2024 RHIC/AGS ANNUAL USERS' MEETING

A New Era of Discovery

Guided by the New Long Range Plan for Nuclear Science

Theoretical progress in small systems calculations

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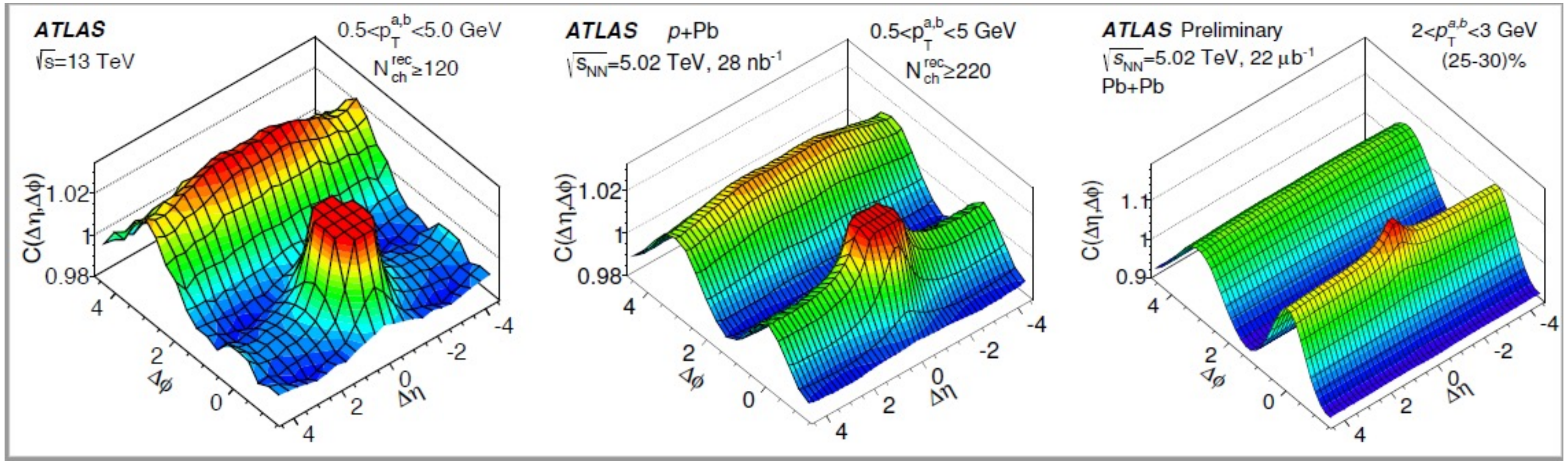
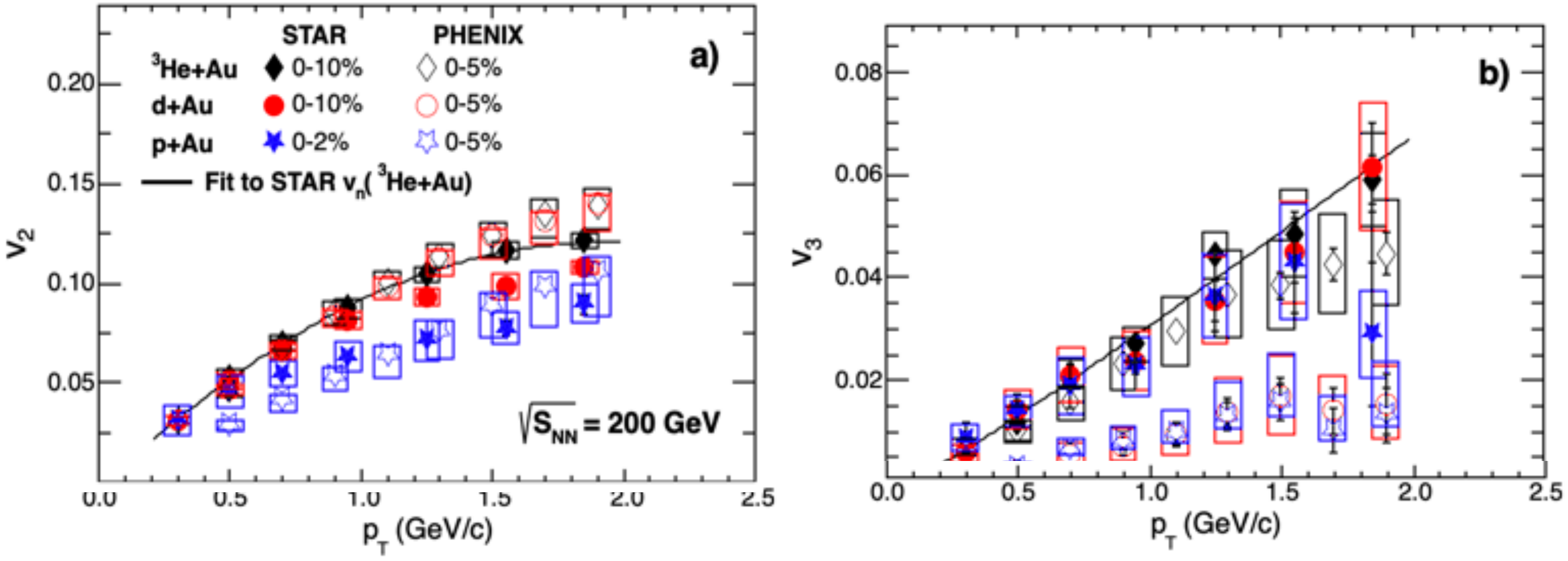
June 11-14, 2024, RHIC/AGS

Collectivity in large and small systems



- Collective flow in p-p, p-Pb and Pb-Pb at the LHC.

ATLAS, Phys. Lett. B789, 444.



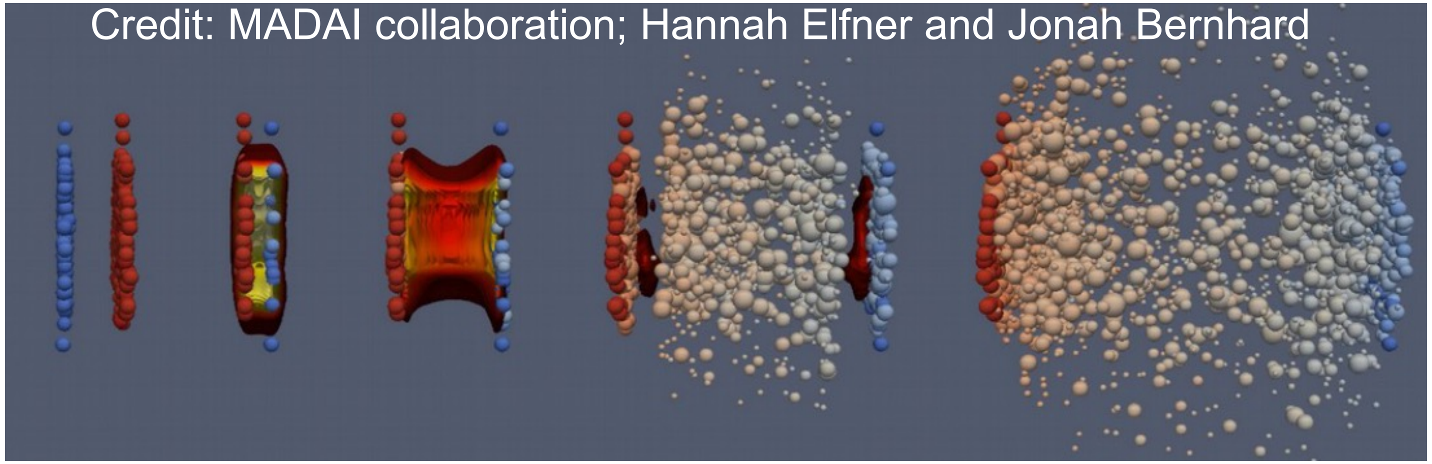
- Collective flow in p-Au, d-Au and He3-Au in RHIC.

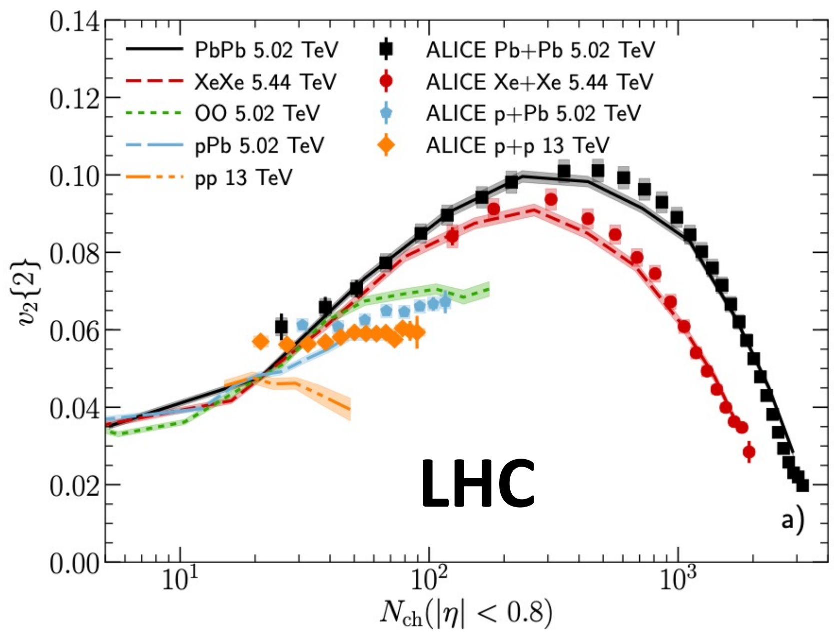
PHENIX: Nature Physics, **15**, pages214–220 (2019);
STAR: PhysRevLett.130.242301.

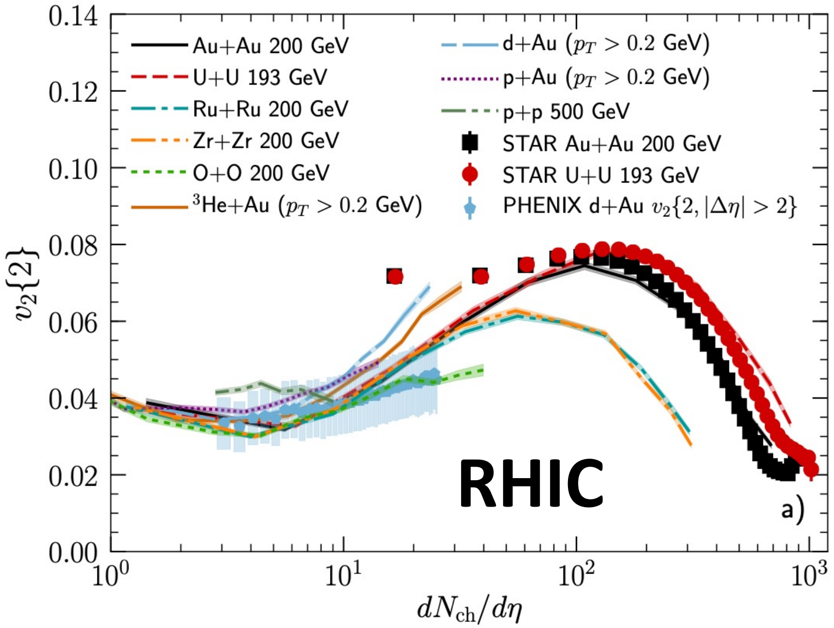
- Collective flow observed from large to small systems.

Standard model of Heavy-Ion Collisions

- **Initial conditions** (3D-Glauber, TRENTo, IP-Glasma, AMPT…)
- **Viscous hydrodynamics** (MUSIC, VISHew, CLVis, Trajectum…)
- **Hadron cascade afterburner** (UrQMD, SMASH, JAM…)



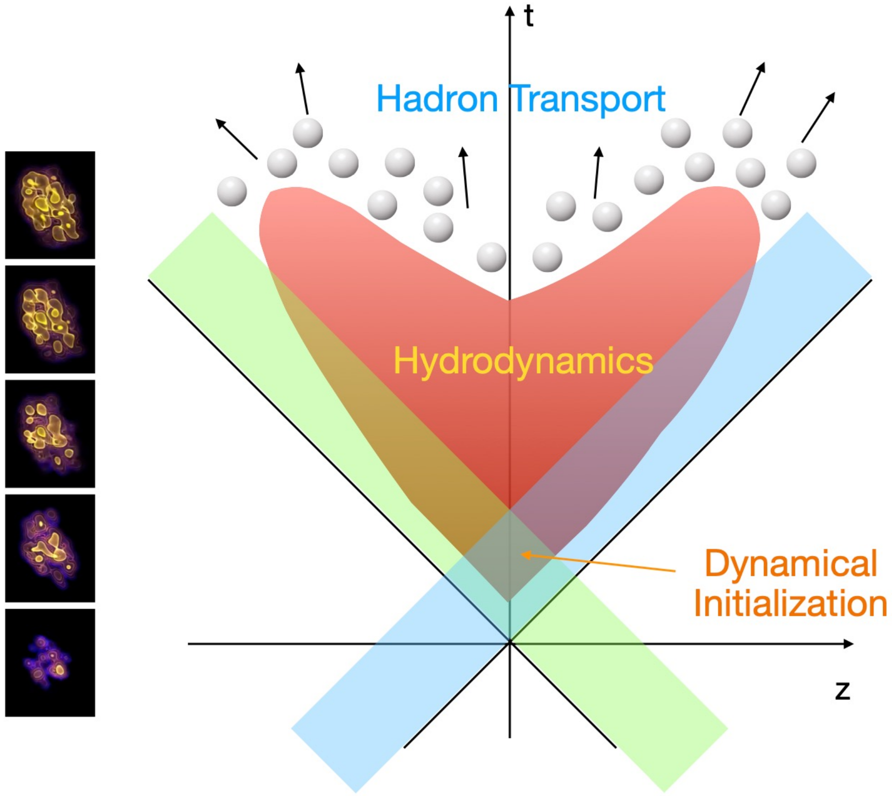




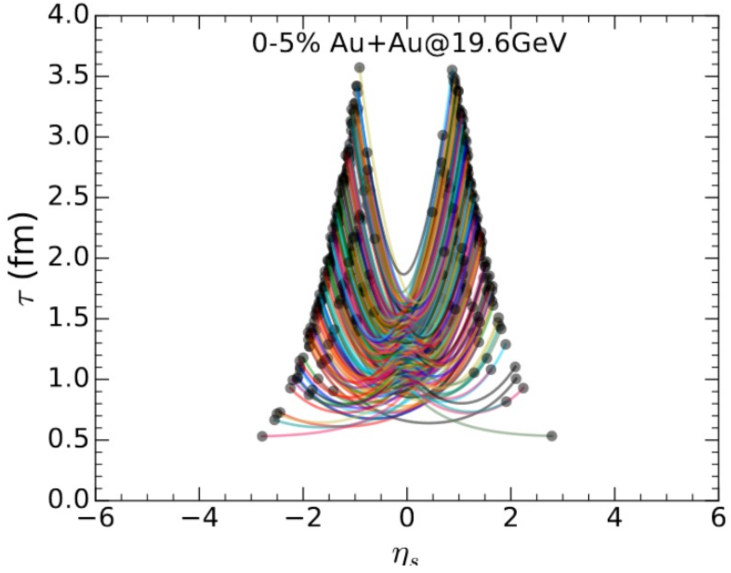
- **One fluid rules them all.**

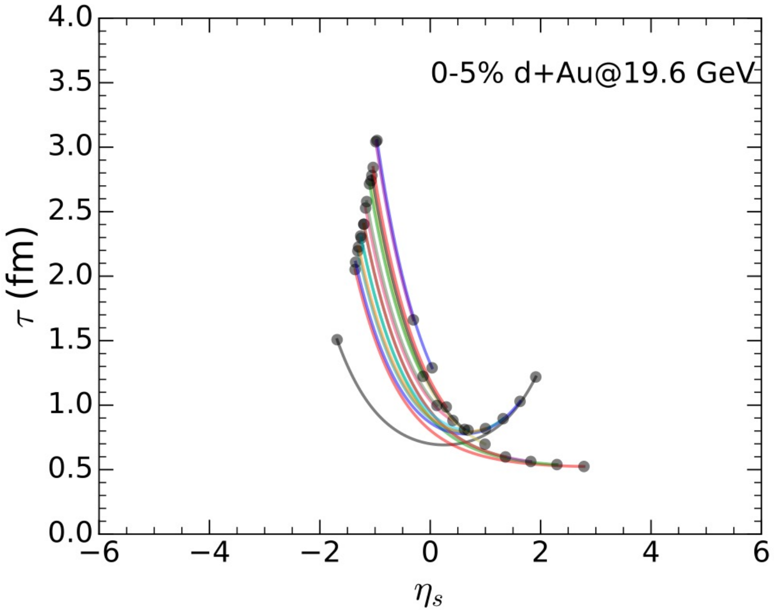
B. Schenke, C. Shen, and P. Tribedy, Phys. Rev. C. 102(4), 044905 (2020).

Dynamic 3+1D simulation



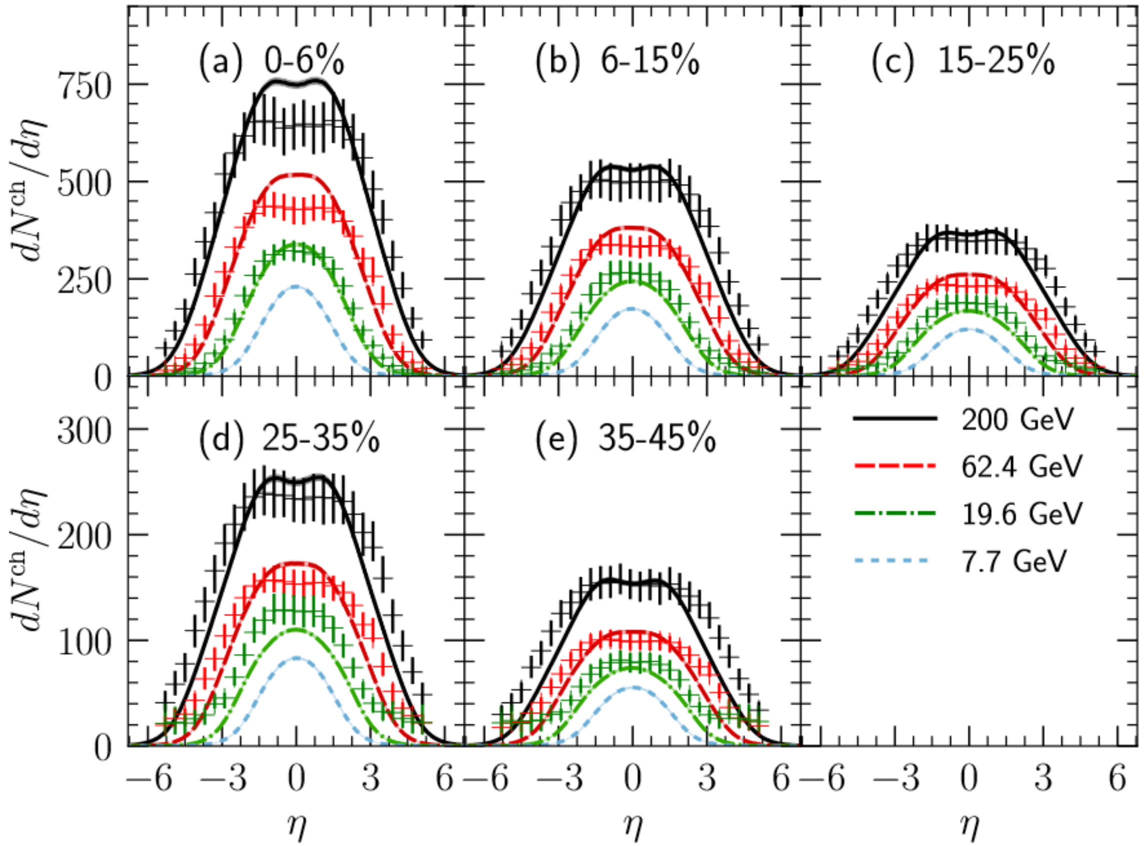
- Collision geometry is determined by MC-Glauber model.
- Incoming quarks are decelerated with a classical string tension with the source terms in hydro.
- Provides e-b-e transverse and longitudinal fluctuations.

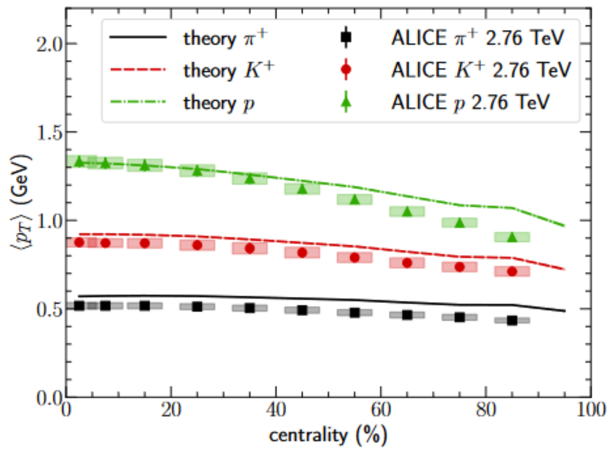


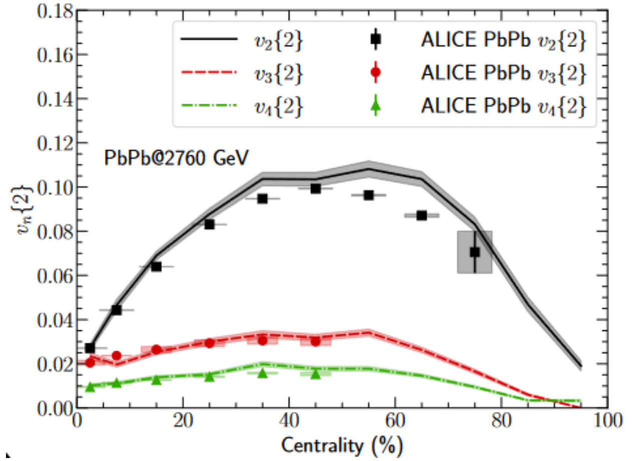


C. Shen and B. Schenke, Phys. Rev. C 97, 024907 (2018), Phys. Rev. C,105 (2022), 064905.

3DGlauber + MUSIC + UrQMD



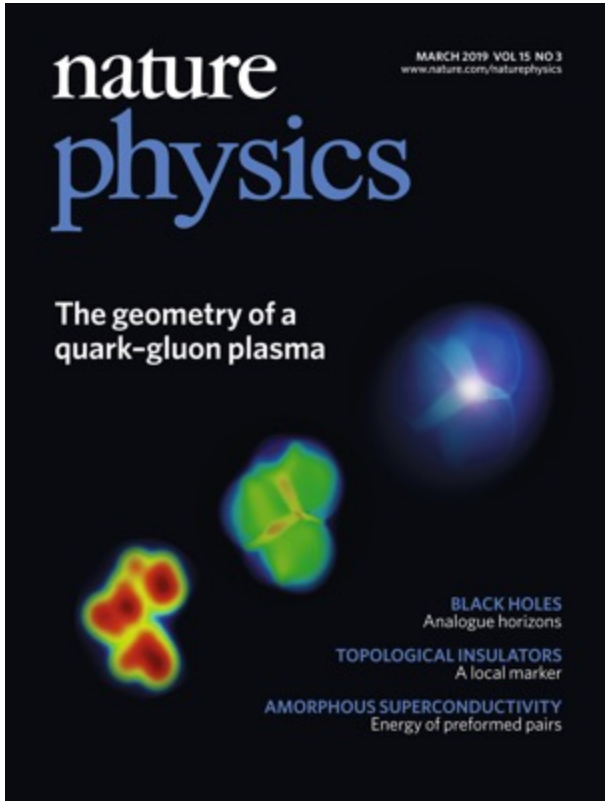


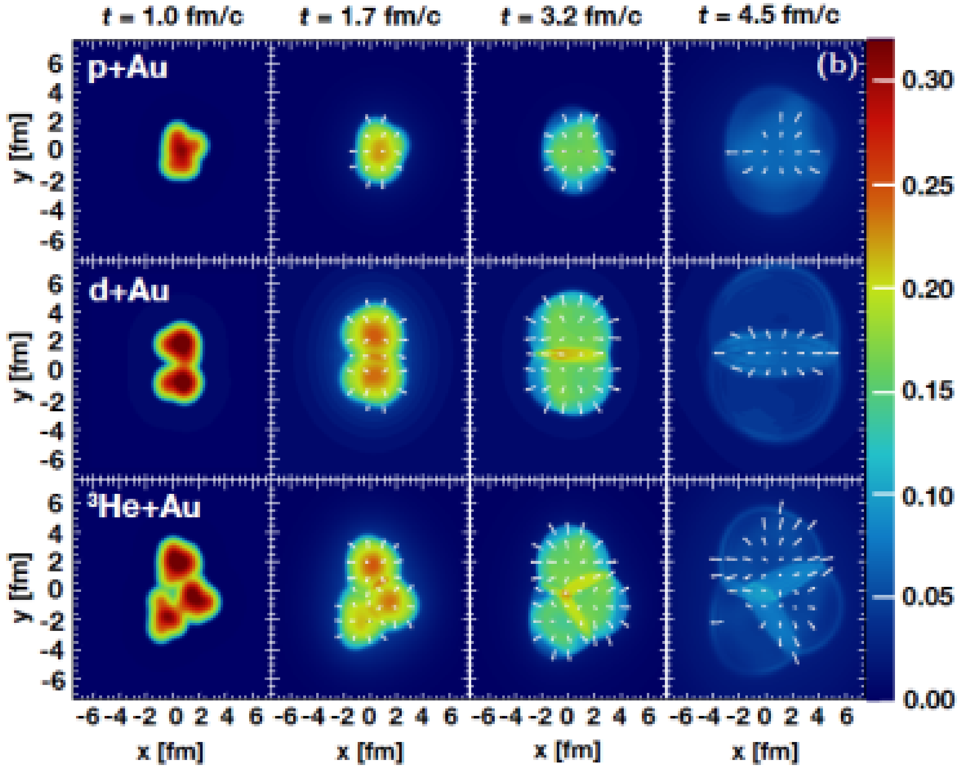


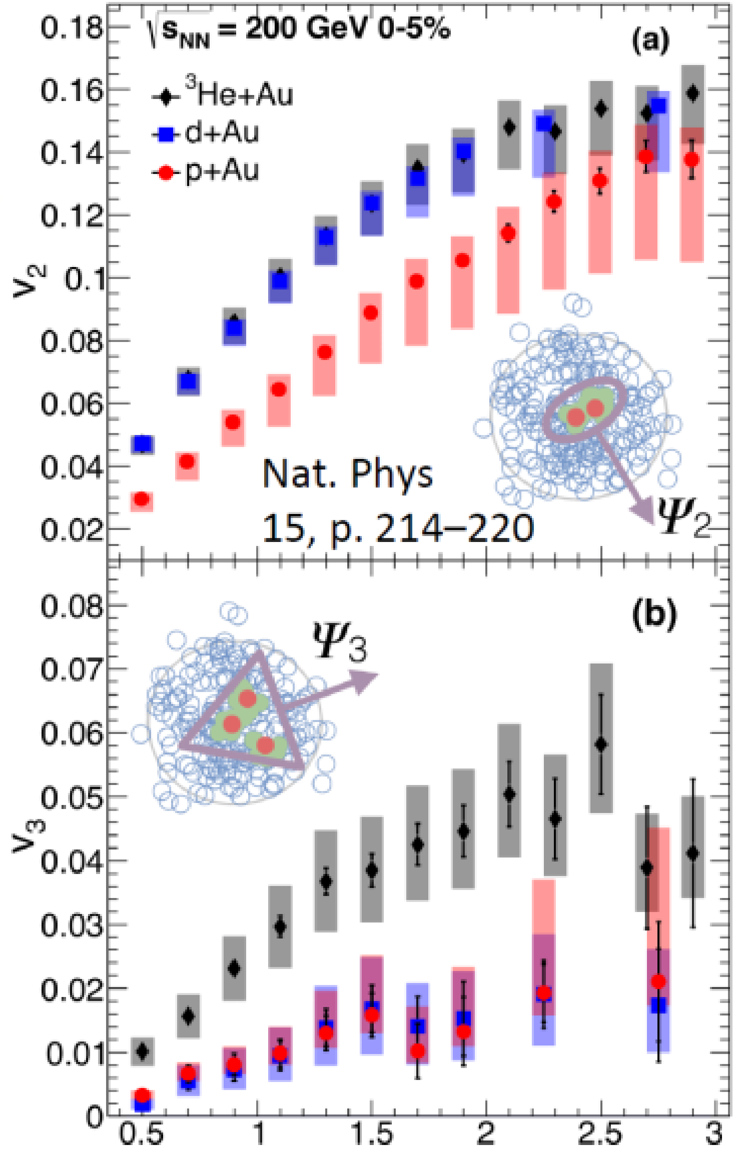
C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905.
C. Shen and B. Schenke Phys. Rev. C 97, 024907 (2018).

- 3D-Glauber + MUSIC + UrQMD works well in describing bulk dynamics observables low energies to high energies in heavy-ion collisions.

Small System Scan at RHIC (PHENIX)







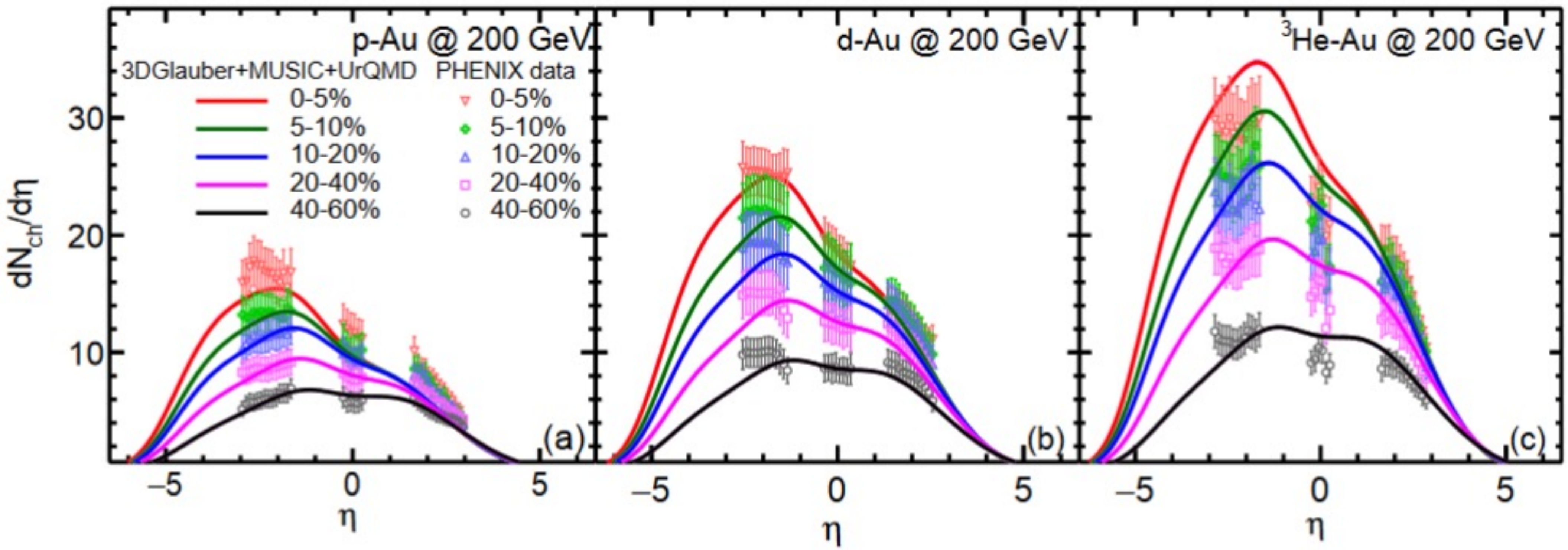
[*Nature Physics*](#) **15**, pages214–220 (2019)

Lower v_2 in p+Au

Higher v_3 in ^{3}He+Au

Clear hierarchy of v_2 and v_3 among three systems in p_T(GeV/c) PHENIX measurements

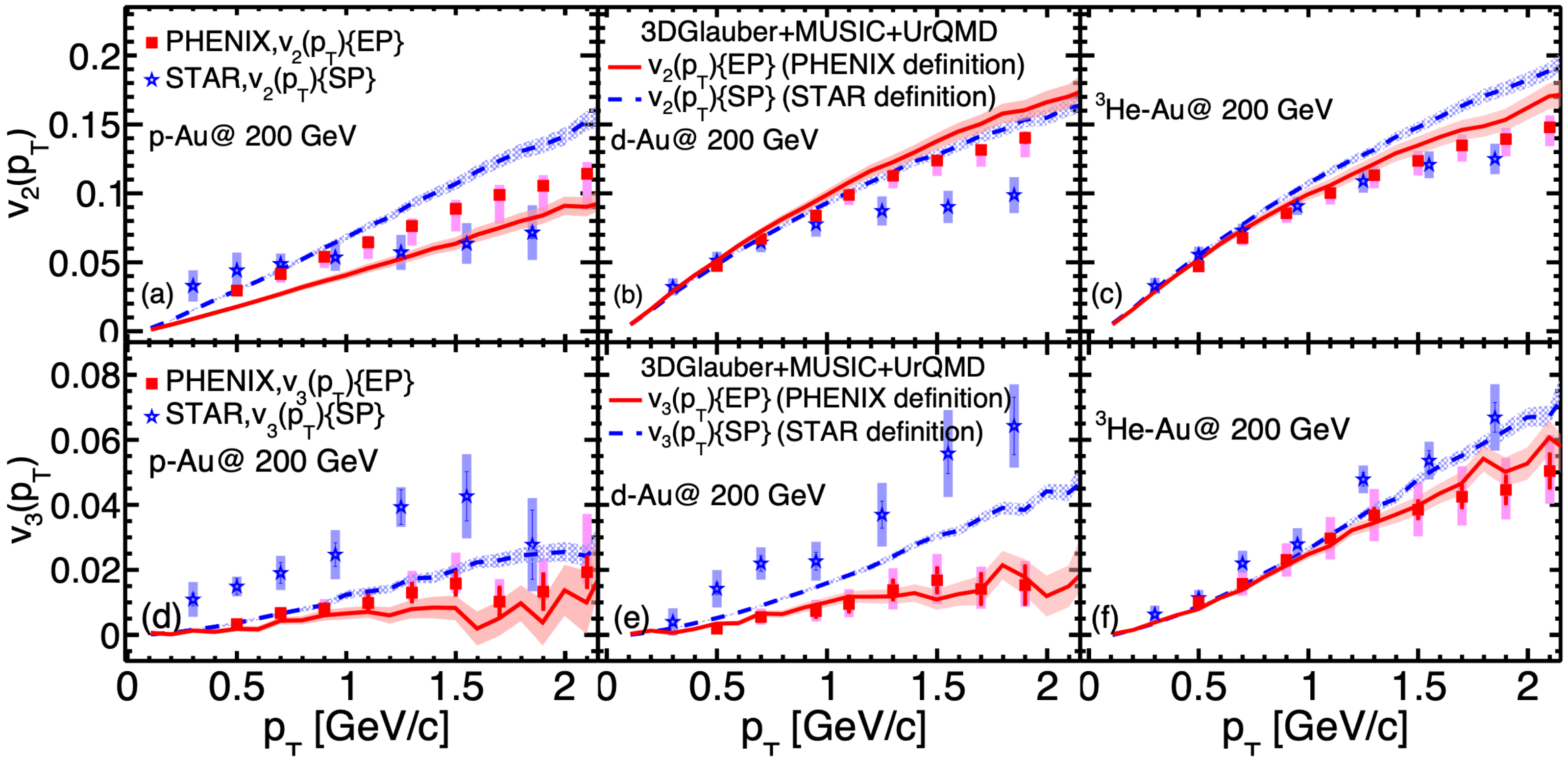
Full (3+1)D simulations in asymmetric systems



W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys. Rev. C 107, 014904 (2023).

- The (3+1)D hybrid model describes the yields and η-dependent $dN_{ch}/d\eta$ for all asymmetric systems
- The asymmetric shape from central to peripheral collisions is well captured.

$v_n(p_T)$ $(n = 2, 3)$ from two-particle correlations



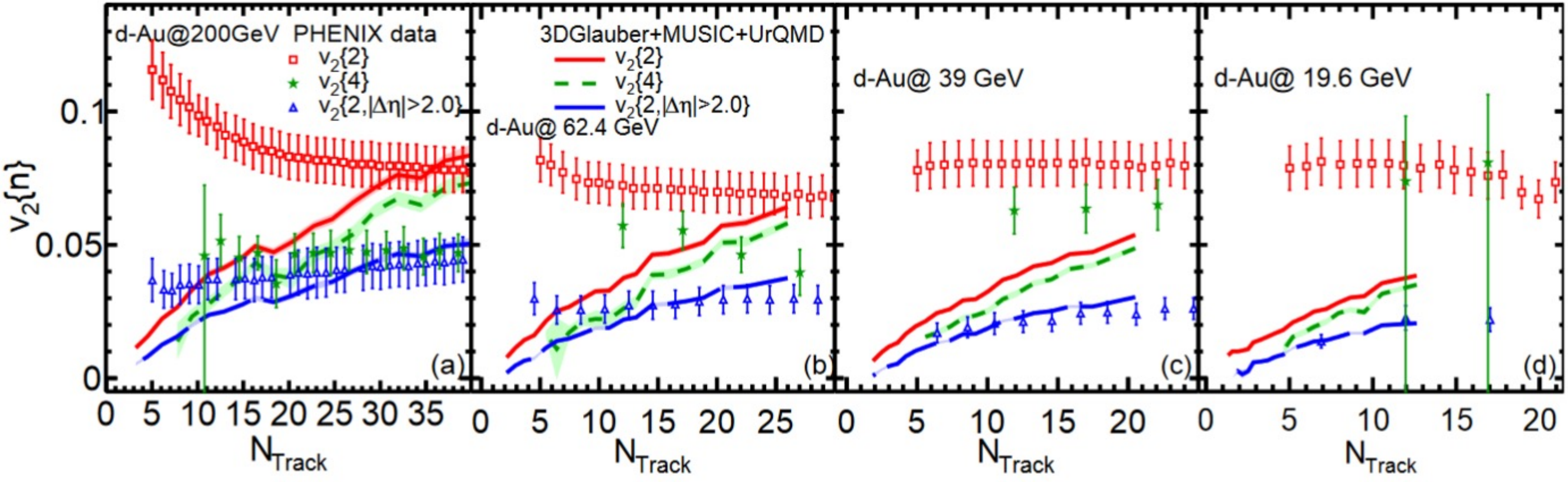
PHENIX η range:
$[-3.9, -3.1]$ $v.s.$ $[-0.35, 0.35]$
$[-3.0, -1.0]$ $v.s.$ $[-0.35, 0.35]$;

STAR η range:
$[-0.9, 0.9]$ and $|\Delta\eta| > 1.0$

W. Zhao, S. Ryu, C. Shen and B. Schenke Phys. Rev. C 107, 014904 (2023).

- Using the PHENIX definition, our 3D hybrid model reproduces the $\boldsymbol{v_2(p_T)}$ and $\boldsymbol{v_3(p_T)}$ for all three systems.
- The 3D hybrid model gives larger $\boldsymbol{v_3(p_T)}$ with the STAR definition in (p, d)+Au collisions than those from PHENIX.
- The longitudinal decorrelation explains 50% difference between PHENIX and STAR $\boldsymbol{v_3}$ measurements.

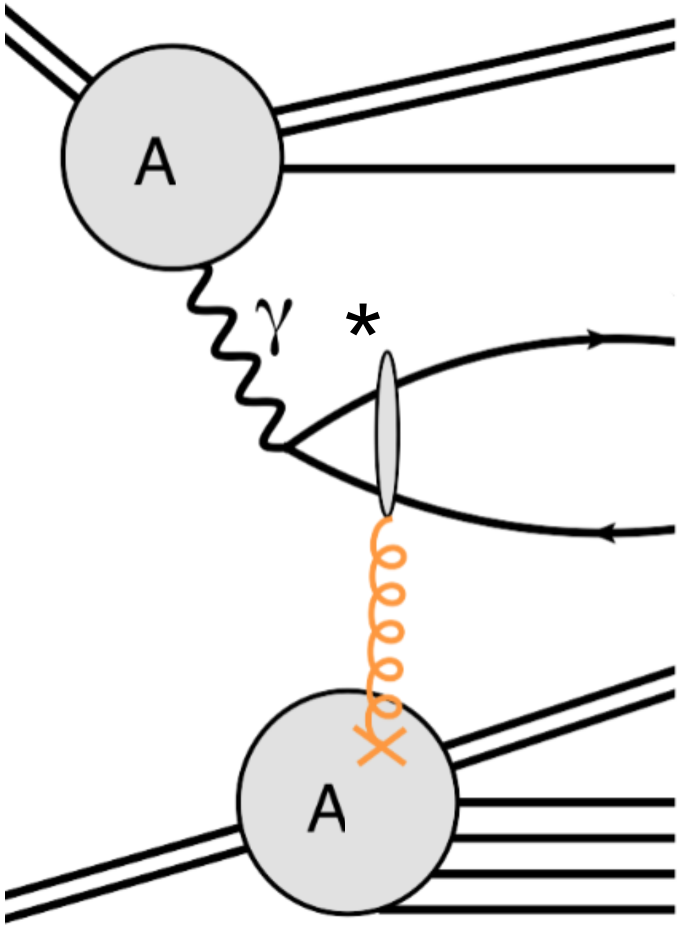
Collective flow in small systems at low energies



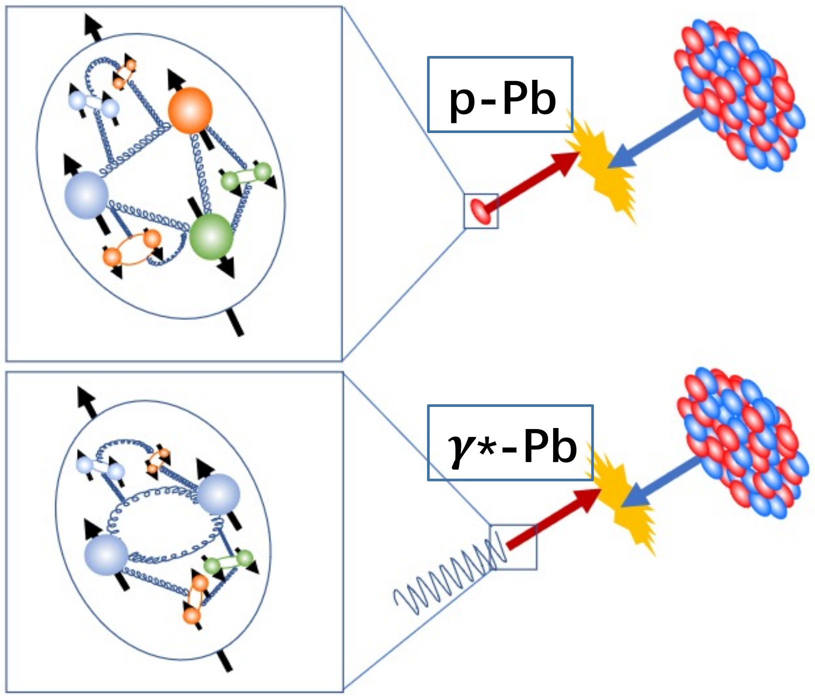
W. Zhao, S. Ryu, C. Shen and B. Schenke Phys. Rev. C 107, 014904 (2023).

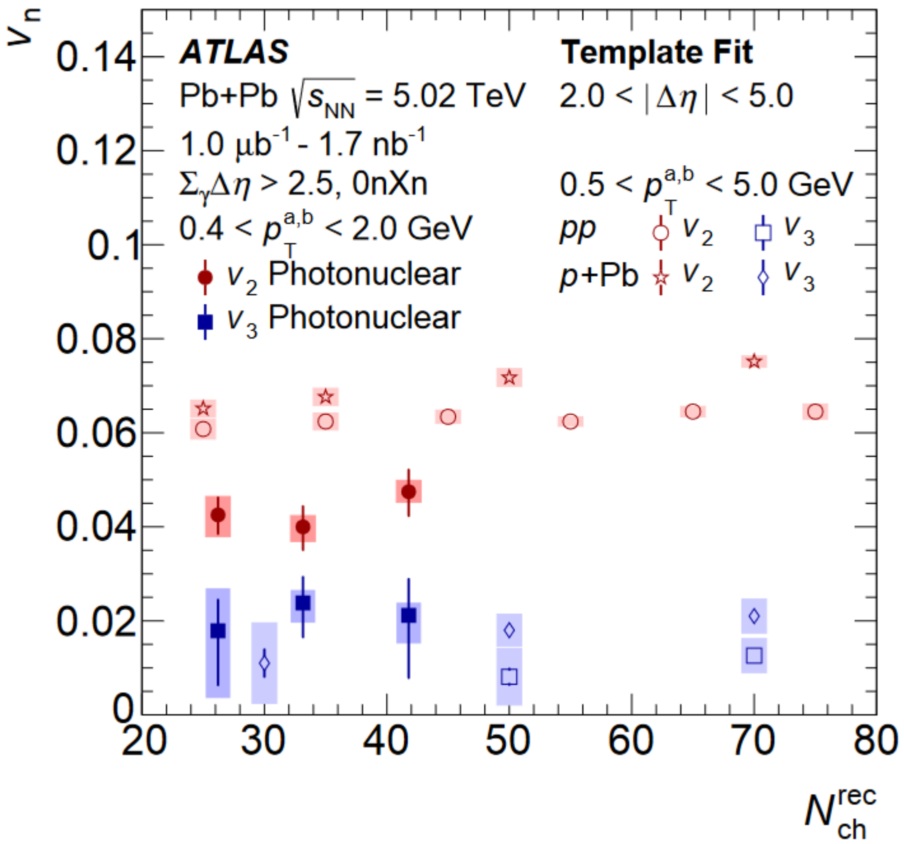
- Collectivity is observed even in small systems at low collision energies.

"Collectivity" in UPC



Taken from Nicole Lewis's slide

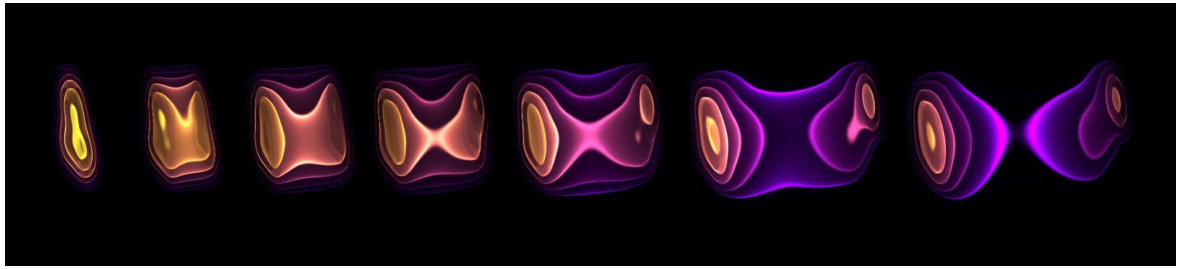


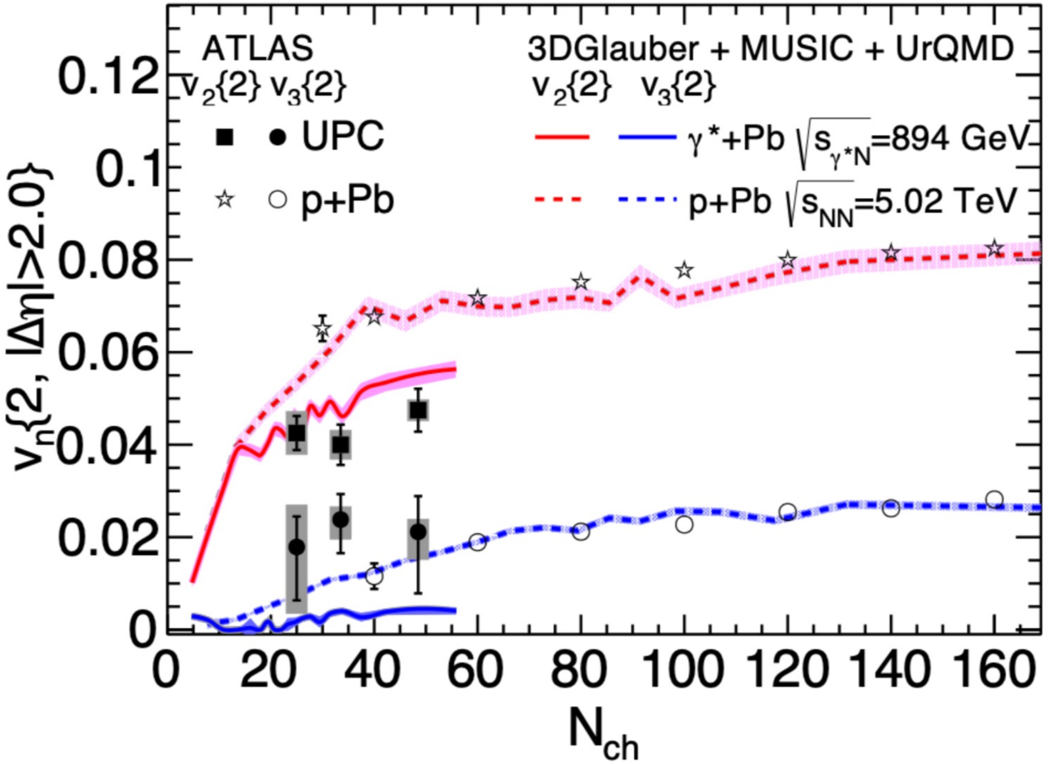


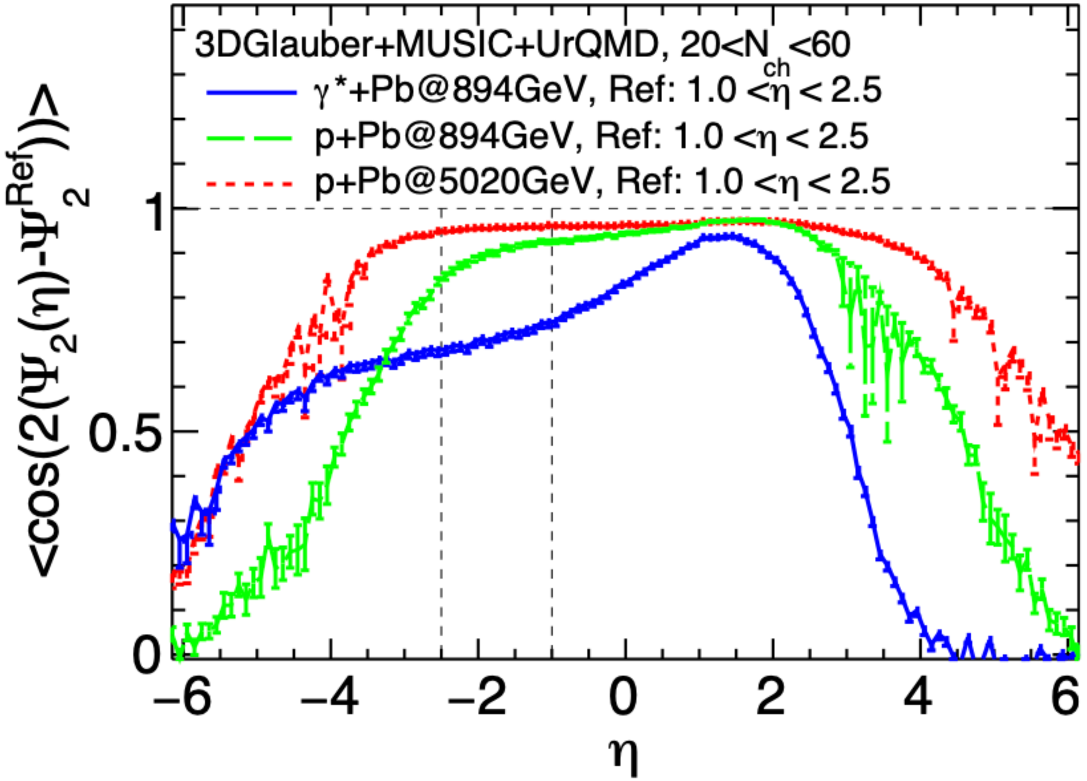
ATLAS Phys. Rev. C 104, 014903 (2021). Y. Shi, etc.al,Phys. Rev. D 103, 054017 (2021).

- UPCs have a similar order of magnitude and trends of collectivity as other previously measured hadronic systems

Hydrodynamic simulations



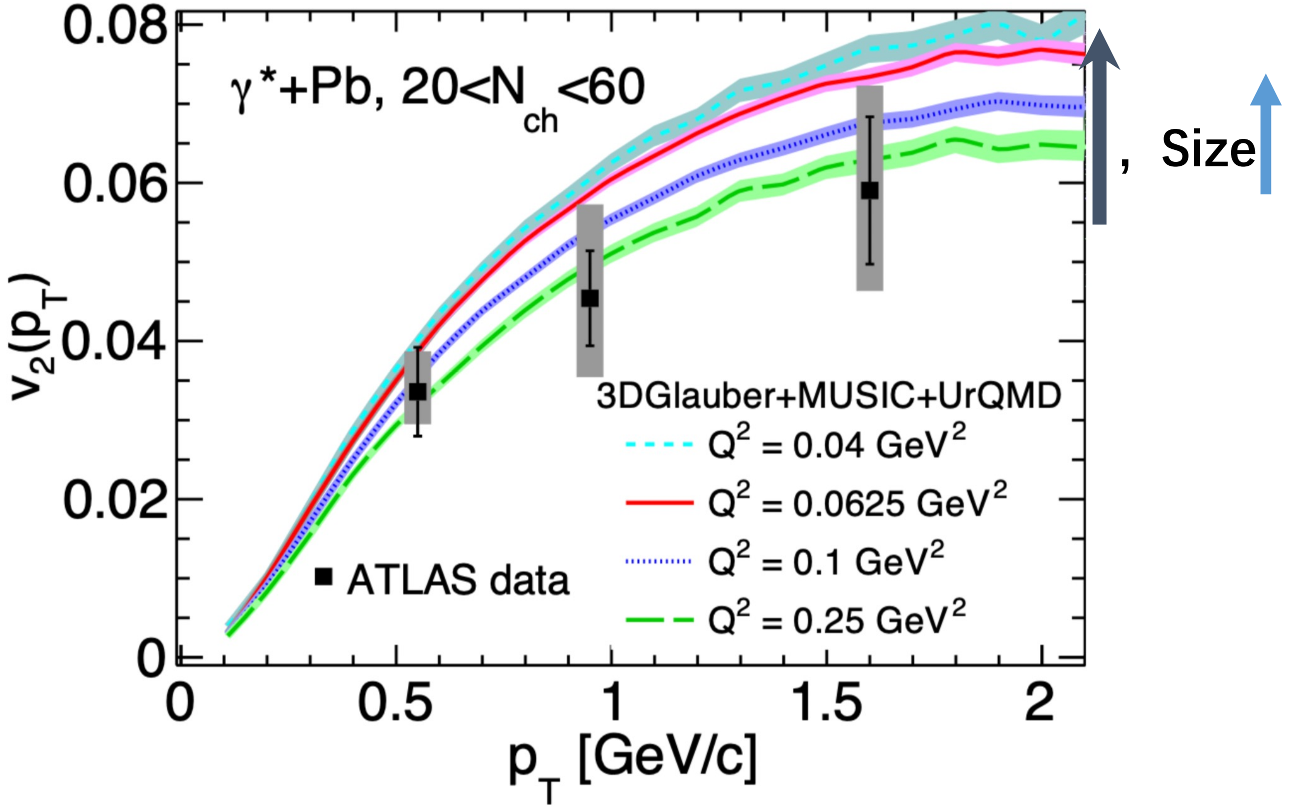


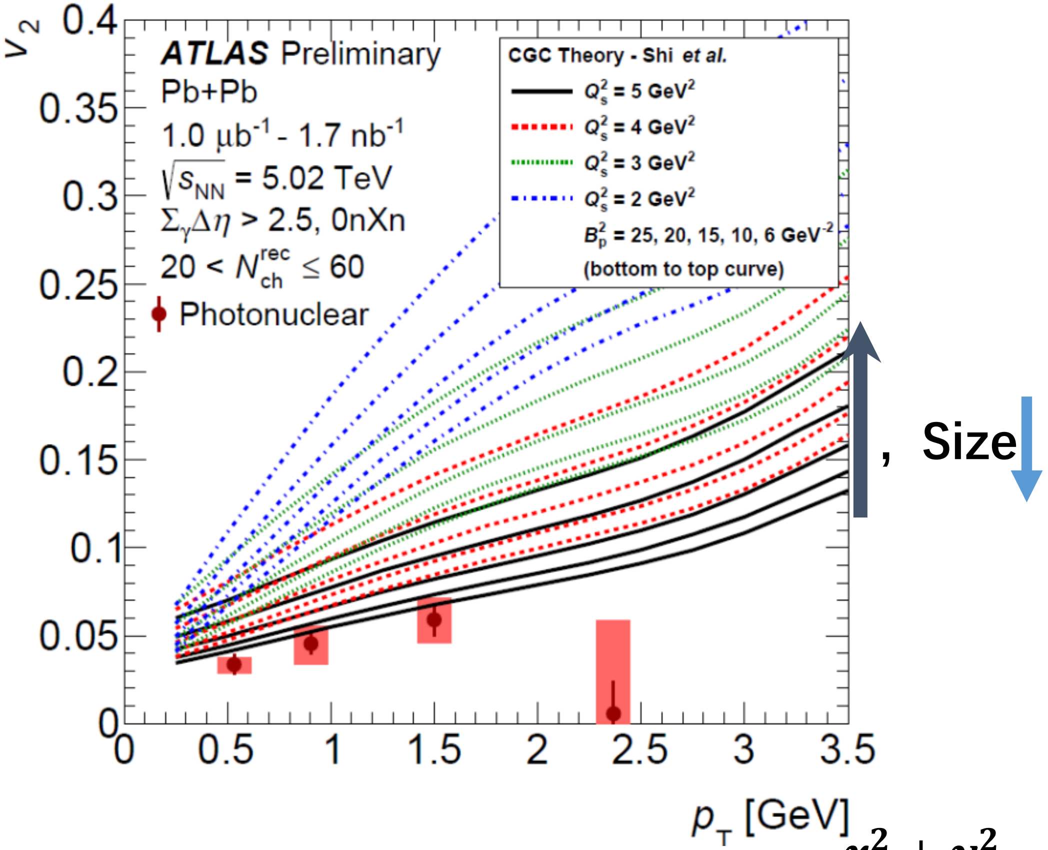


- 3D hydrodynamics describes the $v_2\ \{2\}$ and hierarchy in γ^*+Pb and p+Pb well.
- The longitudinal flow decorrelation is stronger in the γ^*+Pb than p+Pb, resulting in the v_2 hierarchy between γ^*+Pb and p+Pb .

W. Zhao, C. Shen and B. Schenke PhysRevLett.129.252302.
C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905.

Photon virtuality dependence of flow





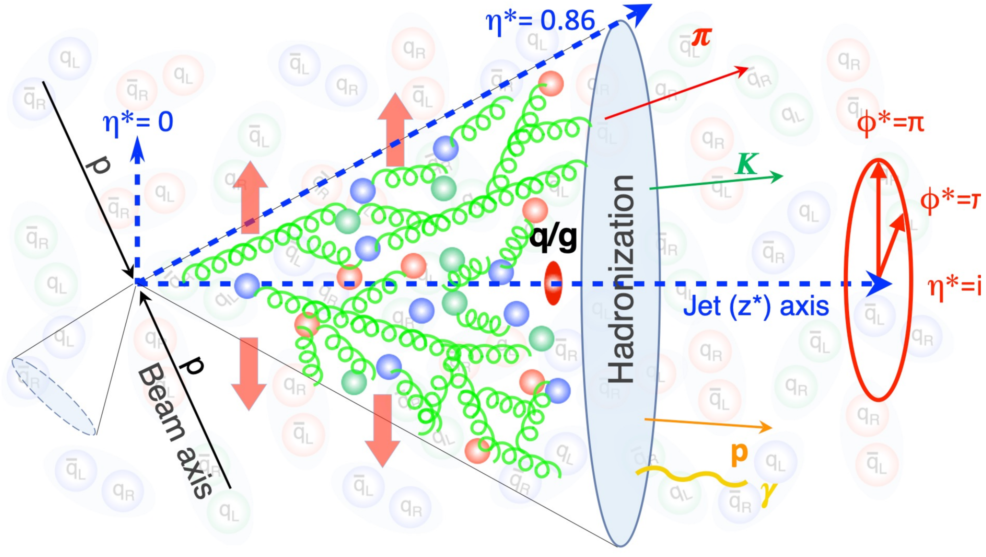
The transverse positions of the valence partons are sampled from a 2D Gaussian $P(x,y) \propto exp[-\frac{x^2+y^2}{2} Q^2]$

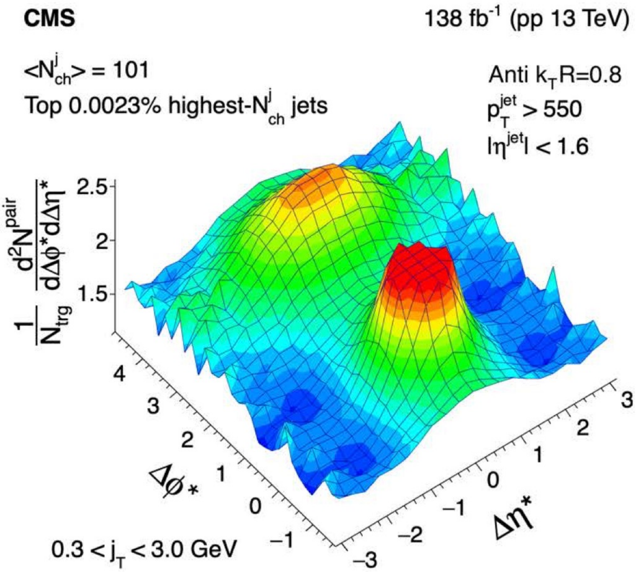
- Hydro: larger transverse space of the geometry allows more shape fluctuations and the v_2 are larger.
- CGC: Larger number of independent domains leads to lower v_2.
- Hydro predicts the opposite trend with Q^2 than the CGC.

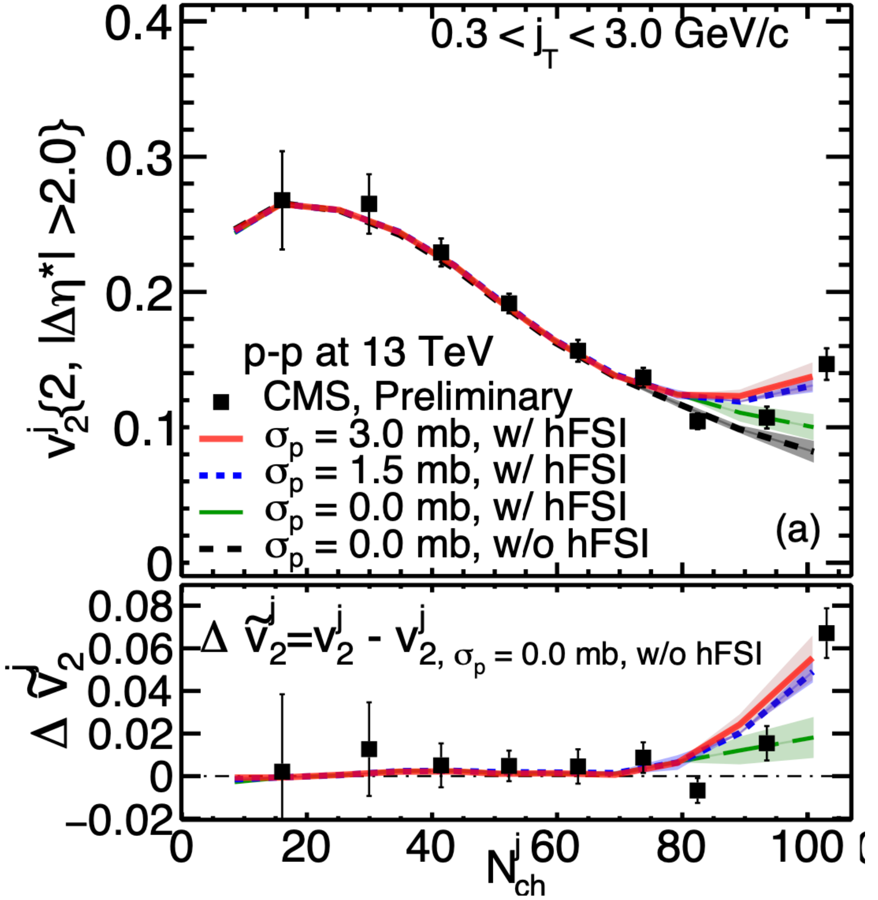
W. Zhao, C. Shen and B. Schenke, PhysRevLett.129.252302. Y. Shi, etc.al,Phys. Rev. D 103, 054017 (2021). B. D. Seidlitz. QM2019.

Smallest QGP droplet?

"Collectivity" inside the high multiplicity jet in p-p



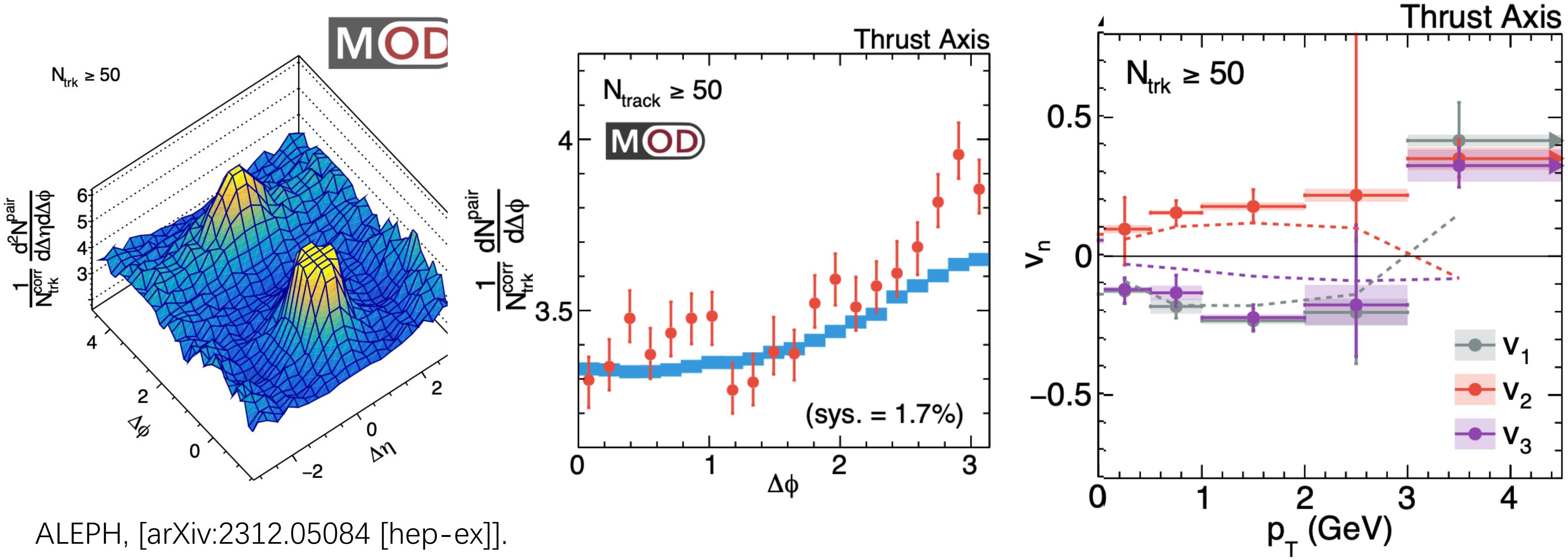




CMS, [arXiv:2312.17103 [hep-ex]].
W. Zhao, Zi-Wei Lin and Xin-Nian Wang [arXiv:2401.13137].

- "Collectivity" features inside high multiplicity jets in p-p.
- Final state interaction enhances the v_2 inside high multiplicity jet in p-p. QGP droplet?

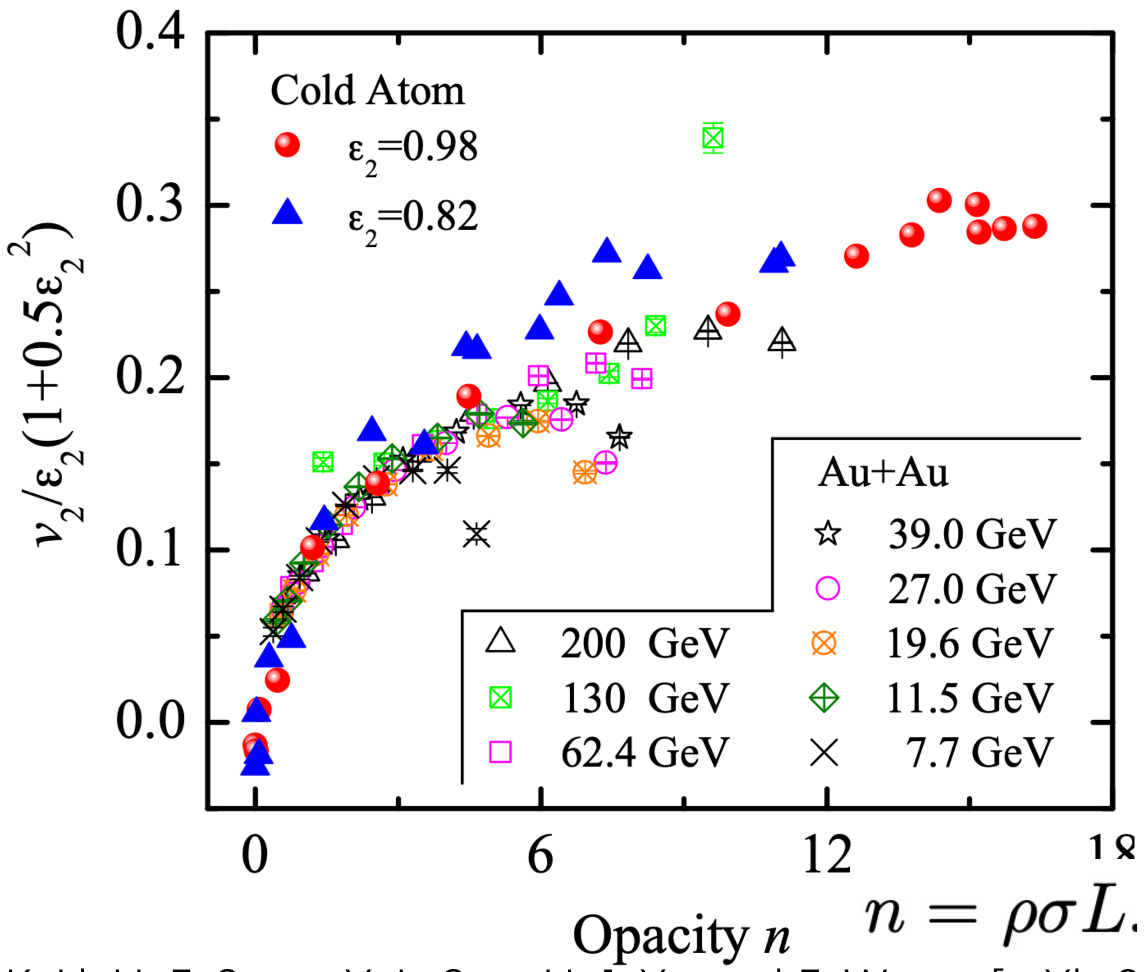
“Collectivity” in high multiplicity e^+e^-

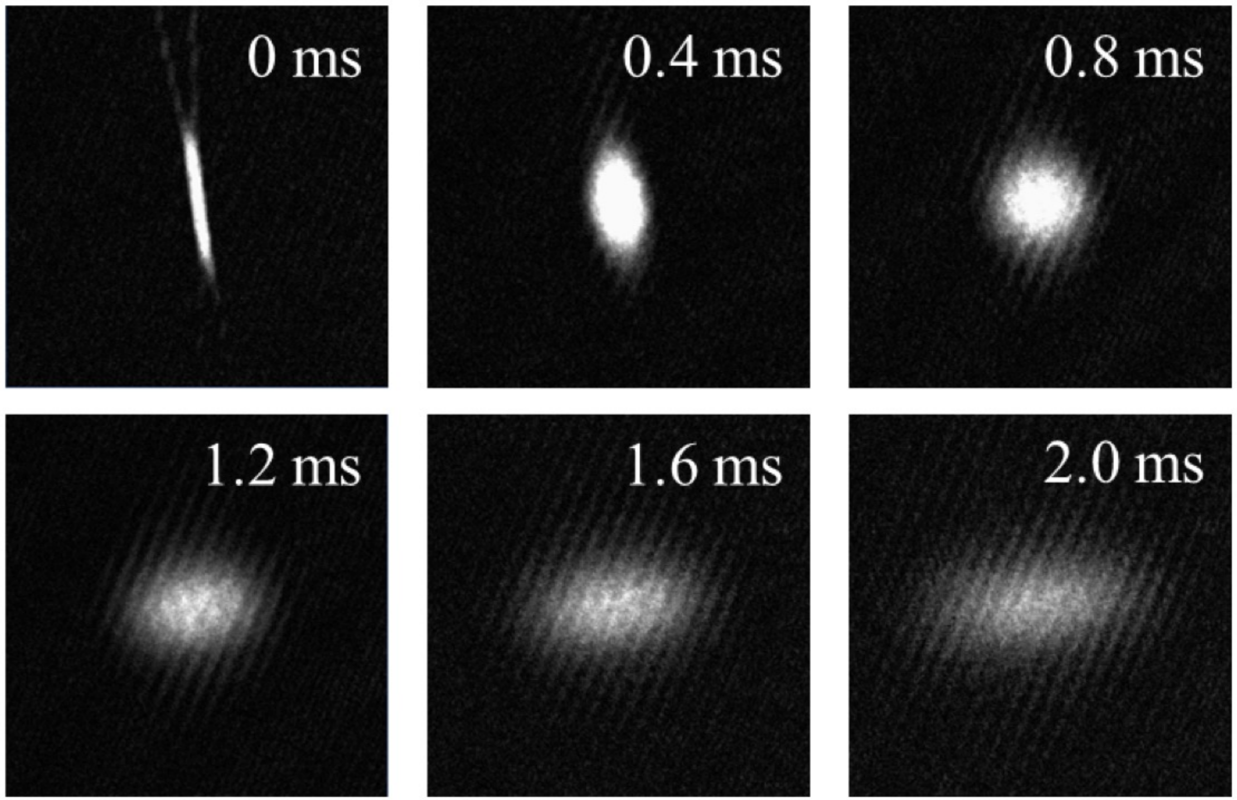


ALEPH, [arXiv:2312.05084 [hep-ex]].

- Pythia8 without long range correlations underestimates the v_2 at high multiplicity e^+e^-.
- Smallest QGP droplet?

"Collectivity" in Cold Atom Systems



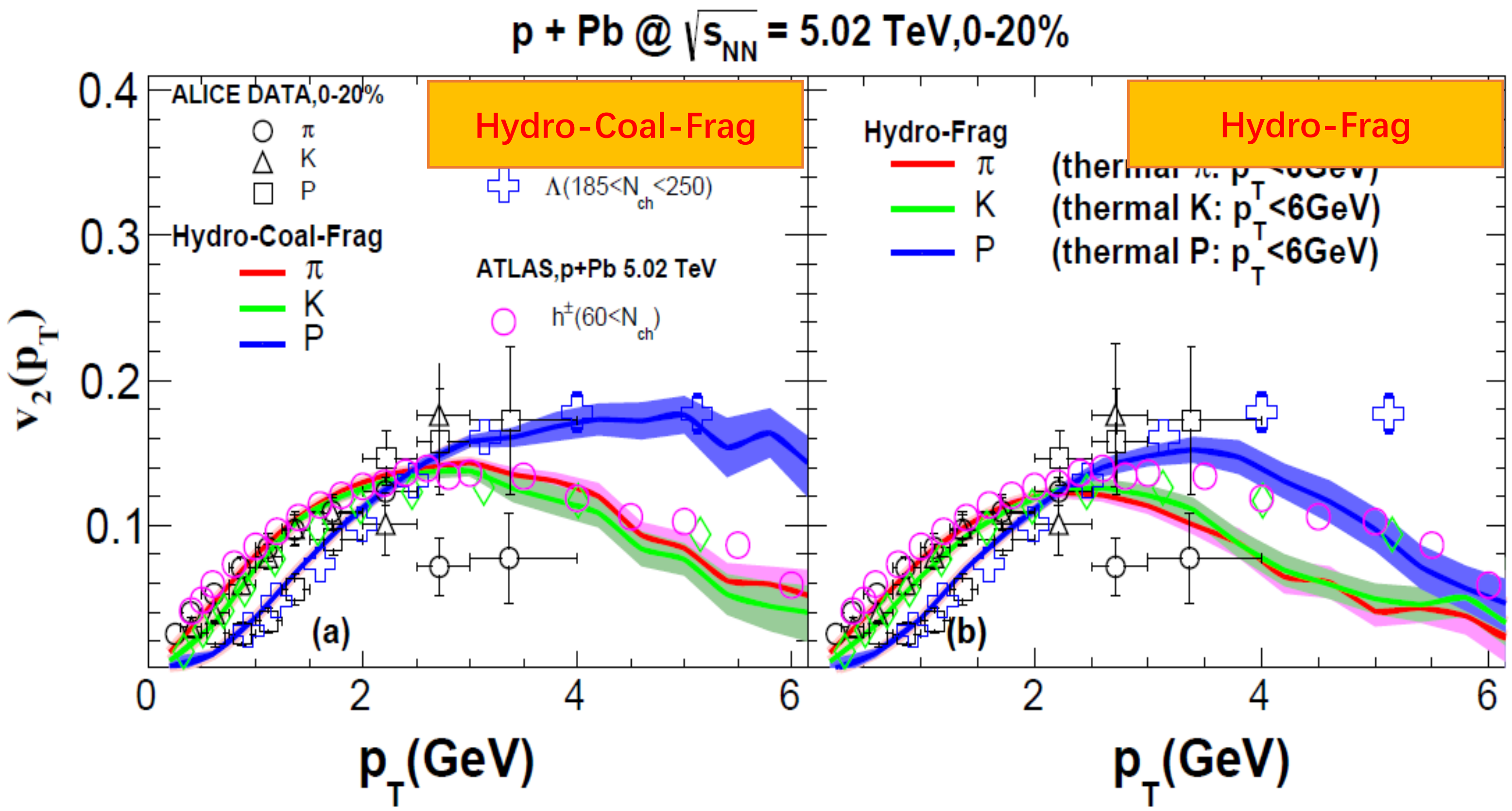


Snapshots of the strongly interacting Fermi gas

K. Li, H. F. Song, Y. L. Sun, H. J. Xu and F. Wang, [arXiv:2405.02847 [cond-mat.quant-gas]]

- A universal behavior is observed between the systems of cold-atom gases and heavy-ion collisions.

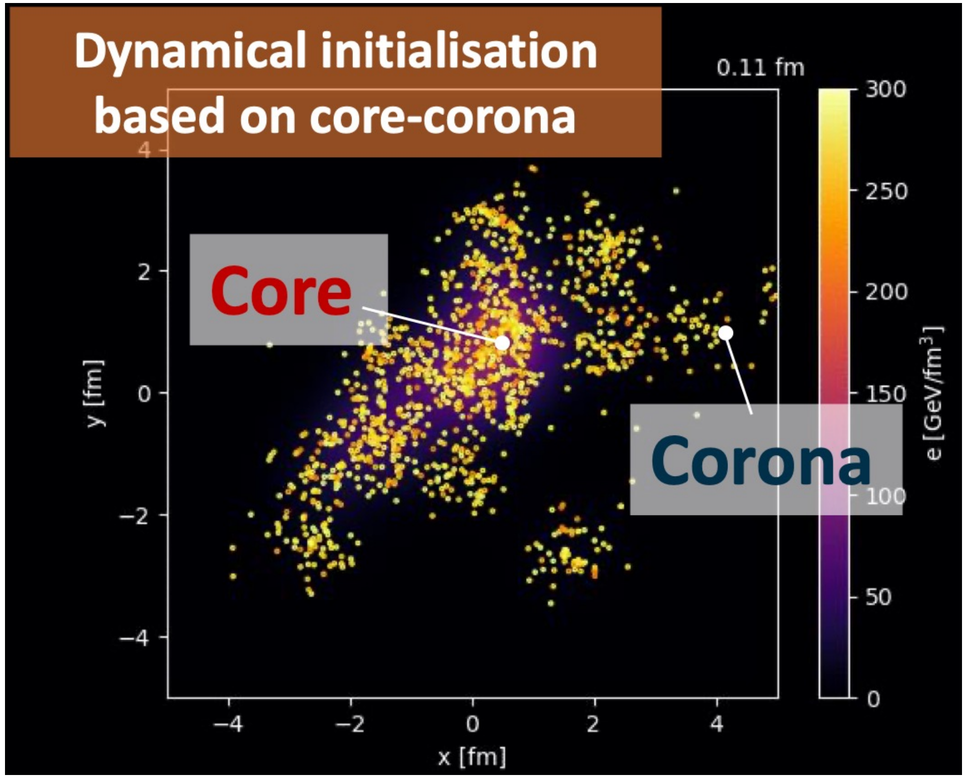
Collectivity at intermediate p_T in small systems

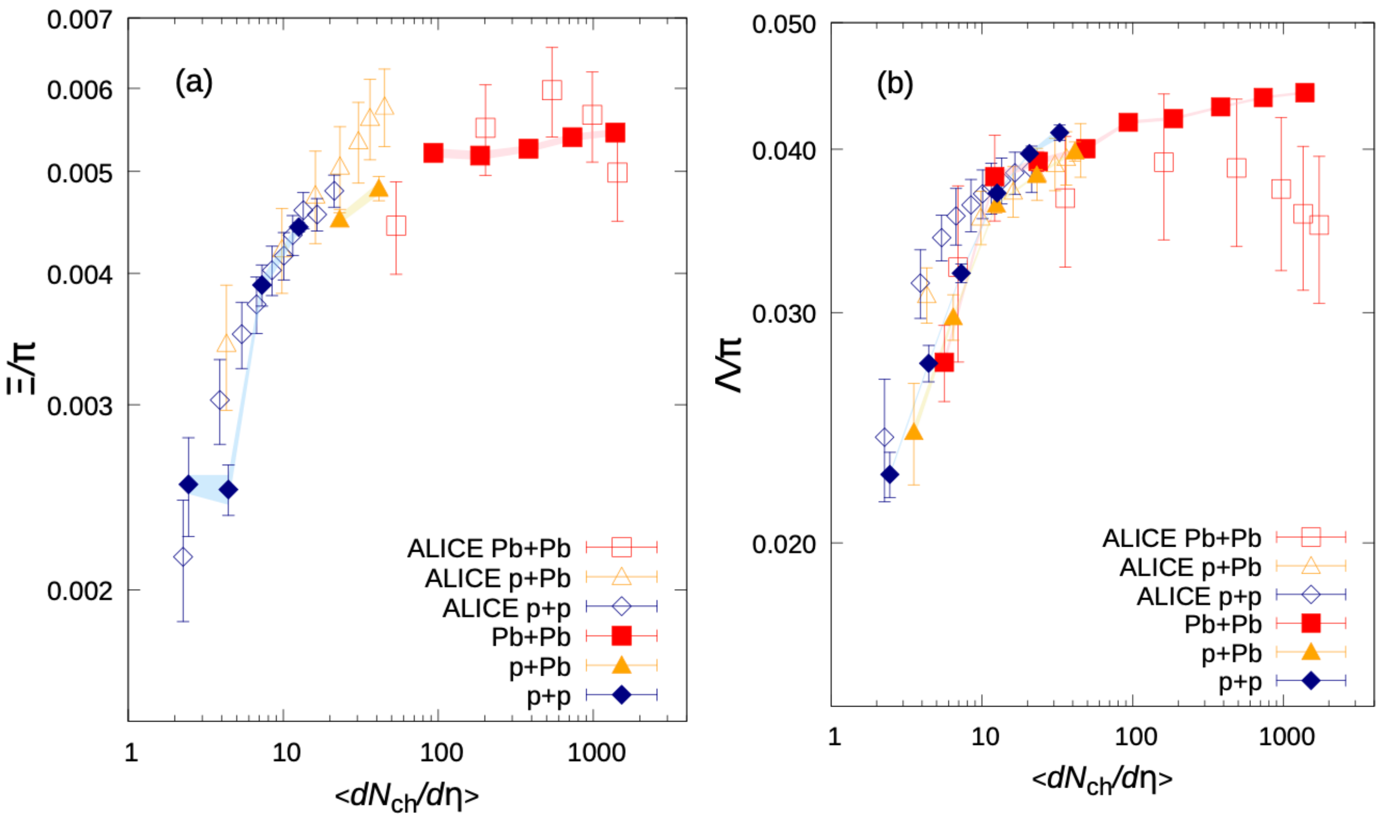


W. Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301 (2020).

- Hydro-Coal-Frag hybrid model well describe the $v_2(p_T)$, Quark coalescence is essential in p-Pb collisions.

Core-Corona model and Strangeness Enhancement



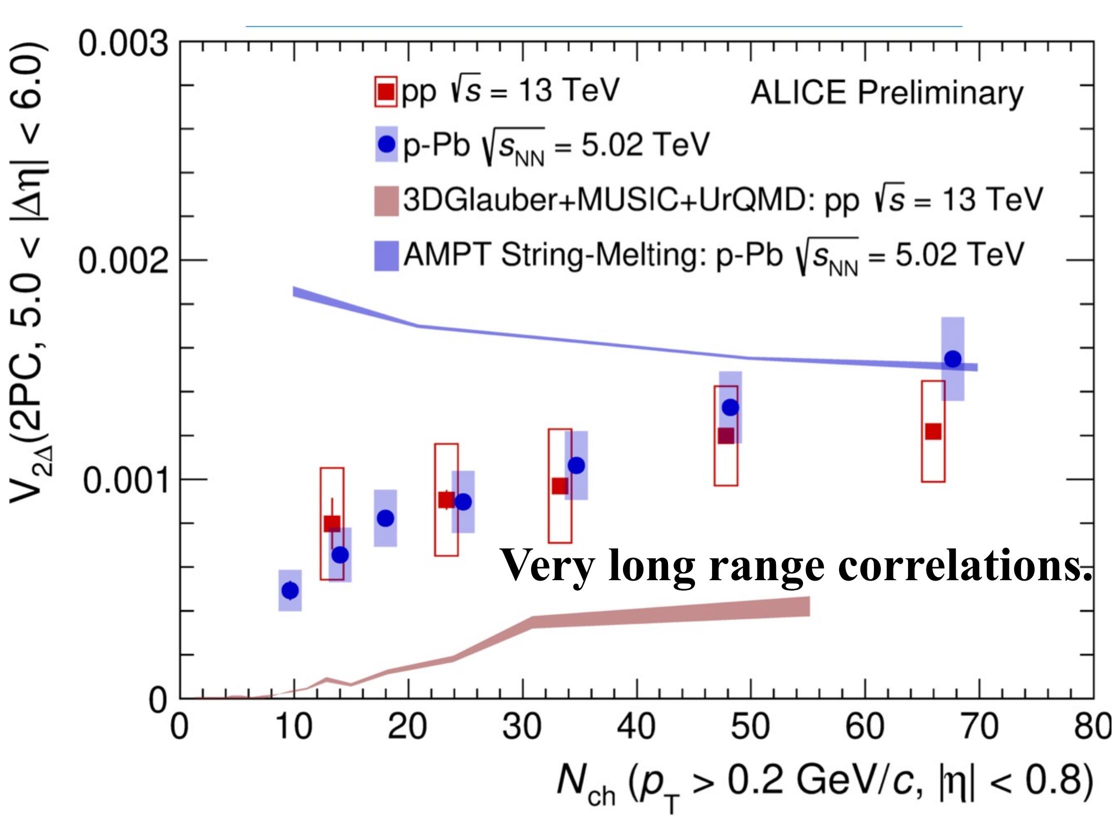


Y. Kanakubo, Y. Tachibana and T. Hirano, PhysRevC.101.024912

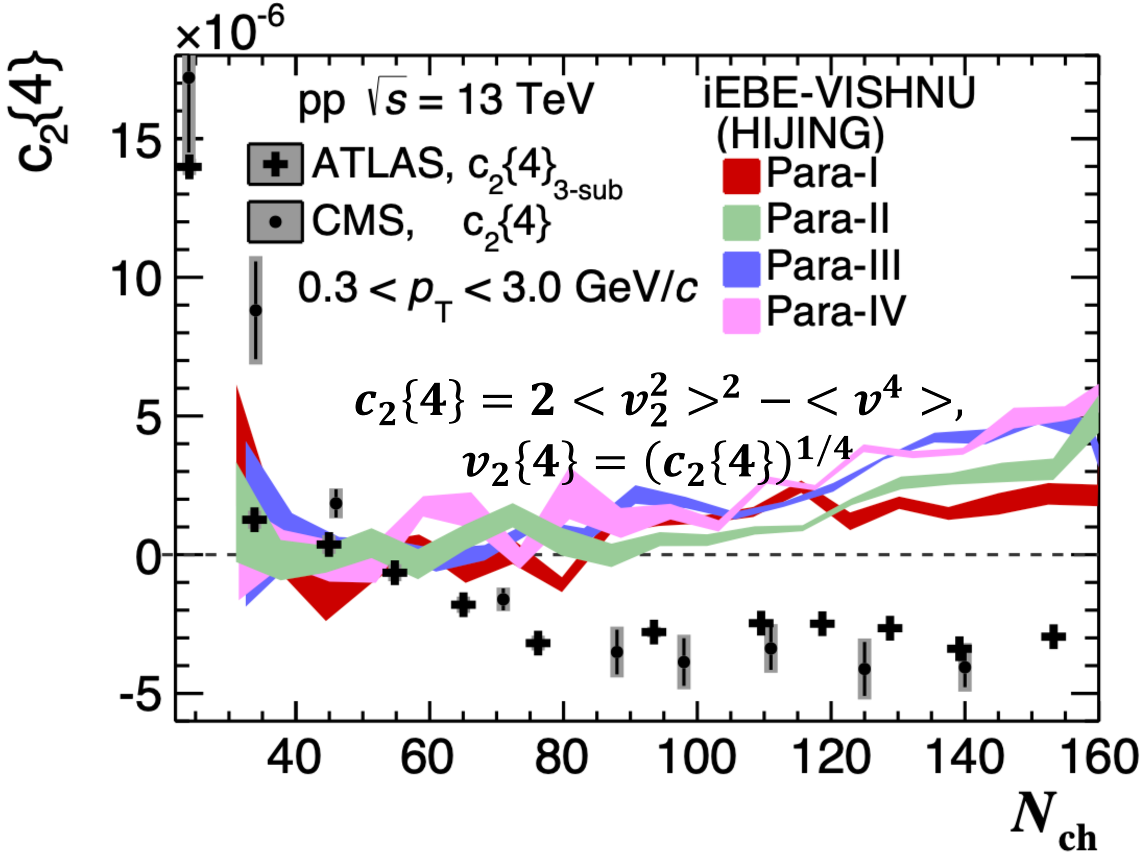
- Hydro-like core dominates at high Multiplicity.
- Because of the interplay between core and corona components, it reasonably describes the strangeness of hadron yield ratios to pions from p-p, pA to AA.

BUT……

Collectivity in proton-proton collisions



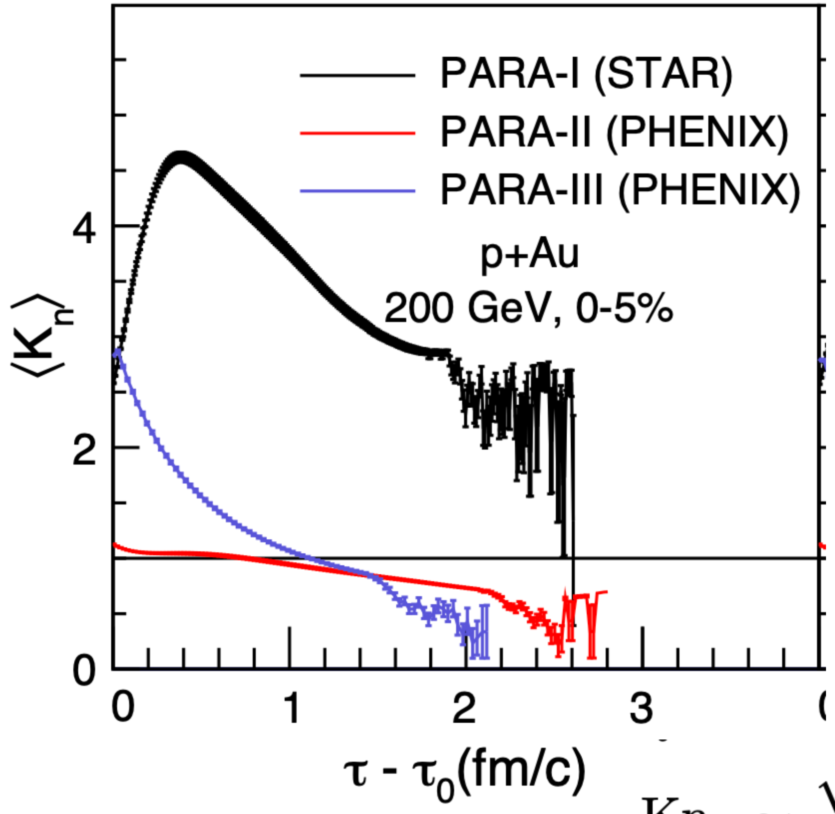
Debojit Sarkar, SQM 2024

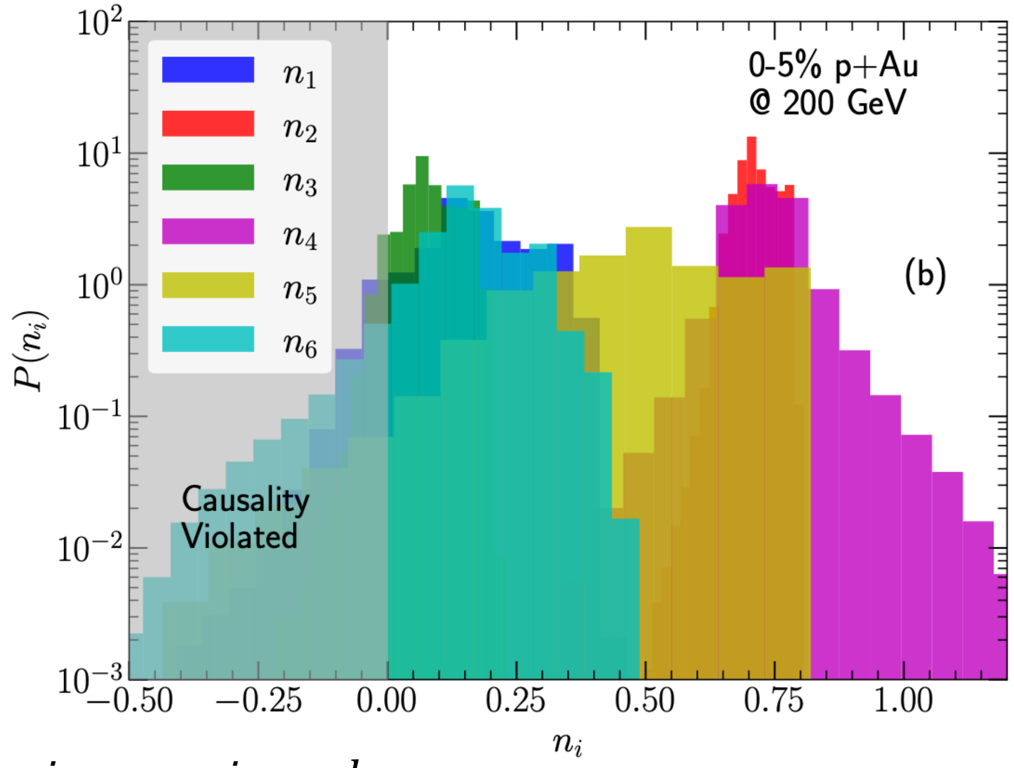


W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song, Phys. Lett. B 780 (2018), 495-500.

- Models extrapolated from AA do not describe the p-p data. Need better description of 3D geometry.
- The sign of $c_2\{4\}$ is opposite between hydro calculations and the data in p-p. Maybe transport model could help (X. L. Zhao, Z. W. Lin, L. Zheng and G. L. Ma, PLB.2023.137799).

Applicability of Hydrodynamics



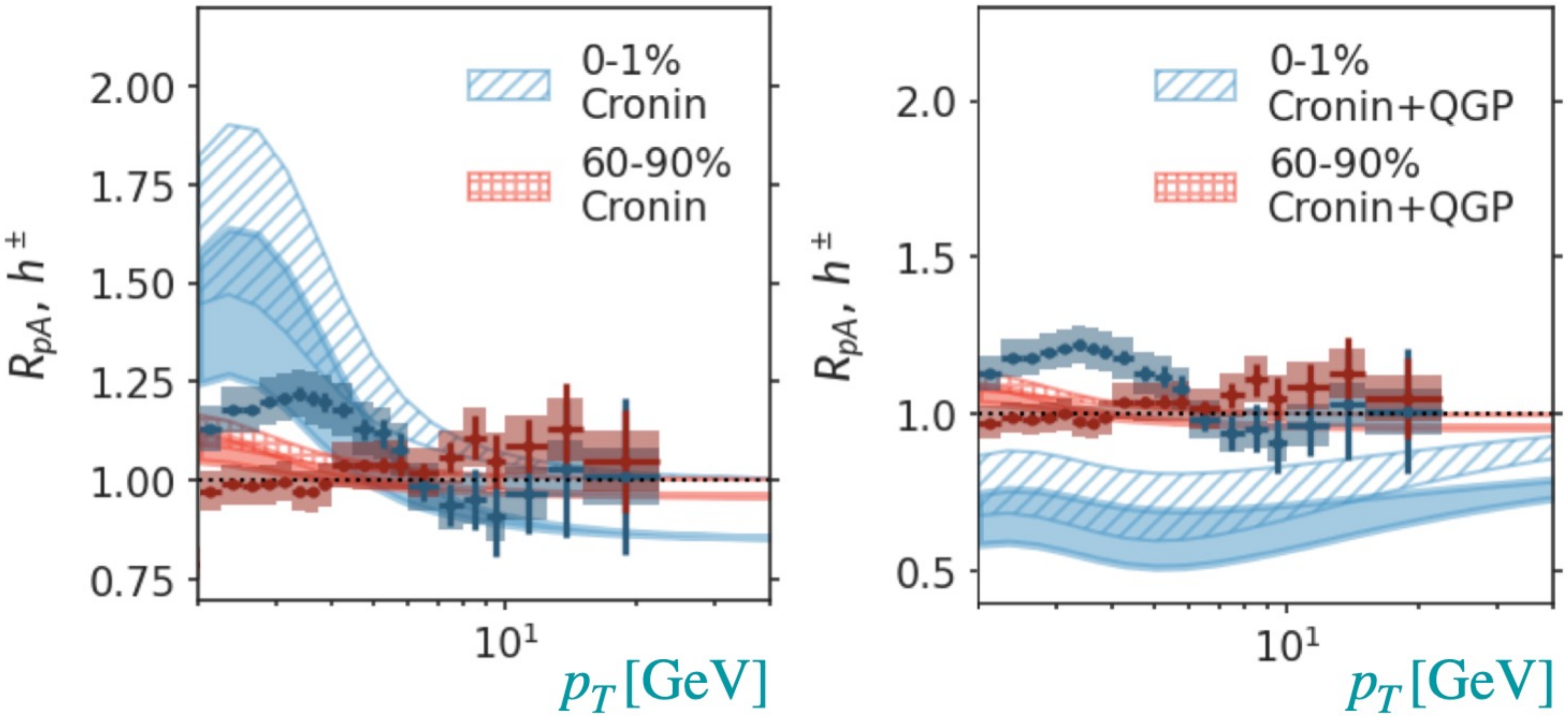


$$\mathrm{Kn}_\sigma \sim \frac{\sqrt{|\sigma_{\mu\nu}\sigma^{\mu\nu}|}}{T}, \sim \frac{\textit{microscopic scale}}{\textit{macroscopic scale}}$$

Z. Wu, B. Fu, S. Zhao, R. Liu and H. Song [arXiv:2307.02995]. C. Chiu and C. Shen, Phys. Rev. C. 103(6), 064901 (2021). Eur.Phys.J.C 82 (2022) 9, 796. Phys. Rev. Lett. 122(12), 122302. Phys. Rev. X. 12(2), 021044 (2022). JHEP 10 (2019) 034.

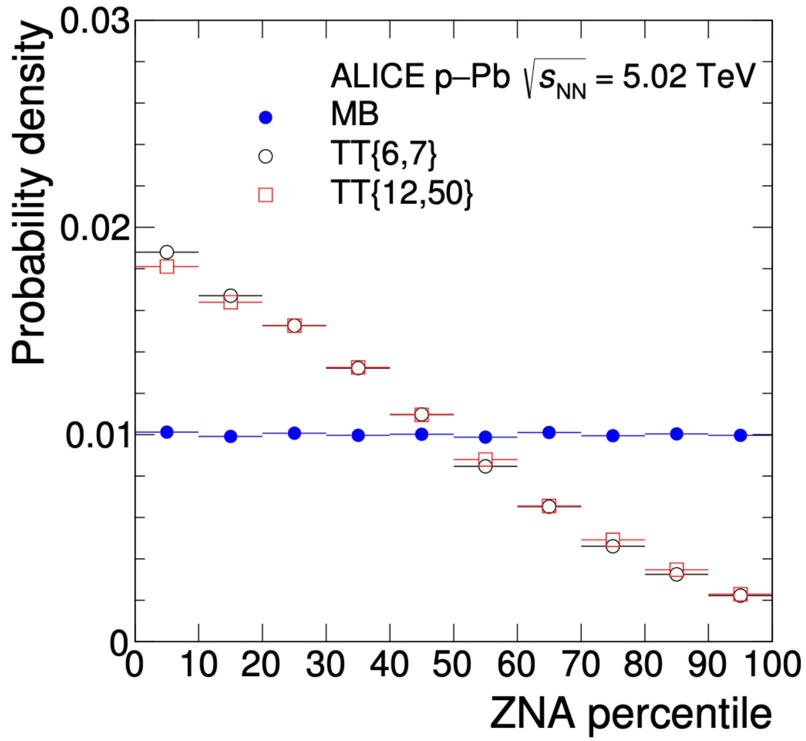
- Large Knudsen is observed in small systems. Far from equilibrium, causality could be violated
- Use non-equilibrium component: Early time free streaming, effective kinetic theory, or core-corona models, Alternative to Israel-Stewart like theories, BDNK, can help.

Hard Probes in small systems



Cold nuclear matter only

Cold nuclear matter + QGP



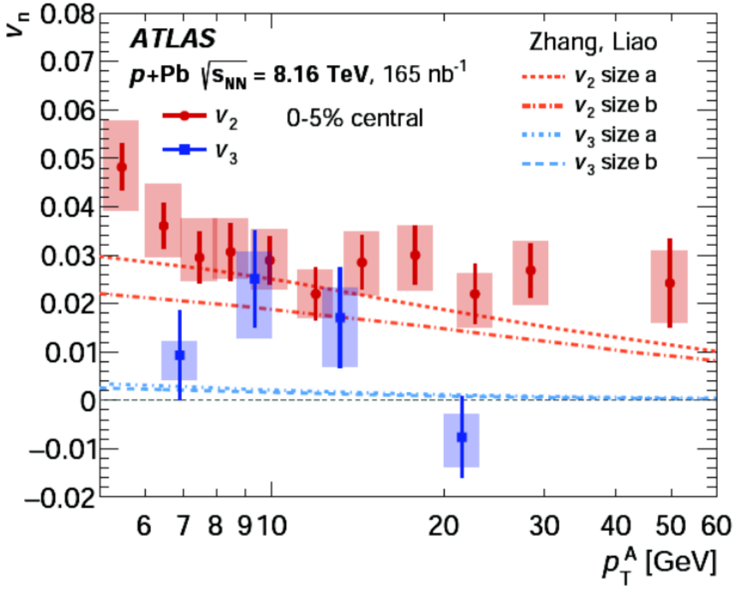
Event activity selection with high-*p*T trigger hadron.

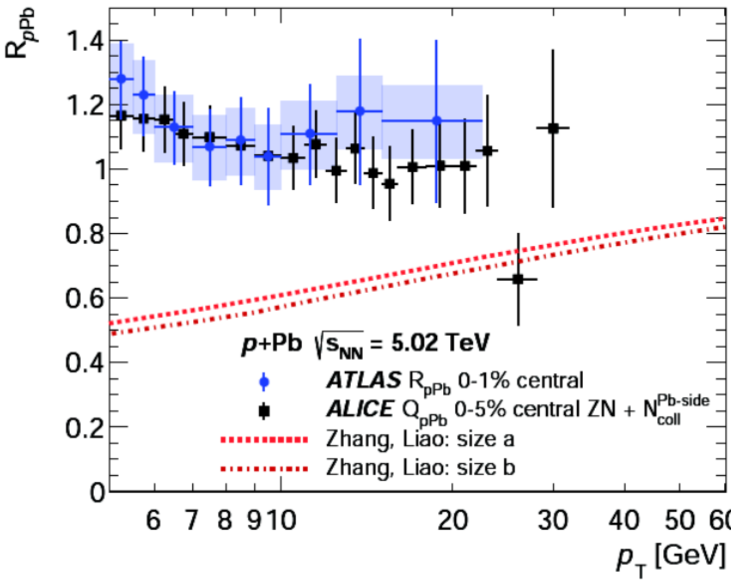
W. Ke, I. Vitev, Phys.Rev.C 107 (2023) 6, 064903. ALICE, PLB: 783 (2018)95-113.

- Model of QGP formation in p+A described by hydrodynamics leads to quenching of hadron spectra that is inconsistent with the p+Pb data.
- In small systems, **Centrality determination is critical !**

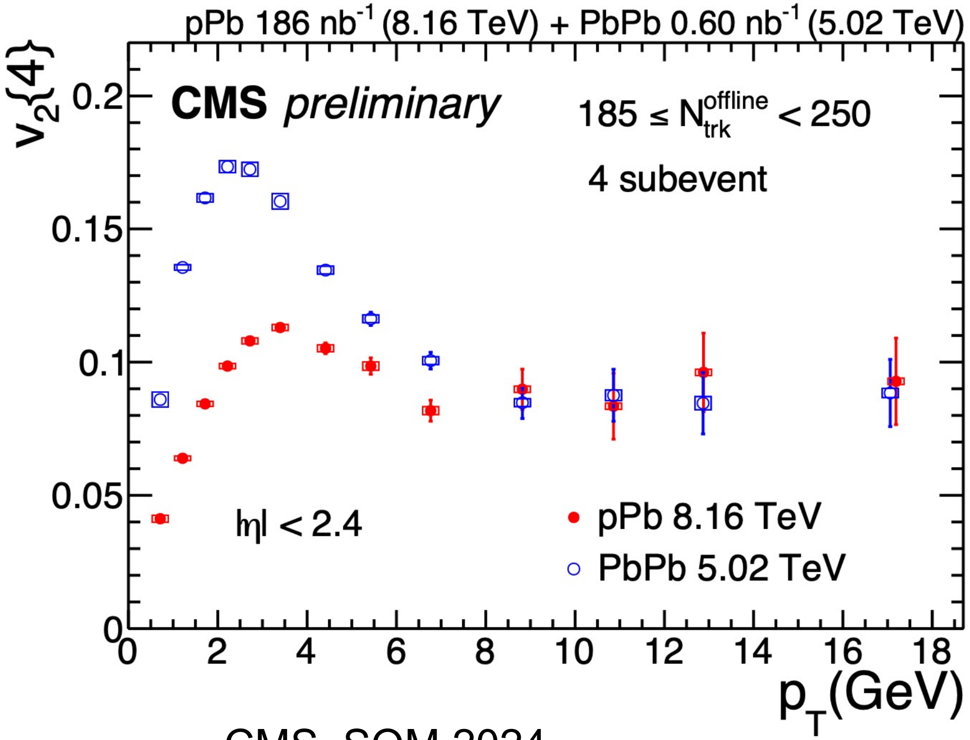
see arXiv: [2308.02650] for soft-hard correlations.

R_{pPb} v.s. $v_2(p_T)$ in pA





ATLAS: arXiv:1910.13978. Model: arXiv:1311.5463.

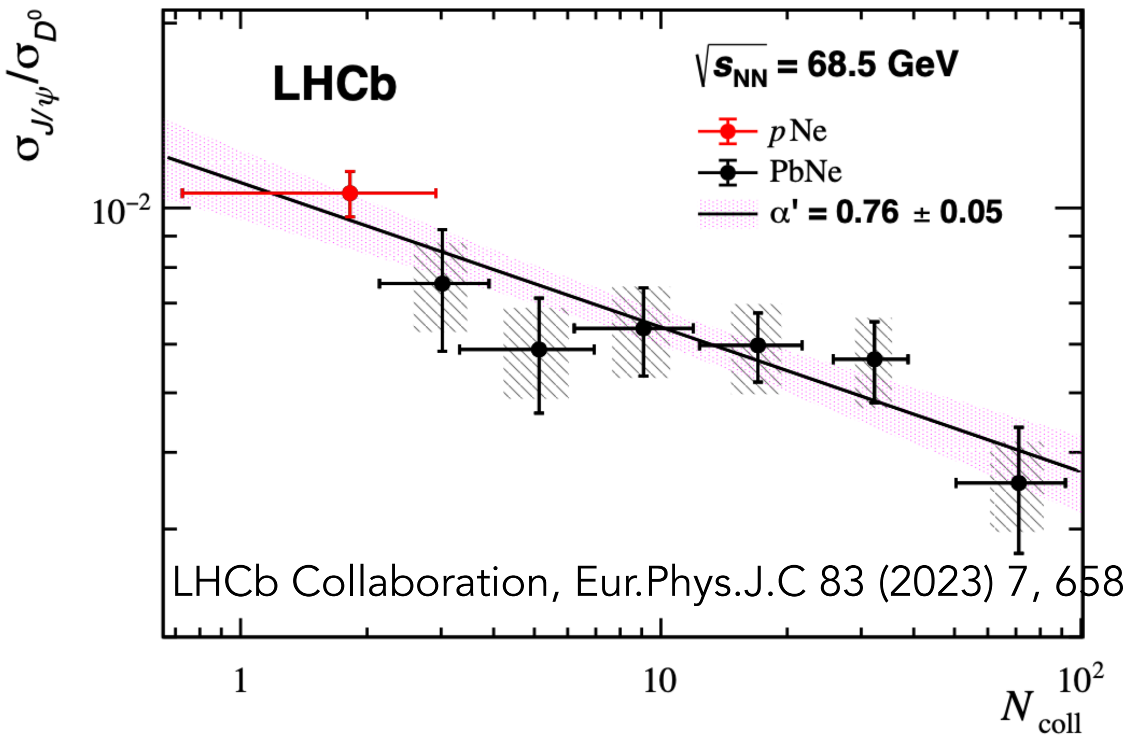


CMS, SQM 2024.

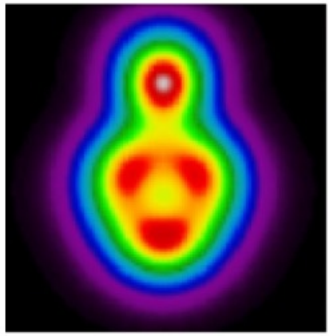
- High p_T R_{pPb} v.s. v_2 (p_T) "puzzle" in p-Pb.
- How to understand new CMS measurements of high p_T flow in pPb?

See *I. Soudi, A. Majumder, arXiv:2308.14702, 2404.05287* for recently progresses.

Bonus

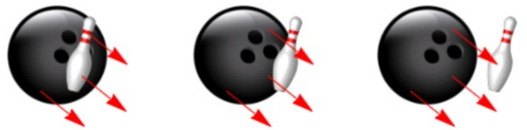


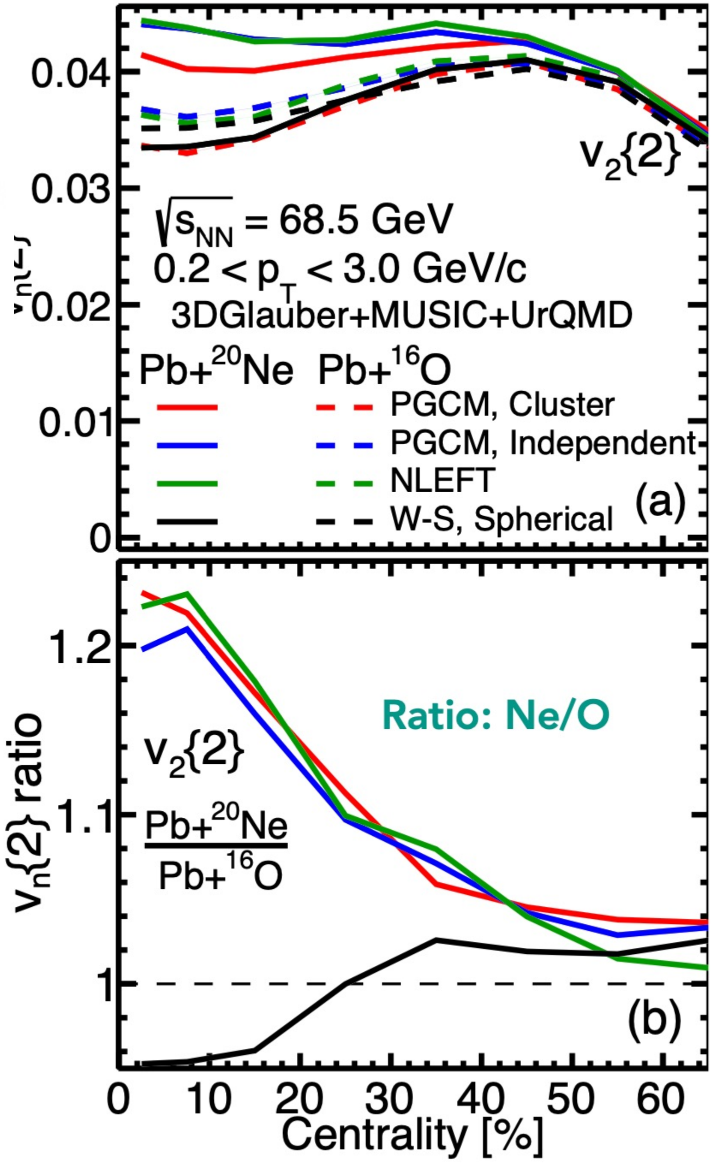
LHCb Collaboration, Eur.Phys.J.C 83 (2023) 7, 658



^{20}Ne

G. Giacalone et al, arXiv:2405.20210





- No QGP-like J/ψ suppression in Pb+Ne.
- Flow sensitive to shapes of Ne and O
- Searching the QGP at LHCb.

Summary

- Hydrodynamics works well in describing collectivity from Pb+Pb, p+Pb to p+p and $\gamma *$ +Pb collisions.
- There are some issues of applicability of hydrodynamics: accuracy, causality, stability
- Jet quenching does not seem to be observed in small systems. R_{pPb} v.s. $v_2(p_T)$ puzzle in pA.
- Where is the QGP smallest boundary?

See contribution to Quark-Gluon Plasma 6 (World Scientific):

Progress and Challenges in Small Systems

Jorge Noronha, Björn Schenke, Chun Shen, Wenbin Zhao

e-Print: 2401.09208 [nucl-th]

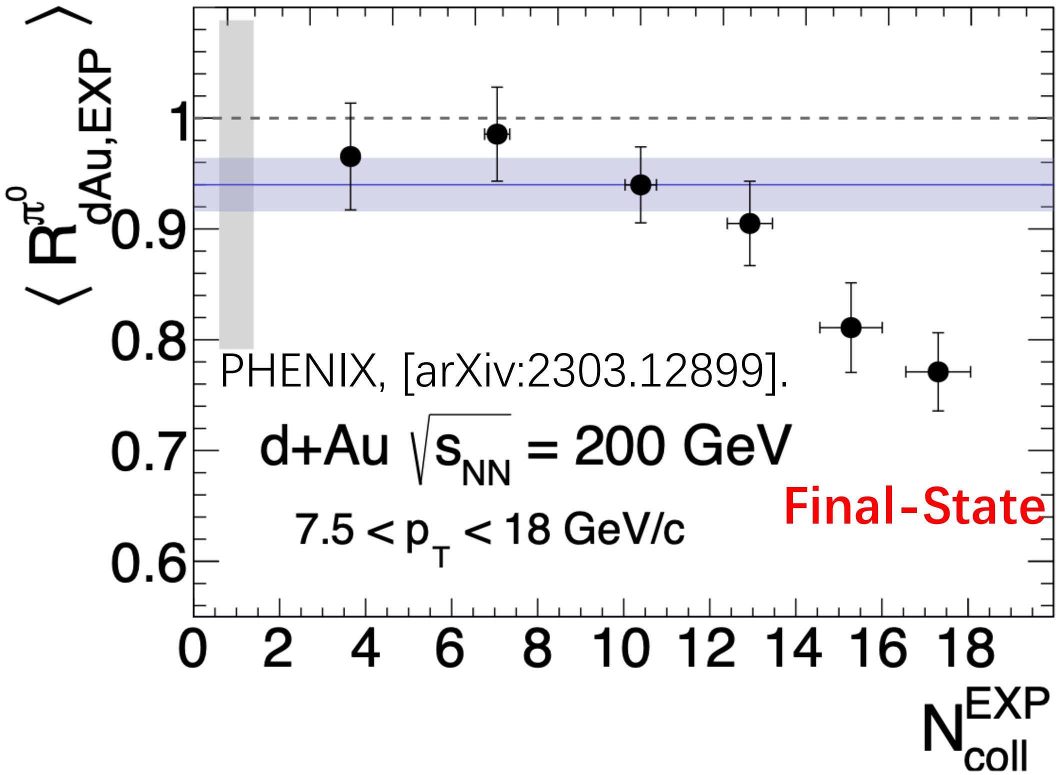
Thanks for Your Attention!

Questions？

Back Up

Back Up

Event-activity with jet events



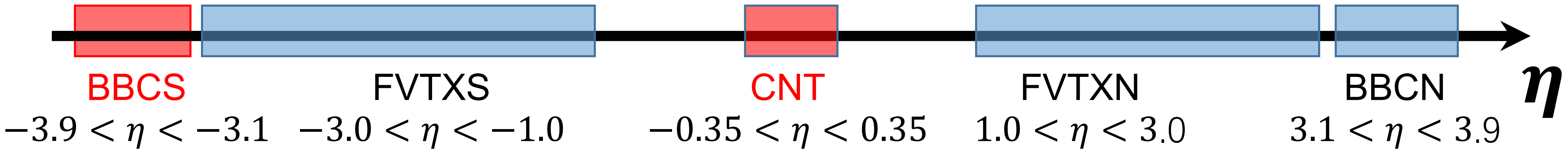
Final-State effect?

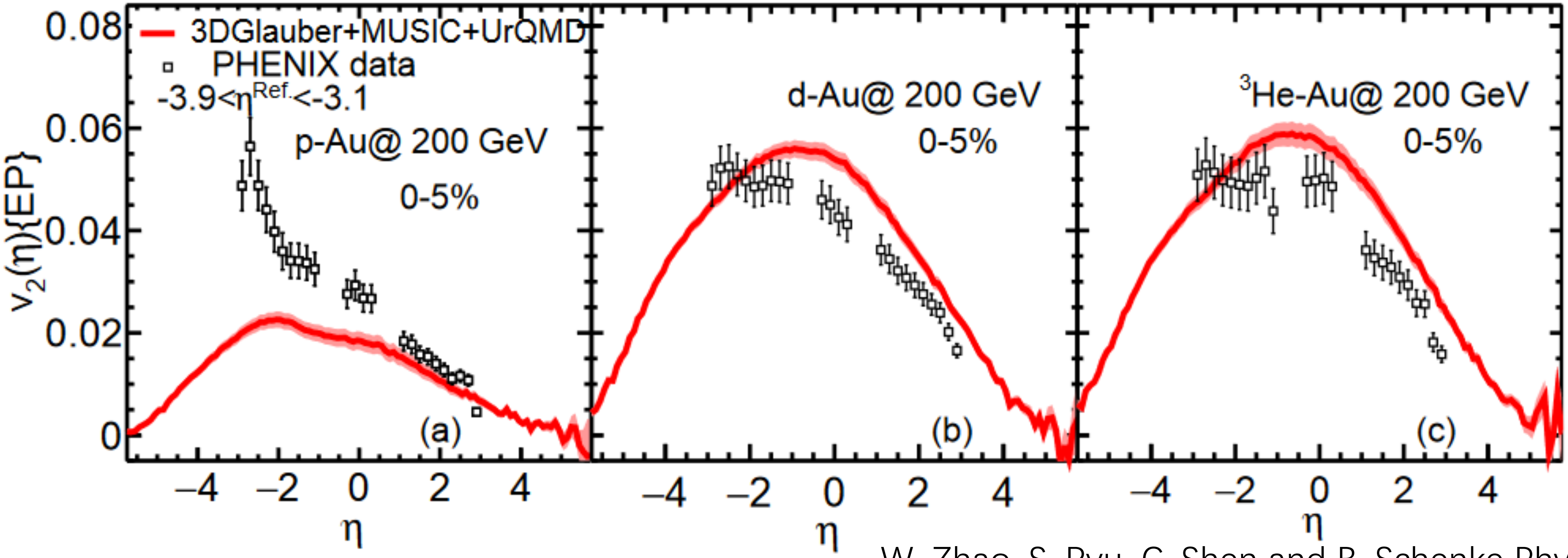
$$N^{EXP}_{coll}(p_T) = \frac{Y^{\gamma^{dir}}_{dAu}(p_T)}{Y^{\gamma^{dir}}_{pp}(p_T)}.$$

$$R^{\pi^0}_{dAu,EXP} = \frac{Y^{\pi^0}_{dAu}}{N^{EXP}_{coll}\, Y^{\pi^0}_{pp}} = \frac{Y^{\pi^0}_{dAu}/Y^{\pi^0}_{pp}}{Y^{\gamma^{dir}}_{dAu}/Y^{\gamma^{dir}}_{pp}}.$$

- PHTNIX use the direct- photon yields to estimate the number of binary collisions (N^{EXP}_{coll}) to reduce the event-selection bias.
- Using a Glauber model *N*coll led to enhancement at low *N*coll is removed now.
- Suppression at large *N*coll remains.

$v_2(\eta)\{EP\}$





$v_2(\eta)\{EP\}$:
correlations: BBCS-CNT

W. Zhao, S. Ryu, C. Shen and B. Schenke Phys. Rev. C 107, 014904 (2023).

- Our 3D hybrid model reproduces the pseudo-rapidity dependence of $v_2(\eta)\{EP\}$ in d+Au and ^{3}He +Au collisions.
- The elliptic flow in η <1 in p+Au collision is underestimated because of the strong longitudinal decorrelation in our model and potential non-flow in the data.

Final state interactions inside the high multiplicity jet in p-p

Initial parton shower → Partonic rescattering → Haronic rescattering

Pythia8 → ZPC → UrQMD

- Initial shower partons generated by the Pythia8 with CP5 tune, the formation time:

$$t_f = \sum_i 2E_i x_i(1 - x_i)/k_{\perp i}^2$$

- Patonic elastic rescattering modeled by ZPC with the parton-parton scatter cross section σ_p.
- Colored hadronization.
- Hadronic rescattering modeled by UrQMD.
- It returns to pythia8 by turning off FSI.

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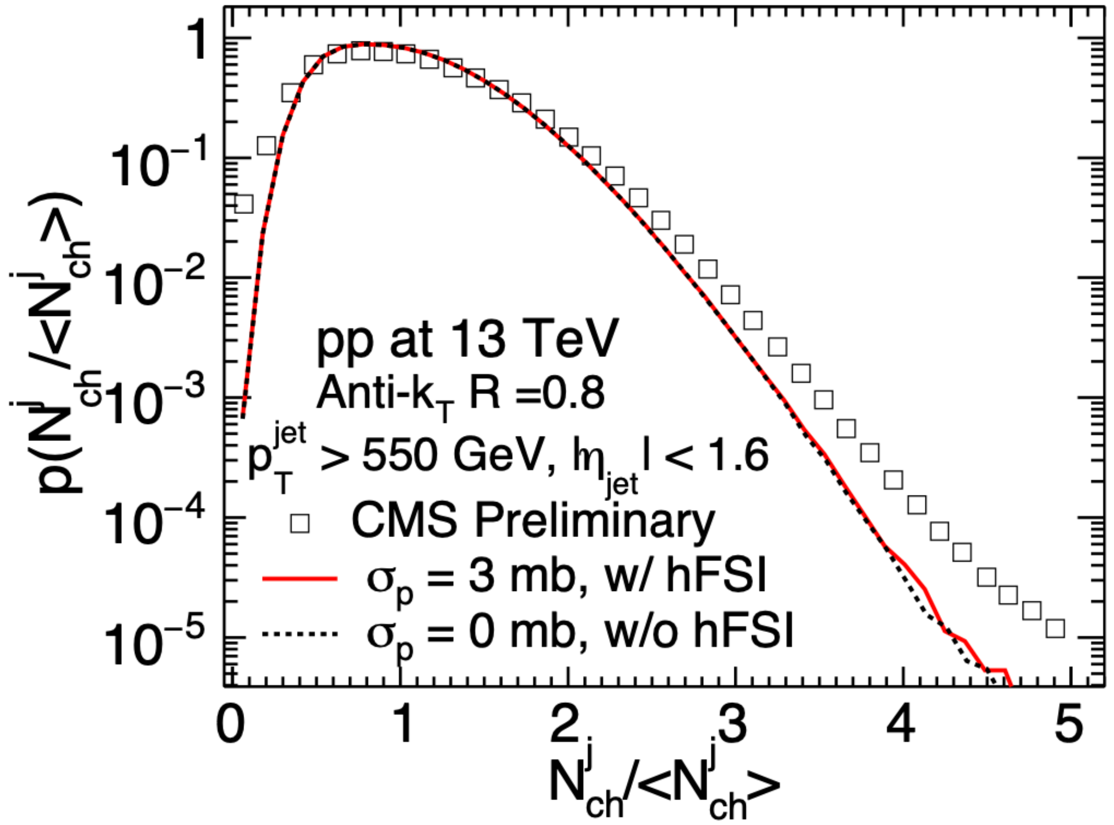
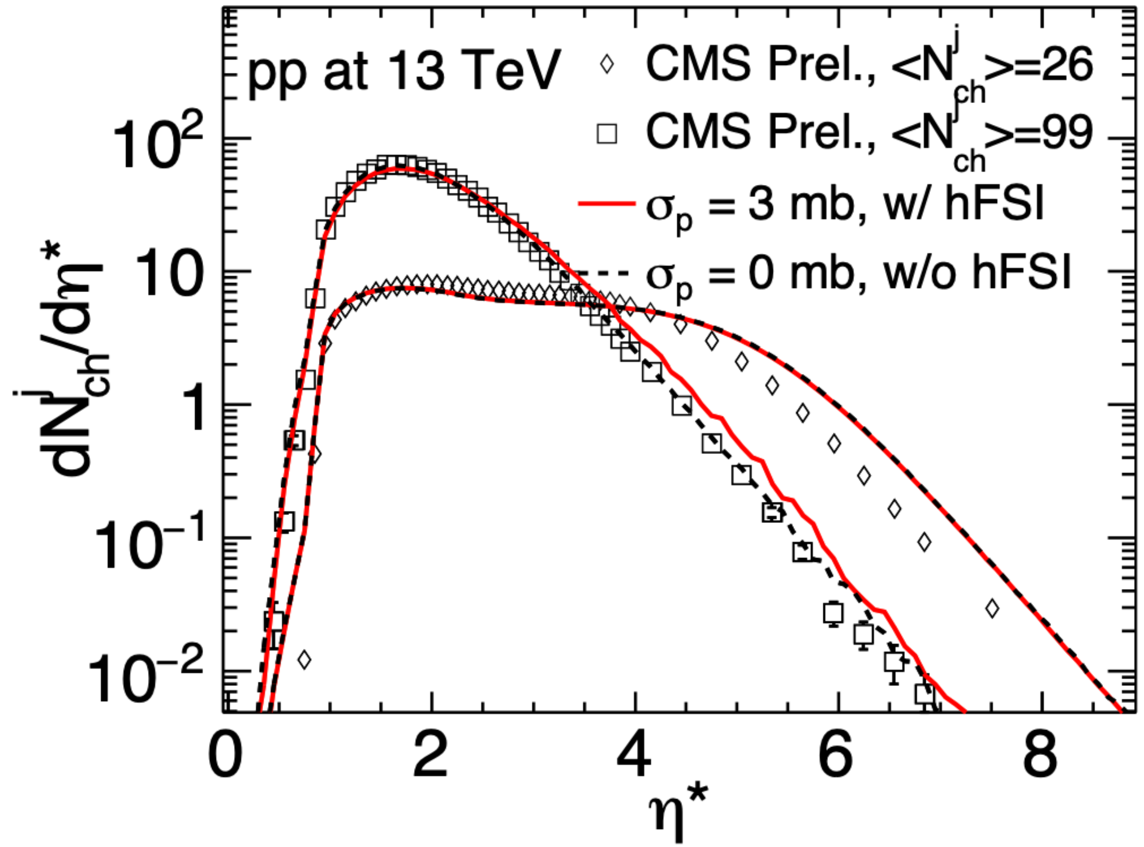
CMS, [arXiv:2312.17103 [hep-ex]].

W. Zhao, Zi-Wei Lin and Xin-Nian Wang [arXiv:2401.13137].

Hadron distributions inside jets in p-p

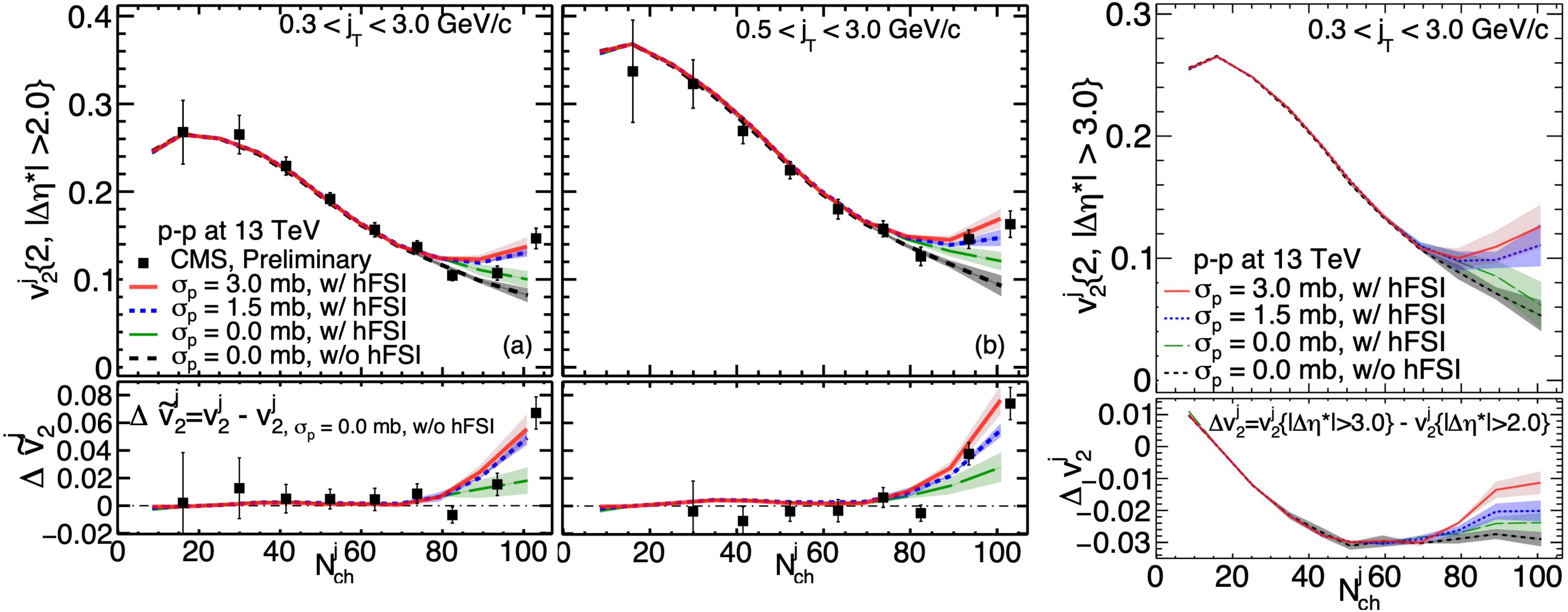




- Pythia8 gives narrower multiplicity distributions. Next step: include inelastic rescattering.
- Higher multiplicity events have the larger initial emission angles.

CMS, [arXiv:2312.17103 [hep-ex]].
W. Zhao, Zi-Wei Lin and Xin-Nian Wang [arXiv:2401.13137].

Collectivity inside high-multiplicity jets in p-p

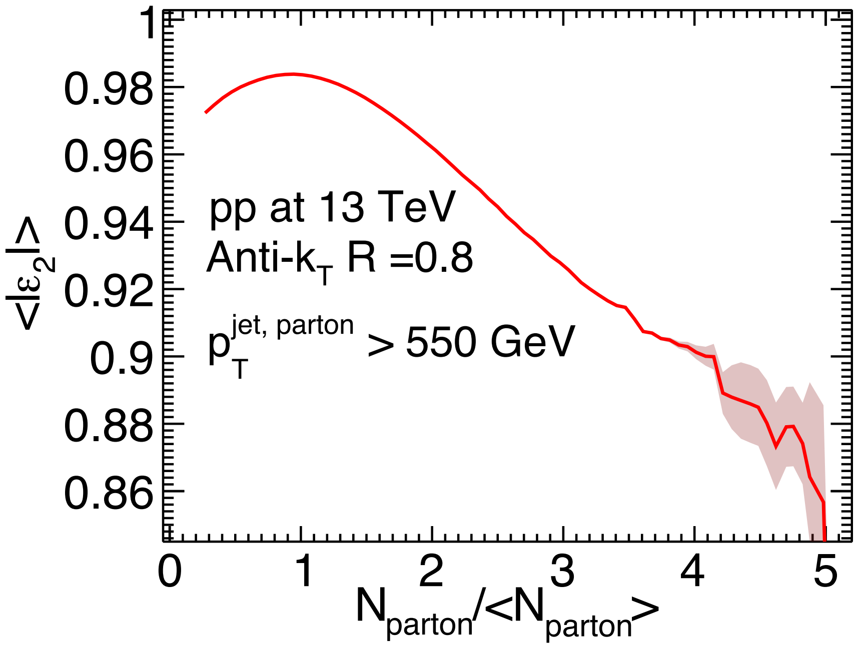


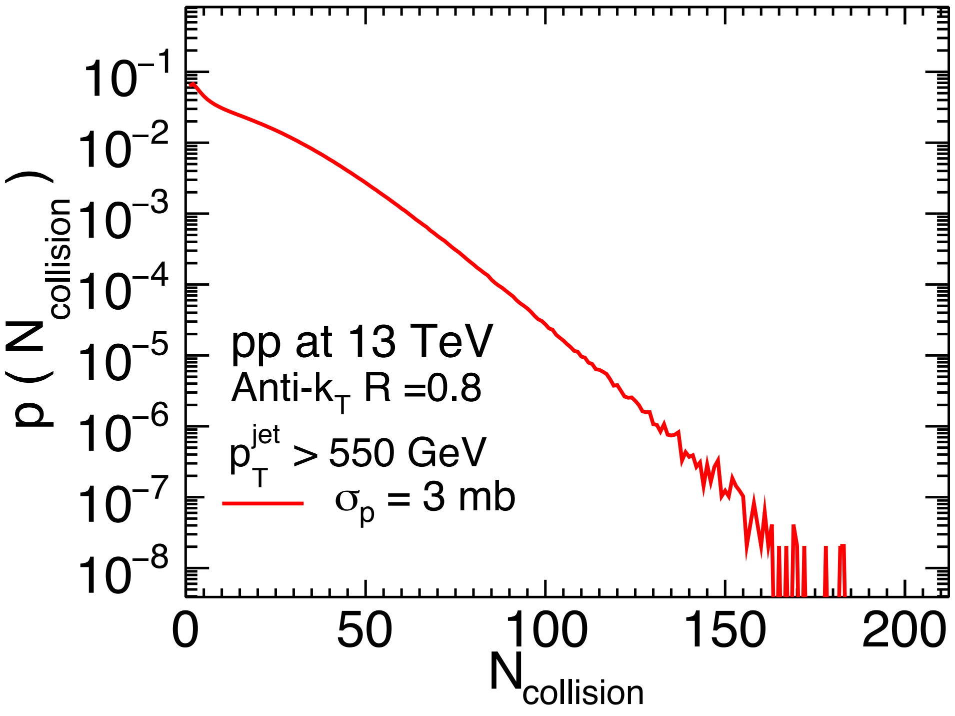
- Final state interaction enhances the v_2 inside high multiplicity jet in p-p. QGP droplet?
- We predict that the Δv_2 between different η −gaps increases at $N_{ch}^{j} > 70$.

CMS, [arXiv:2312.17103 [hep-ex]].
W. Zhao, Zi-Wei Lin and Xin-Nian Wang [arXiv:2401.13137].

Collisions inside high-multiplicity jets in p-p

$$\varepsilon_n e^{in\Phi_n} = -\frac{\int r\, dr\, d\varphi\, r^n\, e^{in\phi}\, e(r,\varphi)}{\int r\, dr\, d\varphi\, r^n\, e(r,\varphi)}$$





- Low multiplicity jet has large initial spatial anisotropy , but it don’t have enough final state interactions to translate into momentum anisotropy
- The high multiplicity jets can have around 100 partonic collision times, which translate initial spatial anisotropy into momentum space.

W. Zhao, Zi-Wei Lin and Xin-Nian Wang [arXiv:2401.13137].