Partonic structure of nuclear medium

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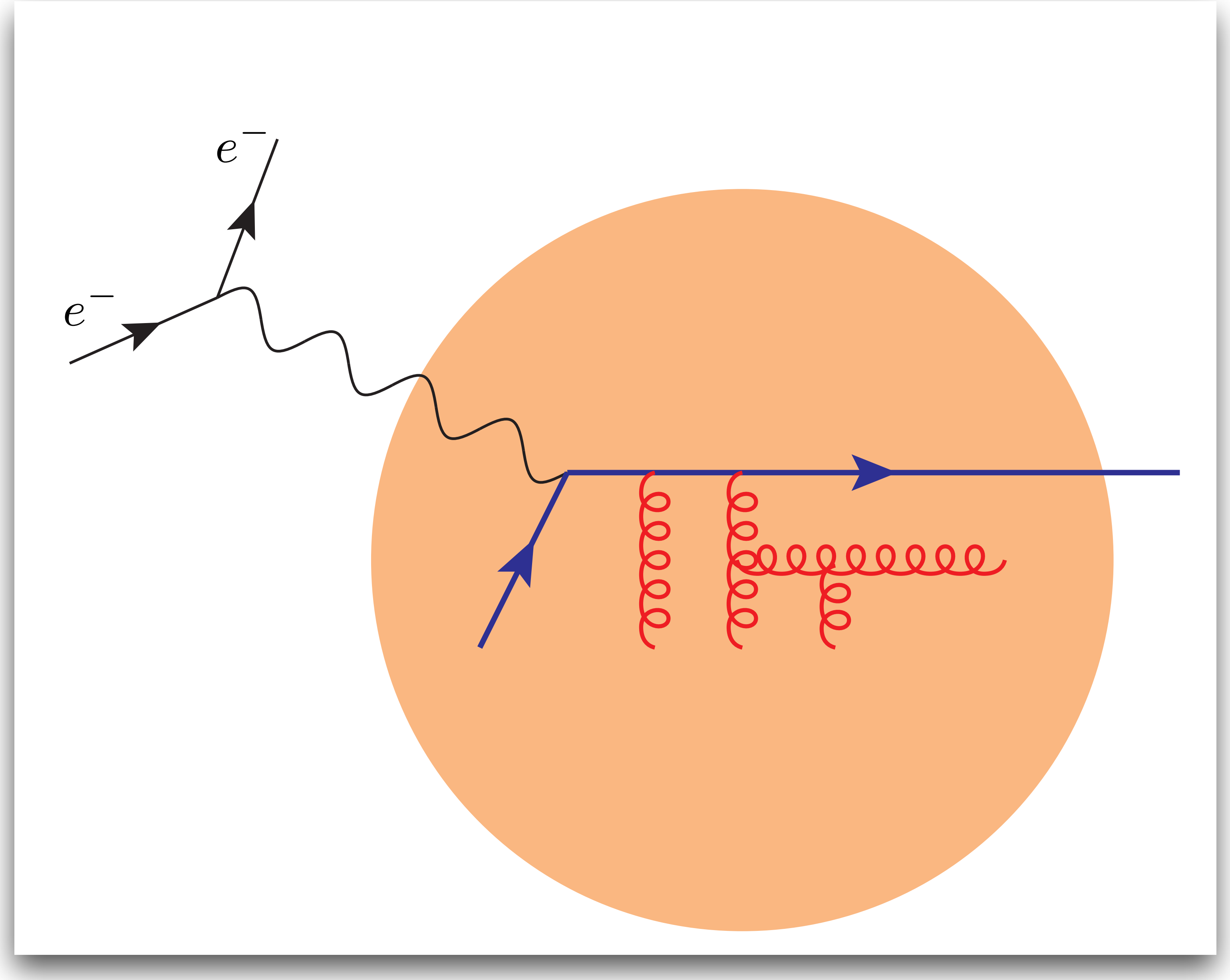
极端条件下的QCD研讨会
烟台, 2026.8.19-20

What is nuclear partonic structure?

Nuclear partonic structure

Nuclear PDFs, Cronin effect, SRC, Neutron skin…



Multiple scattering in medium

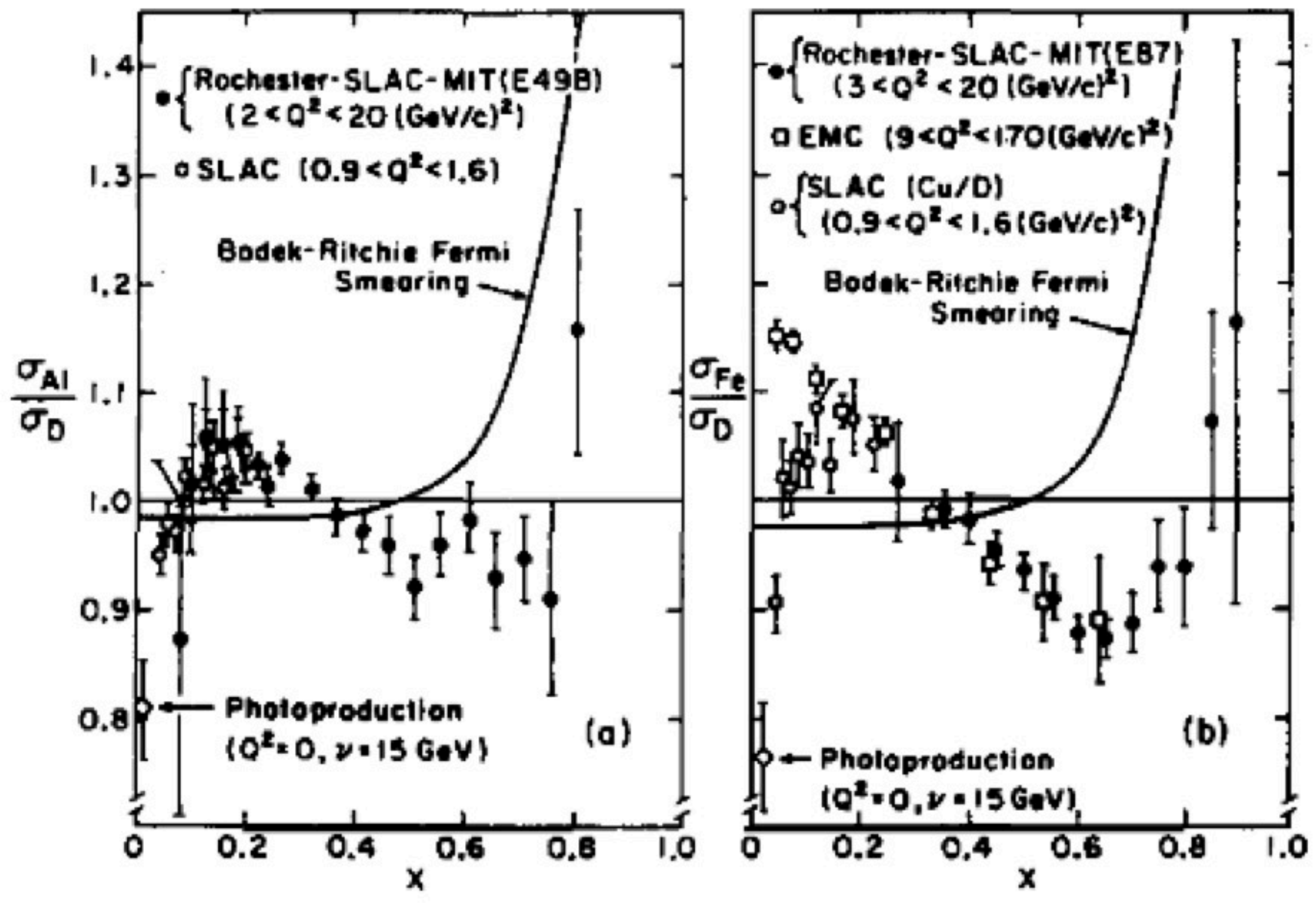
Multiparton quantum correlation, parton energy loss, …

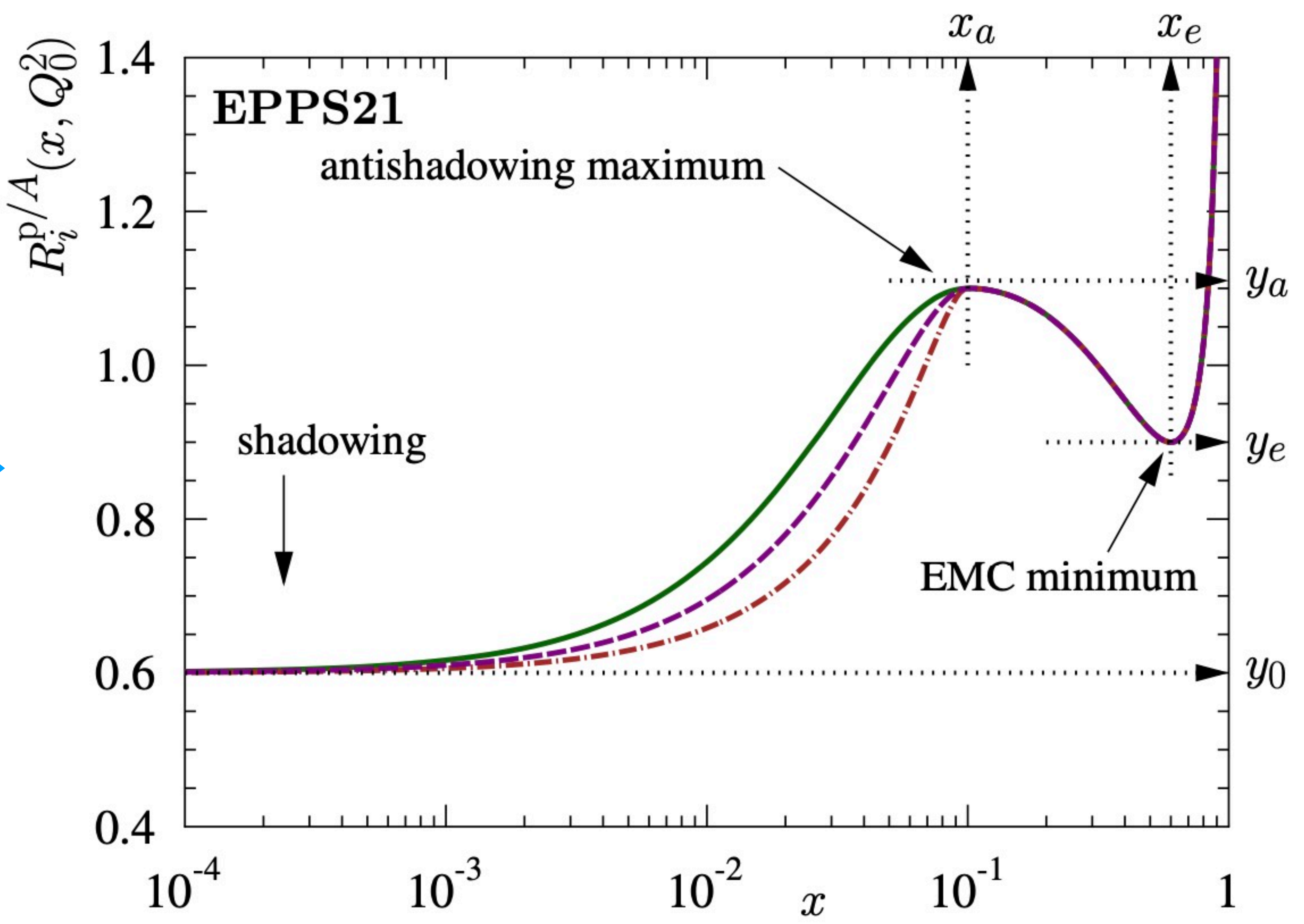
- NPDFs can be accessed in pA and eA collisions, key input for event generators (PYTHIA, HIJING…)
- Nuclear structure is a critical intersection point between low-energy and high energy nuclear physics

Long standing problems of nuclear partonic structure

✦ One-dimensional nuclear partonic structure

Four Decades of the EMC Effect





Abstract

Using the data on deep inelastic muon scattering on iron and deuterium the ratio of the nucleon structure functions $F_2^N(Fe)/F_2^N(D)$ is presented. The observed x-dependence of this ratio is in disagreement with existing theoretical predictions.

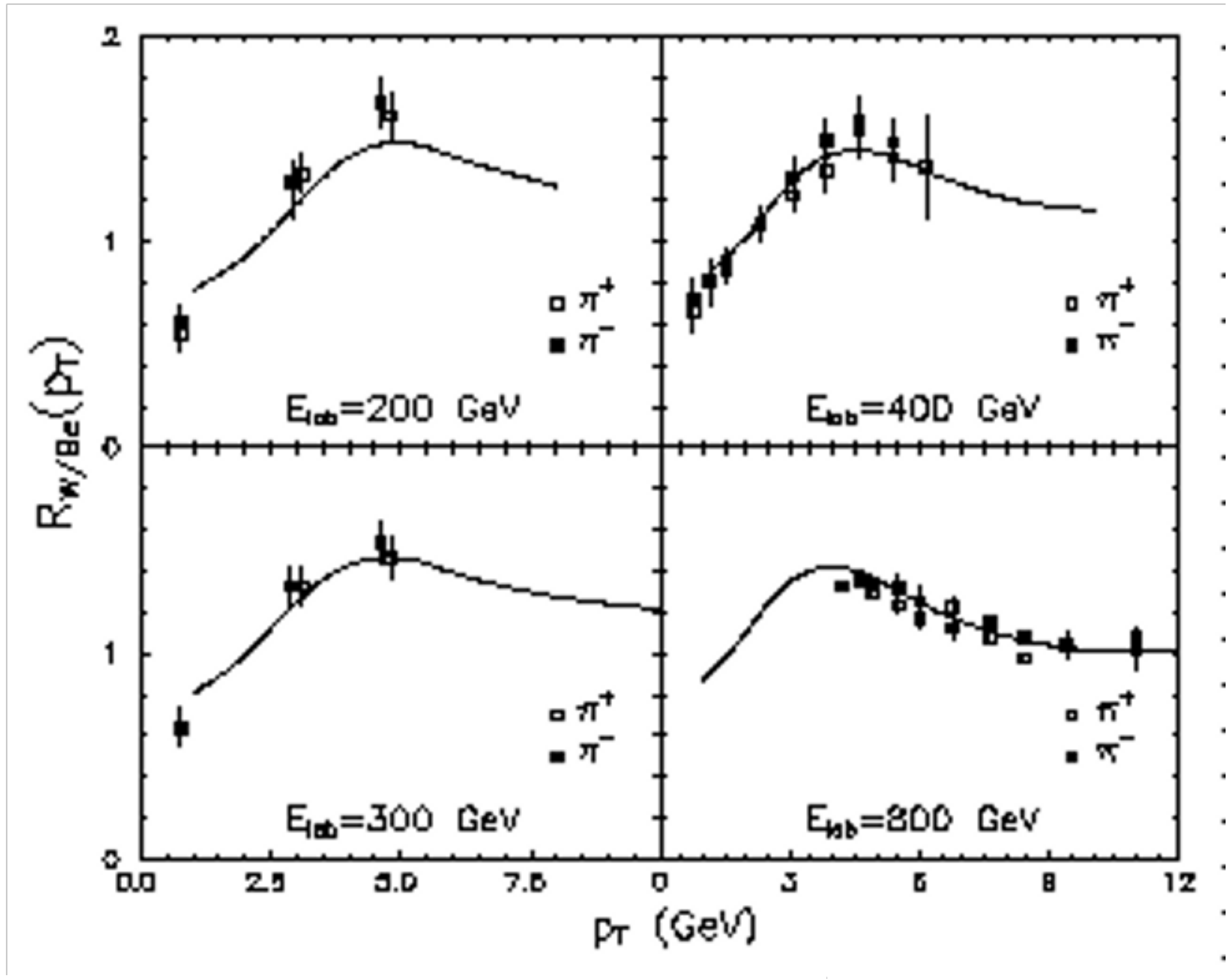
$$R_i^A = \frac{f_{i/A}(x, Q^2)}{f_{i/p}(x, Q^2)}$$

For recent review: Ann. Rev. Nucl. Part. Sci. 2024. 74:1–41

Long standing problems of nuclear partonic structure

✦ Three-dimensional nuclear partonic structure

Cronin effect

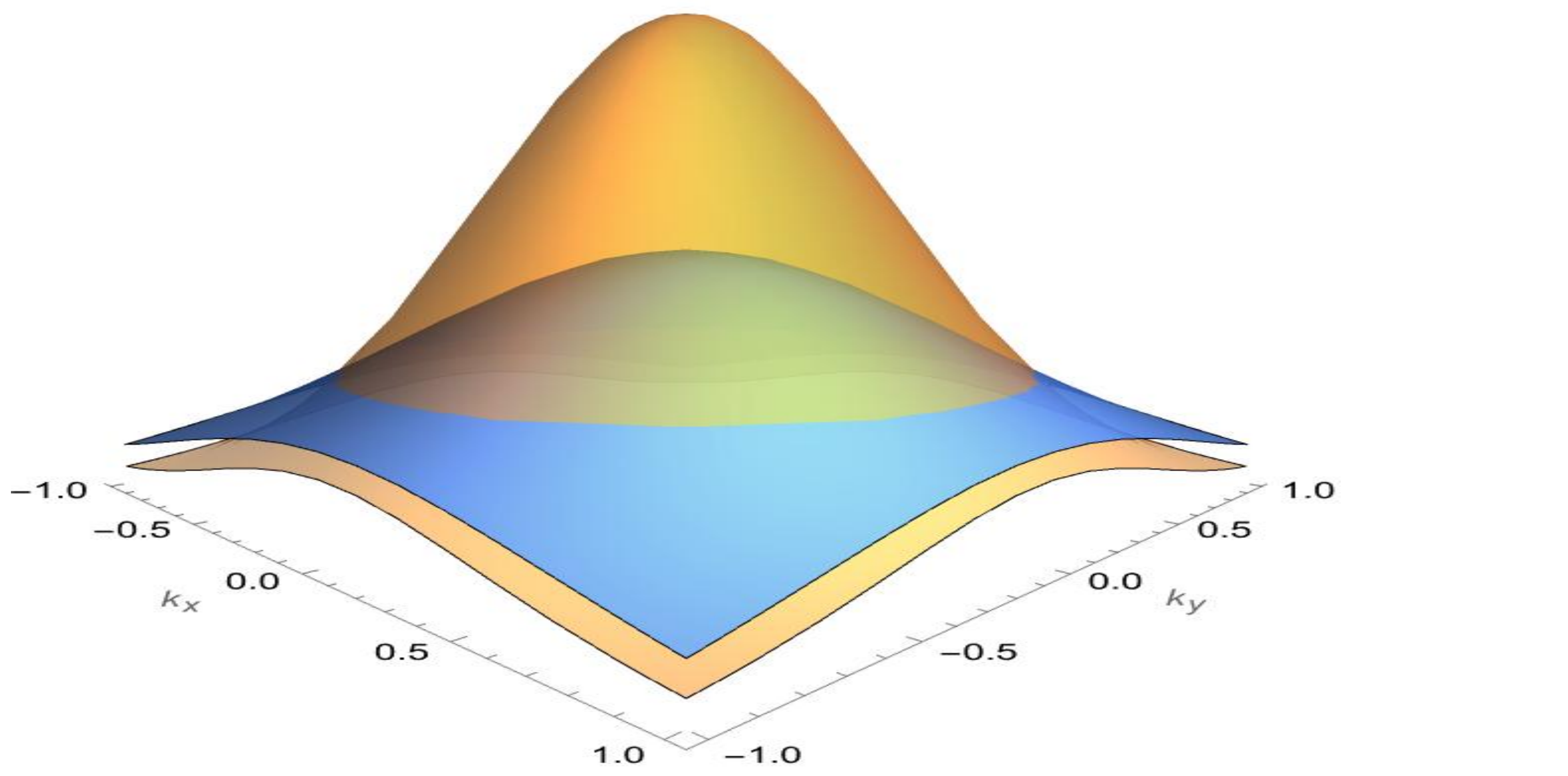


$$p + A \to \mathrm{hadron(p)} + X$$

$$R(p_T) = \frac{B}{A}\frac{d\sigma_{pA}/d^2p_T}{d\sigma_{pB}/d^2p_T}$$

E100 Collaboration, PRD 11, 3105（1975）

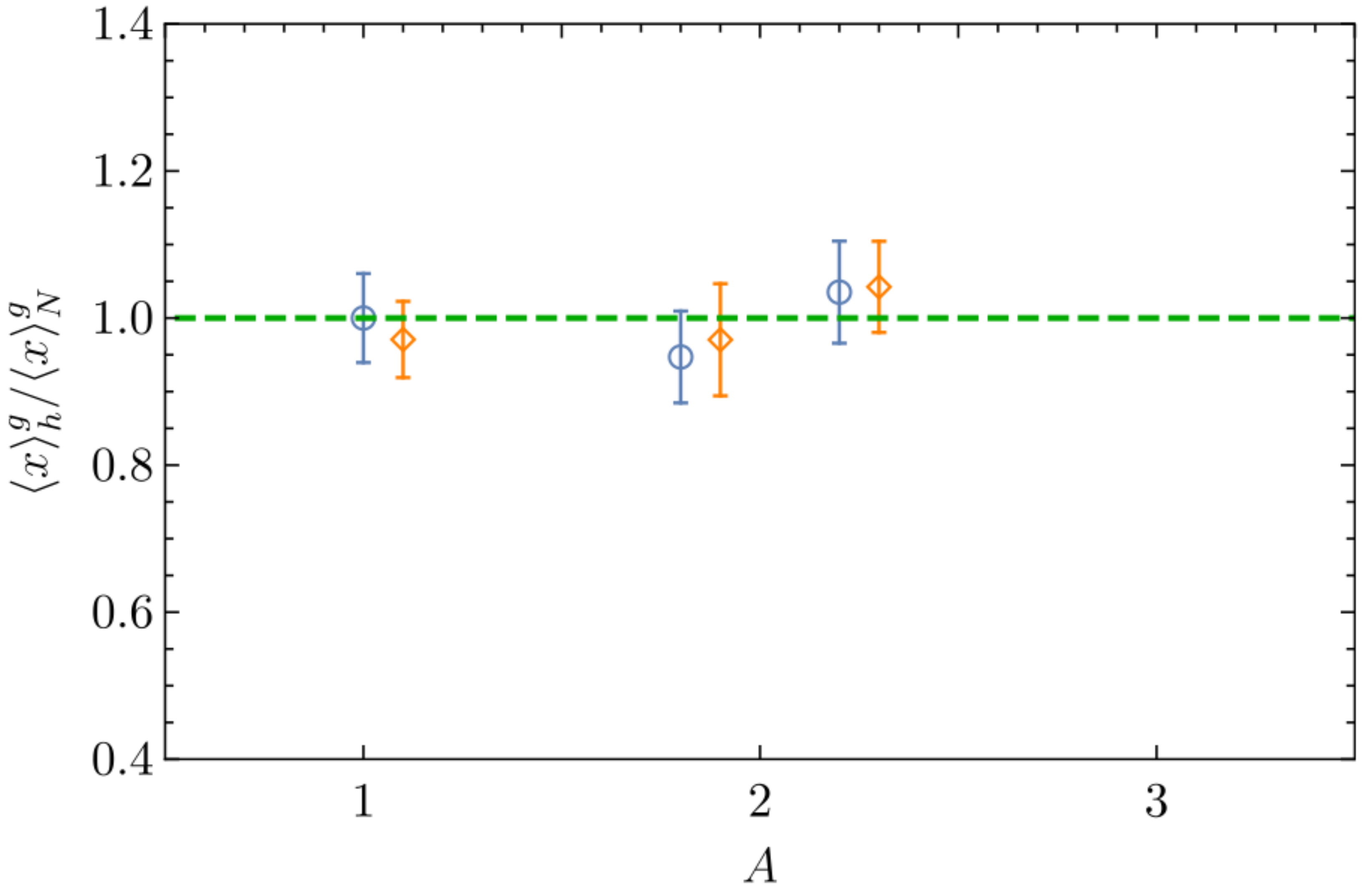
- Naive Gaussian model



$$F_{i/p}(x, k_T) = f_{i/p}(x)\frac{e^{-k_T^2/\langle k_T^2\rangle}}{\pi\langle k_T^2\rangle}, \qquad \langle k_T^2\rangle_A \to \langle k_T^2\rangle_p + \left\langle \frac{2\mu^2 L}{\lambda}\right\rangle \xi^2$$

Efforts from lattice QCD

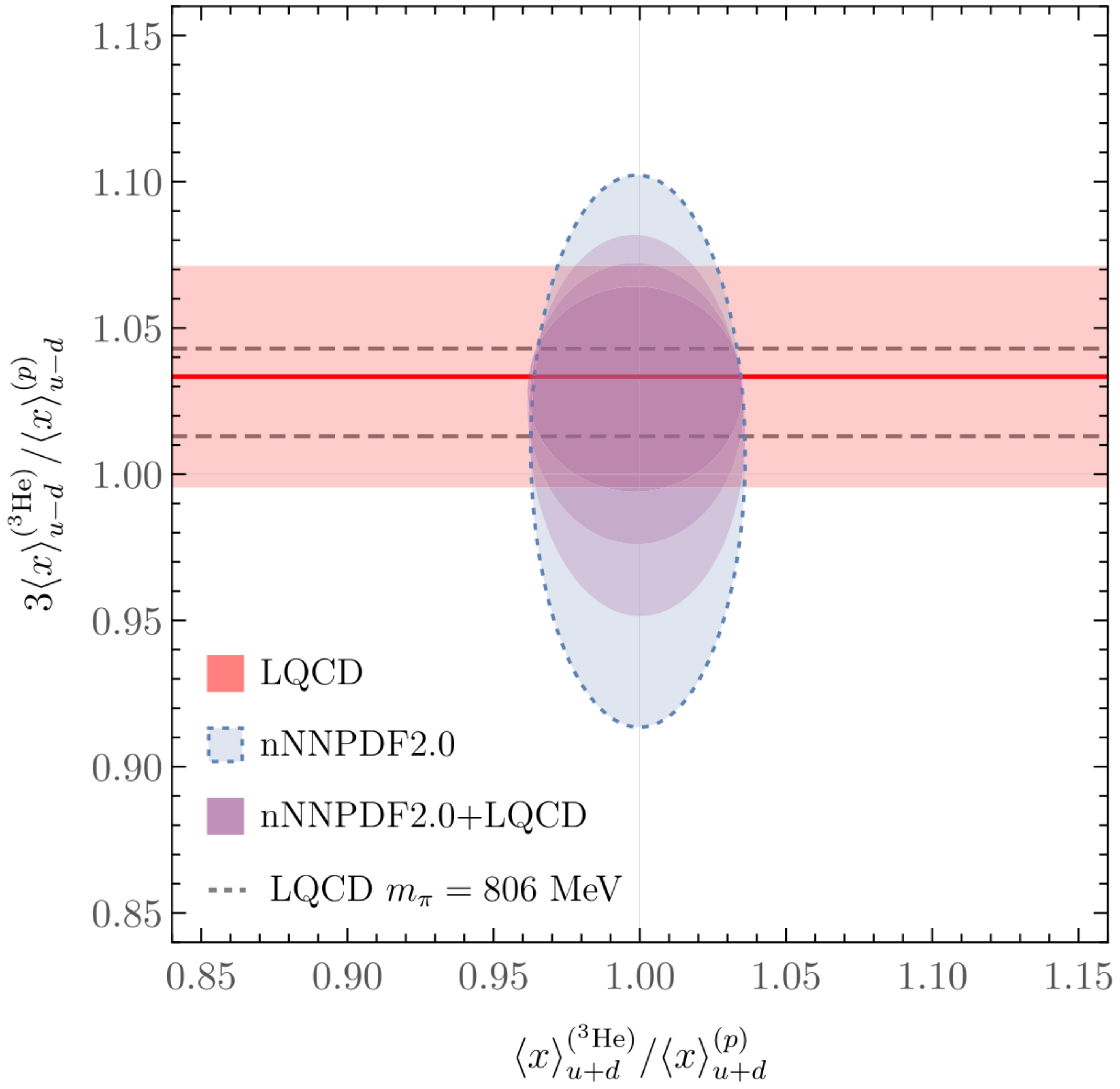
✦ **Limited to light nuclei $A \leq 3$ and unphysical pion masses**



Less than 10% gluon EMC effect

NPL QCD Collaboration

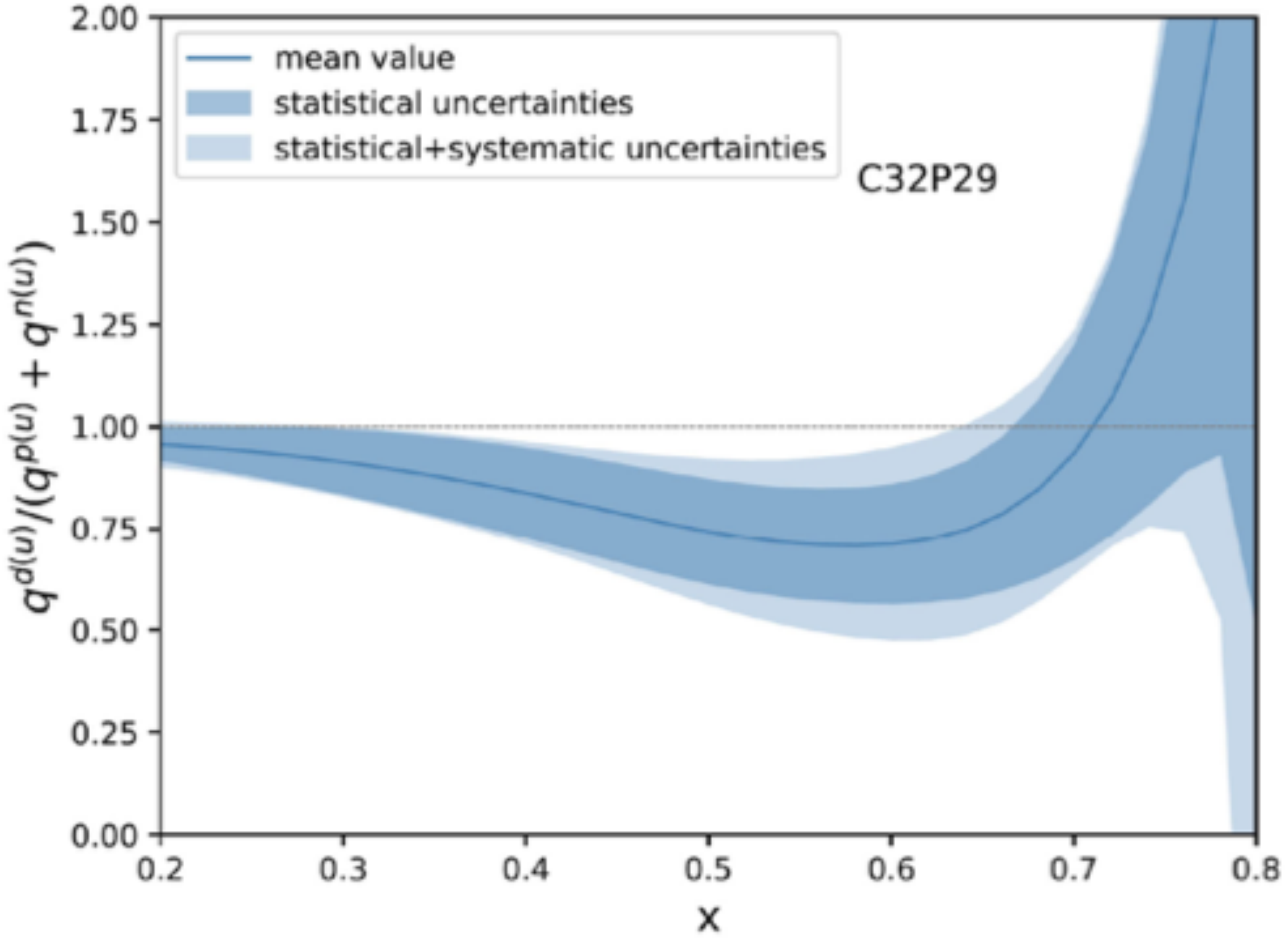
PRD 96, 094512（2017）



No significant EMC effect for u-d

NPL QCD Collaboration

PRL 126, 202001（2021）



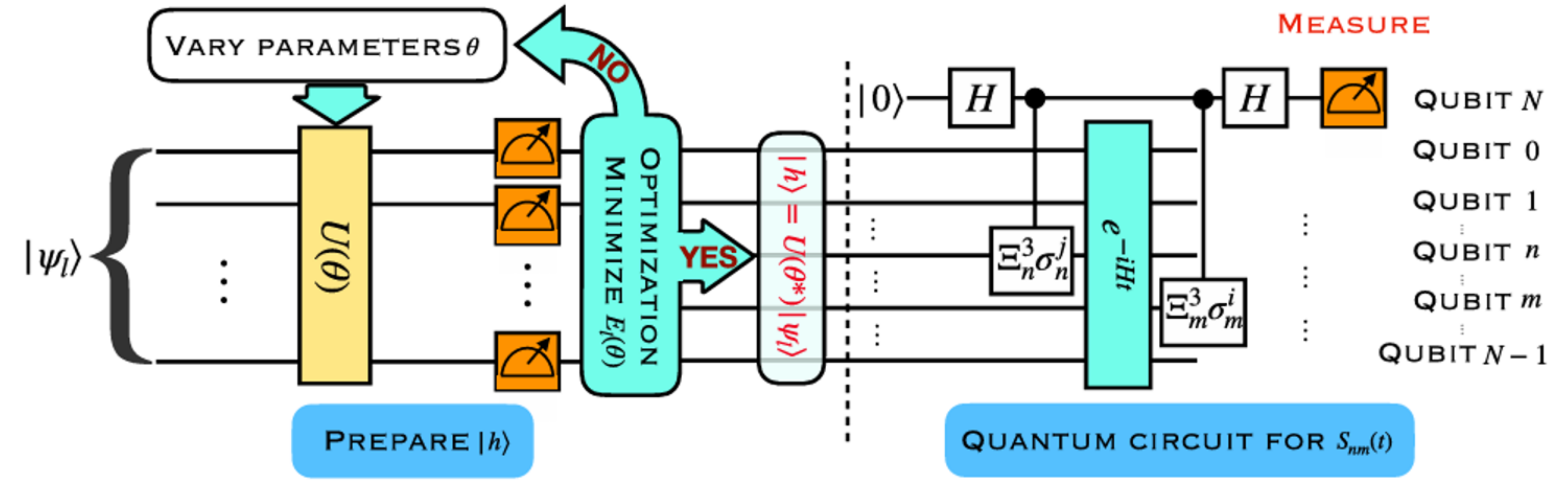
No definitive conclusion

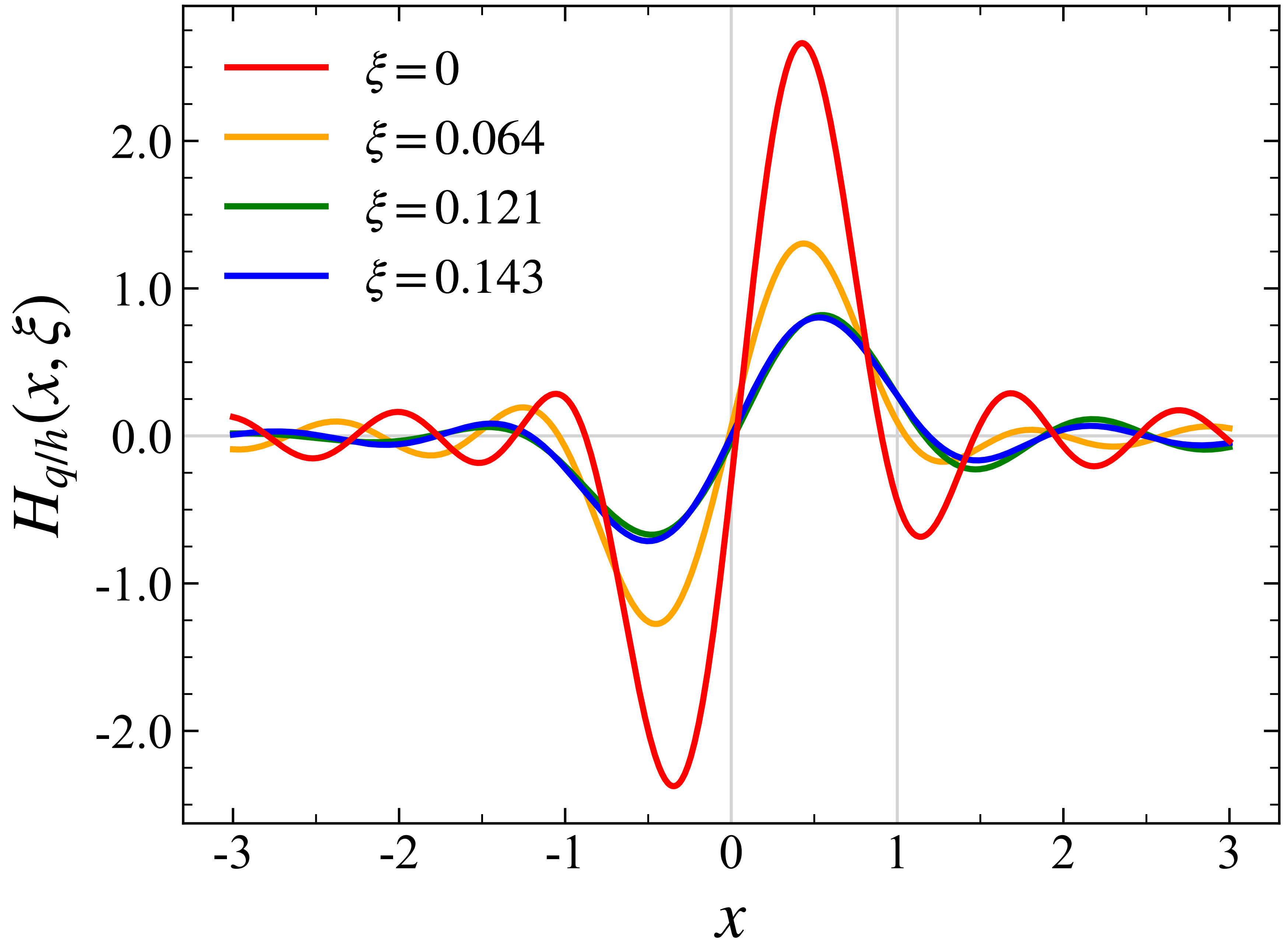
CLQCD Collaboration

PRD 111, 074506（2025）

Promising future from quantum computing?

✦ Progress on hadron PDFs (QuNu)





$$f_{q/h}(x) = \int_{-\infty}^{\infty} \frac{dy^-}{2\pi} e^{ixp^+y^-} \langle h | \bar{\psi}(0) \frac{\gamma^+}{2} \mathscr{W}(0,y^-) \psi(y^-) | h \rangle$$

$$f_{q/A}(x) = \int_{-\infty}^{\infty} \frac{dy^-}{2\pi} e^{ixp^+y^-} \langle A | \bar{\psi}(0) \frac{\gamma^+}{2} \mathscr{W}(0,y^-) \psi(y^-) | A \rangle$$

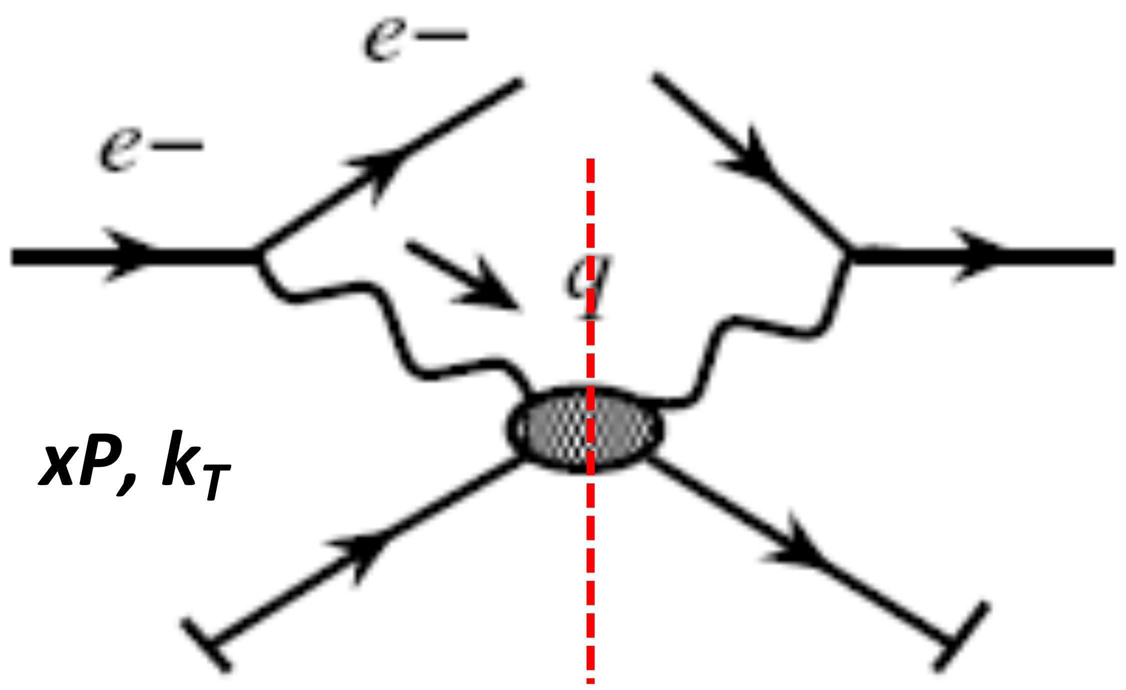
- PDF in NJL: PRD (letter, 2022)
- LCDA in NJL: SCPMA (2023)
- Scattering amplitude: PRD (2023)
- GPD in Schwinger: 2606.22602
- DIS in SU(2): 2606.17003
- Review in SCPMA (2025)

How to reliably probe the nuclear partonic structure?

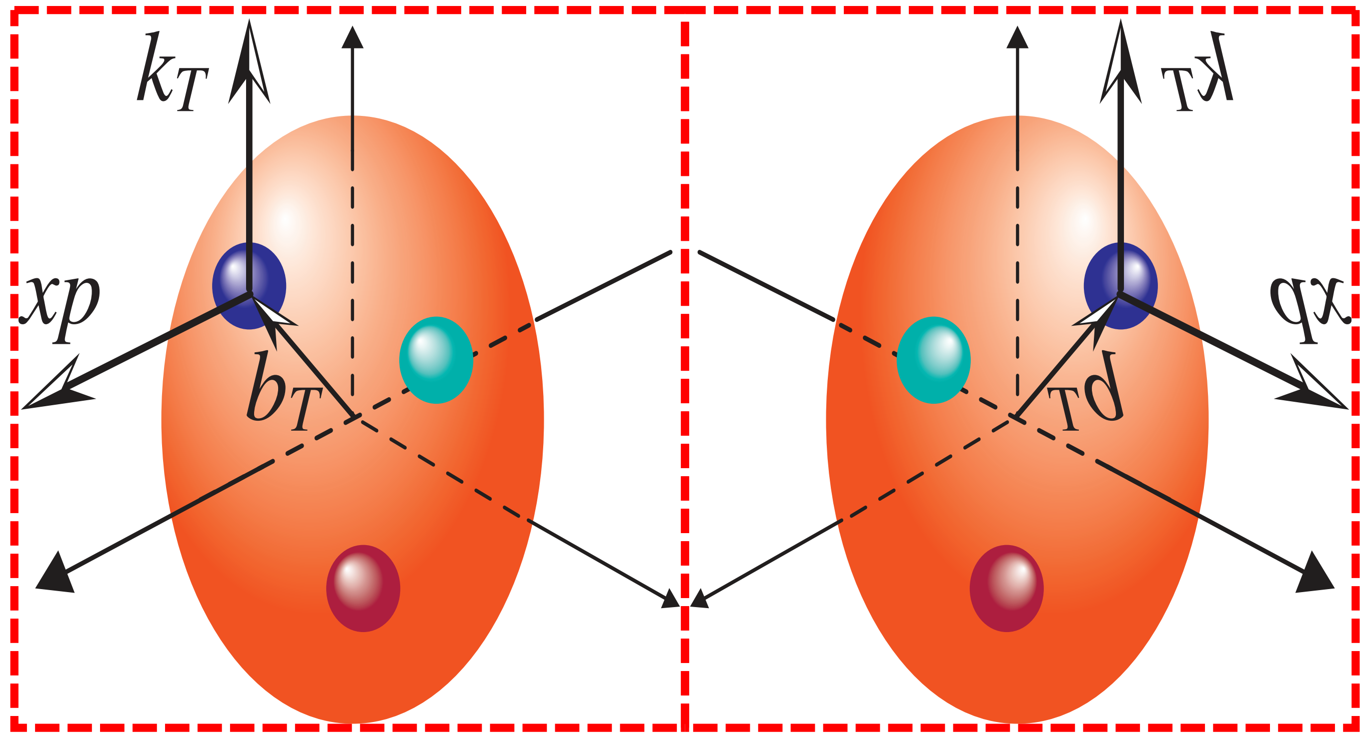
✦ **Indispensable joint efforts from experiments and QCD theory**

QCD factorization theorem

$$\sigma^{\mathrm{DIS}}_{\mathrm{tot}} \sim$$



$\otimes$



Experimental measurements

Hard part controlled by pQCD theory

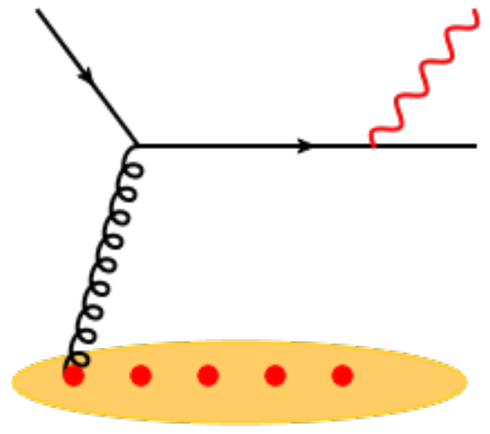
Nucleon partonic structure

How to reliably probe the nuclear partonic structure?

✦ Generalized QCD factorization - twist expansion

perturbative expansion

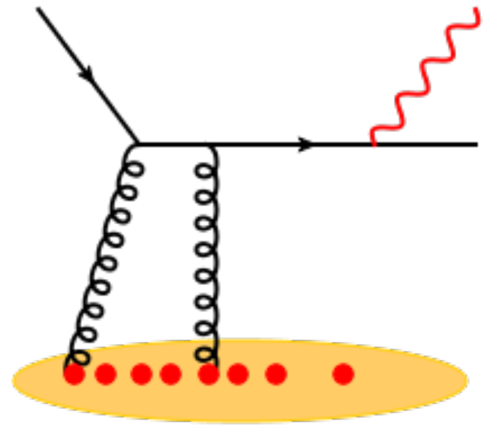
$$\sigma^h_{phys} = \left[\alpha_s^0 C_2^{(0)} + \alpha_s^1 C_2^{(1)} + \alpha_s^2 C_2^{(2)} + \ldots\right] \otimes T_2(x)$$



Multiple scattering expansion

$$+ \frac{1}{Q}\left[\alpha_s^0 C_3^{(0)} + \alpha_s^1 C_3^{(1)} + \alpha_s^2 C_3^{(2)} + \ldots\right] \otimes T_3(x)$$

$$+ \frac{1}{Q^2}\left[\alpha_s^0 C_4^{(0)} + \alpha_s^1 C_4^{(1)} + \alpha_s^2 C_4^{(2)} + \ldots\right] \otimes T_4(x)$$



$$+ \ldots$$

✦ The power suppressed high twist correction is enhanced by nuclear size

$$\frac{1}{Q^2} \rightarrow \frac{A^{1/3}}{Q^2}$$

J. Qiu, G. Sterman, NPB 1990

J. Qiu, X. Luo, PRD 1998

How to reliably probe the nuclear partonic structure?

✦ **Generalized QCD factorization - twist expansion**

$$\boxed{\sigma^h_{phys} = \left[\alpha_s^0 C_2^{(0)} + \alpha_s^1 C_2^{(1)} + \alpha_s^2 C_2^{(2)} + \ldots\right] \otimes T_2(x)}$$

$$\cancel{+ \frac{1}{Q}\left[\alpha_s^0 C_3^{(0)} + \alpha_s^1 C_3^{(1)} + \alpha_s^2 C_3^{(2)} + \ldots\right] \otimes T_3(x)}$$

$$\cancel{+ \frac{1}{Q^2}\left[\alpha_s^0 C_4^{(0)} + \alpha_s^1 C_4^{(1)} + \alpha_s^2 C_4^{(2)} + \ldots\right] \otimes T_4(x)}$$

$$\cancel{+ \ldots}$$

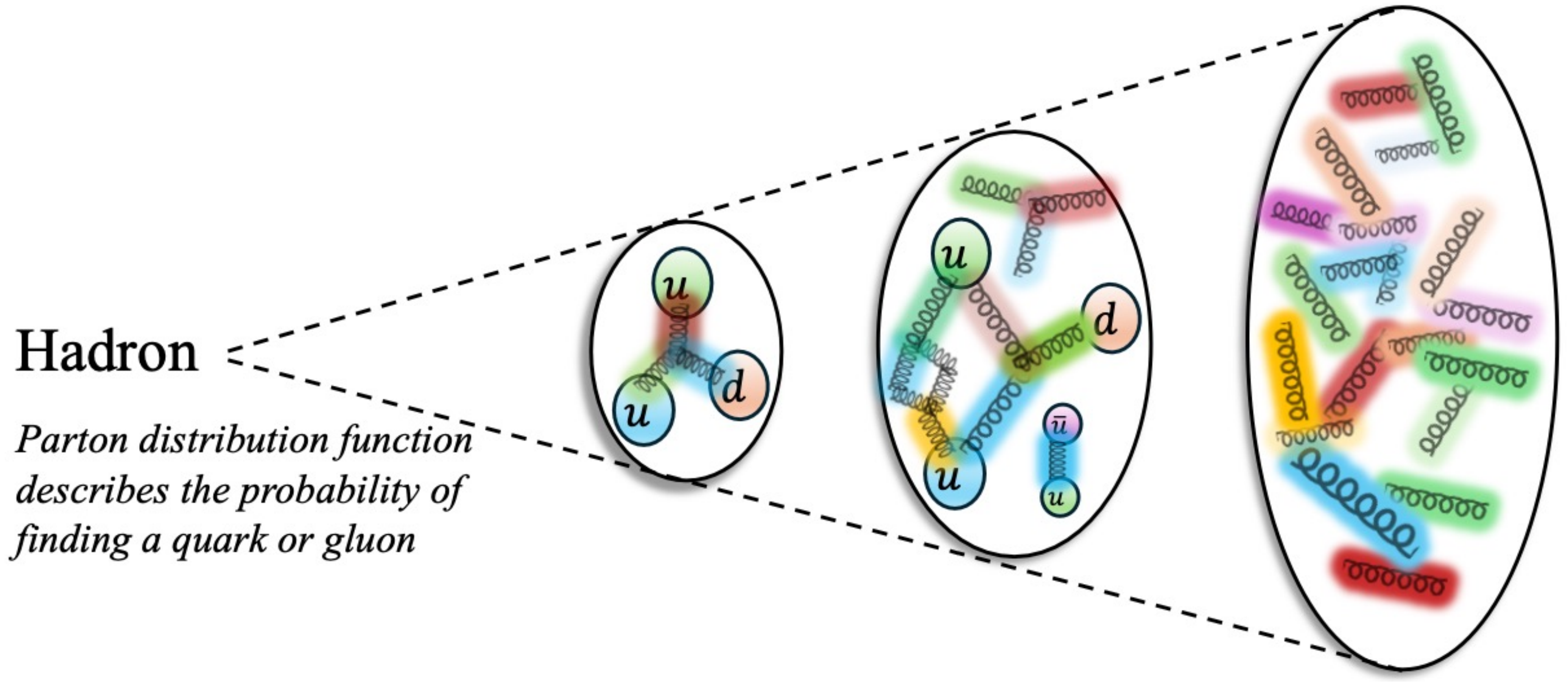
✦ **"standard" treatment in HEP: consider only leading twist nuclear partonic structure, assume the same hard scattering**

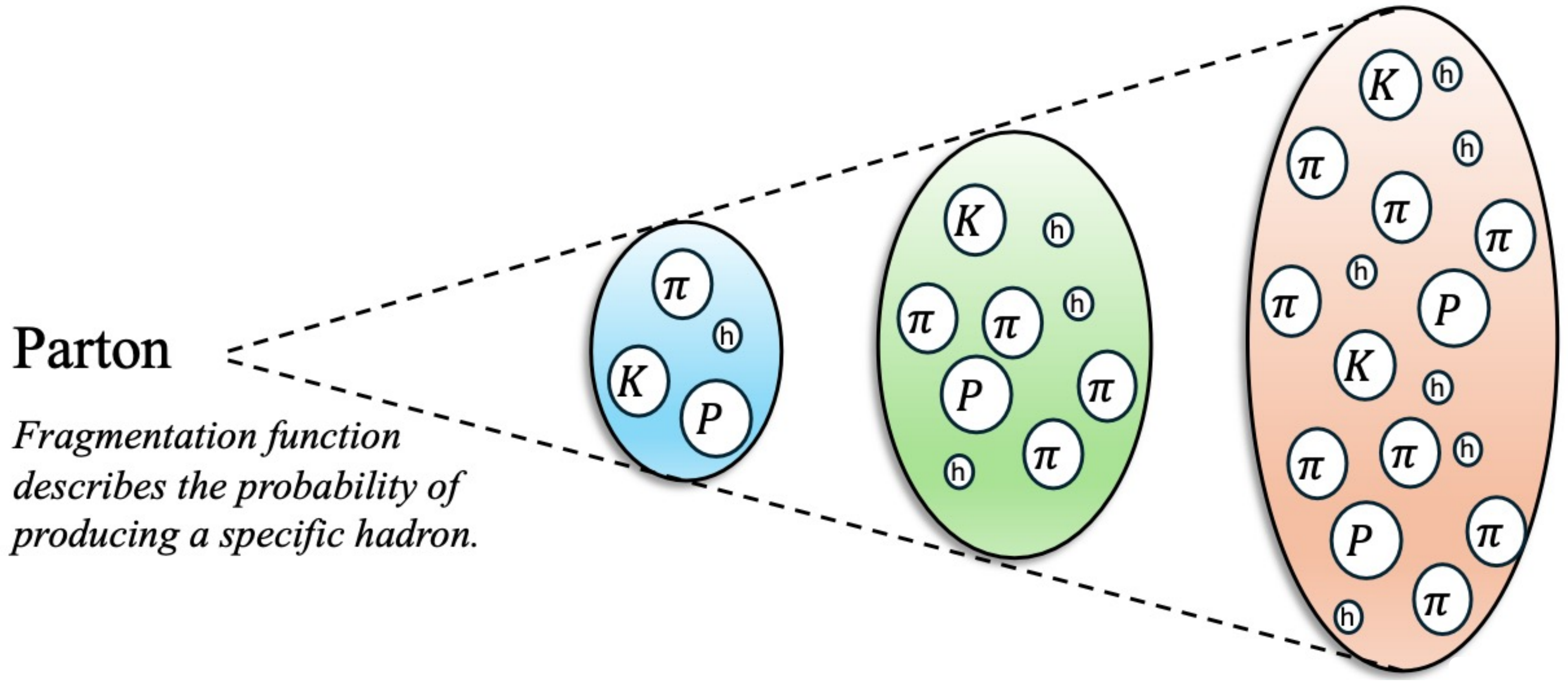
Methodology for global extraction of PDFs

Recent efforts from NPC collaboration

✦ **Nonperturbative Physics Collaboration, start from 2023**

SJTU（高俊）+ IMP（沈晓民、赵宇翔、周一雨）+ SCNU（邢宏喜）





✦ **Parton fragmentation in vacuum at NLO and $\mathrm{N^2LO}$ (PRL 24, 25, PRD 24, 25)**

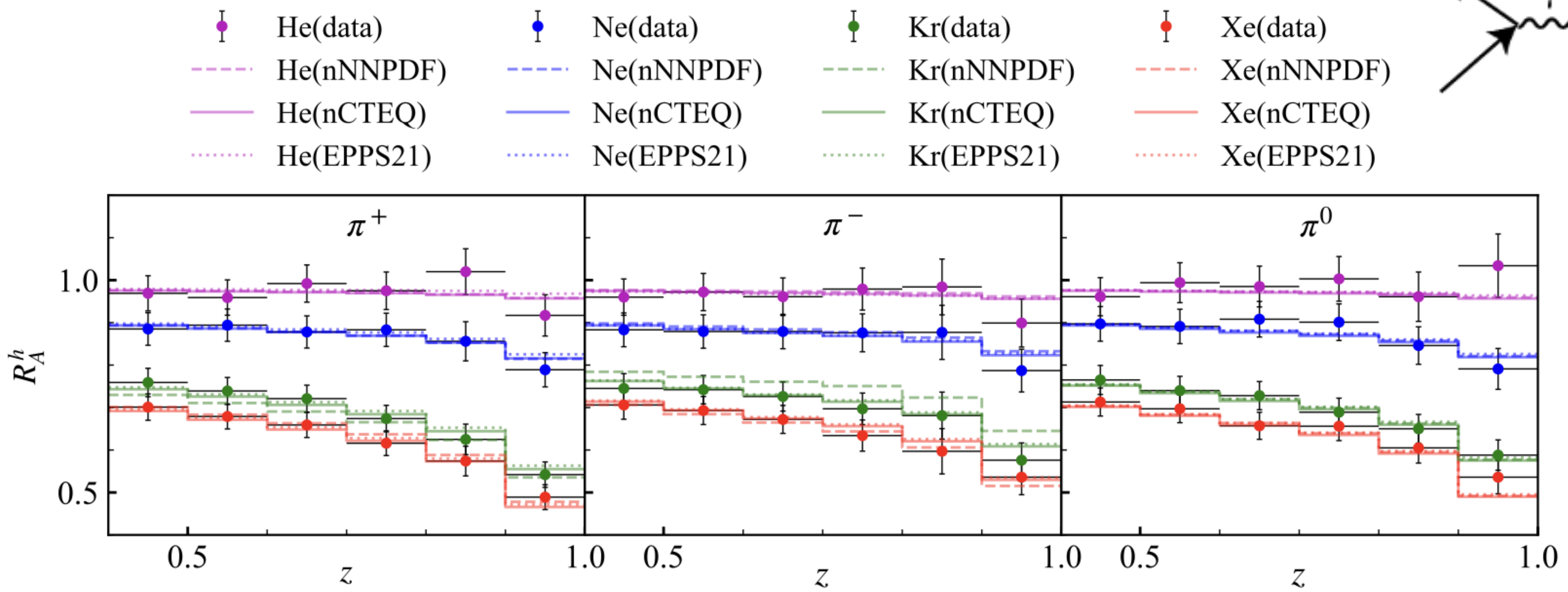
✦ **Parton fragmentation in e^+e^- at $\mathrm{N^3LO}$ (杨通智等，PRL 25)**

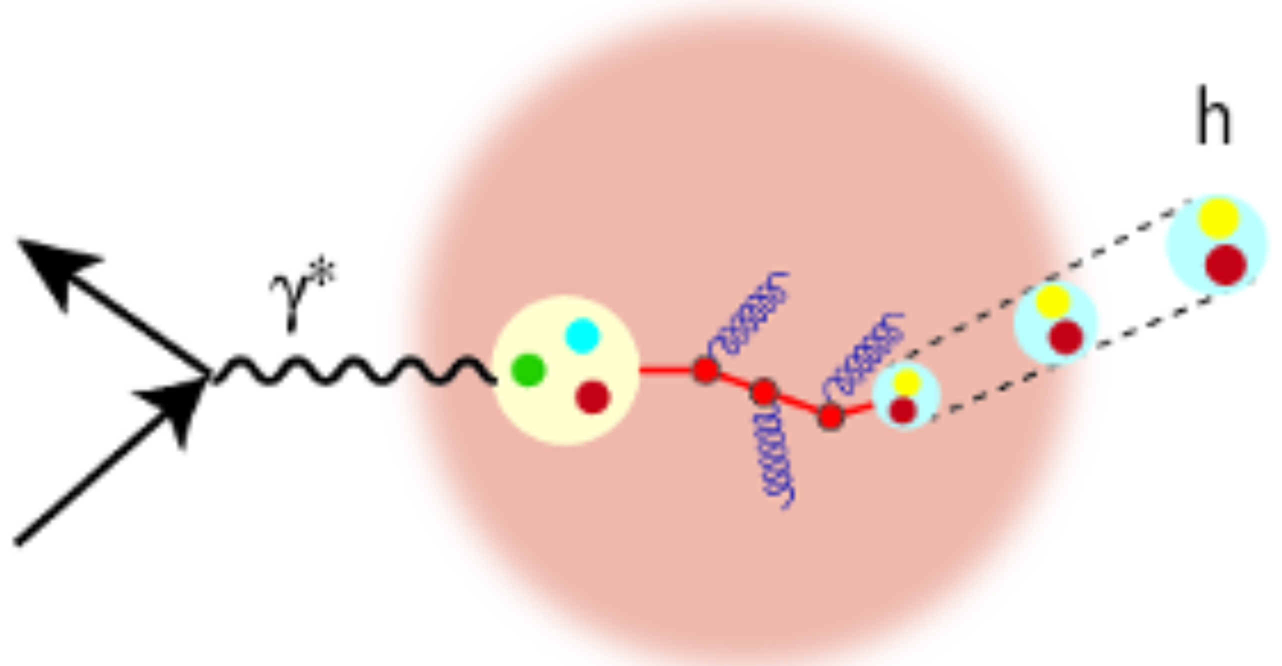
✦ **Proton spin structure (on going)**

✦ **Parton distribution and fragmentation in nuclear medium (2607.08669)**

Recent efforts from NPC collaboration

✦ Nuclear modified parton fragmentation





$$D^h_{i/A}(z, Q^2, \nu) = D^h_i(z, Q^2) - \mathcal{F}_A(A, \nu) \times D'^h_i(z, Q^2)$$

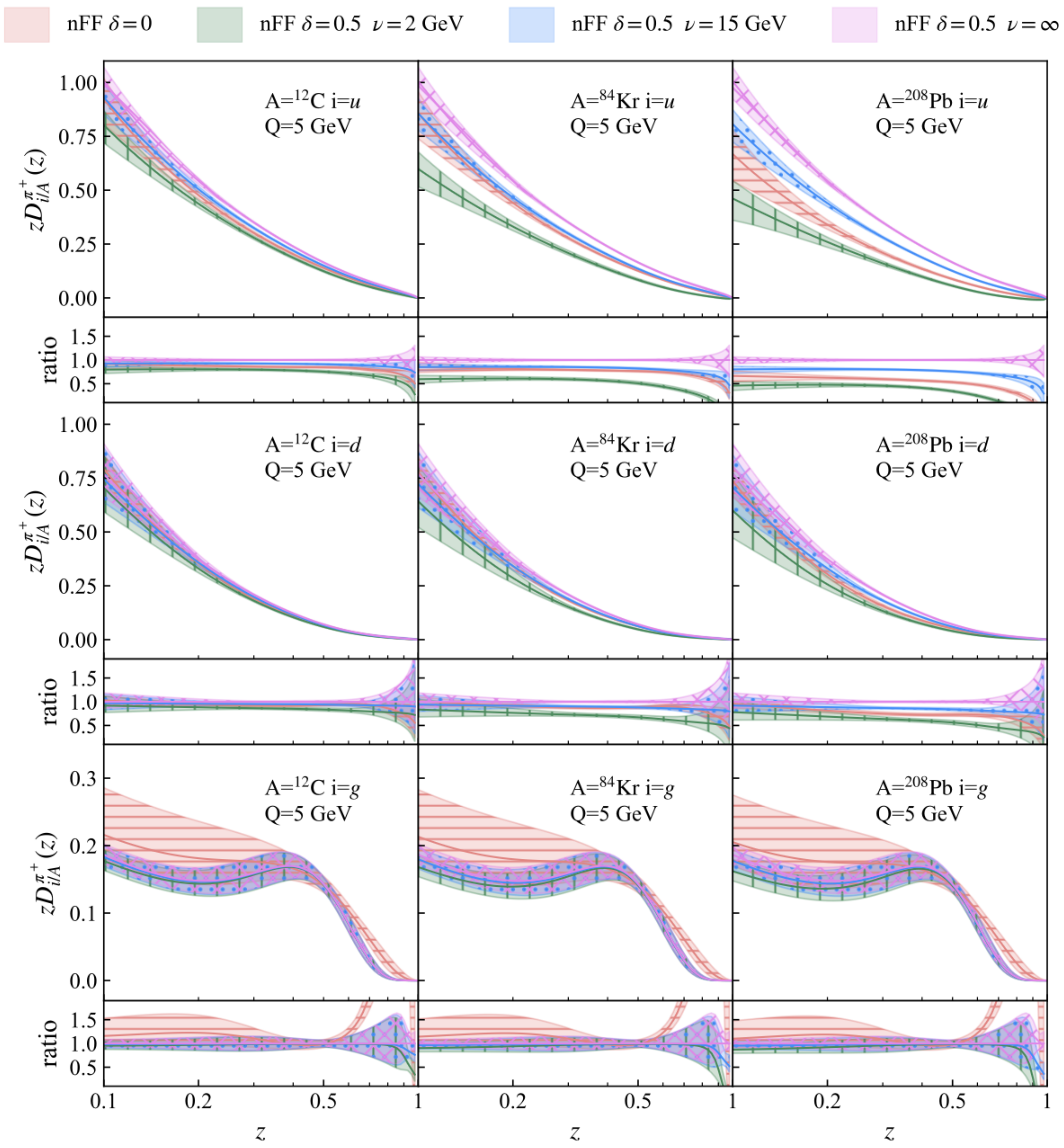
$$\mathcal{F}_A(A, \nu) = \frac{f(A)}{(\nu/\nu_0)^\delta}$$

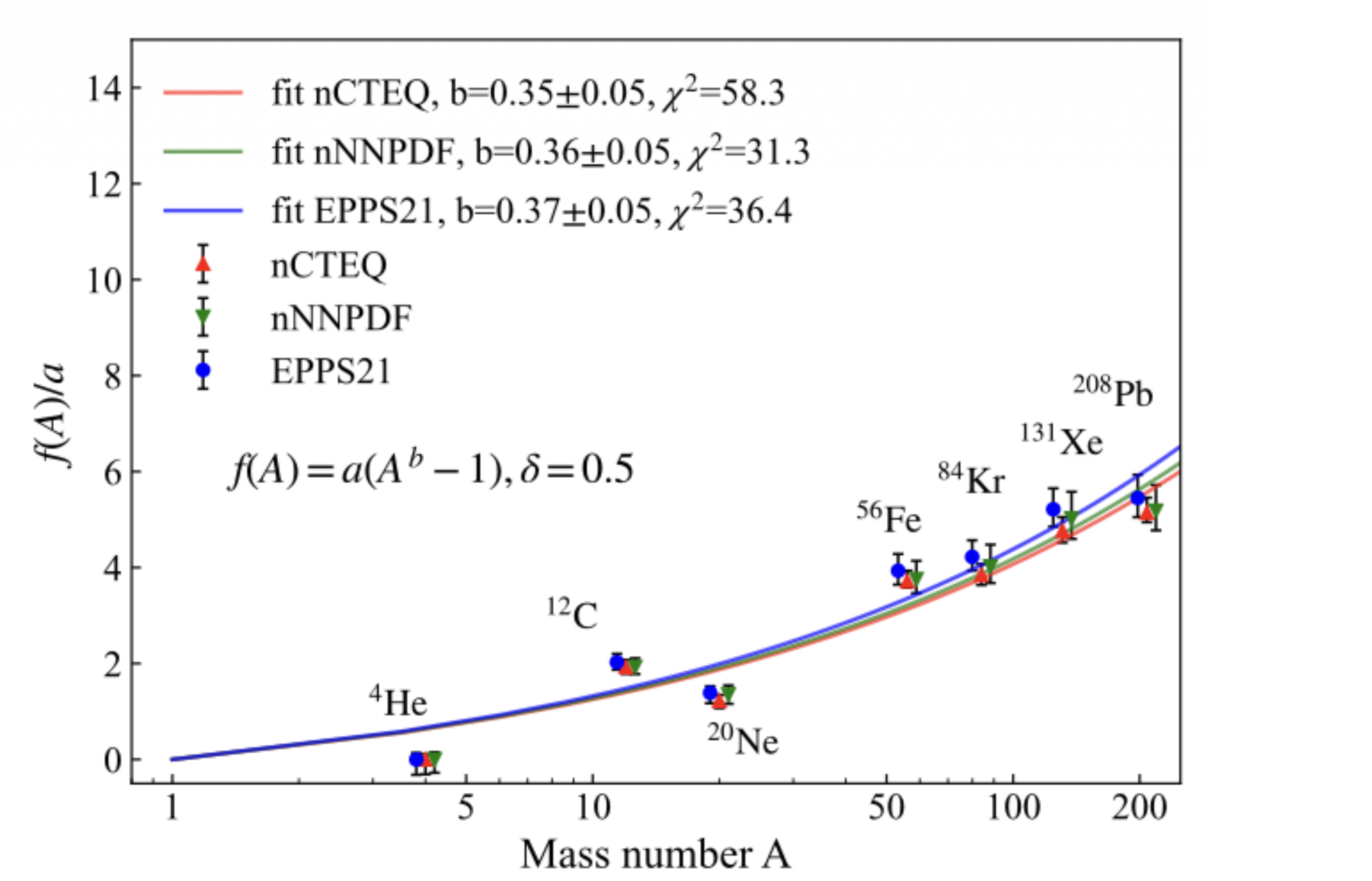
NPC, 2607.08699

Recent efforts from NPC collaboration

✦ Nuclear modified parton fragmentation

NPC, 2607.08699



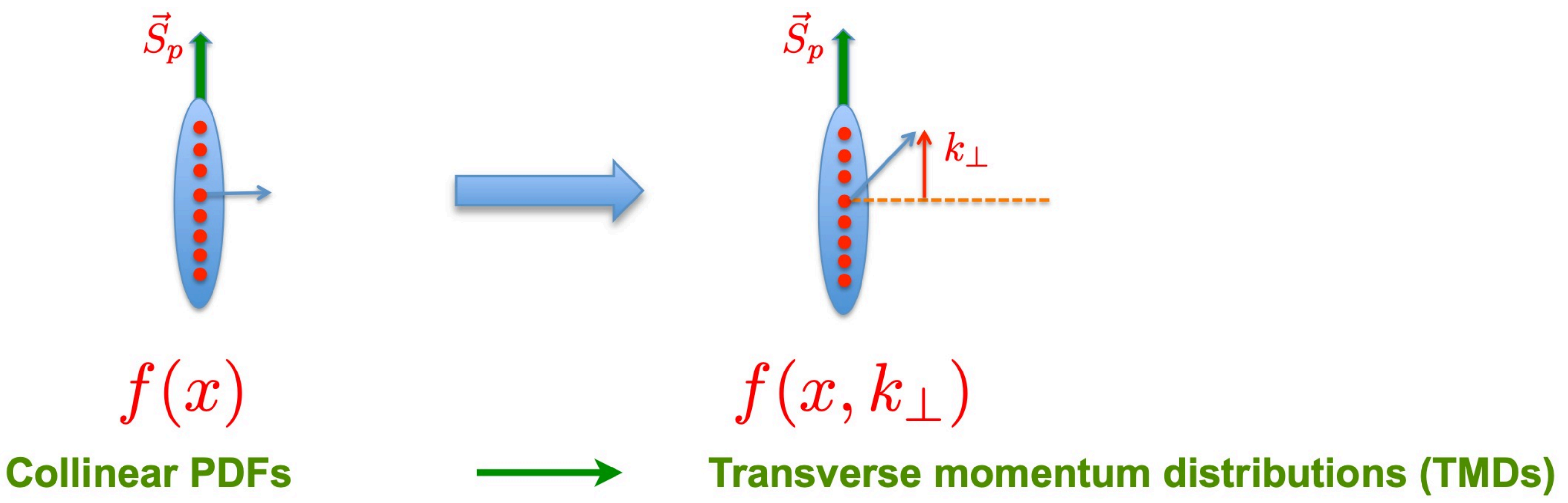


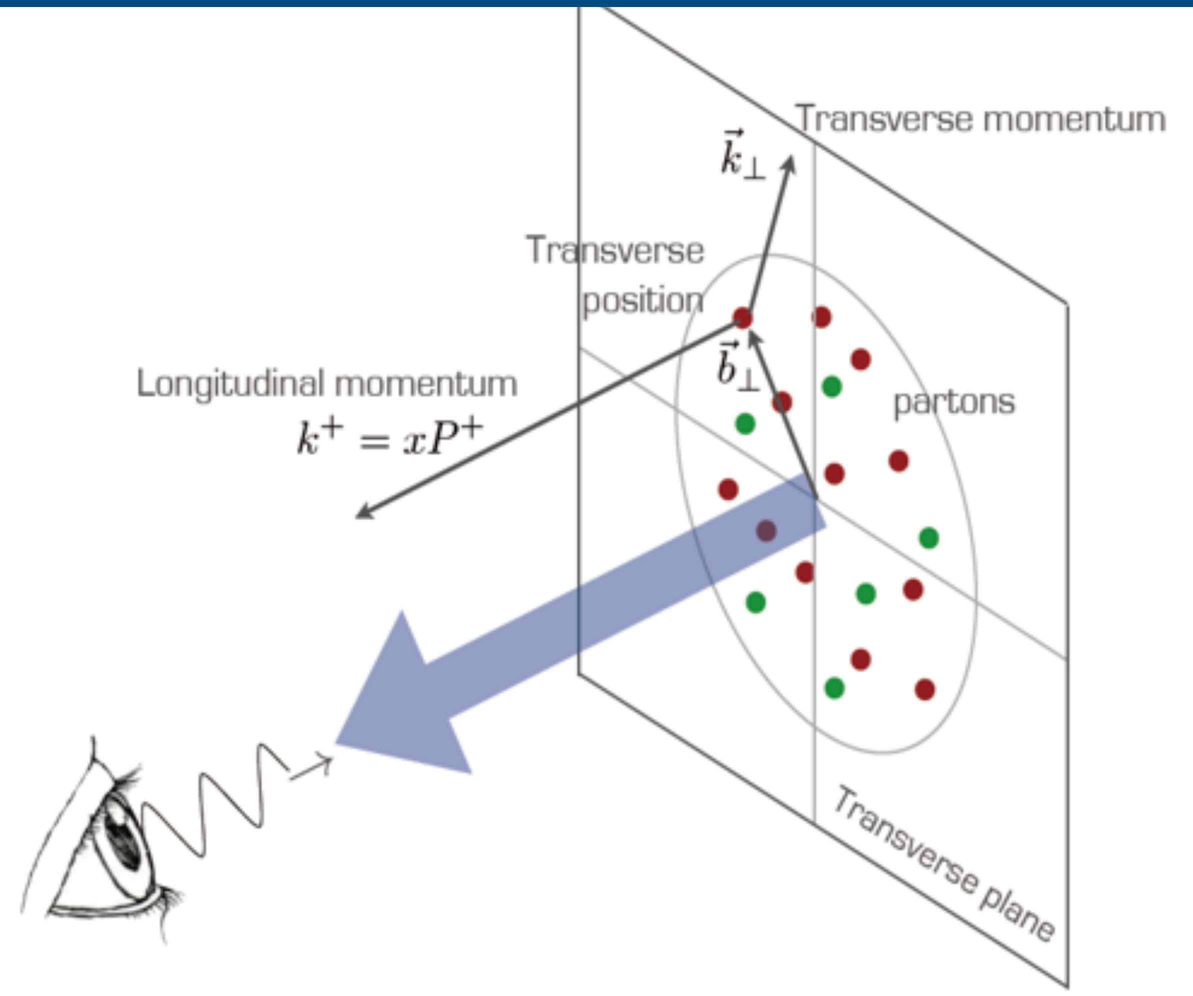
$$D^h_{i/A}(z,Q^2,\nu) = D^h_i(z,Q^2) - \mathcal{F}_A(A,\nu) \times D'^h_i(z,Q^2)$$

$$\mathcal{F}_A(A,\nu) = \frac{f(A)}{(\nu/\nu_0)^\delta}$$

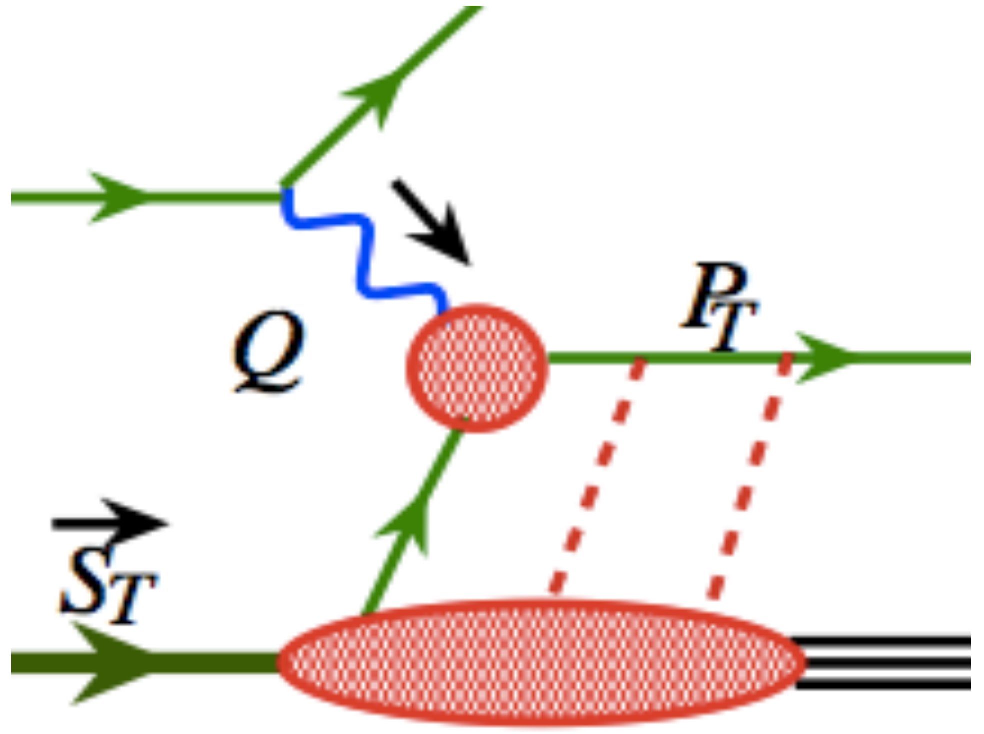
Global analysis of nuclear TMD

✦ Transverse momentum dependent PDFs (TMDs)





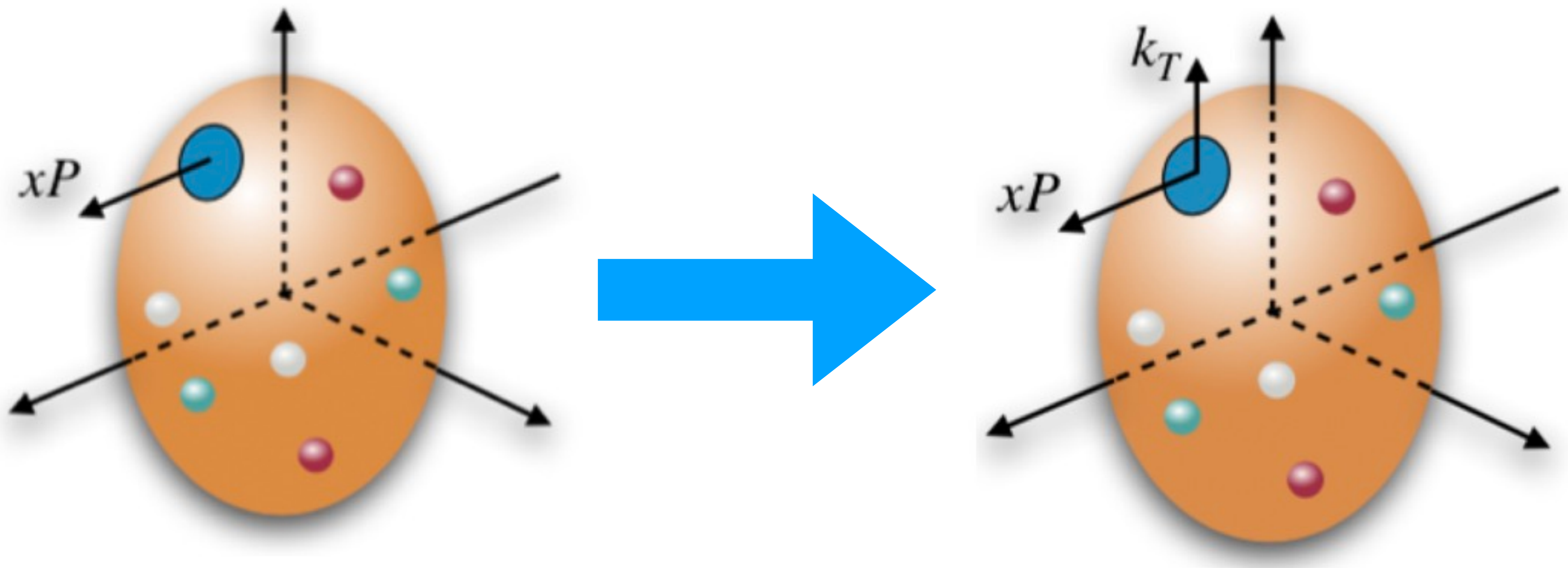
- Probing nucleon 3D structure requires two momentum scales
- Hard scale $Q_1 \gg 1/fm$ localizes the probes (particle nature of quarks/gluons)
- Soft scale $Q_2 \sim 1/fm$ accesses the transverse motion of quarks/gluons

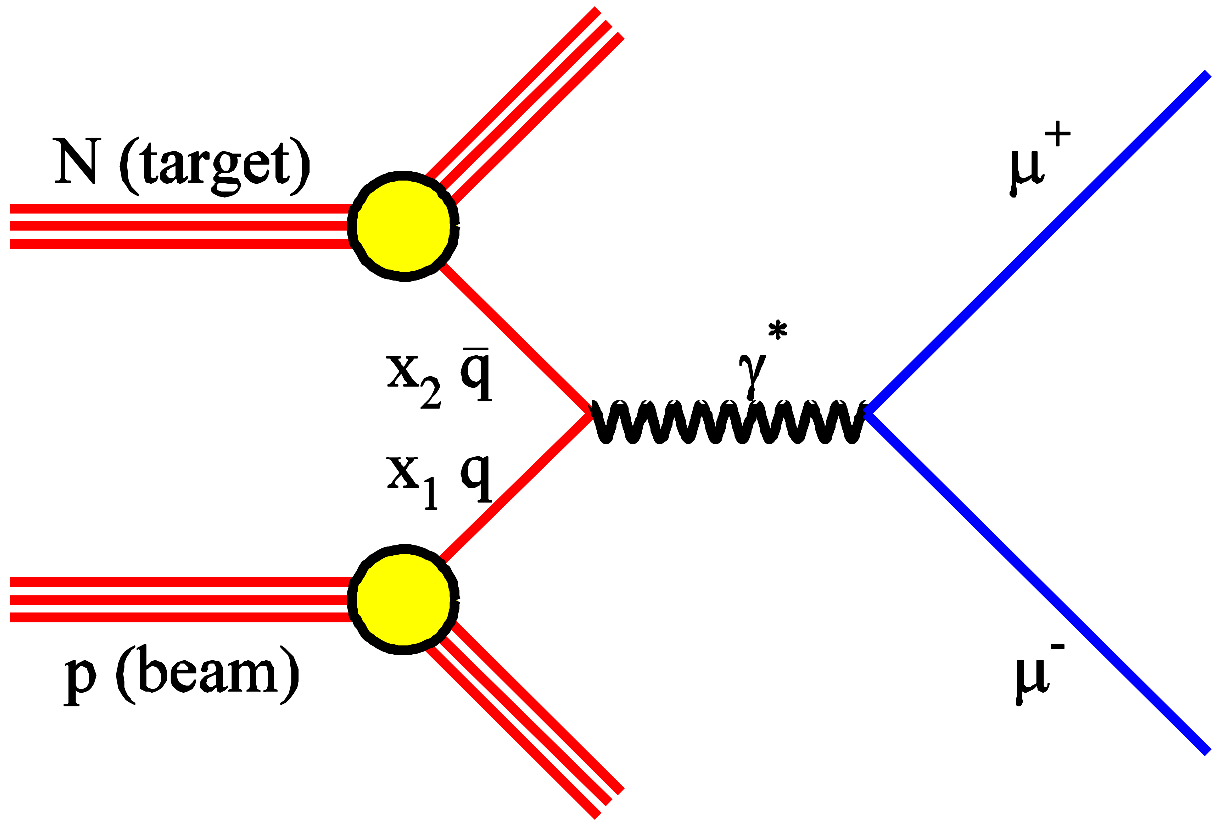


SIDIS: Q>>P_T

Global analysis of nuclear TMD

✦ From collinear (1D) to TMD (3D)



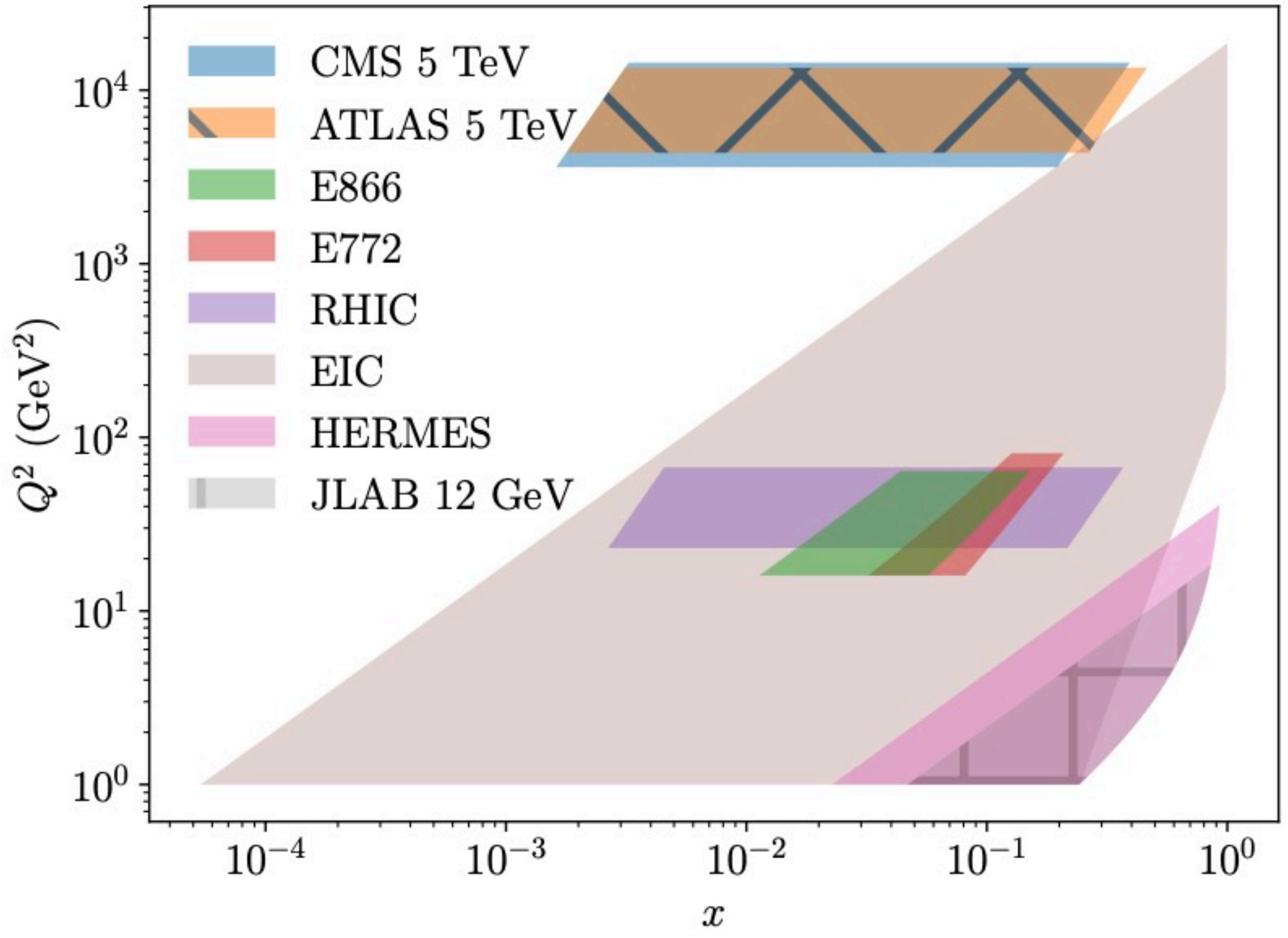


Drell-Yan Measurements

- $R_{AB} = \frac{d\sigma_A}{dq_\perp} / \frac{d\sigma_B}{dq_\perp}$
  - -E866
  - -E772
  - -Prelim. RHIC
- $d\sigma/dq_\perp$ (p Pb)
  - ATLAS
  - CMS

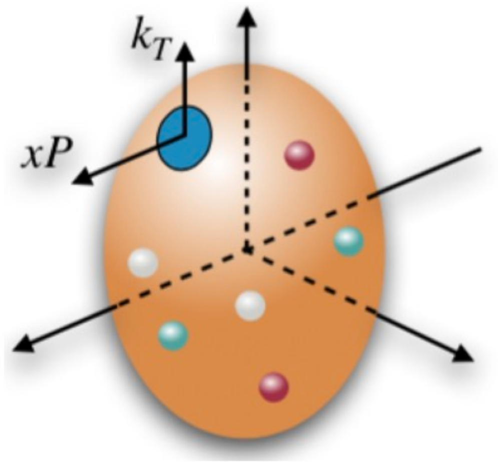
SIDIS Measurements

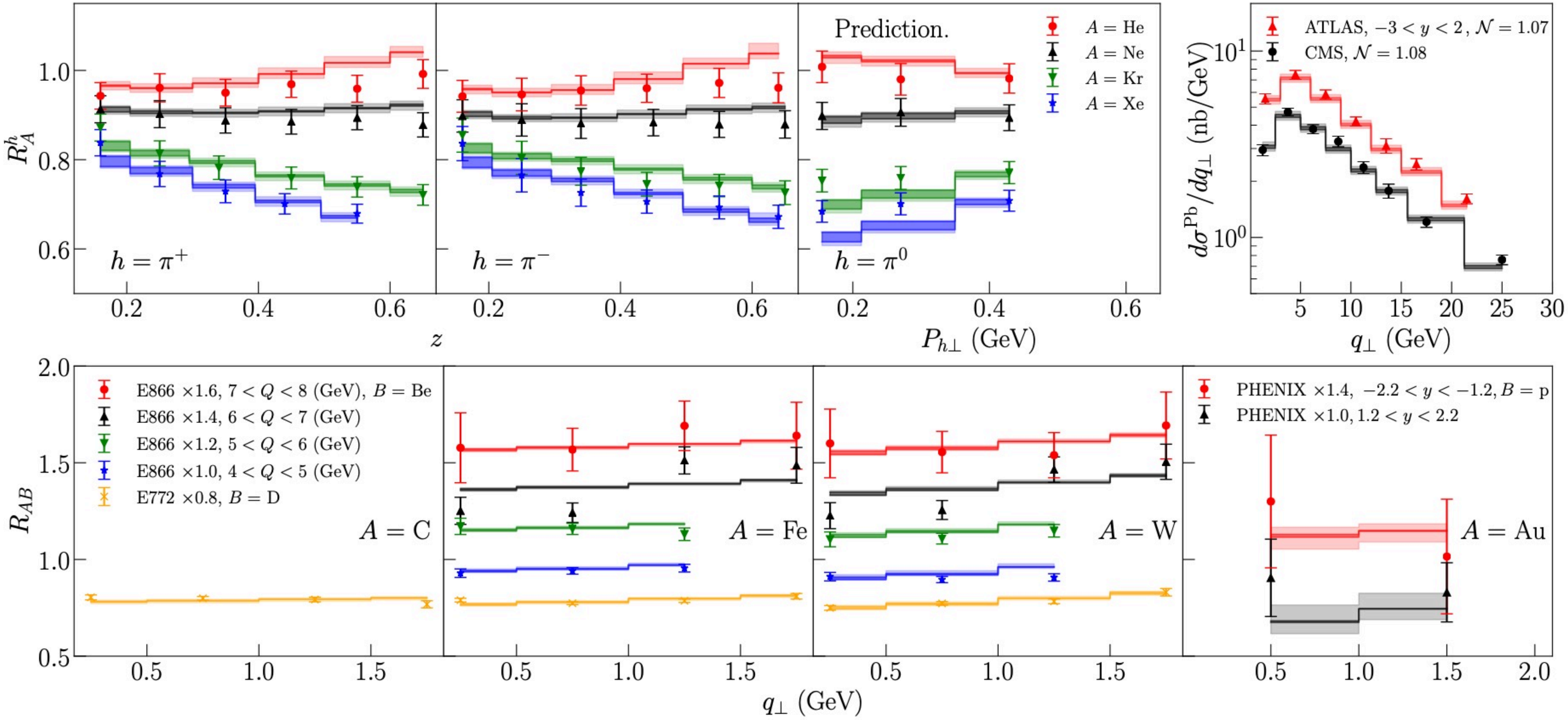
- Multiplicity ratio $R_h^A = M_h^A / M_h^D$.
  - -HERMES 2007
  - -Prelim. JLab
  - -Planned JLab
  - -Possible EIC.



Global analysis of nuclear TMD

Alrashed, Anderle, Kang, Terry, **HX**, PRL 2022

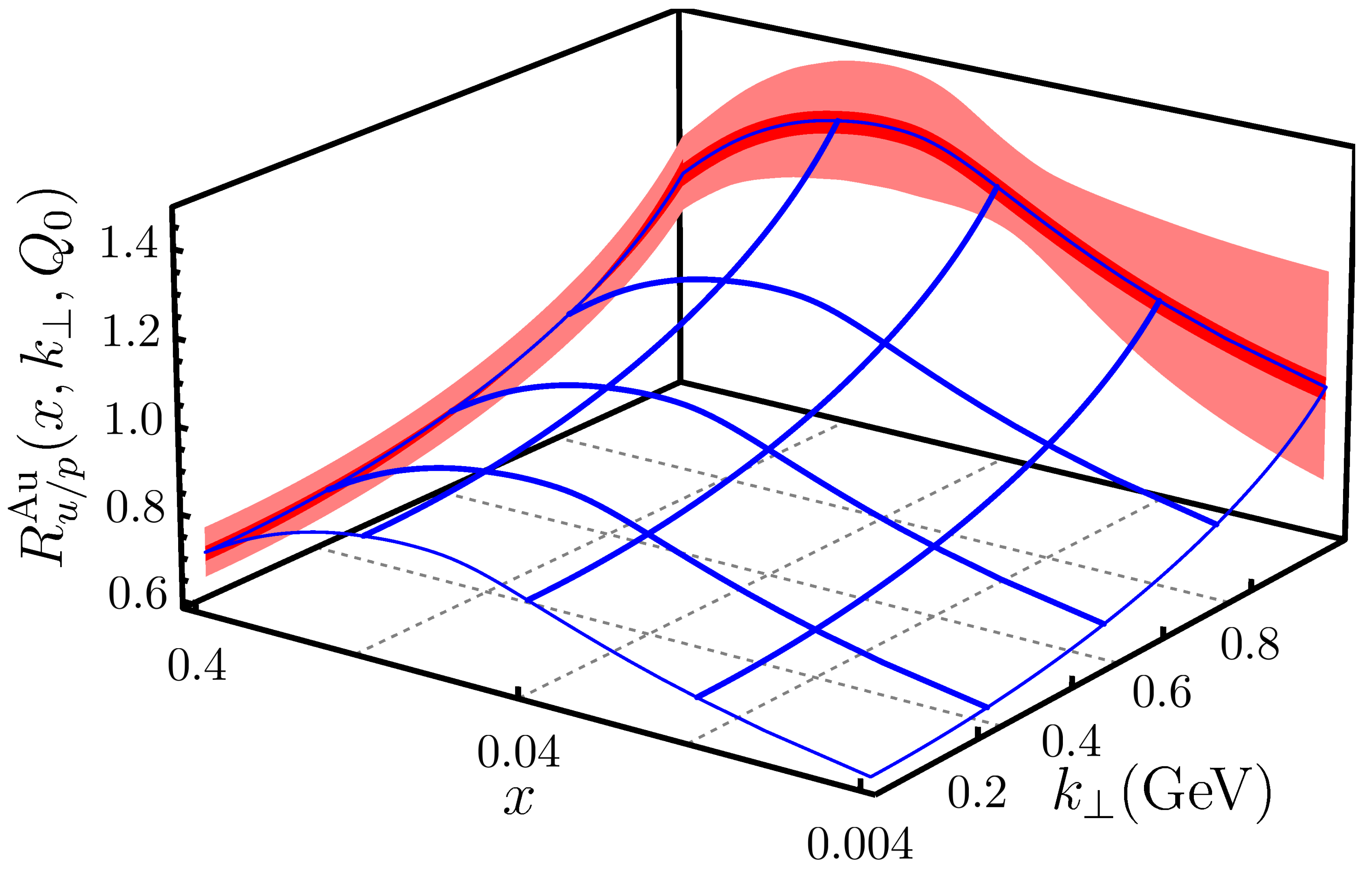




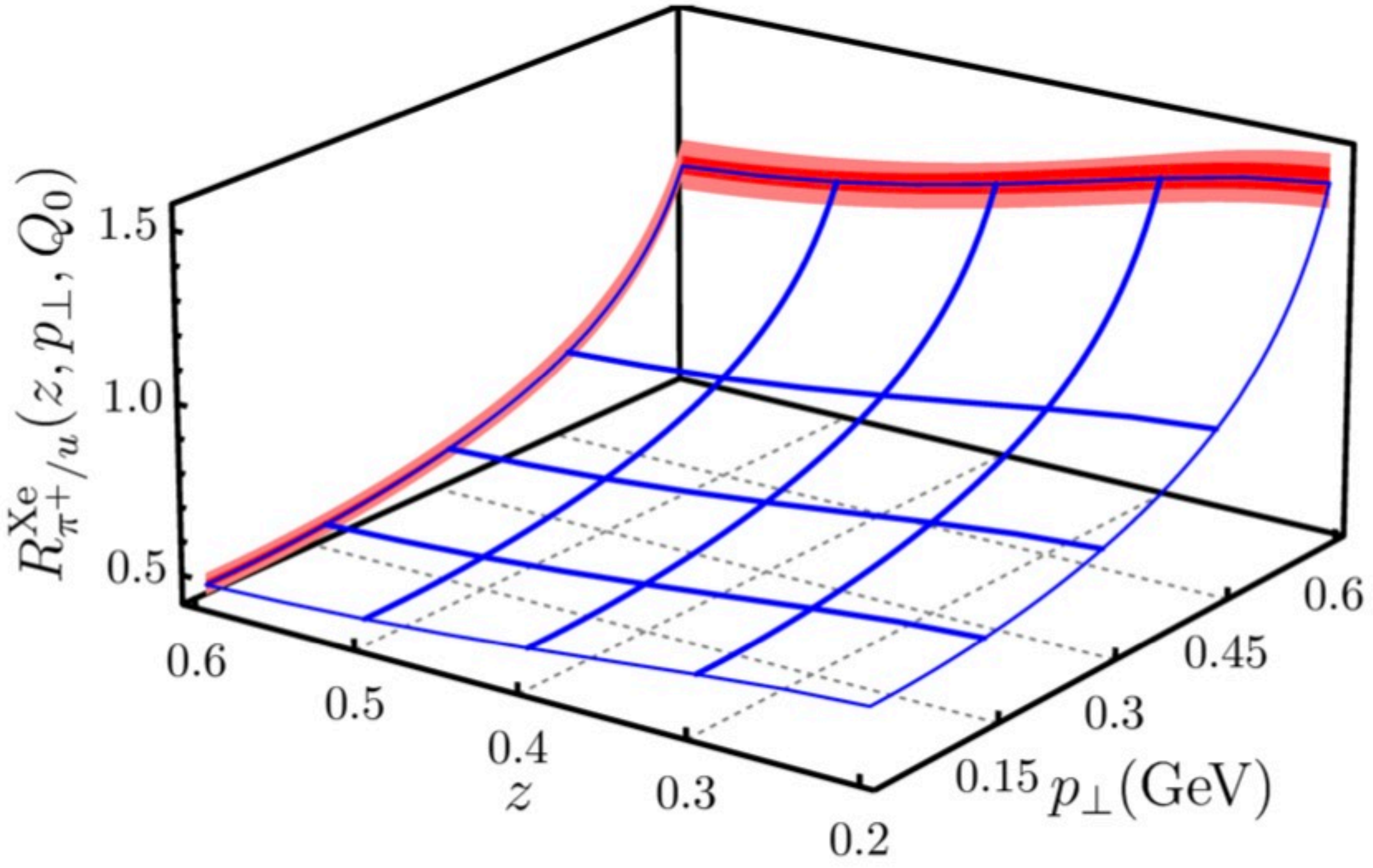
Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

Three-dimension imaging in nuclei

$$R_{u/p}^{\mathrm{Au}}(x,k_\perp,Q_0)=\frac{f_{u/p}^{\mathrm{Au}}(x,k_\perp,Q_0)}{f_{u/p}(x,k_\perp,Q_0)}$$



$$\mathcal{R}_{\pi^+/u}^{\mathrm{Xe}}(z,p_\perp,Q_0)=\frac{D_{\pi^+/u}^{\mathrm{Xe}}(z,p_\perp,Q_0)}{D_{\pi^+/u}(z,p_\perp,Q_0)}$$



- **First time quantitative determination of nuclear TMDs**
- **Identification of transverse momentum broadening in nuclei**

Alrashed, Anderle, Kang, Terry, **HX**, PRL 2022
Alrashed, Kang, Terry, **HX**, Zhang, 2312.09226
Zhou, Kang, **HX**, 2609.xxxxx

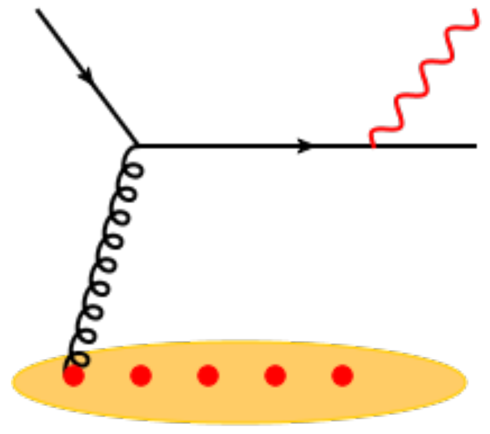
How to reliably probe the nuclear partonic structure?

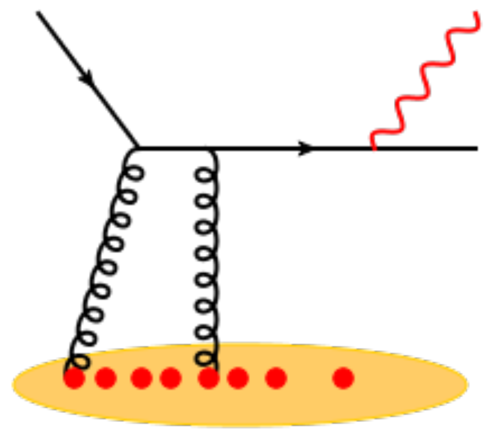
✦ Generalized QCD factorization - twist expansion

perturbative expansion

Multiple scattering expansion

$$
\begin{aligned}
\sigma^h_{phys} = \; & \left[\alpha_s^0 C_2^{(0)} + \alpha_s^1 C_2^{(1)} + \alpha_s^2 C_2^{(2)} + \ldots\right] \otimes T_2(x) \\
& + \frac{1}{Q}\left[\alpha_s^0 C_3^{(0)} + \alpha_s^1 C_3^{(1)} + \alpha_s^2 C_3^{(2)} + \ldots\right] \otimes T_3(x) \\
& + \frac{1}{Q^2}\left[\alpha_s^0 C_4^{(0)} + \alpha_s^1 C_4^{(1)} + \alpha_s^2 C_4^{(2)} + \ldots\right] \otimes T_4(x) \\
& + \ldots
\end{aligned}
$$





✦ The power suppressed high twist correction is enhanced by nuclear size

$$\frac{1}{Q^2} \rightarrow \frac{A^{1/3}}{Q^2}$$

NLO QCD factorization at twist-4:

Kang, Wang, Wang, **HX**, PRL 2014

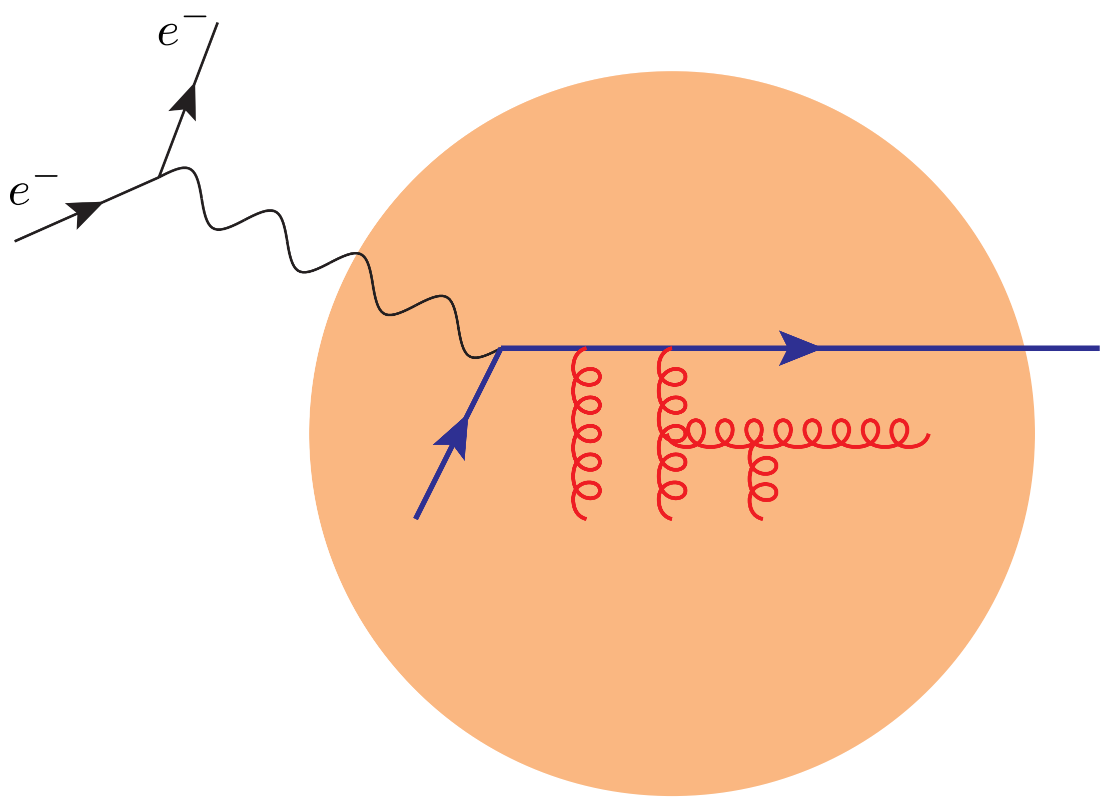
Kang, Qiu, Wang, **HX**, PRD 2016

High twist in nuclear medium

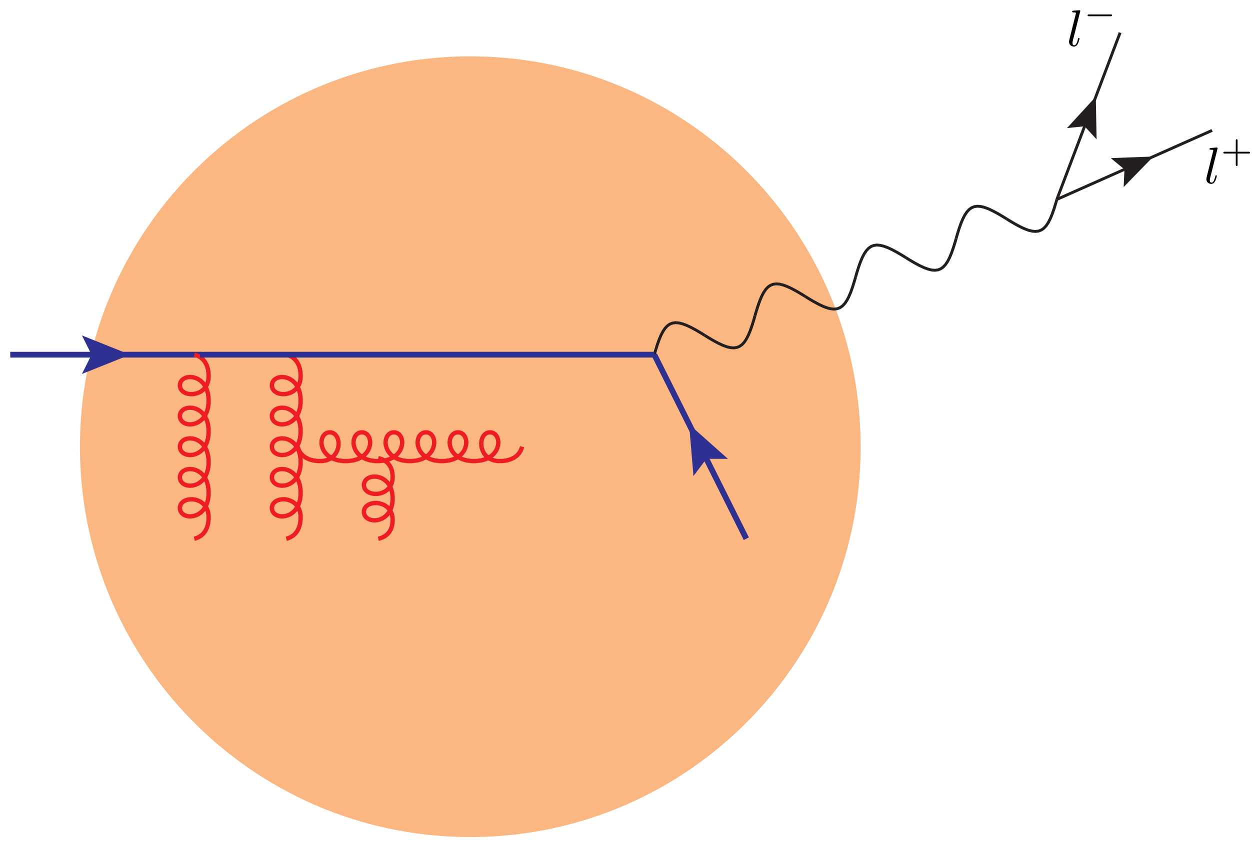
✦ Transverse momentum broadening in nucleus

$$\Delta\langle \ell_{hT}^2\rangle = \langle \ell_{hT}^2\rangle_{eA} - \langle \ell_{hT}^2\rangle_{ep} = \left(\frac{4\pi^2\alpha_s}{N_c} z_h^2\right) \frac{\sum_q e_q^2 \boxed{T_{qg}(x_B,0,0)} D_{h/q}(z_h)}{\sum_q e_q^2 f_{q/A}(x_B) D_{h/q}(z_h)}$$

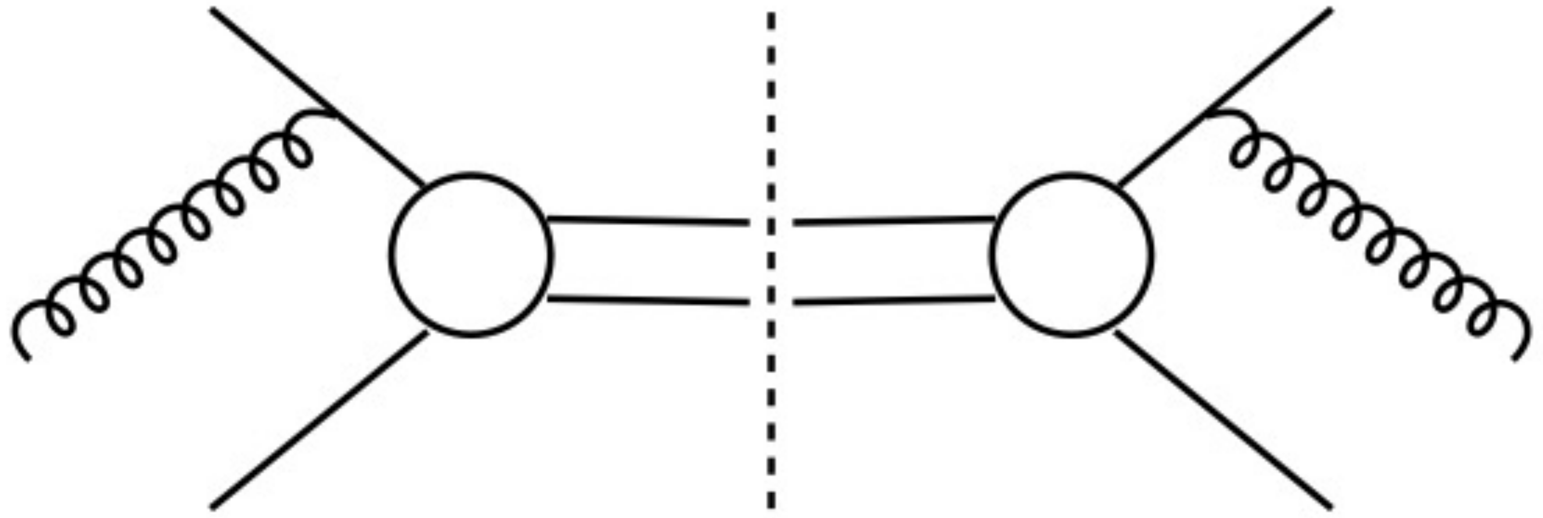
Jet transport parameter: $T_{qg}(x_B,0,0,\mu^2) \approx \frac{N_c}{4\pi^2\alpha_s} f_{q/A}(x_B,\mu^2) \int dy^- \hat{q}(\mu^2, y^-)$



SIDIS off nucleus



DY in pA

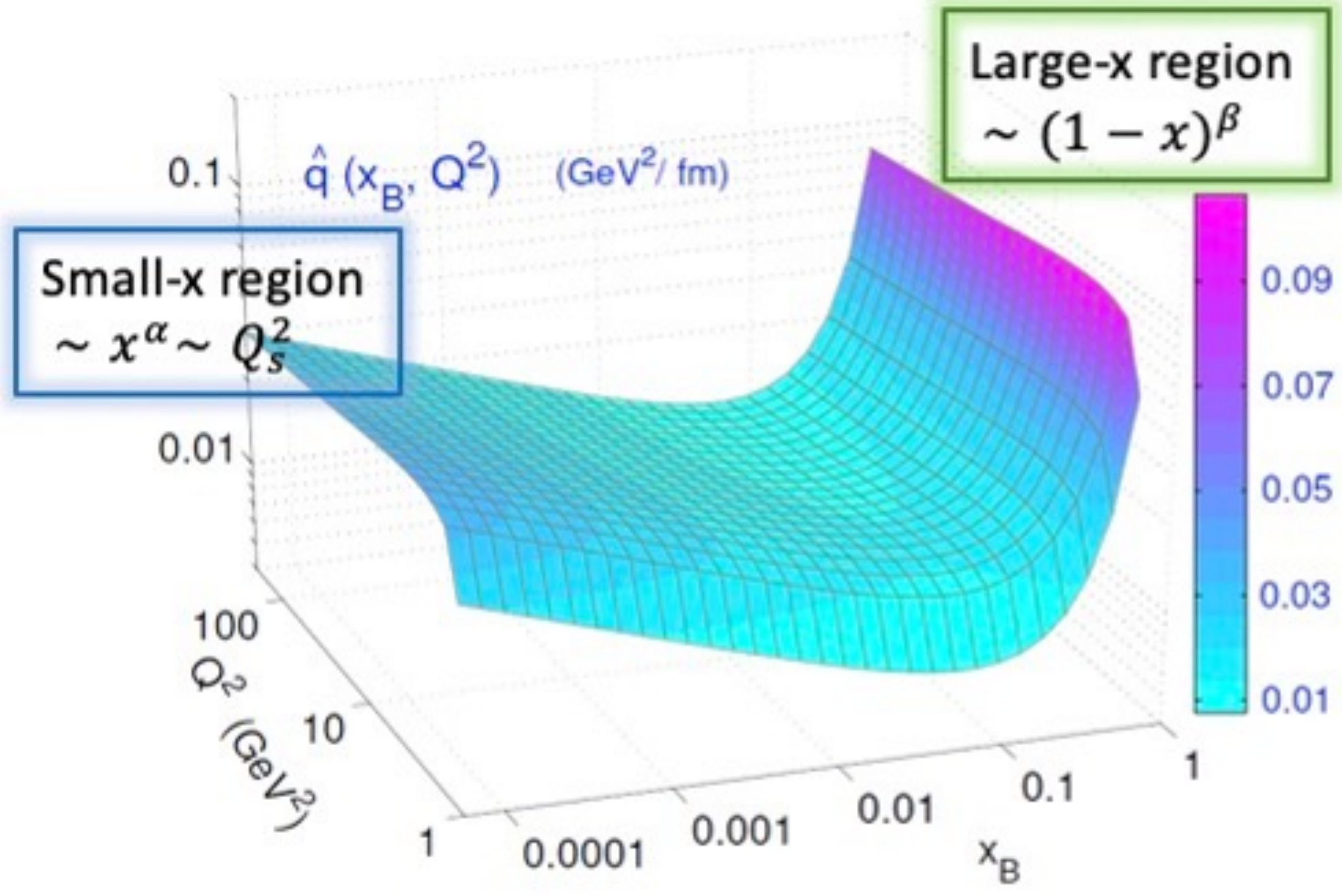


Heavy quarkonium in pA

Global analysis of jet transport parameter in CNM

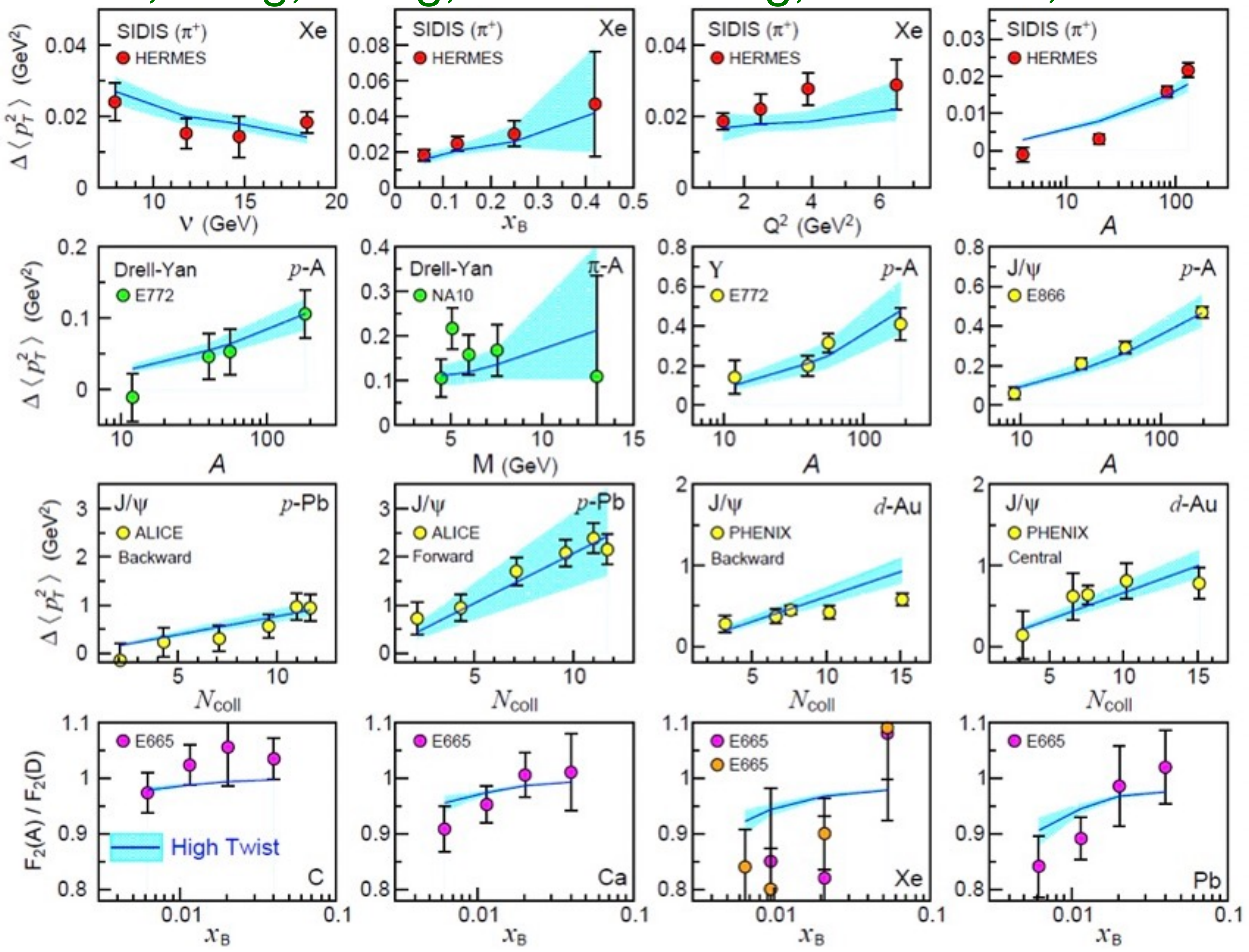
Optimal $\hat{q}(x, Q^2)$

$$\hat{q}(x,Q^2) = \hat{q}_0 \alpha_s(Q^2) x^{\alpha} (1-x)^{\beta} [\ln(Q^2/Q_0^2)]^{\gamma}$$



$$\hat{q}_0 = 0.0191 \pm 0.0061\ \mathrm{GeV^2/fm}, \quad \alpha = -0.182 \pm 0.050$$
$$\beta = -2.85 \pm 1.87, \quad \gamma = 0.264 \pm 0.169\,.$$

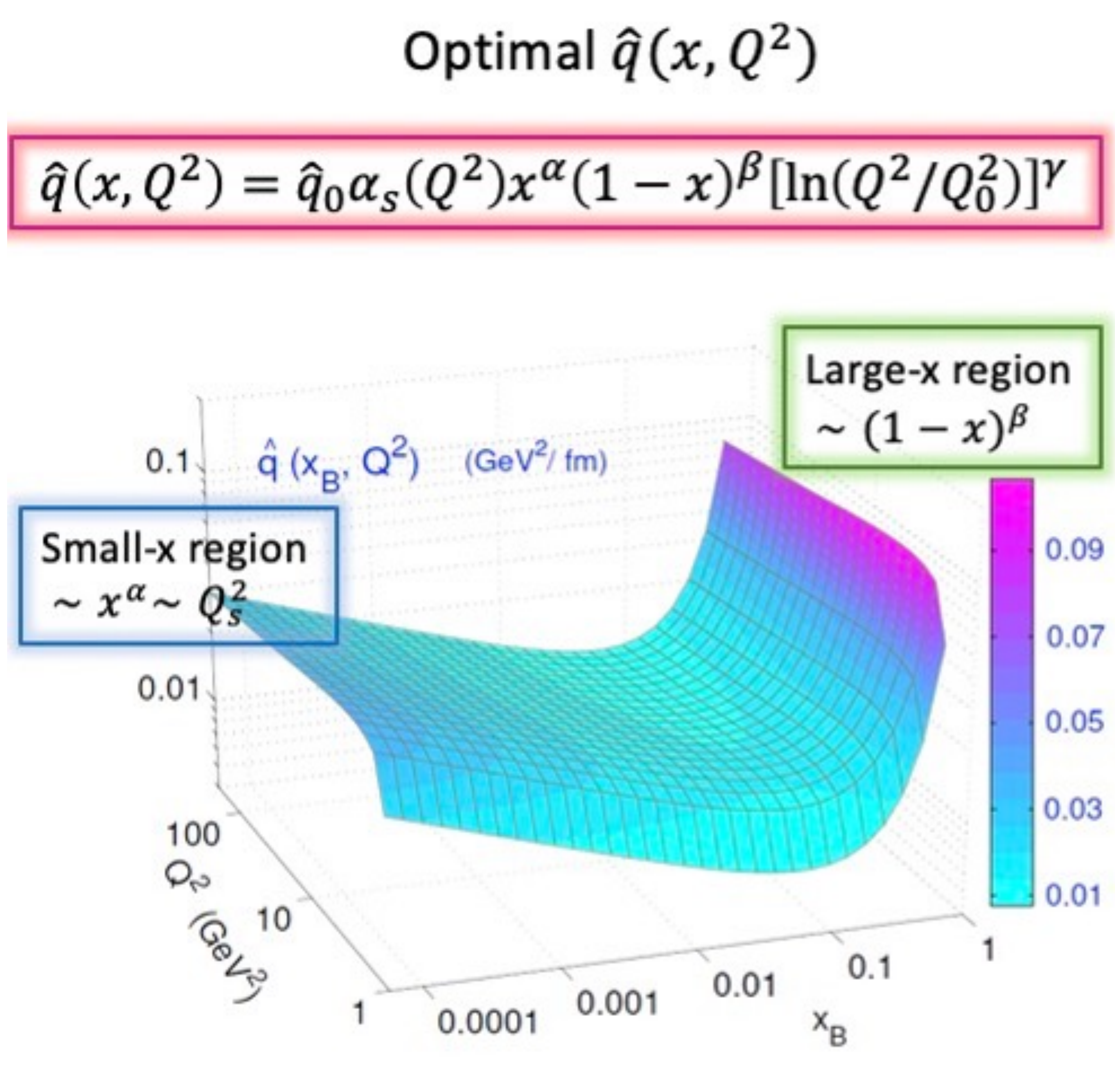
Ru, Kang, Wang, **HX** and Zhang, PRD 2021; CPC 2026



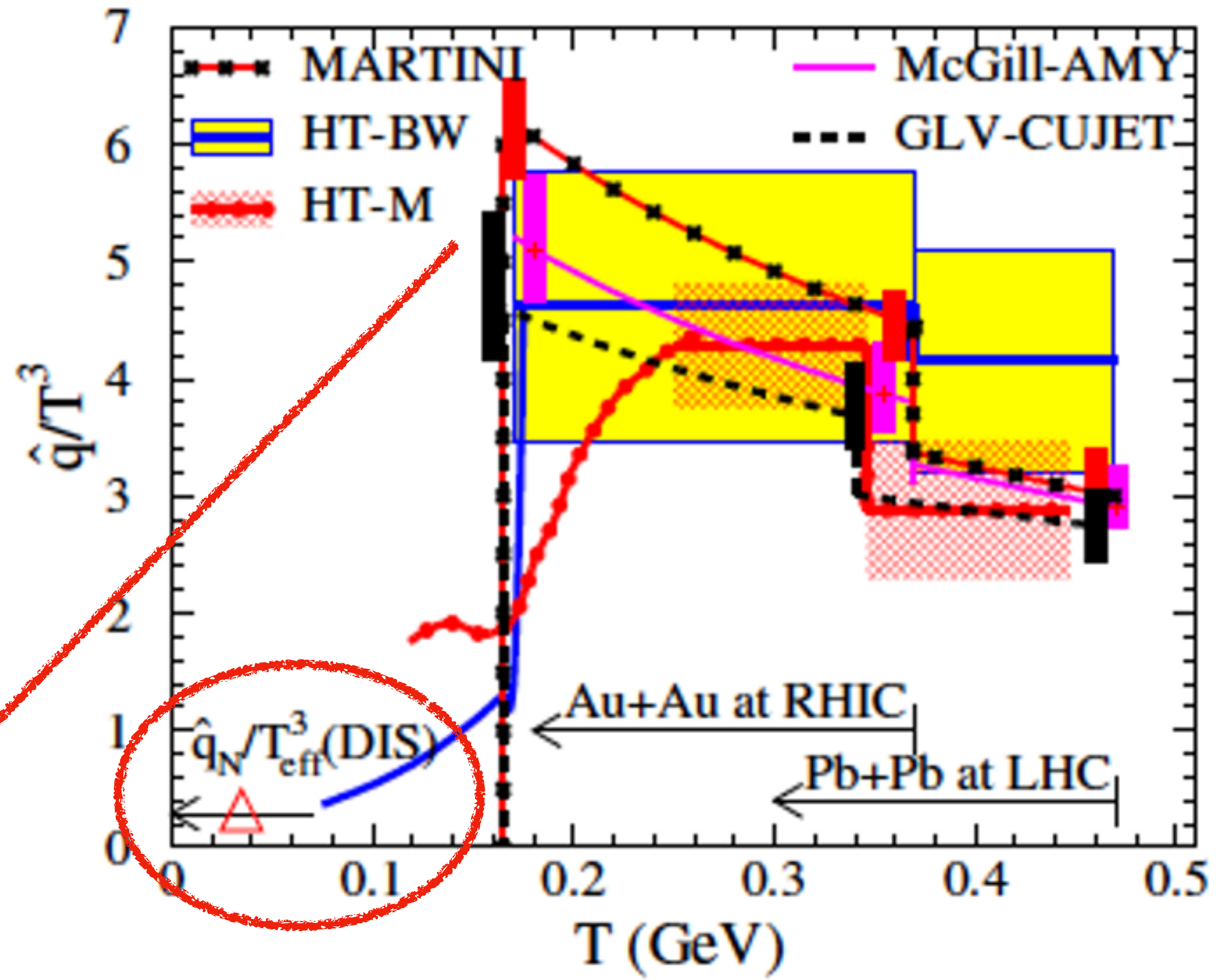
$\hat{q}$ in CNM is not a constant and order of magnitude smaller than QGP!

Global analysis of jet transport parameter in CNM

Ru, Kang, Wang, **HX** and Zhang, PRD 2021; CPC 2026



$\hat{q}_0 = 0.0191 \pm 0.0061$ GeV^2/fm, $\alpha = -0.182 \pm 0.050$
$\beta = -2.85 \pm 1.87$, $\gamma = 0.264 \pm 0.169$.



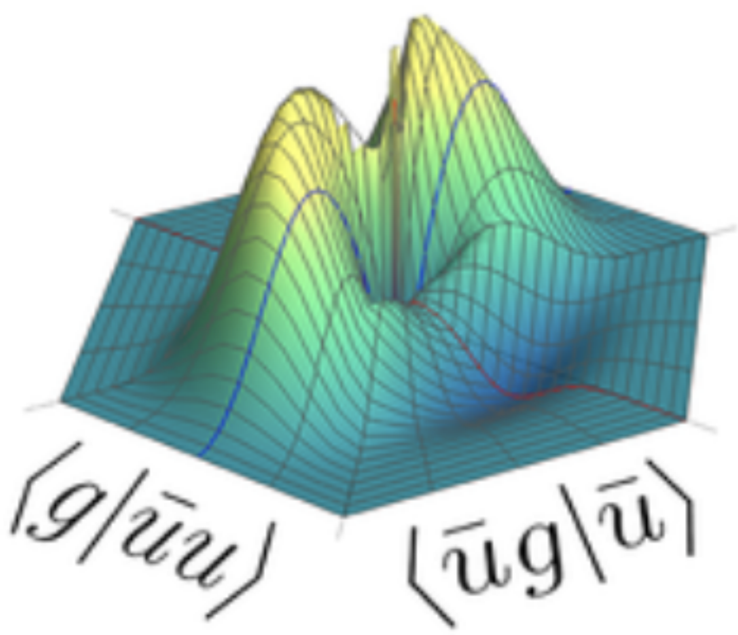
Jet transport at CEP? Holography QCD by M. Huang and D. Hou

High twist in nuclear medium

✦ What's the meaning of high-twist matrix element?

$$T_{qg}(x_1,x_2,x_3) = \int \frac{dy^-}{2\pi} e^{ix_1p^+y^-} \int \frac{dy_1^- dy_2^-}{4\pi} \; e^{ix_2p^+(y_1^- - y_2^-)} e^{ix_3p^+y_2^-} \langle A|\bar{\psi}_q(0)\gamma^+ F_\sigma^+(y_2^-) F^{\sigma+}(y_1^-)\psi_q(y^-)|A\rangle$$

Quark-gluon quantum correlation in nucleus



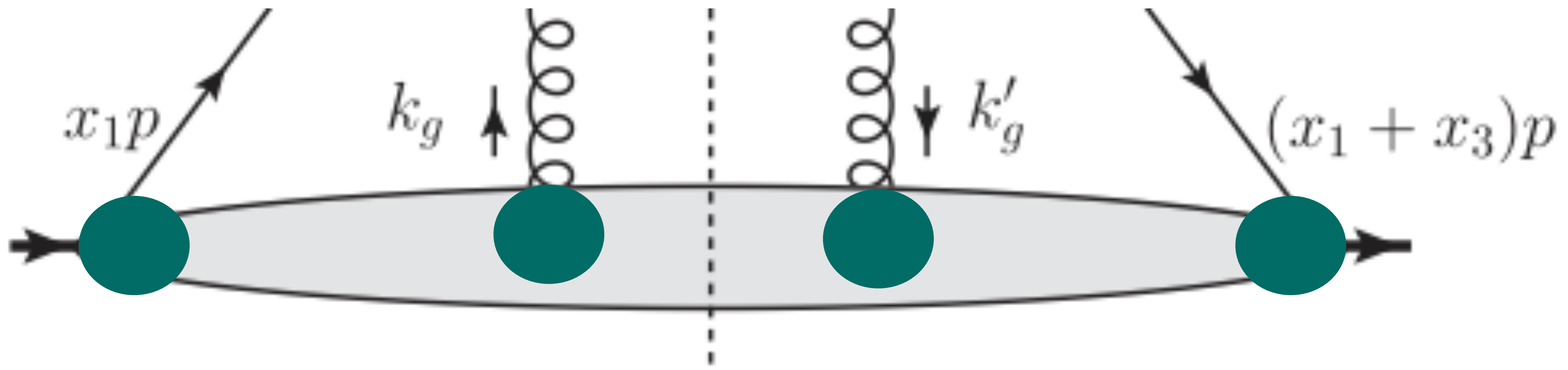
EDITORS' SUGGESTION

Determination of Quark-Gluon-Quark Interference within the Proton

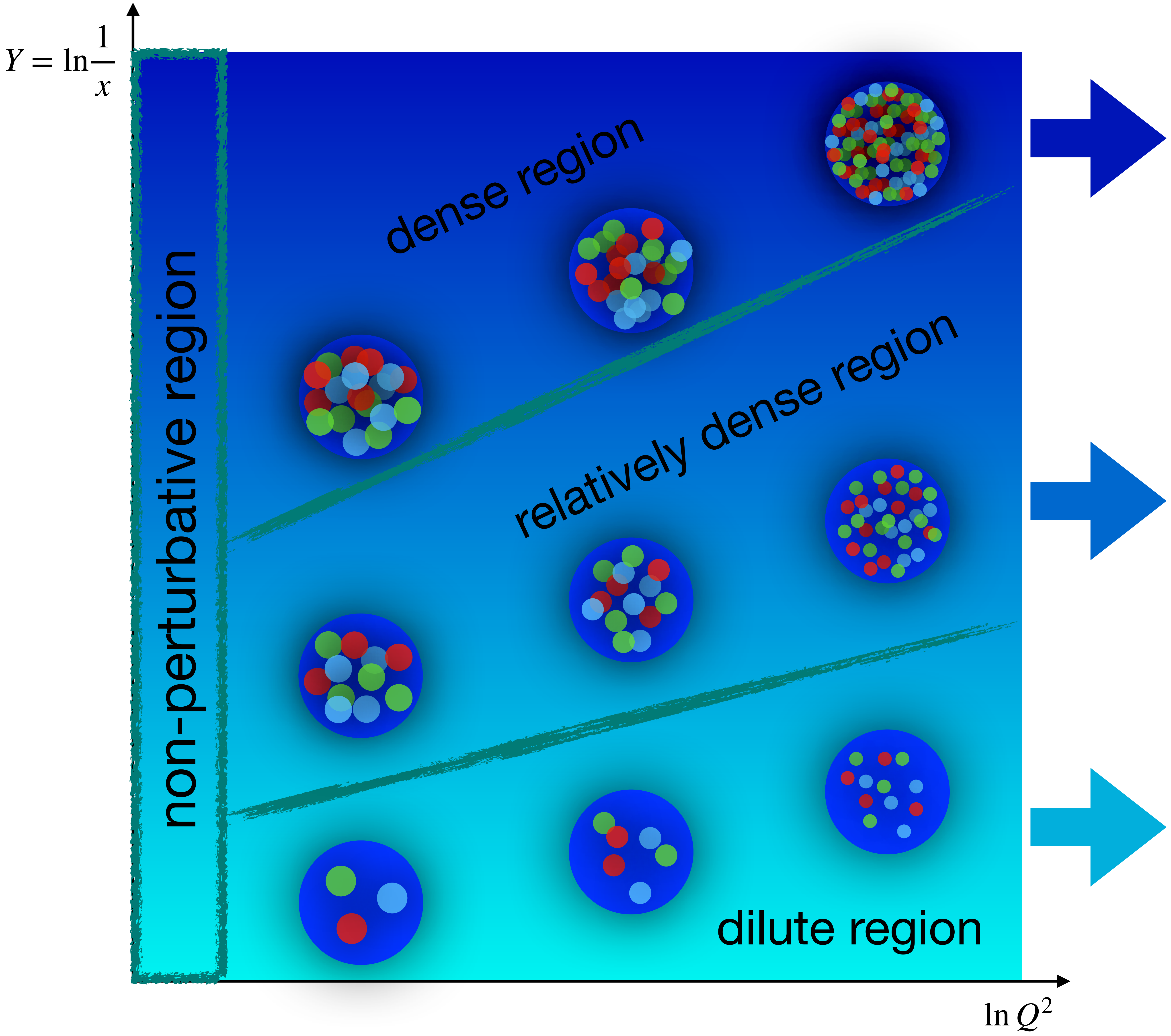
Alexey Vladimirov, Guillermo Portela, and Simone Rodini

Phys. Rev. Lett. **137**, 061902 (2026) - Published 3 August, 2026

A proof-of-concept global QCD fit finds the quark-gluon-quark interference comparable in size to polarized quark density contributions, which suggests a more quantum nature of the proton than assumed.



QCD "phase diagram" for nuclei



Dense region: $x \ll \mathcal{O}(1)$

Probing length $\lambda \sim 1/xp \gg L \sim A^{1/3}$

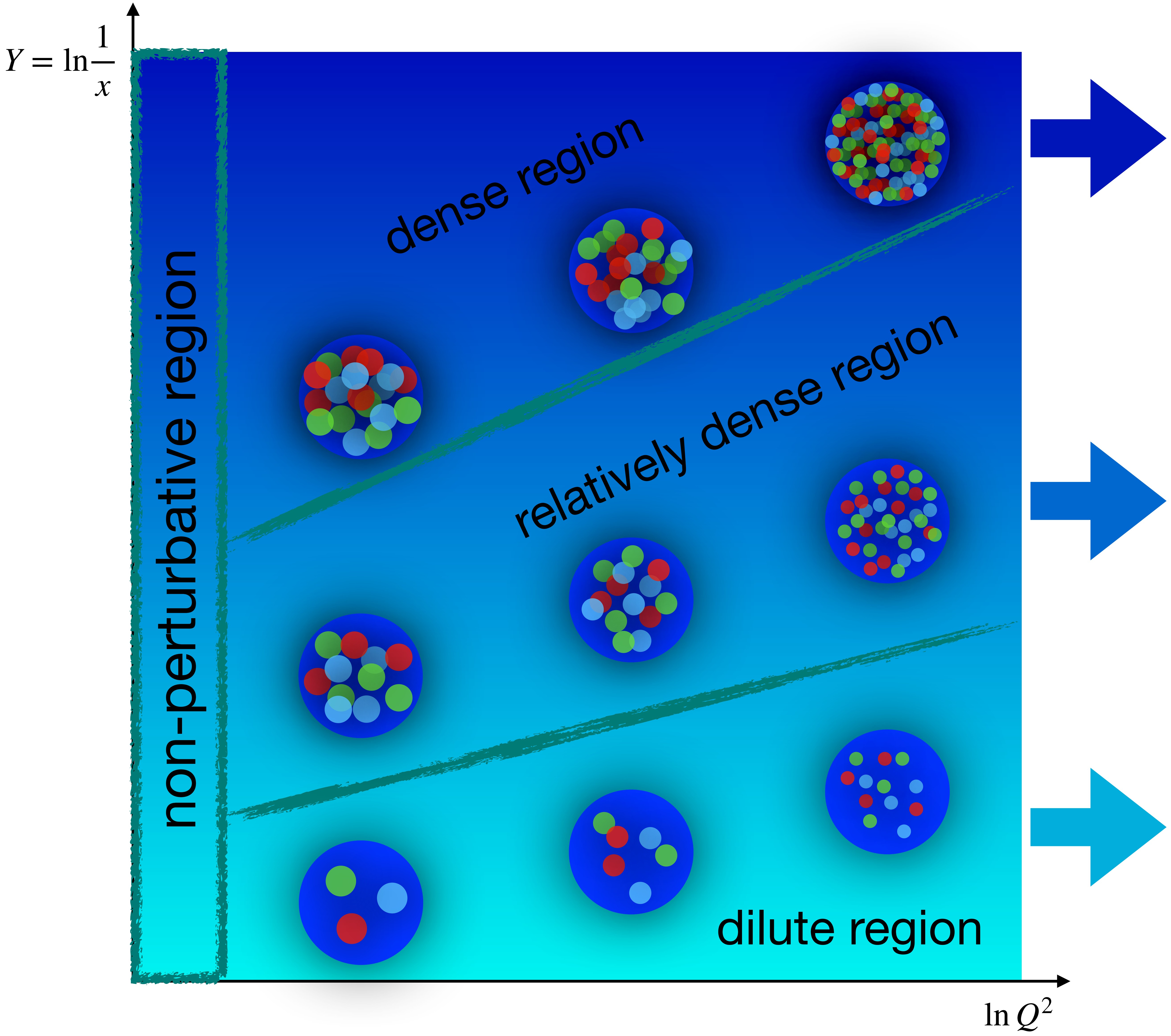
Relatively dense region: $x \lesssim \mathcal{O}(1)$

Probing length $\lambda \sim 1/xp \lesssim L \sim A^{1/3}$

Dilute region: $x \sim \mathcal{O}(1)$

Probing length $\lambda \sim 1/xp \ll L \sim A^{1/3}$

QCD factorization from dilute to dense region



Color Glass Condensate (CGC)

Wilson lines, nonlinear BK/JIMWLK evolution

See review: Gelis, Iancu, Venugopalan, 2003

High-twist formalism

Multi-parton correlation, DGLAP-type evolution

Qiu, Stermann, 1991

Kang, Wang, Wang, **Xing**, 2014

Leading twist collinear factorization

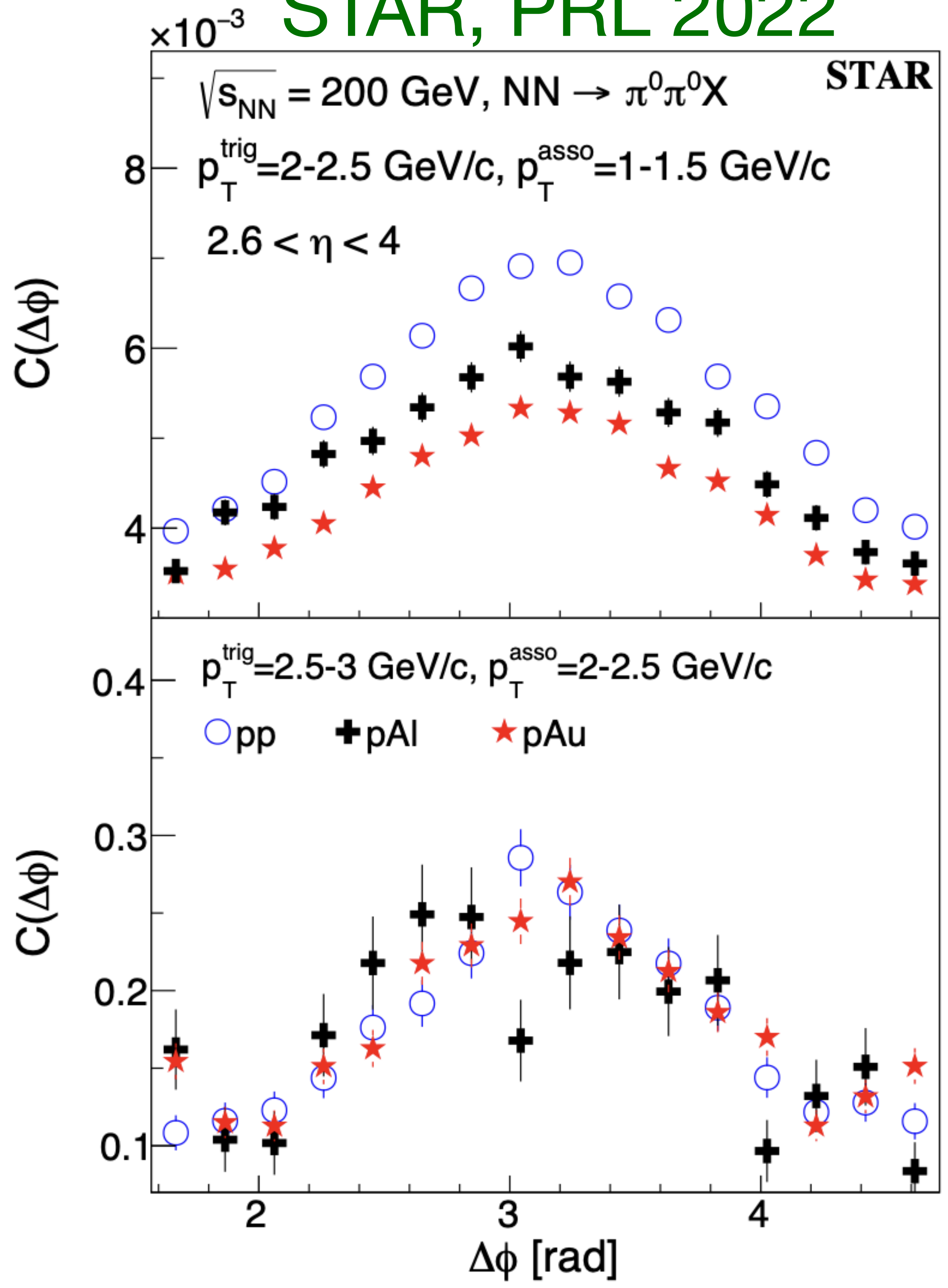
PDF, DGLAP evolution

Collins, Soper, 1981

CGC evidence from STAR?

✦ Dihadron correlation in pA collisions

STAR, PRL 2022



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Evidence for Nonlinear Gluon Effects in QCD and Their Mass Number Dependence at STAR

M. S. Abdallah[5], B. E. Aboona[55], J. Adam[6], L. Adamczyk[2], J. R. Adams[39], J. K. Adkins[30], G. Agakishiev[28], I. Aggarwal[41], M. M. Aggarwal[41] *et al.* (STAR Collaboration)

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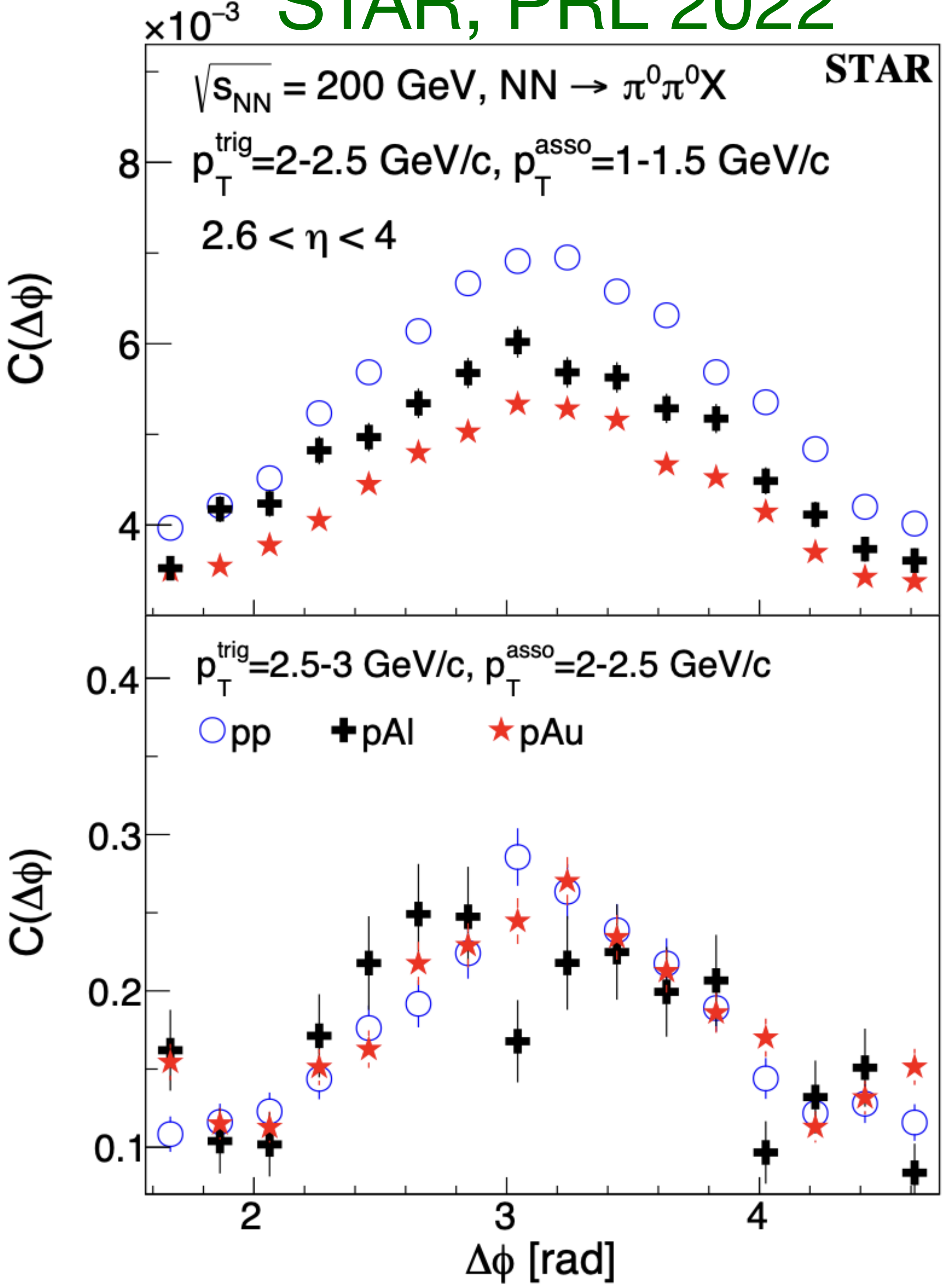
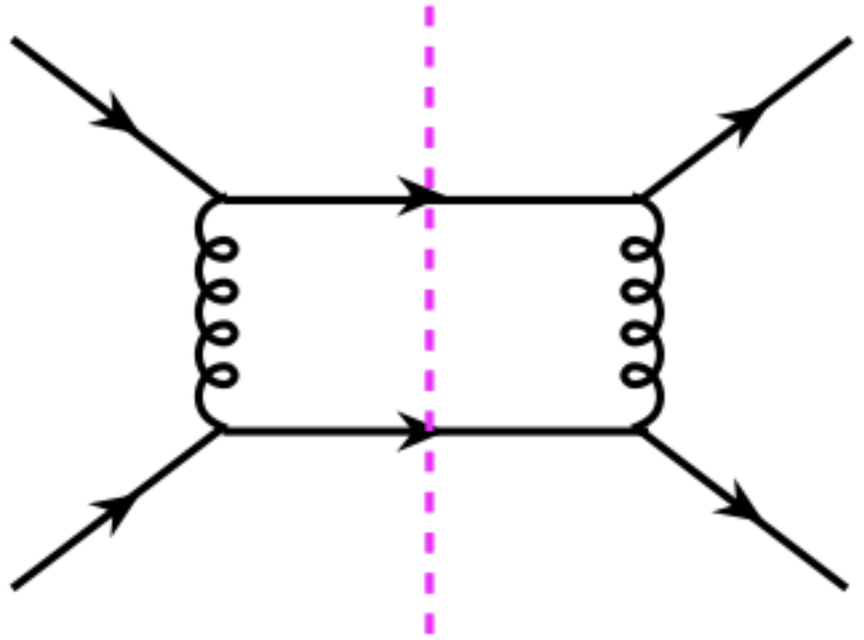
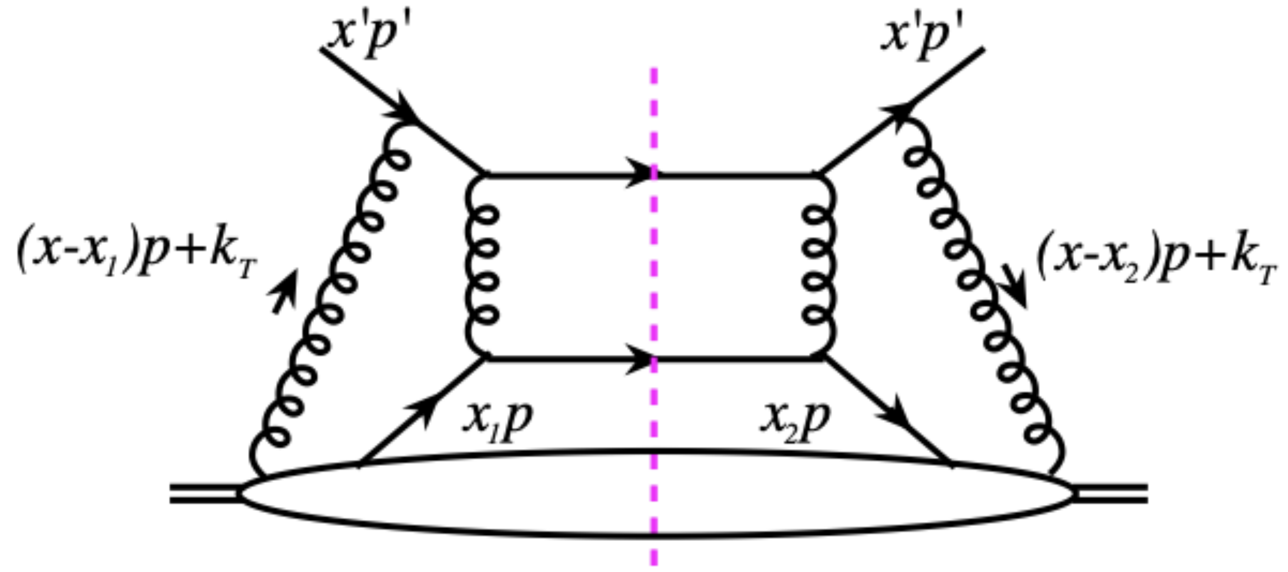
CGC evidence from STAR?

✦ Dihadron correlation in pA collisions

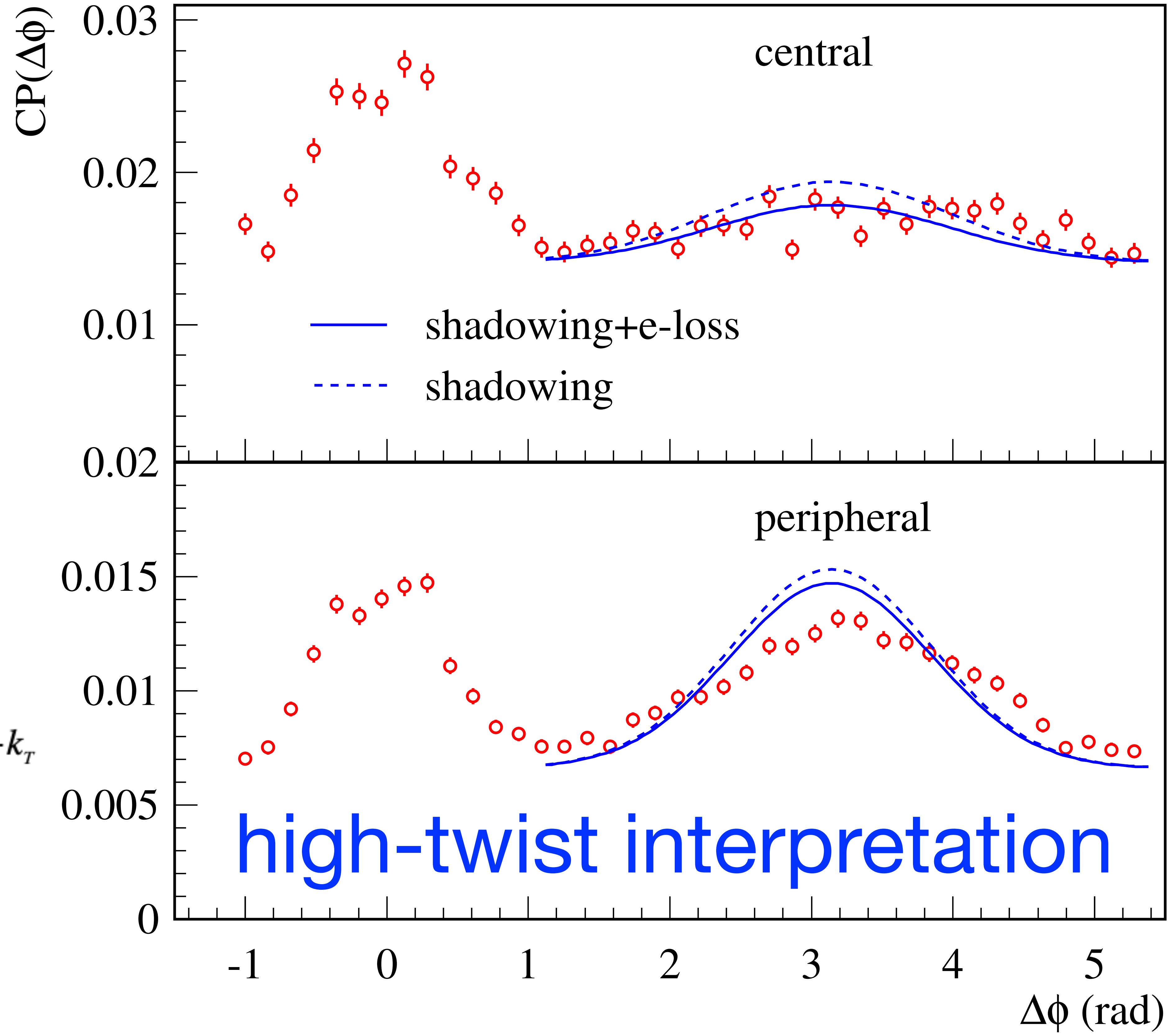
STAR, PRL 2022





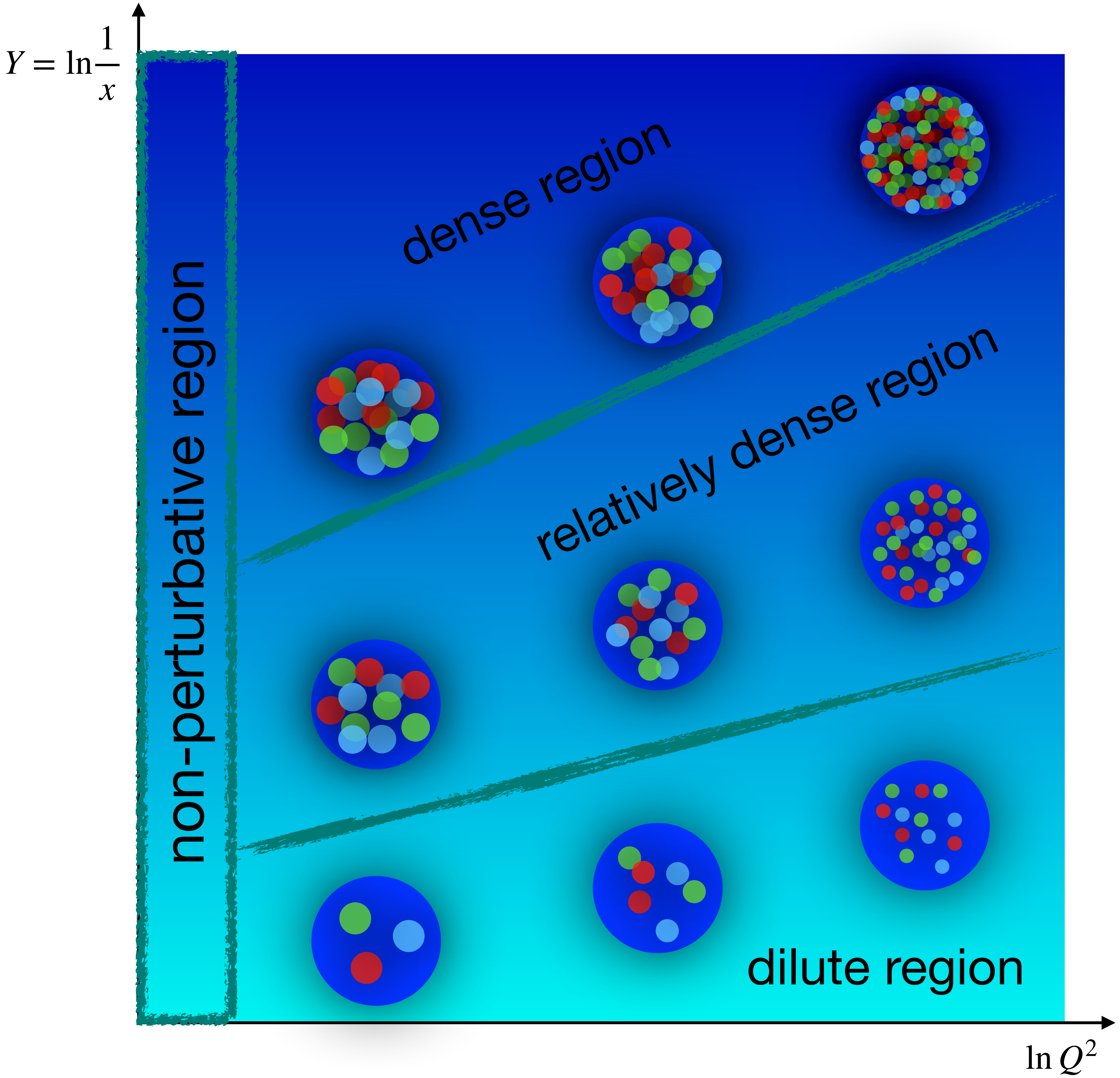


Kang, Vitev, Xing, PRD 2012

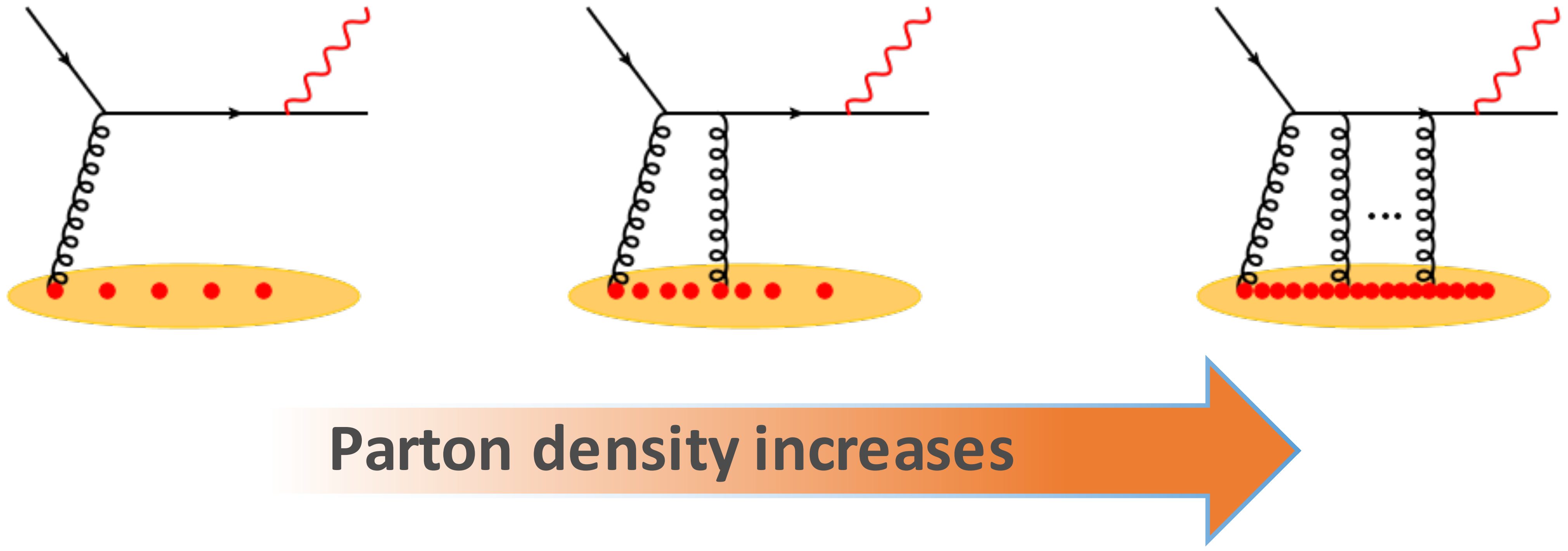


- Both CGC and high-twist expansion can describe the backward suppression and broadening, which one is correct?

A unified factorization from dilute to dense region



✦ Photon production in pA collisions



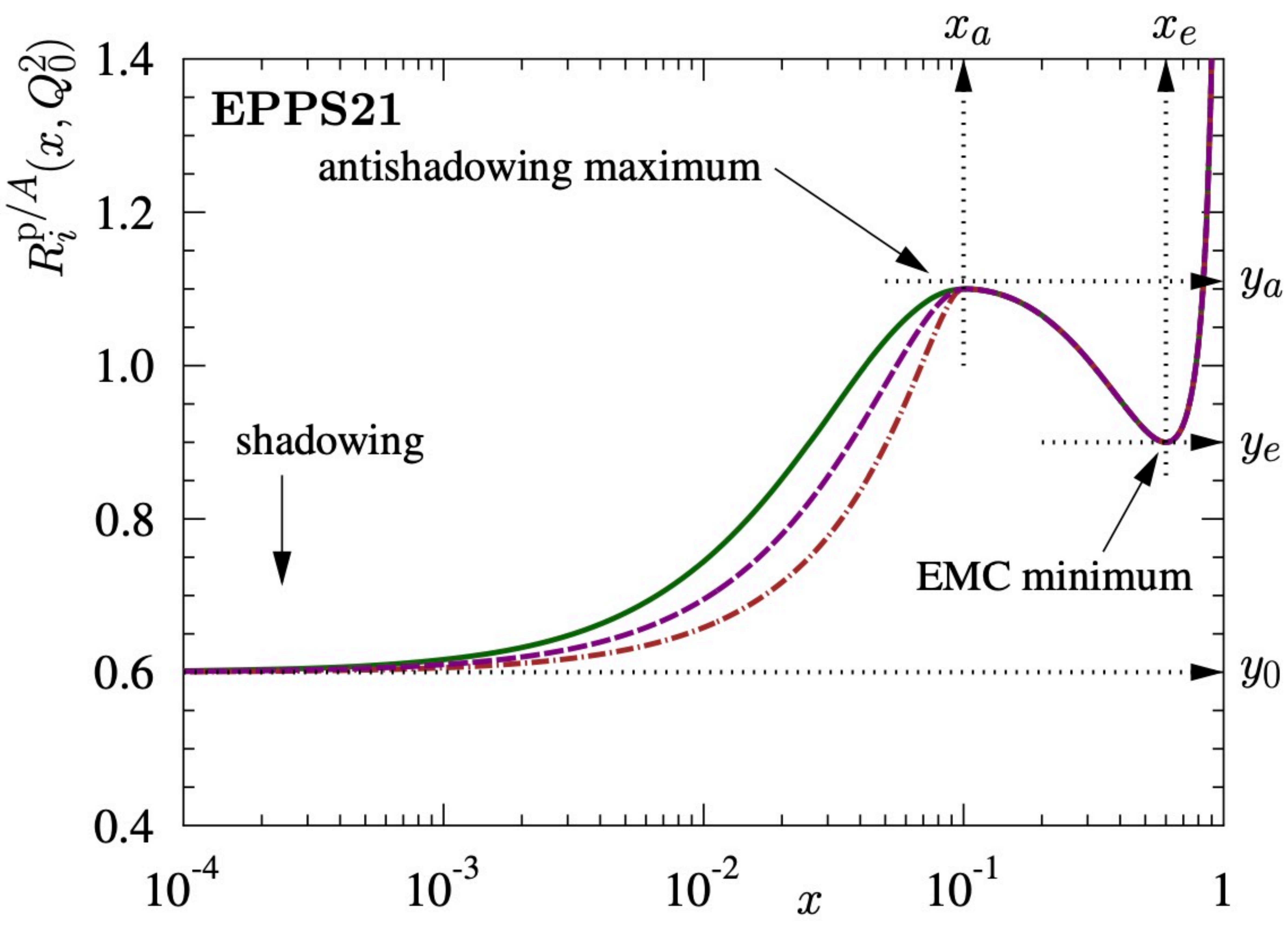
$$E_\gamma \frac{d\sigma^{\mathrm{CGC_{sub}}}}{d^3 \boldsymbol{p}_\gamma}\bigg|_{p_{\gamma\perp} > Q_s} = E_\gamma \frac{d\sigma^{\mathrm{LT}}}{d^3 \boldsymbol{p}_\gamma} + E_\gamma \frac{d\sigma^{\mathrm{T4}}}{d^3 \boldsymbol{p}_\gamma} + \cdots$$

leading twist   twist-4

Fu, Kang, Salazar, Wang, **HX**, PRL 2025

Fu, Kang, Salazar, Wang, **HX**, PRD 2025

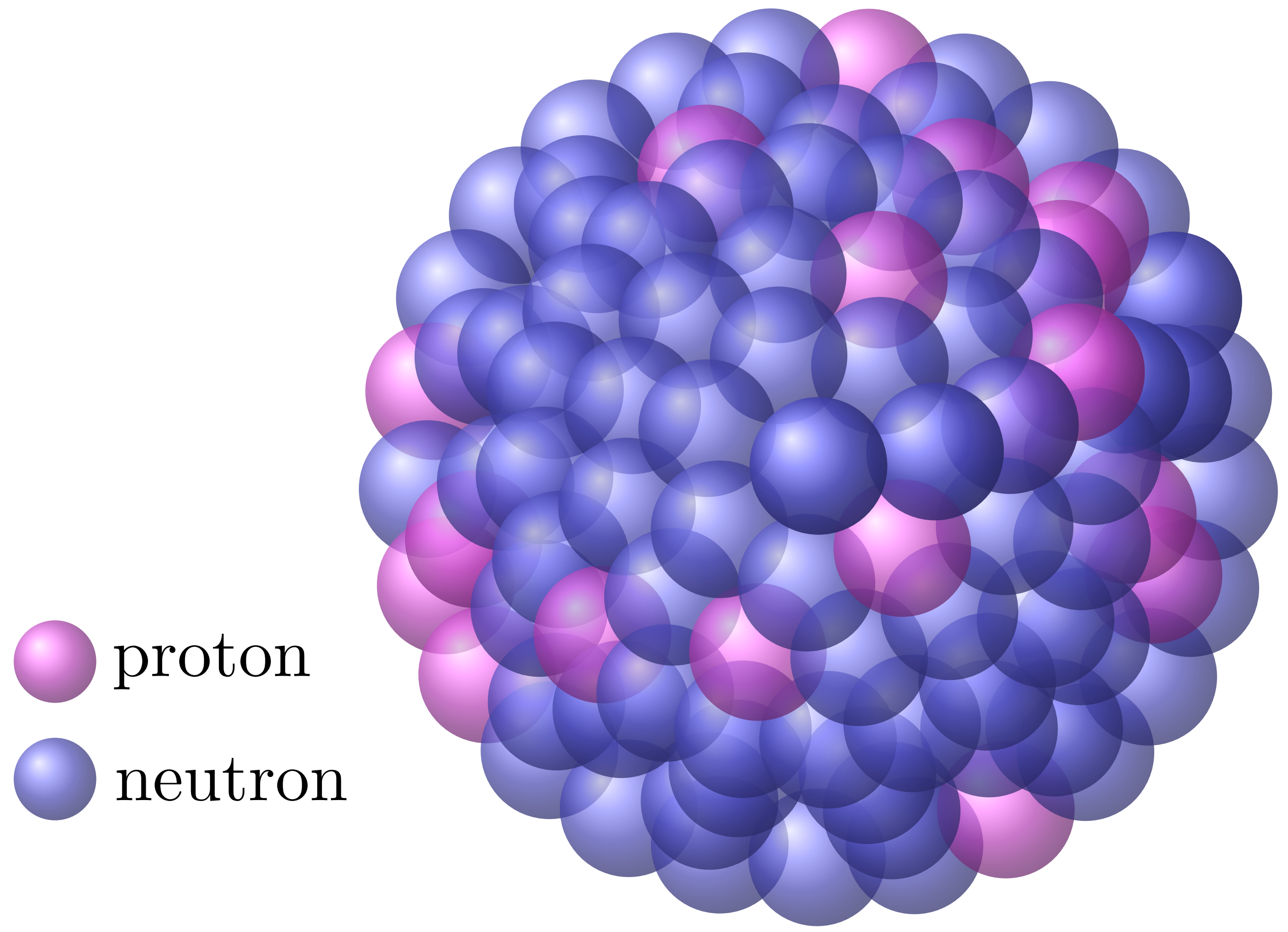
From partonic structure to nucleon structure

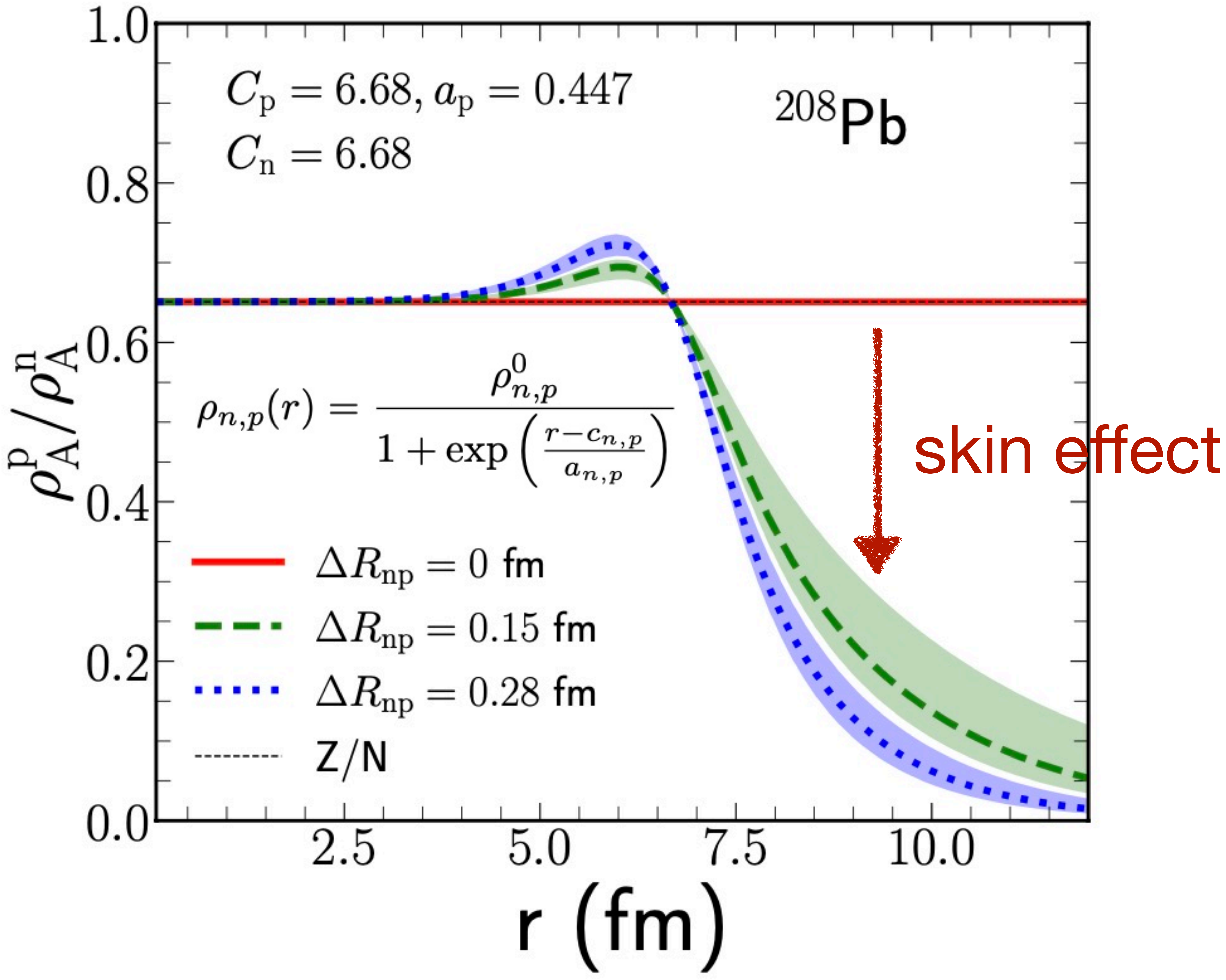


How to link the nuclear structure in two different scales?

Neutron skin

✦ Woods-Saxon nuclear distribution





Neutron skin from elastic scattering

✦ Current knowledge on neutron skin

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

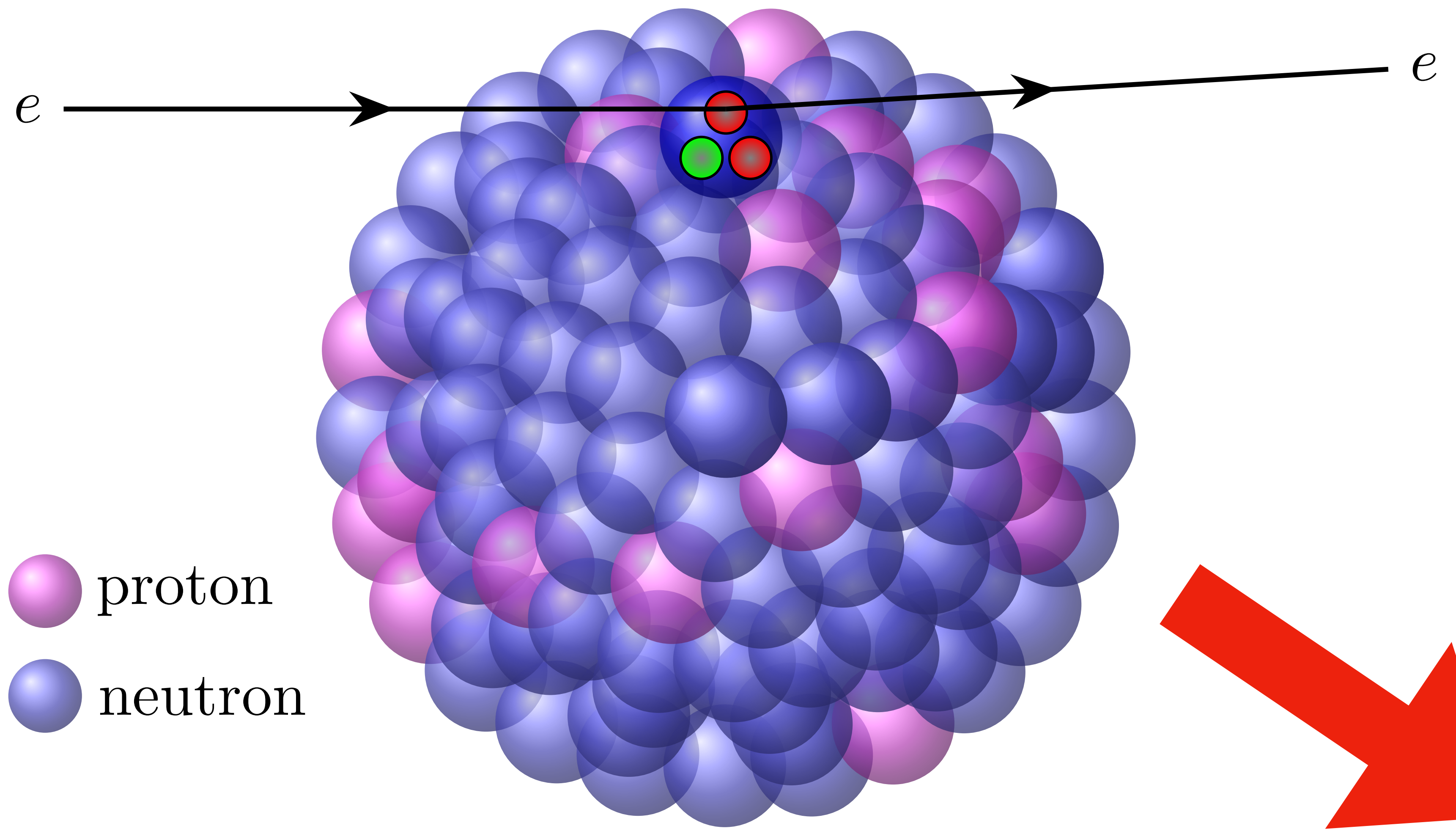


TABLE I. Values of the neutron skins in ^{208}Pb from a variety of experimental methods.

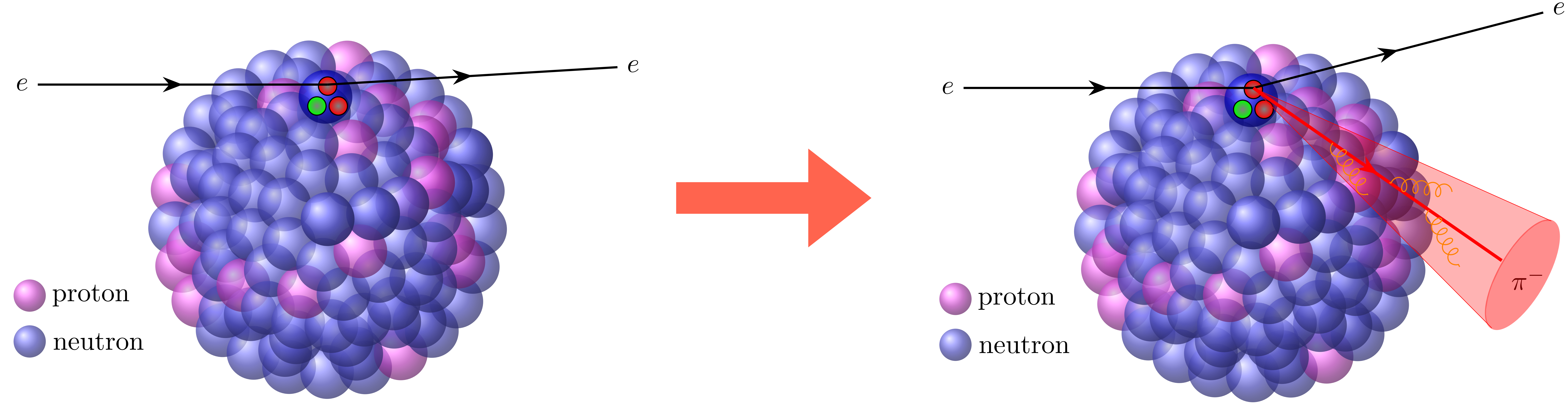
Type of measurement	Extracted neutron skin in ^{208}Pb
Proton-nucleus scattering [6]	0.083 - 0.111
Proton-nucleus scattering [7]	0.20 ± 0.04
Polarized proton-nucleus scattering [8]	0.16 ± 0.05
Polarized proton-nucleus scattering [9]	$0.211\ ^{+0.054}_{-0.063}$
Pionic probes [10]	0.11 ± 0.06
Coherent π photoproduction [11]	$0.15 \pm 0.03^{+0.01}_{-0.03}$
Coherent π photoproduction [12]	$0.20\ ^{+0.01}_{-0.03}$
Antiprotonic atoms [13]	$0.20\ (\pm 0.04)\ (\pm 0.05)$
Antiprotonic atoms [14]	$0.16\ (\pm 0.02)\ (\pm 0.04)$
Antiprotonic atoms [15]	0.15 ± 0.02
Electric dipole polarizability [16]	0.13 - 0.19
Electric dipole polarizability [17]	$0.165\ (\pm 0.09)(\pm 0.013)\ (\pm 0.021)$
Electric dipole polarizability *via* polarized scattering at forward angle [18]	$0.156\ ^{+0.025}_{-0.021}$
Pygmy dipole resonances [22]	0.18 ± 0.035
(α, α') GDR 120 MeV [23]	0.19 ± 0.09
parity-violating electron scattering[19]	$0.33^{+0.16}_{-0.18}$
parity-violating electron scattering[20]	0.283 ± 0.071

crucial for constraining the fundamental properties of cold nuclear matter and the equation of state of neutron star

Neutron skin from deep inelastic scattering

- A new proposal in deep inelastic scattering at EIC

Zhang (张善良), Wang, Wang, **HX**, 2506.10694



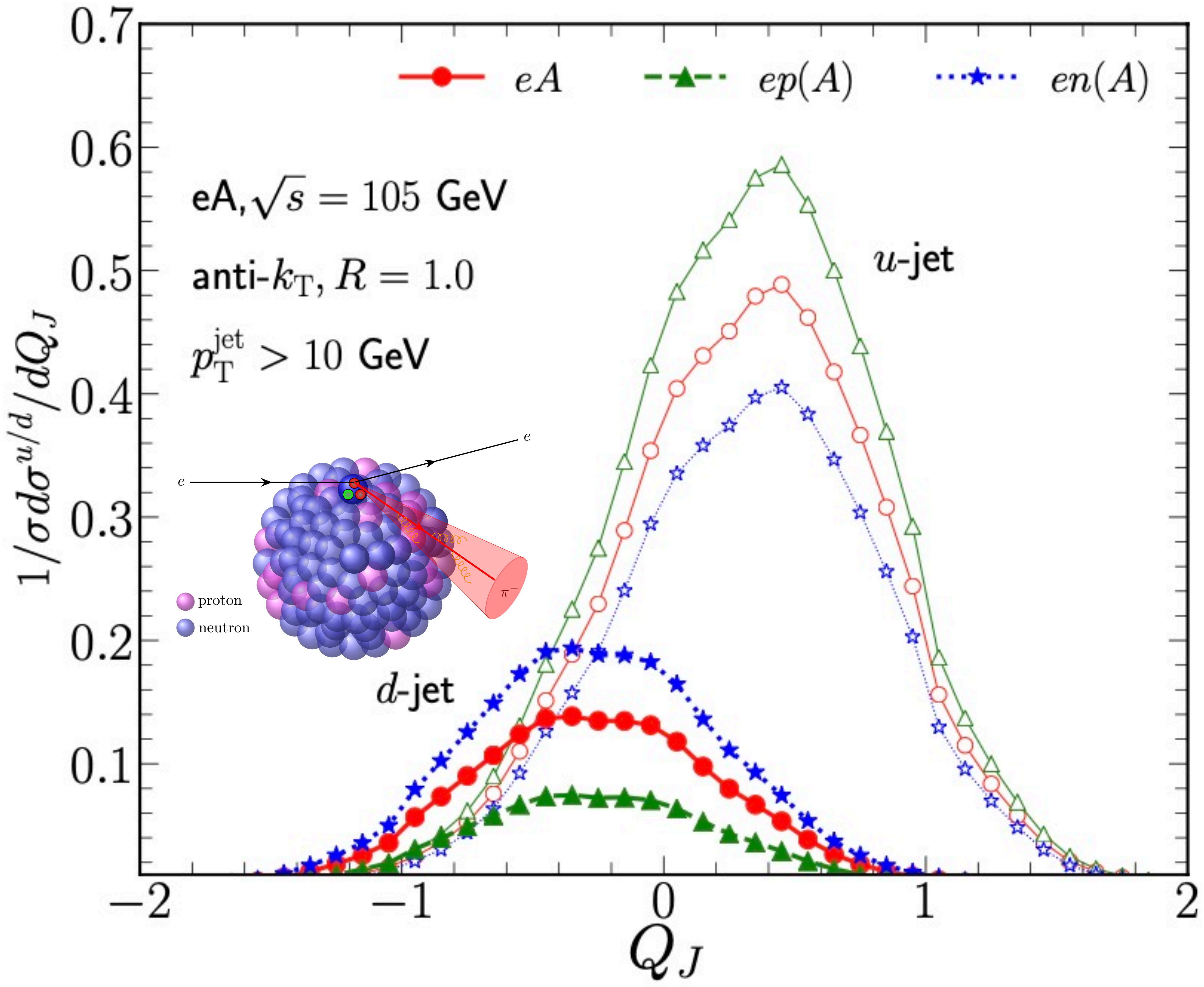
Linking physics phenomena at both low and high collision energies

Neutron skin from deep inelastic scattering

- ✦ Jet charge in deep inelastic scattering
  - TMD factorization

$$\frac{d\sigma}{dQ_J} = \sum_i e_i^2 \mathcal{F.T.}\Big\{\tilde{f}_{i/A}(x, b_T) S_J(b_T, R) \times H_{ei\to ei}(Q)\mathcal{G}_i(Q_J, p_T^J R)\Big\},$$

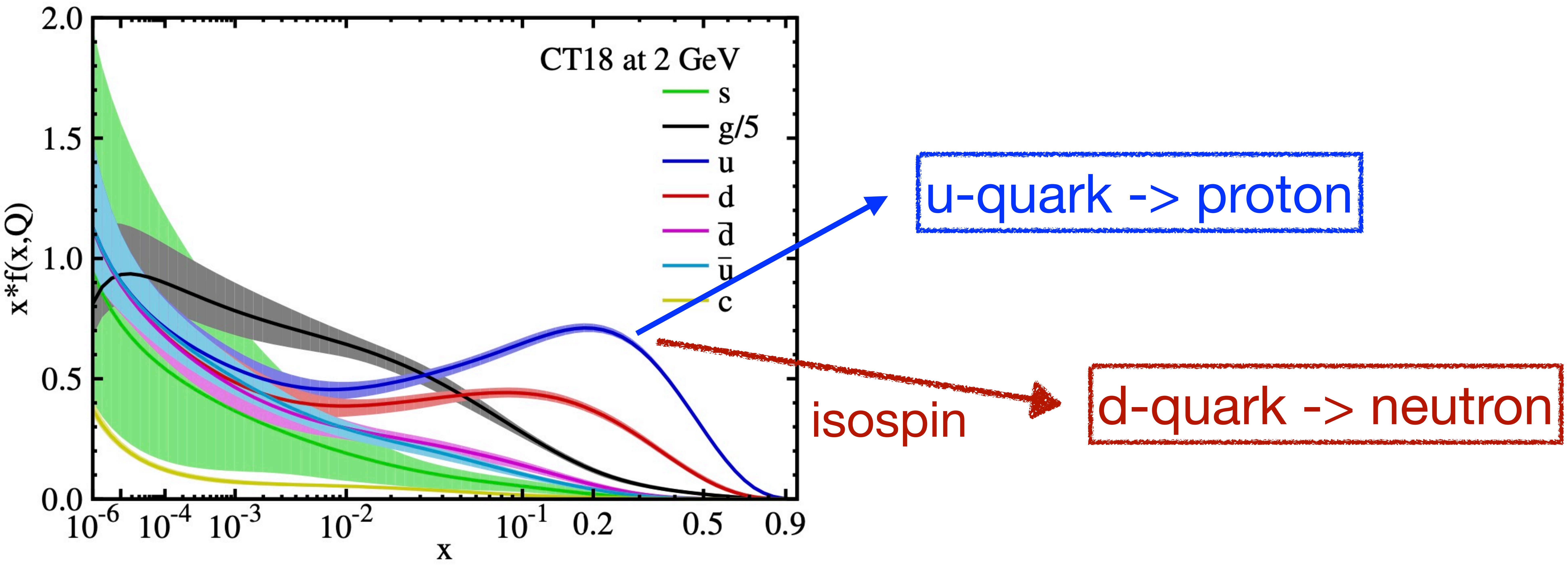
$$Q_J = \sum_{h\in \text{jet}} \left(\frac{p_T^h}{p_T^J}\right)^{\kappa} Q_h$$



Intrinsic correlation between final-state jet charge distribution and initial-state partonic distributions in nucleons

Neutron skin from deep inelastic scattering

✦ Using PDFs to tag flavor information of nucleon

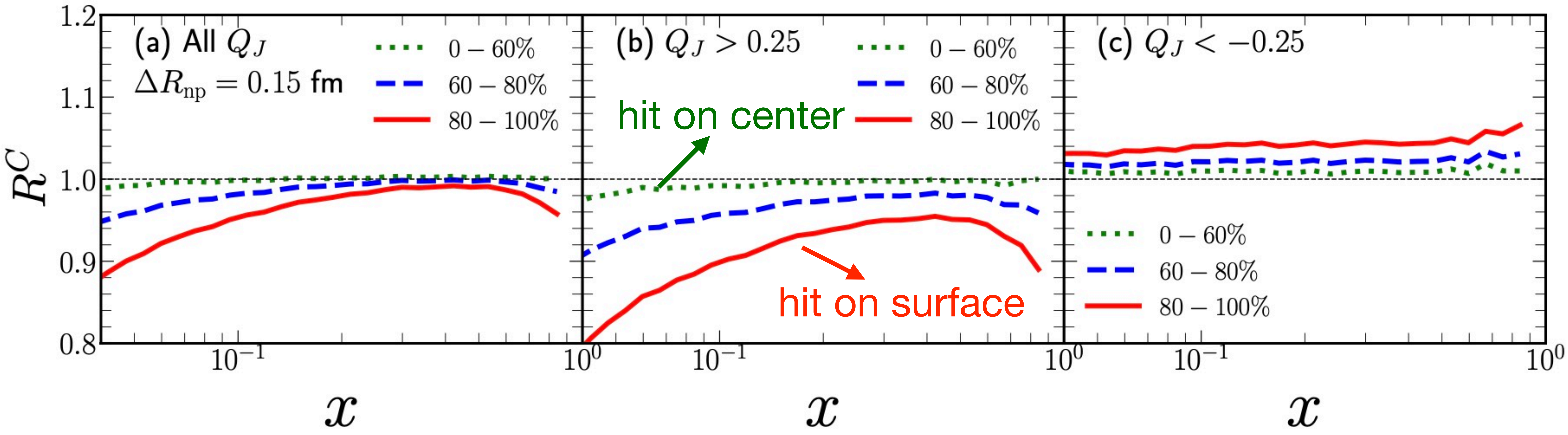


• Correlation between struck nucleon and PDFs using isospin symmetry

Neutron skin from deep inelastic scattering

✦ Centrality-dependent nuclear modification

$$R^C(x, Q_J) = \frac{d\sigma^{\mathrm{C}}/dxdQ_J}{d\sigma^{\mathrm{MB}}/dxdQ_J}$$



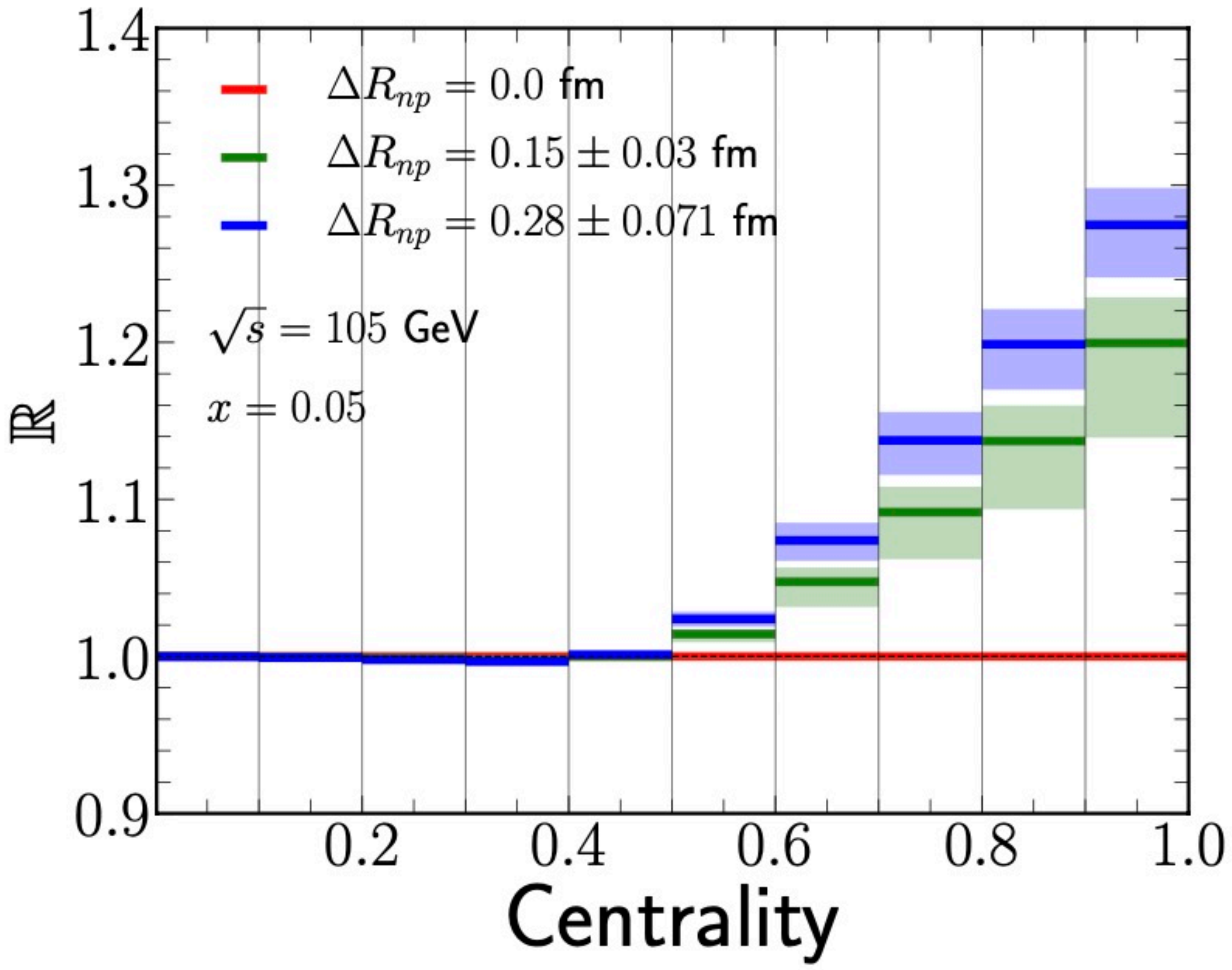
- Positive (negative) jet charge suppression (enhancement) in e+Pb collision
- A proxy for the spatial position of the struck nucleon within the nucleus

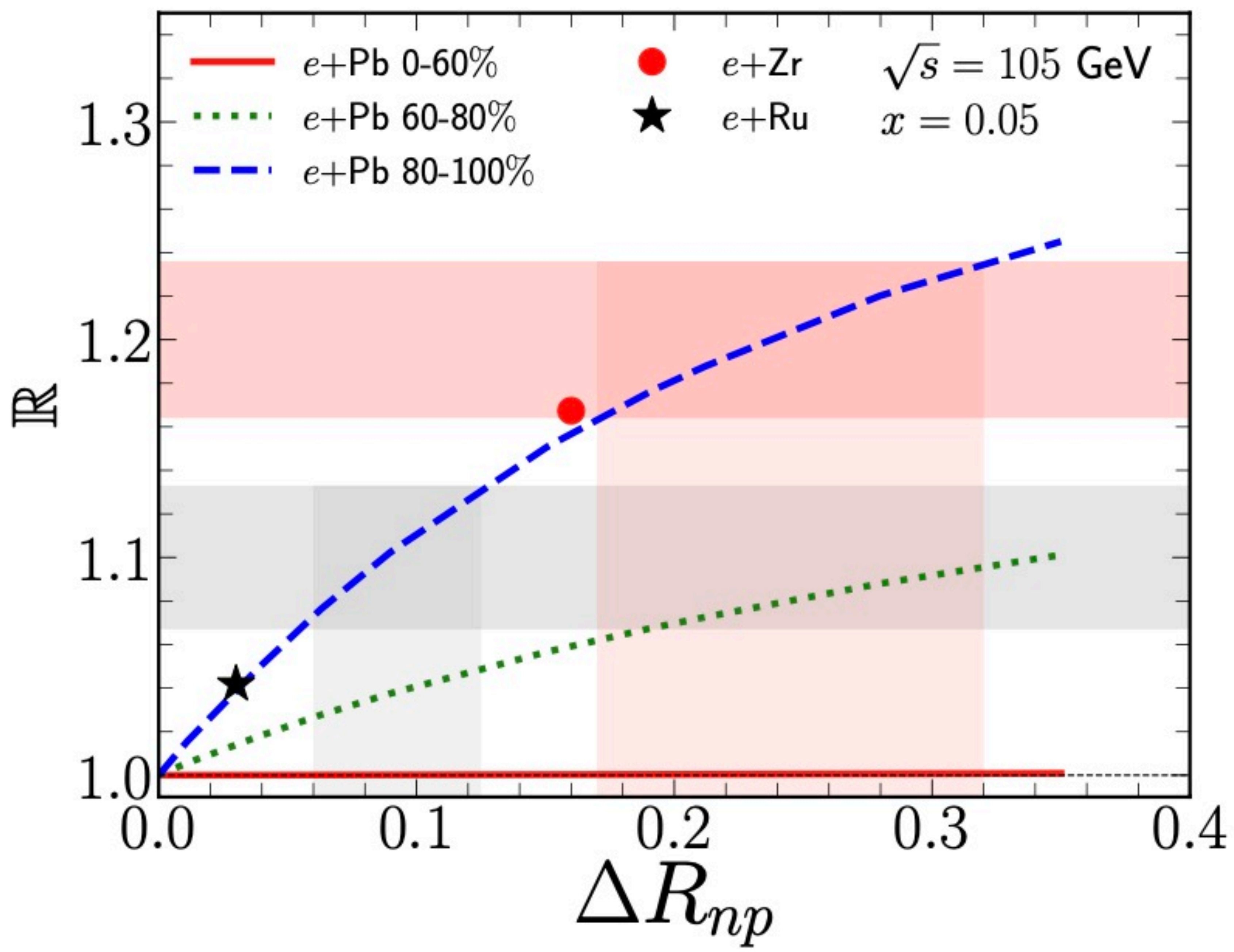
Neutron skin from deep inelastic scattering

✦ Centrality-dependent nuclear modification: double ratio

$$\mathbb{R} \equiv \frac{R^C(x, Q_J \leq -Q_c)}{R^C(x, Q_J \geq Q_c)} = \frac{d\sigma^{\mathrm{C}}/dxdQ_J|_{Q_J\leq -Q_c}}{d\sigma^{\mathrm{C}}/dxdQ_J|_{Q_J\geq Q_c}} \frac{d\sigma^{\mathrm{MB}}/dxdQ_J|_{Q_J\geq Q_c}}{d\sigma^{\mathrm{MB}}/dxdQ_J|_{Q_J\leq -Q_c}}$$

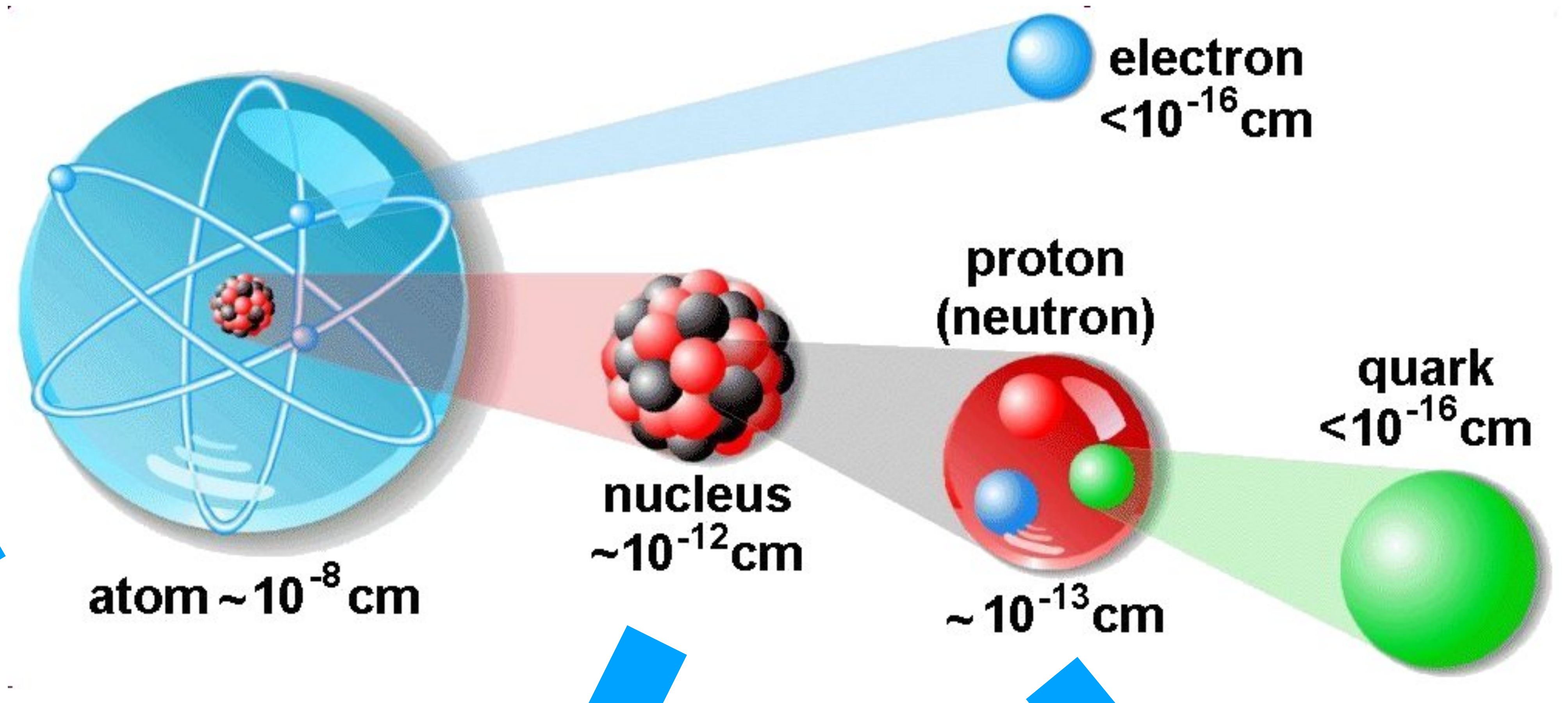
Zhang, Wang, Wang, **HX**, 2506.10694



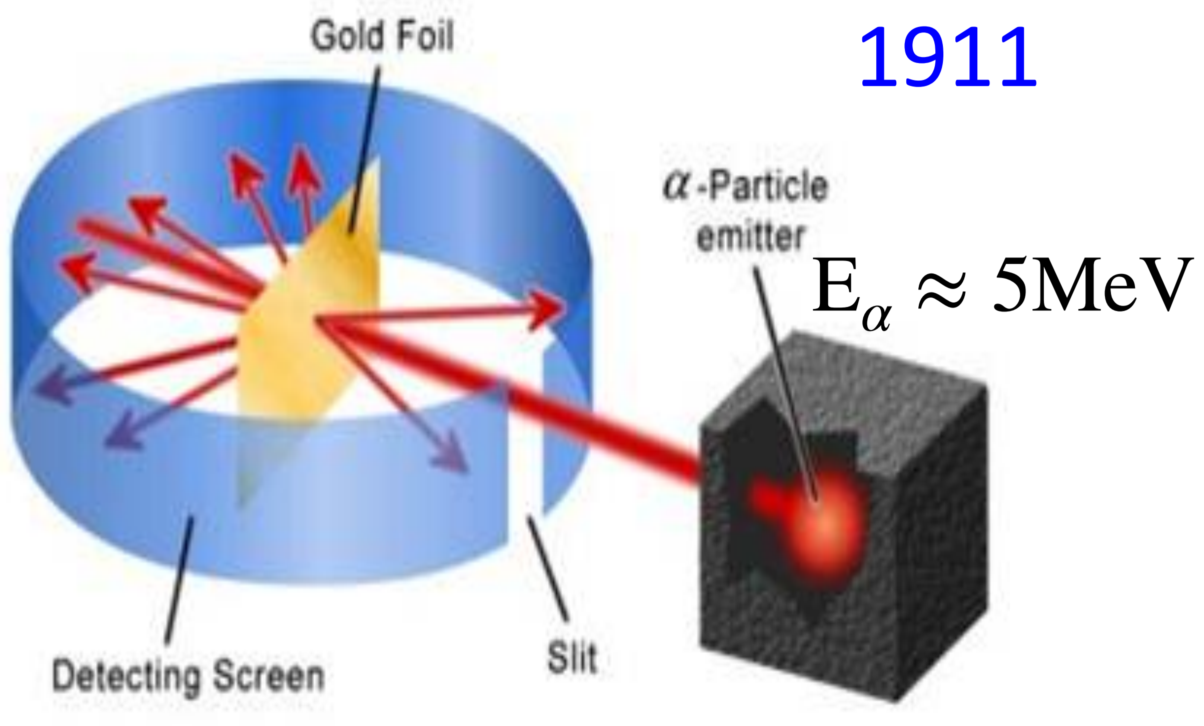


- Jet charge distribution in eA DIS: a novel probe for high precision determination of neutron skin thickness
- Stay tuned for hard probes in HICs

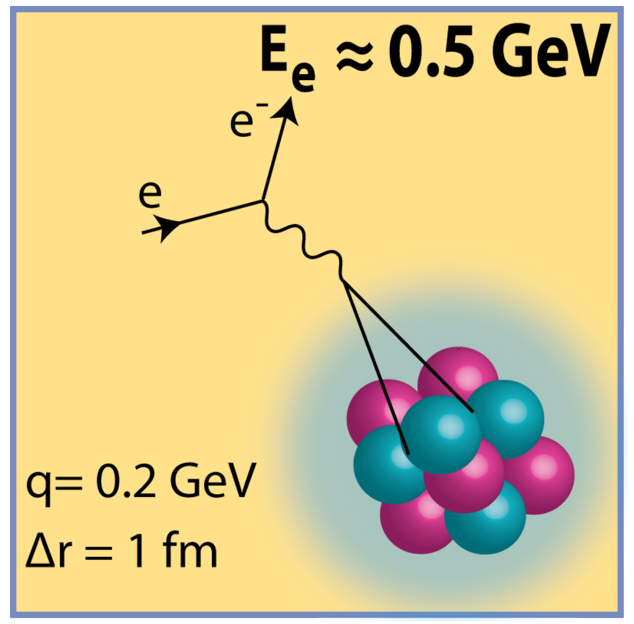
Summary

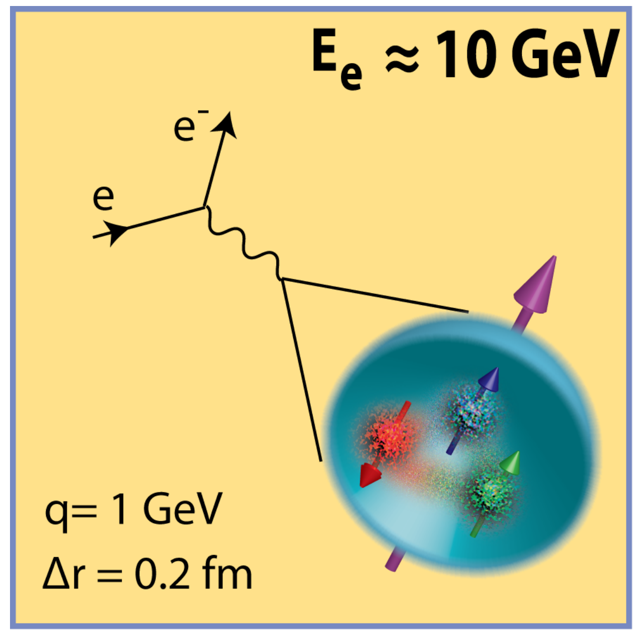


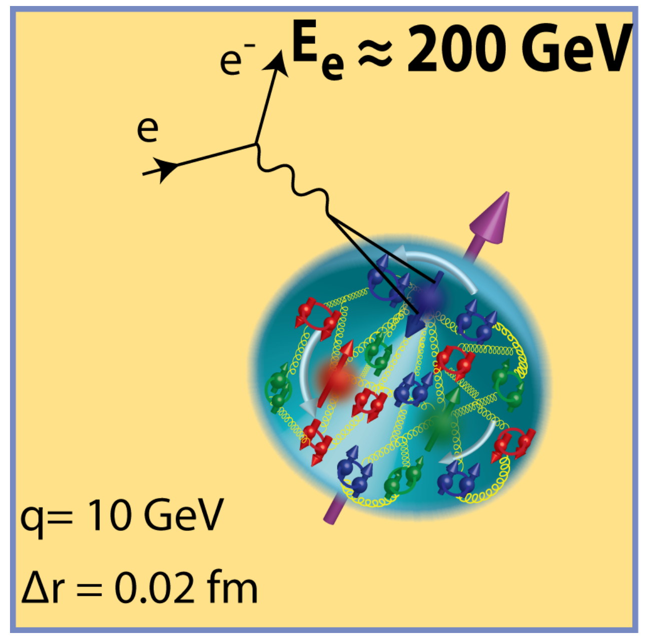
1911



Rutherford scattering







Probing nuclear structure at different scales in high energy scatterings

Thanks for your attention!

Backup

✦ Nuclear PDFs

$$f_{i/A}(x,\mu;b) = \frac{T_A^p(b)}{T_A(b)} f_i^{p/A}(x,\mu) + \frac{T_A^n(b)}{T_A(b)} f_i^{n/A}(x,\mu)$$

Thickness function: $T_A(b) = \int dz \rho_A(r)$

✦ Woods-Saxon parameters

TABLE I. WS parameters and neutron skin thickness for $^{208}_{82}$Pb, $^{96}_{44}$Ru and $^{96}_{40}$Zr used in our numerical calculations.

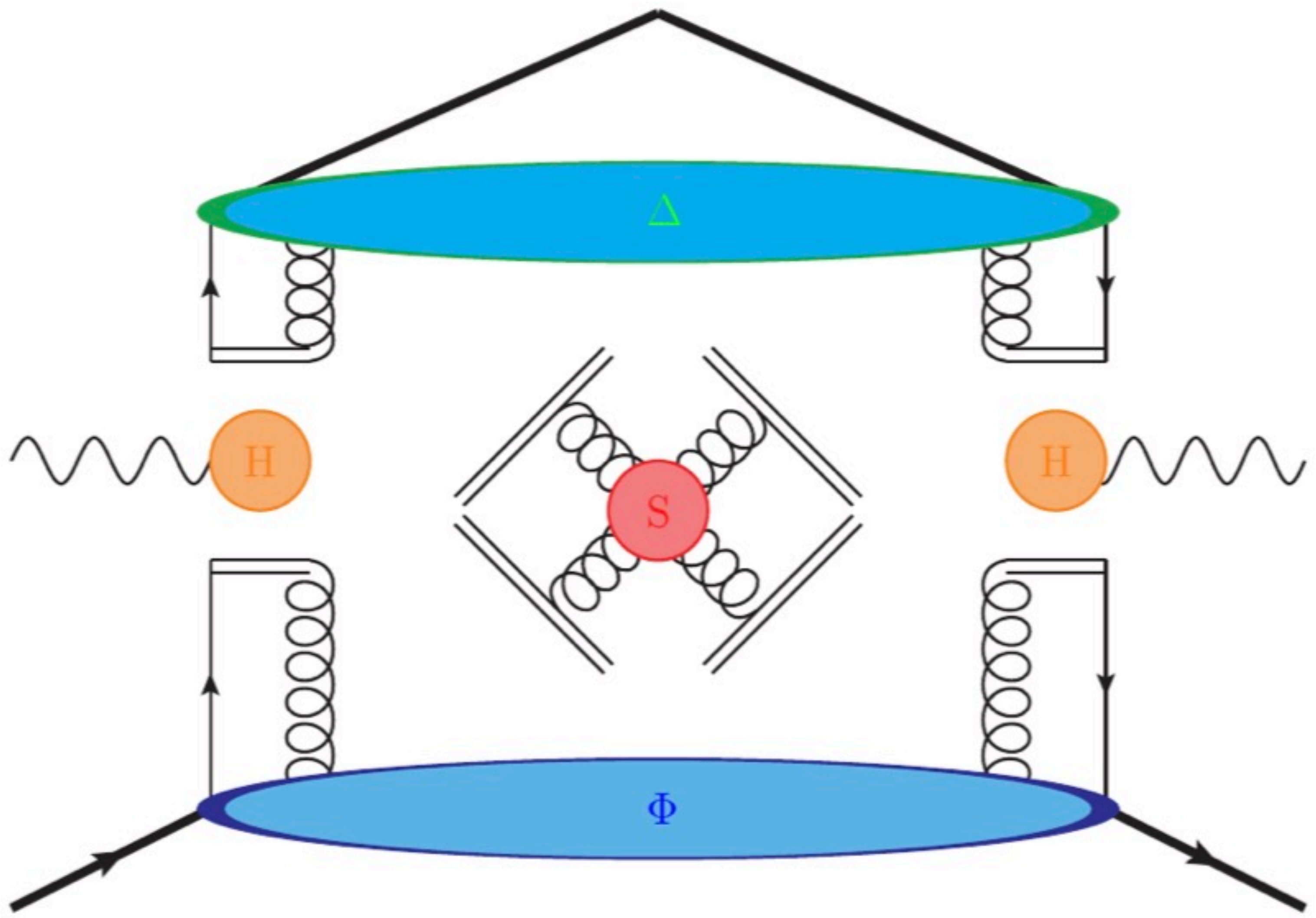
nucleus	c_p [fm]	a_p [fm]	c_n [fm]	a_n [fm]	ΔR_{np}
$^{208}_{82}$Pb [7]	6.68	0.448	6.69	0.448	0
$^{208}_{82}$Pb [7]	6.68	0.448	6.69	$0.566^{+0.028}_{-0.045}$	0.15 ± 0.03
$^{208}_{82}$Pb [10]	6.68	0.448	6.69	$0.654^{+0.044}_{-0.046}$	0.28 ± 0.071
$^{96}_{44}$Ru [21]	5.06	0.493	5.075	0.505	0.03
$^{96}_{40}$Zr [21]	4.915	0.521	5.015	0.574	0.16

$$\rho_{n,p}(r) = \frac{\rho^0_{n,p}}{1+\exp\left(\frac{r-c_{n,p}}{a_{n,p}}\right)}$$

Nuclear partonic structure - 3D imaging

✦ TMD factorization for cross section

$$\frac{d\sigma^A}{dx\,dQ^2\,dz\,d^2P_{h\perp}} = \sigma_0\,H(Q)\sum_q e_q^2 \int_0^\infty \frac{b\,db}{2\pi} J_0\left(\frac{bP_{h\perp}}{z}\right) f^A_{q/n}(x,b;Q)\,D^A_{h/q}(z,b;Q)$$



✦ TMDs

$$f^A_{q/n}(x,b;Q) = \left[C_{q\leftarrow i}\otimes f^A_{i/n}\right](x,\mu_{b_*})\exp\left\{-S_{\rm pert}(\mu_{b_*},Q) - S^f_{\rm NP}(b,Q,A)\right\}$$

$$D^A_{h/q}(z,b;Q) = \frac{1}{z^2}\left[\hat{C}_{i\leftarrow q}\otimes D^A_{h/i}\right](z,\mu_{b_*})\exp\left\{-S_{\rm pert}(\mu_{b_*},Q) - S^D_{\rm NP}(b,z,Q,A)\right\}$$

Our assumptions

- Perturbative information is left unchanged by the nuclear medium. $C_{q\leftarrow i}$, $\hat{C}_{i\leftarrow q}$, and $S_{\rm pert}$ are unchanged.
- Non-perturbative information is modified. $f^A_{i/n}$, $D^A_{h/i}$, $S^D_{\rm NP}$, and $S^f_{\rm NP}$ are altered.

Nuclear partonic structure - 3D

✦ TMDs

$$f^A_{q/n}(x,b;Q) = \left[C_{q\leftarrow i}\otimes f^A_{i/n}\right](x,\mu_{b_*})\exp\left\{-S_{\text{pert}}(\mu_{b_*},Q) - S^f_{\text{NP}}(b,Q,A)\right\}$$

$$D^A_{h/q}(z,b;Q) = \frac{1}{z^2}\left[\hat{C}_{i\leftarrow q}\otimes D^A_{h/i}\right](z,\mu_{b_*})\exp\left\{-S_{\text{pert}}(\mu_{b_*},Q) - S^D_{\text{NP}}(b,z,Q,A)\right\}$$

Collinear Distributions

We use the EPPS16 parameterization for $f^A_{i/n}$ (NLO). EPPS, EPJC 2017

We use the LIKEn parameterization for $D^A_{h/i}$ (NLO). Zurita, 2021

Perturbative order in our analysis

Work at NLO+NNLL for the TMDs.

Non-perturbative parametrization

$$S^f_{\text{NP}}(b,Q,A) = S^f_{\text{NP}}(b,Q) + a_N\left(A^{1/3}-1\right)b^2$$

$$S^D_{\text{NP}}(z,b,Q,A) = S^D_{\text{NP}}(z,b,Q) + b_N\left(A^{1/3}-1\right)\frac{b^2}{z^2}$$