LHCb实验中重离子碰撞的理论研究

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第6届LHCb前沿物理研讨会

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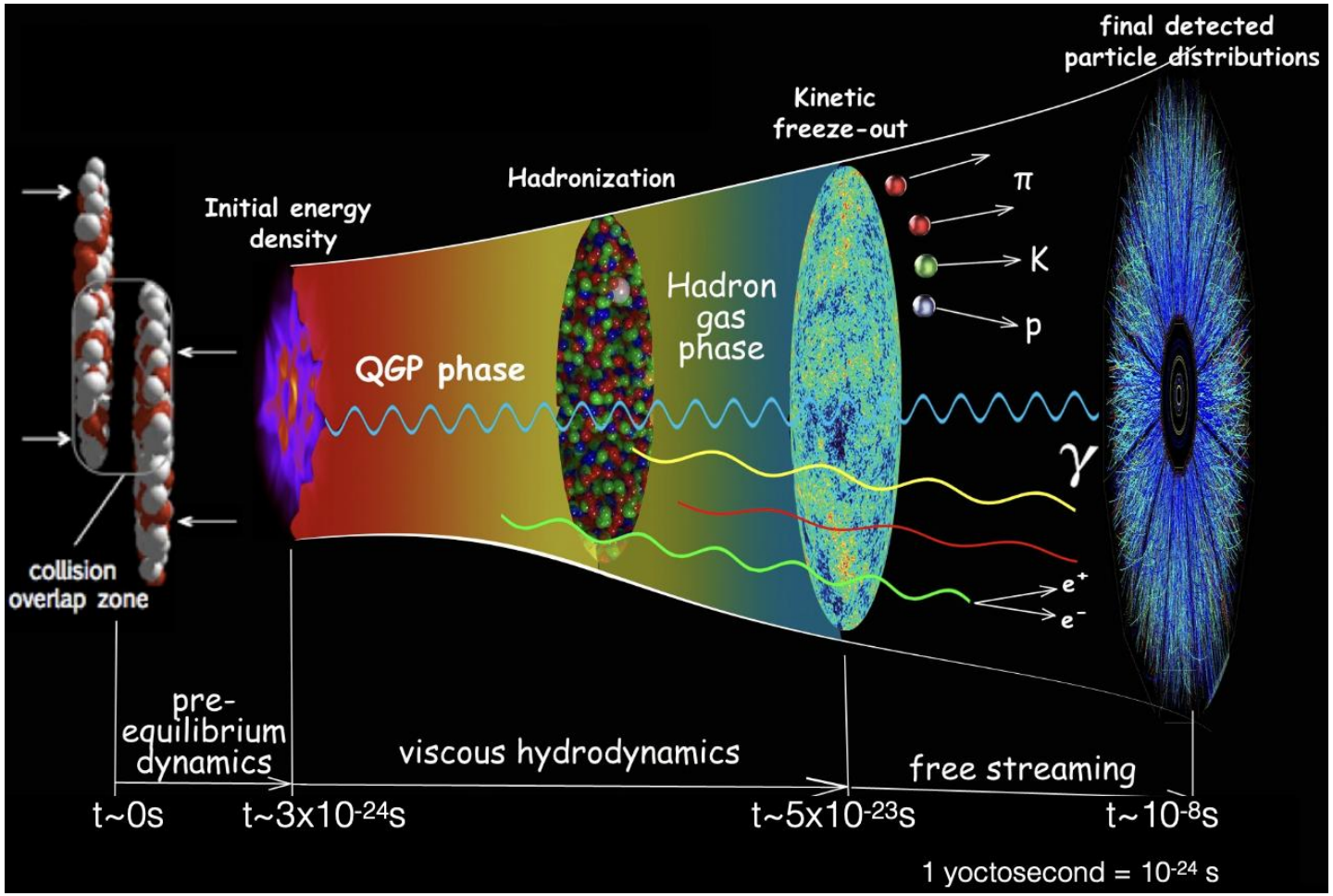
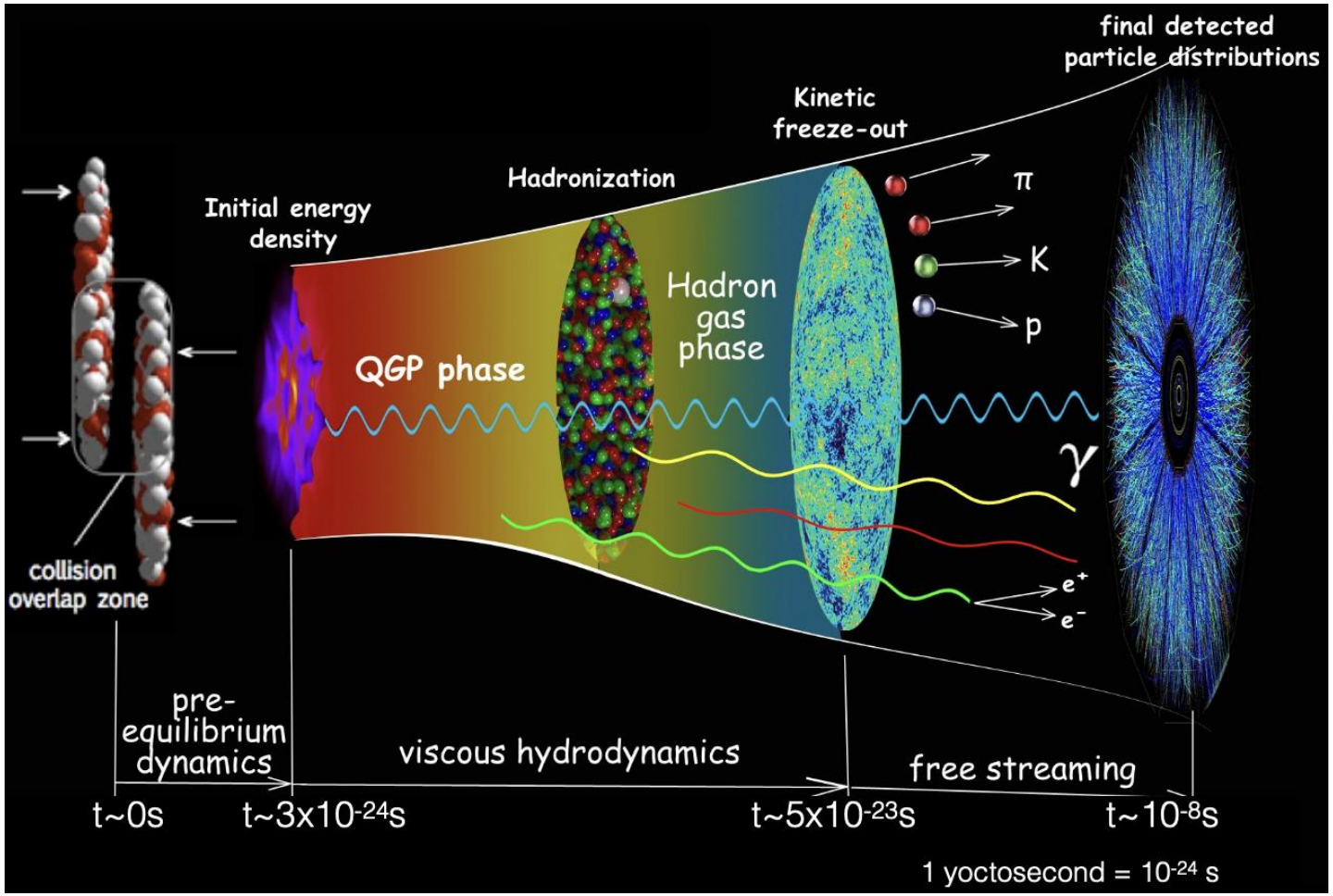
Nuclear Matter under Extreme Conditions



Credit: Chun Shen

- Heavy-ion collision dynamics is complex with multiple length/time scales.

Nuclear Matter under Extreme Conditions

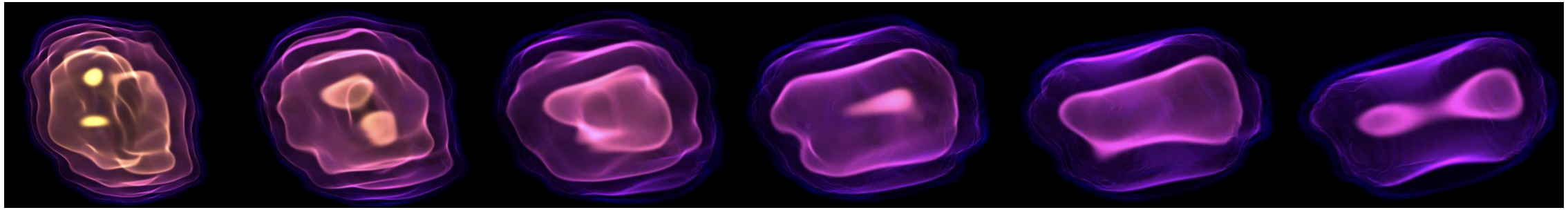


Credit: Chun Shen

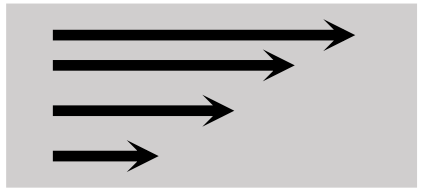
- Heavy-ion collision dynamics is complex with multiple length/time scales.
- What is the **smallest QGP droplet**?
- What is the **structure of QCD phase diagram**?
- How does the strongly coupled liquid emerge from fundamental QCD interactions?
- Constrain the **nuclear structures** by final state observables.
- Hard Probes, jet, heavy flavours, interact with medium.
- Probe Hadron structures, exotic hadrons.

QGP transport property

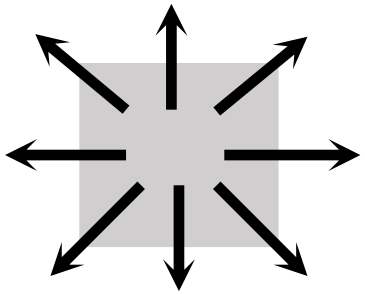
- Quark Gluon Plasma behaviors like fluid, evolved in relativistic viscous hydrodynamics.



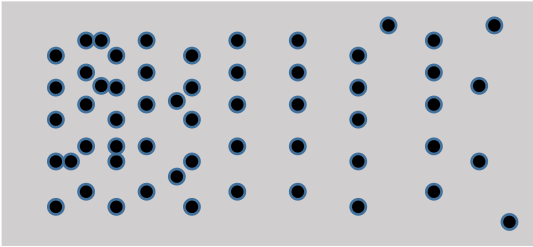
- Effects from dissipative components.



Shear viscosity acts against the buildup of flow gradients.

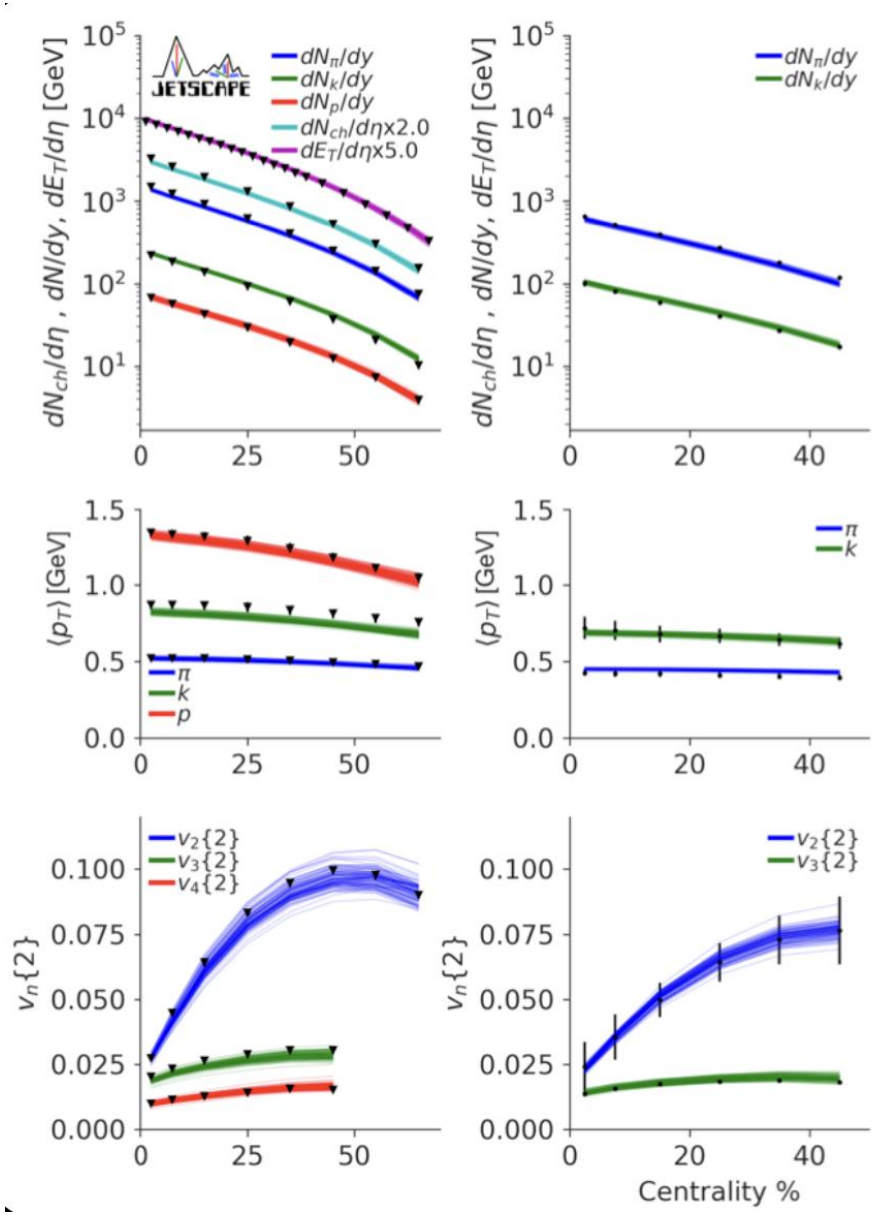


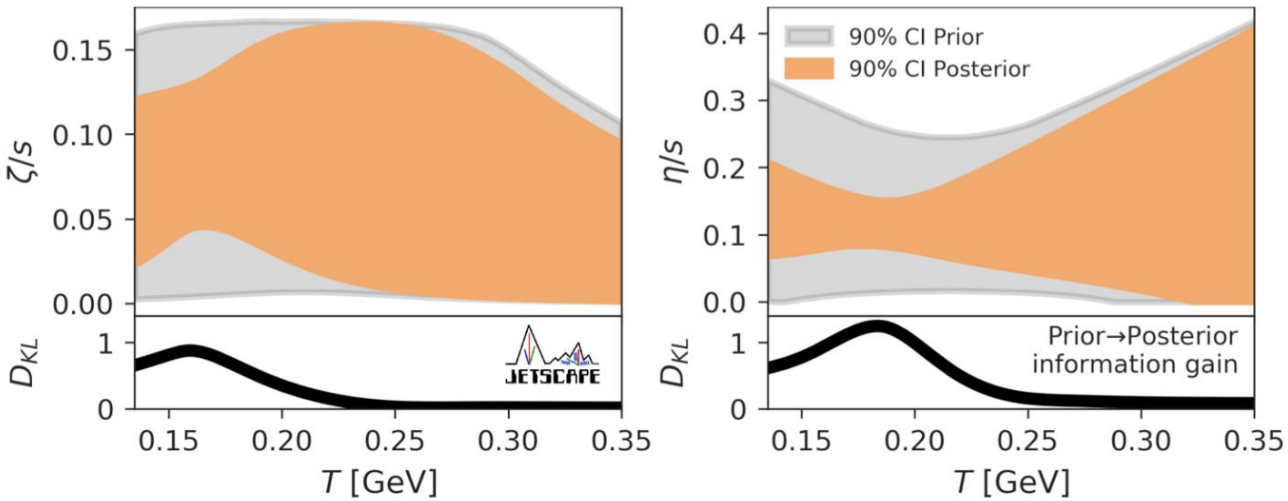
Bulk viscosity acts against the buildup of radial flow and longitudinal expansion



Diffusion current acts again the buildup of charge density inhomogeneity (smooth out such gradients)

Global Bayesian Constrains on QGP Viscosity

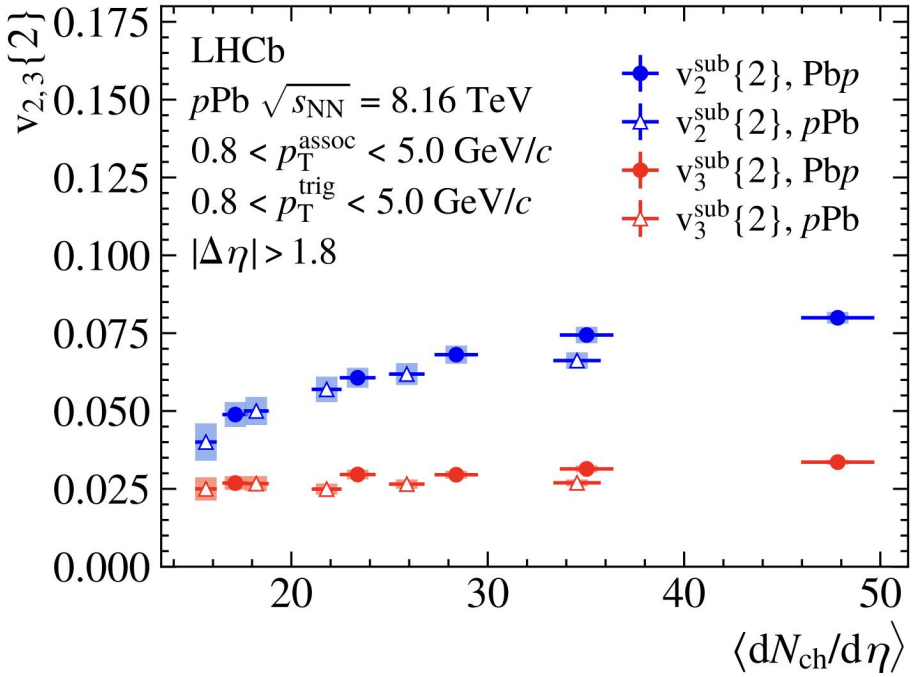


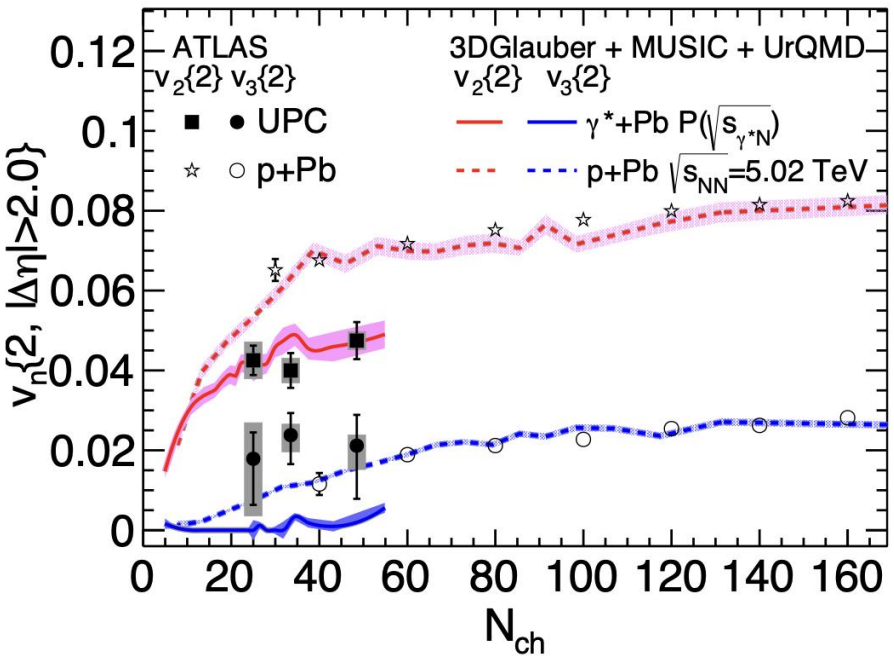


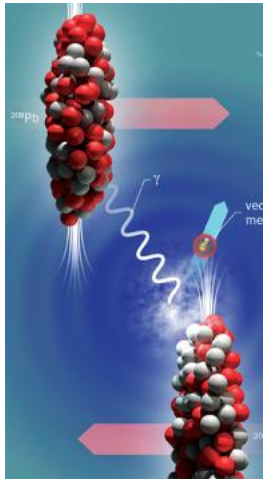
- An era of extracting robust and precise properties of QCD matter from **multi-messenger** measurements.

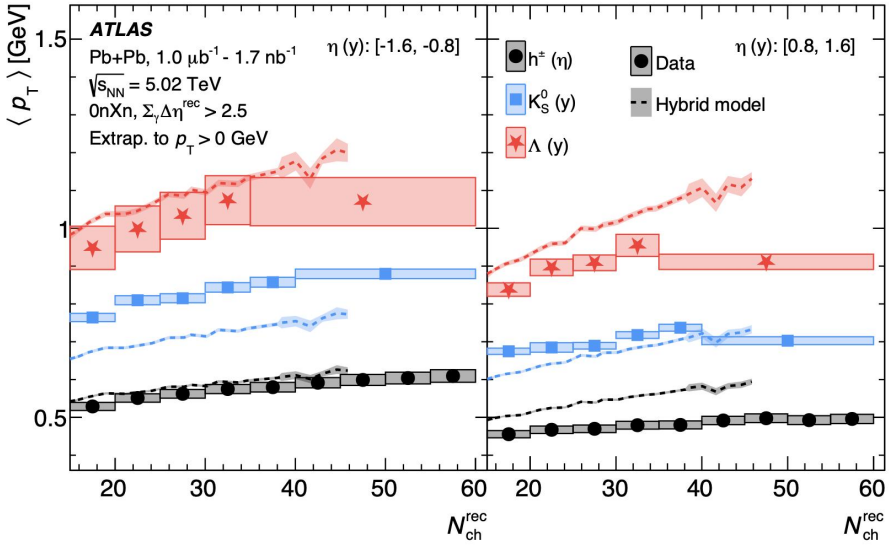
JETSCAPE, Everett et al.,
PRL. 126 (2021) 24, 242301;PRC 103 (2021) 5, 054904 .
Bernhard et al., Nature Phys. 15, no.11, 1113-1117 (2019).

Collectivity in Small Systems



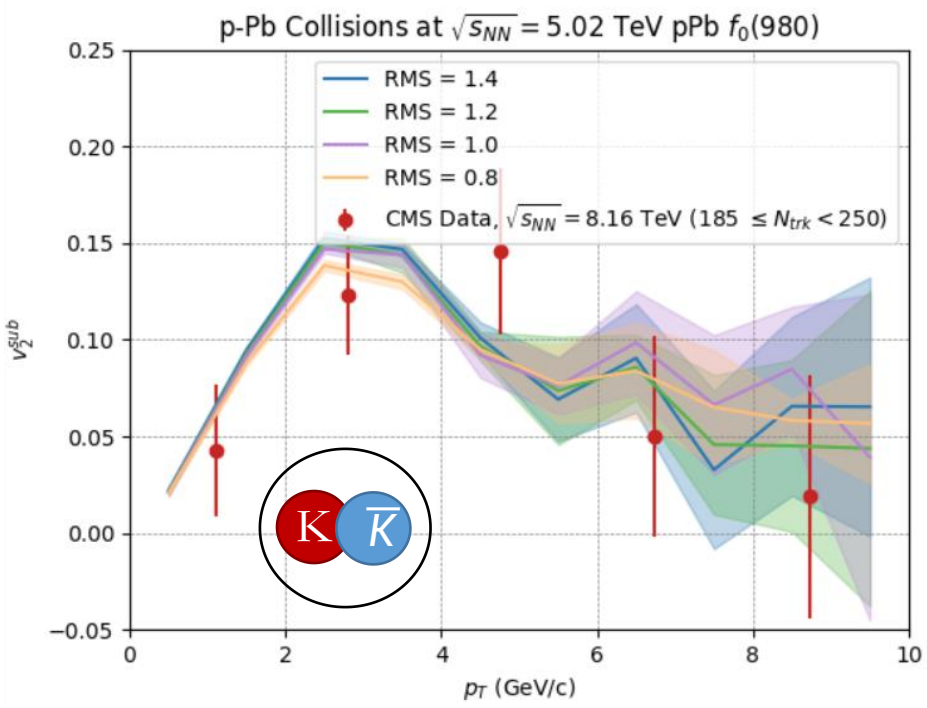


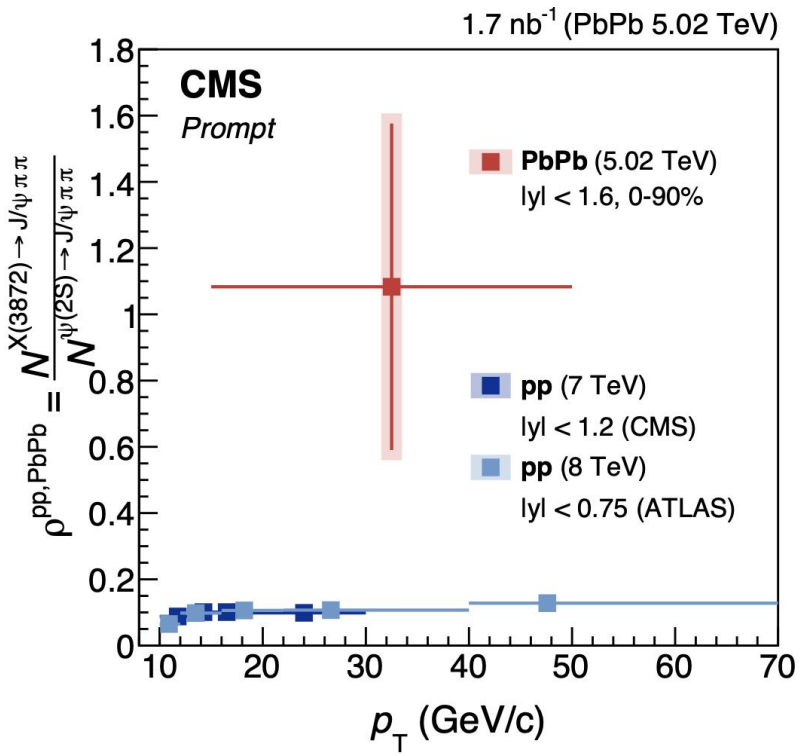




LHCb: [arXiv:2505.09273].
ATLAS: Phys. Rev. C 104, 014903 (2021); Phys. Rev. C 111, 064908 (2025)
Model: W. Zhao, C. Shen and B. Schenke, PhysRevLett.129.252302.

Exotic hadron productions





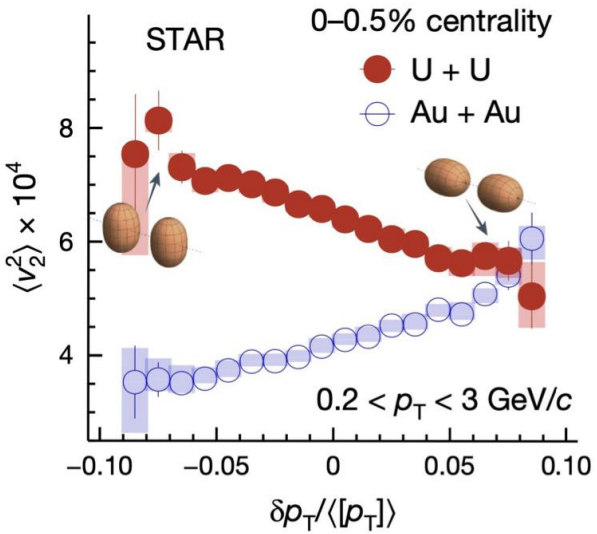
CMS, [arXiv:2312.17092].

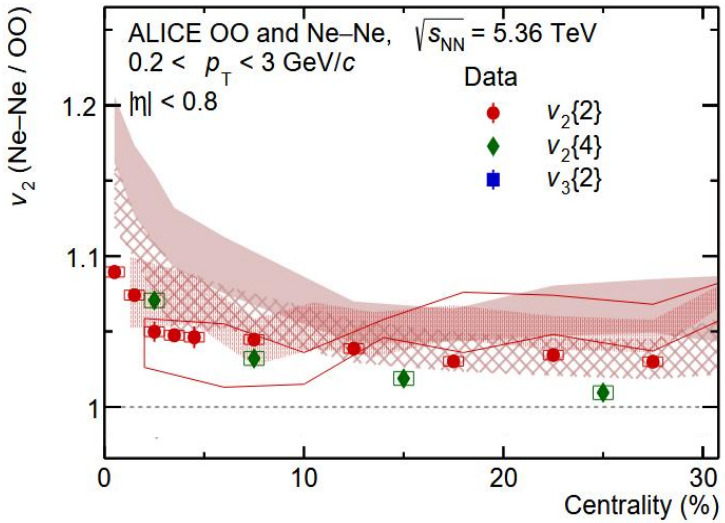
CMS: [arXiv: 2102.13048]

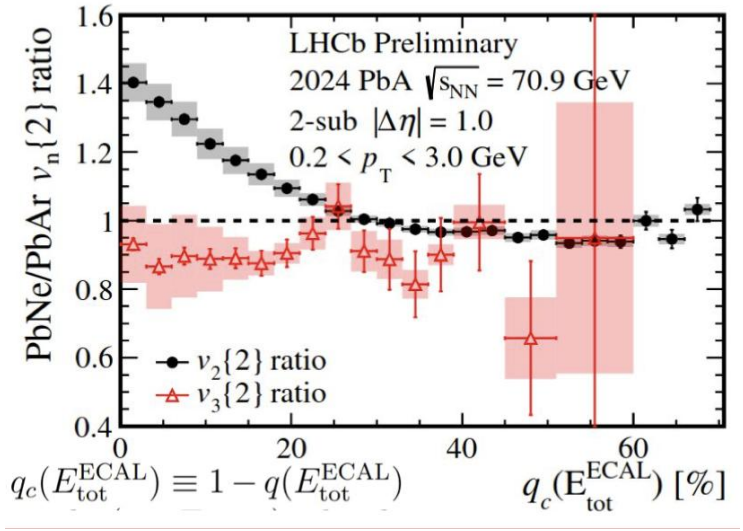
Yi. Wang, W. Zhao, C. Ko, J. Xie, F. Guo, H. Song, [arXiv: 2511.03638].

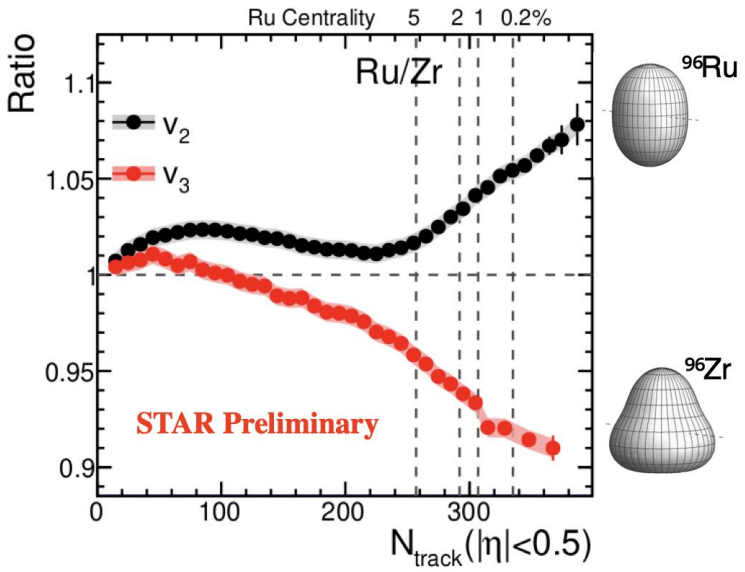
- The CMS flow measurement is the consistent with $K-\bar{K}$ **molecular** picture of $f_0(980)$.
- X-3872 productions in Heavy-ion Collisions.

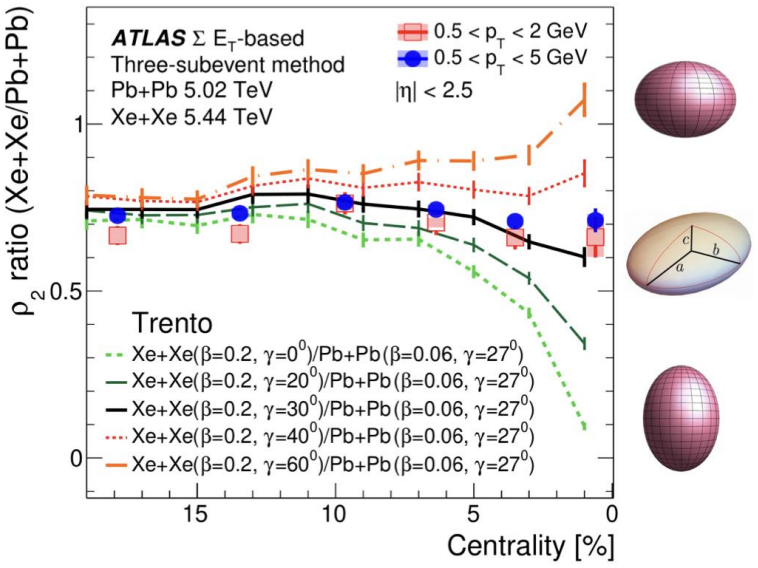
Imaging the Nuclear Structures





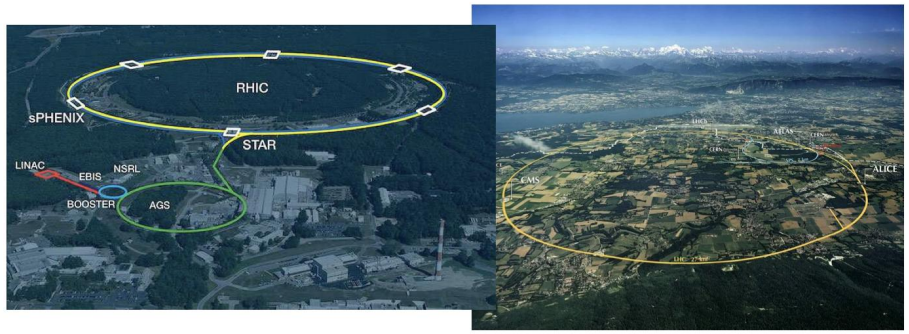


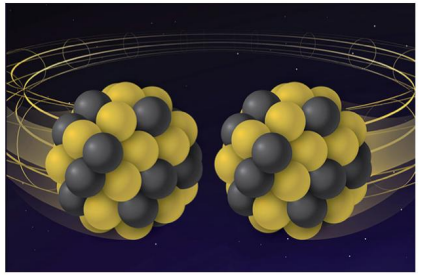




- ALICE: [arXiv:2509.06428].
- ATLAS: [arXiv:2509.05171].
- CMS: [arXiv:2510.02580].
- LHCb: [arXiv:2509.12399].
- STAR, ***Nature*** 635, 67 (2024).
- STAR: [arXiv: 2109.00131].
- ATLAS: arXiv:2205.00039].
- .....

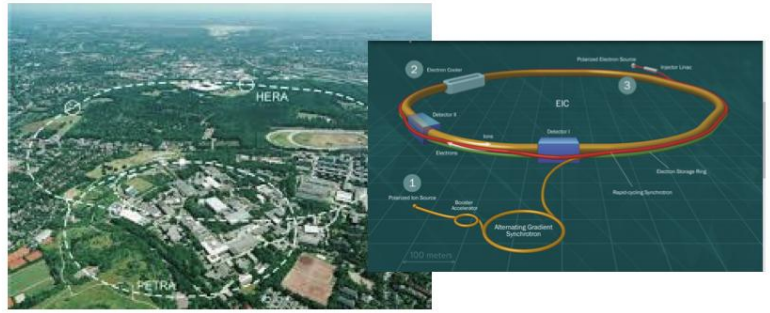
Heavy-ion Collisions and DIS/UPC

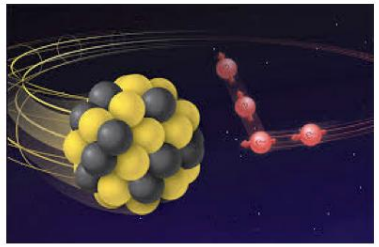


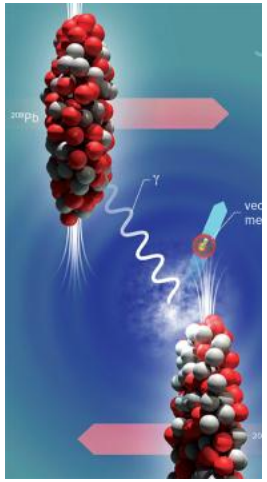


- **Heavy-ion Collisions:** High center-of-mass energies available.
- **Multi-Stage process:**

Initial state => QGP => Hadronic Scatter







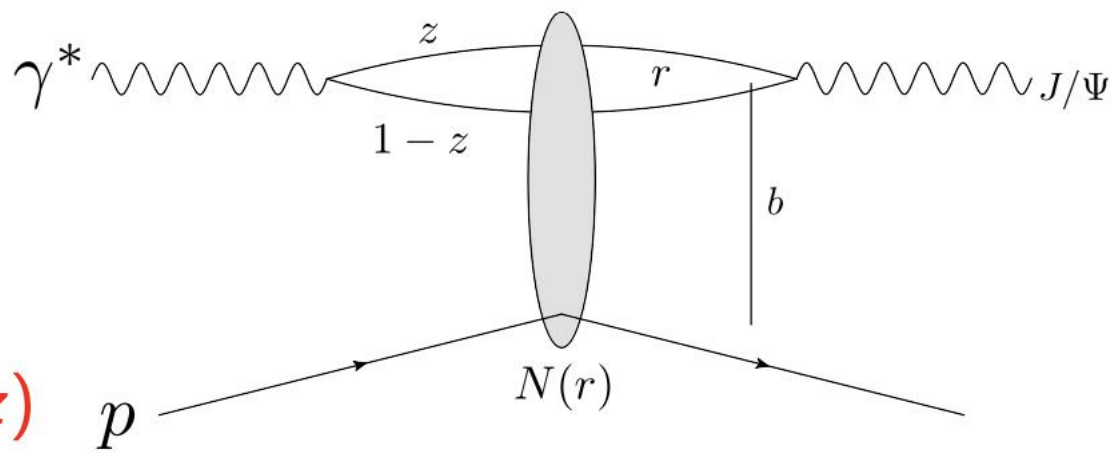
- **DIS/UPC:**
- Pin down kinematics, clean probes of QCD dynamics.
- Collision energy is limited.

- It is the same nucleus at small x: probe the initial state in DIS/UPC, then apply to heavy ion simulations.

Imaging nuclei with photon-nucleus reactions

High energy factorization:

1. $\gamma^* \to q\bar{q}$ splitting, wave function $\Psi^{\gamma}(r, Q^2, z)$
2. $q\bar{q}$ dipole scatters elastically N(r, x, b)
3. $q\bar{q} \to J/\Psi$, wave function $\Psi^{V}(r, Q^2, z)$



Diffractive scattering amplitude

$$\mathcal{A}^{\gamma^* p \to Vp} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^{\gamma *} \Psi^{V}(r, z, Q^2) \mathbf{e}^{-\mathbf{i}\mathbf{b}\cdot\mathbf{\Delta}} N(r, x, b)$$

Impact parameter, b, is the Fourier conjugate of the momentum transfer, $\Delta \approx \sqrt{-t}$, N(r, x, b) dipole-target scattering amplitude.

***A* ~Fourier transform of the spatial structure function of target ($T_{p/A}$).**

Miettinen, Pumplin, PRD 18, 1978; Caldwell, Kowalski, 0909.1254; Mäntysaari, Schenke, 1603.04349; Mäntysaari, 2001.10705

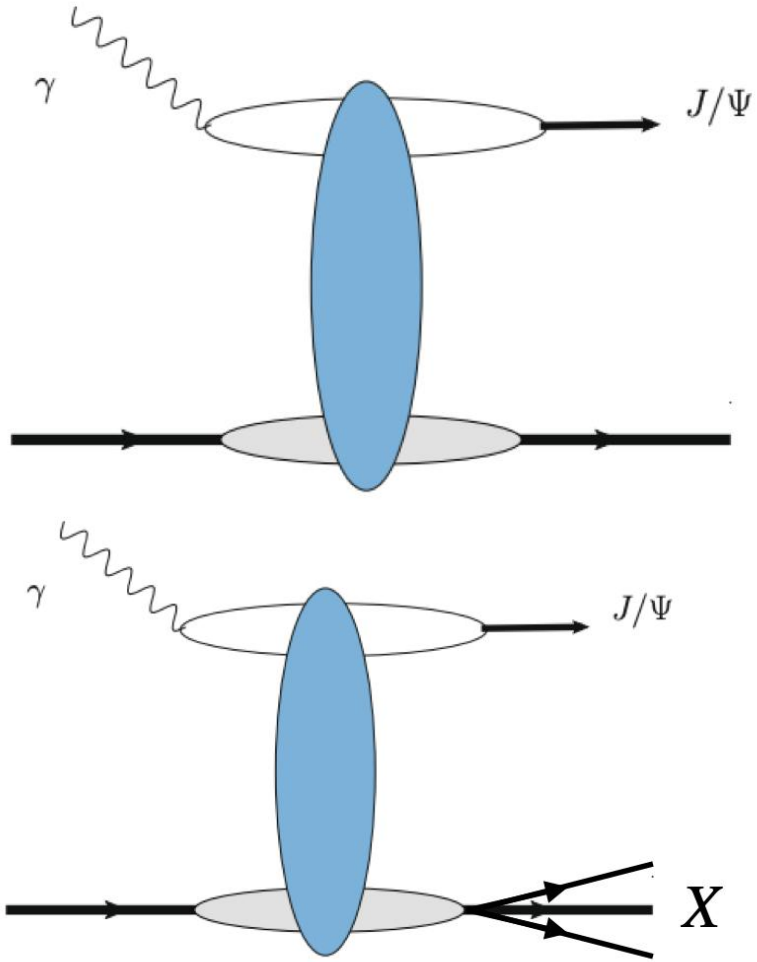
Coherent and incoherent processes

- **Coherent** $\sigma_{\text{coherent}} \sim |\langle \mathcal{A} \rangle_\Omega|^2$

Target stays intact, (|initial state> = |final state>)
Probes the average shape of the target.

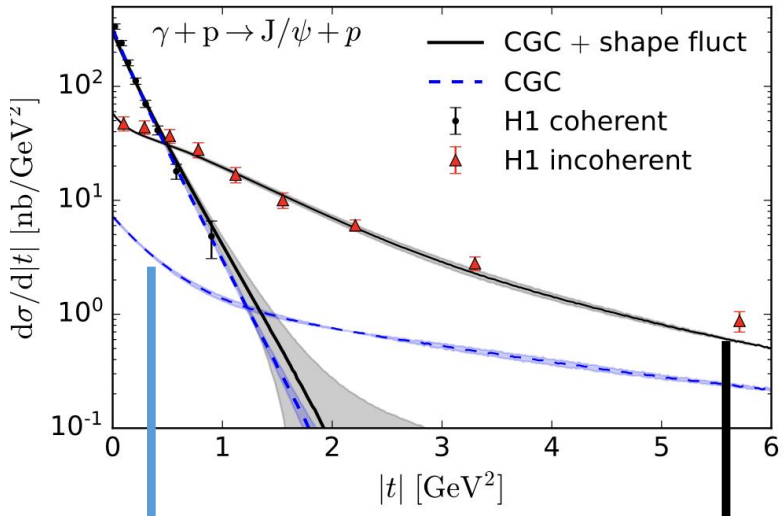
- **Incoherent** $\sigma_{\text{incoherent}} \sim \langle |\mathcal{A}|^2 \rangle_\Omega - |\langle \mathcal{A} \rangle_\Omega|^2$

Target breaks apart, (|initial state> ≠ |final state>)
Probes the variance of event-by-event initial state fluctuations in target structure.



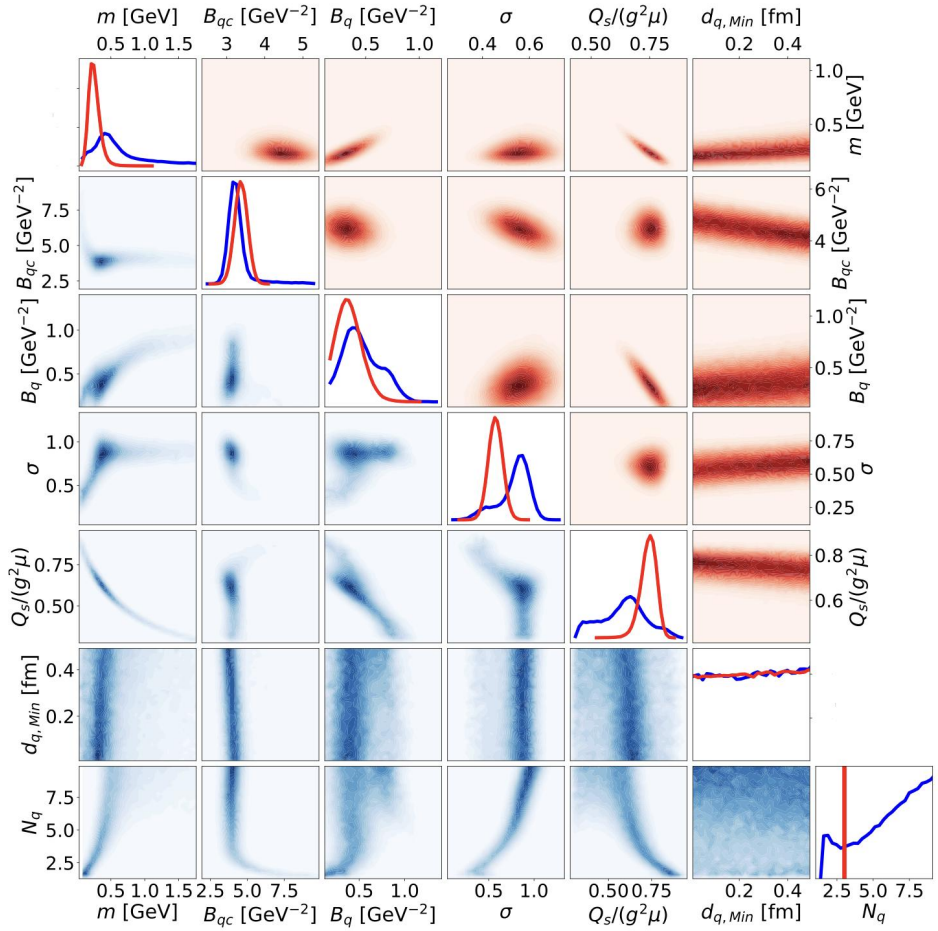
Miettinen, Pumplin, PRD 18, 1978; Caldwell, Kowalski, 0909.1254; Mäntysaari, Schenke, 1603.04349; Mäntysaari, 2001.10705

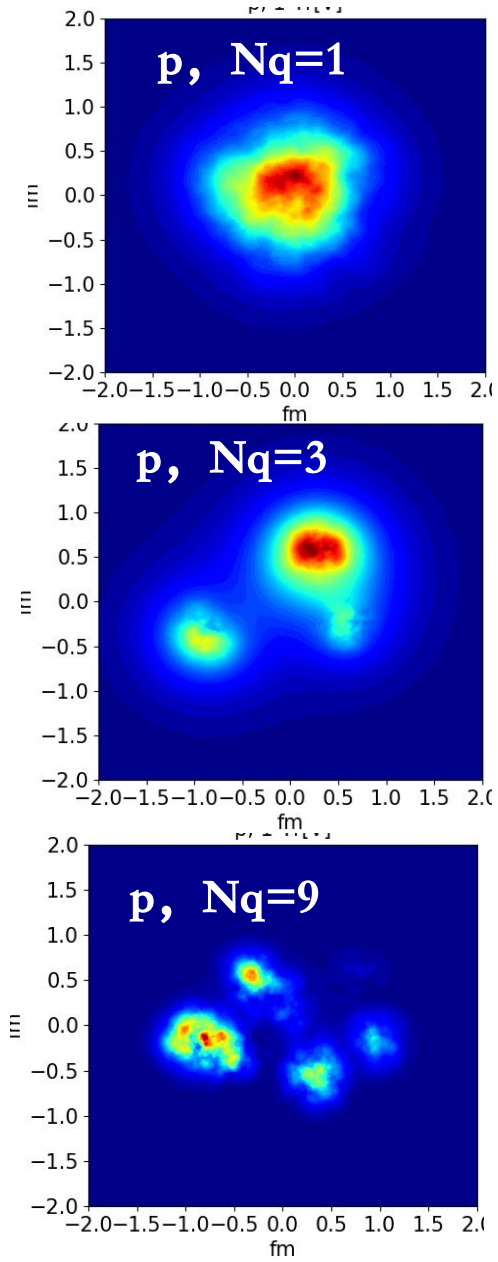
Proton geometry fluctuations



No subnucleon fluctuations

With subnucleon fluctuations



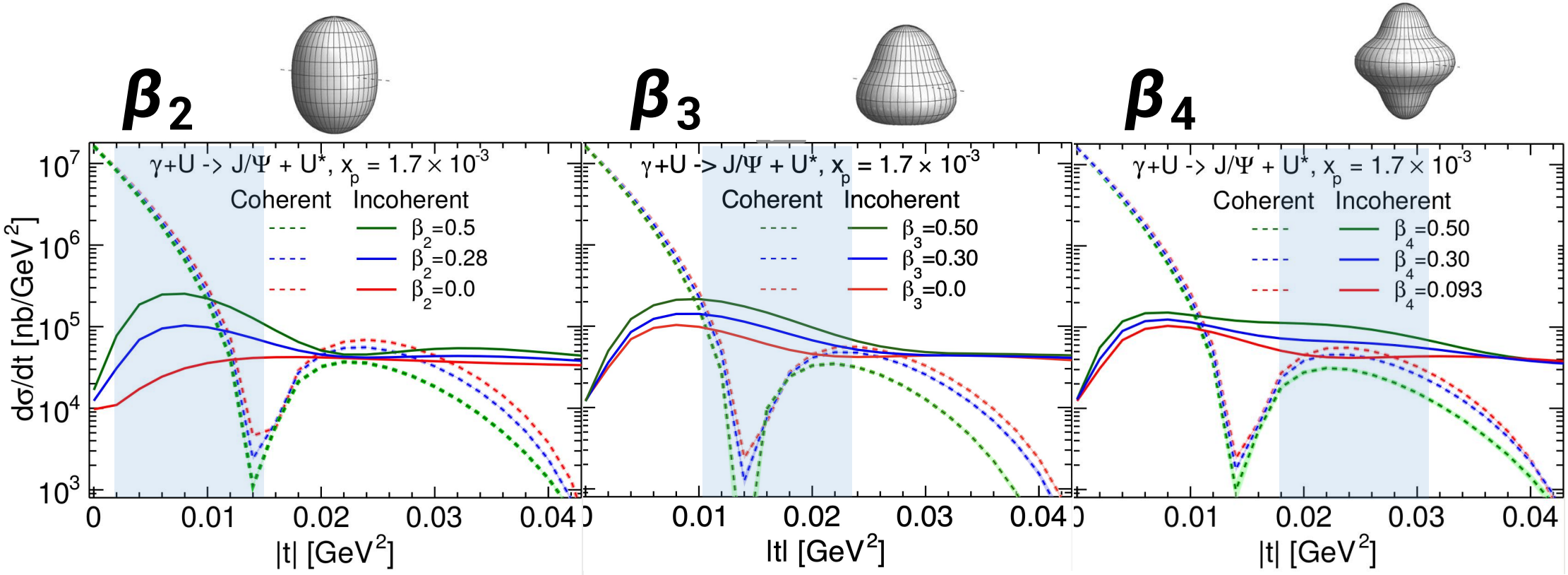


- Probe the event-by-event sub-nucleon fluctuations.
- Bayesian inference of the fluctuating proton shape.
- The extracted 2D RMS proton radius $R_{rms} = \sqrt{2(B_{qc} + B_q)} \sim$ **0.6 fm**.

H. Mäntysaari, Schenke , PhysRevLett.108.252301 , PhysRevC.86.034908;
H. Mäntysaari, F. Salazar and B. Schenke, Phys. Rev. D 106, 074019 (2022).
H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348.

Multi-scale imaging of Nuclear shape

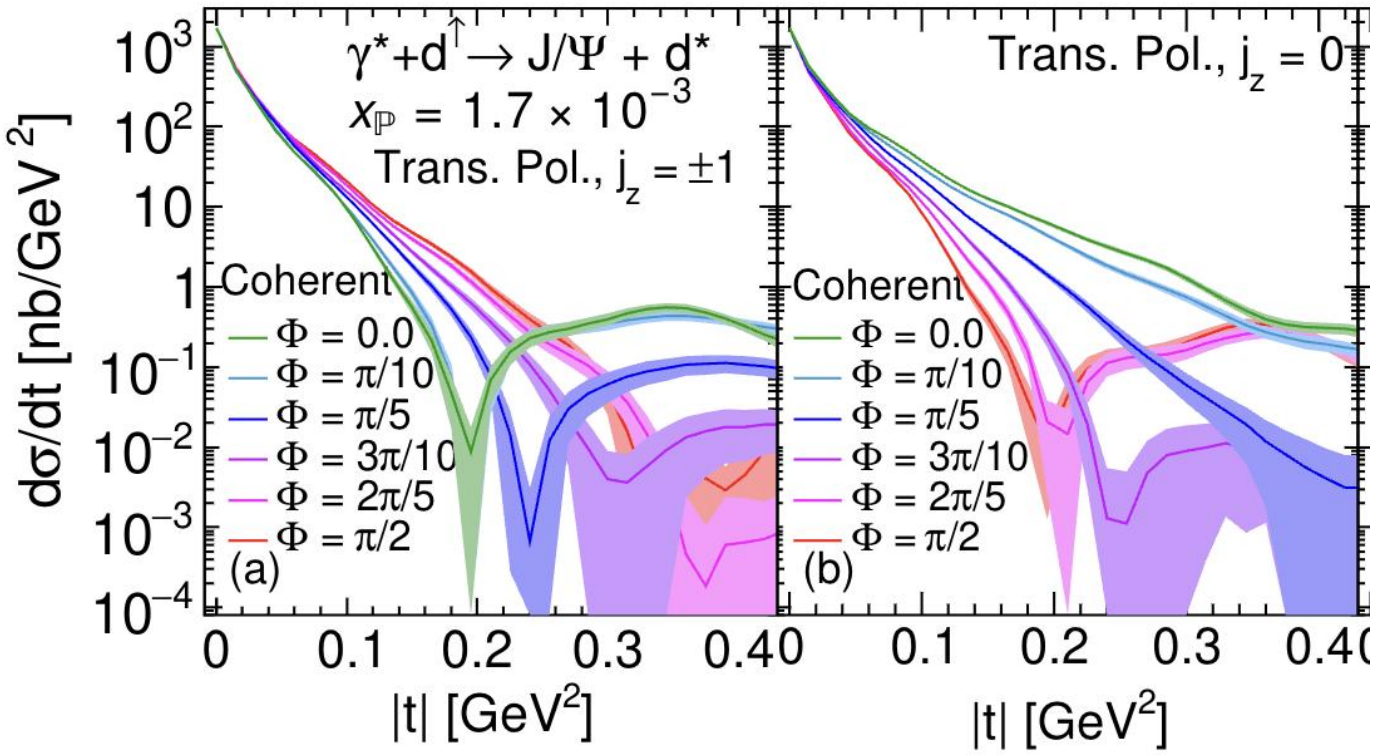
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \quad , \quad R(\Theta,\Phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\beta_3 Y_{30}(\Theta)+\beta_4 Y_{40}(\Theta)\right]$$

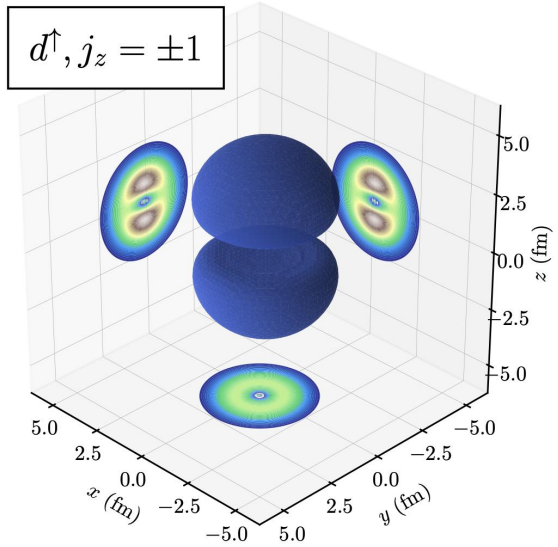


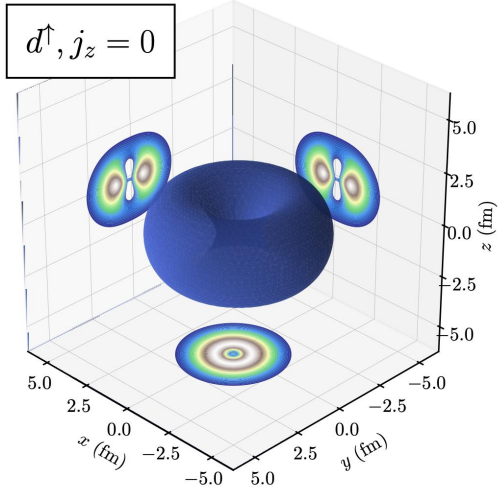
H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, PhysRevLett.131.062301.

- "**X-ray vision**" for atoms.

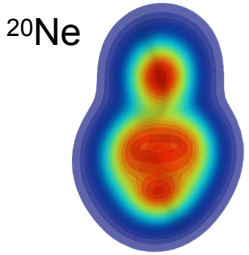
Re-construct 3D profile of polarized light ion





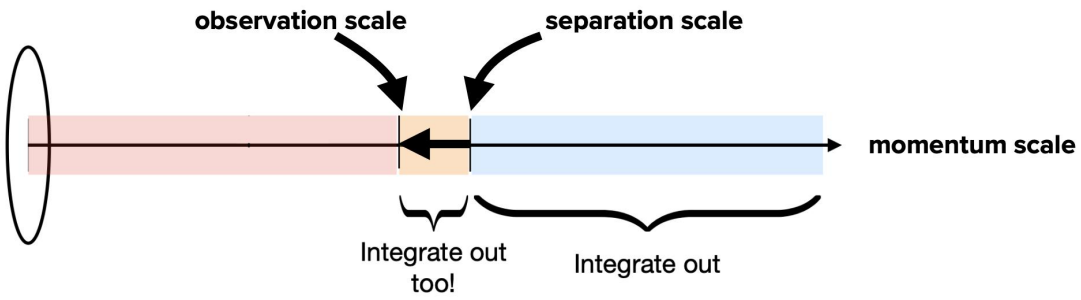


- Re-construct the **3D nucleon density profile** of the polarized light nuclei.
- **Polarize the ^{20}Ne?**

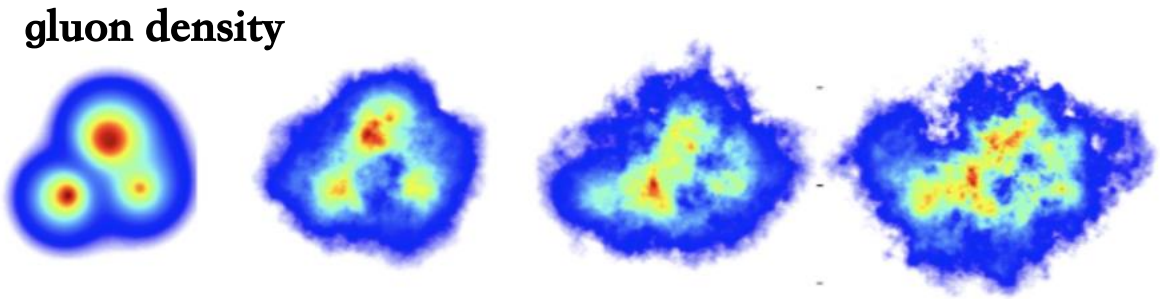


H. Mäntysaari, F. Salazar, B.Schenke, C. Shen and W. Zhao, PLB.2024.139053.
P. Bozek and W. Broniowski, PRL.121.202301.

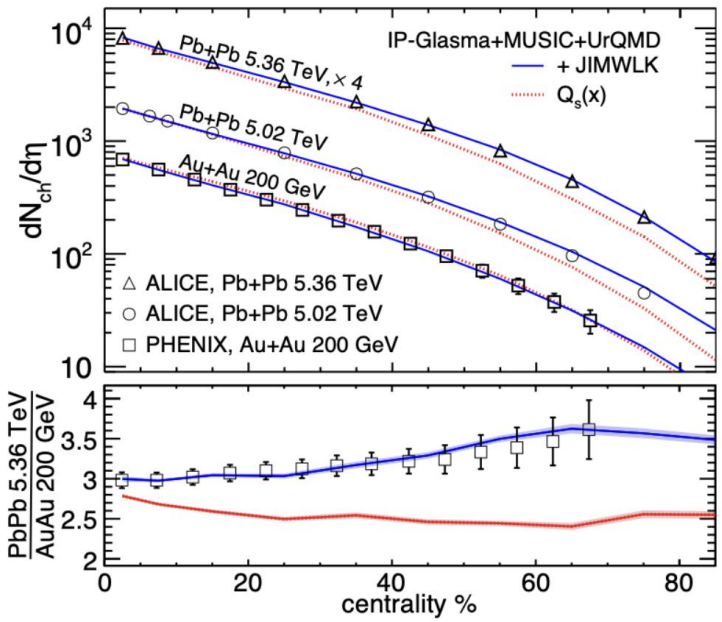
Energy evolution of initial state

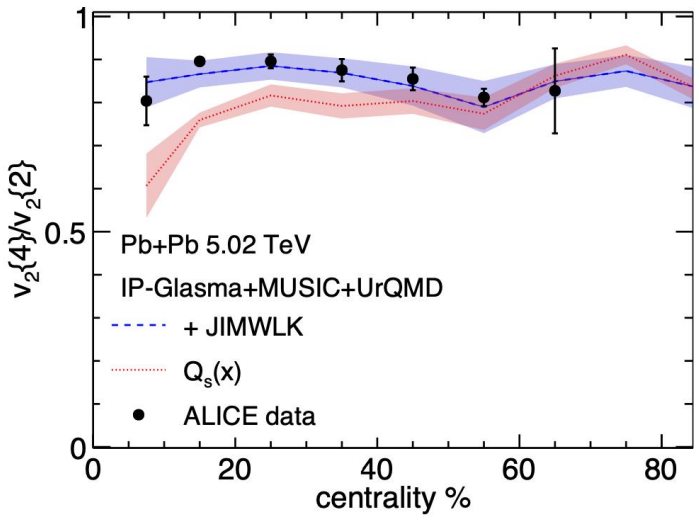


A. Morreale and F. Salazar, Universe 7, no.8, 312 (2021).



Low energy (UPC/DIS) → High energy (LHC)





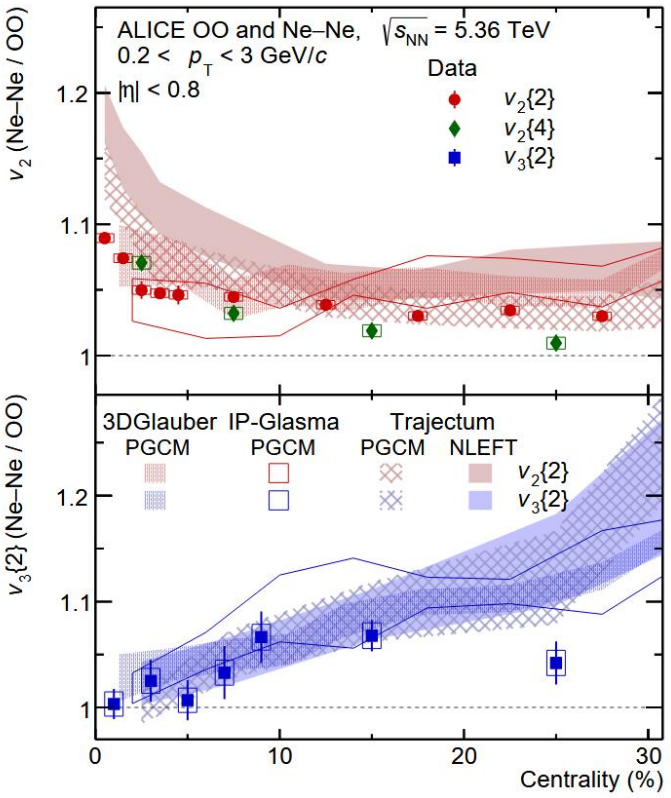
- Energy evolution of the initial state is important to final state observables.

H. Mäntysaari and B. Schenke, PRD 98 (2018) 034013.
H. Mäntysaari, B. Schenke, C, Shen and W. Zhao, PRL. 135, 022302 (2025)

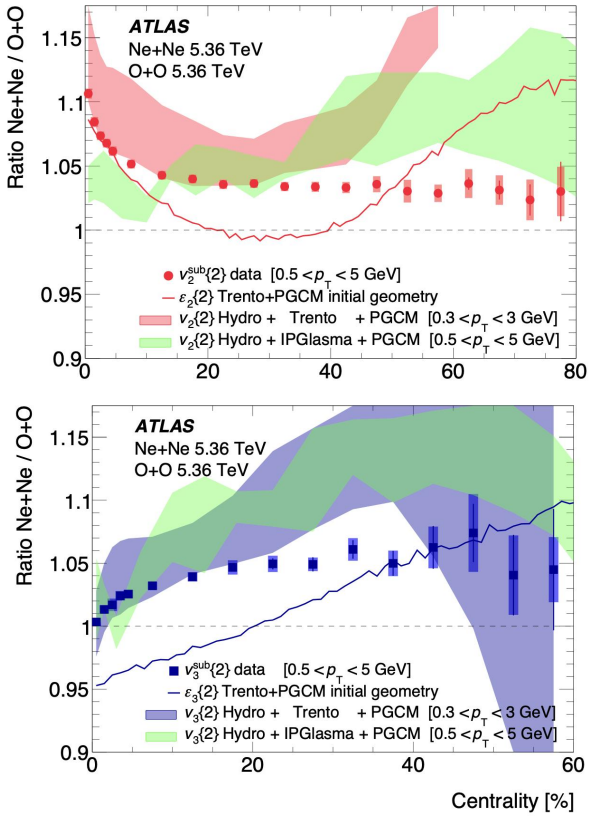
+ JIMWLK: CGC + energy evolution

$Q_s(x)$: CGC (change the $Q_s(x)$ only)

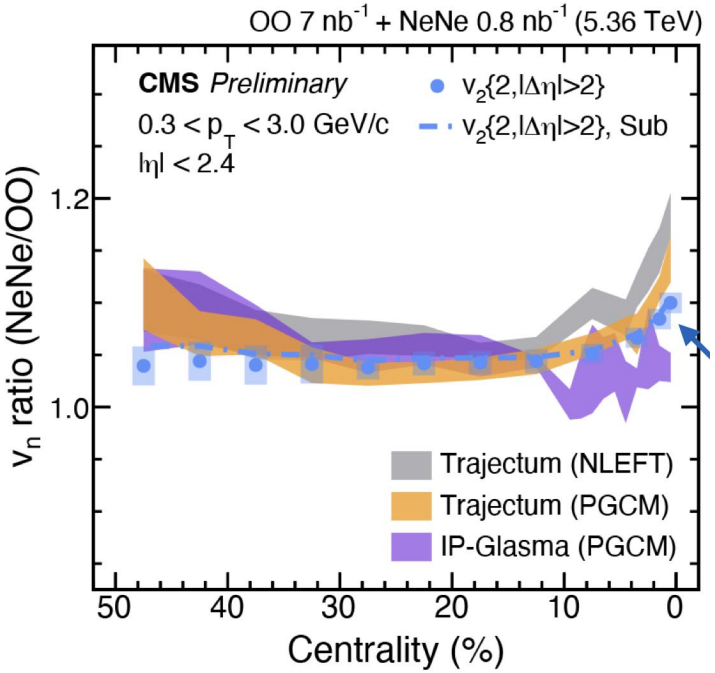
Flow ratio NeNe/OO



ALICE: [arXiv:2509.06428].



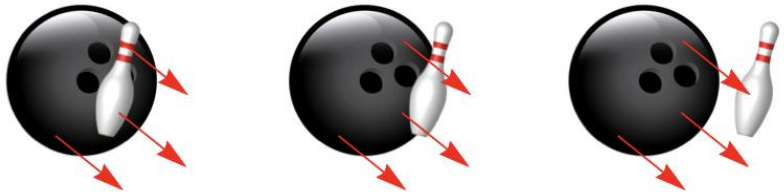
ATLAS: [arXiv:2509.05171].



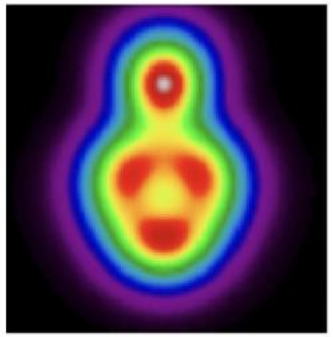
CMS: [arXiv:2510.02580].

- **Trajectum:** Fit Pb-Pb LHC flow data, [PRL,135, 012302]
- **IPGlasma + JIMWLK:** Fit J/Ψ data + energy evolution [PRL, 135,022302]
- **3DGlauber:** Fit dAu, AuAu at RHIC, then extrapolate to LHC. [JETSCAPE, in preparation]

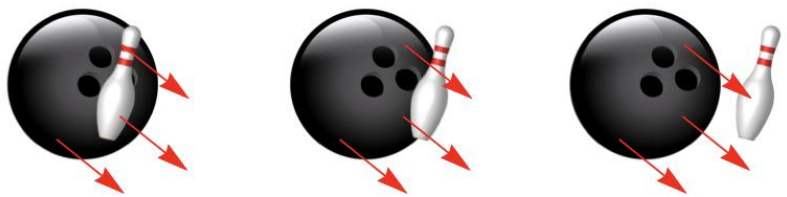
Opportunities of light-ion Collisions

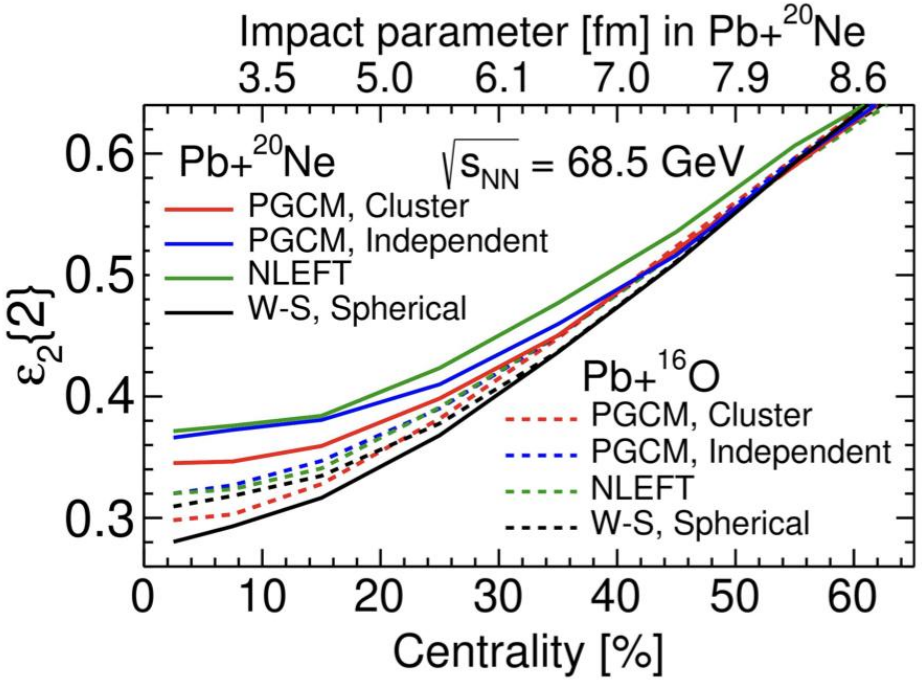


High Energy Bowling Allay



^{20}Ne



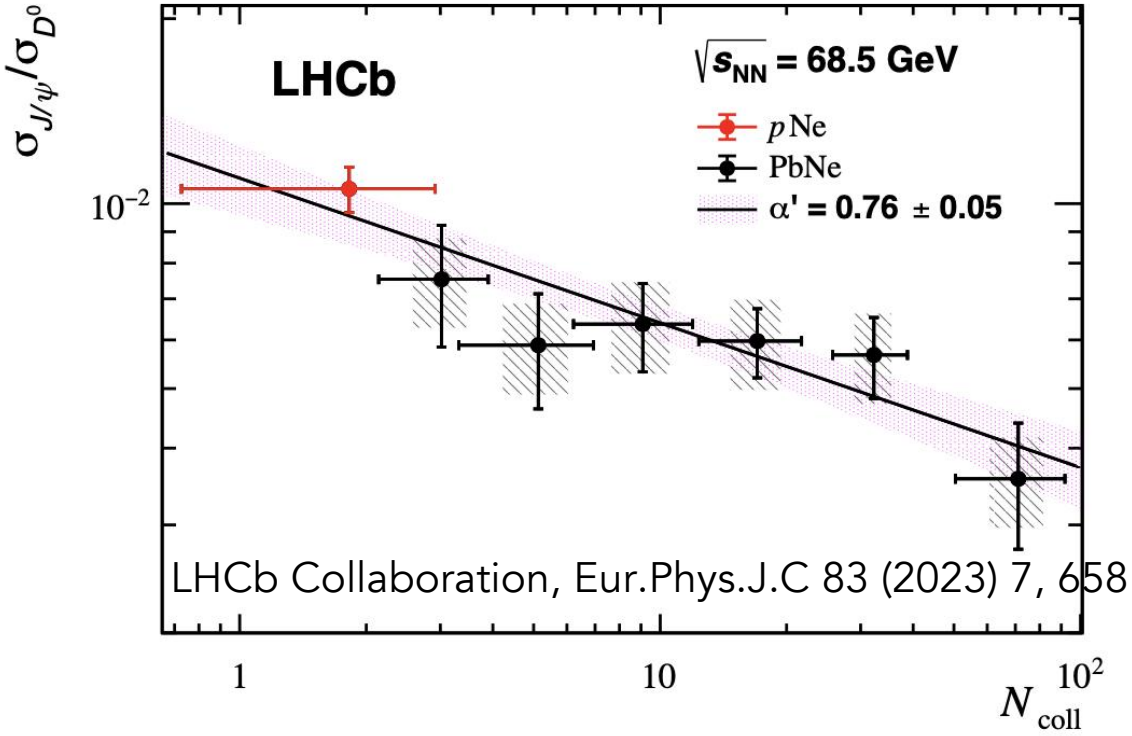


Pb + Ne-20 collisions: A high energy bowling allay!

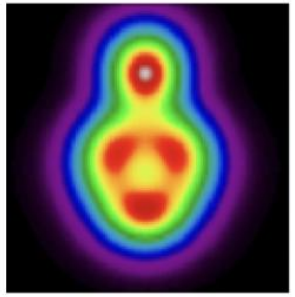
G. Giacalone W. Zhao et al Phys. Rev. Lett. 134, 082301 (2025)

- Connecting *ab initio* inputs of light-nuclei with relativistic nuclear collisions.
- Easier to image the shapes of light-nuclei than symmetric light-ion collisions.

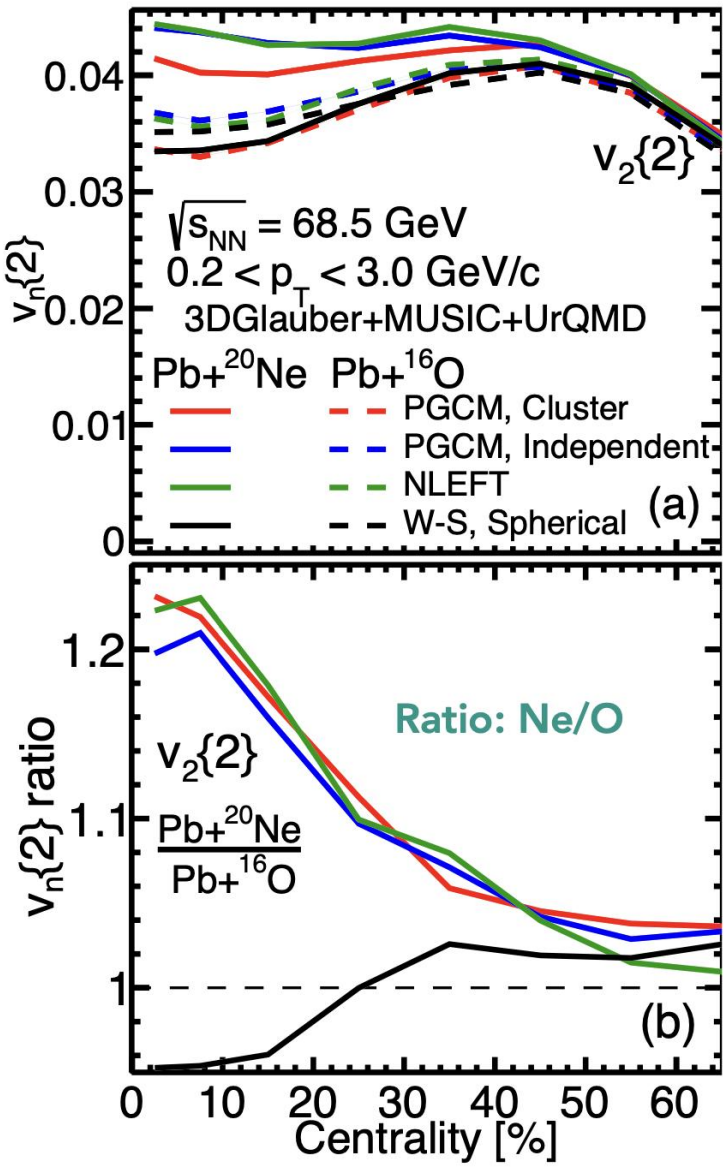
A Probe of Quark-Gluon Plasma



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



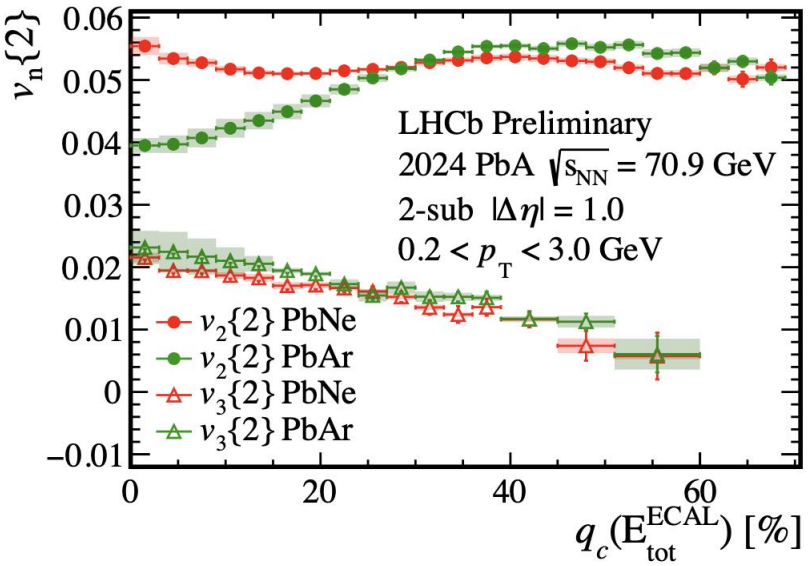
^{20}Ne

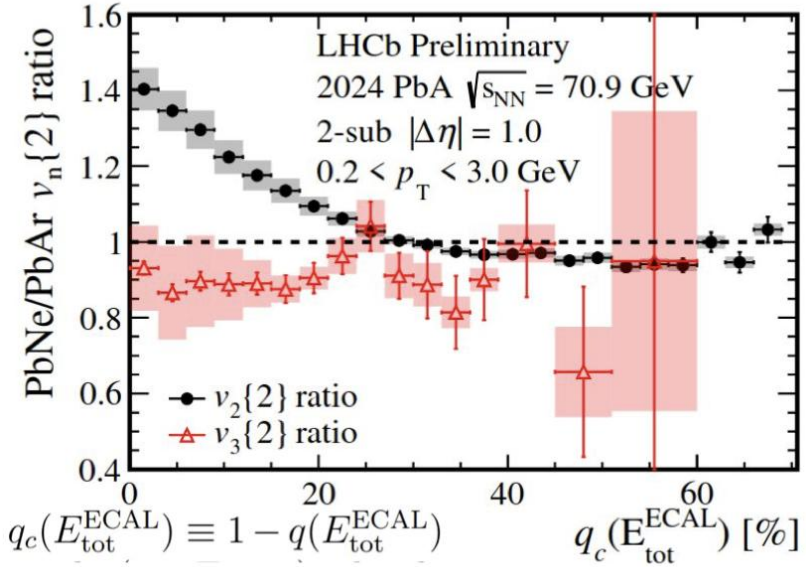


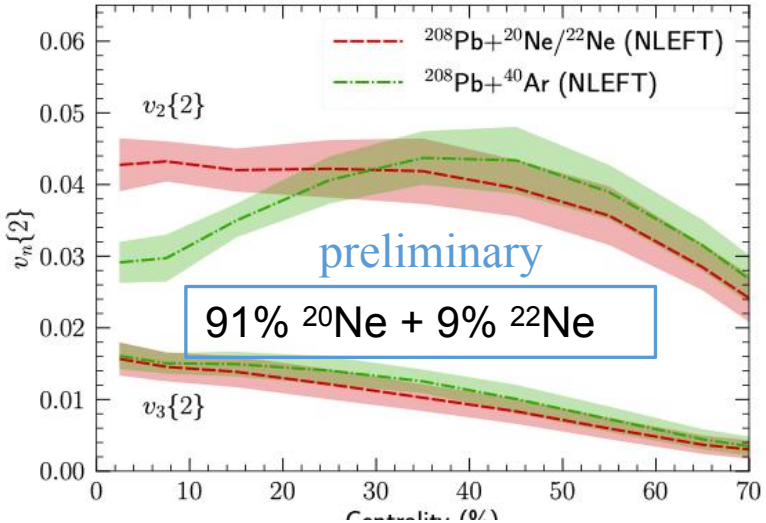
- No QGP-like J/ψ suppression in Pb+Ne.
- Flow sensitive to shapes of Ne and O
- Searching the QGP at LHCb.

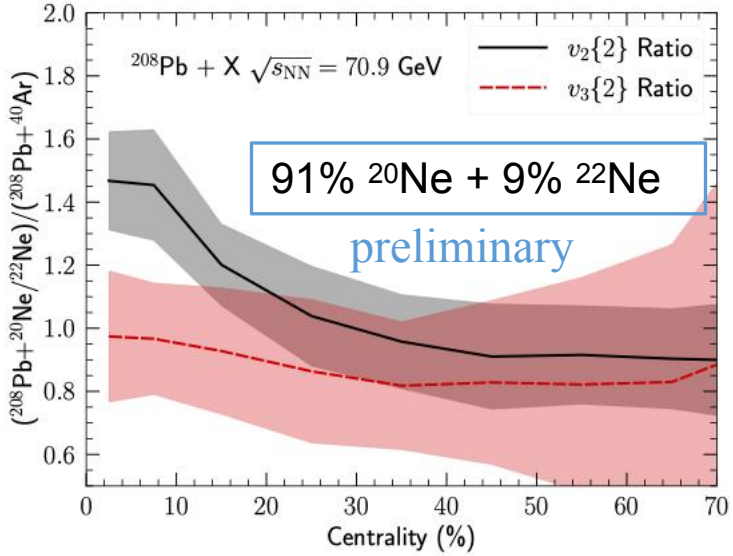
G. Giacalone W. Zhao et al Phys. Rev. Lett. 134, 082301 (2025)

Playing Relativistic Bowling Ball



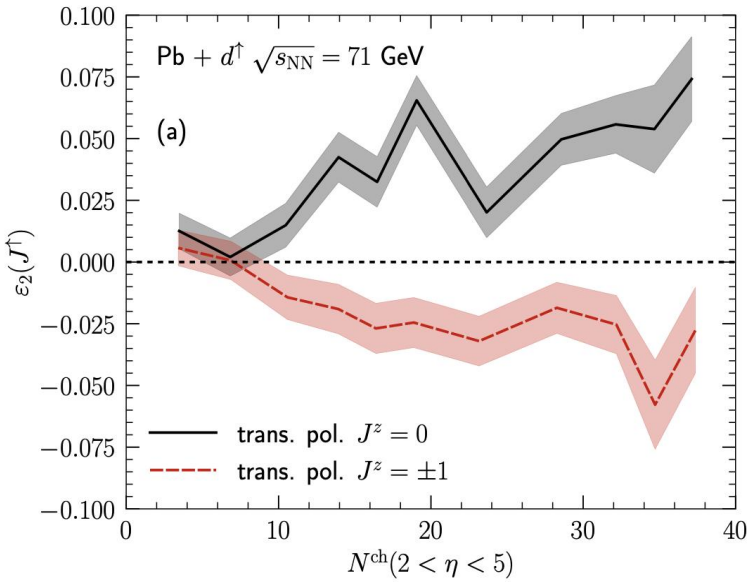


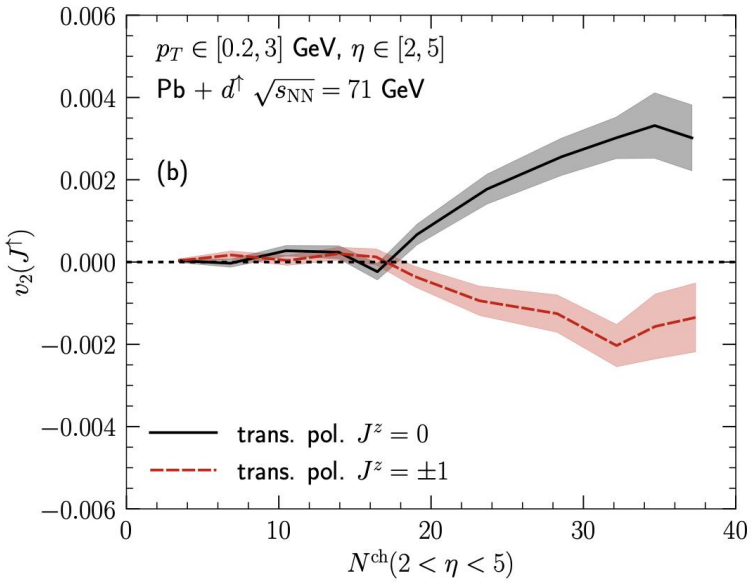


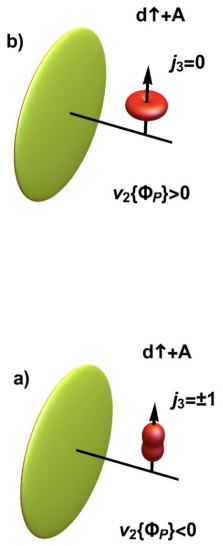


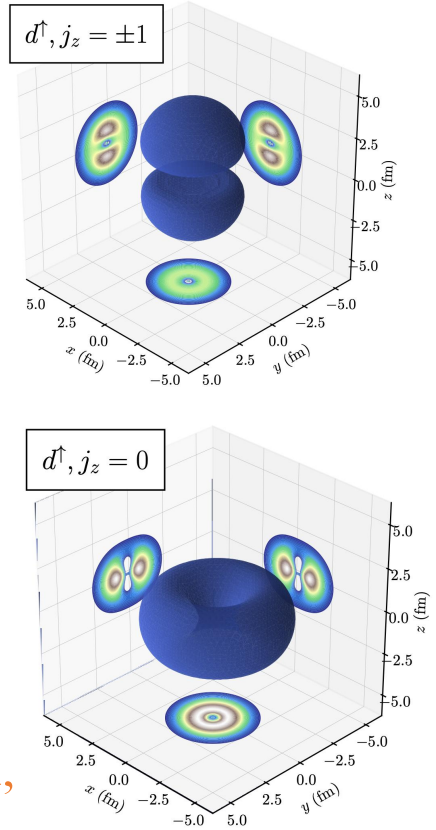
LHCb: [arXiv:2509.12399].

Collective flow in Polarized deuterons + Nuclei





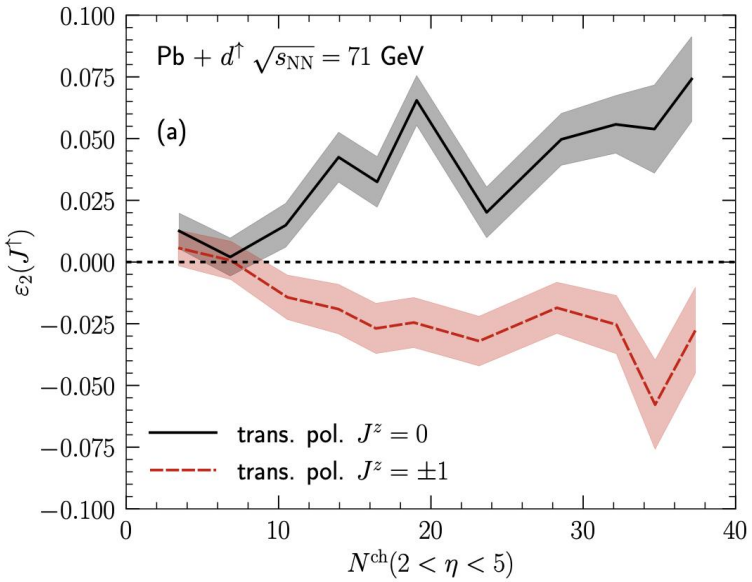


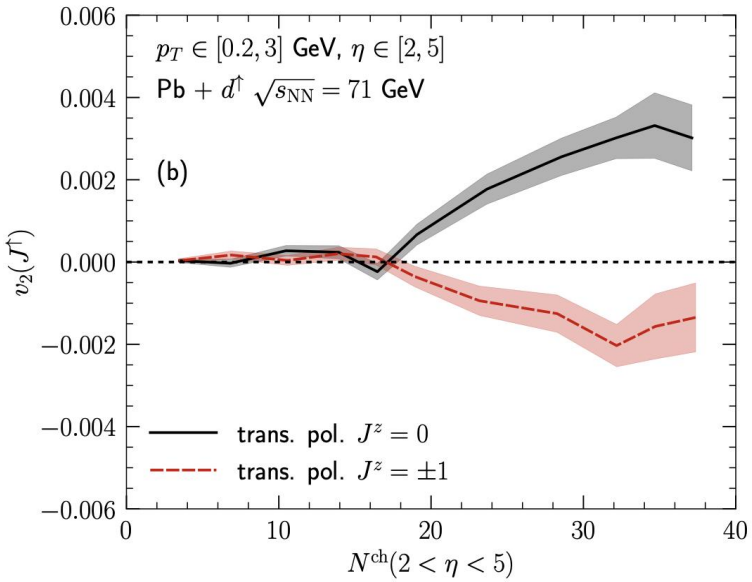


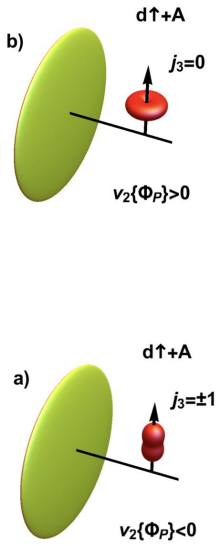
- **Different sign** for $J_z = \pm 1$ and $J_z = 0$. (see also: [P. Bozek and W. Broniowski, PhysRevLett.121.202301.])

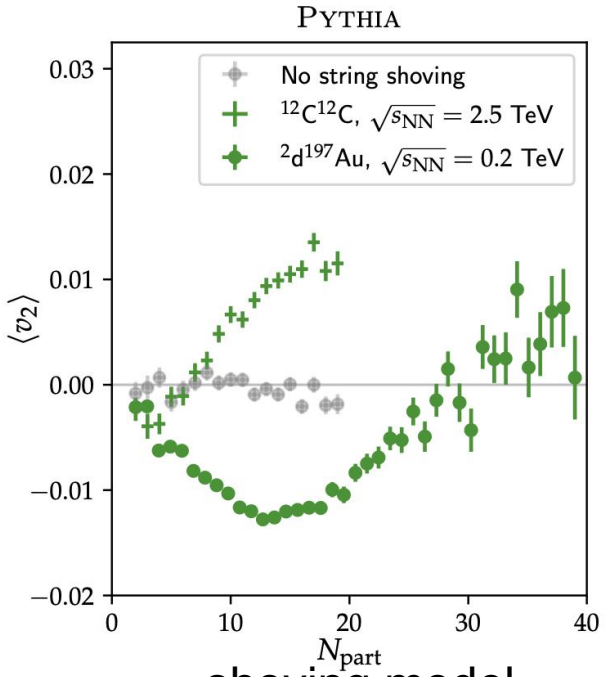
H. Mantysaari, B. Schenke, C. Shen and W. Zhao, [arXiv:2509.00511].
LHCb: [arXiv:2509.12399].

Collective flow in Polarized deuterons + Nuclei









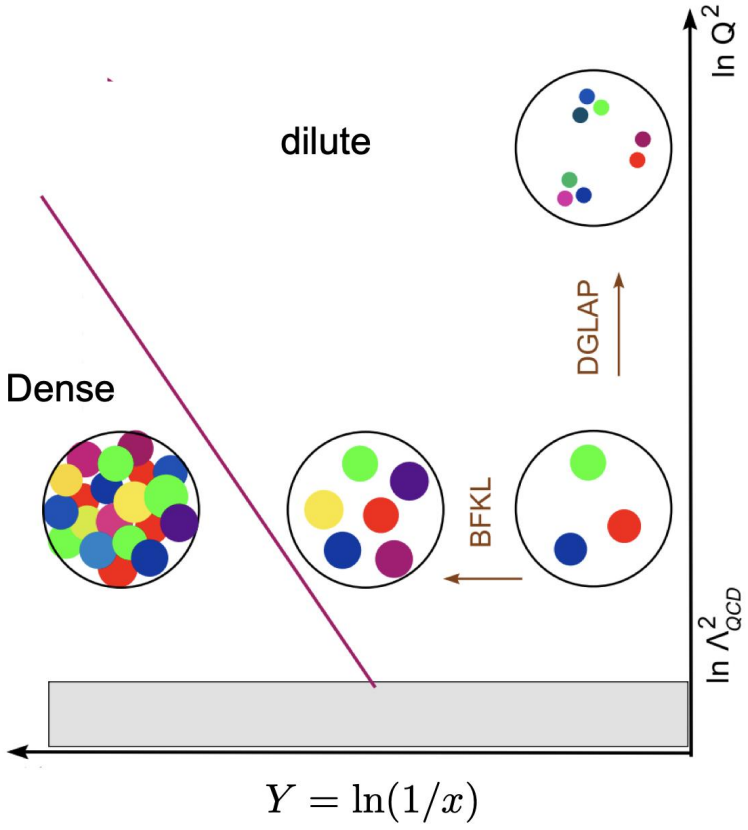
shoving model.
2409.16093

- **Different sign** for $J_z = \pm 1$ and $J_z = 0$. (see also: [P. Bozek and W. Broniowski, PhysRevLett.121.202301.])
- **Opposite sign** comparing to PYTHIA string shoving model [C. Bierlich, P. Christiansen, G. Gustafson, L. Lönnblad, R. Törnkvist, K. Zapp, 2409.16093.].

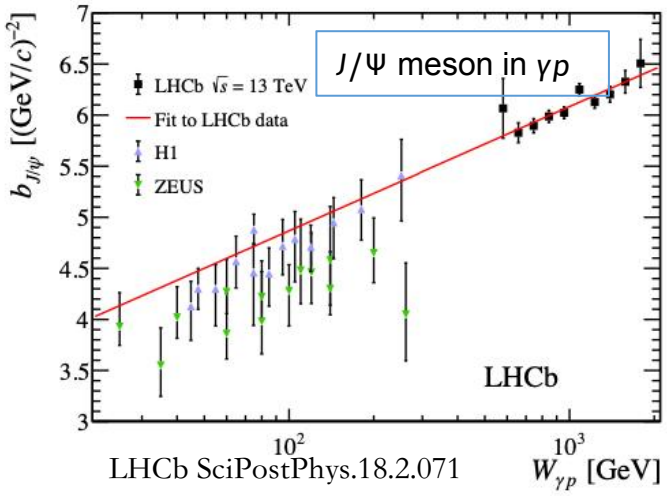
H. Mantysaari, B. Schenke, C. Shen and W. Zhao, [arXiv:2509.00511].

LHCb: [arXiv:2509.12399].

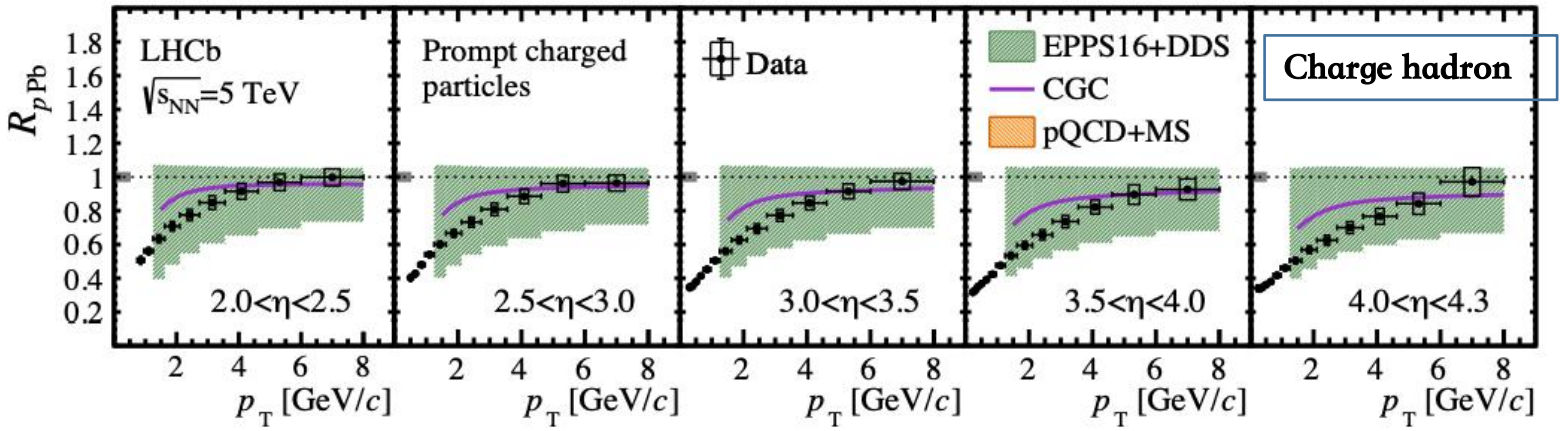
Probing Gluon Saturations



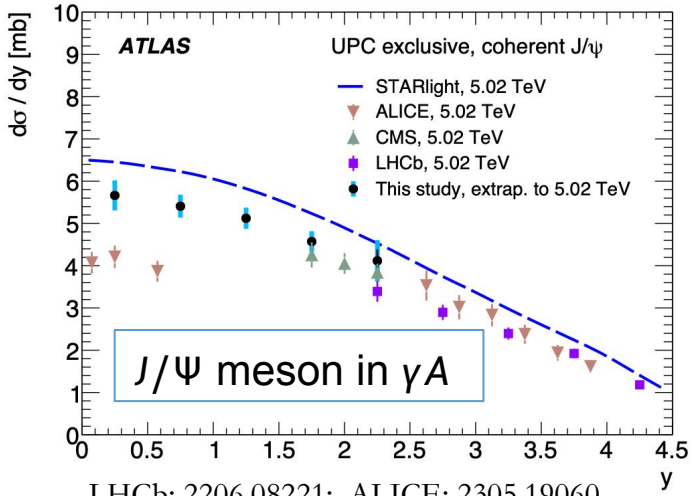
Wealth of Data for the Gluon Saturation Searching



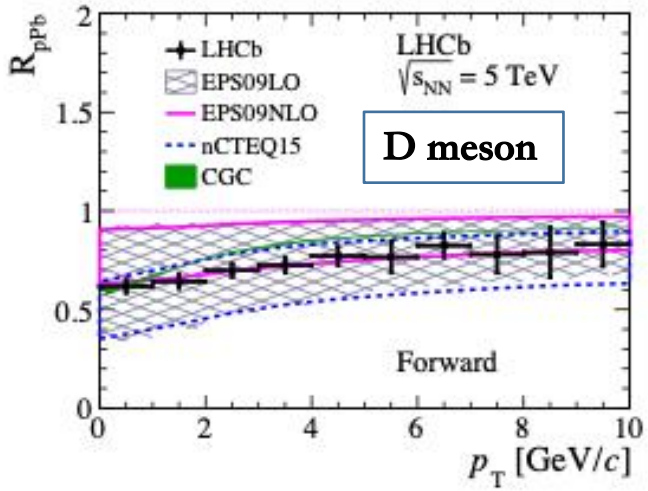
LHCb SciPostPhys.18.2.071



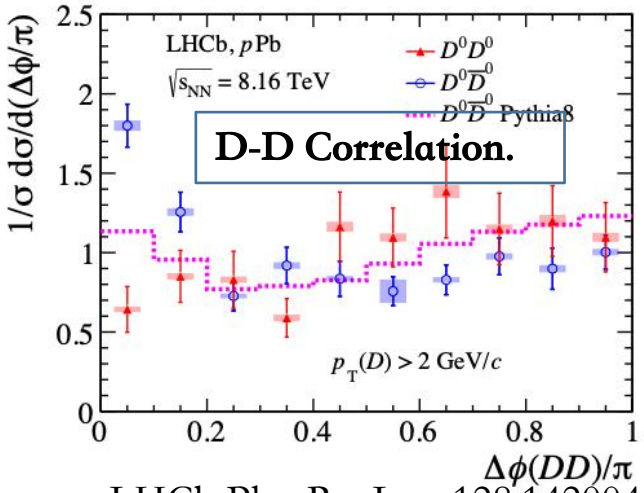
LHCb PhysRevLett.128.142004



LHCb: 2206.08221; ALICE: 2305.19060
CMS: 2303.16984; ATLAS: 2509.04135

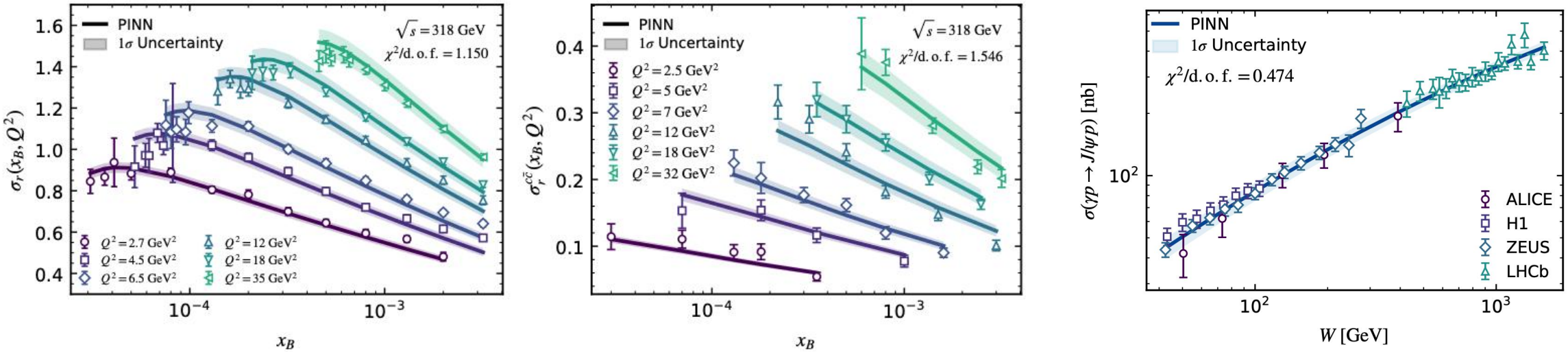


LHCb JHEP01(2024)070.



LHCb PhysRevLett.128.142004

Physics-Informed Global Extraction of the Universal Dipole Amplitude



Loss function in the PINN $\mathcal{L}(\theta, \mathbf{p}) = w_1\mathcal{L}_{\mathrm{ciBK}} + w_2\mathcal{L}_{\mathrm{data}} + w_3\mathcal{L}_{\mathrm{phy}},$

- $w_1\mathcal{L}_{\mathrm{ciBK}}$: for ciBK evolution
- $w_2\mathcal{L}_{\mathrm{data}}$: quantifies agreement with data
- $w_3\mathcal{L}_{\mathrm{phy}}$: additional physical constraints

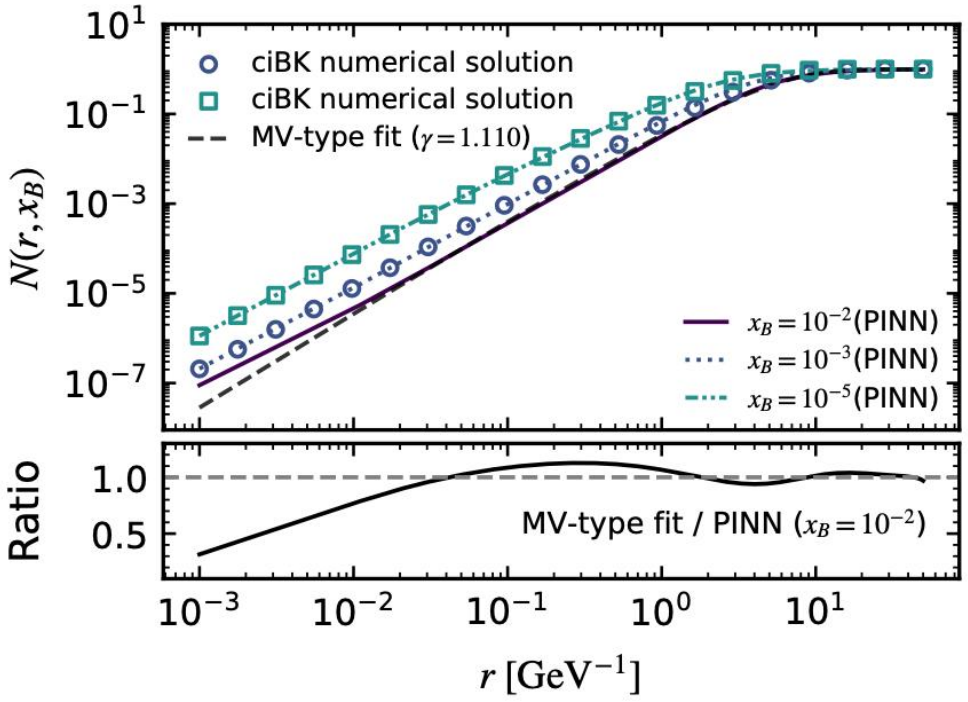
- PINN extracts an **universal** amplitude constrained by the **CiBK.**
- **Simultaneously** constrained by reduced **total** and **charm quark** DIS cross sections, exclusive **J/ψ data.**

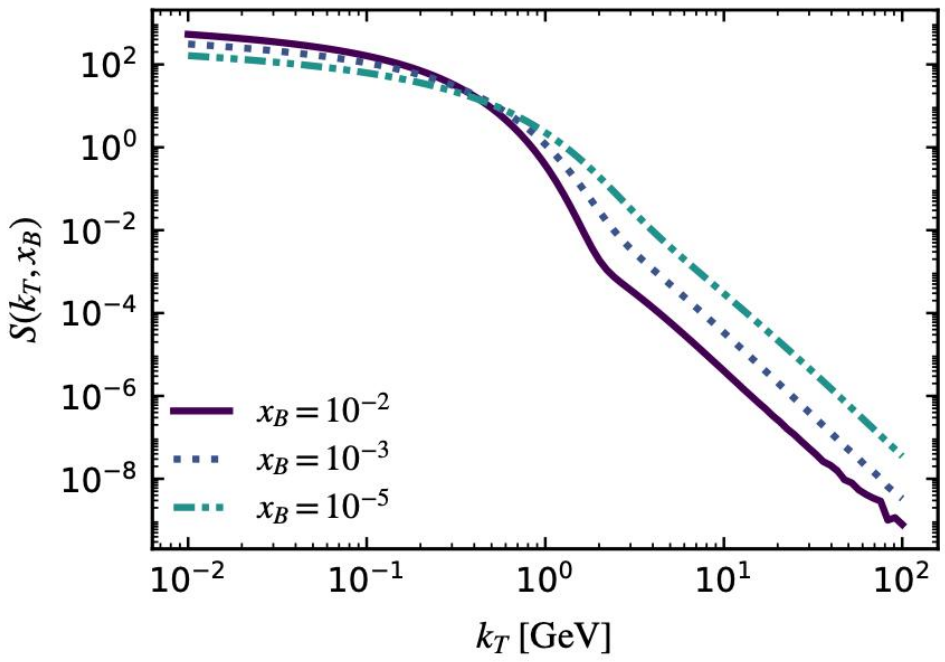
S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008.

The dipole amplitude is available: **https://doi.org/10.5281/zenodo.18826120**

- **Recent NLO extraction**: C. Casuga and H. Mantysaari, [arXiv:2604.22332].

Dipole Amplitude of Proton



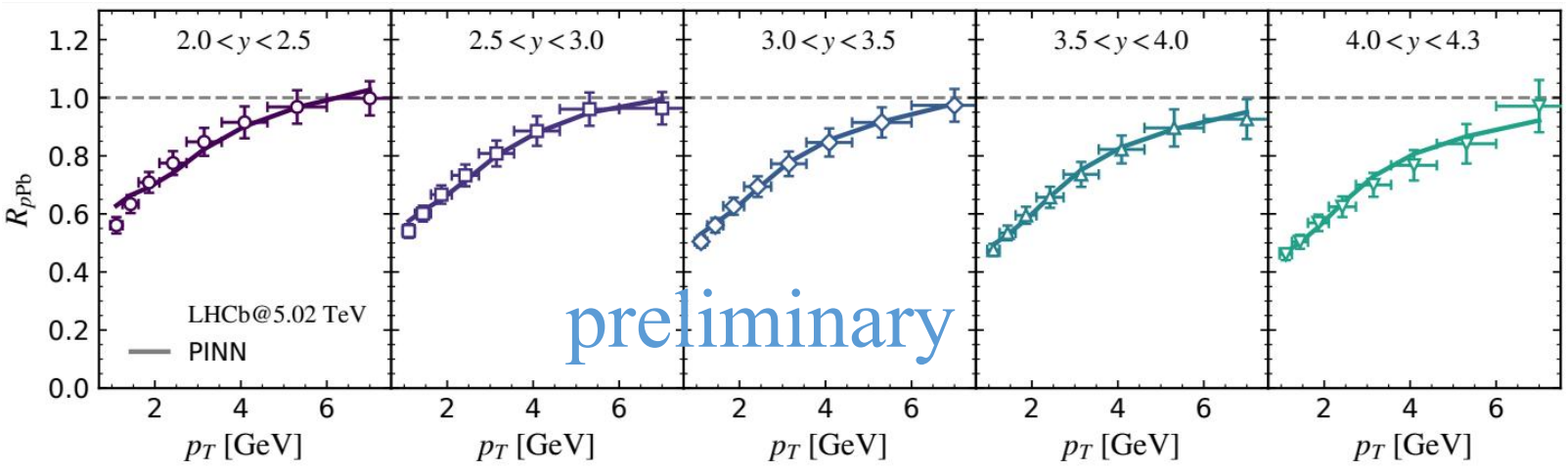


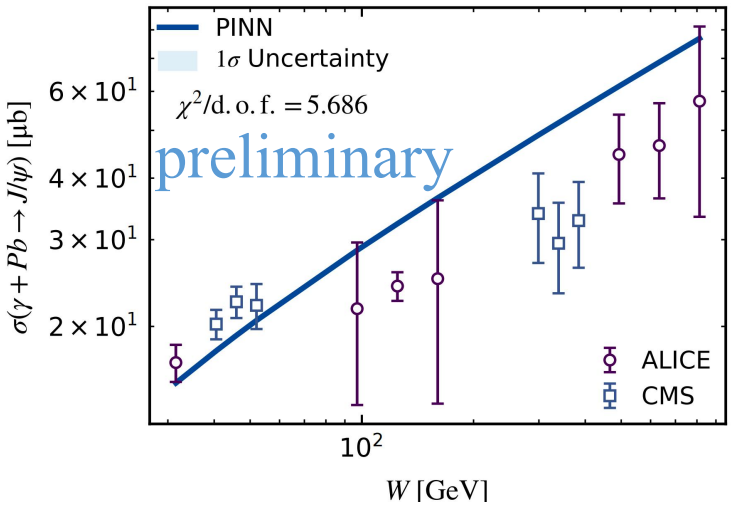
- **Without** imposing priori MV-type parametrization of initial condition.
- Keep the **positivity for the momentum-space amplitude.**

S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008.

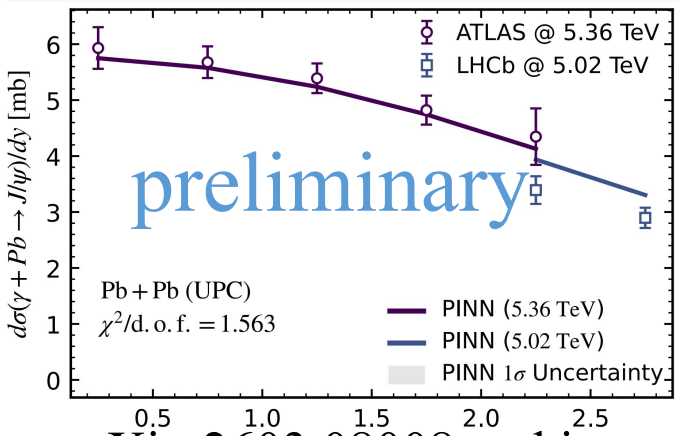
The dipole amplitude is available: **https://doi.org/10.5281/zenodo.18826120**

Global Extraction of the Nuclear Dipole Amplitude





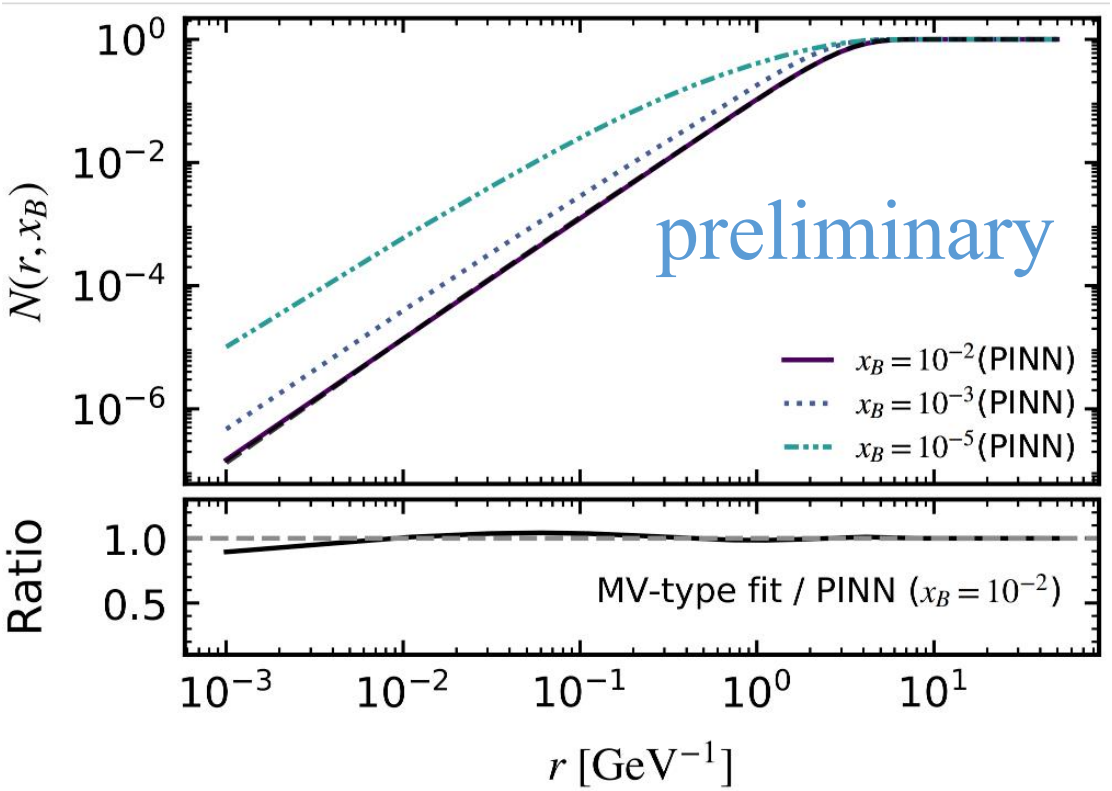
- PINN extracts an **universal** Pb amplitude constrained by **RpPb** an exclusive **J/ψ data.**



S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008 and in progess.

The dipole amplitude is available: https://doi.org/10.5281/zenodo.18826120

Dipole Amplitude of Pb



- **Without** imposing priori MV-type parametrization of initial condition.
- MV-type fit of Pb is **better than proton.**

S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008 and in progess.

The dipole amplitude is available: **https://doi.org/10.5281/zenodo.18826120**

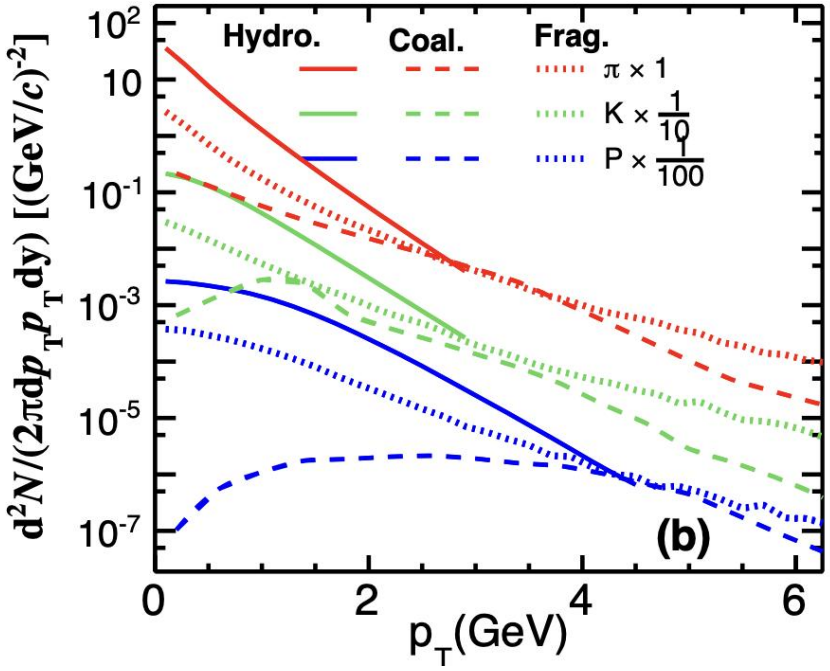
Summary

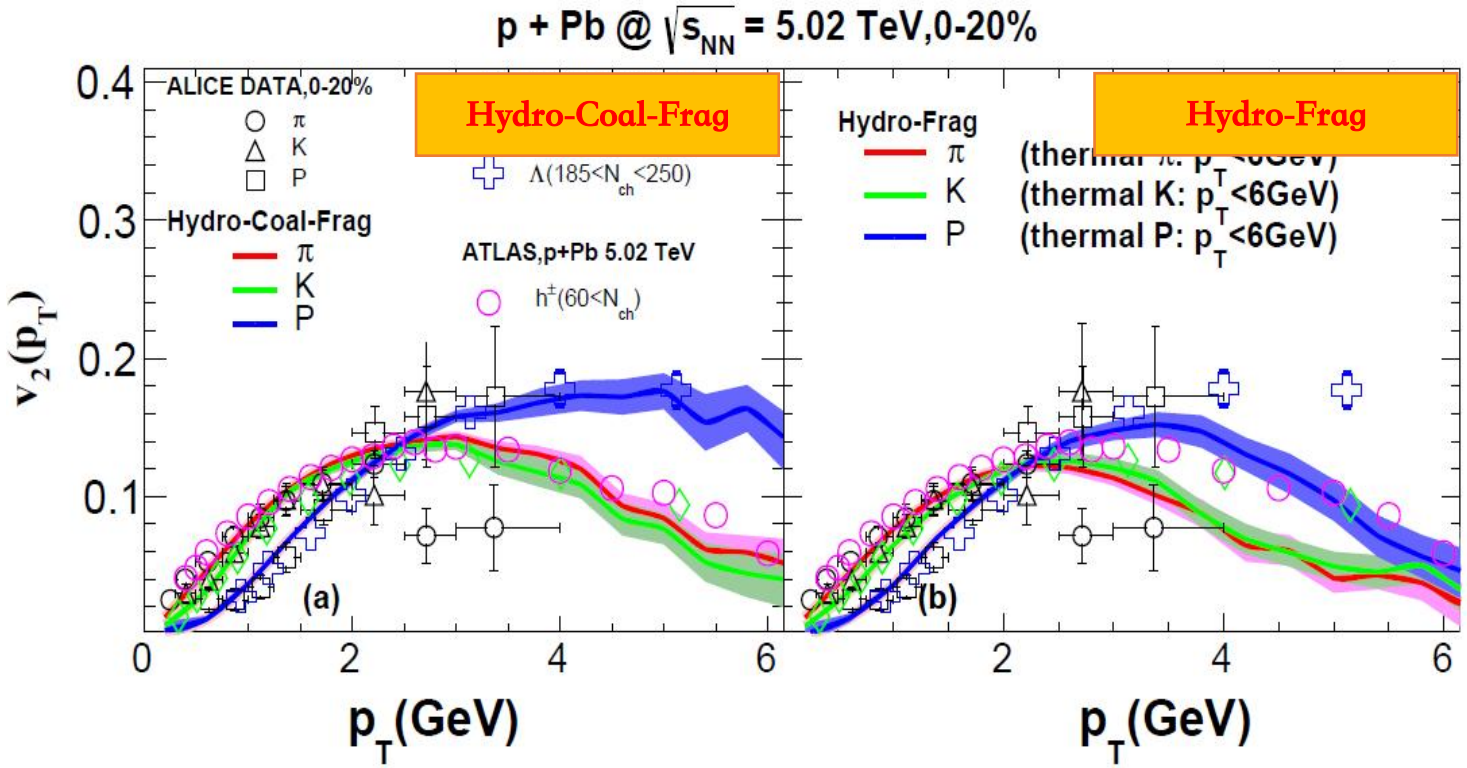
- Heavy-ion Collision have been into the **multi-messenger** era.
- We are searching the **"smallest droplet"** on the earth.
- UPC/EIC provide **a multi-scale image** tool for nuclei, serve as a **complementary tool** to constrain initial conditions.
- LHCb provides a unique opportunity to study **nuclear structures, small-system QGP** and **gluon saturation signals.**

Thanks for Your Attention!

Back Up

Study the hadronization mechanisms

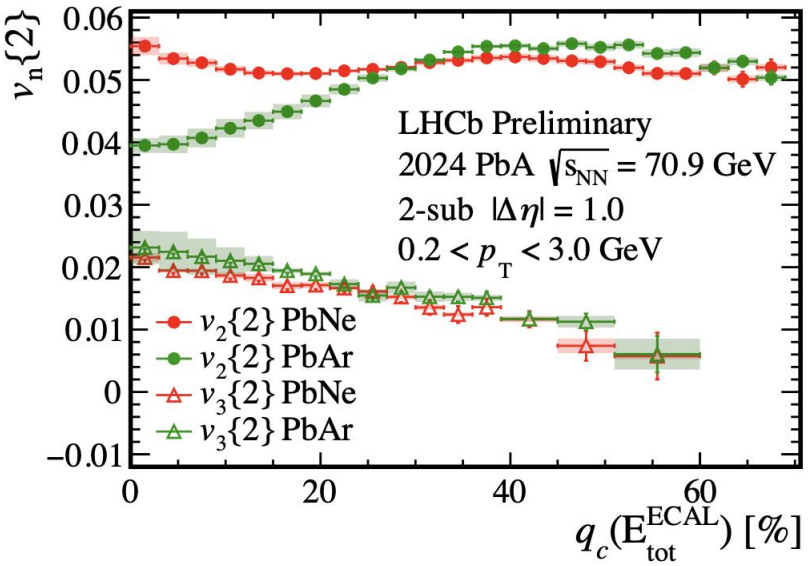


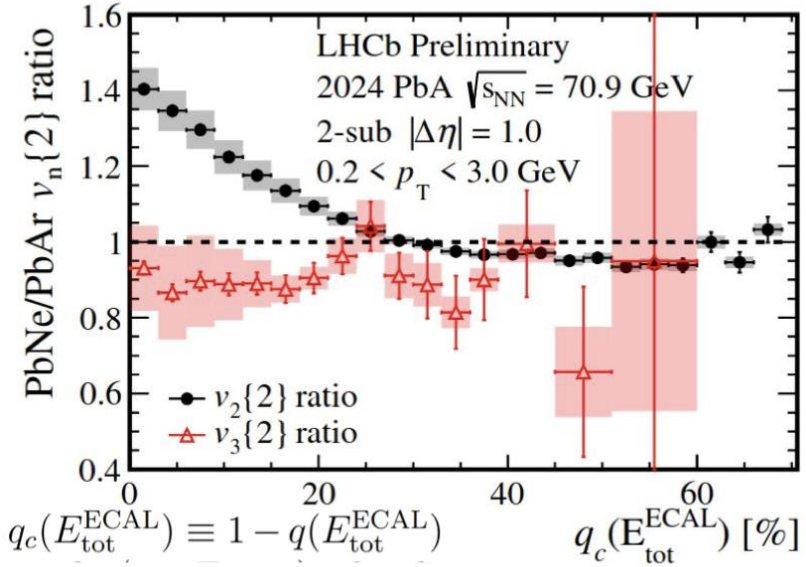


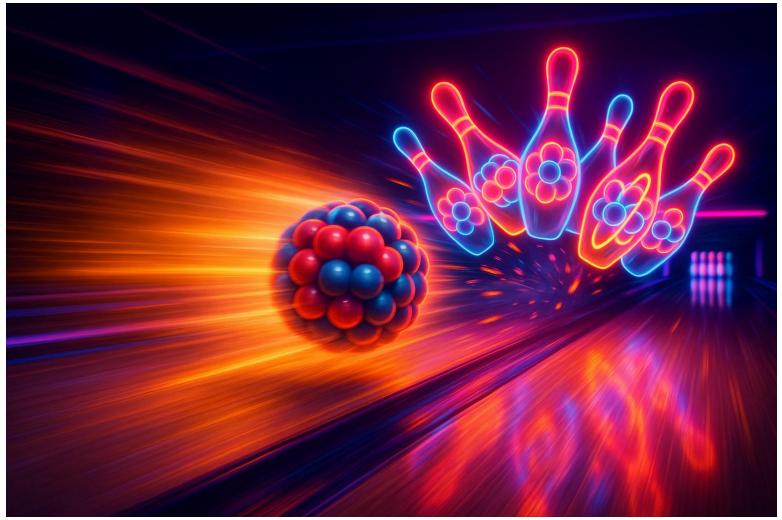
W,Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301 (2020).
ALICE: [arXiv:2411.09323].

- Probe the **partonic degree of freedom** in heavy-ion Collisions.

Playing Relativistic Bowling Ball



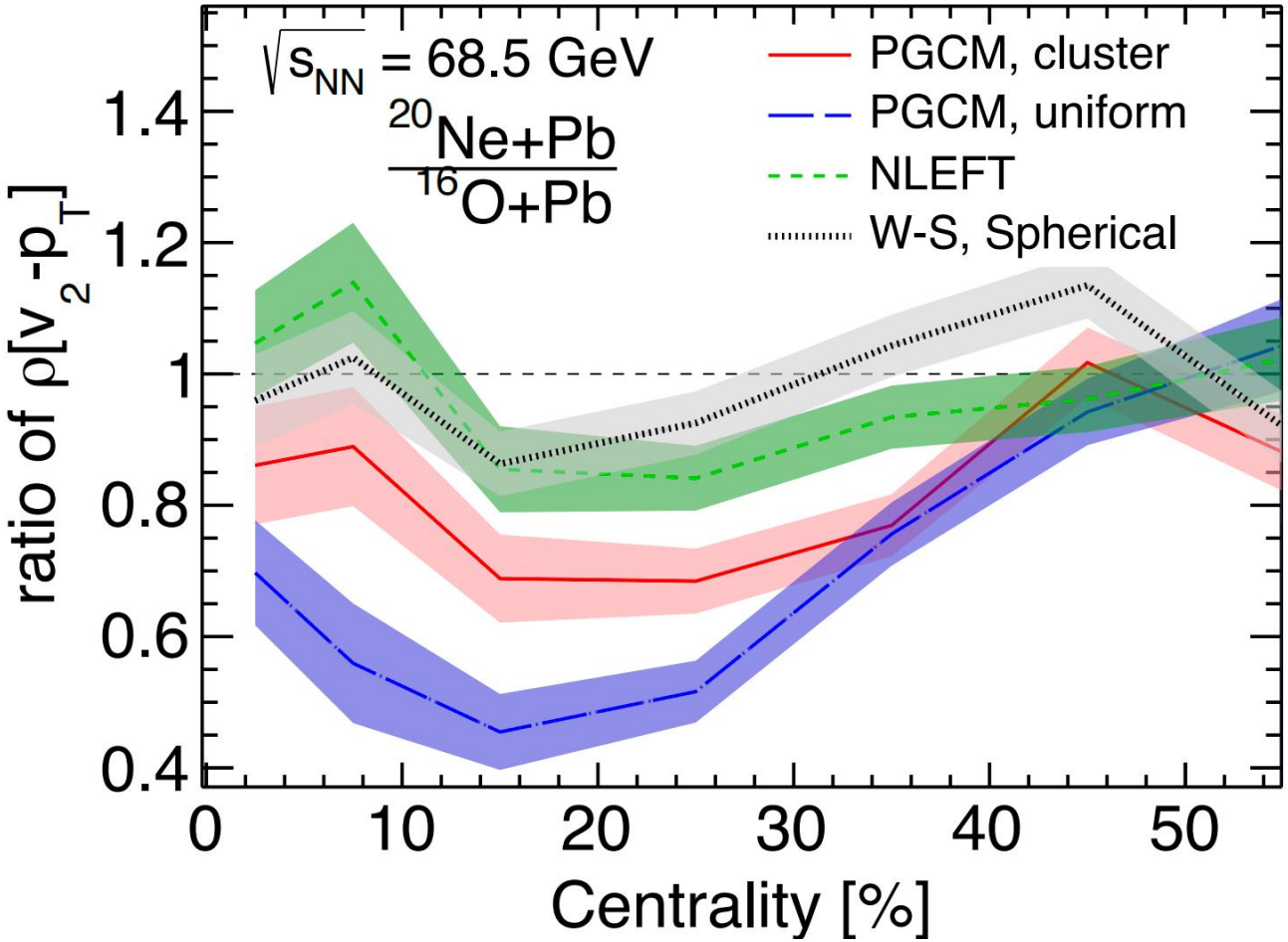




(Generated by ChatGPT)

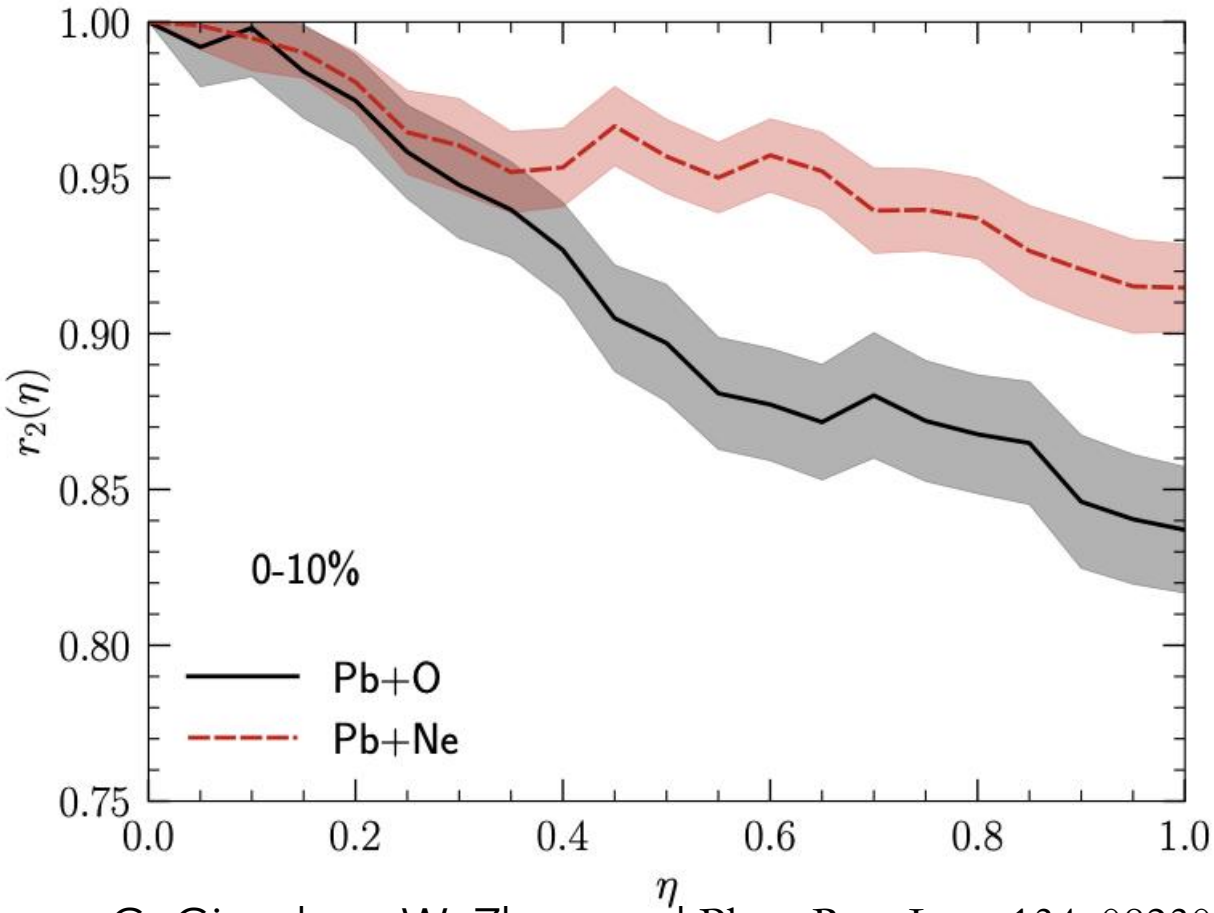
LHCb: [arXiv:2509.12399].

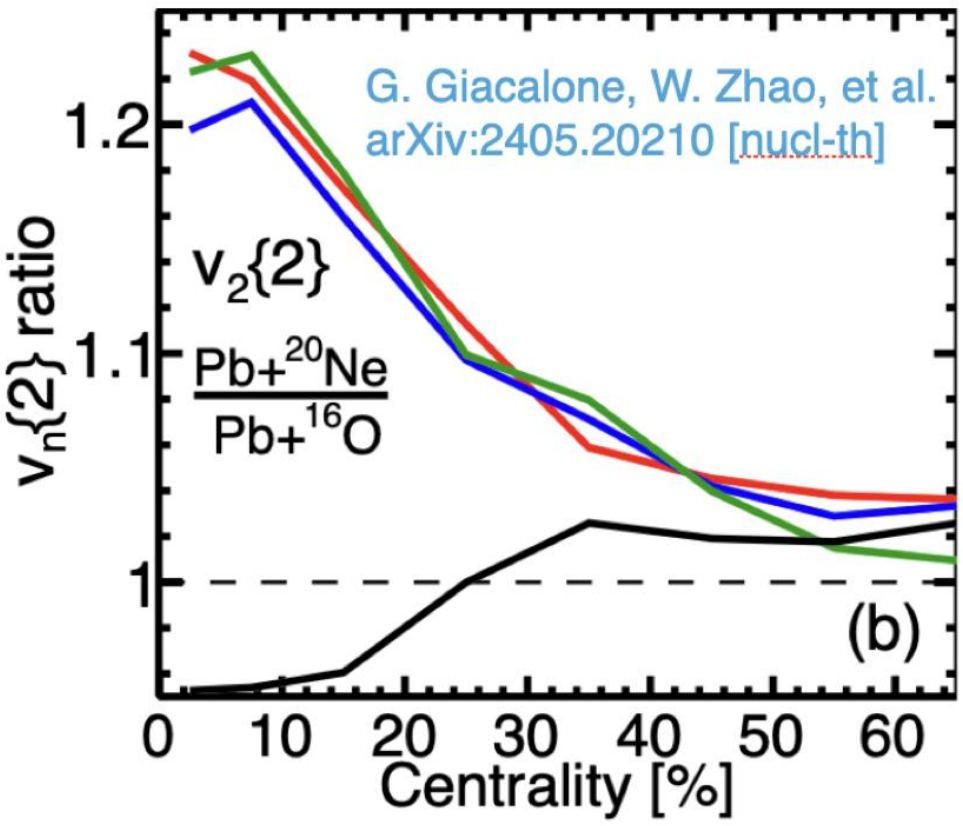
Tell Different Bowling Pining Shapes



- The ratio of $v_2 - p_T$ correlators.

Longitudinal Dynamics





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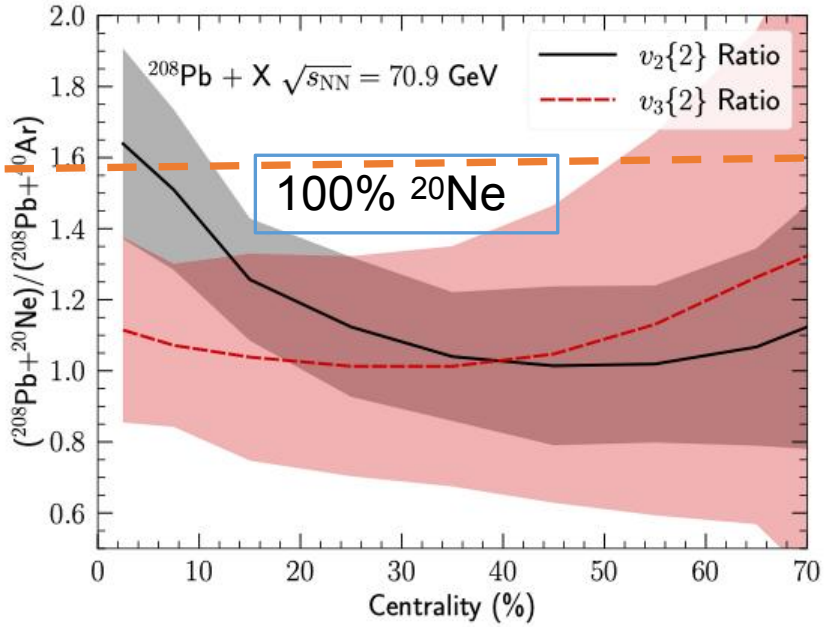
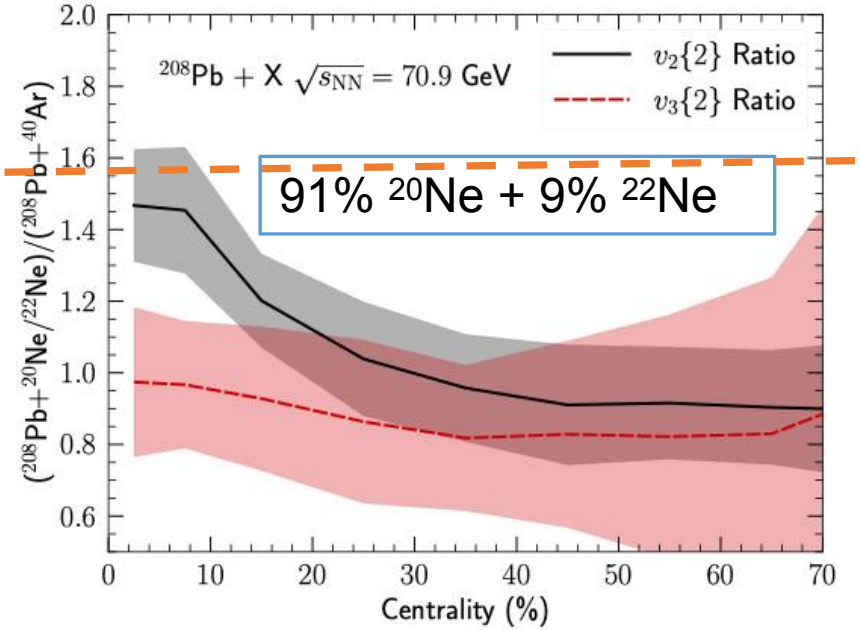
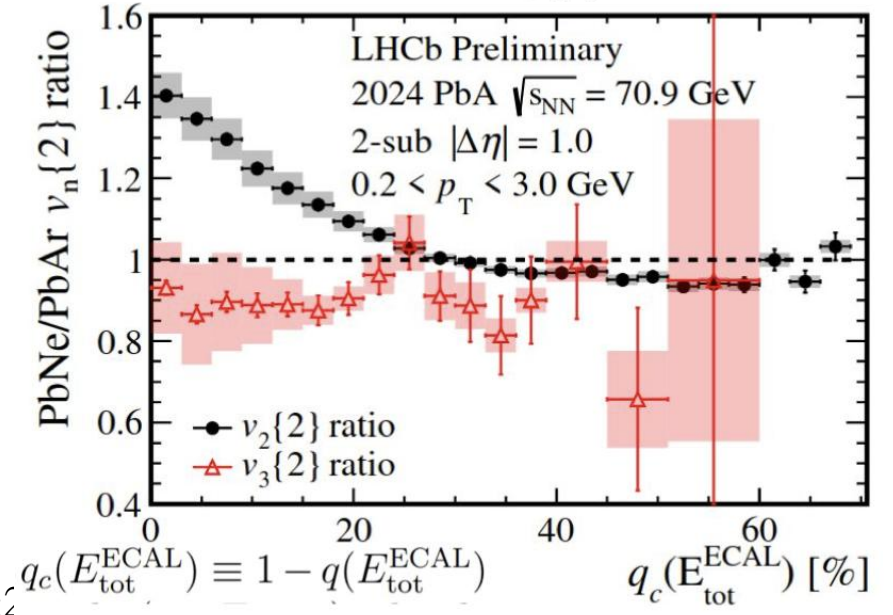
- The elliptic flow decorrelation in PbO is larger than in PbNe collisions.

Playing Relativistic Bowling Ball



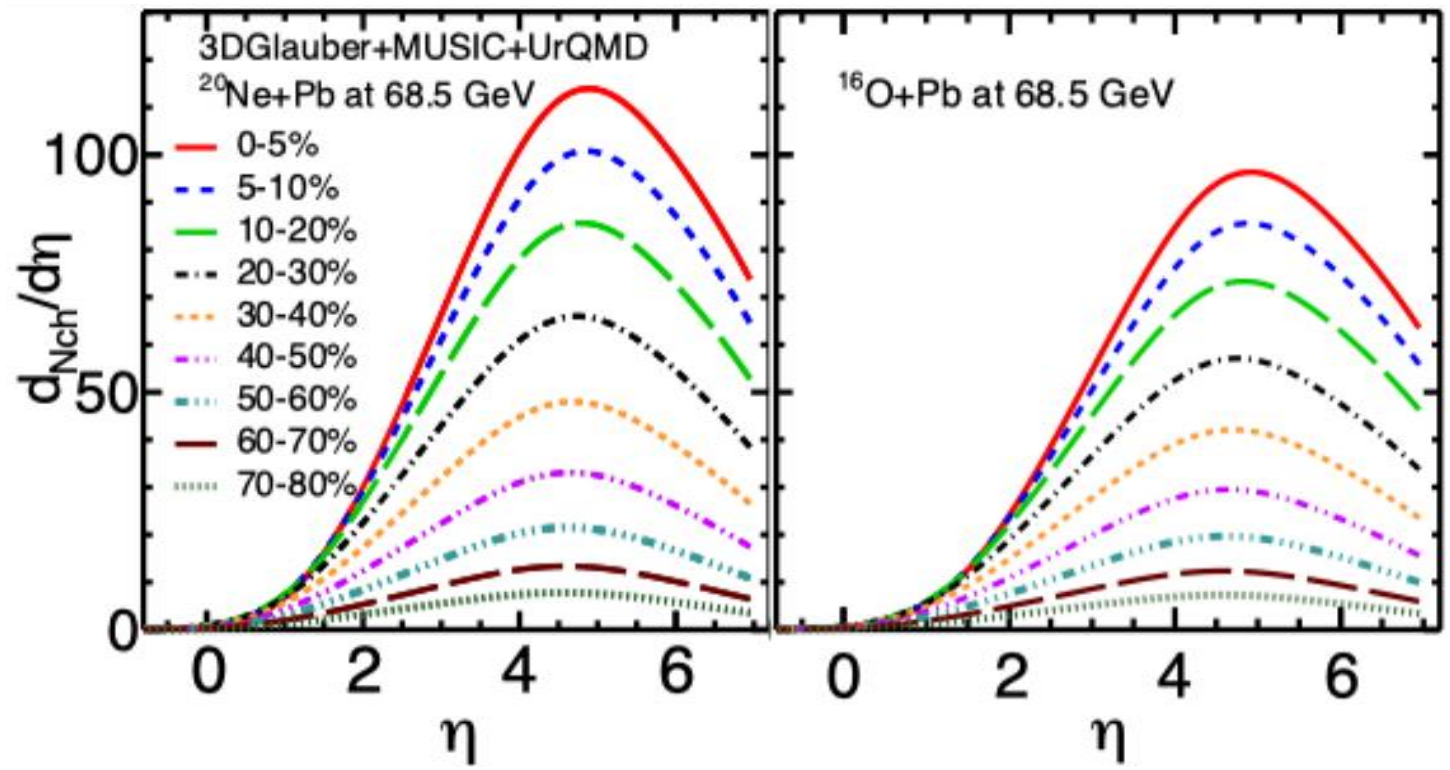


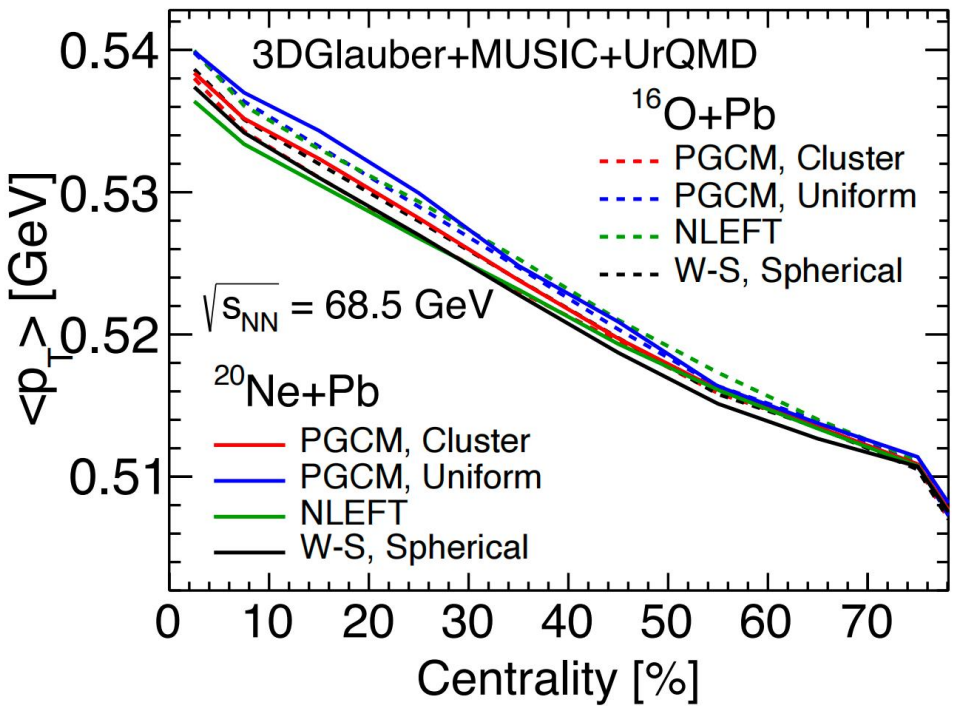
- Mixing 9% of ^{22}Ne has a sizable effect on the v_n ratio.



LHCb: [arXiv:2

3+1 D Hydrodynamics Simulations





- Strong asymmetric in longitudinal direction, need 3+1D simulations.
- Mean p_T.

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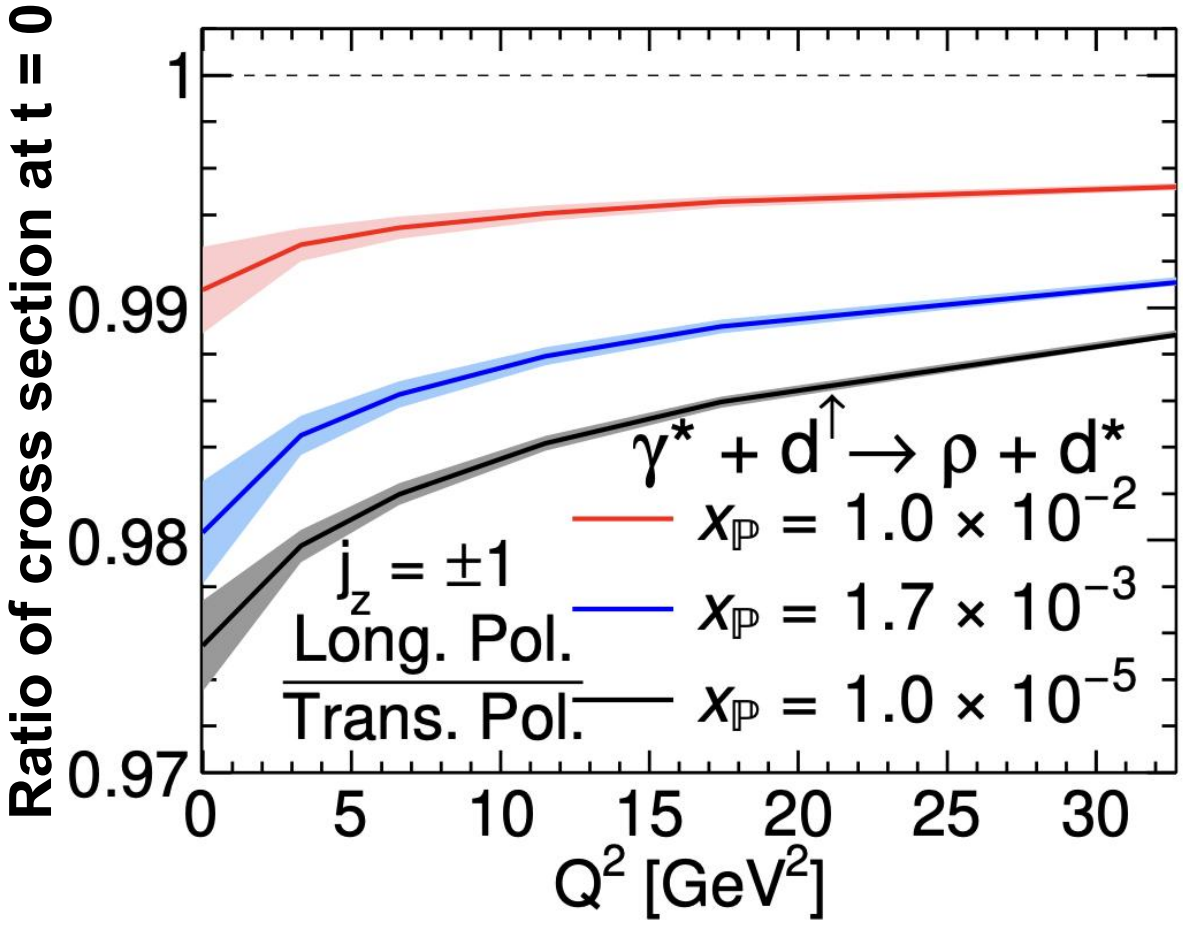
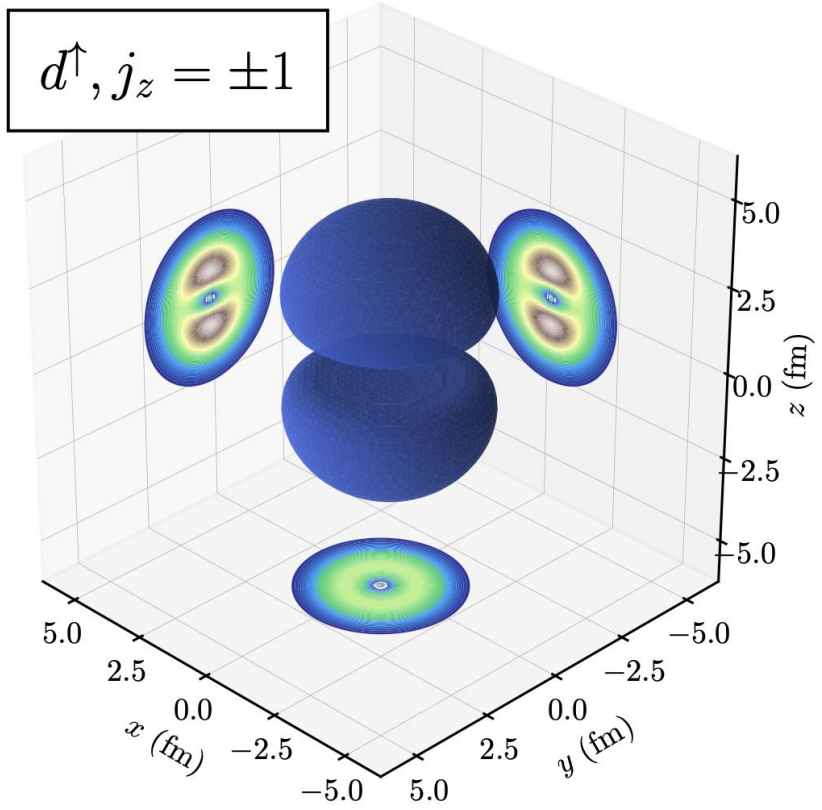
Probe Saturation Signal in $e + d^{\uparrow}$

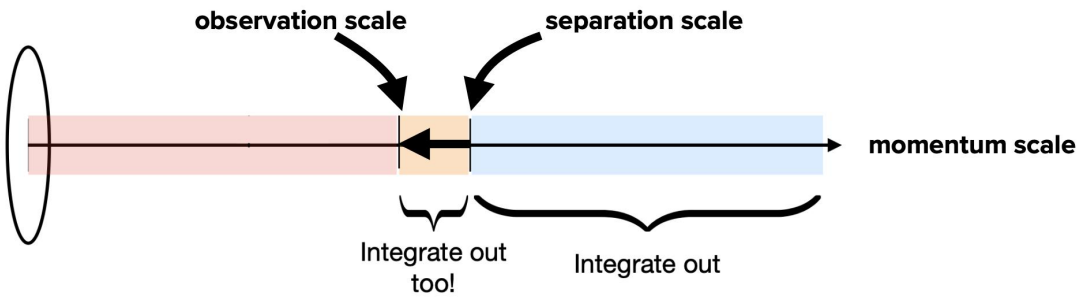




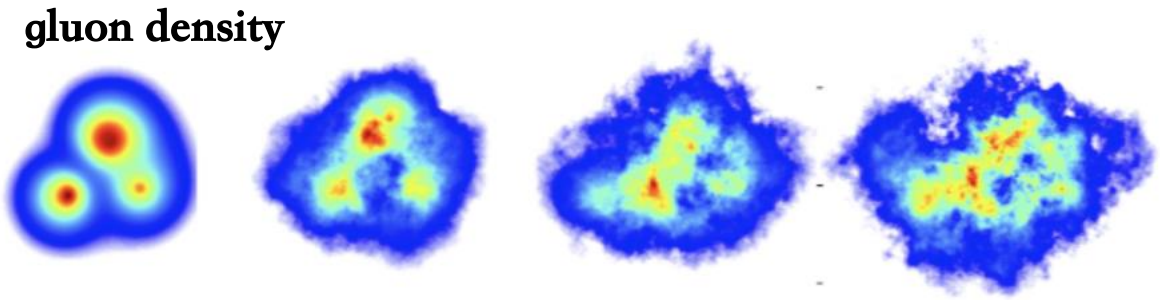
- Longitudinal-to-transverse ratio is below one.
- Smaller Q^2, the smaller ratio; Smaller x, smaller ratio.

H.Mantysaari, F. Salazar, B.Schenke, C. Shen and W. Zhao, physletb.2024.139053.

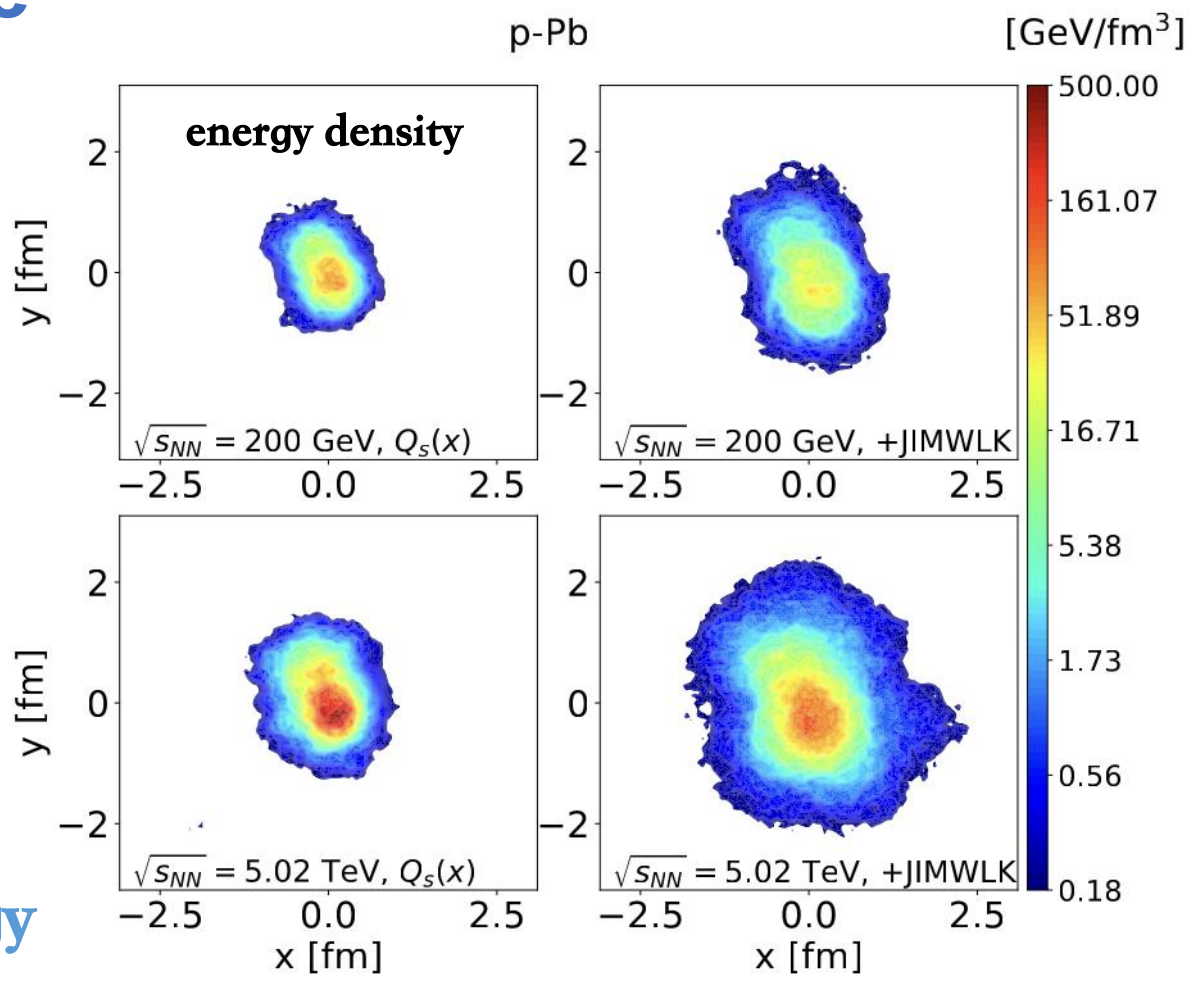
Energy evolution of initial state



A. Morreale and F. Salazar, Universe 7, no.8, 312 (2021).



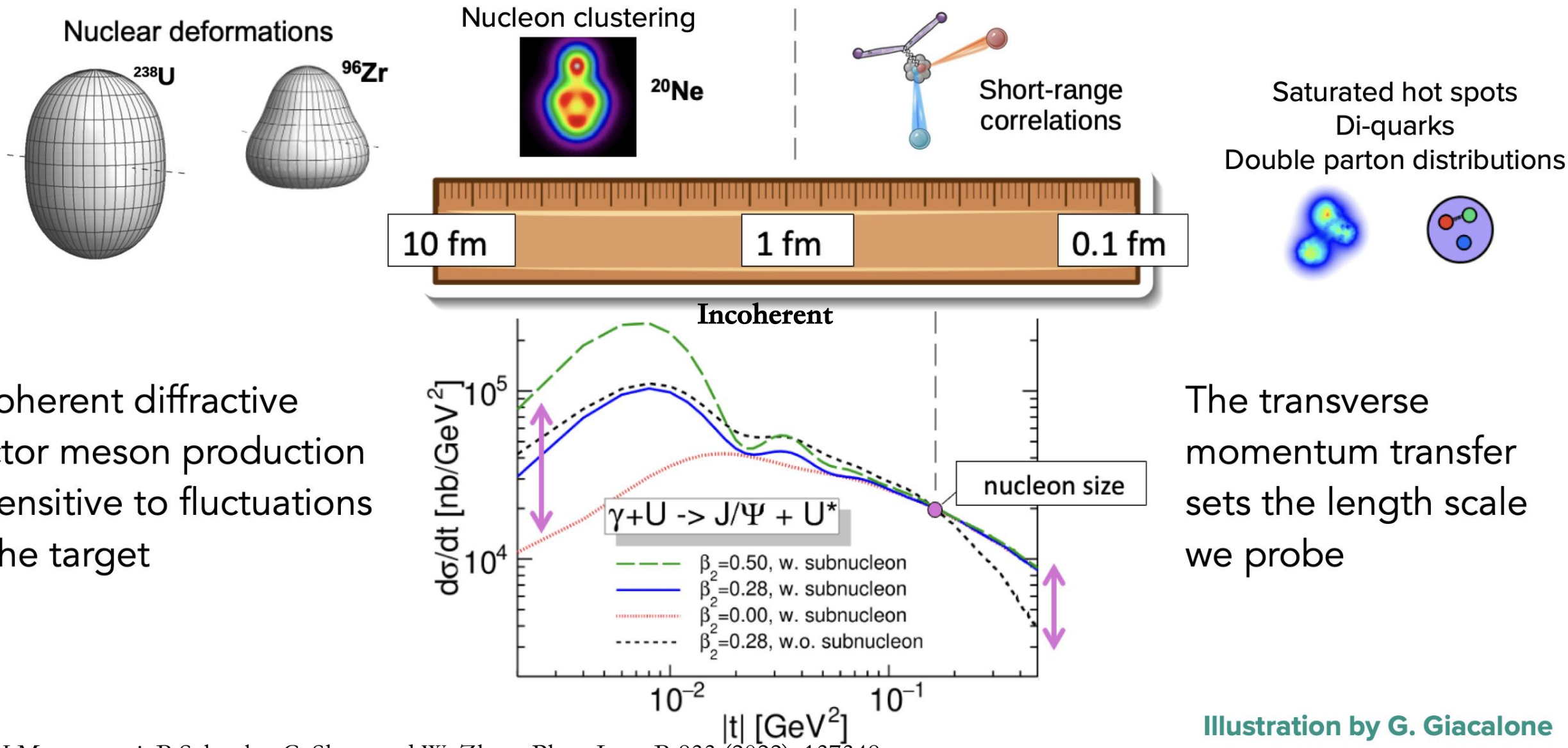
Low energy (UPC/DIS) → High energy (LHC)



- Energy evolution of the initial state.

H. Mäntysaari and B. Schenke, PRD 98 (2018) 034013.
H. Mäntysaari, B. Schenke, C, Shen and W. Zhao, PRL. 135, 022302 (2025)

“X-ray vision” for atoms.



Incoherent diffractive vector meson production is sensitive to fluctuations in the target

The transverse momentum transfer sets the length scale we probe

Illustration by G. Giacalone

H.Mantysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348.
H.Mantysaari, B.Schenke, C. Shen and W. Zhao, PhysRevLett.131.062301.