Nuclear effect at EIC

- nTMD & neutron skin

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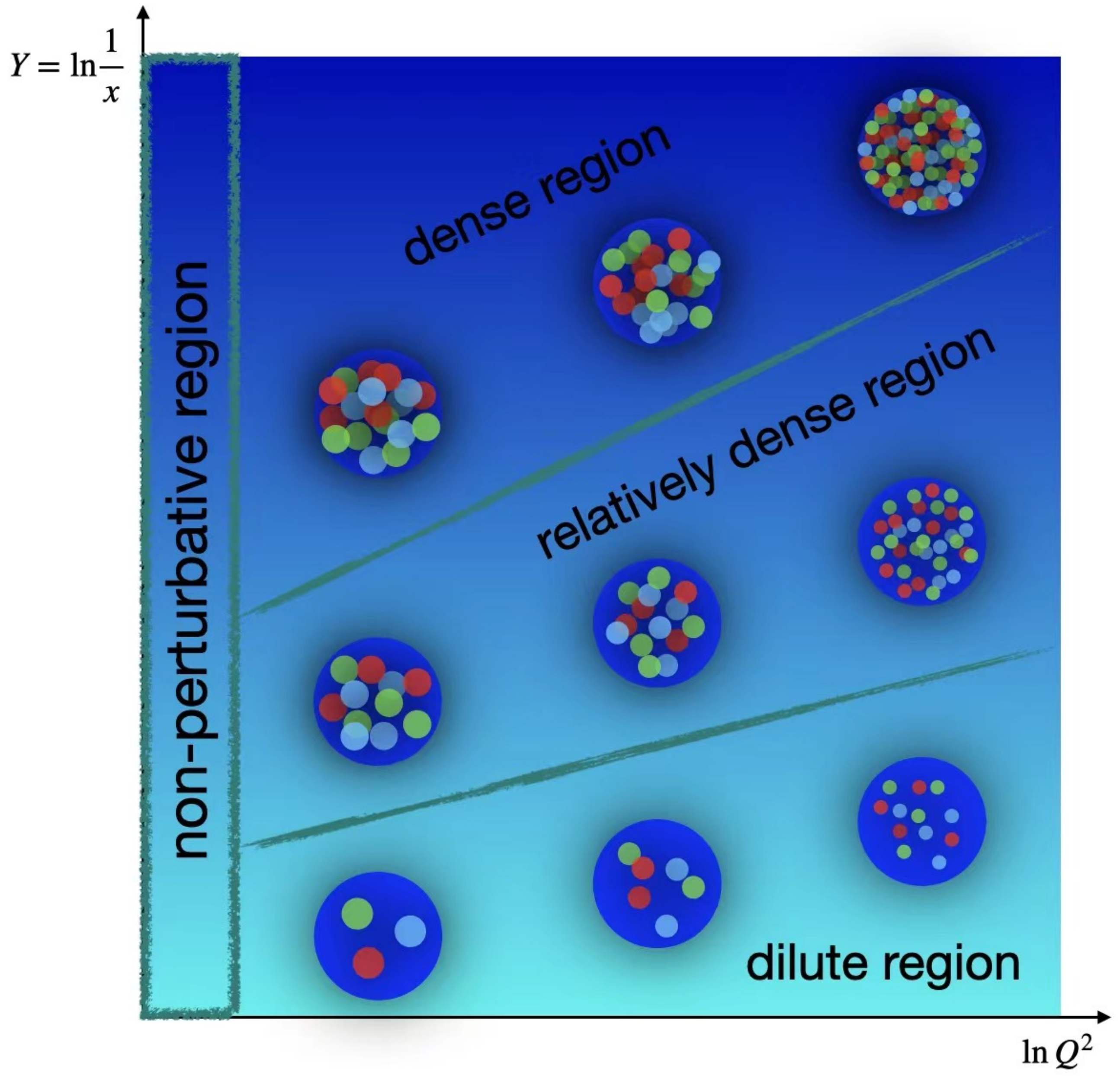
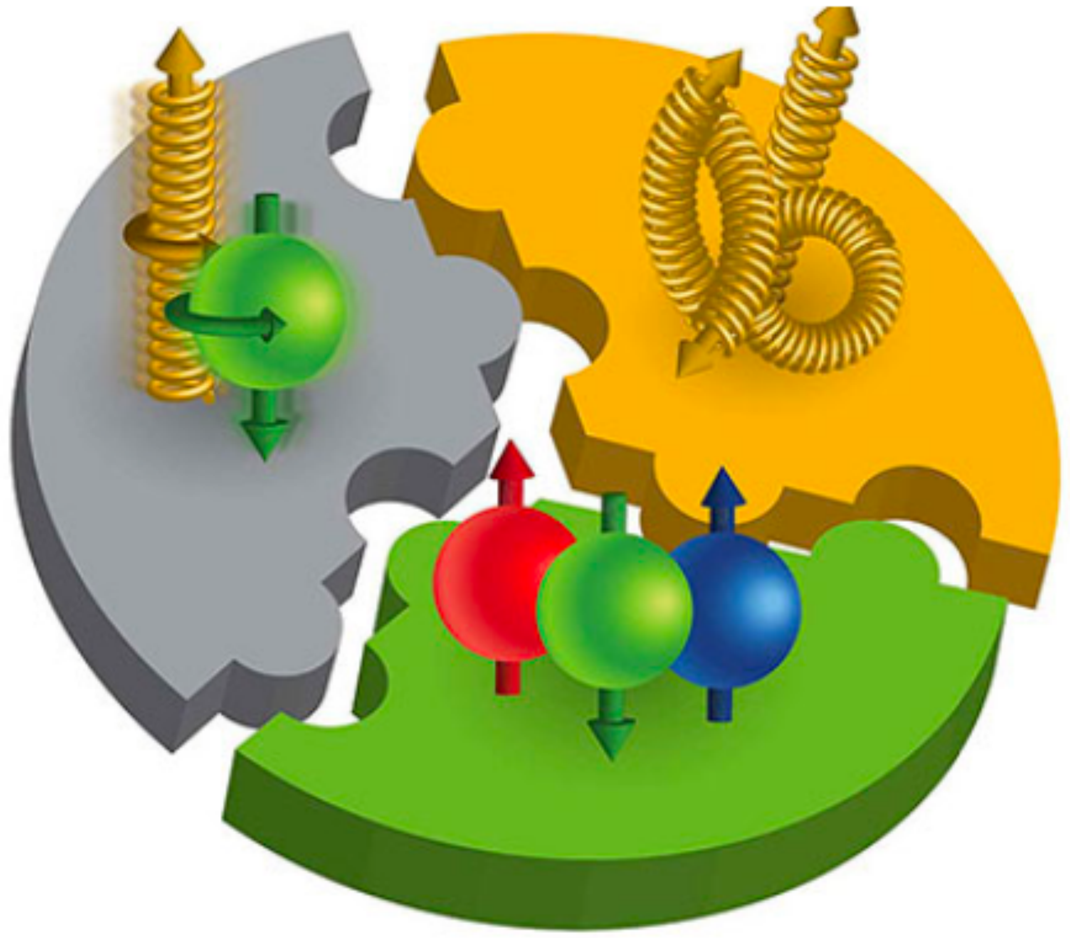
Outline

- ✦ Introduction
- ✦ Nuclear TMDs from global analysis
- ✦ Neutron Skin from hard probe at EIC
- ✦ Summary

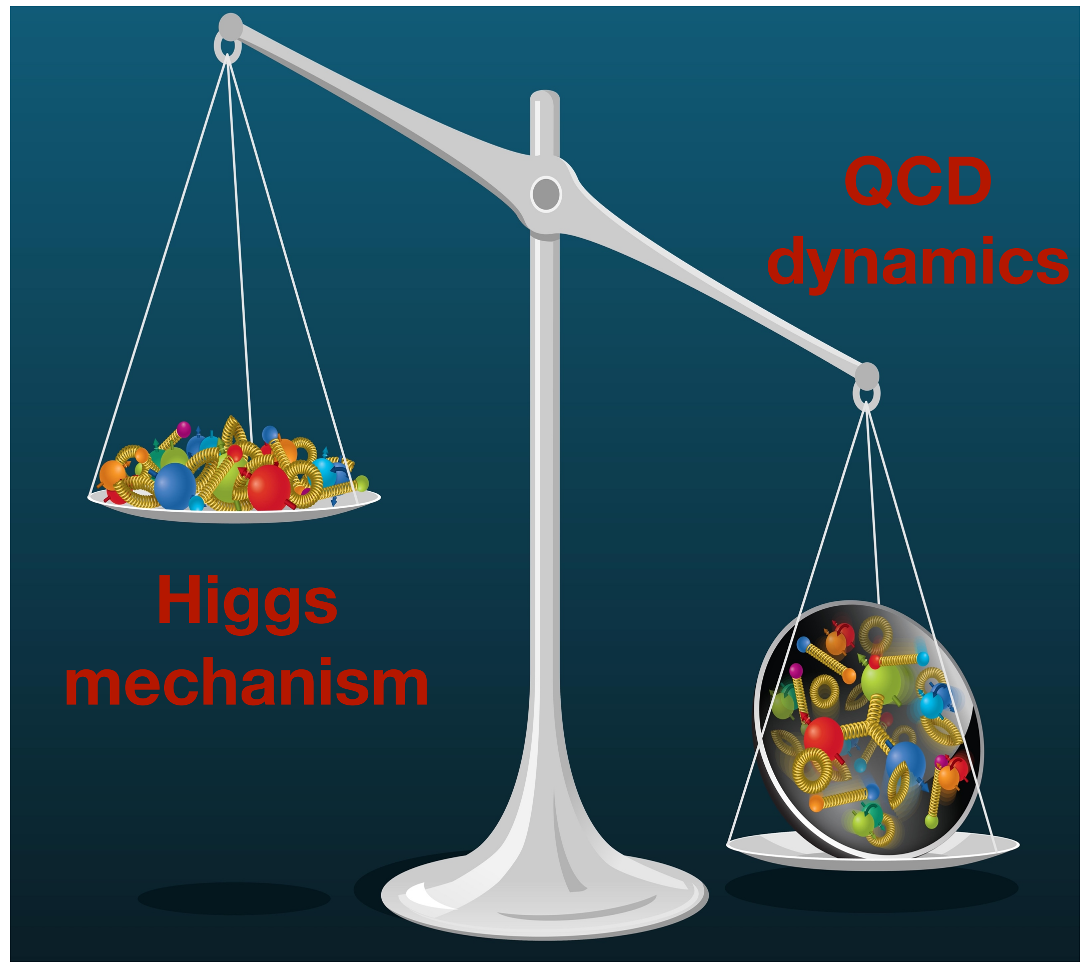
Scientific goals at EIC worldwide



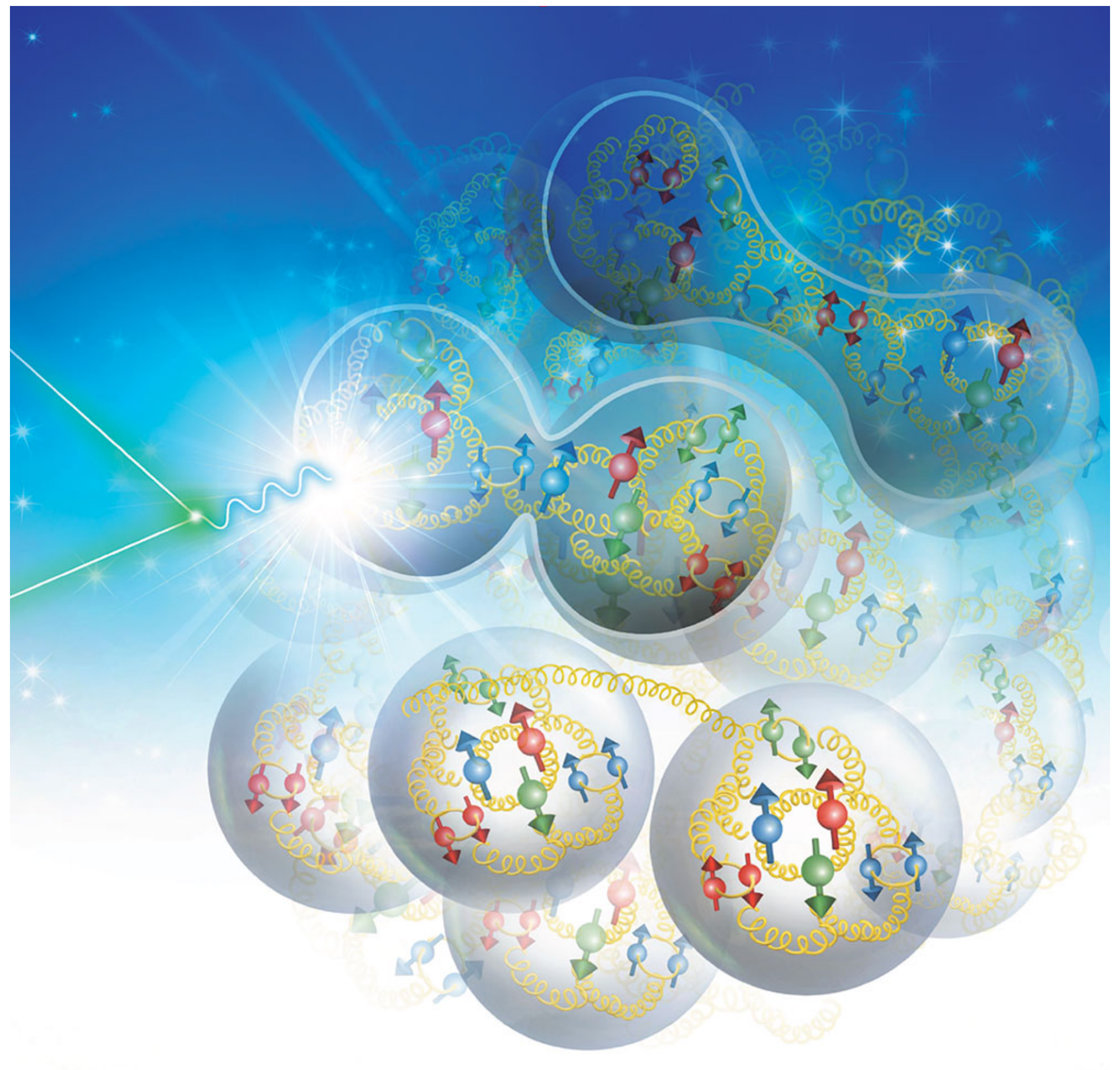
The energy momentum distribution of partons in nucleon/nuclei



The origin of proton spin



The origin of proton mass

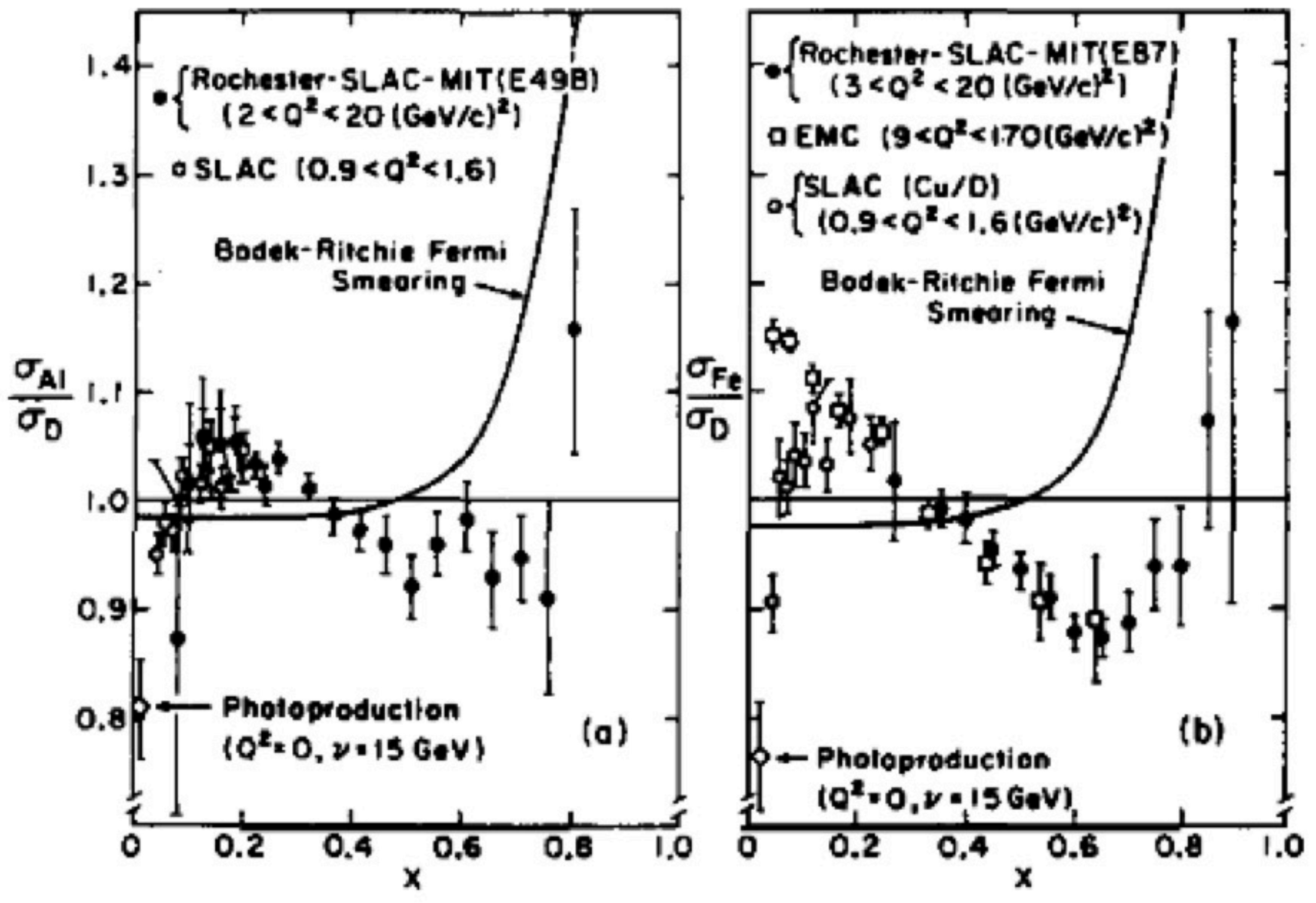


nuclear effects

“Old” and long standing problems of nuclear partonic structure

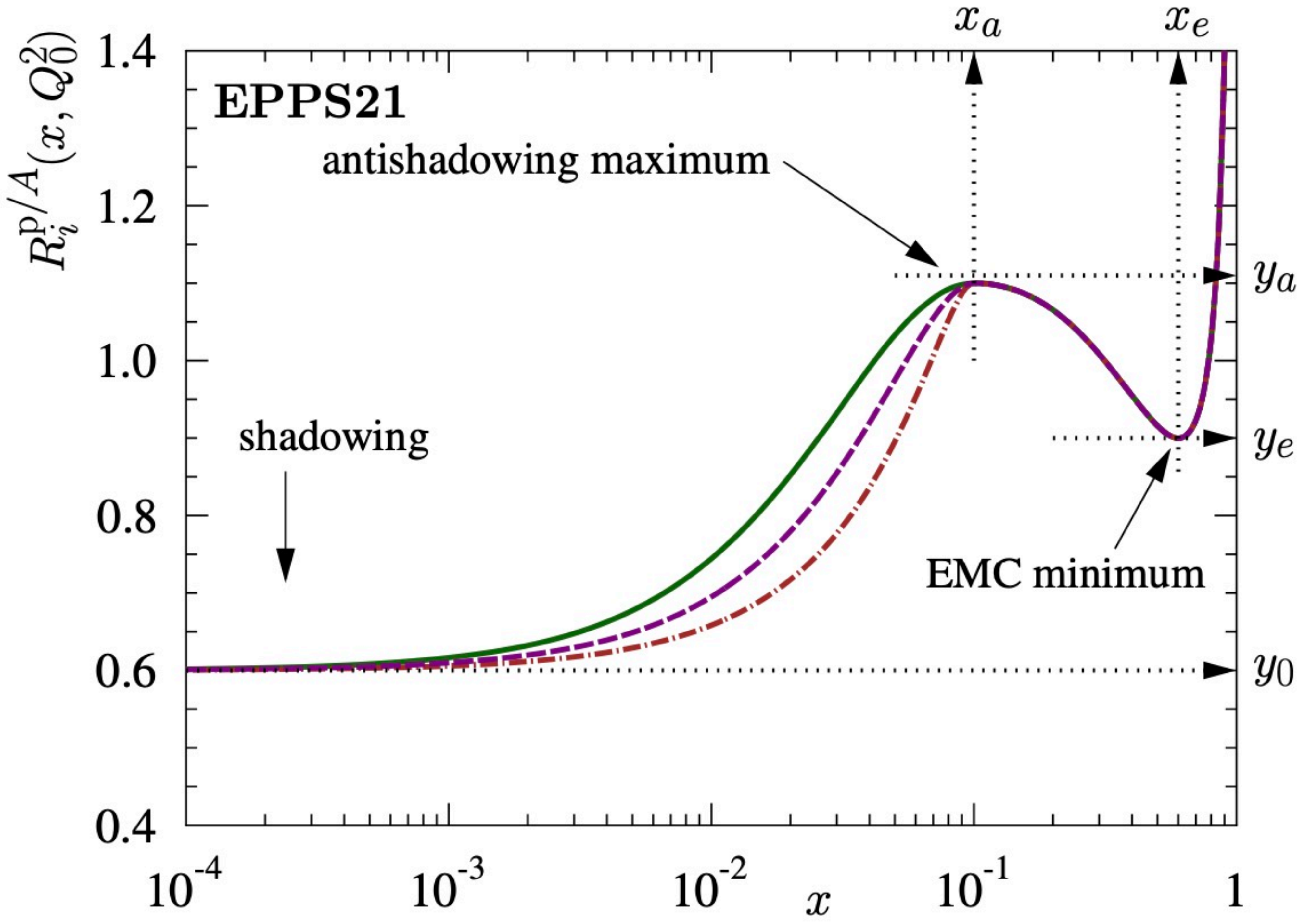
✦ One-dimensional nuclear partonic structure

Four Decades of the EMC Effect



EMC Collaboration, 1983

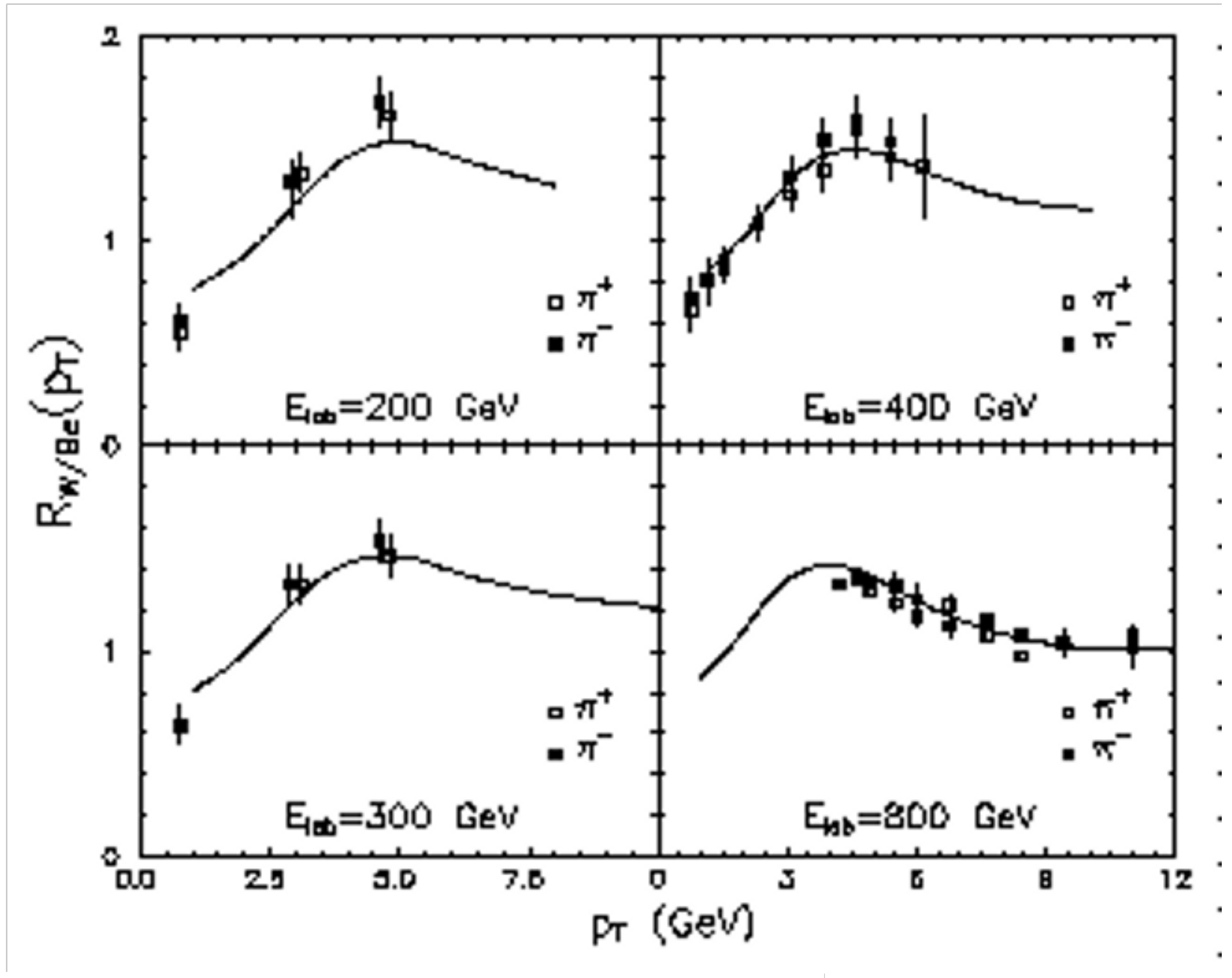
$$R_i^A = \frac{f_{i/A}(x,Q^2)}{f_{i/p}(x,Q^2)}$$



“Old” and long standing problems of nuclear partonic structure

✦ Three-dimensional nuclear partonic structure

Cronin effect

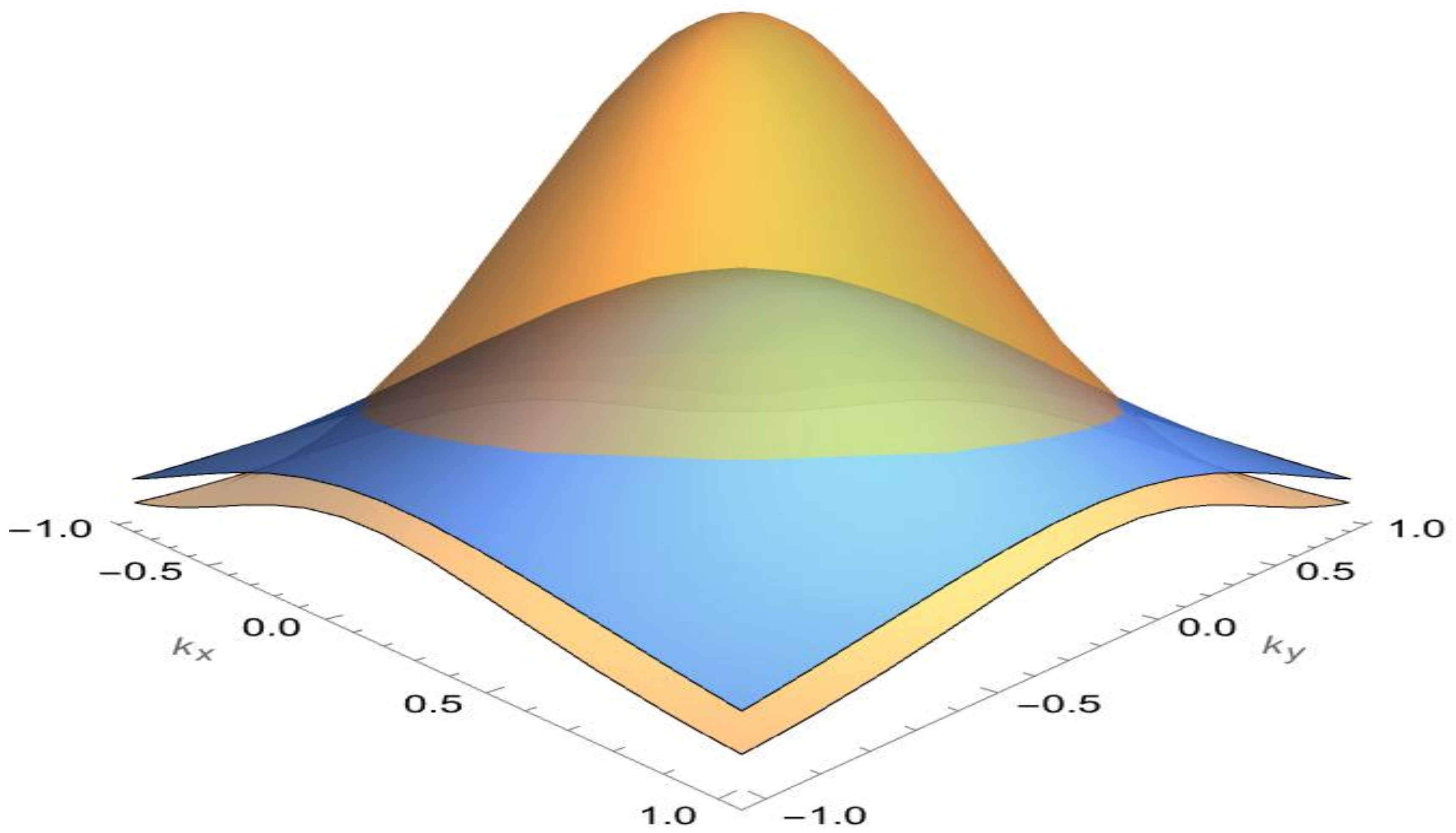


$p + A \rightarrow \text{hadron(p)} + X$

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

E100 Collaboration, PRD 11, 3105（1975）

- Naive Gaussian model



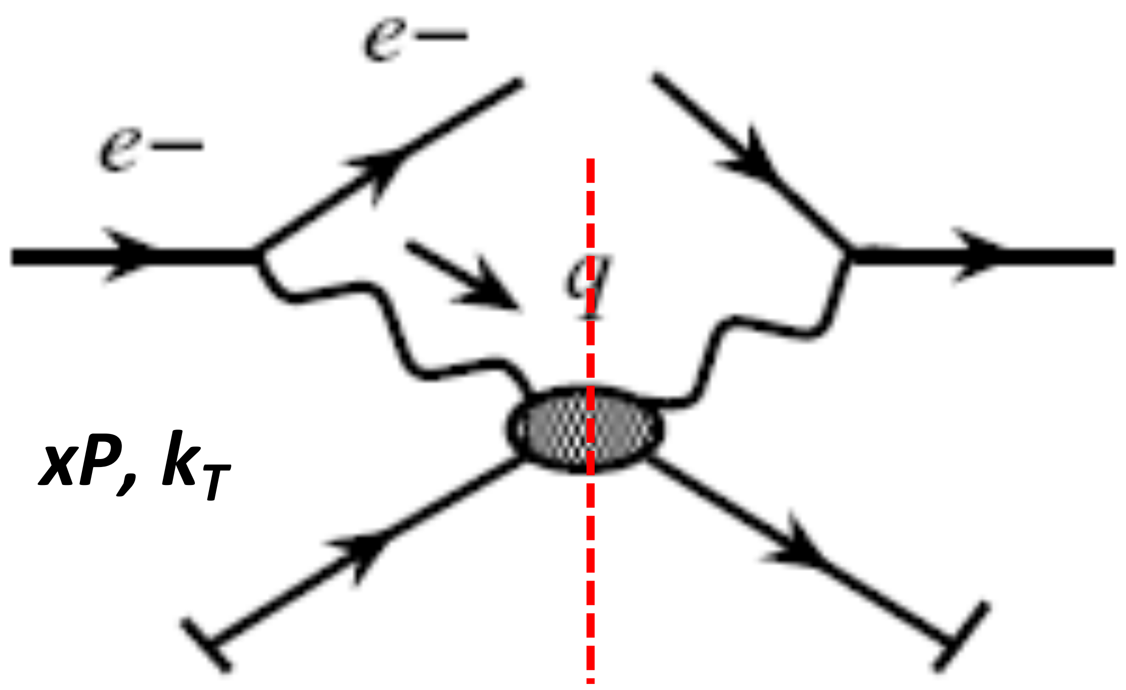
$$F_{i/p}(x, k_T) = f_{i/p}(x) \frac{e^{-k_T^2/\langle k_T^2 \rangle}}{\pi \langle k_T^2 \rangle}, \qquad \langle k_T^2 \rangle_A \rightarrow \langle k_T^2 \rangle_p + \left\langle \frac{2\mu^2 L}{\lambda} \right\rangle \xi^2$$

How to probe the nucleon/nuclear partonic structure?

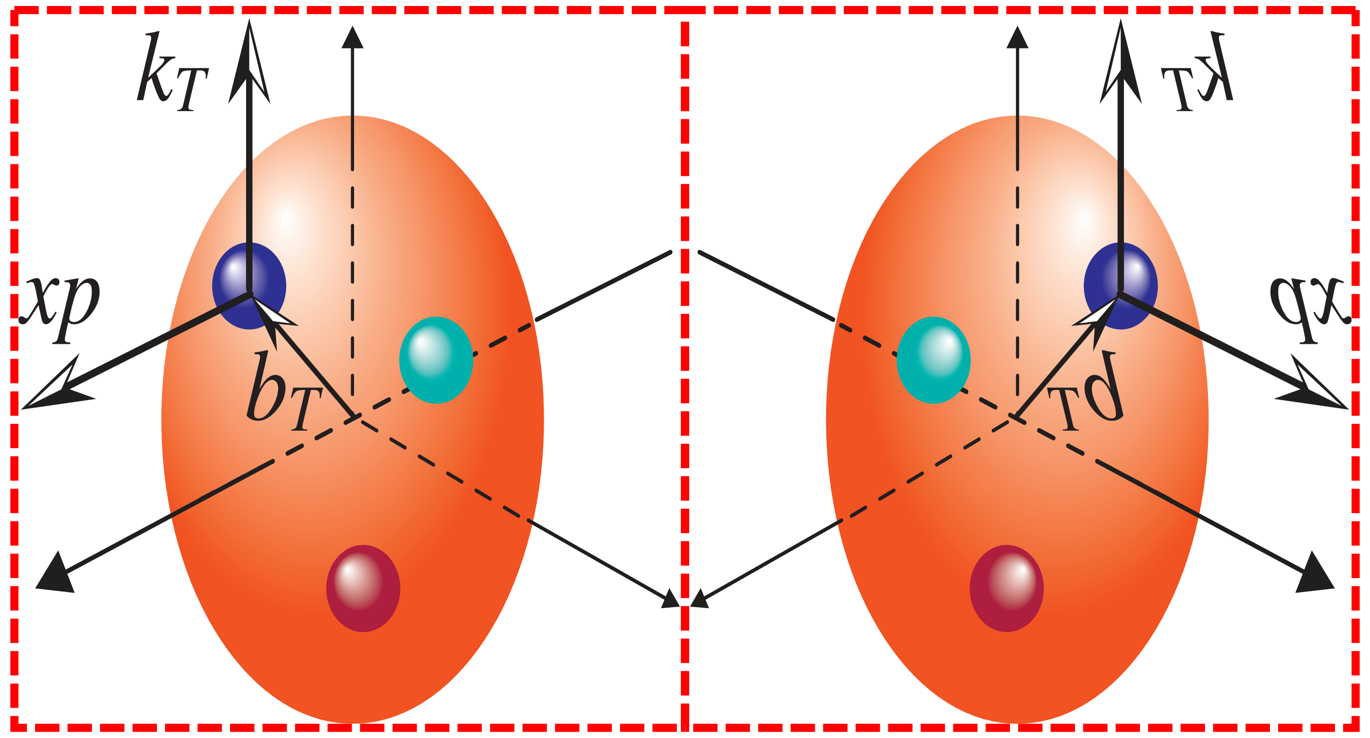
✦ Indispensable joint efforts from experiments and QCD theory

QCD factorization theorem

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



$\otimes$



Experimental measurements

Hard part controlled by pQCD theory

Nucleon partonic structure

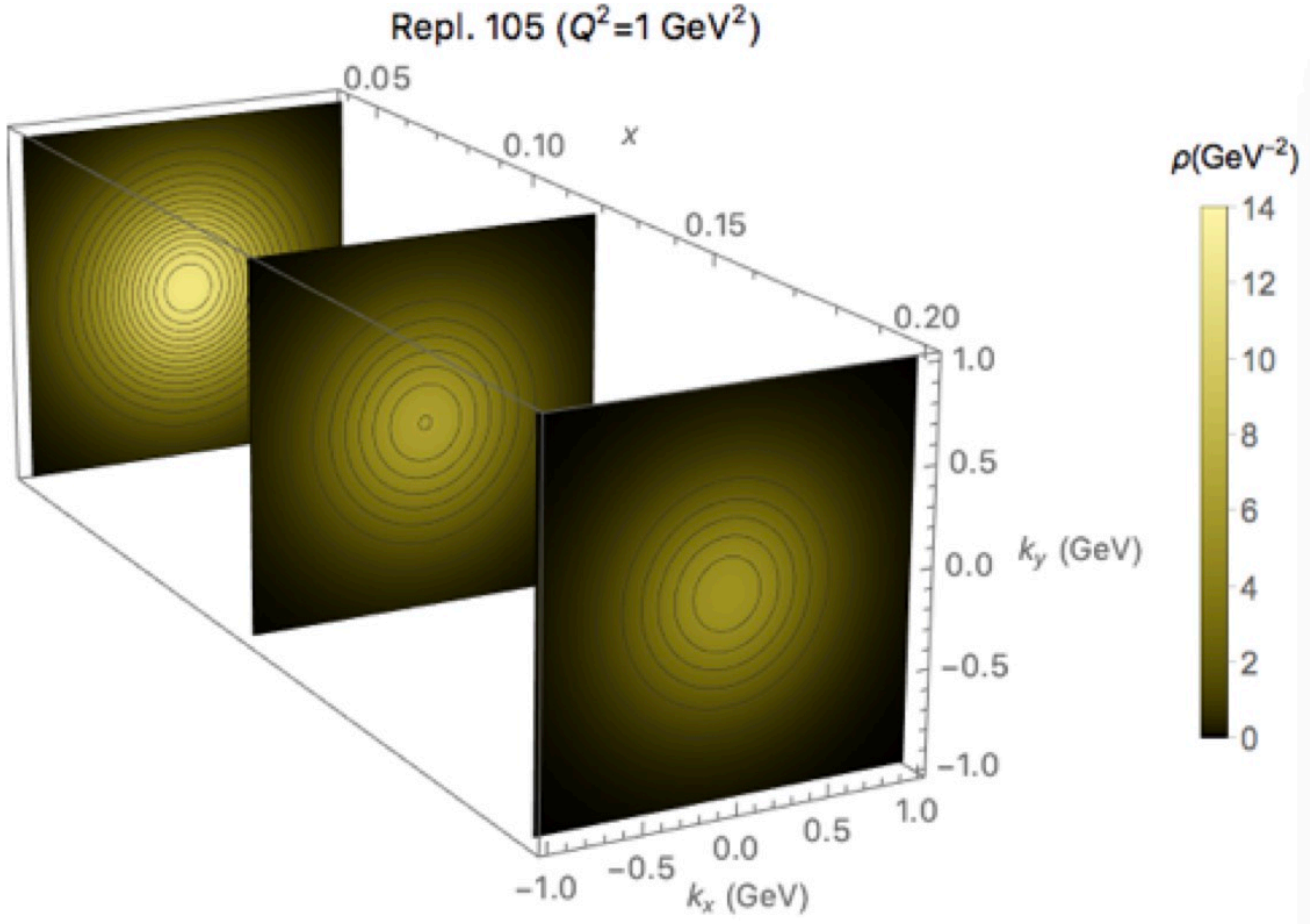
Nucleon partonic structure - 3D imaging

TMDs: explore the flavor-spin-motion correlation

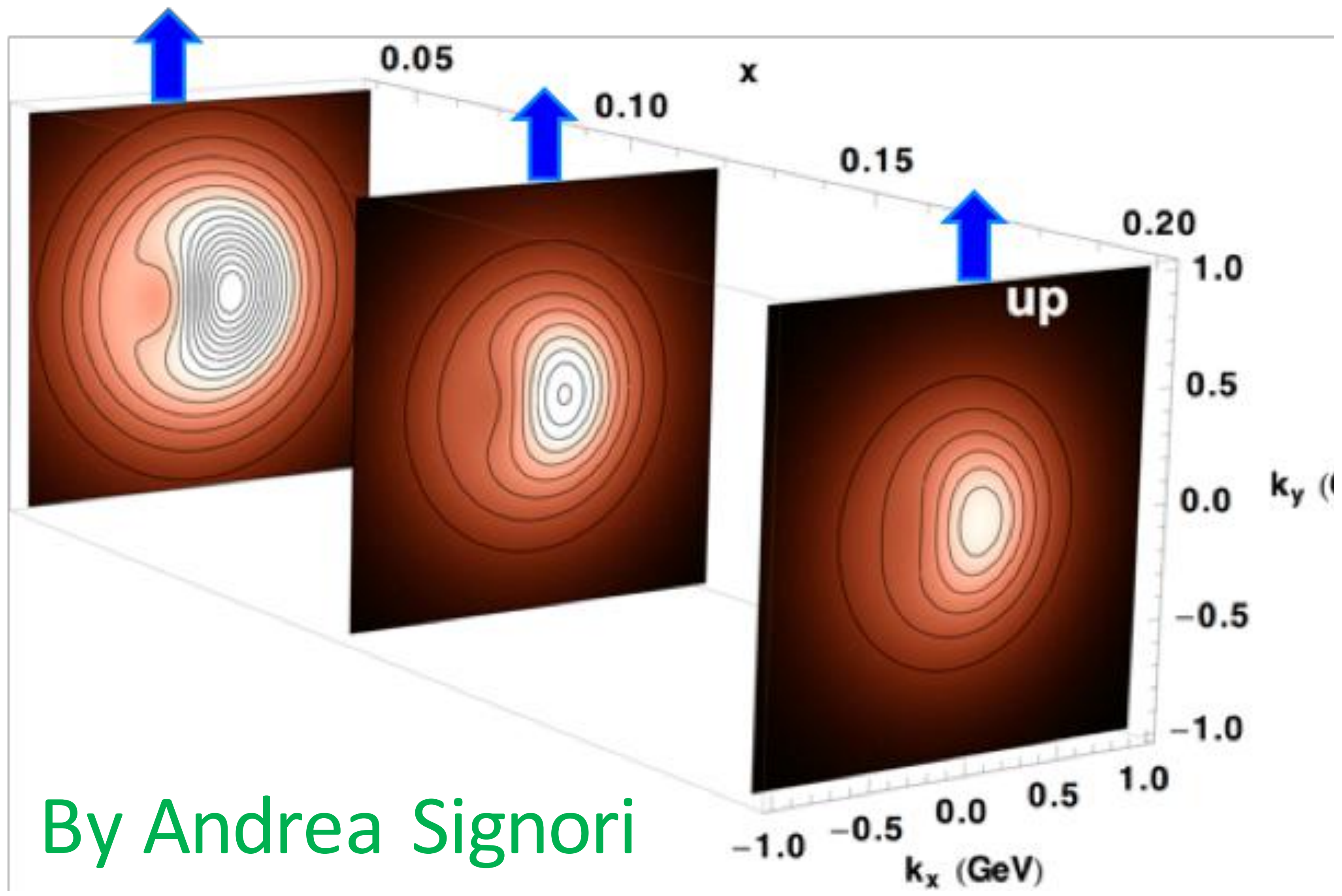
TMDs		Quark polarization		
		Unpolarized (U)	Longitudinally polarized (L)	Transversely polarized (T)
Nucleon polarization	U	f_1 Unpolarized		$h_1^\perp$ Boer–Mulders
	L		g_{1L} Helicity	$h_{1L}^\perp$ Longi-transversity
	T	$f_{1T}^\perp$ Sivers	g_{1T} Trans-helicity	h_1 Transversity $h_{1T}^\perp$ Pretzelosity

Nucleon partonic structure - 3D imaging

Unpolarized proton



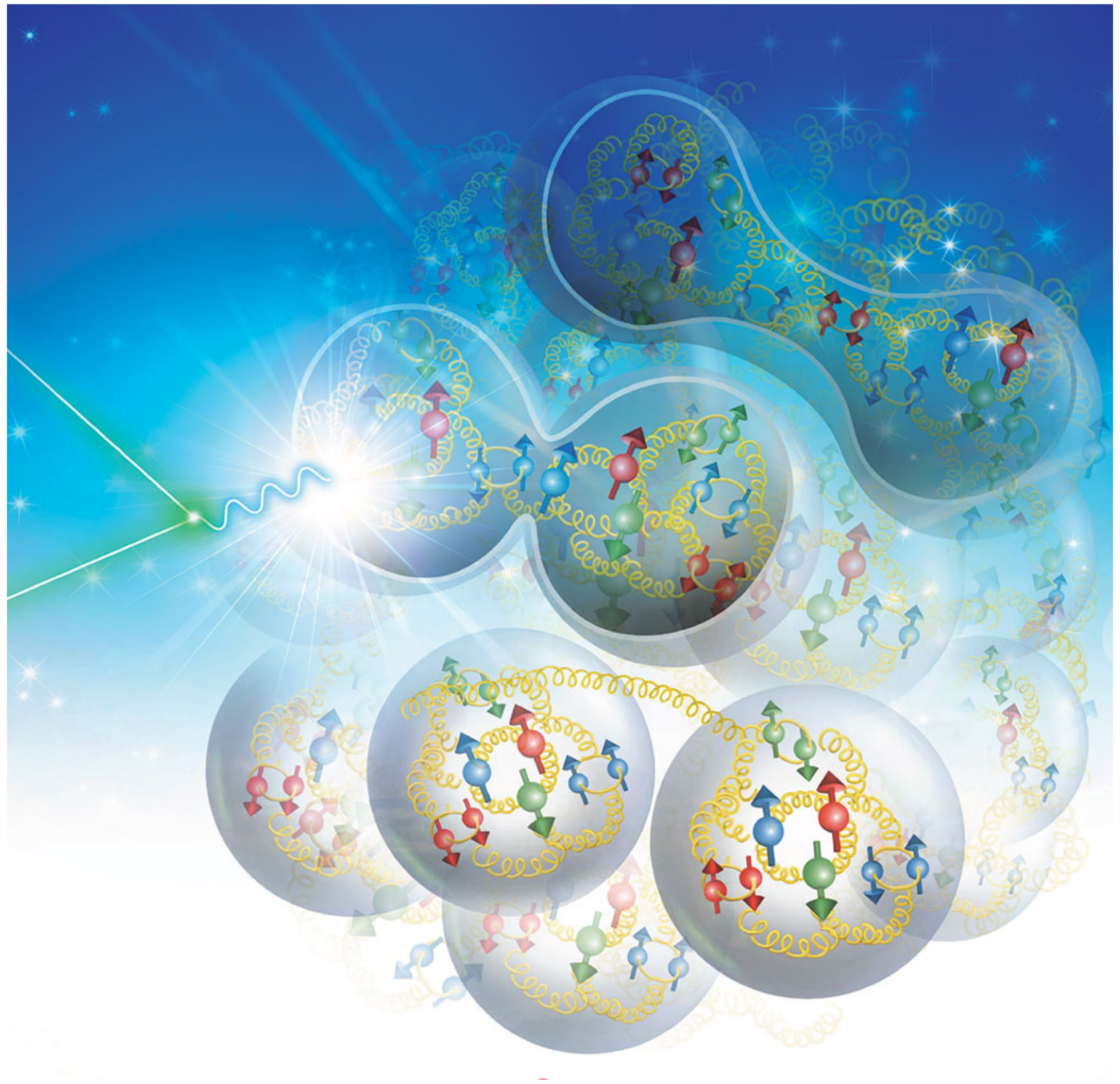
Transversely polarized proton

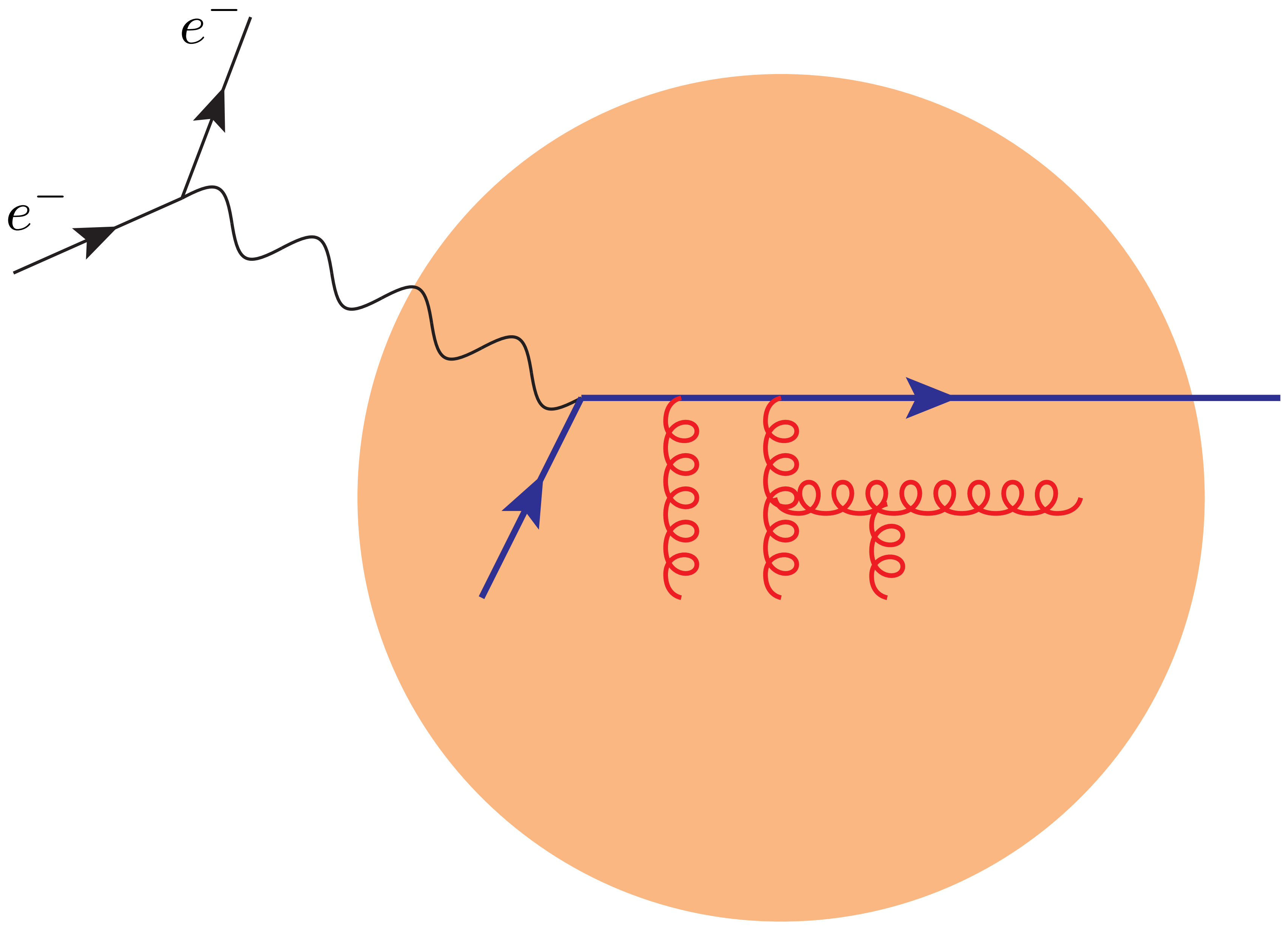


Transversely polarized quark distribution is distorted!

Tianbo Liu, Aug. 7

What if the nucleon is bounded in nucleus?





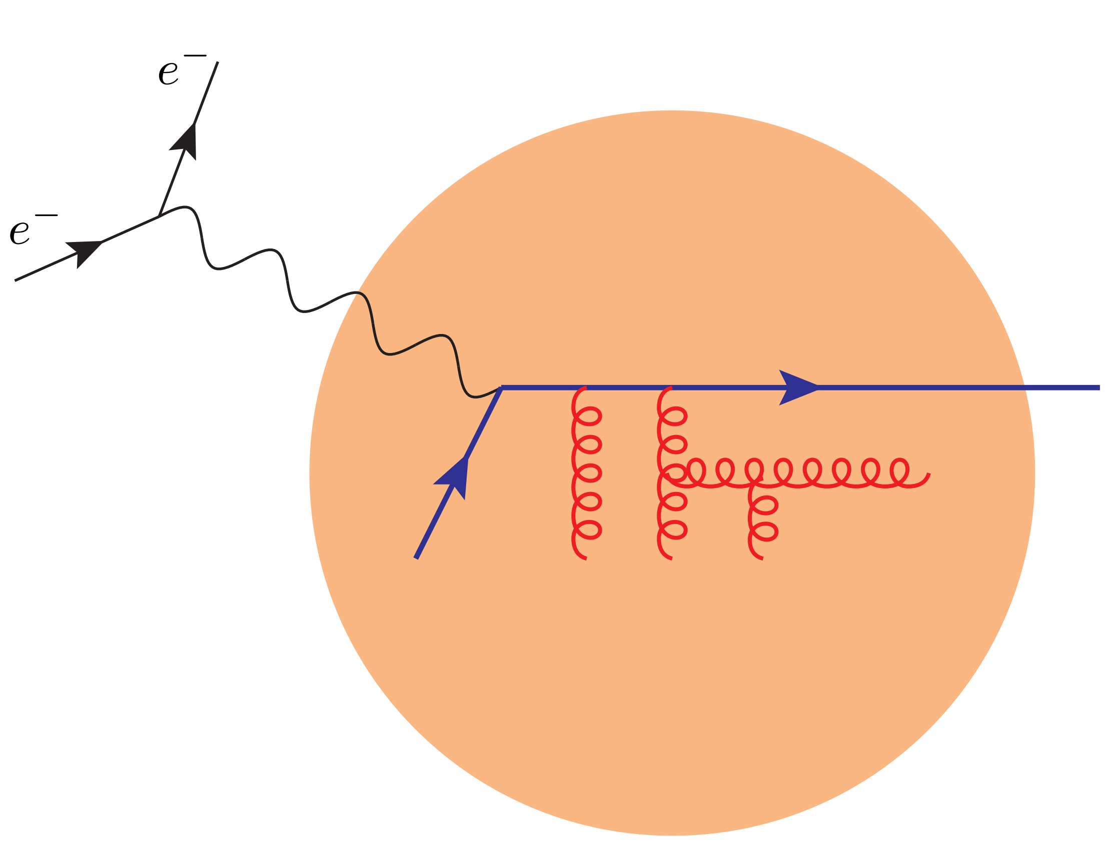
Nuclear partonic structure

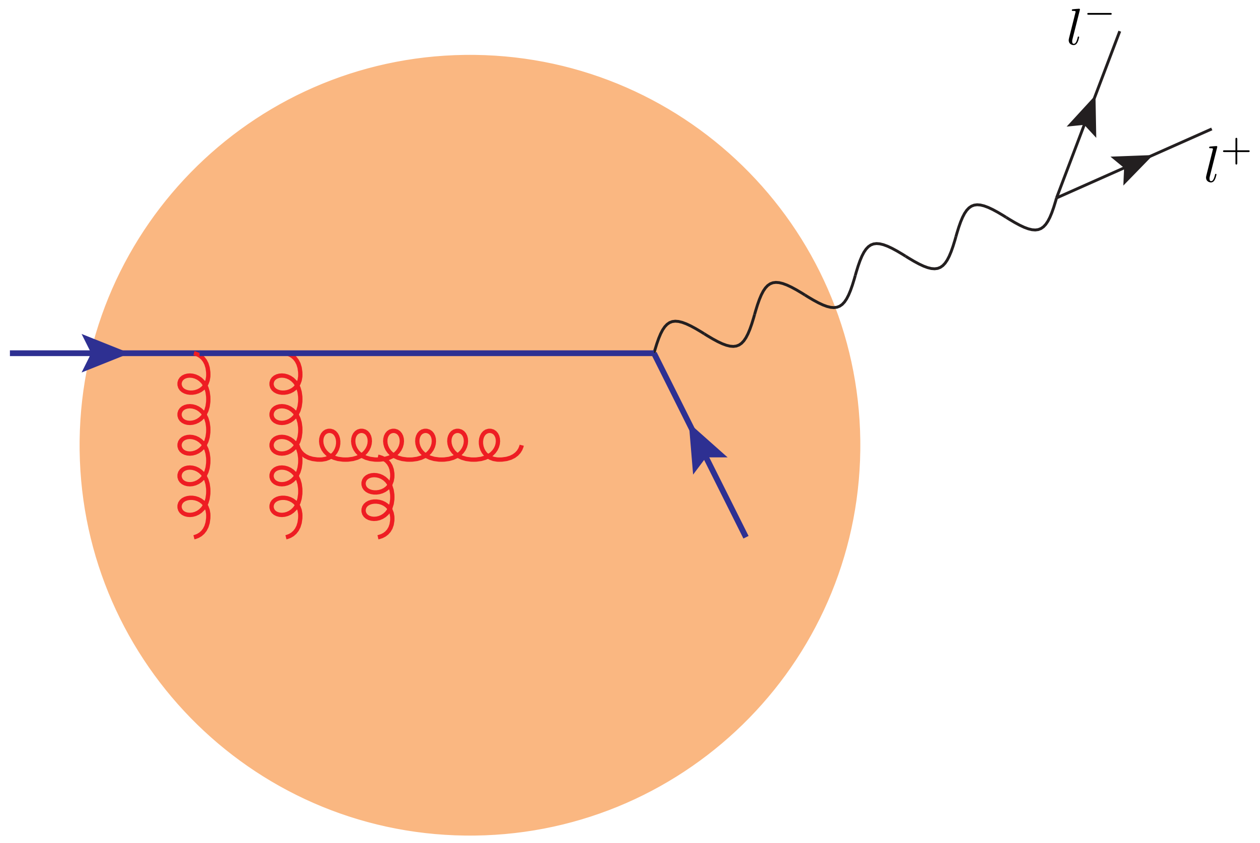
Parton propagating in nuclear medium

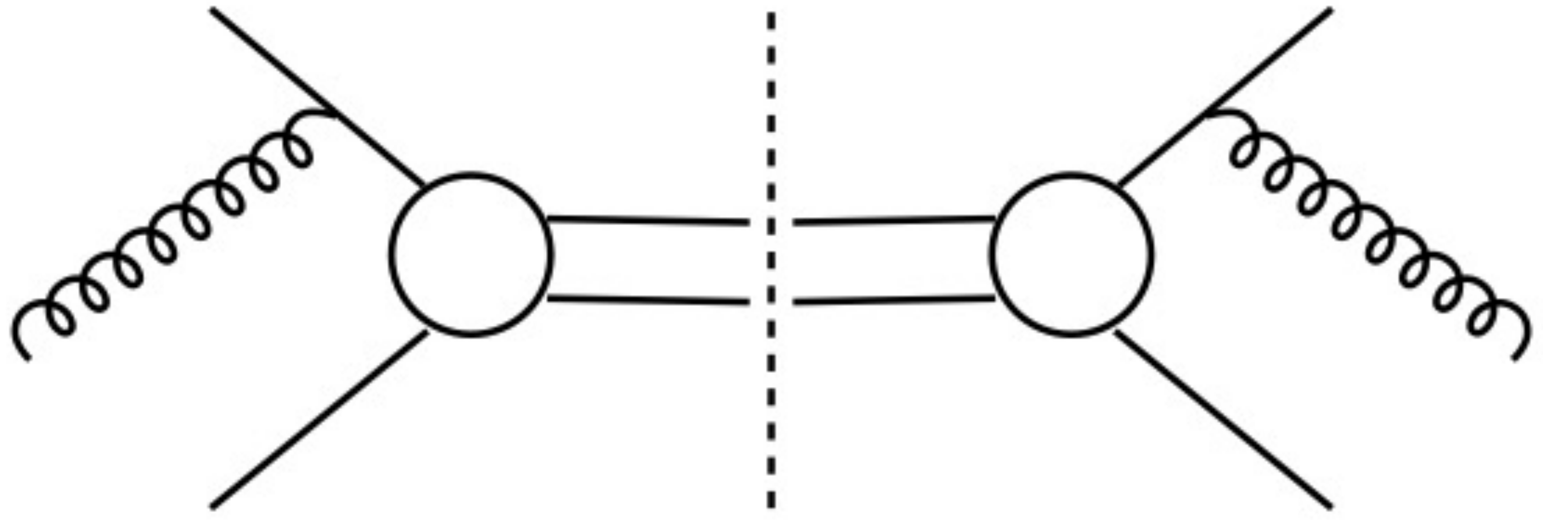
Two mechanisms leading to nontrivial nuclear effects !

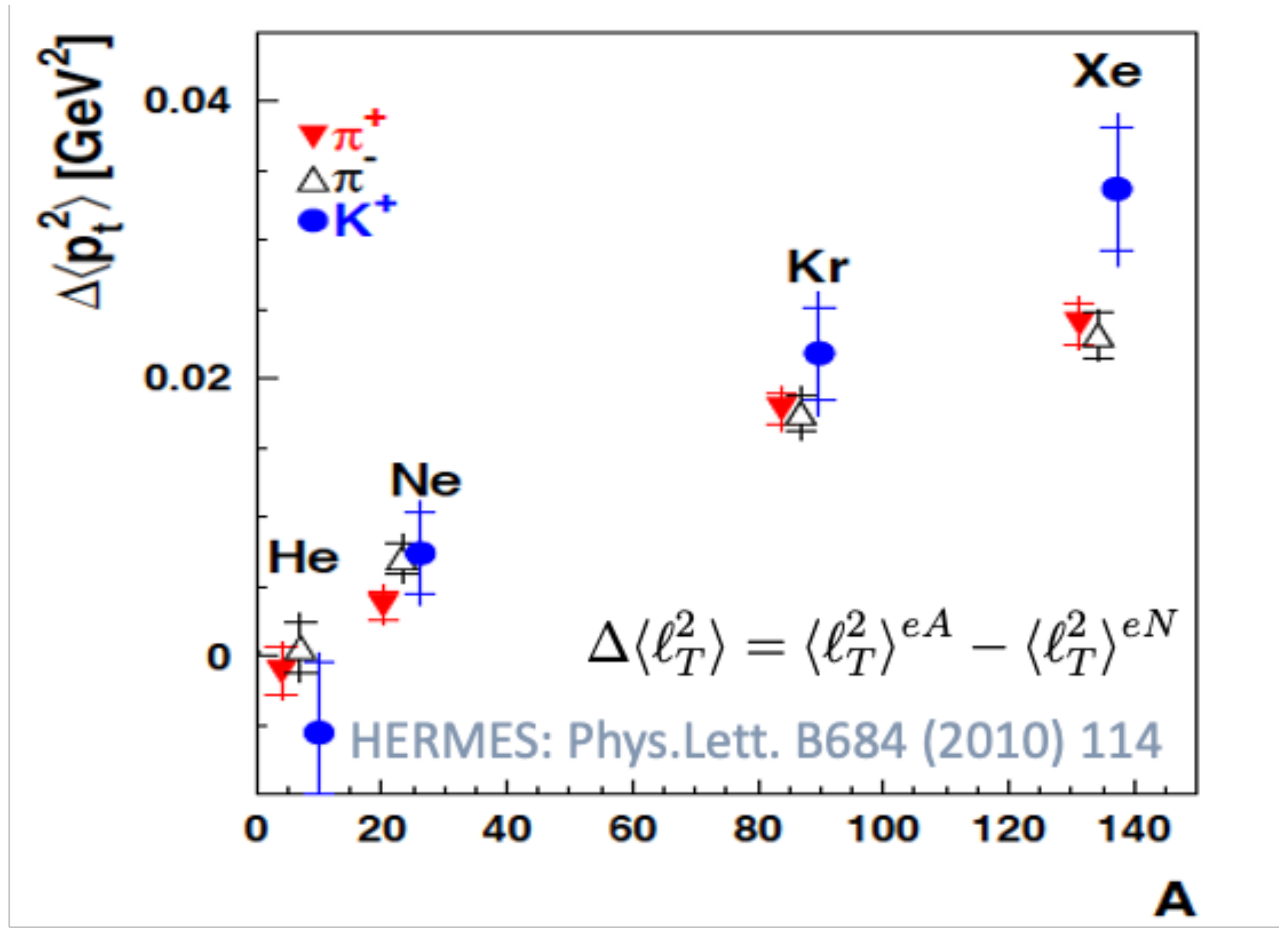
Observable 1: nuclear modification with one hard scale (mass)

transverse momentum broadening in nucleus

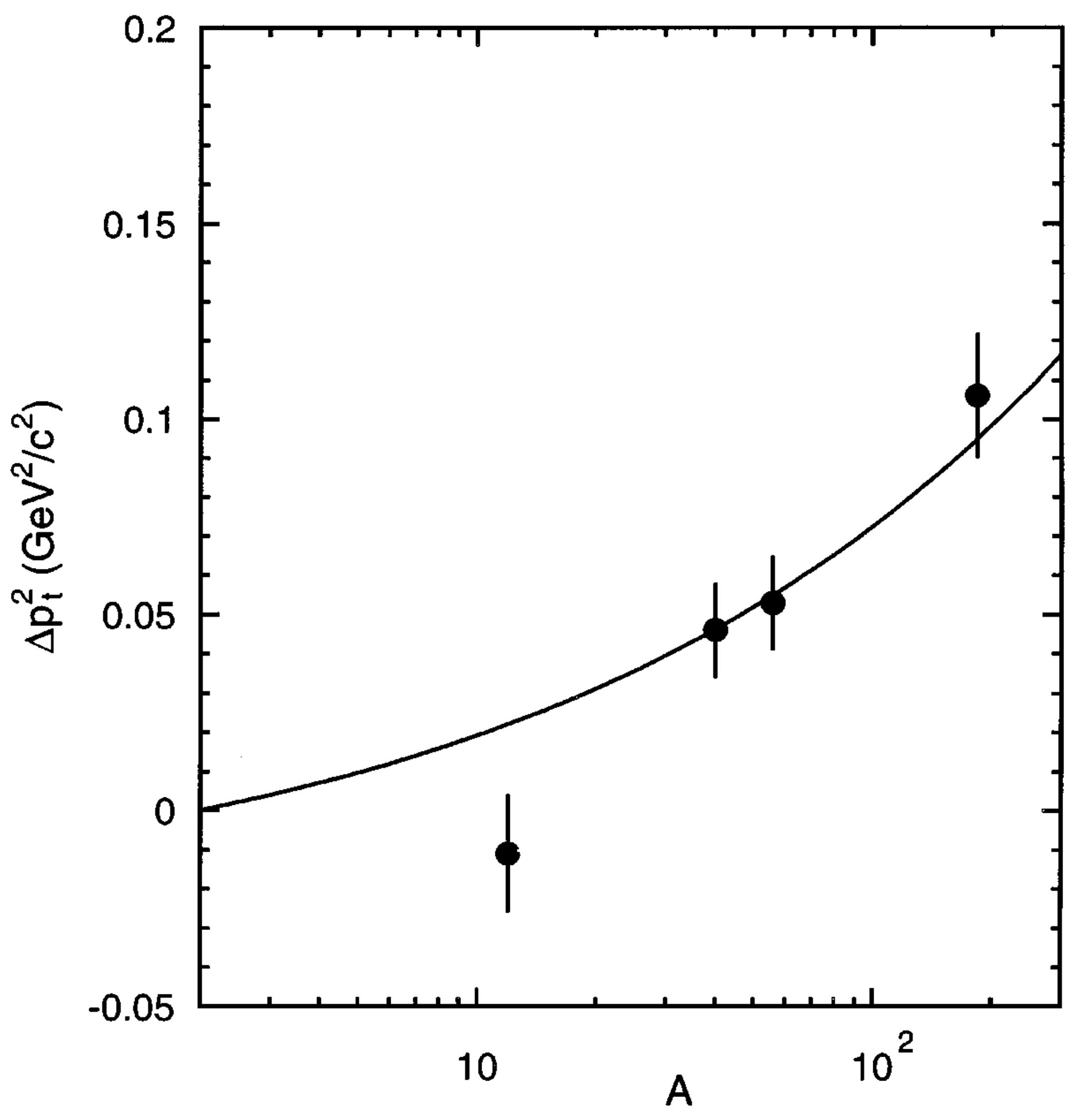




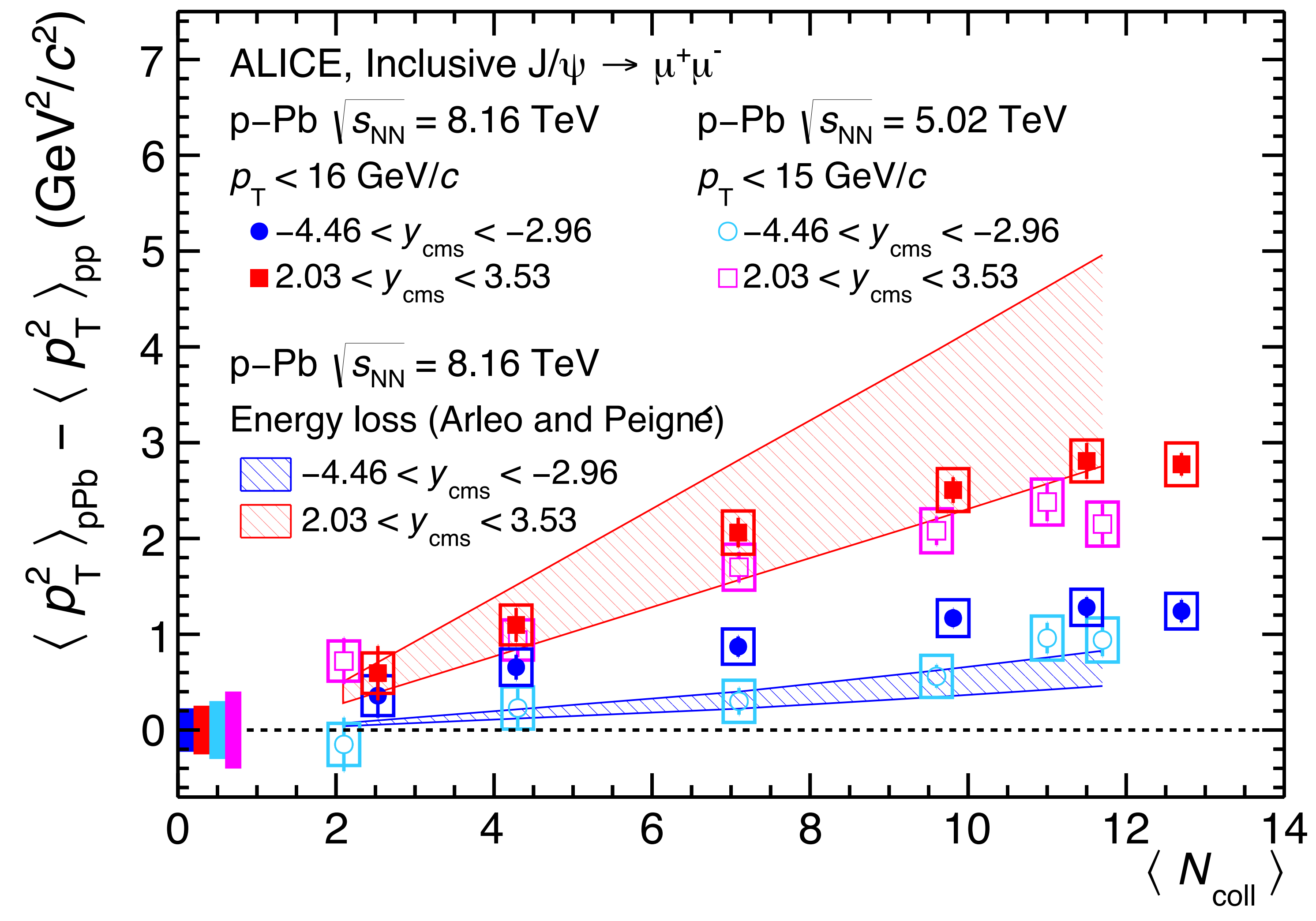




SIDIS off nucleus



DY in pA, E772 1991



Heavy quarkonium in pA
ALICE 2020

Generalized factorization formalism

perturbative expansion →

power expansion ↓

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

- Nuclear enhanced power correction

  J. Qiu, G. Sterman, NPB 1990

  J. Qiu, X. Luo, PRD 1998

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

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

- Only one hard scale: Q^2

- High twist collinear factorization - nuclear modification from multiple scattering
- SIDIS: A direct probe of the nuclear quark-gluon quantum correlation

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

- Twist-4 matrix element:

$$T_{qg}(x_1, x_2, x_3) = \int \frac{dy^-}{2\pi} e^{ix_1 p^+ y^-} \int \frac{dy_1^- dy_2^-}{4\pi} e^{ix_2 p^+ (y_1^- - y_2^-)} e^{ix_3 p^+ y_2^-} \theta(y_2^-)\theta(y_1^- - y^-) \times \langle A|\bar{\psi}_q(0)\gamma^+ F_\sigma^{\ +}(y_2^-) F^{\sigma+}(y_1^-)\psi_q(y^-)|A\rangle.$$

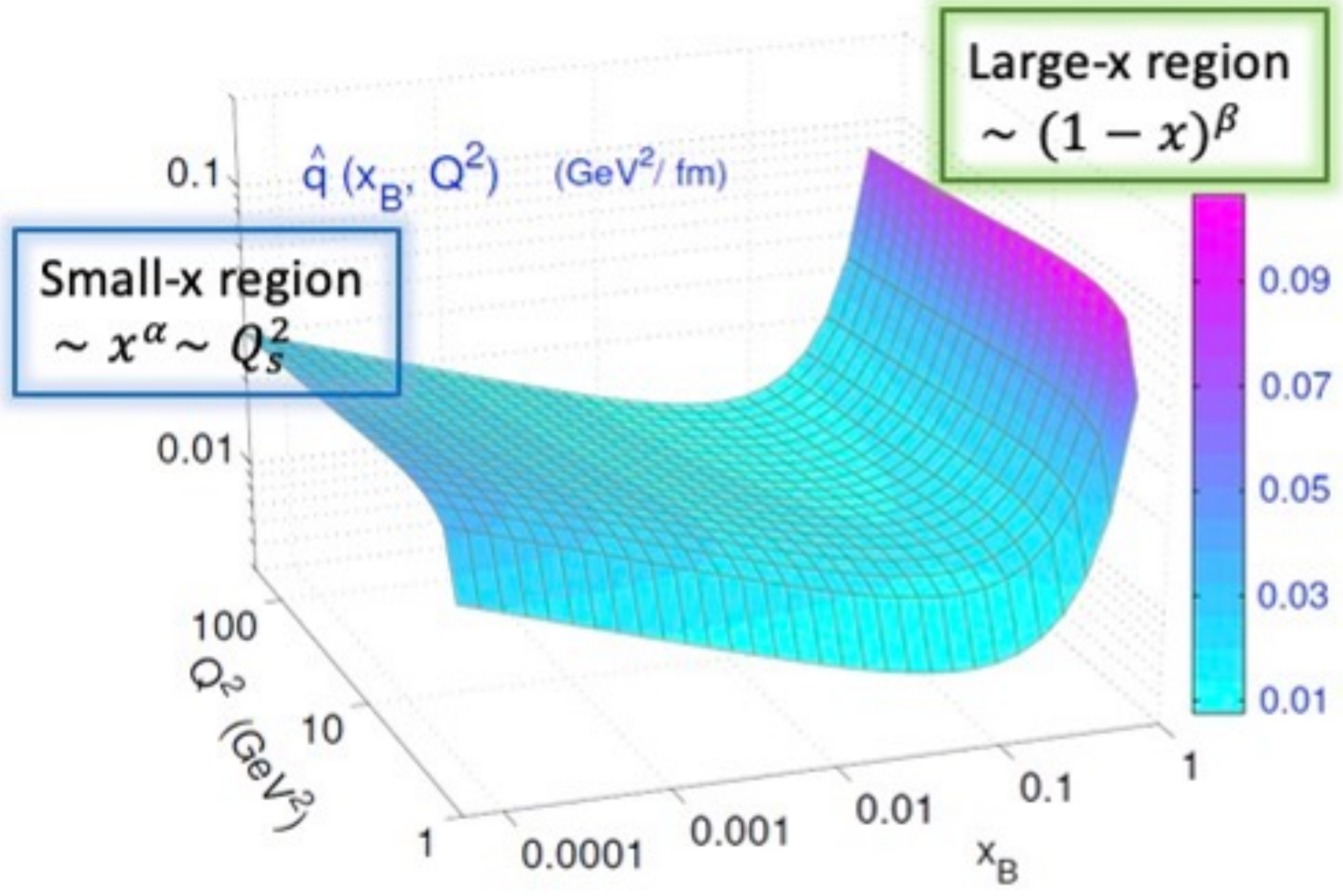
Global extraction of nuclear partonic structure - $\hat{q}$

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

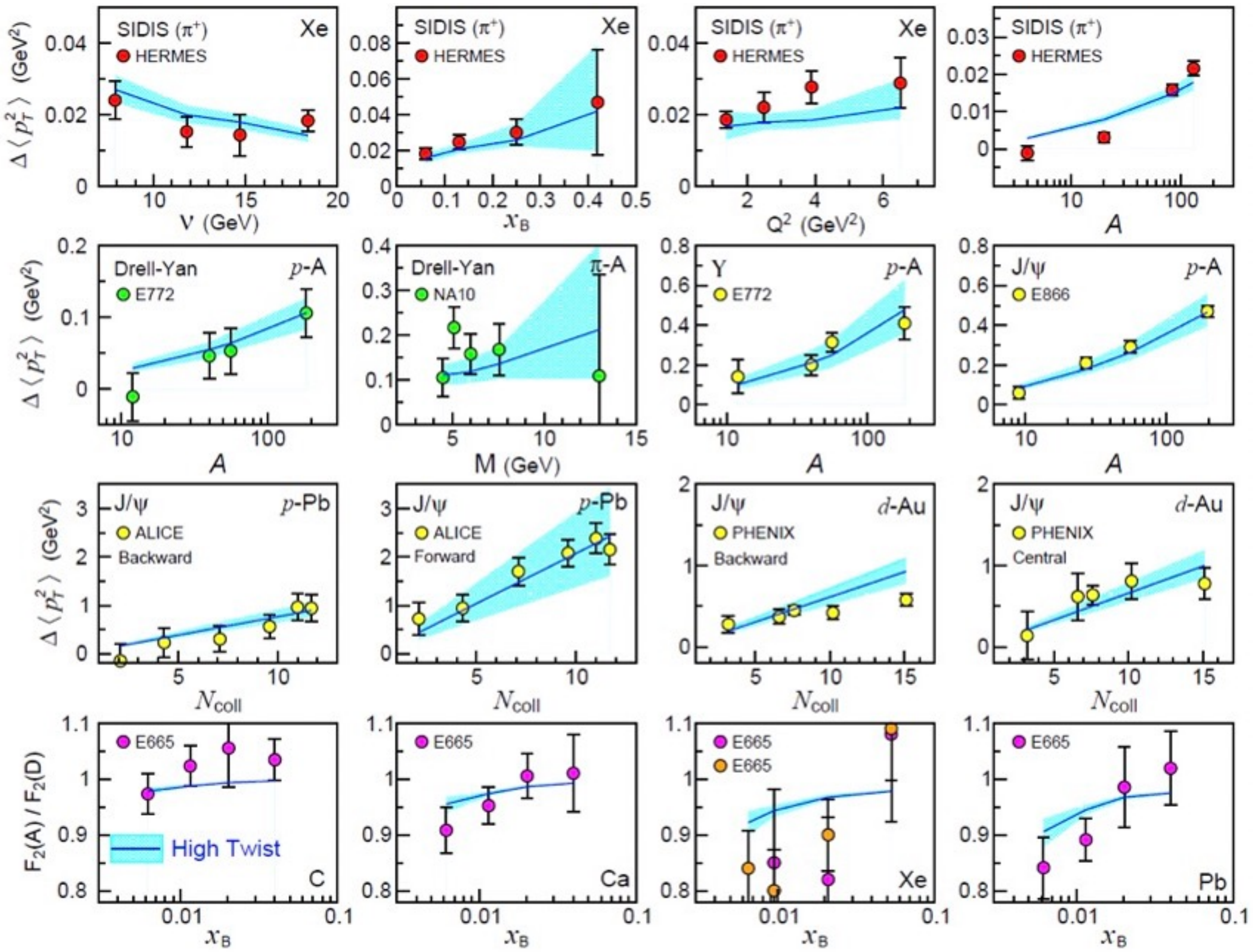
Ru, Kang, Wang, **HX** and Zhang, PRD 2021; 2302.02329

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

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



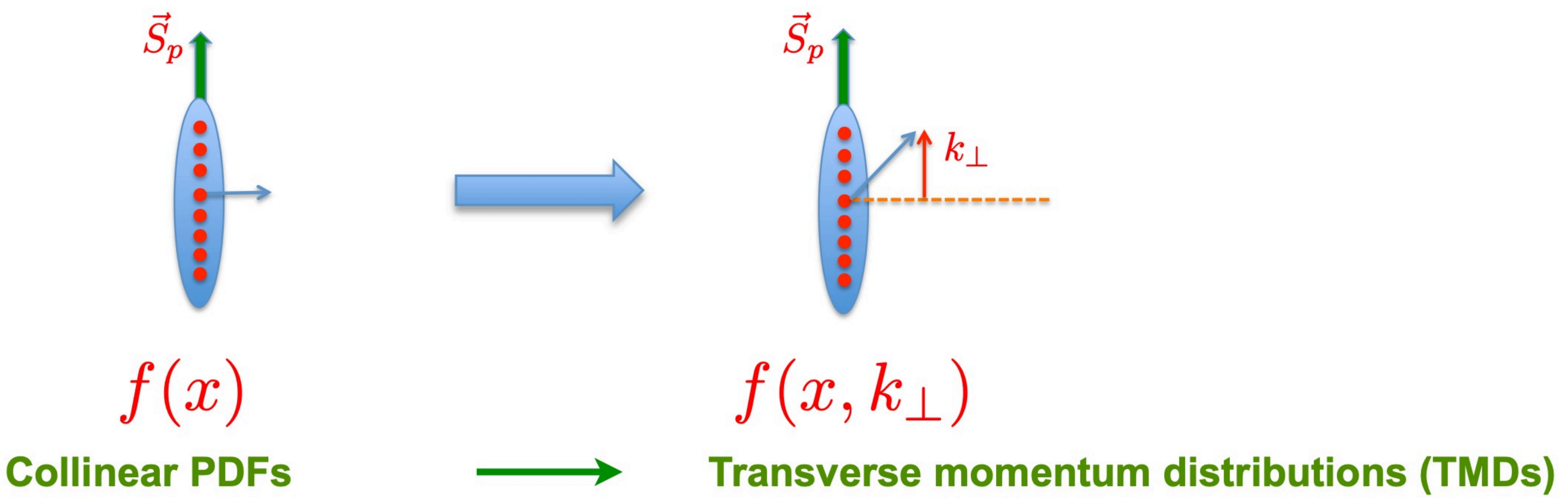
$\hat{q}_0 = 0.0191 \pm 0.0061$ GeV^2/fm, $\alpha = -0.182 \pm 0.050$
$\beta = -2.85 \pm 1.87$, $\gamma = 0.264 \pm 0.169$.

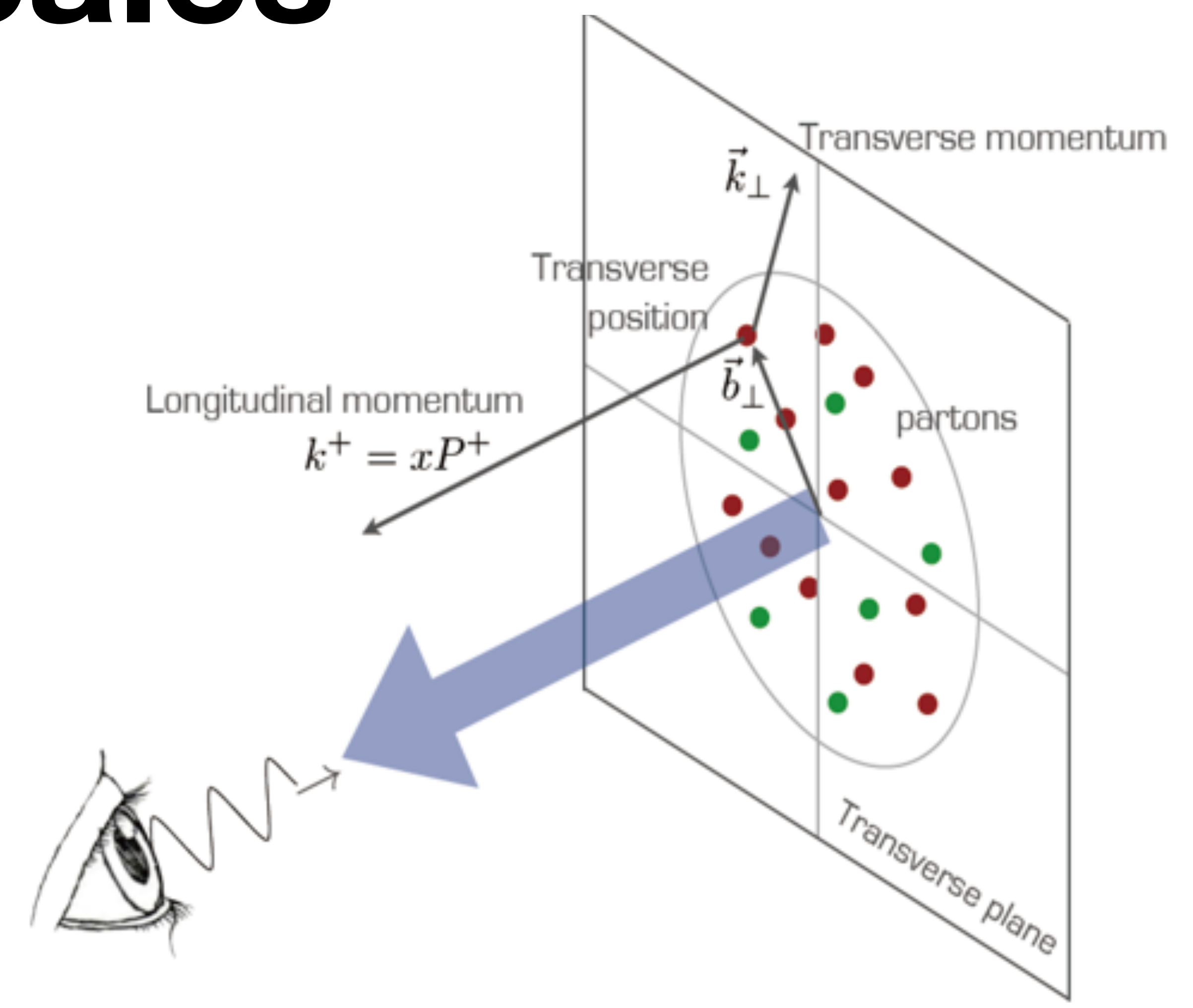


$\hat{q}$: jet transport parameter

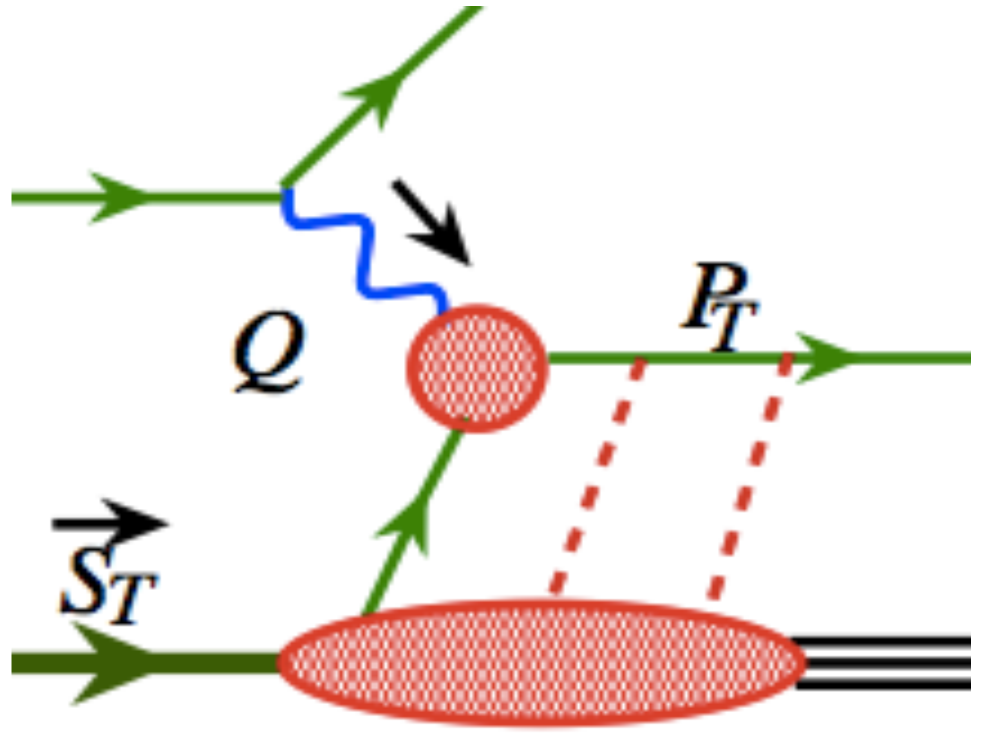
Observable 2: nuclear modification with two scales

✦ 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

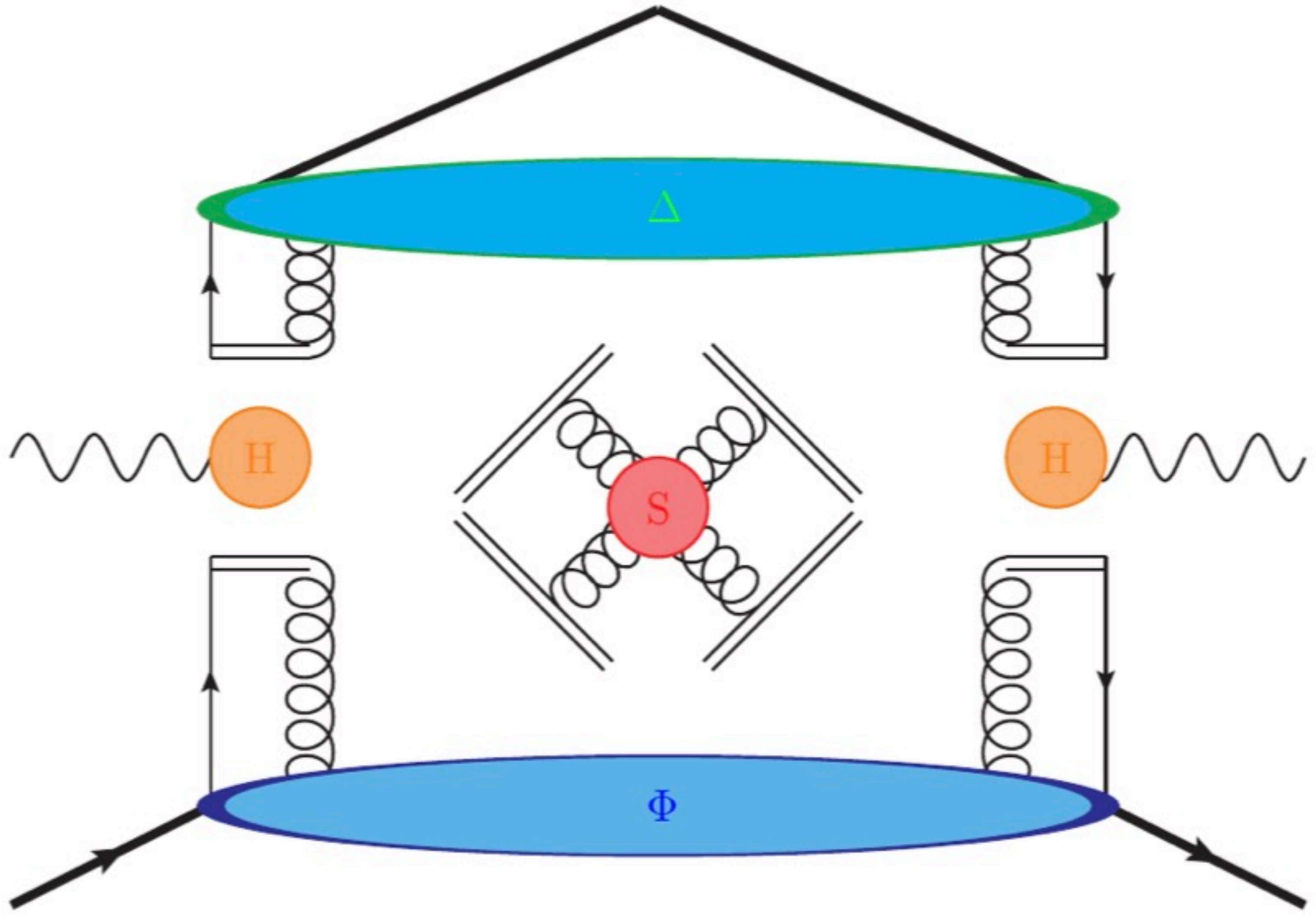


SIDIS: $Q \gg P_T$

Nuclear partonic structure - 3D imaging

✦ TMD factorization for cross section

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



✦ TMDs

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

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

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. $f_{i/n}^A$, $D_{h/i}^A$, $S_{\rm NP}^D$, and $S_{\rm NP}^f$ are altered.

Nuclear partonic structure - 3D

✦ TMDs

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

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

Collinear Distributions

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

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

Perturbative order in our analysis

Work at NLO+NNLL for the TMDs.

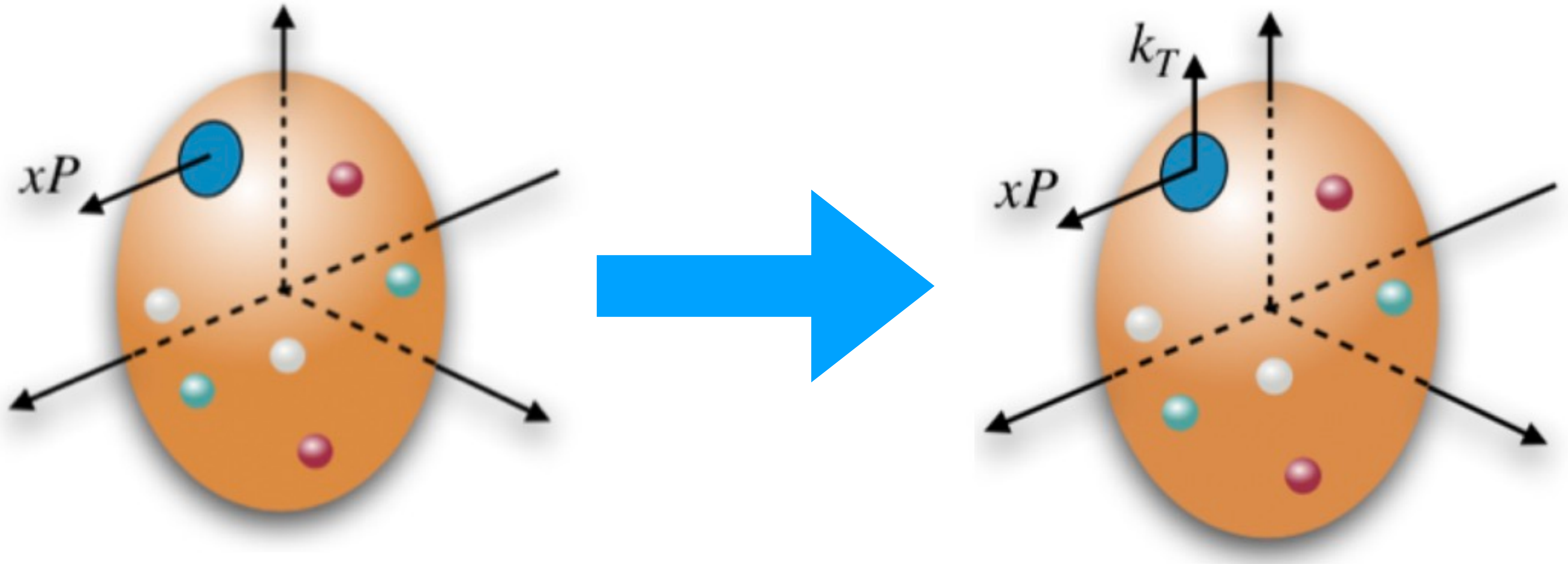
Non-perturbative parametrization

$$S_{\rm NP}^{f}(b,Q,A) = S_{\rm NP}^{f}(b,Q) + a_N\left(A^{1/3}-1\right)b^2$$

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

Nuclear partonic structure - 3D

✦ From collinear (1D) to TMD (3D)



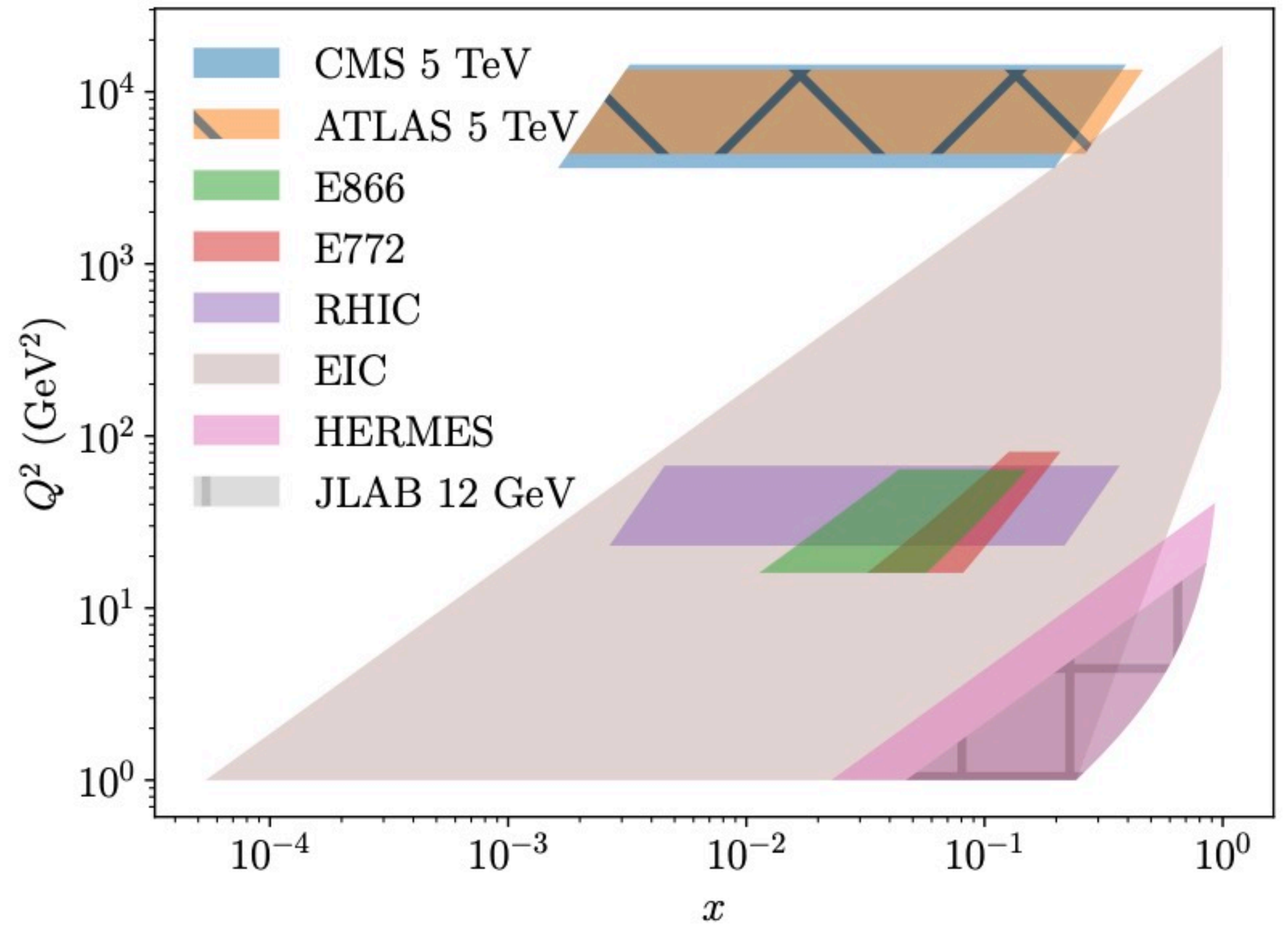
Collaboration	Process	Baseline	Nuclei	N_{dat}	χ^2
HERMES [36]	SIDIS (π)	D	Ne, Kr, Xe	27	16.3
RHIC [44]	DY	p	Au	4	2.0
E772 [42]	DY	D	C, Fe, W	16	20.1
E866 [43]	DY	Be	Fe, W	28	43.3
CMS [45]	γ^*/Z	NA	Pb	8	9.7
ATLAS [46]	γ^*/Z	NA	Pb	7	13.1
Total				90	105.2

Drell-Yan Measurements

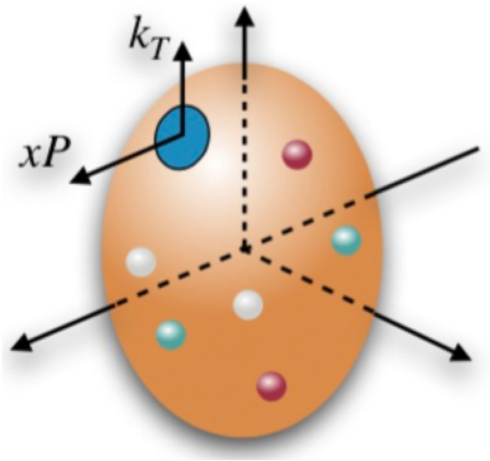
- $R_{\text{AB}} = \frac{d\sigma_A}{dq_\perp} / \frac{d\sigma_B}{dq_\perp}$
  -E866
  -E772
  -Prelim. RHIC
- $d\sigma/dq_\perp$ (p Pb)
  ATLAS
  CMS

SIDIS Measurements

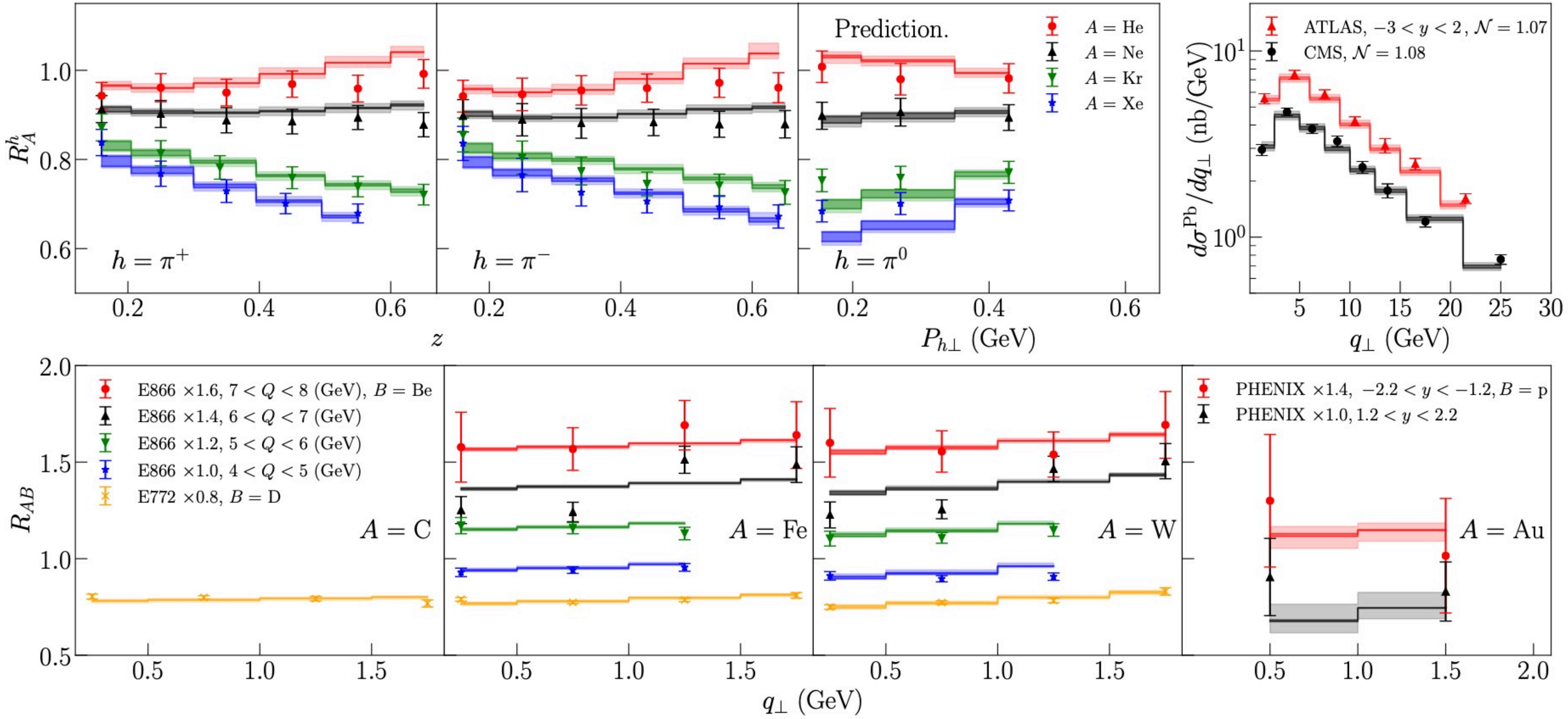
- Multiplicity ratio $R_h^A = M_h^A / M_h^D$.
  -HERMES 2007
  -Prelim. JLab
  -Planned JLab
  -Possible EIC.



nuclear 3D imaging - global extraction from world data



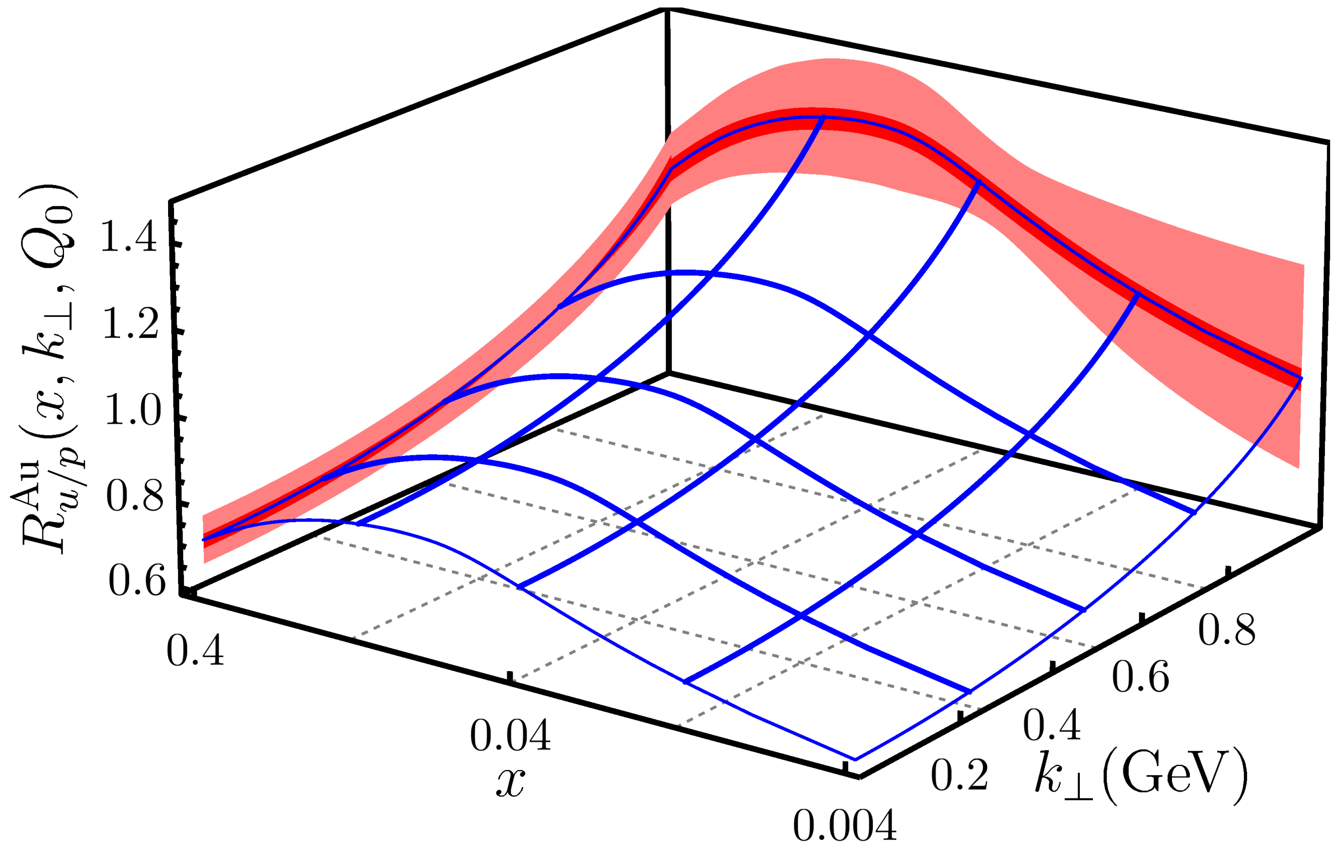
Alrashed, Anderle, Kang, Terry, **HX**, PRL 2022



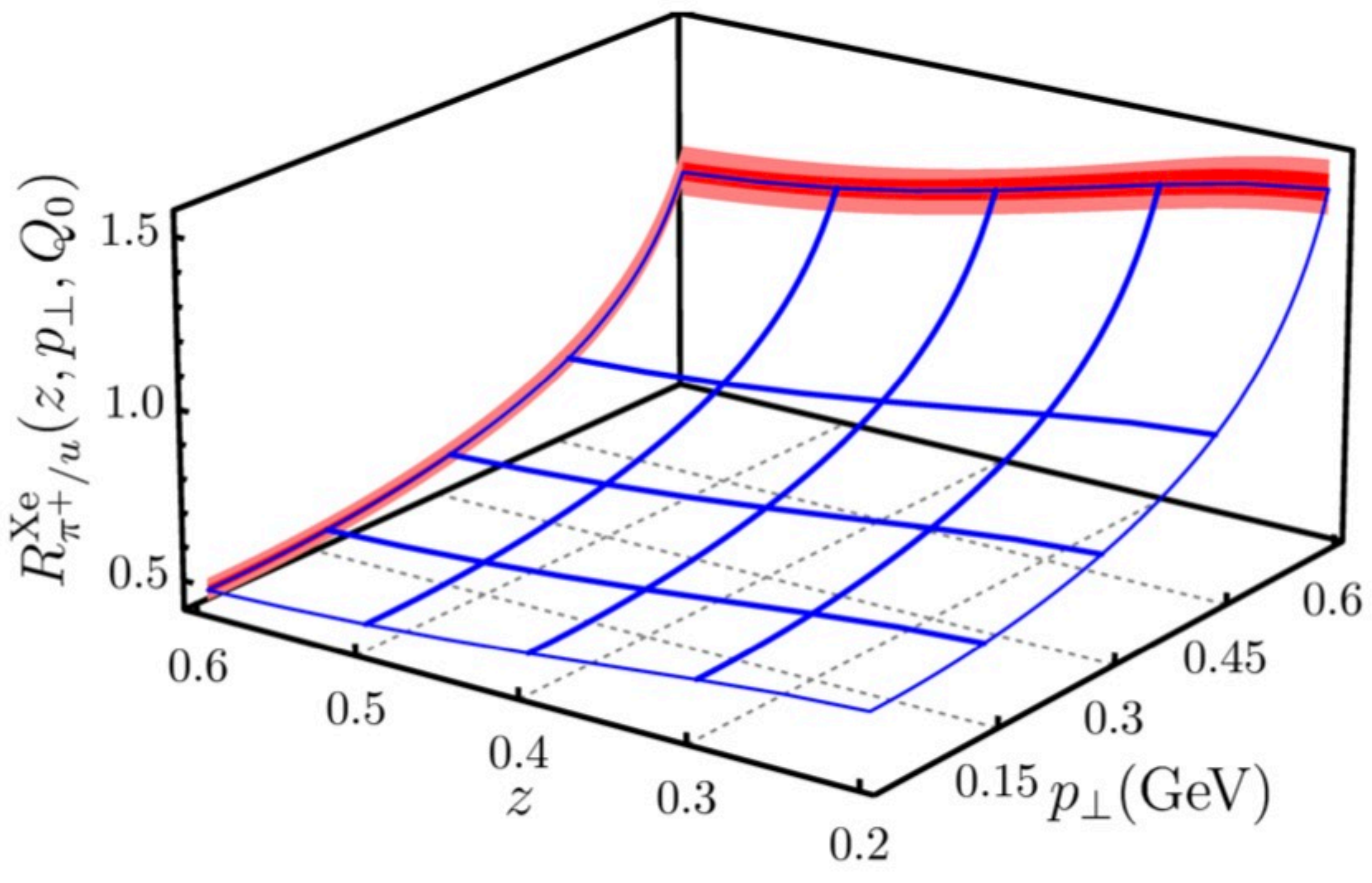
Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

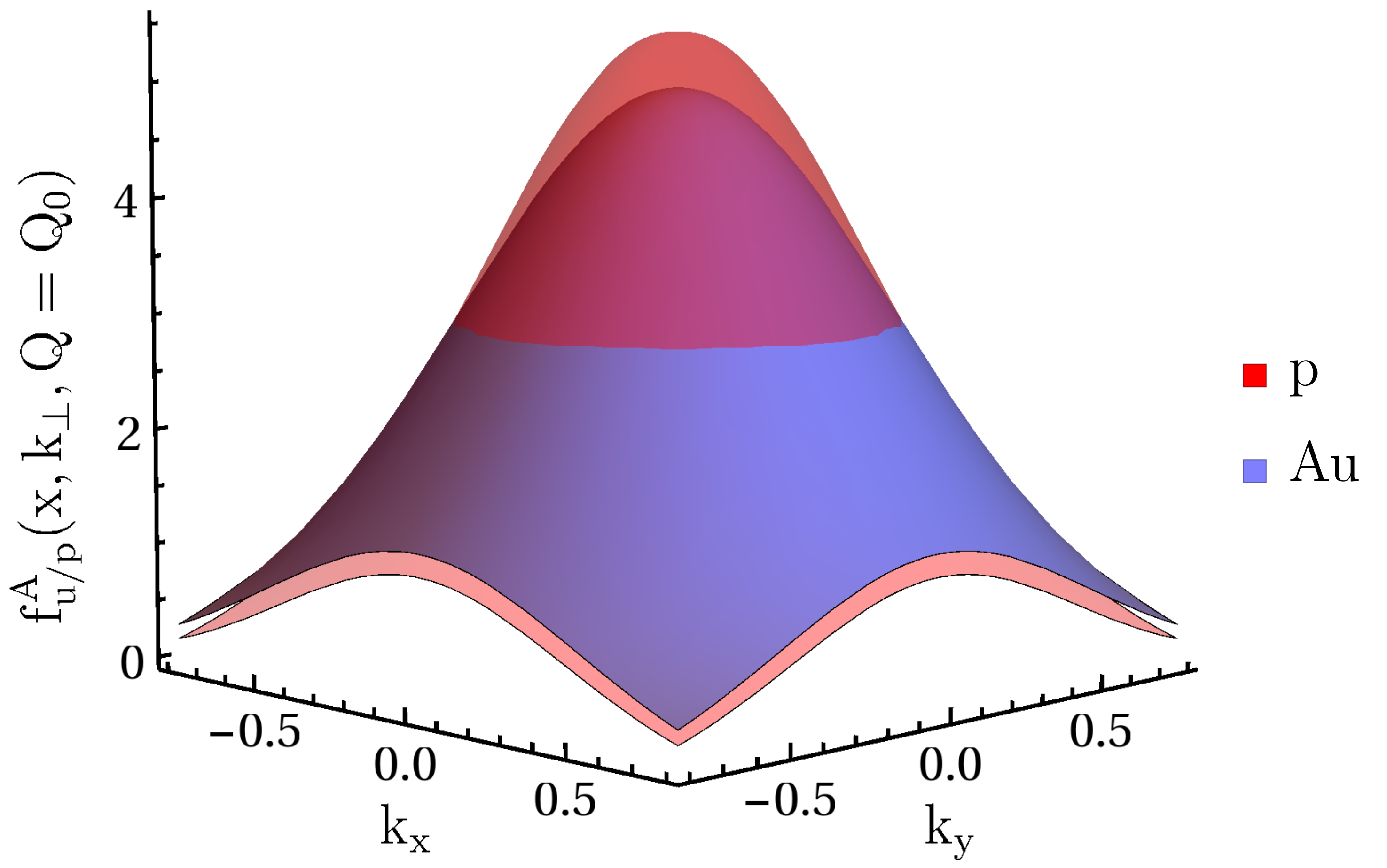
Three-dimension imaging in nuclei

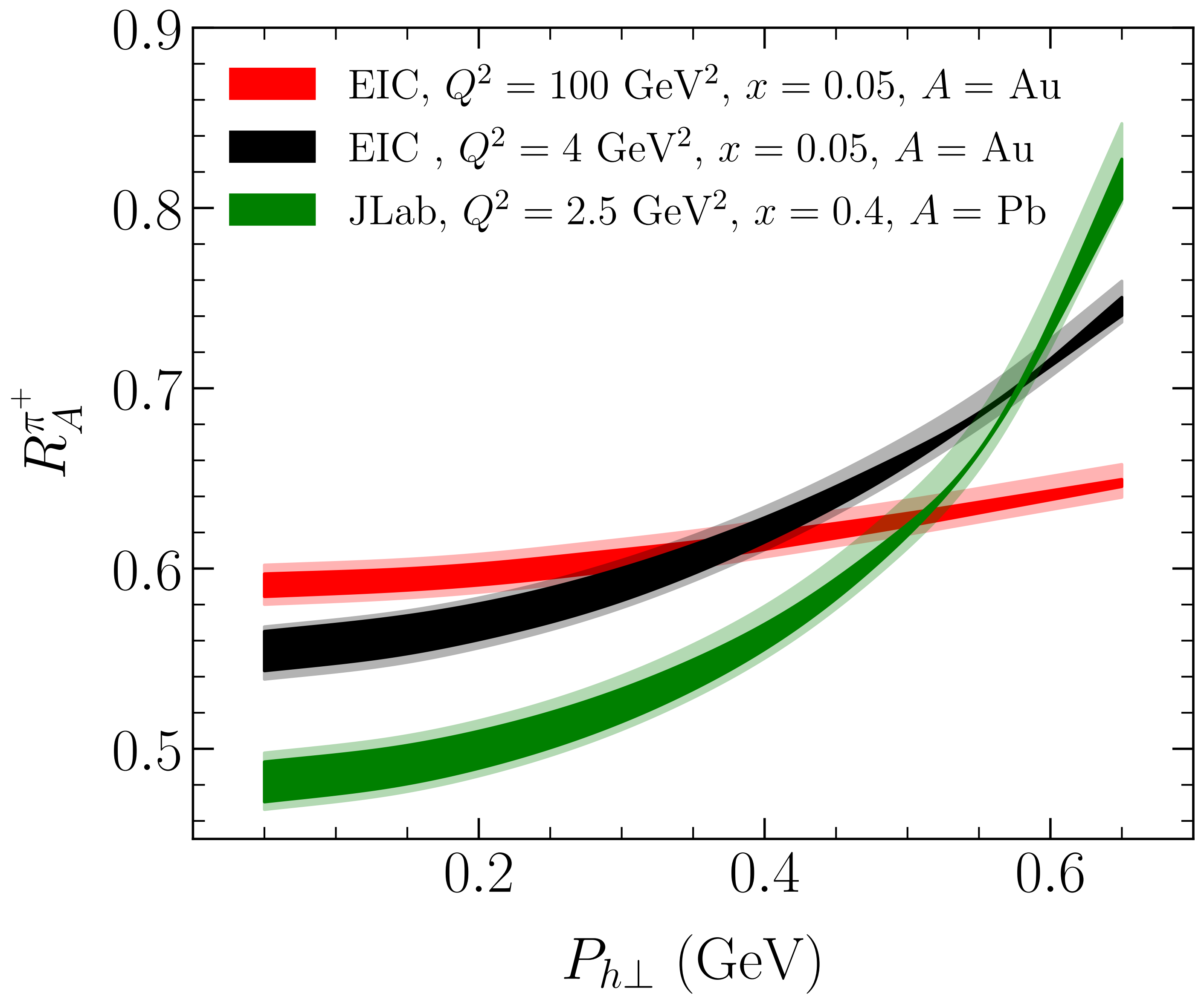
$$R^{\mathrm{Au}}_{u/p}(x,k_\perp,Q_0) = \frac{f^{\mathrm{Au}}_{u/p}(x,k_\perp,Q_0)}{f_{u/p}(x,k_\perp,Q_0)}$$



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



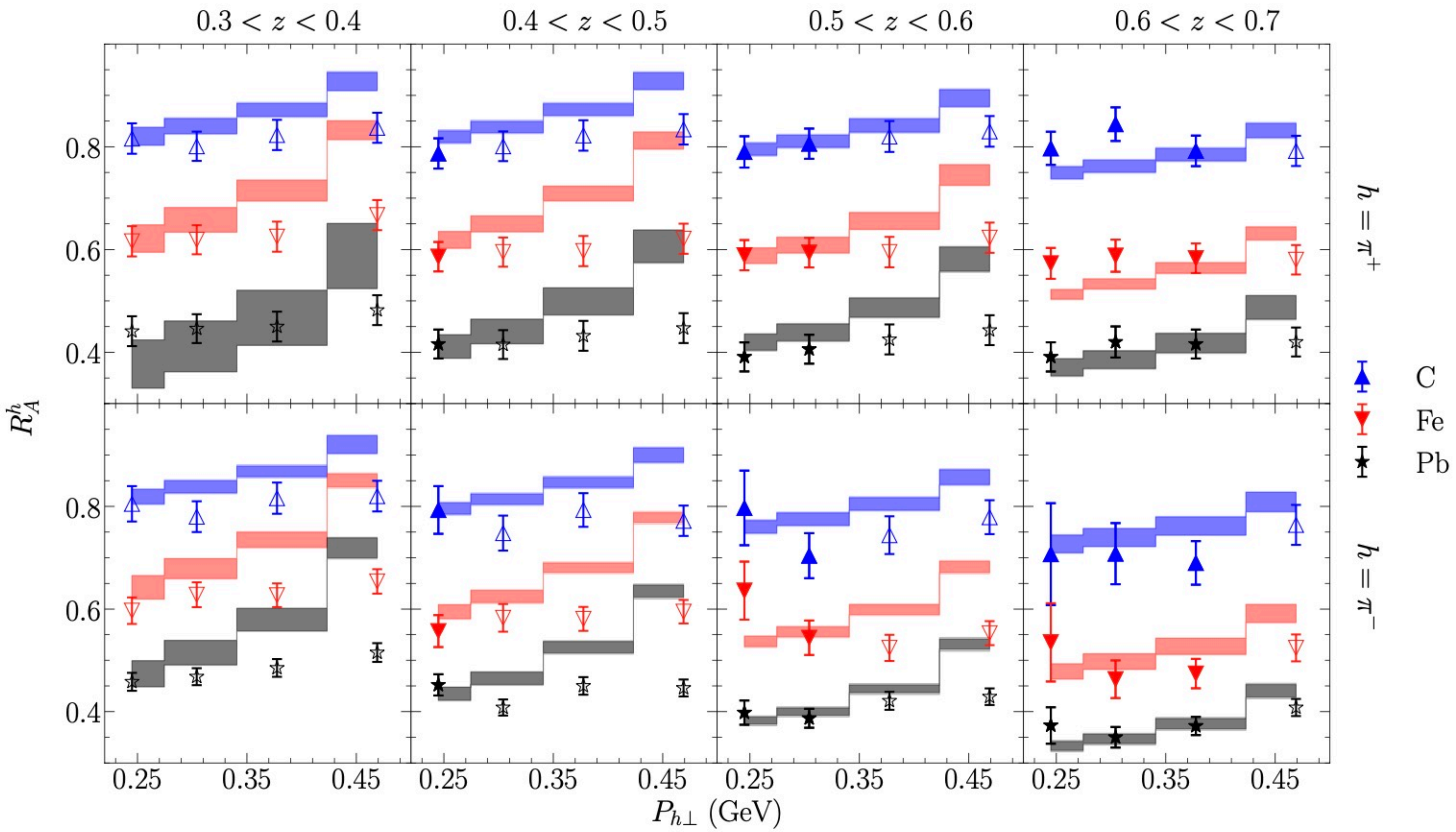


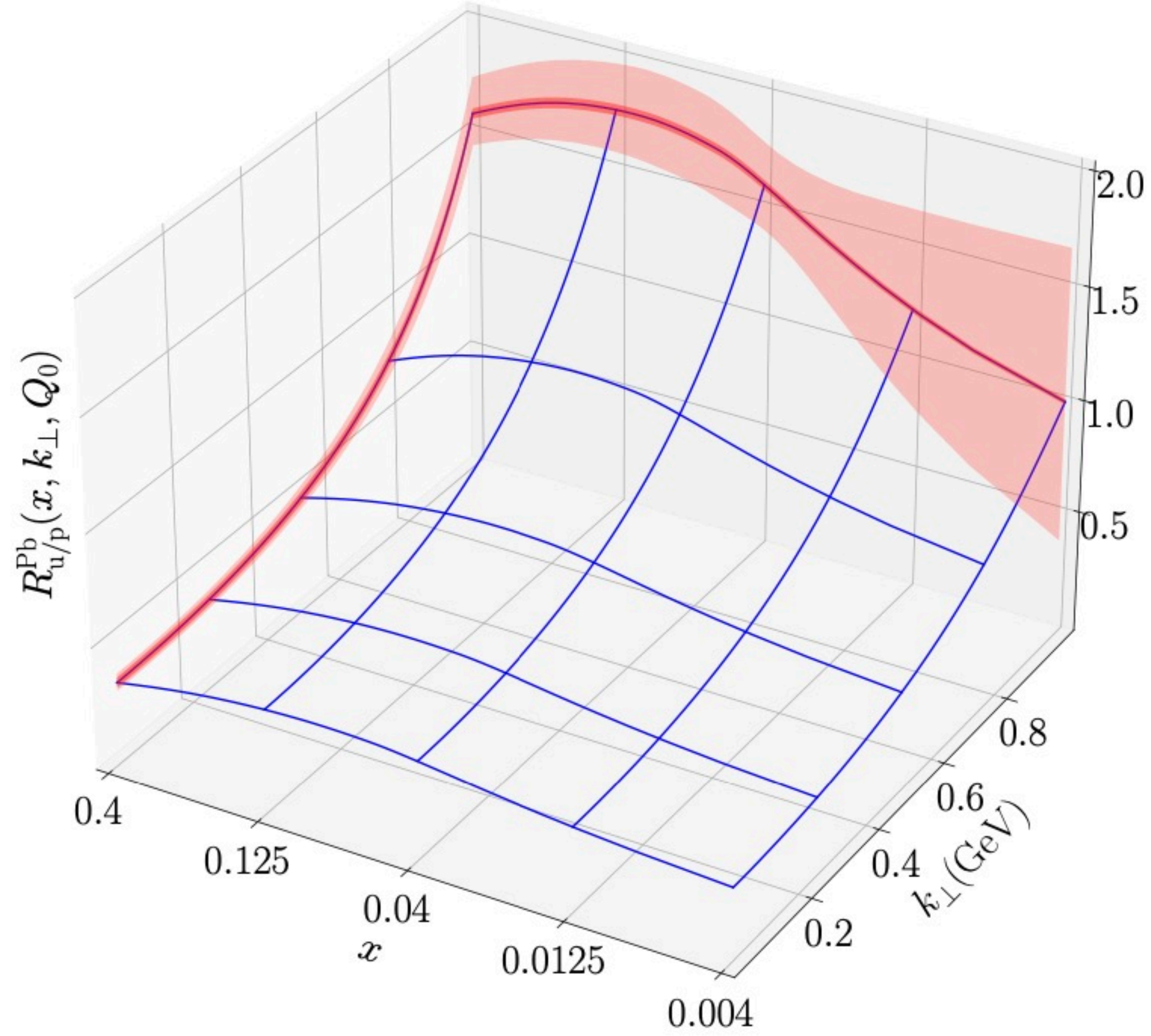


- First time quantitative determination of nuclear TMDs
- Identification of transverse momentum broadening in nuclei

Impact from JLab measurements

Alrashed, Kang, Terry, **HX**, Zhang, arXiv: 2312.09226



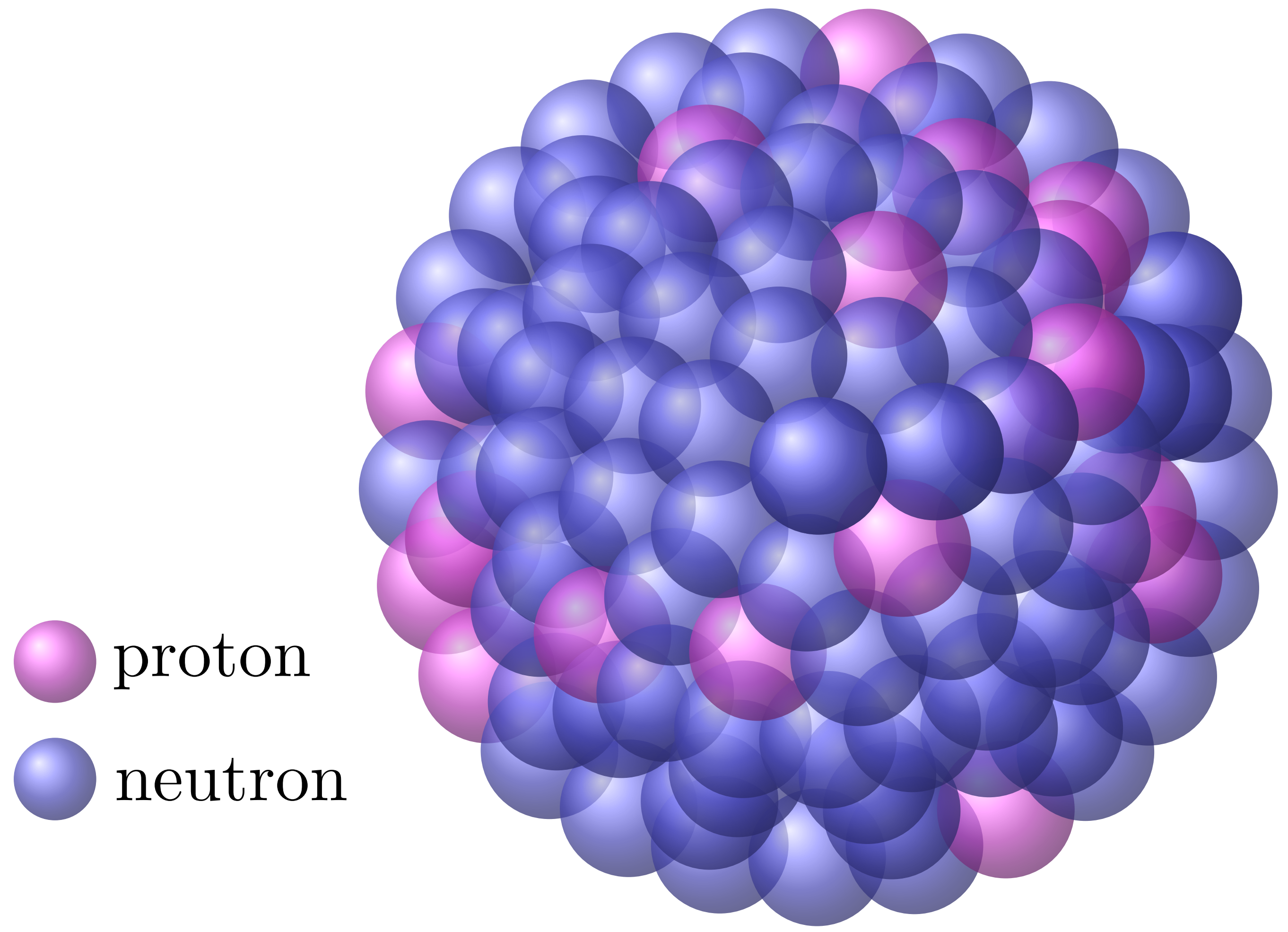


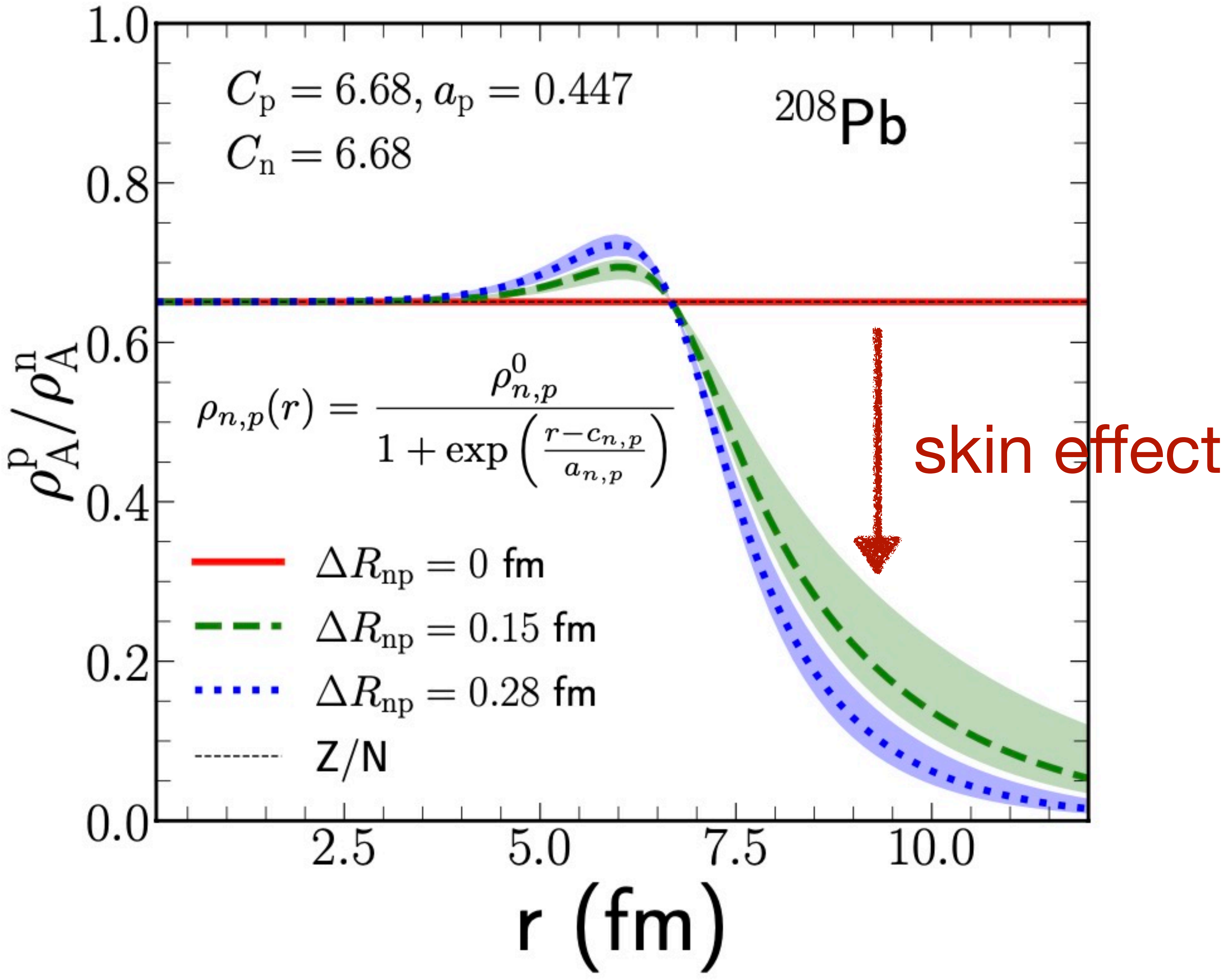
$$U_{\rm NP}^{fA}(x,b,\zeta) = U_{\rm NP}^{f}(x,b,\zeta)\exp\left\{-g_q^A\left(A^{1/3}-1\right)b^2\left(\frac{\zeta_A}{\zeta}\right)^{\Gamma}\right\}$$

- Additional constrain power on the scale dependence from JLab measurements

Neutron skin

✦ Woods-Saxon nuclear distribution





Neutron skin from elastic scattering

✦ Current knowledge on neutron skin

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

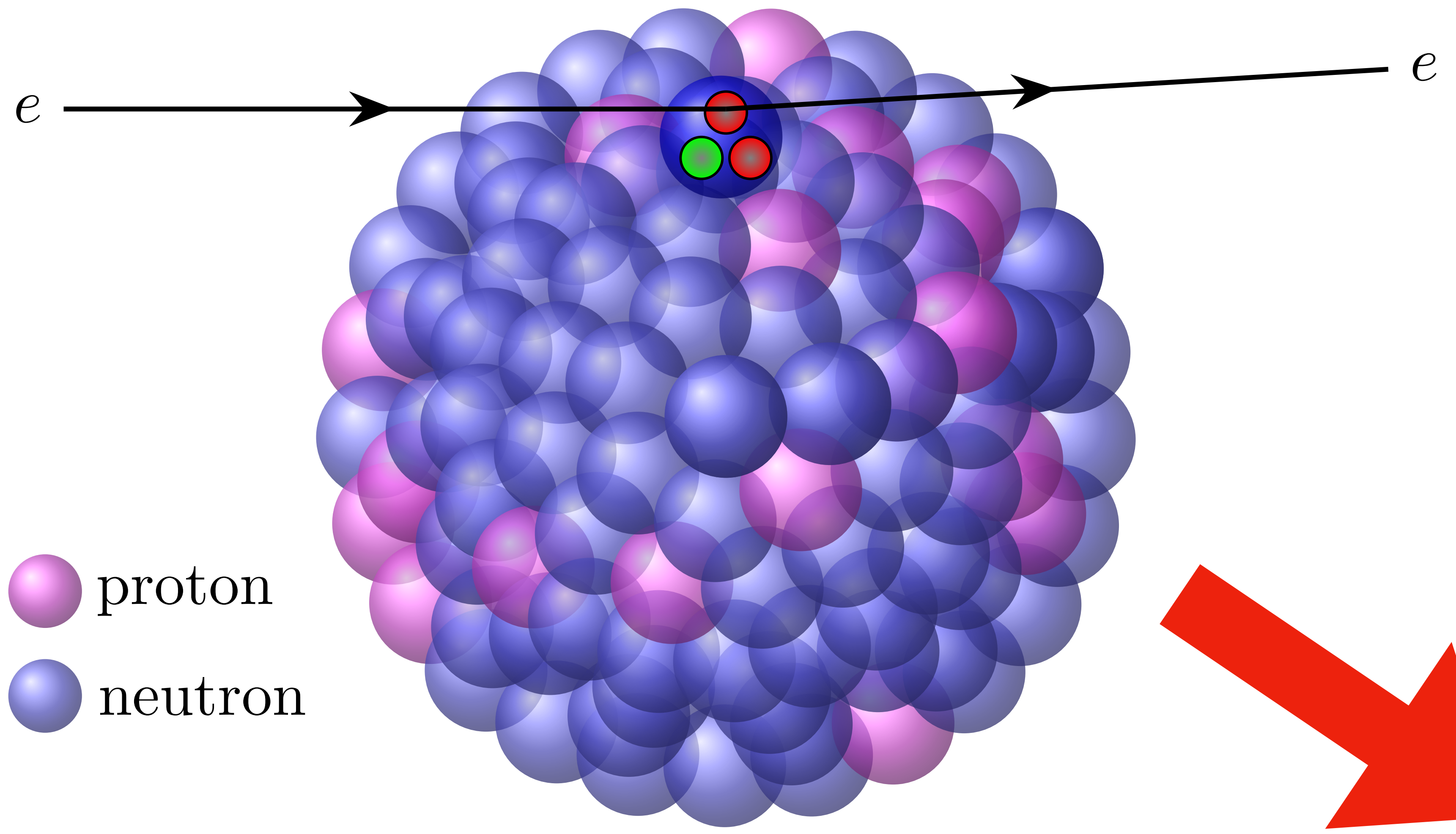


TABLE I. Values of the neutron skins in ^{208}Pb from a variety of experimental methods.

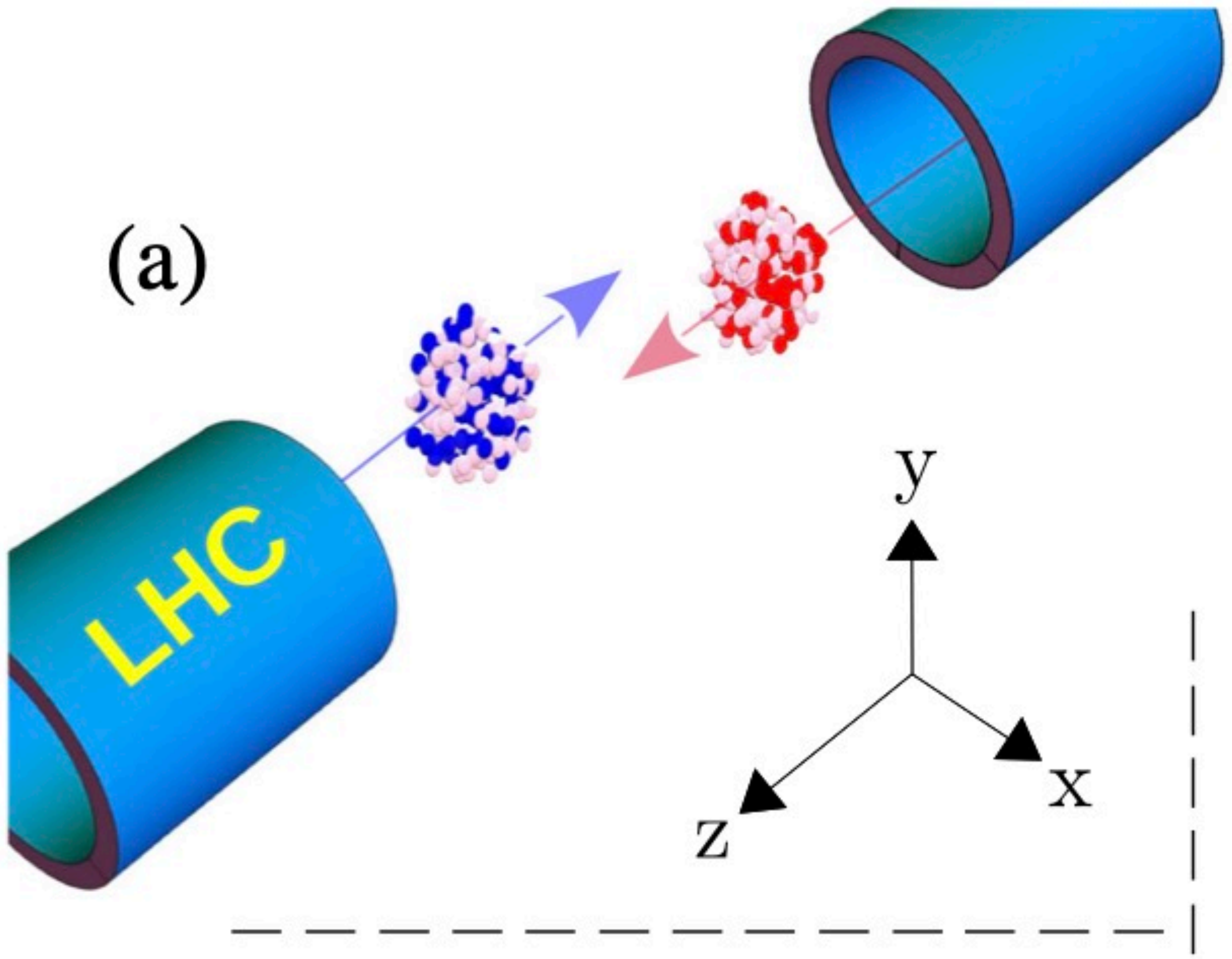
Type of measurement	Extracted neutron skin in ^{208}Pb
Proton-nucleus scattering [6]	0.083 - 0.111
Proton-nucleus scattering [7]	0.20 ± 0.04
Polarized proton-nucleus scattering [8]	0.16 ± 0.05
Polarized proton-nucleus scattering [9]	$0.211^{+0.054}_{-0.063}$
Pionic probes [10]	0.11 ± 0.06
Coherent π 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 (± 0.04) (± 0.05)
Antiprotonic atoms [14]	0.16 (± 0.02) (± 0.04)
Antiprotonic atoms [15]	0.15 ± 0.02
Electric dipole polarizability [16]	0.13 - 0.19
Electric dipole polarizability [17]	0.165 (±0.09)(± 0.013) (±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

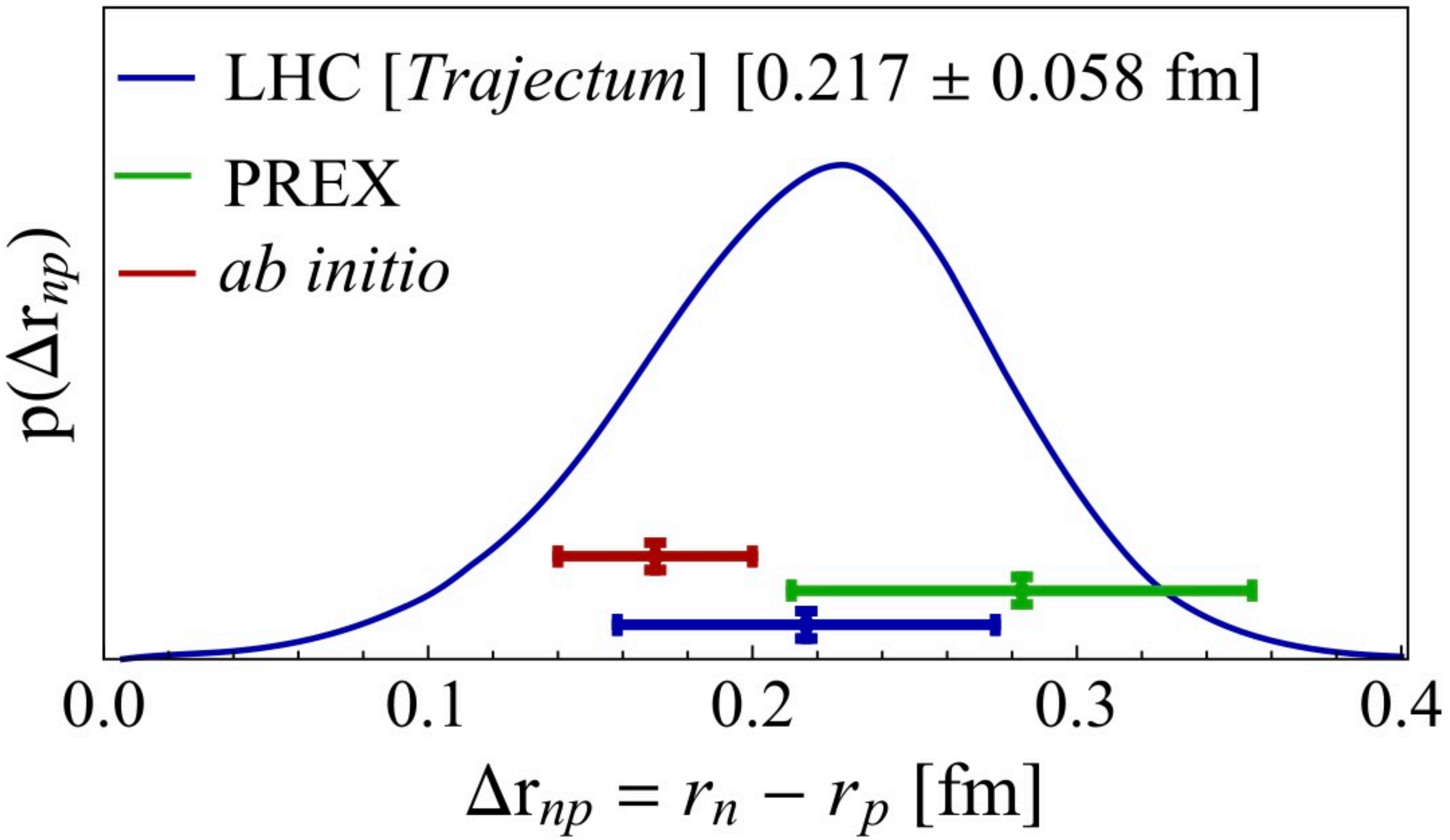
crucial for constraining the fundamental properties of cold nuclear matter and the equation of state of neutron star

Neutron skin from heavy ion collisions

- ✦ New idea using heavy ion collisions

Giacalone, Nijs, Schee, PRL 2023



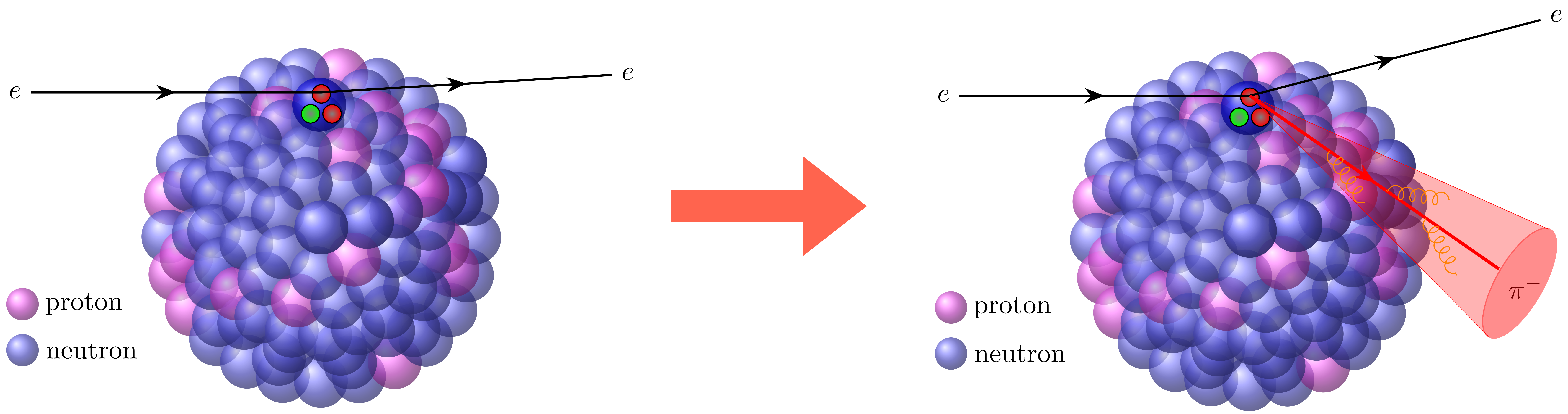


Extract neutron skin thickness of Pb using soft probe + hydrodynamic model at LHC

Neutron skin from deep inelastic scattering

- A new proposal in deep inelastic scattering at EIC

Zhang, Wang, **HX**, arXiv: 2408.xxxxx



Linking physics phenomena at both low and high collision energies

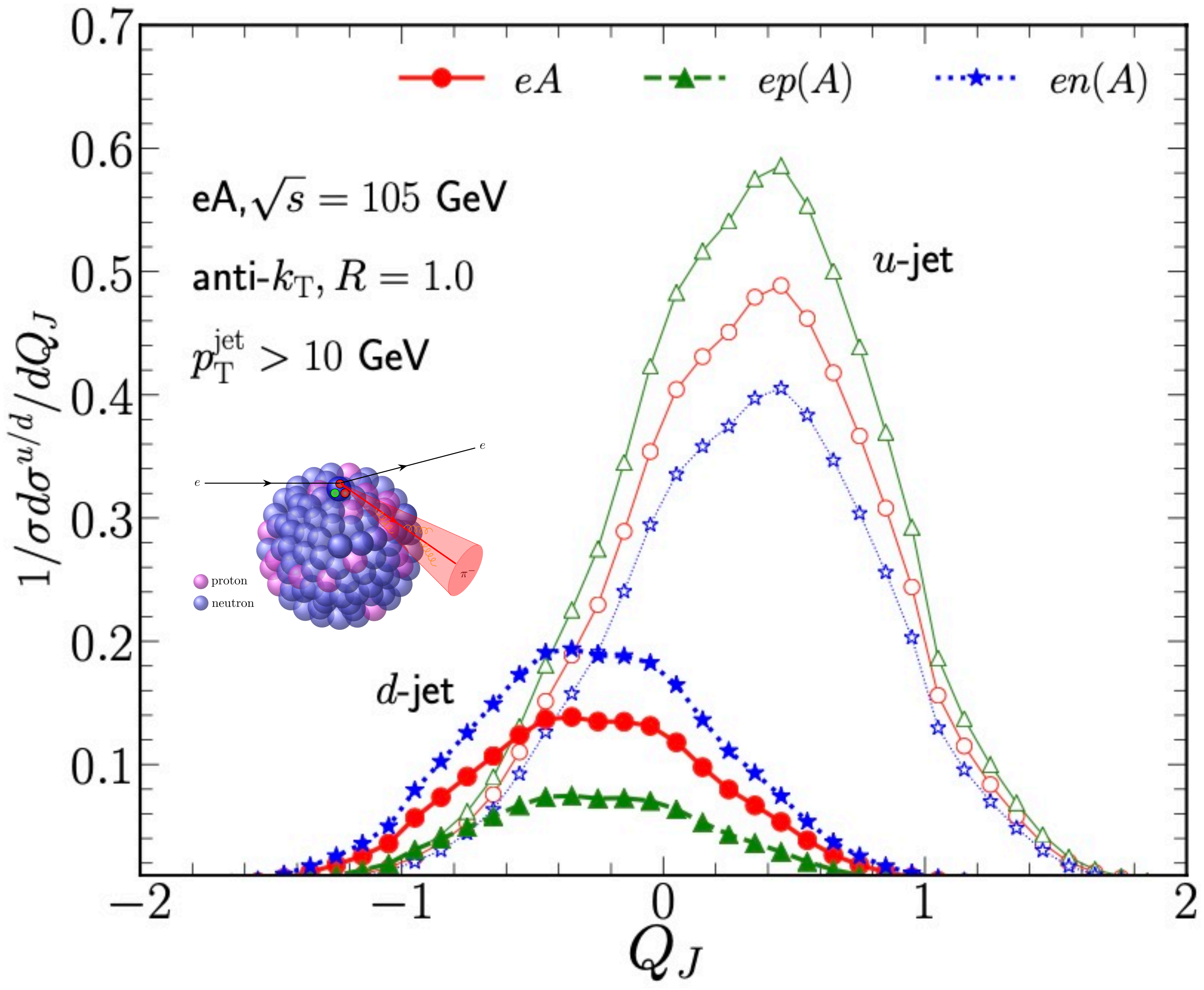
Neutron skin from deep inelastic scattering

✦ Jet charge in deep inelastic scattering

- TMD factorization

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

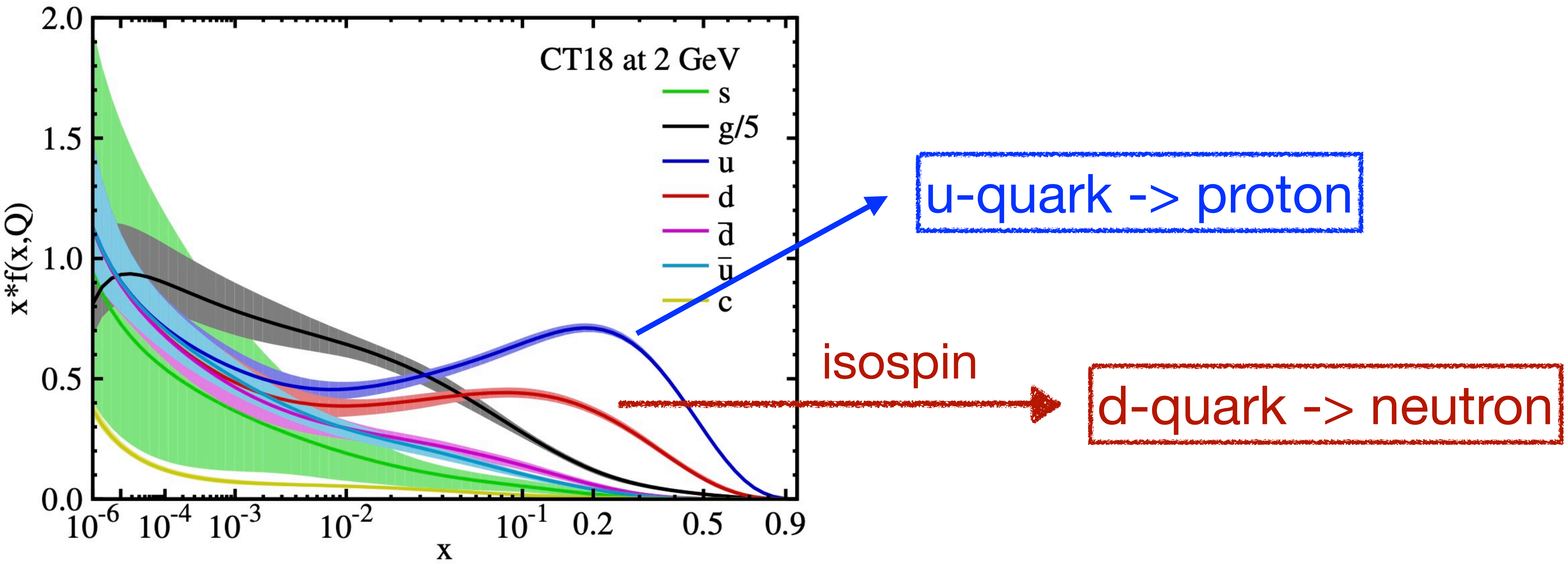
$$Q_J = \sum_{h \in \text{jet}} \left(\frac{p_T^h}{p_T^J} \right)^\kappa Q_h$$



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

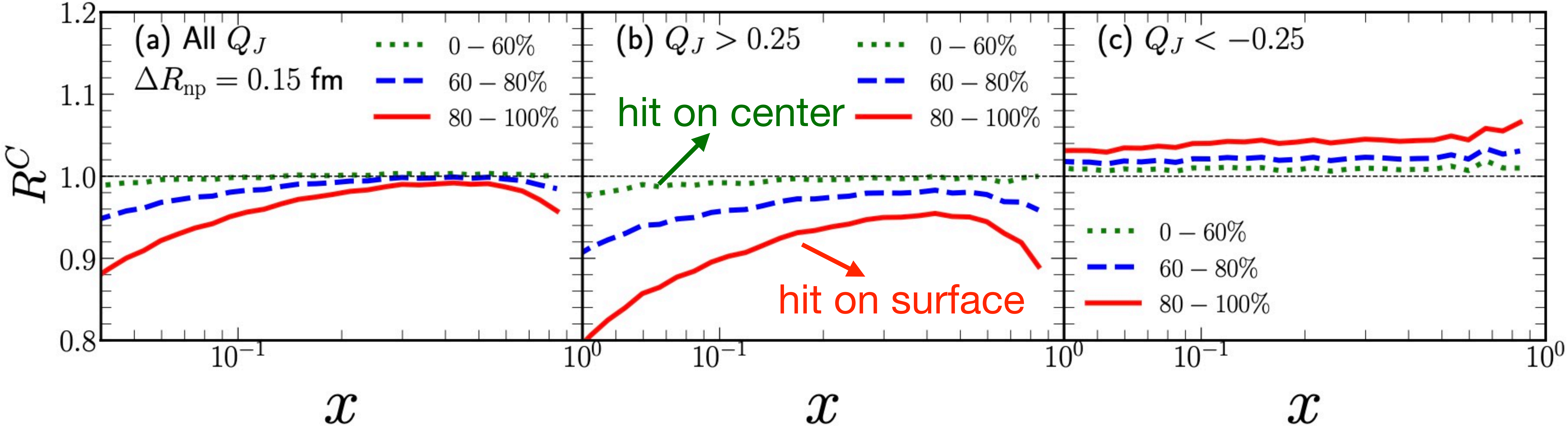


- Correlation between struck nucleon and PDFs using isospin symmetry

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

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

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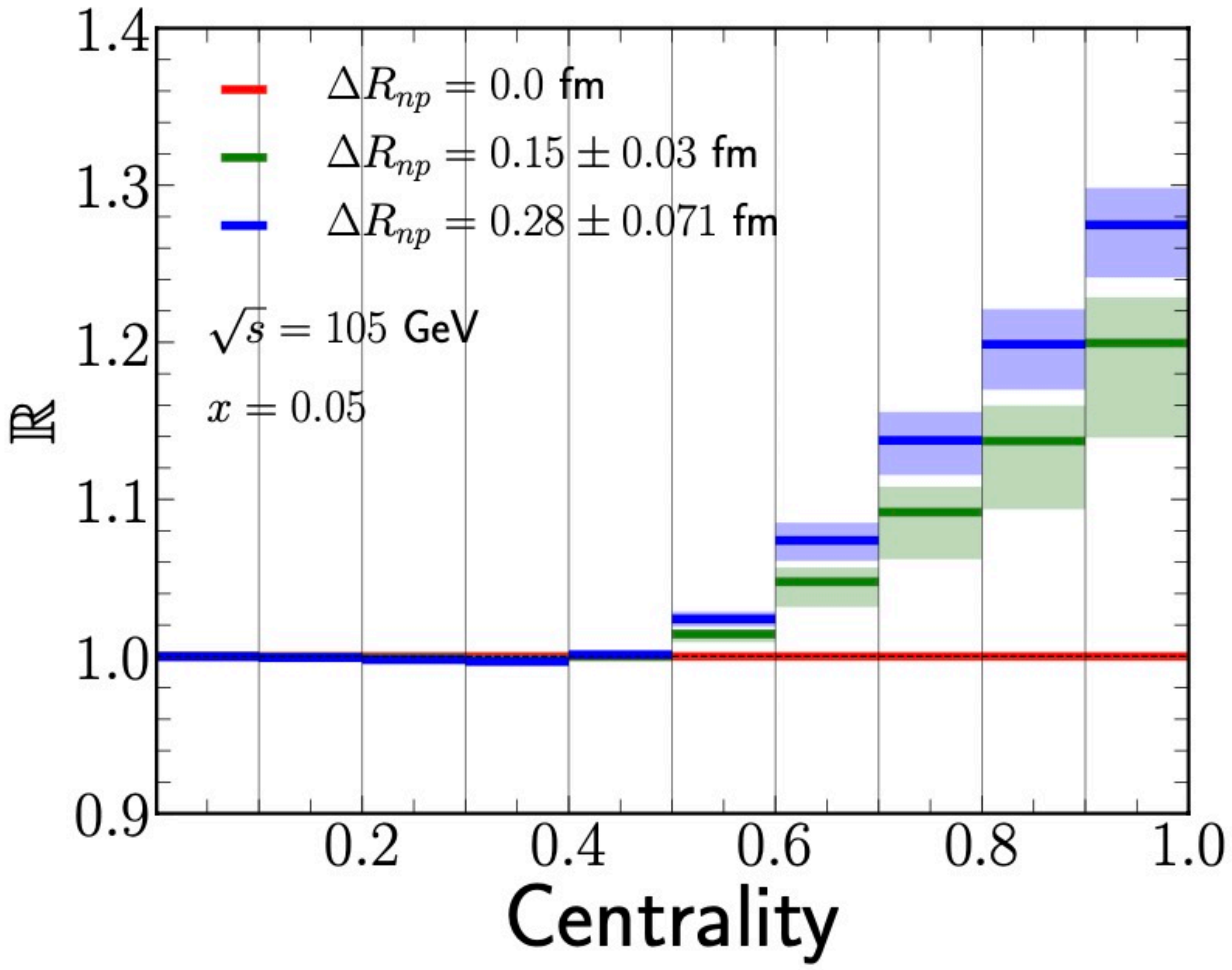

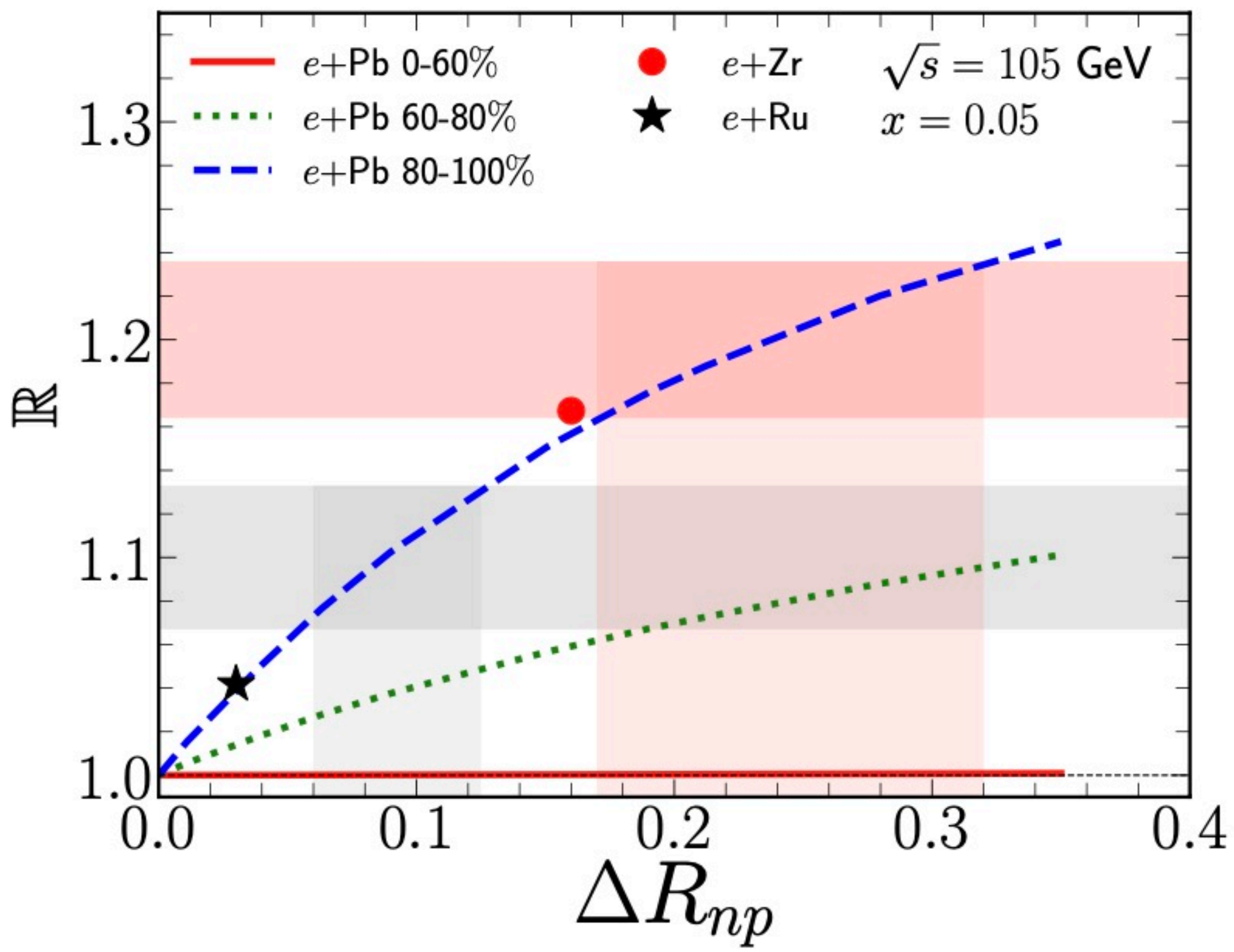

- Jet charge distribution in eA DIS: a novel probe for high precision determination of neutron skin thickness

Summary

- Focus on nuclear partonic structure in high energy nuclear collisions.
- For one scale observables, we use high-twist factorization formalism to extract the twist-4 quark-gluon correlation in nucleus.
- For two scale observables with distinct difference, we use TMD factorization formalism to extract for the first time the 3D partonic structure of nuclei.
- New proposal to probe neutron skin thickness using jet charge measurements in eA DIS at EIC.

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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

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