CMS Overview on Soft Probes

ANPhA 2025

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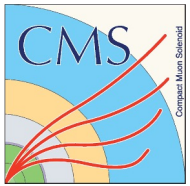
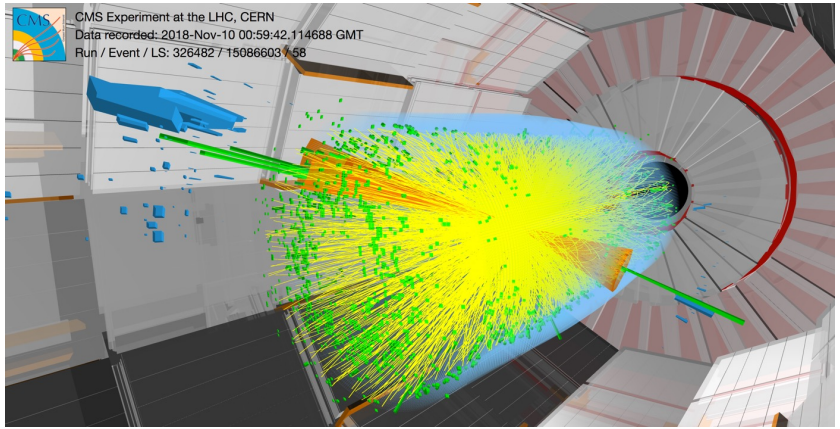
On behalf of the CMS Collaboration



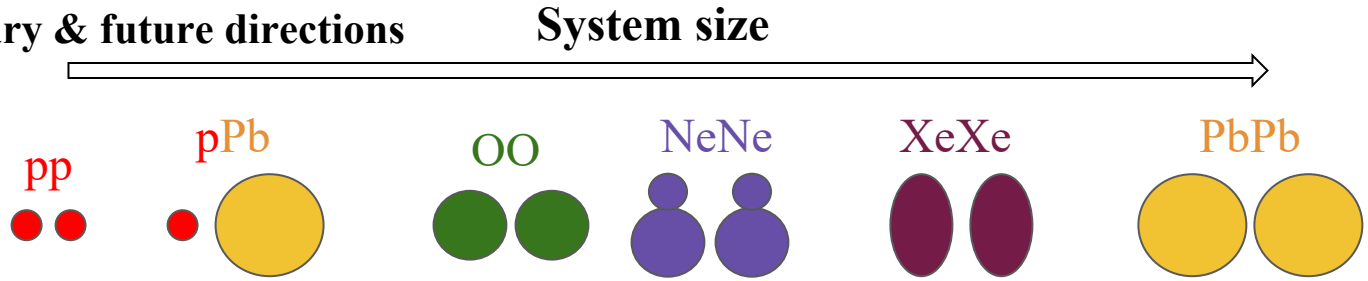
Outline

- **Global observables and properties of the bulk**
- **System-size overview**: pp, pPb → light ions → AA
- **CMS results**:
  - Multiplicity
  - Anisotropic flow (v_2, v_3)
  - Geometry-sensitive ratios
  - Collectivity in jets
  - Baryon-to-Meson ratio

CMS @LHC



- **Summary & future directions**



Multiplicity and energy density

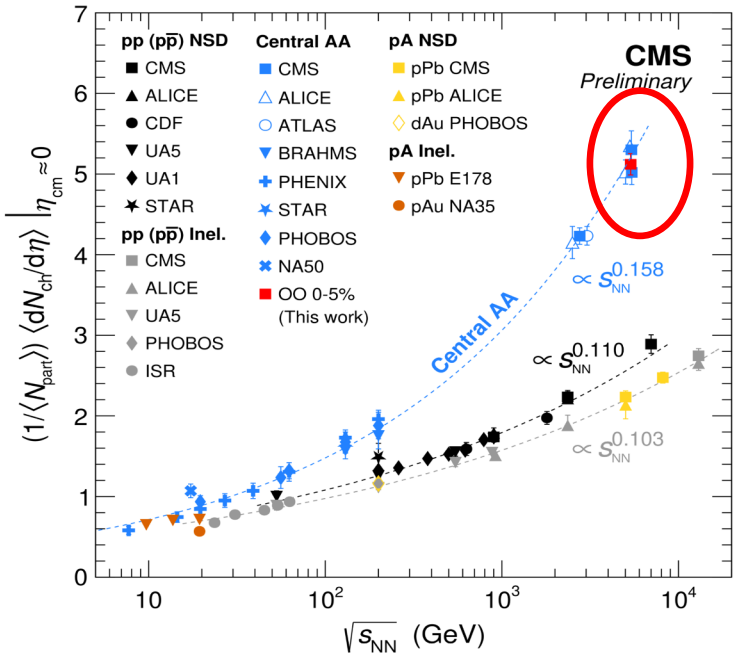
PbPb: $dN_{ch}/d\eta \sim 2032 \pm 91$ (syst)
OO: $dN_{ch}/d\eta \sim 135 \pm 3$ (syst)

Energy density ≈ 4 x RHIC (fixed τ_0)
Lower limit, likely τ_0(LHC) < τ_0(RHIC)

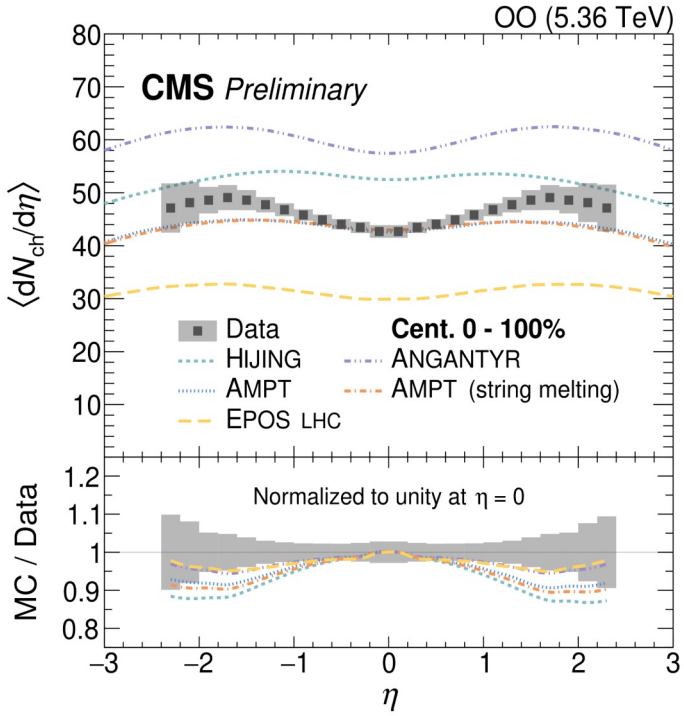
$$\varepsilon(\tau) = \frac{1}{\tau_0 A}\frac{dN}{dy}\langle m_t \rangle$$

- In pp vs central PbPb, the conversion of energy to multiplicity behaves differently
  - Is OO more pp-like or AA-like?
- Central OO is AA-like in terms of multiplicity production
- Very far from superposition of pp or pA collisions!

CMS-HIN-25-010



Charged particle multiplicity



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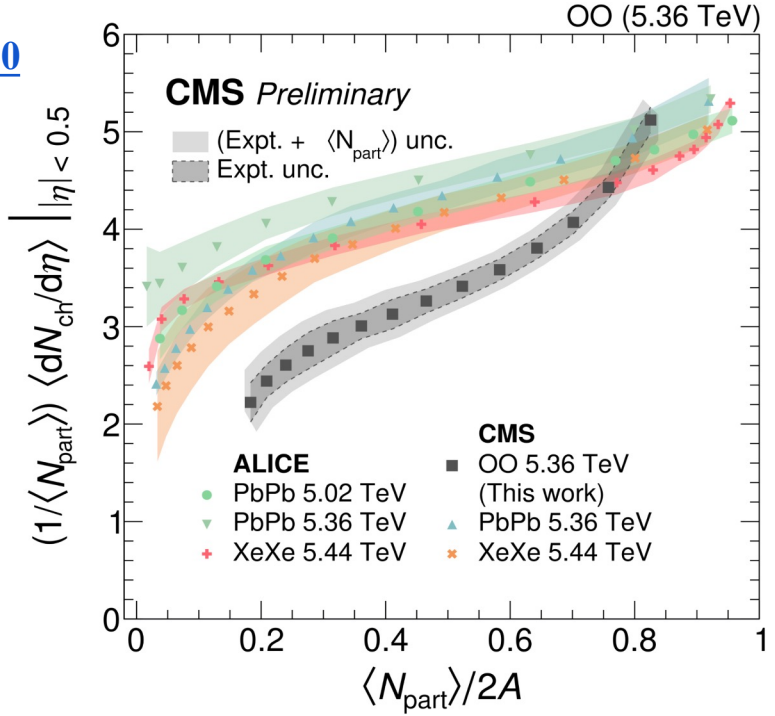
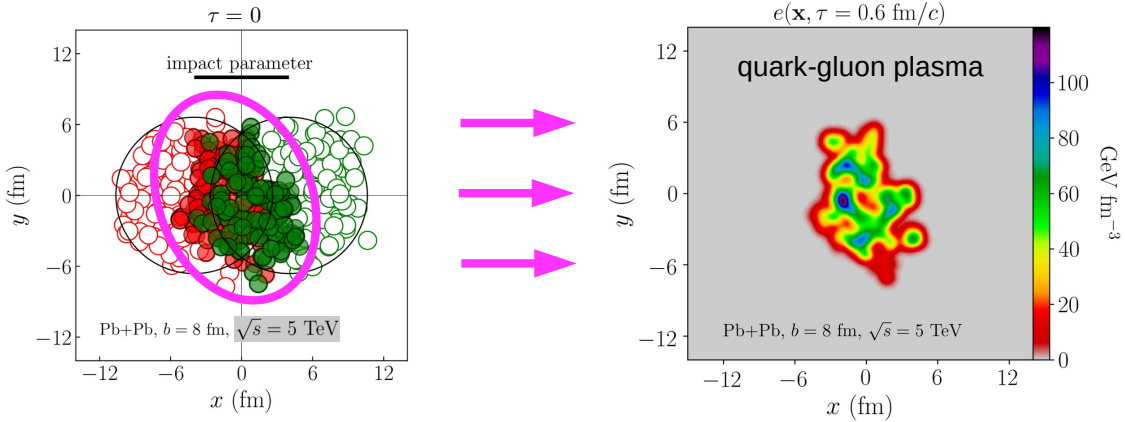
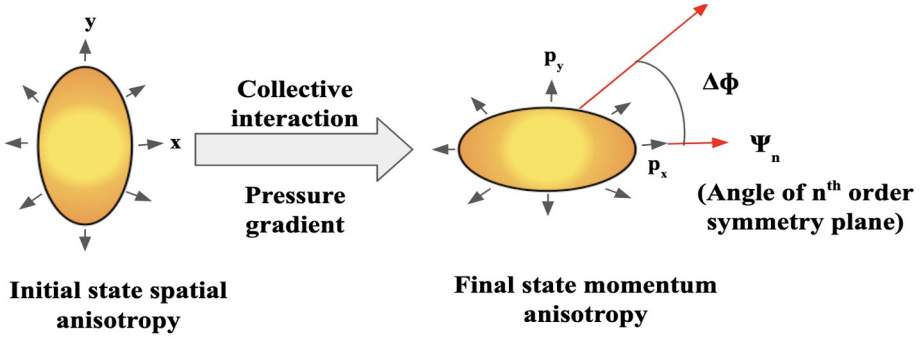


- Strong constraint power for MC generators
- AMPT does best fit for overall scale

- OO dN/dη per participant increases faster than PbPb or XeXe
- Maximal value is similar

Emergent phenomena in strong-interaction matter





- Effective fluid description.
- Equation of state from lattice QCD. Large number of DOF (~40): QGP.
- Relevant temperature at top LHC energy: ≈ 220 MeV (2.6 x 10^{12} K).

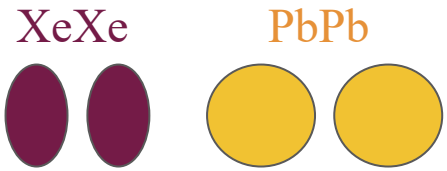
Extending the flow measurement

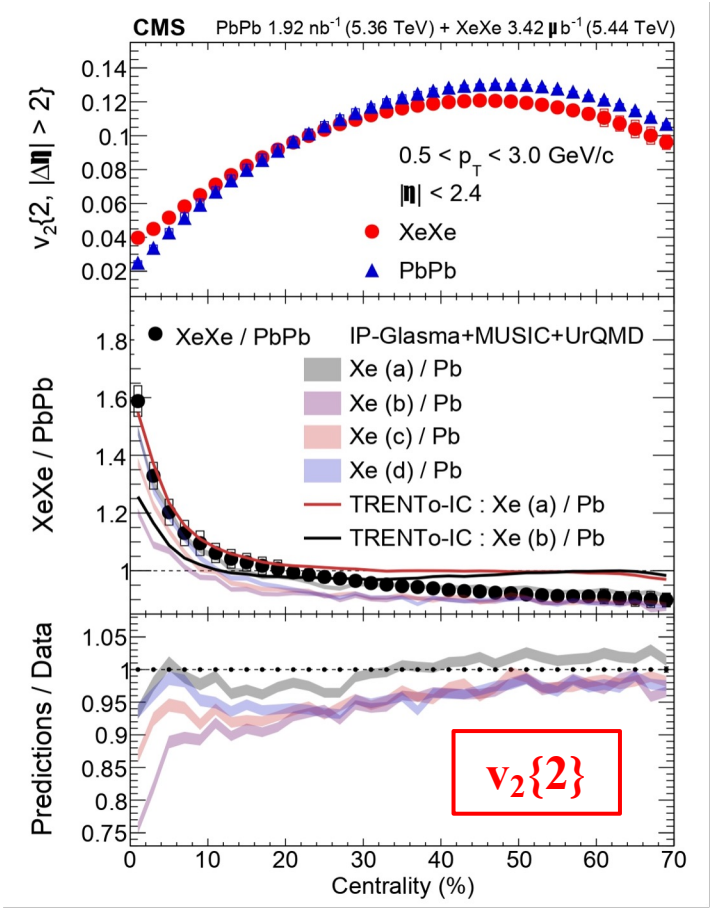
- Xe-Xe vs. Pb-Pb. and/or O-O vs. Ne-Ne

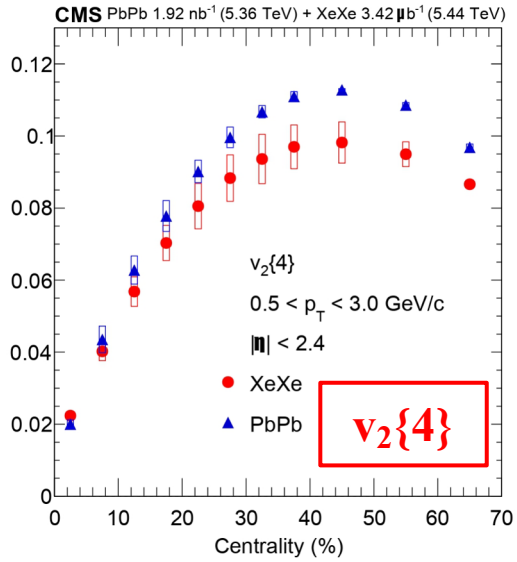
- ❑ Nuclear deformation effect (if any) and system size
- ❑ New interplay bet. nuclear structure & initial state
- ❑ Bridges the gap between p-p, p-Pb and Pb-Pb
- ❑ Opportunity to test the scaling behavior in fluctuation dynamics
- ❑ Confronting state-of-the-art hydrodynamic calculations with the wealth of the flow data

Collective behavior : from the largest systems (Xe, Pb)

- QGP formed in large systems (PbPb, XeXe) - heavy-ion collisions
  - Observed through multiparticle correlations involving flow harmonics







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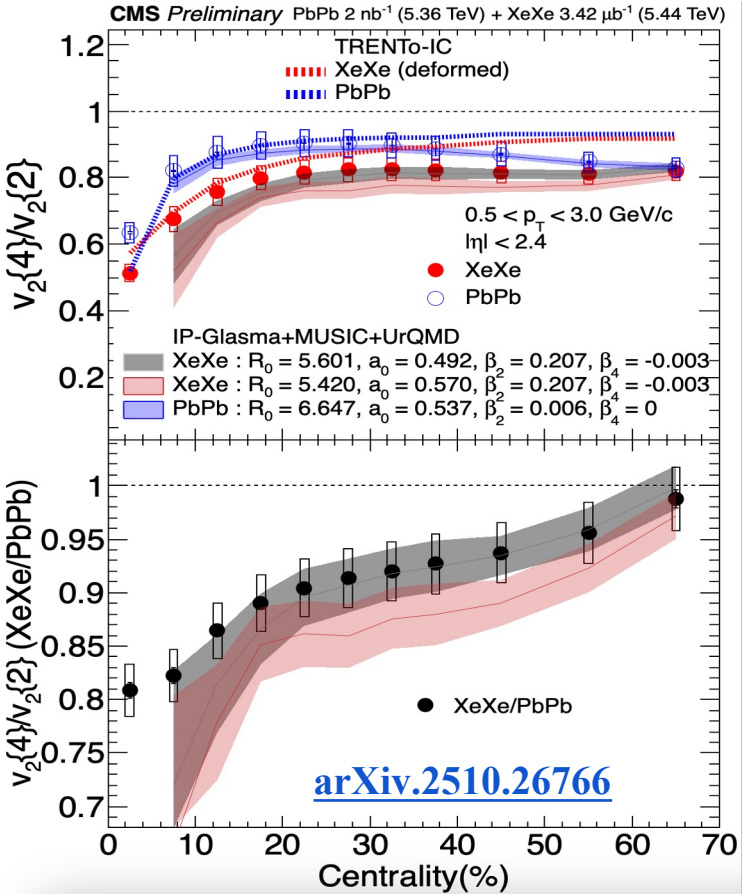
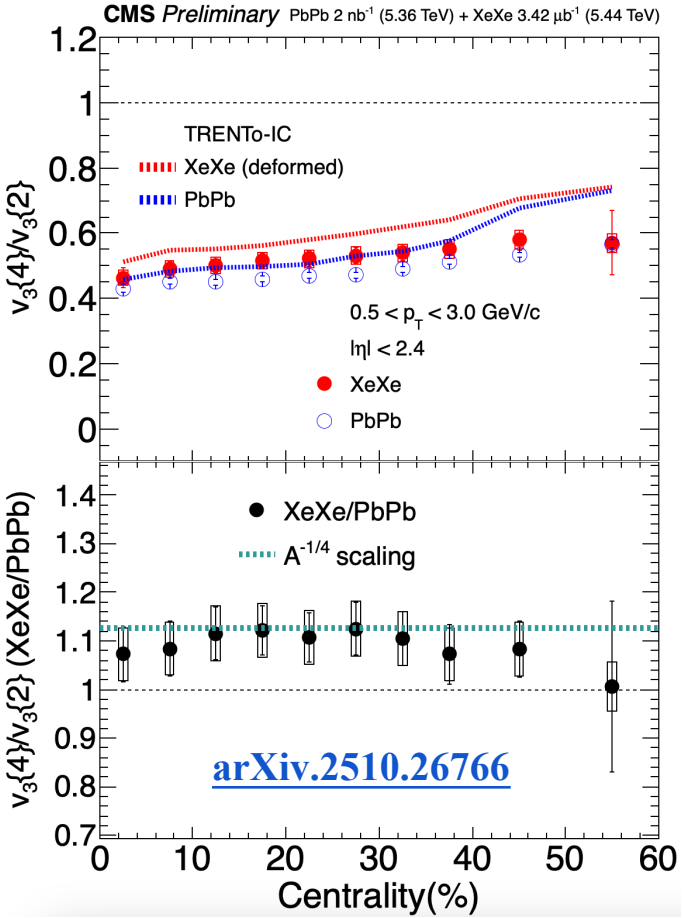
Xe-Xe vs. Pb-Pb



- $v_2\{4\}/v_2\{2\}$: relative fluctuations of v_n ; = 1 if v_n is the same for all events, smaller than 1 otherwise
  - Initial-state prediction deviates from data in peripheral collisions : non-linear hydro response

- $v_2\{4\}/v_2\{2\}$ known to be sensitive to neutron skin (a_0). Hydrodynamic predictions
  - Keeping same $\beta_2 = 0.207$, compared with two different a_0
  - Individual comparison + ratio (XeXe/PbPb) : closer match with ($a_0 = 0.492$, $\beta_2 = 0.207$)

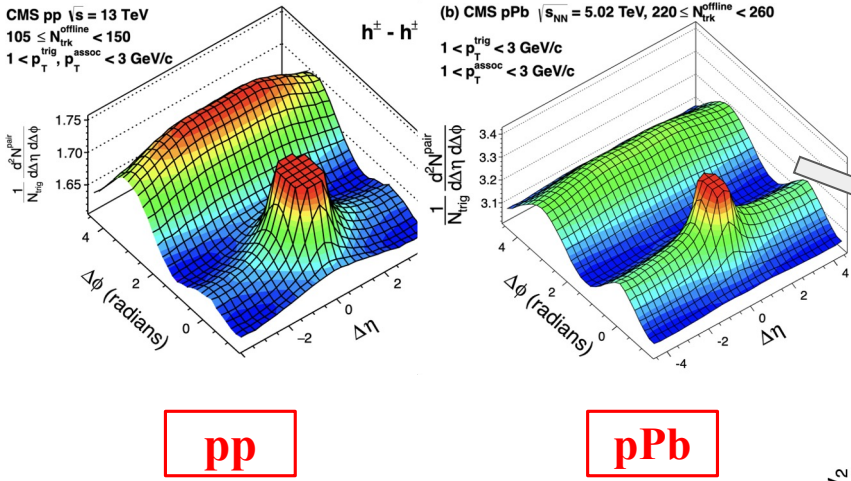
Xe-Xe vs. Pb-Pb



- $v_3\{4\}/v_3\{2\}$: expected to be proportional to $A^{-1/4}$
  - $v_3\{4\}/v_3\{2\}$ (XeXe/PbPb) should be $\cong (129/208)^{-1/4} \cong 1.1268560$
  - very good agreement within uncertainty
- Initial-state prediction by TRENTo-IC : $\varepsilon_3\{4\}/\varepsilon_3\{2\}$ follows the same order as $v_3\{4\}/ v_3\{2\}$
  - overshoots the data point
  - Nonlinear hydro response of vn to ε_n

Collectivity in smaller systems (pp, pPb)

- Small systems (pp, pPb) show "QGP-like" effects : **near-side ridge structure**

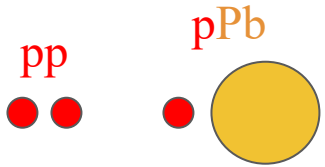


pp **pPb**

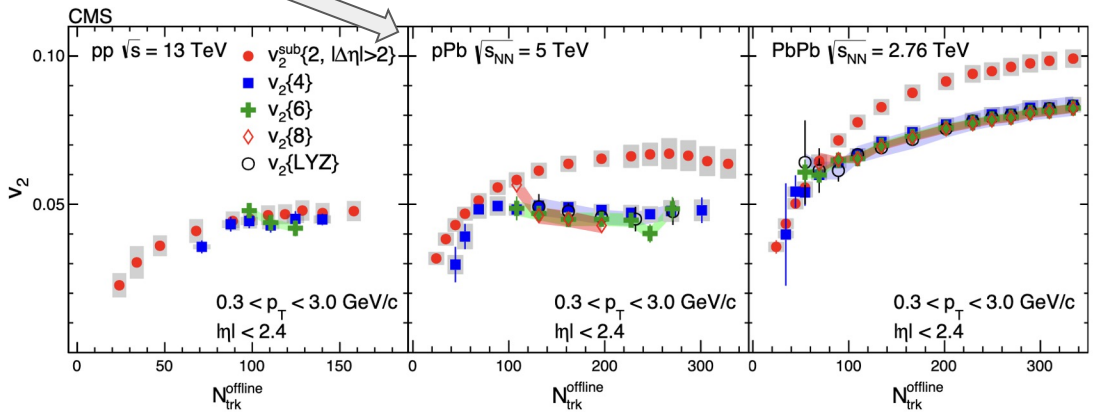
2D (Δη, Δφ) correlation

[Phys. Lett. B 765 (2017) 193]

[Phys. Lett. B 724 (2013) 213]



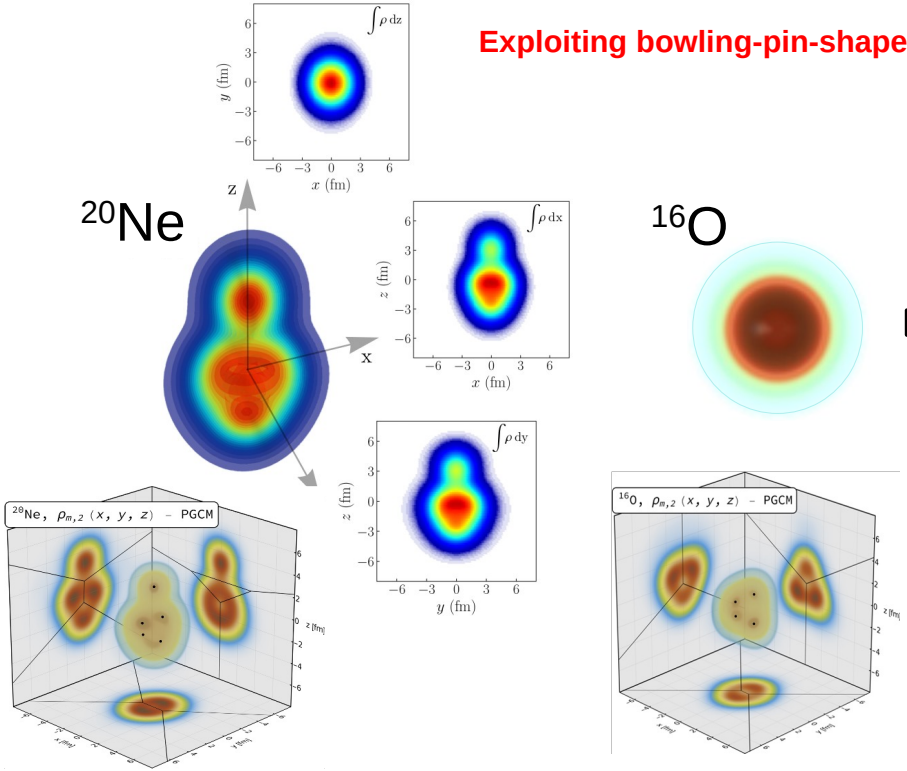
Multi-particle flow correlations

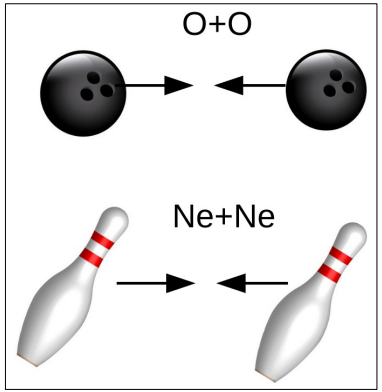


Opportunity from O+O and Ne+Ne collisions

Transparent evidence of the “geometric” origin of flow in a smaller system?

Exploiting bowling-pin-shaped ^{20}Ne.

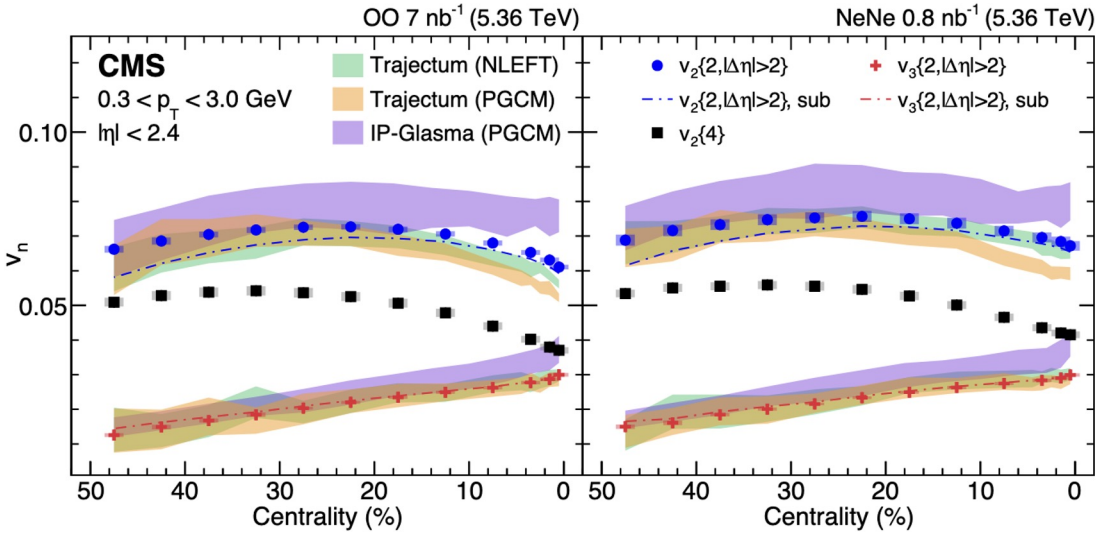




- Exploiting ab initio predictions
- Different N-body correlation

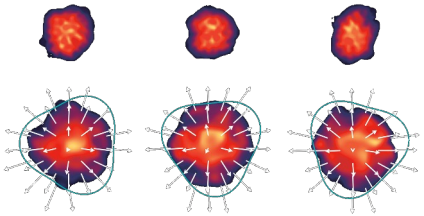
Anisotropic flow (v2, v3) in OO and NeNe

- v2{2} and v2{4} show the typical centrality dependence as observed in PbPb collisions
- v3{2} (fluctuations) increases as a function of centrality
- Hydrodynamic models provide overall a good description
- Strong sensitivity on the modelling of the initial conditions (ab-initio nuclear structure)



arXiv.2510.02580

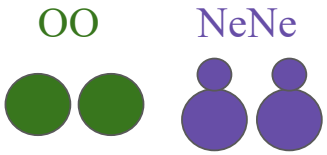
Decreasing overlap region

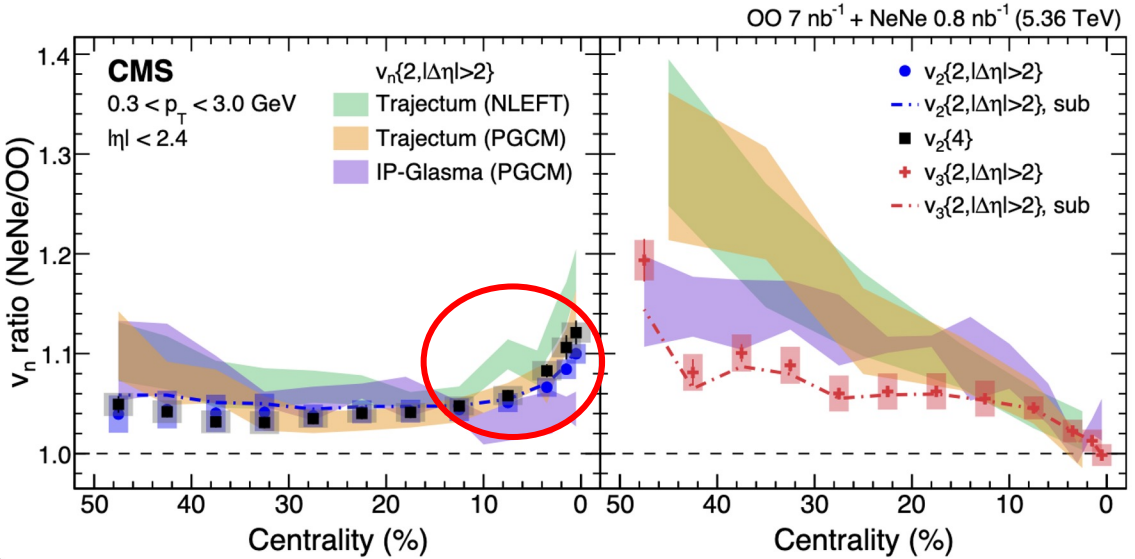


Energy density fluctuations

v_2 ratio (NeNe/OO): dependence on initial geometry

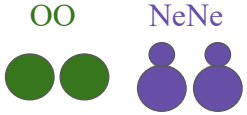
arXiv.2510.02580

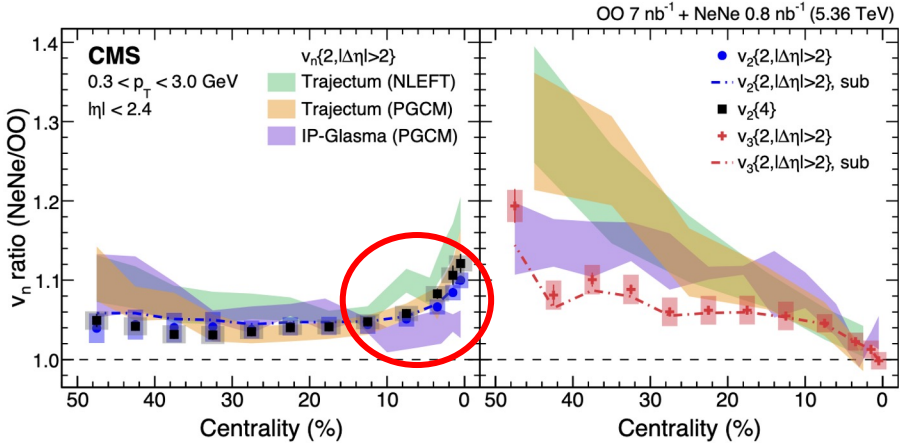




- **Elliptic flow ratio** between NeNe and OO : **constrain initial-geometry effects**
  - **Rising trend towards central collisions - sensitivity to nuclear deformation**
  - **Similar values for both 2- and 4-particle correlations**
- **Trajectum:** captures the **rising trend** in central collisions
- IP-Glasma+MUSIC+UrQMD - weaker centrality dependence of the v_2 ratio

v_2 ratio (NeNe/OO): dependence on initial geometry





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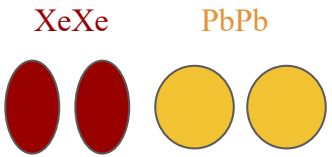
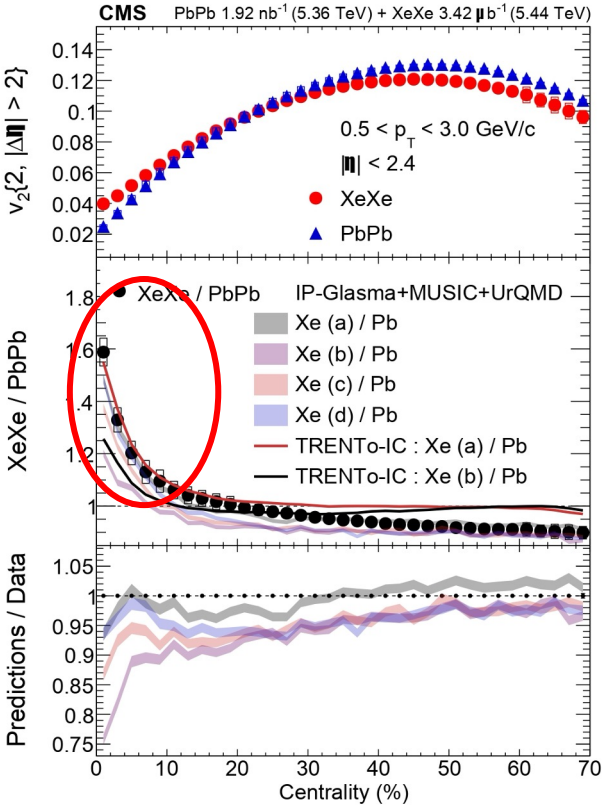
- Similar rising trend also observed for XeXe/PbPb ratio, where **Xe : more elliptic (deformed) than Pb**

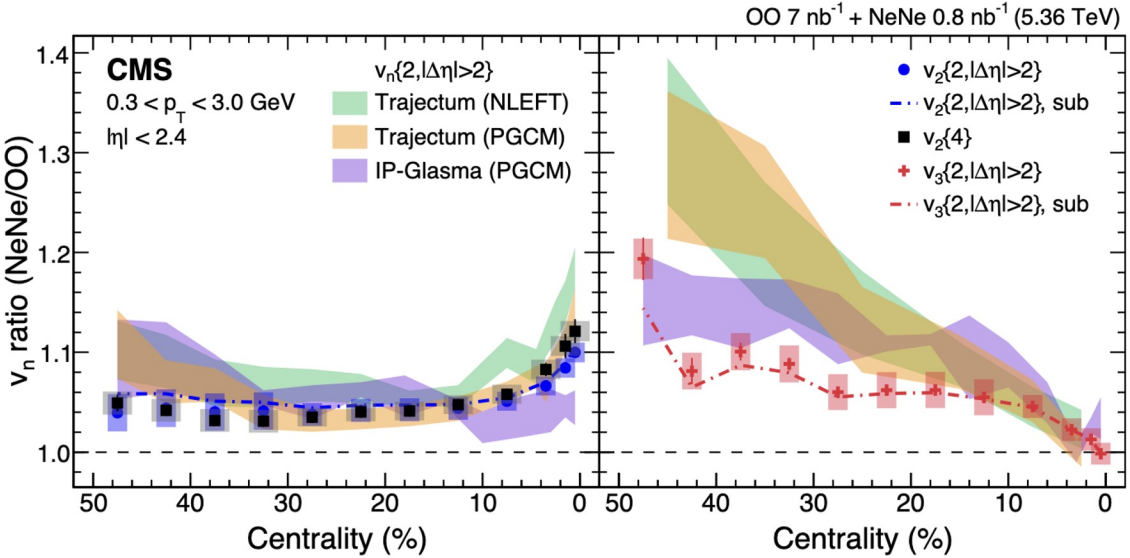


- Trend is properly captured by IP-Glasma predictions with a **deformed Xe** rather than spherical



arXiv.2510.26766

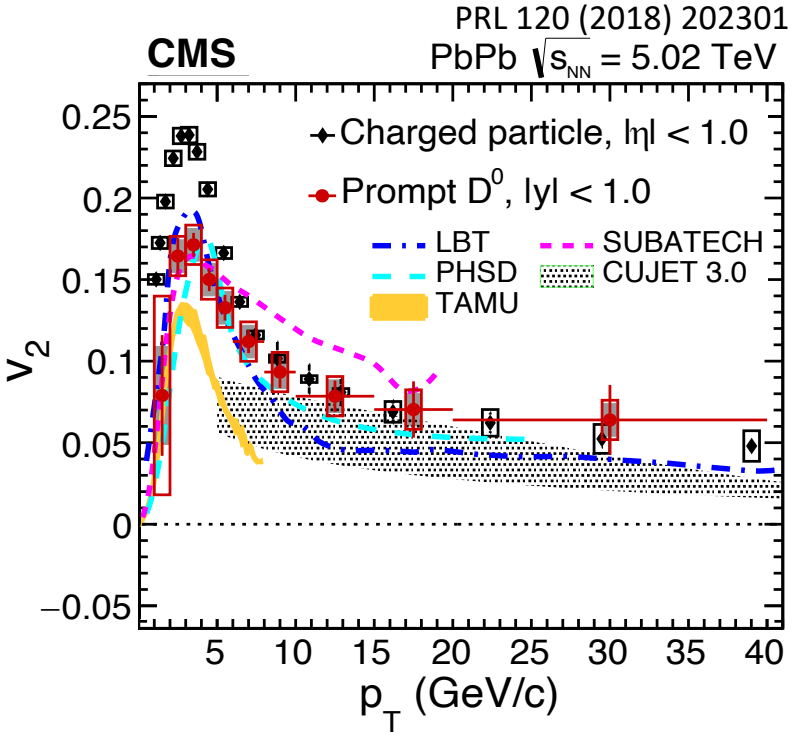
v_3 ratio (NeNe/OO): dependence on initial geometry fluct.

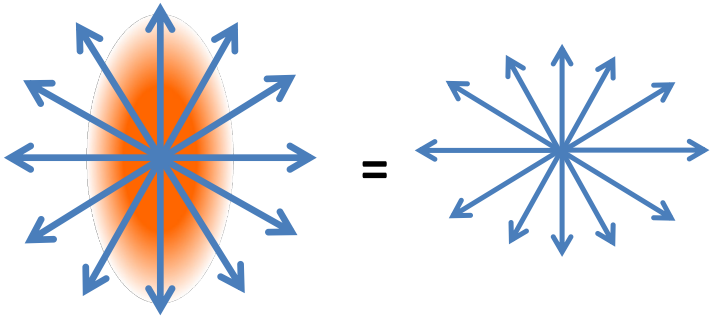


arXiv.2510.02580

- Triangular flow (v3) ratio between NeNe and OO:
  - **NeNe/OO > 1 for all centralities**
  - Decreasing trend towards central collisions
  - Reasonable agreement with hydrodynamic predictions in central collisions
  - Fail to capture the overall trend quantitatively

High p_T vn and jet quenching

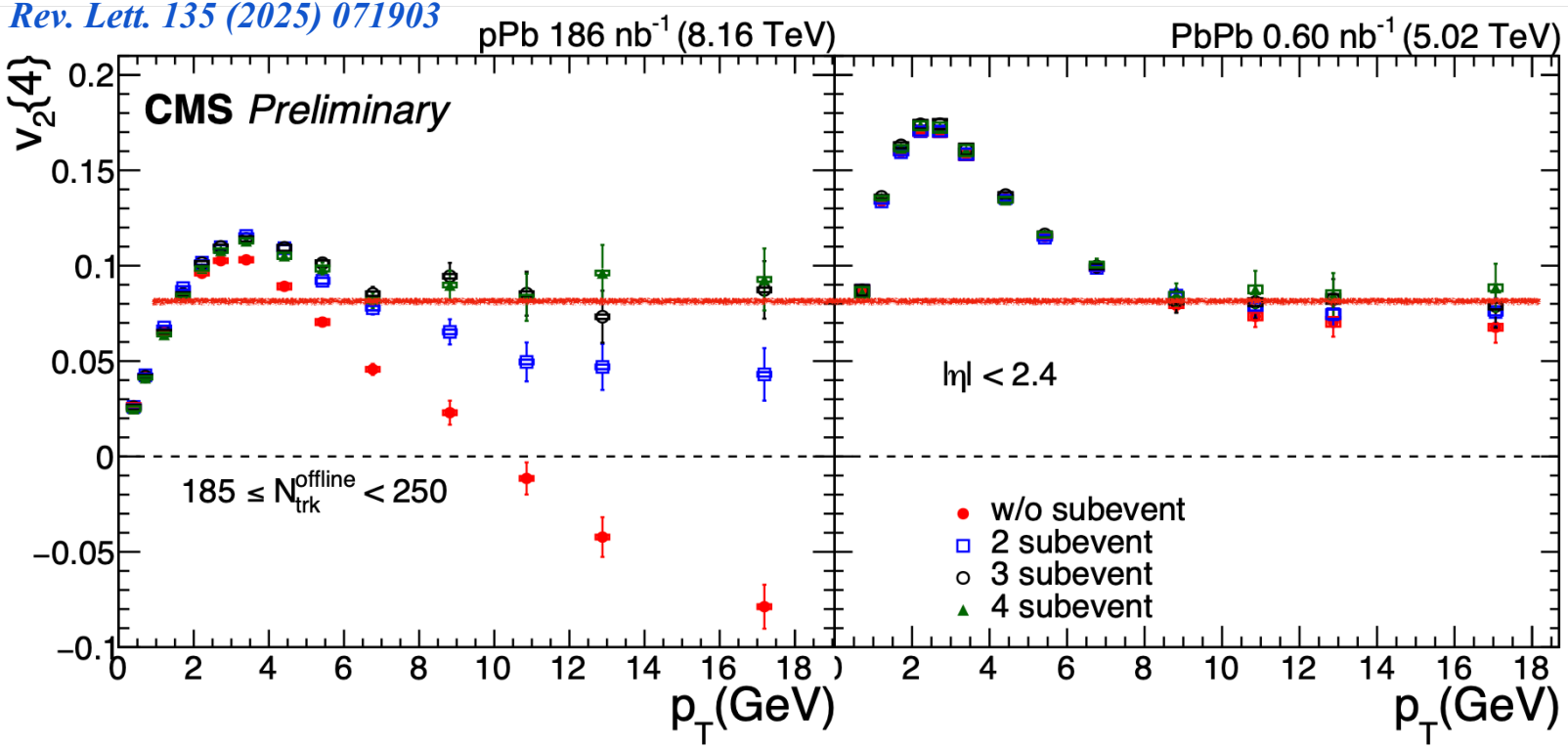




High p_T v_n from path length dependence jet quenching in AA provide another tool to search for jet quenching in small system

High p_T vn in pPb

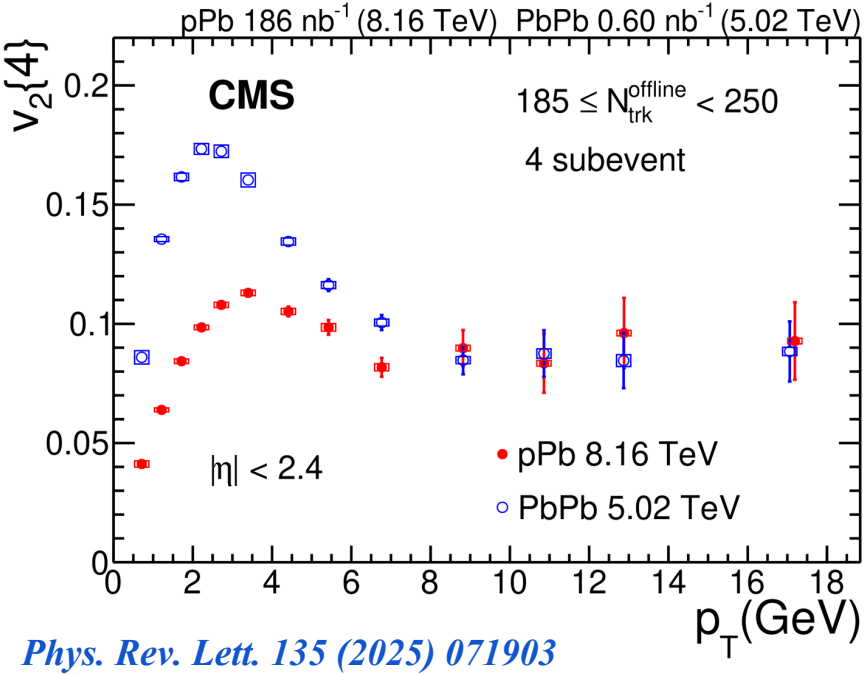
Phys. Rev. Lett. 135 (2025) 071903

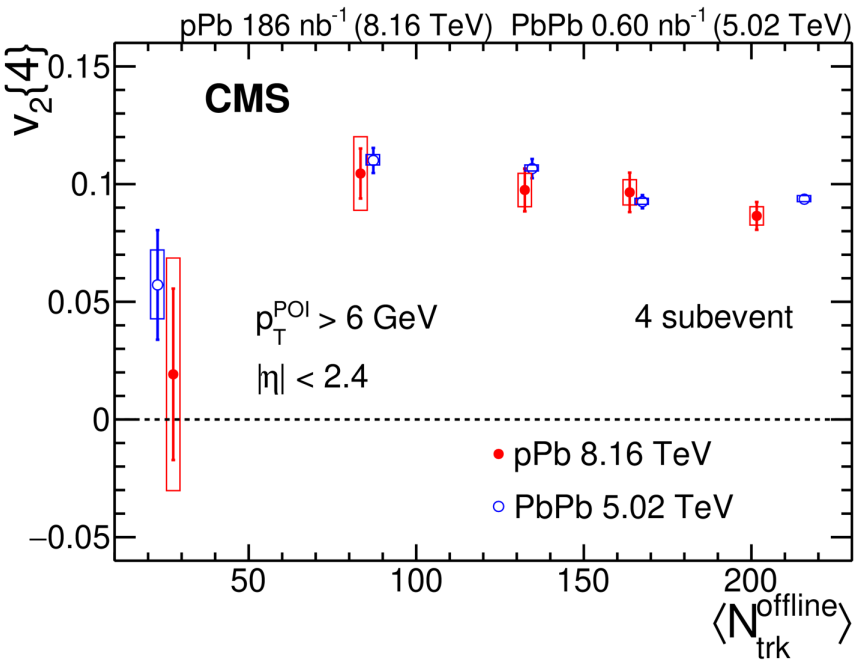


4-particle correlation with 4 sub-events to suppress non-flow

Significant v2 signal up to ~18 GeV

High p_T vn in pPb





Phys. Rev. Lett. 135 (2025) 071903

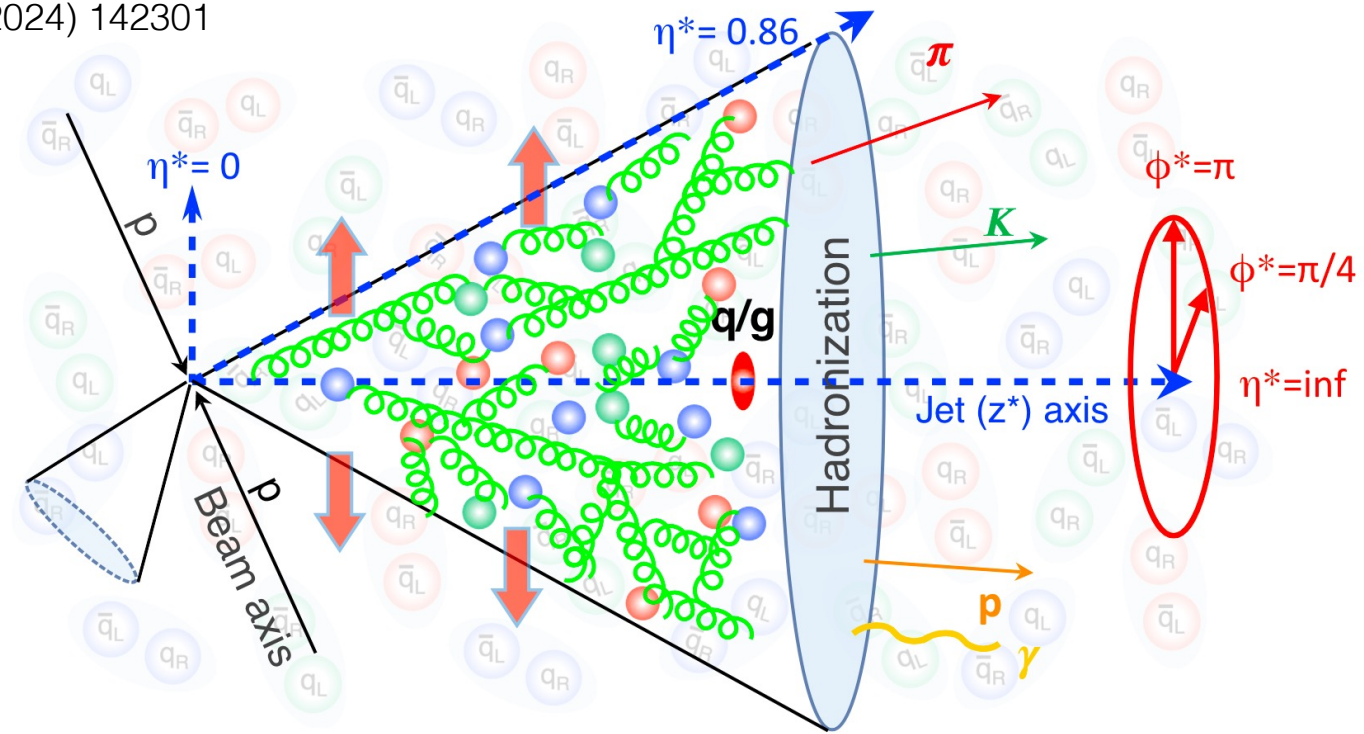
Consistent v2 at high pT in pPb and PbPb

Tend to decrease towards low multiplicity

Indication of jet quenching? Why not observed in jet measurements?

Collectivity in jets

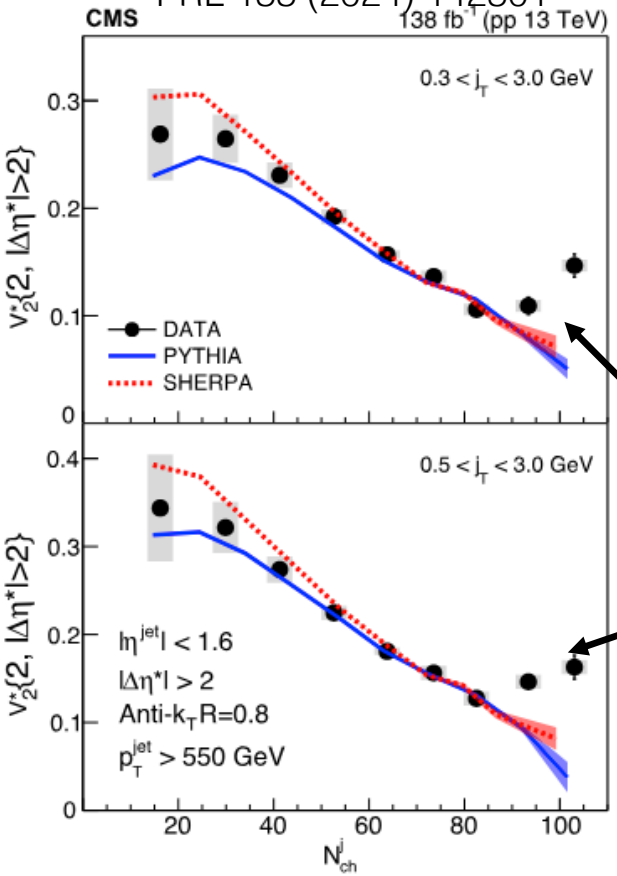
PRL 133 (2024) 142301

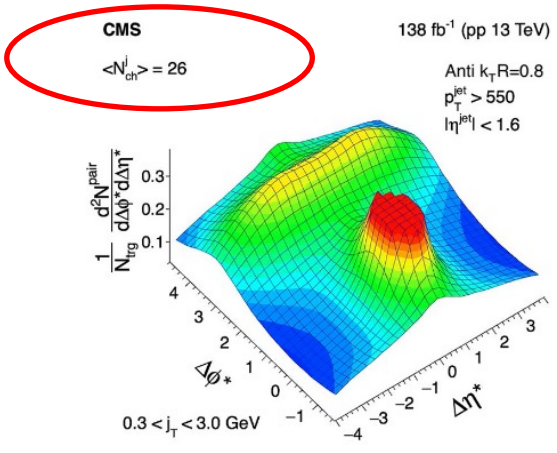


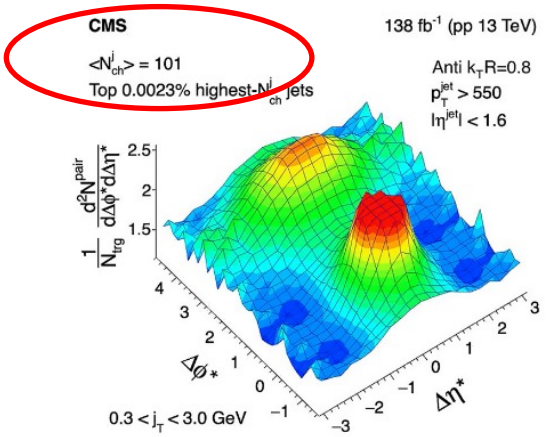
A parton shower could exhibits collective expansion as long as there are many fragments

Collectivity in jets

PRL 133 (2024) 142301





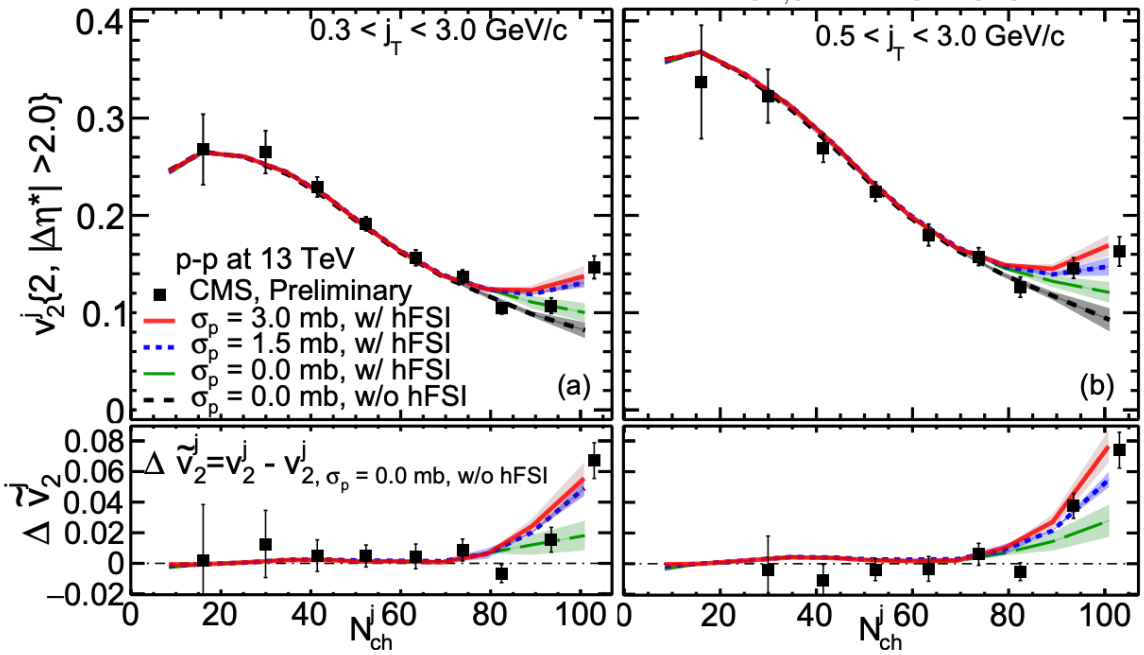


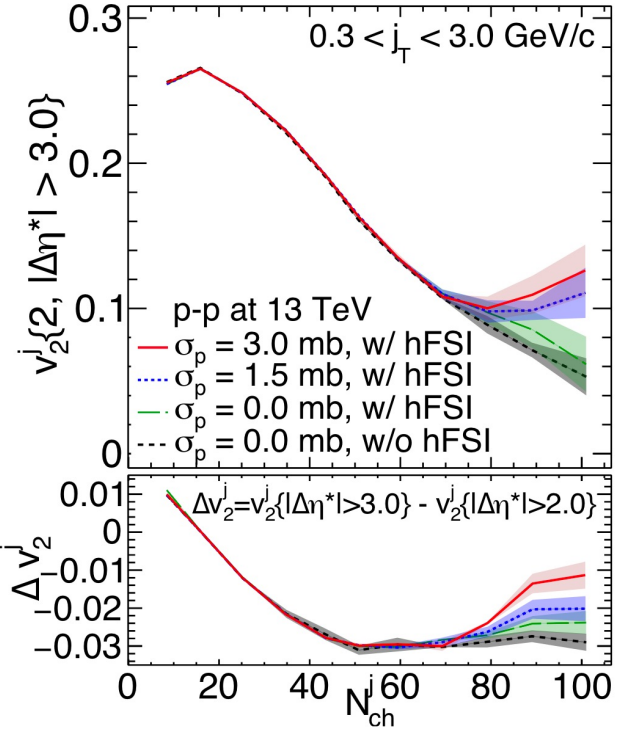
- A rising trend of v_2^* at high $N_{ch}^j > 80$
- Onset of collectivity?

Collectivity in jets

PRL 133 (2024) 142301

W. Zhao et. al.,arXiv:2401.13137



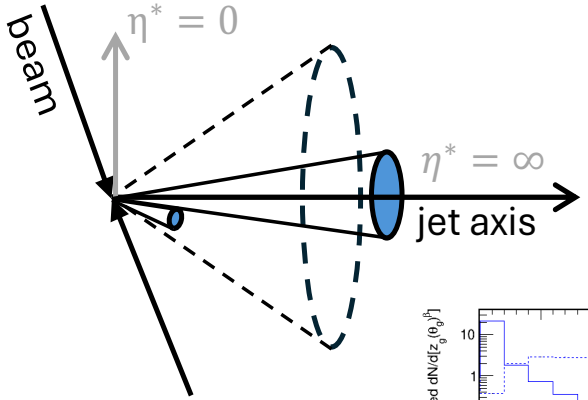


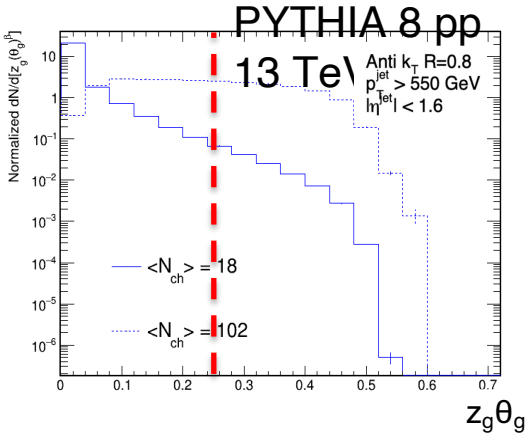
Enhancement of v_2 inside jets observed at high multiplicity

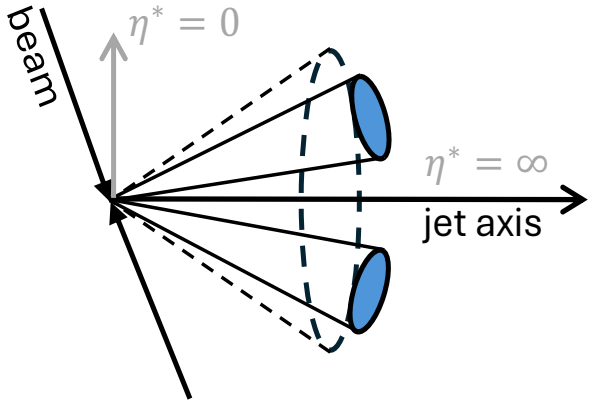
Only models with parton interactions inside jet capture data

Jet substructure engineering

Will elliptic flow in jets be correlated with the jet substructure?



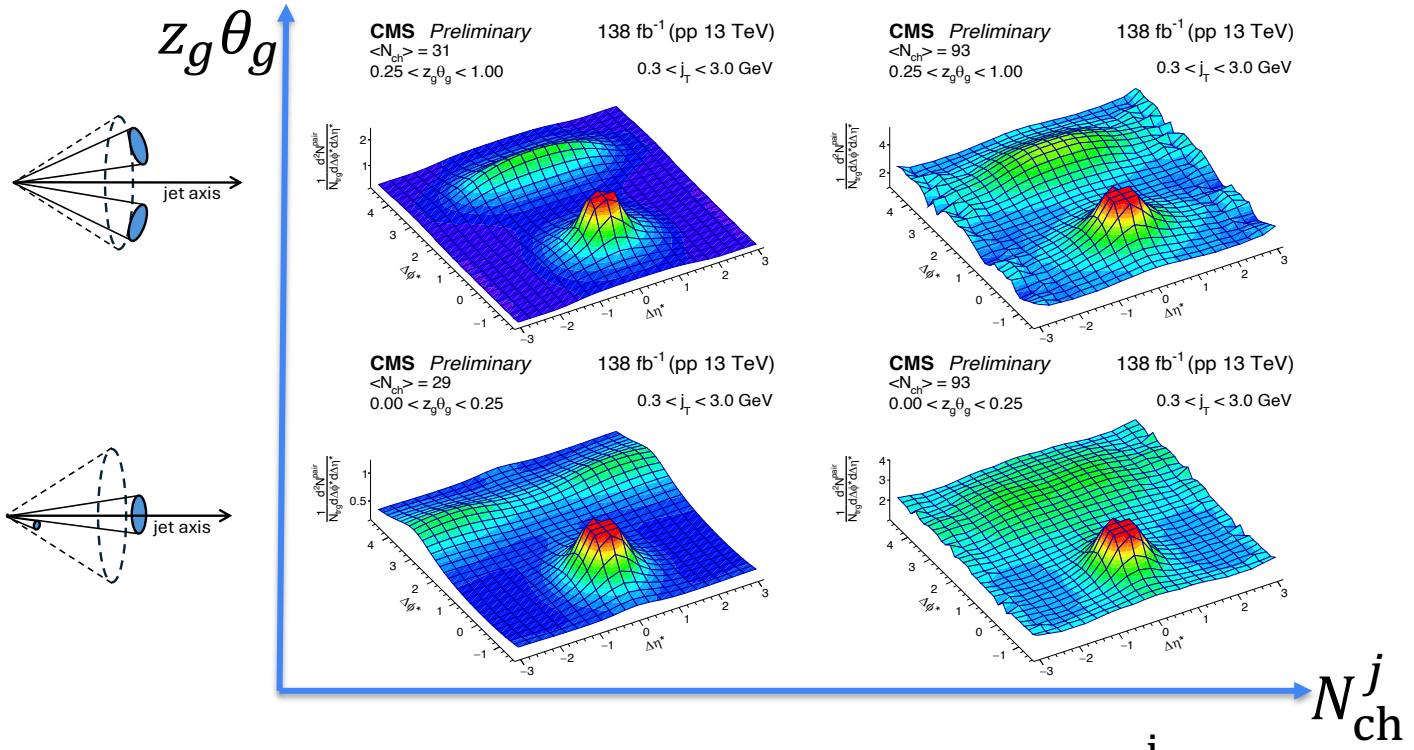




Small $z_g\theta_g$

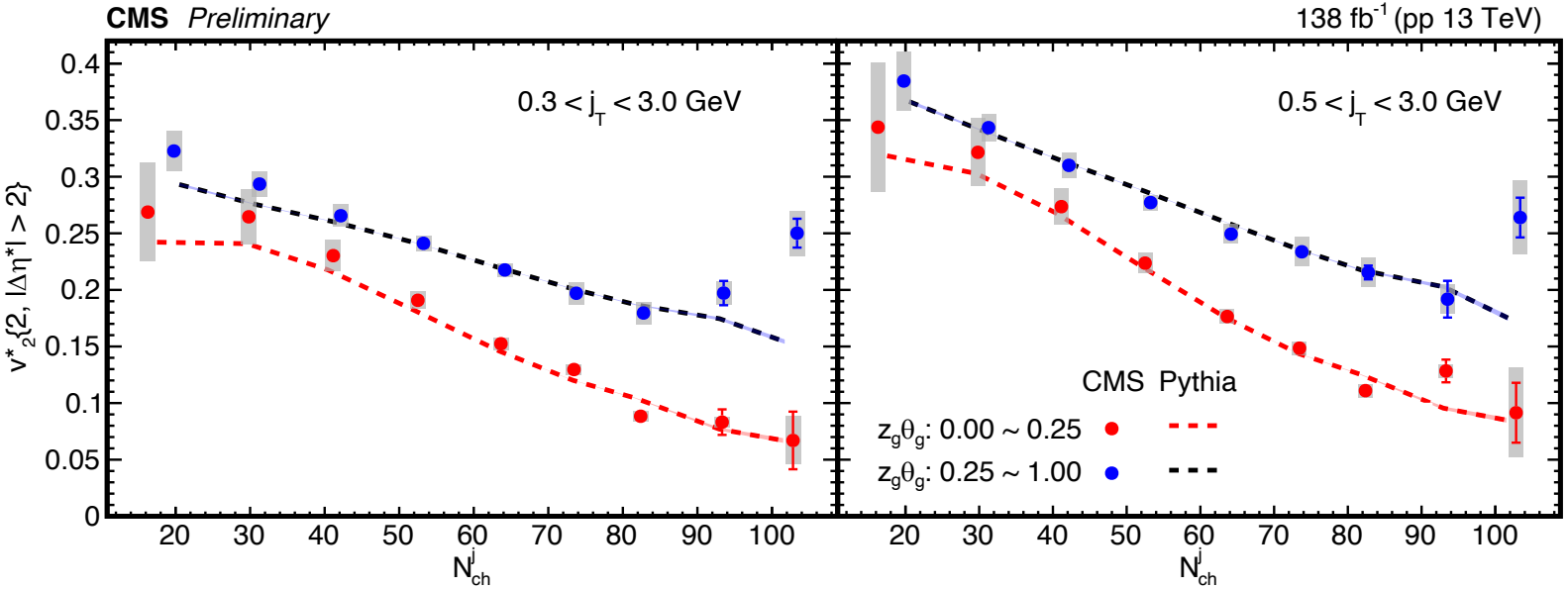
Large $z_g\theta_g$

Jet substructure engineering



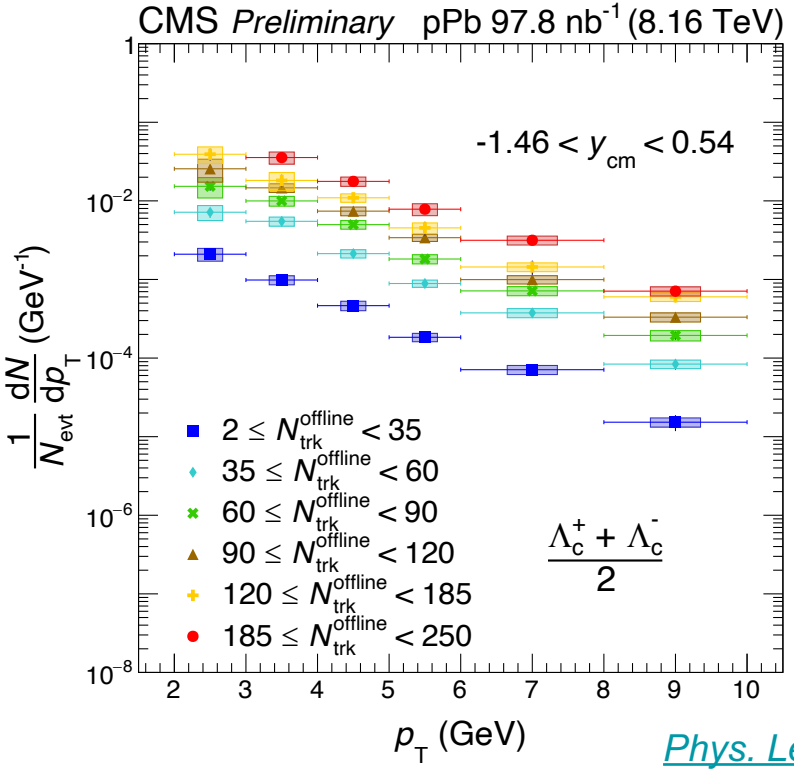
long-range near-side pattern emerges in high N^j_{ch} jets with two-prong structures?!

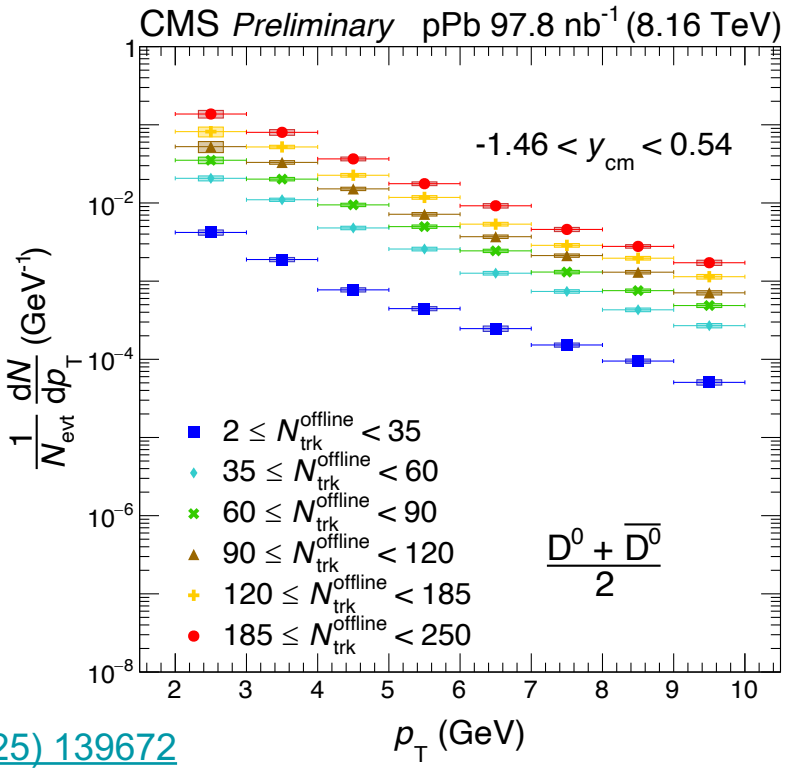
Jet substructure engineering



- Larger v_2^* overall for two-prong jets due to back-to-back correlations between two subjets.
- Rising v_2^* at high N_{ch}^{j} only for two-prong jets due to the initial-state jet geometry?

Λ_c^+ to D^0 p_T-spectra in p-Pb



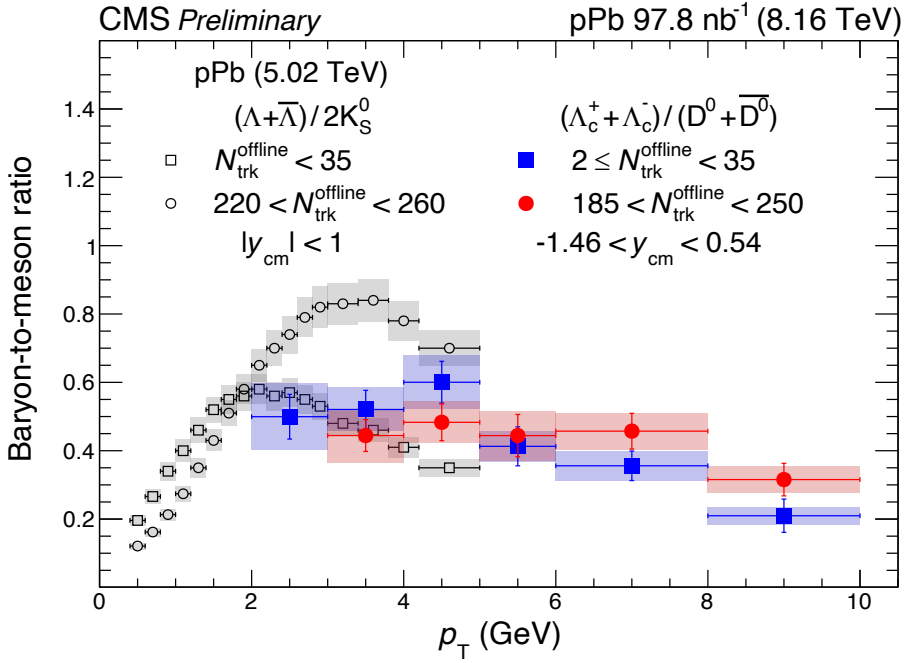


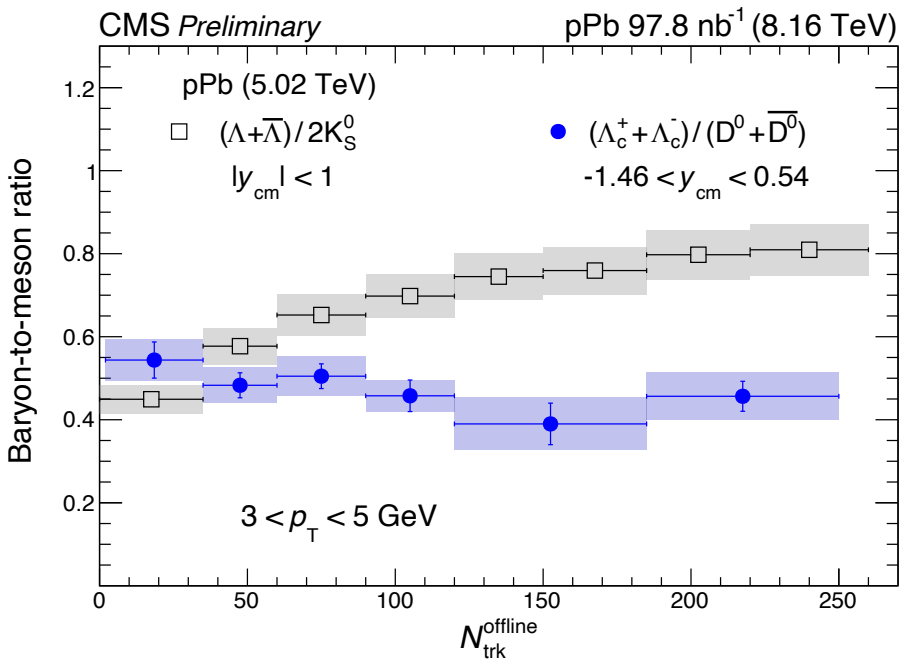
Phys. Lett. B 868 (2025) 139672

High precision spectra over large range of multiplicity

Λ_c^+ to D^0 p_T-spectra in p-Pb

Phys. Lett. B 868 (2025) 139672





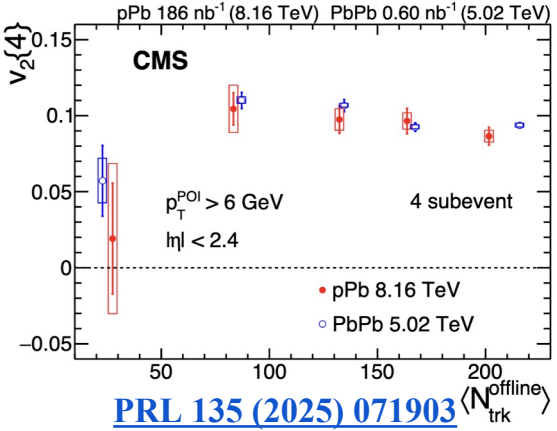
No enhancement of HF baryon-meson ratio at high multiplicity

Less pronounced medium effects due to larger mean free path?

Summary

- CMS is obtaining a wealth of physics results from the first three LHC heavy-ion runs
- Recent CMS results extend understanding of collectivity
  - map geometry, fluctuations, and nonlinear response across system sizes
  - probes initial-state conditions and nonlinear response
  - Significant high pT v2 in pPb – jet quenching?
  - Collectivity in high multiplicity jets – implications in small system?
  - No obvious sign of parton medium interaction in pPb from multiplicity dependence Λ_c to D^0 ratio

Future prospects in light ions



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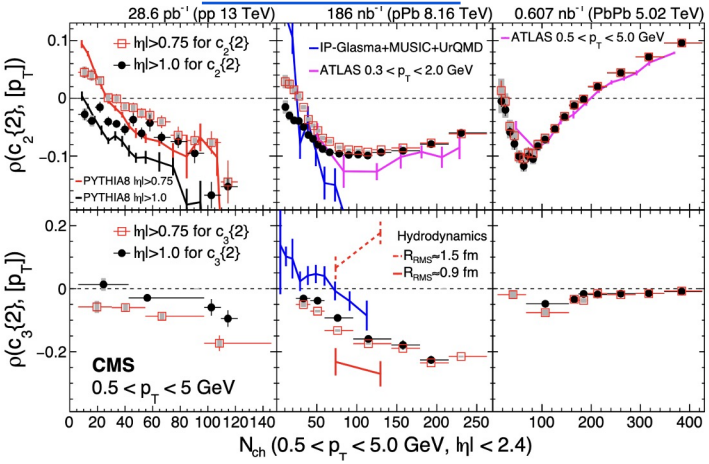
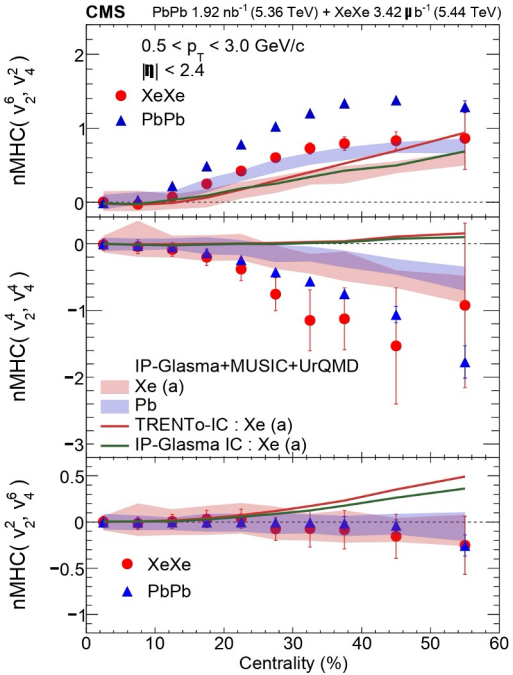
- Differential flow with subevents across different systems
  - Evolution of collectivity into intermediate–p_T and its path-length sensitivity

- Mixed-harmonic cumulants
  - Stringent conditions on the initial-state and properties of QGP

- v_n-[p_T] correlations
  - Shape-size correlations

arXiv.2410.04578





arXiv.2510.26766