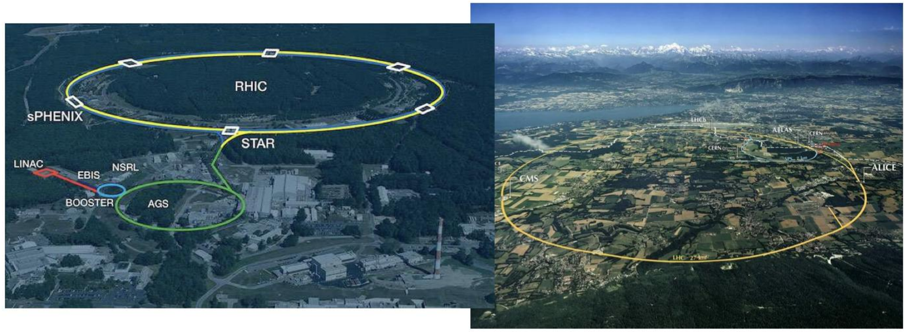
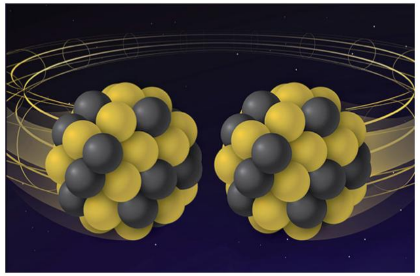
Fluctuating Proton Geometry: Constraints from Charge Radius, Diffraction, and Flow

Wenbin Zhao
Central China Normal University

5th edition of the International Small Systems workshop
2026.07.02 (Online)

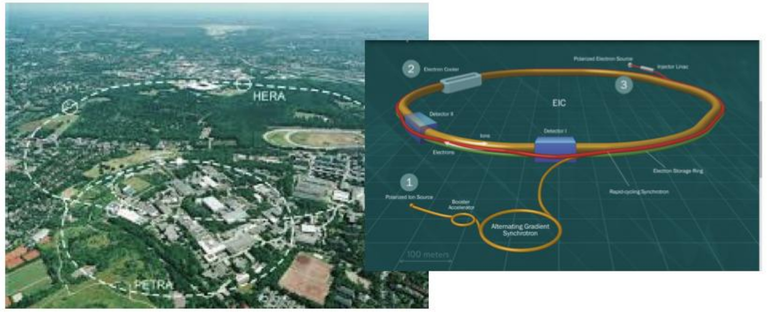
Heavy-ion Collisions and DIS/UPC

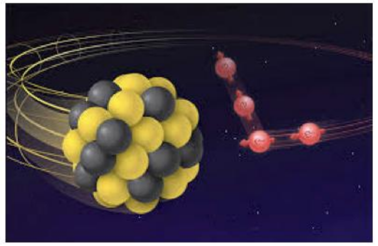


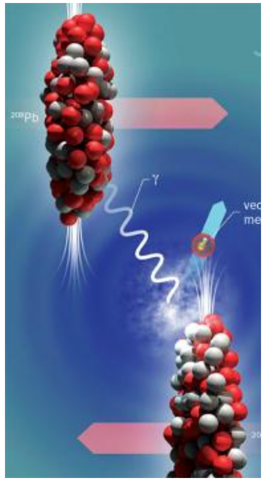


- **Heavy-ion Collisions:** High center-of-mass energies available.
- **Multi-Stage process:**

Initial state => QGP => Hadronic Scatter







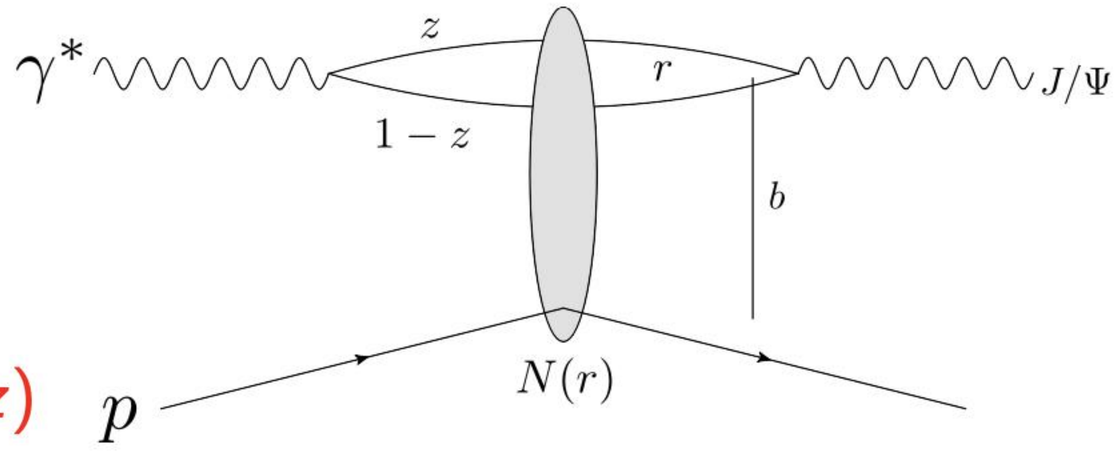
- **DIS/UPC:**
- Pin down kinematics, clean probes of QCD dynamics.
- Collision energy is limited.

- 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

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

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

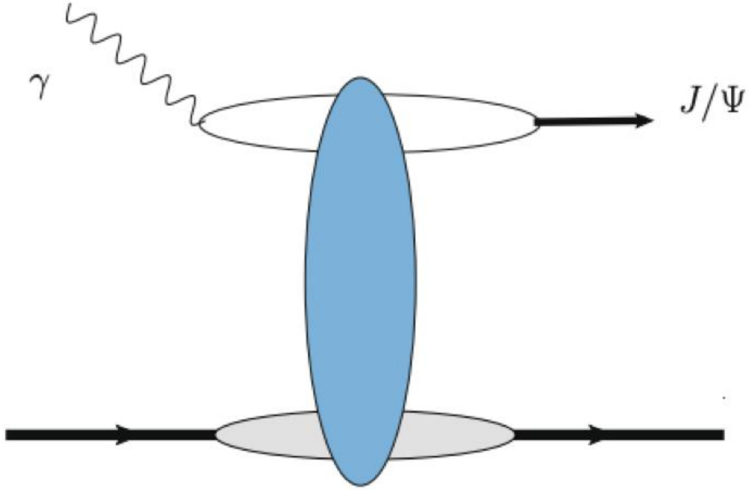
$\boldsymbol{A}$ ~Fourier transform of the spatial structure function of target ($\boldsymbol{T_{p/A}}$).

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

Coherent and incoherent processes

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

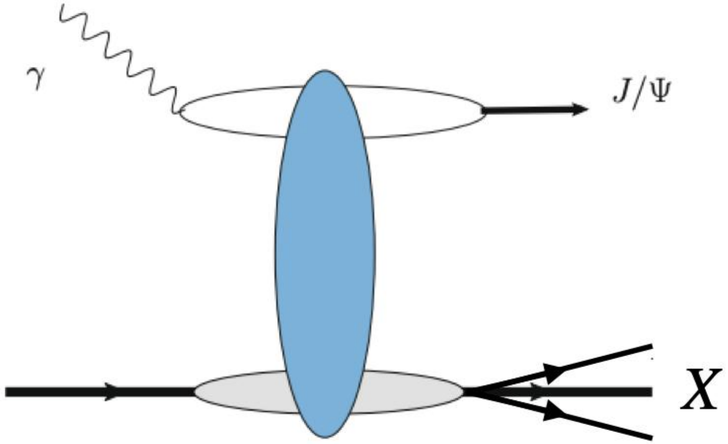
Target stays intact, (|initial state> = |final state>)
Probes the average shape of the target.



- **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 (hot spot)

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

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

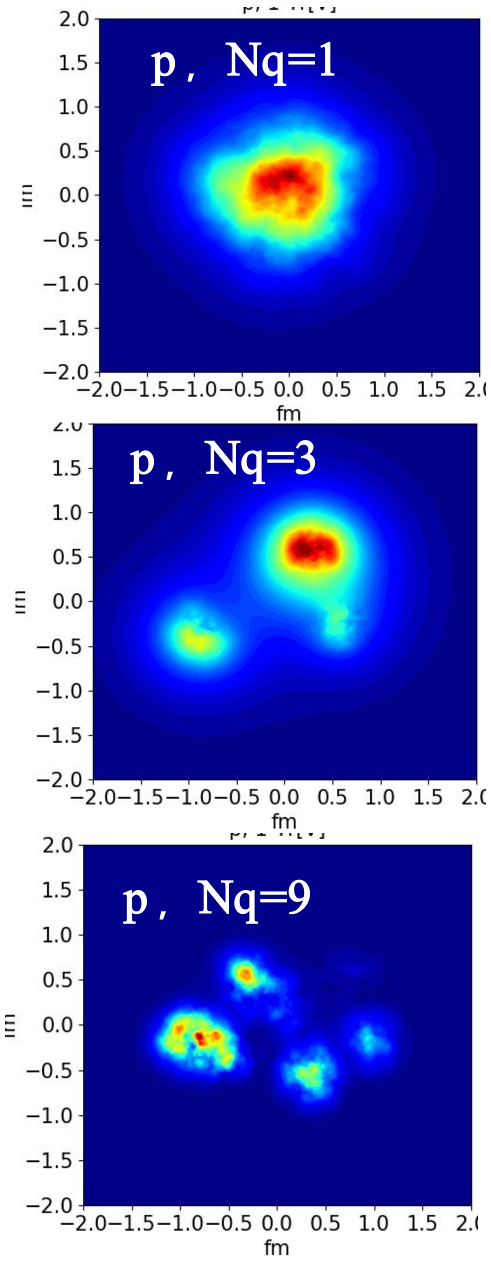
- The density profile of each spot is:

$$T_q(\vec{b}) = \frac{1}{2\pi B_q} e^{-b^2/(2B_q)}$$

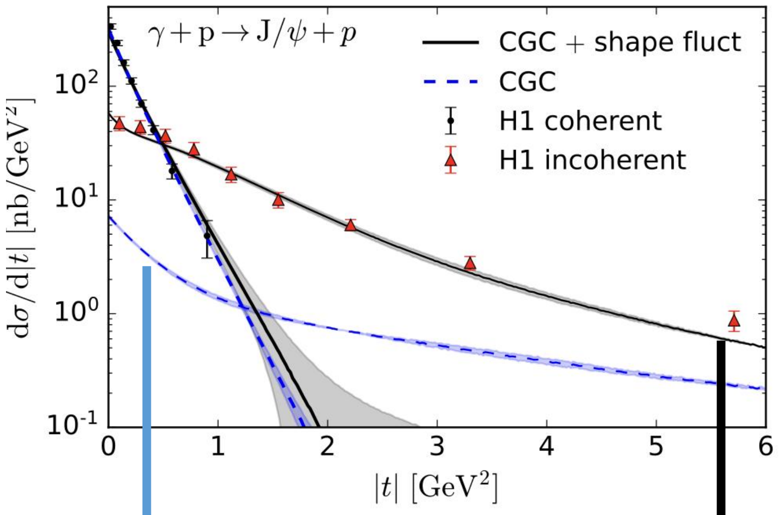
- The spot positions $\overrightarrow{b_i}$ are sampled from:

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

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

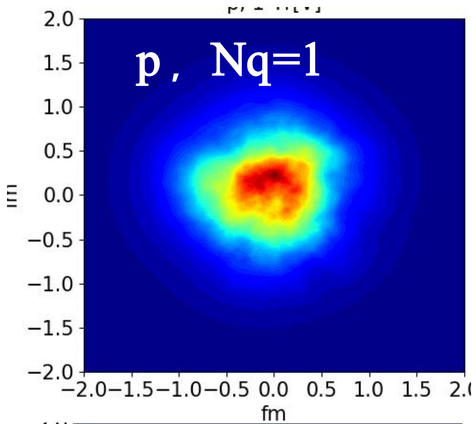


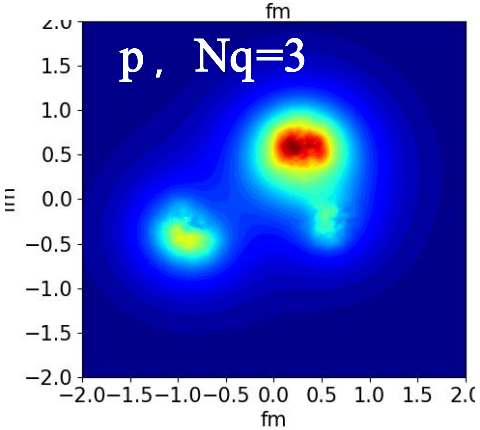
Proton geometry fluctuations

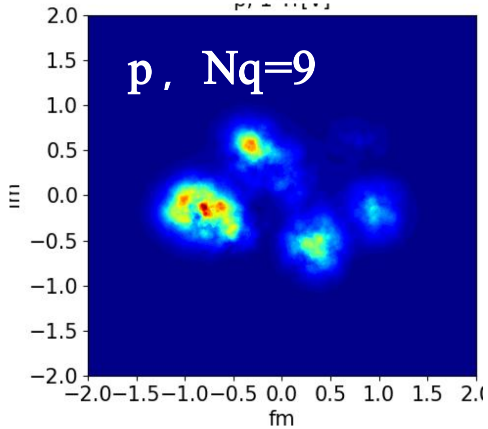


No subnucleon fluctuations

With subnucleon fluctuations

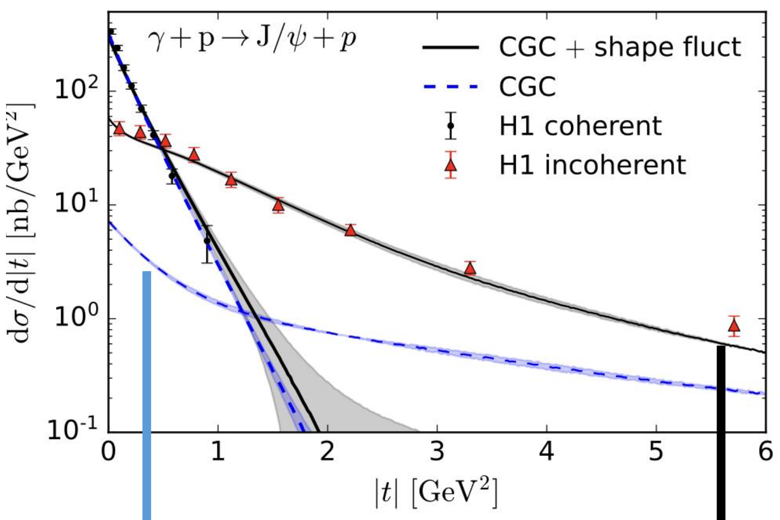






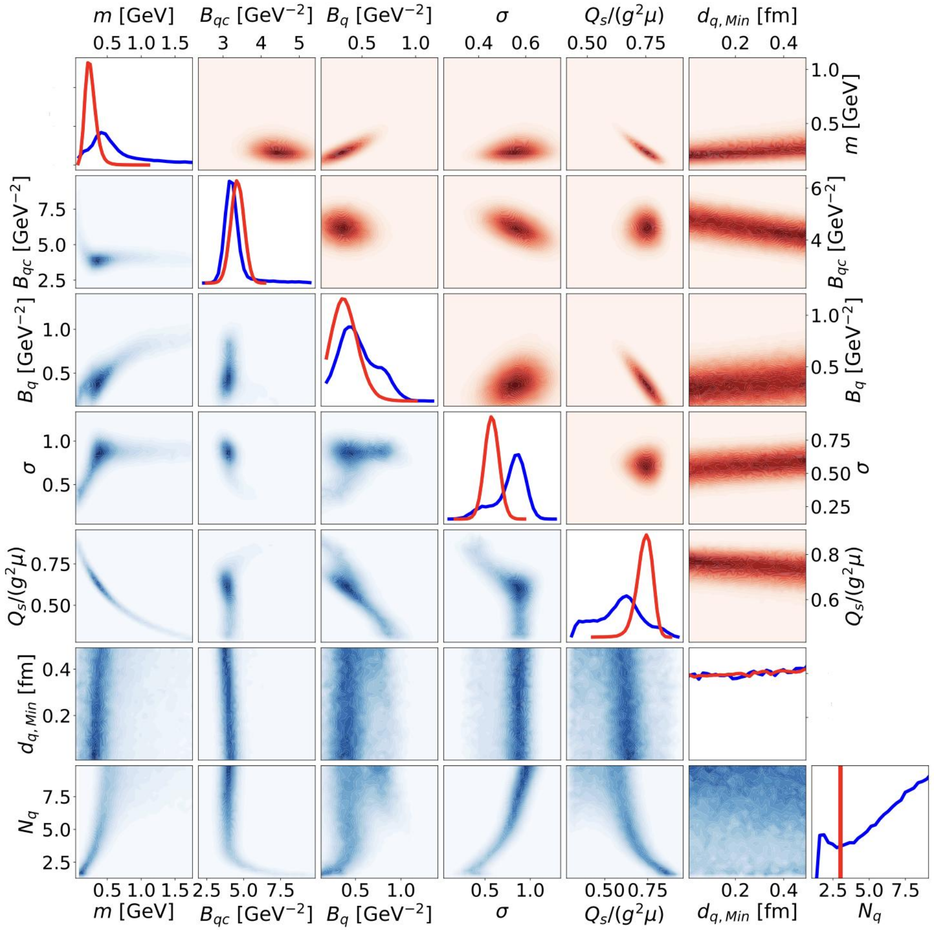
H. Mäntysaari, Schenke , PhysRevLett.108.252301 , PhysRevC.86.034908 ;
H. Mäntysaari, F. Salazar and B. Schenke, Phys. Rev. D 106, 074019 (2022).
H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348.

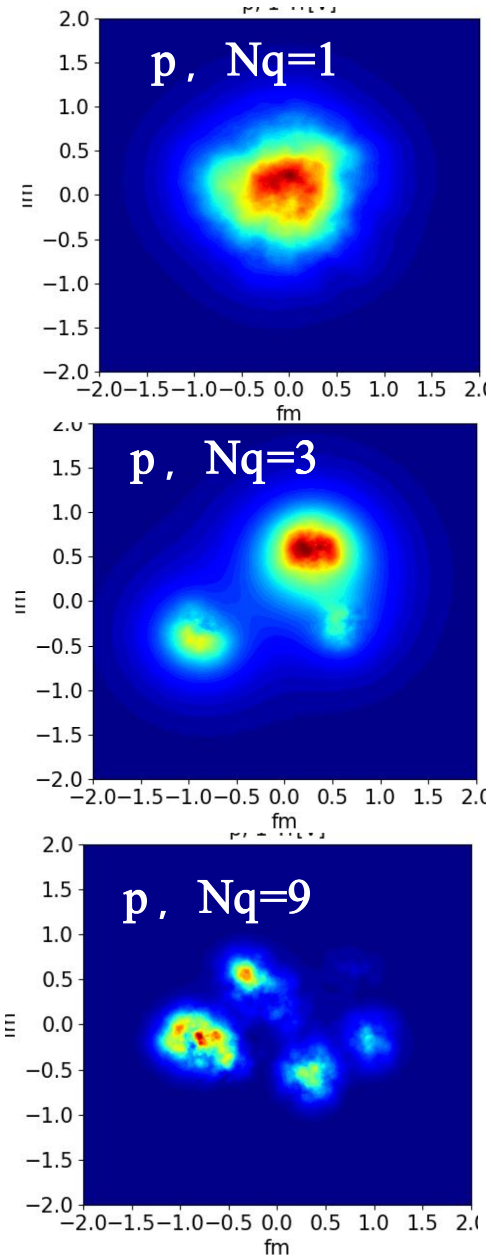
Proton geometry fluctuations



No subnucleon fluctuations

With subnucleon fluctuations





- The extracted proton radius $R\sim$ **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).
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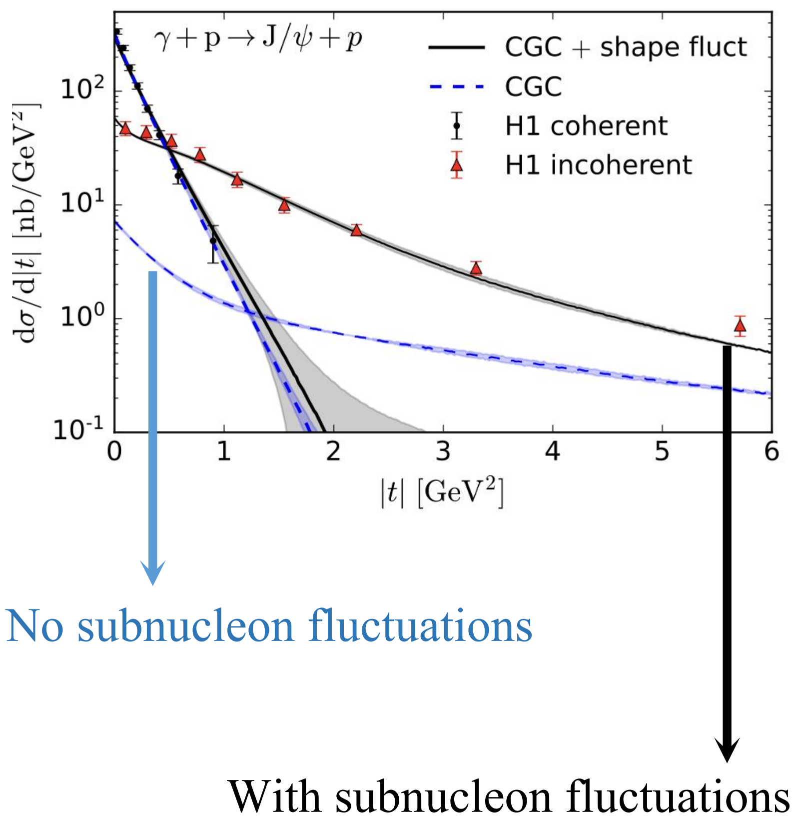
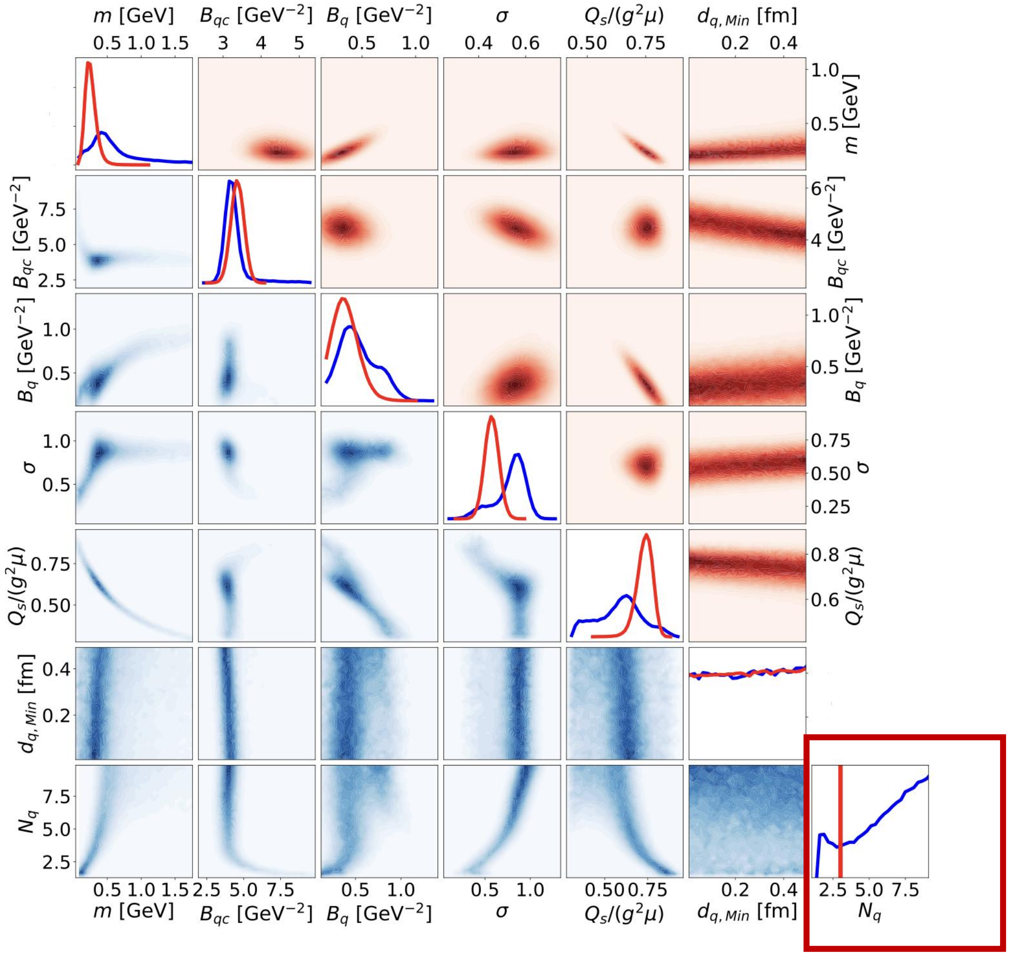
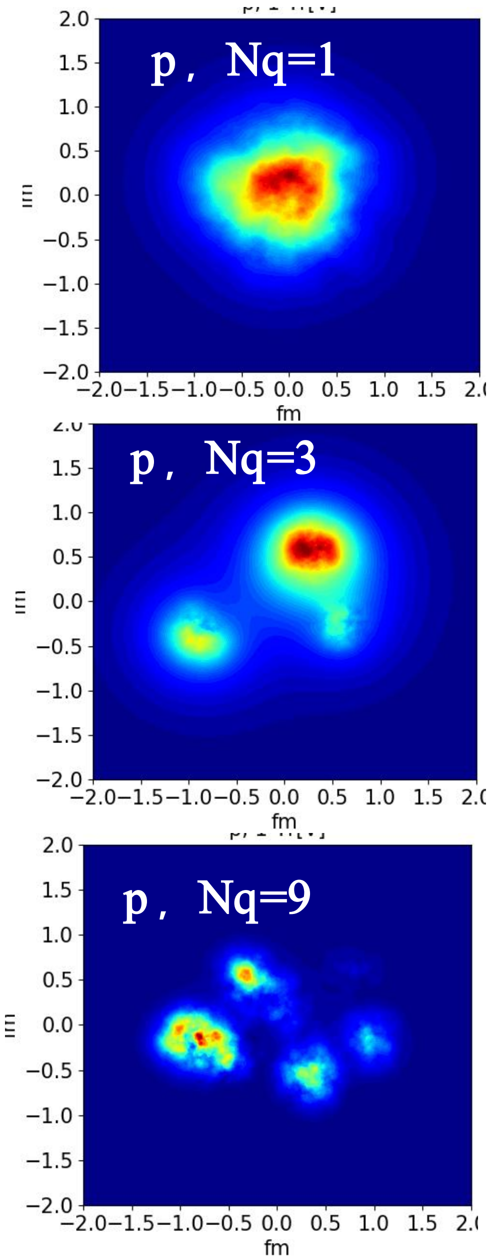
Proton geometry fluctuations





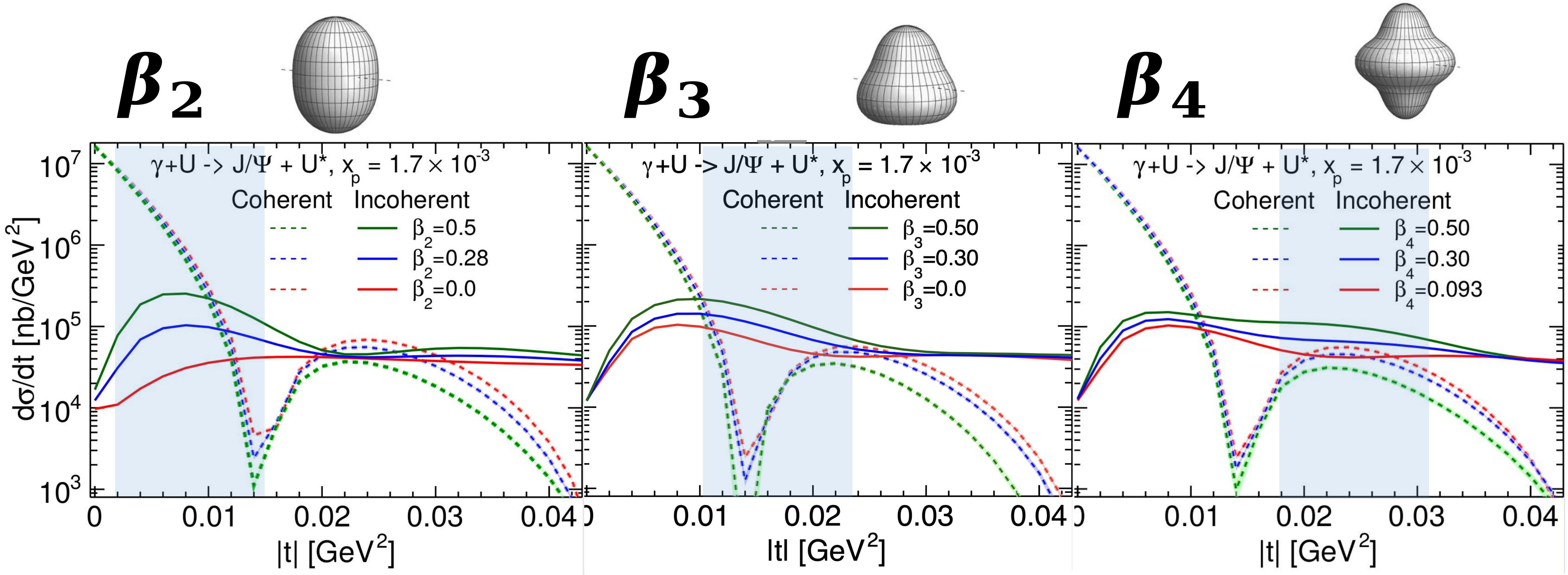


- The extracted proton radius ***R* ~ 0.6 fm**.
- Nq = 1 (no sub-nucleonic structure) is **excluded** by data.

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

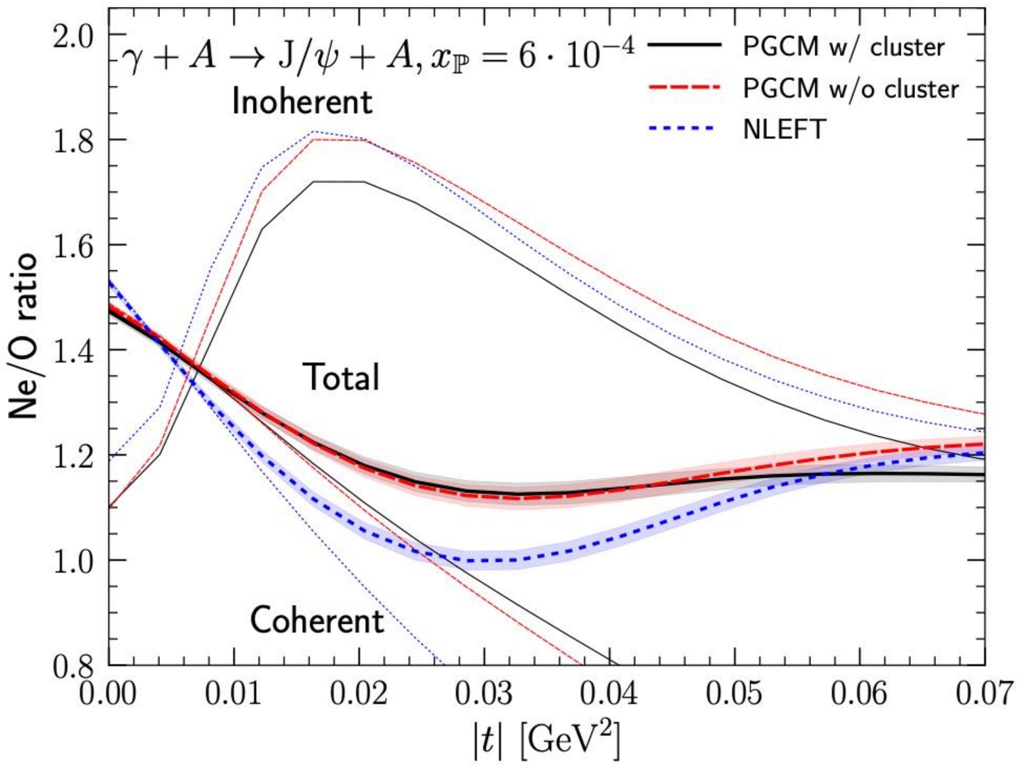
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left([r-R(\Theta,\Phi)]/a\right)}\ ,\quad R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\left(\cos\underline{\gamma} Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\underline{\beta_3}Y_{30}(\Theta)+\underline{\beta_4}Y_{40}(\Theta)\right]$$

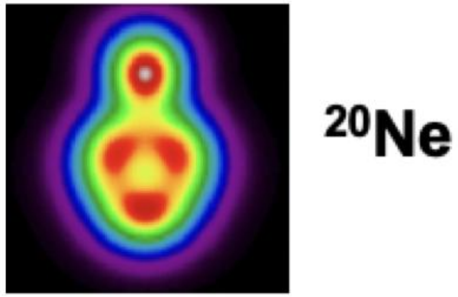


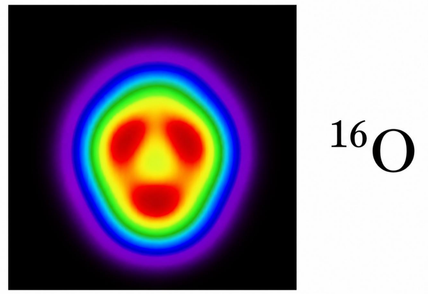
H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, PhysRevLett.131.062301.

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

Imaging of Light Nuclei Shape



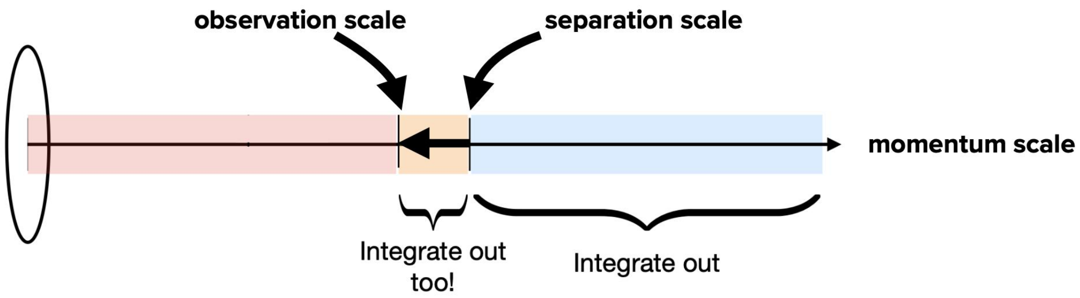




H. Mantysaari, H. Roch, B. Schenke, C. Shen and W. Zhao, [arXiv:2605.00454 [hep-ph]].
H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, PhysRevLett.131.062301.

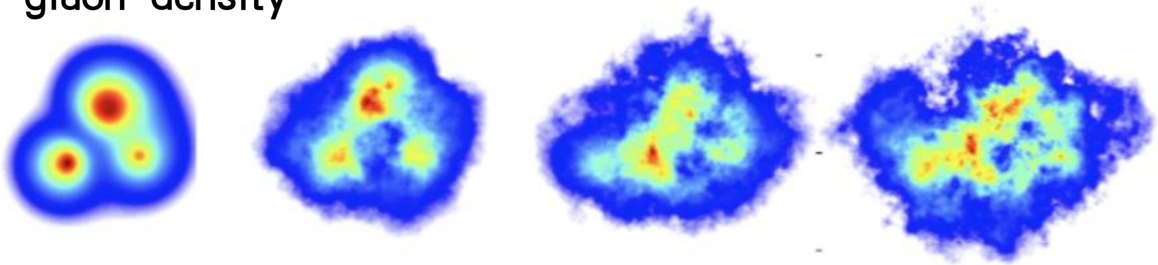
- Probing the bowling-pin shape of Ne-20 in UPCs

Energy evolution of initial state



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

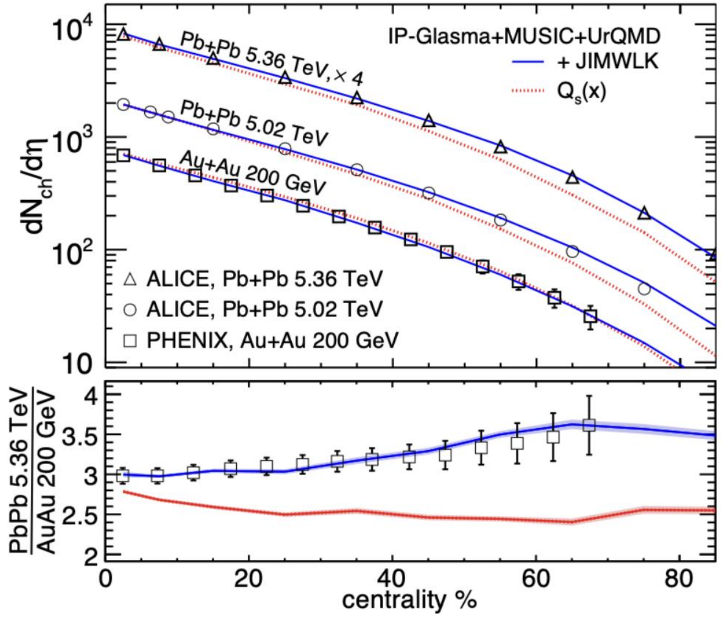
gluon density

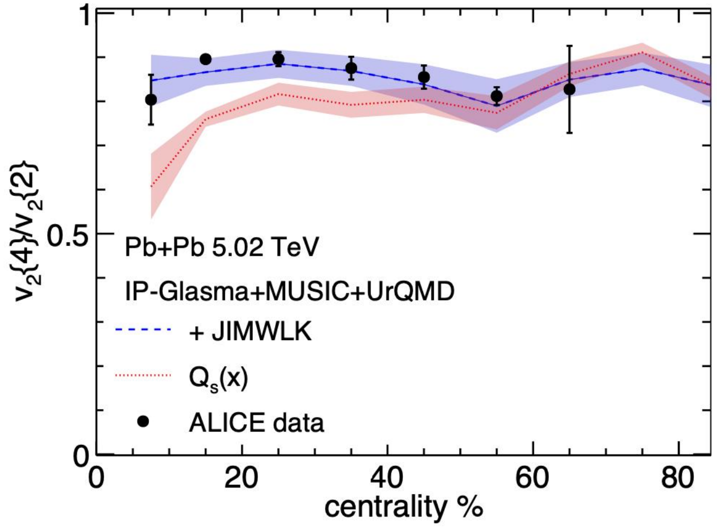


Low energy (UPC/DIS) → High energy (LHC)

- Energy evolution of the initial state 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)

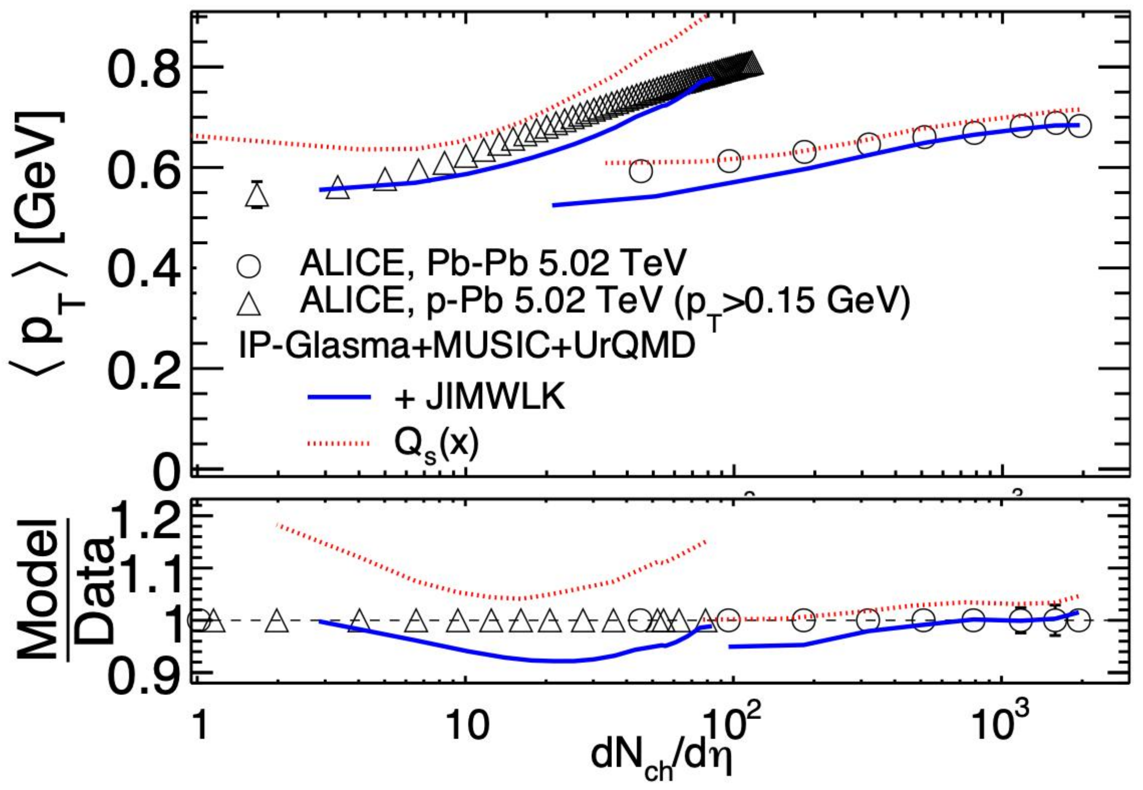


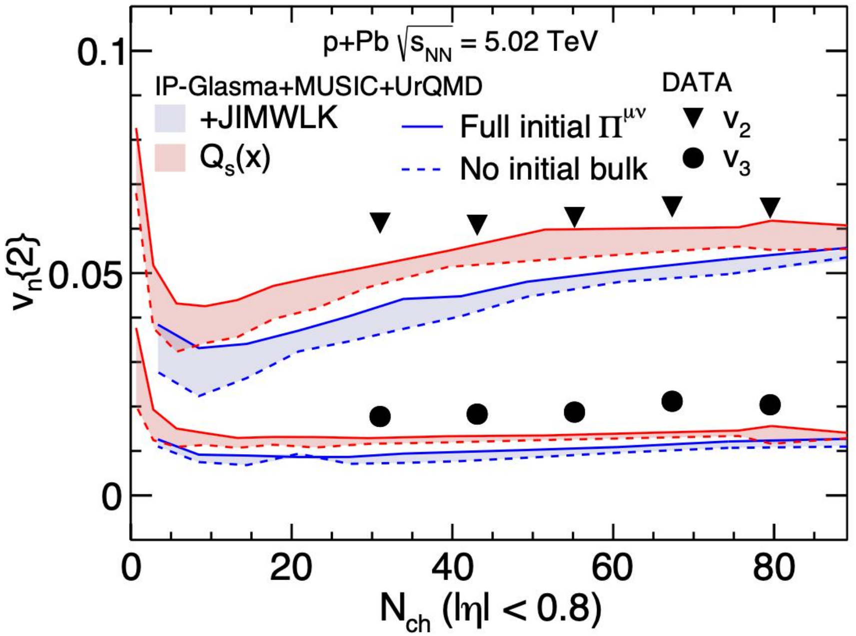


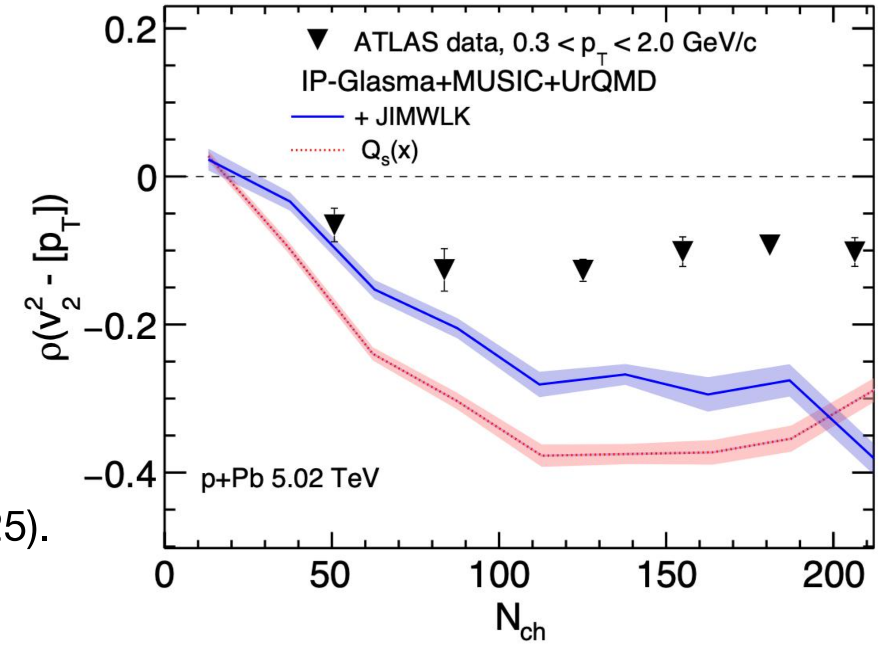
+ JIMWLK: CGC + energy evolution

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

Energy evolution of initial state



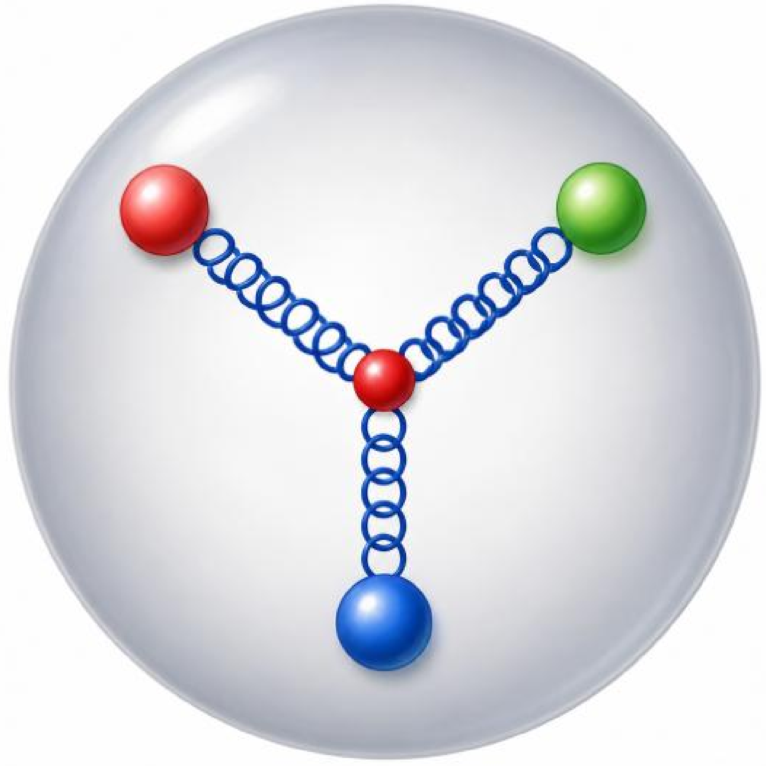




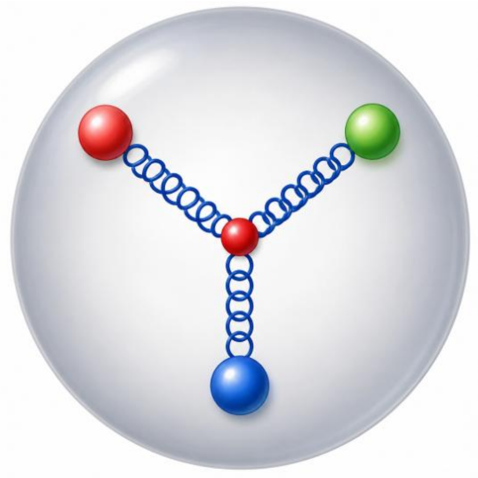
- Energy evolution will **reduce the mean p_T**.
- Energy evolution is more important for small systems.

H. Mäntysaari, B. Schenke, C, Shen and W. Zhao, PRL. 135, 022302 (2025).
H. Mäntysaari, B. Schenke, C, Shen and W. Zhao, [arXiv: 2511.03588].

Stringy Proton



Proton geometry fluctuations (stringy proton)



- Sample 3 valence quarks with Gaussion, $\boldsymbol{B_q = R_{ch}}$ **≈ 0.87fm (not a free parameter anymore)**.

$$T_q(\vec{b}) = \frac{1}{2\pi B_q} e^{-b^2/(2B_q)}$$

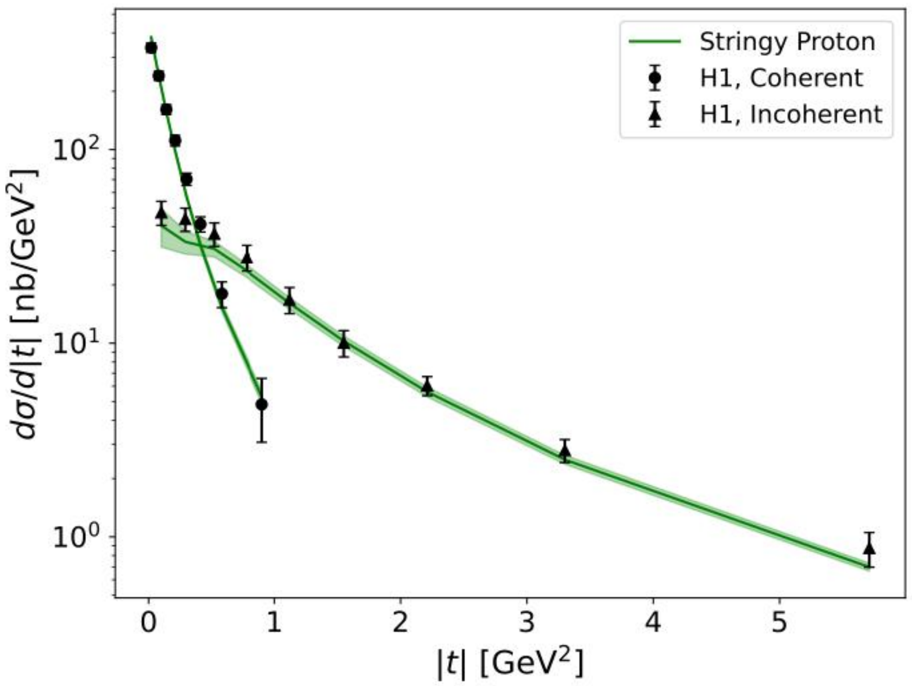
- Construct Y-shaped geometry, connect via Fermat point
- Place gluons along strings: Sample points on strings; Add Gaussian gluonic hot spot.
- Add log-normal Q_s fluctuations:

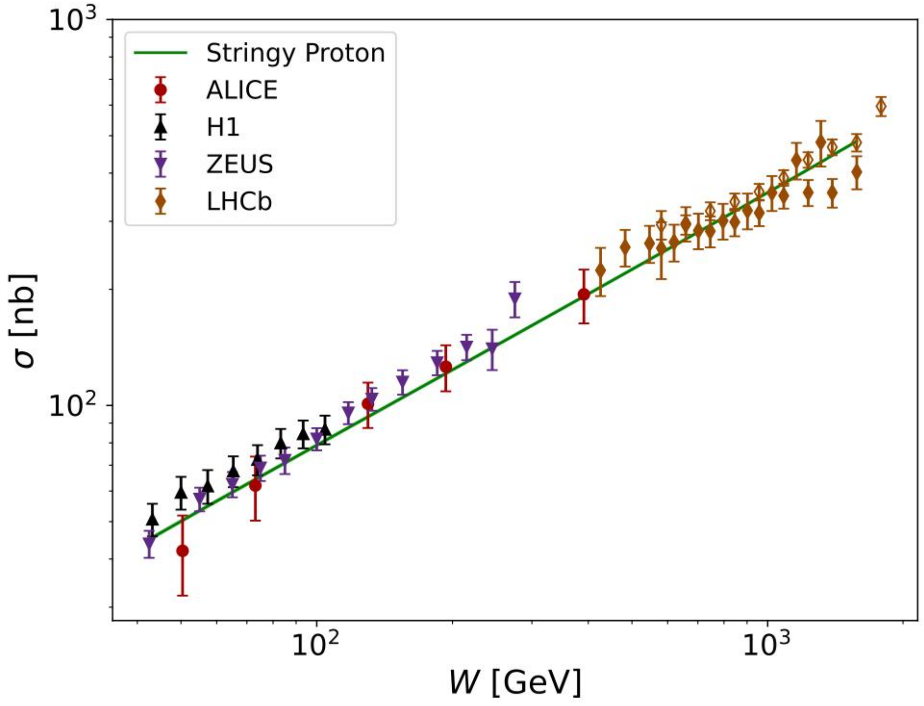
$$T_p(\mathbf{b}_\perp) = \frac{1}{N_q} \sum_{i=1}^{N_q} p_i T_q(\mathbf{b}_\perp - \mathbf{b}_{\perp,i}), \qquad P(\ln p_i) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\ln^2 p_i}{2\sigma^2}\right].$$

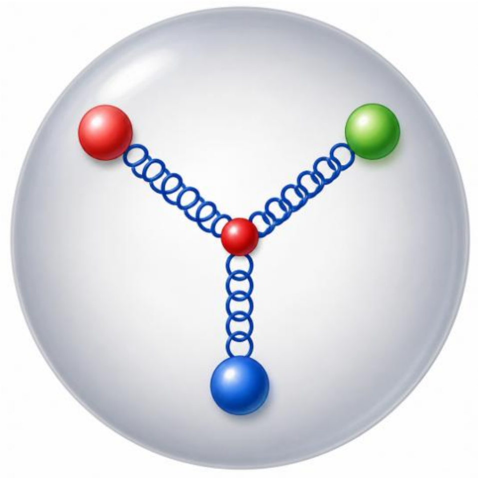
⇒ Event-by-event shape + density fluctuations.
⇒ Automatically get: $\boldsymbol{R_g \leq R_{ch}}$.

- Lattice QCD : Y-shaped flux tubes (Bissey et al., PRD 76 (2007));
- Baryon junction picture : Rossi, Veneziano, Nucl. Phys. B 123 (1977); D. Kharzeev, Phys.Lett. B 378, 238–246 (1996)).
- Proton = 3 valence quarks connected by gluonic strings.

Fix the Proton geometry by diffractive J/Ψ

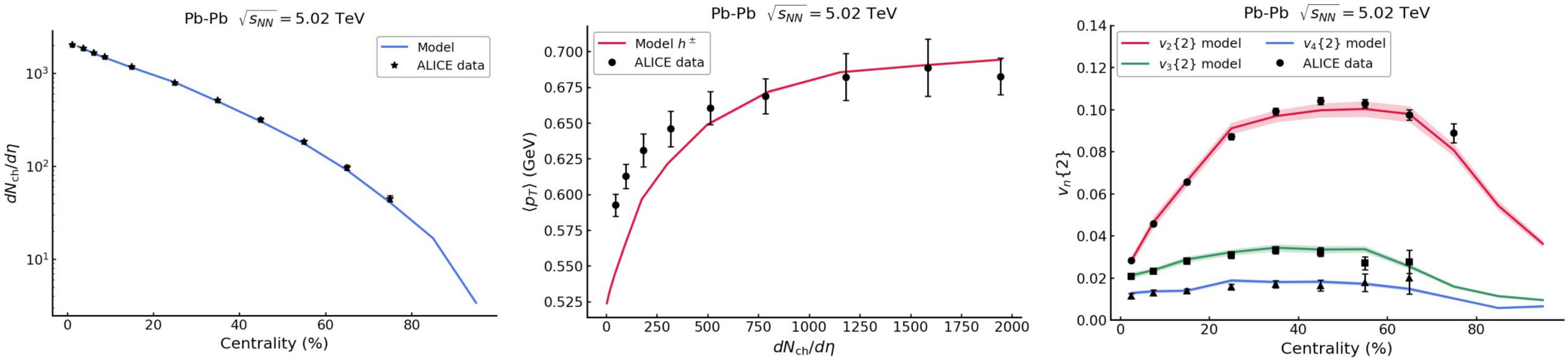






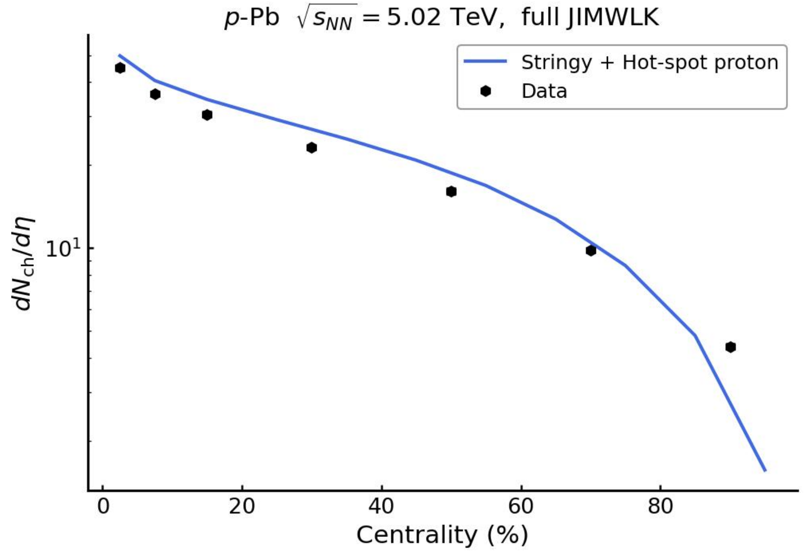
- The t-differential and integrated J/ψ cross sections show good agreement with the data.
- **With the charge radius fixed** and the remaining parameters fitted to diffractive data, the model gives a consistent description of the proton structure.

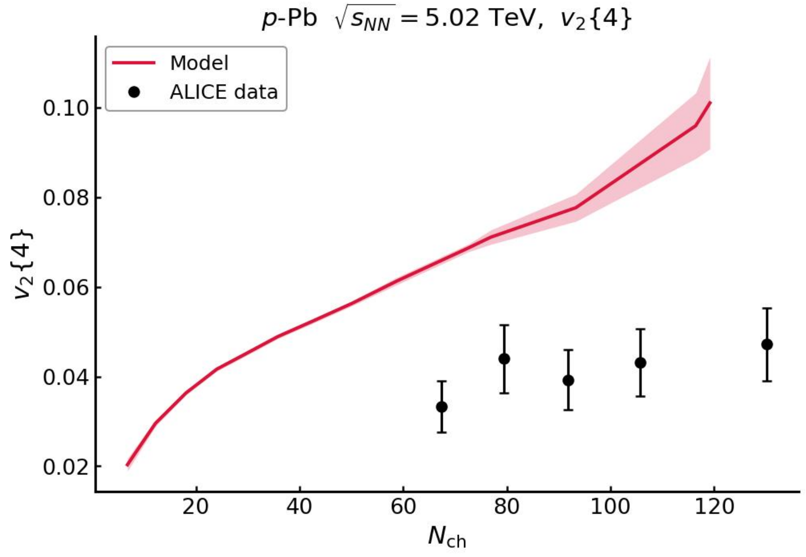
From DIS to heavy-ion collisions

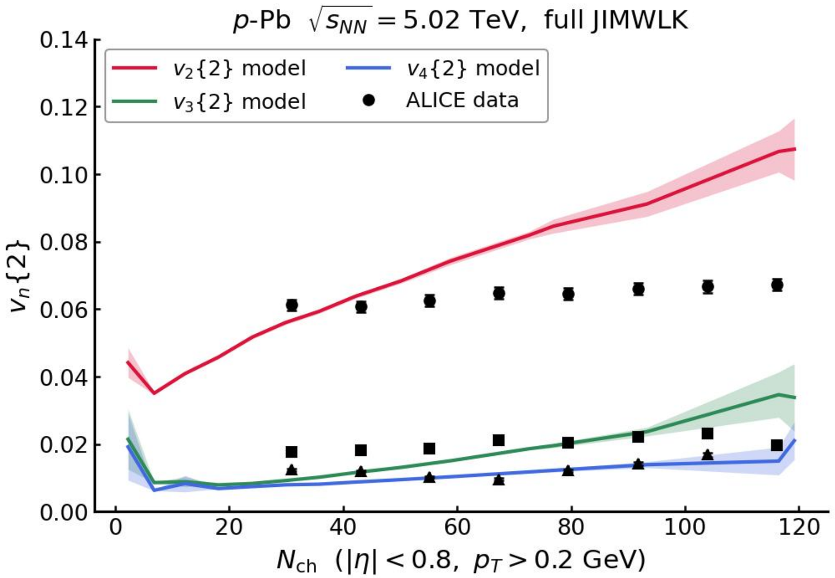


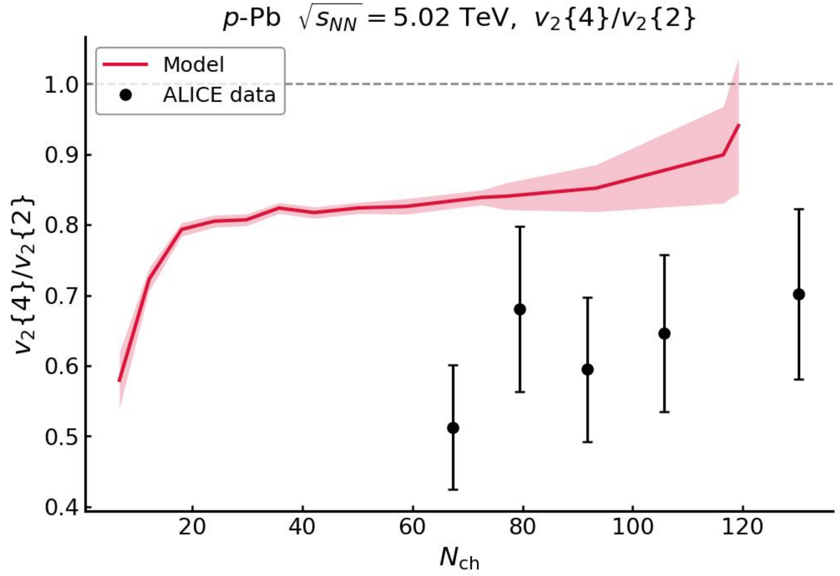
- Apply the stringy proton implemented in IP-Glasma to HIC systems with MUSIC+UrQMD.
- Well describe the flow observables in the heavy-ion collisions.

p-Pb collisions

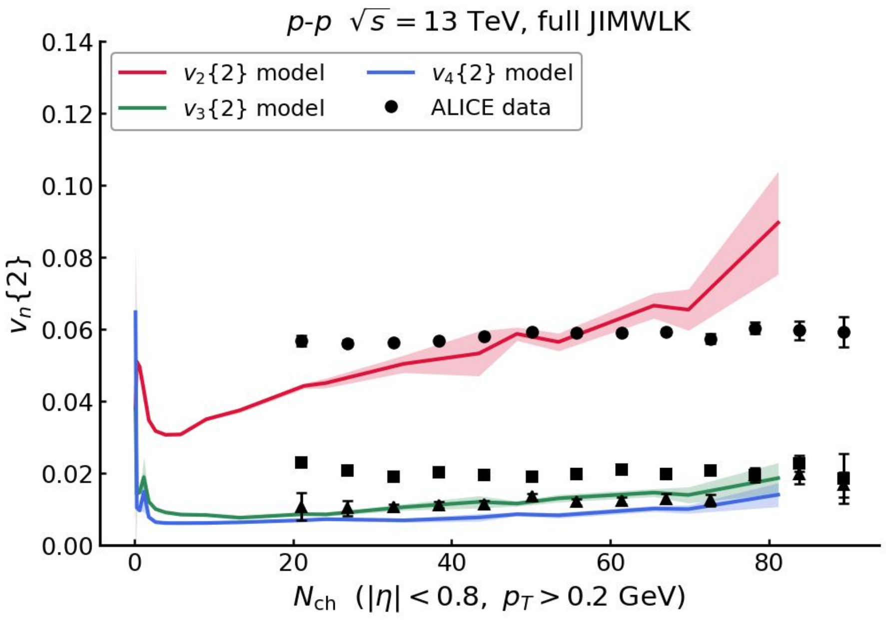




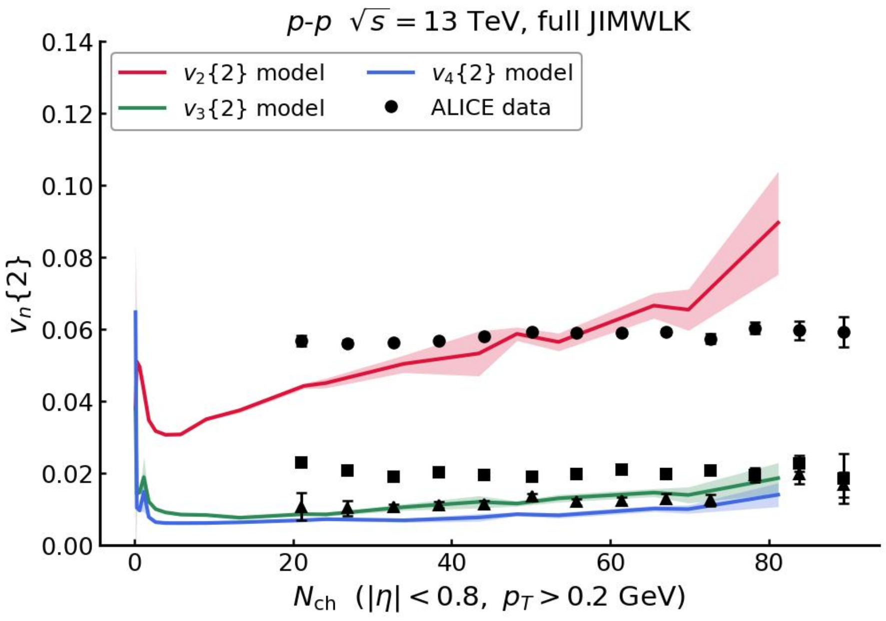


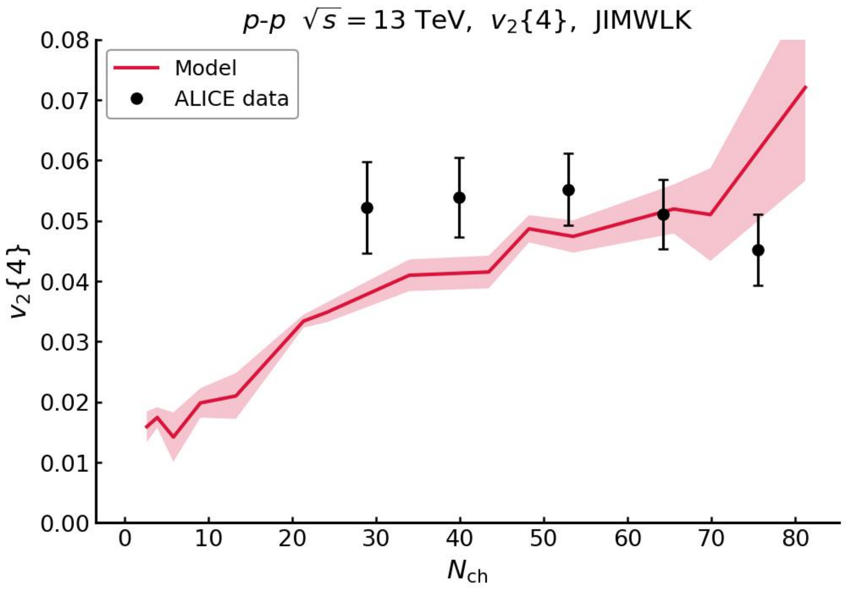


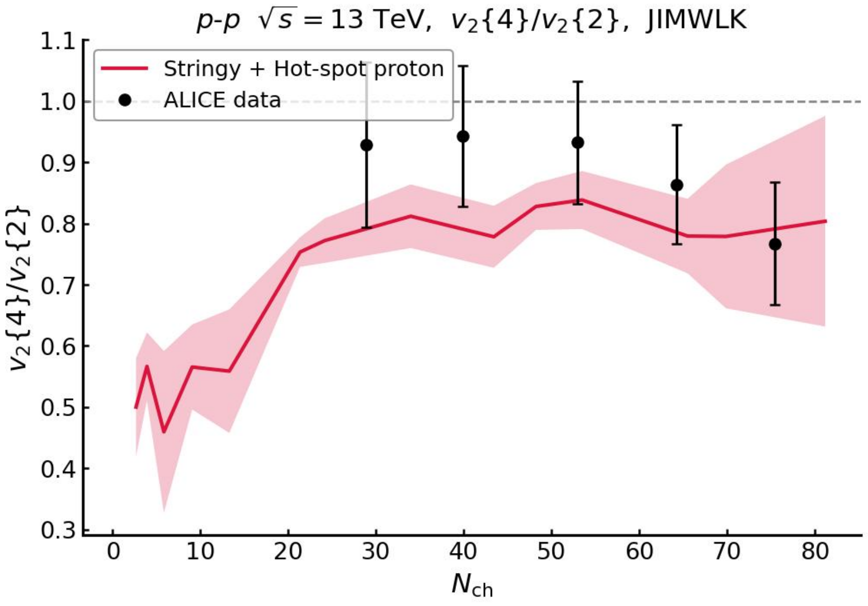
p-p collisions



p-p collisions

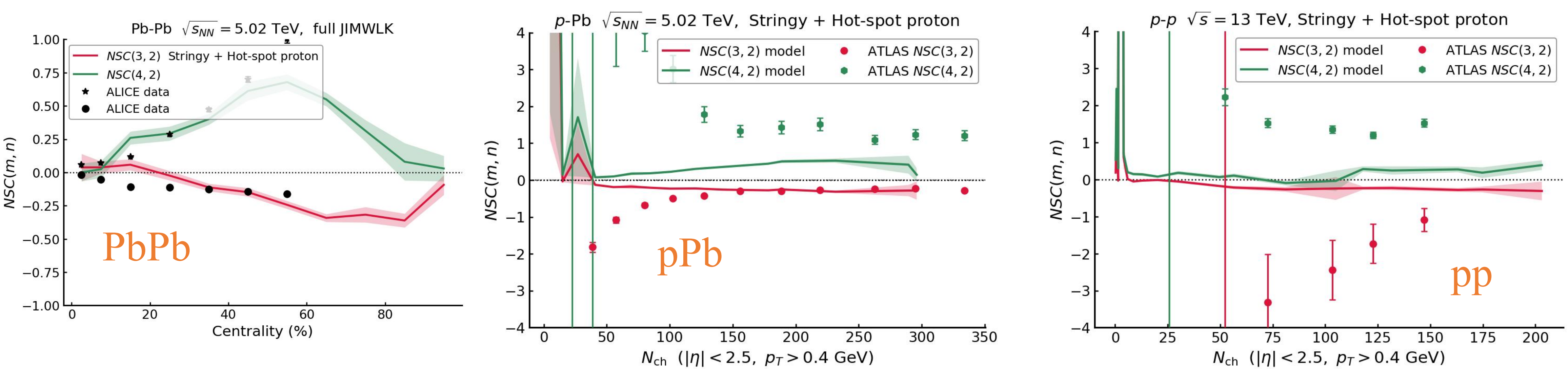






- **Real $v_2\{4\}$** in p-p from hydro simulations!

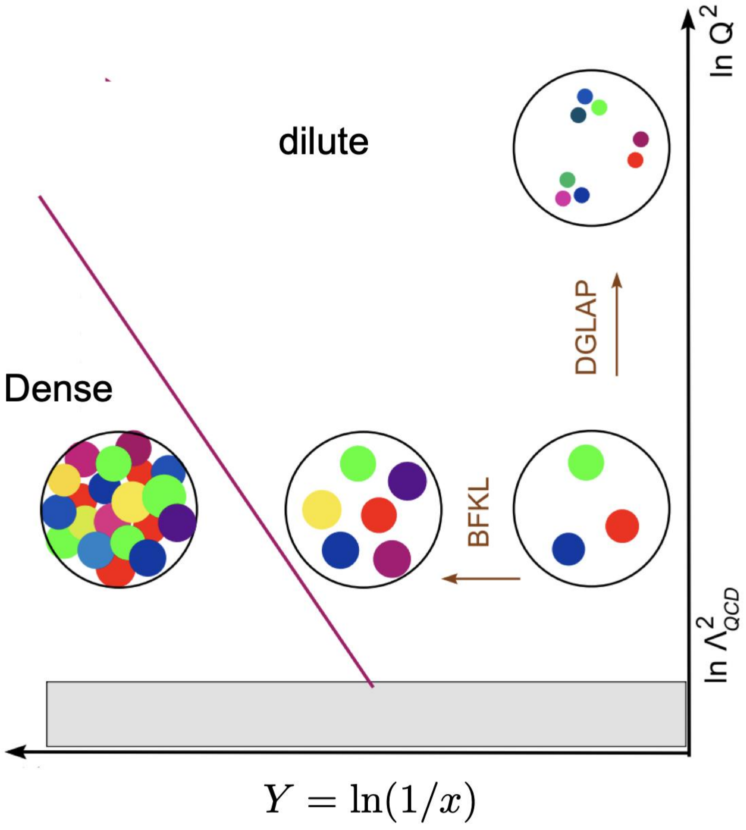
Normalized Symmatric Cumulant

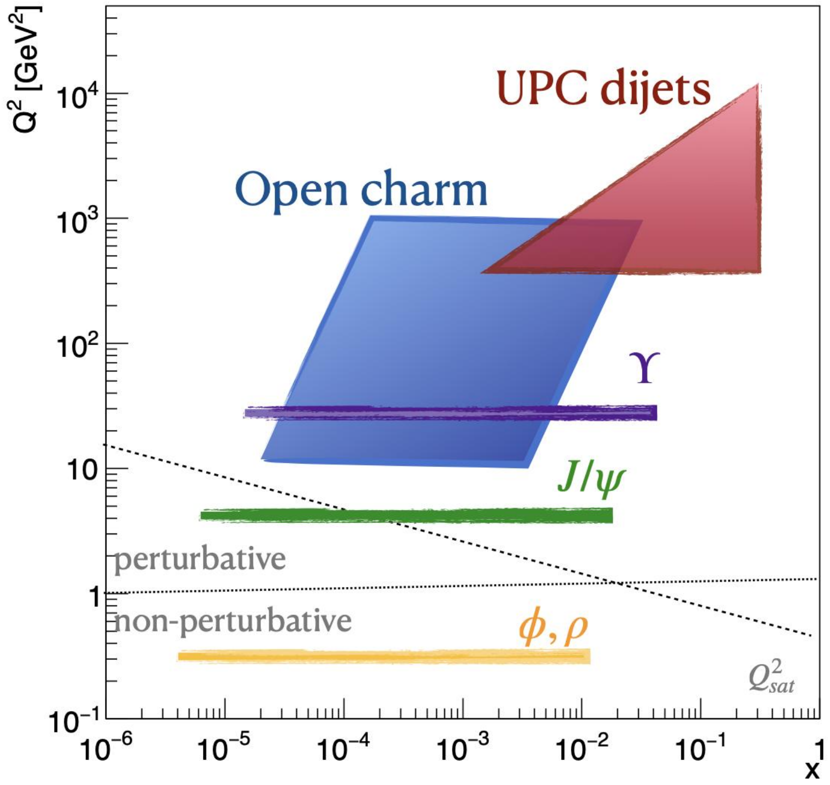


$$NSC^v(m,n) = \frac{SC^v(m,n)}{\langle v_m^2\rangle\langle v_n^2\rangle} = \frac{\langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle}{\langle v_m^2\rangle\langle v_n^2\rangle}$$

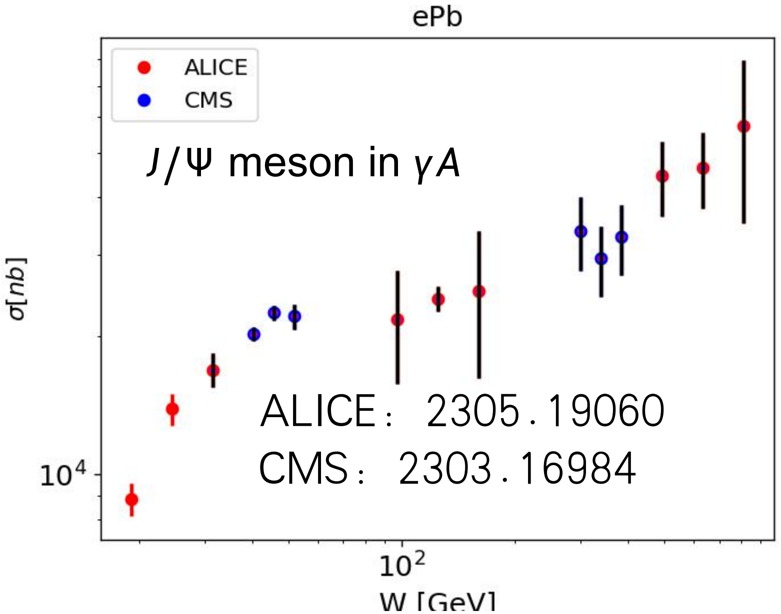
- **Correct sign** of the NSC(4,2) and NSC(3,2) in PbPb, pPb, and **in pp** from hydro simulations.
- If correlations are caused by long-range collective correlations, then **|NSC(4,2)| < 1** and **|NSC(3,2)| < 1** should hold.

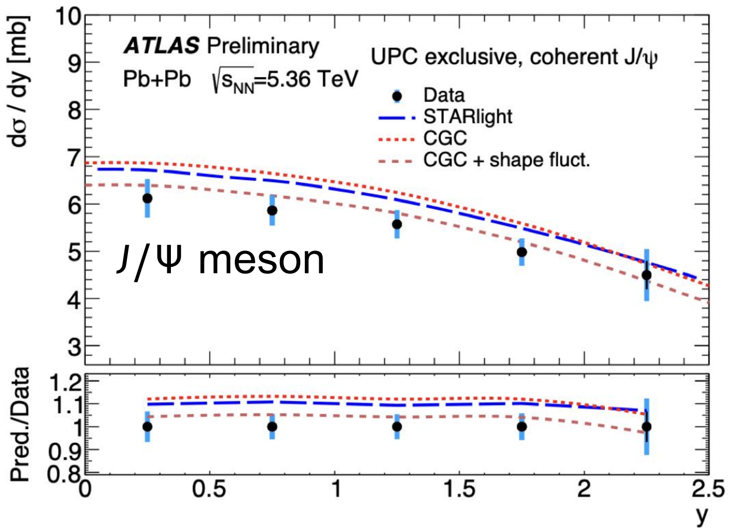
Probing gluon saturations in UPC

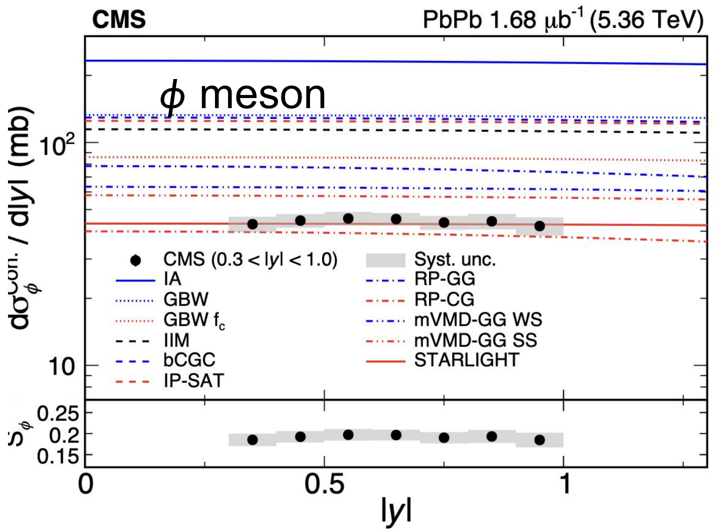


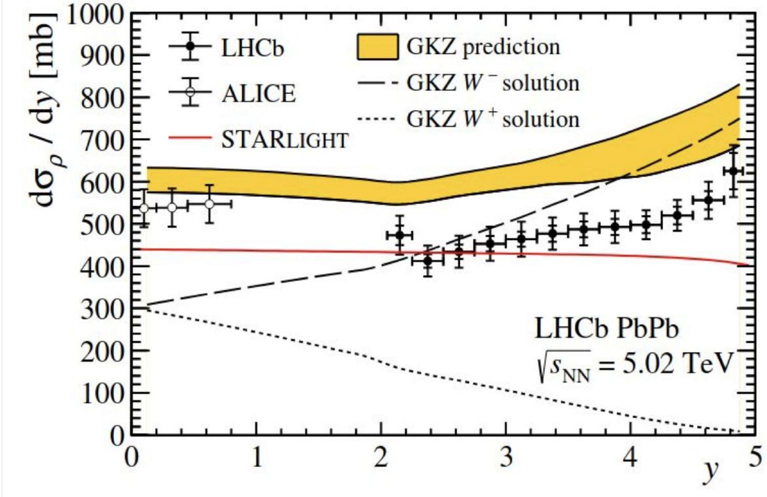


Wealth of vector meson productions in UPCs

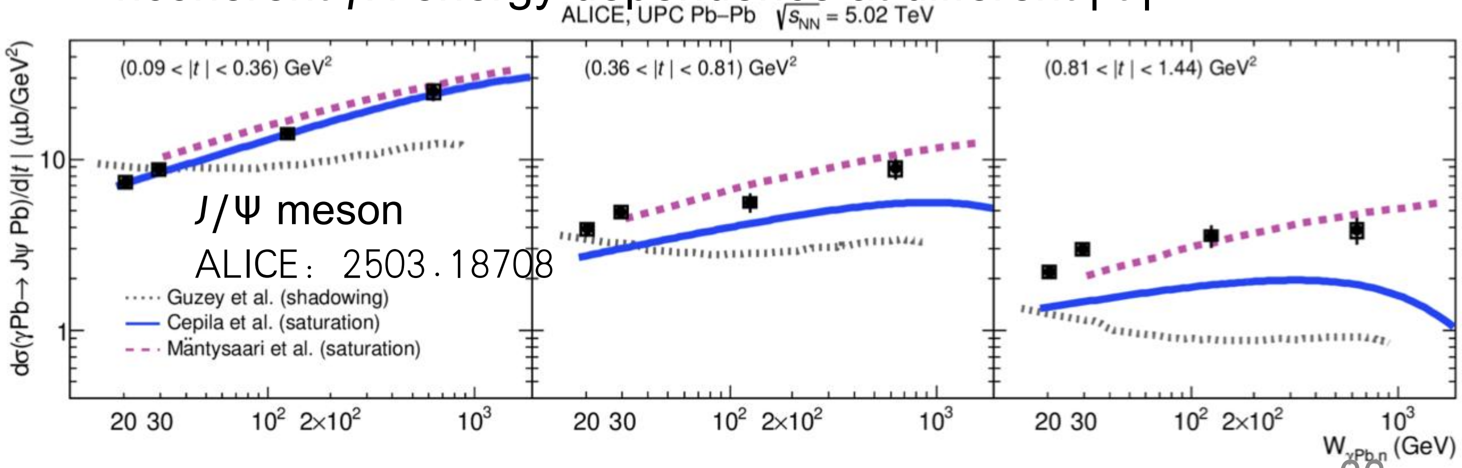




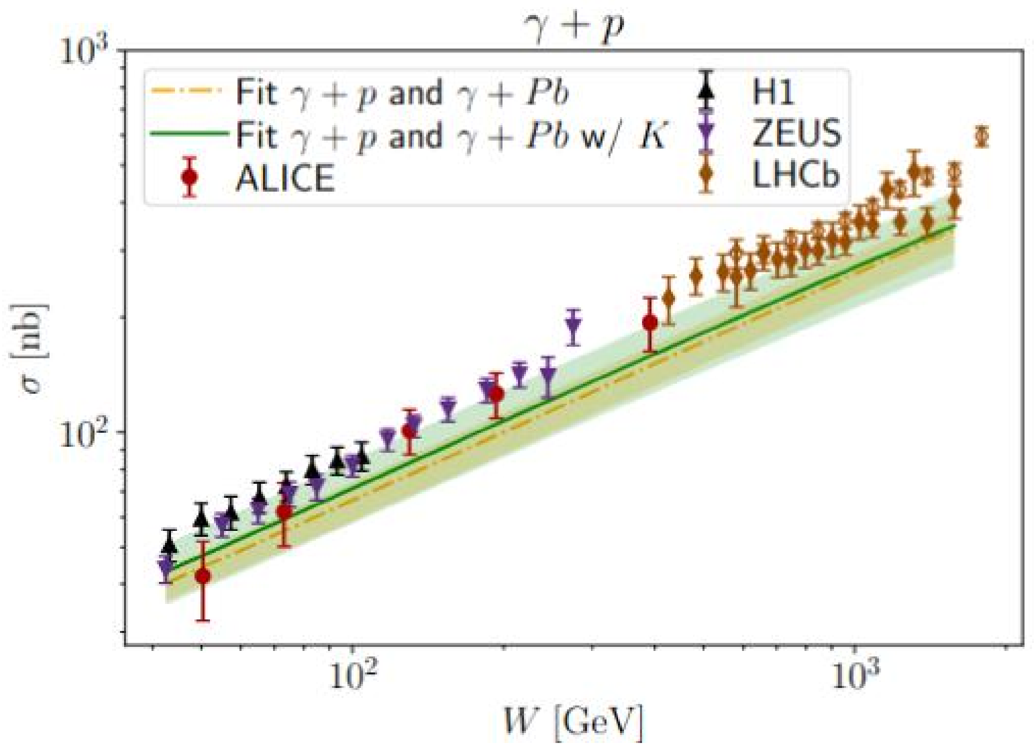


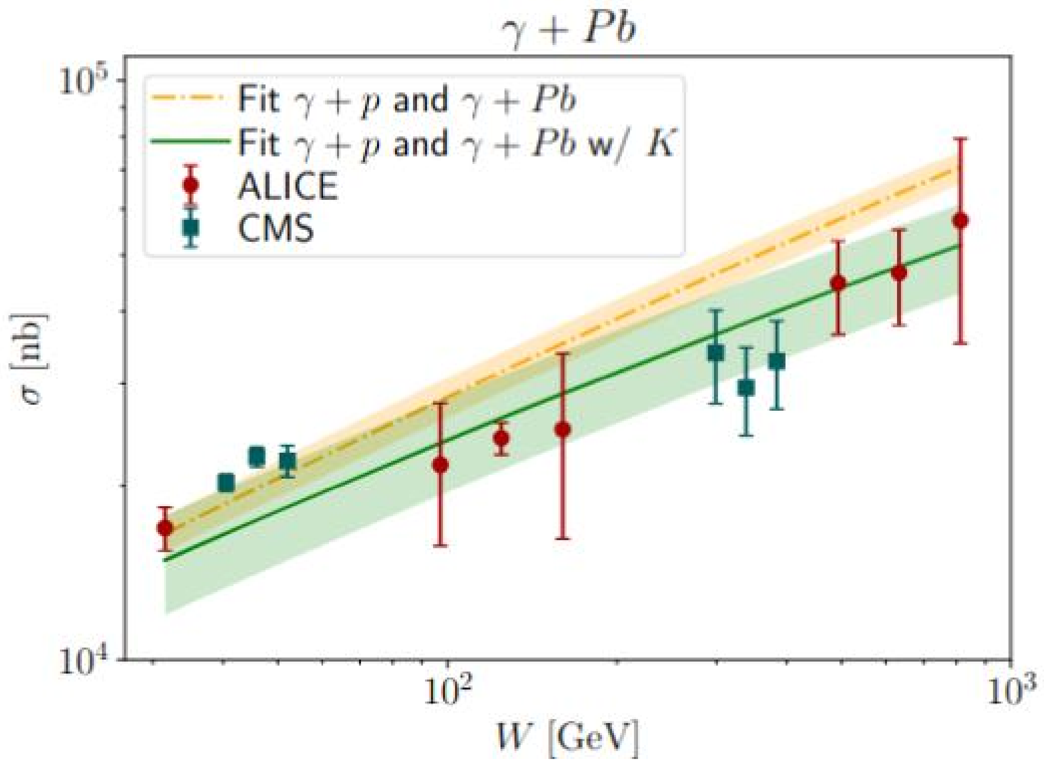


- Incoherent γA energy dependence at different | t |



Global Bayesian analysis of J/ψ photoproduction on proton and Pb





H. Mantysaari, H. Roch, F. Salazar, B. Schenke, C. Shen and W. Zhao, Phys. Rev. D 113 (2026), 014038.

- CGC model has **tension** to fit the γp and γPb data simultaneously. (See also: J. Penttala and C. Royon, PLB. 864, 139394 (2025).)
- K~0.3 here for the green lines.

Corrections for Electromagnetic Ion Dissociation (EMD) in UPC

A First Account of the Impact of Ion Electromagnetic Dissociation on Event Exclusivity in Ultraperipheral LHC Collisions

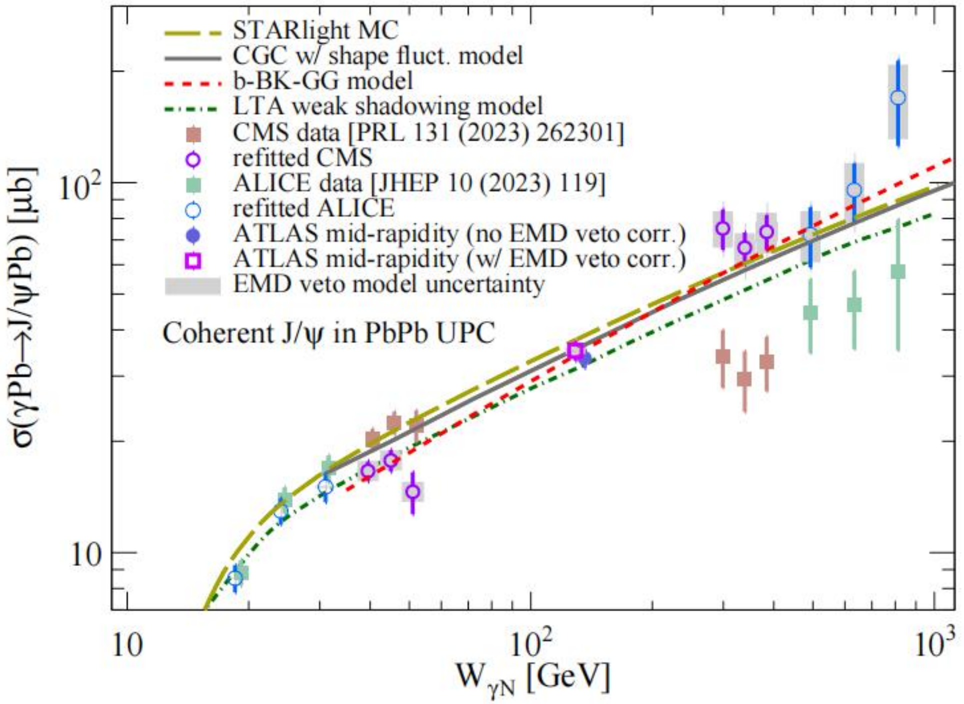
M. Dyndal*

AGH University of Krakow, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Krakow, PL

L. A. Harland-Lang†

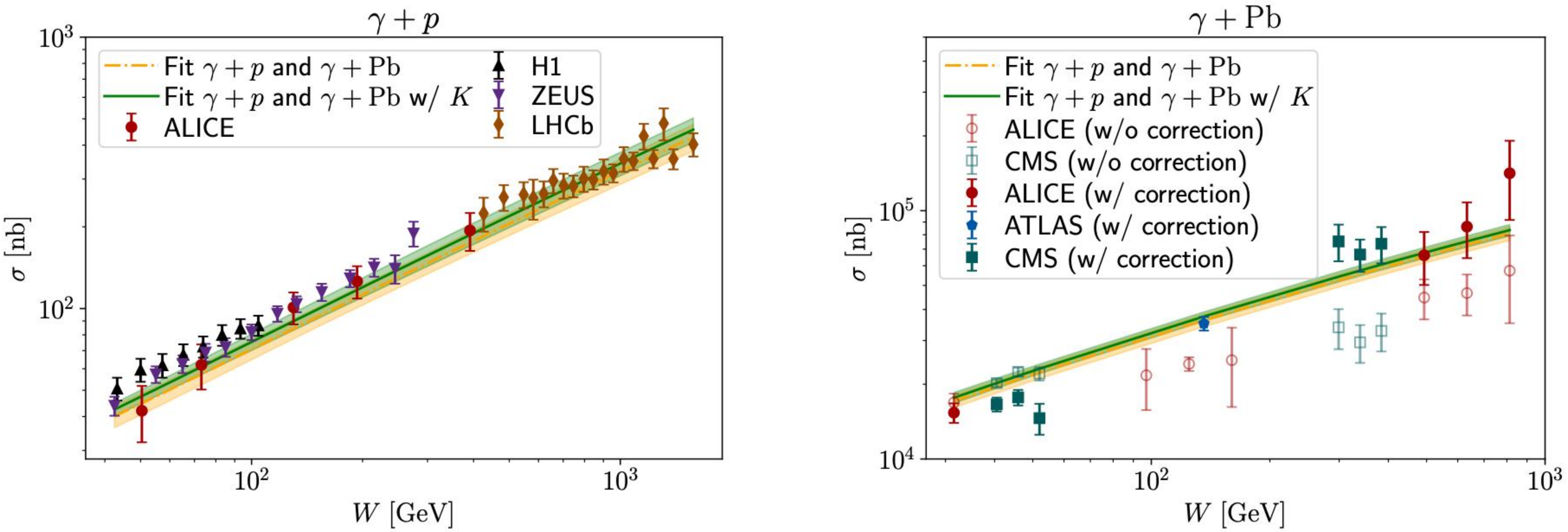
Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK

[M. Dyndal and L. A. Harland-Lang, [arXiv:2604.19879]].



- EMD occurs when photon excites the ion, which de-excites by emitting particles.
- It usually forward neutrons, but at high photon energies it produces mid-rapidity hadrons.
- It can trigger the experimental exclusivity veto and reduce the J/ψ photoproduction.

Revisiting the EMD-corrected J/ψ Production

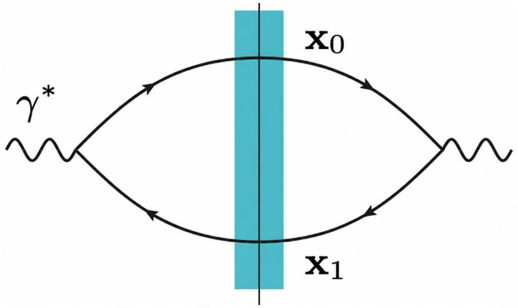


H. Mantysaari, H. Roch, B. Schenke, C. Shen and W. Zhao, arXiv:2606.20362.

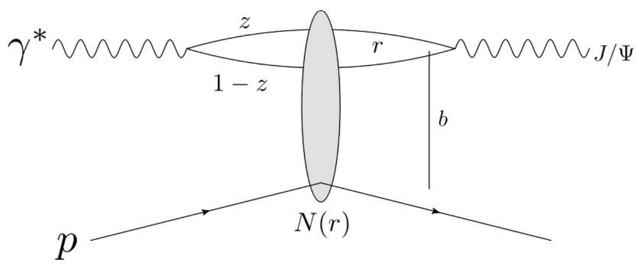
- The **tension** between the CGC model and the simultaneous description of the γp and EMC-corrected γPb data has **disappeared**.
- K~0.94 here for the green lines.

Global Extraction of the Universal Dipole Amplitude from an Unbiased Initial Condition

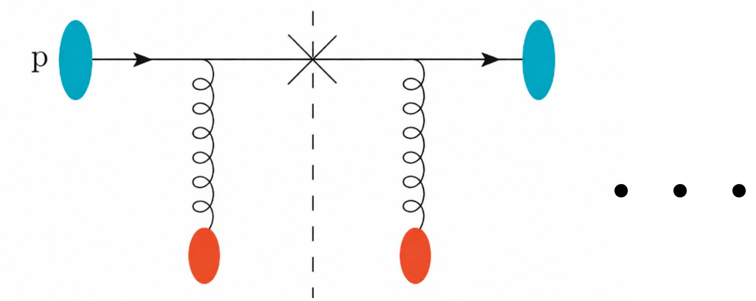
Universal Dipole Amplitude



$\sigma_{L,T}^{\gamma^* p \to \gamma^* p} \propto N(x, r_T, b)$



$\sigma_{L,T}^{\gamma^* p \to V p} \propto N(x, r_T, b)$



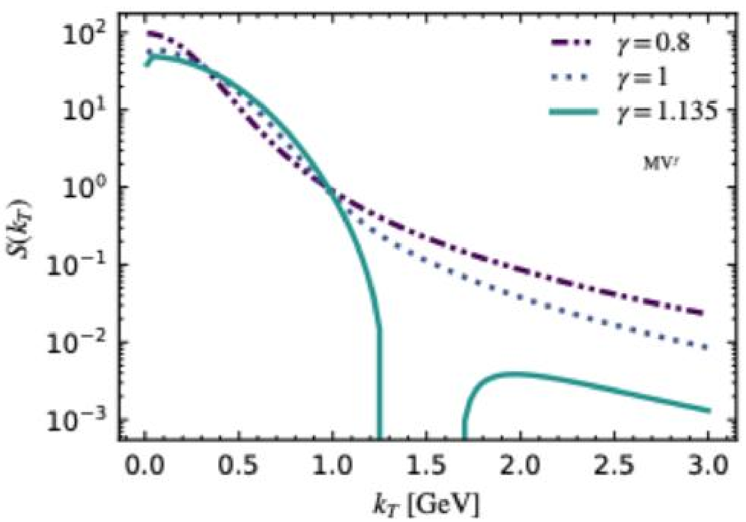
$\sigma^{pp \to h+X} \propto S(x, k_T)$ $\quad S(k_T, Y) = \int d^2\mathbf{r} e^{i\mathbf{k}_T \cdot \mathbf{r}} [1 - N(r, Y)].$

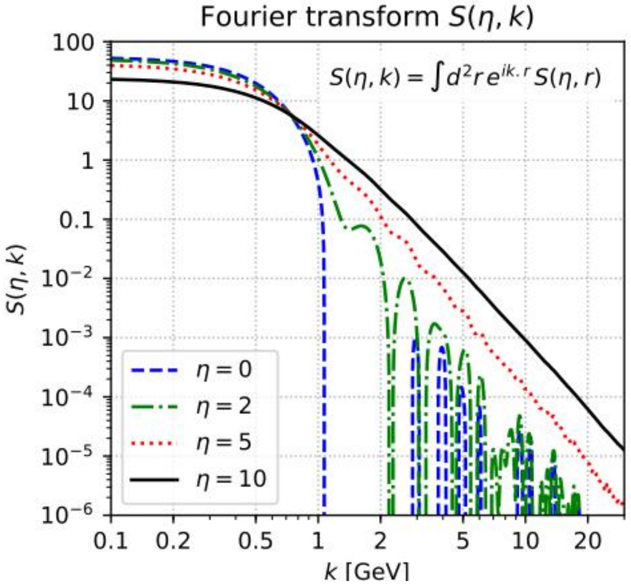
$$\frac{d\sigma^{pA \to hX}}{d^2 p_\perp dy} = \frac{1}{(2\pi)^2} \int_{x_F}^{1} \frac{dz}{z^2} \left[\sum_q x_1 q(x_1, \mu^2) \tilde{S}_F\left(\frac{p_\perp}{z}, x_2\right) D_{h/q}(z, \mu^2) \right.$$

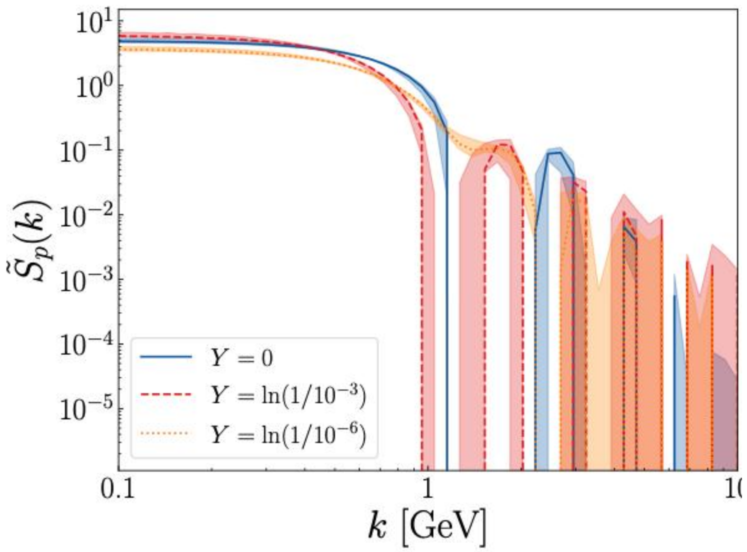
$$\left. + x_1 g(x_1, \mu^2) \tilde{S}_A\left(\frac{p_\perp}{z}, x_2\right) D_{h/g}(z, \mu^2) \right]$$

- The small-x dipole amplitude is **universal** across several processes.
- The dipole amplitude should be **positive** in both coordinate and momentum space.

Problem for ~ 20 Years







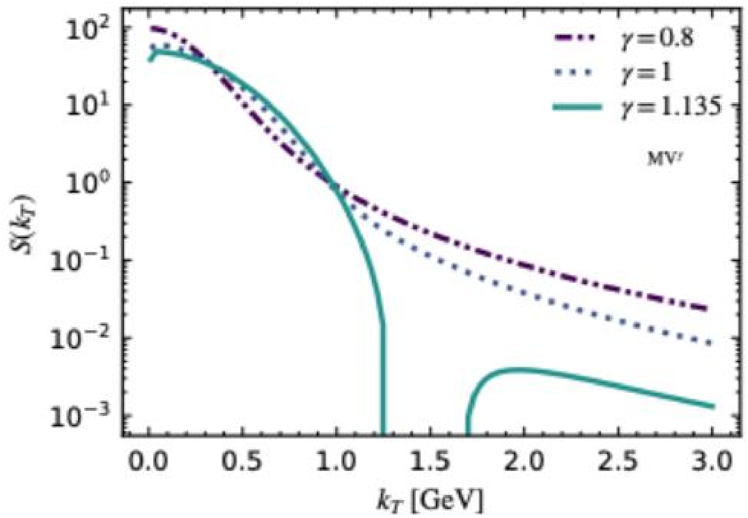
$$S(k_T,Y)=\int d^2\mathbf{r}e^{i\mathbf{k}_T\cdot\mathbf{r}}\left[1-N(r,Y)\right].$$

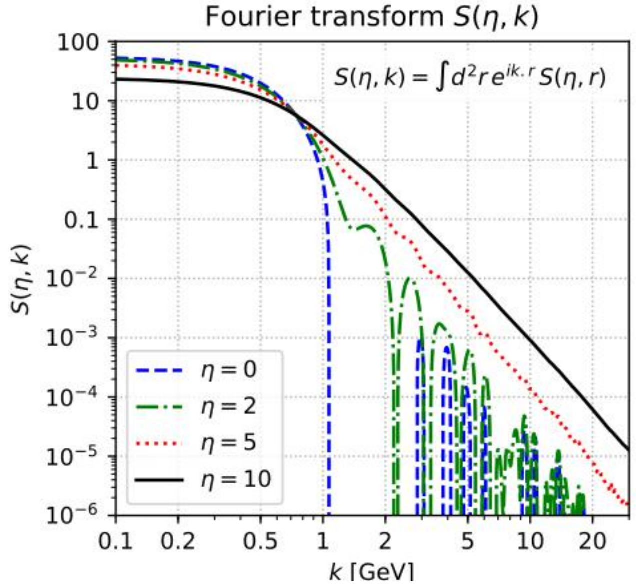
- Using MV-type parametrization, no one can fit the ep data while keeping the S(kT) positive.

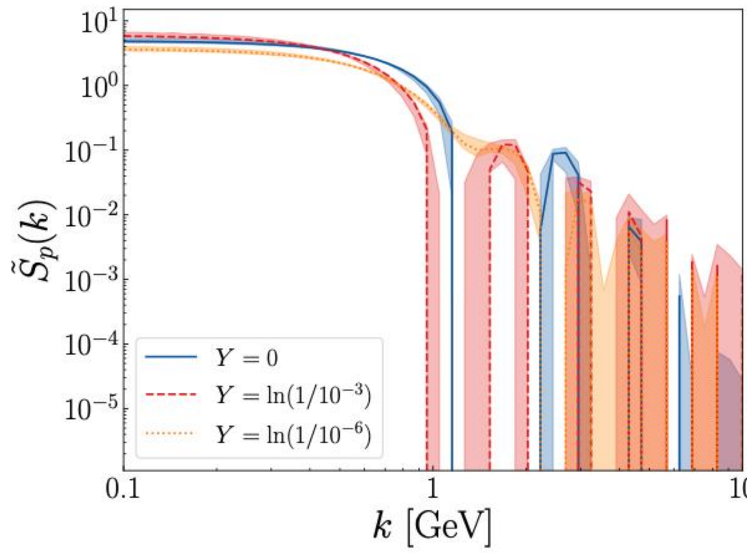
References	χ^2/d.o.f. ($\sigma_r^{\rm total}$)	χ^2/d.o.f. ($\sigma_r^{c\bar{c}}$)	χ^2/d.o.f. (J/ψ)	$S(k_T)>0$?	Universal N?
Albacete *et al.* [Albacete:2010sy] (LO BK + LO Impact Factor)	~ 1.1	~ 1.3	N/A	No	No
B. Ducloué *et al.* [Ducloue:2019jmy] (ciBK + LO Impact Factor)	~ 1.0	N/A	N/A	No	No
Casuga *et al.* [Casuga:2025etc] (KCBK + NLO Impact Factor, Bayesian)	~ 1.2	~ 2.7	N/A	No	Yes
Casuga *et al.* [Casuga:2026xxt] (NLO+NLL BK + NLO Impact Factor, Bayesian)	~ 1.2	~ 2.4	N/A	No	Yes
This work, without "$S(k_T)>0$" constraint (ciBK + LO Impact Factor, PINN)	0.868	1.160	0.691	No	Yes
This work, with "$S(k_T)>0$" constraint (ciBK + LO Impact Factor, PINN)	**1.48**	**1.56**	**1.13**	**Yes**	**Yes**

AAMQS: EPJC, 771 (2011), 1705;
B. Duclouw, E. Iancu, G. Soyez and D. N. Triantafyllopoulos,PLB 803 (2020), 135305
C. Casuga, H. Hanninen and H. Mantysaari, PRD 112 (2025), 034003;

Problem for ~ 20 Years







$$S(k_T, Y) = \int d^2\mathbf{r} e^{i\mathbf{k}_T\cdot\mathbf{r}} \left[1 - N(r, Y)\right].$$

- Using MV-type parametrization, no one can fit the ep data while keeping the S(kT) positive.

References	χ^2/d.o.f. (σ_r^{total})	χ^2/d.o.f. ($\sigma_r^{c\bar{c}}$)	χ^2/d.o.f. (J/ψ)	$S(k_T) > 0$?	Universal N?
Albacete *et al.* [Albacete:2010sy] (LO BK + LO Impact Factor)	~ 1.1	~ 1.3	N/A	No	No
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Casuga *et al.* [Casuga:2025etc] (KCBK + NLO Impact Factor, Bayesian)	~ 1.2	~ 2.7	N/A	No	Yes
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B. Duclouw, E. Iancu, G. Soyez and D. N. Triantafyllopoulos,PLB 803 (2020), 135305
C. Casuga, H. Hanninen and H. Mantysaari, PRD 112 (2025), 034003;

Physics-Informed Global Extraction of the Universal Dipole Amplitude

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

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

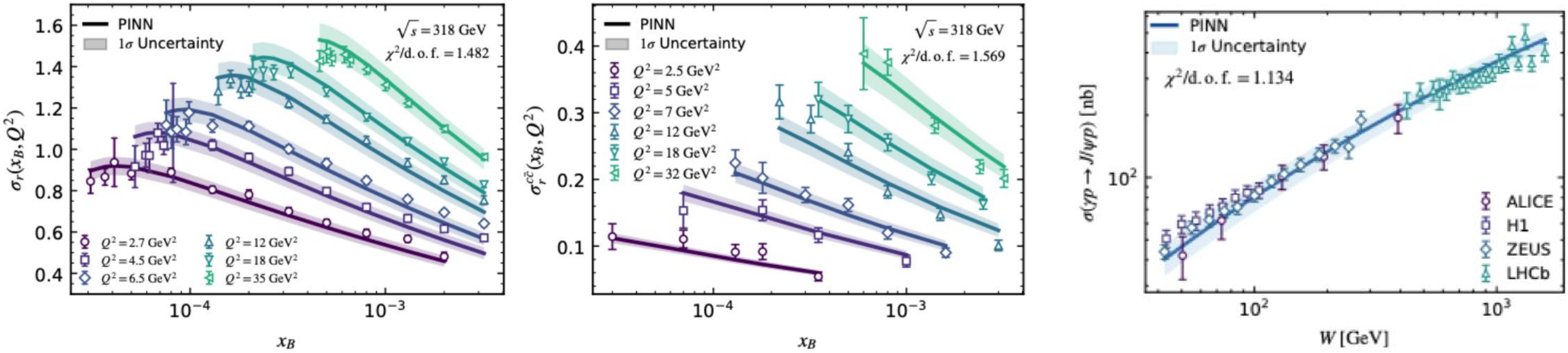
→ Extract **Universal, Unbiased** Dipole Amplitude

- PINN extracts an **universal** amplitude constrained by the **collinear improves BK.**
- **Without imposing** a priori MV-type parametrization of the initial condition.

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

Physics-Informed Global Extraction of the Universal Dipole Amplitude



- 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.

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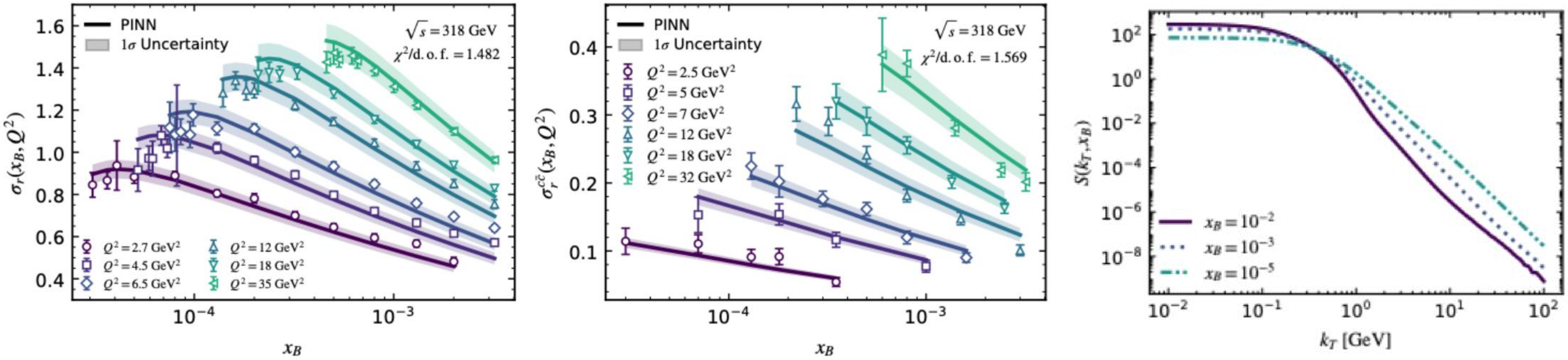
Physics-Informed Global Extraction of the Universal Dipole Amplitude

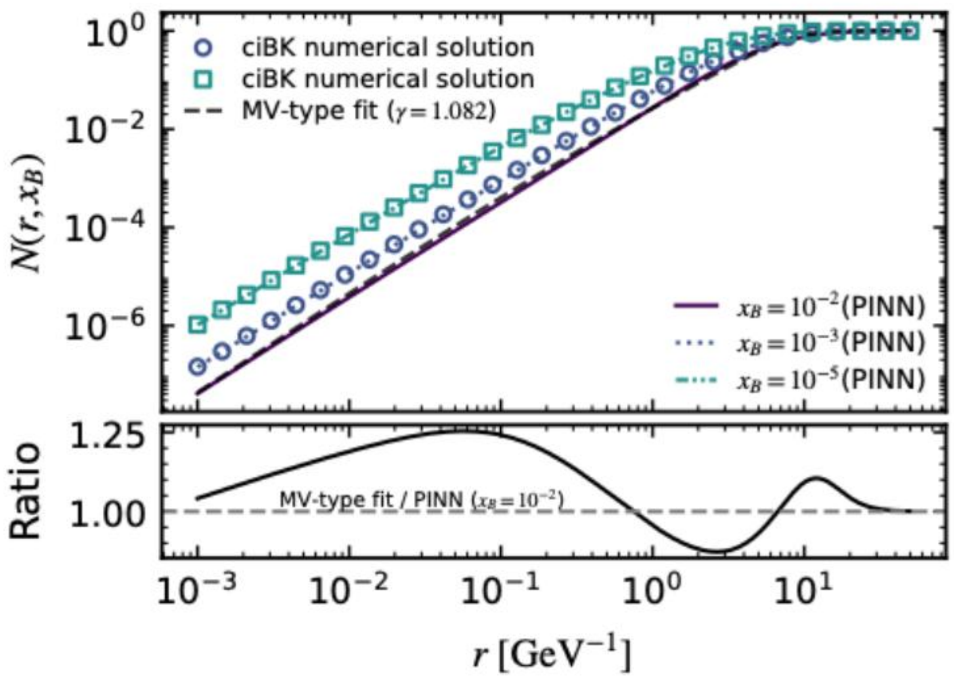


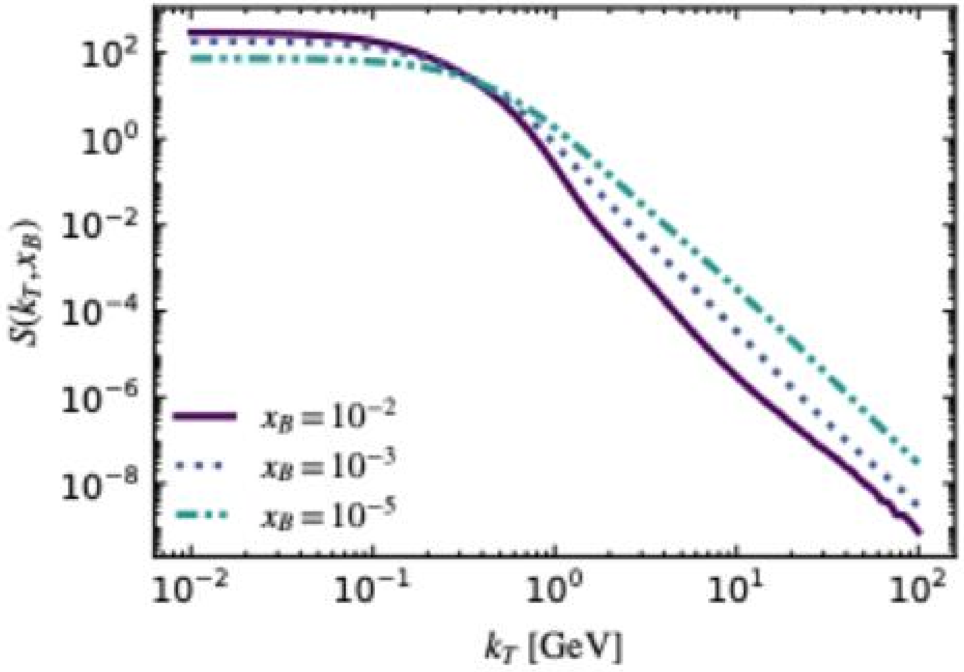
- PINN extracts an **universal** amplitude constrained by the **CiBK.**
- **Simultaneously** constrained by reduced **total** and **charm quark** DIS cross sections, exclusive **J/ψ data.**
- Keep the **positivity for the momentum-space amplitude.**

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**

Dipole Amplitude of Proton



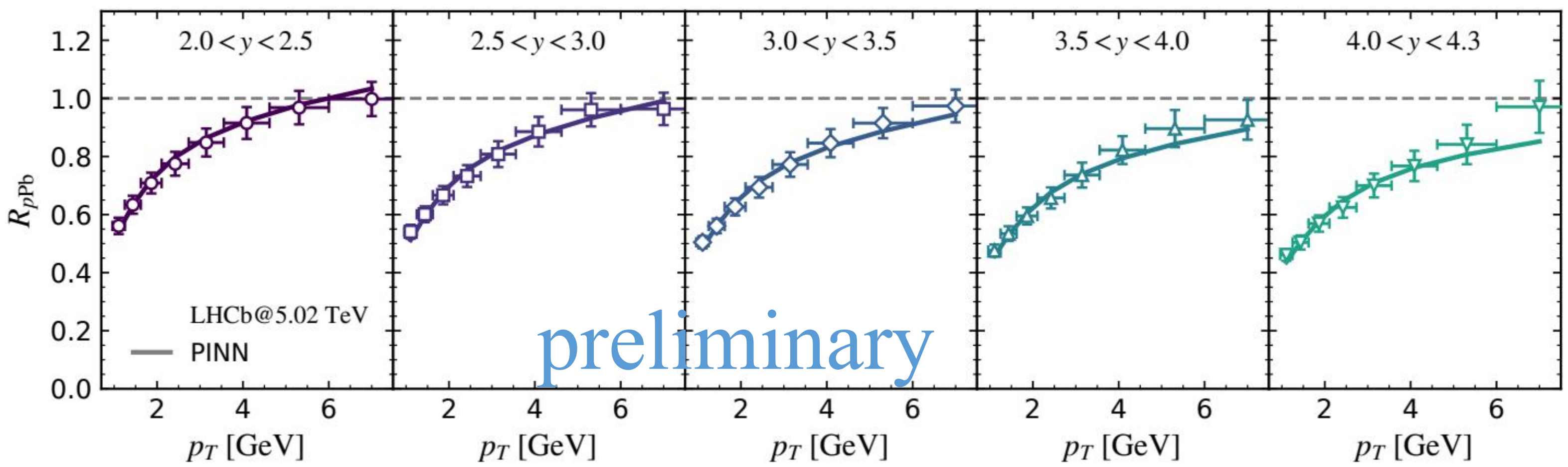


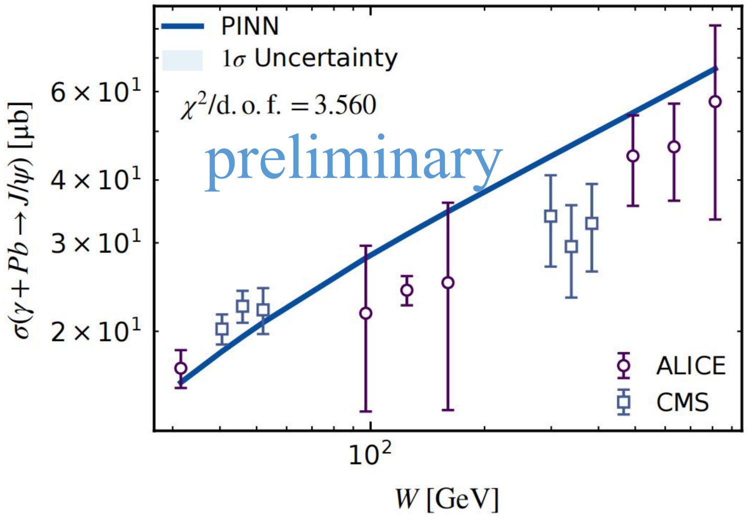
- To solve this problem, which has persisted for 20 years, we need to **go beyond** the MV parametrization.

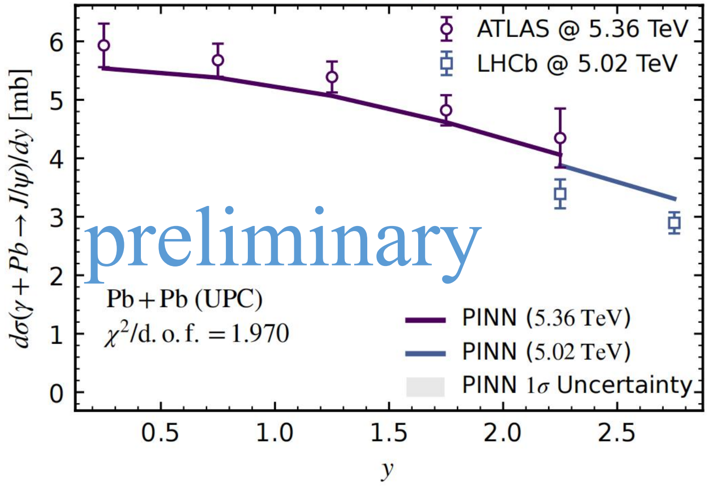
S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008.

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

Global Extraction of the Nuclear Dipole Amplitude





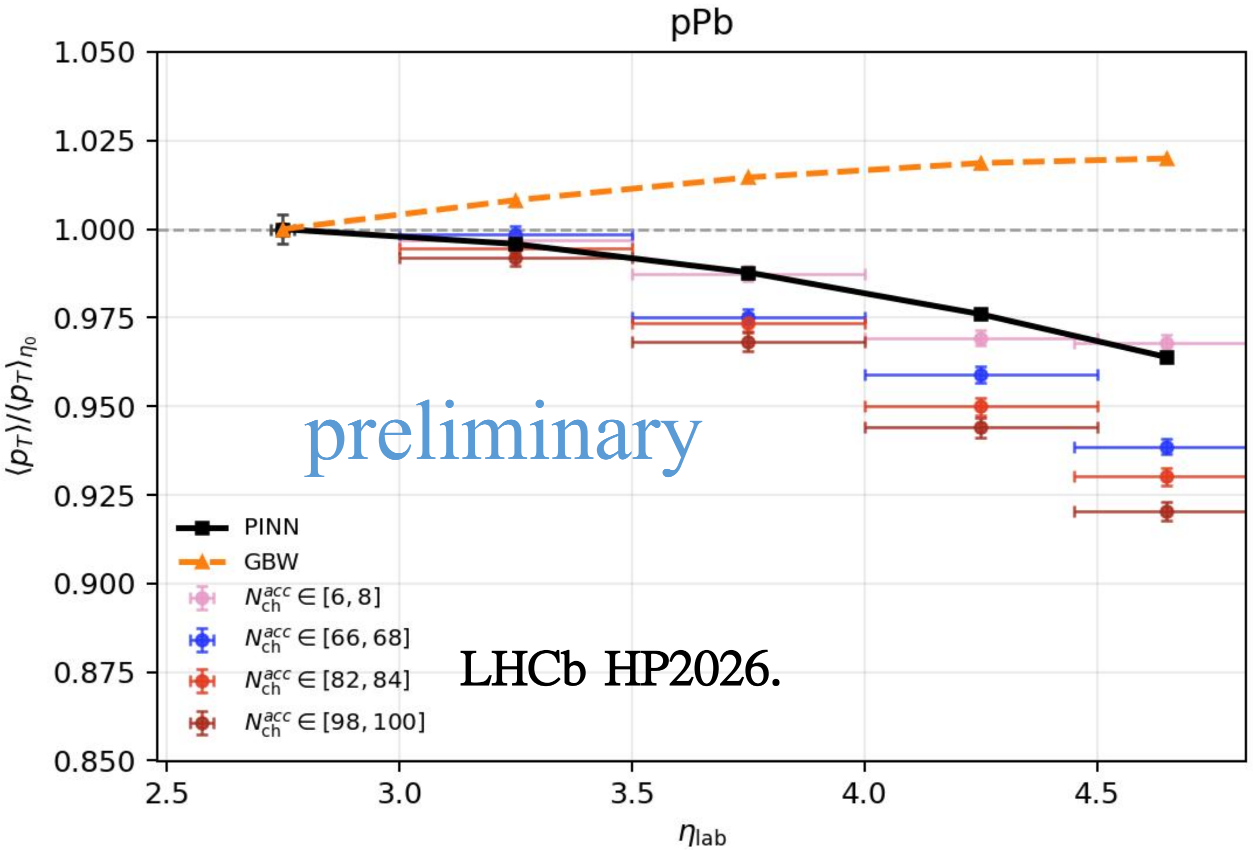


- RpPb greatly **suppresses the uncertainty** from the FF and PDF.
- Every parameter **plays two roles**.
- There is some **tension** between the RpPb and J/ψ data. (EMD correction for J/ψ data?)

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

Mean p_T ratio v.s. η

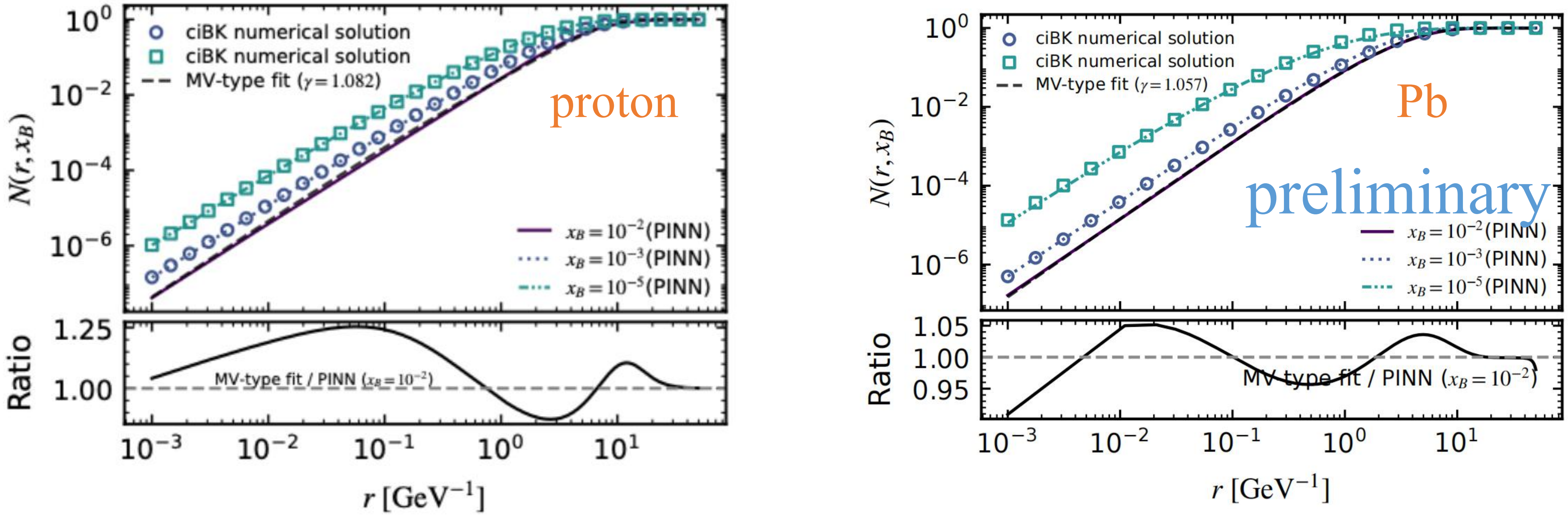


- Our CGC calculation of Mean p_T ratio v.s. η is **consistent** with the LHCb measurments at low Nch.
- In pPb, high Nch implies hydrodynamic behavior, while **low Nch results in CGC dominance.**

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

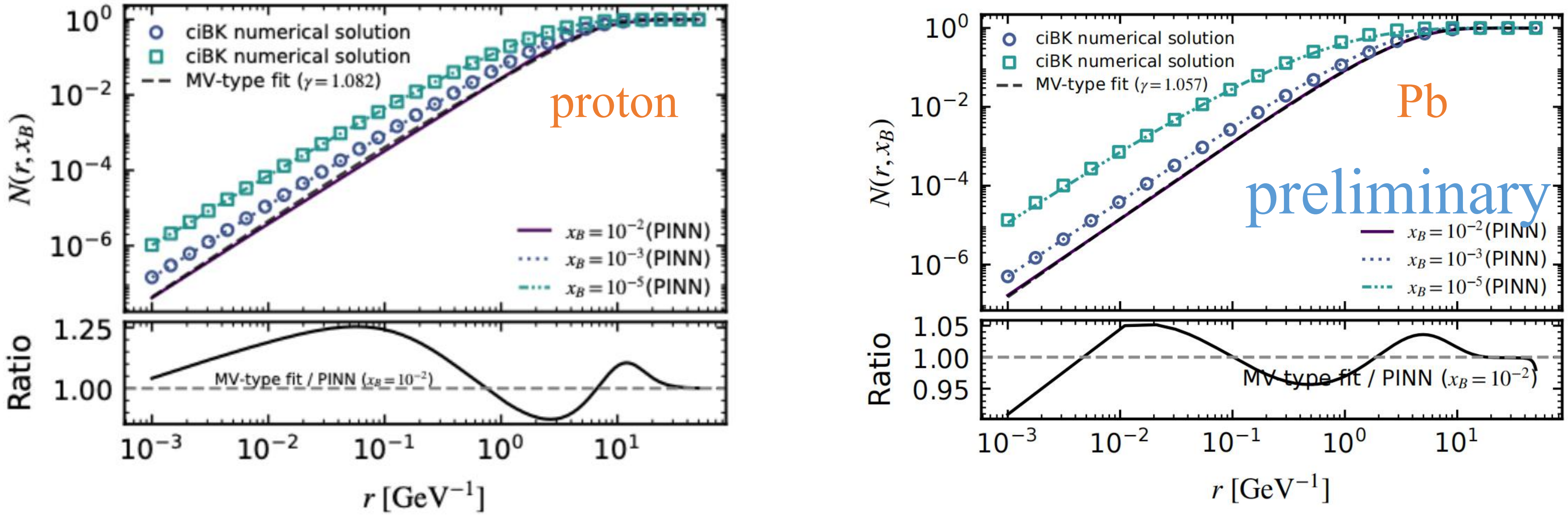


- The MV-type fit works better for Pb than for proton. (**MV model is designed for large nuclei.)**

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



- The MV-type fit works better for Pb than for proton. (**MV model is designed for large nuclei.)**
- From the **unbiased** global fit, we obtain a ratio of $\frac{Q^2_{s0,Pb}}{Q^2_{s0,p}} \sim 3.1$.

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

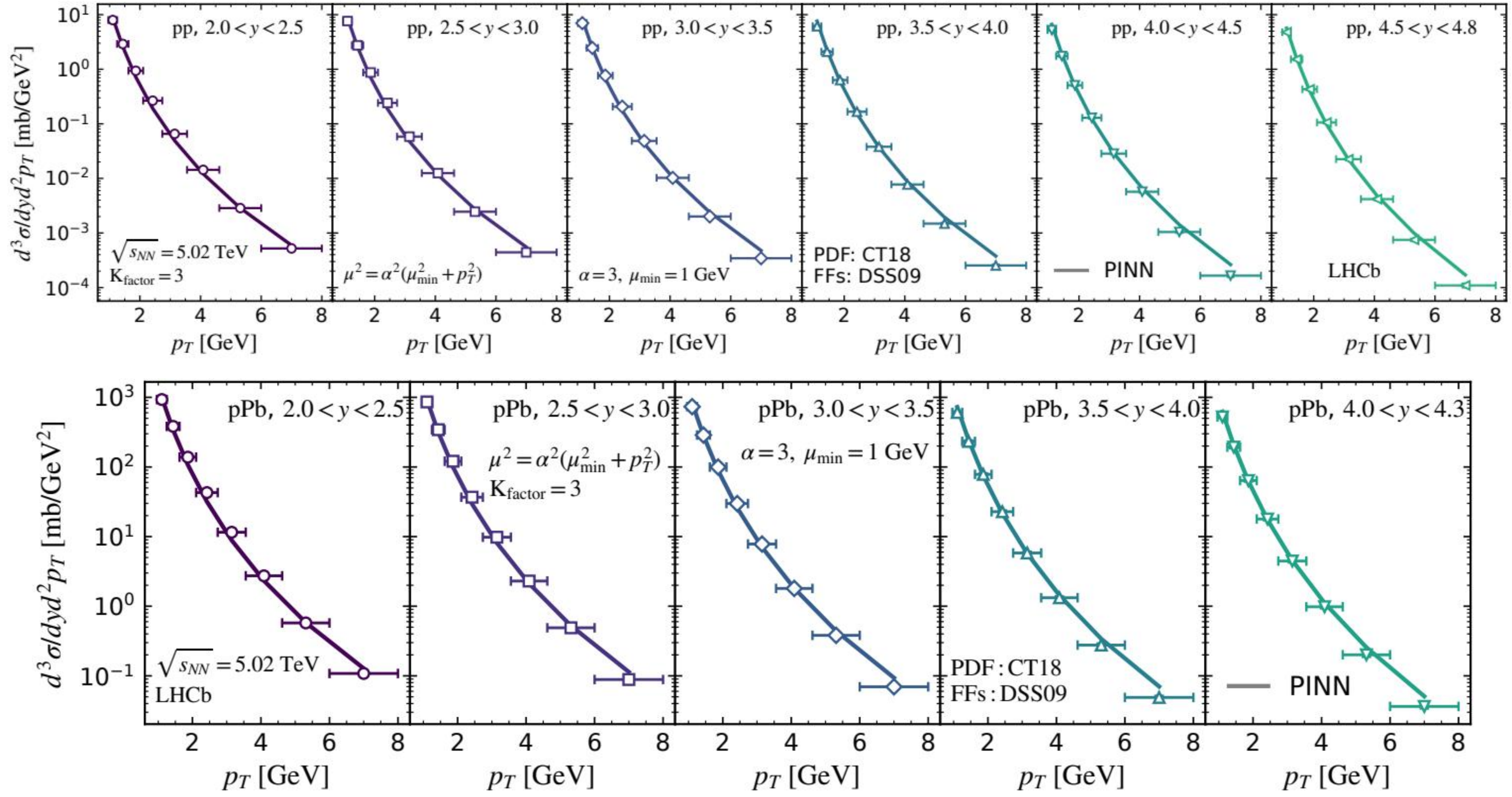
- A comprehensive analysis of UPC/DIS and heavy-ion collision data across various energies will provide a precise understanding of **gluon saturation**, the **initial conditions** of heavy-ion collisions, and the **QGP properties**.
- The neural network method offers a novel approach to solving problems in the small-x area.
- From the **unbiased** global fit, we obtain a ratio: $\frac{Q^2_{s0,Pb}}{Q^2_{s0,p}} \sim 3.1$.

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

Thanks for Your attentions.

Back Up

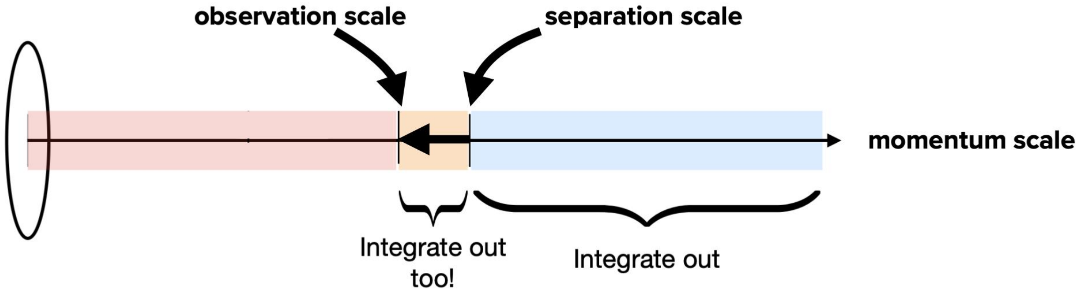
dN/dpT for pp and pPb

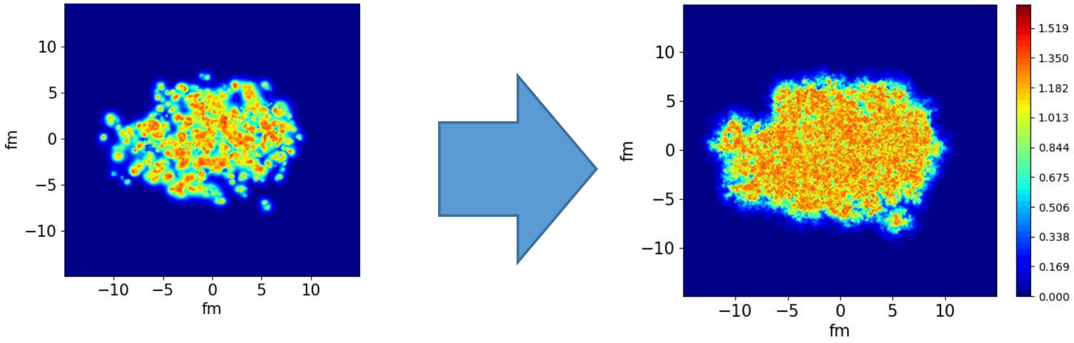


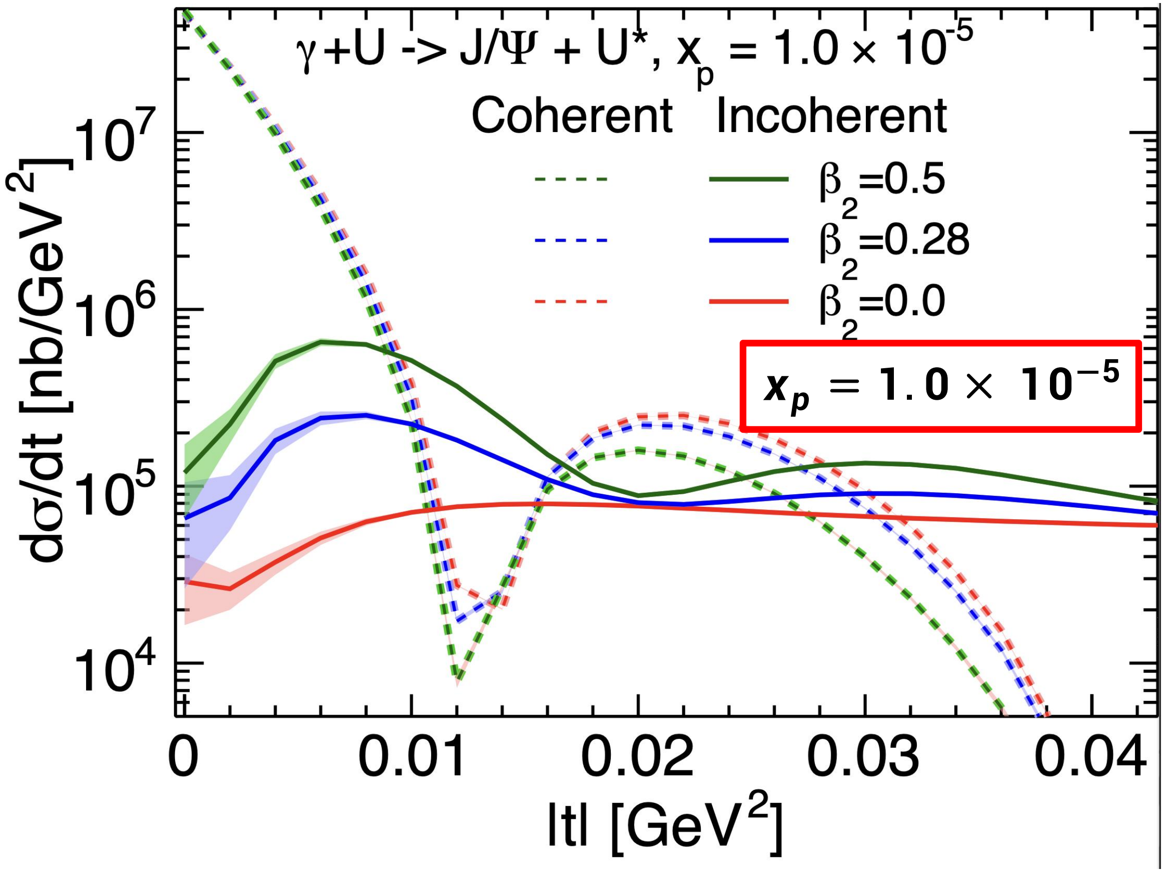
S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008 and in progess.

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

Energy evolution to smaller *x*







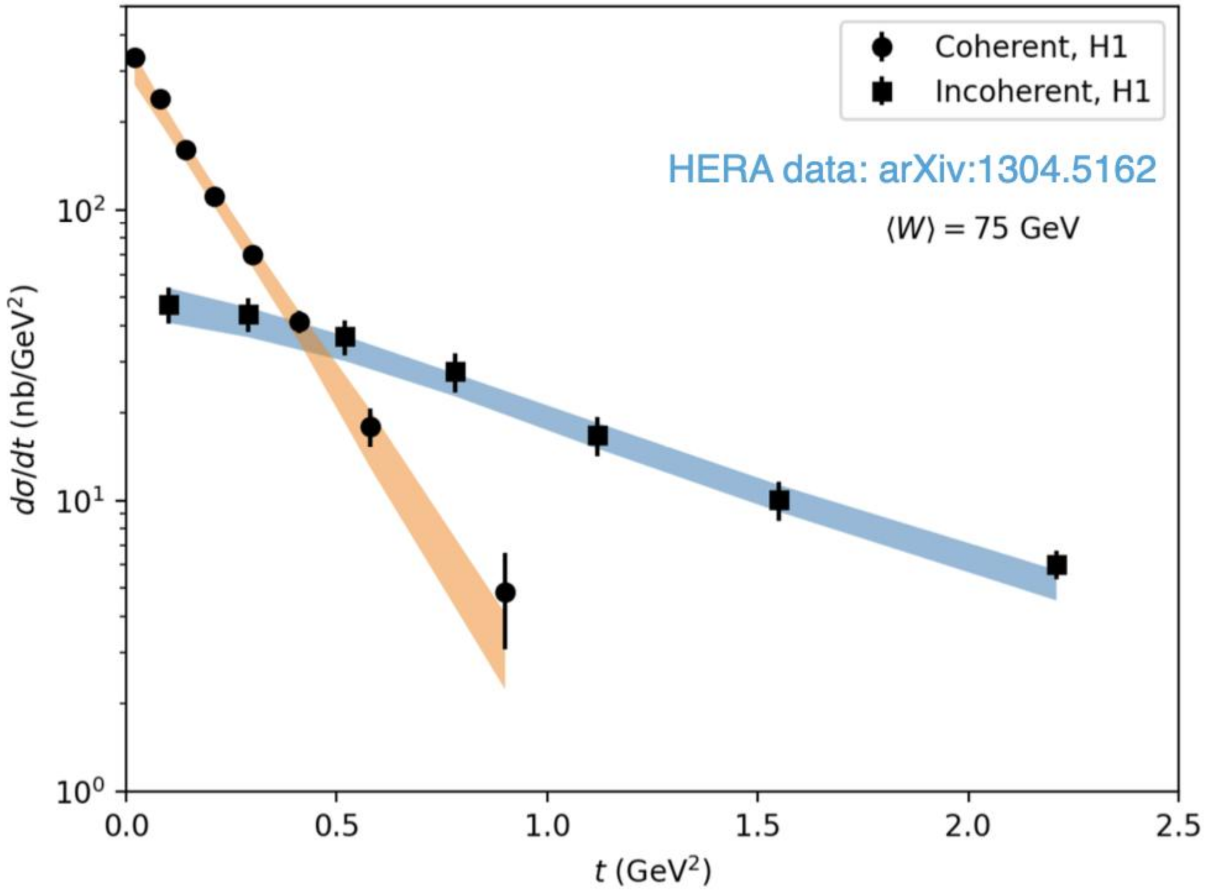
- Energy evolution **doesn't wash out** this effects.

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

Model parameters and the Exp. Data ($\gamma^* + p \rightarrow J/\psi + p^*$)

Parameterize proton shape (T_p)

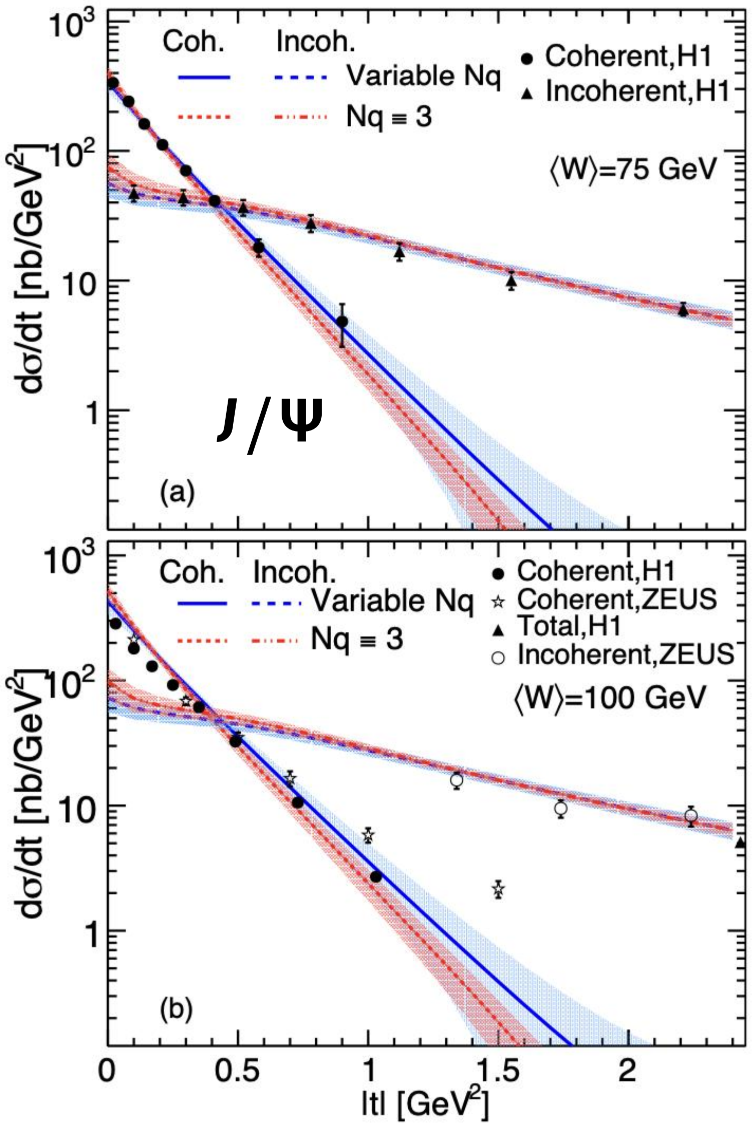
- Number of hot spots N_q
- Proton size B_{qc}
- Hot spot size B_q
- Hot spot density fluctuations σ
- Min. distance between hot spots $d_{q,min}$
- Overall color charge density: $Qs(x)/g^2\mu$
- Infrared regulator m

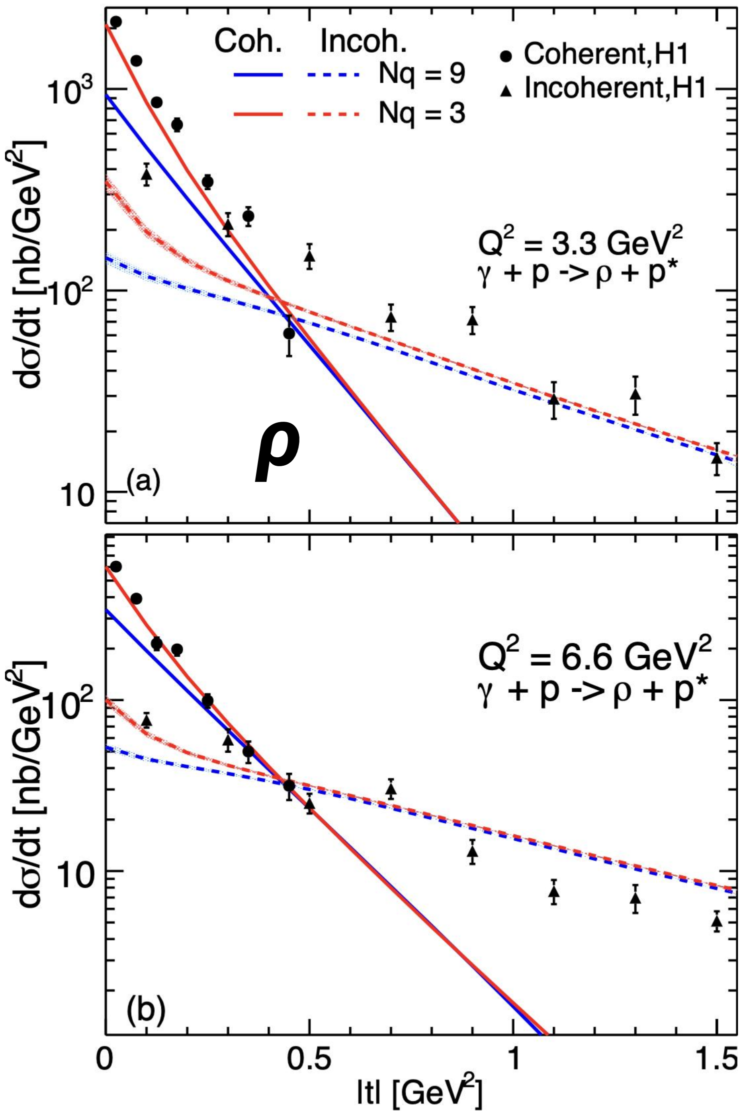


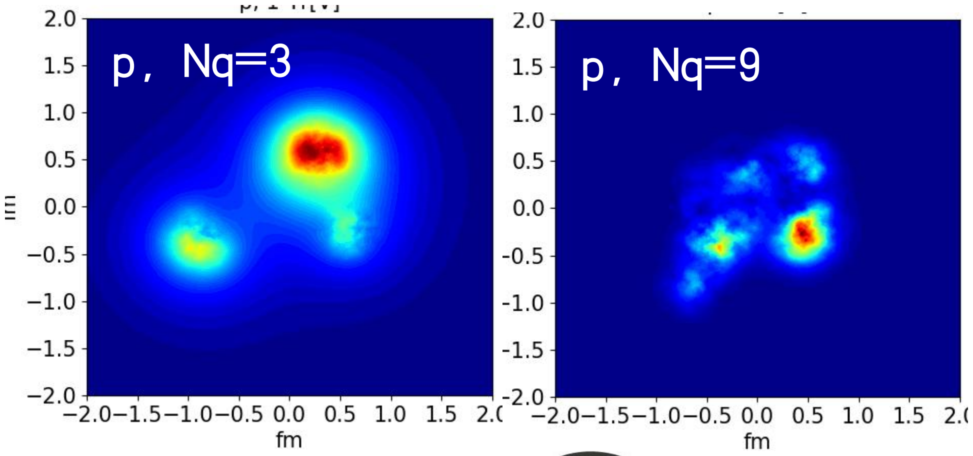
- 7D parameter space; generated 1000 training points for the model emulator

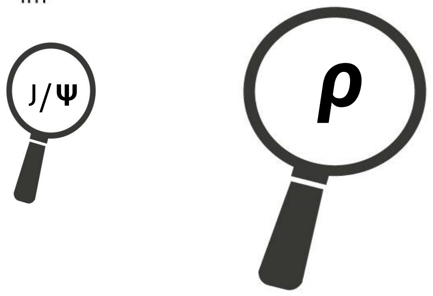
H.Mantysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348.

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.