Heavy Ion Physics in the EIC Era

July 29, 2024 - August 23, 2024

Searching the smallest fluid on the earth

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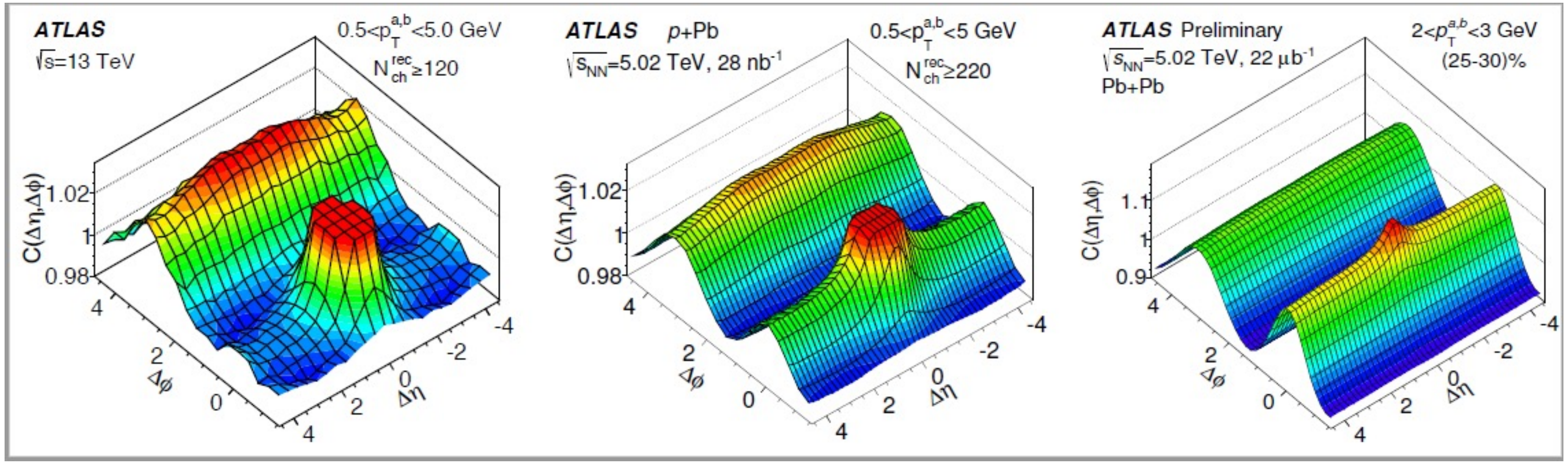
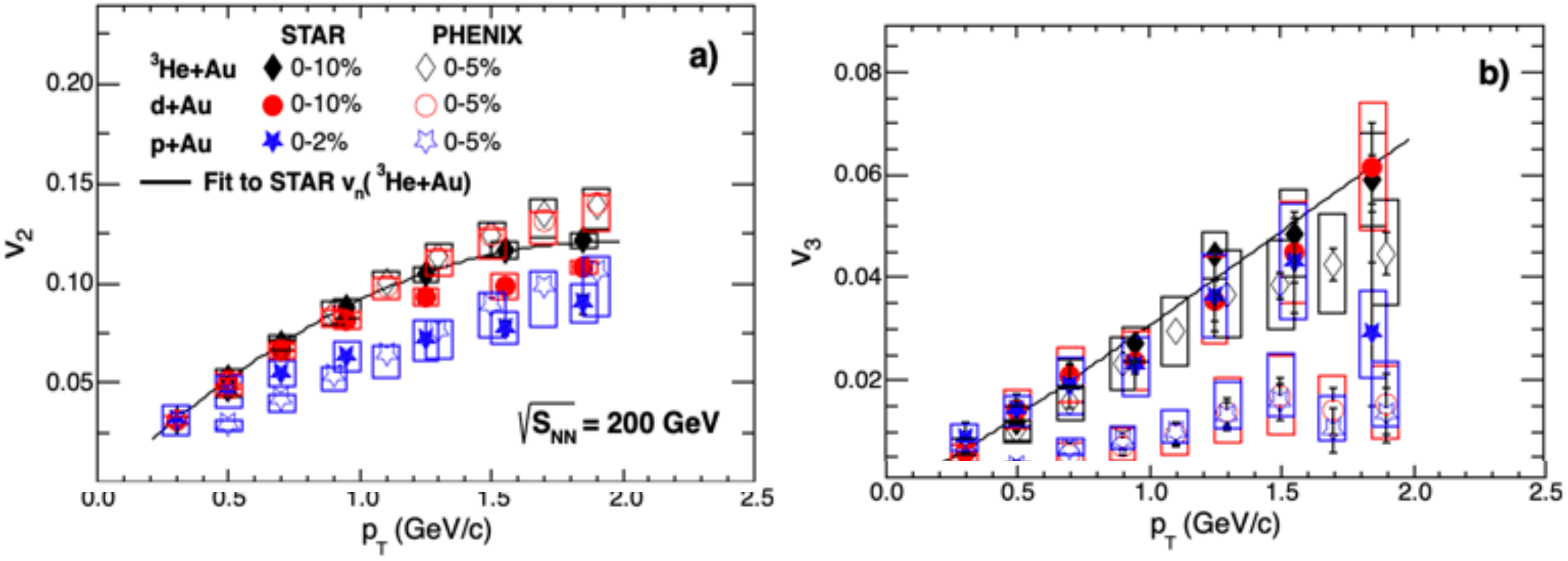
INT, July 29 – August 23, 2024

Collectivity in large and small systems



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

ATLAS, Phys. Lett. B789, 444.



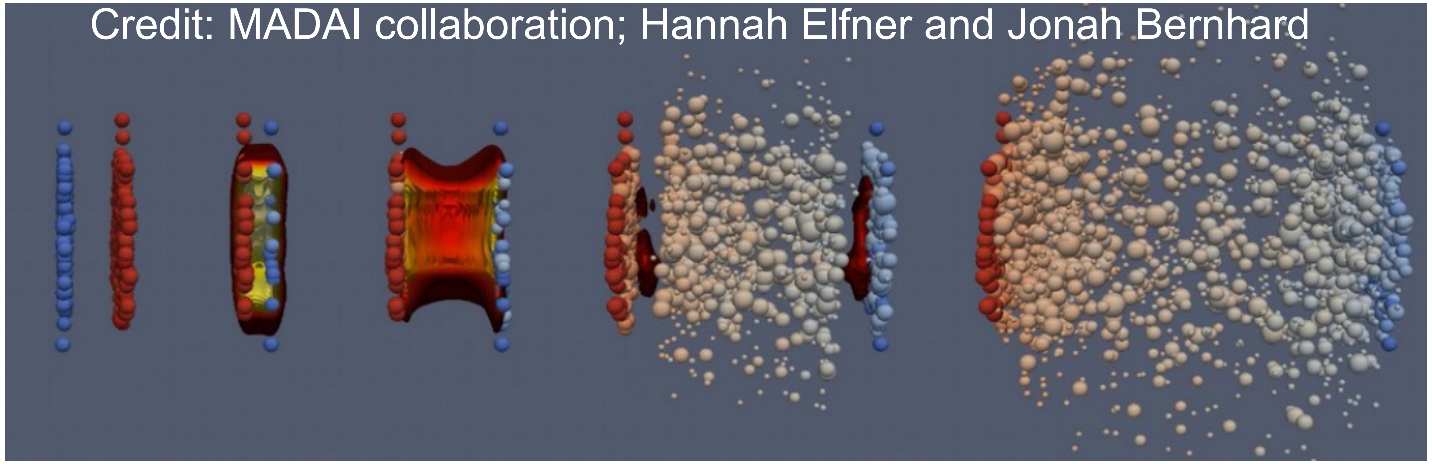
- Collective flow in p-Au, d-Au and He3-Au in RHIC.

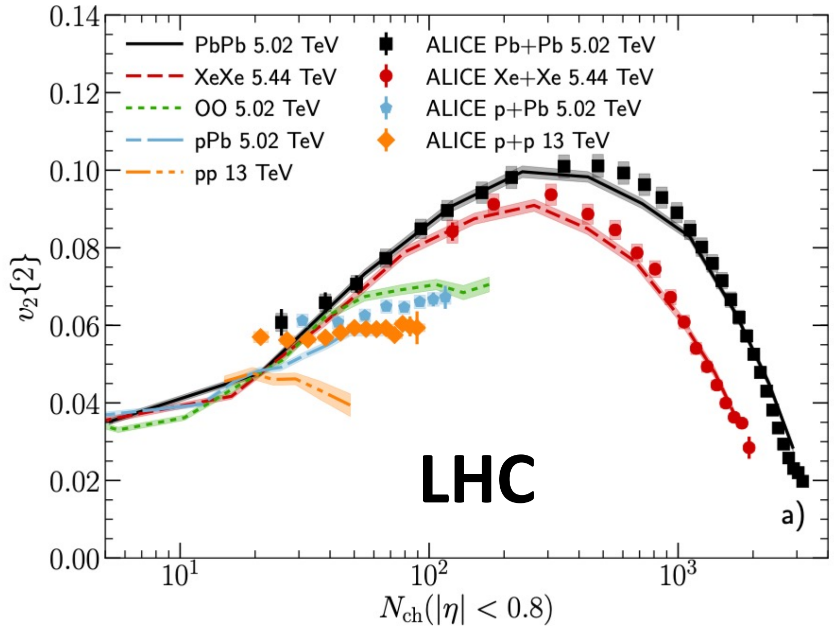
PHENIX: Nature Physics, **15**, pages214–220 (2019); STAR: PhysRevLett.130.242301.

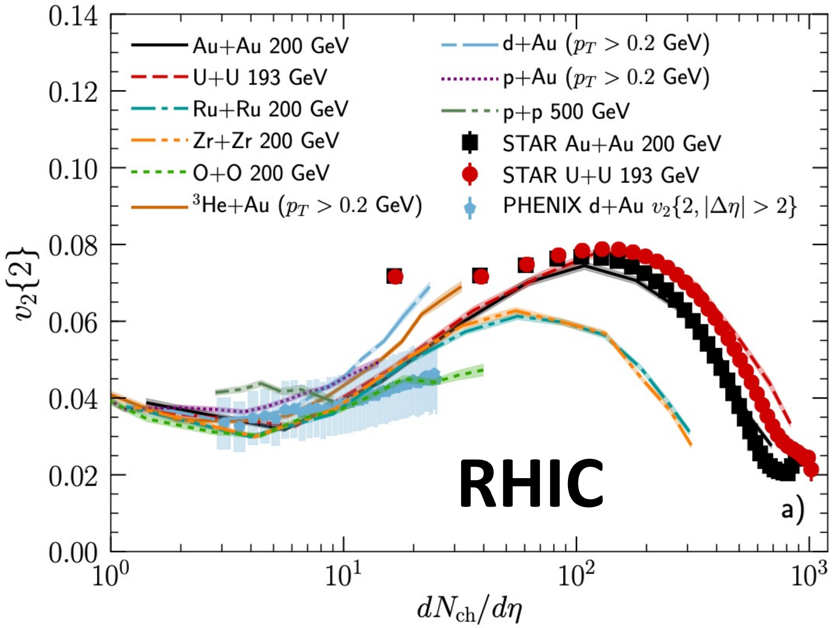
- Collective flow observed from large to small systems.

Standard model of Heavy-Ion Collisions

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





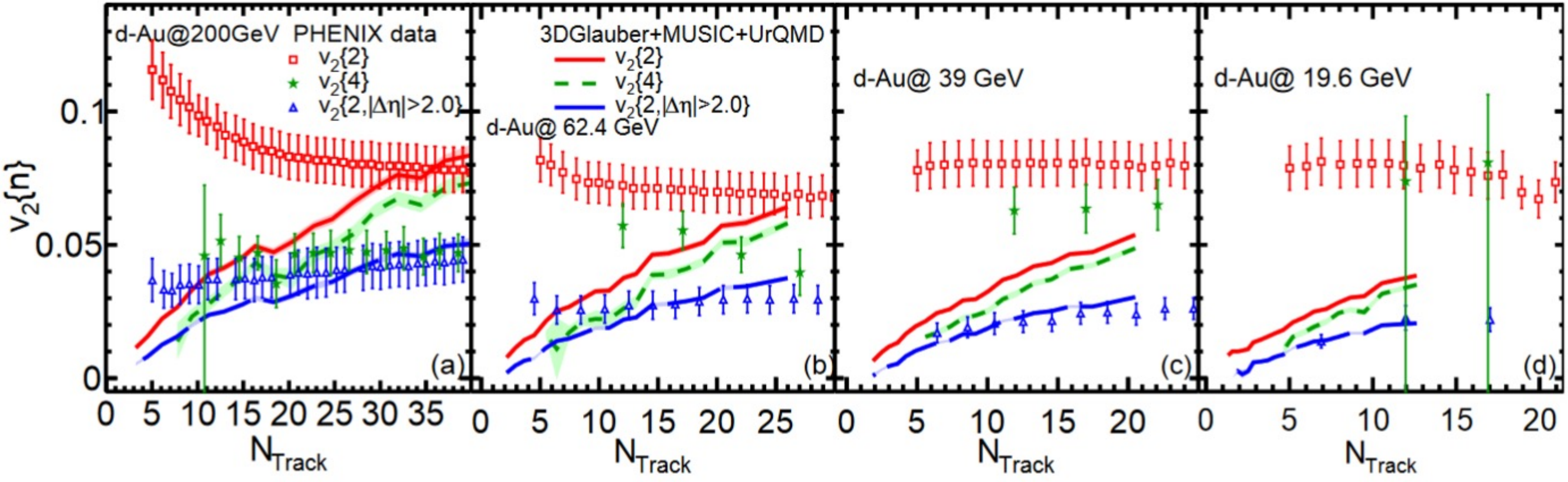


B. Schenke, C. Shen, and P. Tribedy, Phys. Rev. C. 102(4), 044905 (2020).

- **One fluid rules them all.**

Initial conditions: Oscar Garcia-Montero, Monday

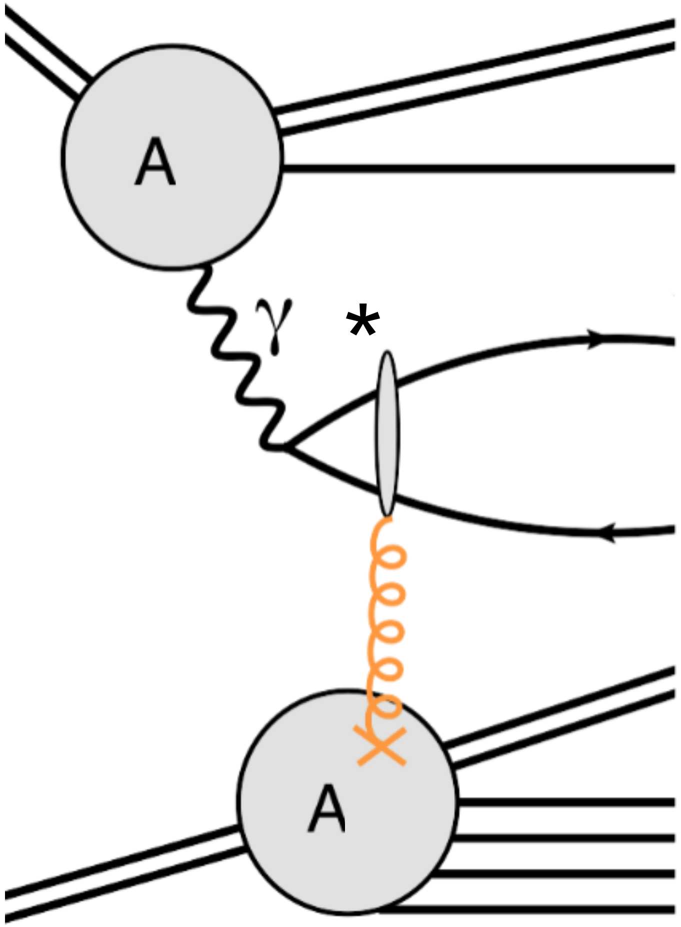
Collective flow in small systems at low energies



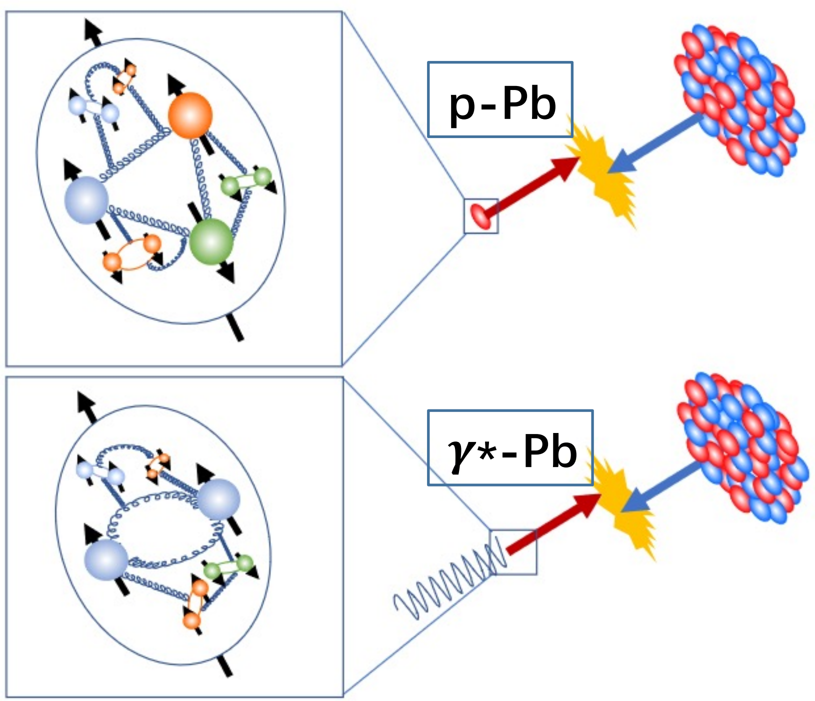
PHENIX, PhysRevLett.120.062302.
W. Zhao, S. Ryu, C. Shen and B. Schenke Phys. Rev. C 107, 014904 (2023).

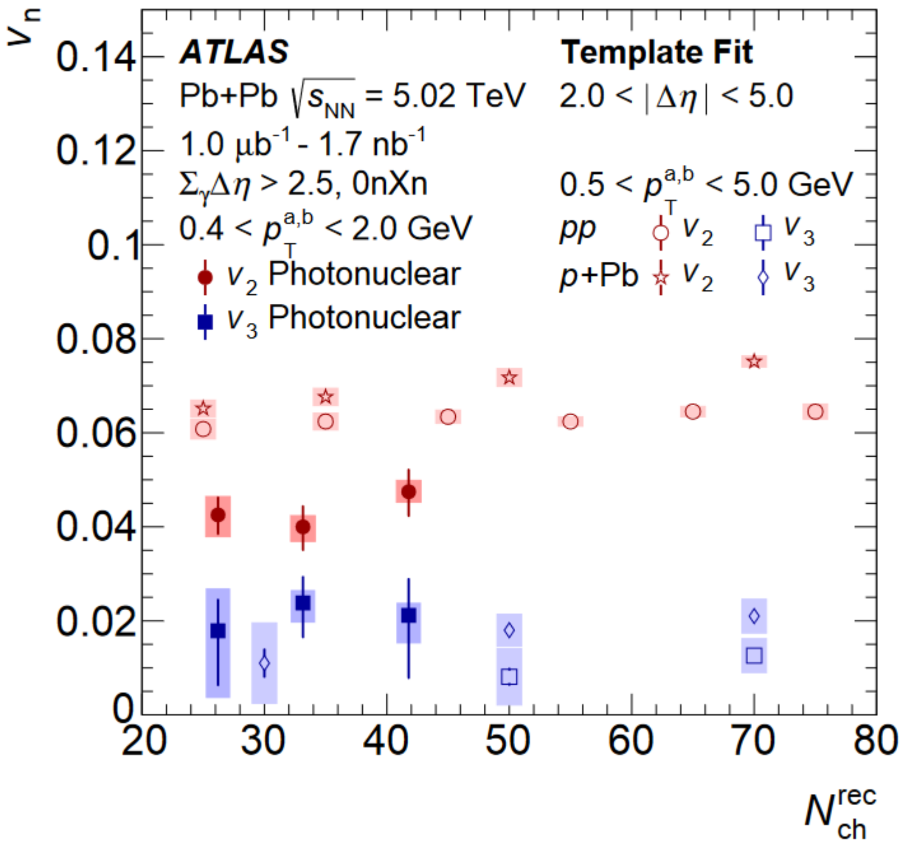
- Collectivity is observed even in small systems at low collision energies.

“Collectivity” in UPC



Taken from Nicole Lewis’s slide

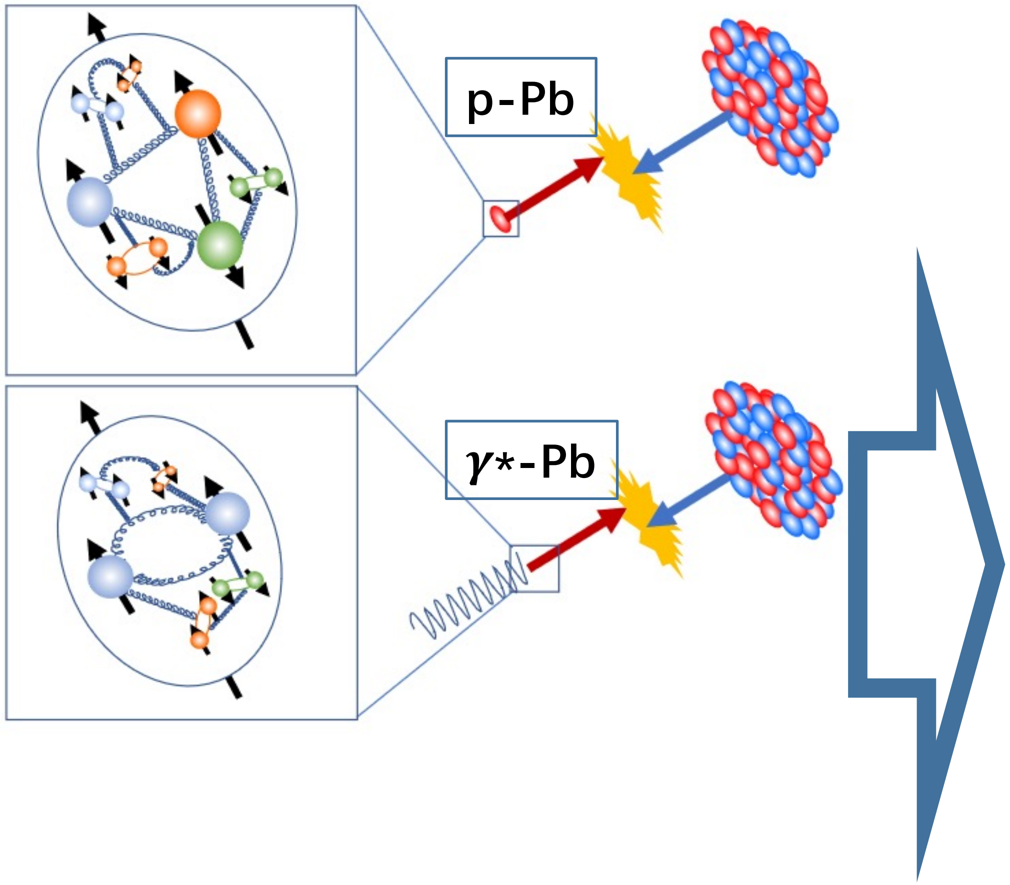




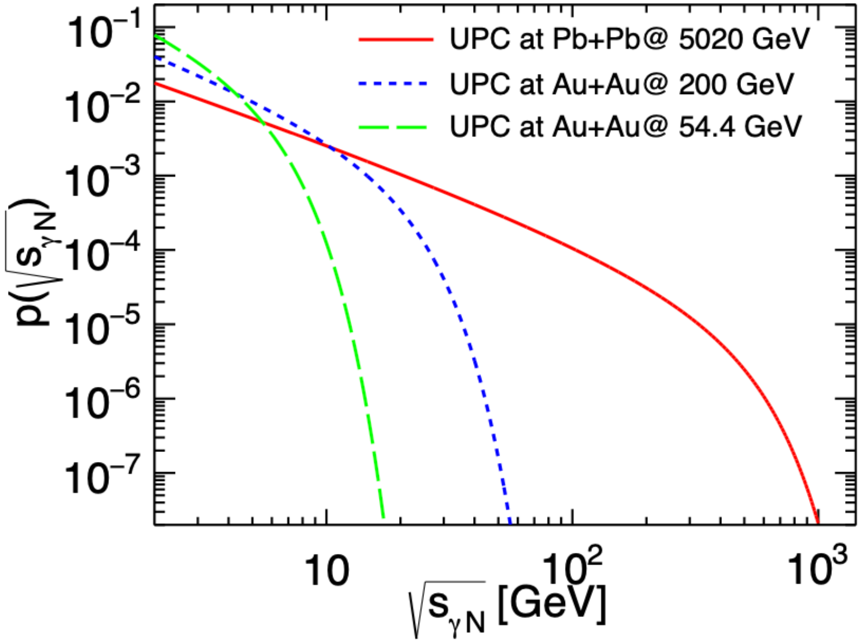
ATLAS Phys. Rev. C 104, 014903 (2021). Y. Shi, etc.al,Phys. Rev. D 103, 054017 (2021).

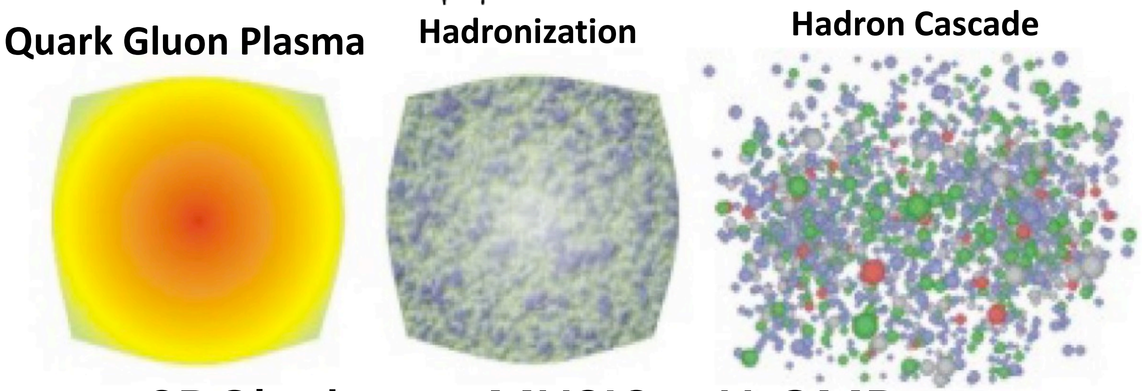
- UPCs have a similar order of magnitude and trends of collectivity as other previously measured hadronic systems

Hydrodynamic simulation of UPC



Y. Shi, etc.al,Phys. Rev. D 103, 054017 (2021).

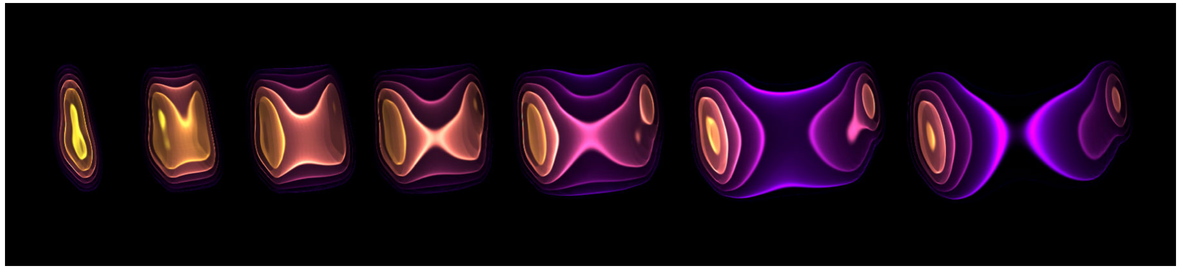


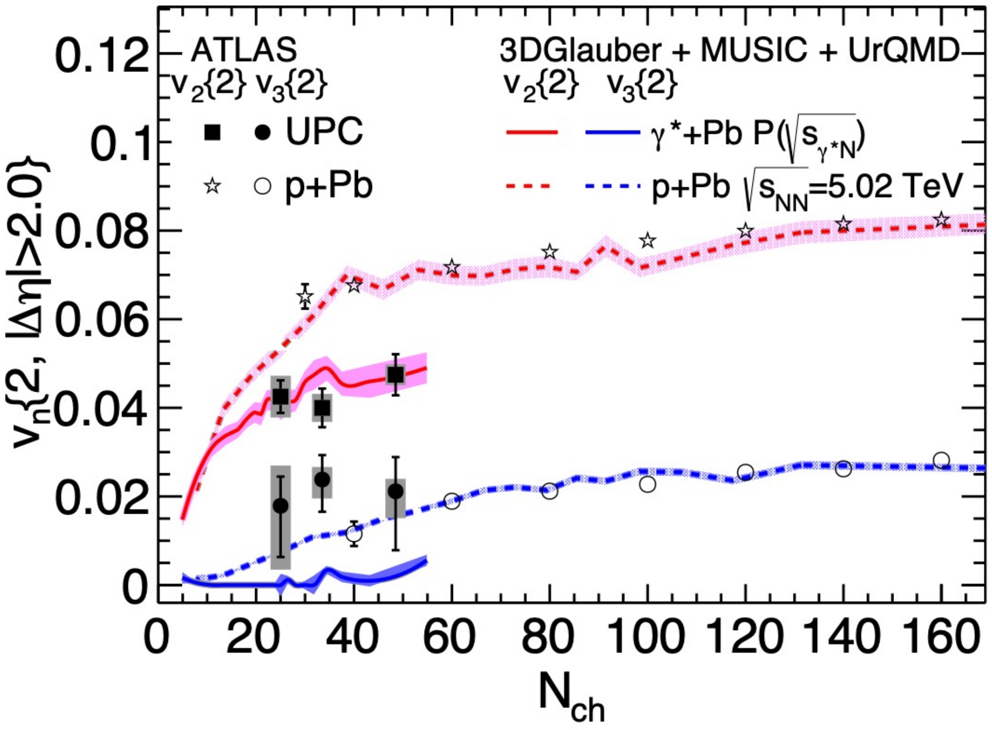


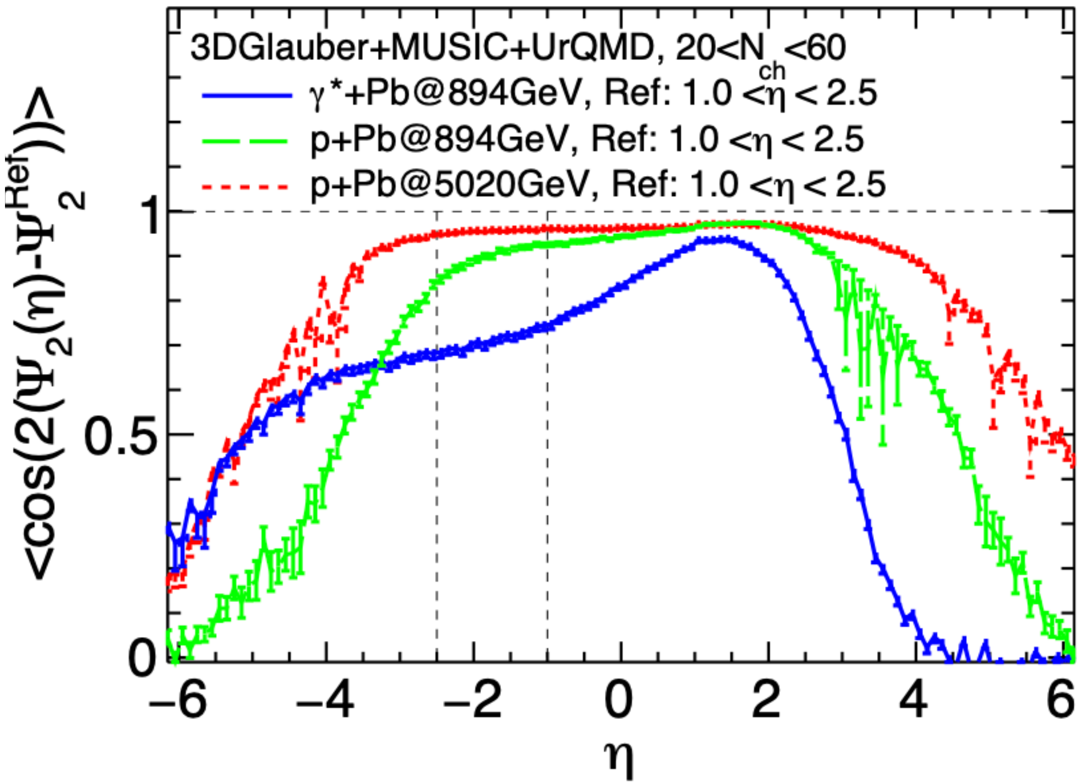
3DGlauber + MUSIC + UrQMD

C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905.
C. Shen and B. Schenke Phys. Rev. C 97, 024907 (2018).
W. Zhao, C. Shen and B. Schenke, PhysRevLett.129.252302.

Hydrodynamics Collectivity in UPCs



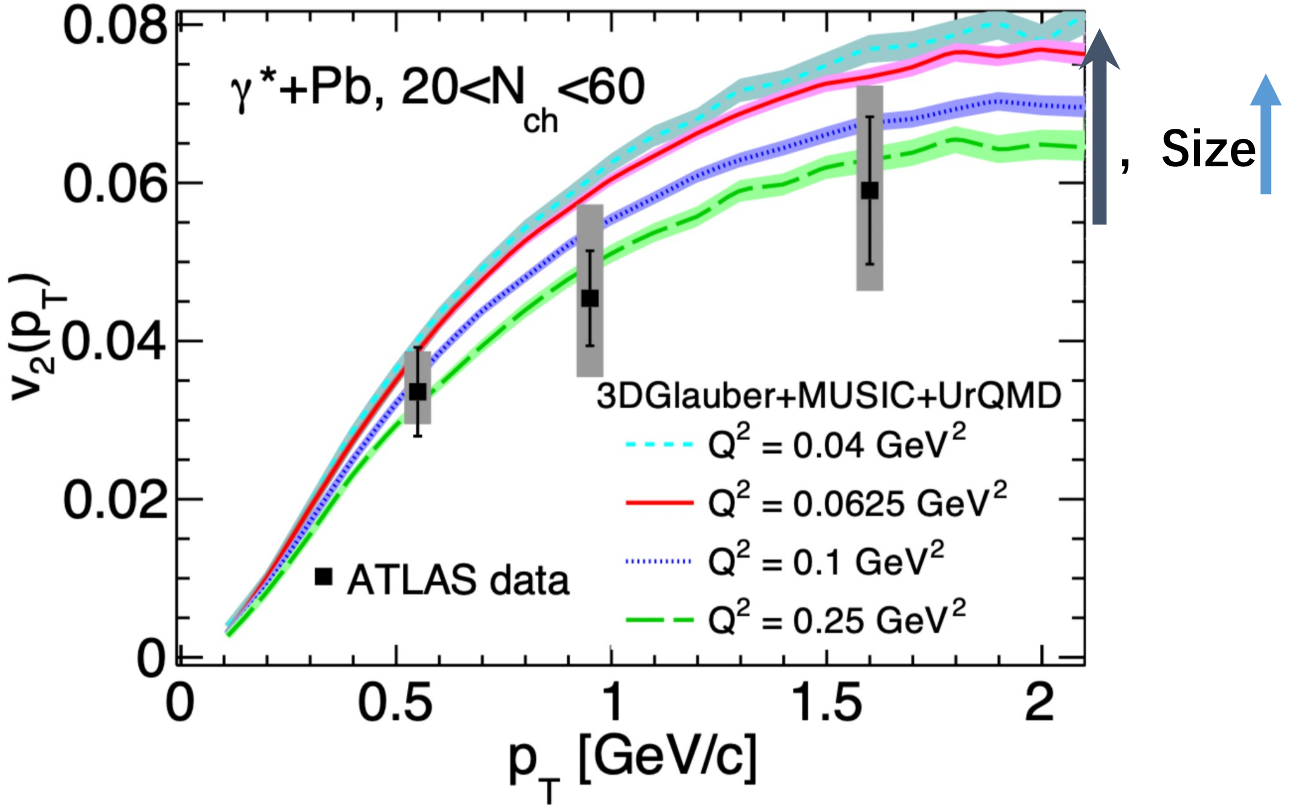


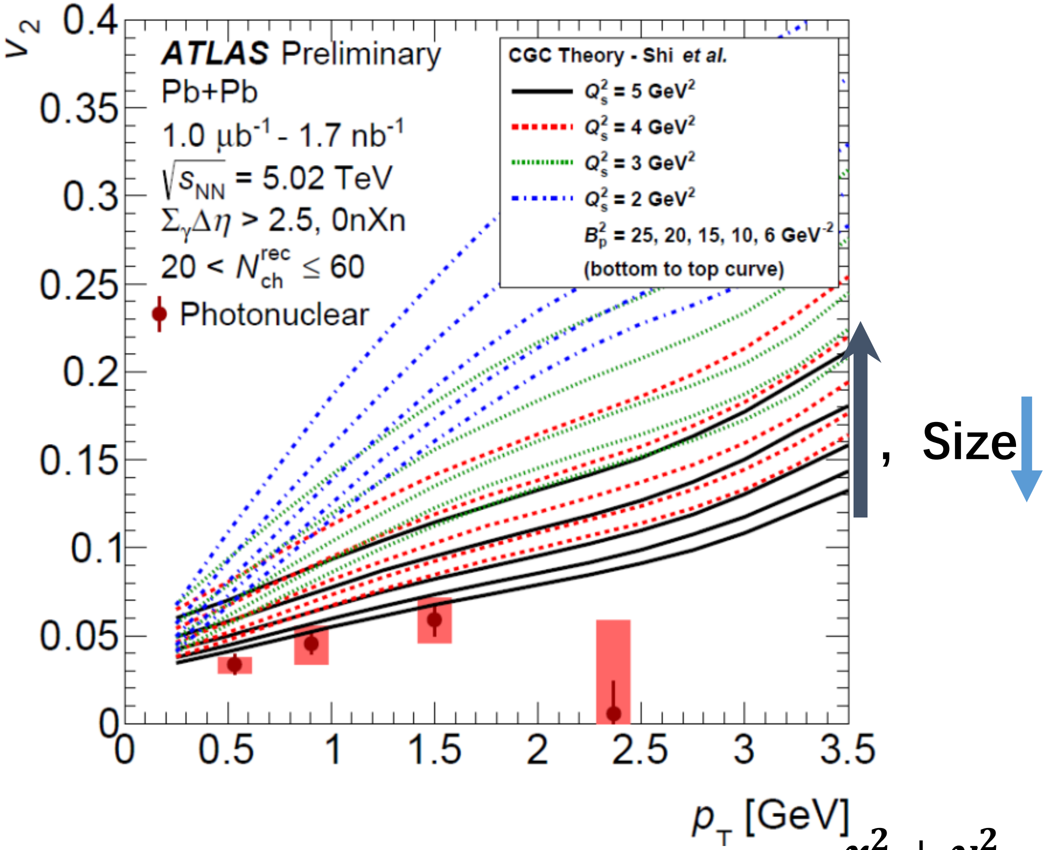


- 3D hydrodynamics describes the $\boldsymbol{v_2\{2\}}$ and hierarchy in $\boldsymbol{\gamma^*}$+Pb and p+Pb well.
- The longitudinal flow decorrelation is stronger in the $\boldsymbol{\gamma^*}$+Pb than p+Pb, resulting in the v_2 hierarchy between γ^*+Pb and p+Pb .

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



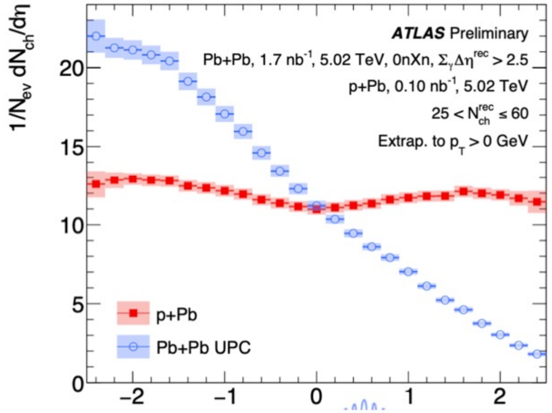


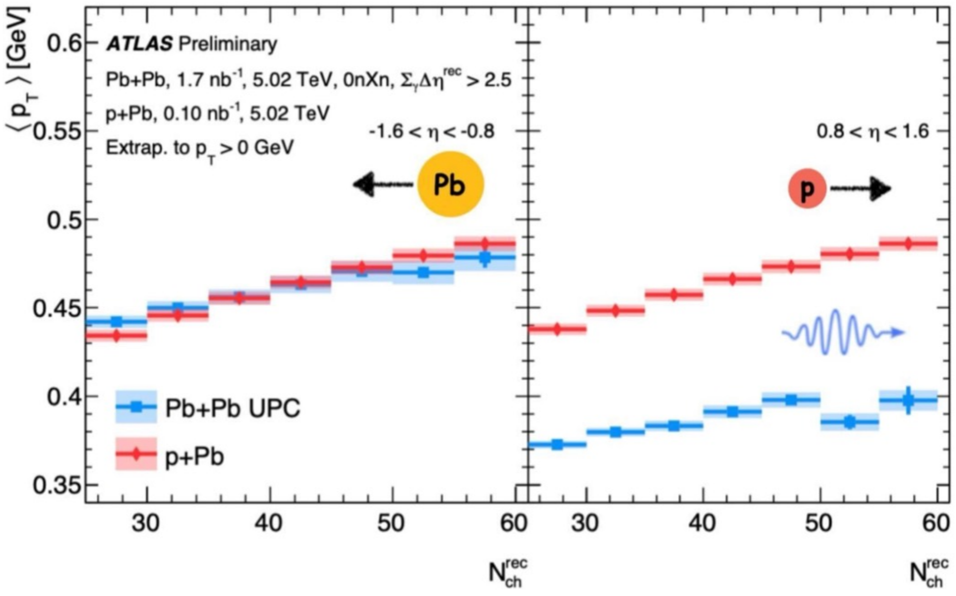
The transverse positions of the valence partons are sampled from a 2D Gaussian $P(x,y) \propto exp[-\frac{x^2+y^2}{2}Q^2]$

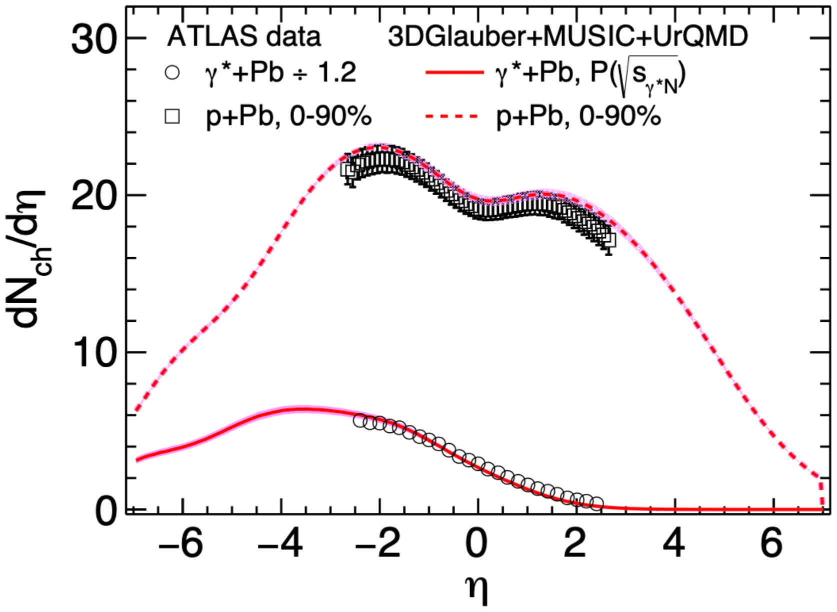
- Hydro: larger transverse space of the geometry allows more shape fluctuations and the v_2 are larger.
- CGC: Larger number of independent domains leads to lower v_2.
- Hydro predicts the opposite trend with Q^2 than the CGC.

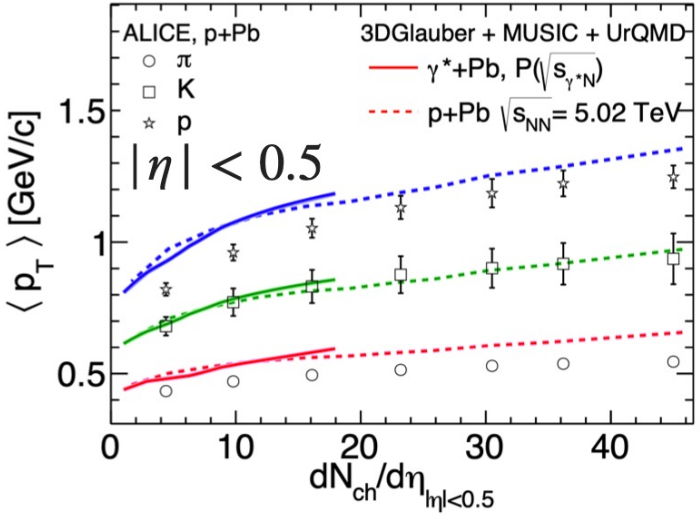
W. Zhao, C. Shen and B. Schenke, PhysRevLett.129.252302. Y. Shi, etc.al,Phys. Rev. D 103, 054017 (2021). B. D. Seidlitz. QM2019.

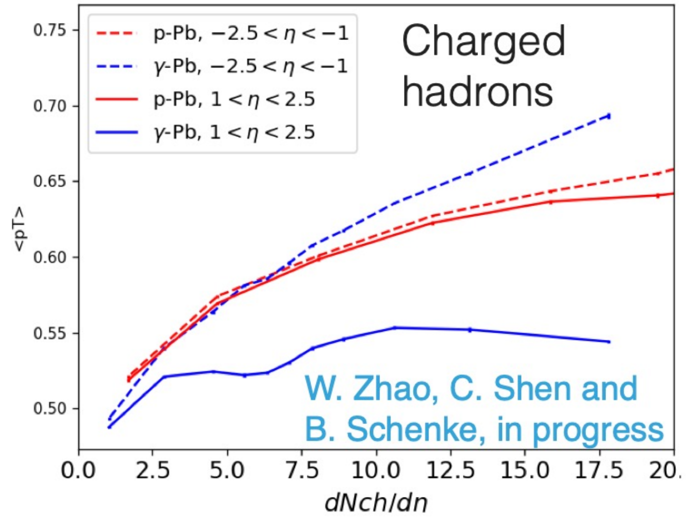
Mean p_T and radial flow in pA and γ A









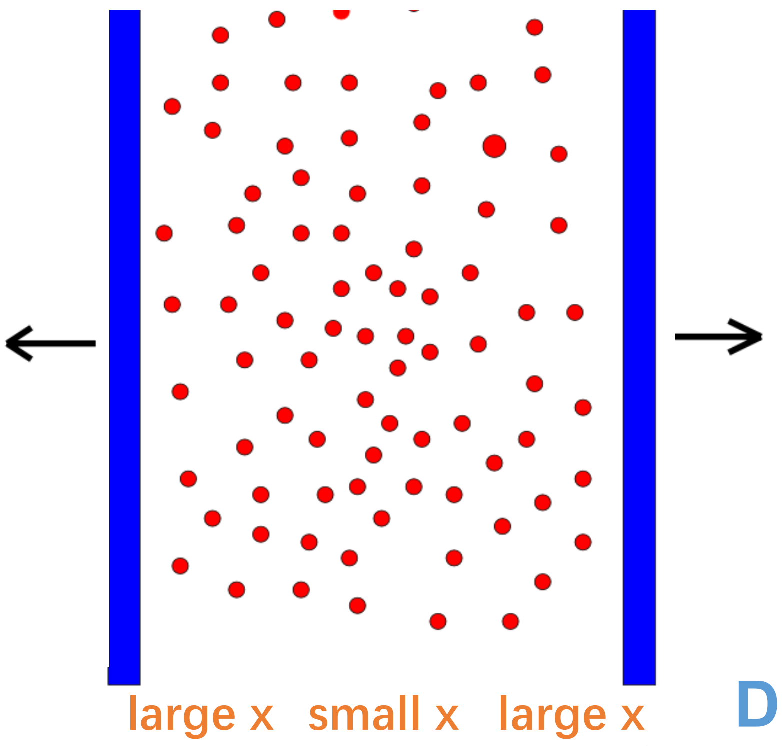


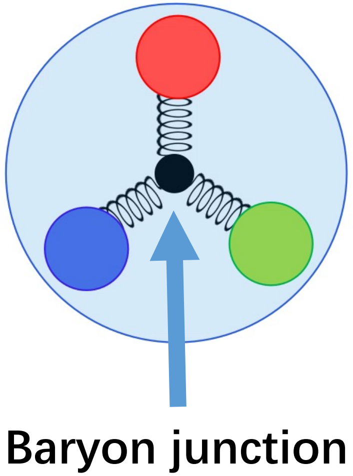
- Our model qualitatively reproduces the rapidity dependence of charged hadron mean p_T in p+Pb and γ*+Pb collisions.
- The reduction of $< p_T >$ is originated by the short fireball lifetime in the γ^* going side.

W. Zhao, C. Shen and B. Schenke, PhysRevLett.129.252302.

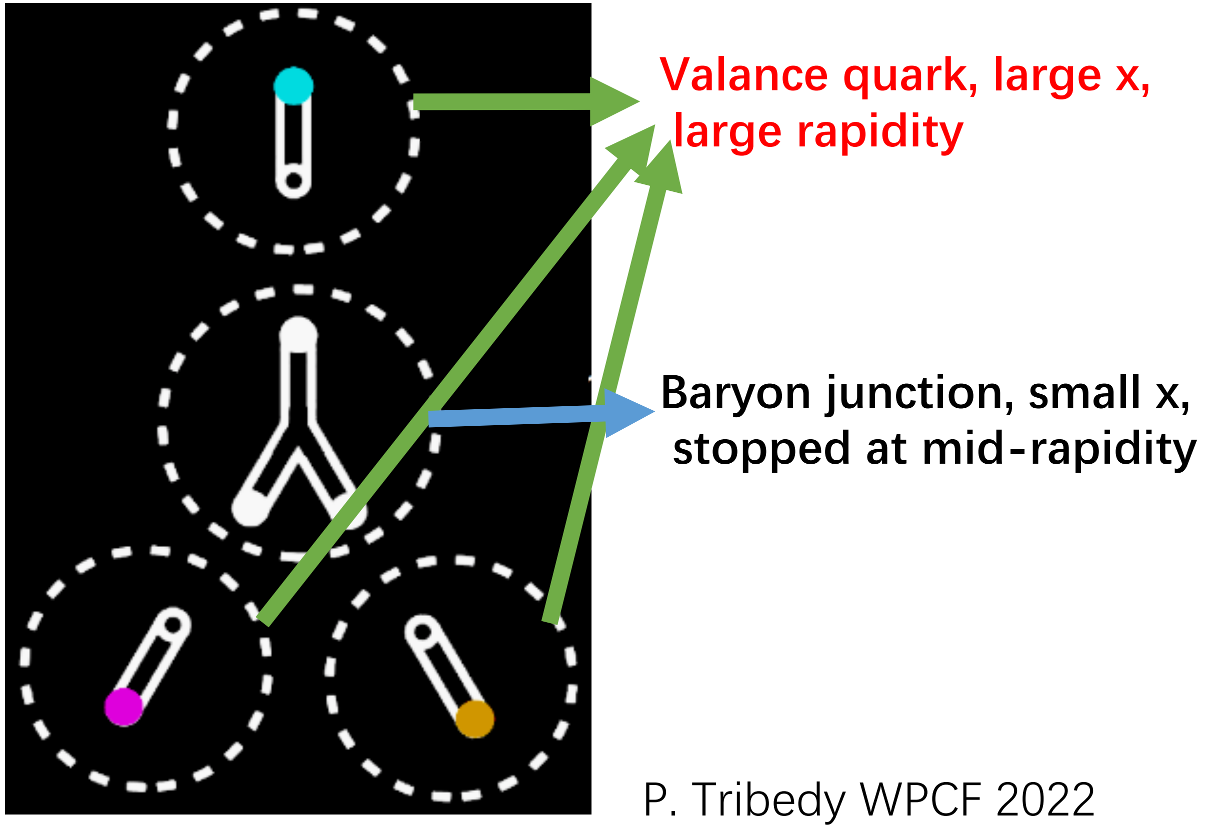
Probing Baryon Junction in UPCs

Baryon Junction Structure picture





David Frenklakh, Wednesday

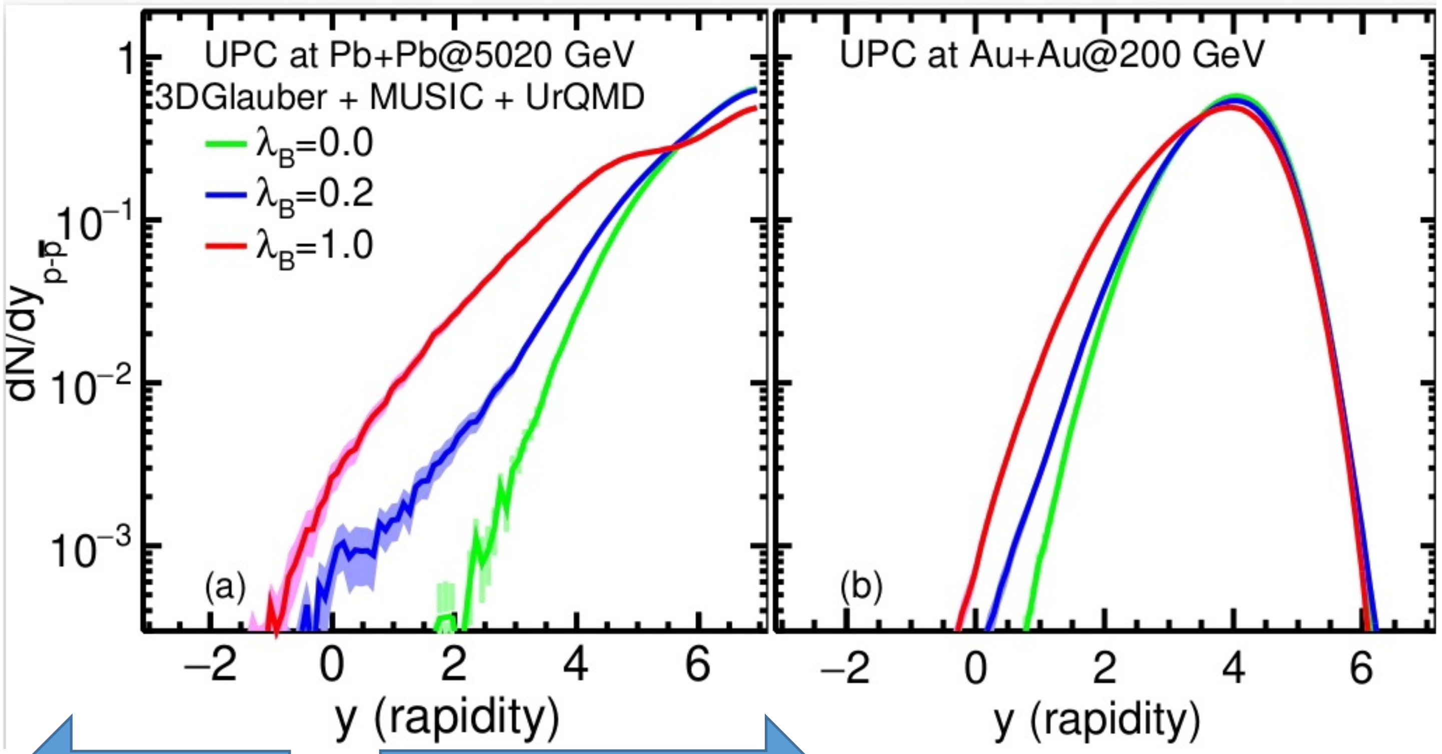


P. Tribedy WPCF 2022

- For UPC events, the virtual photon decomposed into q and $\bar{q}$, with a baryon-free object.
- **Baryon junction picture**: baryon number is carried by the baryon junction, technically gluons, helping the transport of baryon number to mid-rapidity in the collision.

D. Kharzeev, Phys.Lett. B 378, 238–246 (1996). J. D. Brandenburg, eta. al [arXiv:2205.05685 [hep-ph]].

dN/dy of net-proton in UPCs



γ^* going

Nucleus going

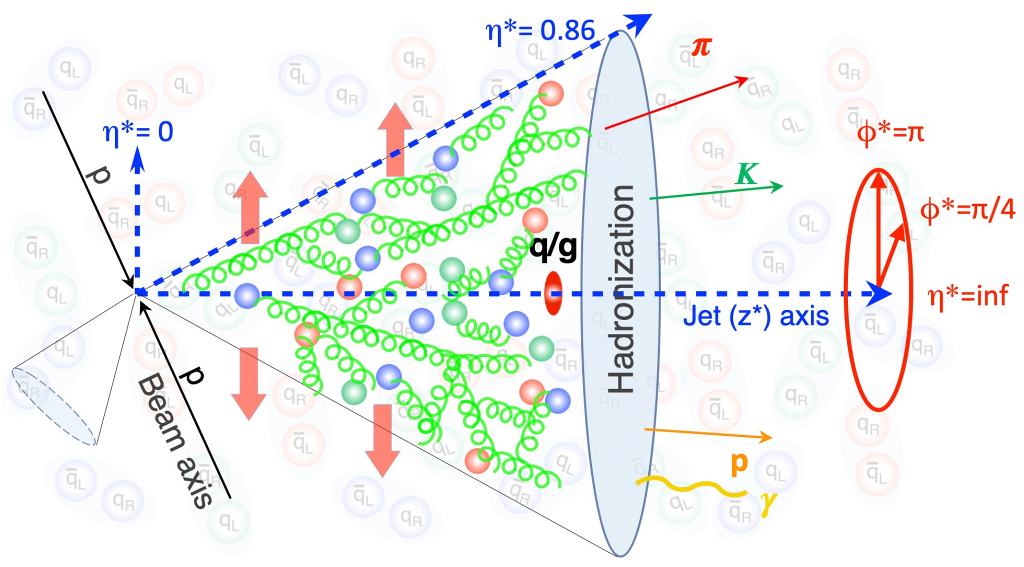
$$P(y^B_{P/T}) = (1-\lambda_B) y_{P/T} + \lambda_B \frac{e^{(y^B_{P/T}-(y_P+y_T)/2)/2}}{4\sinh((y_P-y_T)/4)}.$$

- No net protons from the vector meson's fragmentation region.
- Larger λ_B generates larger dN/dy of net-proton at γ^* side.

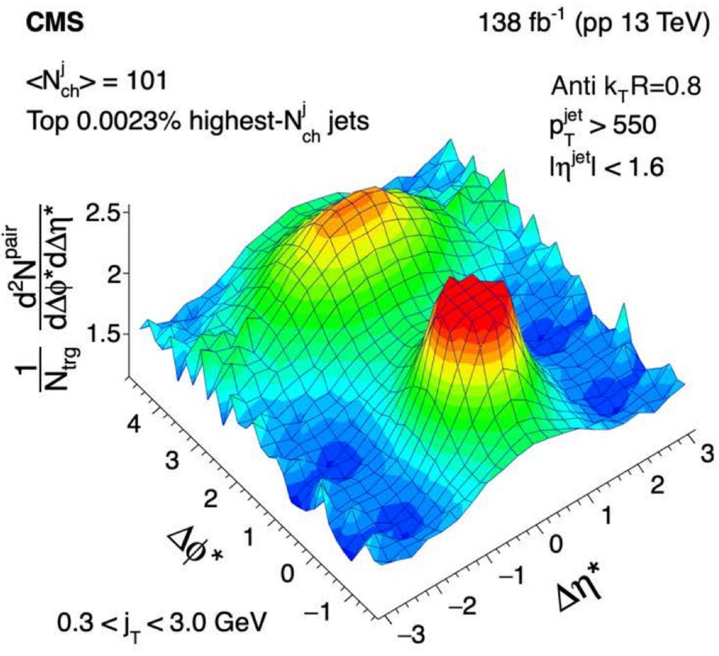
C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905. W. Zhao, C. Shen and B. Schenke [arXiv:2203.06094] and in preparation.

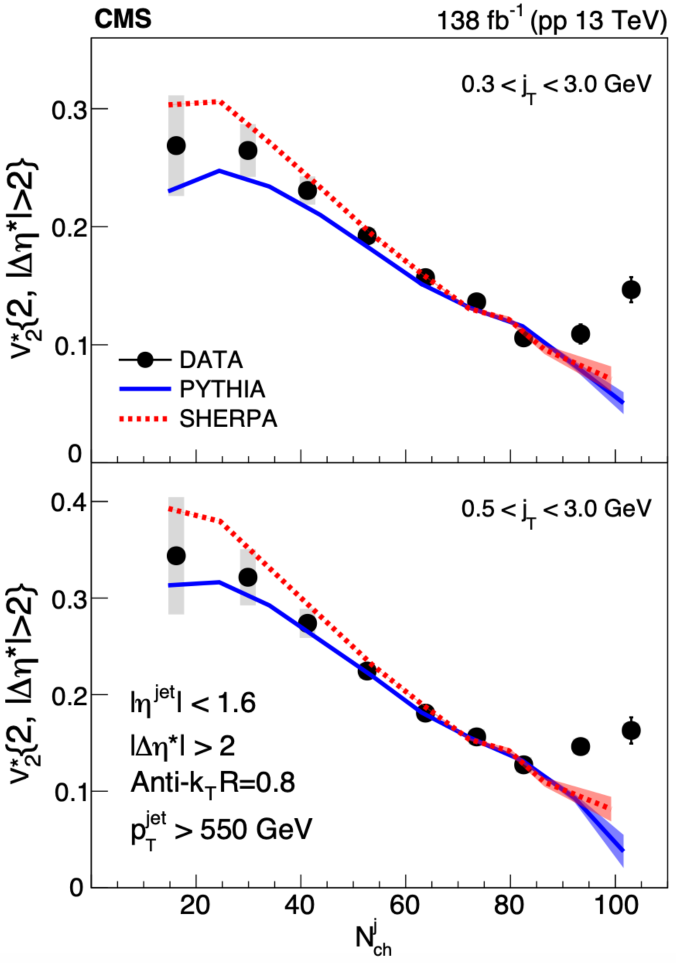
Where is the smallest QGP droplet boundary?

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



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



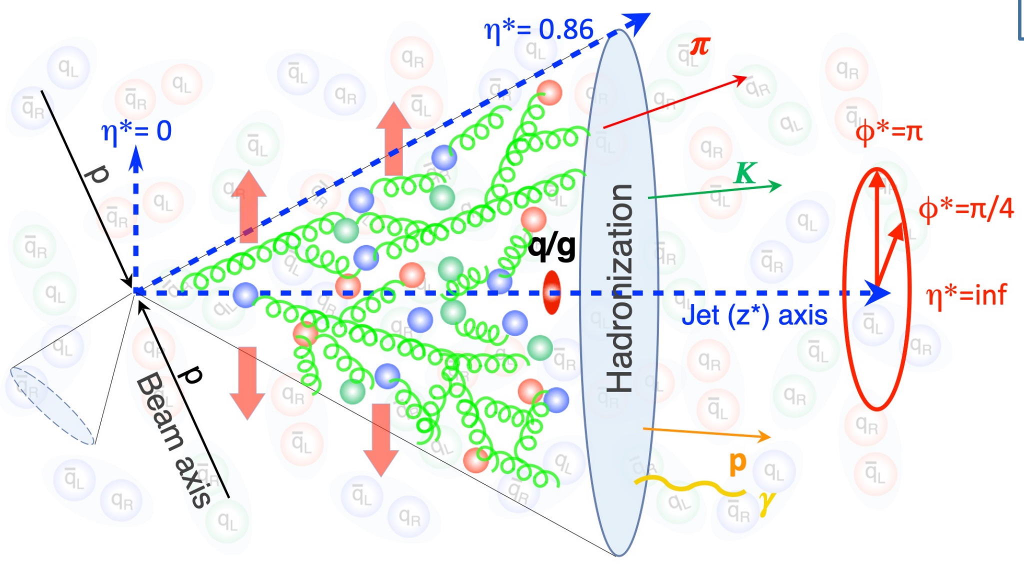


- "Collectivity" features inside high multiplicity jets in p-p.
- QGP droplet inside high multiplicity jet in p-p?

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.

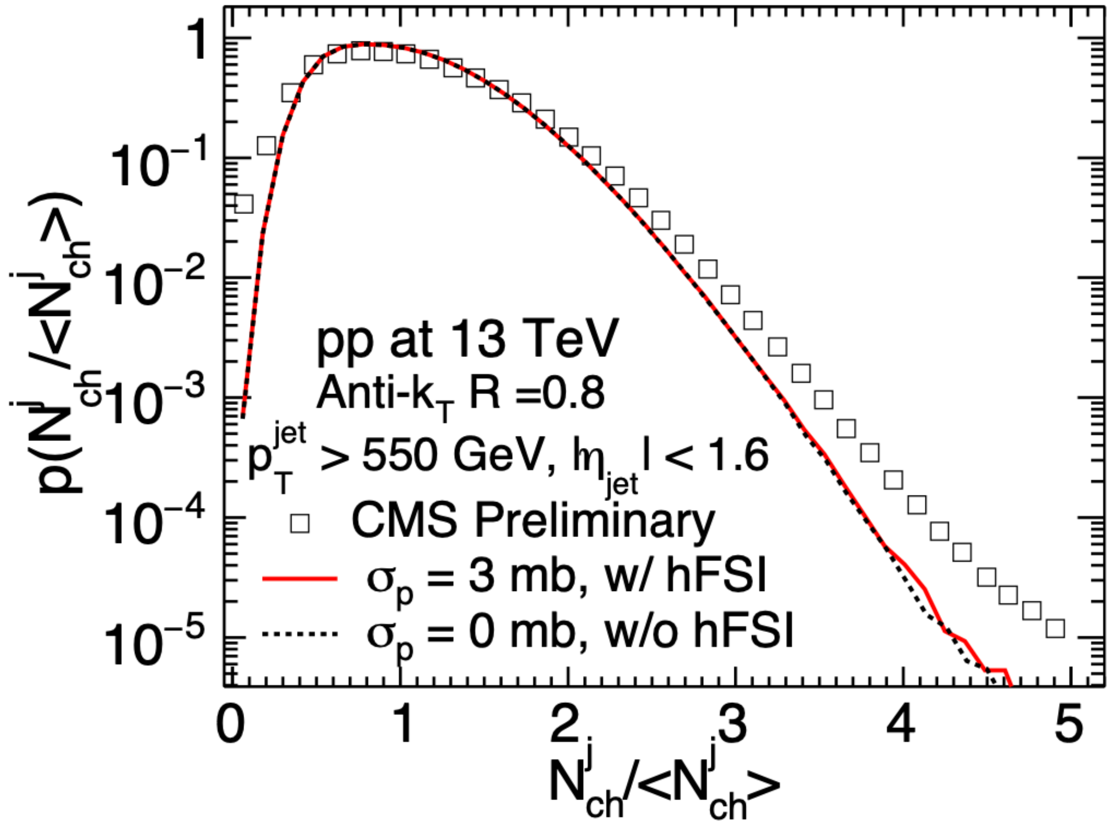
- Assign hadronization time 1 fm/c.
- Hadronic rescattering modeled by UrQMD.
- It returns to pythia8 by turning off FSI.
- Don't need to assume the system is thermalized.

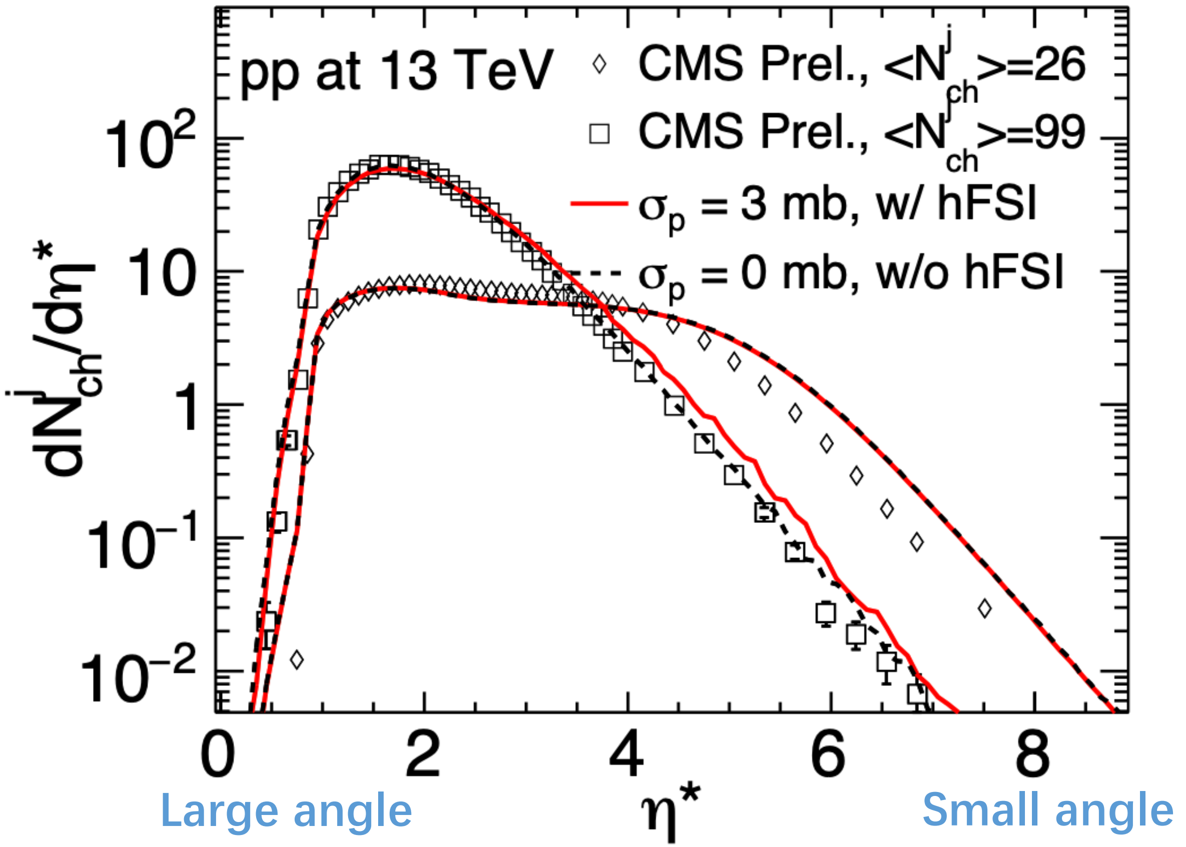
ZPC: Ziwei Lin, Tuesday

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

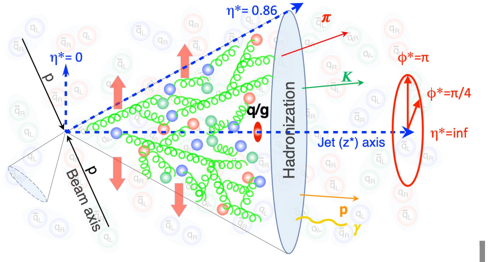
W. Zhao, Zi-Wei Lin and Xin-Nian Wang [arXiv:2401.13137].

Hadron distributions inside jets in p-p



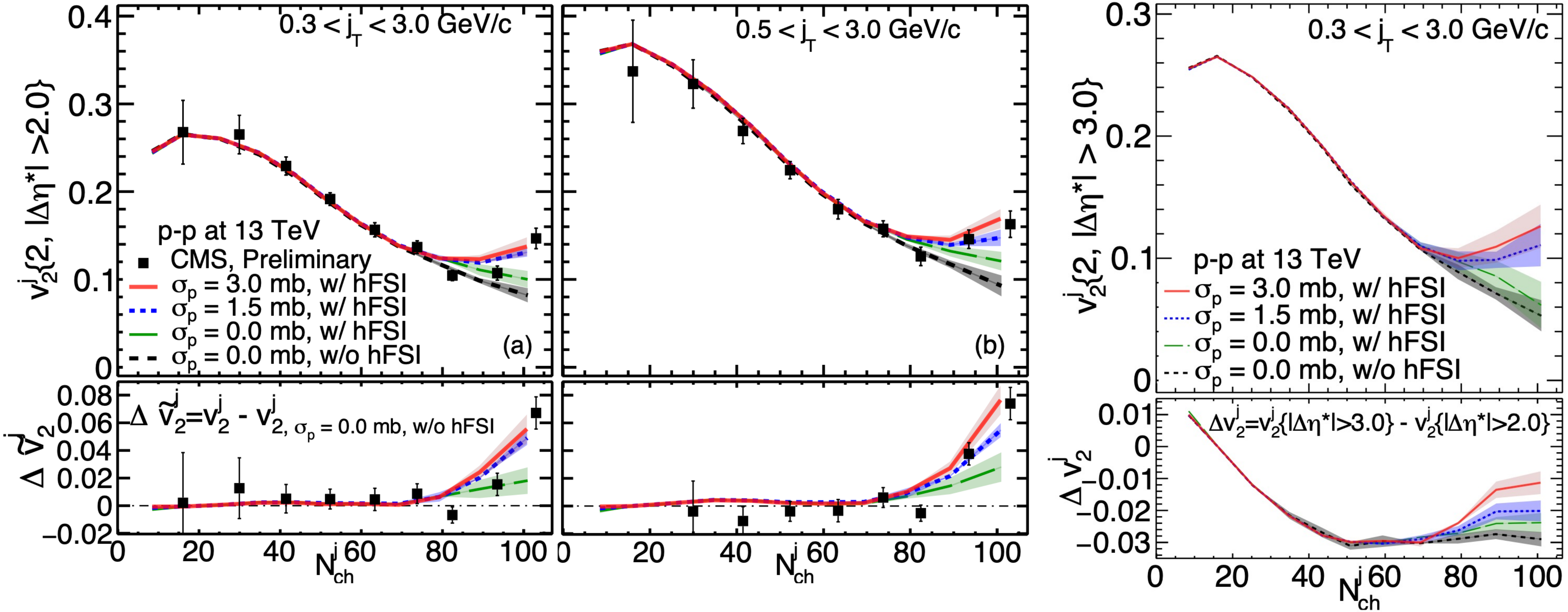


- Pythia8 gives narrower multiplicity distributions. Next step: include inelastic rescattering.
- Higher multiplicity events have the larger initial emission angles.



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

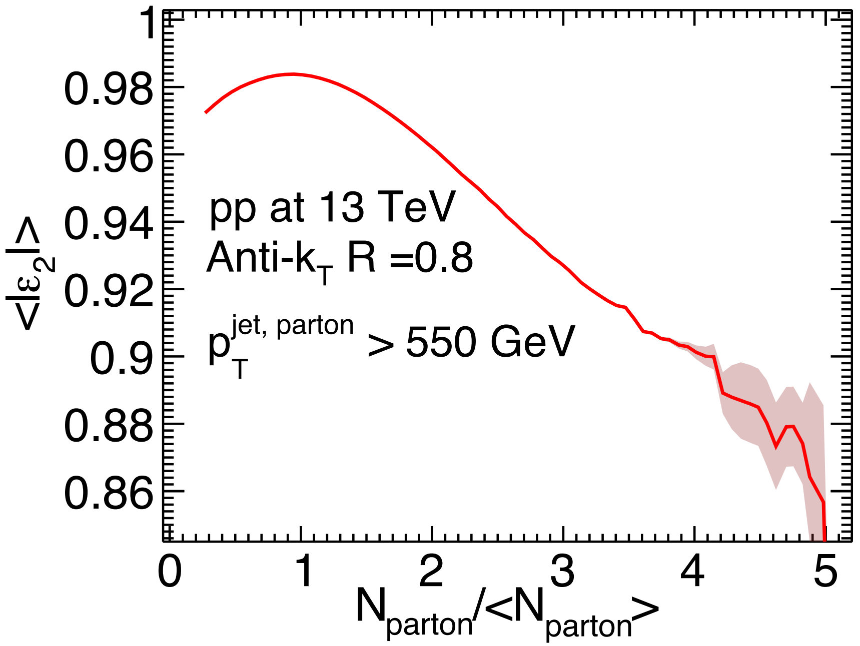


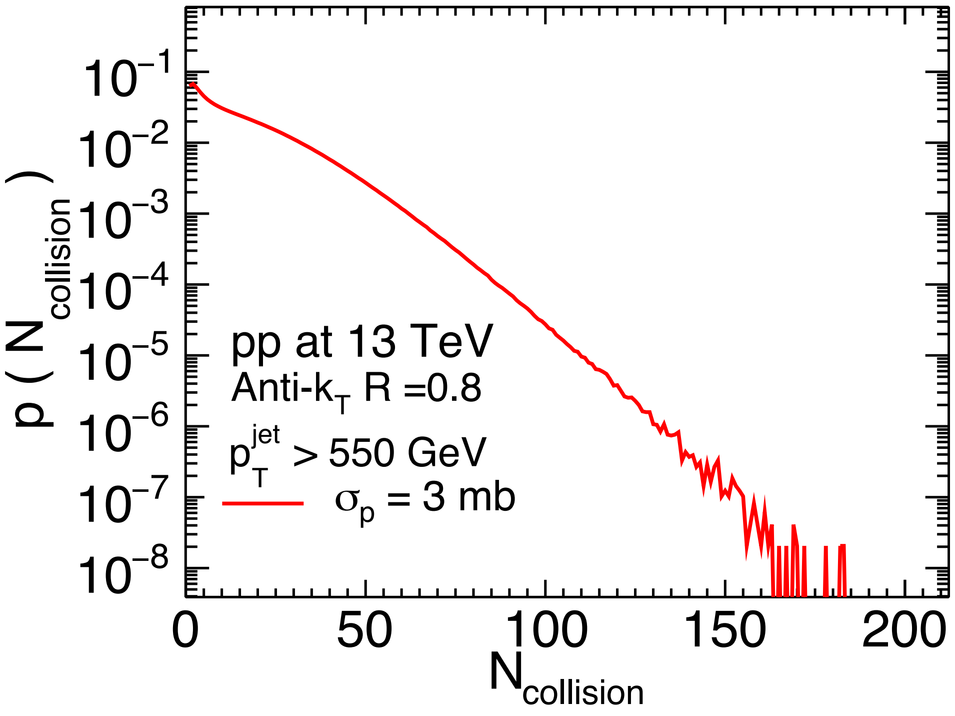
- Final state interaction enhances the v_2 inside high multiplicity jet in p-p. QGP droplet?
- We predict that the Δv_2 between different η −gaps increases at $N_{ch}^{j} > 70$.

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

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

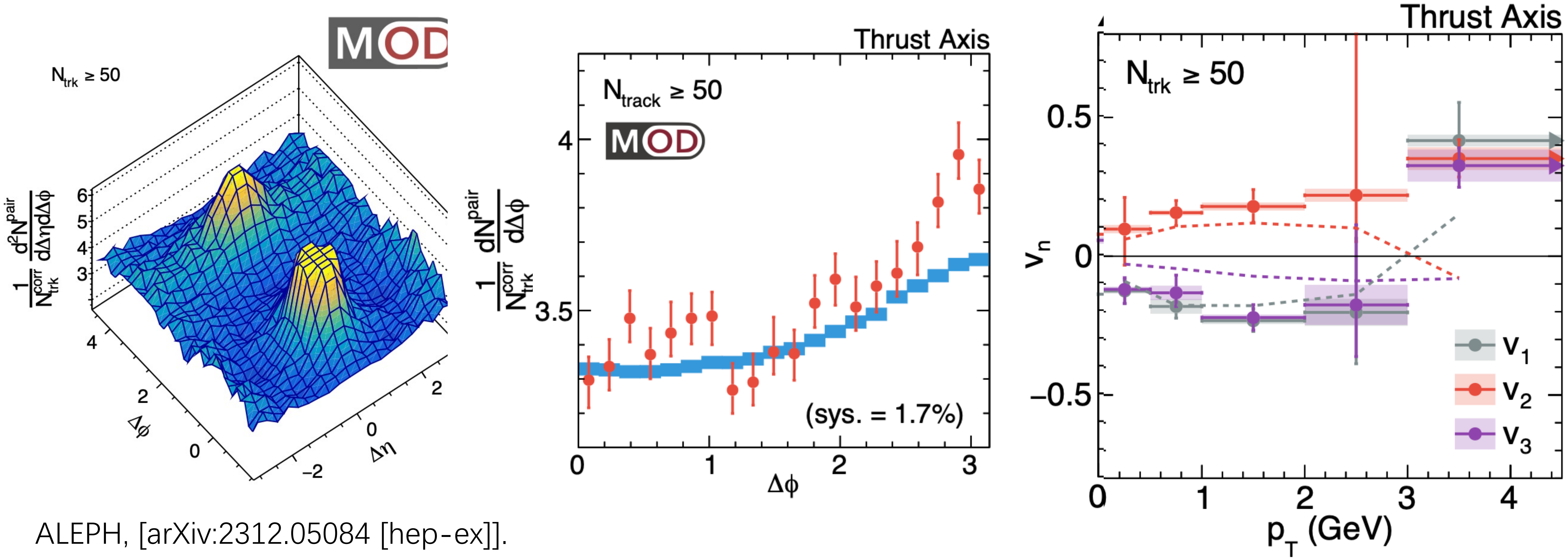




- Low multiplicity jet has large initial spatial anisotropy , but it don't have enough final state interactions to translate into momentum anisotropy
- The high multiplicity jets can have around 100 partonic collision times, which translate initial spatial anisotropy into momentum space.

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

"Collectivity" in high multiplicity e^+e^-

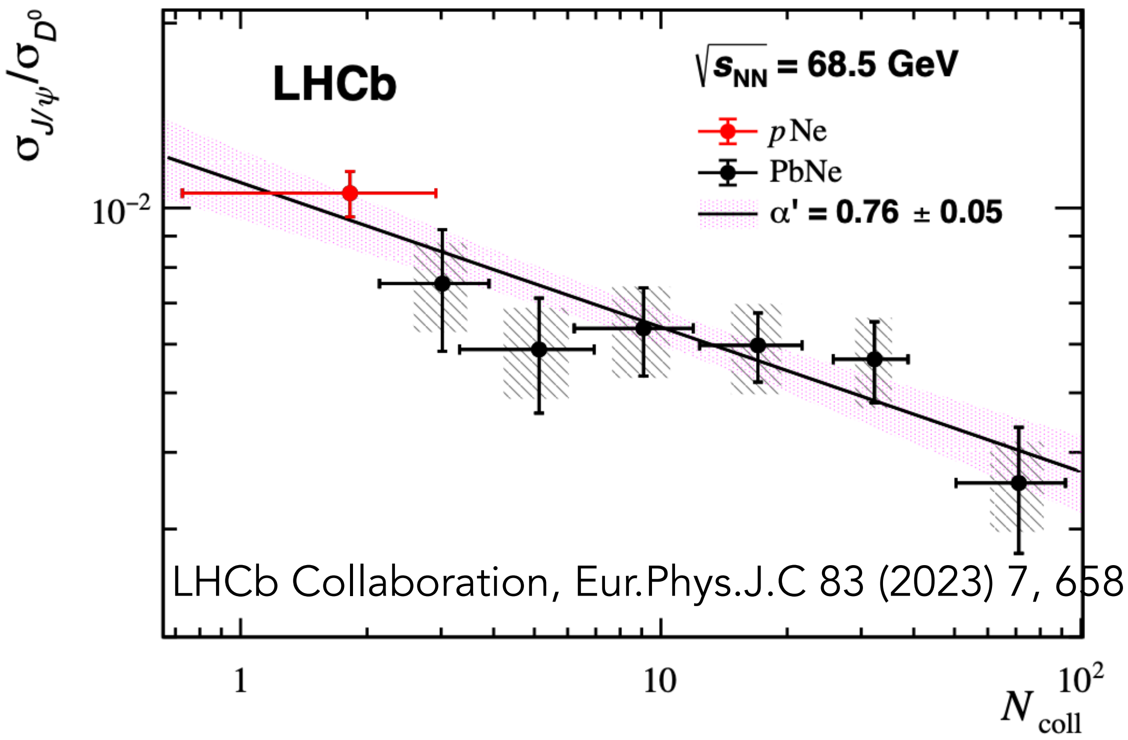


ALEPH, [arXiv:2312.05084 [hep-ex]].

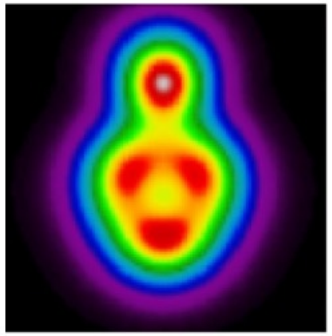
- Pythia8 without long range correlations underestimates the v_2 at high multiplicity e^+e^-.
- Smallest QGP droplet?

Bonus of studying the collectivity

Imaging the nuclear shape

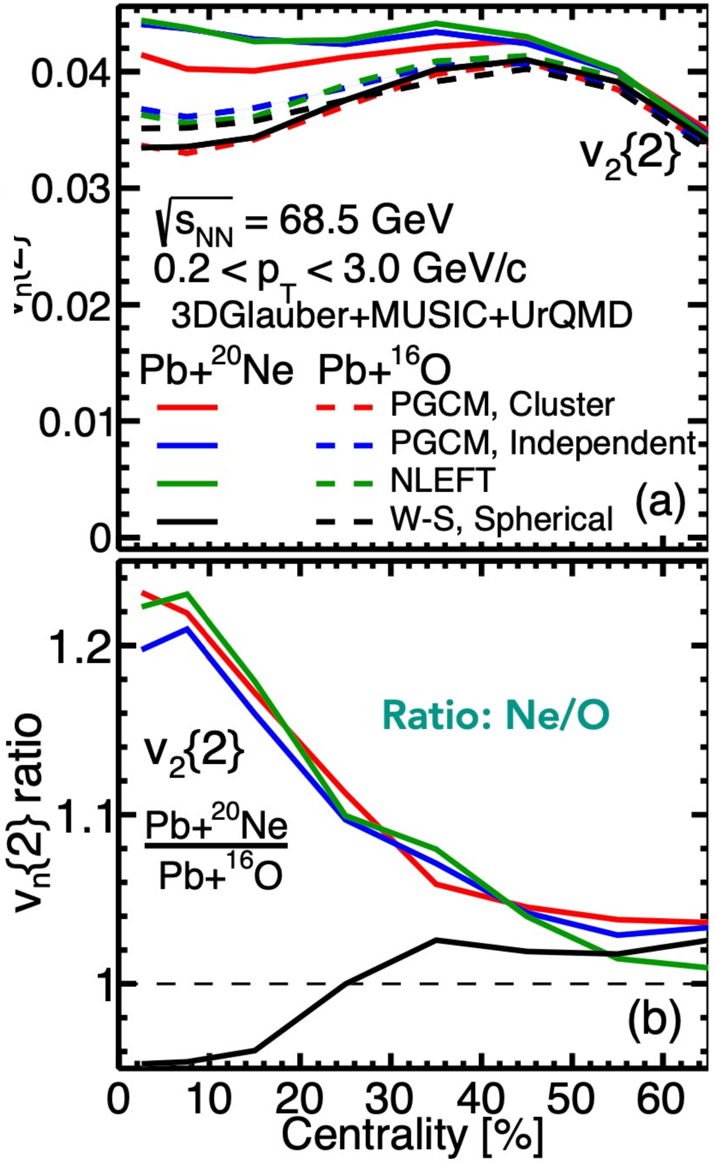


LHCb Collaboration, Eur.Phys.J.C 83 (2023) 7, 658



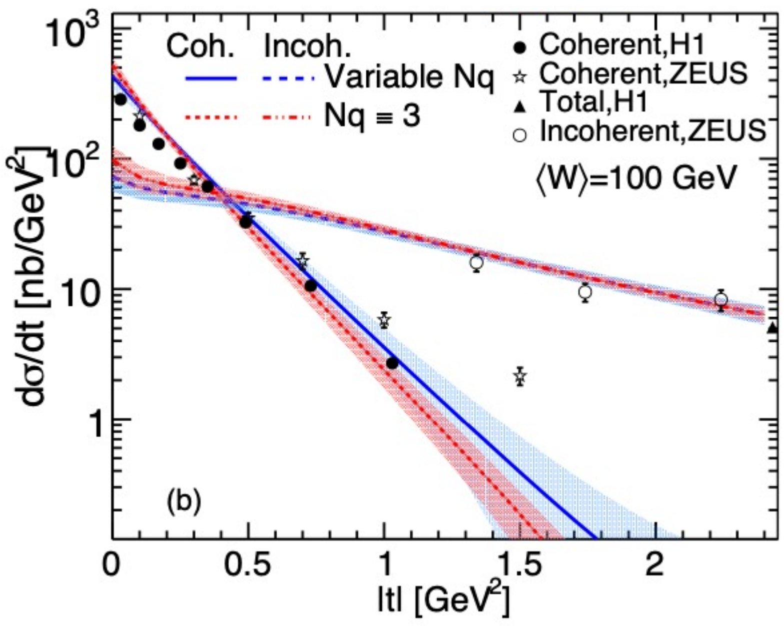
^{20}Ne

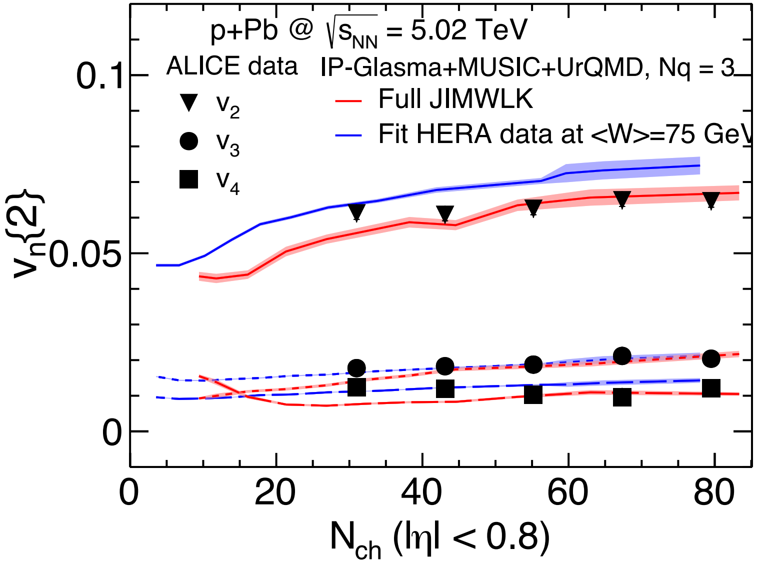
G. Giacalone et al, arXiv:2405.20210

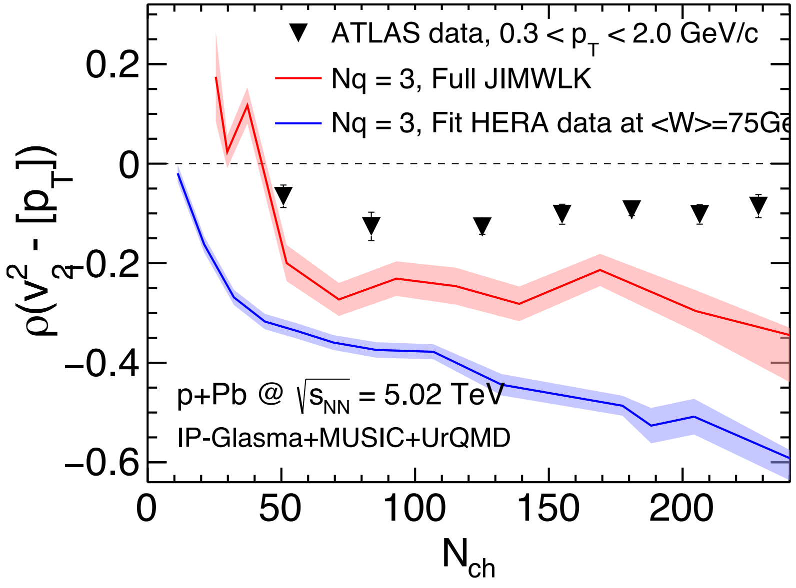


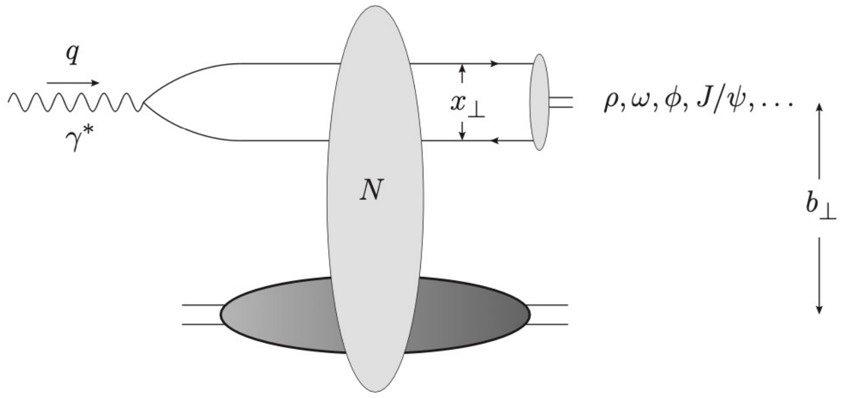
- No QGP-like J/ψ suppression in Pb+Ne.
- Flow sensitive to shapes of Ne and O
- Searching the QGP at LHCb.

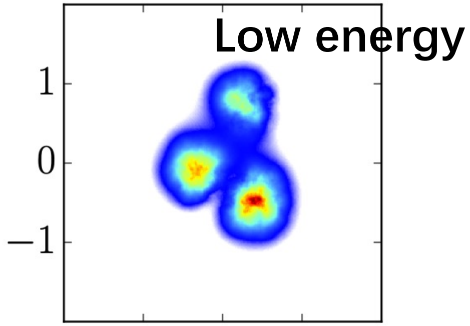
Study energy evolution of proton geometry

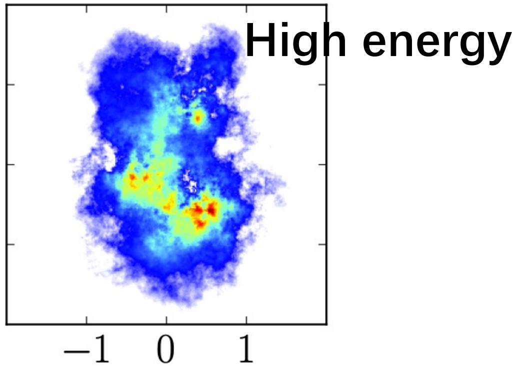








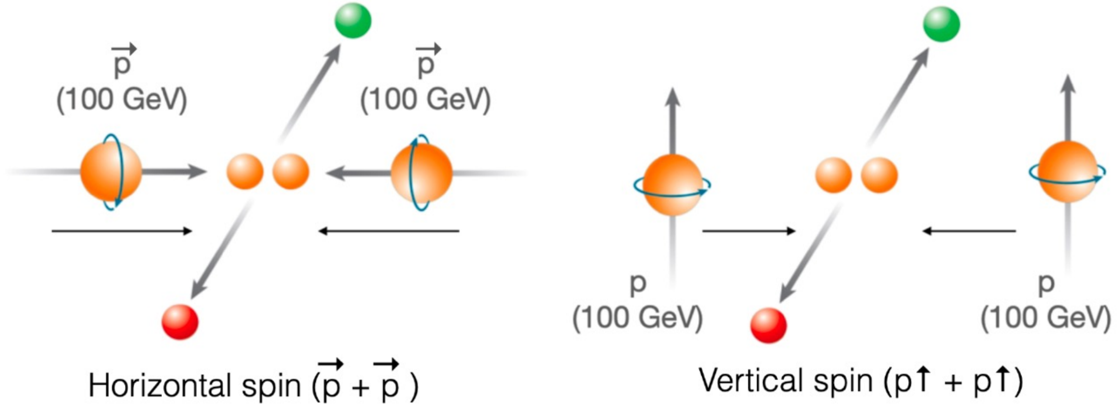


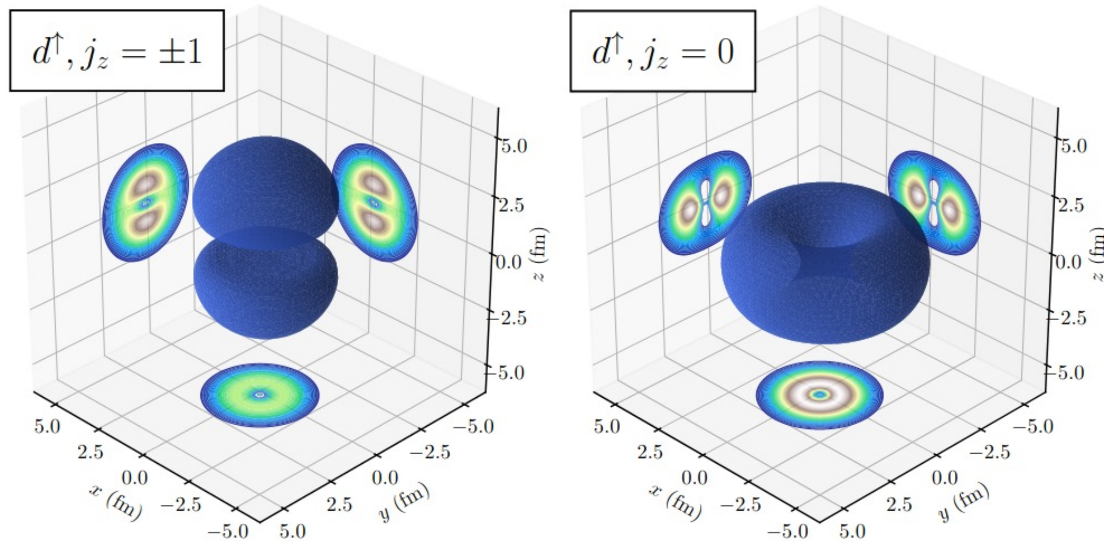


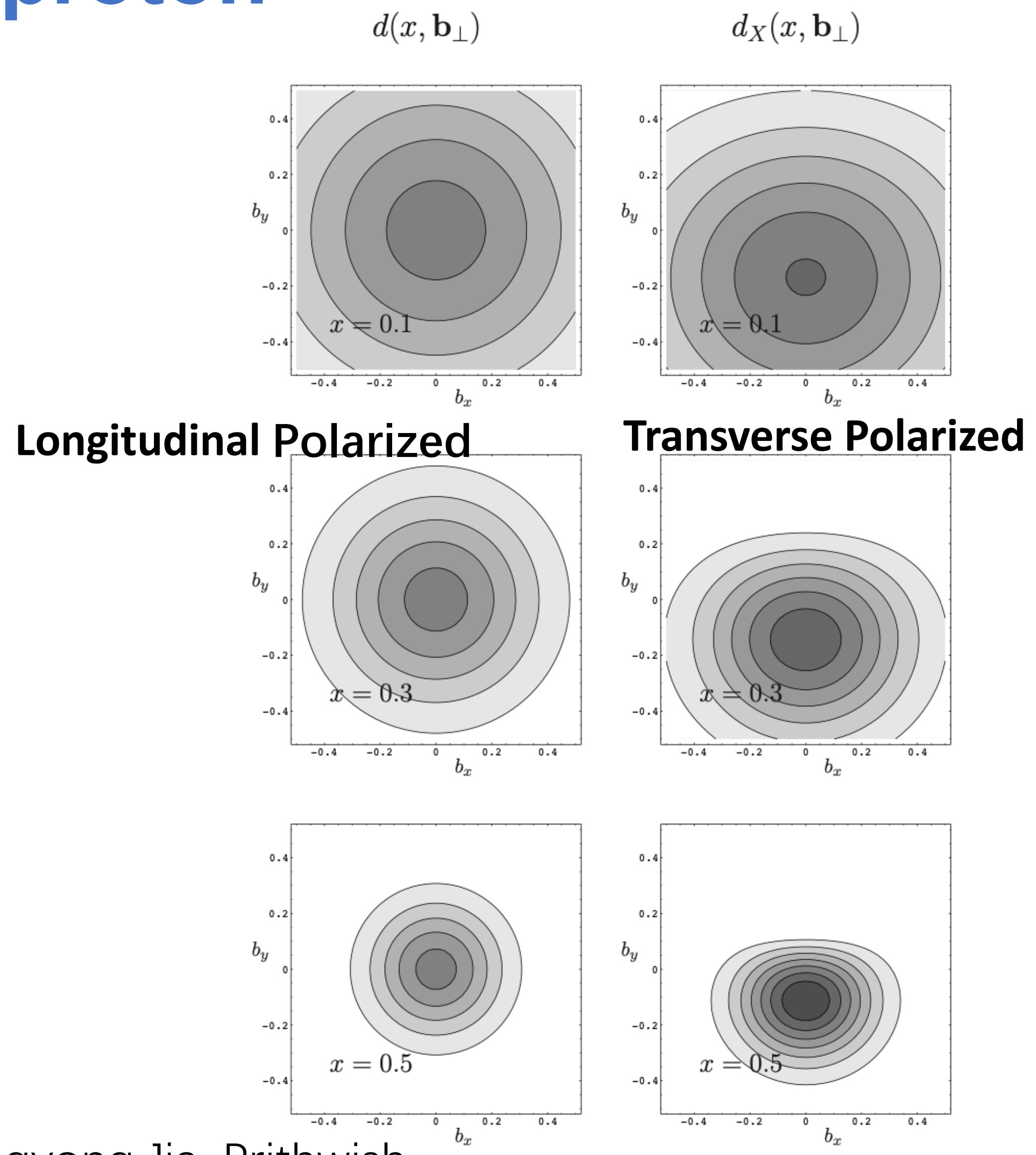
H.Mantysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348.
H. Mantysaari, B. Schenke, PhysRevD.98.034013.

- Flow observables are sensitive to shapes of proton and its energy evolution.

Connect to the GPD of polarized proton







- Can flow observables probe the shape of the polarized proton or light nuclei?

Discussion with Jiangyong Jia, Prithwish.

M. Burkardt, Int. J. Mod. Phys. A 18 (2003), 173-208.

P. Bozek and W. Broniowski, PhysRevLett.121.202301

Summary

- Hydrodynamics works well in describing collectivity from Pb+Pb, p+Pb to p+p and $\gamma*$ +Pb collisions.
- Final state interactions are essential for producing the flow-like long-range correlation inside high multiplicity jet events in p-p.
- Similar flow-like long-range correlation observed in high multiplicity e^+e^-.
- 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

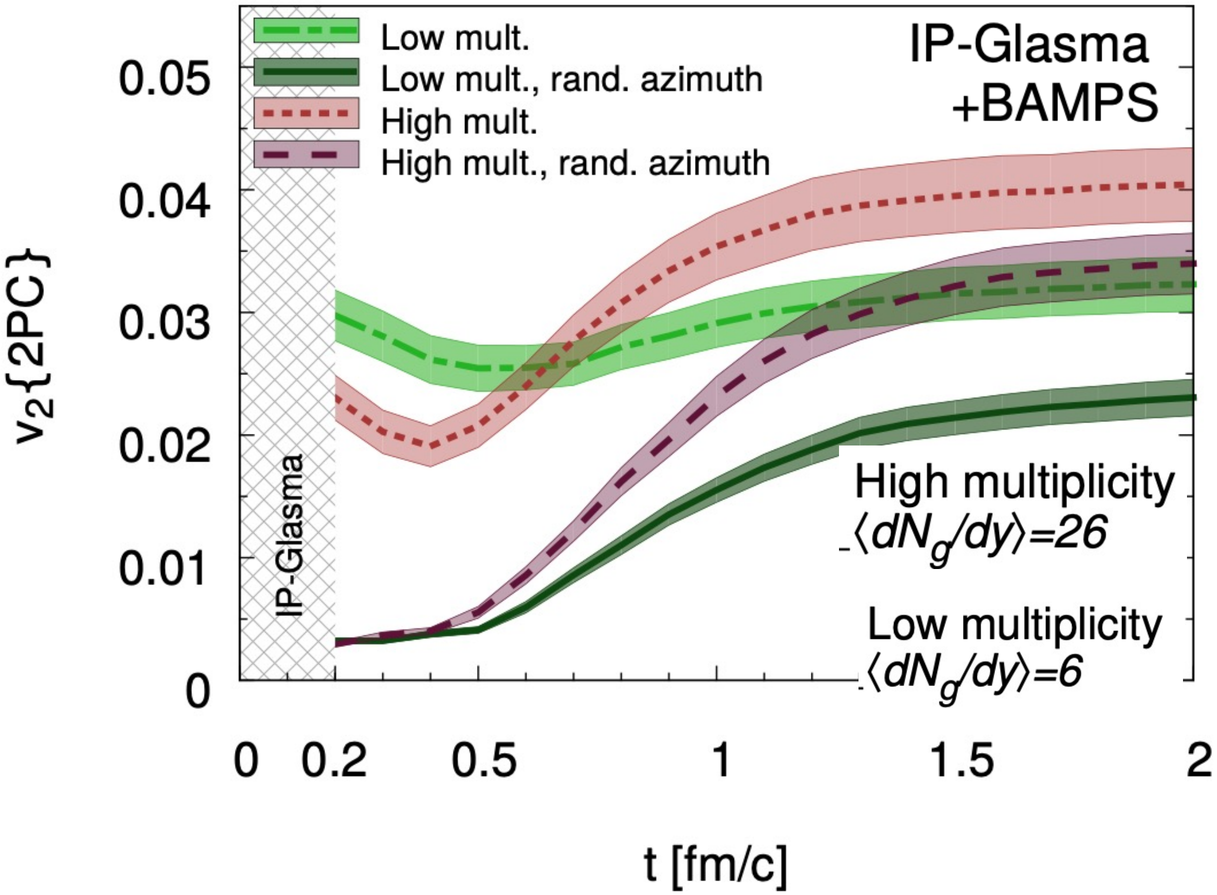
e-Print: 2401.09208 [nucl-th]

Thanks for Your Attention!

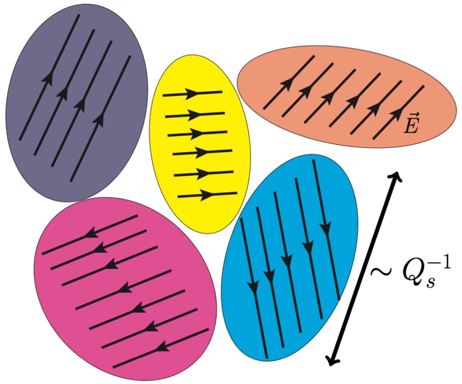
Questions？

Back Up

More is different



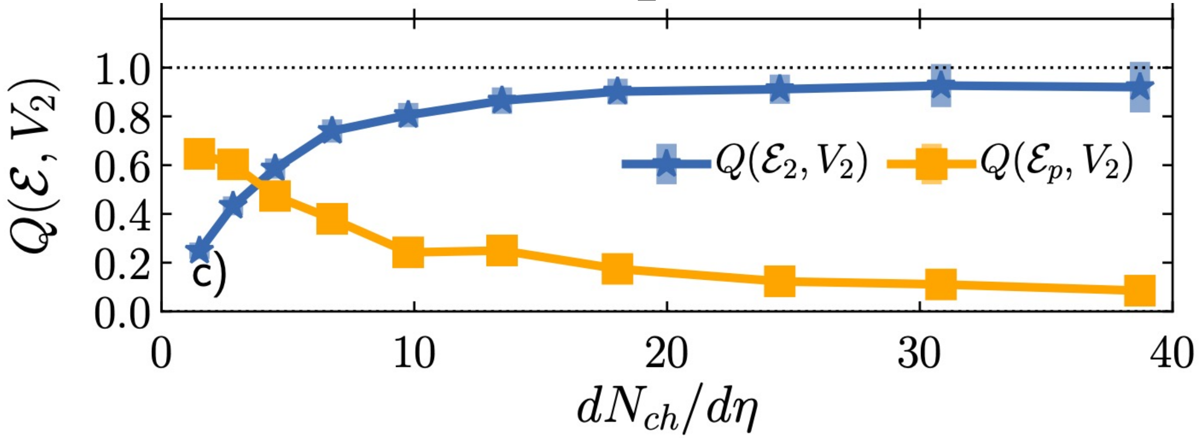
M. Greif, etc. al. PhysRevD.96.091504



Two (or more) quarks scattering off the same domain receive similar kick, leads to the initial state correlations.

$Q(\mathcal{E}_2, V_2)$ **initial geometry - final v_2 correlations.**

$Q(\mathcal{E}_p, V_2)$ **initial momentum anisotropy - final v_2 correlations.**



G. Giacalone, B. Schenke and C. Shen, PhysRevLett.125.192301

- Final state interaction is important in developing collectivity in high multiplicity events.

Energy distributions in UPCs

A. J. Baltz *et al.* Phys. Rept. 458, 1-171 (2008)

- The energy of incoming quasi-real photon fluctuates event by event

$$\frac{dN^\gamma}{dk_\gamma} = \frac{2Z^2\alpha}{\pi k_\gamma}\left[w_R^{AA}K_0(w_R^{AA})K_1(w_R^{AA}) - \frac{(w_R^{AA})^2}{2}(K_1^2(w_R^{AA}) - K_0^2(w_R^{AA}))\right]$$

$w_R^{AA} = 2k_\gamma R_A/\gamma_L,\ \gamma_L = \sqrt{s_{\rm NN}}/(2m_N)$

- The center of mass collision energy for the $\gamma^* + A$ system fluctuates

$$\sqrt{s_{\gamma N}} = (2k_\gamma\sqrt{s_{\rm NN}})^{1/2}$$

- The center of mass rapidity of $\gamma^* + A$ collision fluctuates in the lab frame

$$\Delta y = y_{\rm beam}(\sqrt{s_{\gamma N}}) - y_{\rm beam}(\sqrt{s_{\rm NN}})$$

C. Shen, W. Zhao and B. Schenke, arXiv:2209.15065 [nucl-th]