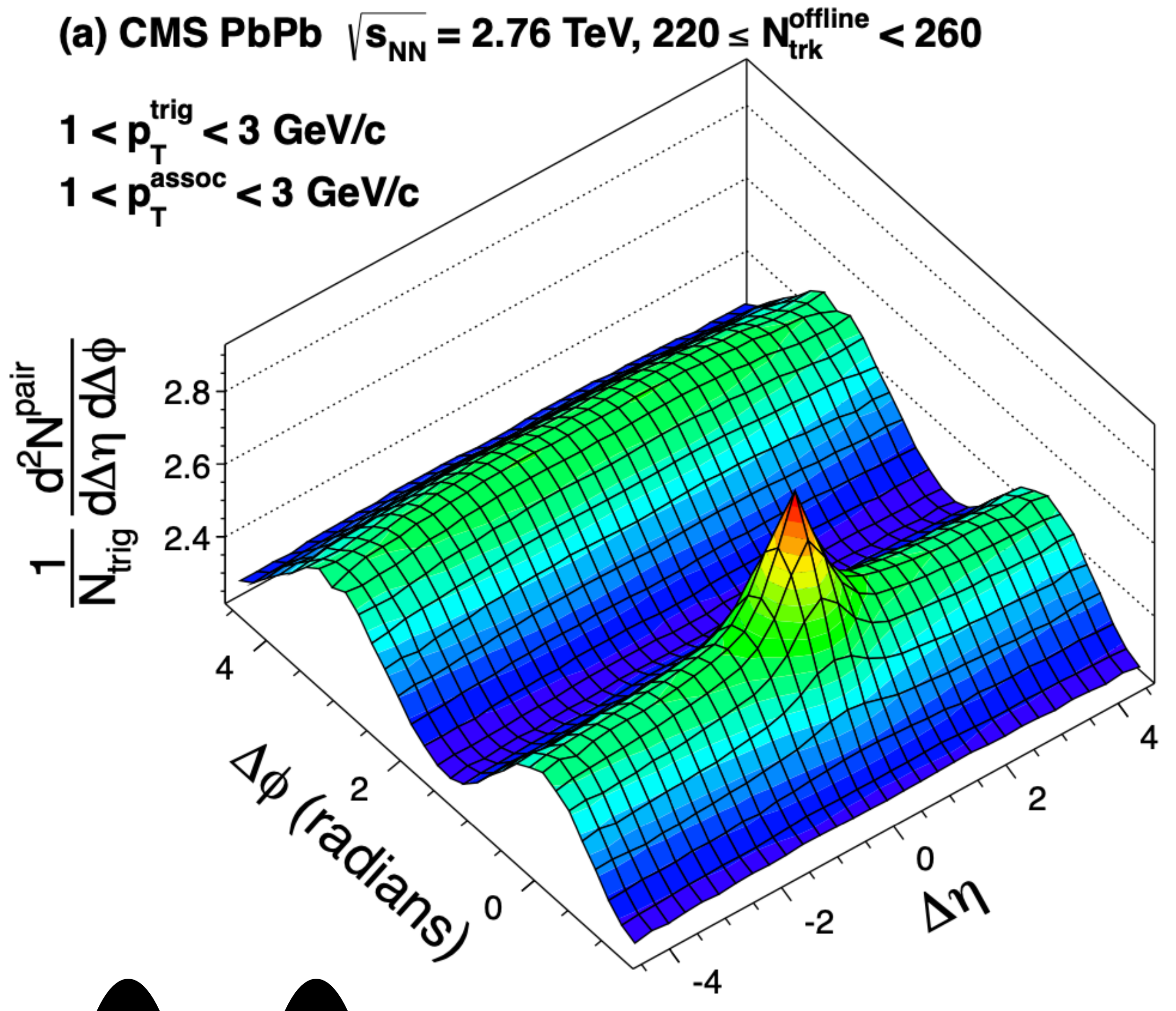
Münster

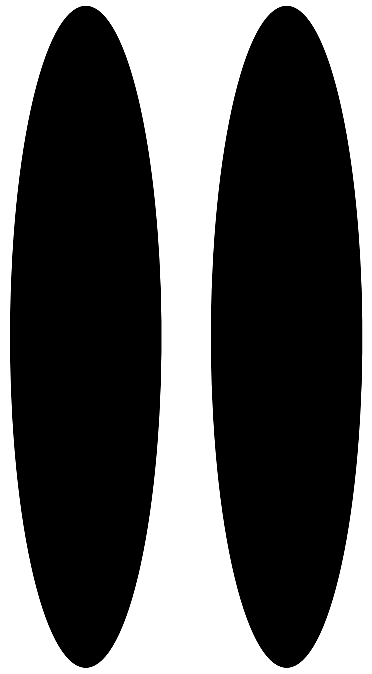
04.09.2024

Long-range corrections with ridge

Pb—Pb

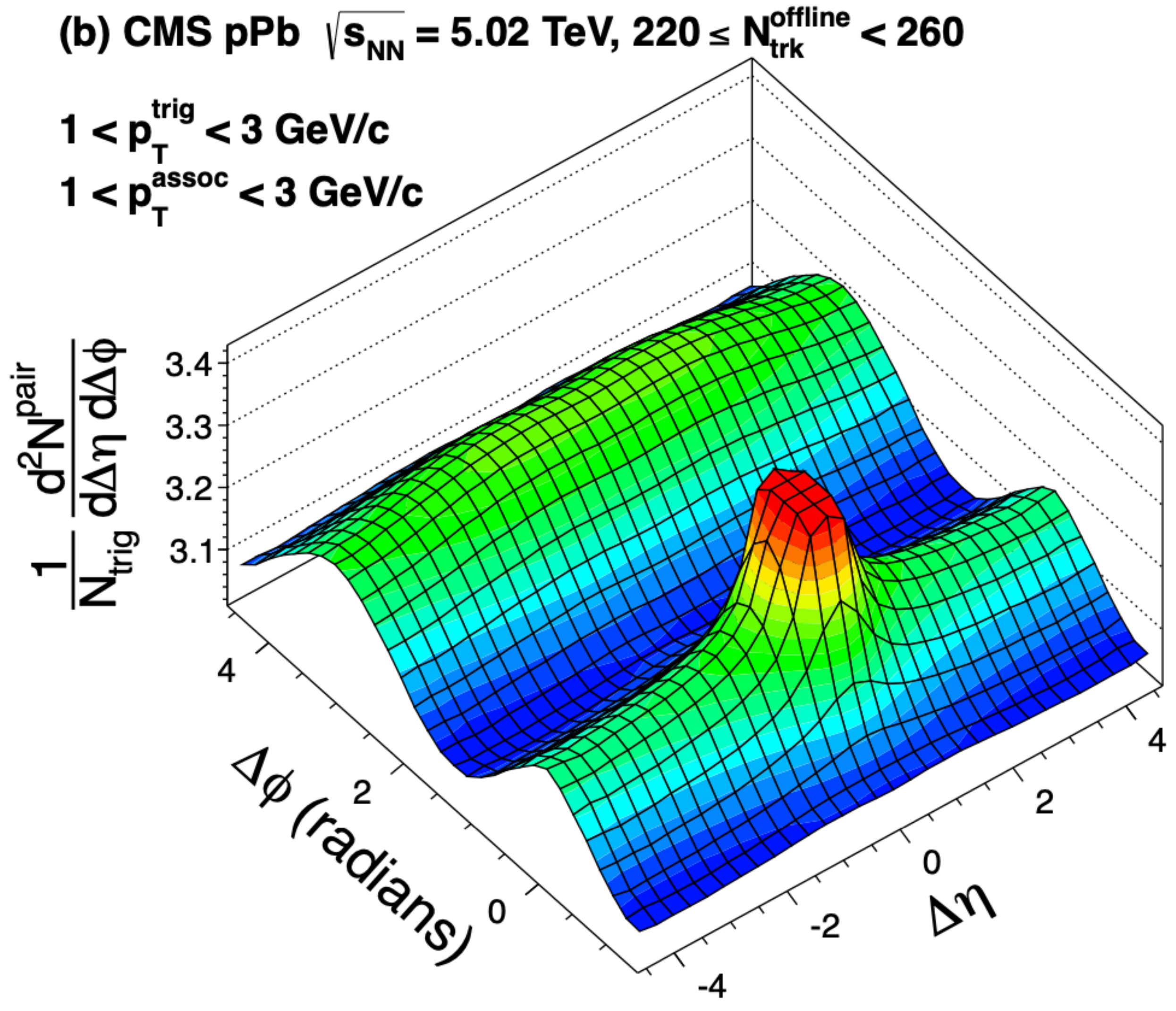
Phys. Lett. B 724 (2013) 213

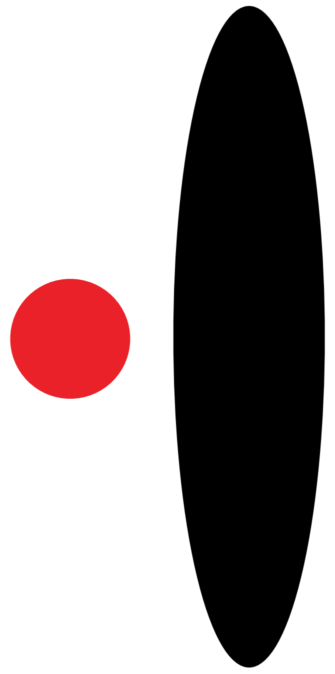




p—Pb

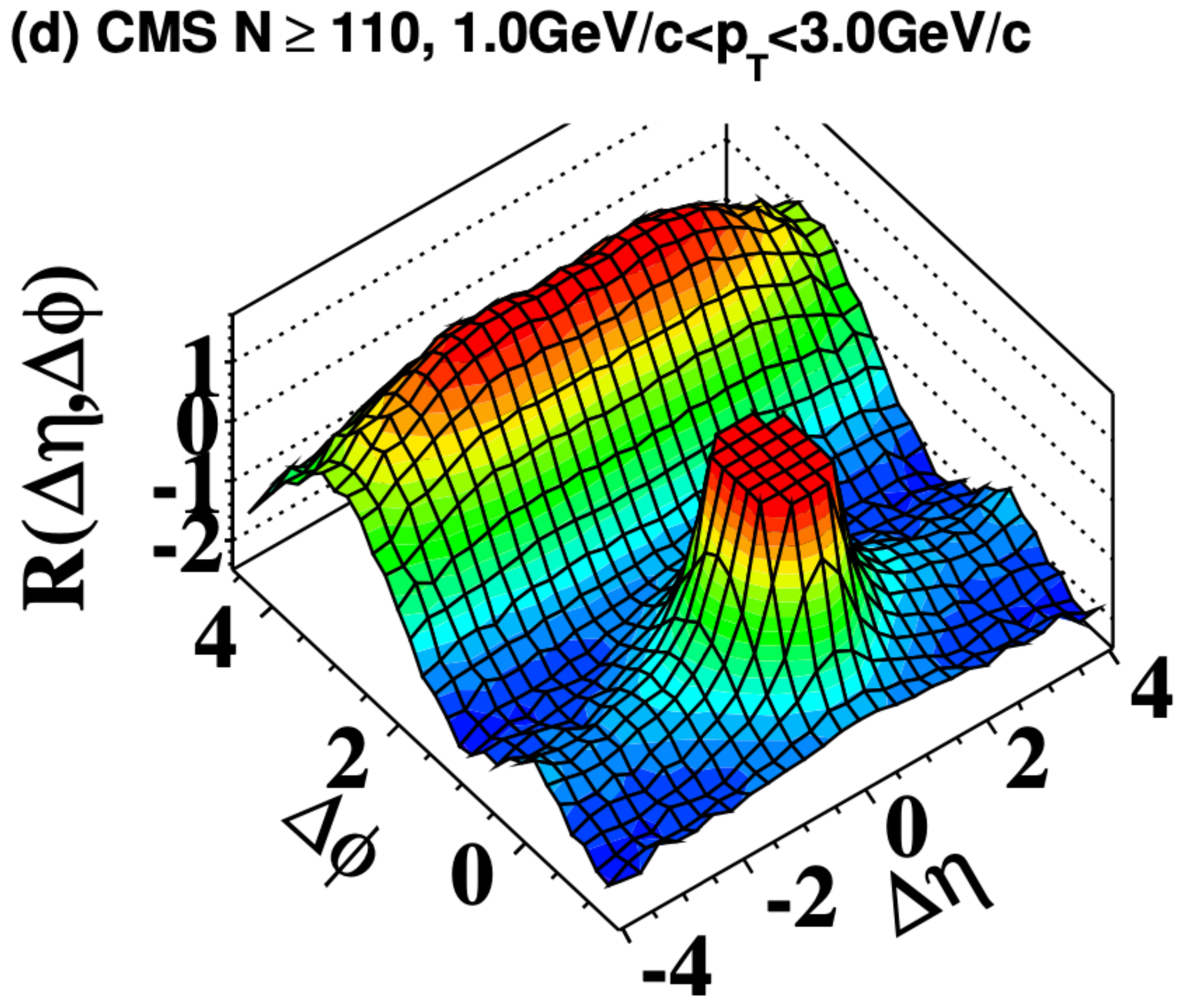
Phys. Lett. B 724 (2013) 213

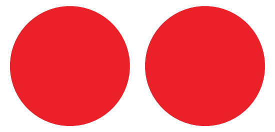




pp

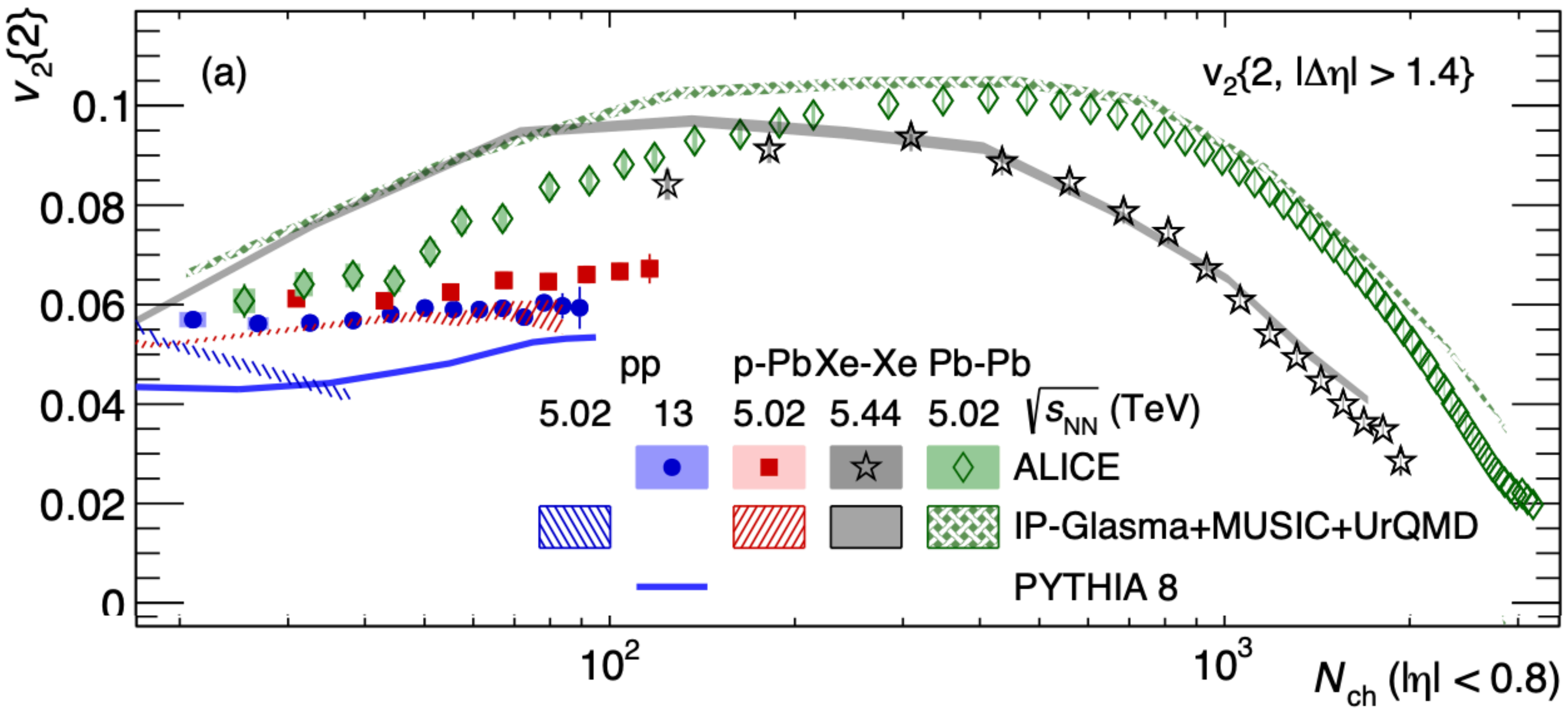
JHEP 1009:091,2010





v_2 from large to small collision systems

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



- Non-zero flow coefficients measured in small collision systems
- Consistent with peripheral Pb—Pb collisions

Flow extraction methods (non-flow treatments)

Fourier fit (FF)

- 2 particle correlations
- Long range in η
- Direct fit with a Fourier expansion

Template fit (TF)

- 2 particle correlations
- Long range in η
- HM = convolution of scaled LM + flow modulation

Event Plane (EP)

- Event plane is evaluated
- Flow coefficients:

$$v_n = \langle cos[n(\varphi - \Psi_n)]\rangle$$

Scalar product (SP)

- Flow coefficients defined via Q-vectors in sub-events

$$v_n(\eta, p_t) = \frac{\langle Q_n u^*_{n,i}(\eta, p_t)\rangle}{2\sqrt{\langle Q^a_n Q^{b\,*}_n\rangle}}$$

$$Q_n = \sum_i u_{n,i} \qquad u_{n,i} = e^{in\phi_i}$$

Q-cumulant (Q)

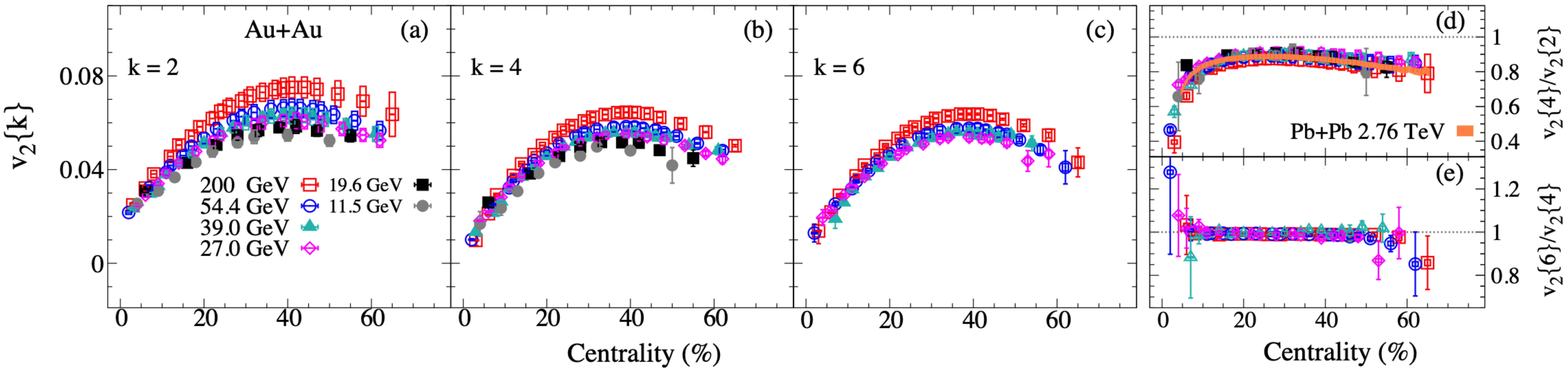
- Multi-particle correlations
- Cumulants

$$v_n\{2\} = \sqrt{c_n\{2\}}\,,$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}\,,$$

Au—Au collisions at different energies

Collision energy dependence

Phys.Rev.Lett. 129 (2022) 25, 252301

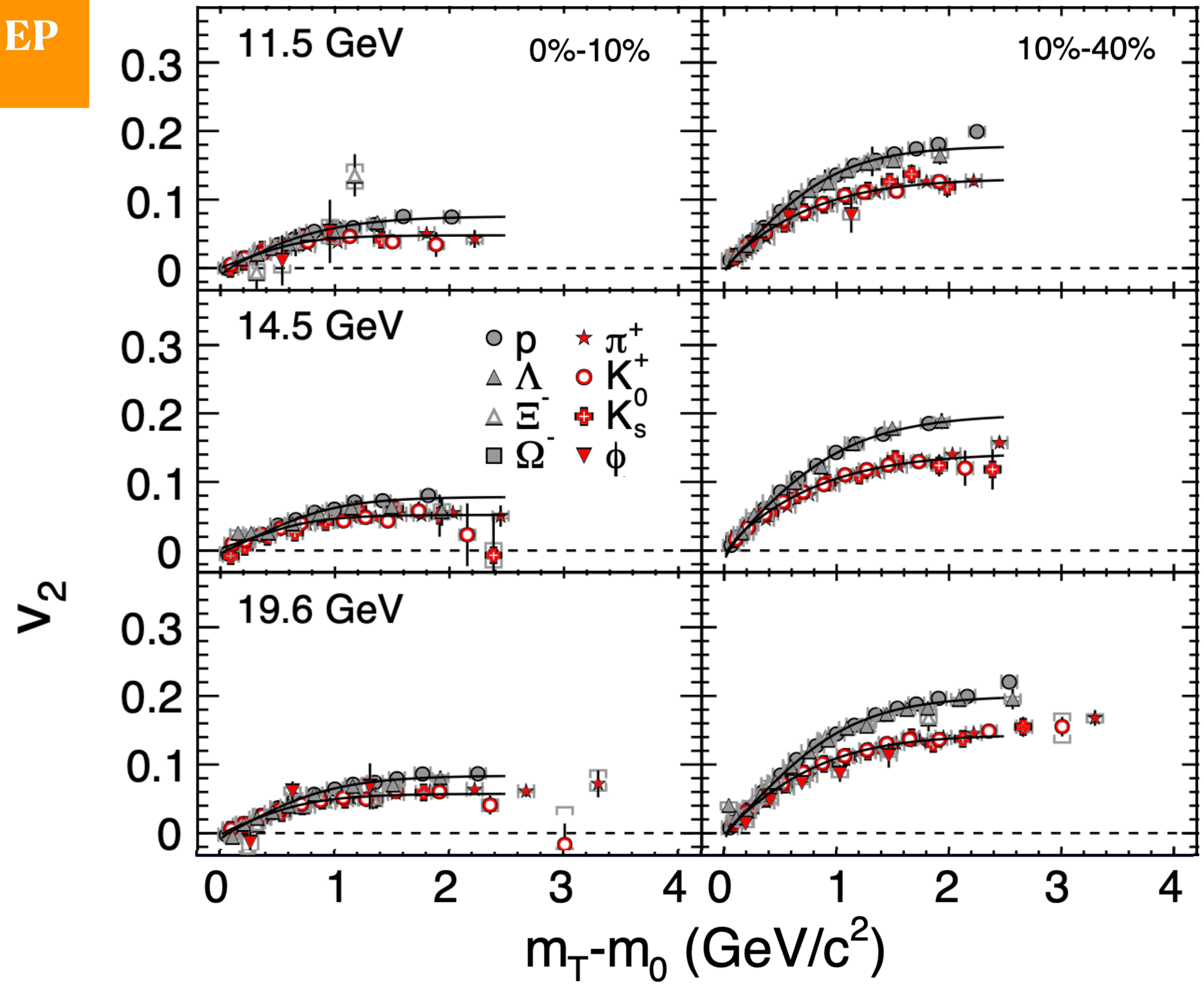


- Amplitude increase with collision energy - reflects the change in the expansion dynamics
- Flow fluctuations:
  - Weakly dependent on the beam energy and centrality - Gaussian-like nature
  - Comparable with Pb—Pb
  - Dominated by initial state eccentricity fluctuations

Collision energy dependence

EP

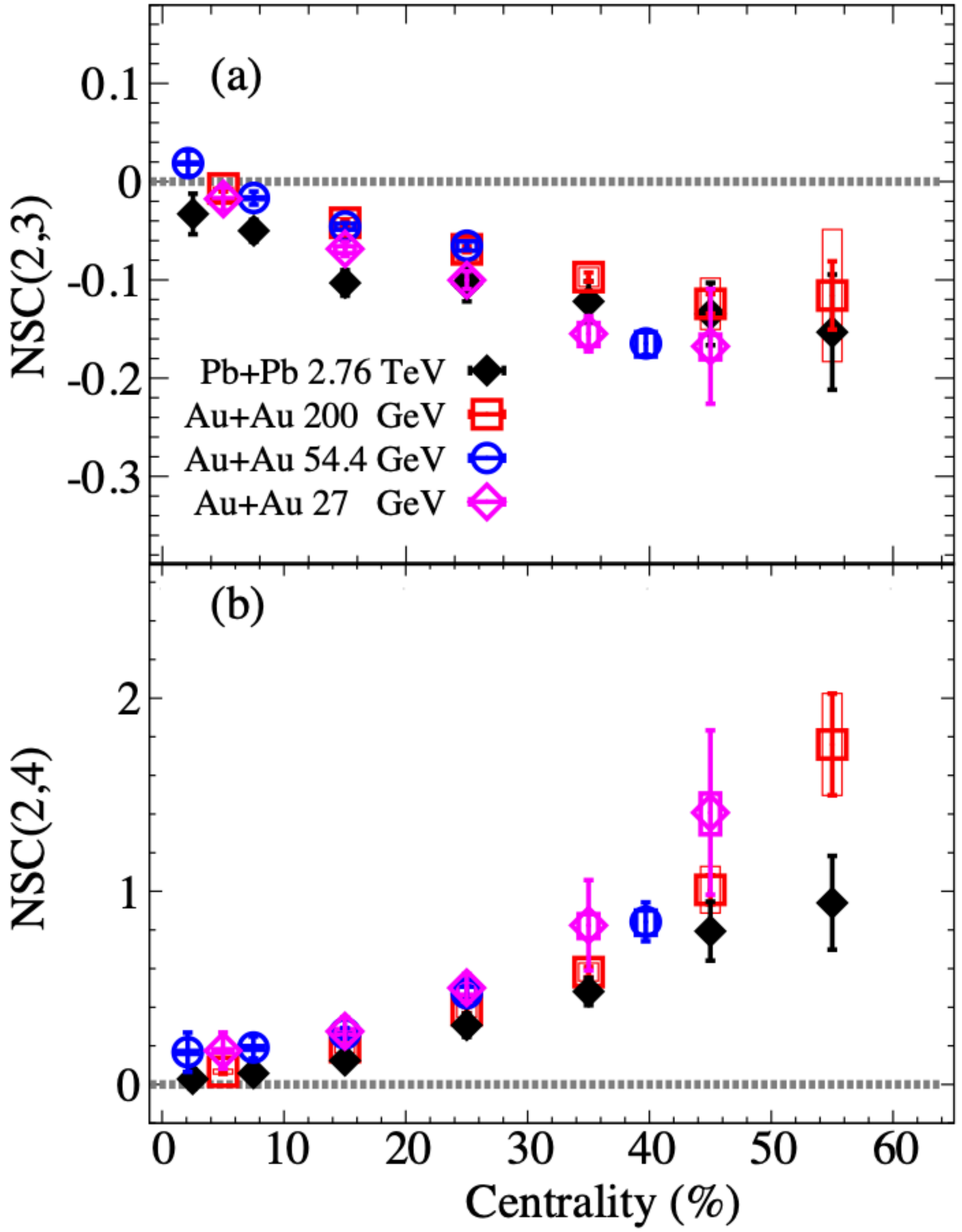
Phys. Rev. C 93, 014907 (2016)



- Baryon-meson splitting and grouping observed down to low energies
- ϕ follows the meson line
- At central collisions - low amplitudes
  - Smaller splitting
- NCQ scaling
  - Holds for particles - no energy dep.
  - Not perfect for antiparticles

Collision energy dependence

Phys.Lett.B 839 (2023) 137755



- Anti-correlation of v_2 and v_3 and correlation of v_2 and v_4
  - Consistent with the initial eccentricity correlations
- Weak beam energy dependence
  - Consistent with LHC measurement

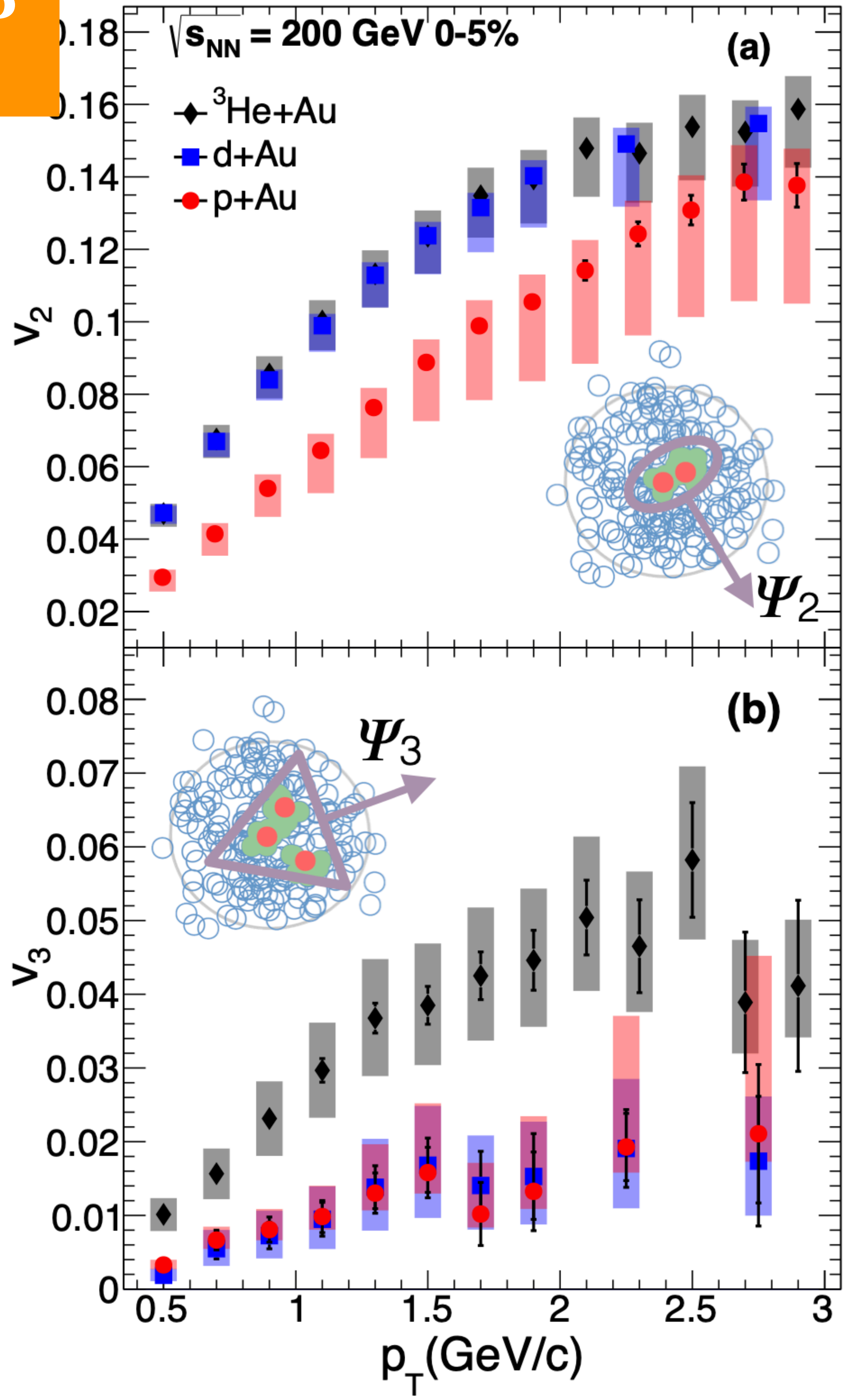
Au—Au collisions at differe energies

Consistent with each other -> consistent with deconfinement picture down to low collision energies with initial-state-driven fluctuations

Different initial geometries

Intrinsic initial geometry dependence

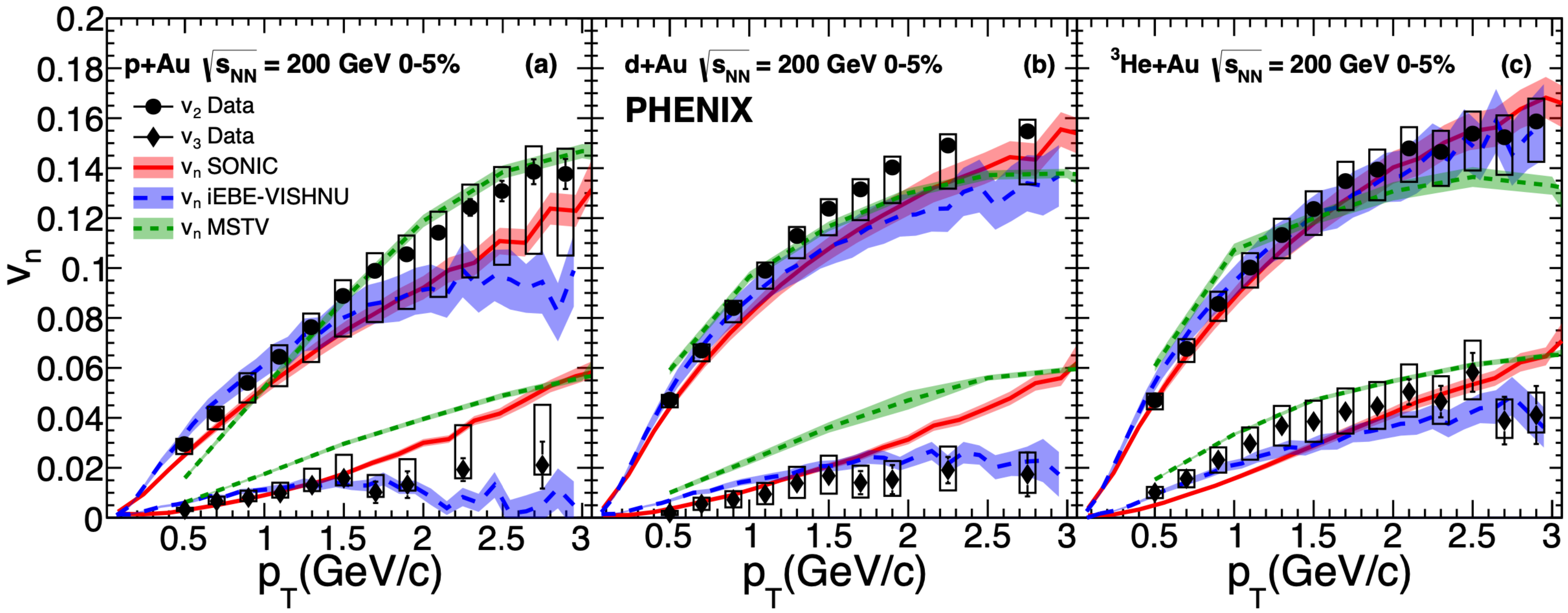
Nature Phys. 15 (2019) 214-220, 2019



- Hydrodynamic predictions observed in data

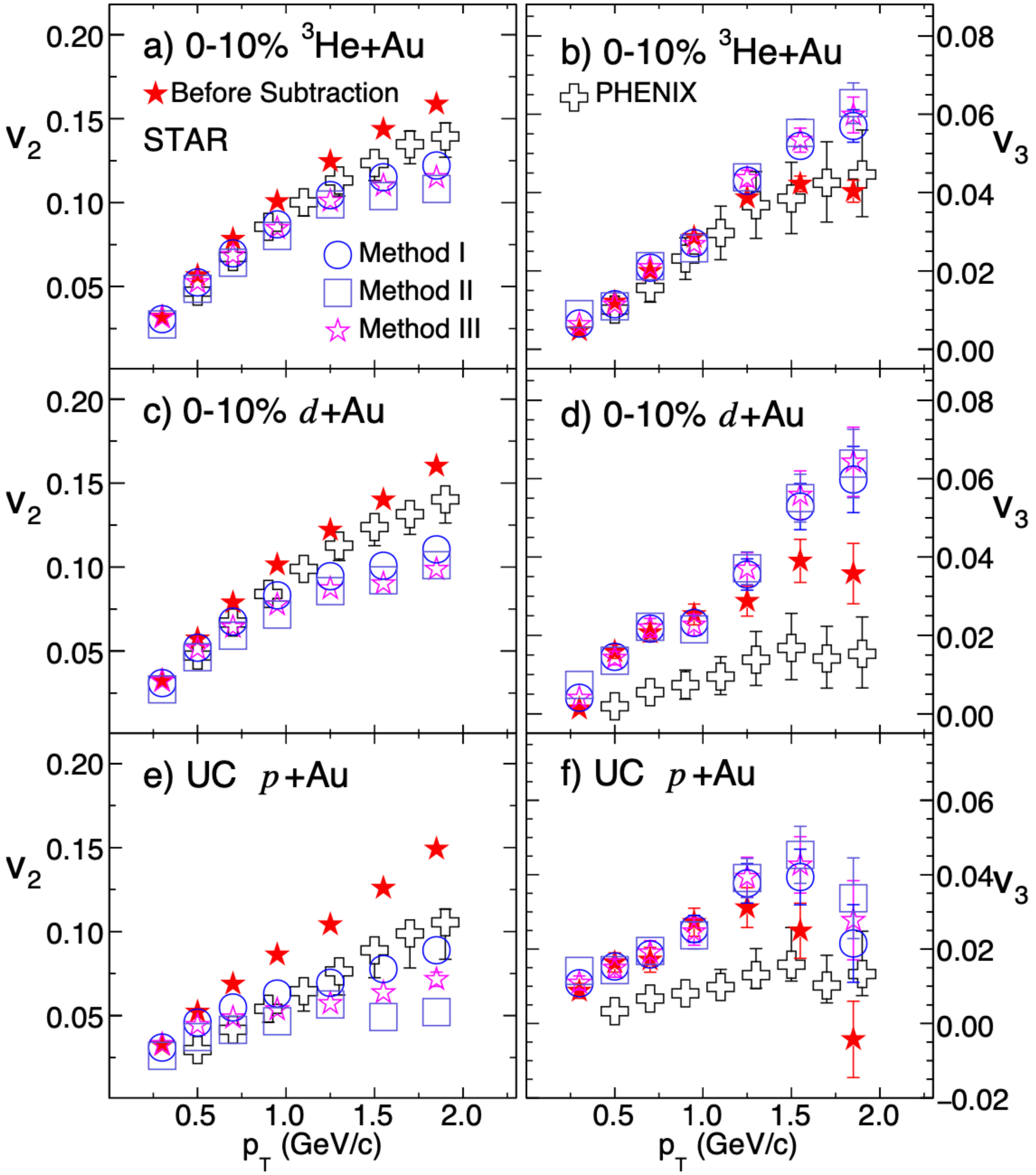
$$v_2^{p+\mathrm{Au}} < v_2^{d+\mathrm{Au}} \approx v_2^{^3\mathrm{He+Au}},$$
$$v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}} < v_3^{^3\mathrm{He+Au}}.$$

- Initial-state momentum correlation models are ruled out



Intrinsic initial geometry dependence II

Phys.Rev.Lett. 130 (2023) 24, 242301



- Significant discrepancy between the results from two experiments
- STAR:
  - v_2 is smaller than measured by PHENIX, but the same system dependence
  - v_3 3 times larger than measured by PHENIX and system independent
  - Not described by hydrodynamical models

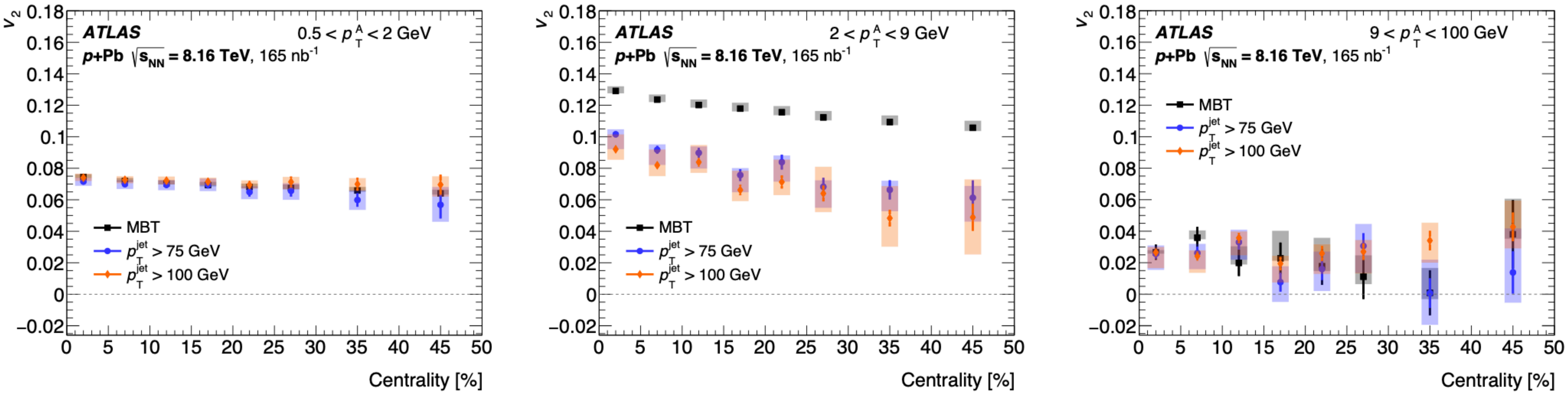
Different initial geometri

Strong dependence on initial geometry not confirmed by both experiments, further measurements needed

Hard scattering influence and jet modification

Event scale dependent in p—Pb

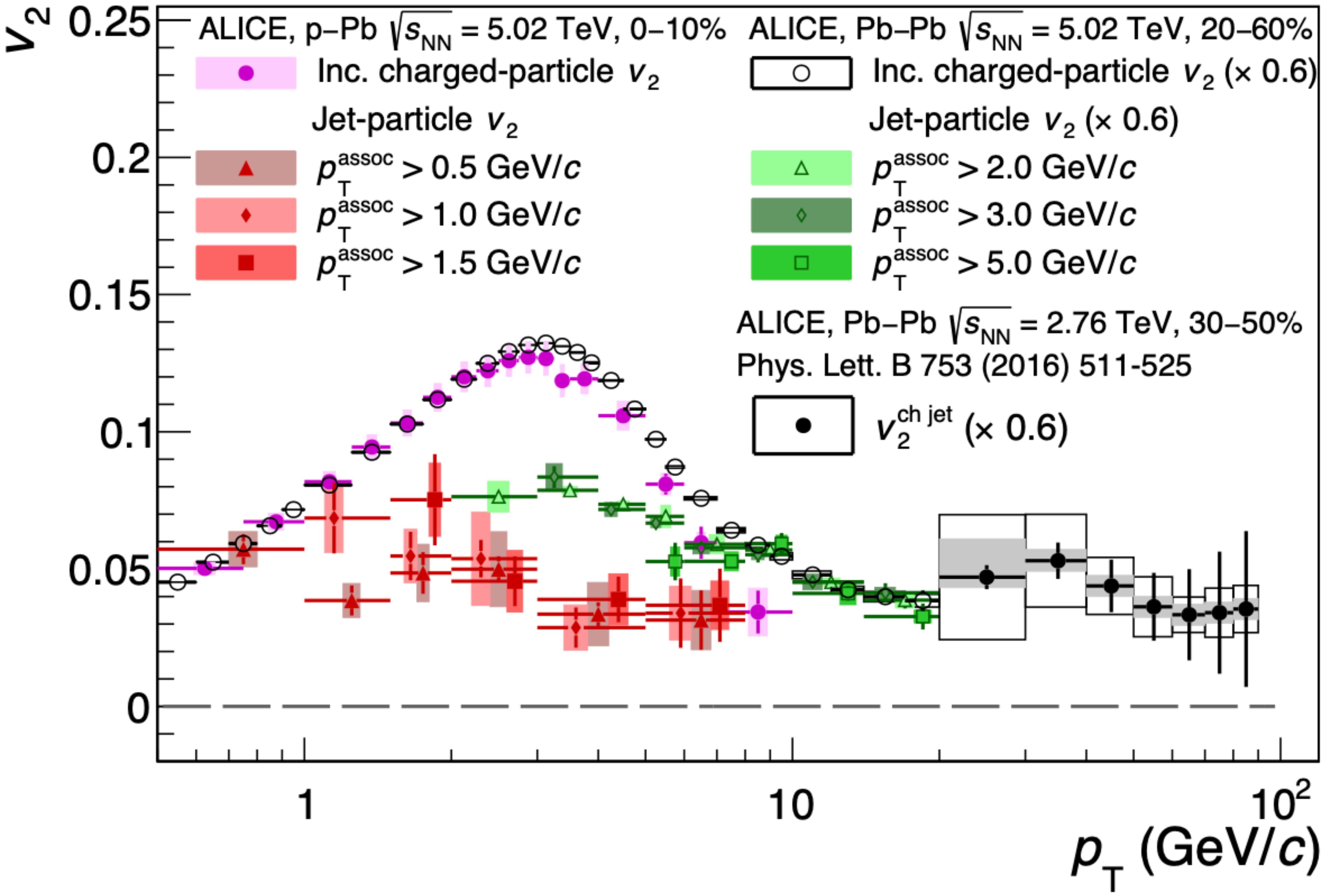
Eur. Phys. J. C 80 (2020) 73



- Presence of a jet - slight influence on the flow
- Low and high p_T
  - In agreement with MB, independent on multiplicity
- Intermediate p_T
  - Lower v_2 than in MB, slight decrease towards low multiplicities in all samples

Jet particle flow in p—Pb

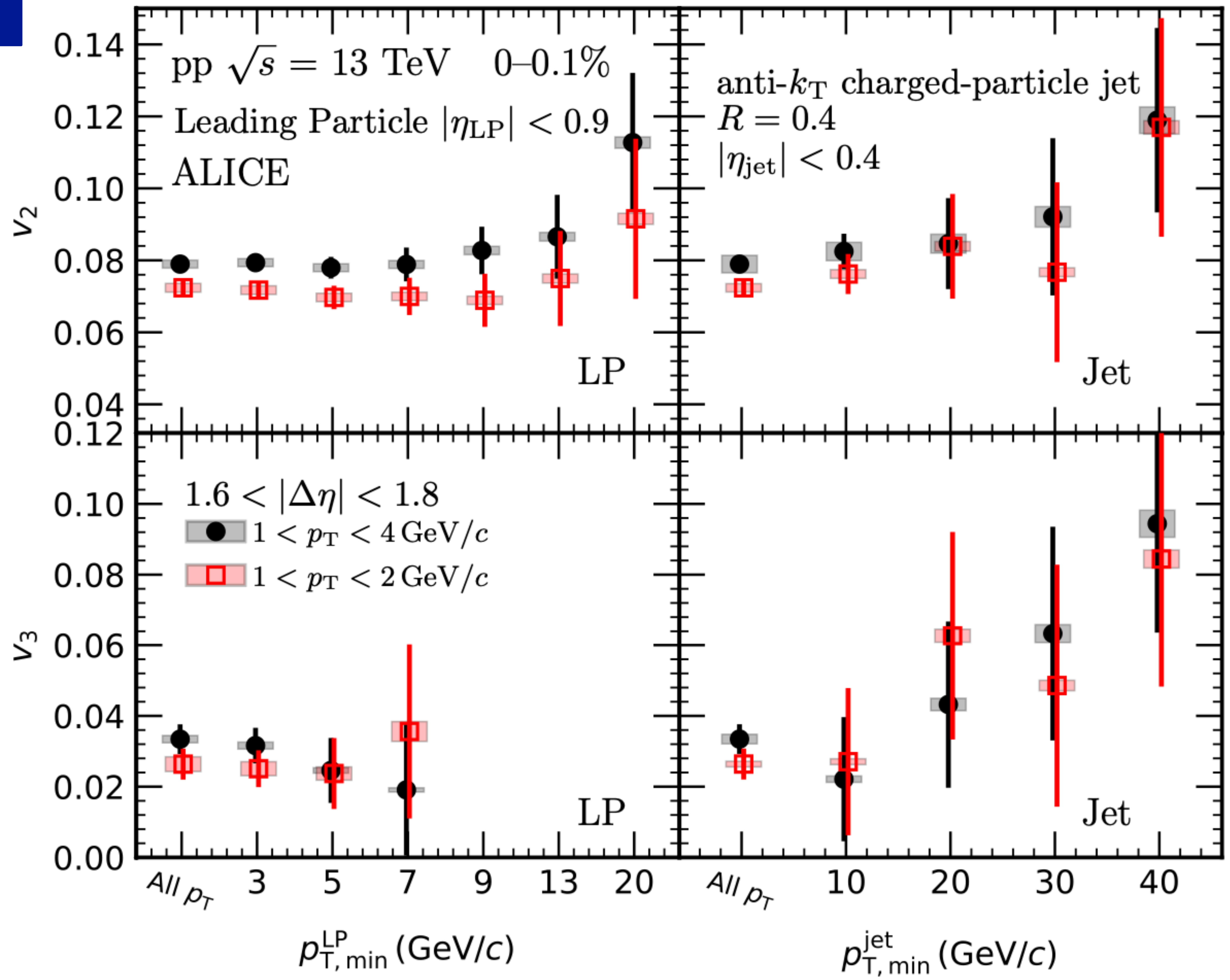
arXiv:2212.12609



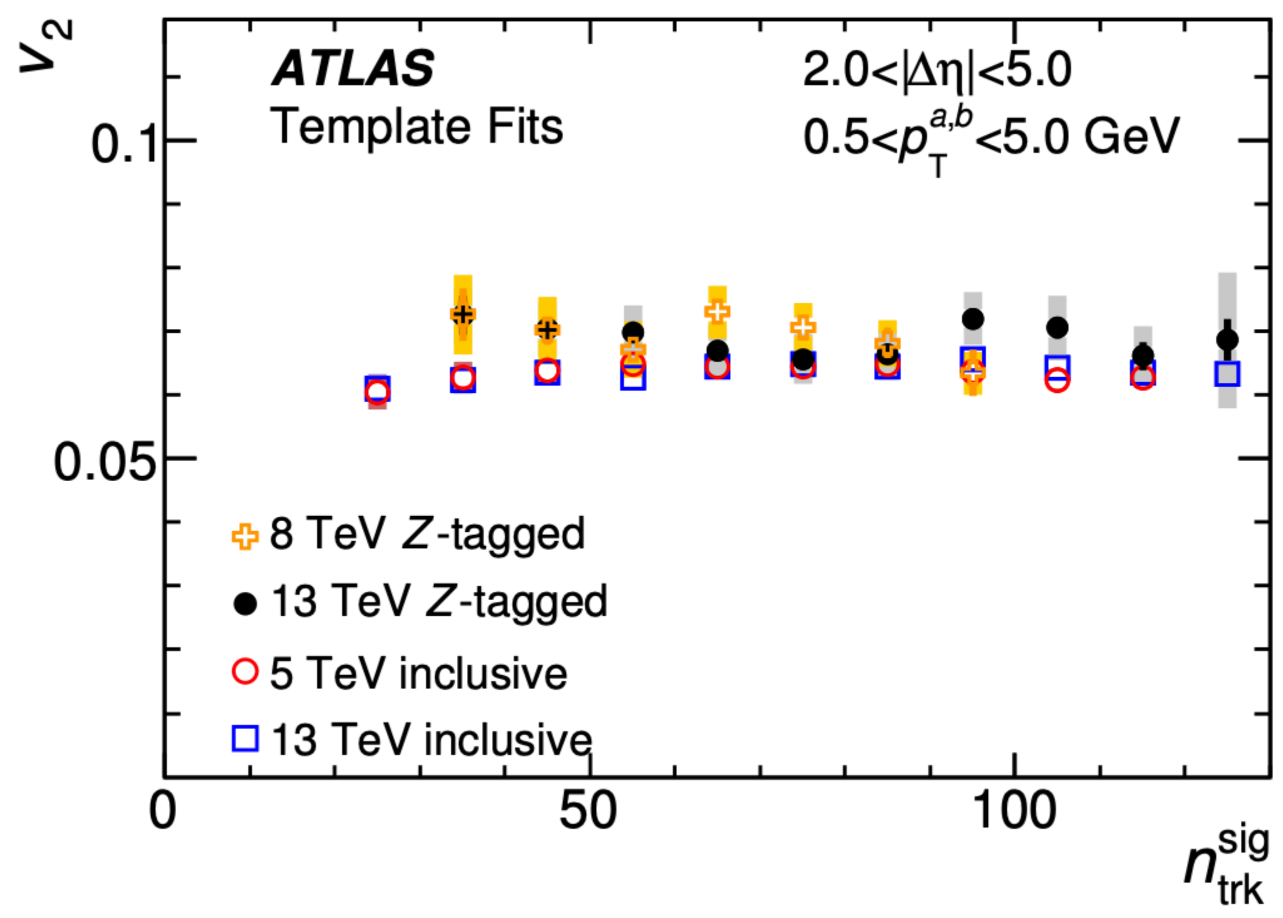
- Non-zero jet v_2 in p—Pb and Pb—Pb collisions
  - Smaller magnitude than inclusive v_2
  - No dependence on p_T^{assoc}
  - At high p_T - similar magnitude as in Pb—Pb
- v_2 driven by the non-equilibrium anisotropic parton escape mechanism

Event scale dependent in pp

JHEP 03 (2024) 092



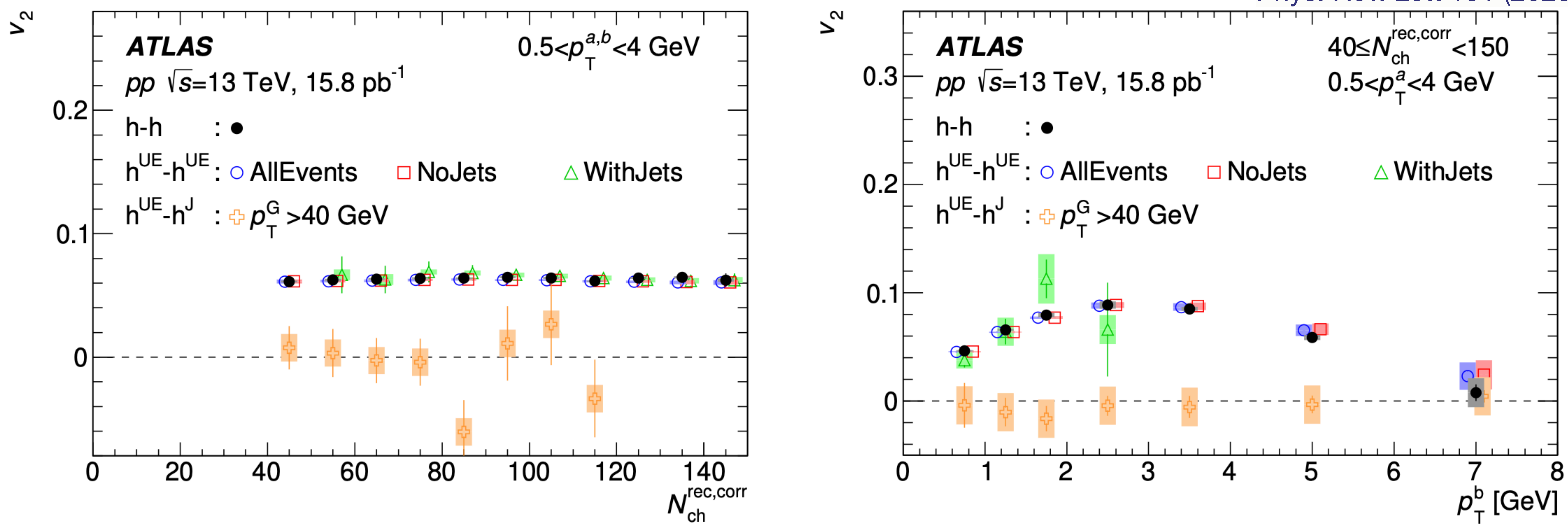
- Flow amplitude independent on hard scattering in the event
  - In agreement with flow amplitudes in events without such hard scattering
  - In agreement with the flow coefficients in present of Z boson



Eur. Phys. J. C 80 (2020) 64

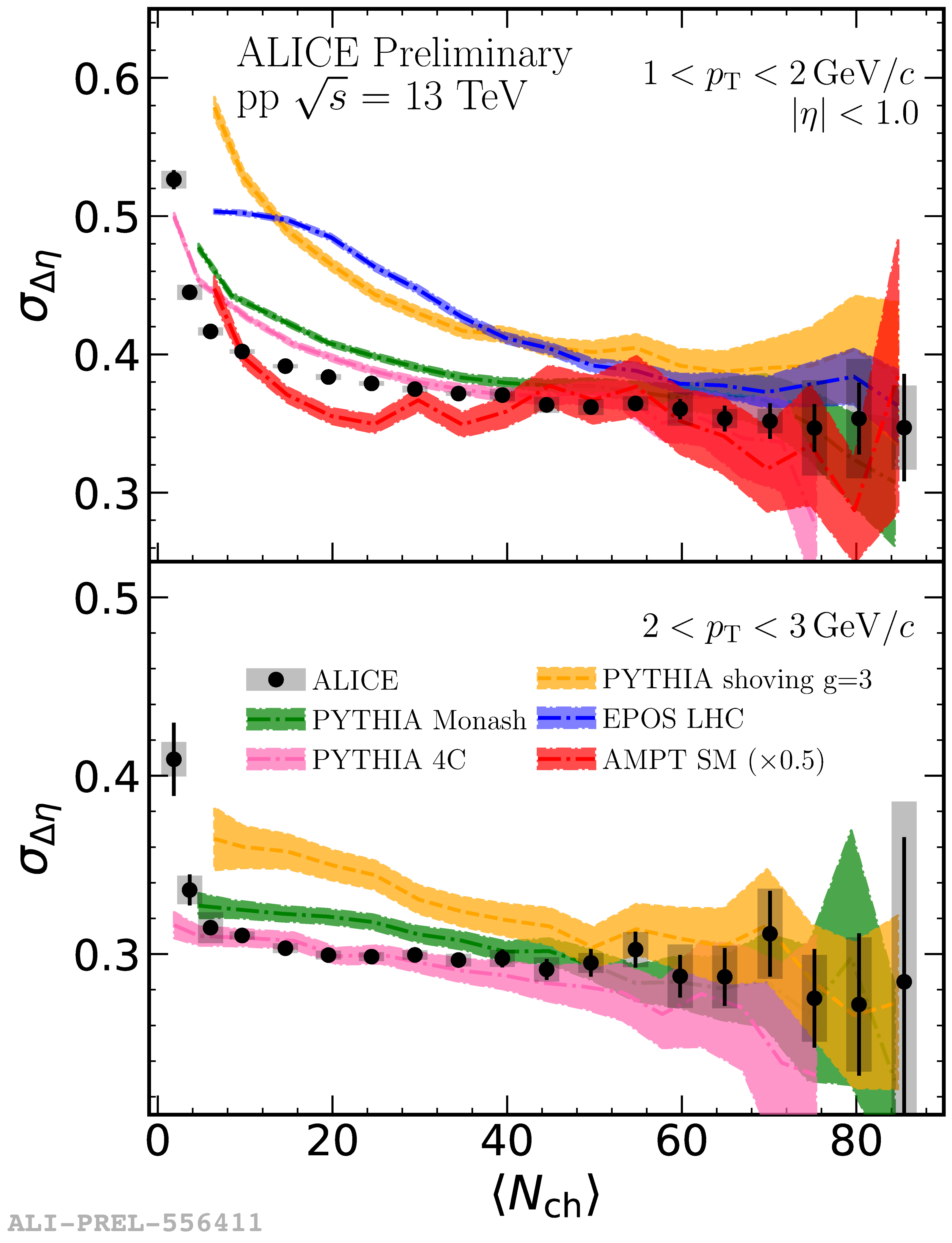
Jet particle flow in pp

Phys. Rev. Lett 131 (2023) 162301

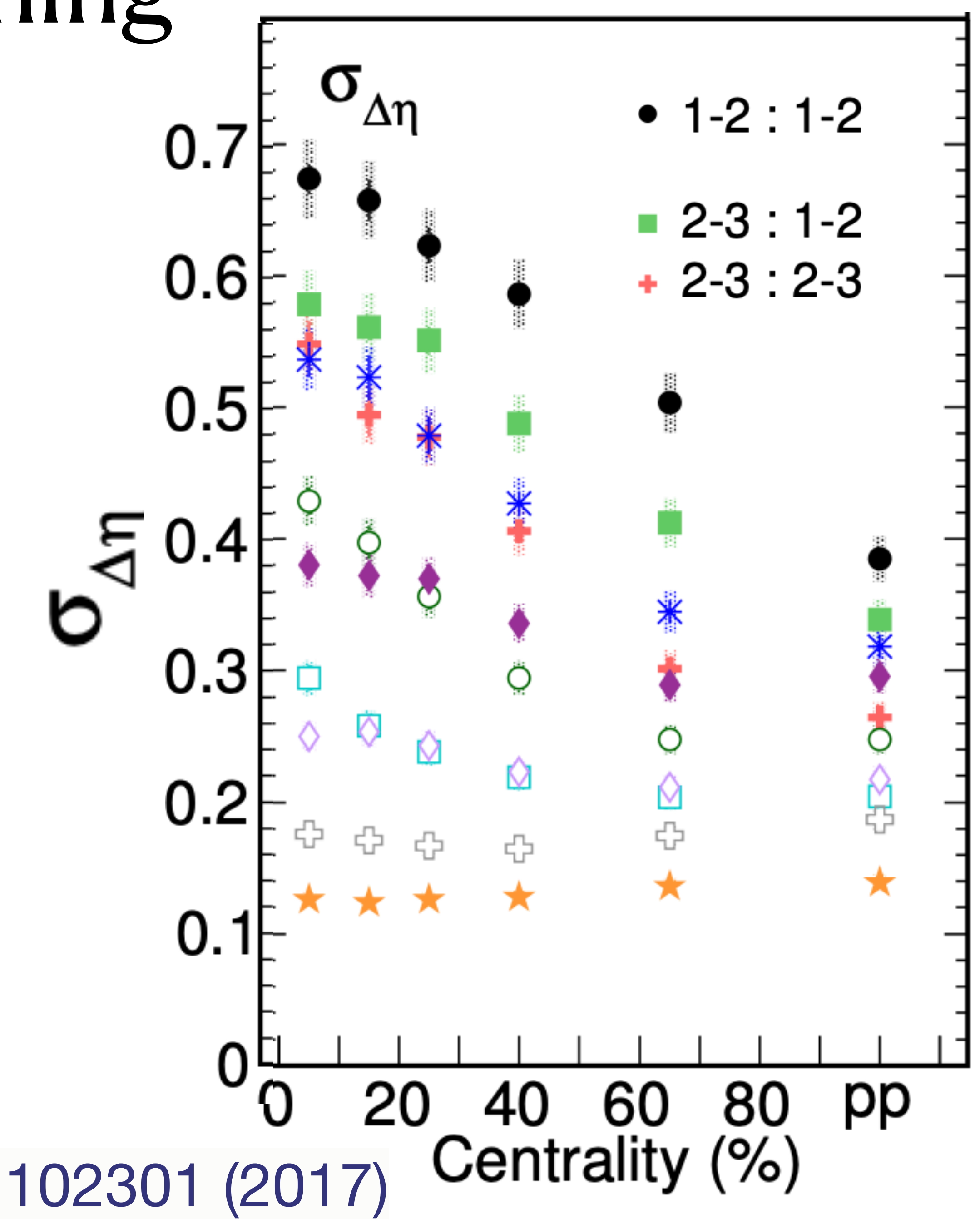


- Presence of a jet with $p_T > 15$ GeV/c does not influence the v_2 of h^{UE}
  - No multiplicity dependence
- v_2 of h^J compatible with zero
  - The inclusive v_2 is not driven by jet fragmentation, but rather by bulk
  - The collective system is too small to influence jets - no energy loss

Jet modulation in pp



- Jet peak width as a function of multiplicity
- No broadening as in Pb—Pb
- Shape qualitatively described by models
- Consistent with direct jet quenching searches



Phys. Rev. Lett. 119, 102301 (2017)

Hard scattering influence and i modificatio

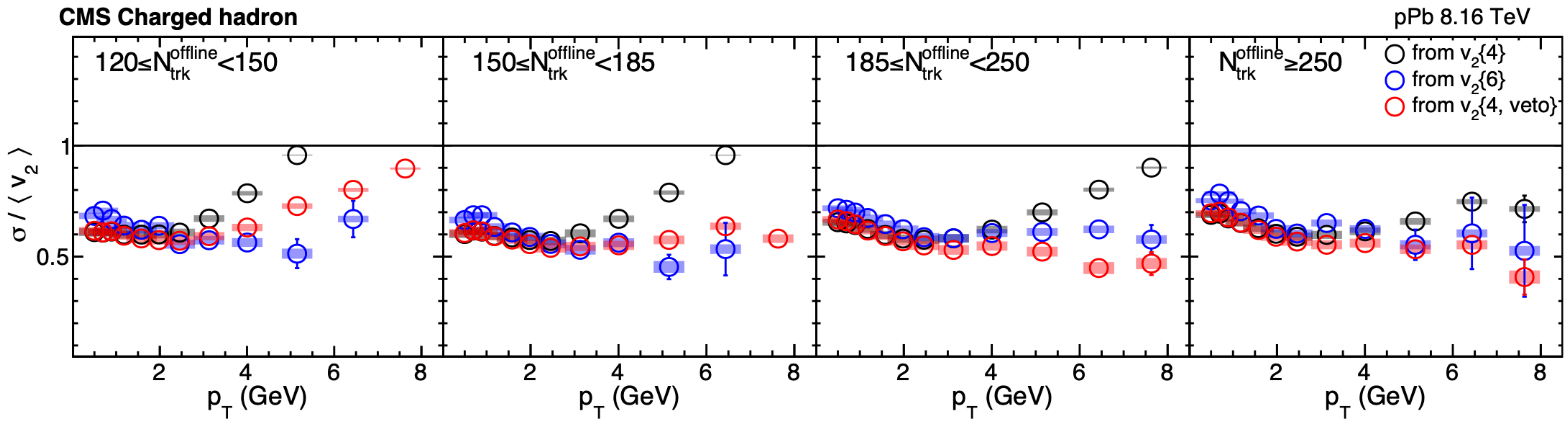
Soft part of the event is not influenced by a hard scale, but zero jet particle v_2 and no jet quenching in pp -> the jets escape before the collectivity develops? No deconfinement in pp? Bigger in p–Pb?

Flow of (identified) particles

Flow fluctuations in p—Pb

SP

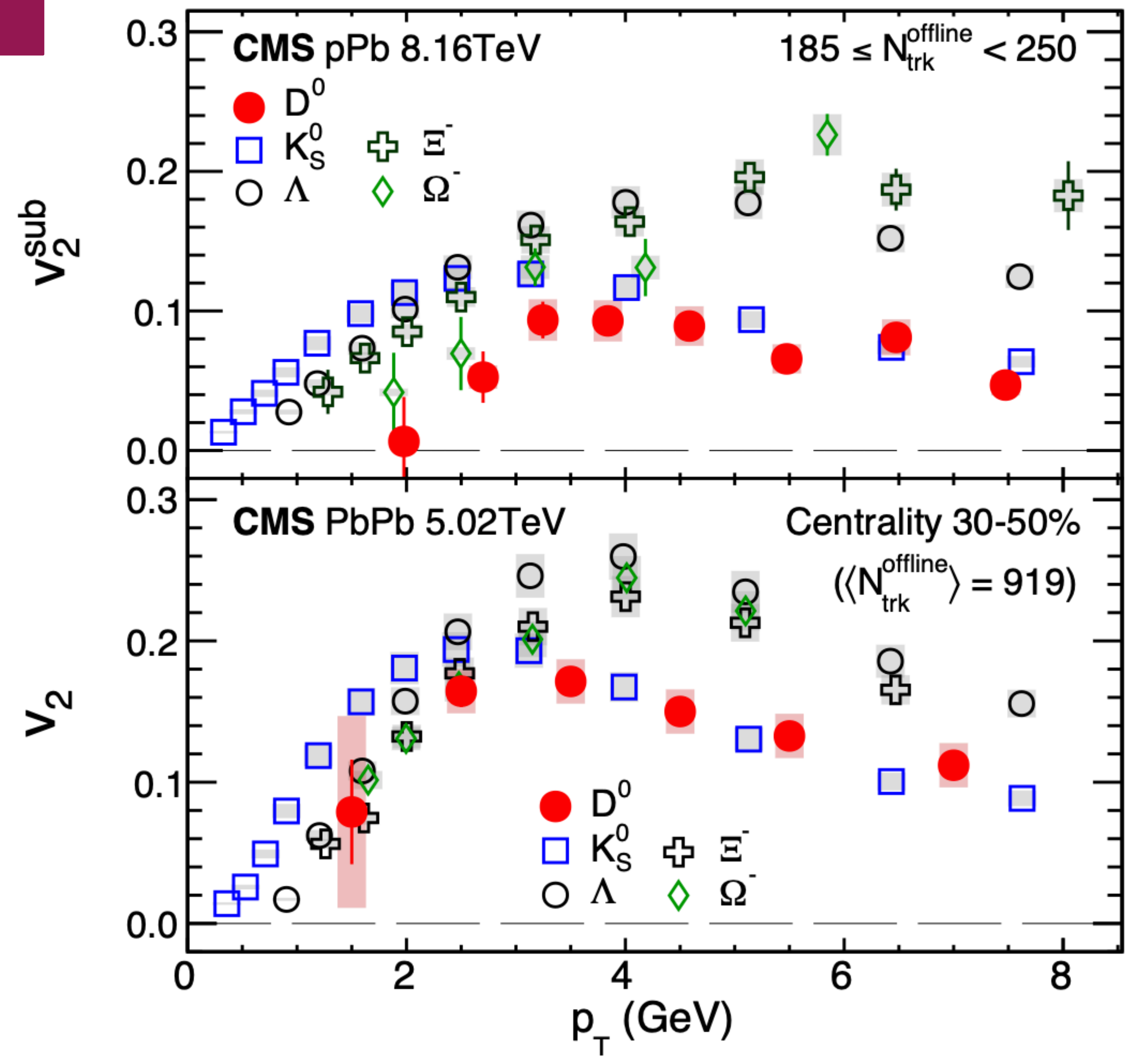
JHEP05(2023)007



- At high p_T - influence of jet non-flow
  - Suppressed with jet veto/ 6 particle correlations
- High mult. p—Pb collisions:
  - At high p_T in agreement with peripheral Pb—Pb
  - At low p_T higher than peripheral Pb—Pb
- No particle species dependence - initial state fluctuations

Identified v_2 in Pb—Pb and p—Pb

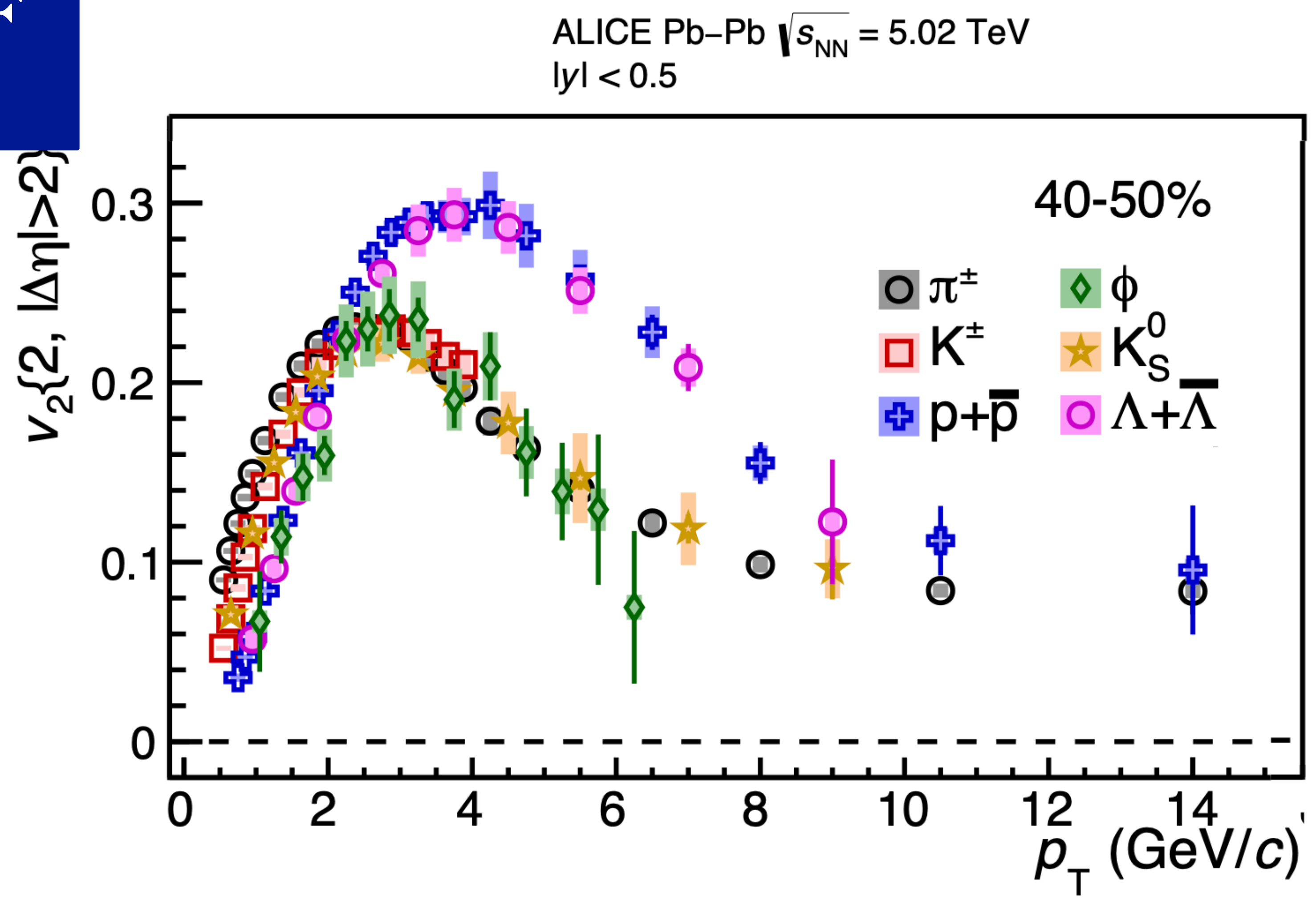
Phys. Rev. Lett. 121, 082301

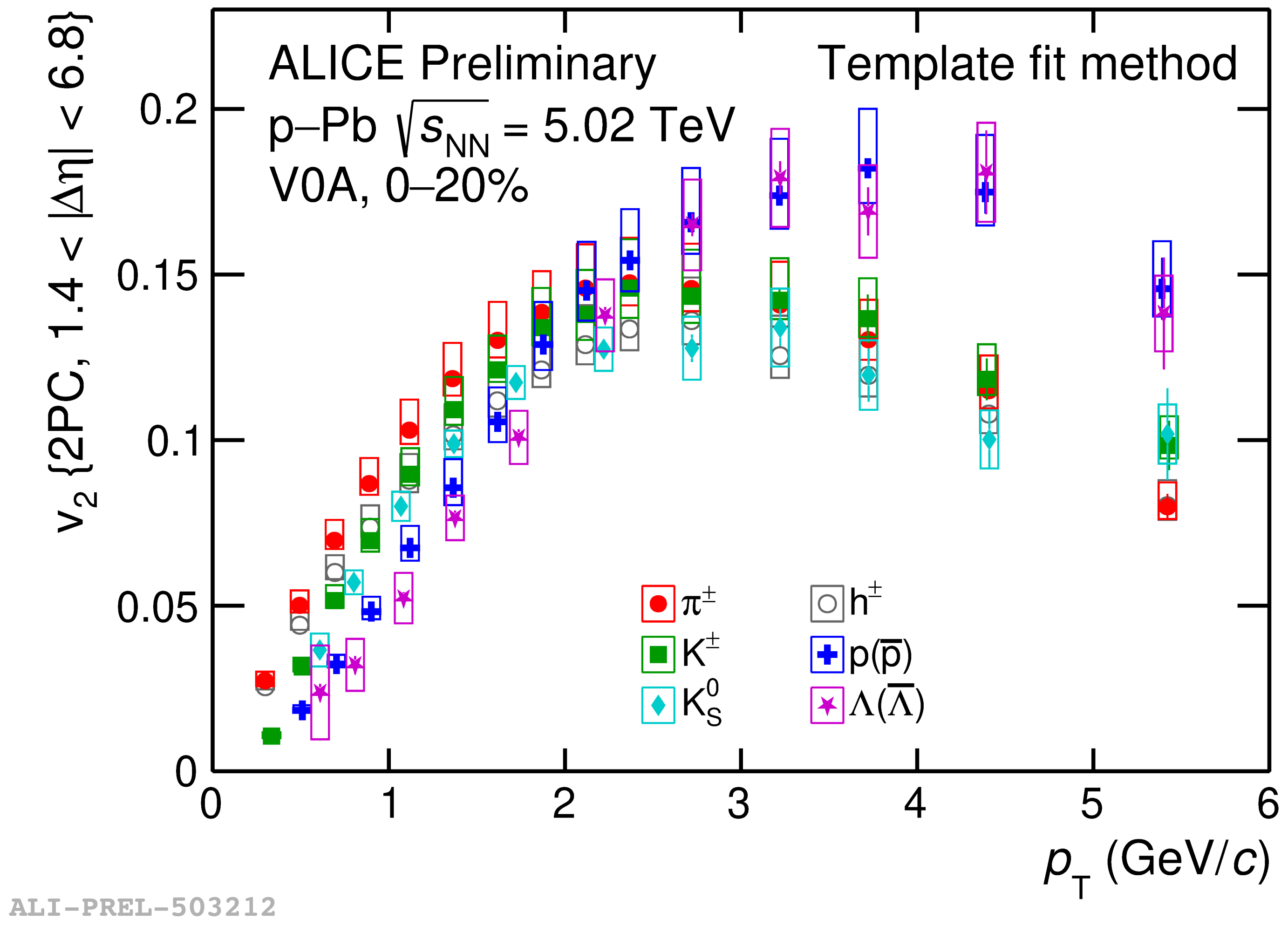


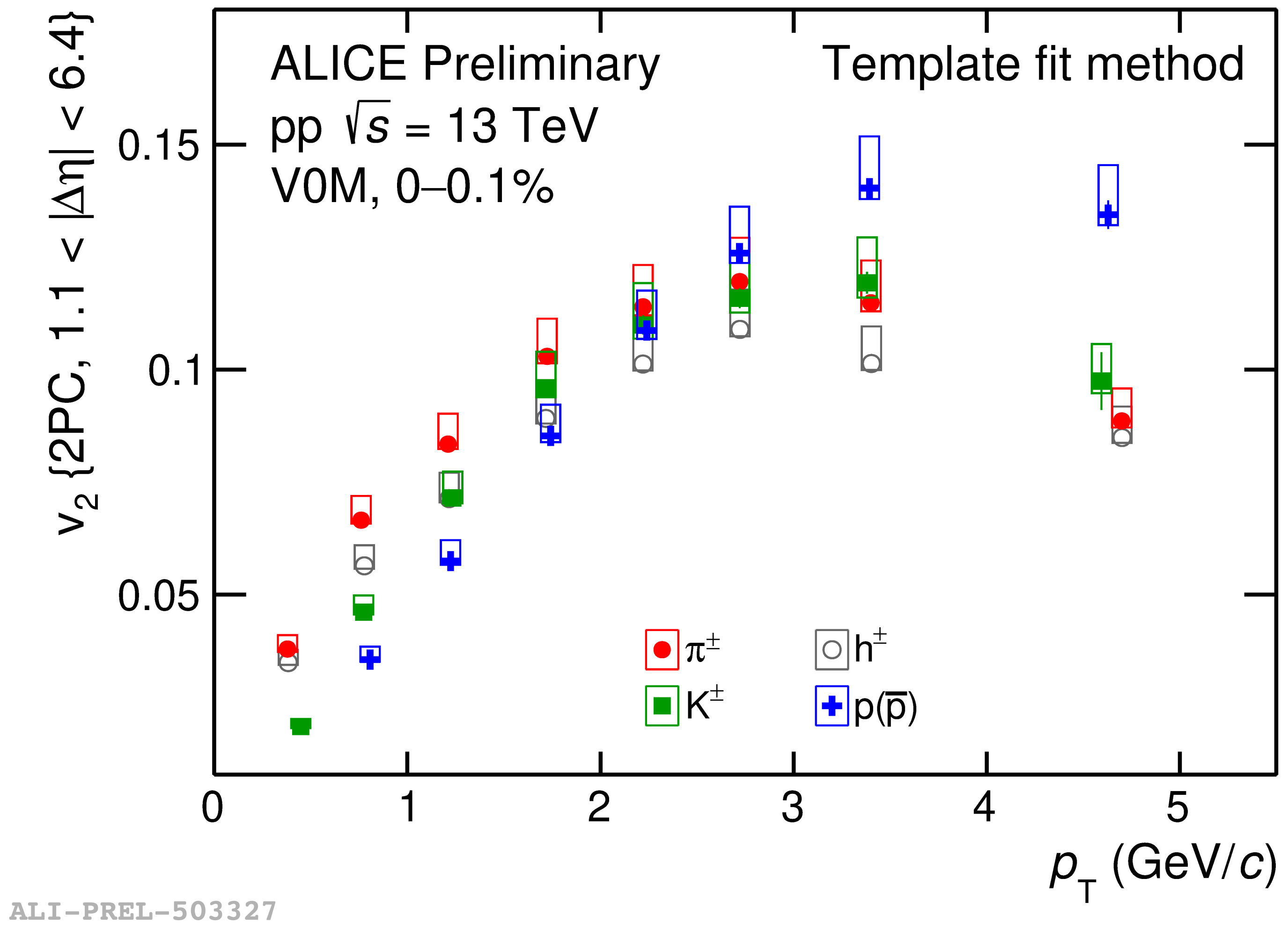
- In Pb—Pb:
  - D⁰ follows the mass ordering and meson group
- In p—Pb:
  - D⁰ follows the meson group
  - Slightly lower v_2 at low p_T (besides mass ordering)
- The collective behaviour of charm quarks is weaker than that of the light-flavour quarks

Identified v_2 in Pb—Pb, p—Pb, pp

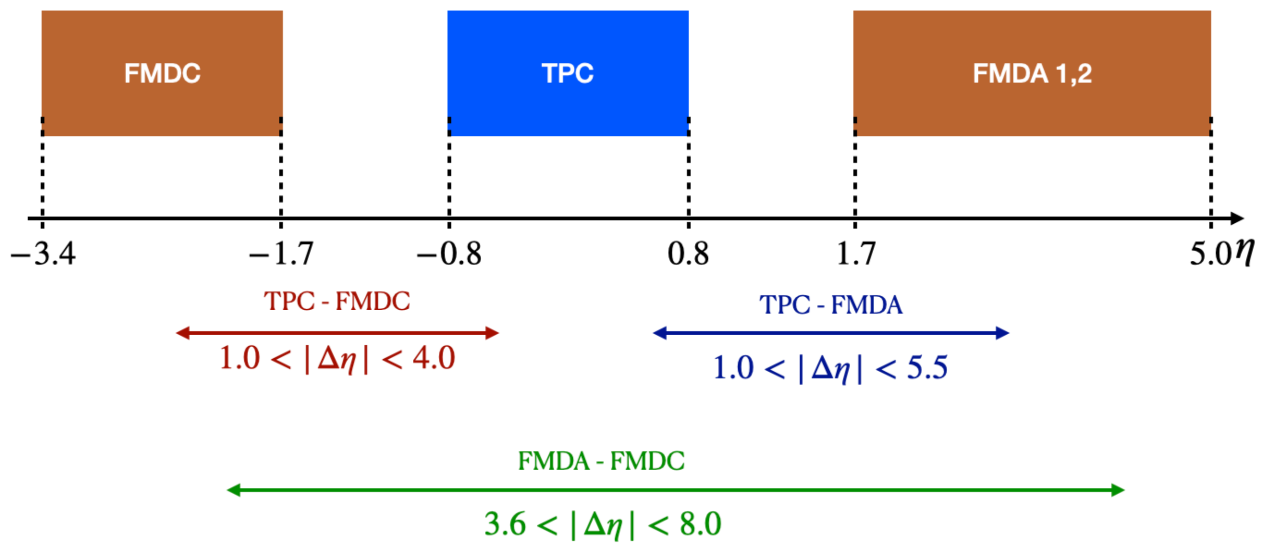
JHEP09(2018)006







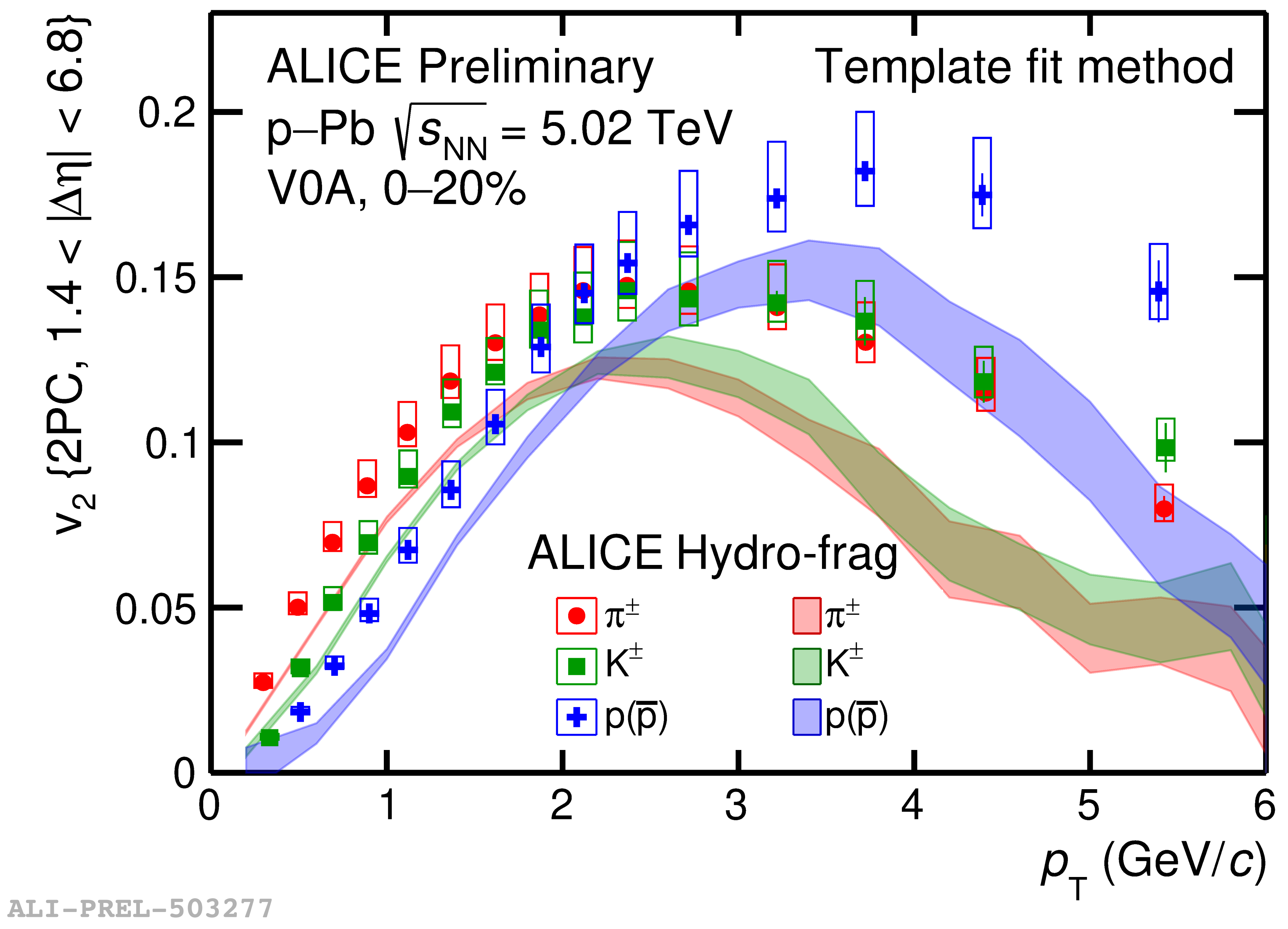
Big eta gap

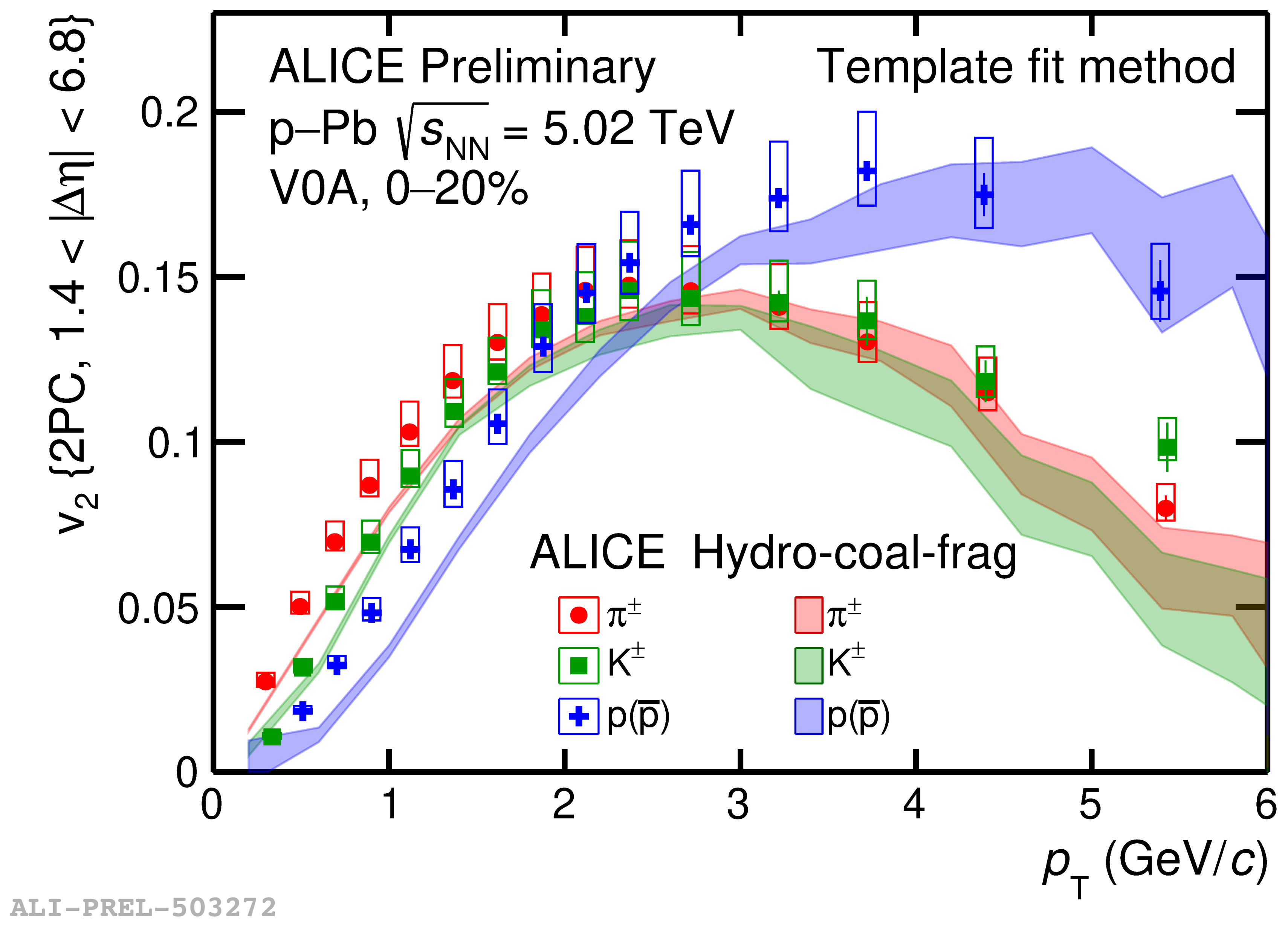


- Similar behaviour in all collision systems
- Mass ordering at low p_T
- Baryon—meson splitting and grouping at intermediate p_T
- Not sufficient statistics at high p_T in small systems

Model comparison in p—Pb

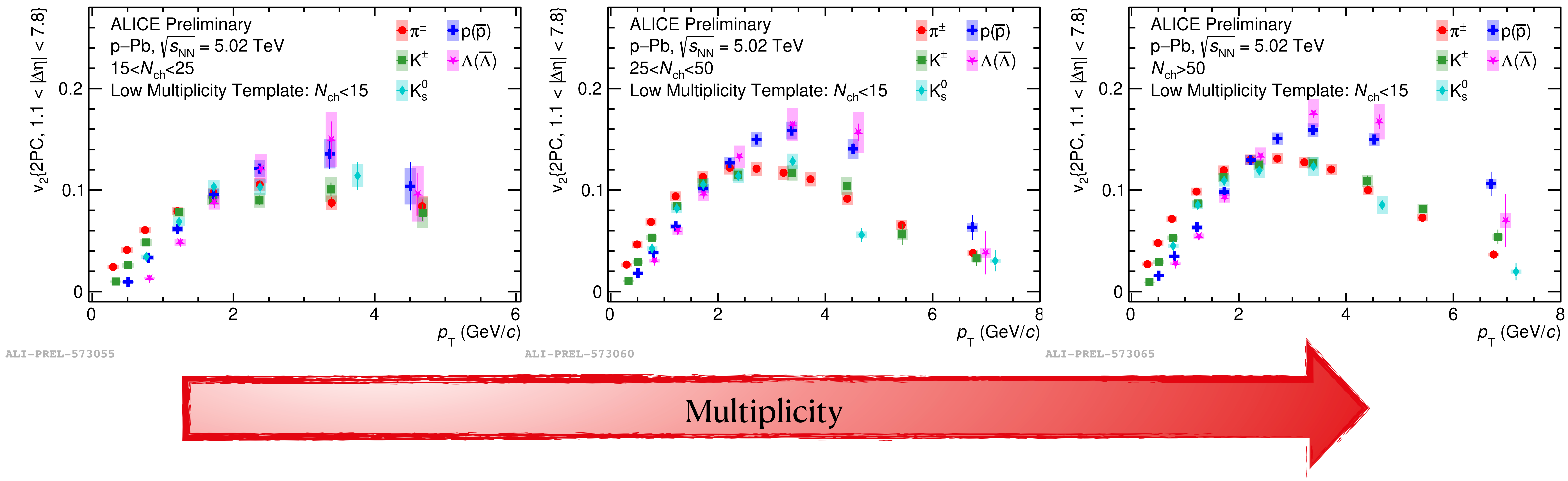
TF





- Mass ordering at low p_T - in both models
- The splitting also in both models
- Amplitude correct when coalescence on

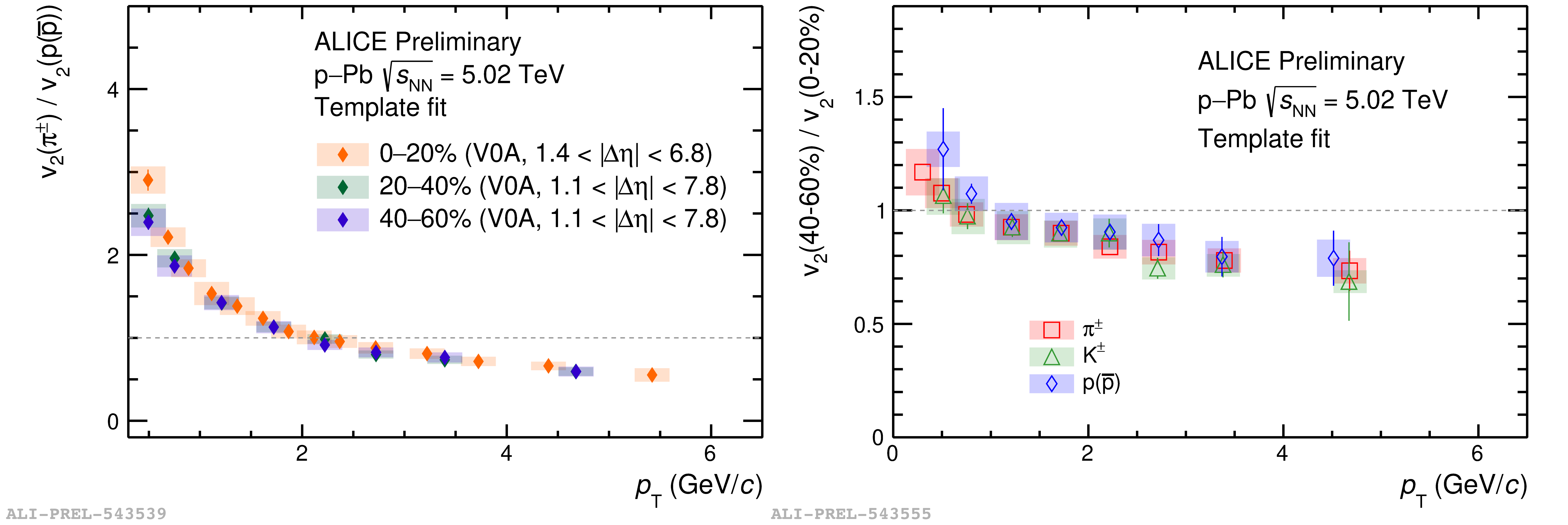
Multiplicity dependence in p—Pb



- Mass ordering at low p_T - preservers down to lowest multiplicities
- The splitting and grouping seams to disappear at low multiplicity
- The amplitude is smaller only at the lowest multiplicity

Multiplicity dependence in p—Pb

TF



- The species ratio is not multiplicity dependent
- The aptitude in different multiplicity classes is scaled the same for different species

Flow of (identified) parti...

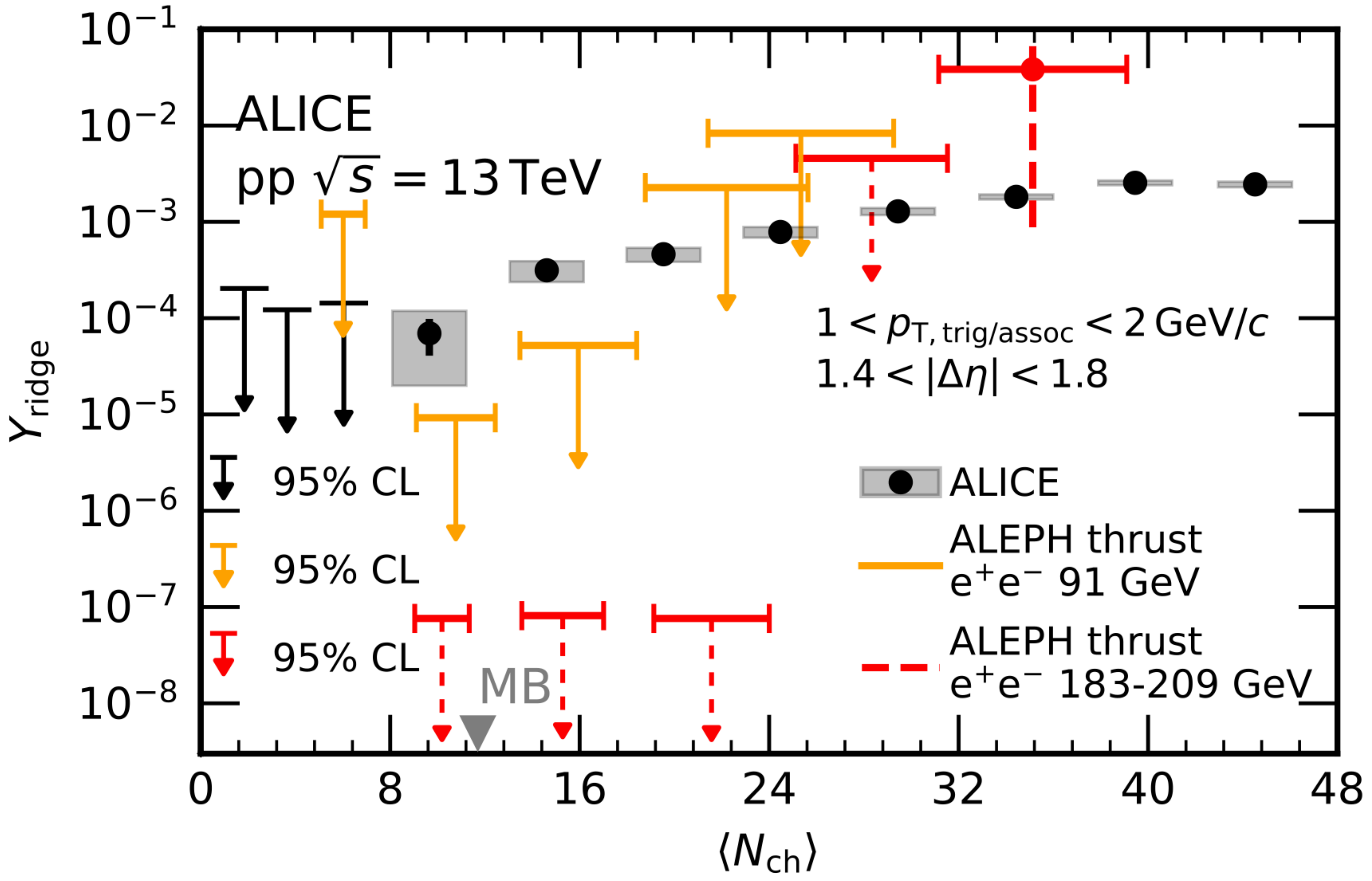
The baryon-meson splitting and grouping persist in small collision systems at lower multiplicities - consistent with the coalescence picture

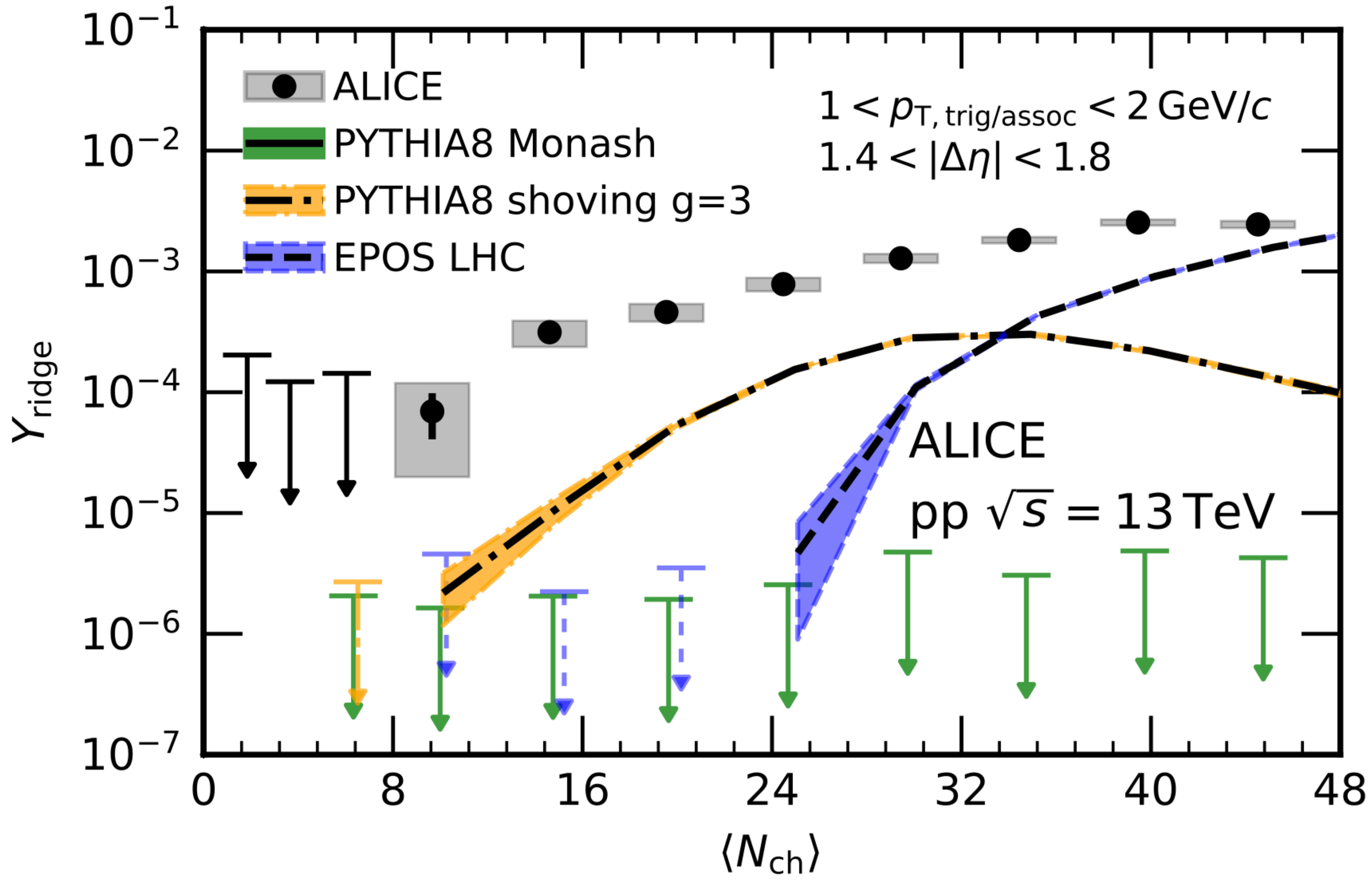
“Exotic” collision systems

Down to the lowest multiplicities

FF

Phys. Rev. Lett. 132 (2024) 172302

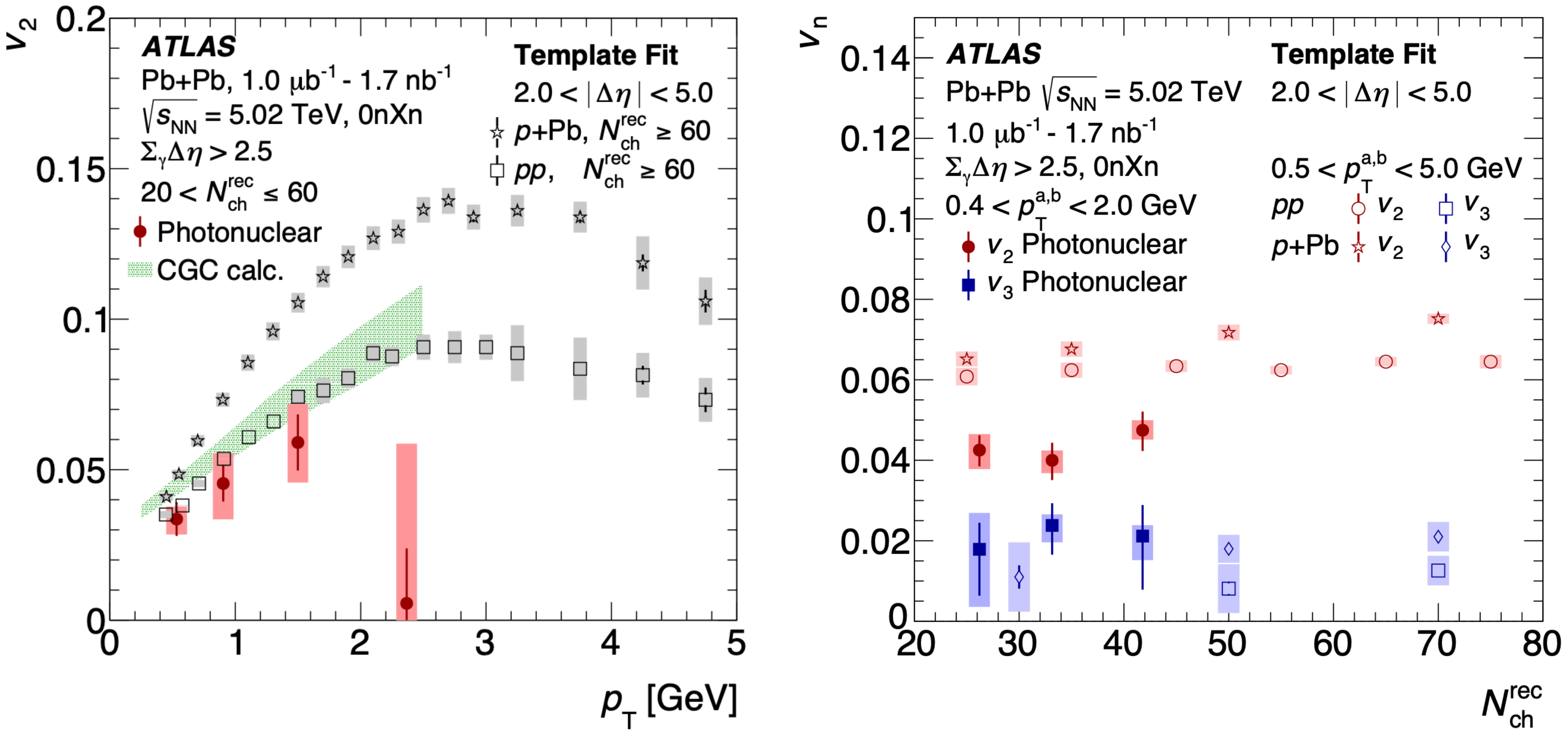




- Non-zero ridge yield at extremely low multiplicities in pp collisions
- At multiplicity within large uncertainties compatible with $e^+ + e^-$
- At multiplicity 8-24 - pp larger than $e^+ + e^-$ —> 5σ (91GeV); 6.3σ (183-209 GeV)
- None of the model describes the data

Down to the smallest systems - γPb

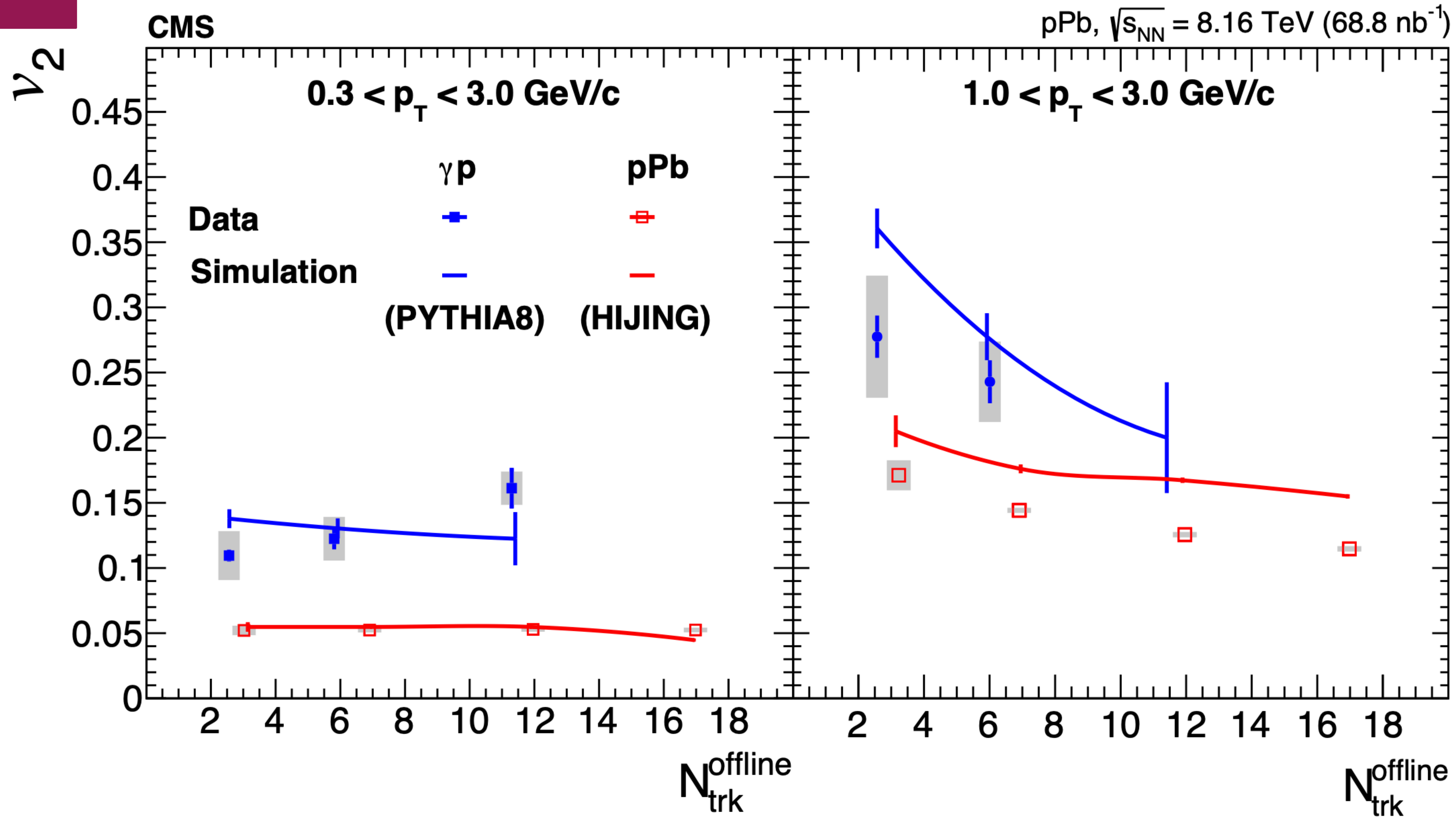
Phys. Rev. C. 104 (2021) 014903



- Non-zero v_2 and v_3 independent of multiplicity, similar to pp and p—Pb
- Smaller v_2, but compatible v_3; Not reliable at high p_T
- No hydro model - expectation of similar v_2 as in p—Pb (vector meson — Pb collision)
- CGC model in fair agreement - not the same parameters as for HF comparisons

Down to the smallest systems - γp

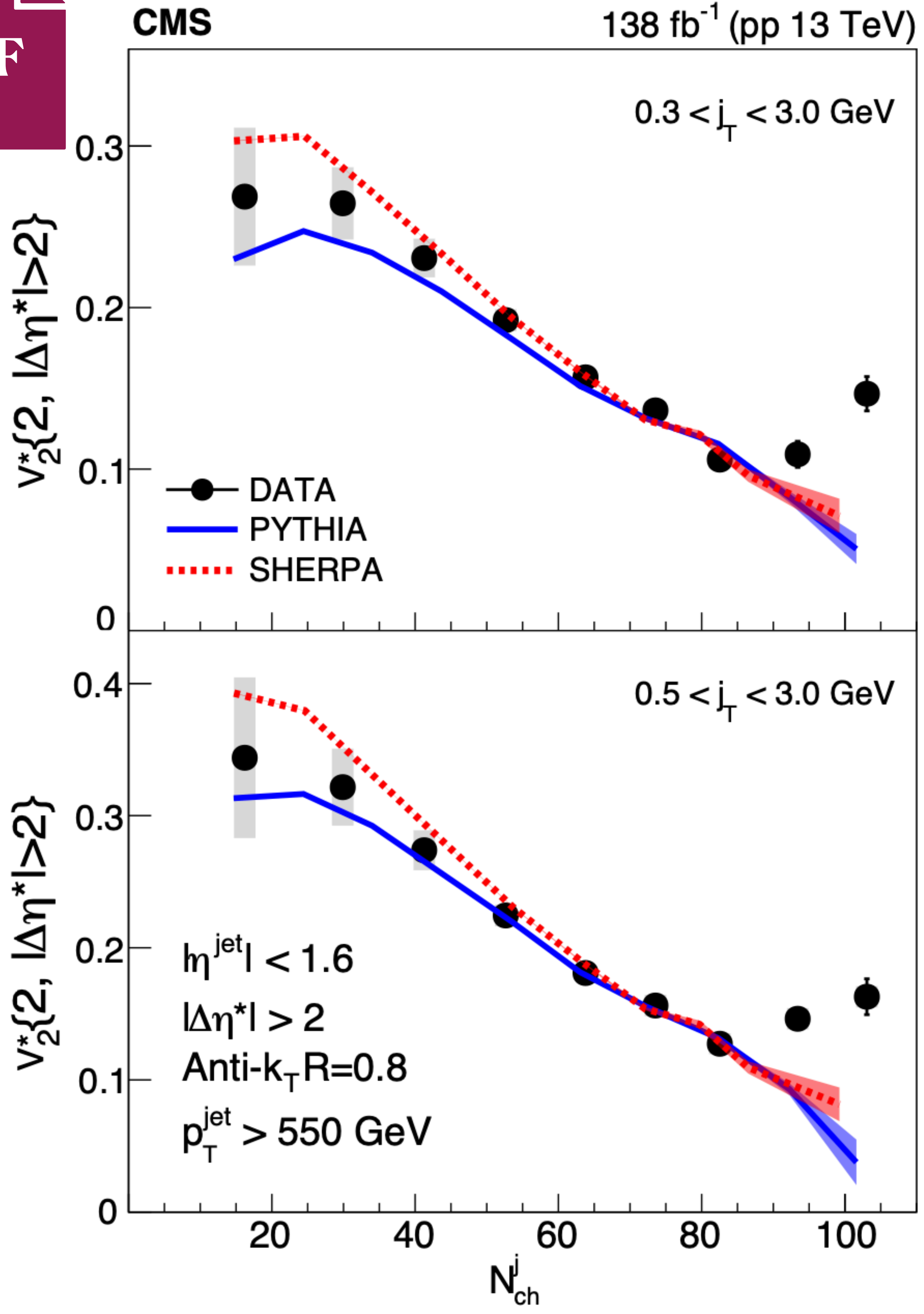
Phys. Lett. B 844 (2023) 137905



- Larger v_2 in γp as in p—Pb
- In agreement with models without collective expansion - no signs of collectivity
- Higher v_2 at higher p_T - possible proton shape fluctuations

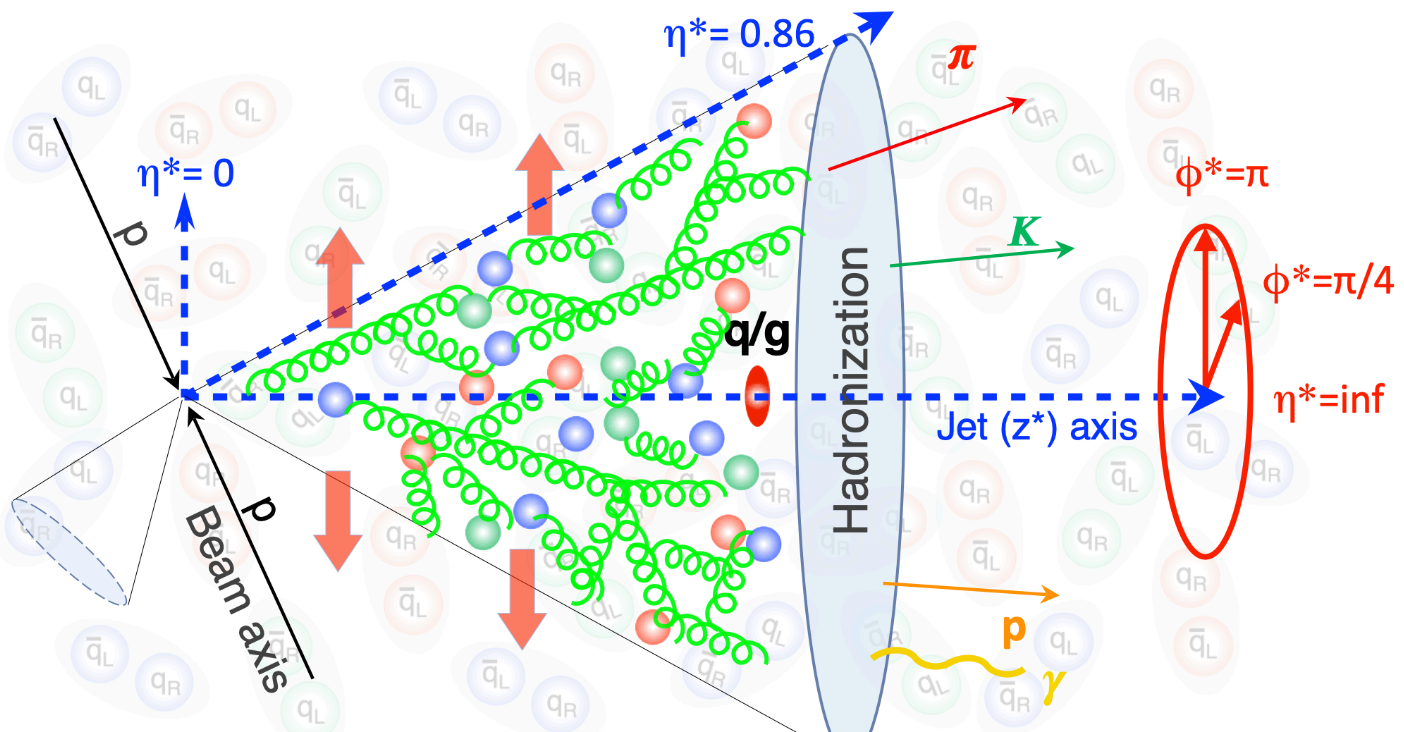
Flow measurement within a jet

FF



arXiv:2312.17103, accepted to PRL

- v_2 measured inside jets, in coordinates w.r.t. jet axis
- Short range correlations ~$1/N^j_{ch}$
  - Observed up to 80 and described by models
- Deviations at larger jet multiplicities
  - 5σ deviation from models
- Indication of an onset of novel QCD phenomena related to non-perturbative dynamics of a parton fragmenting in the vacuum?



“Exotic” collision syste

Long range ridge down to the lowest multiplicities and v_2 inside jet not explainable with back-to-back correlations: What is really the limit of observing collective effects?

Conclusion

- Different collision energies: Consistent with each other -> consistent with deconfined system down to low collision energies with initial-state-driven fluctuations
- Strong dependence on initial geometry not confirmed by both experiments, further measurements needed
- Soft part of the event is not influenced by a hard scale, but zero jet particle v_2 and no jet quenching in pp
- The baryon-meson splitting and grouping persist in small collision systems at lower multiplicities - consistent with the coalescence picture
- Long range ridge down to the lowest multiplicities and v_2 inside jet not explainable with back-to-back correlations

Outlook

- Can be the initial geometry dependence confirmed by another analysis?
- Can be the deconfinement formation in small systems be actually concluded?
- Do the jets escape before the collectivity develops in pp?
- Is the collective system bigger in p—Pb, so that non-zero jet particle flow is formed?
- What is really a limit of observing collective effects?

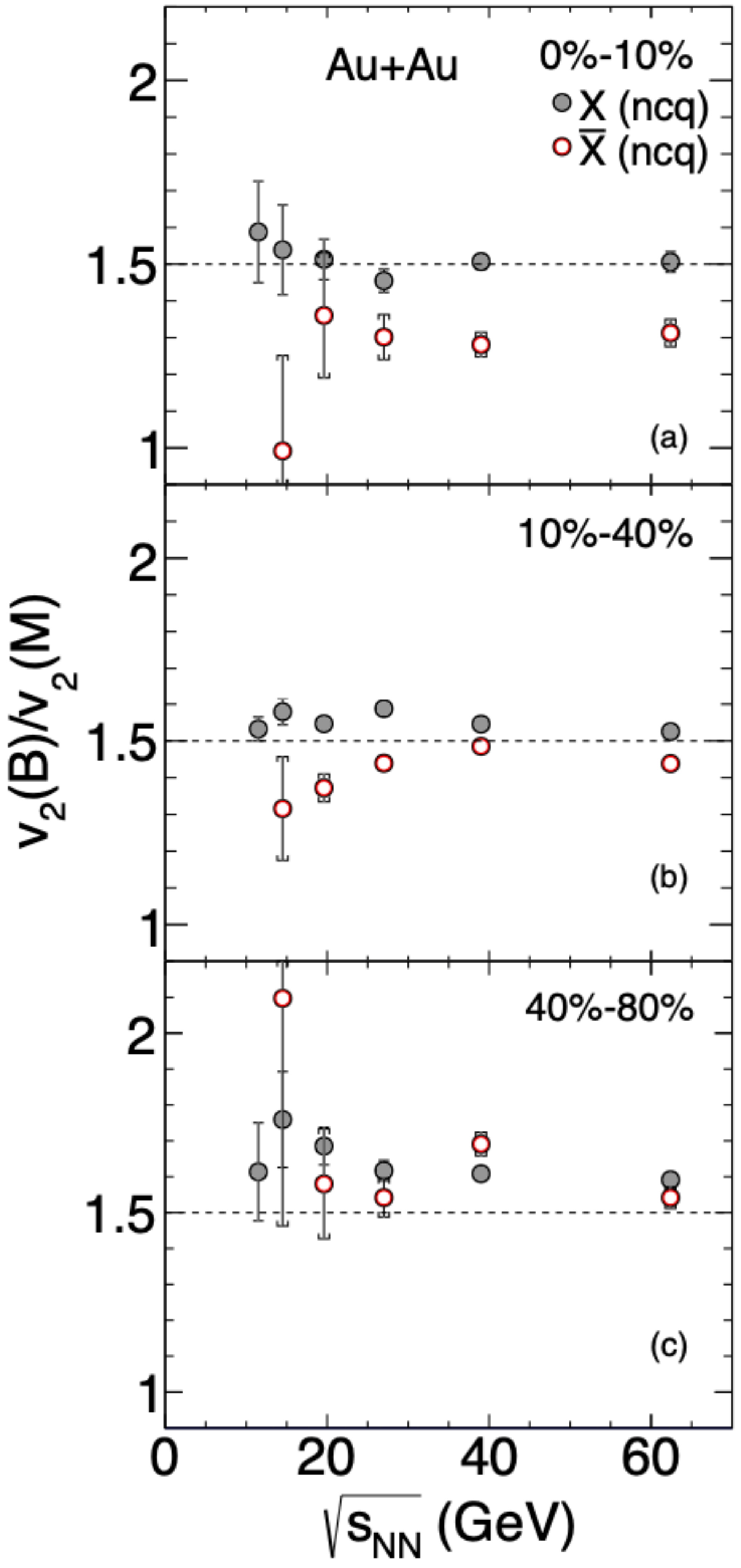
Thank you for your attention!

Questions

Back up

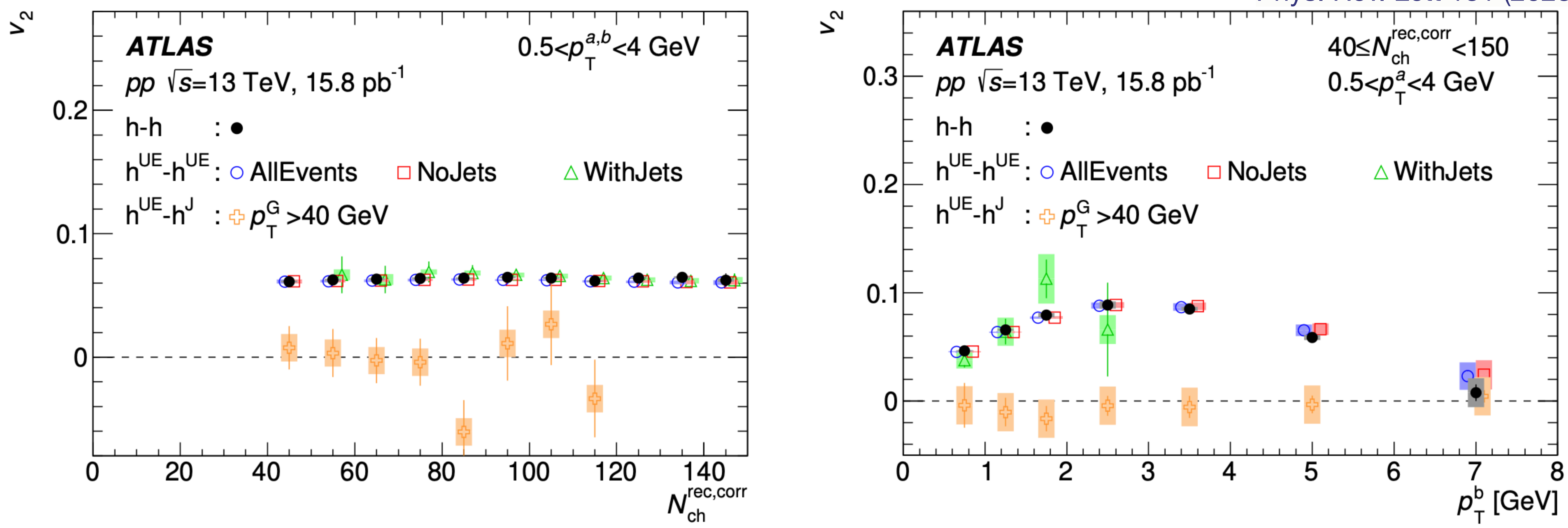
NCQ - energy dependence

Phys. Rev. C 93, 014907 (2016)



Jet flow in pp

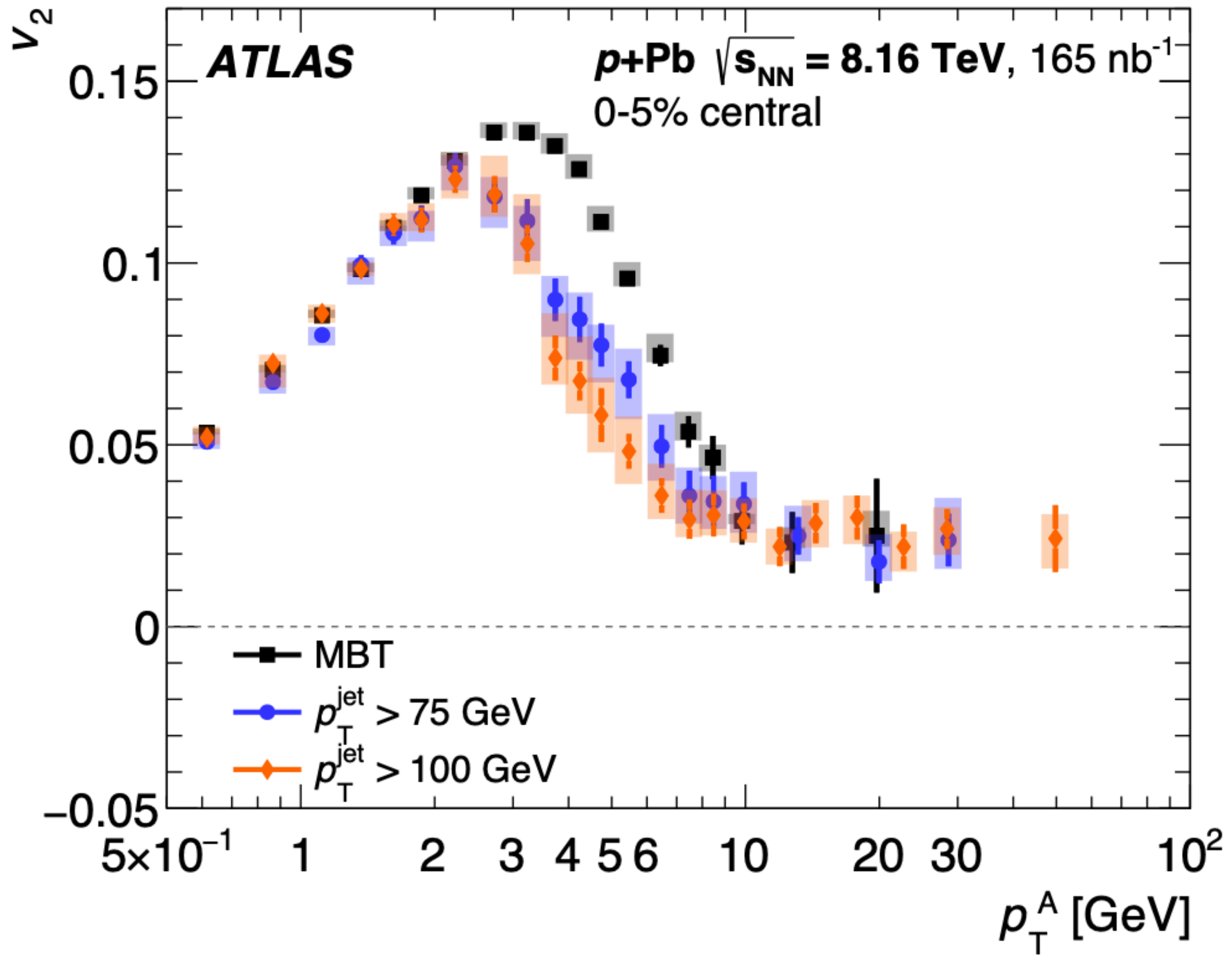
Phys. Rev. Lett 131 (2023) 162301

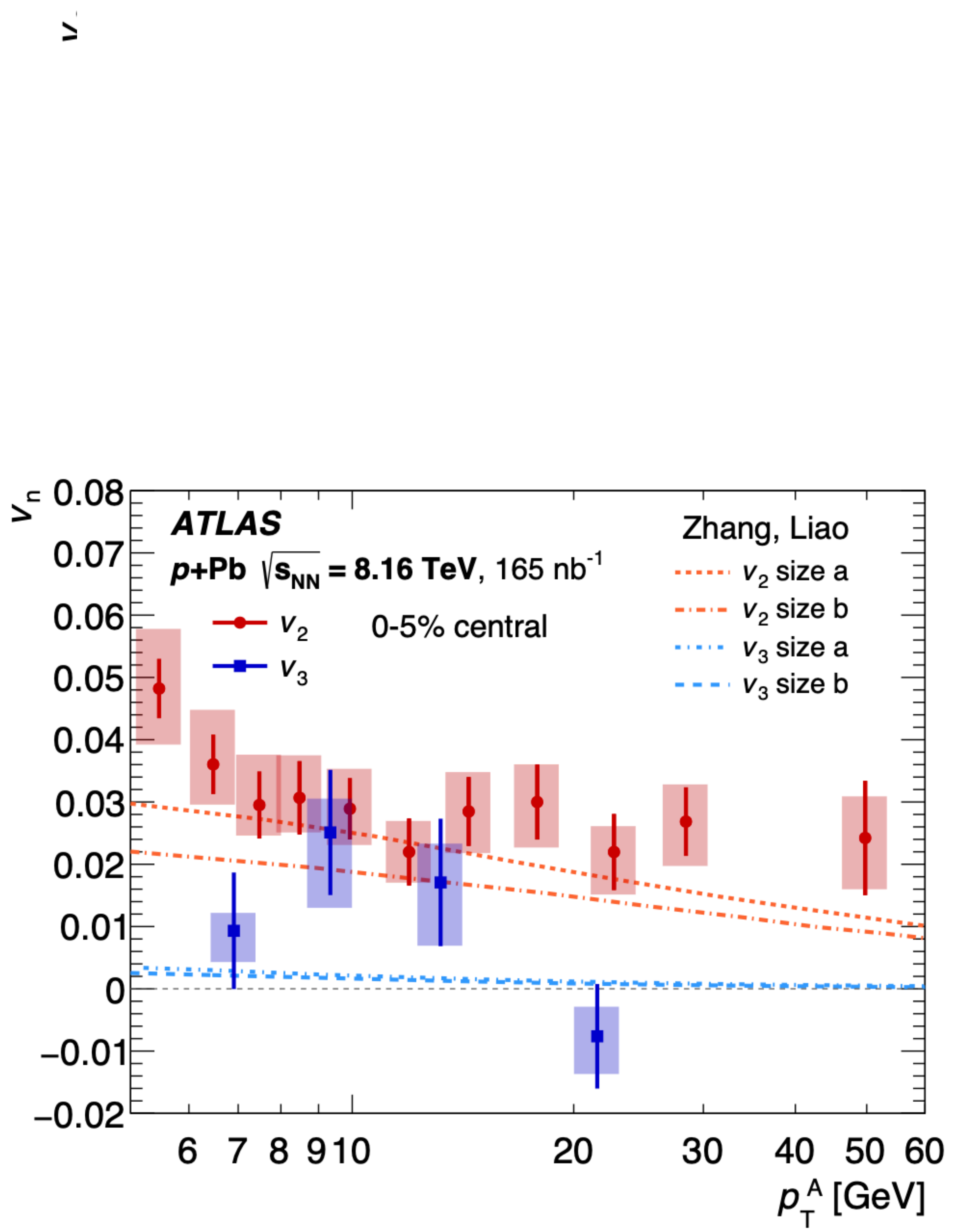


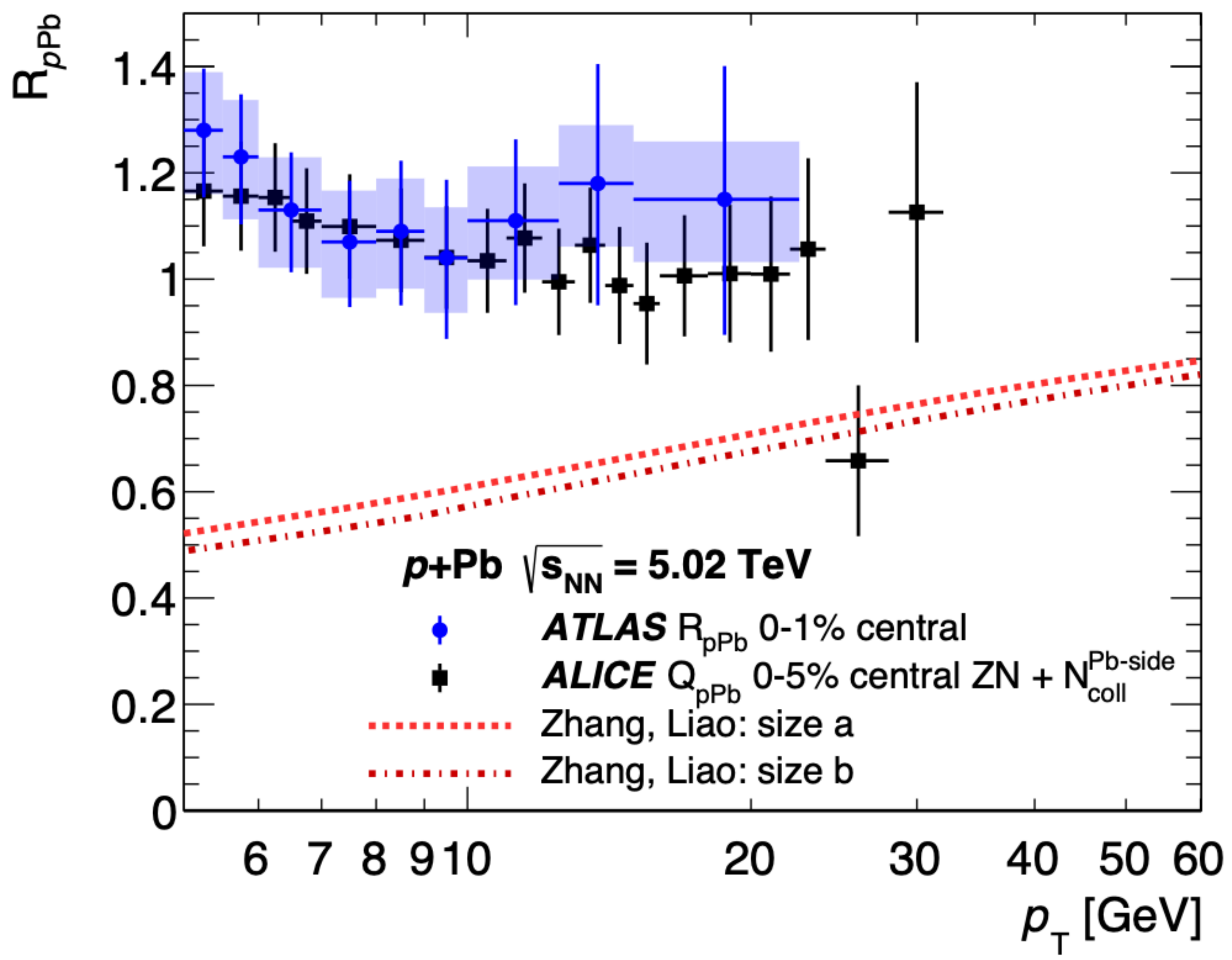
- $h^{UE} - h^{UE}$(*AllEvents*): 2PC where both tracks are h^{UE}. About 14% of *h*-*h* 2PC pairs are removed by the abovementioned rejection.
- $h^{UE} - h^{UE}$(*NoJets*): 2PC using events with no jets with $p_T^G > 15$ GeV.
- $h^{UE} - h^{UE}$(*WithJets*): 2PC using events with at least one jet with $p_T^G > 15$ GeV.
- $h^{UE} - h^J$: 2PC performed between h^{UE} and h^J.

Event scale dependent in p—Pb

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

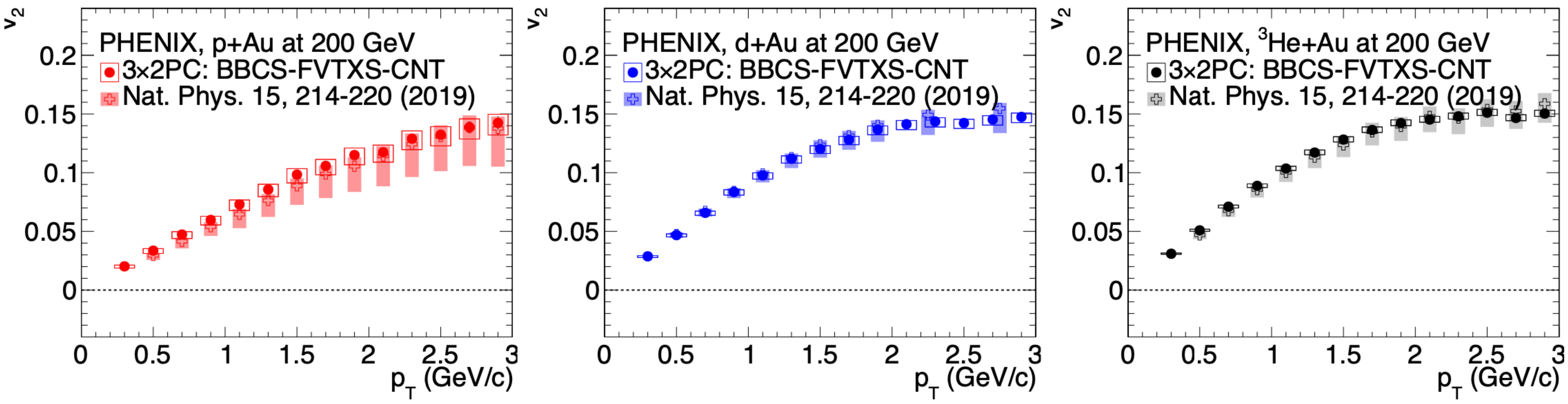






Intrinsic initial geometry dependence III

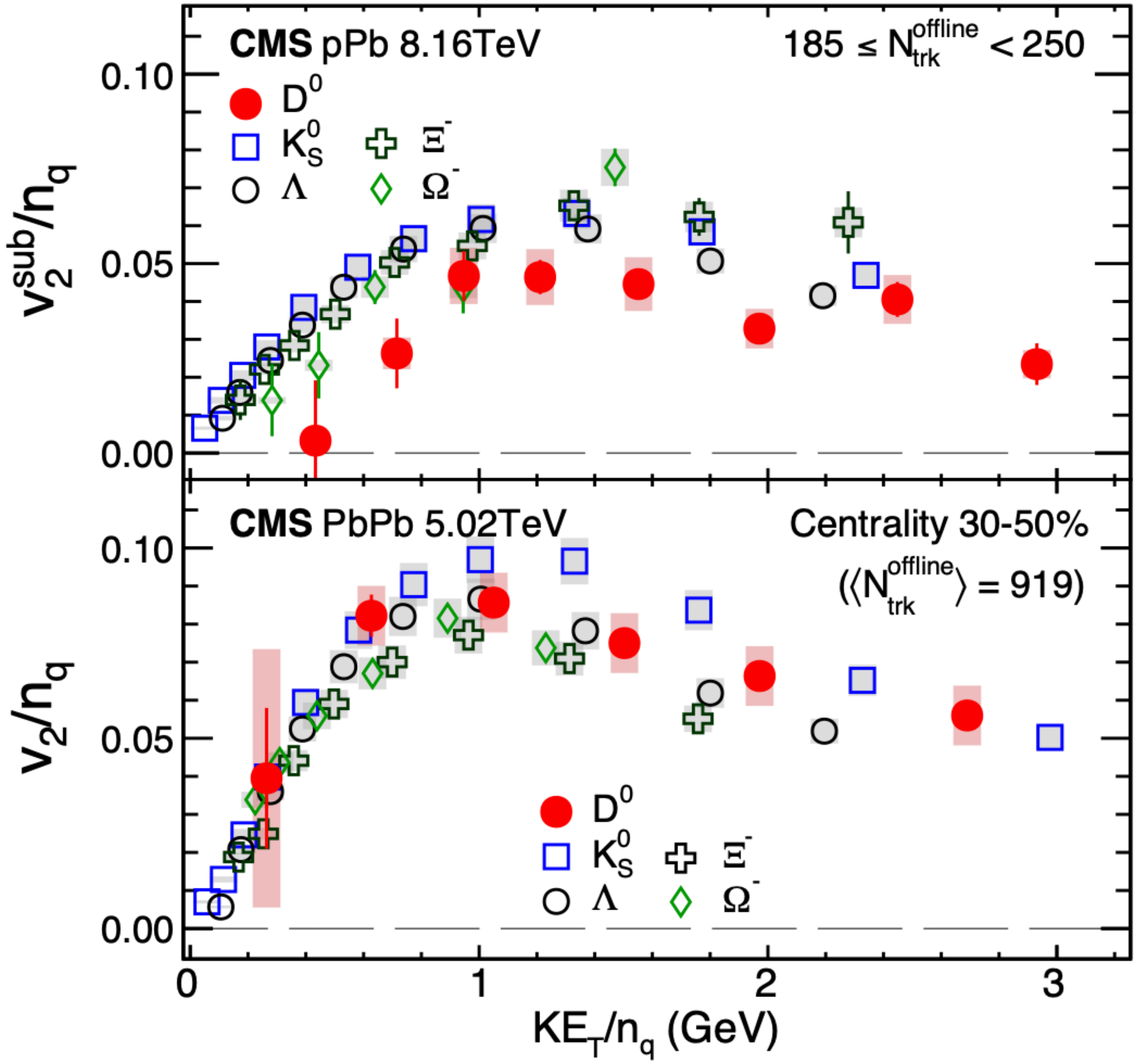
Phys. Rev. C 105, 024901



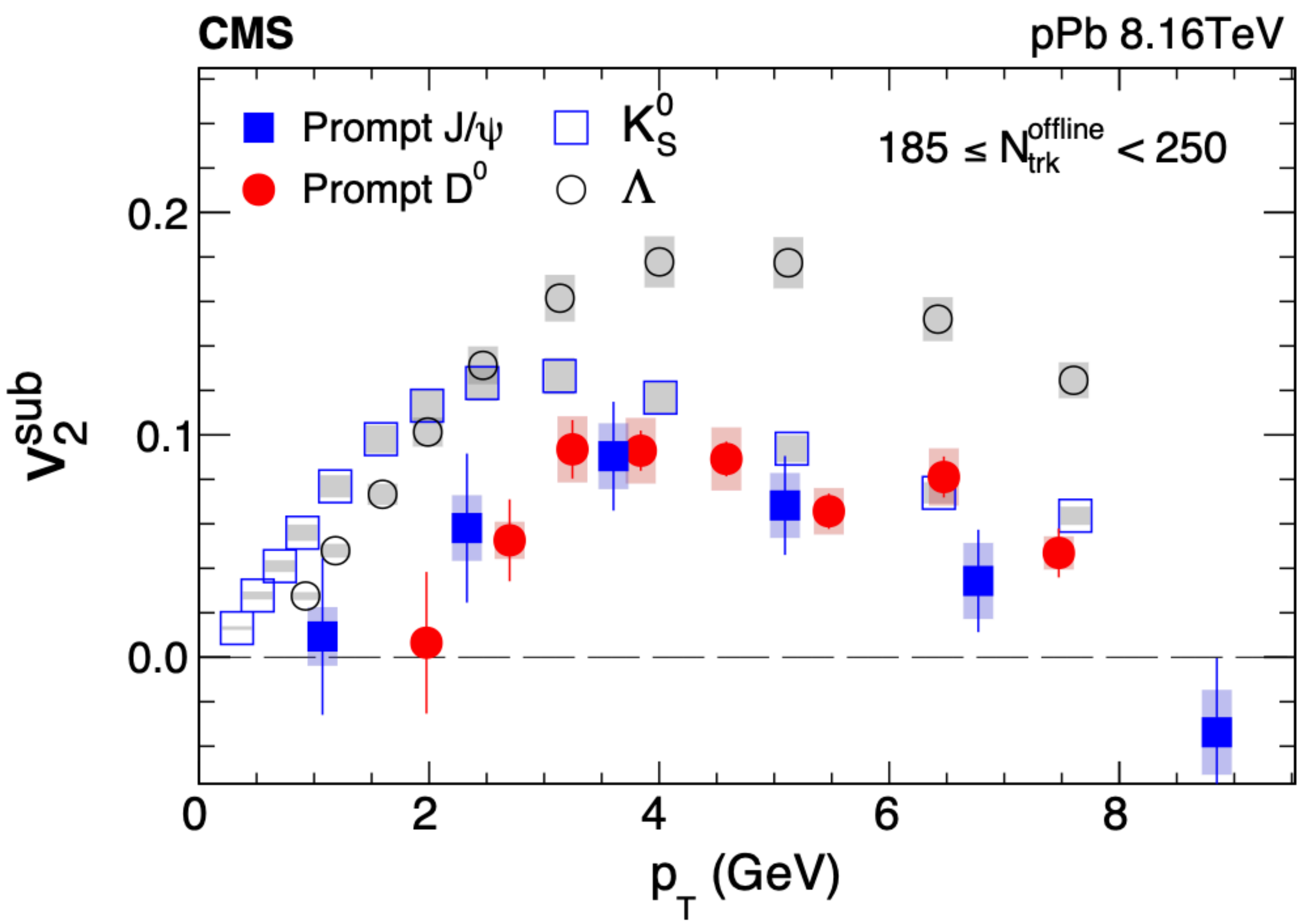
- Flow coefficients remeasured with a different method
- The same result

Identified v_2 in Pb—Pb and p—Pb

Phys. Rev. Lett. 121, 082301

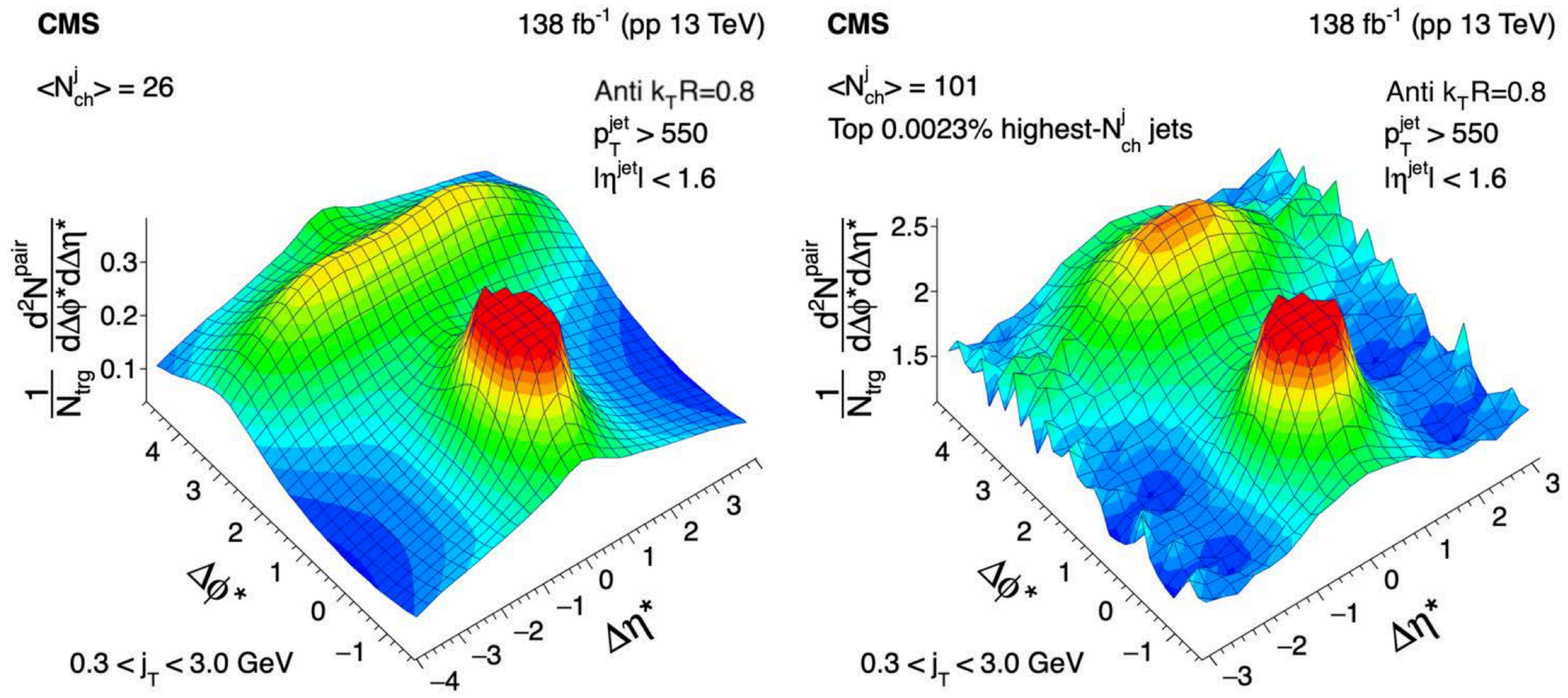


HF flow in p—Pb

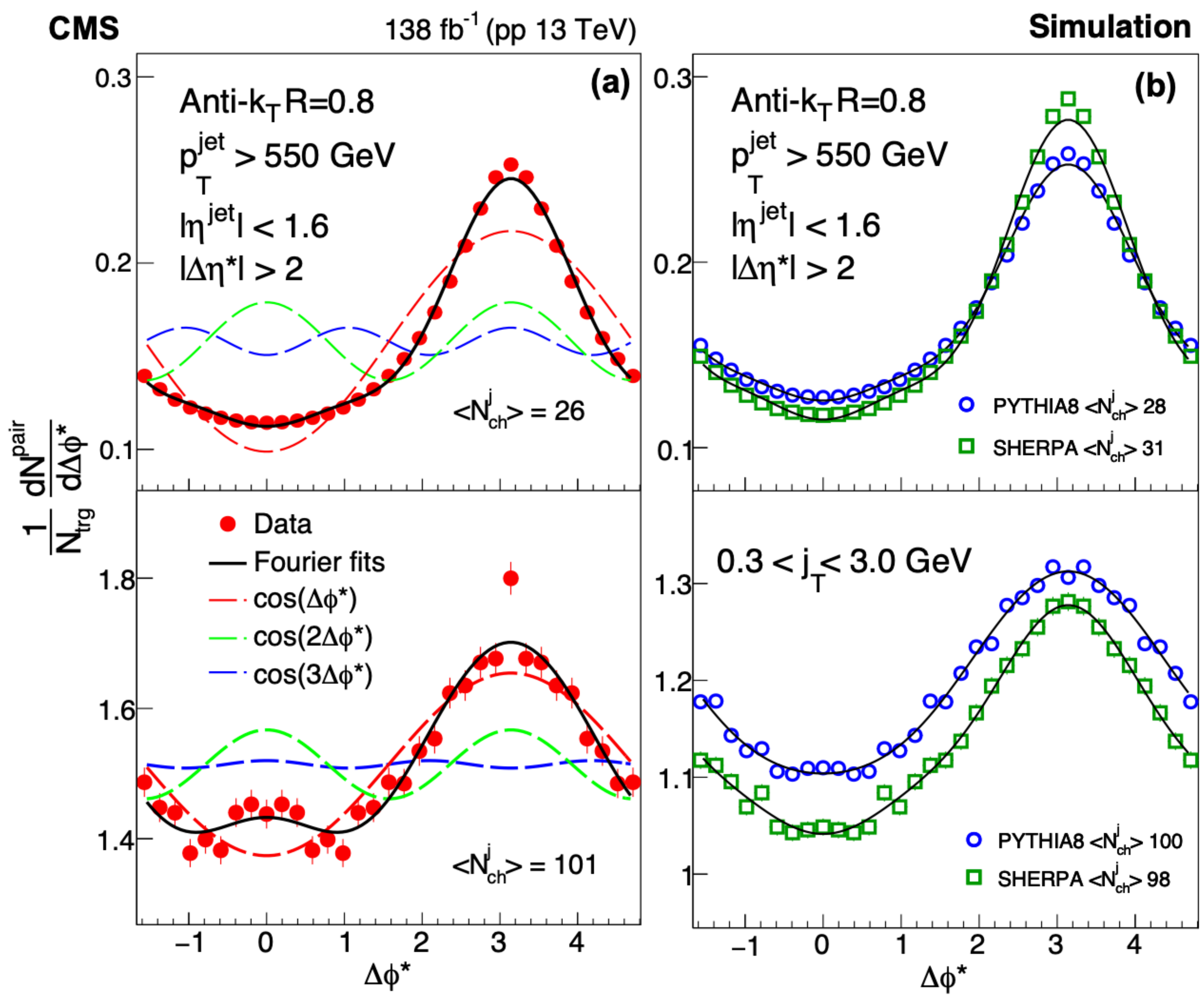


https://arxiv.org/pdf/1810.01473

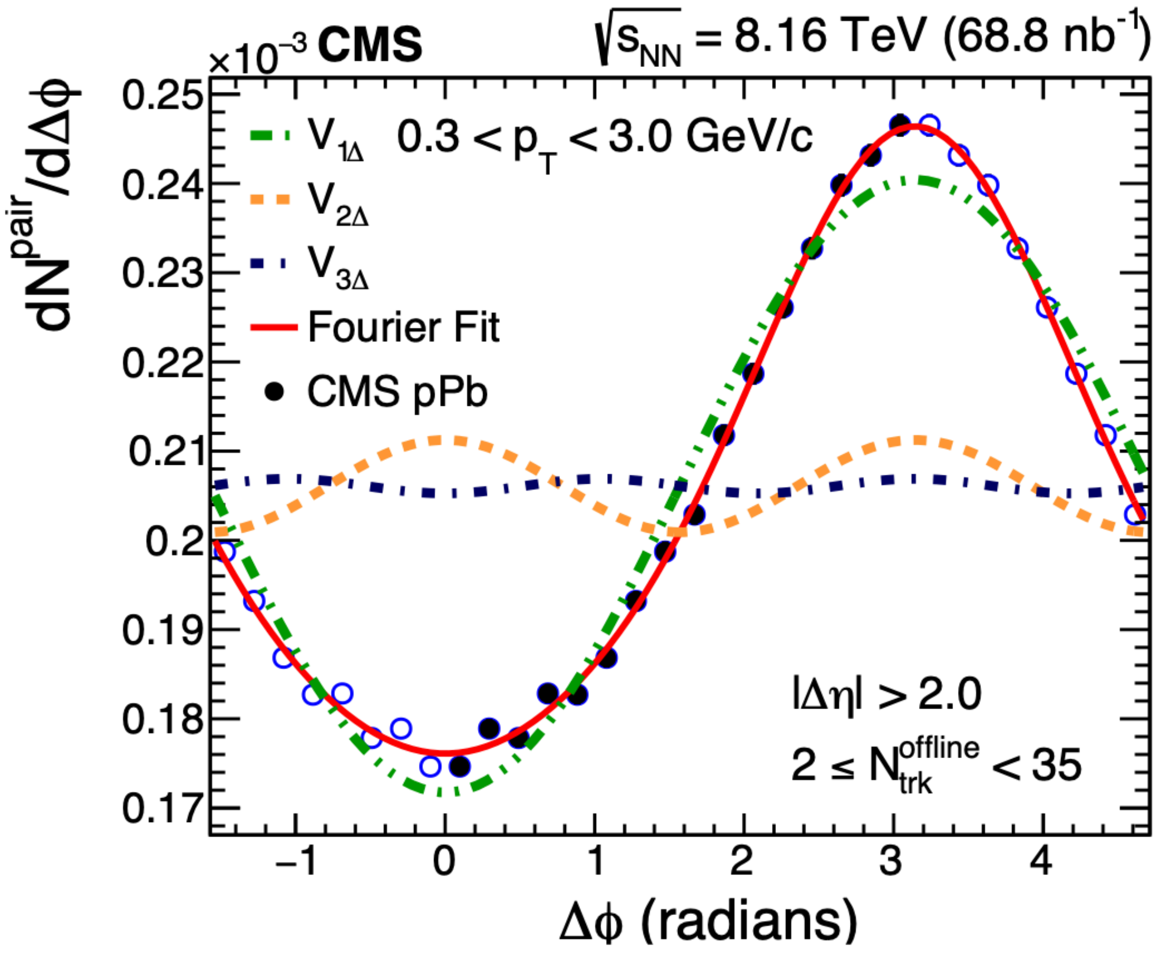
Flow measurement within a jet

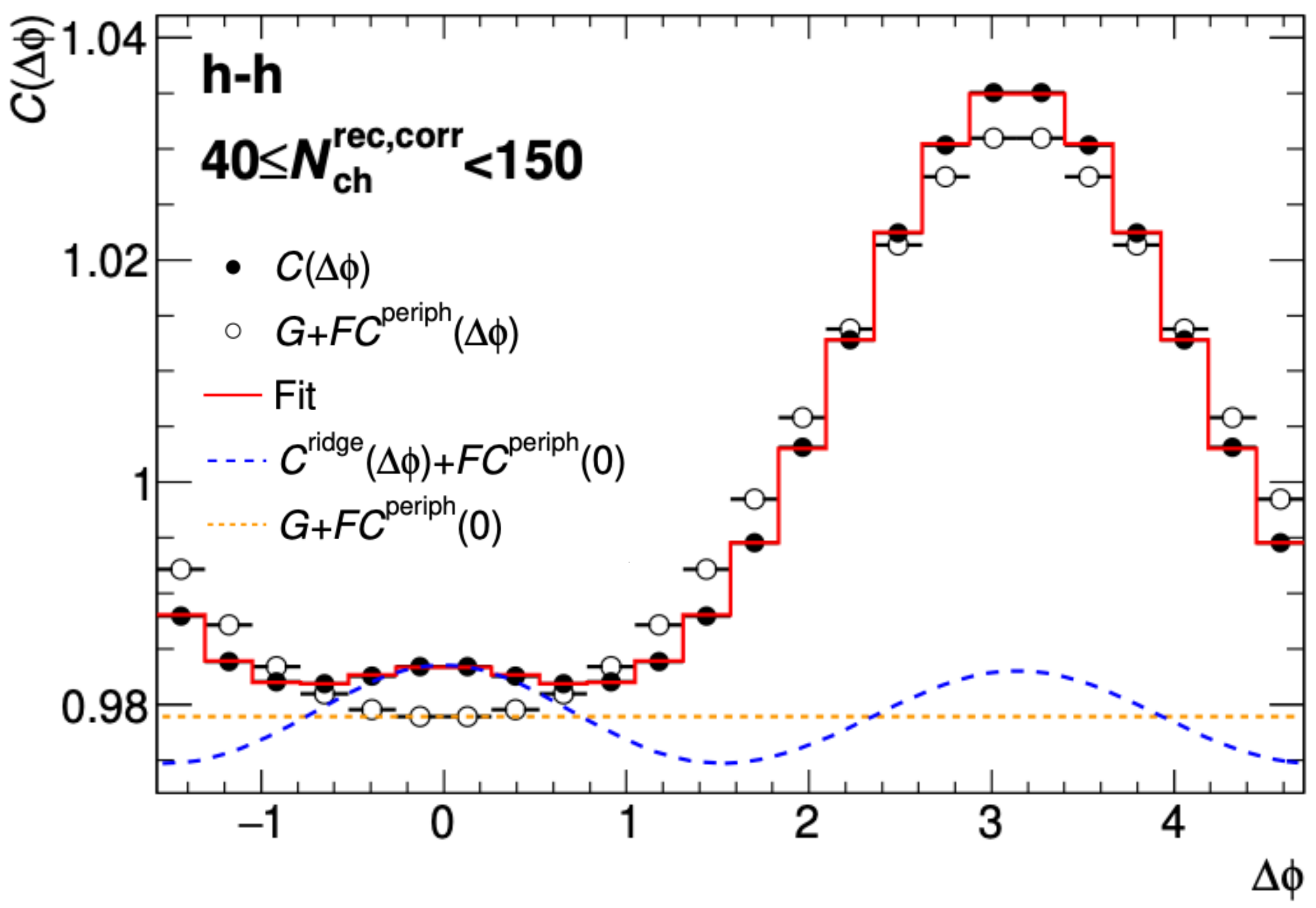


Flow measurement within a jet



Flow extraction methods (non-flow treatments)





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- 2 particle correlations
- Long range in η
- Direct fit with a Fourier expansion

Template fit (TF)

- 2 particle correlations
- Long range in η
- HM = convolution of scaled LM + flow modulation