# Extracting the Universal Small-x Dipole Amplitude with PINNs

Speaker: Si-Wei Dai

Collaborated with Fu-Peng Li, Long-Gang Pang, Guang-You Qin, Shu-Yi Wei, Han-Zhong Zhang and Wenbin Zhao

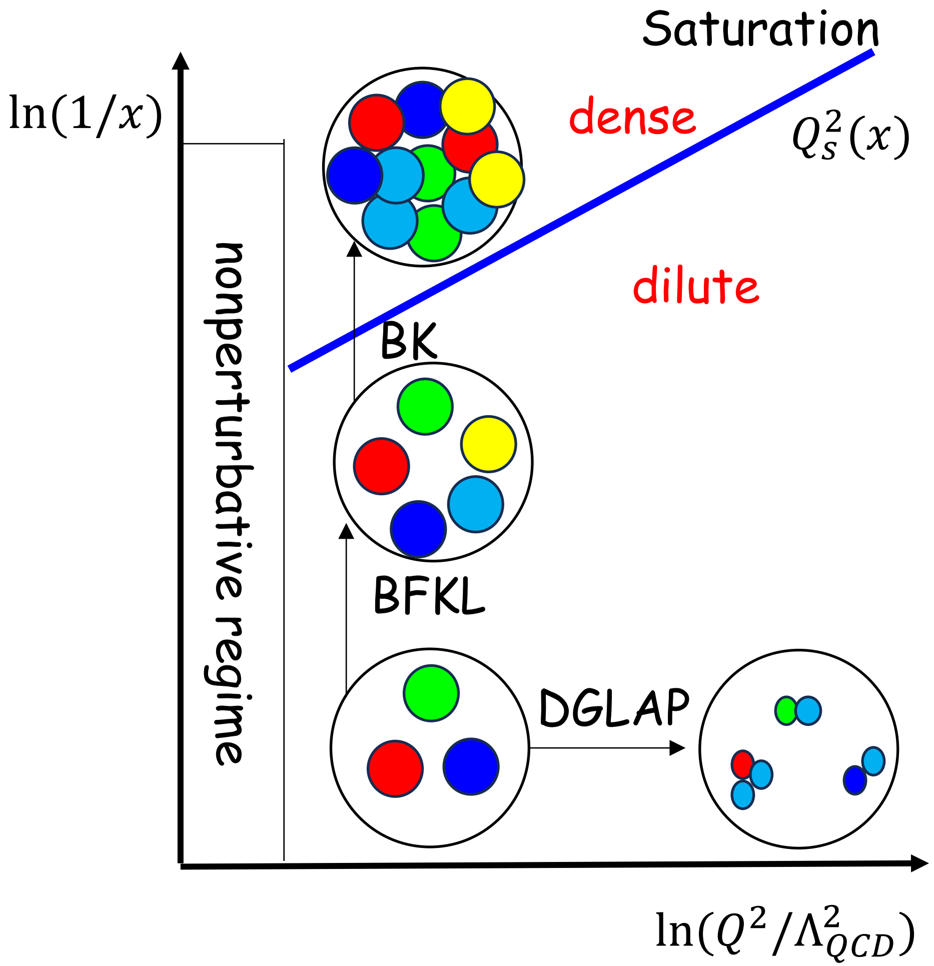
arXiv:2603.08008

# Outline

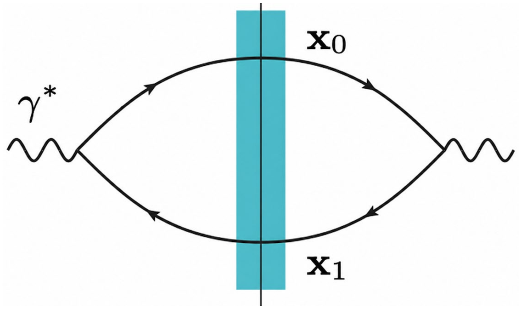
- Introduction
- Physics-Informed Neural Networks
- Results
- Summary

# High-energy QCD and the small-x regime

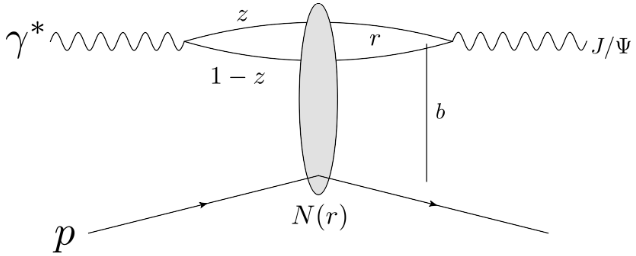
- As $x$ decreases, gluon densities grow rapidly.
- The growth eventually requires nonlinear dynamics and saturation.
- The Color Glass Condensate (CGC) provides an effective framework for the dense small-x regime.
- The saturation scale $Q_s$ is an emergent scale that characterizes saturation.
- JIMWLK/BK evolution governs the small-x evolution of Wilson-line correlators.



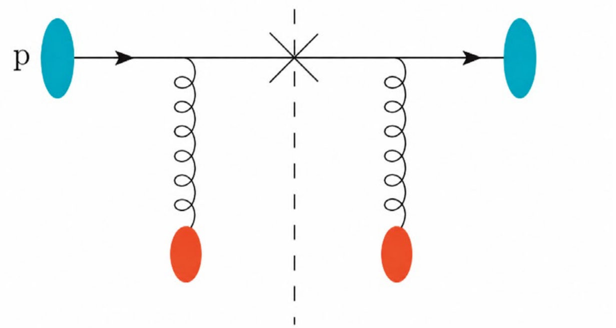
# Why the dipole amplitude matters




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




$$\sigma_{L,T}^{\gamma^* p \to V p} \propto |N(x, \mathbf{r}_T, \mathbf{b})|^2$$



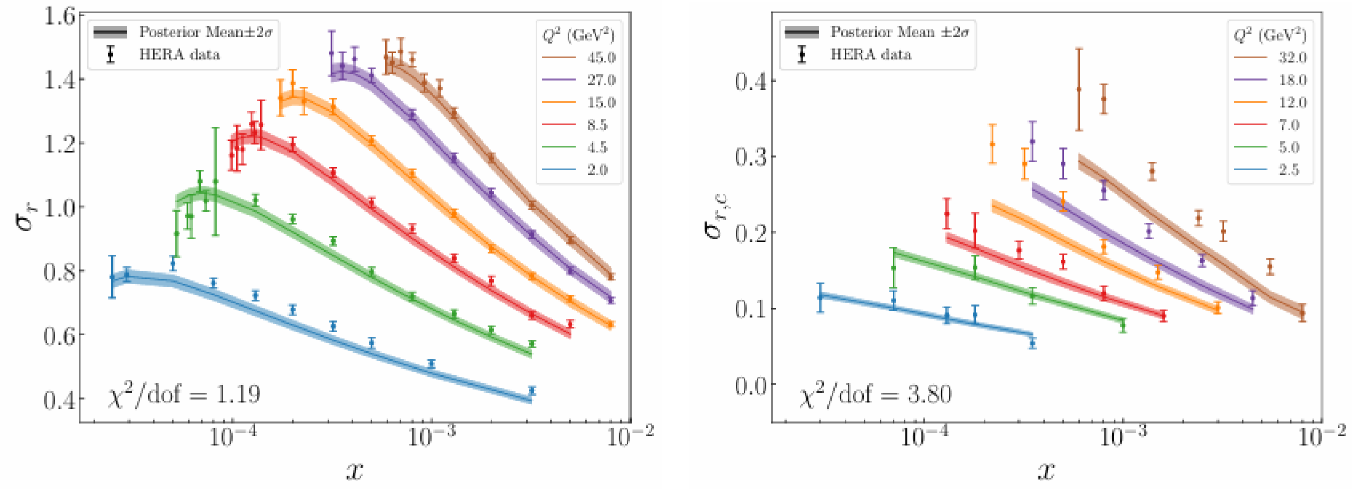

$$\sigma^{pp \to h+X} \propto S(x, k_T)$$

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

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

F. Dominguez, C. Marquet, B. W. Xiao and F. Yuan, Phys. Rev. D 83, 105005 (2011); Phys. Rev. Lett. 106, 022301 (2011).
G. A. Chirilli, B. W. Xiao and F. Yuan, Phys. Rev. D 86, 054005 (2012); Phys. Rev. Lett. 108, 122301 (2012).

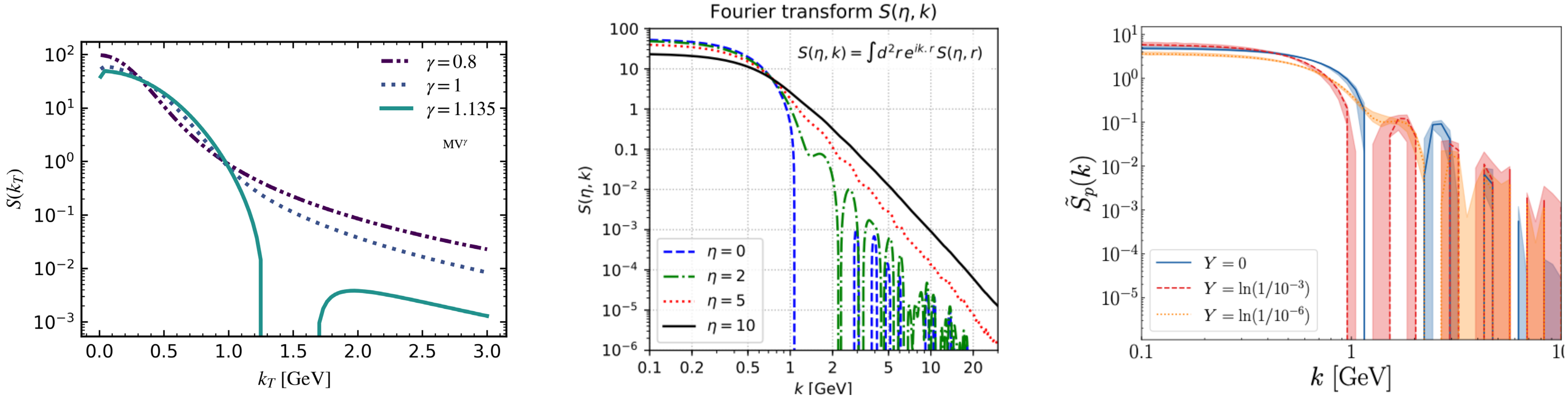
# Challenge 1: Tension between Total and Charm




[C. Casuga, H. Hanninen and H. Mantysaari, PRD 112 (2025), 034003]

- The extraction of the dipole amplitude typically relies on a parametrized ansatz for the initial condition (e.g. the GBW or MV model).
- It is challenging to simultaneously describe total reduced and charm cross sections.

# Challenge 2: Positivity in Momentum Space



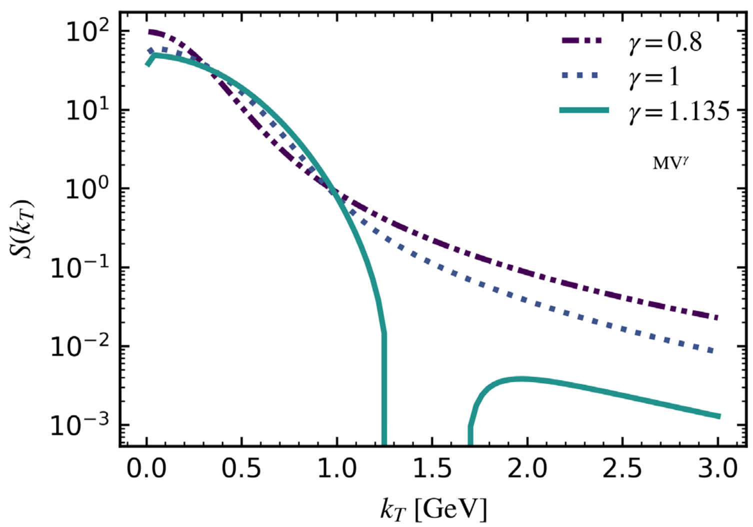

$$S(k_T, Y) = \int d^2\mathbf{r} e^{i\mathbf{k}_T \cdot \mathbf{r}} [1 - N(r, Y)]$$

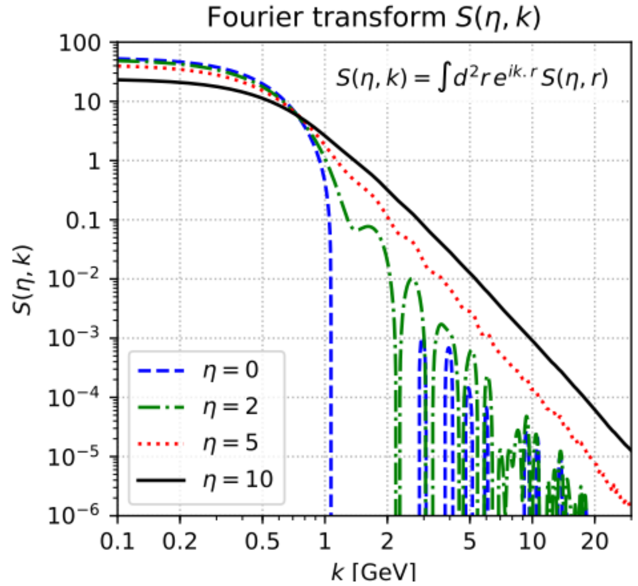
- Using MV-type parametrization, Positivity and smoothness in momentum space are not guaranteed.
- Our goal:

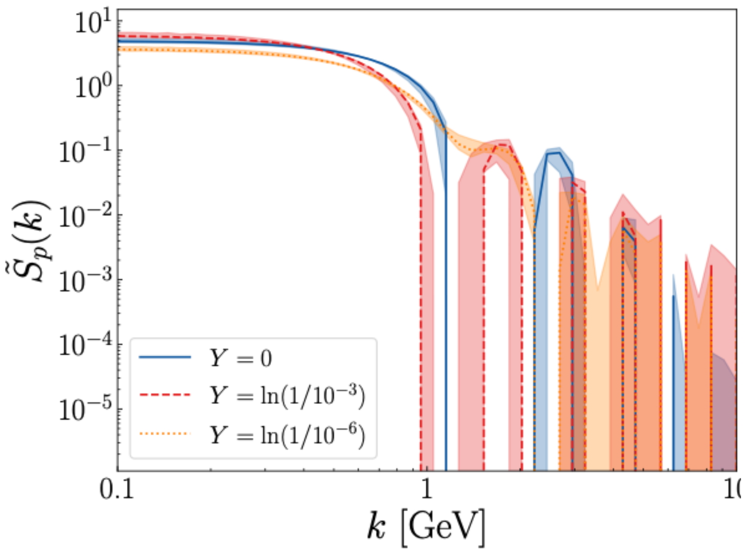
1. Minimize parametrization bias
2. Simultaneously describe total reduced and charm cross sections
3. Maintain a smooth, non-negative $S(k_T, Y)$


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

# Challenge 2: Positivity in Momentum Space




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

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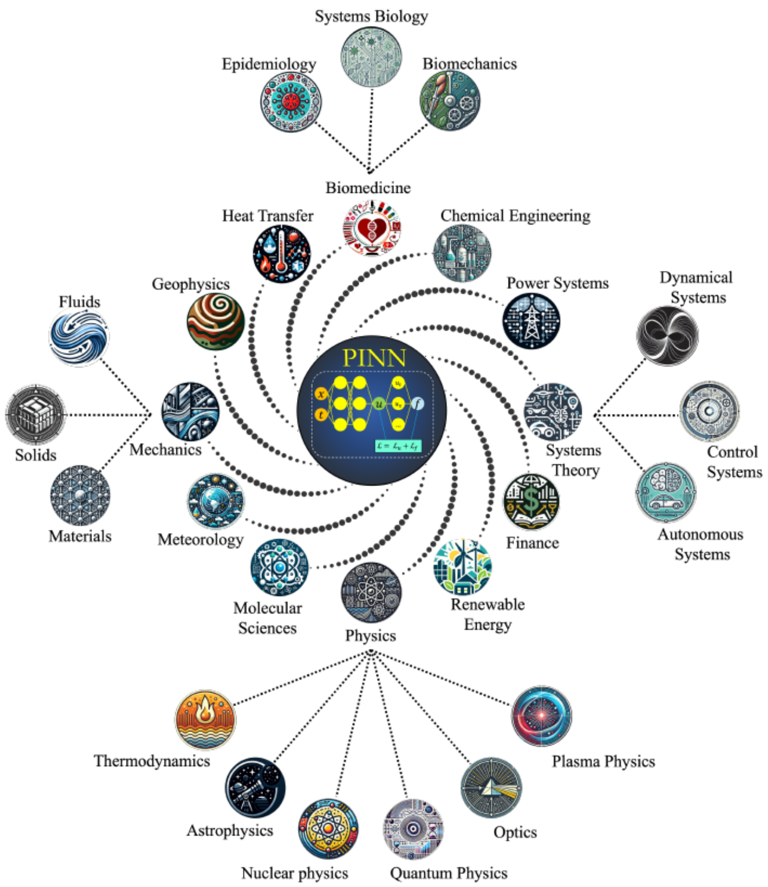
Physics-Informed Neural Networks !

# Physics-Informed Neural Networks (PINNs)




[J. D. Toscano, arXiv:2410.13228v2]

- Unlike standard data-driven networks, PINNs explicitly embed physical laws (e.g., differential equations) directly into the loss functions.

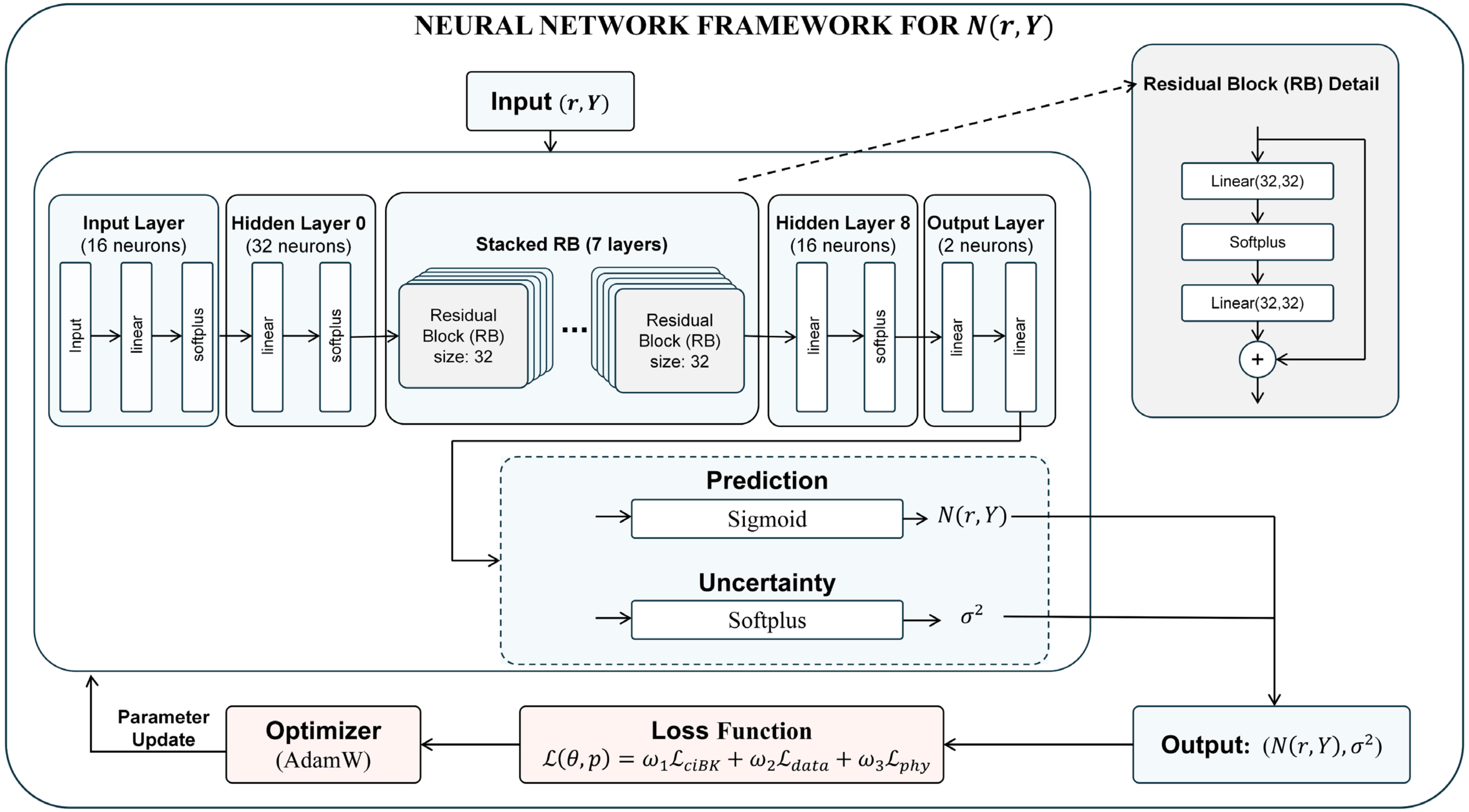
- The network is penalized not only for disagreeing with data, but also for violating the underlying dynamics. This reduces reliance on a purely data-driven fit.

- We enforce the ciBK equation as a physical constraint alongside the DIS data.

The ciBK equation: [Phys. Lett. B 803, 135305 (2020), JHEP 07, 196 (2021)]

$$\frac{\partial N(r,Y)}{\partial Y} = \frac{\bar{\alpha}_s(r^2)}{2\pi} \int d^2\mathbf{r}_1 \frac{r^2}{r_1^2 r_2^2} \left[\frac{r^2}{\min(r_1^2, r_2^2)}\right]^{\pm\bar{\alpha}_s A_1} \times \mathcal{K}_{\mathrm{DLA}}(\rho) \Big[N(r_1, Y-\delta_1) + N(r_2, Y-\delta_2) - N(r,Y) - N(r_1, Y-\delta_1) N(r_2, Y-\delta_2)\Big],$$

# The PINN framework



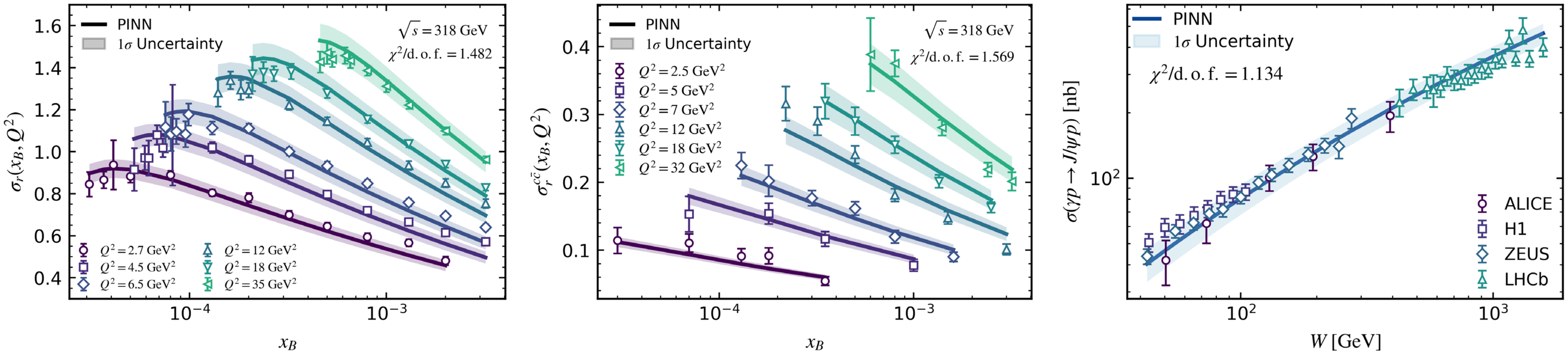

$$\mathcal{L}_{\text{ciBK}}(r,Y) = \frac{\partial \mathcal{N}_\theta(r,Y)}{\partial Y} - \int d^2\mathbf{r}_1\, K_{\text{ciBK}}(\mathbf{r},\mathbf{r}_1,\mathbf{r}_2)\,\mathcal{F}[\mathcal{N}_\theta]$$

$$\mathcal{L}_{\text{data}} = \sum_{\mathcal{O}} \sum_{i=1}^{N_{\mathcal{O}}} \lambda_{\mathcal{O}} \left[ \frac{(\mathcal{O}_i^{\text{th}} - \mathcal{O}_i^{\text{exp}})^2}{2((\sigma_i^{\text{NN}})^2 + (\sigma_i^{\text{exp}})^2)} + \frac{1}{2} \ln((\sigma_i^{\text{NN}})^2 + (\sigma_i^{\text{exp}})^2) \right]$$

$$\mathcal{L}_{\text{phy}} = \lambda_{\text{IR}} \| N(r_{\max}, Y) - 1 \|^2_{r_{\max} = 50\ \text{GeV}^{-1}} + \lambda_{\text{pos}} \| \min(0, S(k_T, Y)) \|^2 + \lambda_{\text{UV}} \left( \left\| \max\left(0, \frac{\partial \ln N(r,Y)}{\partial \ln r^2} - 1\right) \right\|^2 + \left\| \min\left(0, \frac{\partial \ln N(r,Y)}{\partial \ln r^2}\right) \right\|^2 \right)_{r < 10^{-3}\ \text{GeV}^{-1}}$$

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

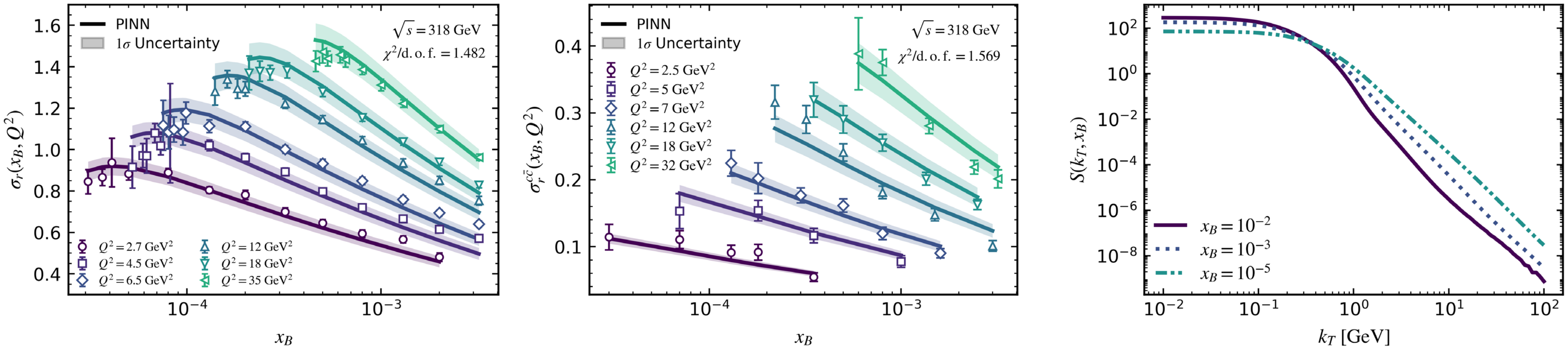
# Global Extraction of the Proton Dipole Amplitude




- The PINN extracts a universal amplitude constrained by the ciBK evolution.
- Simultaneously constrained by reduced total and charm quark DIS cross sections, exclusive J/ψ data.

SWD, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. B. Zhao, arXiv:2603.08008.
**The dipole amplitude is available: https://doi.org/10.5281/zenodo.18826120**

# Global Extraction of the Proton 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.
- The extracted momentum-space S-matrix remains smooth and non-negative over the range shown.

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

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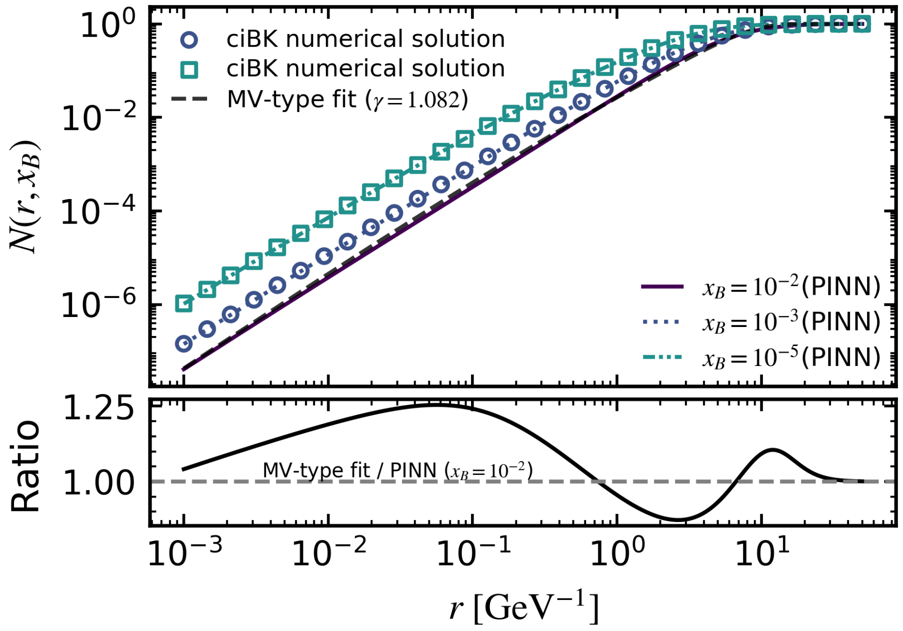
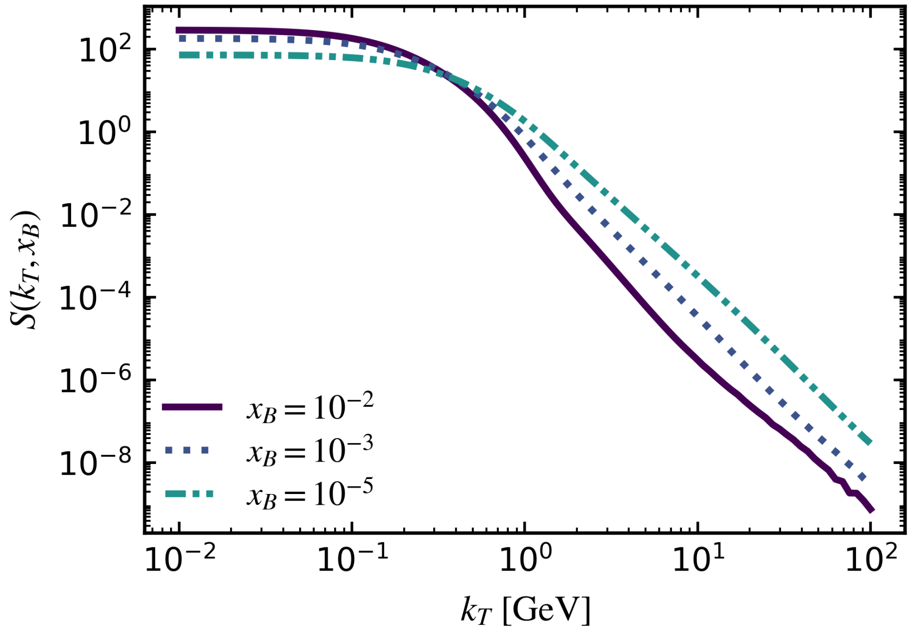
# Dipole amplitude of proton



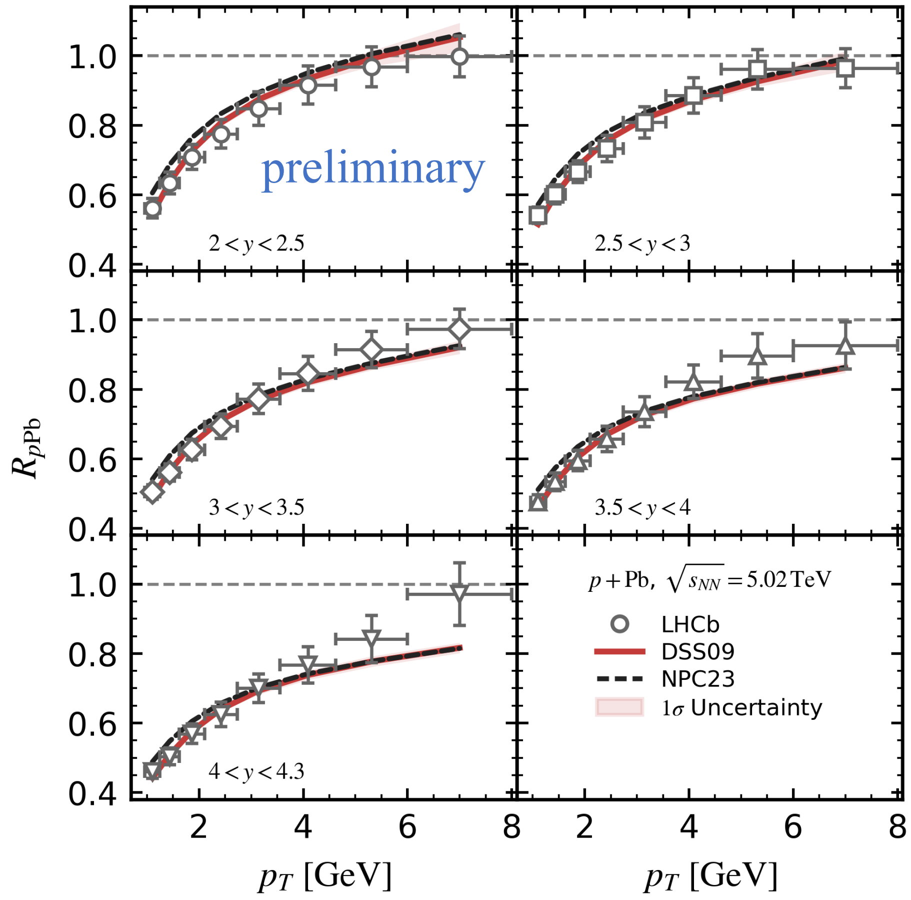



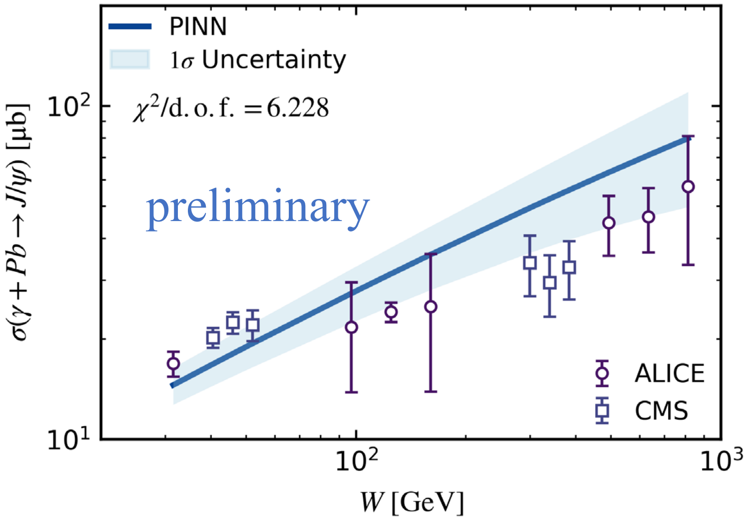

- The extracted initial dipole amplitude cannot be faithfully described by an MV-type function.
- The momentum-space dipole amplitude is smooth and non-negative over the range shown.

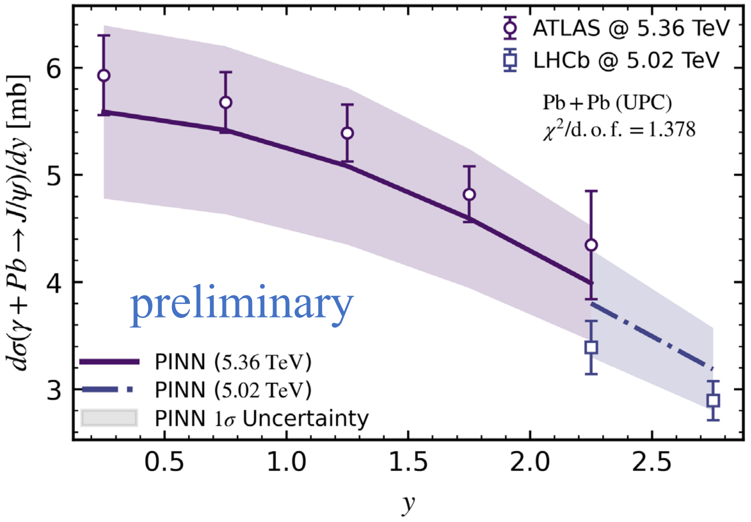
SWD, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. B. Zhao, arXiv:2603.08008.

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

# Toward a Global Extraction of the Nuclear Dipole Amplitude



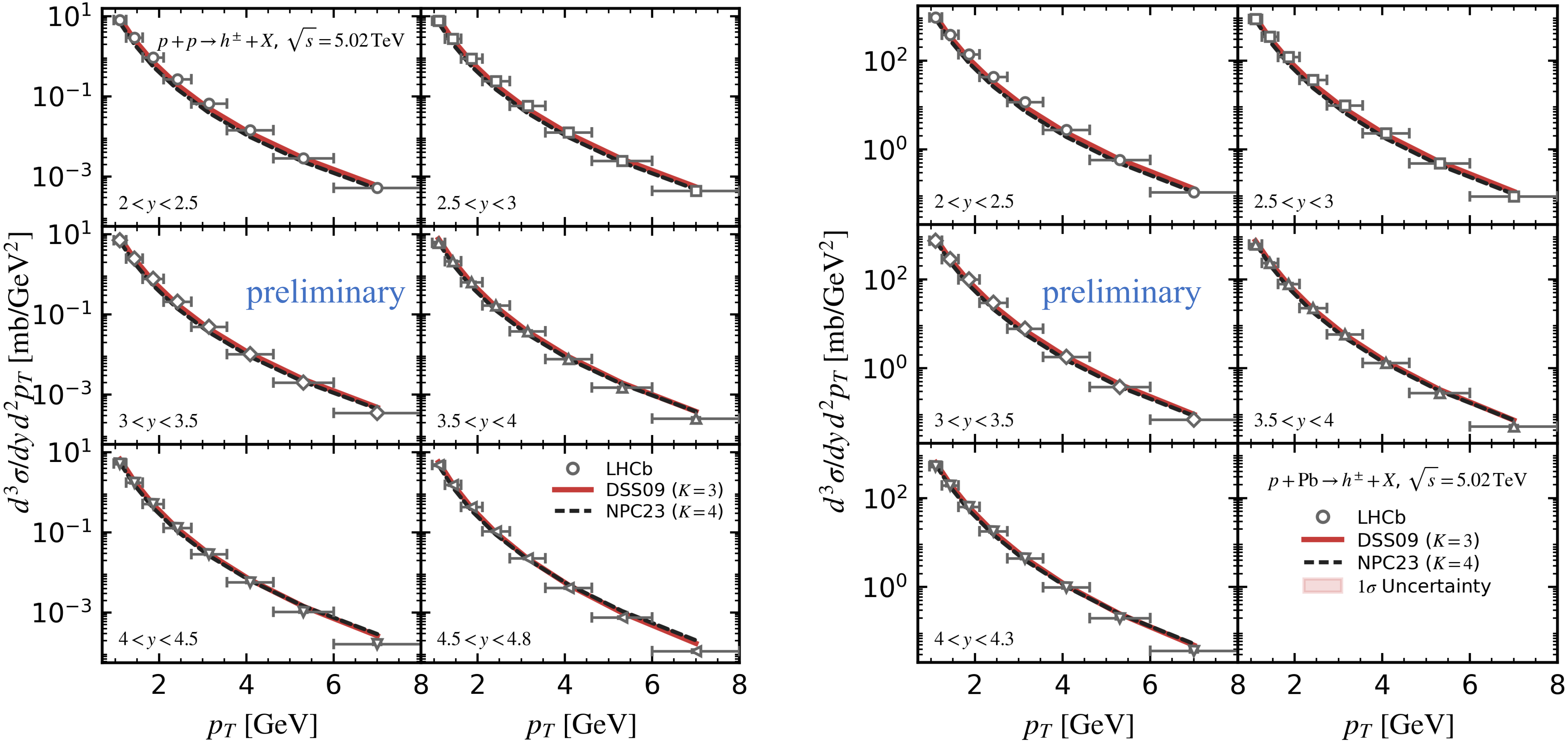




- $R_{pPb}$ greatly suppresses the uncertainty from the FF and PDF.
- Some tension remains between the $R_{pPb}$ and J/ψ constraints.

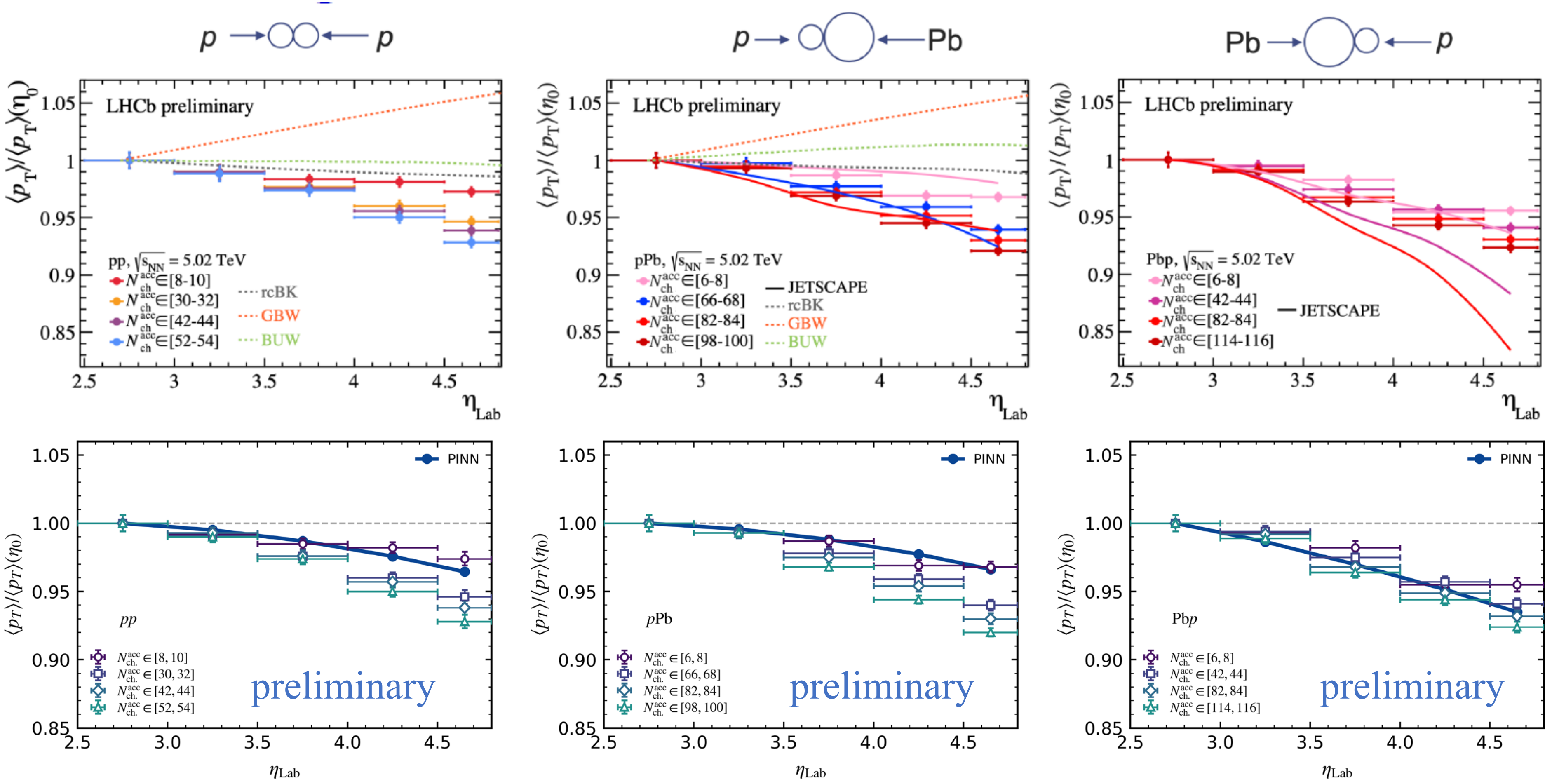
SWD, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. B. Zhao, arXiv:2603.08008 and in progress.

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

# $p_T$ spectra in pp and pPb collisions

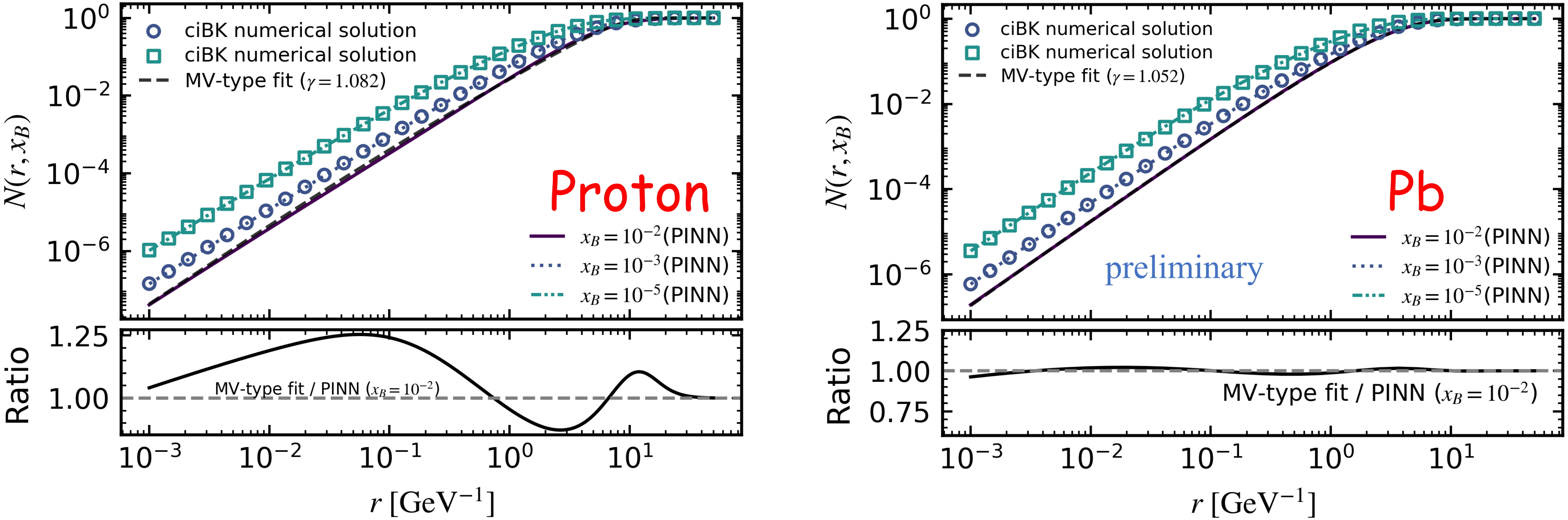


# Mean-$p_T$ ratio vs. η




- Our CGC calculation of Mean $p_T$ ratio v.s. η is consistent with the LHCb measurements at low $N_{ch}$.
- In pPb, the high $N_{ch}$ data may require additional final-state dynamics, whereas the low $N_{ch}$ data are consistent with initial-state CGC dominance.

# 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 saturation scale ratio of $\frac{Q^2_{s0,Pb}}{Q^2_{s0,p}}\sim\mathbf{3.17}$.

SWD, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. B. Zhao, arXiv:2603.08008.
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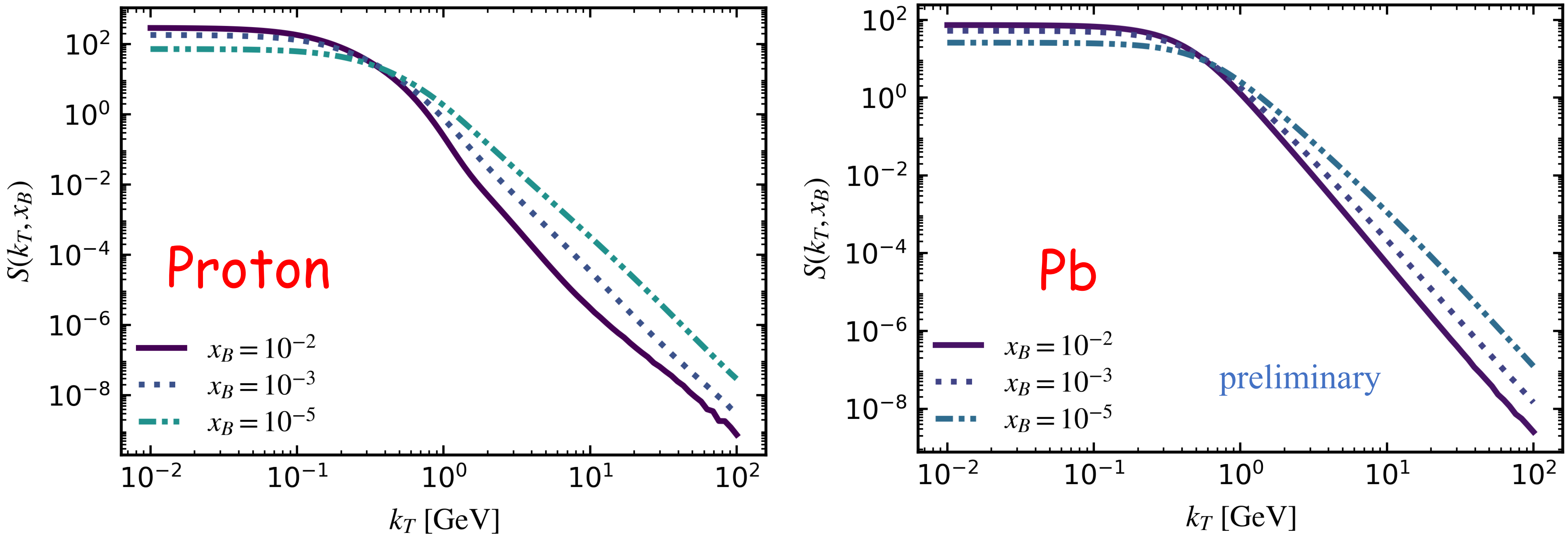
# Dipole Amplitude of Pb




- 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 **saturation scale** ratio of $\frac{Q^2_{s0,Pb}}{Q^2_{s0,p}}$ ~**3.17**.
- The extracted Pb momentum-space S-matrix remains non-negative over the range shown.

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

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

# Summary

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- We have performed a global, dynamics-constrained determination of the universal small-$x$ dipole amplitude using a physics-informed neural network.
- Within the fitted kinematic region, the resulting amplitude simultaneously describes the reduced total, charm cross section, and exclusive vector-meson production.
- With Fourier-positivity regularization imposed on the momentum-space $S$-matrix, the momentum-space dipole amplitude is smooth and non-negative over the range shown.
- Separately, the same PINN strategy can be applied to pA data to extract nuclear dipole amplitudes.
- we obtain a saturation scale ratio of $\frac{Q^2_{s0,Pb}}{Q^2_{s0,p}} \sim \mathbf{3.17}$
- tabulated PINN solution: https://doi.org/10.5281/zenodo.18826120

# Back Up

| References | $\chi^2$/d.o.f. ($\sigma_r^{\text{total}}$) | $\chi^2$/d.o.f. ($\sigma_r^{c\bar{c}}$) | $\chi^2$/d.o.f. ($J/\psi$) | $S(k_T) > 0$? | Universal $N$? |
|---|---|---|---|---|---|
| Albacete *et al.* [Albacete:2010sy] (LO BK + LO Impact Factor) | $\sim 1.1$ | $\sim 1.3$ | N/A | No | No |
| B. Ducloué *et al.* [Ducloue:2019jmy] (ciBK + LO Impact Factor) | $\sim 1.0$ | N/A | N/A | No | No |
| Casuga *et al.* [Casuga:2025etc] (KCBK + NLO Impact Factor, Bayesian) | $\sim 1.2$ | $\sim 2.7$ | N/A | No | Yes |
| Casuga *et al.* [Casuga:2026xxt] (NLO+NLL BK + NLO Impact Factor, Bayesian) | $\sim 1.2$ | $\sim 2.4$ | 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** |

# Corrections for Electromagnetic Ion Dissociation (EMD) in UPC

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

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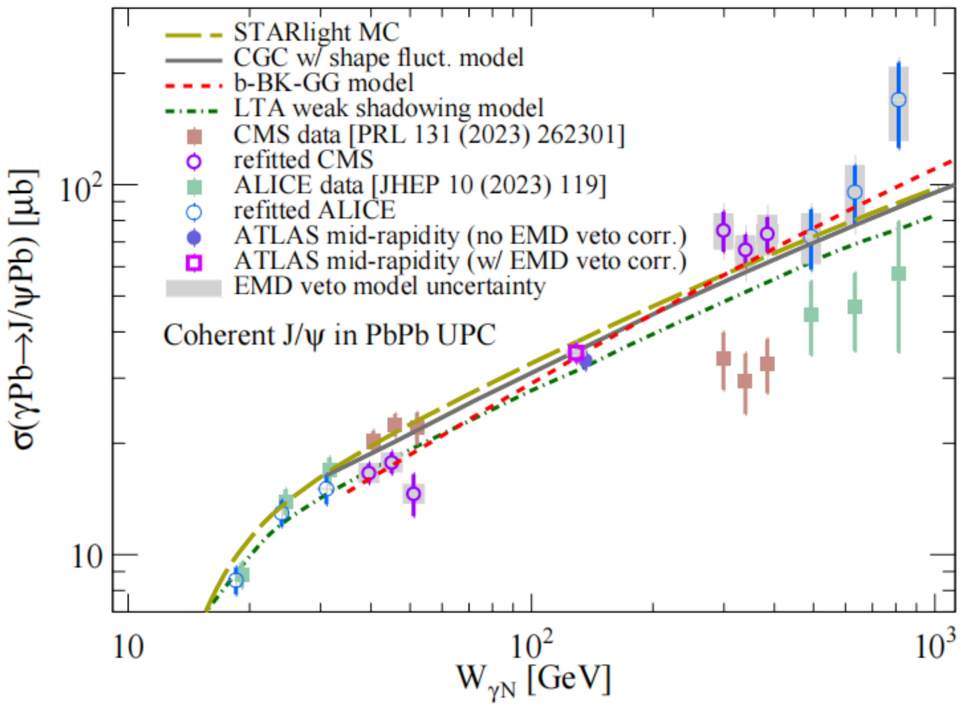
[M. Dyndal and L. A. Harland-Lang, [arXiv:2604.19879]].




- 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.