Connections between Heavy-ion Collisions and Electron-Ion Collisions

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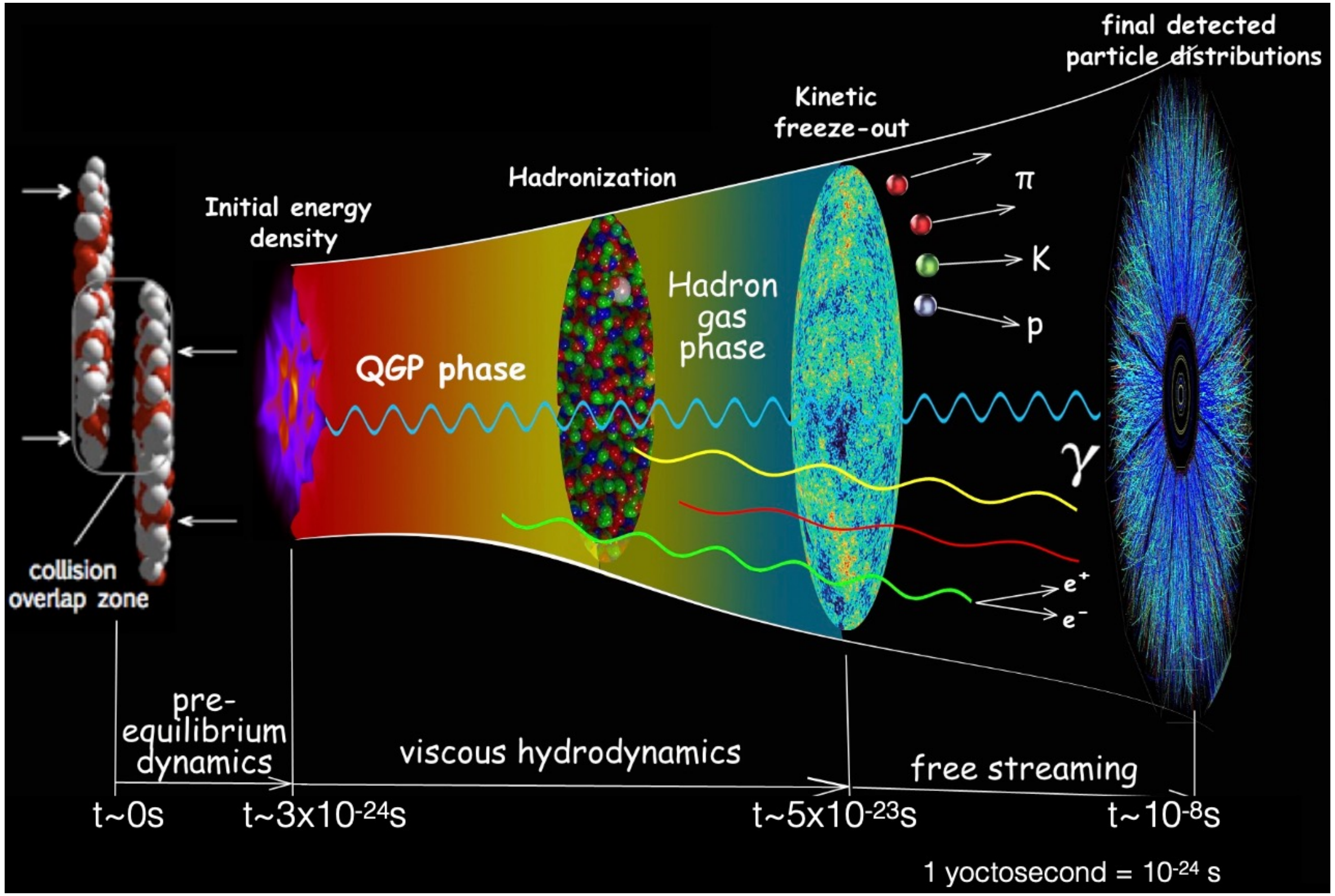
Nov. 1st, 2025, Xinxiang, Henan, China

Nuclear Matter under Extreme Conditions

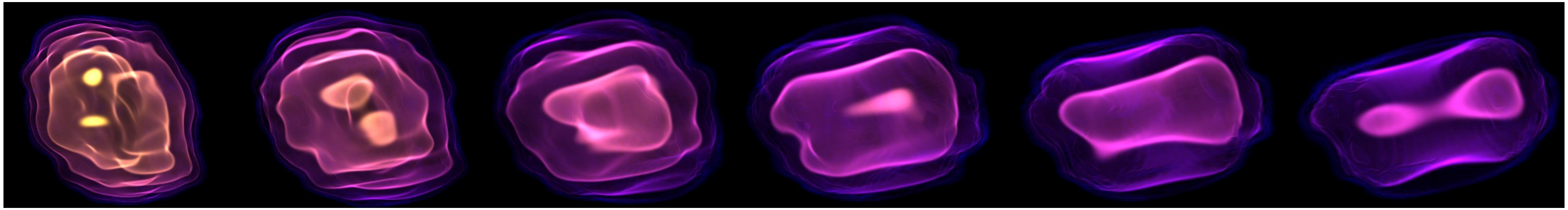


Credit: Chun Shen

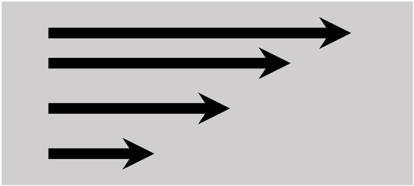
- Heavy-ion collision dynamics is complex with multiple length/time scales.
- What is the **smallest QGP droplet**?
- What is the **structure of QCD phase diagram**?
- How does the strongly coupled liquid emerge from fundamental QCD interactions?
- Constrain the **nuclear structures** by final state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

QGP transport property

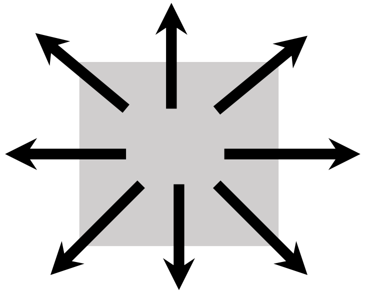
- Quark Gluon Plasma behaviors like fluid, evolved in relativistic viscous hydrodynamics.



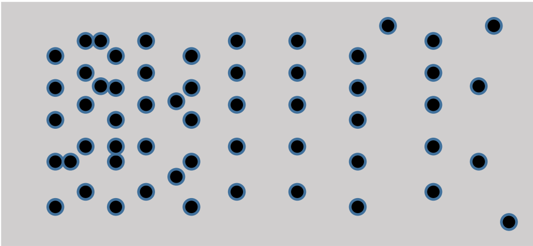
- Effects from dissipative components.



Shear viscosity acts against the buildup of flow gradients.

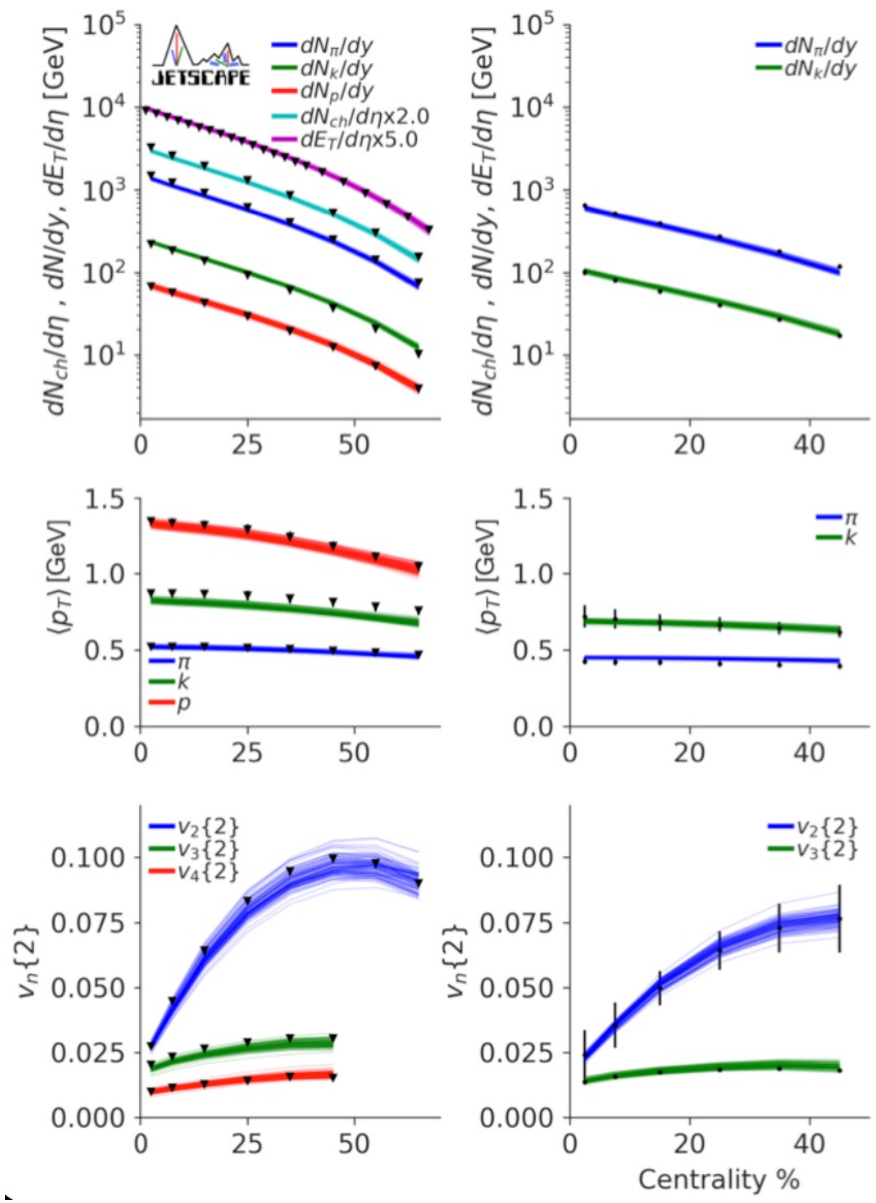


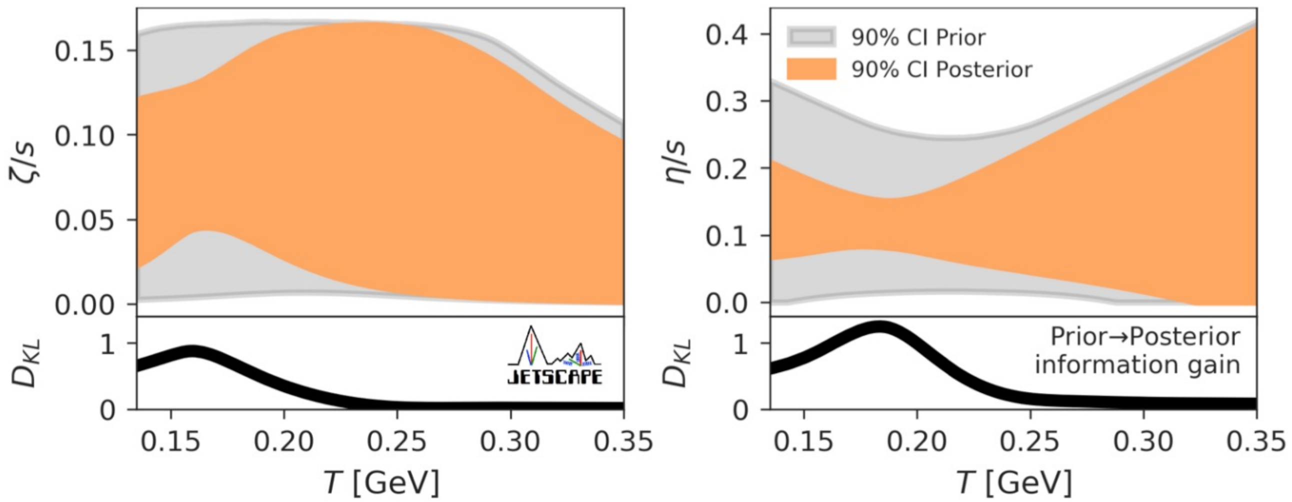
Bulk viscosity acts against the buildup of radial flow and longitudinal expansion



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

Global Bayesian Constrains on QGP Viscosity

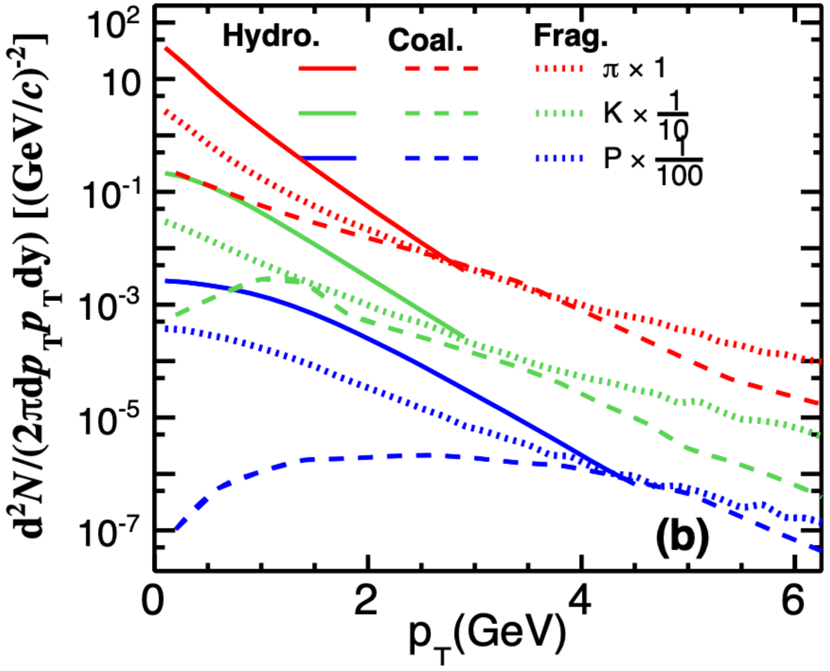


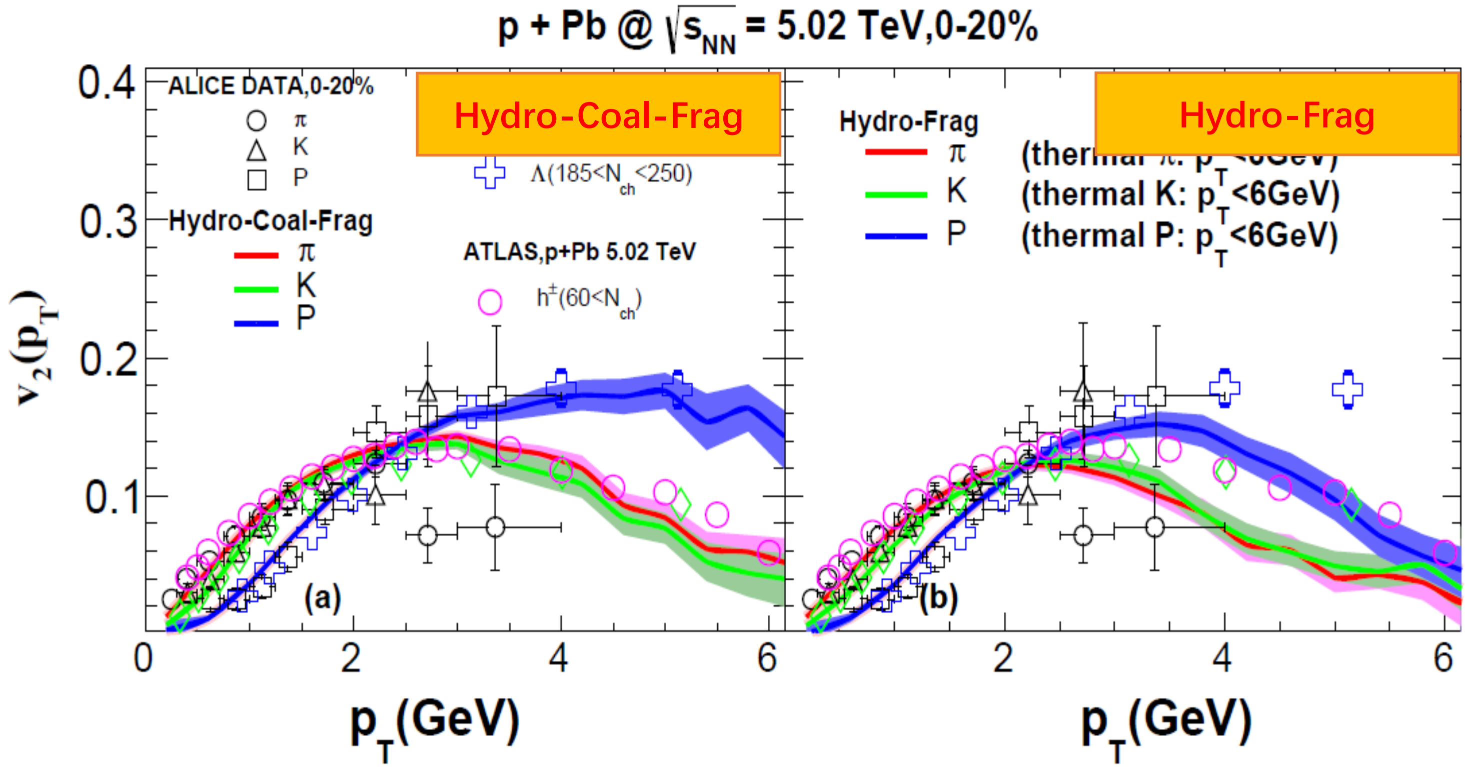


- An era of extracting robust and precise properties of QCD matter from **multi-messenger** measurements.

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).

Study the hadronization mechanisms





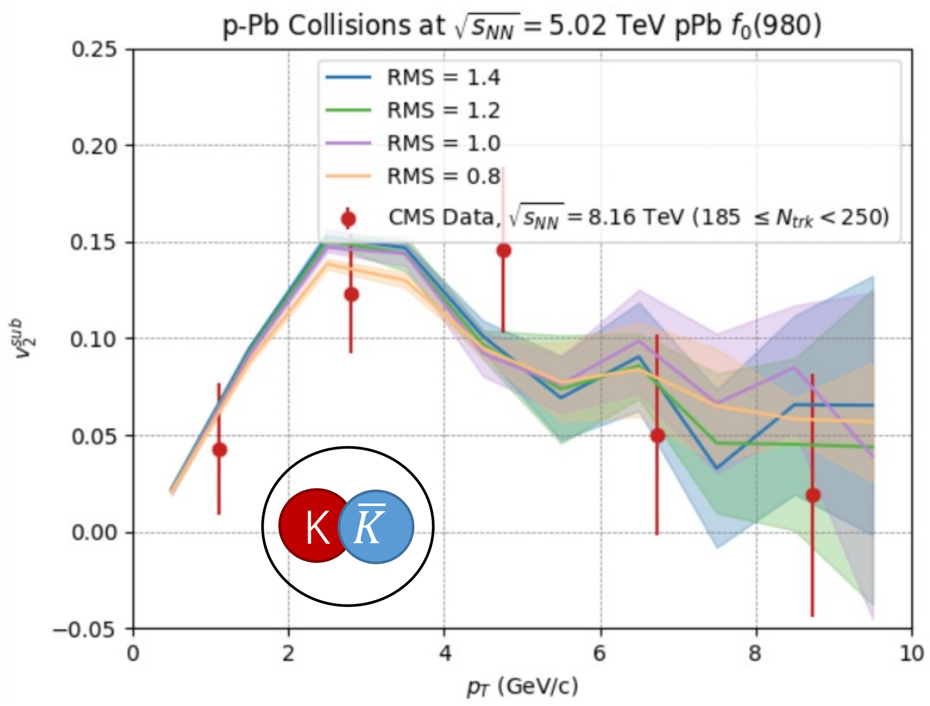
Hydro. Coalescence,fragmentation fragmentation

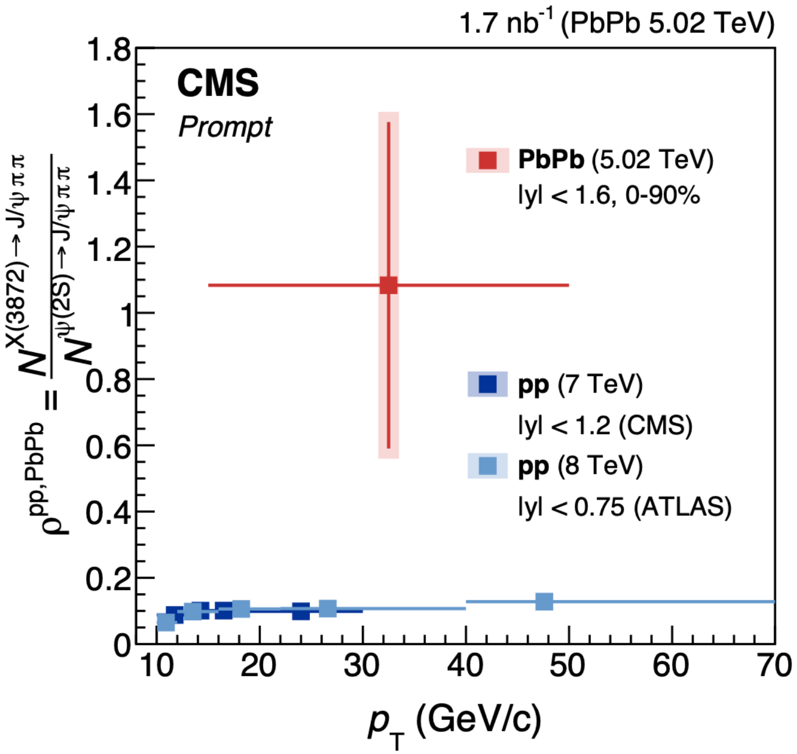
0 3GeV 5GeV P_T

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.

Exotic hadron productions





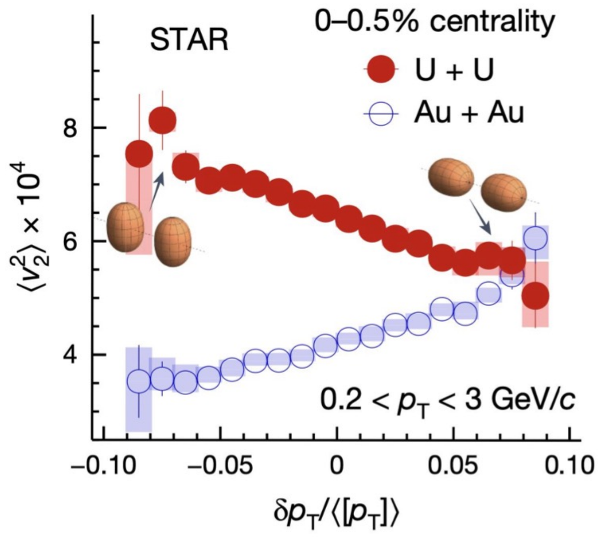
CMS, [arXiv:2312.17092].

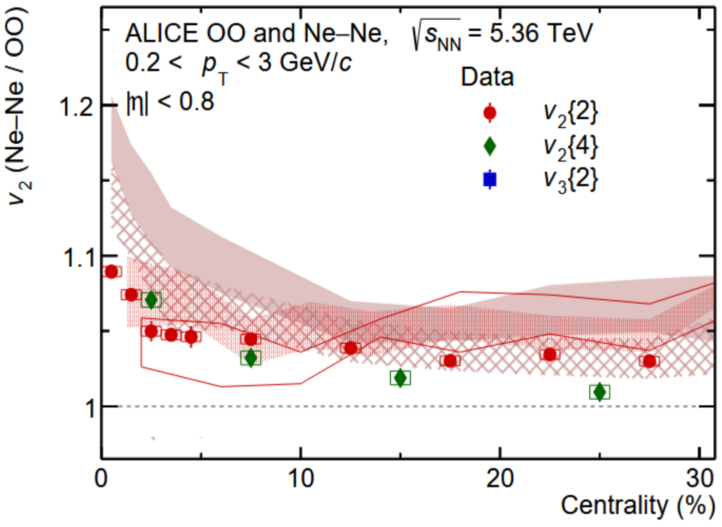
CMS: [arXiv: 2102.13048]

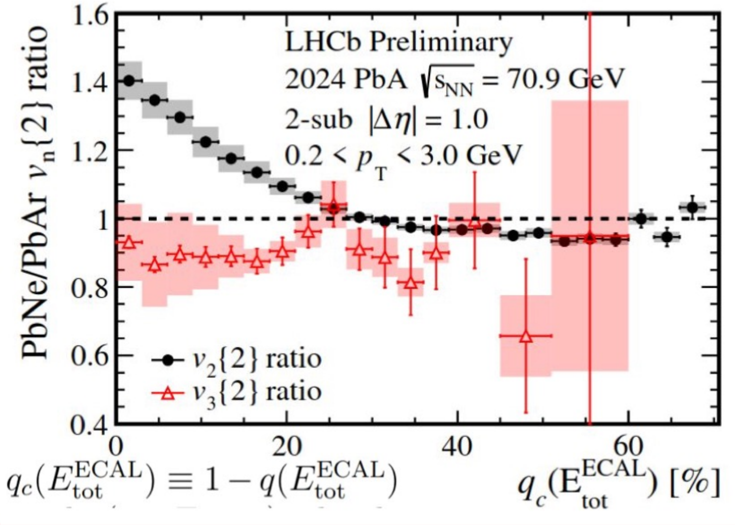
Yi. Wang, W. Zhao, C. Ko, J. Xie, F. Guo, H. Song, in preparation.

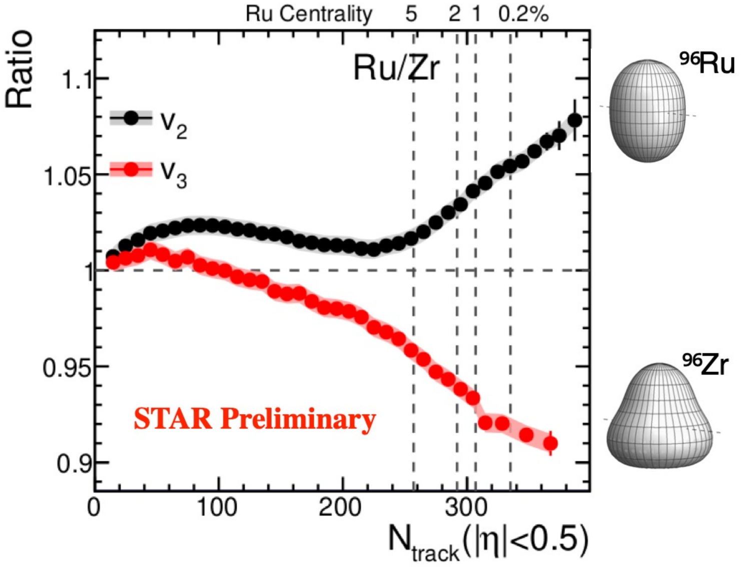
- The CMS flow measurement is the consistent with **$K - \bar{K}$ molecular** picture of $f_0(980)$.
- X-3872 productions in Heavy-ion Collisions.

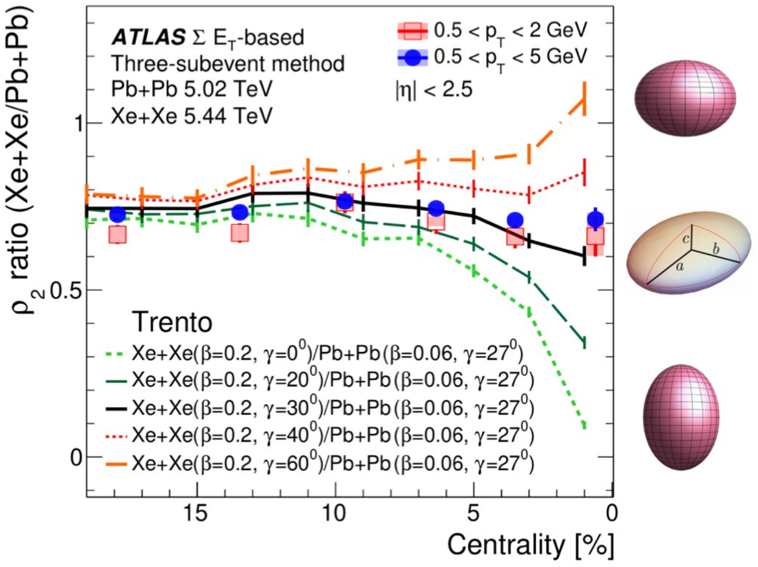
Imaging the Nuclear Structures





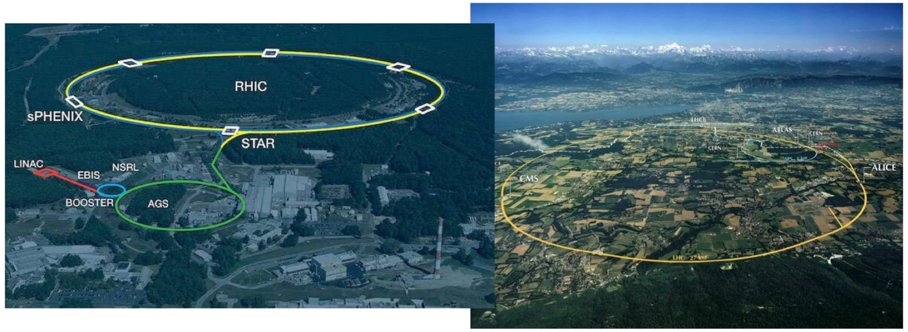


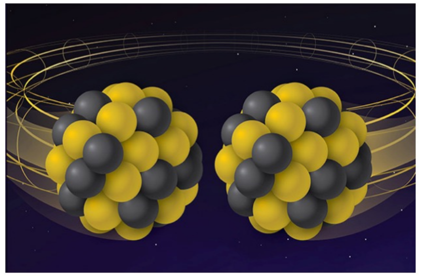




- ALICE: [arXiv:2509.06428].
- ATLAS: [arXiv:2509.05171].
- CMS: [arXiv:2510.02580].
- LHCb: [arXiv:2509.12399].
- STAR, ***Nature*** 635, 67 (2024).
- STAR: [arXiv: 2109.00131].
- ATLAS: arXiv:2205.00039].

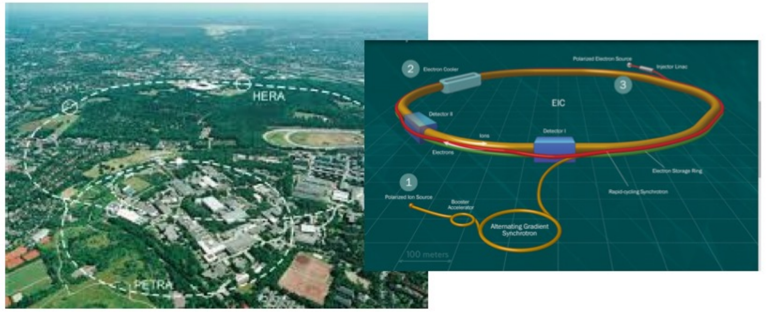
Heavy-ion Collisions and DIS/UPC

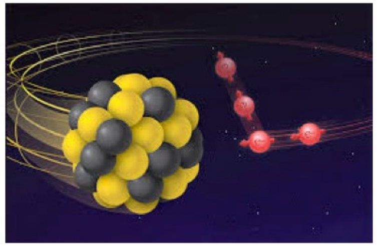


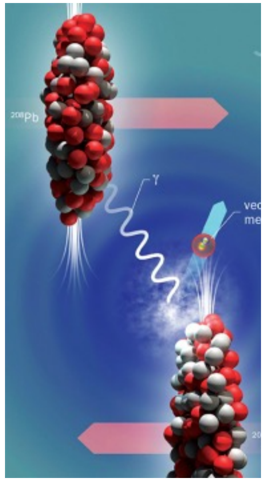


- **Heavy-ion Collisions:** High center-of-mass energies available.
- **Multi-Stage process:**

Initial state => QGP => Hadronic Scatter







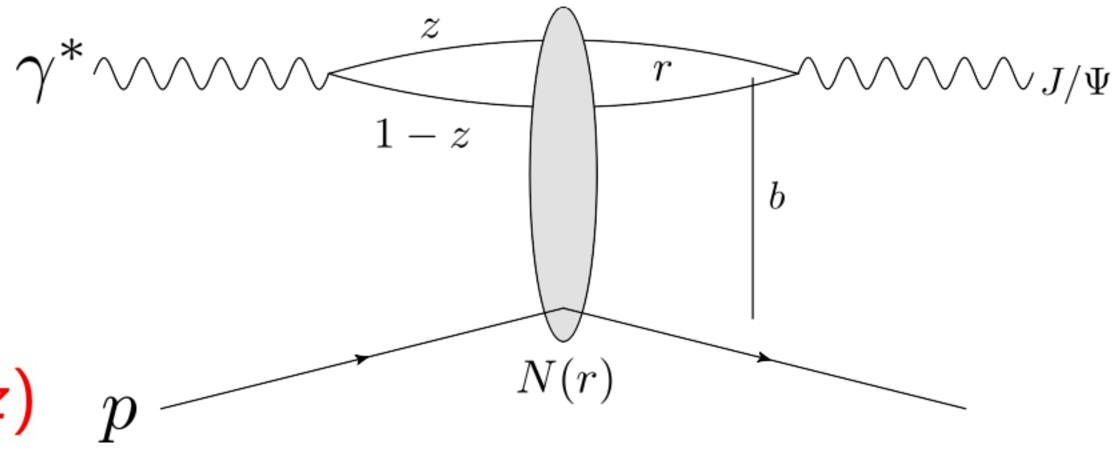
- **DIS/UPC:**
- Pin down kinematics, clean probes of QCD dynamics.
- Collision energy is limited.

- 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

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

Liu Xinyan, Oct. 30
Zaochen Ye, Otc. 31

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

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

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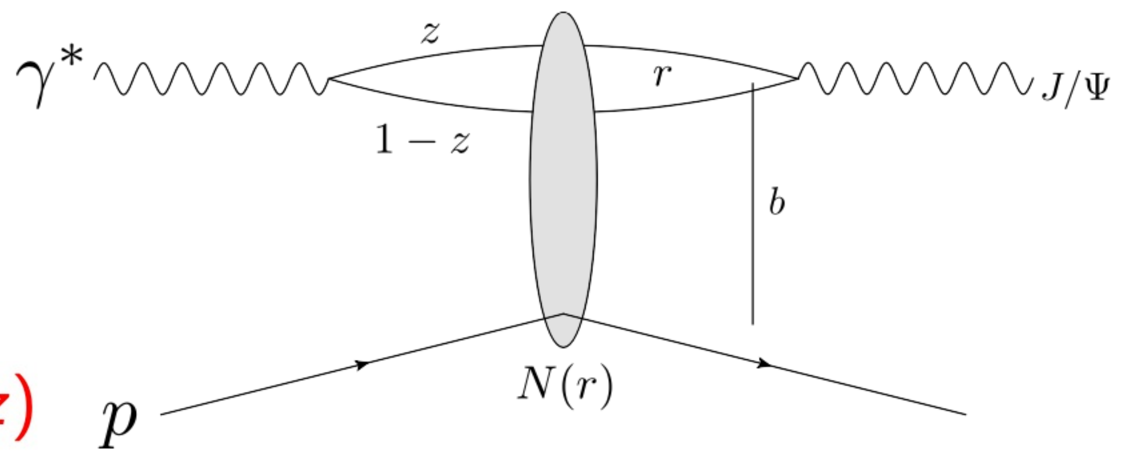

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Impact parameter, b, is the Fourier conjugate of the momentum transfer, $\Delta \approx \sqrt{-t}$
N(r, x, b) dipole-target scattering amplitude.

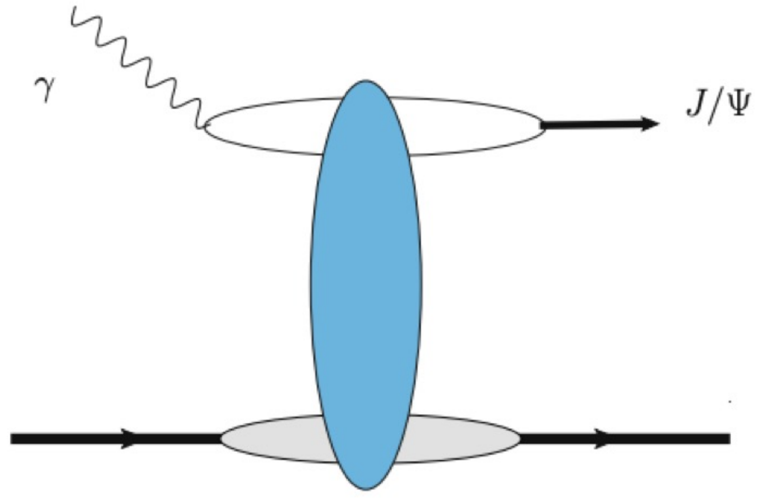
A ~Fourier transform of the spatial structure function of target ($T_{p/A}$).

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

Coherent and incoherent processes

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

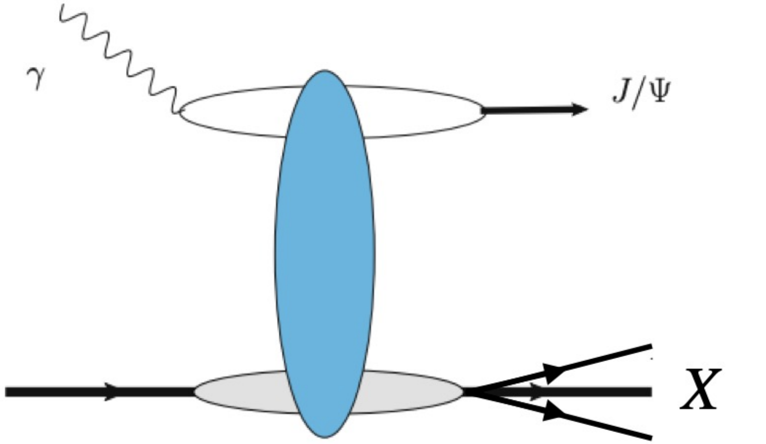
Target stays intact, (Iinitial state> = Ifinal state>)
Probes the average shape of the target.



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

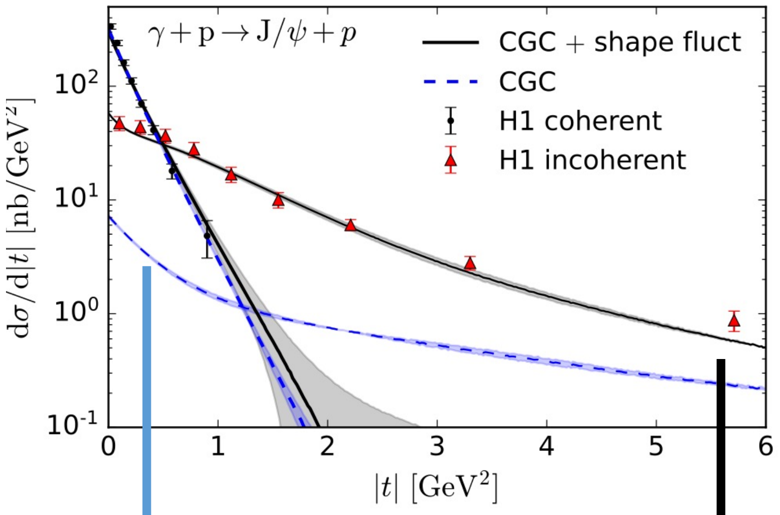
Target breaks apart, (|initial state> ≠ |final state>)

Probes the variance of event-by-event initial state fluctuations in target structure.



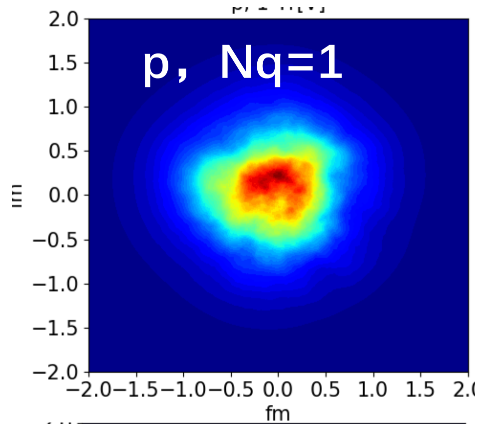
Miettinen, Pumplin, PRD 18, 1978; Caldwell, Kowalski, 0909.1254; Mäntysaari, Schenke, 1603.04349; Mäntysaari, 2001.10705

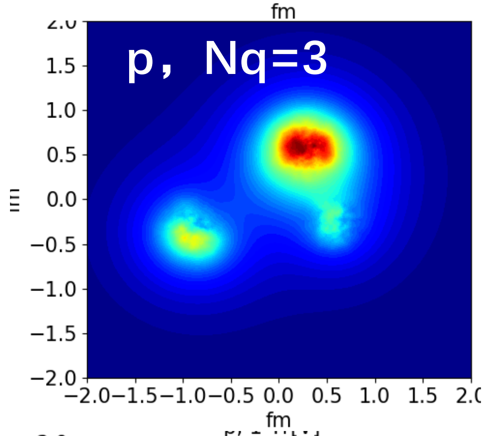
Proton geometry fluctuations

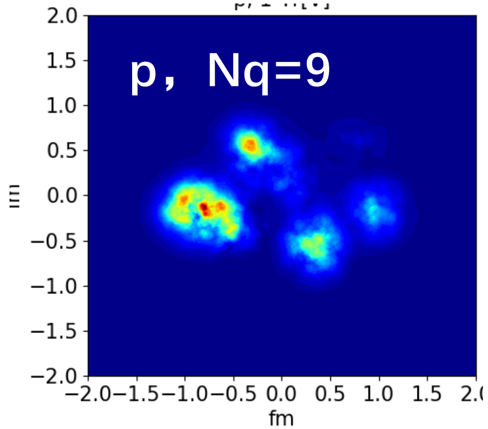


No subnucleon fluctuations

With subnucleon fluctuations



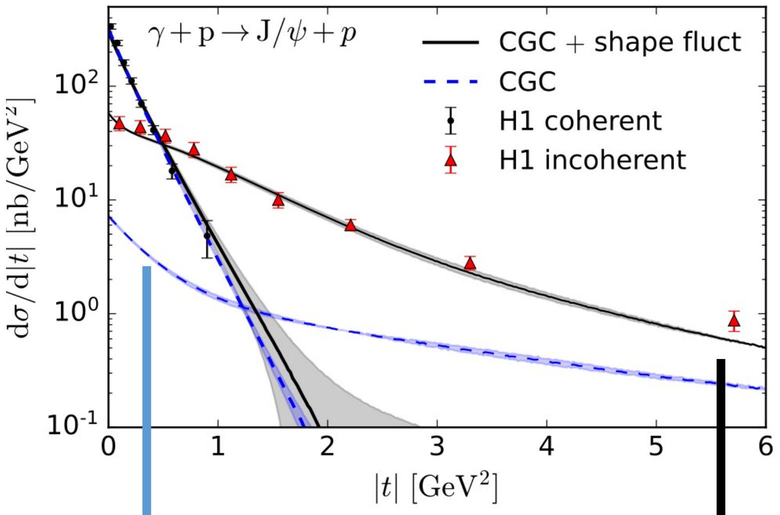




- Probe the event-by-event sub-nucleon fluctuations.

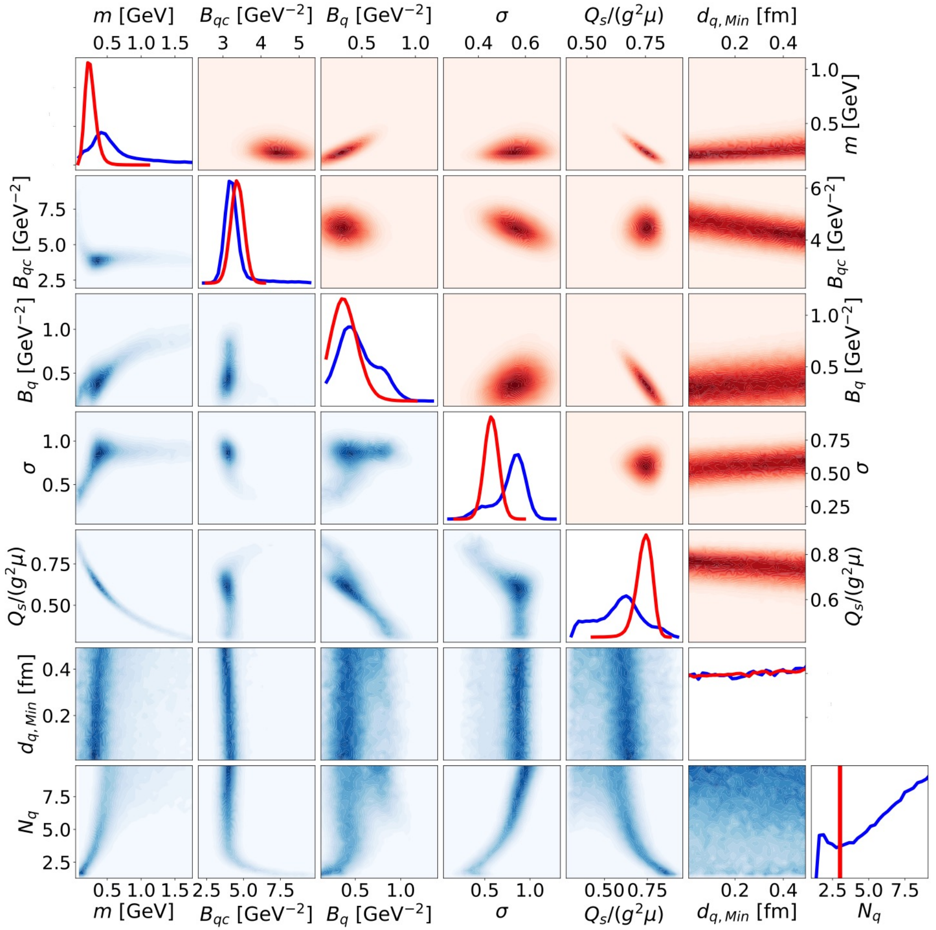
H. Mäntysaari, Schenke , PhysRevLett.108.252301 , PhysRevC.86.034908 ;
H. Mäntysaari, F. Salazar and B. Schenke, Phys. Rev. D 106, 074019 (2022).
H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348.

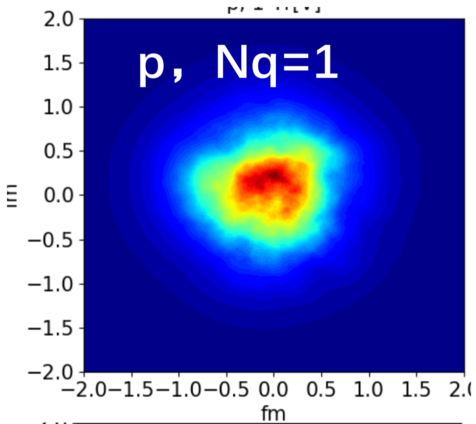
Proton geometry fluctuations

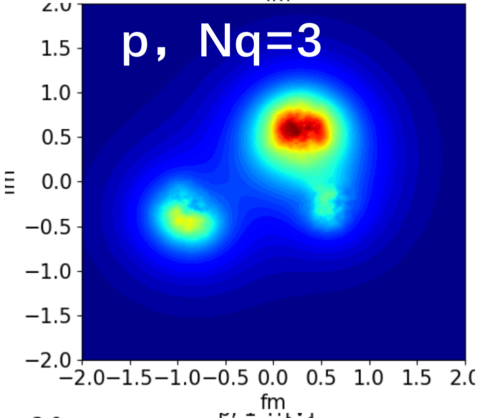


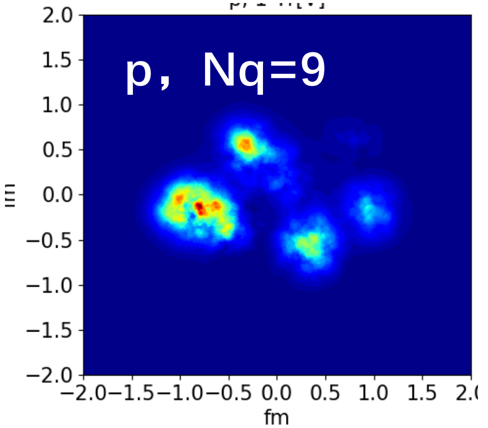
No subnucleon fluctuations

With subnucleon fluctuations







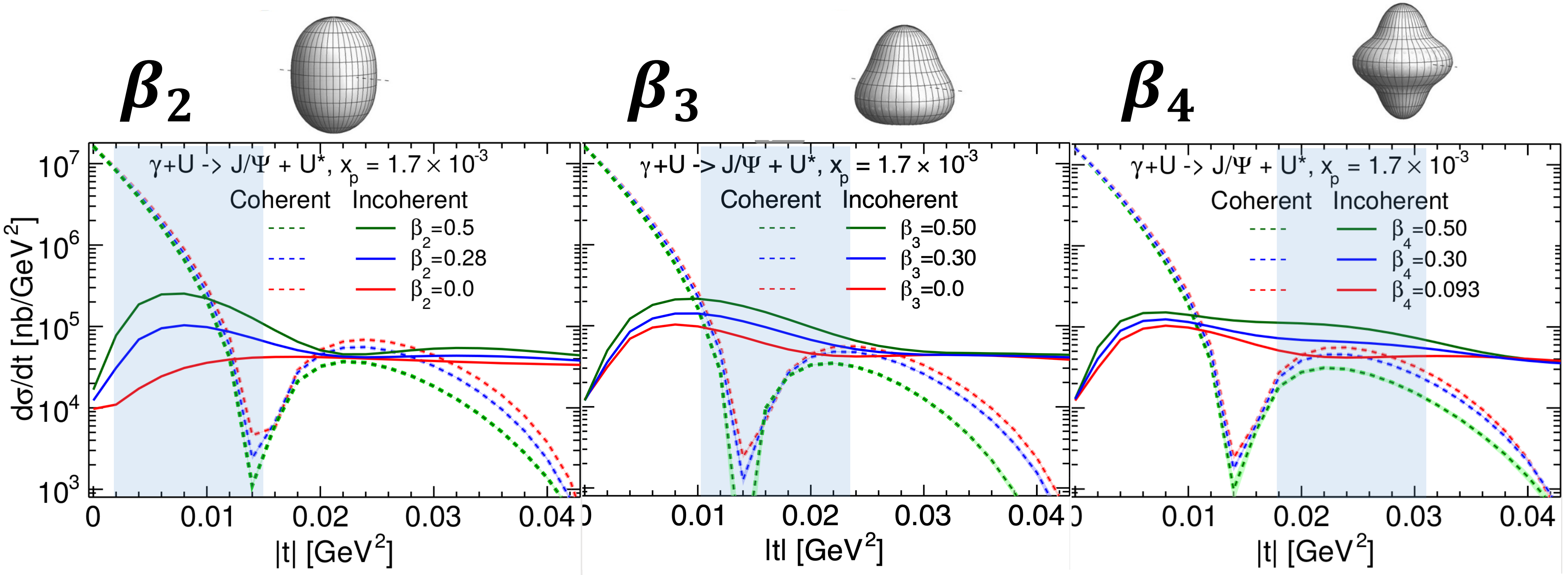


- Probe the event-by-event sub-nucleon fluctuations.
- Bayesian inference of the fluctuating proton shape.
- The extracted 2D RMS proton radius $R_{rms} = \sqrt{2(B_{qc} + B_q)}$ ~ **0.6 fm**.

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

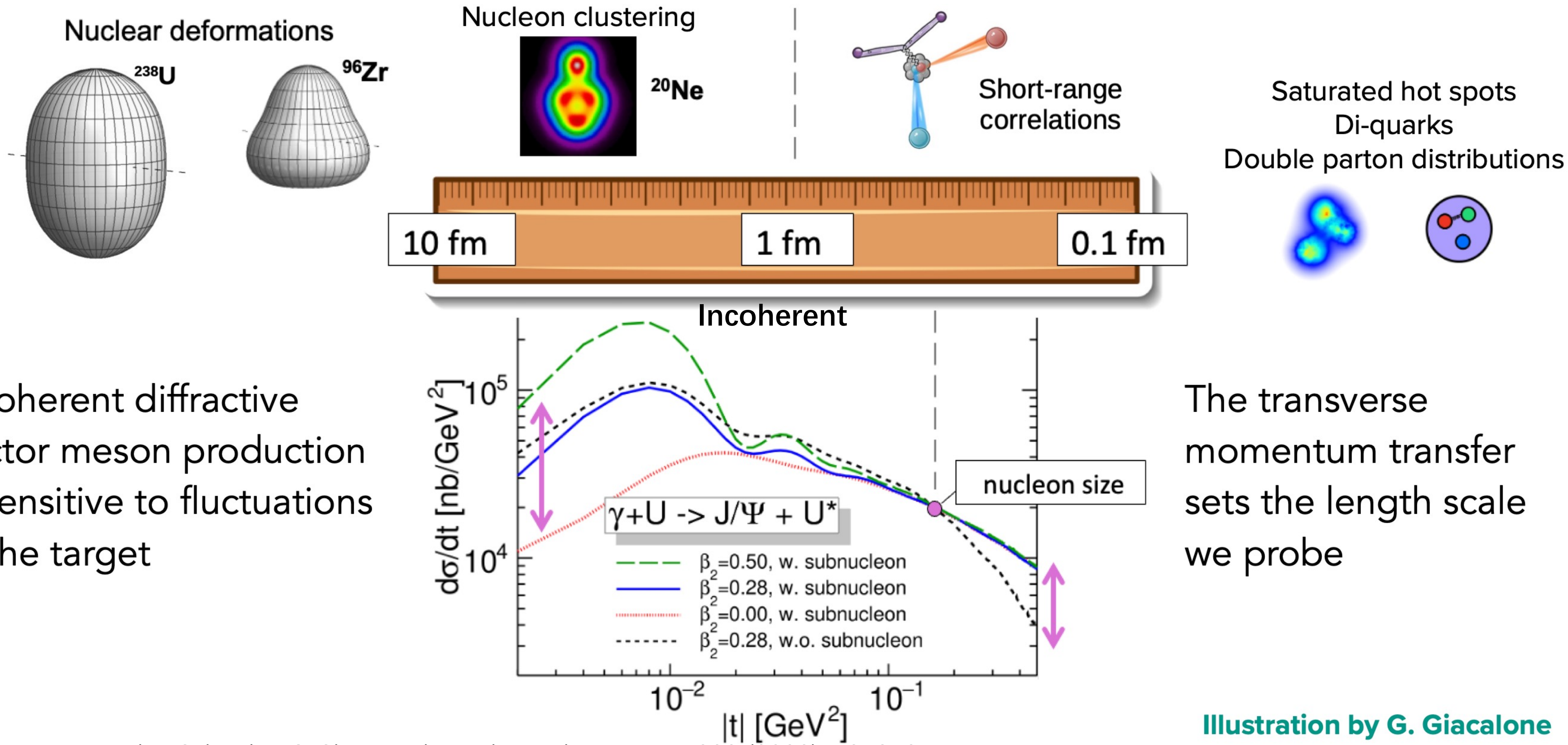
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)}\ ,\quad R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\left(\cos\underline{\gamma}Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\underline{\beta_3}Y_{30}(\Theta)+\underline{\beta_4}Y_{40}(\Theta)\right]$$



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

- "**Multi-scale imaging**" for atoms.

“X-ray vision” for atoms.



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

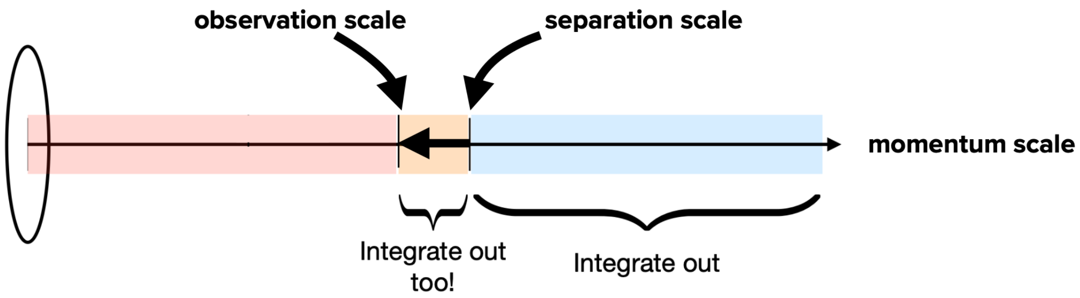
The transverse momentum transfer sets the length scale we probe

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.

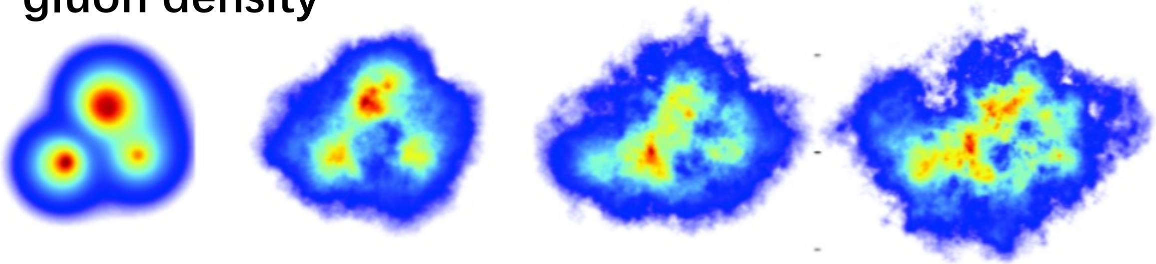
Energy Evolution of Initial Conditions

Energy evolution of initial state



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

gluon density

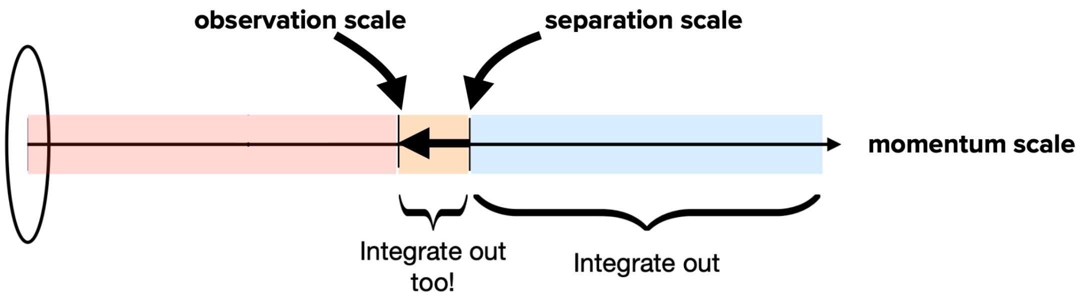


Low energy (UPC/DIS) → High energy (LHC)

- 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)

Energy evolution of initial state



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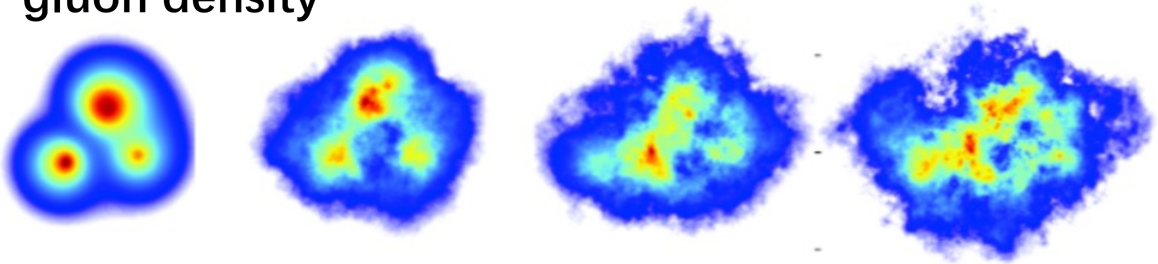

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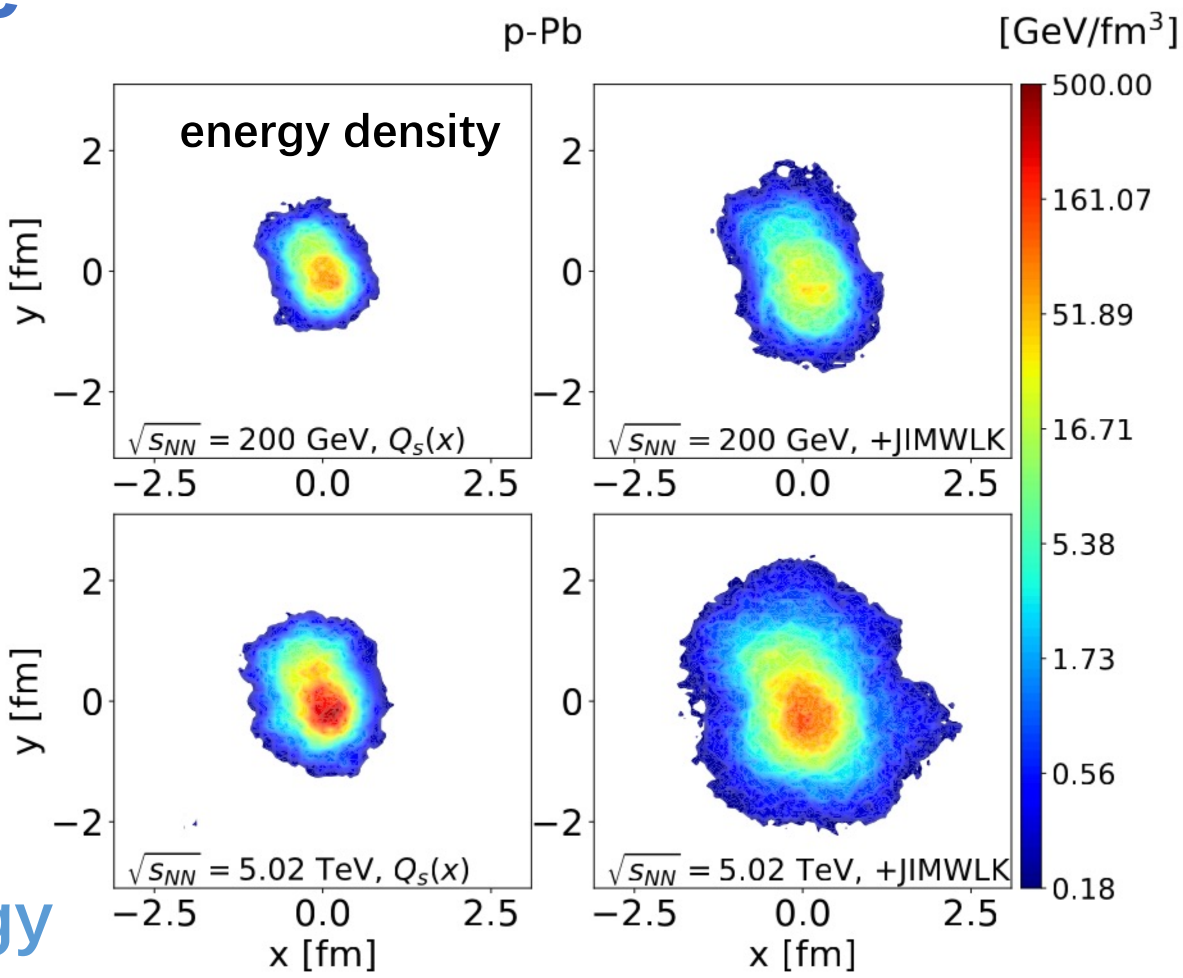

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H. Mäntysaari and B. Schenke, PRD 98 (2018) 034013.
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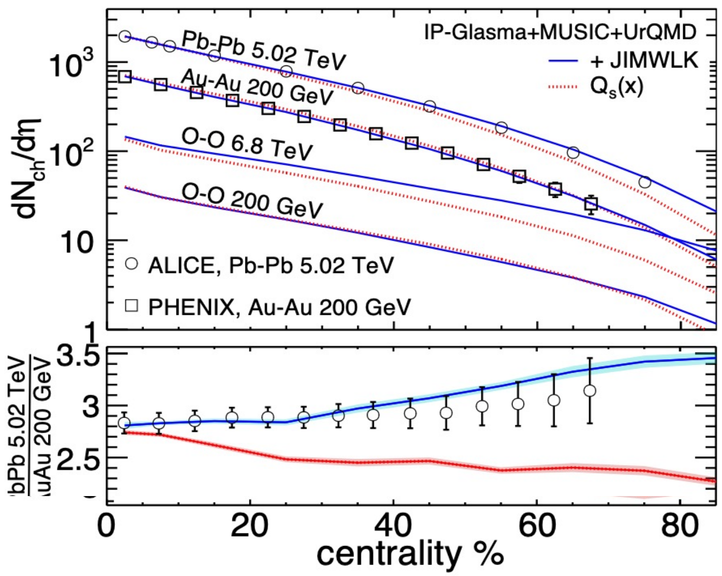
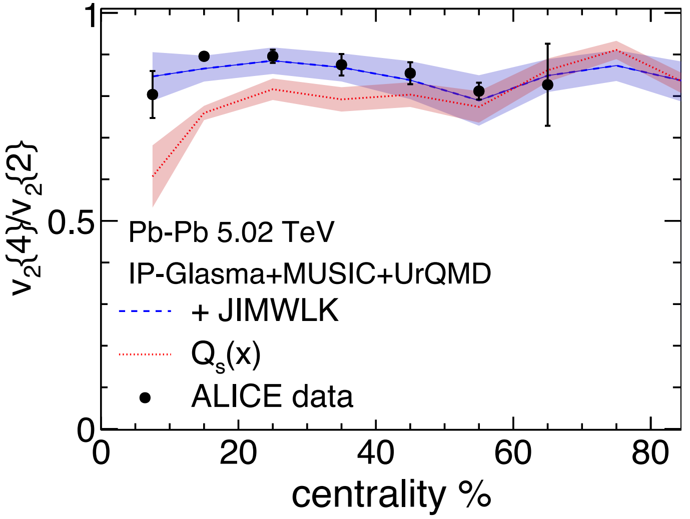
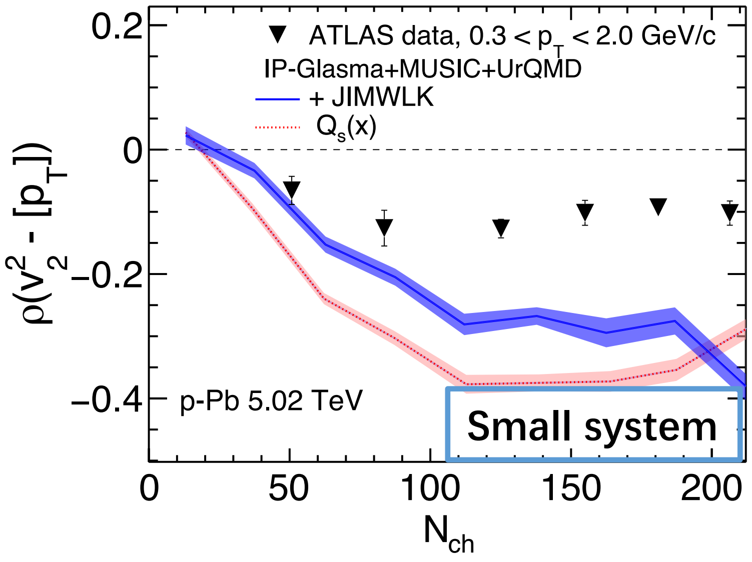
Effects of energy evolution on heavy-ion observables







+ JIMWLK: CGC + energy evolution + Hydrodynamics

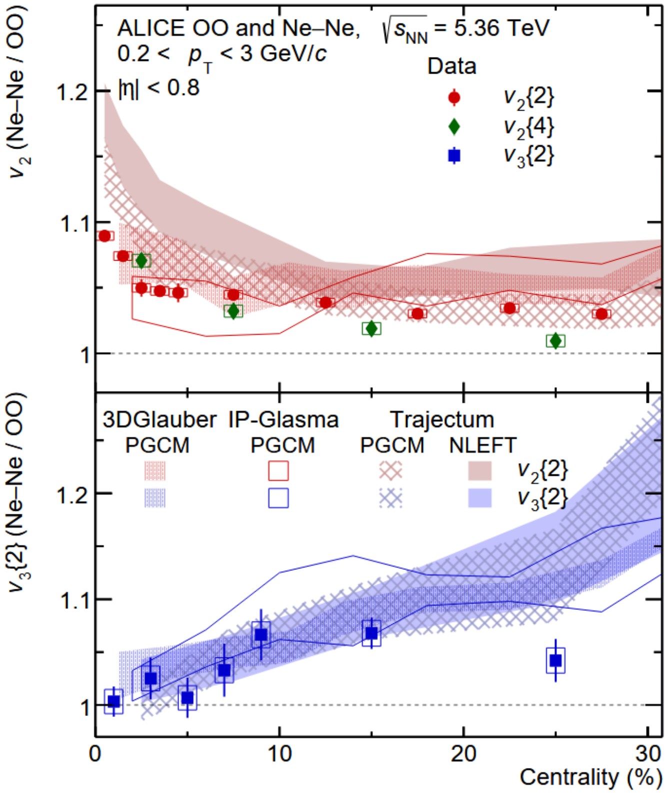
$\boldsymbol{Q_s(x)}$: CGC (change the $Q_s(x)$ only for different energies) + Hydrodynamics

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

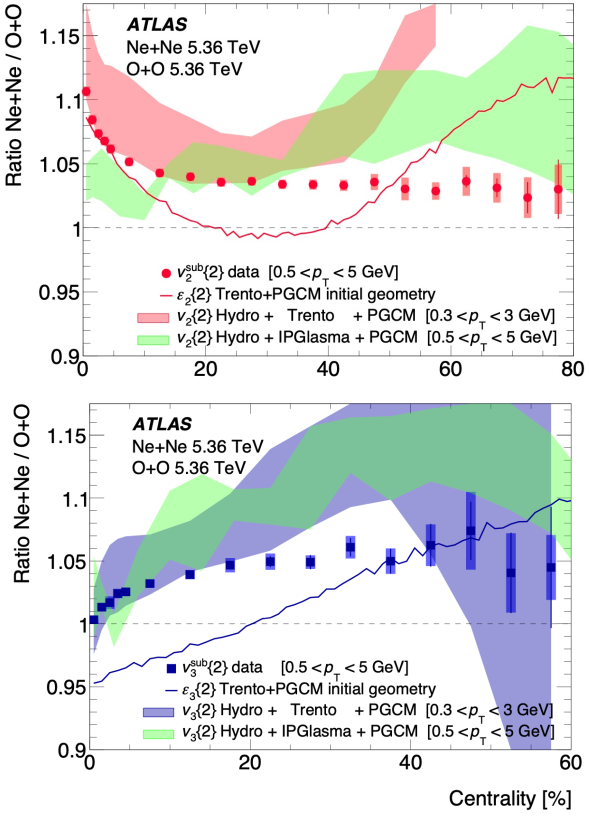
- The energy evolution of the initial state is important in Bayesian analysis when comparing data across different collision energies.

Flow ratio NeNe/OO

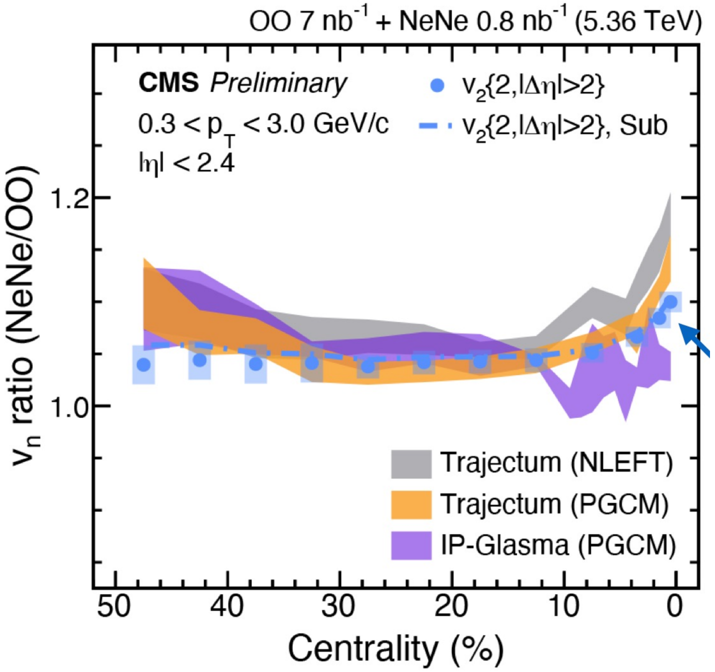
彭佳腾, Oct. 30



ALICE: [arXiv:2509.06428].



ATLAS: [arXiv:2509.05171].

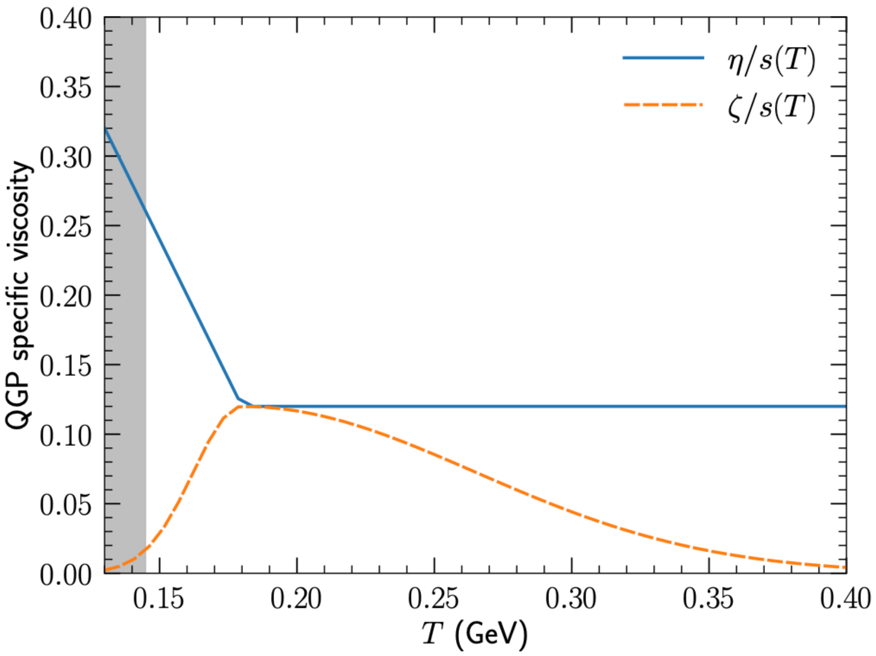


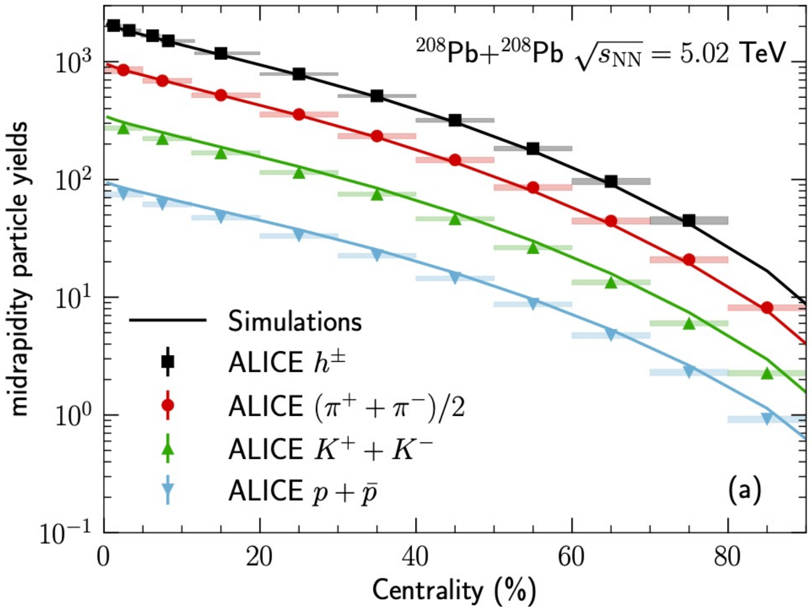
CMS: [arXiv:2510.02580].

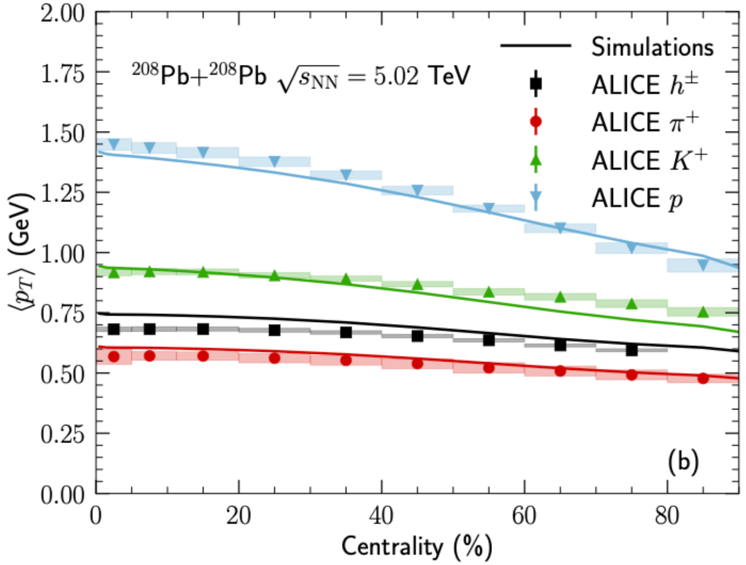
- **Trajectum:** Fit Pb-Pb LHC flow data, [PRL,135, 012302]
- **IPGlasma + JIMWLK:** Fit J/Ψ data + energy evolution [PRL, 135,022302]
- **3DGlauber:** Fit dAu, AuAu at RHIC, then extrapolate to LHC. [JETSCAPE, in preparation]

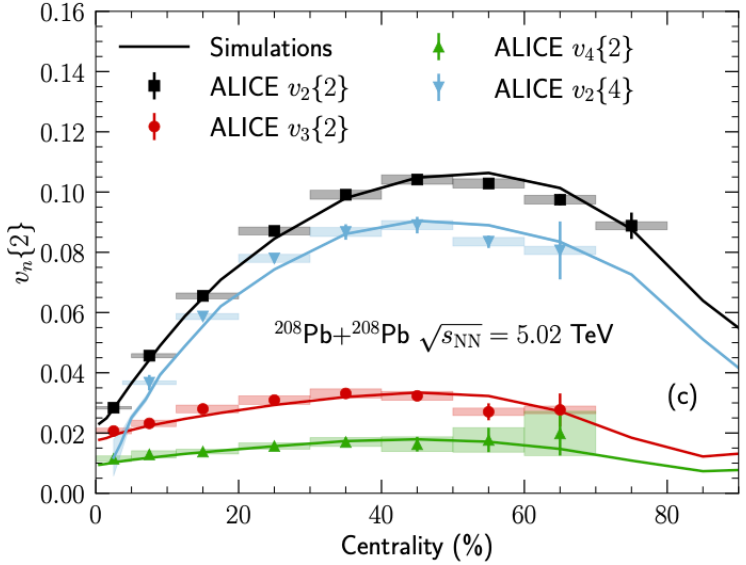
Probing nuclear structure in high energy heavy ions

Hydrodynamic baseline





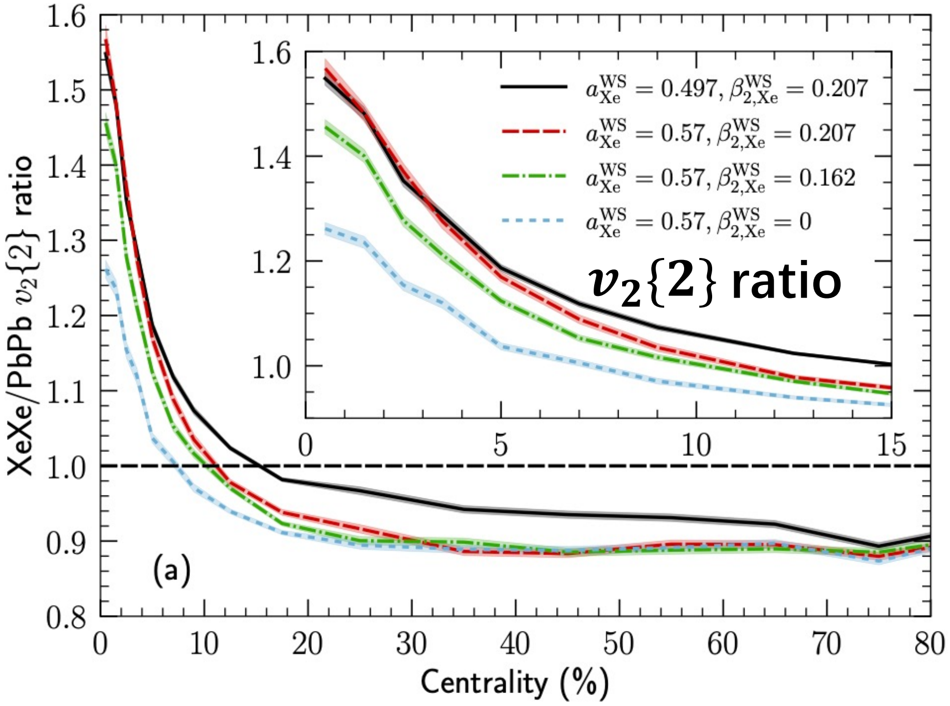


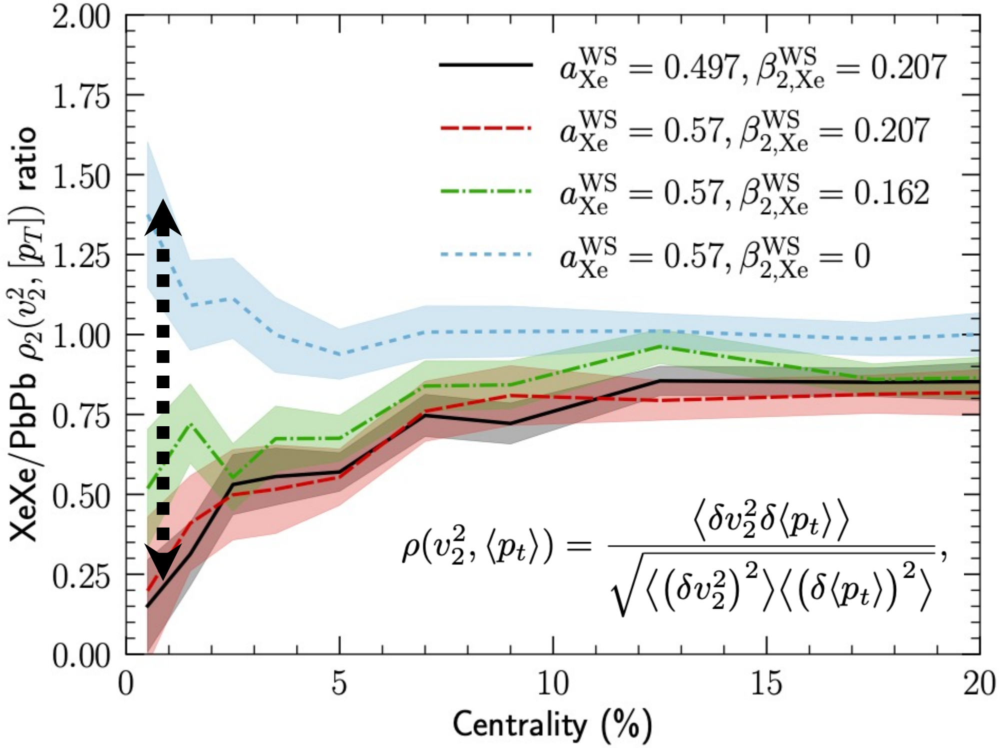


- Hydrodynamic parameters are turned to fit the multiplicity, mean p_T and integrated flow in Pb-Pb.

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, Phys. Rev. C 110, no.5, 054913 (2024).

Deformations

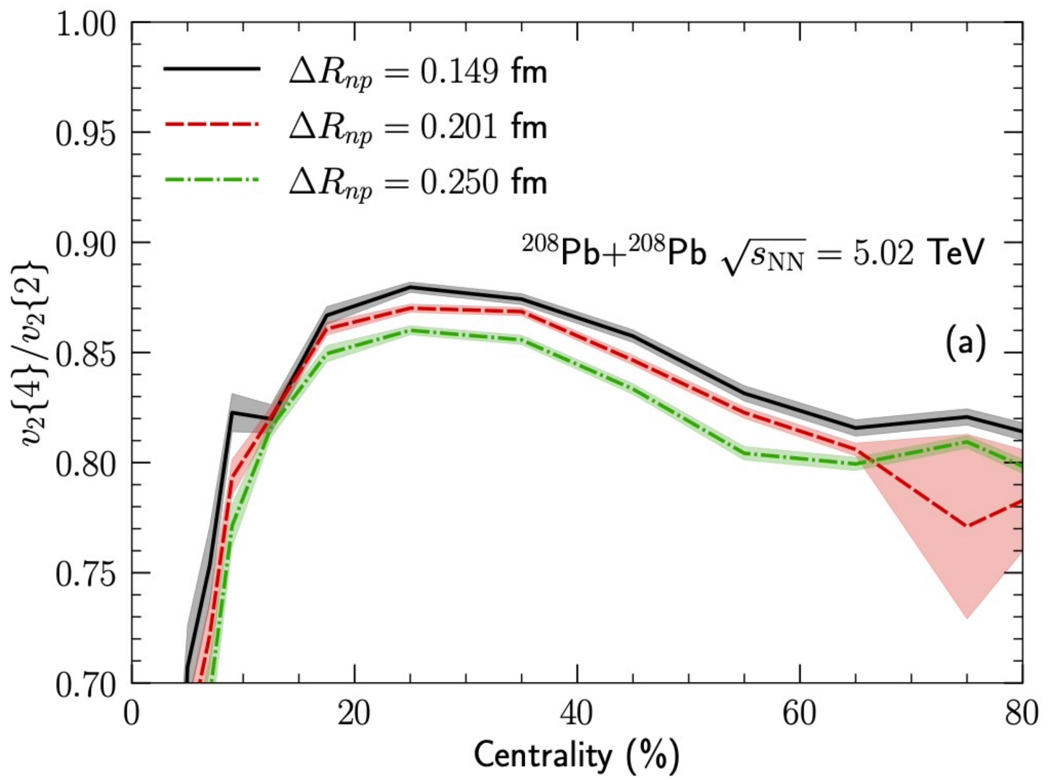


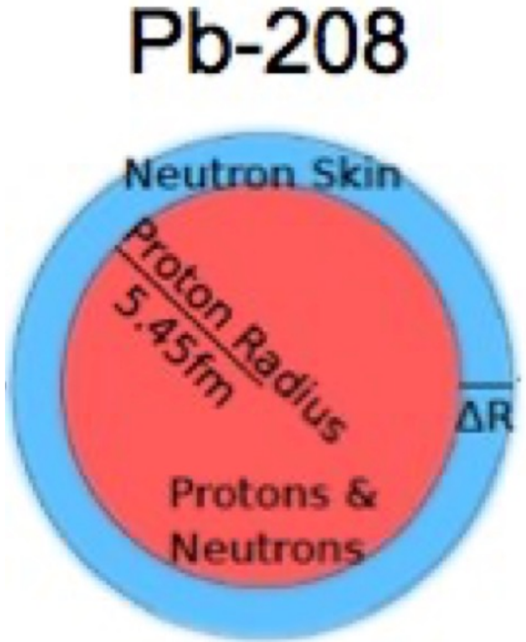


- v_2 ratios sensitive to β_2.
- $v_2 - [p_T]$ correlator is very sensitive to β_2 .

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, Phys. Rev. C 110, no.5, 054913 (2024).

Constraining the neutron skin of Pb-208





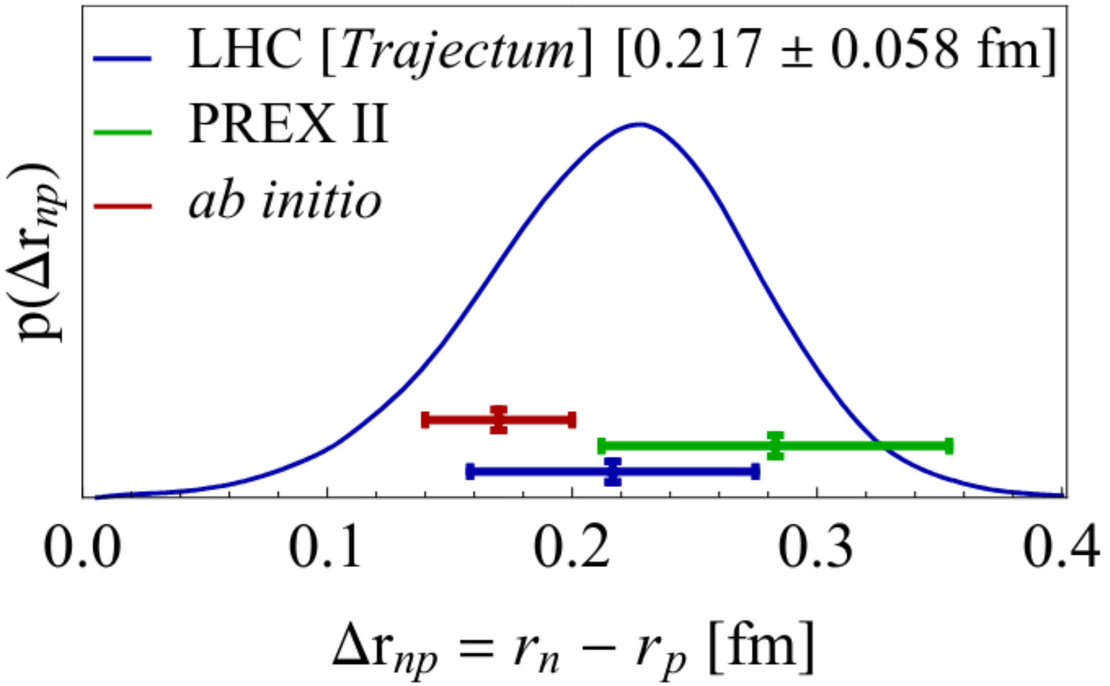
$$\Delta R_{np} = R_p - R_n,$$

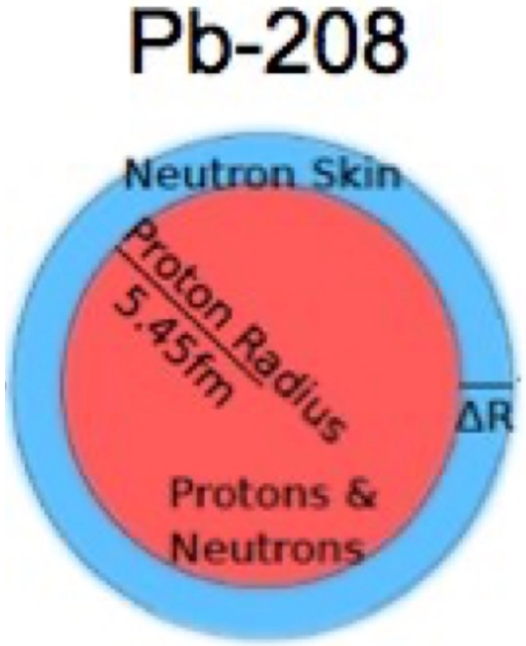
$$R_{p,n} = \sqrt{\int d^3 r r^2 \rho^{\mathrm{WS}}_{p,n}(r,\theta) \Big/ \int d^3 r \rho^{\mathrm{WS}}_{p,n}(r,\theta)}.$$

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, Phys. Rev. C 110, no.5, 054913 (2024).

- $v_2\{4\}/v_2\{2\}$ is a sensitive probe to skin depth of the nuclear mass density.

Constraining the neutron skin of Pb-208





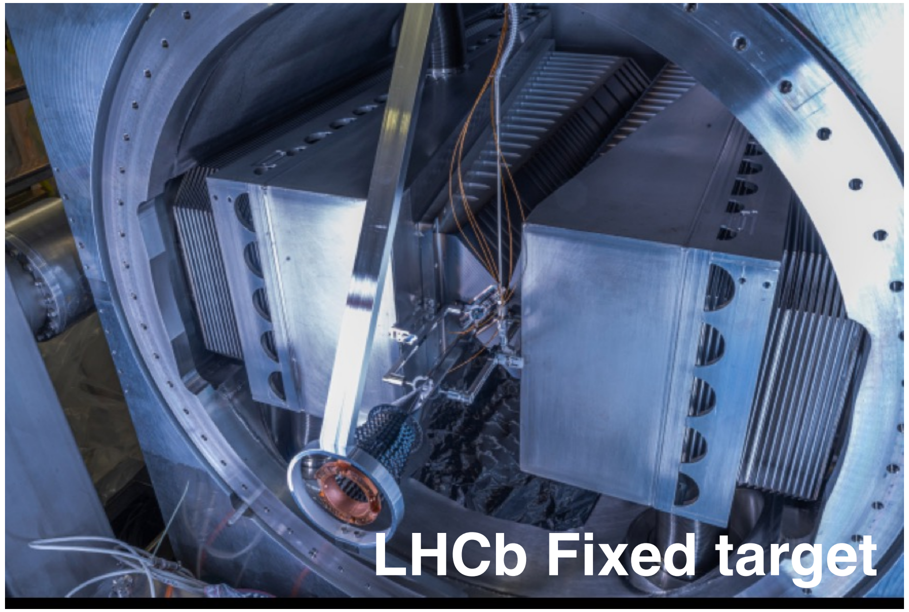
$$\Delta R_{np} = R_p - R_n,$$

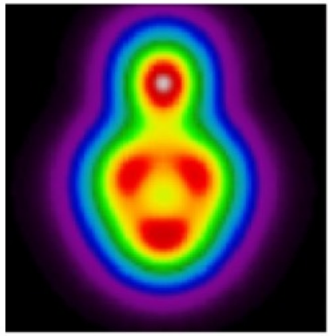
$$R_{p,n} = \sqrt{\int d^3r r^2 \rho^{\mathrm{WS}}_{p,n}(r,\theta) \Big/ \int d^3r \rho^{\mathrm{WS}}_{p,n}(r,\theta)}.$$

G. Giacalone, G. Nijs and W. van der Schee, Phys. Rev. Lett. 131, no.20, 20 (2023).

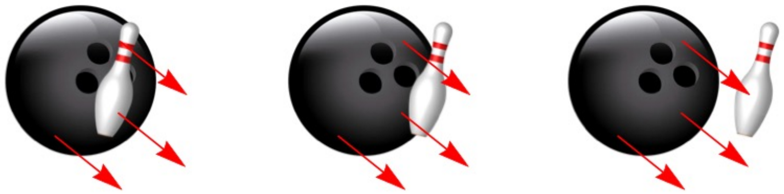
- Bayesian inference of the Pb-208 neutron skin.

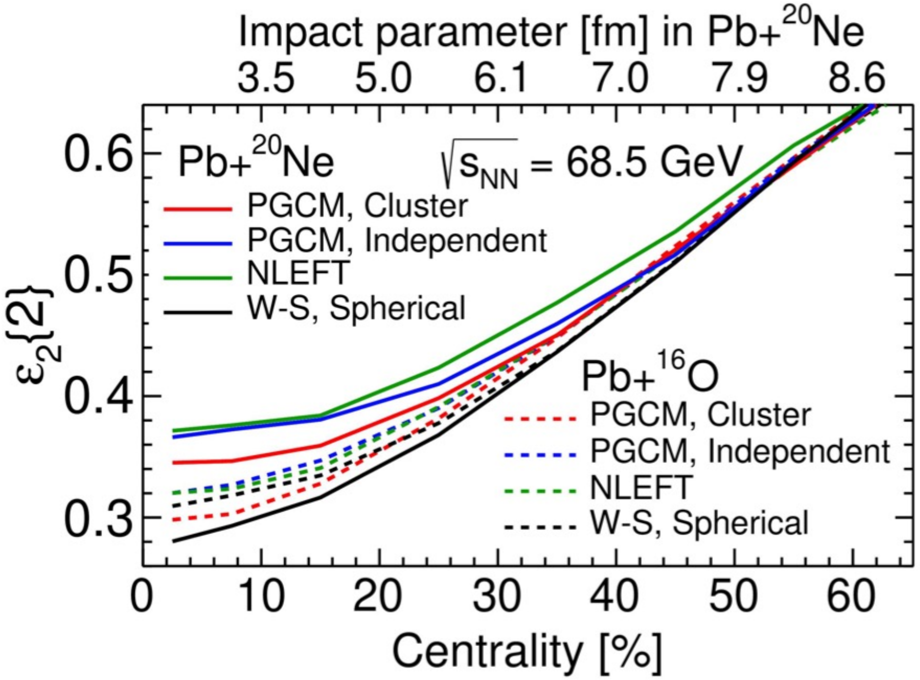
High Energy Bowling Allay





^{20}Ne



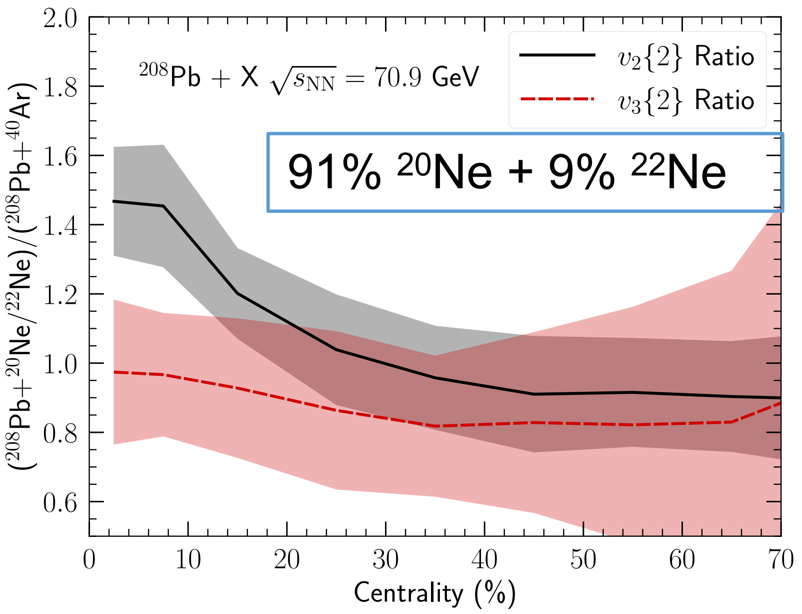


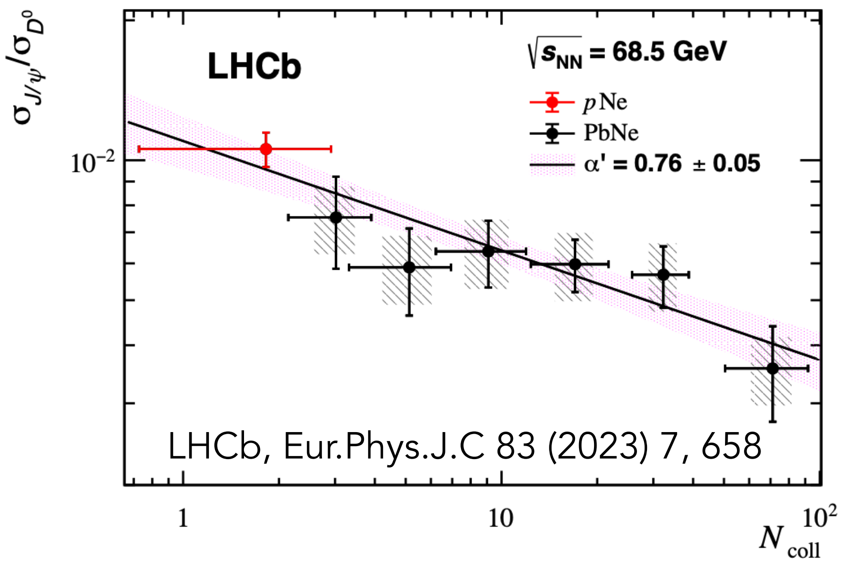
Pb + Ne-20 collisions: A high energy bowling allay!

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

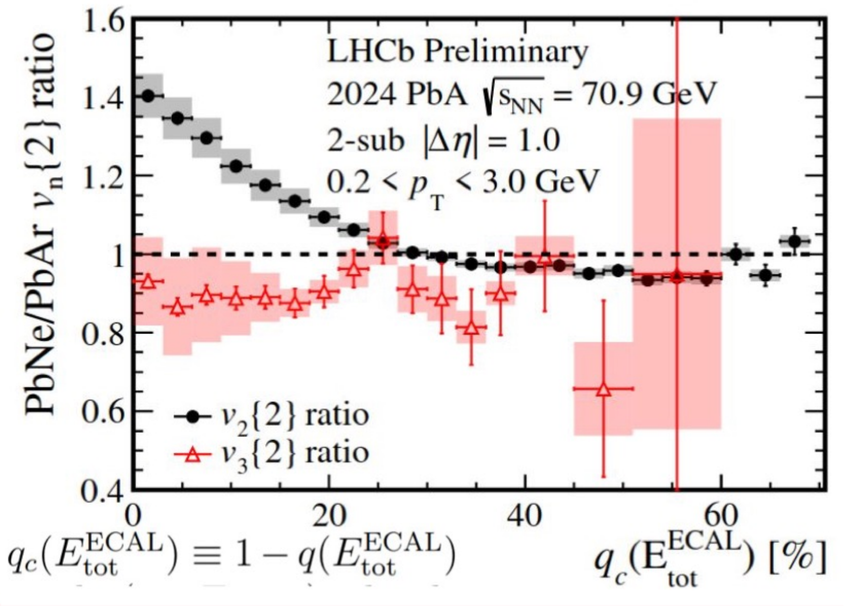
- Connecting *ab initio* inputs of light-nuclei with relativistic nuclear collisions.

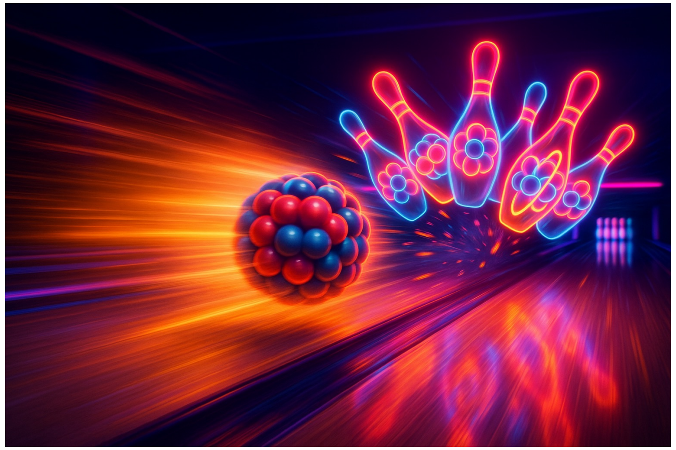
Playing Relativistic Bowling Ball





- No QGP-like J/ψ suppression in Pb+Ne.
- Flow sensitive to shapes of Ne-20.
- Searching the QGP at LHCb.





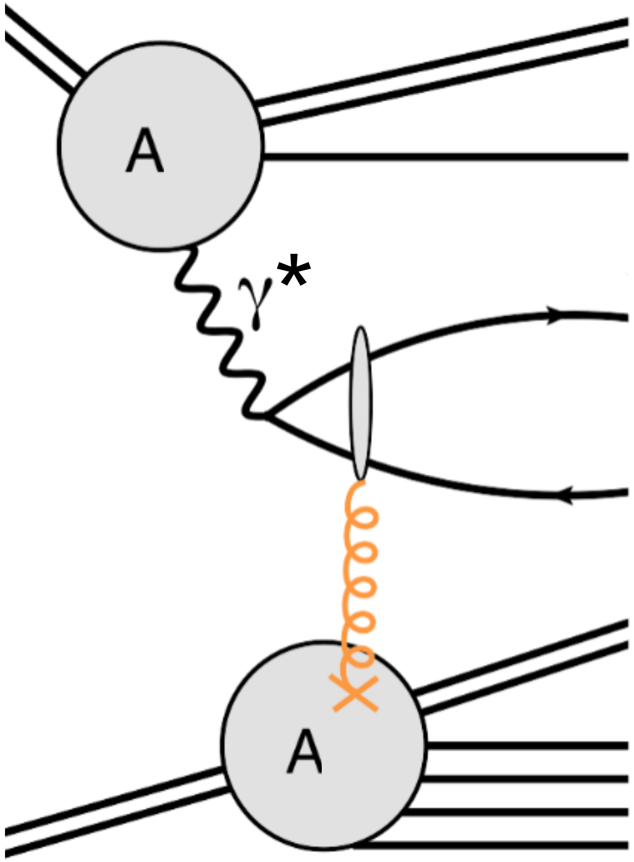
(Generated by ChatGPT)

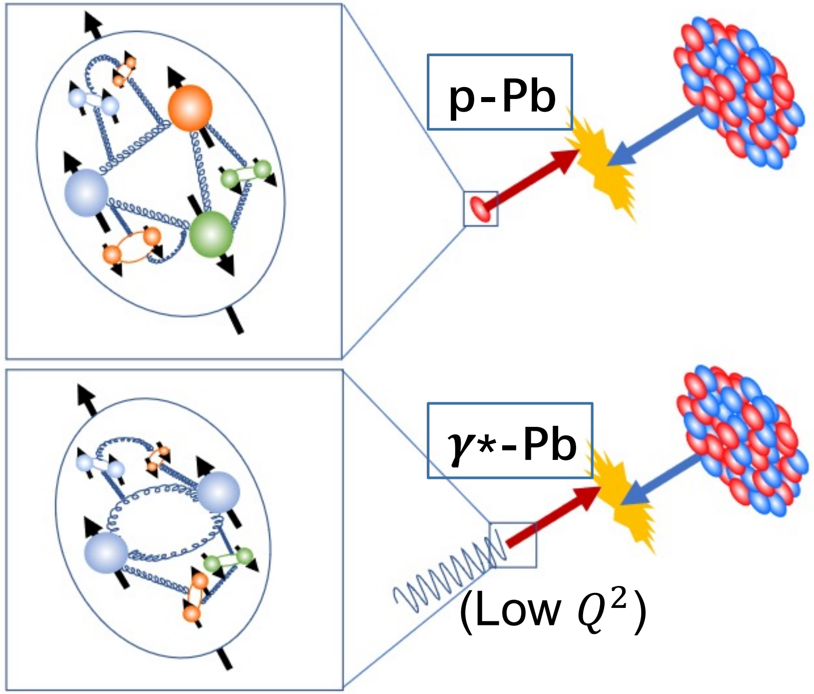
王剑桥, Oct. 31

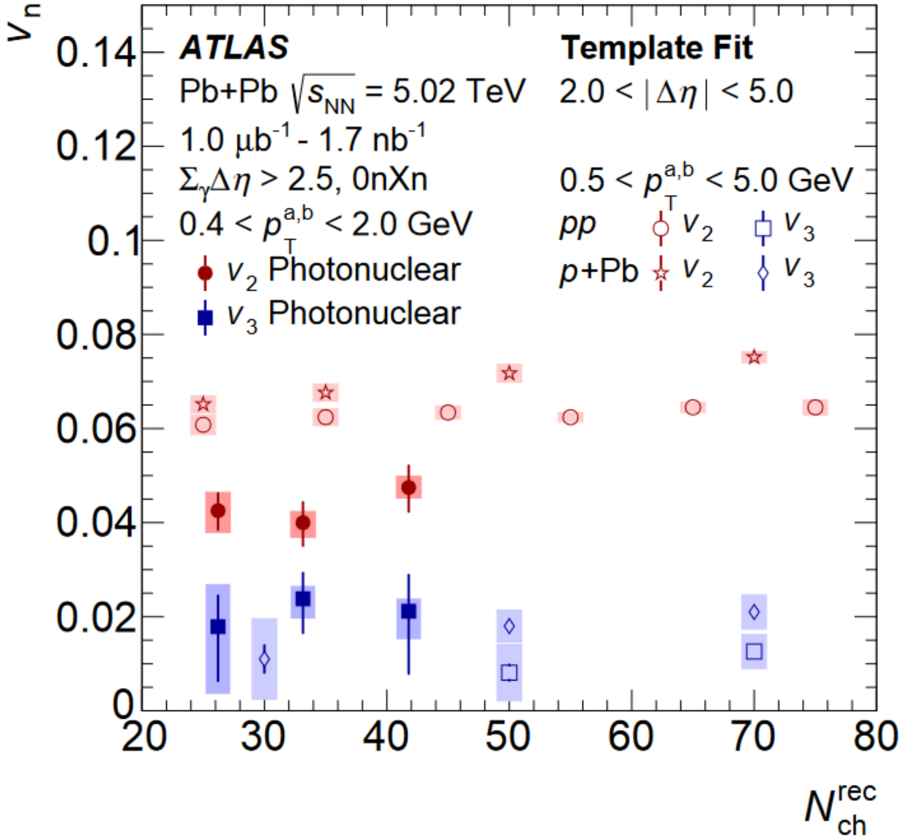
LHCb: [arXiv:2509.12399].

Searching the “smallest” droplet

“Collectivity” in UPC



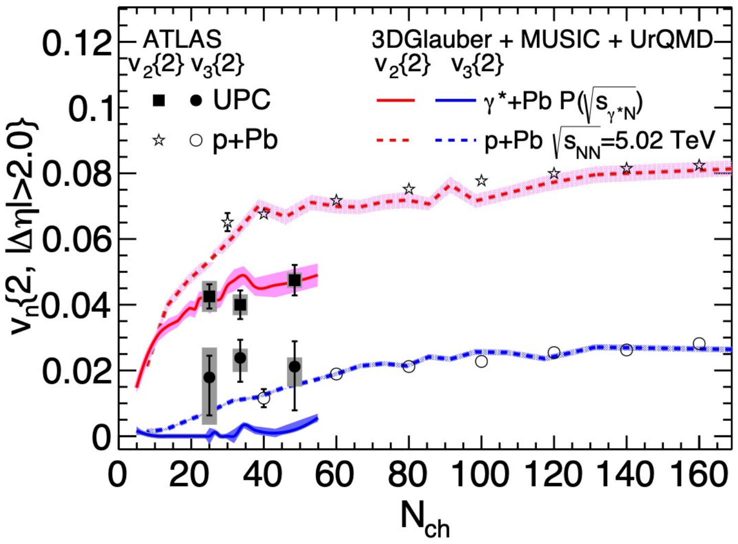


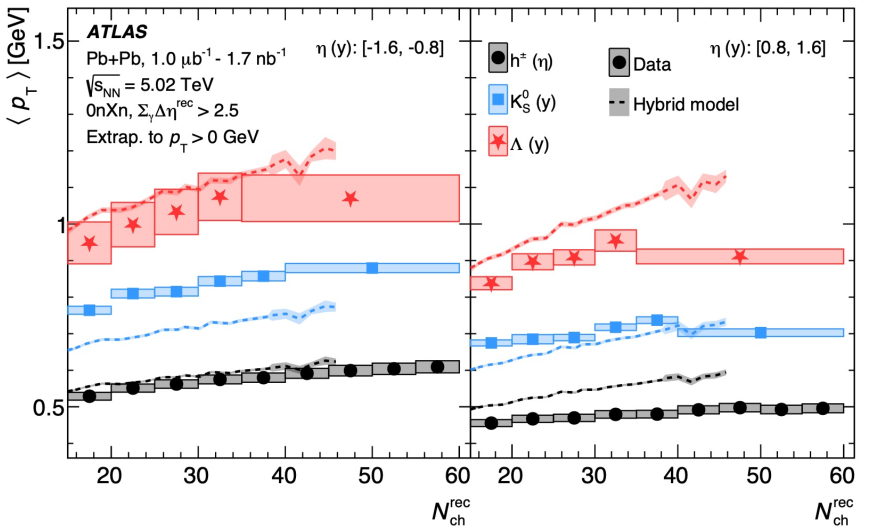


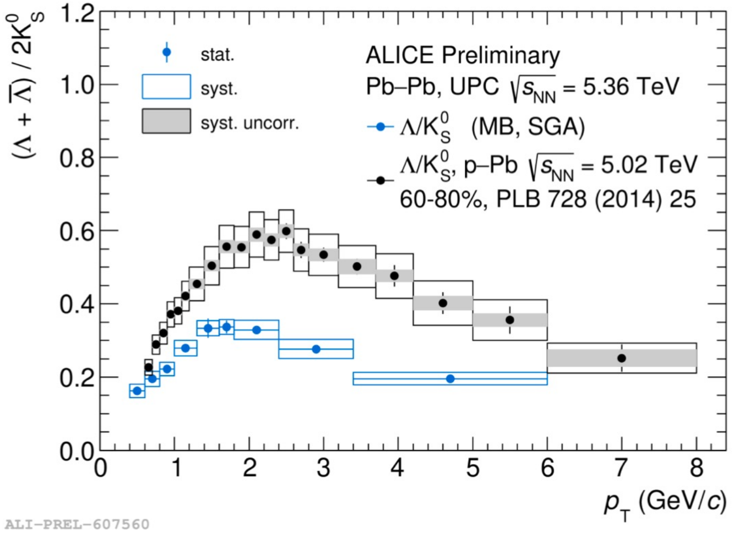
ATLAS Phys. Rev. C 104, 014903 (2021). Y. Shi, etc.al,Phys. Rev. D 103, 054017 (2021).

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

Search “QGP” in UPCs

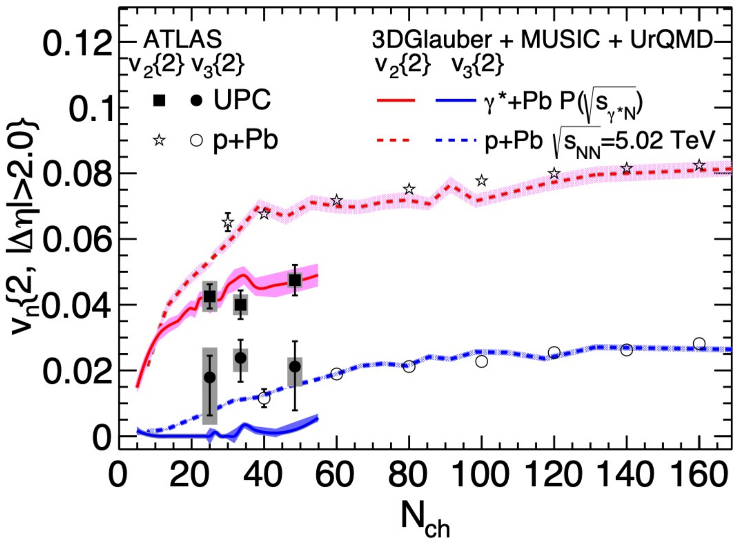


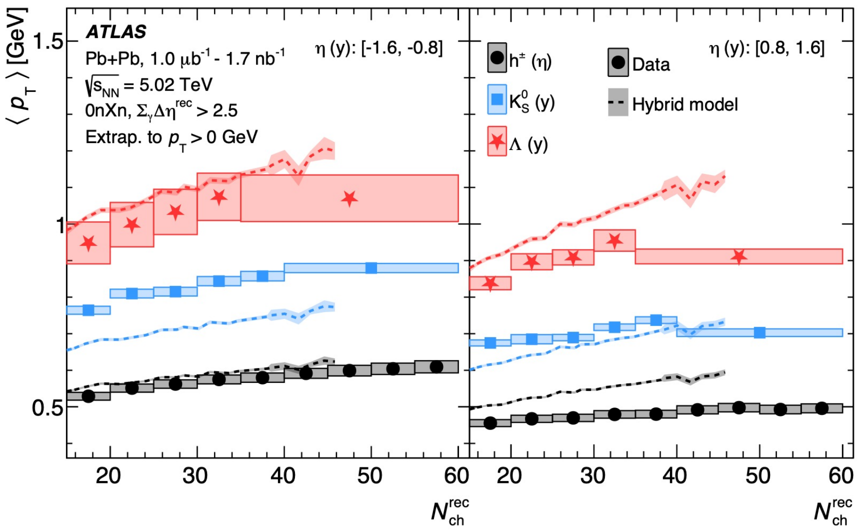


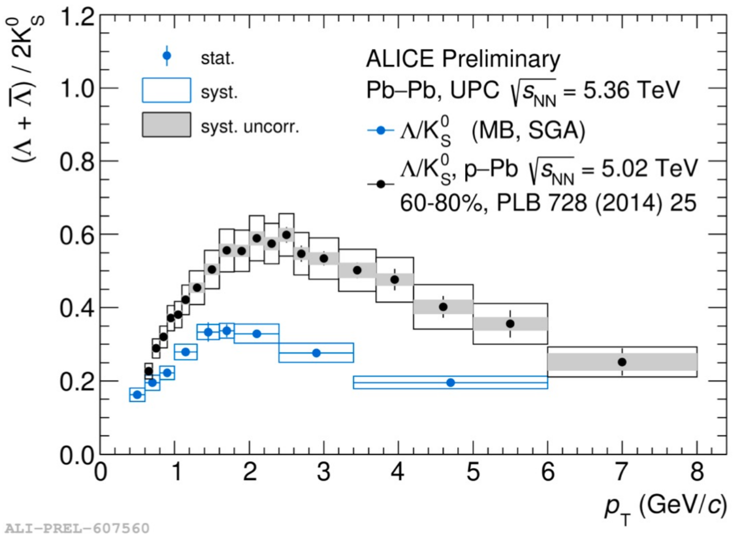


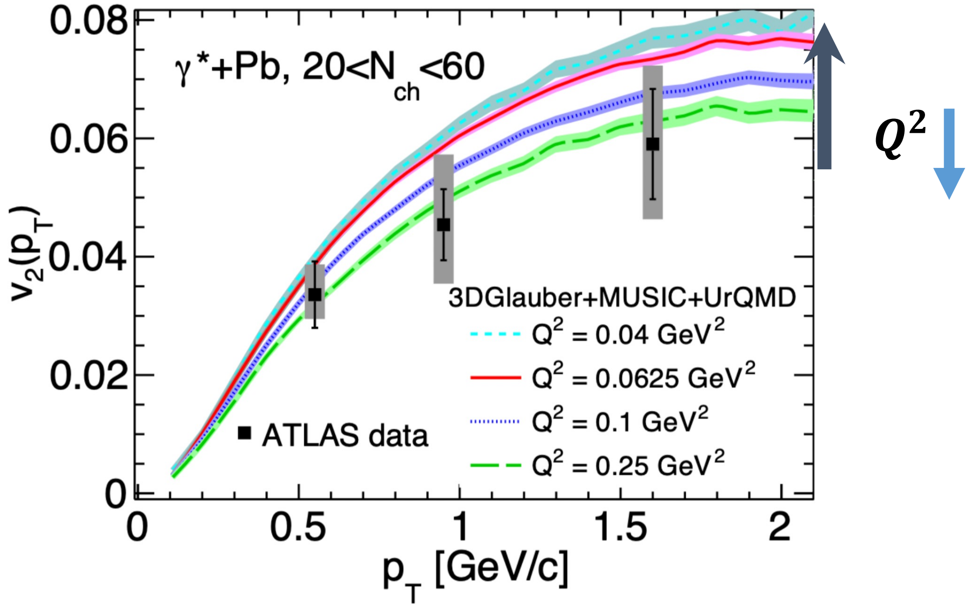
- More **QGP-attributed** signatures in UPC.

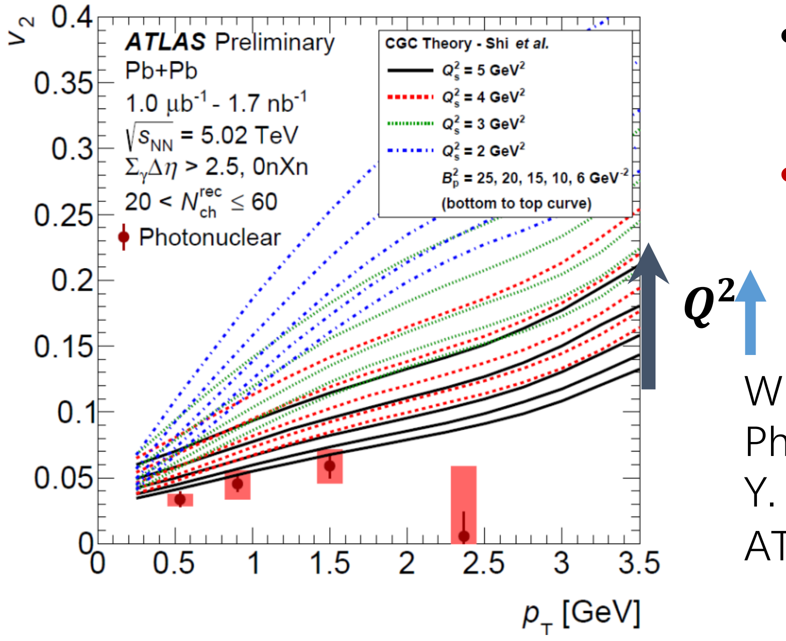
Search “QGP” in UPCs







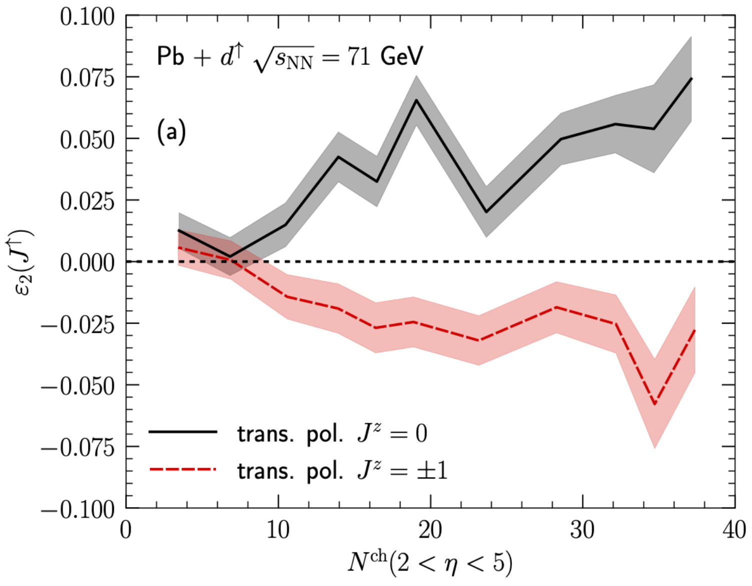


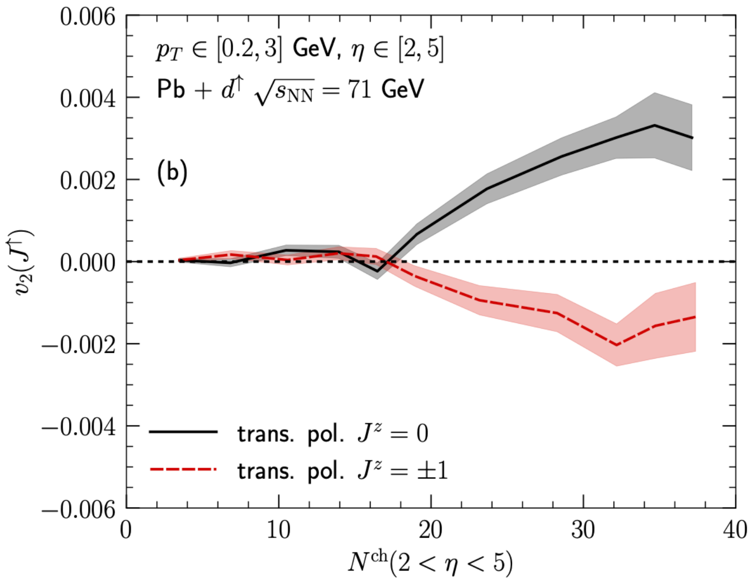


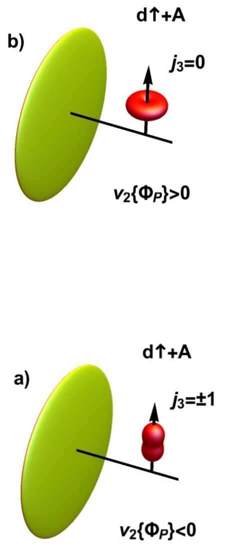
- More **QGP-attributed** signatures in UPC.
- **Opposite** virtuality dependence of flow in UPC predicted by Hydro and CGC.

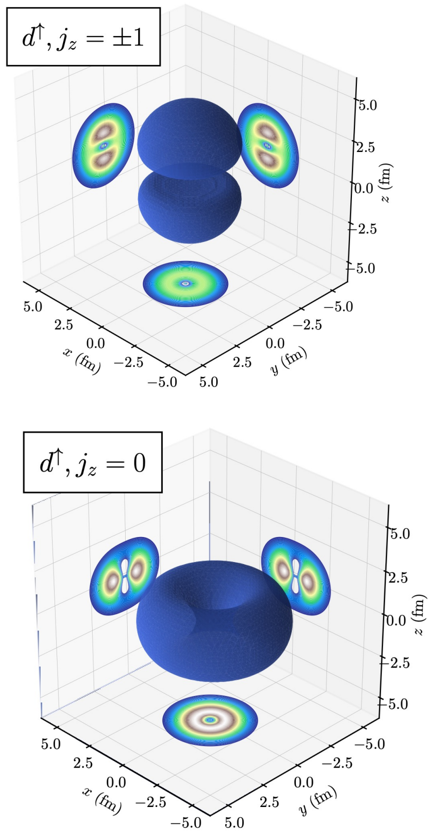
W. Zhao, C. Shen and B. Schenke PhysRevLett.129.252302.
Y. Shi, etc.al,Phys. Rev. D 103, 054017 (2021).
ATLAS, Phys. Rev. C 111, 064908 (2025)

Collective flow in Polarized deuterons + Nuclei





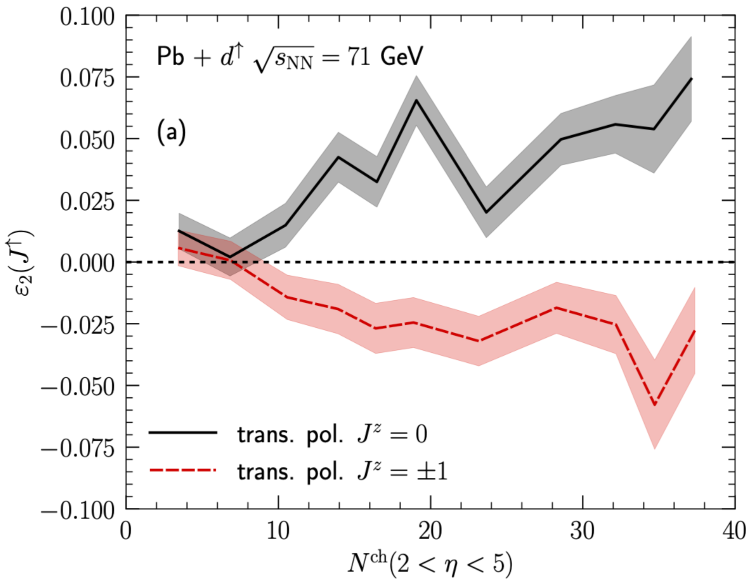


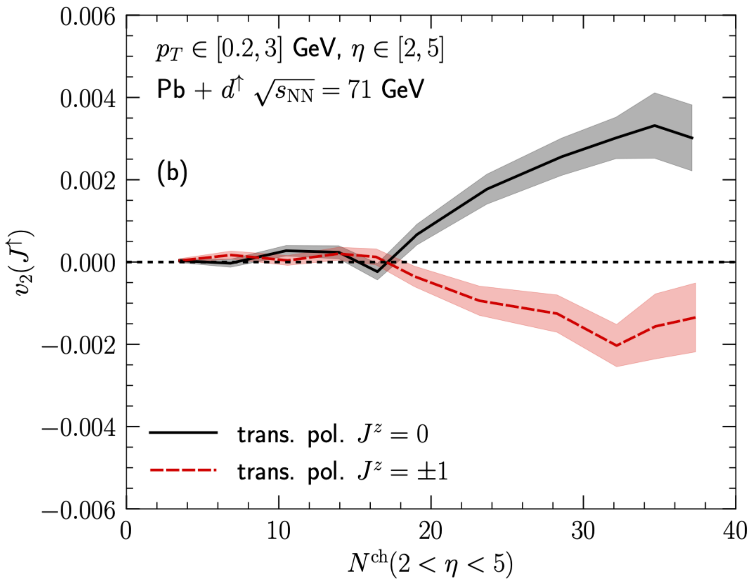


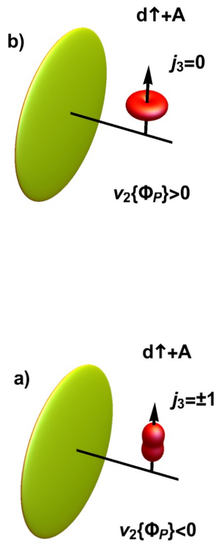
- **Different sign** for $J_z = \pm1$ and $J_z = 0$. (see also: [P. Bozek and W. Broniowski, PhysRevLett.121.202301.])

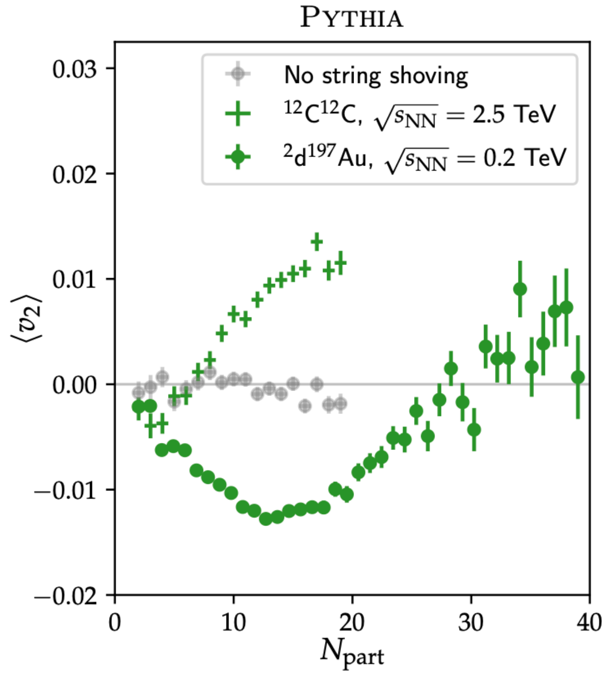
H. Mantysaari, B. Schenke, C. Shen and W. Zhao, [arXiv:2509.00511].
LHCb: [arXiv:2509.12399].

Collective flow in Polarized deuterons + Nuclei









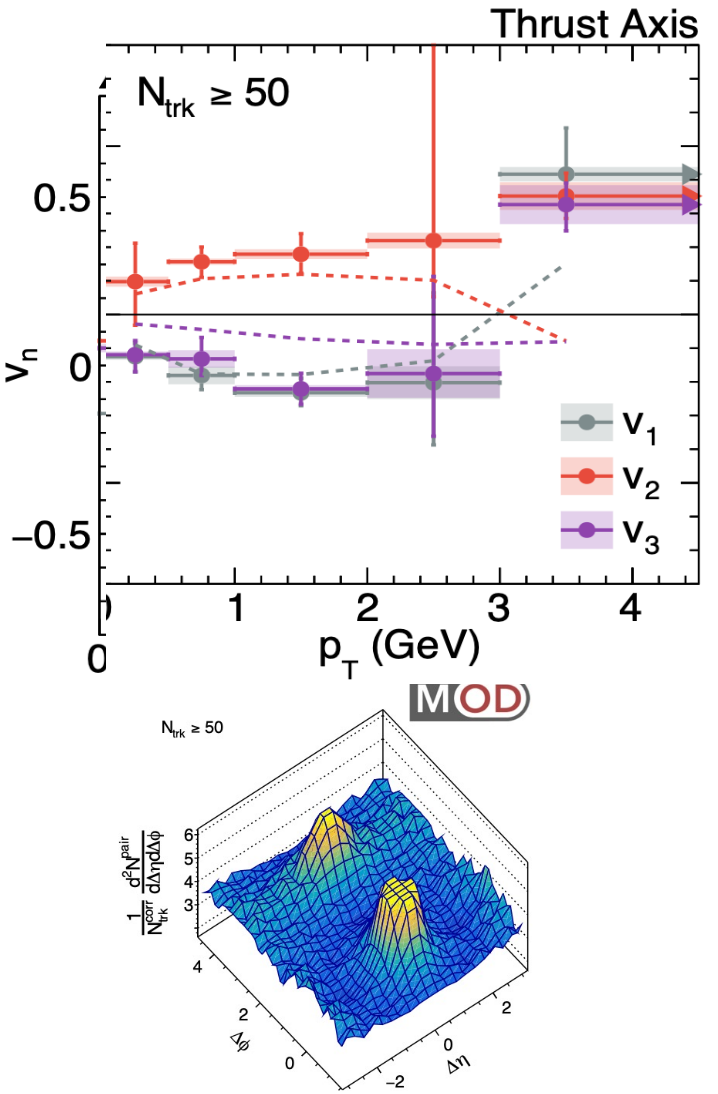
shoving model.
[arXiv: 2409.16093]

- **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].

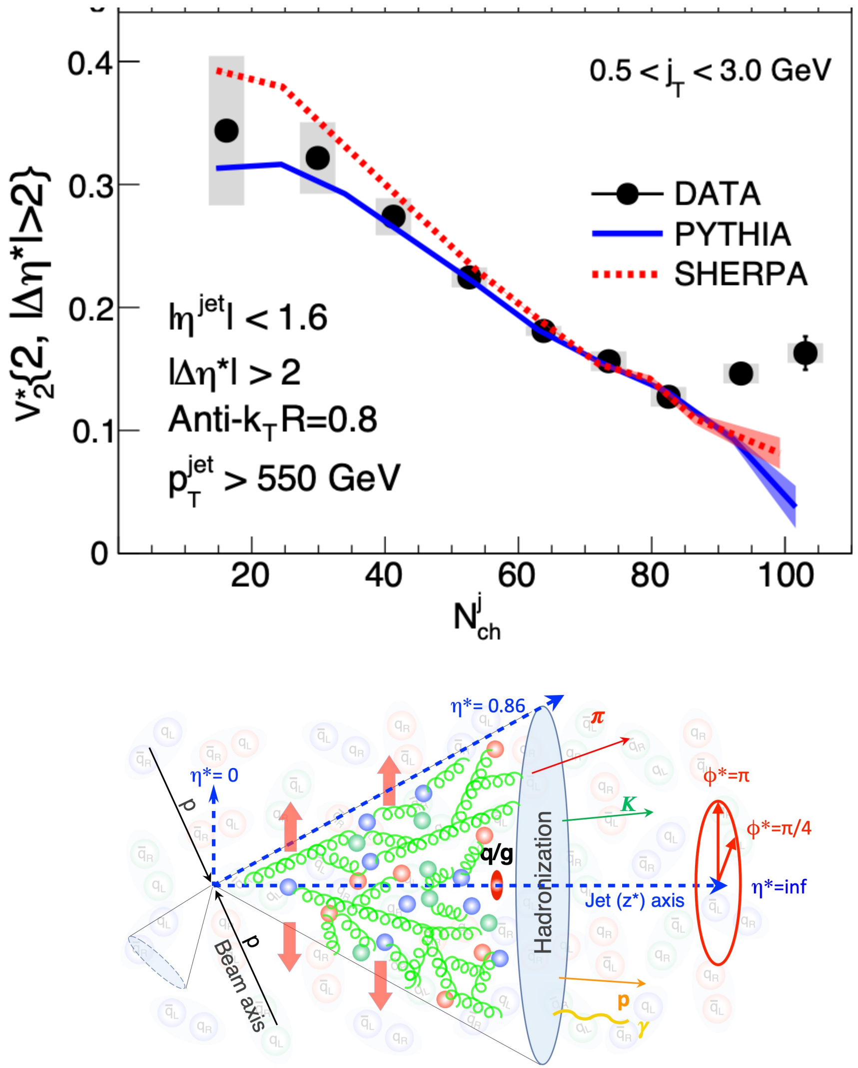
Searching the “smallest” droplet

- “Collectivity” in e^+e^-.



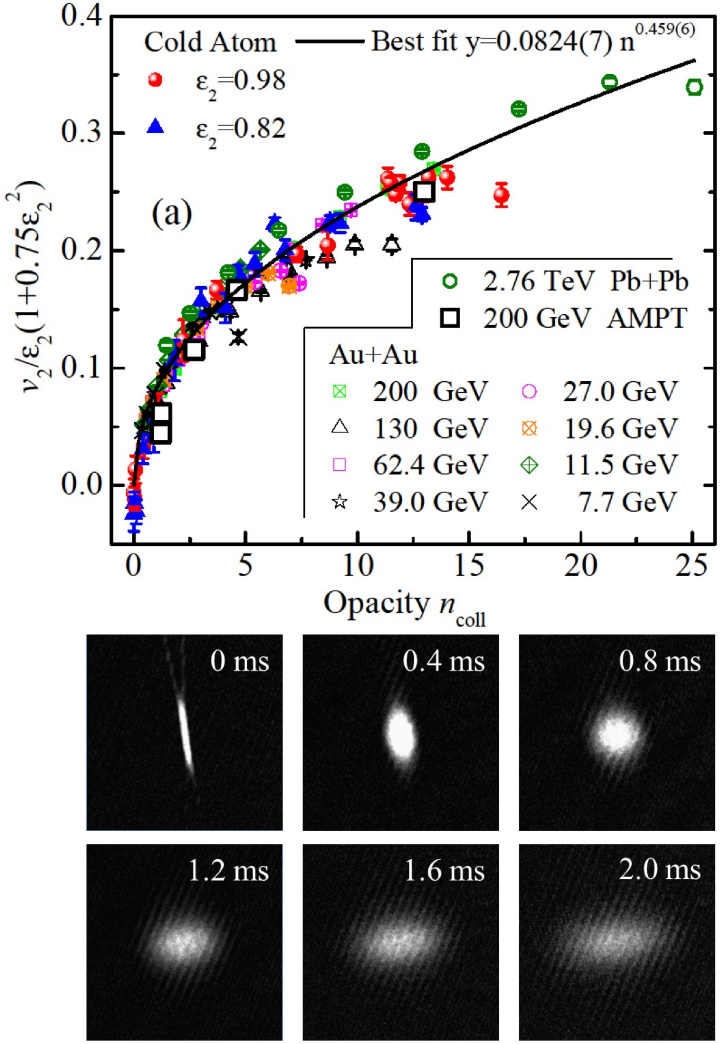
ALEPH, [arXiv:2312.05084].

- “Collectivity” inside jet.



CMS: arXiv: 2312.17103.

- “Collectivity” in Cold atom.



[arXiv:2405.02847]

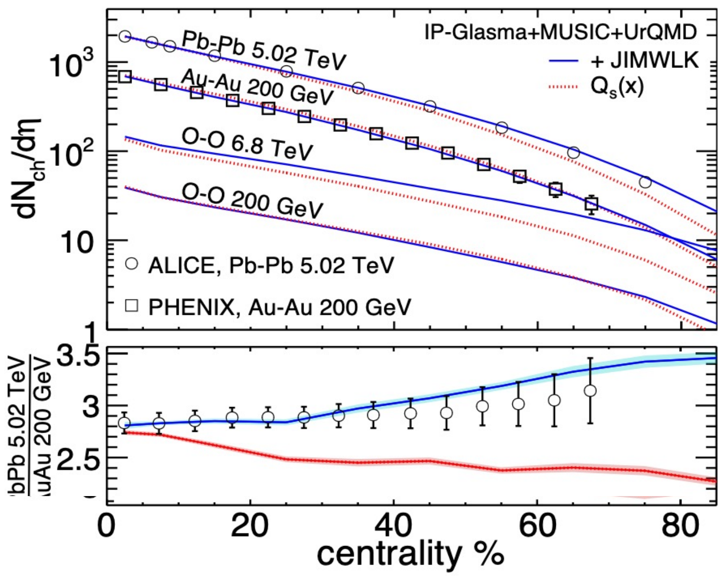
Summary

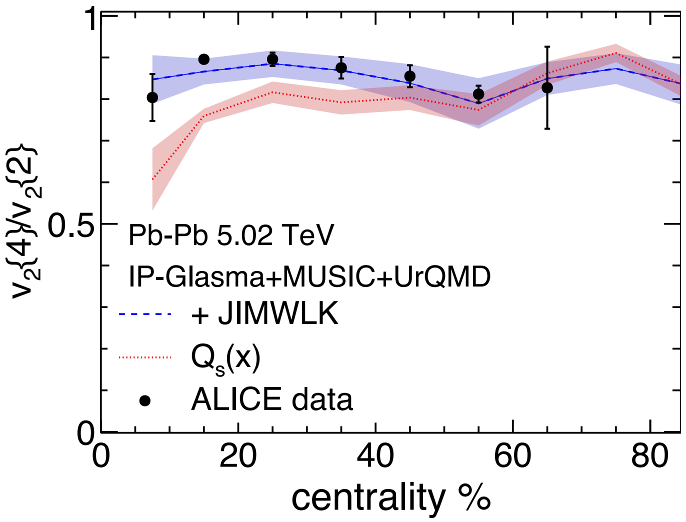
- Heavy-ion Collision have been into the **multi-messenger** era.
- We are searching the **"smallest droplet"** on the earth.
- UPC/EIC provide **a multi-scale image** tool for nuclei, serve as a **complementary tool** to heavy-ion observables to constrain initial conditions.
- A comprehensive analysis of UPC/DIS and heavy-ion collision data across various energies will provide a precise understanding of **gluon saturation**, the **initial conditions** of heavy-ion collisions, and the **QGP properties**.

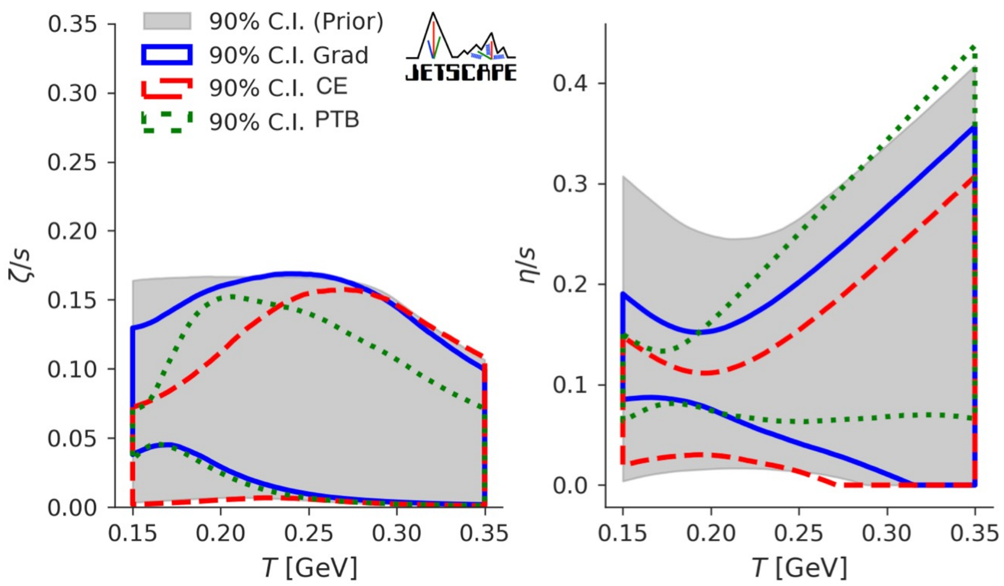
Thanks for Your Attention!

Back Up

Effects of energy evolution on heavy-ion observables







+ JIMWLK: CGC + energy evolution + Hydrodynamics

$\boldsymbol{Q_s(x)}$: CGC (change the $Q_s(x)$ only for different energies) + Hydrodynamics

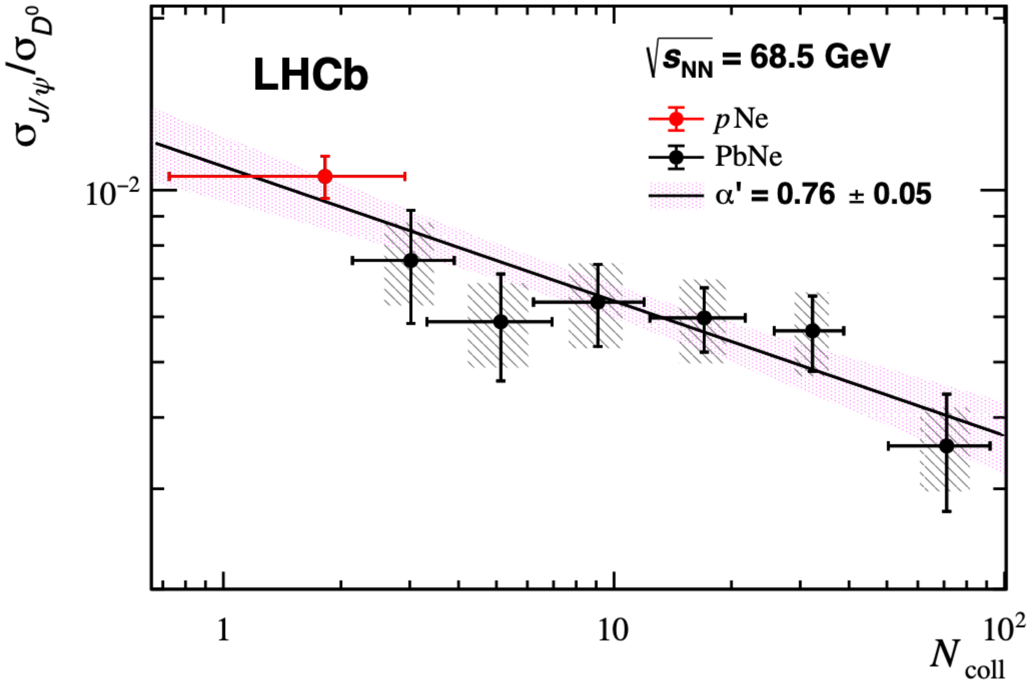
JETSCAPE, PRC.103.054904

Bayesian fitting to the RHIC and LHC data.

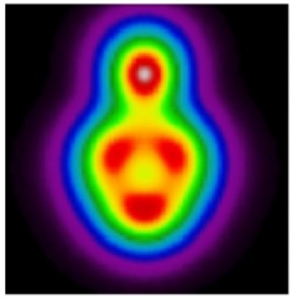
H. Mäntysaari, B. Schenke, C, Shen and W. Zhao, PRL. 135, 022302 (2025)

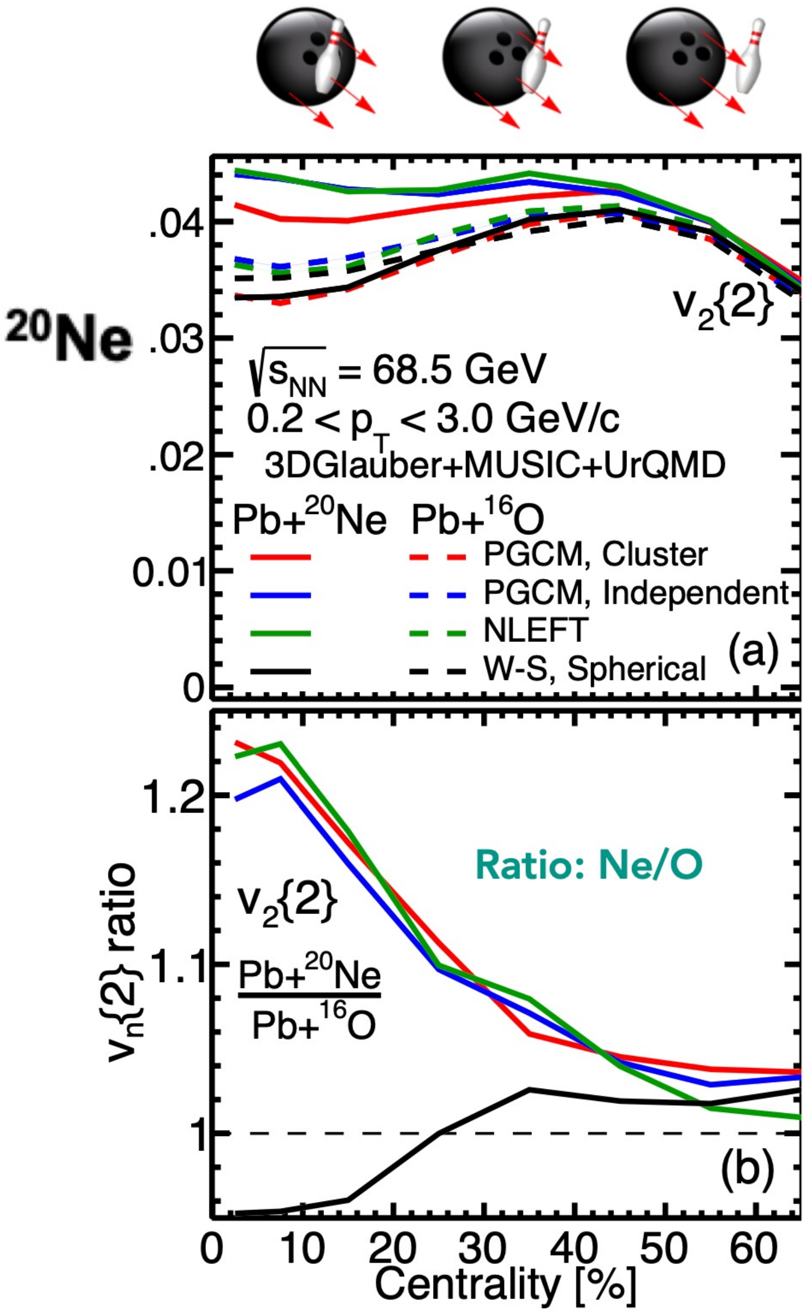
- The energy evolution of the initial state is important in Bayesian analysis when comparing data across different collision energies.

A Probe of Quark-Gluon Plasma



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





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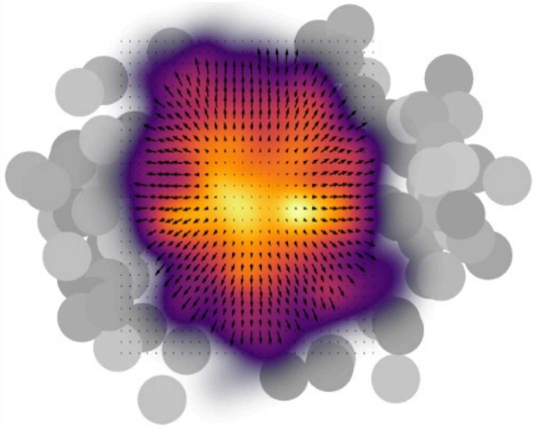
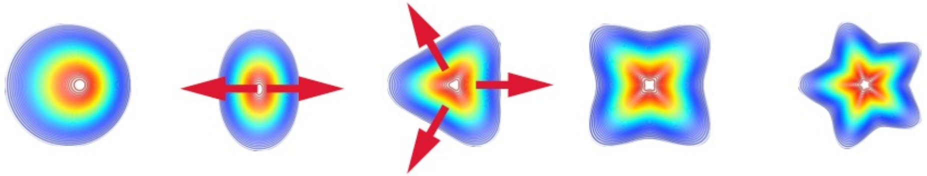
- Flow sensitive to shapes of Ne-20.
- Searching the QGP at LHCb.

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

Anisotropic Flows





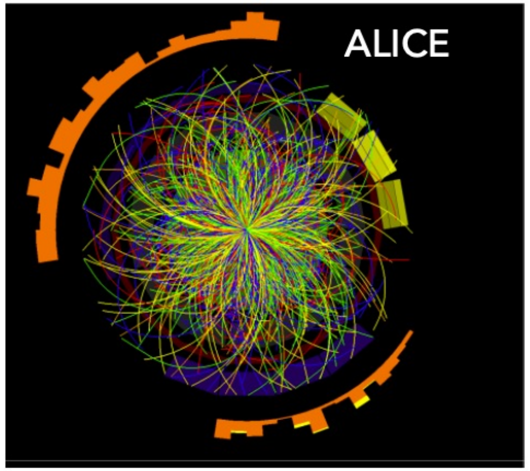
initial fluctuating geometric deformation can be decomposed into spatial eccentricities

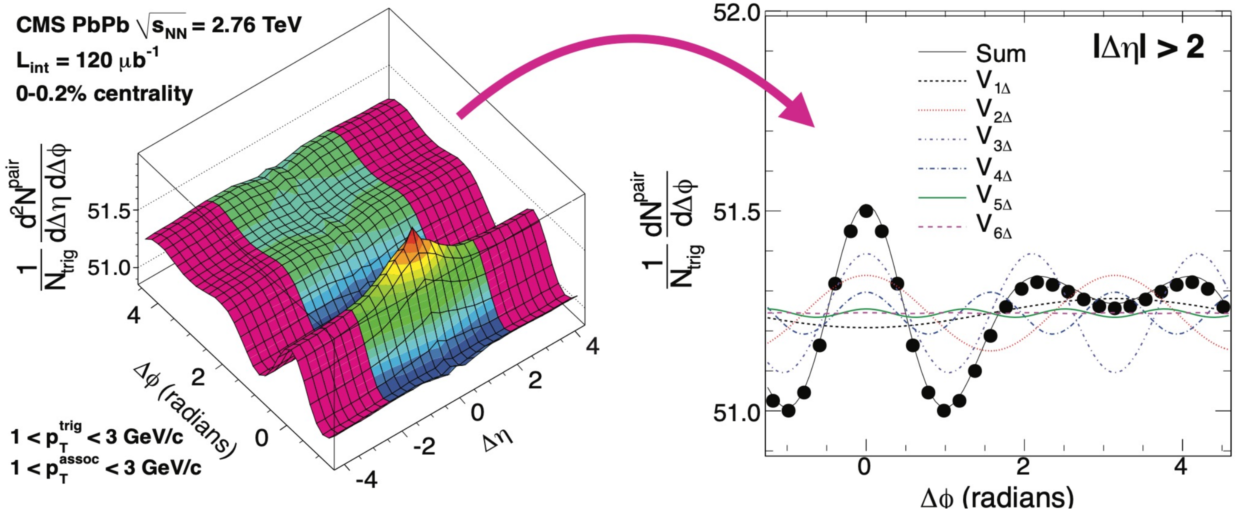
Initial spatial eccentricities

$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}{\langle r^n \rangle^2}}$$

average over energy density

ϵ_2 ellipticity, ϵ_3 triangularity, ...





Fourier decomposition of final particle azimuthal distribution

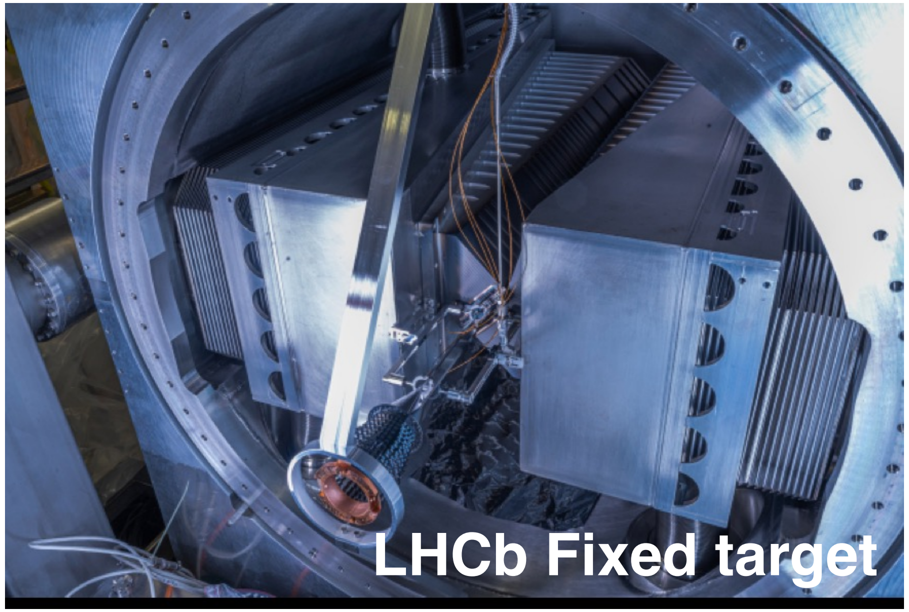
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]\right)$$

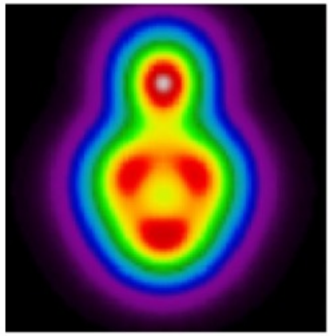
$$v_2 = \langle \cos[2(\phi - \Psi_2)] \rangle$$

average over azimuthal distribution

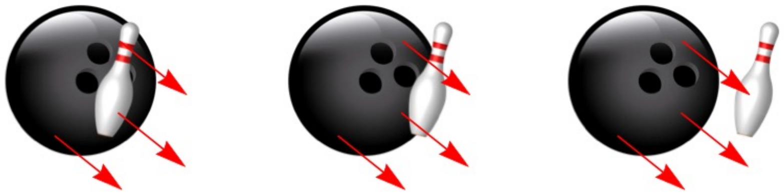
v_2 elliptic flow, v_3 triangular flow, ...

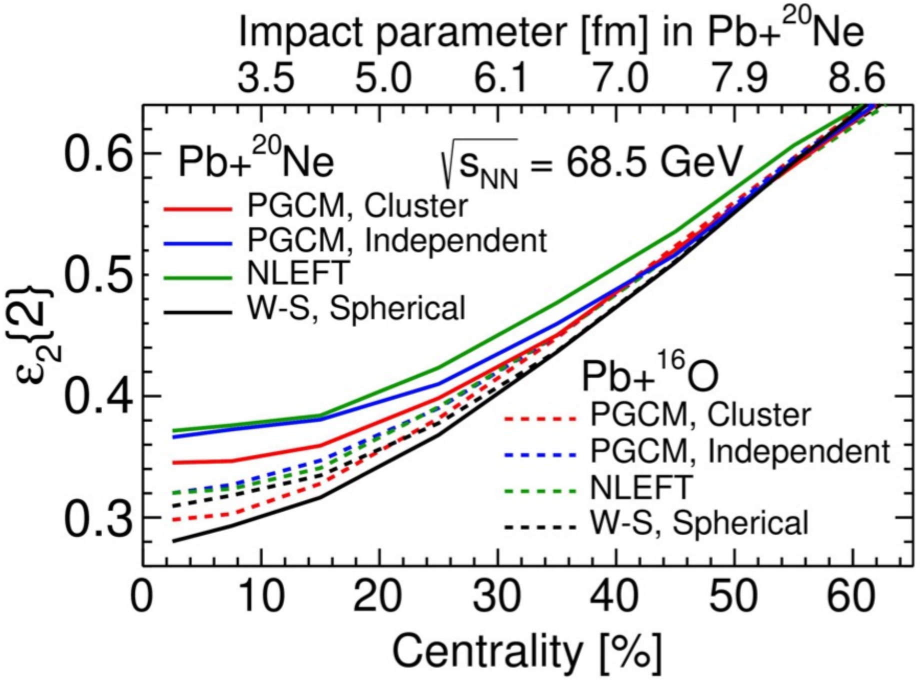
High Energy Bowling Allay





^{20}Ne



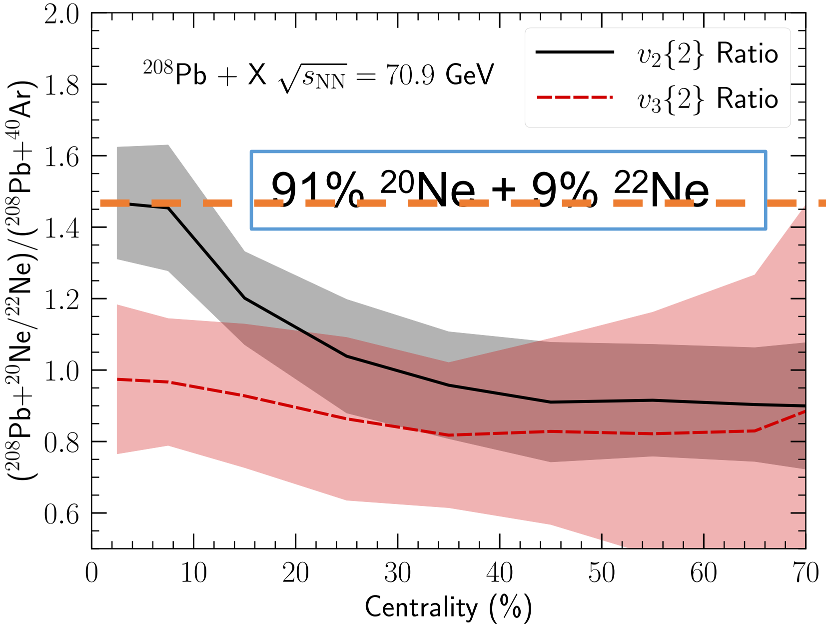


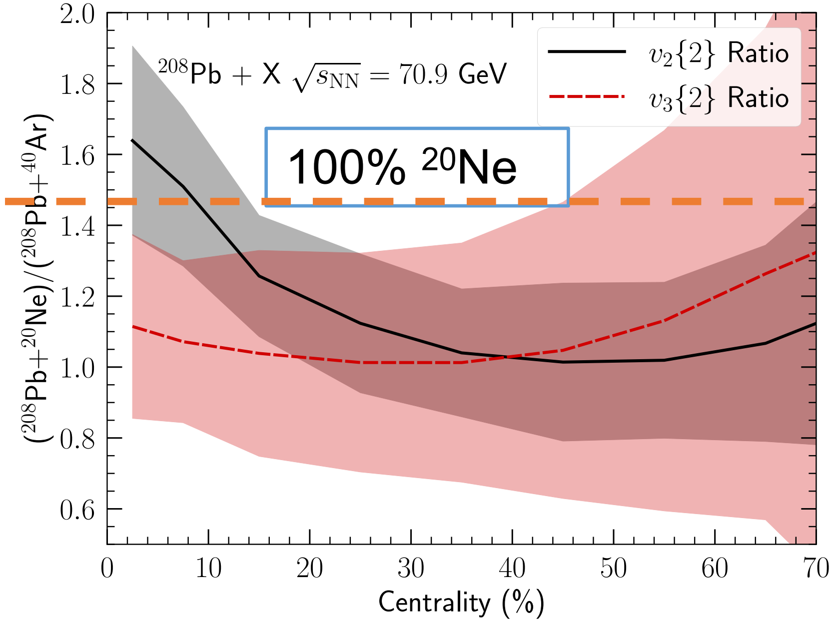
Pb + Ne-20 collisions: A high energy bowling allay!

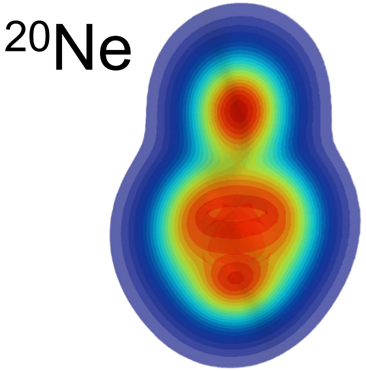
G. Giacalone W. Zhao et al Phys. Rev. Lett. 134, 082301 (2025)

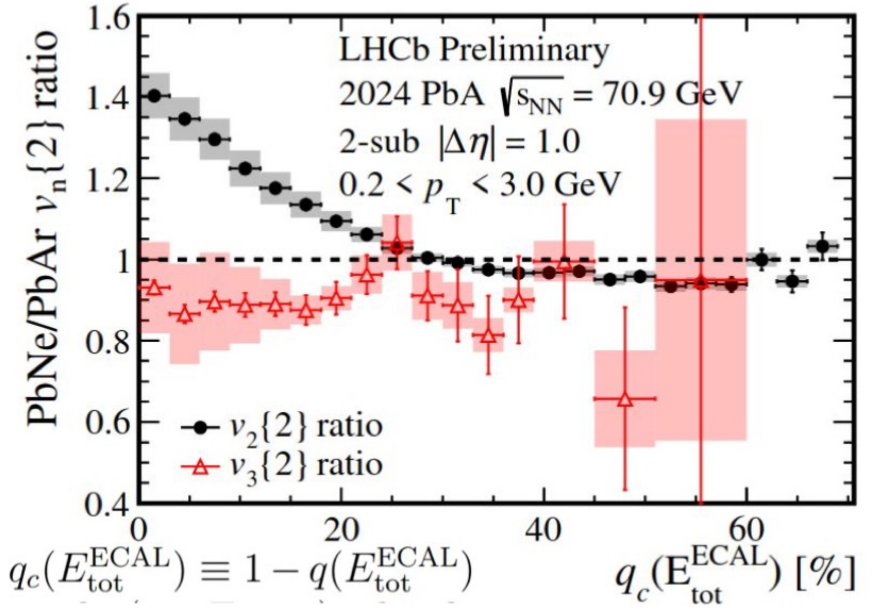
- Connecting *ab initio* inputs of light-nuclei with relativistic nuclear collisions.

Playing Relativistic Bowling Ball







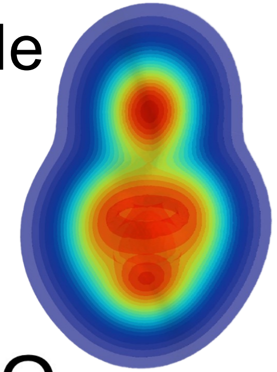


- Mixing 9% of ^{22}Ne has a sizable effect on the v_n ratio.

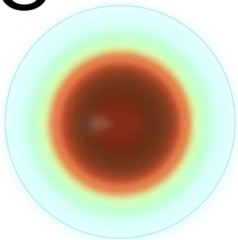
LHCb: [arXiv:2509.12399].

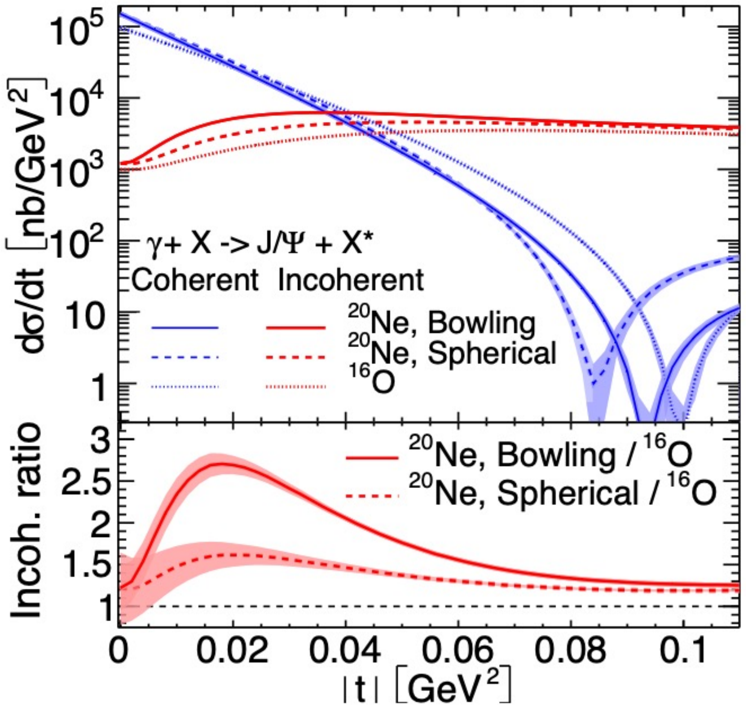
Probing light nuclei structures

^{20}Ne



^{16}O

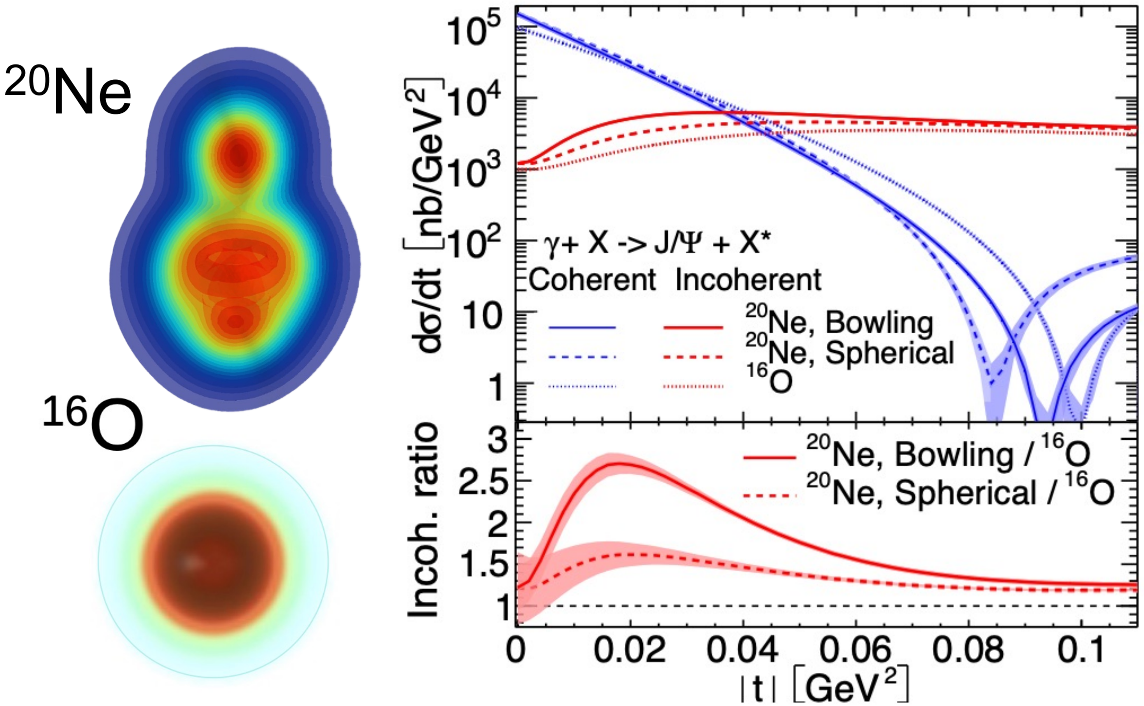




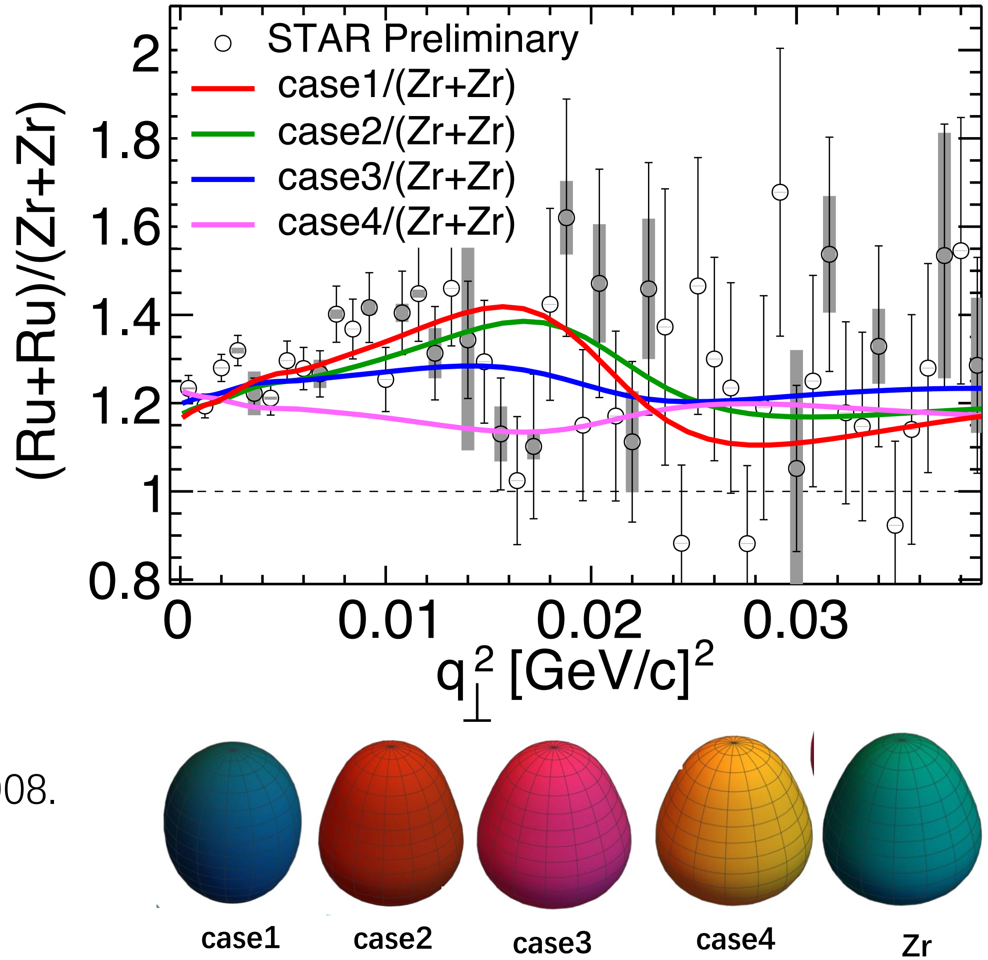
H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, PRL.131.062301.

H. Mäntysaari, F. Salazar, B.Schenke, C. Shen and W. Zhao PRC.109.024908.

Probing light nuclei structures



H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, PRL.131.062301.
H. Mäntysaari, F. Salazar, B.Schenke, C. Shen and W. Zhao PRC.109.024908.



- Probe light nuclear structures by diffractive V.M. productions, complementary to heavy-ion observables. (See also J. P. Blaizot and G. Giacalone, [arXiv:2504.15421].)

Proton geometry fluctuations

- Proton's event-by-event fluctuating density profile:

$$T_p(\mathbf{b}_\perp) = \frac{1}{N_q}\sum_{i=1}^{N_q} p_i T_q(\mathbf{b}_\perp - \mathbf{b}_{\perp,i}), \quad P\left(\ln p_i\right) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{\ln^2 p_i}{2\sigma^2}\right].$$

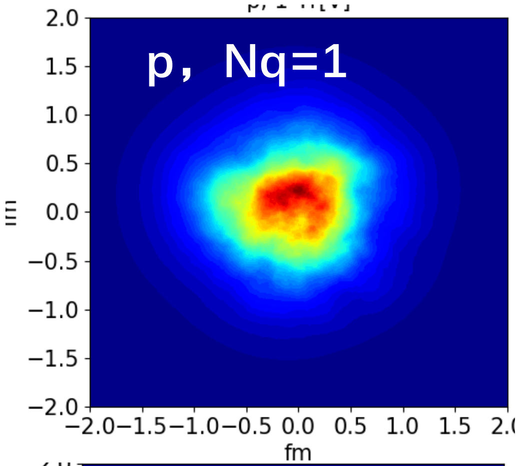
- The density profile of each spot is:

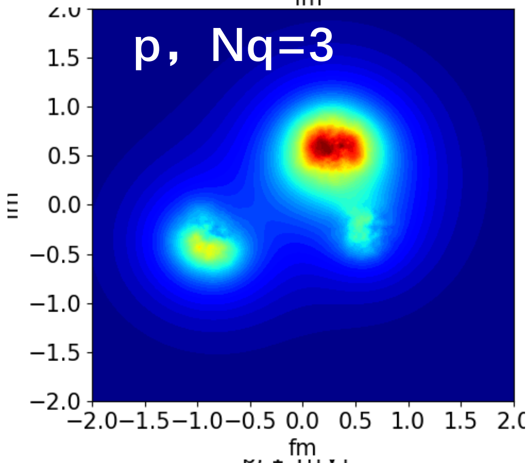
$$T_{\mathrm{q}}(\vec{b}) = \frac{1}{2\pi B_{\mathrm{q}}} e^{-b^2/(2B_{\mathrm{q}})}$$

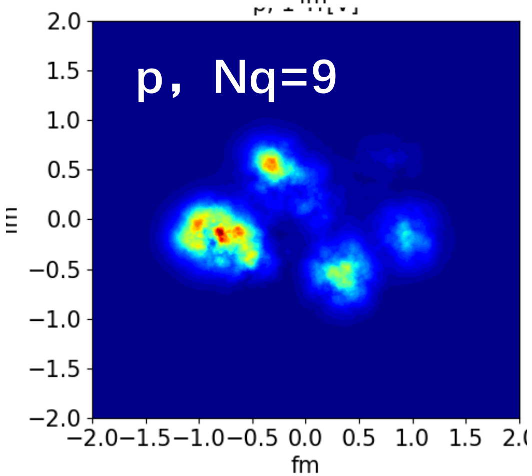
- The spot positions $\overrightarrow{b_i}$ are sampled from:

$$P(b_i) = \frac{1}{2\pi B_{\mathrm{qc}}} e^{-b_i^2/(2B_{\mathrm{qc}})}$$

Schenke , etc.al. PhysRevLett.108.252301 ,
PhysRevC.86.034908, Mäntysaari, Schenke, 1603.04349;



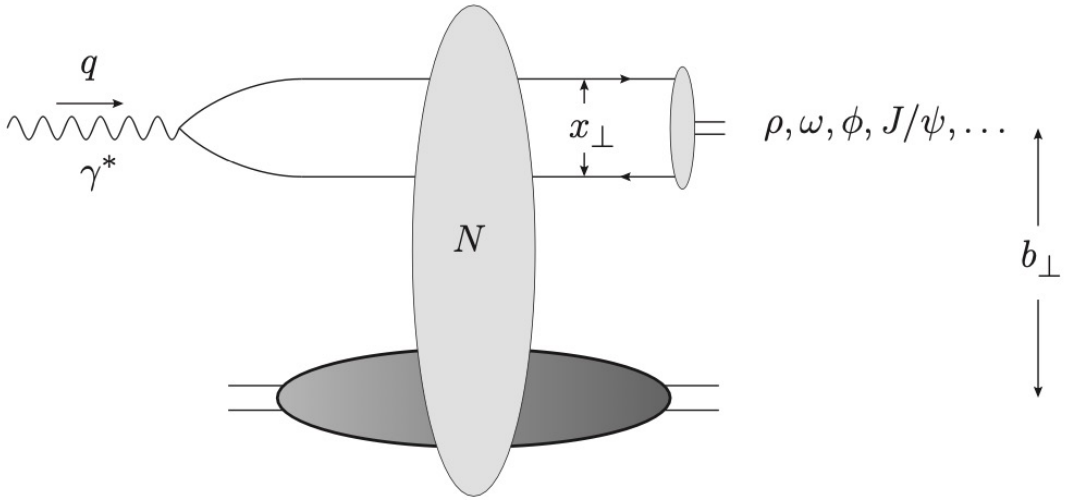


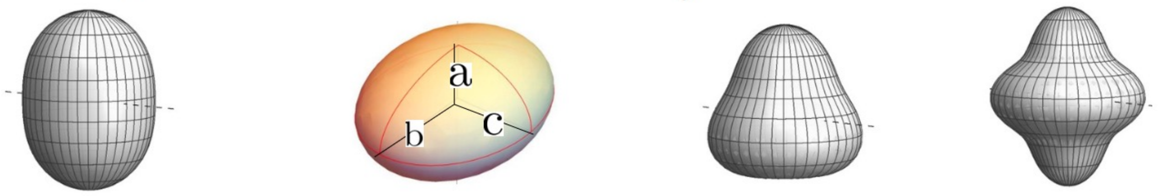


Nuclear structure

Generalized Woods-Saxon profile

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

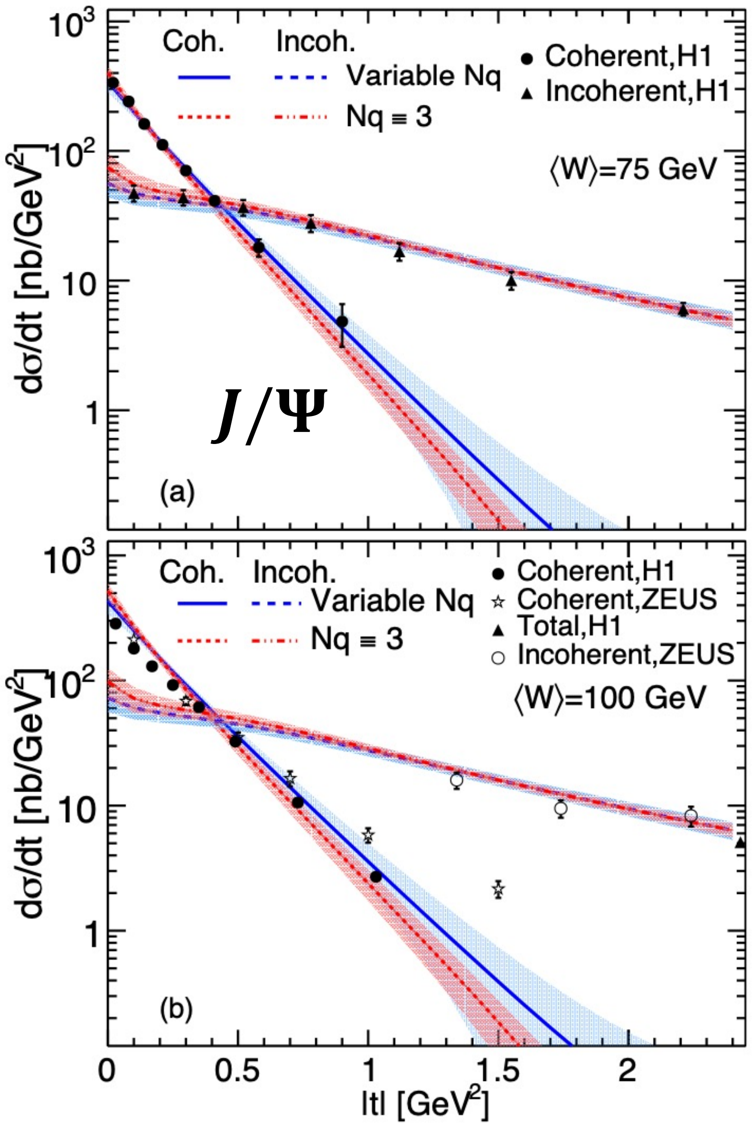


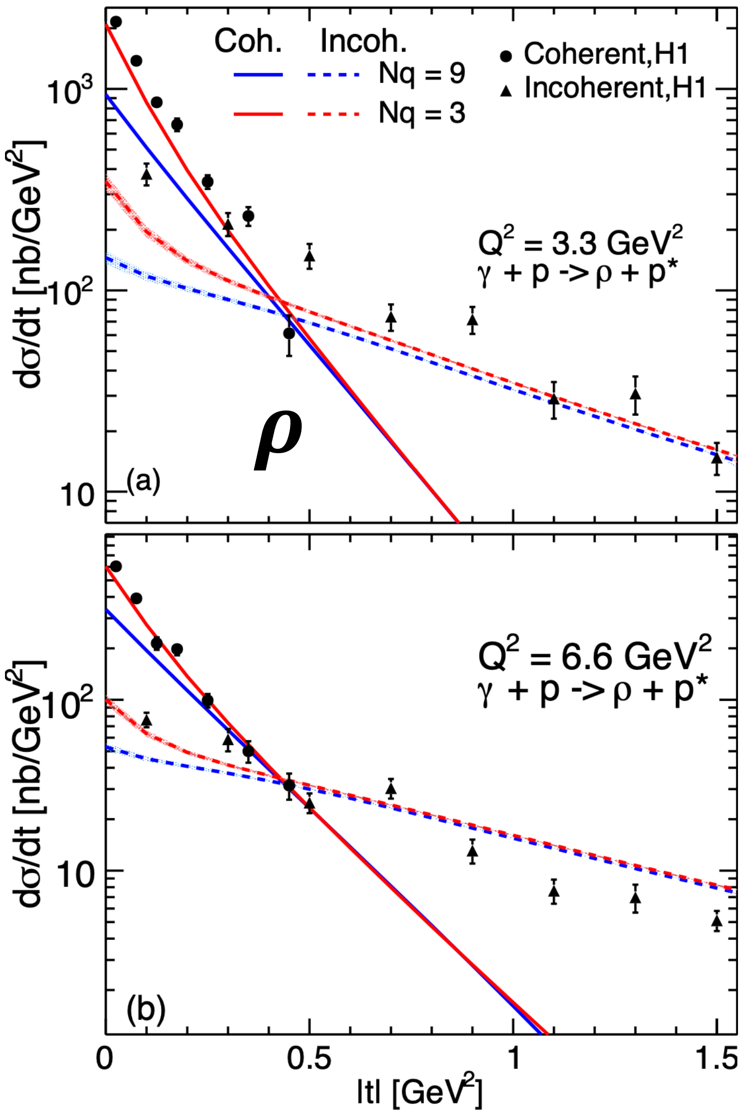


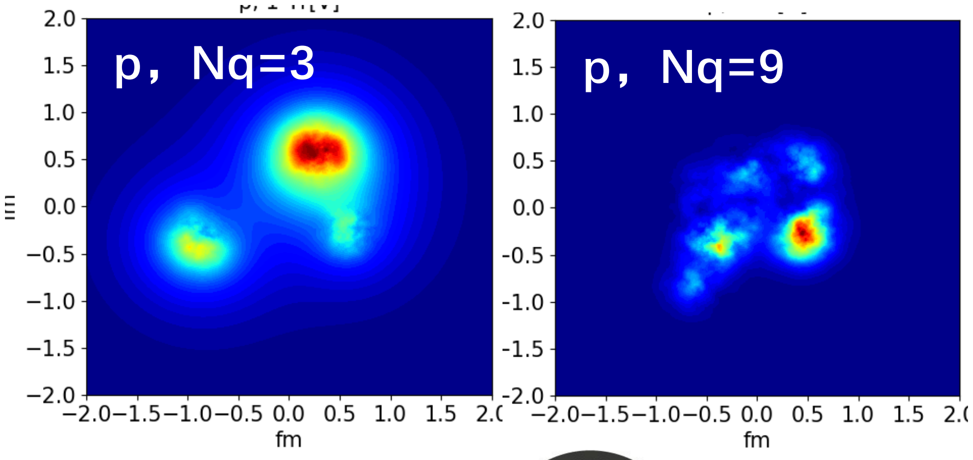
Taken from Giuliano’s slide

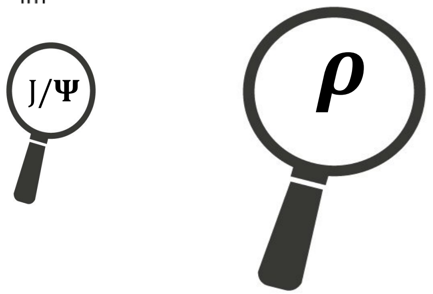
- Different deformation parameters controls the geometric deformation at **different length scale**.

Probing nucleon at different resolutions





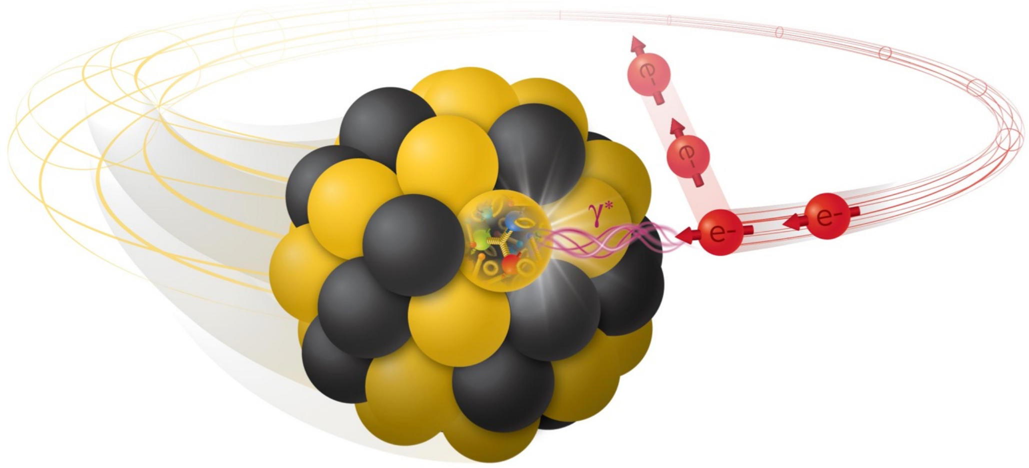


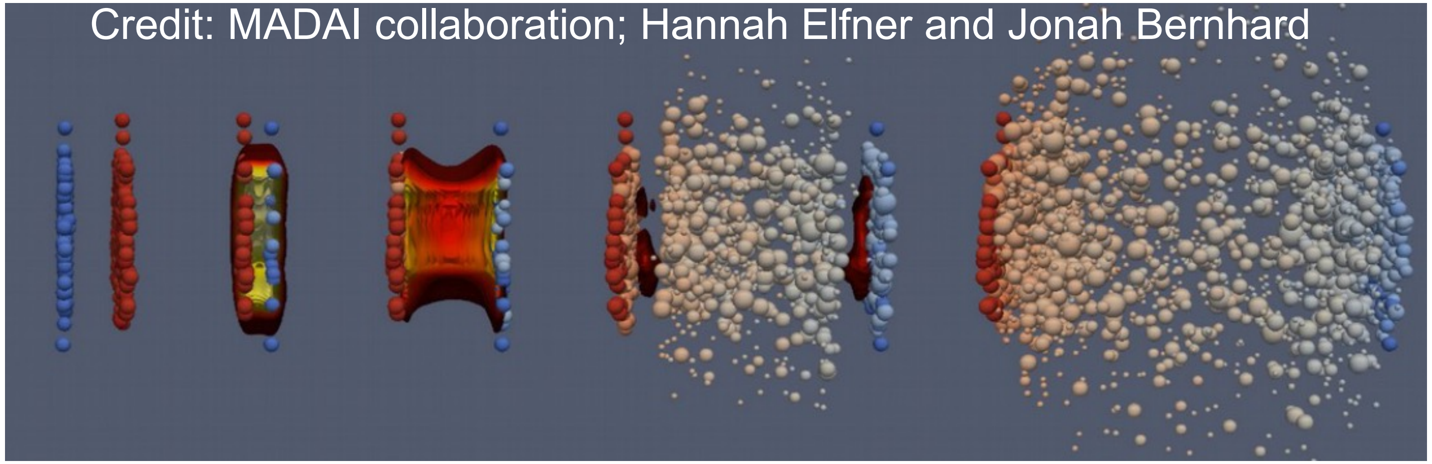


- The ρ mesons probe proton fluctuations at large length scales.
- Sizeable differences observed for ρ productions between Nq=3 and Nq=9 MAPs.

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

UPC/DIS and Heavy-ion Collisions





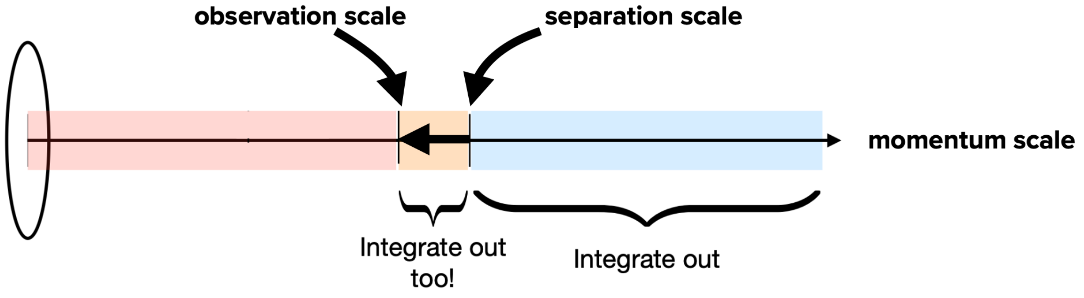
- **UPC/DIS:**
- Clean probes of QCD dynamics
- Collision energy is limited.

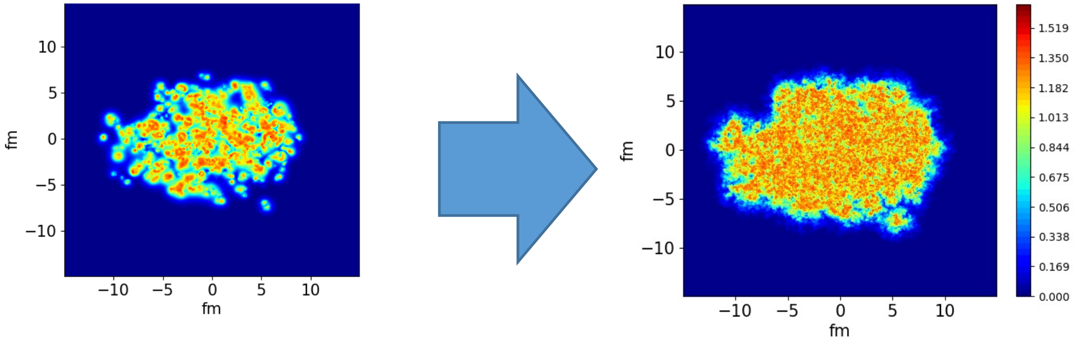
- **Heavy-ion Collisions:** High center-of-mass energies available.
- **Multi-Stage process:**

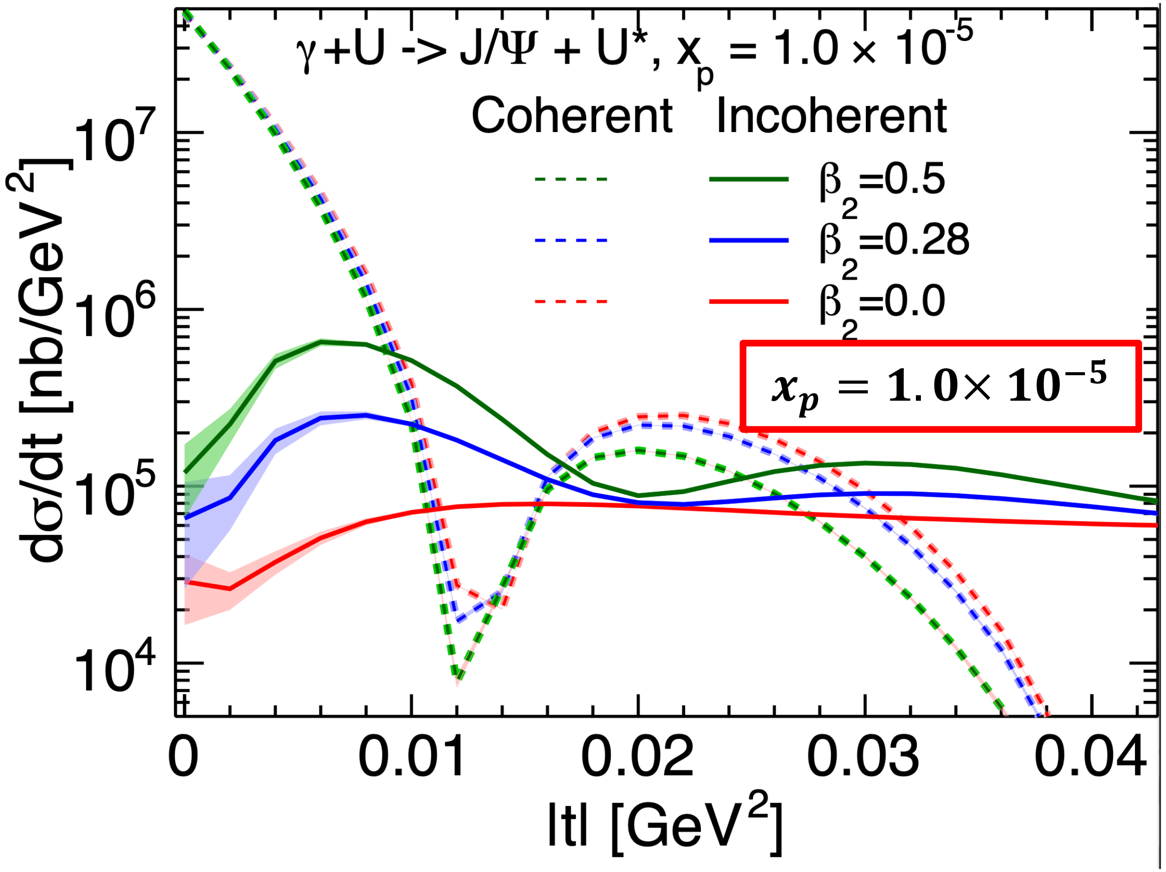
Initial state => QGP => Hadronic Scatter

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

Energy evolution to smaller x





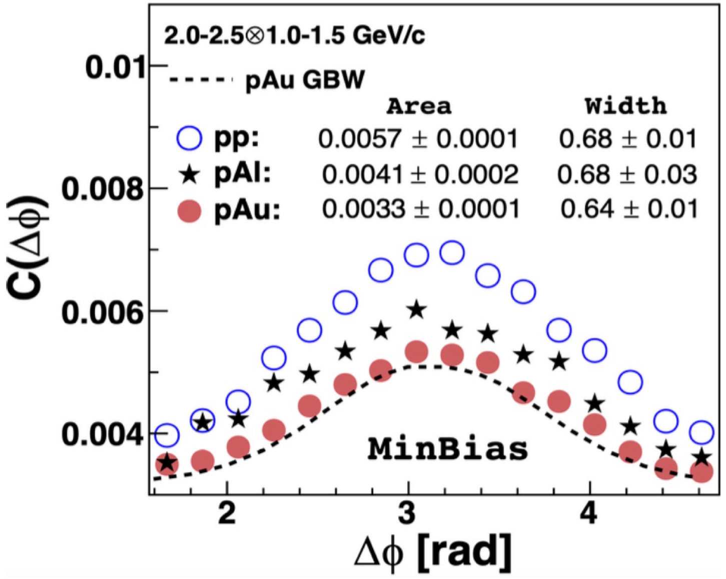


- Energy evolution **doesn't wash out** this effects.

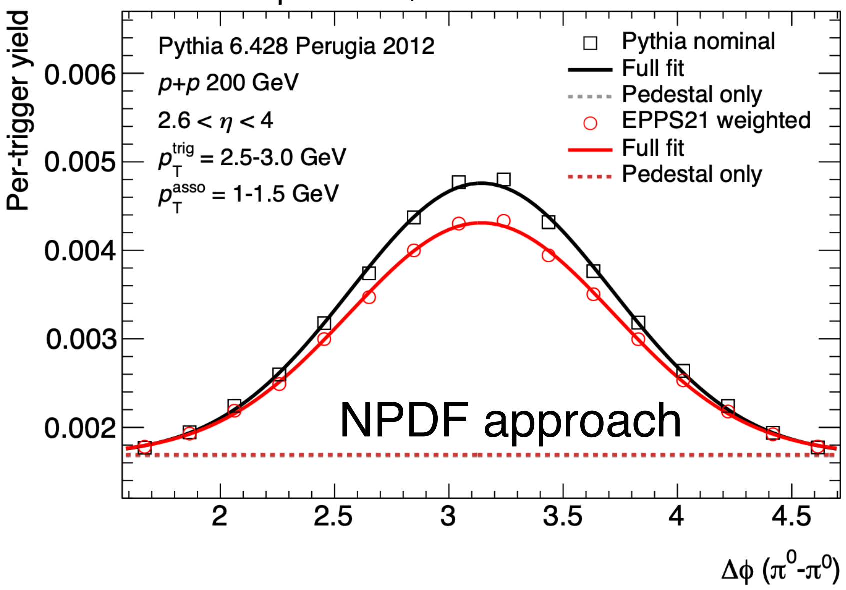
H.Mantysaari, B.Schenke, C. Shen and W. Zhao PhysRevLett.131.062301.
H.Mantysaari, B.Schenke PRD, 98, 034013.
T. Lappi and H. Mantysaari, EPJC 73, 2307 (2013).
Yuri V. Kovchegov, QUANTUM CHROMODYNAMICS A T HIGH ENERGY

Forward di-hadron correlations to probe gluon saturations

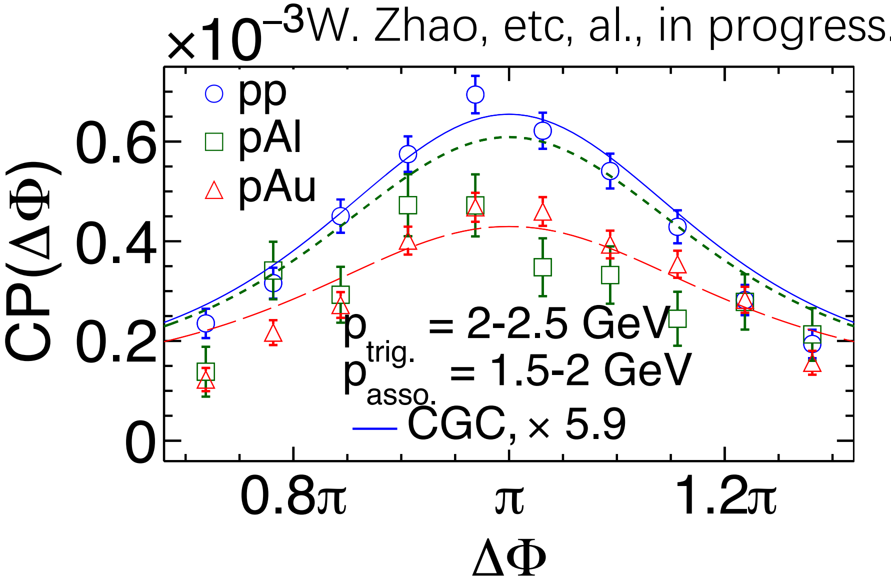
STAR: PRL.129.092501



D. V. Perepelitsa, PRC.111.054901



W. Zhao, etc, al., in progress



- Di-hadron data shows **nuclear size dependent suppression**. NPDF and CGC approaches have the similar results.

See also:

- J. L. Albacete and C. Marquet, Phys. Rev. Lett. 105, 162301 (2010)
- T. Lappi and H. Mantysaari, Nucl. Phys. 908, 51-72 (2013).
- van Hameren, etc, al. JHEP 12, 034 (2016).
- A. Stasto, etc. al, Phys. Lett. B 784, 301-306 (2018).
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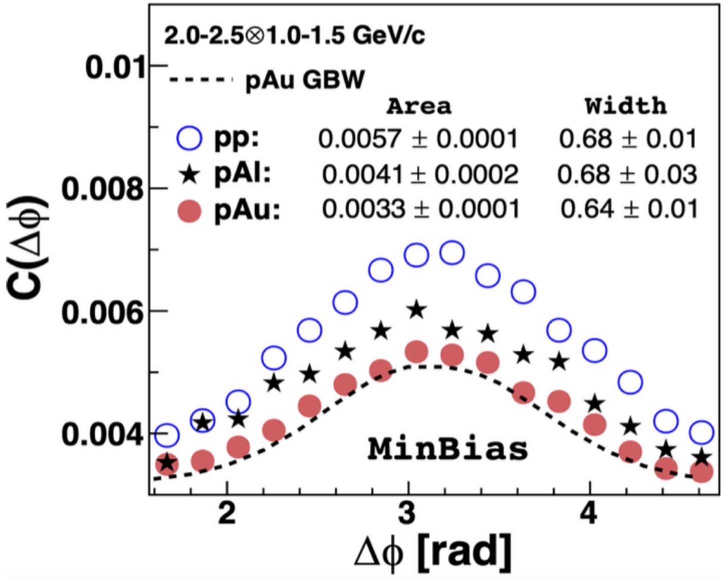

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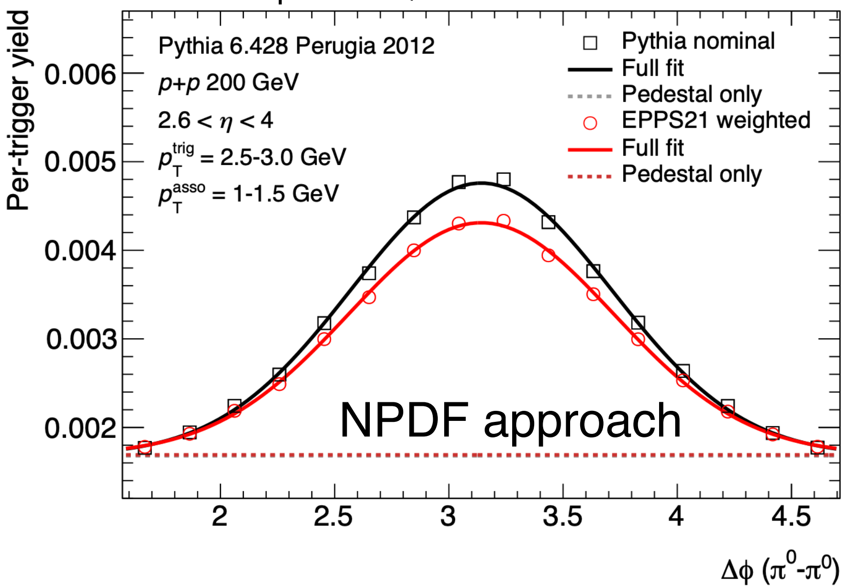

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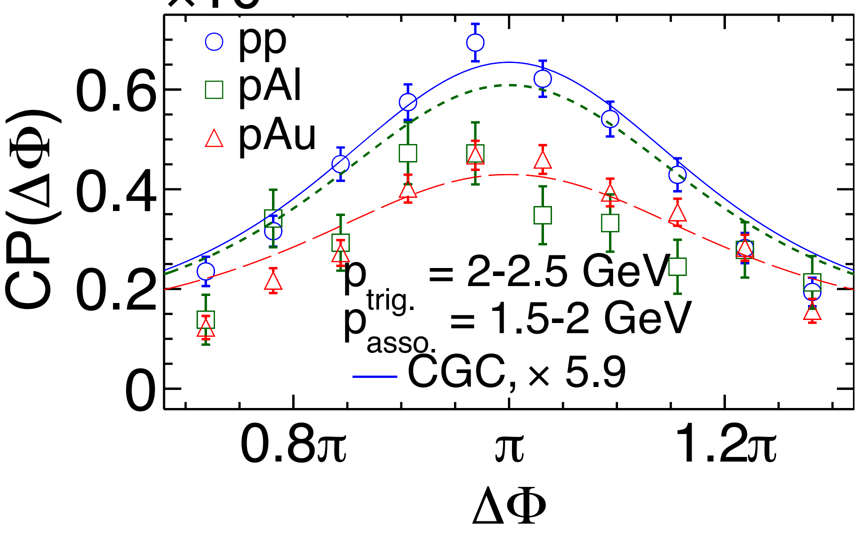

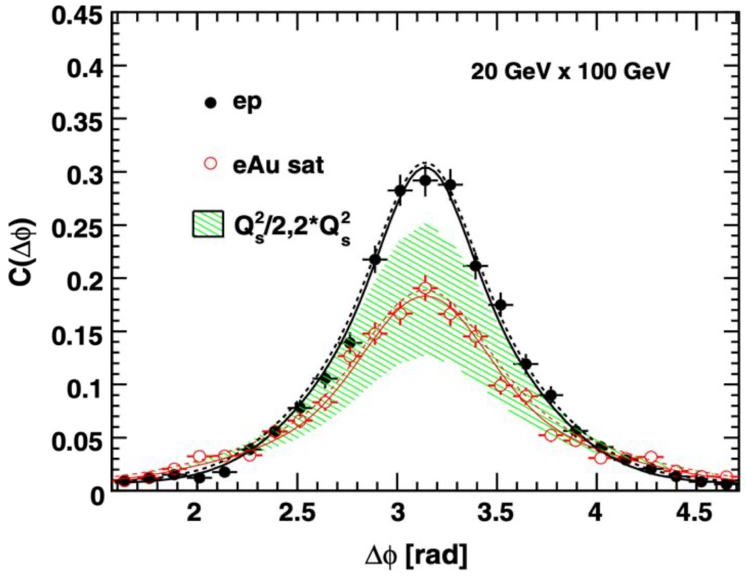

L. Zheng et al., PRD 89 (2014) 074037

- Di-hadron data shows **nuclear size dependent suppression**. NPDF and CGC approaches have the similar results.
- EIC/UPC provide the **clean environment** for dihadron correlations .

See also:

- J. L. Albacete and C. Marquet, Phys. Rev. Lett. 105, 162301 (2010)
- T. Lappi and H. Mantysaari, Nucl. Phys. 908, 51-72 (2013).
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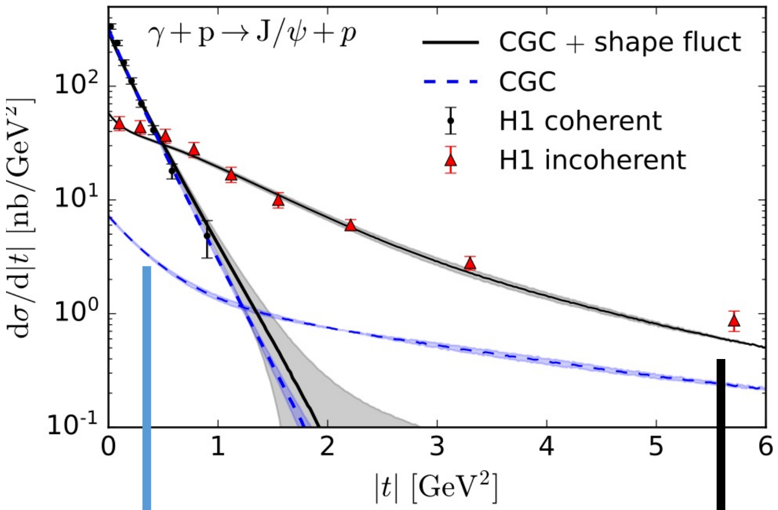
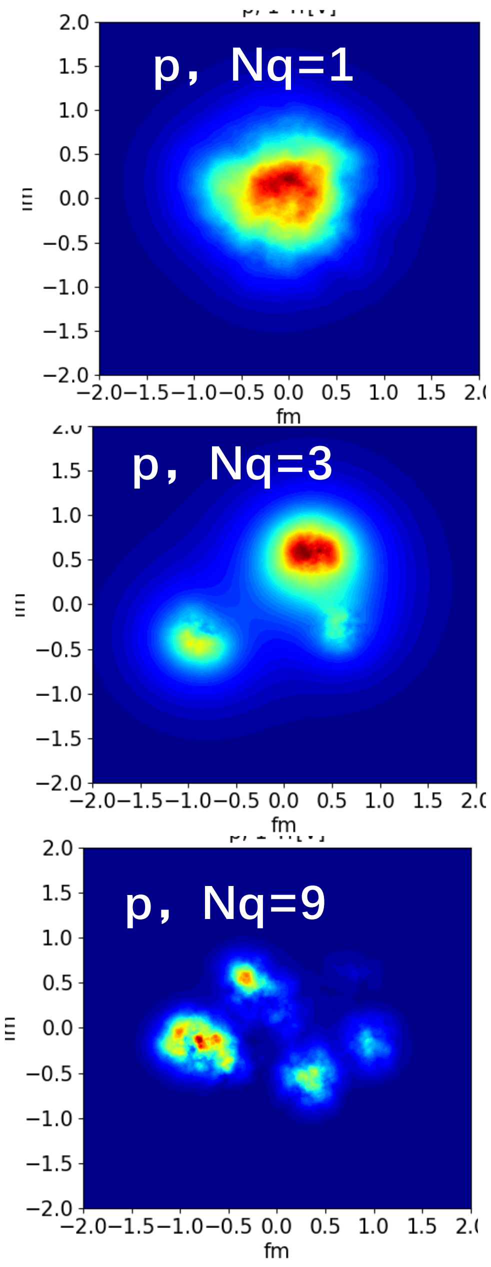
Proton geometry fluctuations



No subnucleon fluctuations

With subnucleon fluctuations



- Probe the event-by-event sub-nucleon fluctuations.

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.

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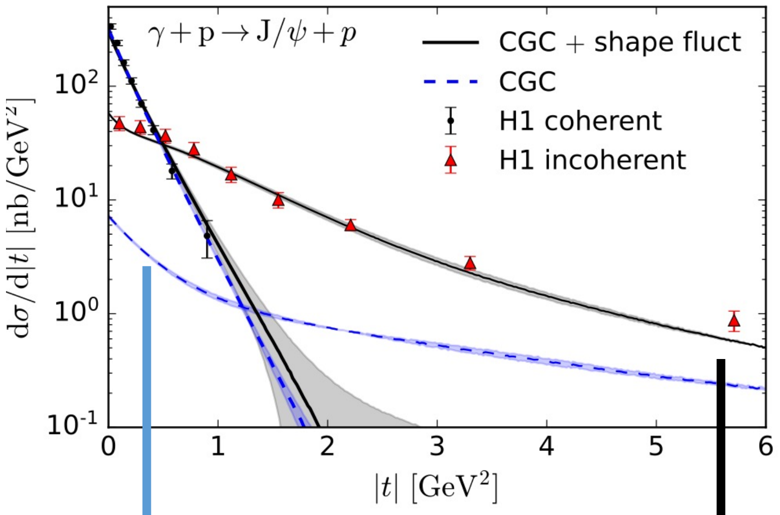

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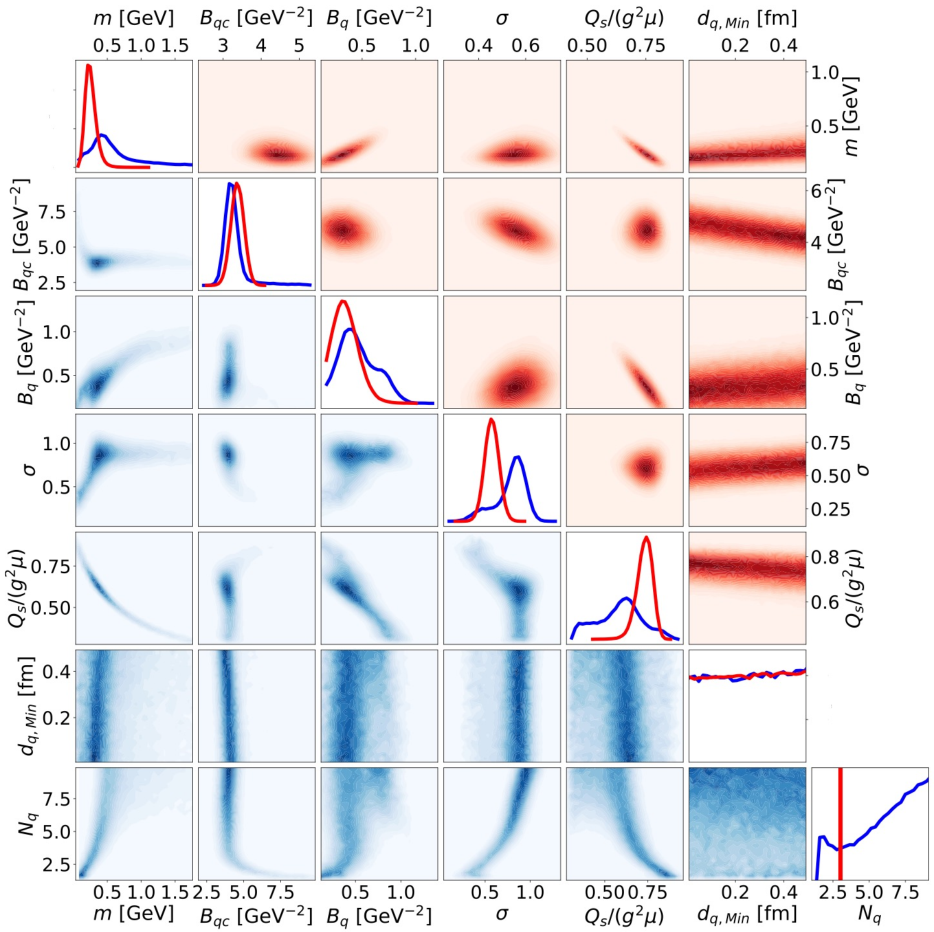
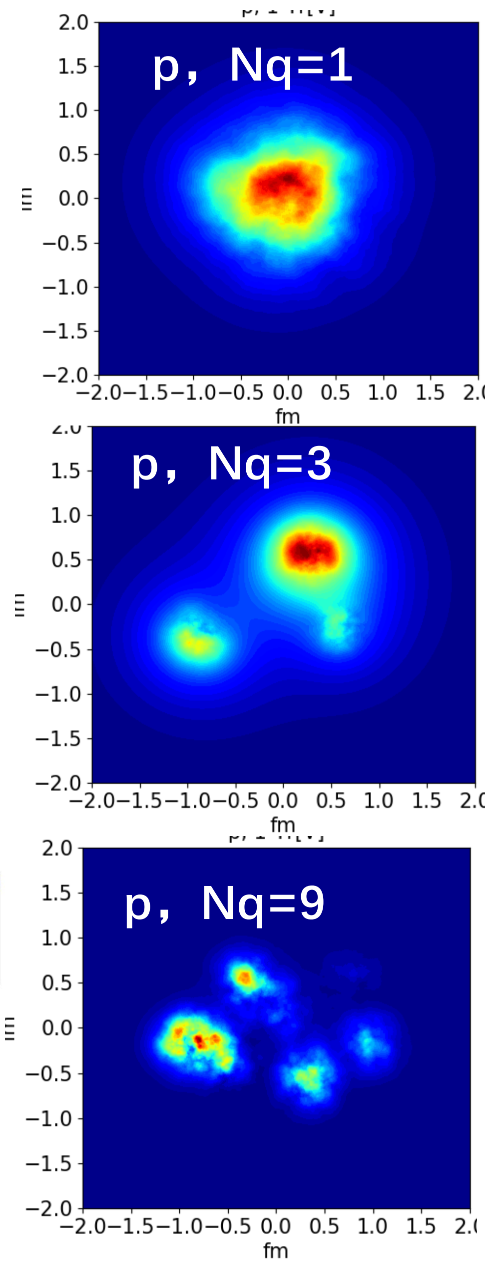
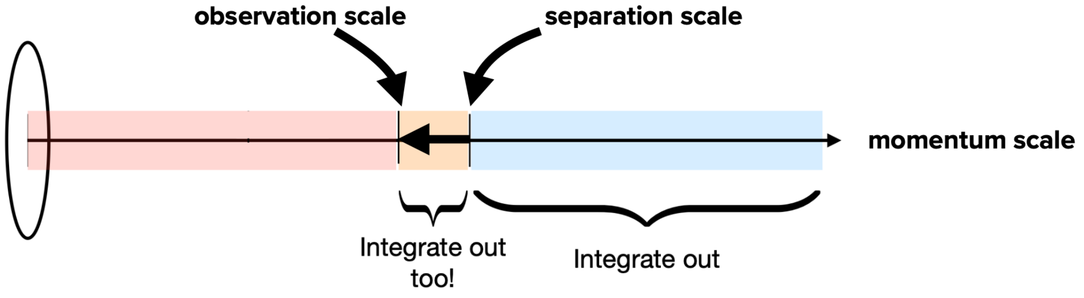


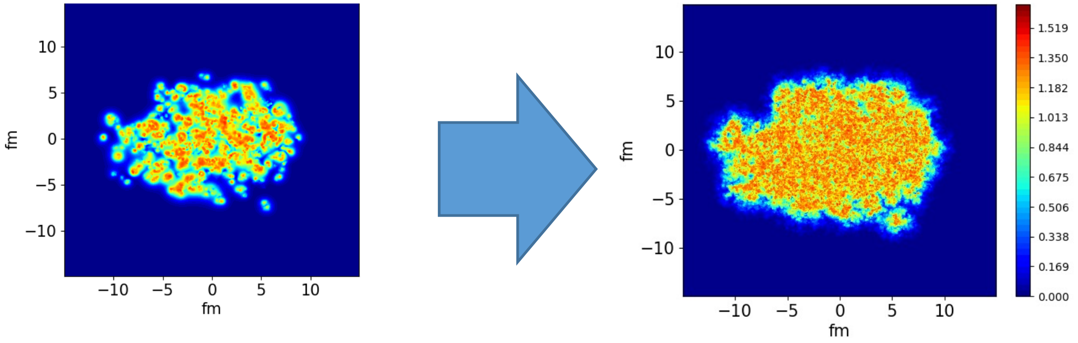


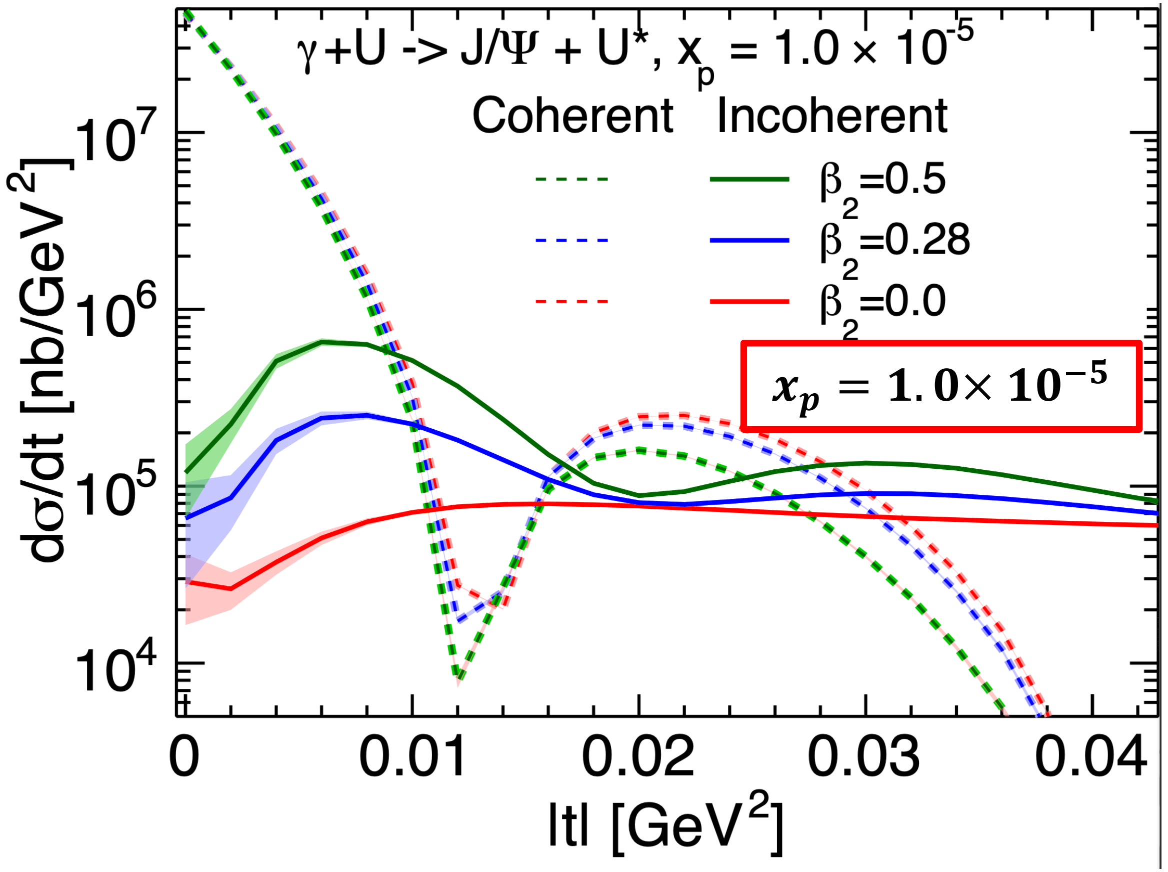
- Probe the event-by-event sub-nucleon fluctuations.
- Bayesian inference of the fluctuating proton shape.

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.

Energy evolution to smaller x







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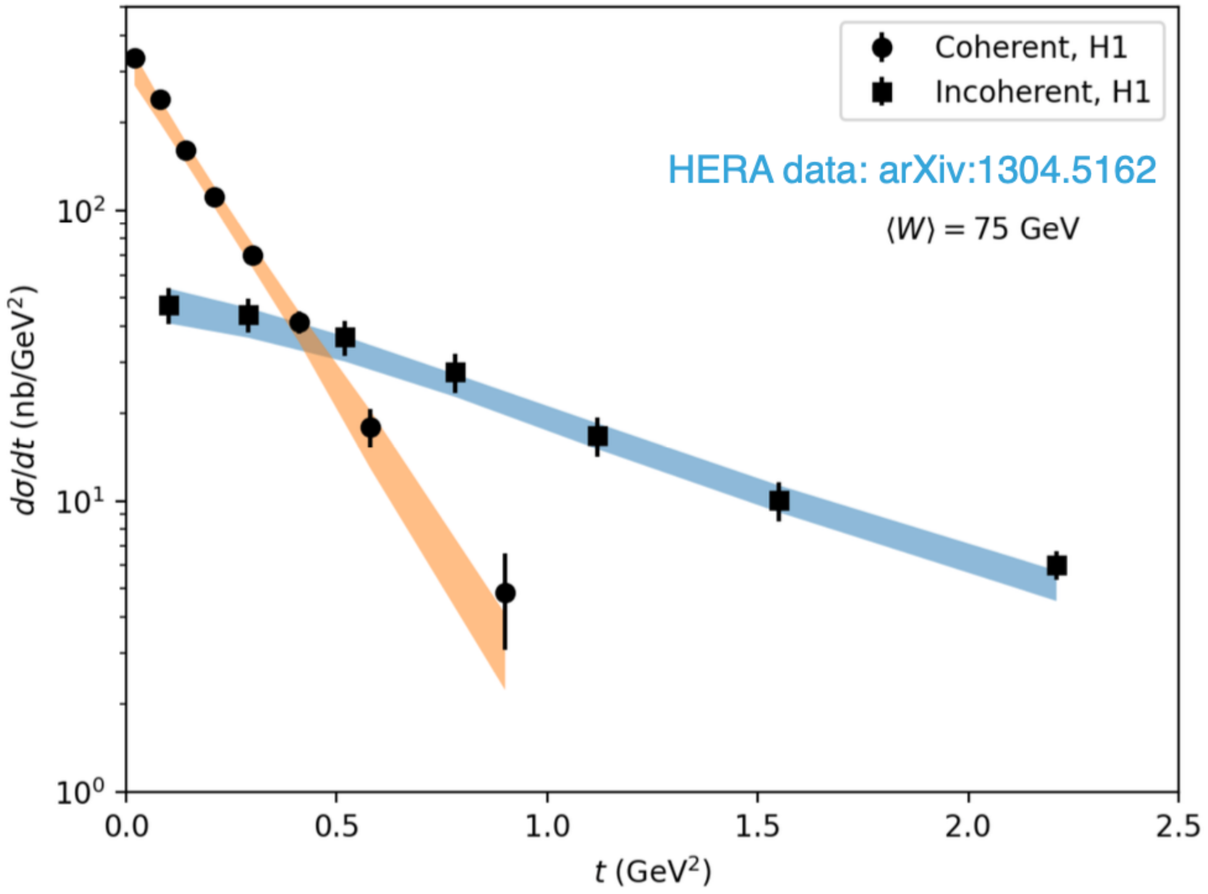
H.Mantysaari, B.Schenke PRD, 98, 034013.
T. Lappi and H. Mantysaari, EPJC 73, 2307 (2013).
Yuri V. Kovchegov, QUANTUM CHROMODYNAMICS A T HIGH ENERGY

Model parameters and the Exp. Data (γ^* + p → J/ψ + p*)

Parameterize proton shape (T_p)

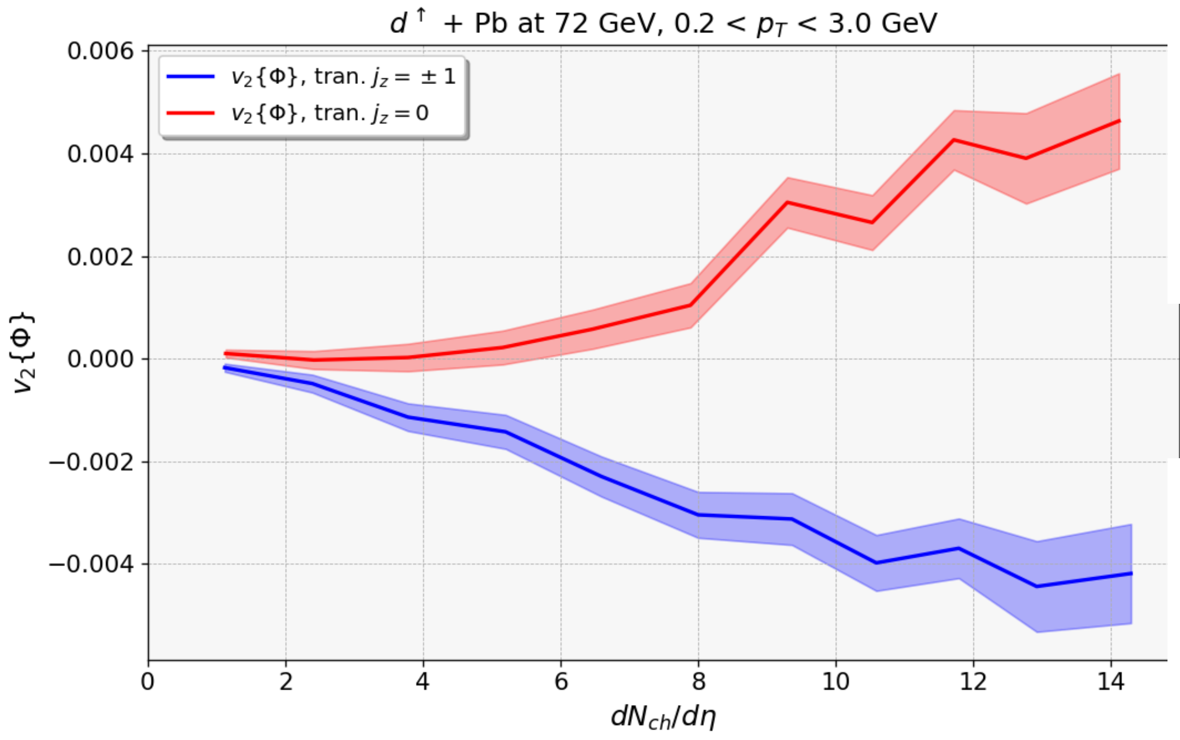
- Number of hot spots N_q
- Proton size B_{qc}
- Hot spot size B_q
- Hot spot density fluctuations σ
- Min. distance between hot spots $d_{q,min}$
- Overall color charge density: $Qs(x)/g^2\mu$
- Infrared regulator m



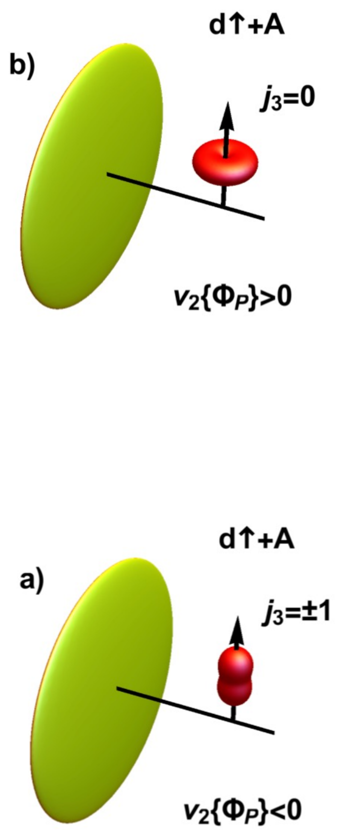
- 7D parameter space; generated 1000 training points for the model emulator

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

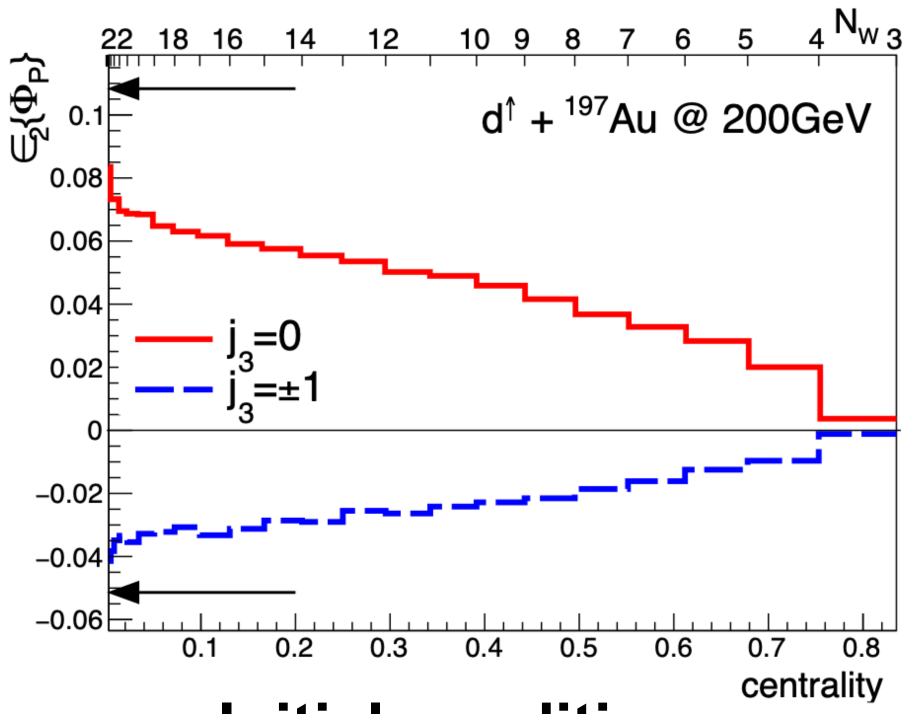
Collective flow in Polarized deuterons + Nuclei



3+1D hydrodynamic simulations.



$$\vec{\epsilon}_n = -\frac{\int \rho d\rho d\alpha e^{in\alpha} \rho^n f(\vec{\rho})}{\int \rho d\rho d\alpha \rho^n f(\vec{\rho})}$$



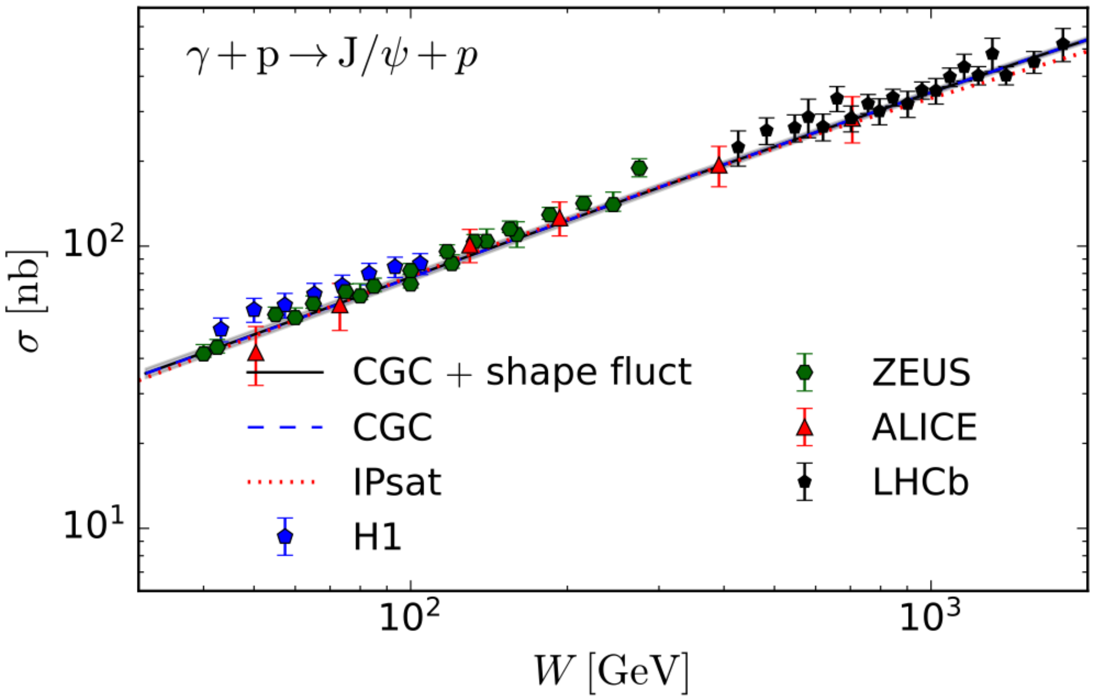
Initial conditions

- Opposite sign of $v_2\{\Phi\}$ between $j_z = \pm 1$ and $j_z = 0$ in $d^{\uparrow} + Pb$.
- Could be tested in the coming LHCb measurement.

H.Mantysaari, B.Schenke, C. Shen and W. Zhao in progress.
LHCb: PoS SPIN2023, 036 (2024).

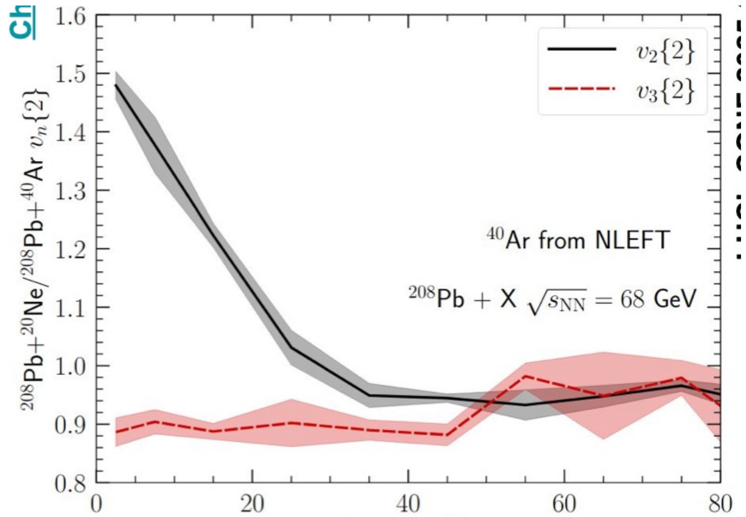
P. Bozek and W. Broniowski, PhysRevLett.121.202301

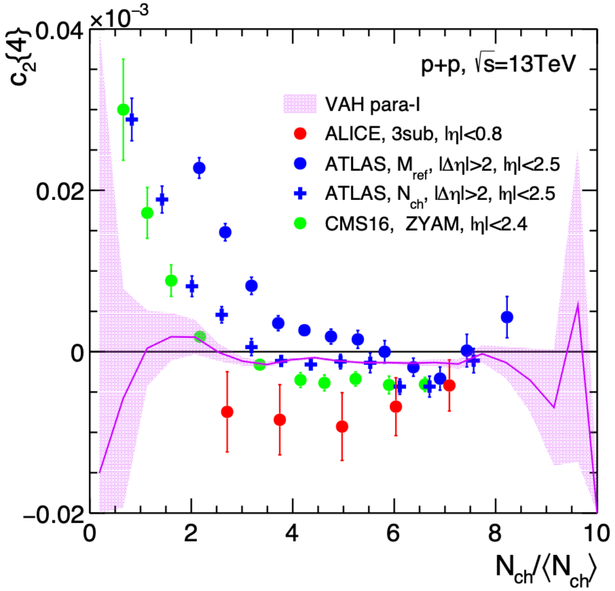
Energy evolution to smaller x

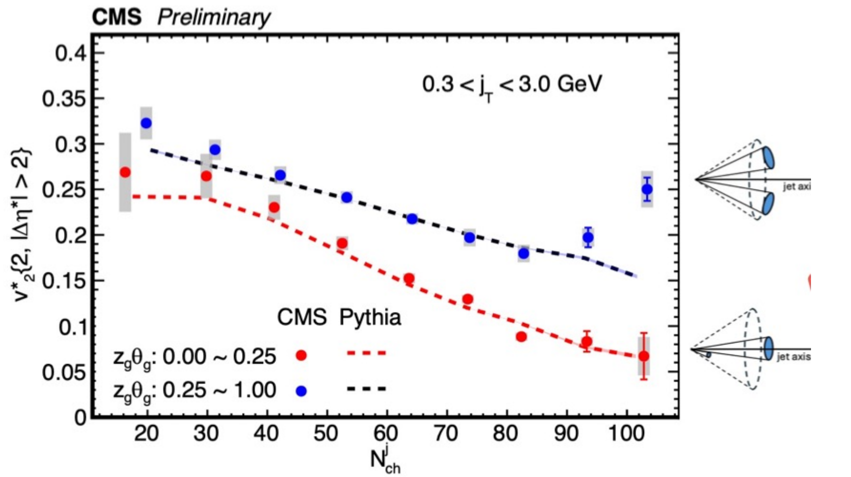


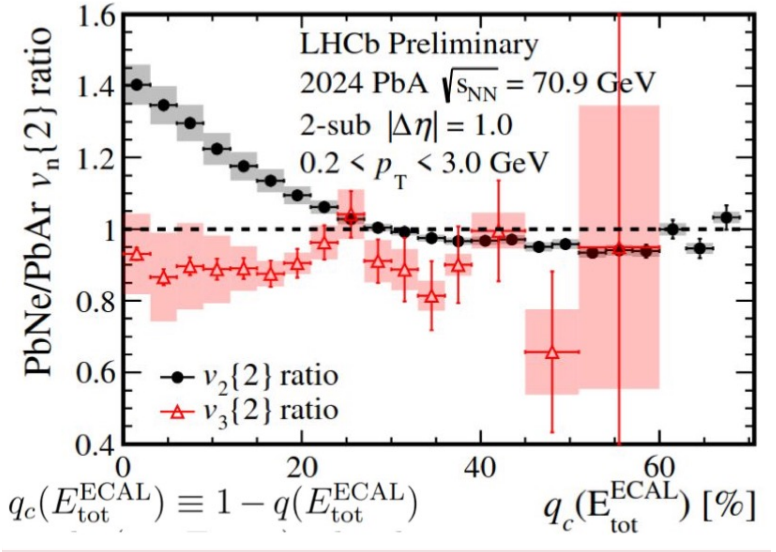
H. Mantysaari, F. Salazar and B. Schenke, Phys. Rev. D 106, no.7, 074019 (2022)

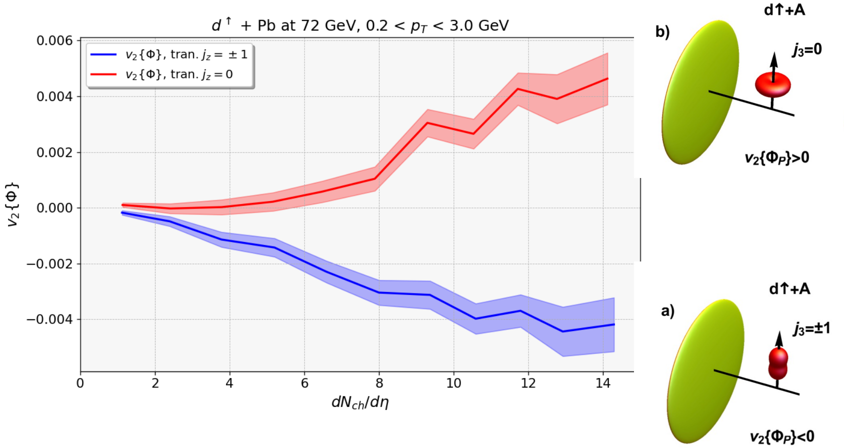
Searching “smallest” droplet

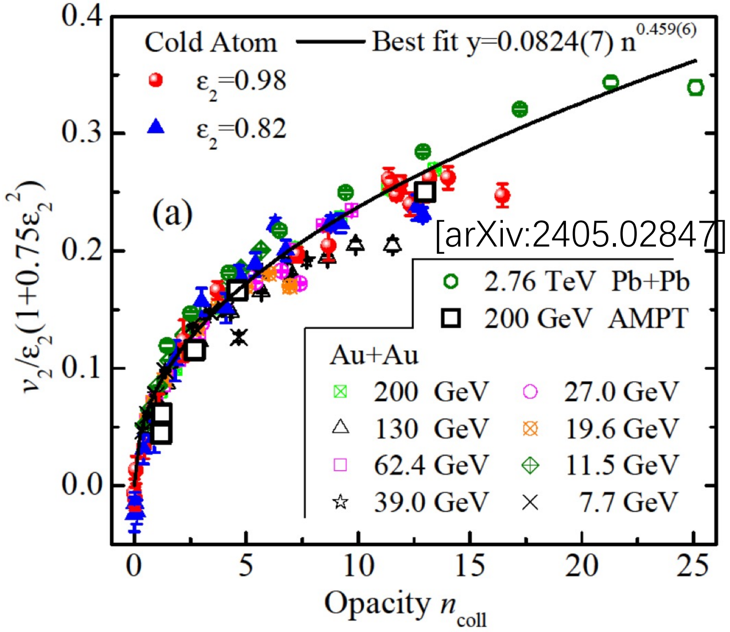




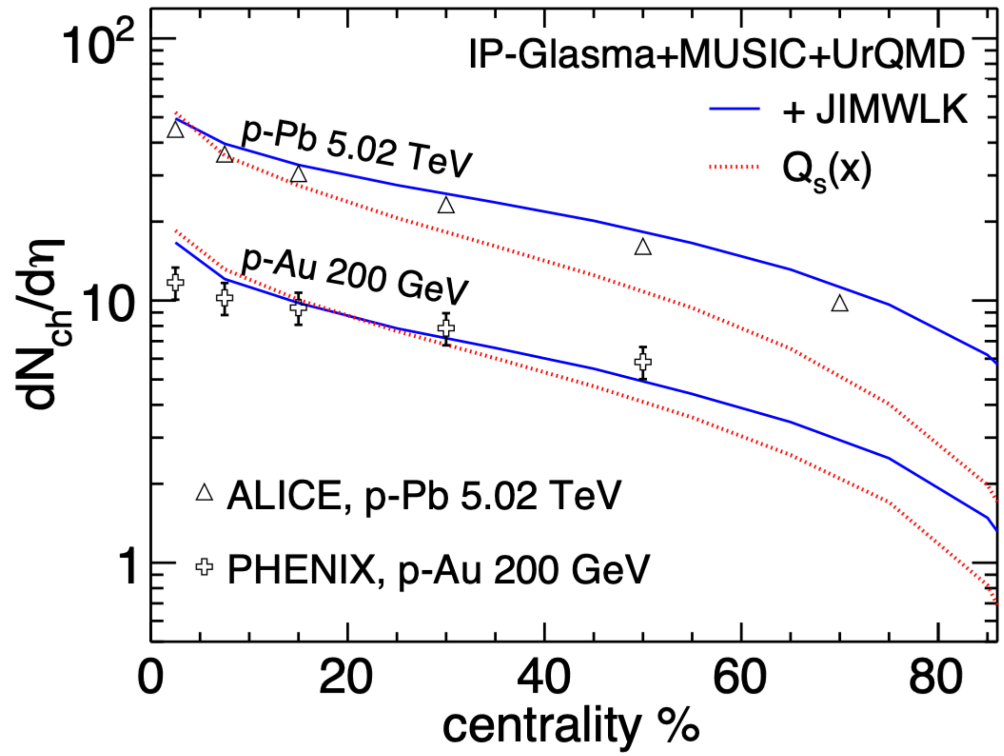


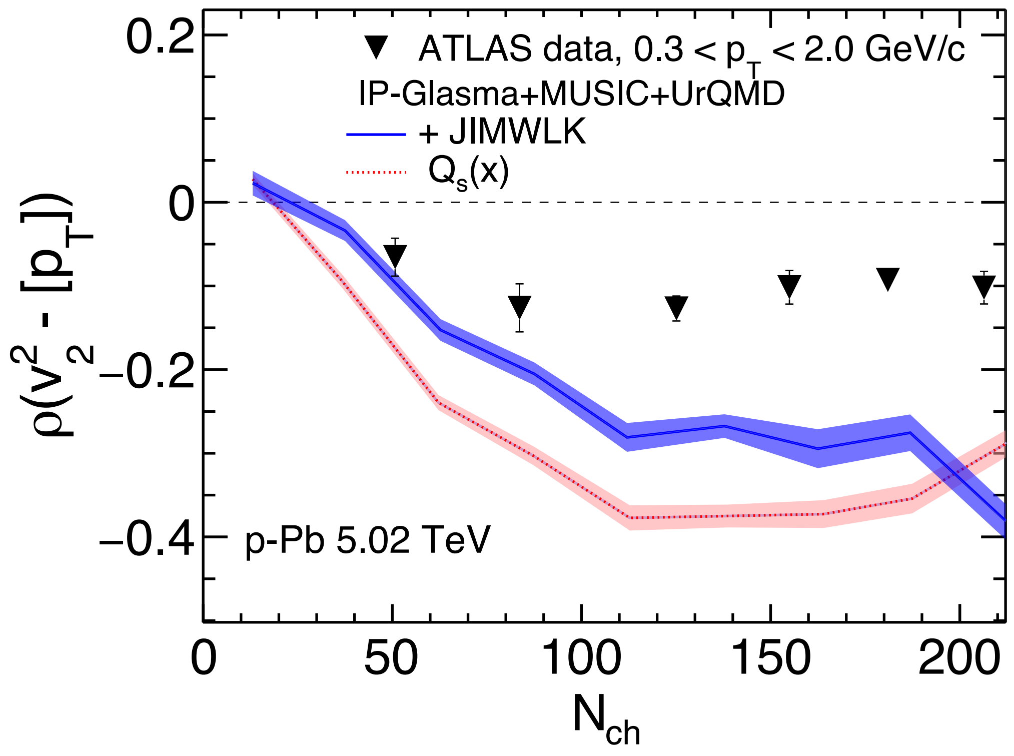






Effects of energy evolution on small systems





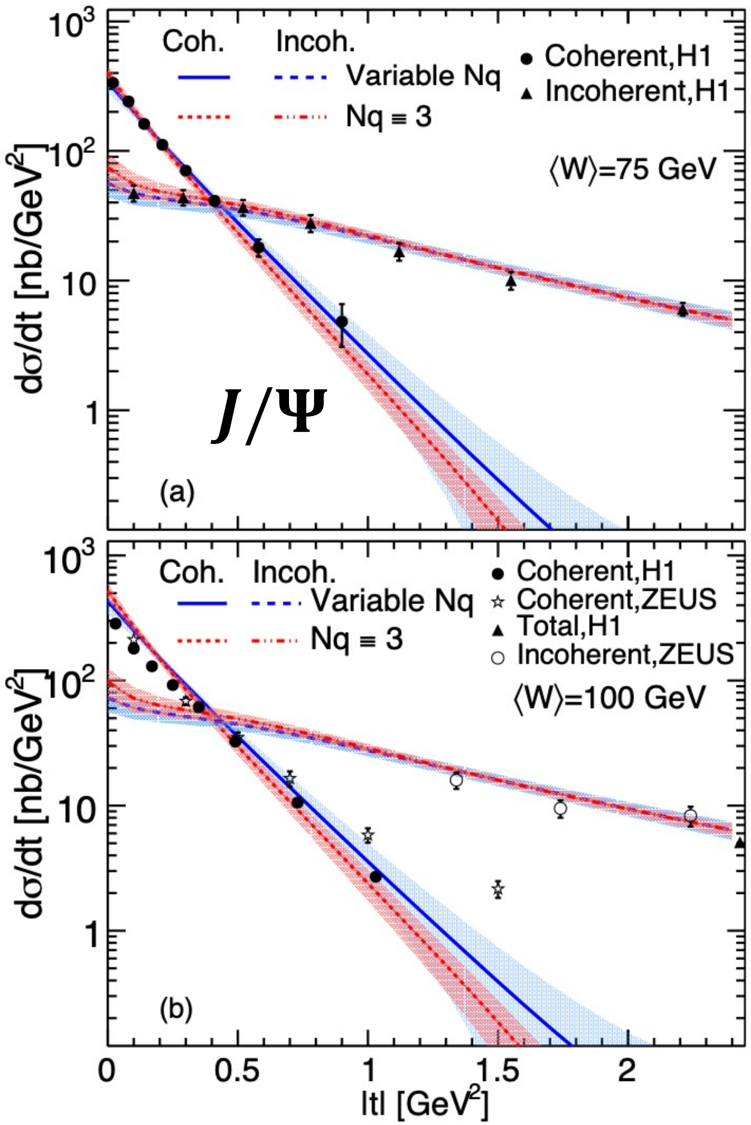
Cite Isabella Danhoni, Aleksas Mazeliauskas

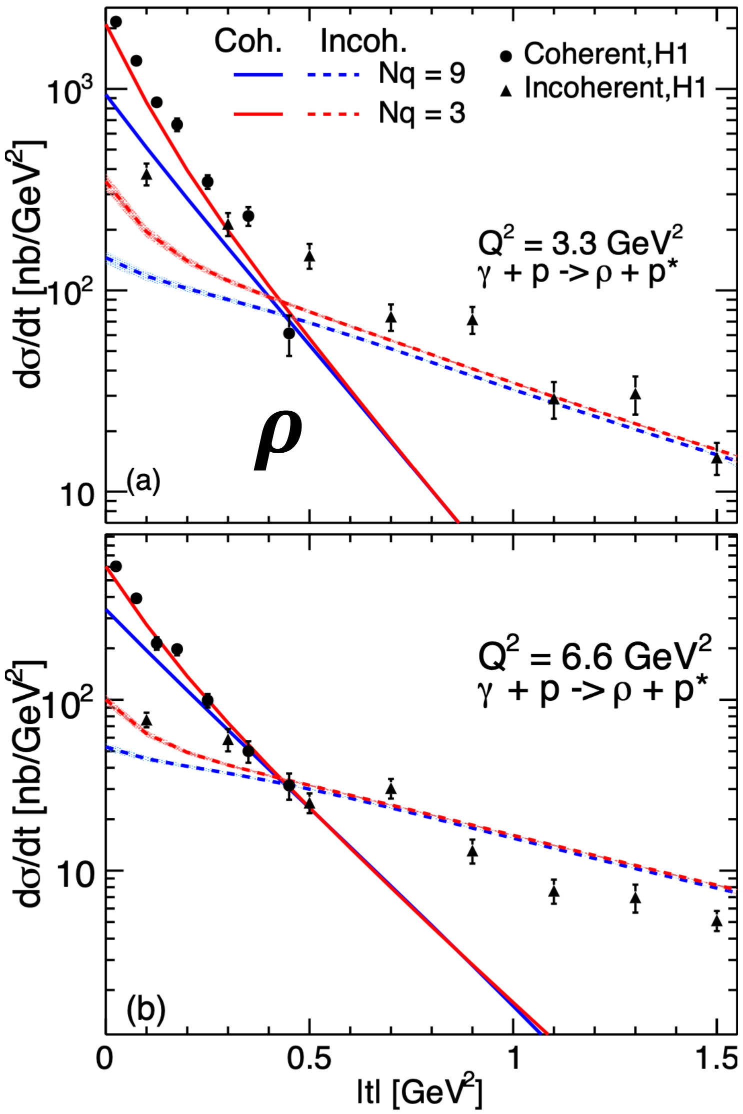
+ JIMWLK: CGC + energy evolution + Hydrodynamics

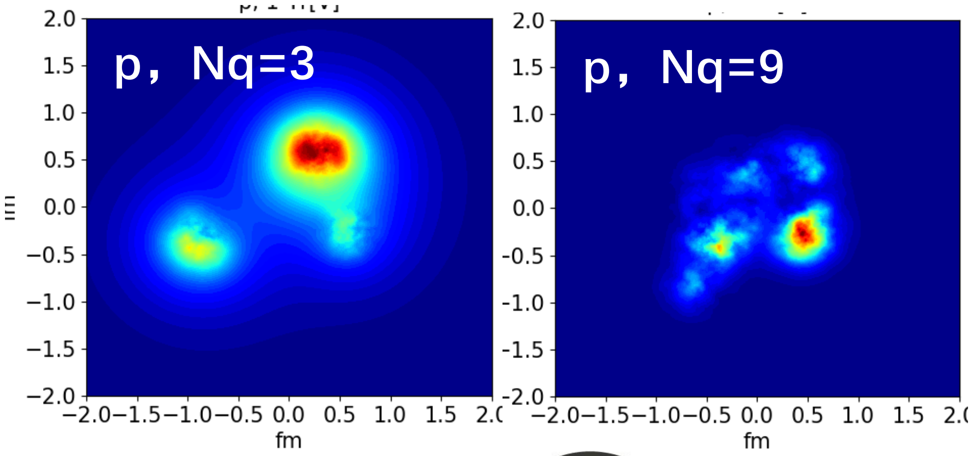
$\boldsymbol{Q_s(x)}$: CGC (change the $Q_s(x)$ only for different energies) + Hydrodynamics

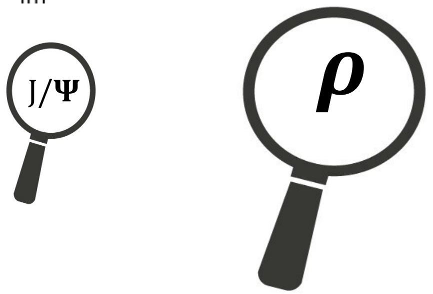
H. Mäntysaari, B. Schenke, C, Shen and W. Zhao, Phys. Rev. Lett. 135, 022302 (2025)

Probing nucleon at different resolutions









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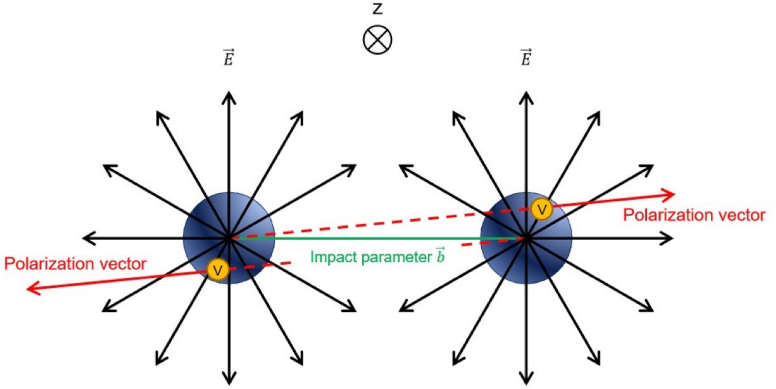
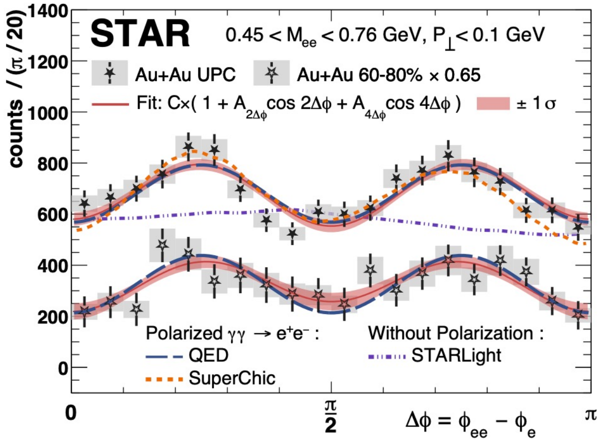
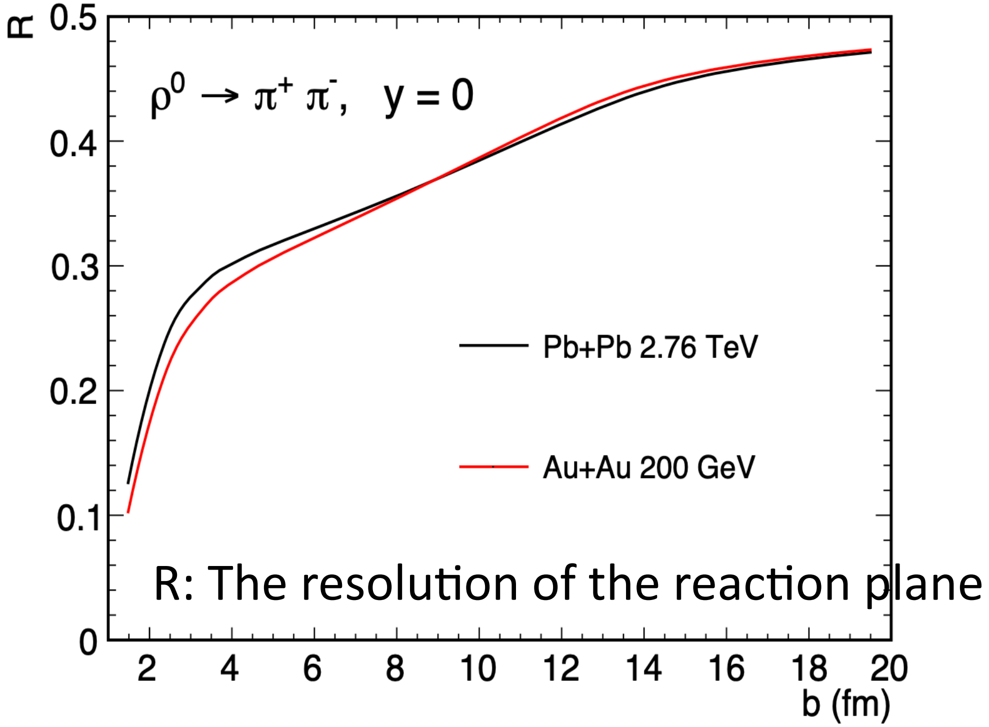
H. Mantysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348, and in progress.

Determine the Reaction Plane





STAR: PhysRevLett.127.052302;



X. Wu, X. Li, Z. Tang, P. Wang and W. Zha, Phys. Rev. Res. 4, no.4, L042048 (2022)

- Photoproduction in HICs is linearly polarized.
- Probe the reaction plane via the feature of linear polarization of the coherent photoproduction process in HICs. -> Connections to the collective flow studying.
- Connections to the collective flow studying.

B-dependence at 0-1% and 0-0.1%