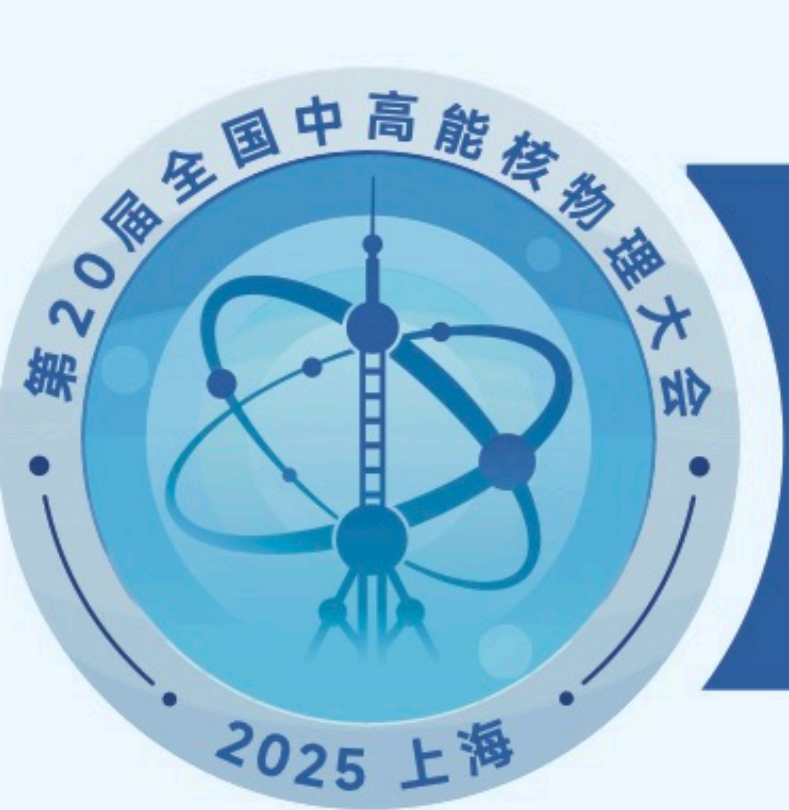




Physics at future EIC and EicC

Hongxi Xing (邢宏喜)



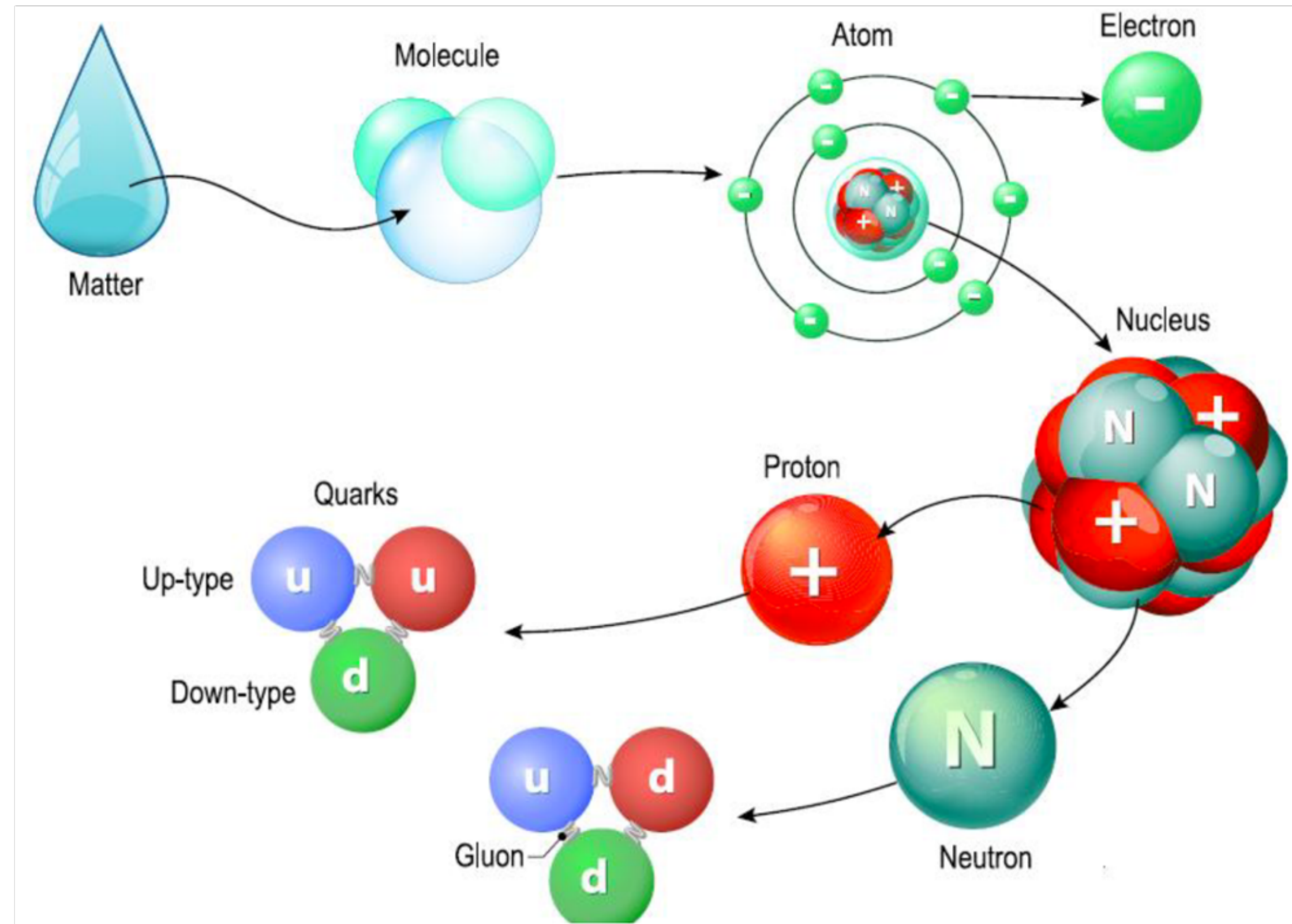
核物理与核技术全国重点实验室
华南师范大学

上海, 2025.4.24-28



- ✦ Introduction to Electron Ion Colliders
- ✦ Selected topics for nucleon/nucleus structure
 - proton mass, spin, 3D structure
 - nuclear effects
- ✦ Summary

The mystery of our visible matter

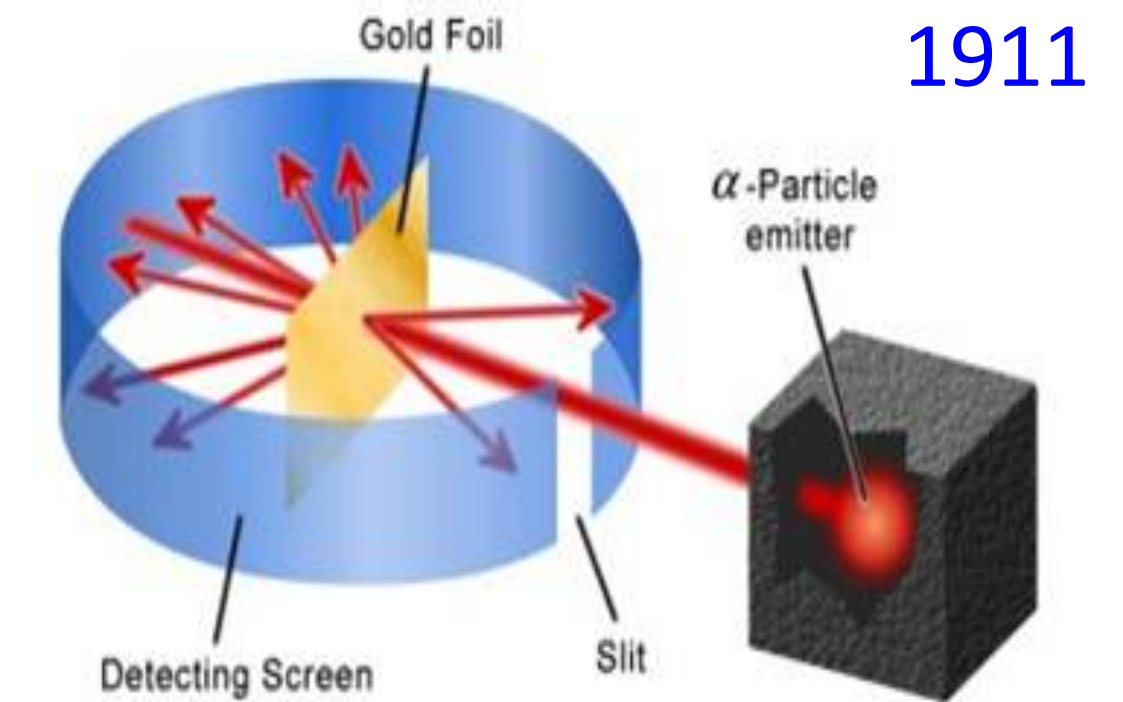


Nuclear Femtography: search for answers to the most fundamental structure at Fermi scale!

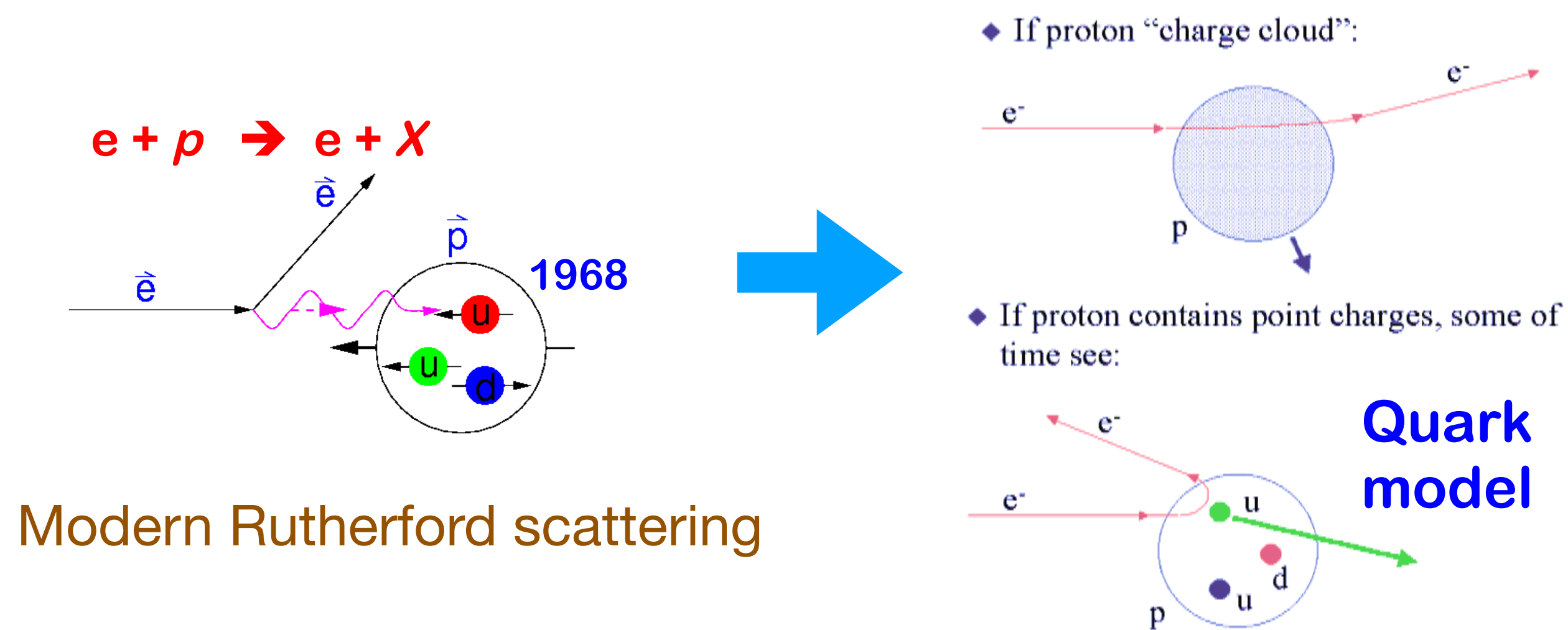
Nucleon partonic structure

◆ Revolution in our view of nuclear structure

- Atom: Dalton 1803
- Nucleus: Rutherford 1911
- Proton: Rutherford 1919
- Neutron: Chadwick 1932
- Quark model: Gell-Mann and Zweig 1964
- Parton model: Feynman 1969
- ...



Rutherford scattering



Modern Rutherford scattering

Quark model

Birth of QCD!

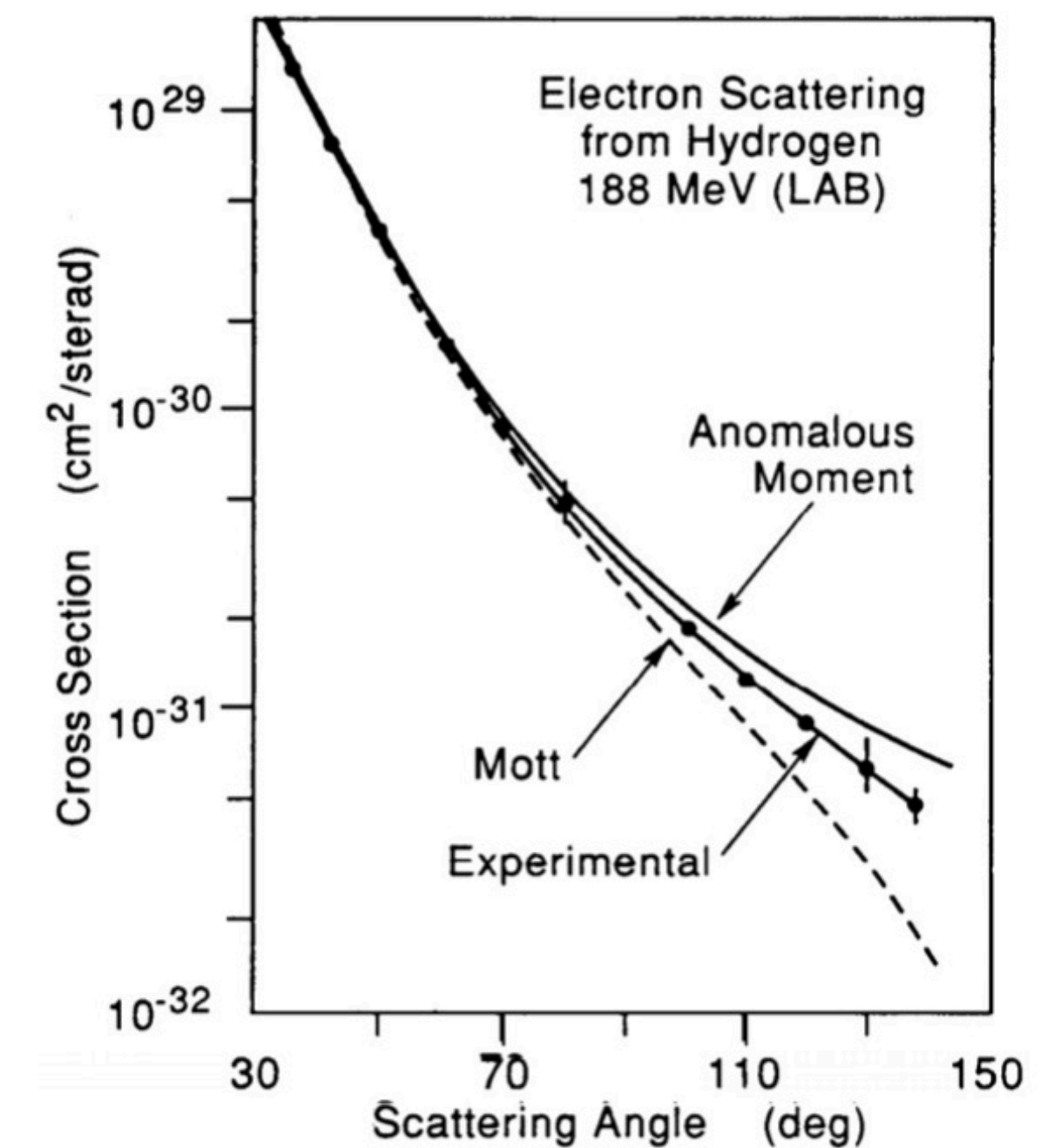
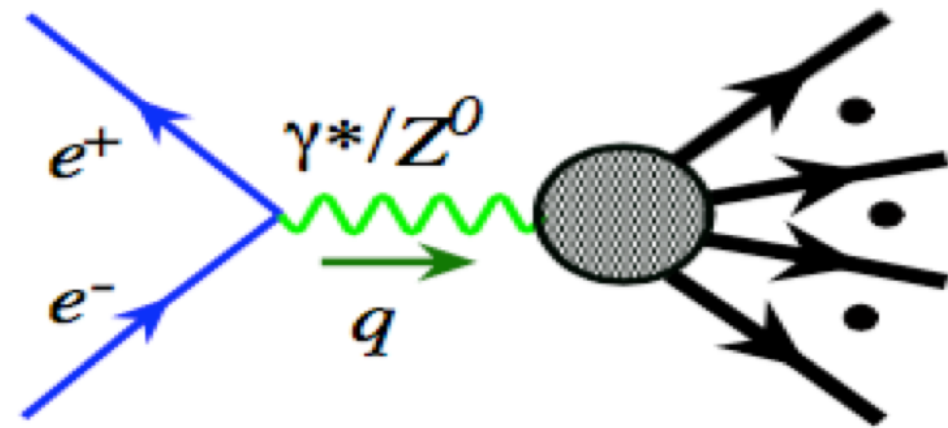


Fig. 5. Elastic electron scattering cross sections from hydrogen compared with the Mott scattering formula (electrons scattered from a particle with unit charge and no magnetic moment) and with the Rosenbluth cross section for a point proton with an anomalous magnetic moment. The data falls between the curves, showing that magnetic scattering is occurring but also indicating that the scattering is less than would be expected from a point proton.

Modern machines to probe the nucleon partonic structure

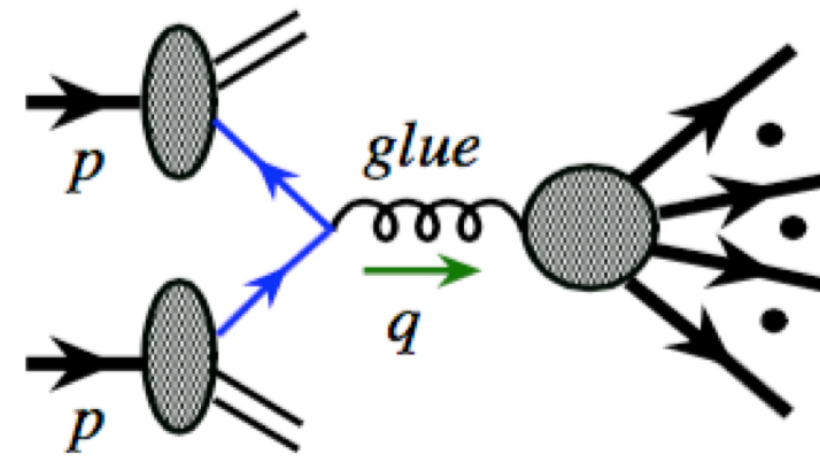
Lepton-lepton colliders



BEPC, SuperKEKB

- ▶ No hadron in the initial-state
- ▶ Hadrons are emerged from energy
- ▶ Not ideal for studying hadron structure

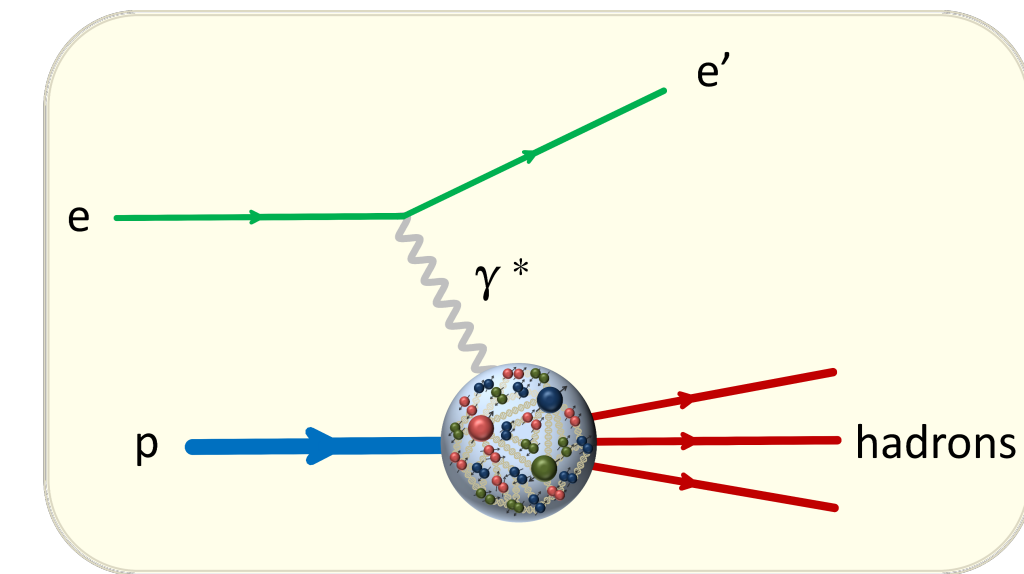
Hadron-hadron colliders



RHIC, LHC

- ▶ Hadrons in the initial-state
- ▶ Hadrons are emerged from energy
- ▶ Currently used for studying hadron structure

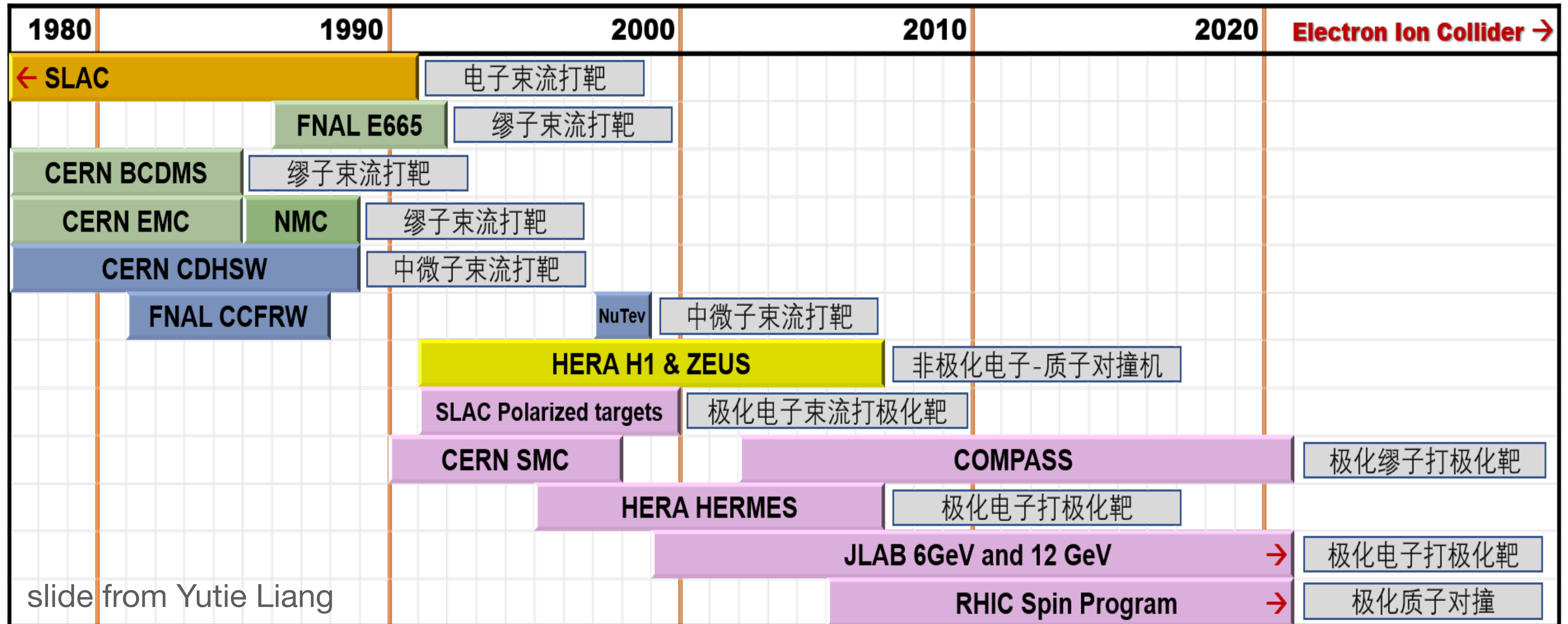
lepton-hadron colliders



HERA, JLab

- ▶ Hadrons in the initial-state
- ▶ Hadrons are emerged from energy
- ▶ Ideal for studying hadron structure

The existing experiments for nucleon structure



Electron Ion Colliders -> the next generation facility specifically for nucleon structure!

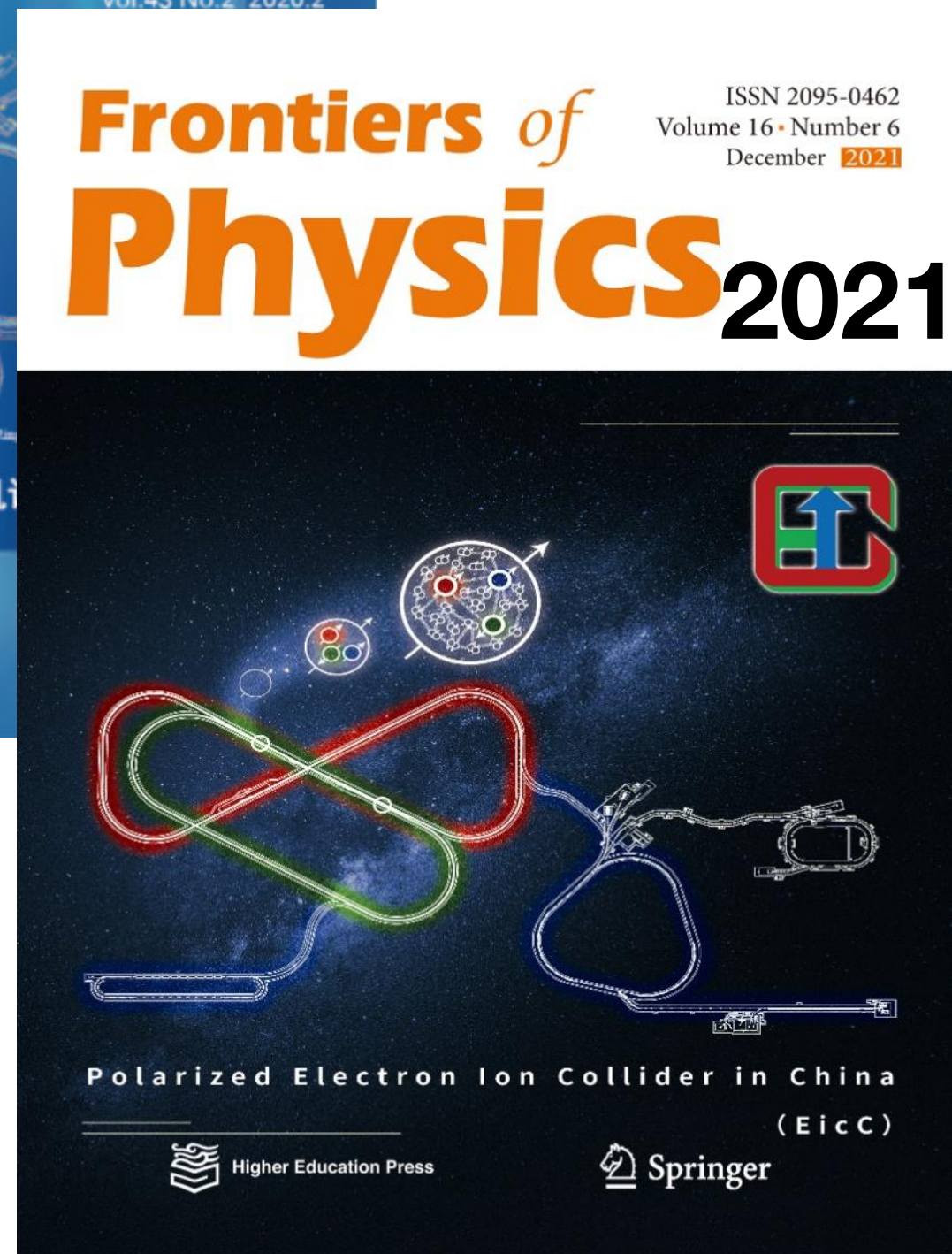
Future opportunities with electron-ion collisions

Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33}/cm^2/s$)	Ions *(depends on)	Polarisation	Status
JLab 11 JLab 22	Running Late 2030's	4.5 — 6.5	10^2 — 10^6	p → Pb	e, p, Light nuclei	Running Concept
FASER FPF/AdvSND	Running 2030's	30 — 90	0.3 — 10	W, Ar	no	Running Advanced
EIC	> 2034	30 — 140	1 — 10	p → U	e,p,d, ³ He	Approved
EicC	> Late 2030's	15—20	2 — 3	p → U	e,p,d, ³ He	Concept
LHeC	> Late 2030's	1200	24	*LHC	e possible	Advanced
Plasma-based schemes	2040's	530 — 9000	10^{-5} — 10^{-1}	*SPS/LHC	e possible	Concept
FCC-eh	> 2050	3500	15	*FCC-hh	e possible	Concept

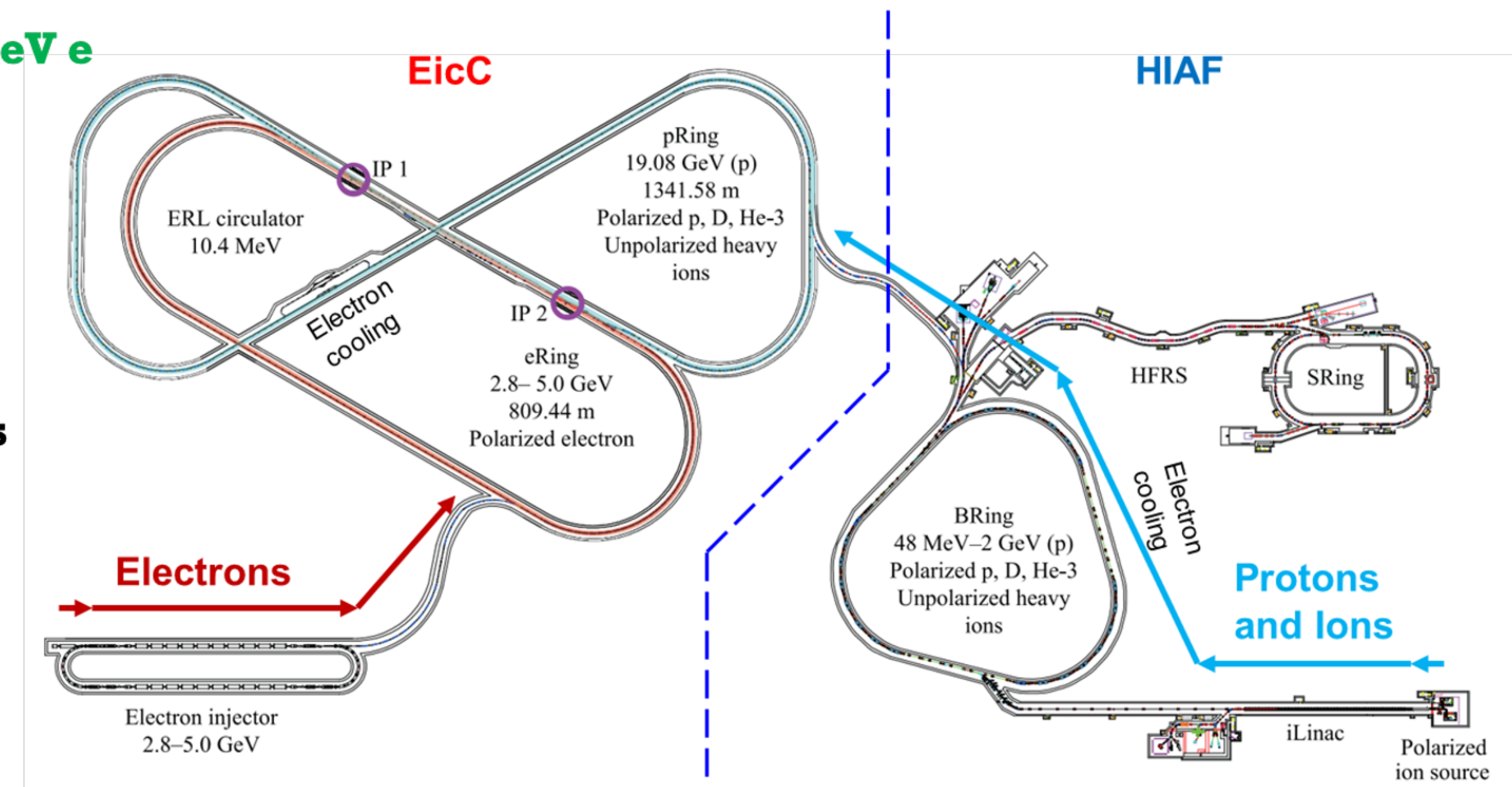
2025 European Particle Physics Strategy (2503.18208)

Electron Ion Collider in China (EicC)

Talk by N. Xu on Monday



- **20 GeV p + 3.5 GeV e**
- $\sqrt{s}$: **16.7 GeV**
- **High Lumi.:**
 $2-4 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- **Polarized beams**



HIAF under construction

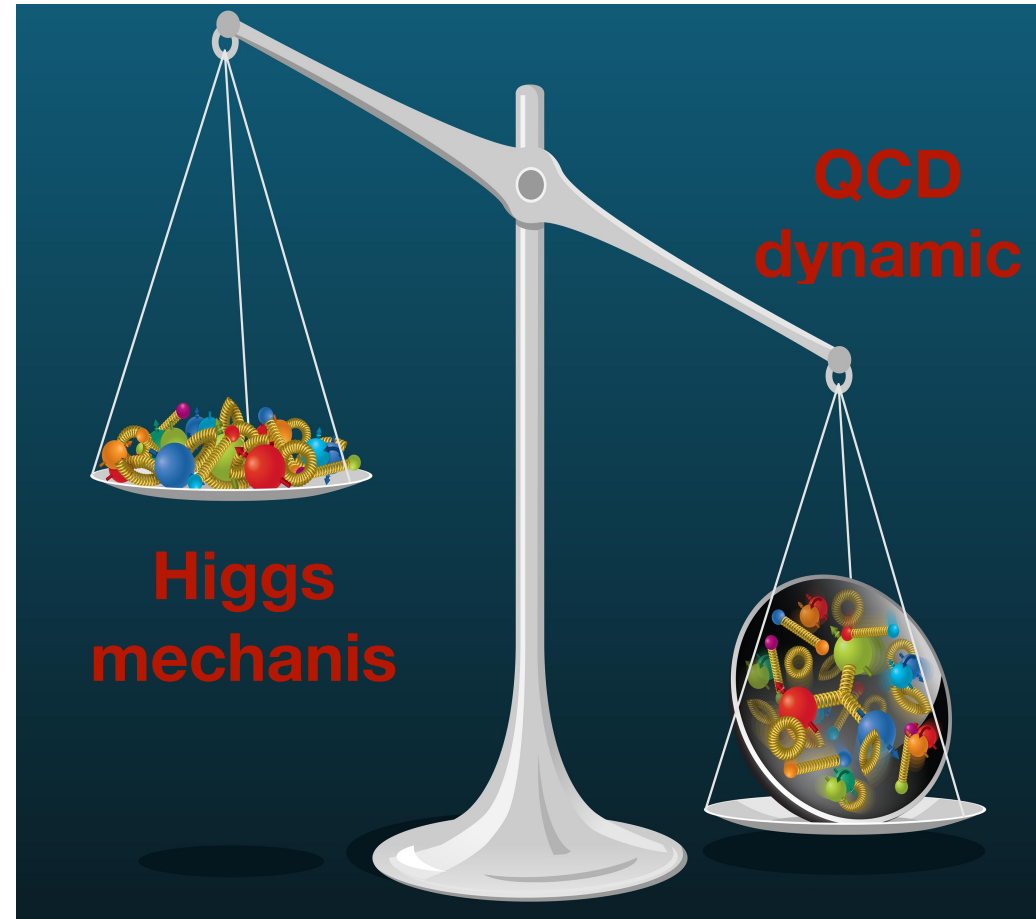
EIC in China



Electron **I**on **C**ollider in **C**hina, EicC

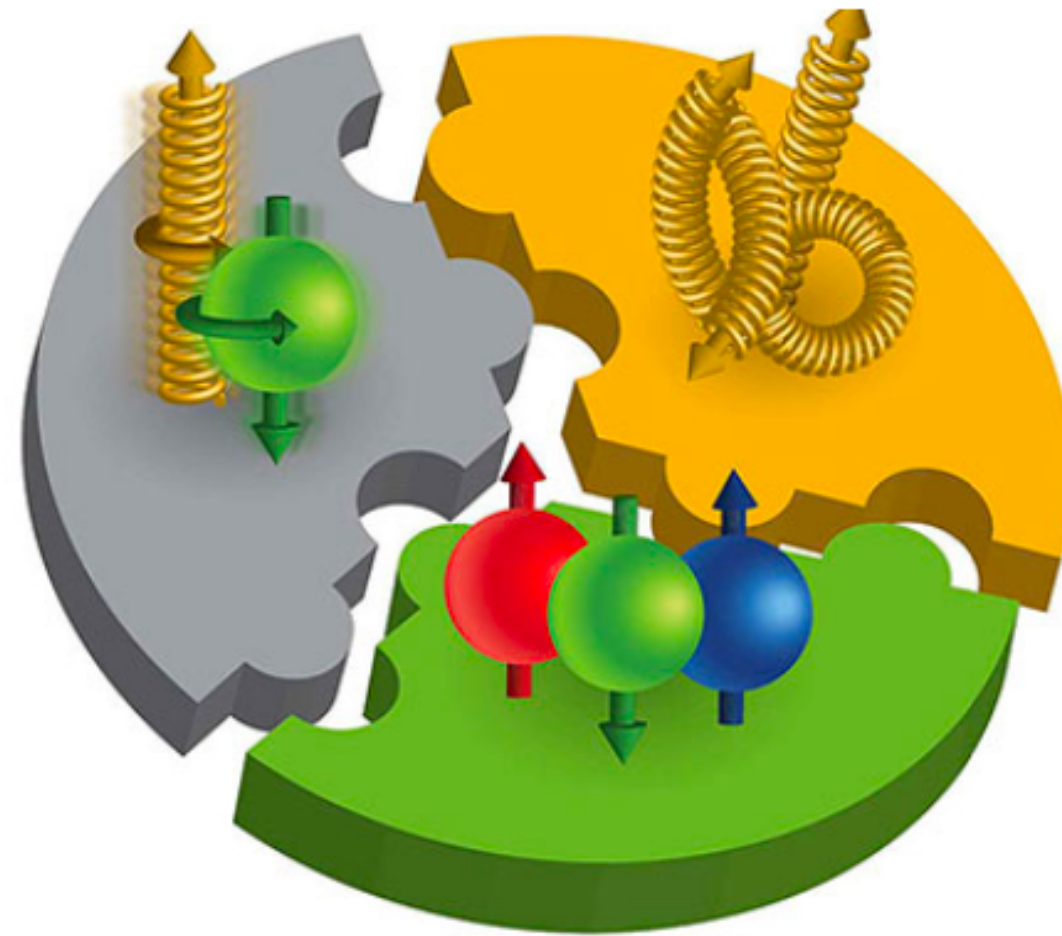
a nuclear facility proposed to be built in Huizhou, China

Science Pillars for EICs



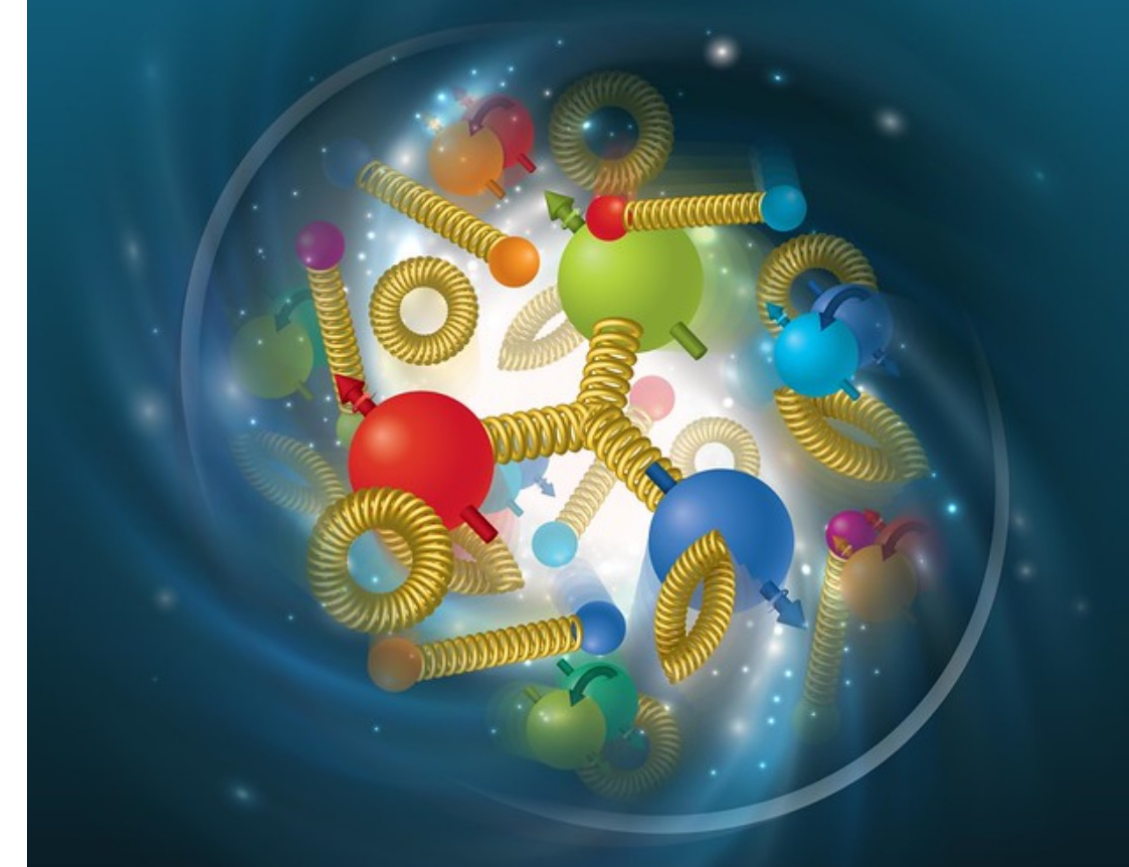
The proton mass decomposition

- ▶ Binding/Mass
- Atom: 0.00000001
- Nucleus: 0.01
- Nucleon: 100



The origin of proton spin

- ▶ No static picture of proton spin
- ▶ Interplay between intrinsic property and interactions of quarks and gluons



Parton distribution in space and momentum inside nucleon

- ▶ How do the nucleon properties emerge from quarks and gluons

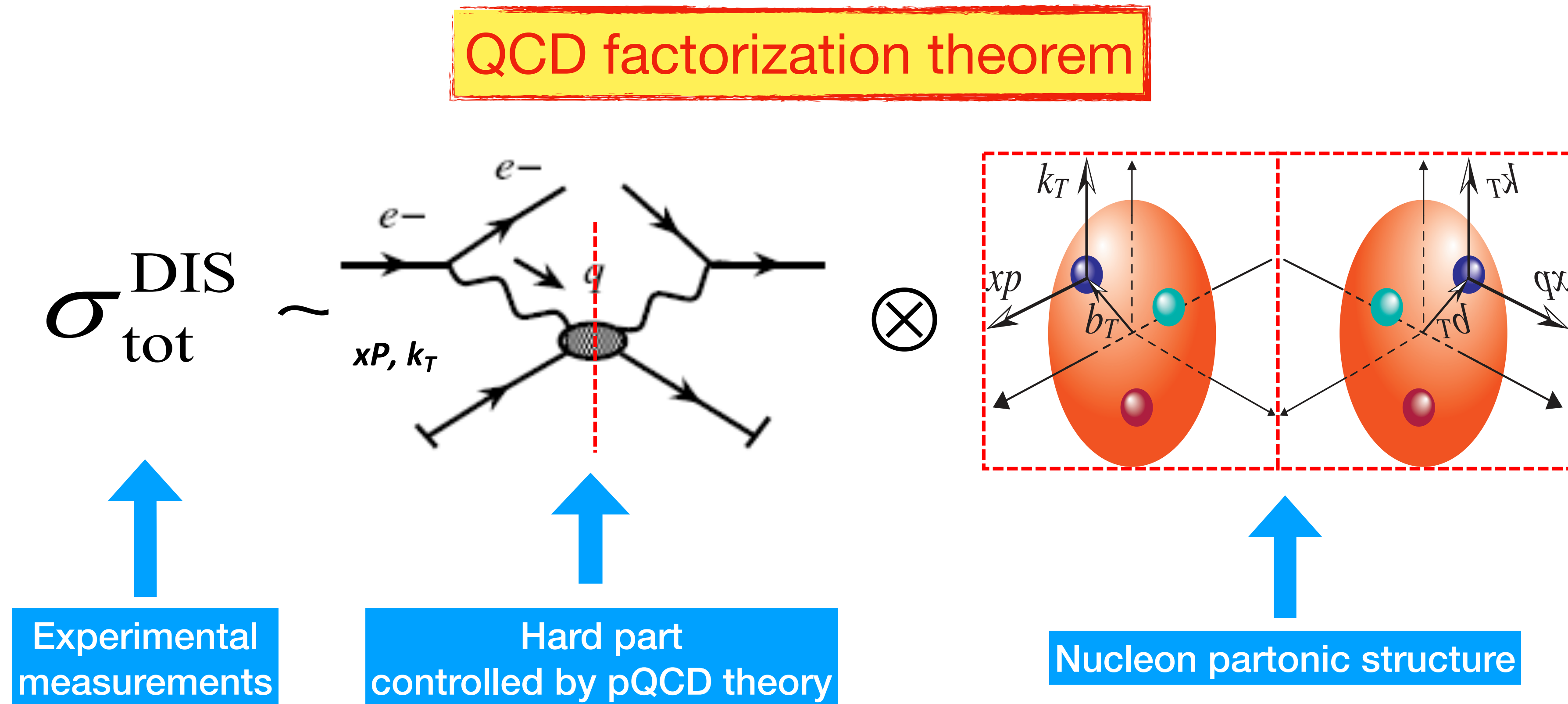


Confined partonic/hadronic states in nucleus

- ▶ gluon saturation
- ▶ Free nucleon vs bound nucleon
- ▶ Quark-gluon interaction with medium

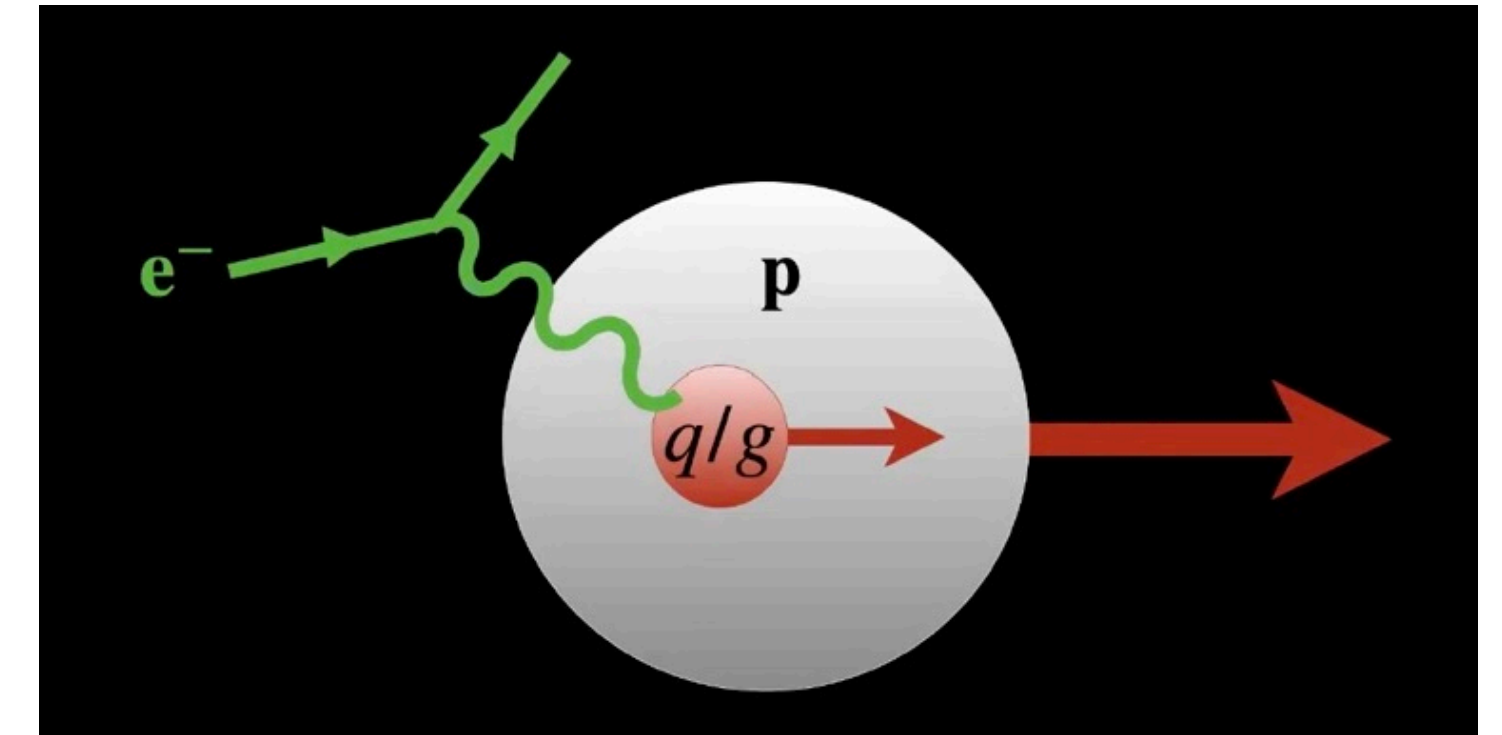
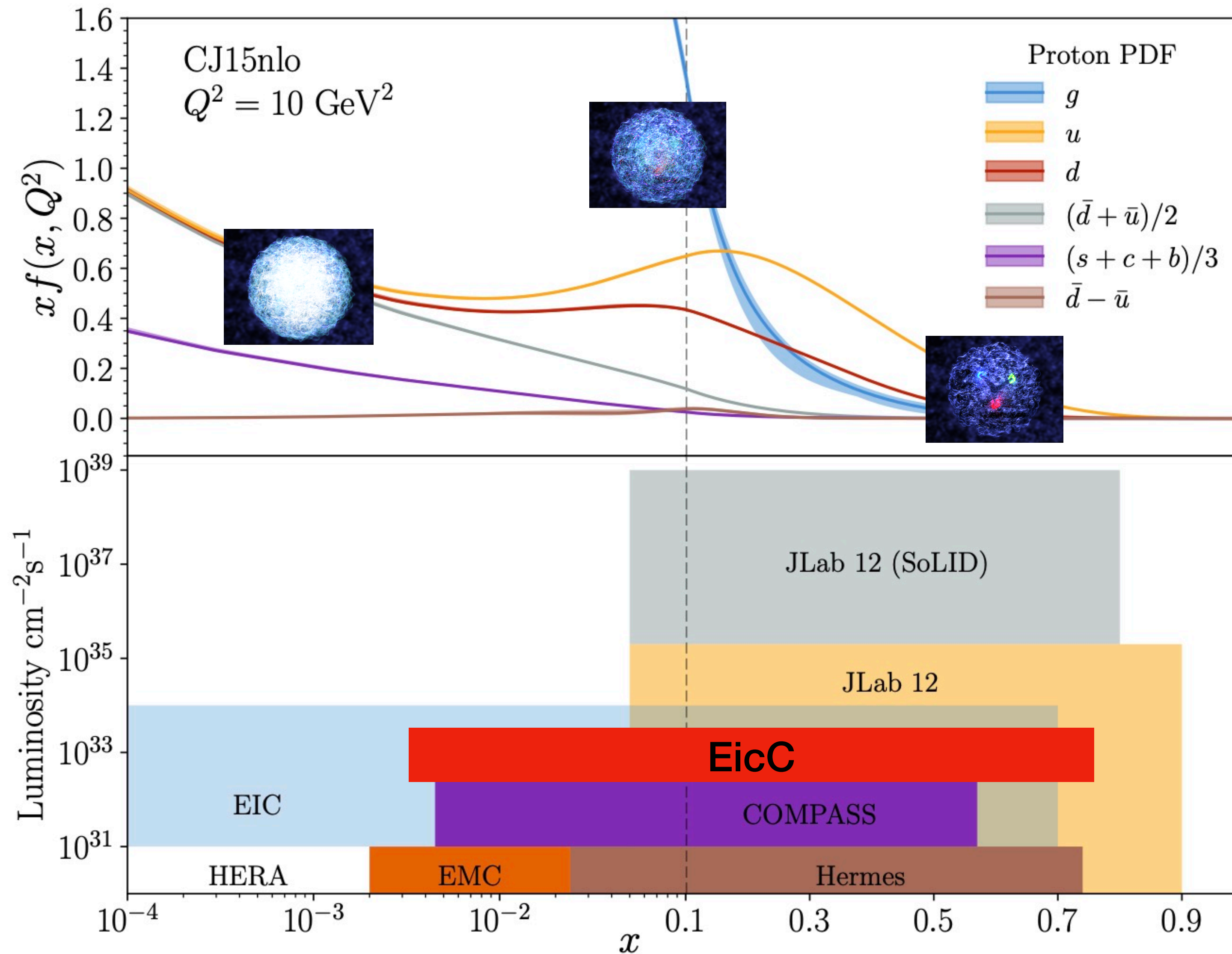
How to probe the nucleon partonic structure?

- ◆ Indispensable joint efforts from experiments and QCD theory



- **Uncertainty principle:** we can't precisely determine the position and momentum of a parton at the same time
- **We can determine the probability of seeing a parton in proton with specific characteristics - PDF**

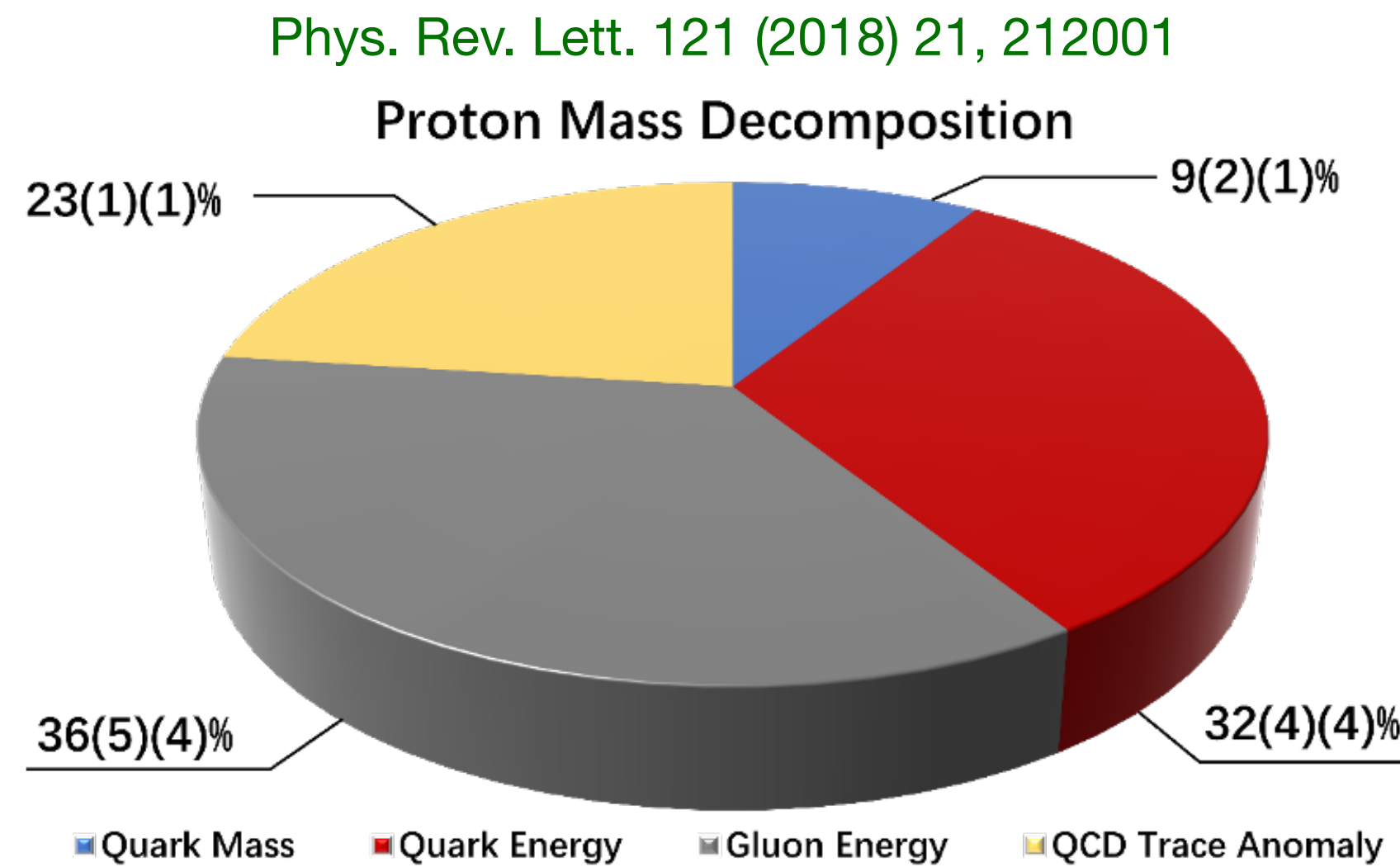
Proton interior in 1-dimension



- ◆ There is no still picture for nucleon structure
- ◆ The x -dependence can not be predicted in theory, it can be only accessed in experiment
- ◆ There is no single machine can map out the full partonic structure of proton!

Proton mass

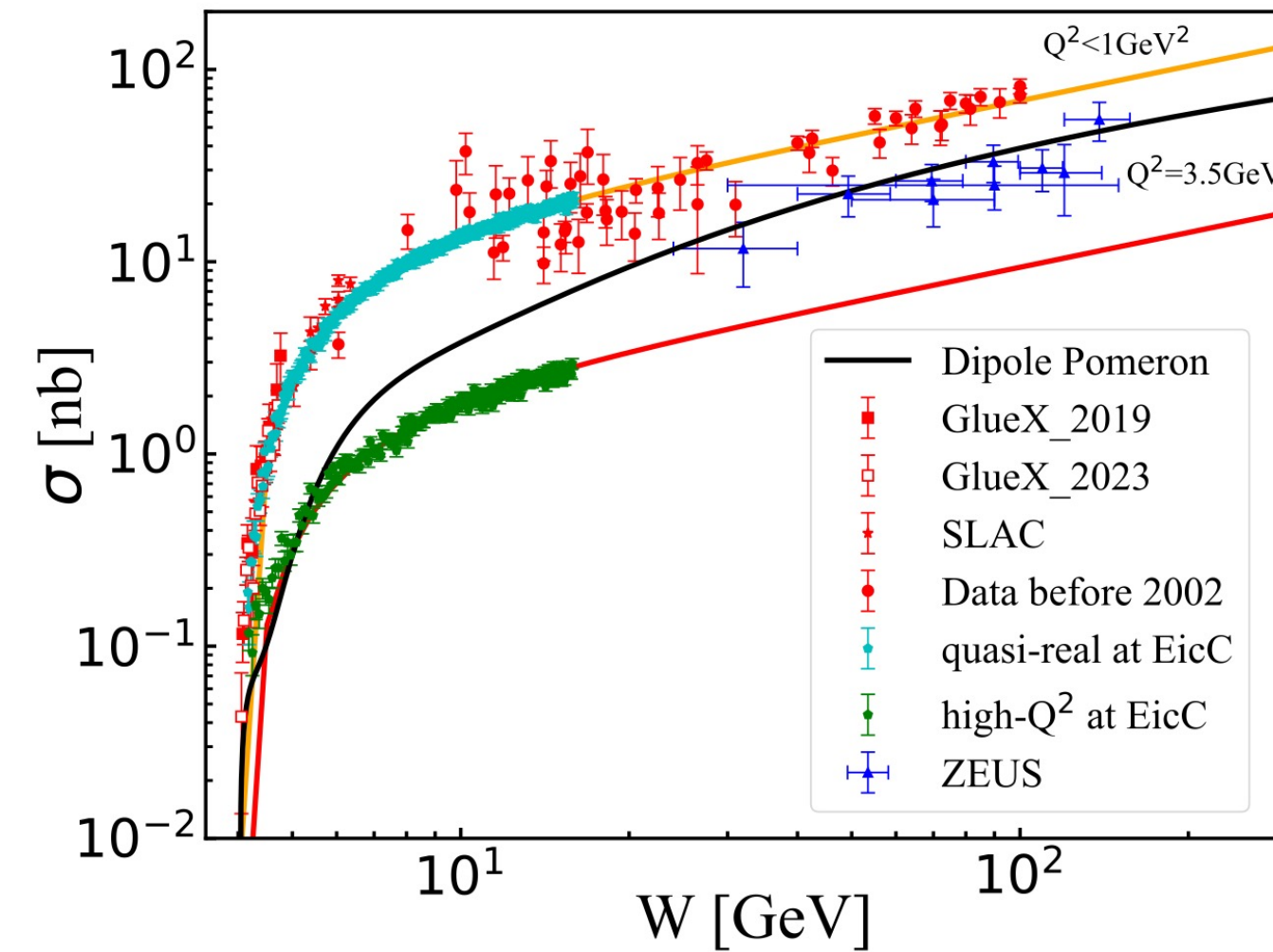
◆ The origin of proton mass



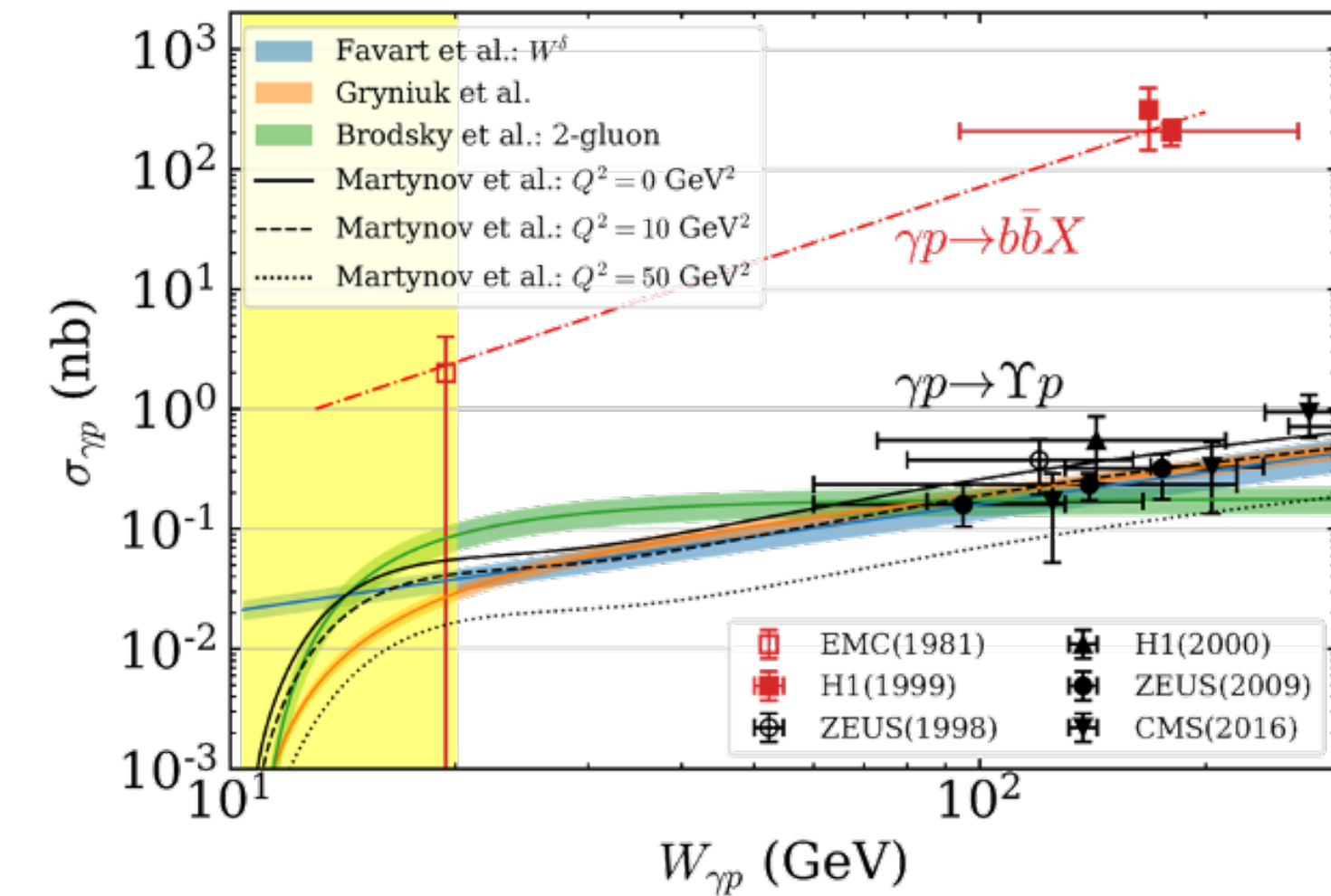
$$M = M_q + M_m + M_g + M_a$$

Ji, Phys. Rev. Lett. 74 (1995), 1071

Ji, Phys. Rev. D 52 (1995), 271



Near threshold J/Ψ production
JLab & EicC & EIC



Near threshold Υ production
EicC & EIC

- Quark energy and gluon energy constrained by PDFs
- Quark mass via πN low energy scattering
- Trace anomaly via near threshold production of heavy quarkonium ?

Proton spin

♦ Naive parton model → spin crises

$$\begin{aligned}\langle p \uparrow | \hat{S} | p \uparrow \rangle &= \frac{1}{18} \{ [(\frac{1}{2} - \frac{1}{2} + \frac{1}{2}) + (-\frac{1}{2} + \frac{1}{2} + \frac{1}{2}) + 4(\frac{1}{2} + \frac{1}{2} - \frac{1}{2})] \\ &\quad + [\frac{1}{2} + \frac{1}{2} + 4\frac{1}{2}] + [\frac{1}{2} + \frac{1}{2} + 4\frac{1}{2}] \} = \frac{1}{2}\end{aligned}$$

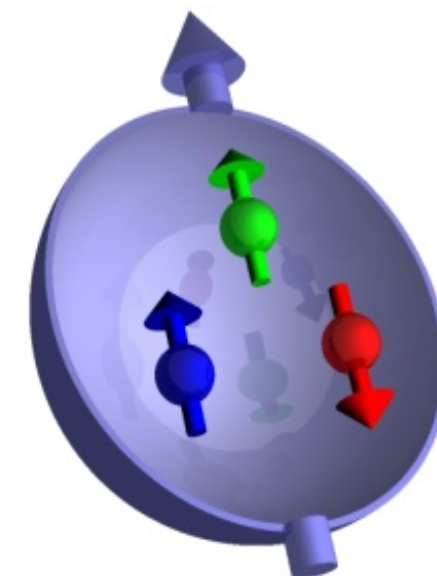
proton spin 1/2 is consistent with naive parton model, but contradict with experiments.

♦ Proton spin decomposition

Jaffe, Manohar; Ji

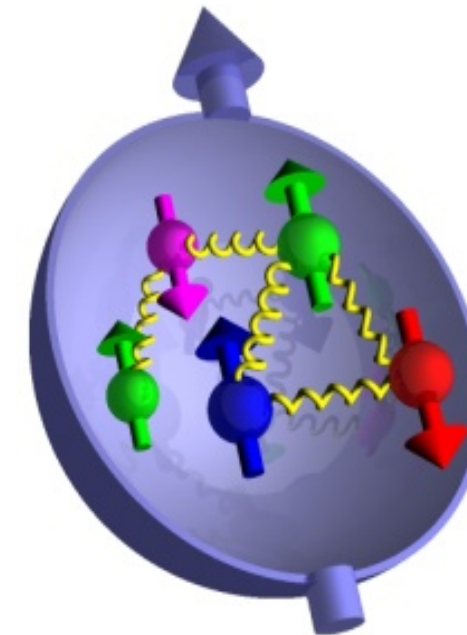
$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} \left| J_{QCD}^z \right| P, \frac{1}{2} \right\rangle = \frac{1}{2} \int_0^1 dx \Delta\Sigma(x, Q^2) + \int_0^1 dx \Delta G(x, Q^2) + \int_0^1 dx \left(\sum_q L_q^z + L_g^z \right)$$

total
quark spin



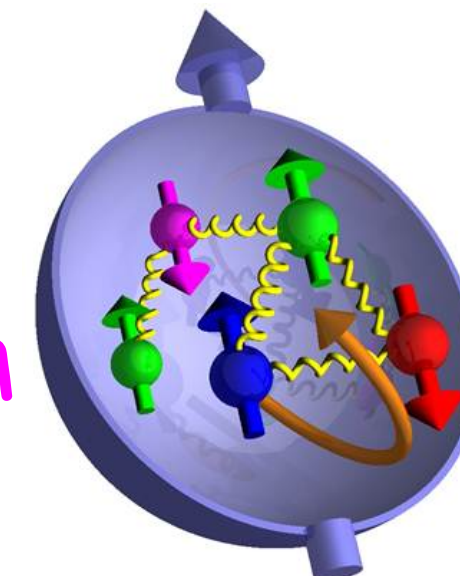
Quark ~ 30%

gluon
spin



gluon ~ 40%

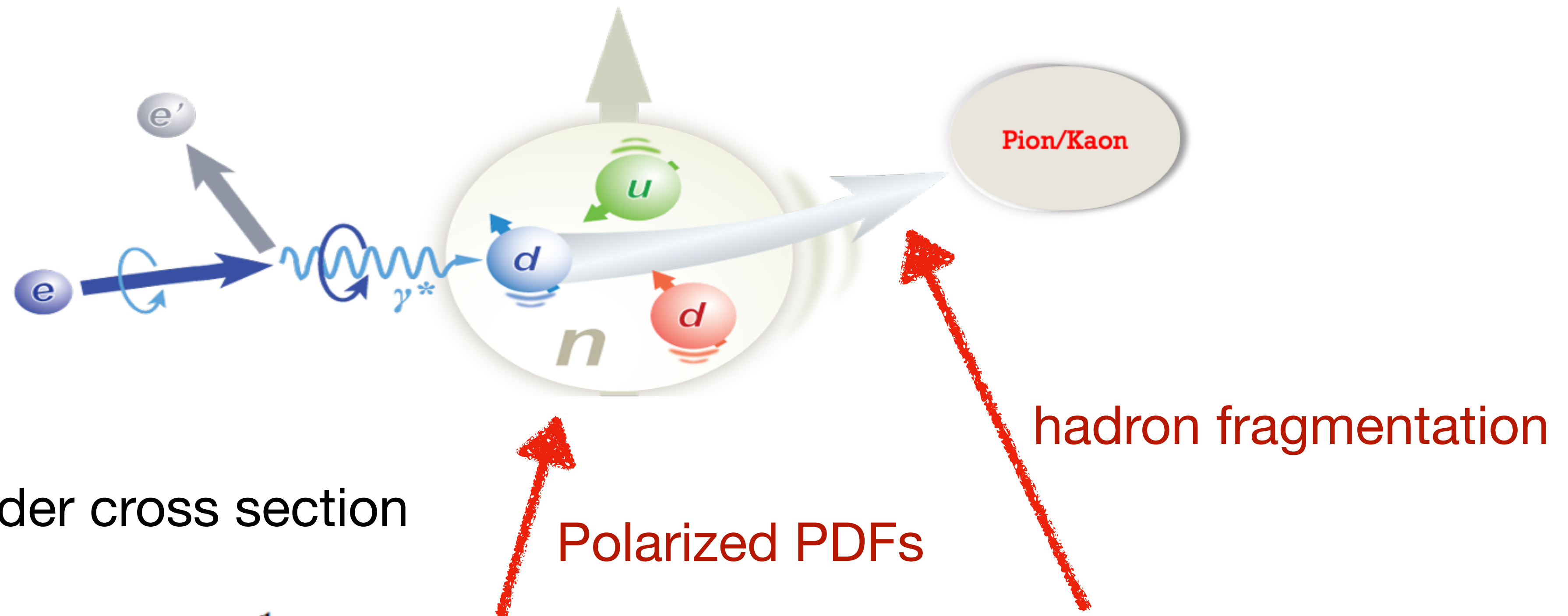
angular
momentum



Orbital angular momentum?

Pin down the proton spin in future EICs

◆ Polarized structure function measurement g_1



- Leading order cross section

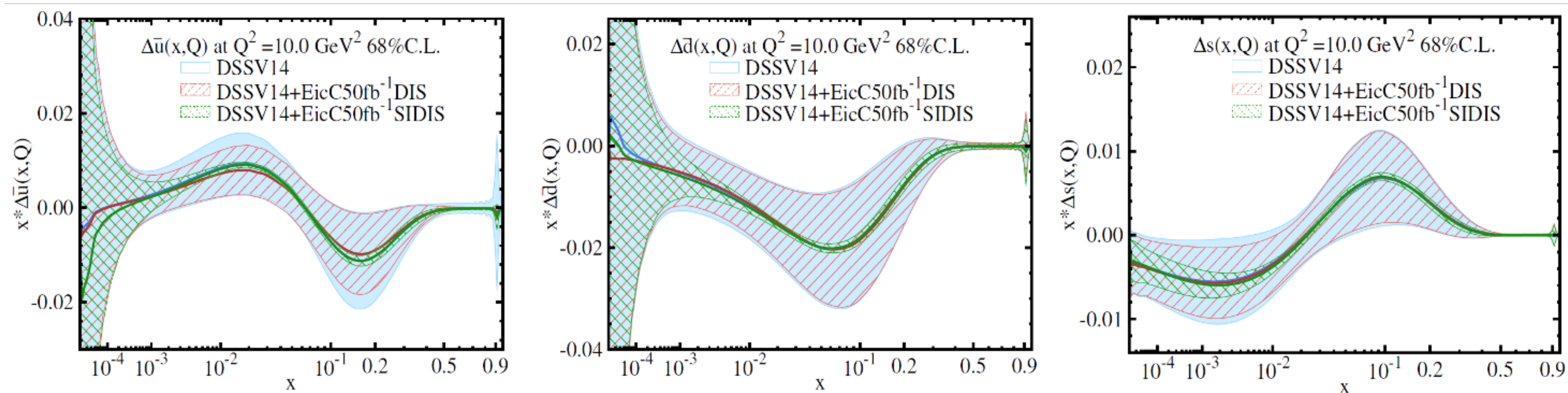
$$g_1^h(x, Q^2, z) = \frac{1}{2} \sum_q e_q^2 \left[\Delta q(x, Q^2) D_q^h(z, Q^2) + \Delta \bar{q}(x, Q^2) D_{\bar{q}}^h(z, Q^2) \right]$$

Extracted nucleon structure information: polarized PDFs (helicity distribution)

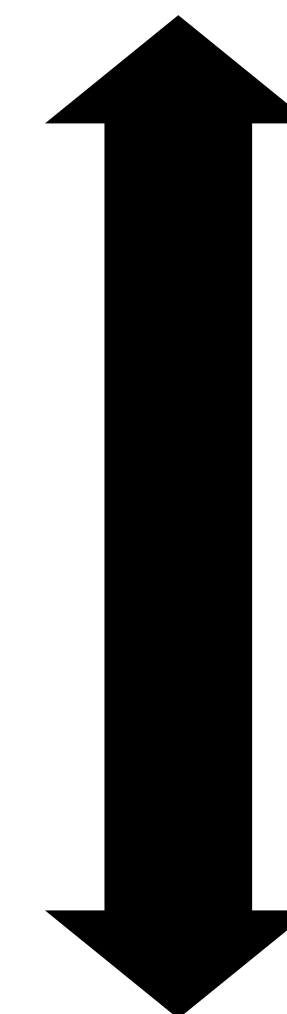
Pin down the proton spin in EIC&EicC

◆ SIDIS for flavor decomposition

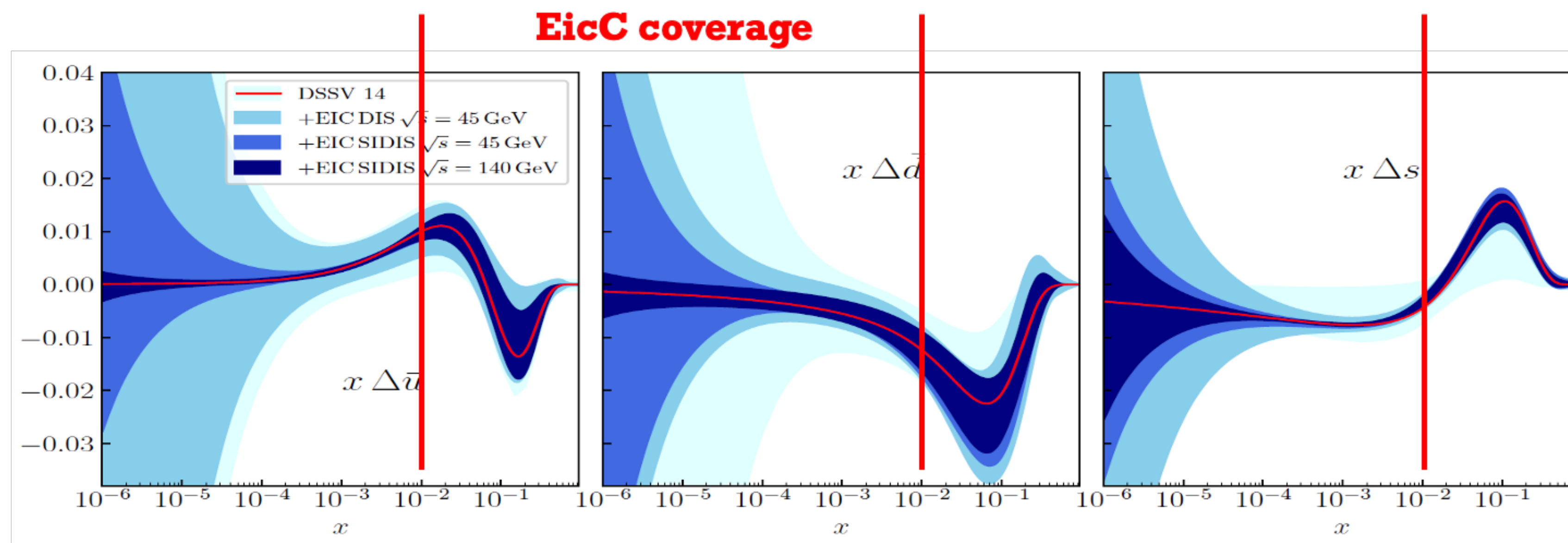
Anderle, Hou, Yuan, **HX**, Zhao, JHEP 2021



EicC white paper



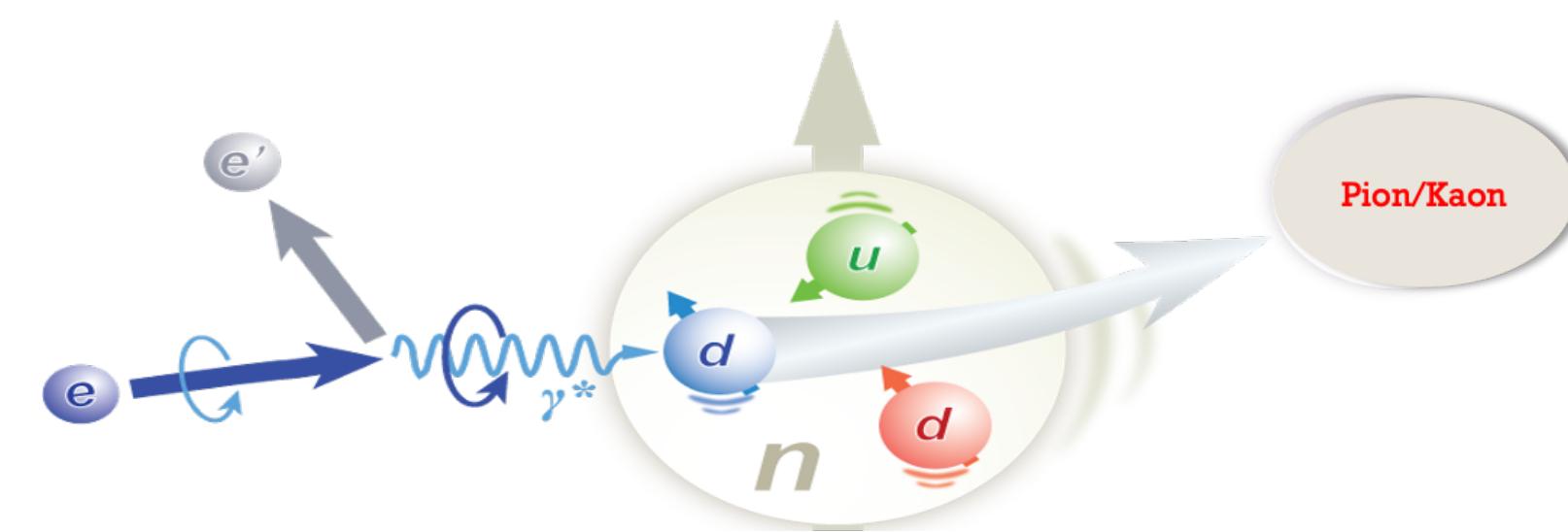
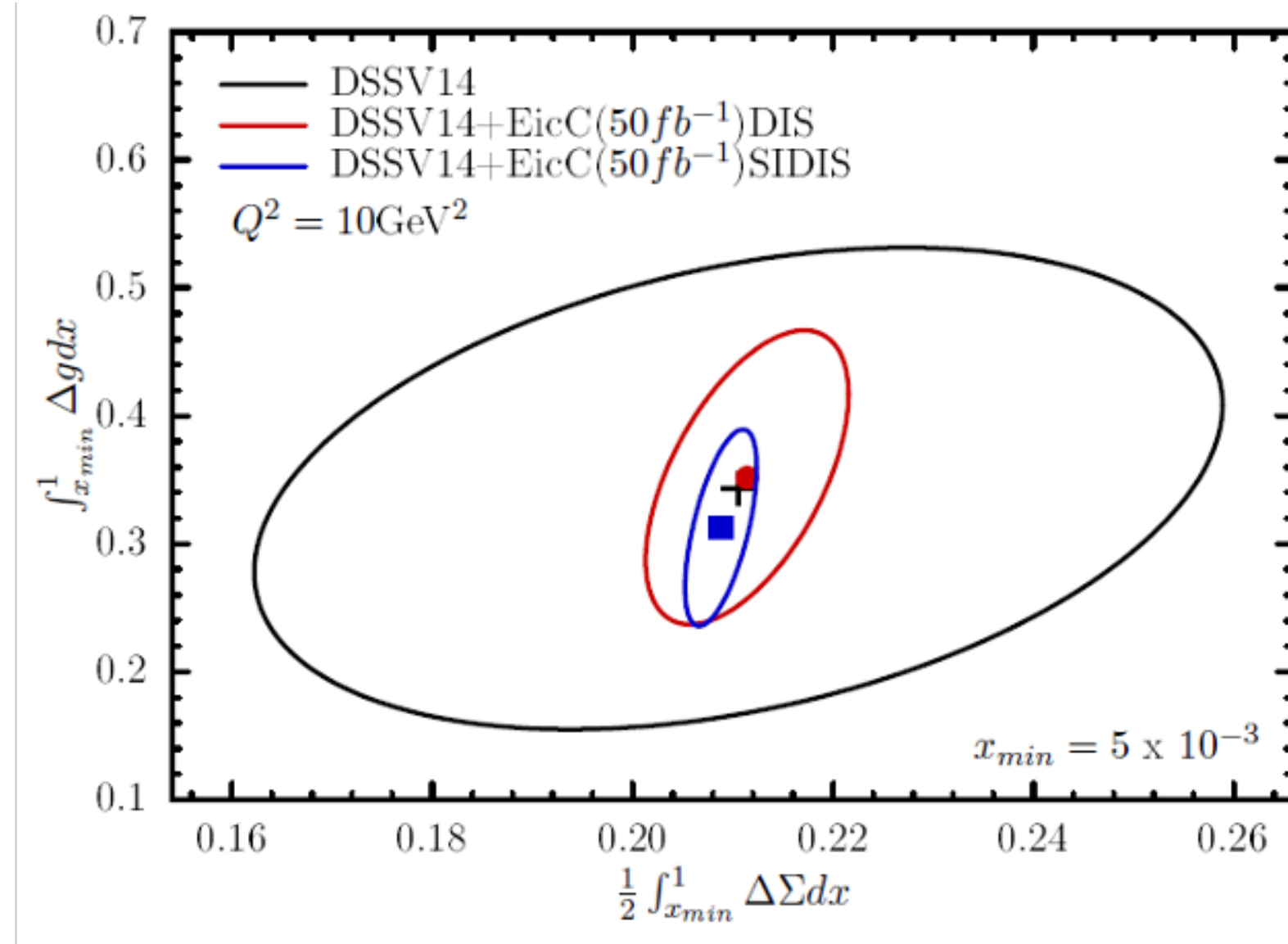
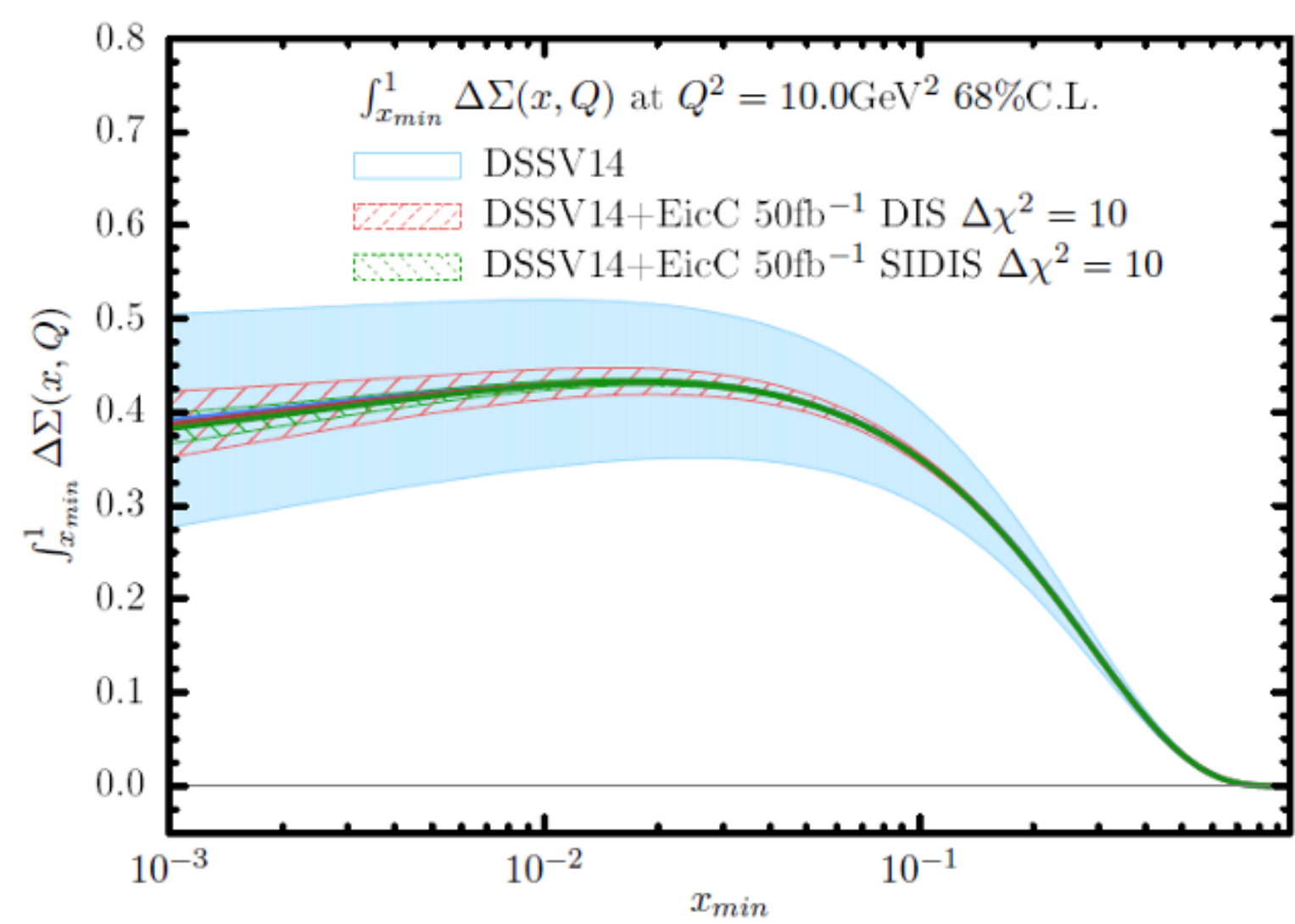
EIC Yellow Report



Pin down the proton spin in EIC&EicC

◆ Parton spin contribution to proton spin

Anderle, Hou, Yuan, **HX**, Zhao, JHEP 2021



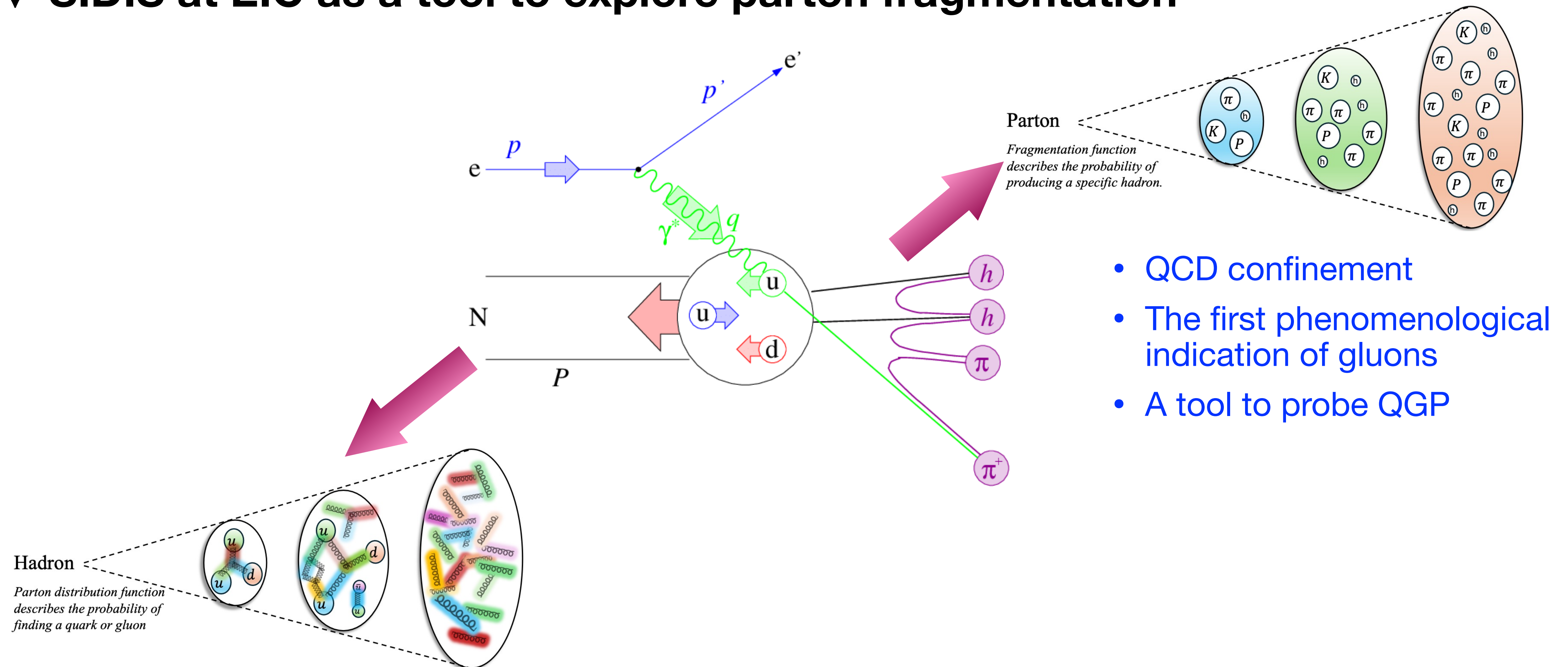
$$g_1^h(x, Q^2, z) = \frac{1}{2} \sum_q e_q^2 \left[\Delta q(x, Q^2) D_q^h(z, Q^2) + \Delta \bar{q}(x, Q^2) D_{\bar{q}}^h(z, Q^2) \right]$$

We need parton fragmentation functions as an input!

The power of EicC for proton spin!

From nucleon structure to hadronization

◆ SIDIS at EIC as a tool to explore parton fragmentation



FF global fitting panorama

◆ Joint efforts from **experiments & theory** in extracting FFs

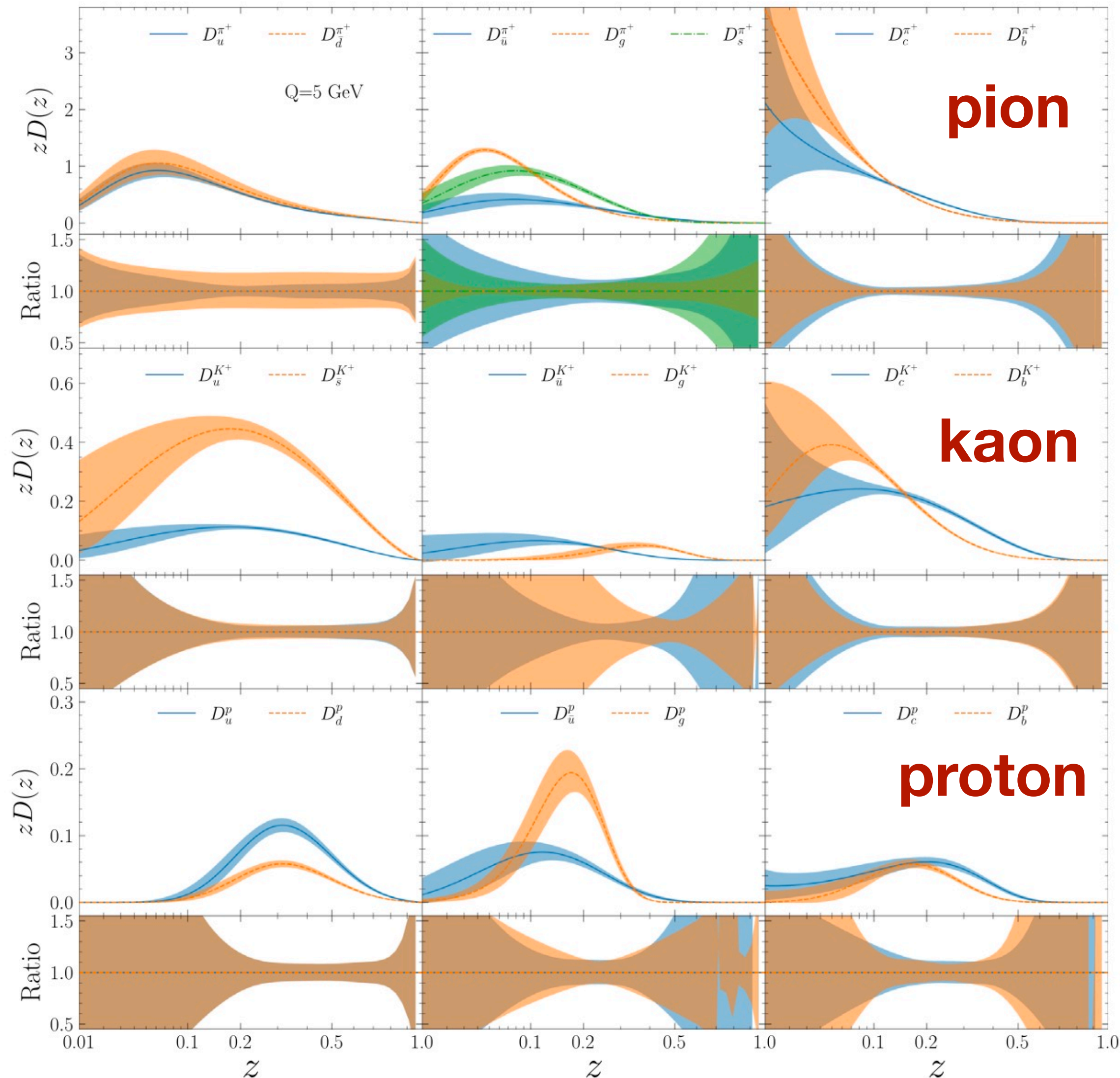
FFs Collab.	NPC	DSS	NNFF	JAM	HKNS	MAPFF
SIA	✓	✓	✓	✓	✓	✓
SIDIS	✓	✓	✗	✗	✗	✓
pp incl. hadron	✓	✓	✗	✗	✗	✗
pp hadron in jet	✓	✗	✗	✗	✗	✗
stat. treatment	Hessian	Hessian	Monte Carlo	Monte Carlo	Hessian	Monte Carlo
parametrization	standard	standard	neural network	standard	standard	neural network
hadron species	$\pi^\pm, K^\pm, p/\bar{p}$ η, k_s^0, Λ	$\pi^\pm, K^\pm, p/\bar{p}$	$\pi^\pm, K^\pm, p/\bar{p}$	$\pi^\pm, K^\pm$	$\pi^\pm, K^\pm, p/\bar{p}$	$\pi^\pm, K^\pm$
pQCD order	NLO/NNLO	NLO	NNLO	NLO	NLO	Approx. NNLO
latest update	PRL 132, 261903 (2024) PRD 110, 114019 (2024)	PRD 95, 094019 (2017) PRD 105, L031502 (2022)	EPJC 77, 516 (2017) EPJC 78, 651 (2018)	PRD 94, 114004 (2016)	PTEP 2016, 113B04 (2016)	PLB 834, 137456 (2022)

NPC: the most precise and complete FFs to date!

New efforts from NPC (SJTU & SCNU & IMP)

◆ NPC23 FFs

Gao, Liu, Shen, **HX**, Zhao, PRL, 2024



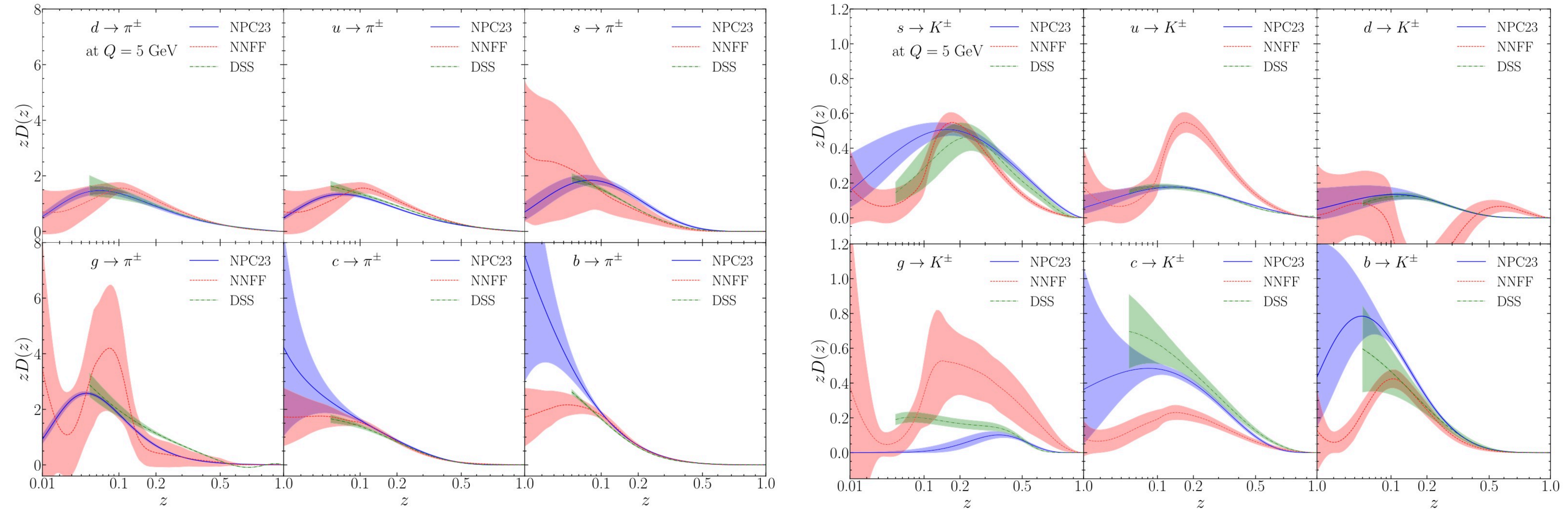
- High precision determination of FFs for charged hadrons
- 4%, 4% and 7% uncertainty for u-quark to pion, kaon, proton at $z=0.3$, respectively
- 3%, 4% and 8% uncertainty for gluon to pion at $z=0.05, 0.1, 0.3$, respectively, mainly due to the jet fragmentation data from LHC
- Heavy quark fragmentation are well constrained in $z=0.1\sim 0.5$

126 Hessian error FFs are all available in LHAPDF

New efforts from NPC

◆ NPC23 vs. others

Gao, Liu, Shen, **HX**, Zhao, PRD Editor's suggestion, 2024

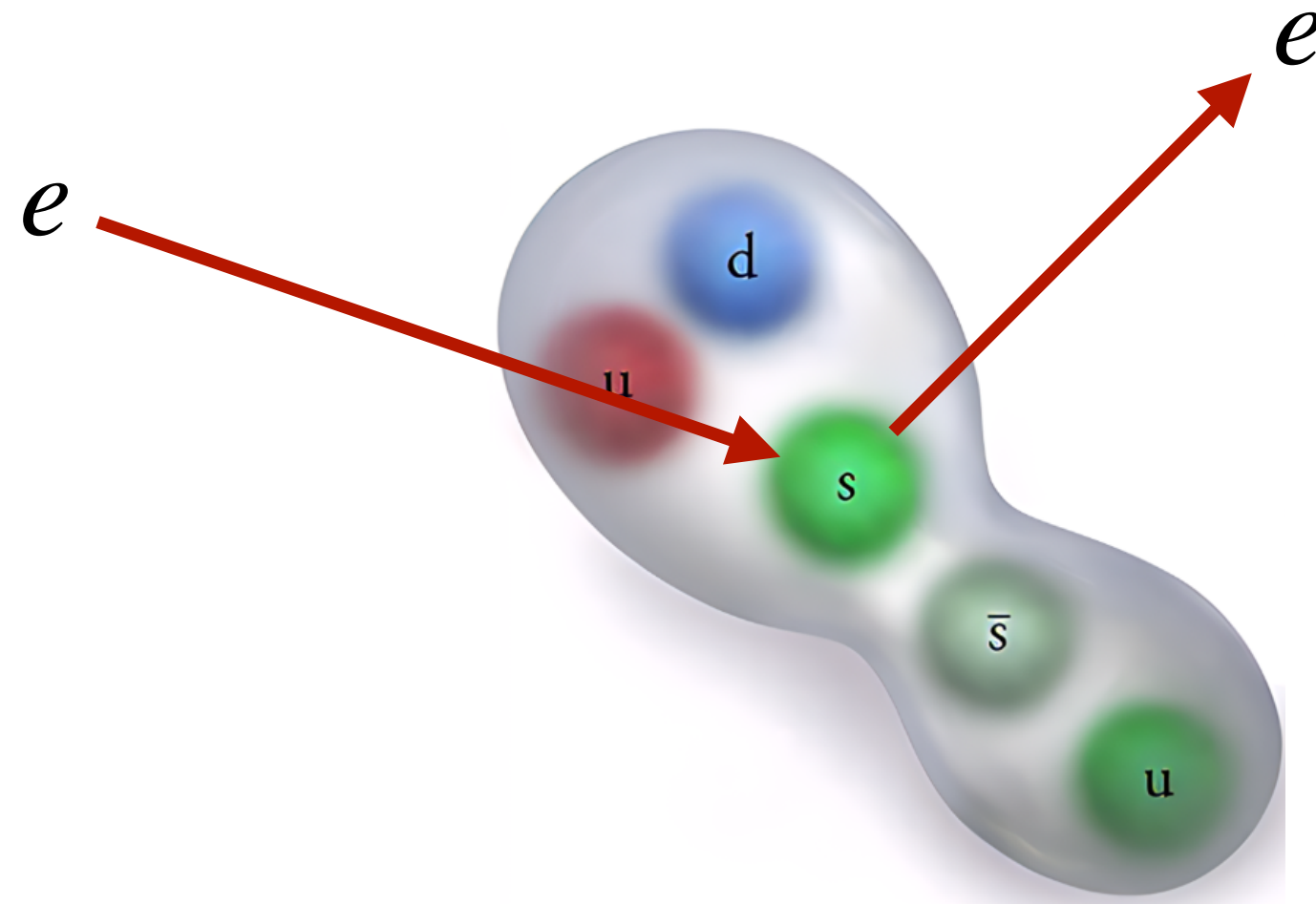


- General agreement for u/d quark to pion
- Discrepancies for FFs to kaon/proton and gluon FFs

What do we learn from NPC ?

◆ Probe the nucleon structure

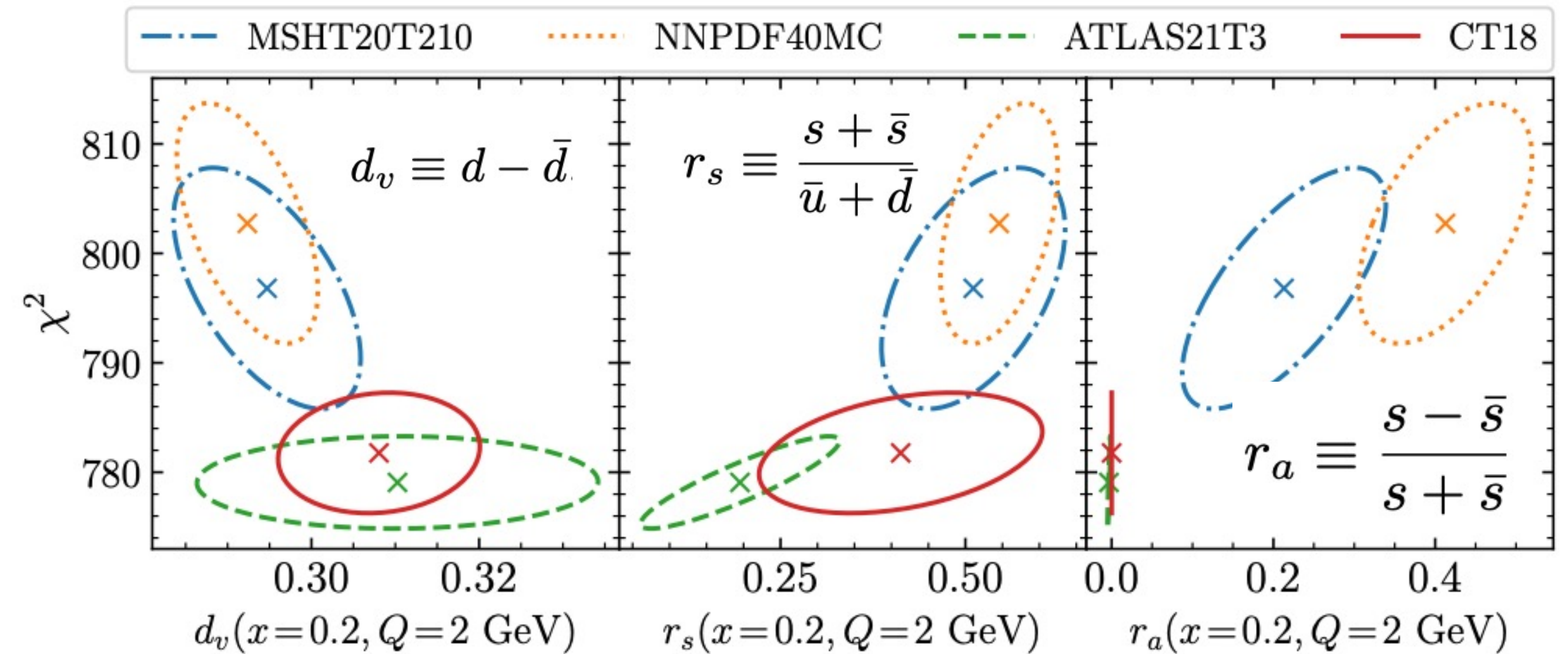
Gao, Shen, **HX**, Zhao, Zhou, arXiv:2502.17837



$$\frac{d^3\sigma^{K^+-K^-}}{dx dy dz} \propto 2(u_v(x) + d_v(x))(D_u^{K^+}(z) - D_{\bar{u}}^{K^+}(z)) + s_v(x)(D_s^{K^+}(z) - D_{\bar{s}}^{K^+}(z)),$$

The puzzle of strange quark asymmetry:

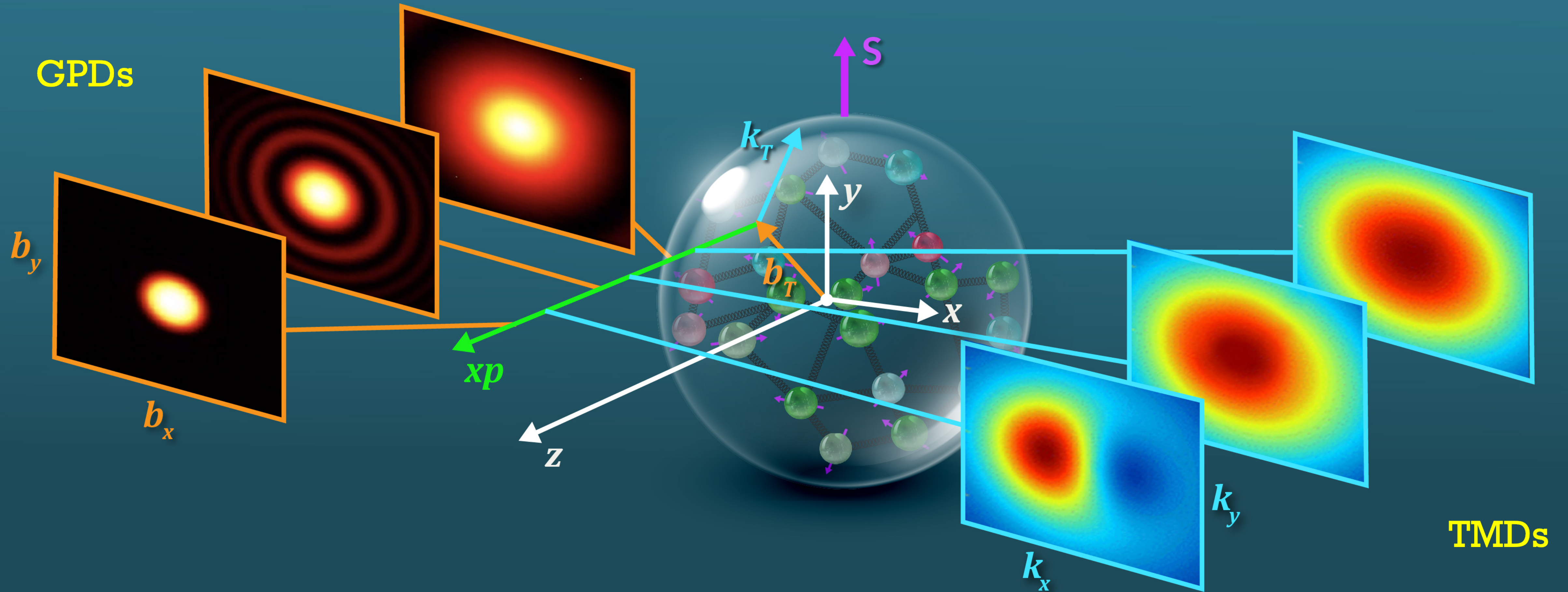
$$s_v = s - \bar{s} = 0?$$



	$d_v(x=0.2, Q=2\text{GeV})$	$r_s(x=0.2, Q=2\text{GeV})$	$r_a(x=0.2, Q=2\text{GeV})$
NNPDF4.0	0.2924 ± 0.0084	0.547 ± 0.079	0.408 ± 0.107
NNPDF4.0(reweighting)	0.3021 ± 0.0069	0.438 ± 0.066	0.281 ± 0.086
MSHT20	0.295 ± 0.011	0.511 ± 0.124	0.213 ± 0.126
MSHT20(profiling)	0.298 ± 0.011	0.481 ± 0.121	0.167 ± 0.136

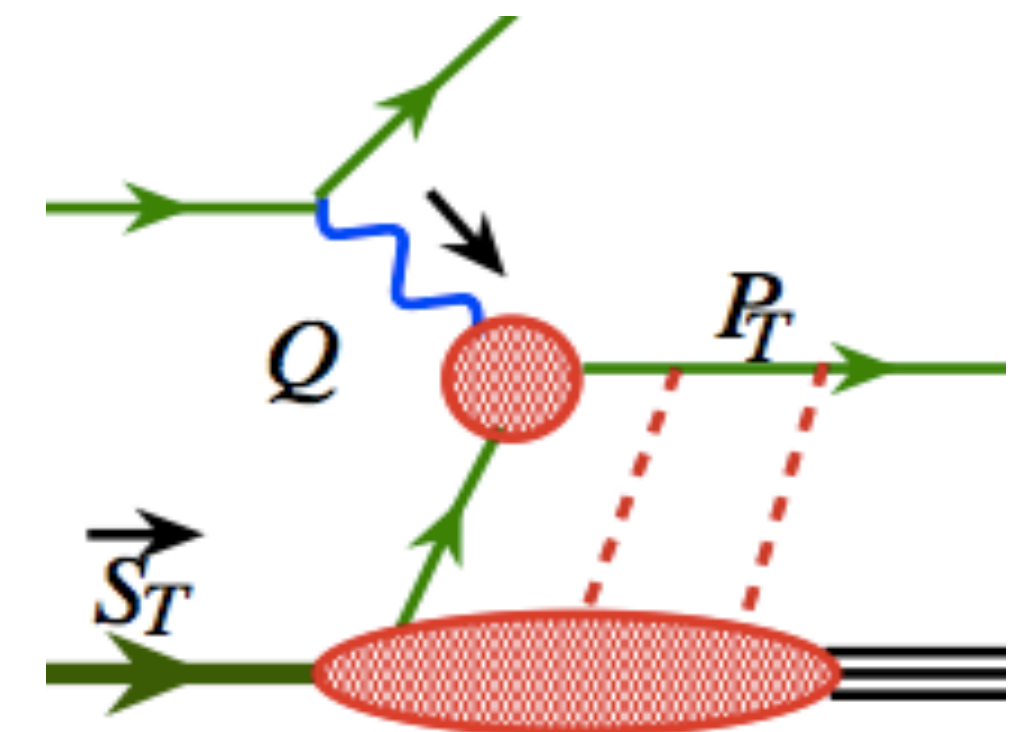
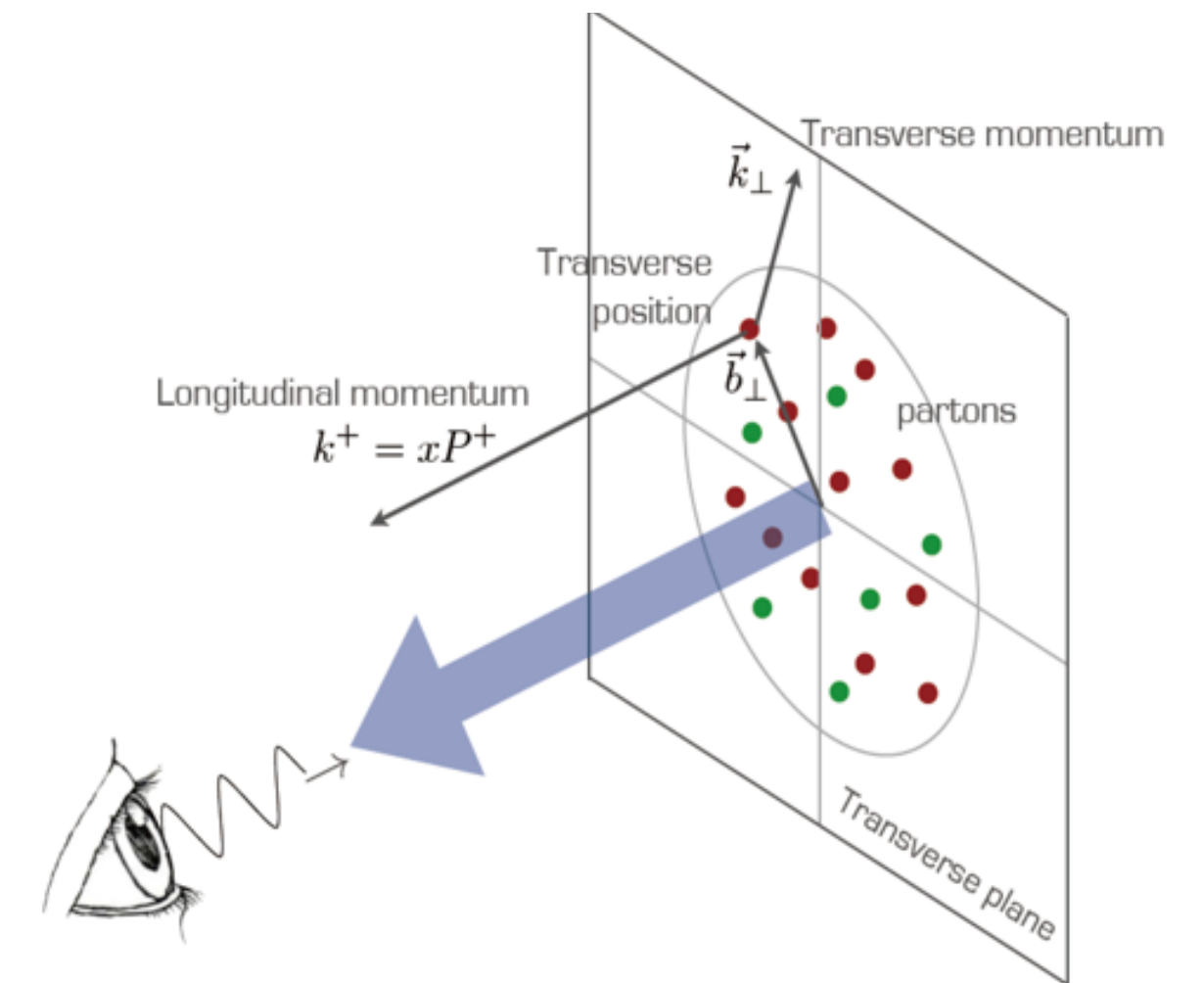
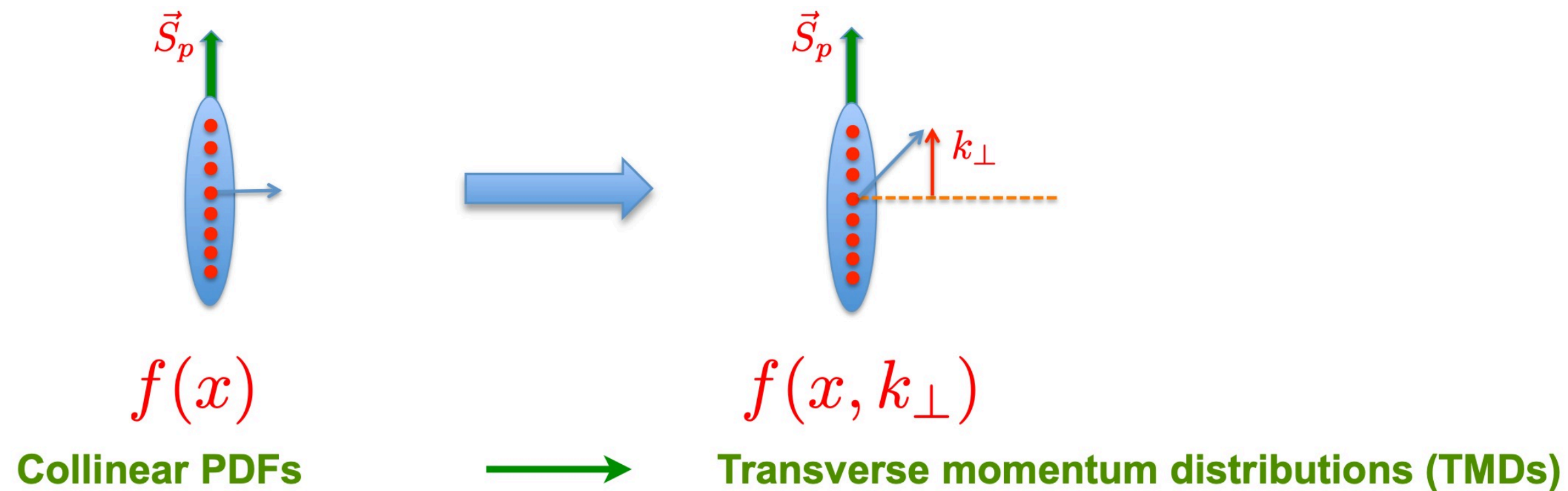
- The impact of NPC FFs on the state-of-the-art PDFs at NNLO
- preference of reduced asymmetry in the strange quark PDFs

Nucleon partonic structure - 3D imaging



Nucleon partonic structure - 3D imaging

◆ Transverse momentum dependent PDFs (TMDs)

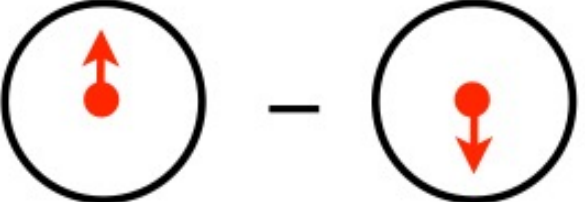
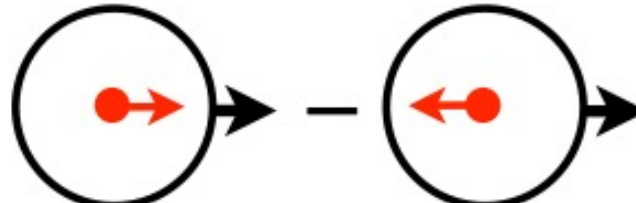
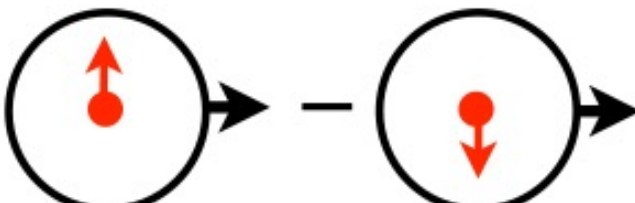
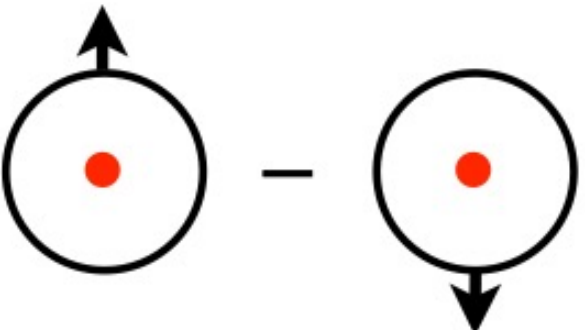
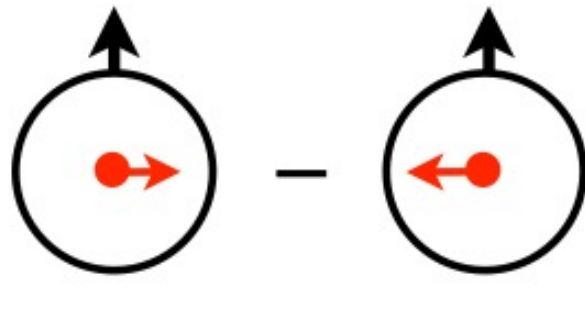


SIDIS: $Q \gg P_T$

- 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

Nucleon partonic structure - 3D imaging

TMDs: explore the flavor-spin-motion correlation

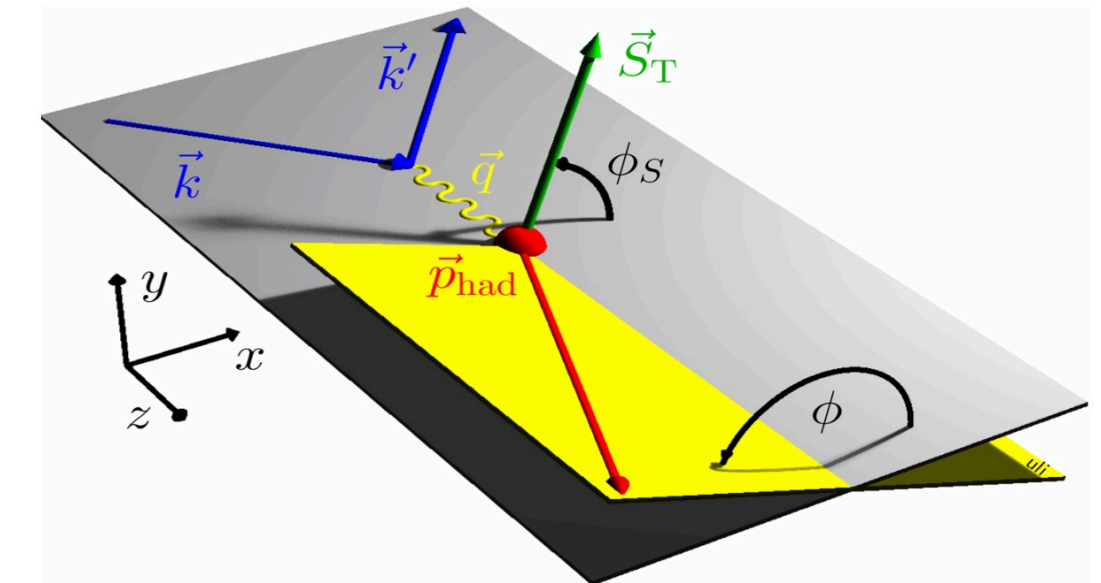
		Quark Polarization		
		Unpolarized	Longitudinally pol.	Transversely pol.
Nucleon Polarization	U	f_1  unpolarized		$h_1^\perp$  Boer-Mulders
	L		g_1  helicity	$h_{1L}^\perp$  longi-transversity (worm-gear)
	T	$f_{1T}^\perp$  Sivers	$g_{1T}^\perp$  trans-helicity (worm-gear)	h_1  transversity $h_{1T}^\perp$  pretzelosity

Nucleon partonic structure - 3D imaging

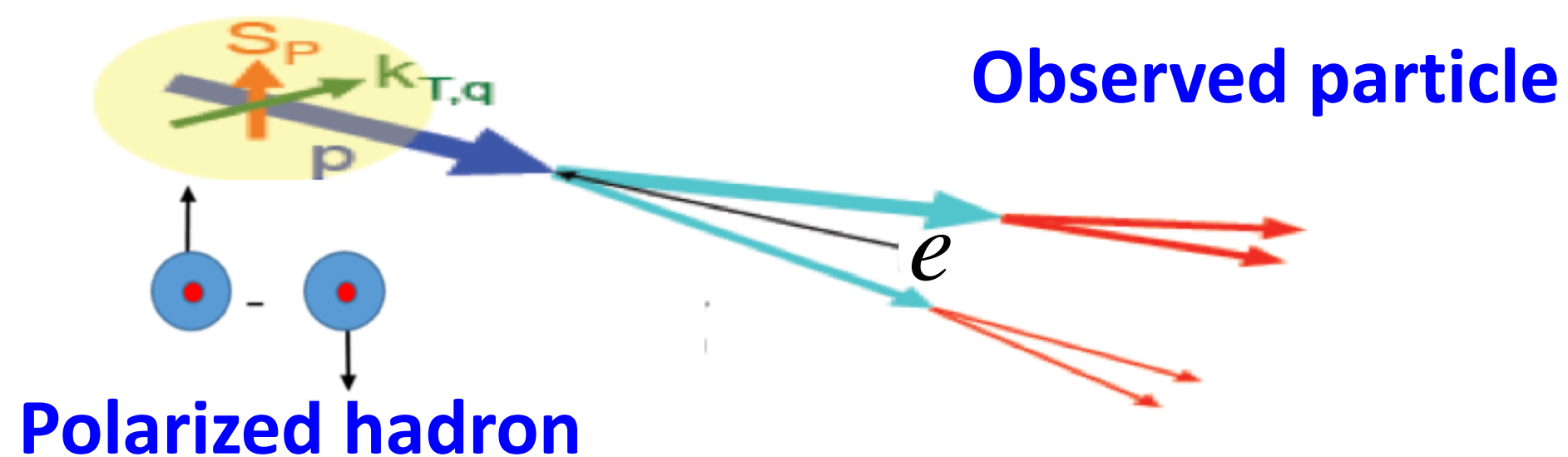
◆ SSA: transverse polarized proton + unpolarized electron

$$A_{UT}(\phi_h, \phi_s) = \frac{1}{S_T} \frac{d\sigma(\phi_h, \phi_s) - d\sigma(\phi_h, \phi_s + \pi)}{d\sigma(\phi_h, \phi_s) + d\sigma(\phi_h, \phi_s + \pi)}$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_s) + A_{UT}^{Sivers} \sin(\phi_h - \phi_s) + A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_s)$$



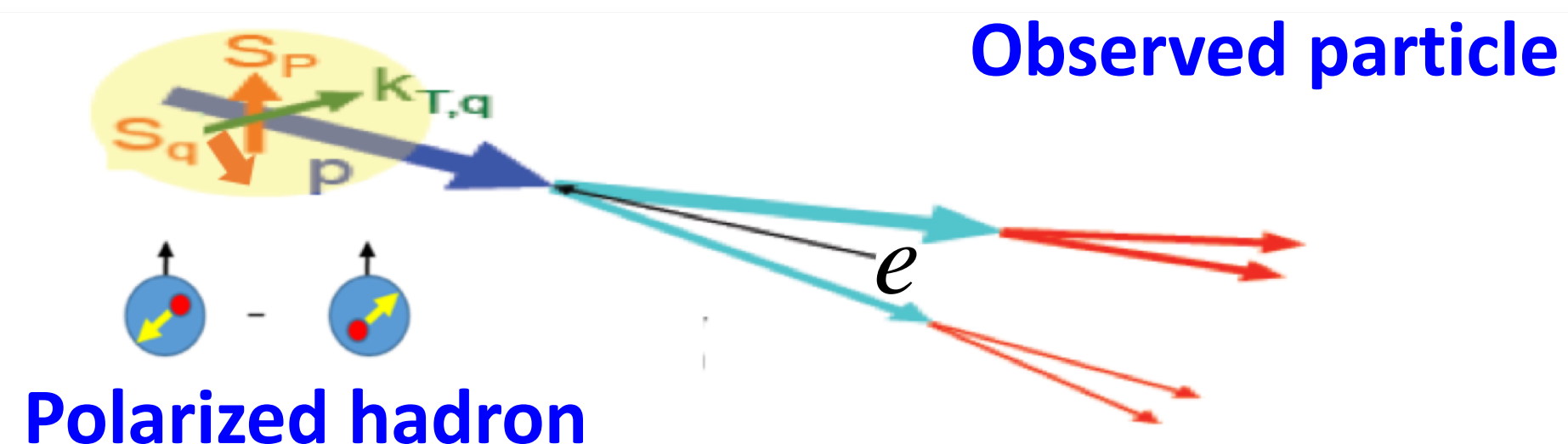
◆ Quantum correlation between proton spin and parton motion



Sivers function $f_{1T}^\perp$: proton spin influences parton's transverse motion

$$A_{UT}^{Sivers} \propto \left\langle \sin(\phi_h - \phi_S) \right\rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

◆ Quantum correlation between proton spin and parton spin

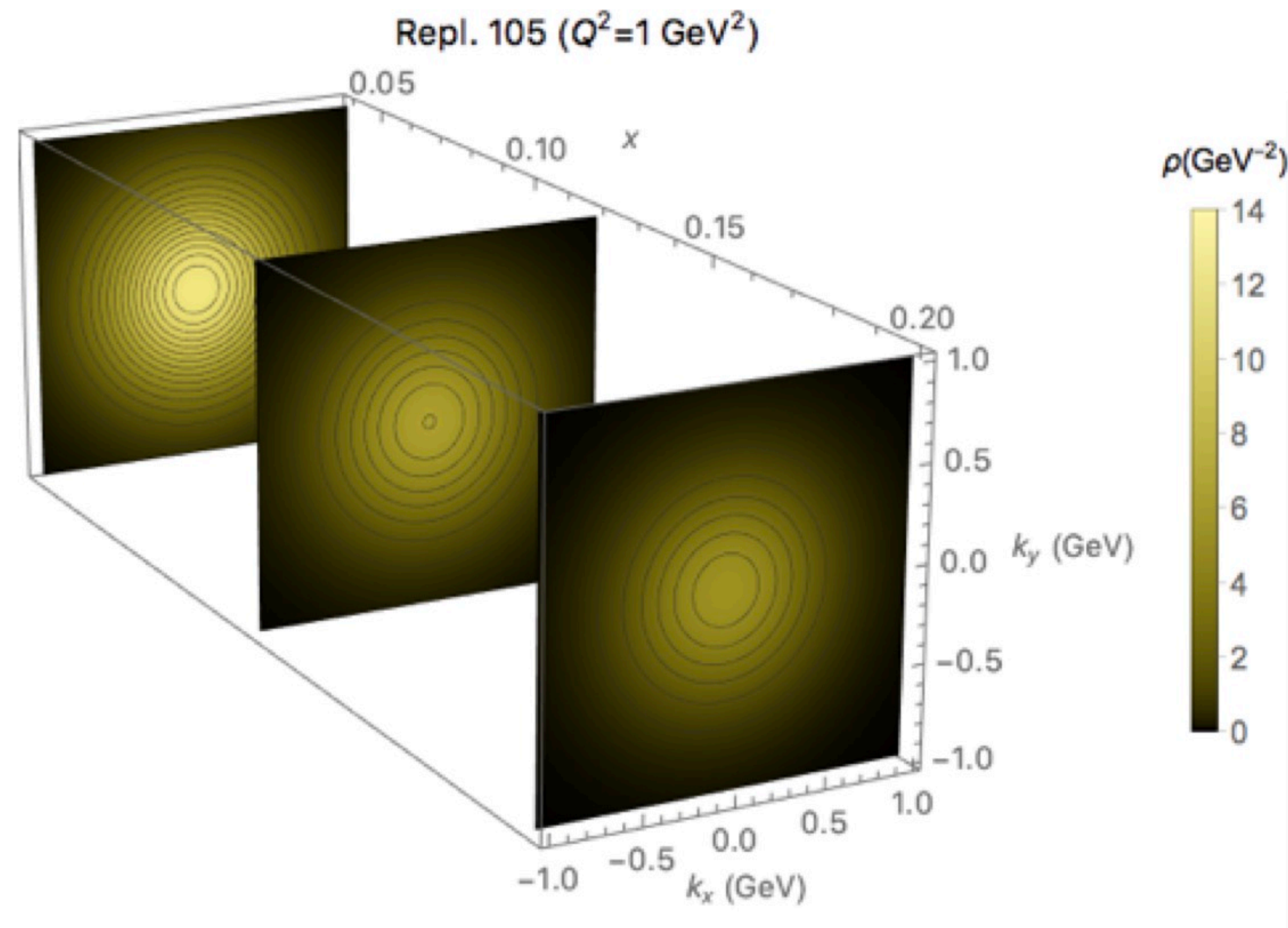


Pretzelosity function $h_{1T}^\perp$: proton spin and parton spin influence parton's transverse motion

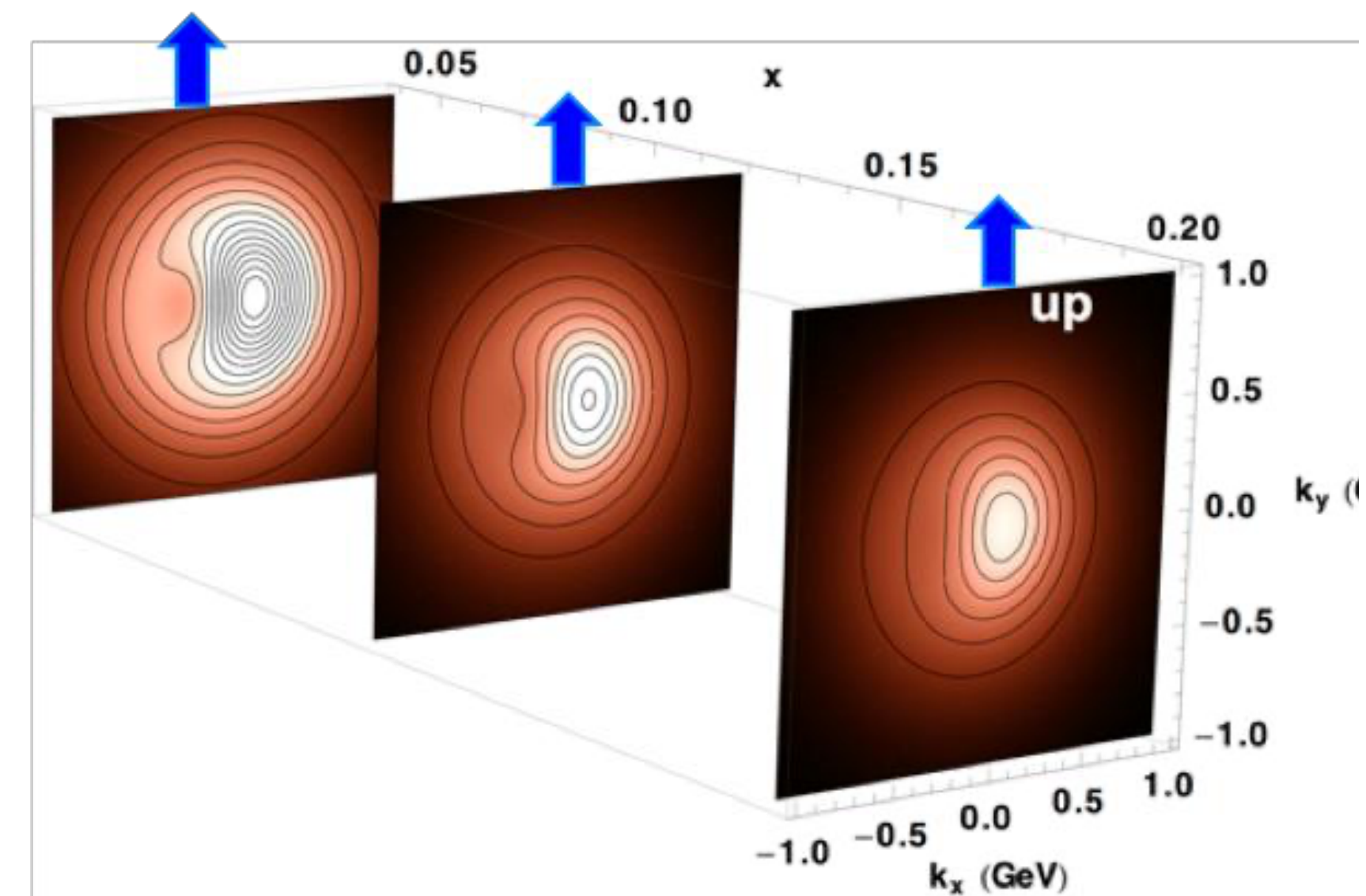
$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

Nucleon partonic structure - 3D imaging

Unpolarized proton



Transversely polarized proton

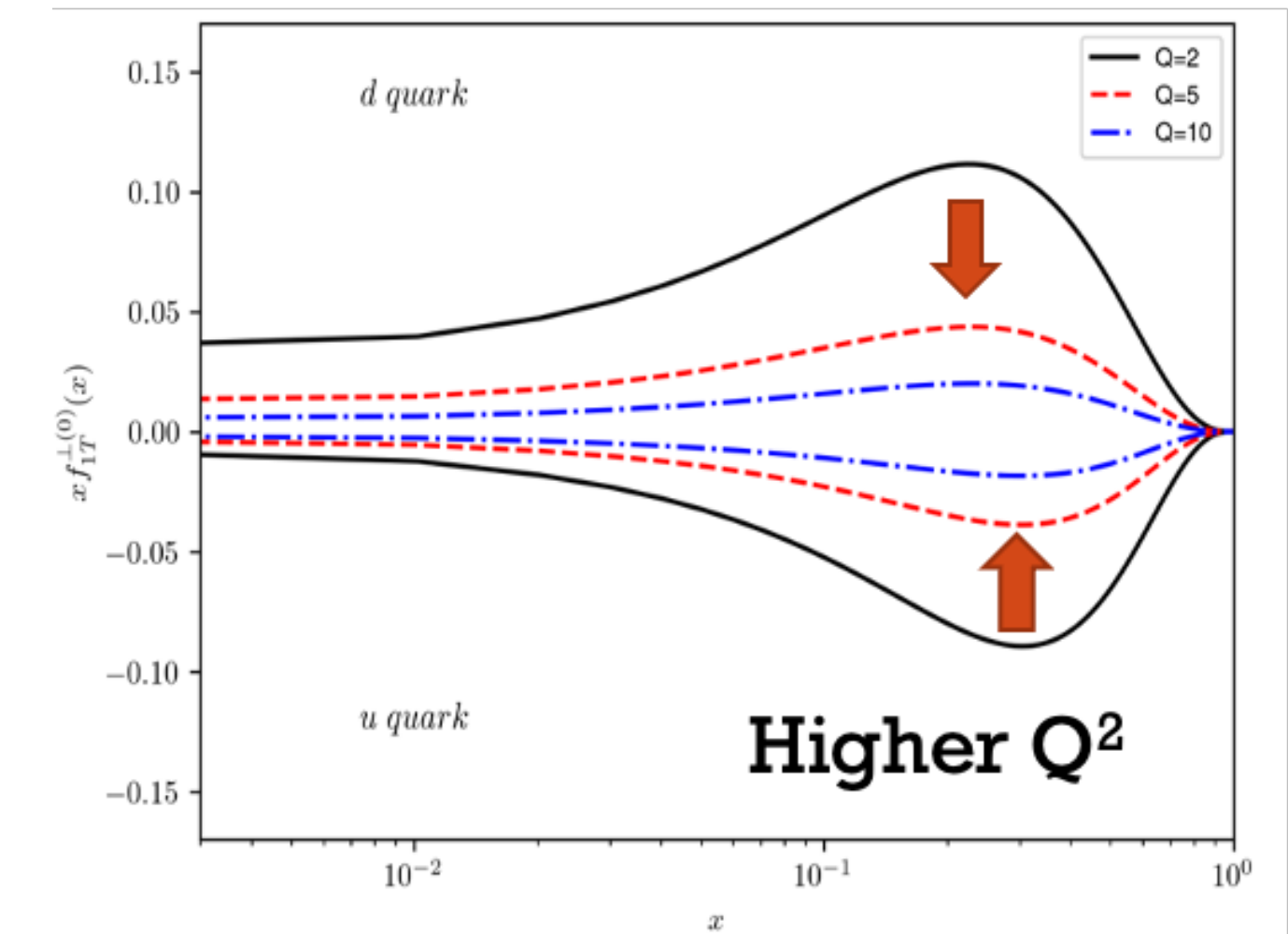
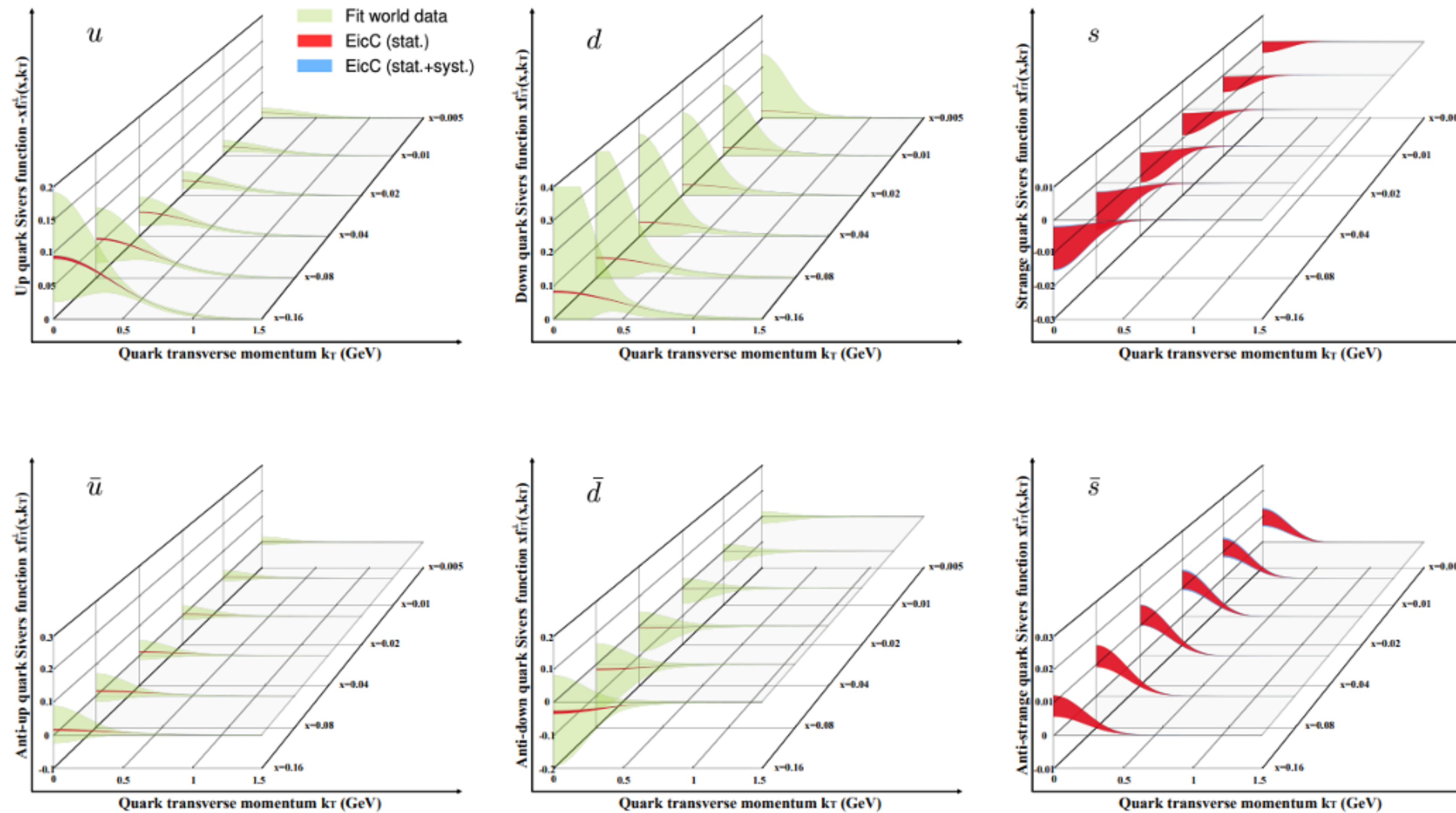


By Andrea Signori

Transversely polarized quark distribution is distorted!

Nucleon 3D imaging at EicC - Sivers effect

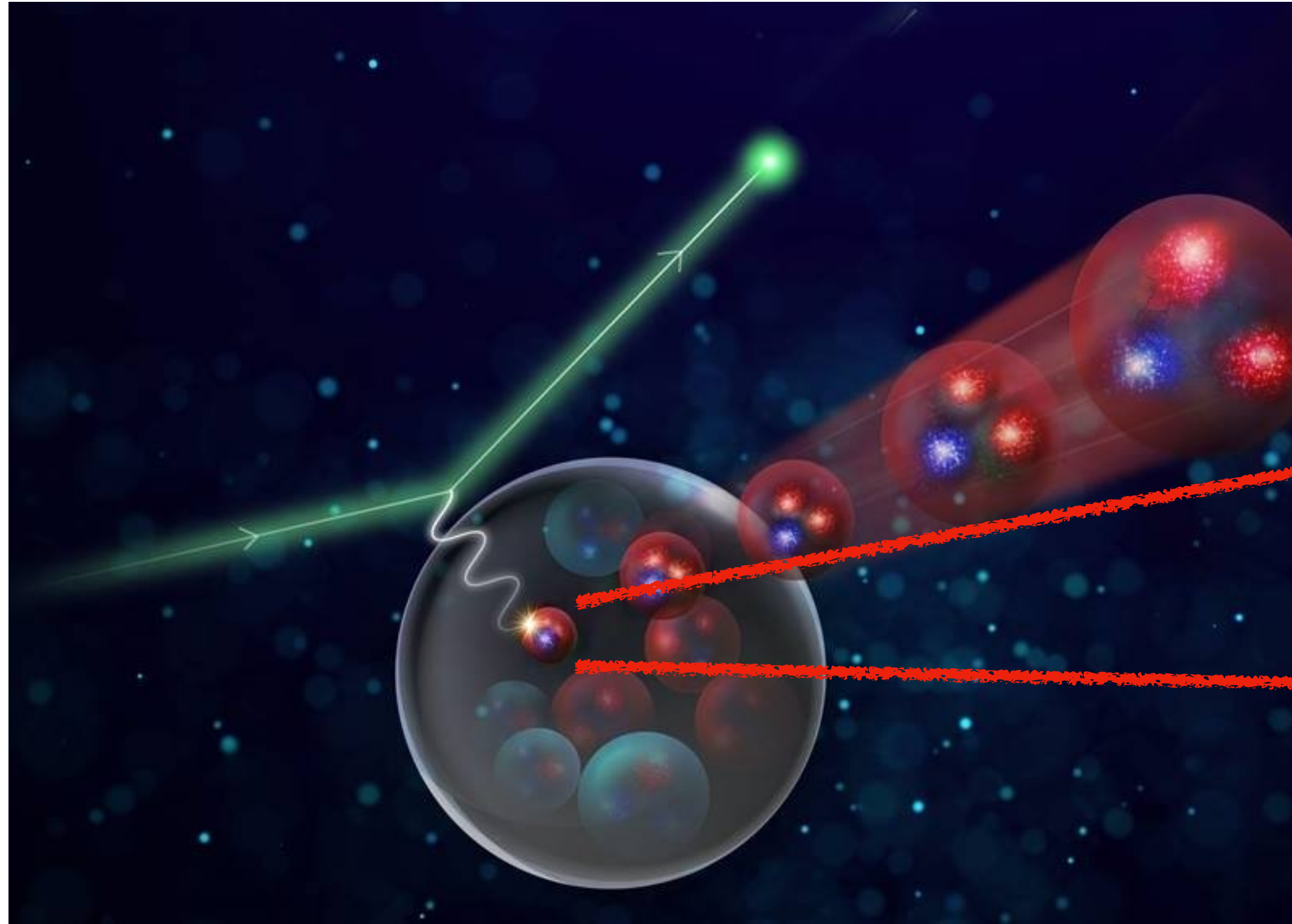
Zeng, Liu, Sun, Zhao, PRD, 2023



- EIC&EicC will perform high precision measurement of SSA, providing the most powerful probe to Sivers effect

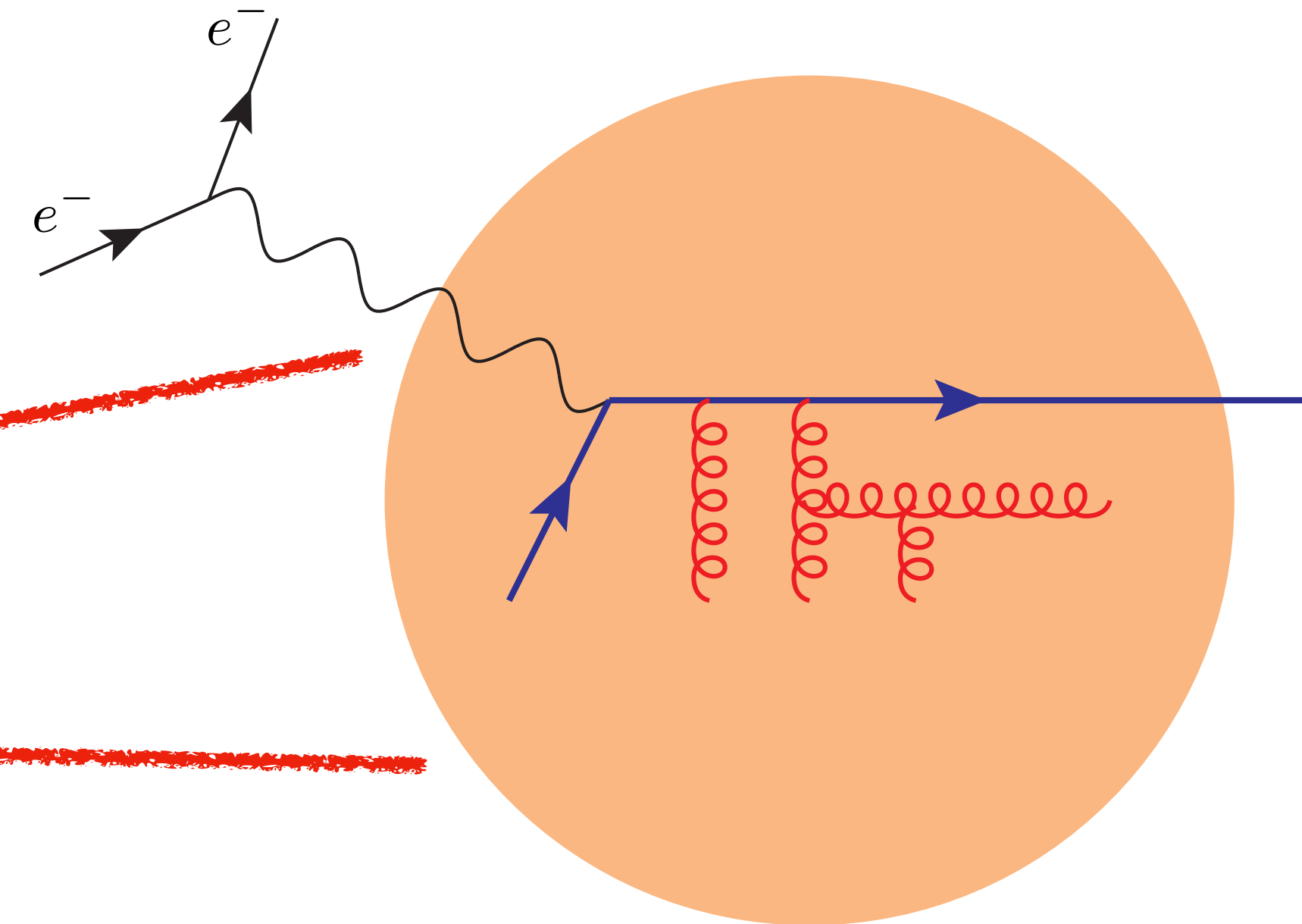
刘天博, Saturday, 8:15-8:40

What if the nucleon is bounded in nucleus?



Initial state

Nuclear partonic structure



Final state

Parton propagating in nuclear medium

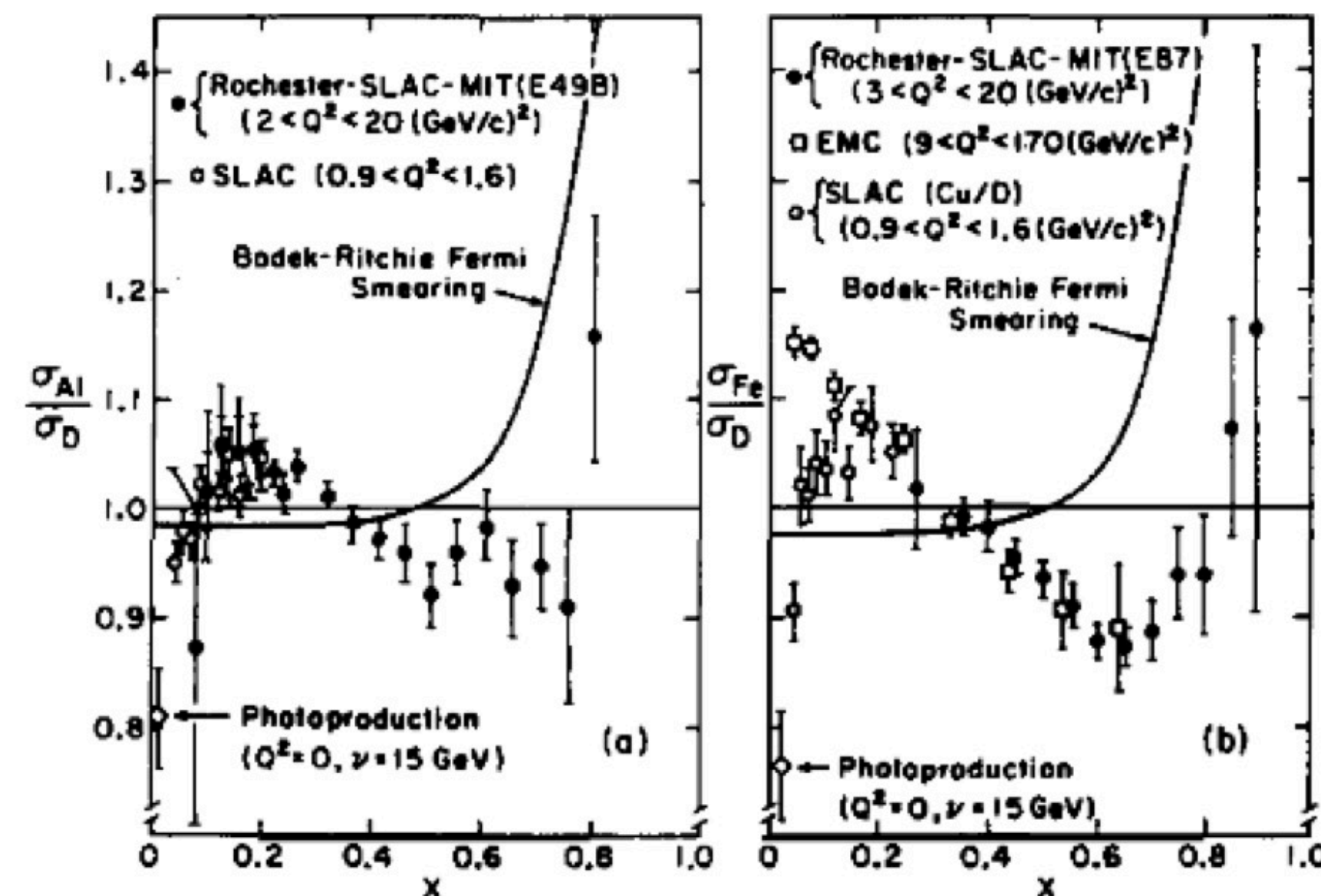
Two mechanisms leading to nontrivial nuclear effects

“Old” and long standing problems of nuclear partonic structure

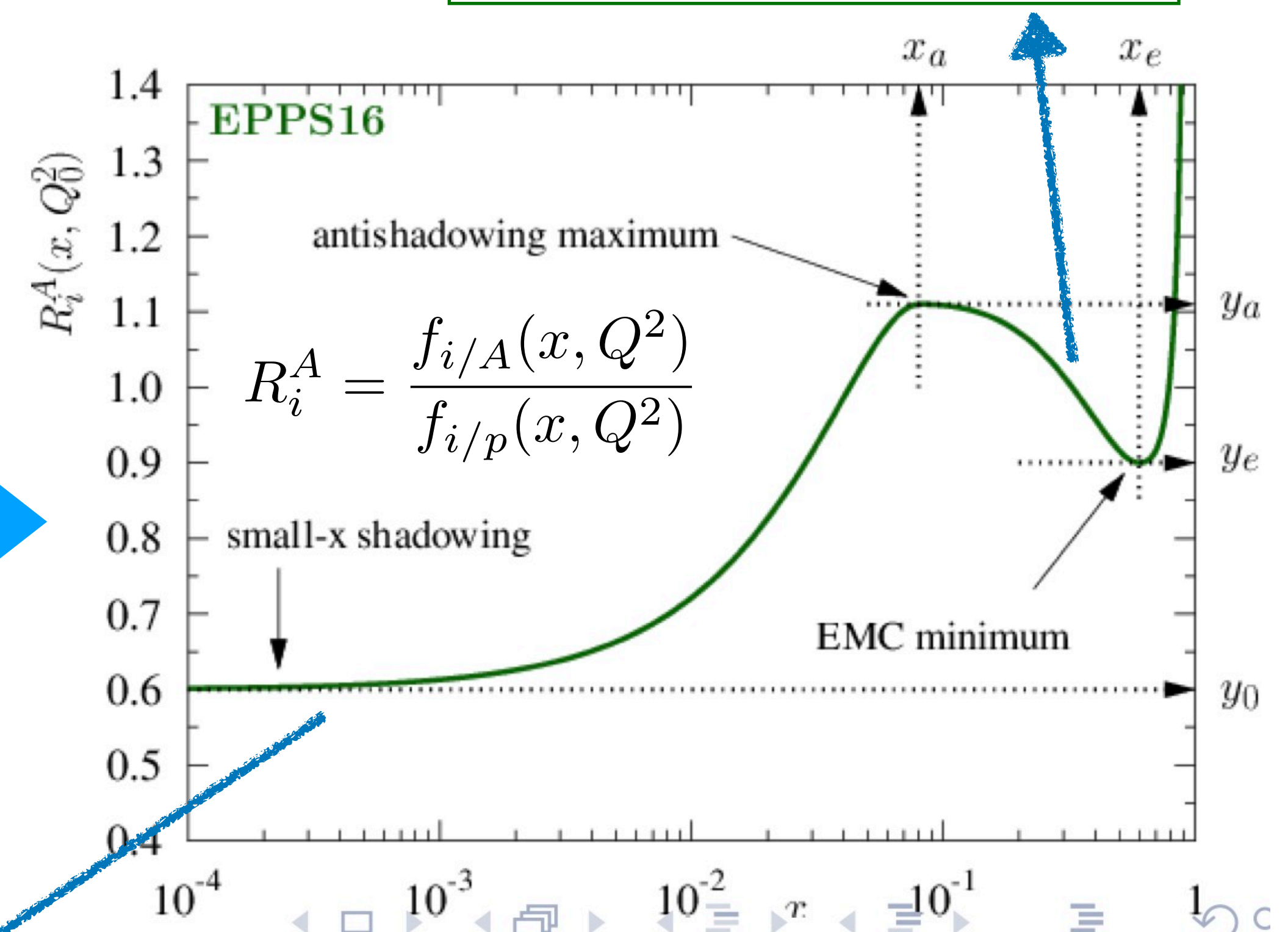
- One-dimensional nuclear partonic structure

Short range correlation?
Talk by Z. Ye on Sunday

Four Decades of the EMC Effect



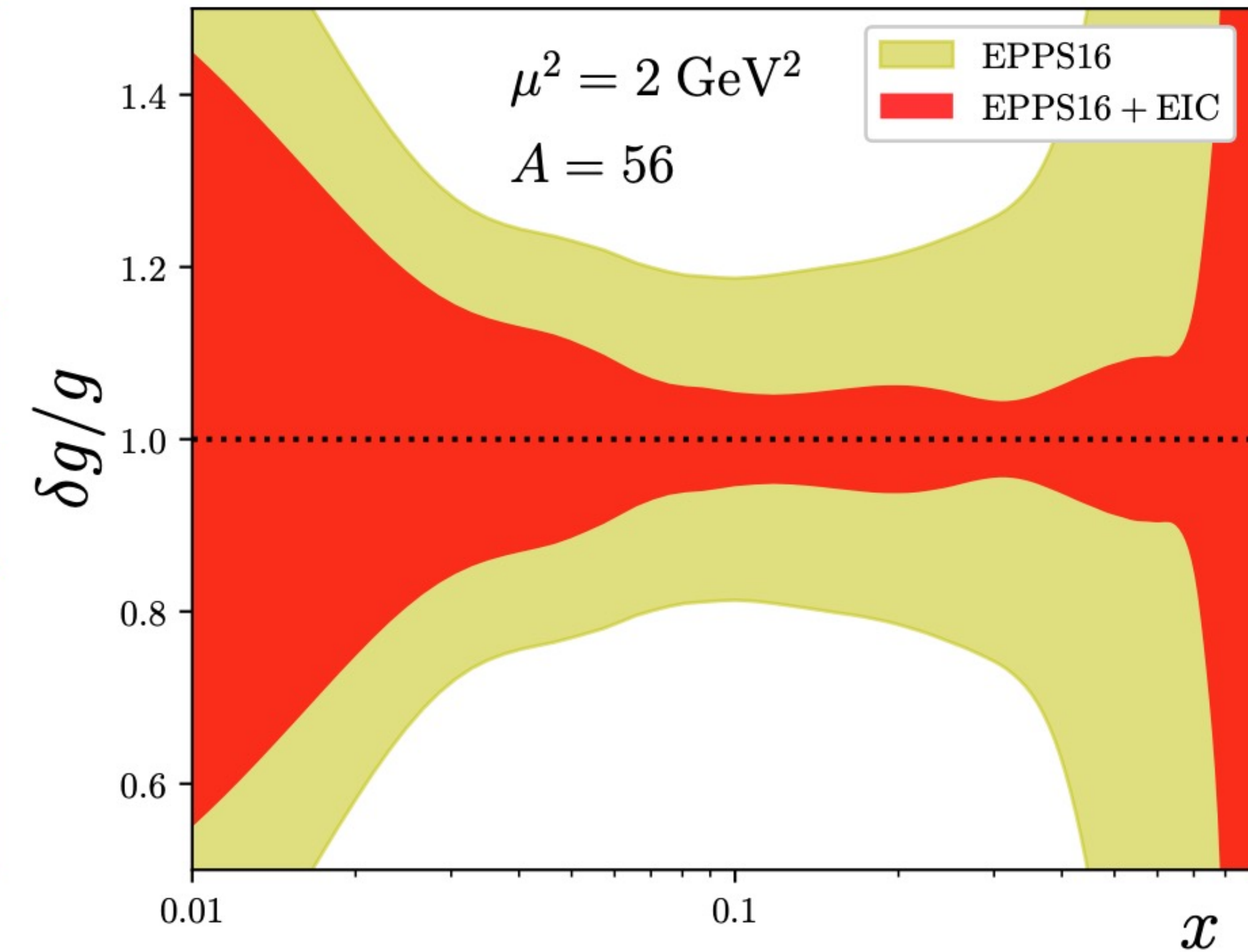
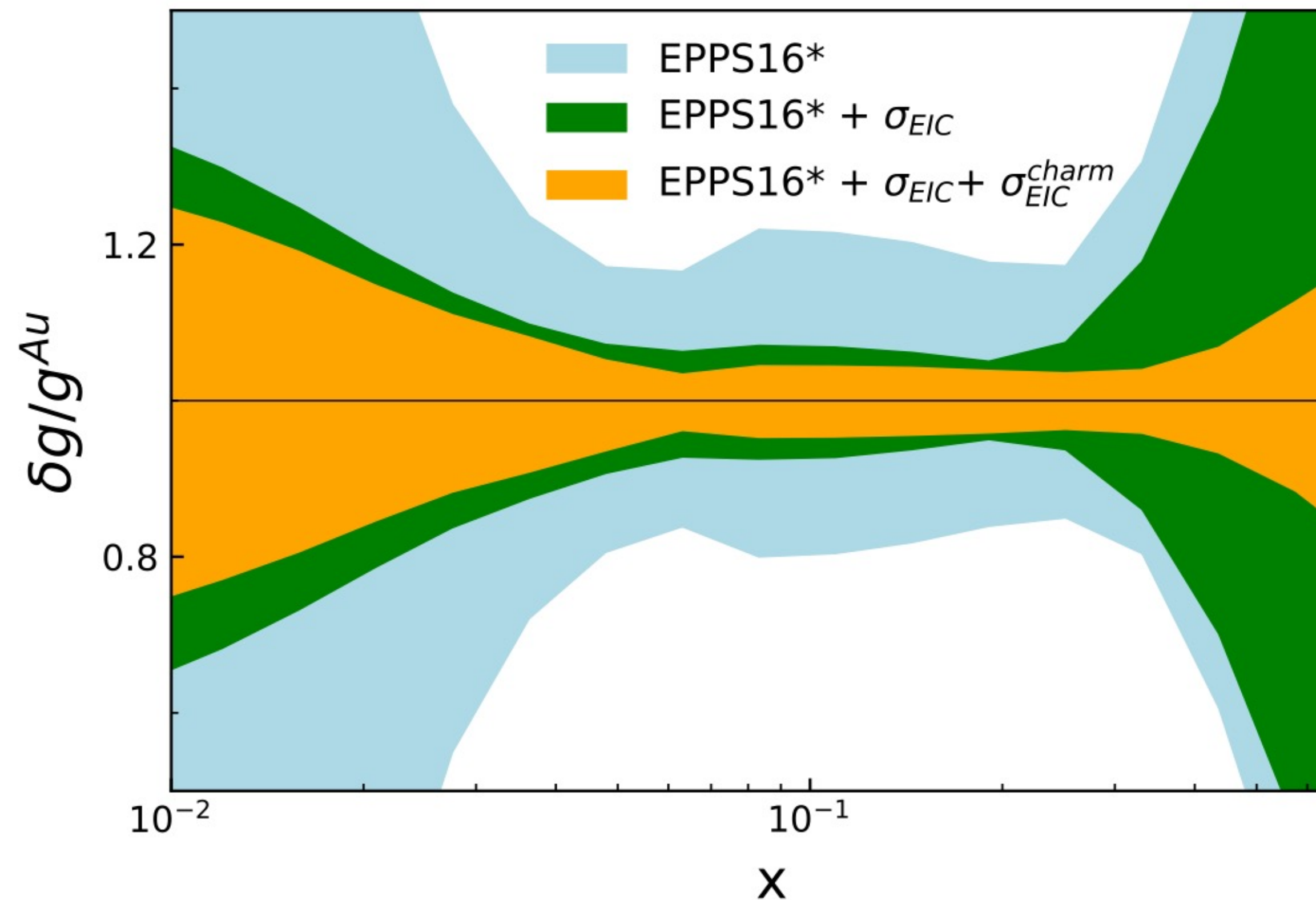
EMC Collaboration, 1983



Gluon saturation: is there a saturation point for the density of gluons at high energies?

“Old” and long standing problems of nuclear partonic structure

- One-dimensional nuclear partonic structure - impact of EIC

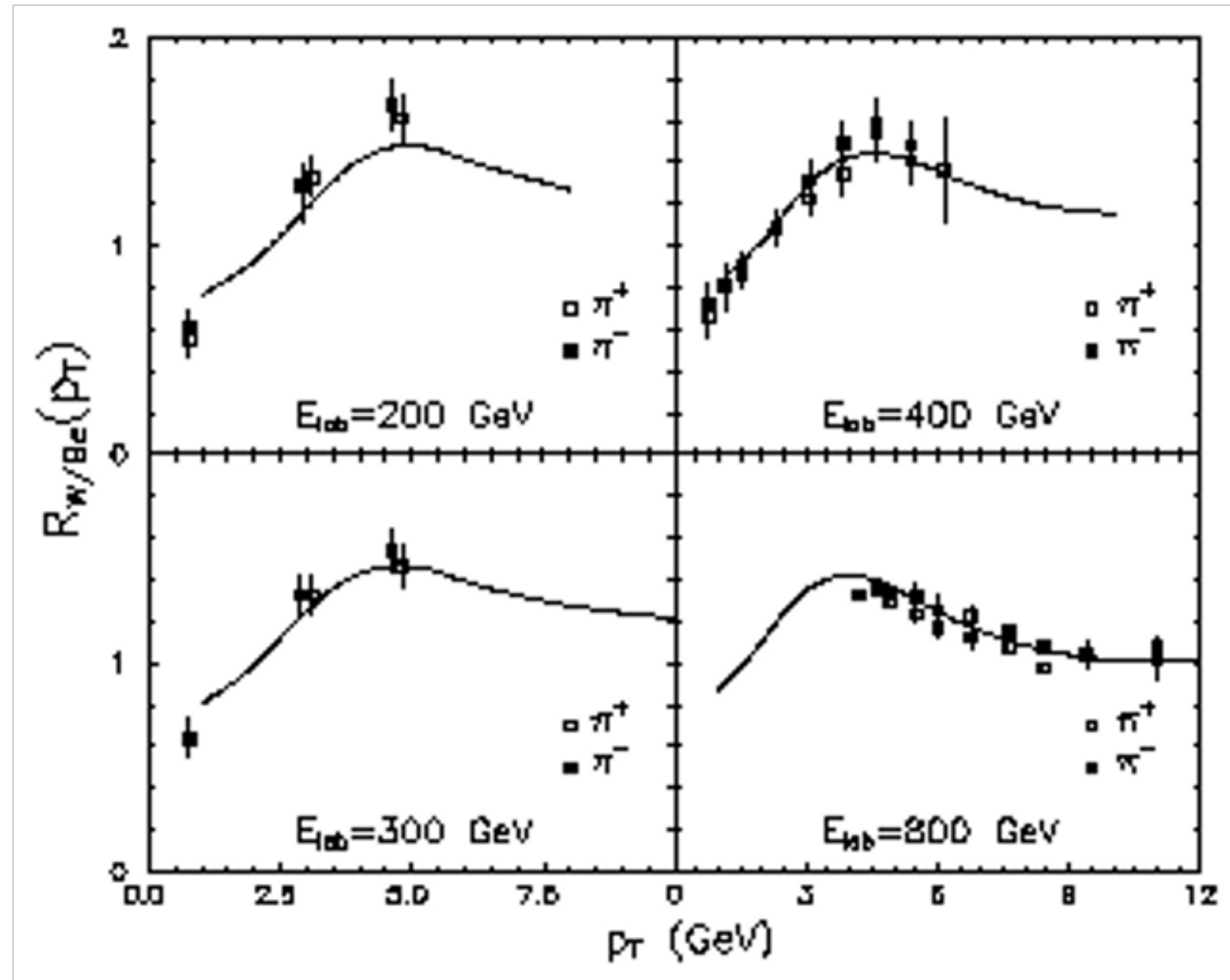


EIC Yellow Report

“Old” and long standing problems of nuclear partonic structure

- Three-dimensional nuclear partonic structure

Cronin effect (50 years)



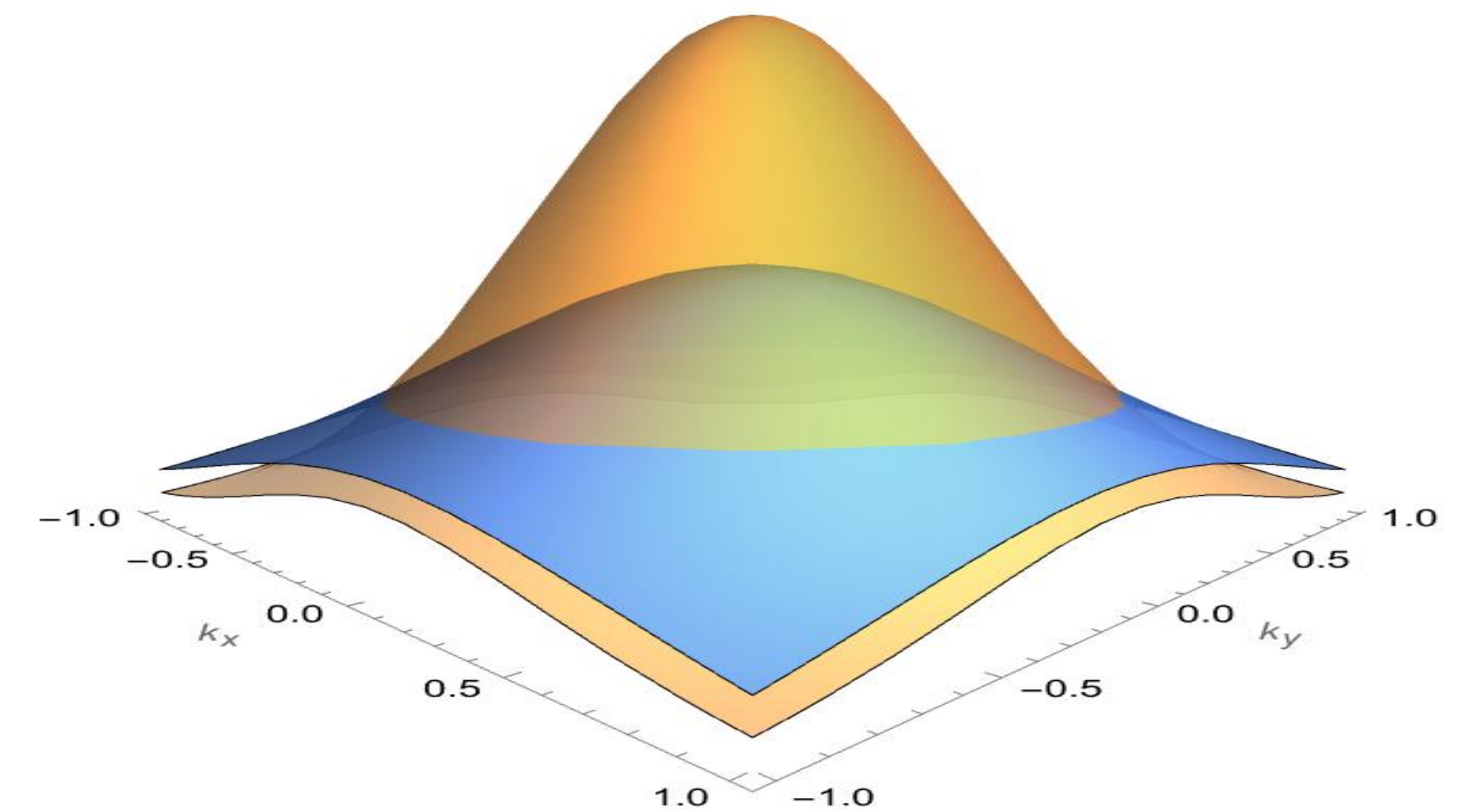
$p + A \rightarrow \text{hadron}(p) + X$

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

E100 Collaboration, PRD 11, 3105 (1975)

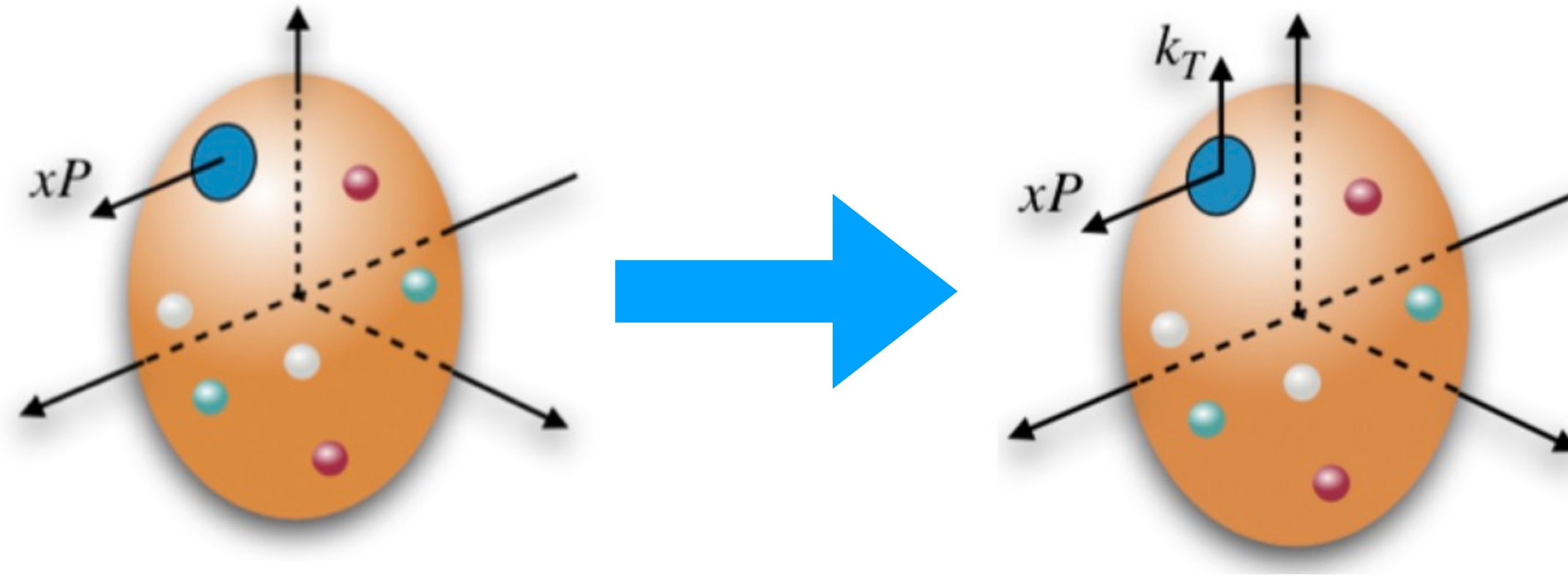
- Naive Gaussian model

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



Nuclear TMDs

- 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

- TMD factorization in nuclear medium

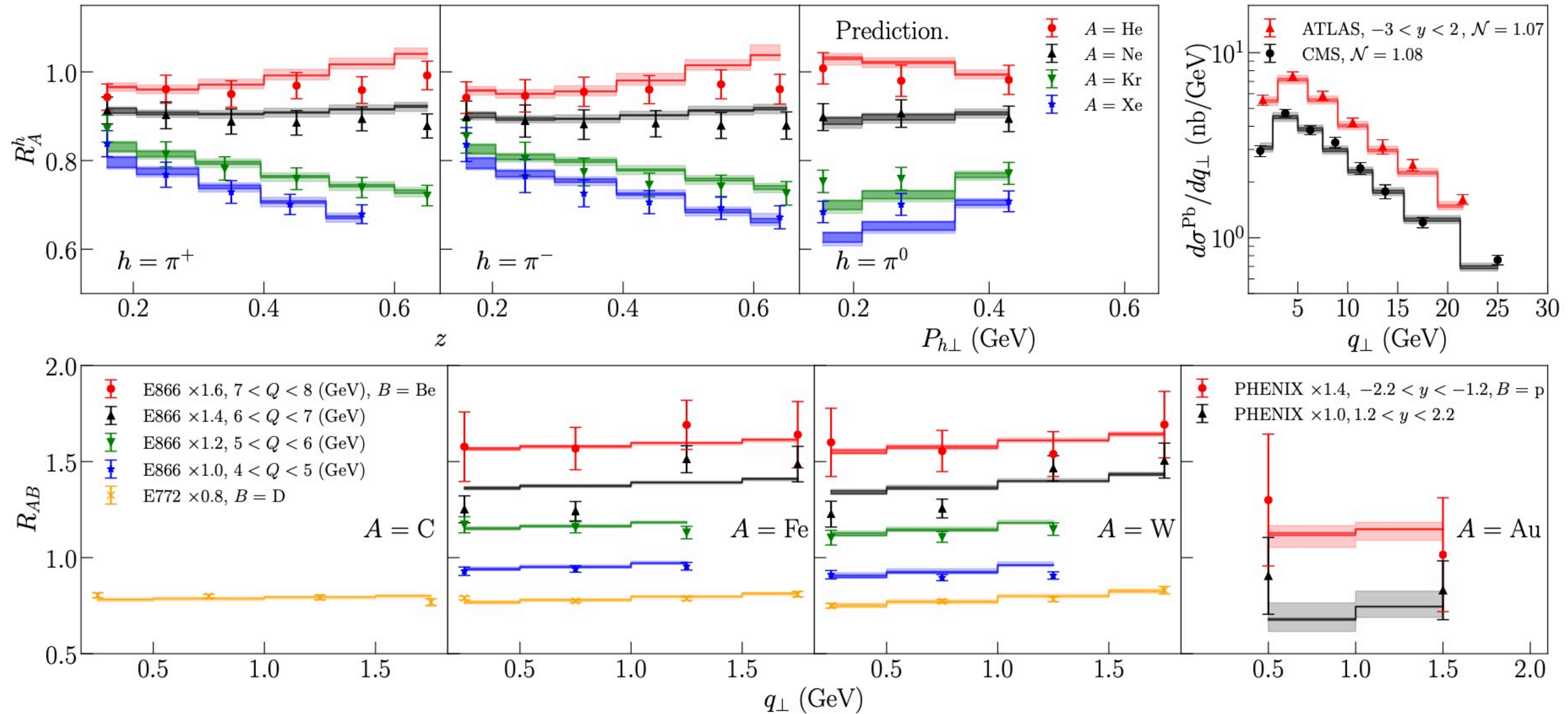
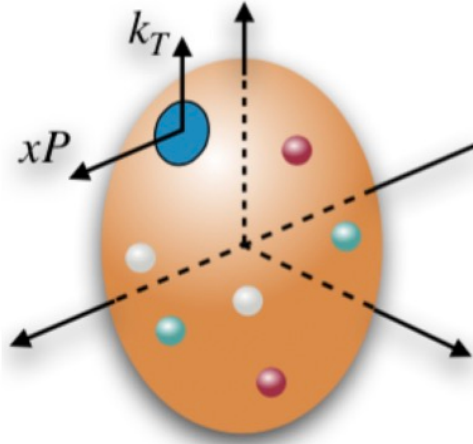
$$\frac{d\sigma^A}{dx dQ^2 dz d^2P_{h\perp}} = \sigma_0 H(Q) \sum_q e_q^2 \int_0^\infty \frac{b db}{2\pi} J_0 \left(\frac{b P_{h\perp}}{z} \right) f_{q/n}^A(x, b; Q) D_{h/q}^A(z, b; Q)$$

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

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

nuclear 3D imaging - global extraction from world data

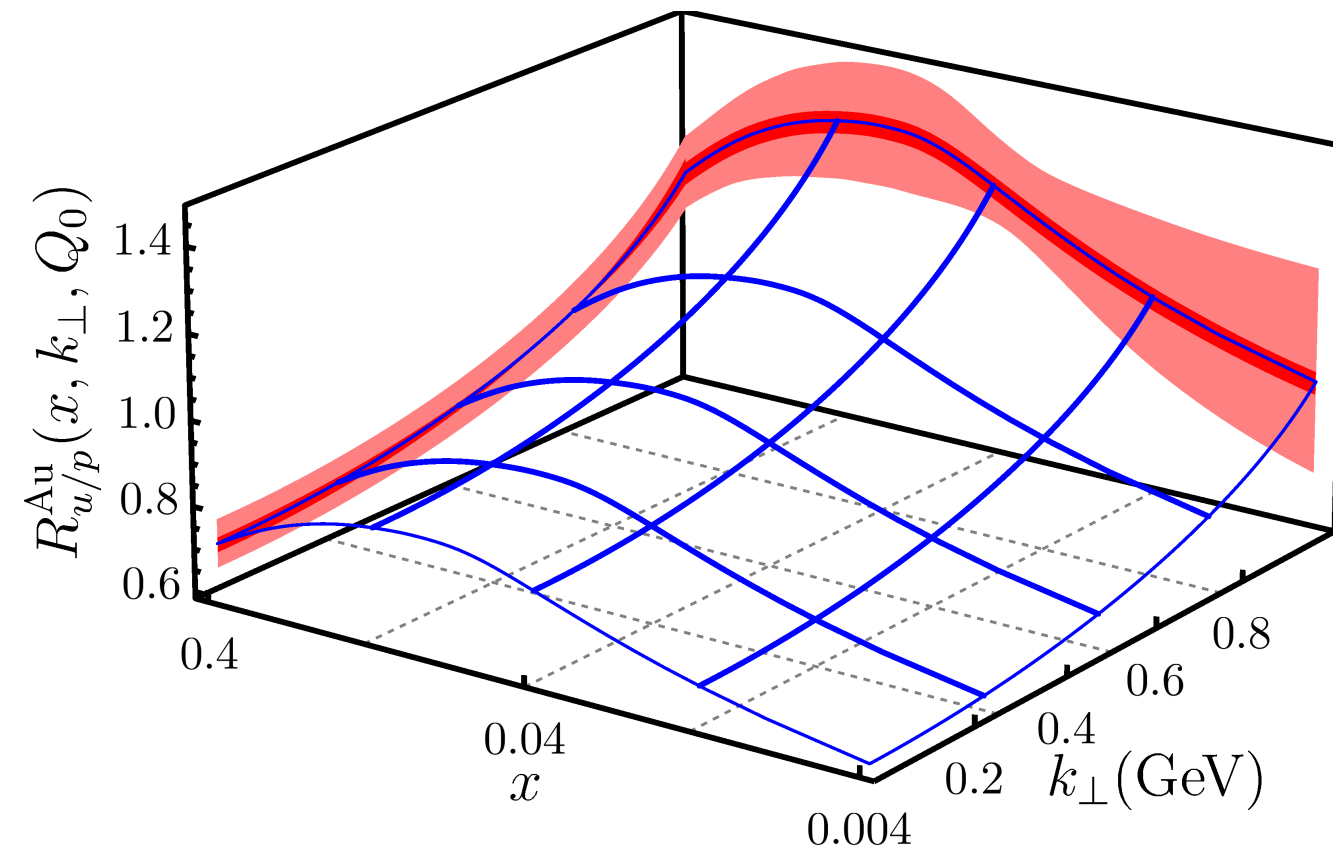
Alrashed, Anderle, Kang, Terry, **HX**, PRL 2022



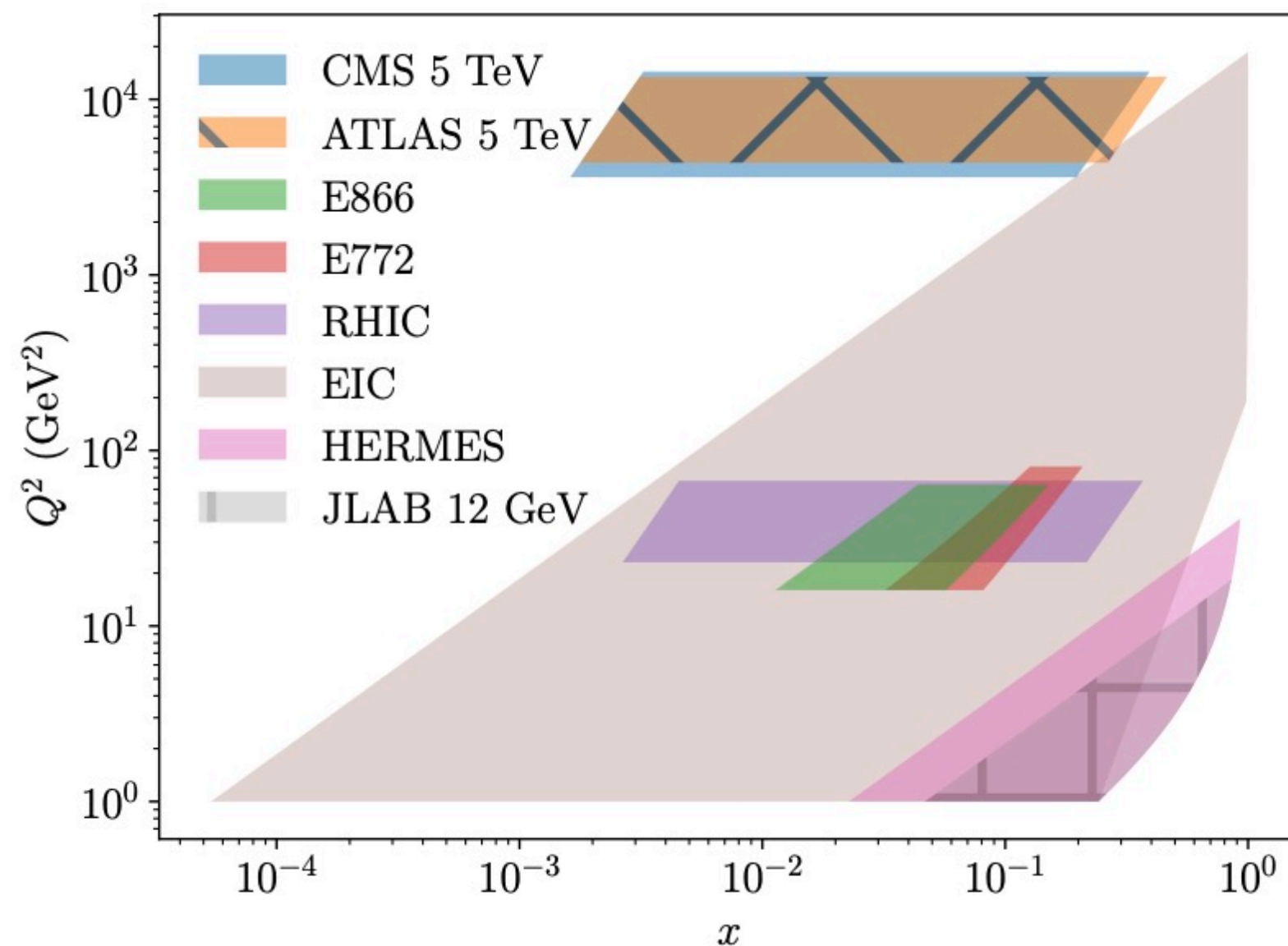
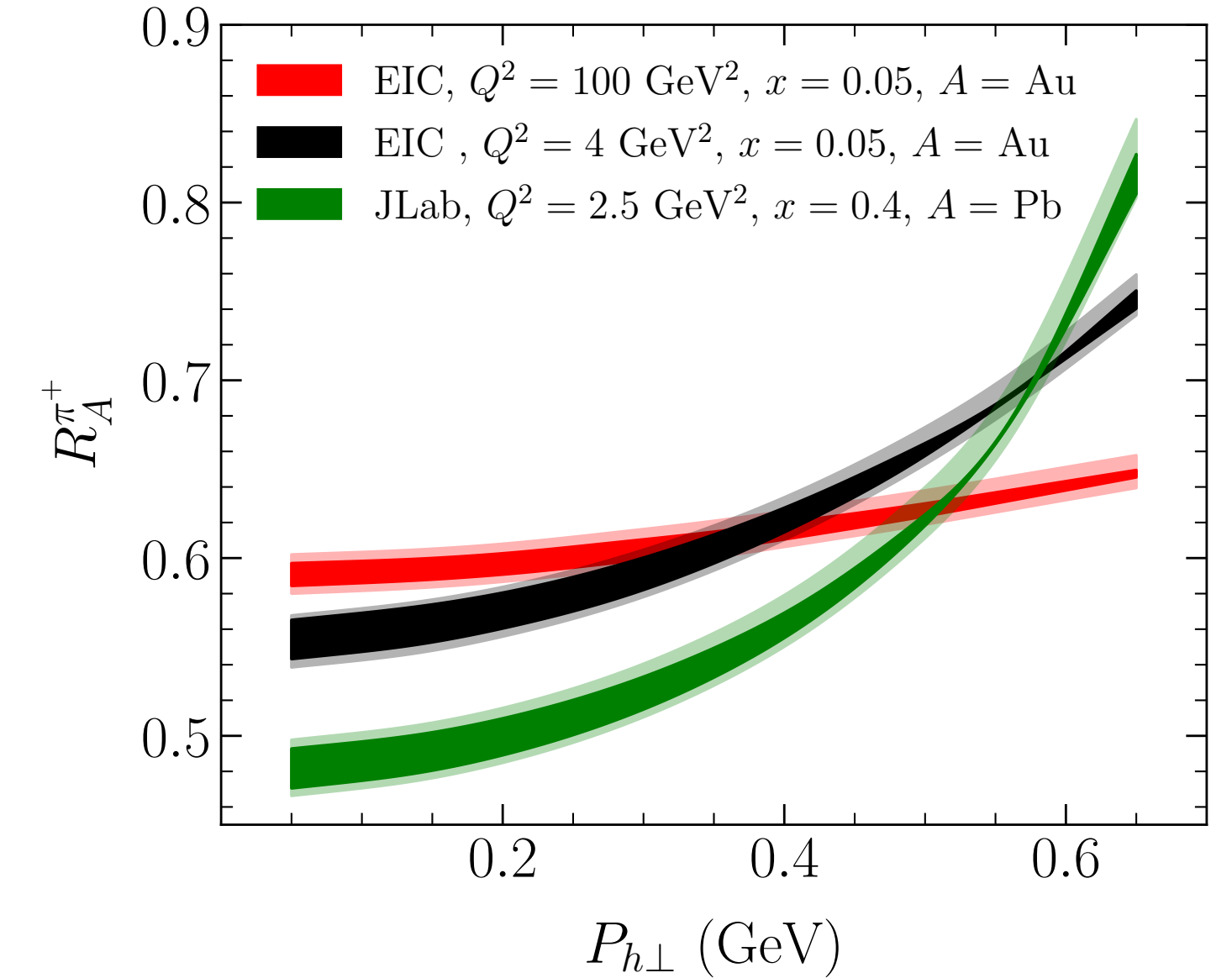
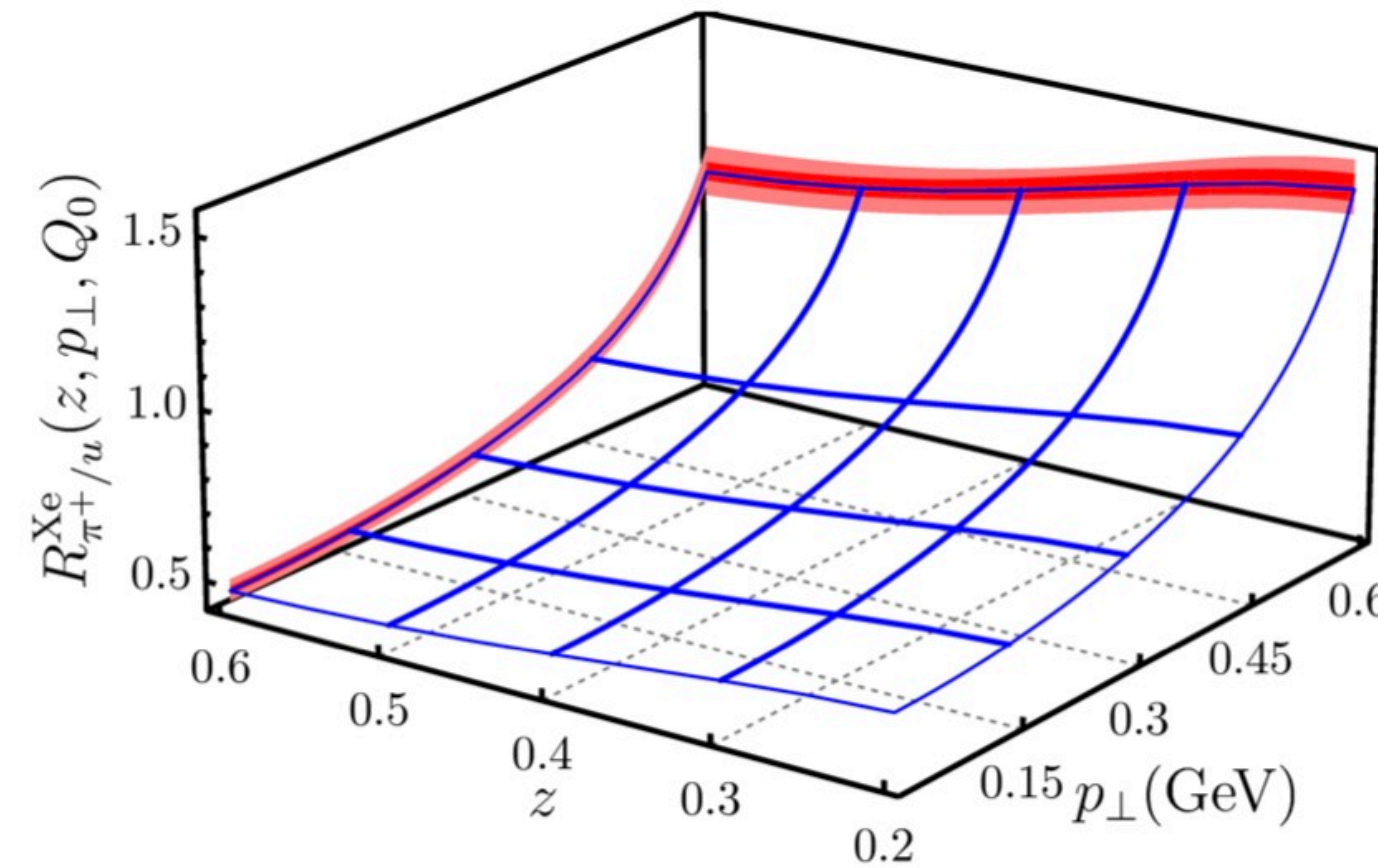
Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

Three-dimension imaging in nuclei

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



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

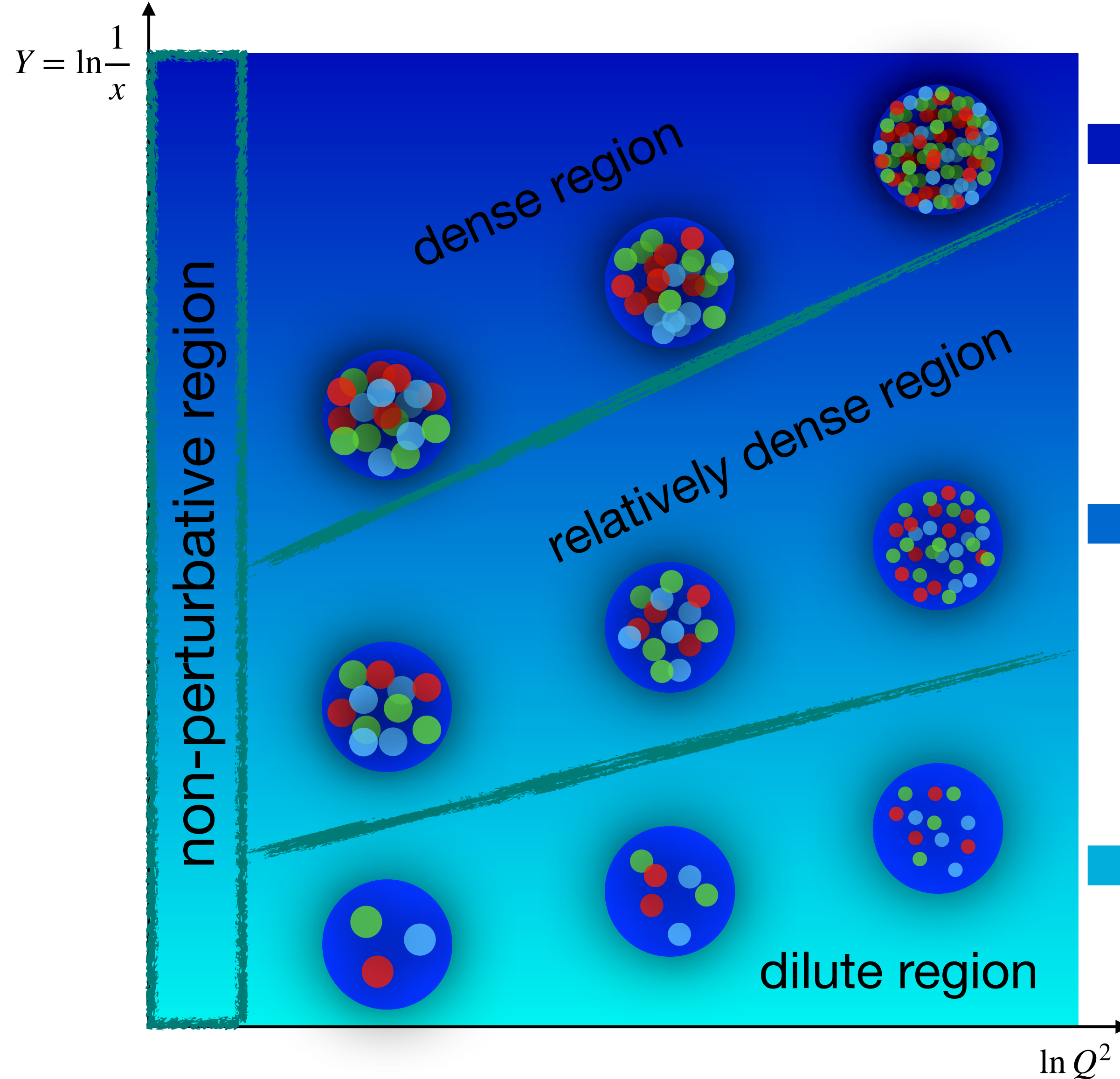


- First time quantitative determination of nuclear TMDs
- Identification of transverse momentum broadening in nuclei

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

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

QCD “phase diagram” for nuclei from dilute to dense region



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

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

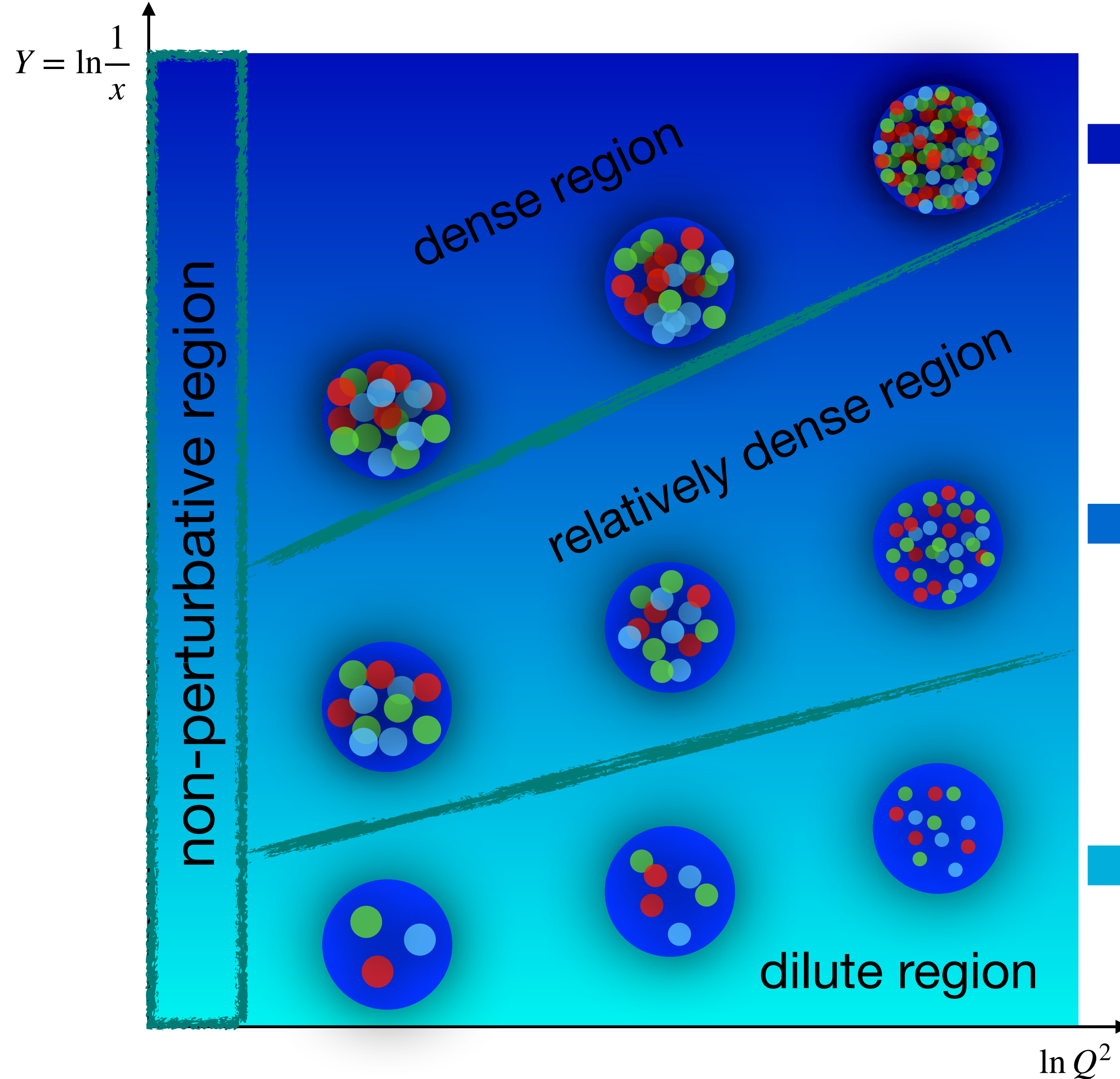
Relatively dense region: $x \lesssim \mathcal{O}(1)$

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 theoretical frameworks 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, PRD, 1991

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

Leading twist collinear factorization

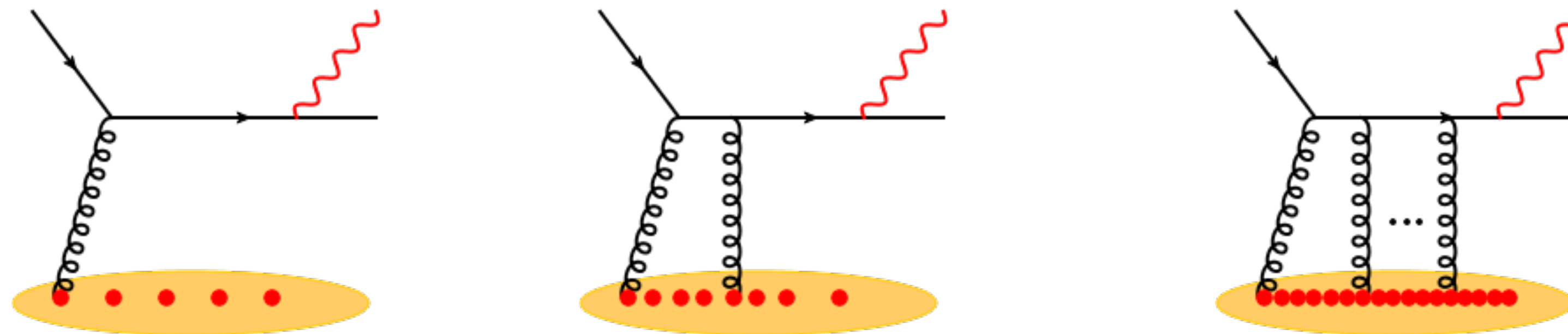
PDF, DGLAP evolution

Collins, Soper, 1981

The correspondence between CGC and high-twist expansion

- Take direct photon production as an example to prove the matching of CGC and HT

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



Parton density increases

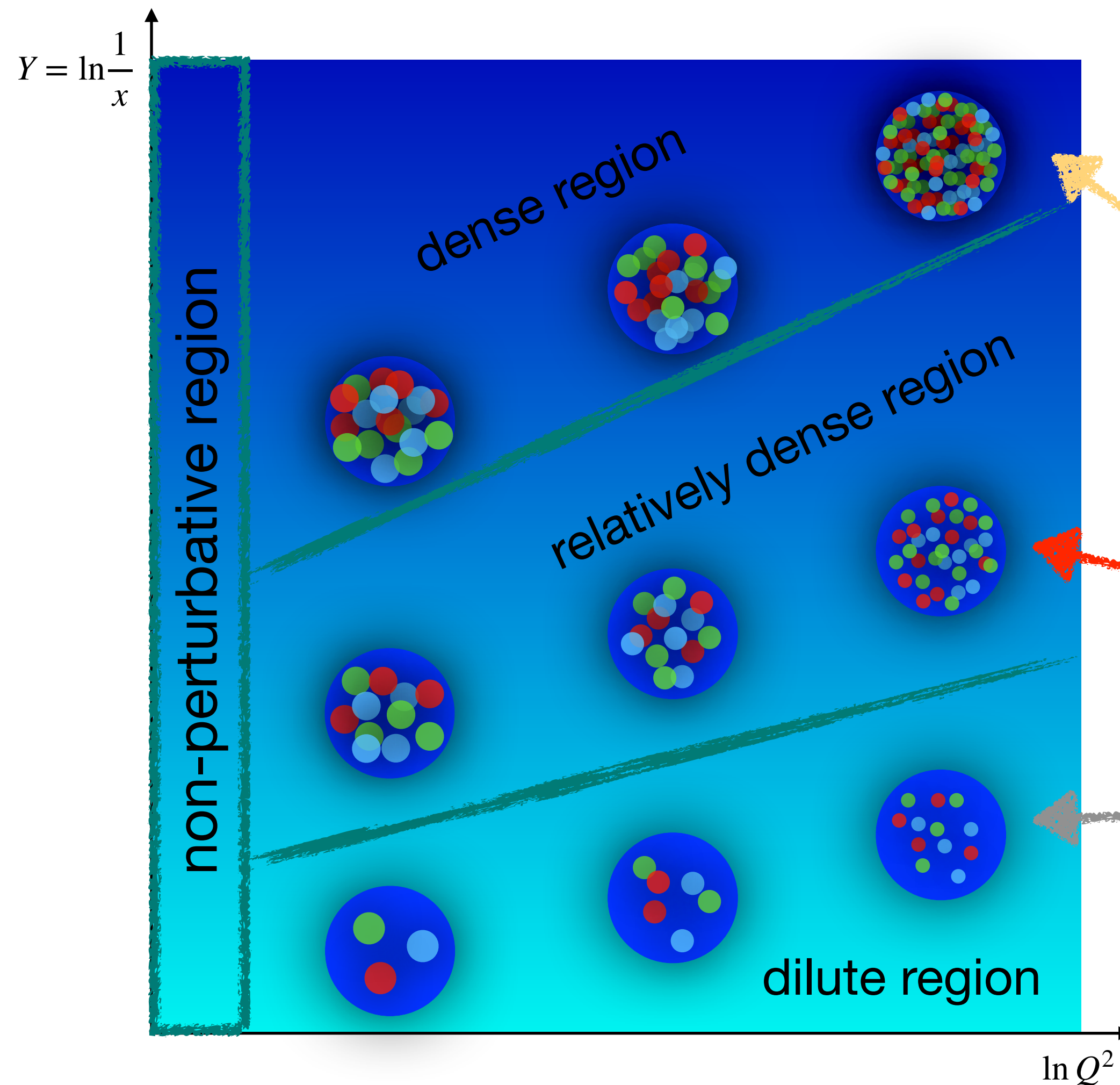
$$d\sigma \sim \frac{1}{p_{\gamma\perp}^4} \left[\underbrace{A}_{\text{leading twist (twist-2)}} + \underbrace{B \frac{\langle k_{\perp}^2 \rangle}{p_{\gamma\perp}^2} + C \frac{\langle k_{\perp}^2 \rangle^2}{p_{\gamma\perp}^4} \dots}_{\text{Higher twist (twist-4 and twist-6)}} \right]$$

$\langle k_{\perp}^2 \rangle \sim Q_s^2 \propto A^{1/3} x^{-\lambda}$

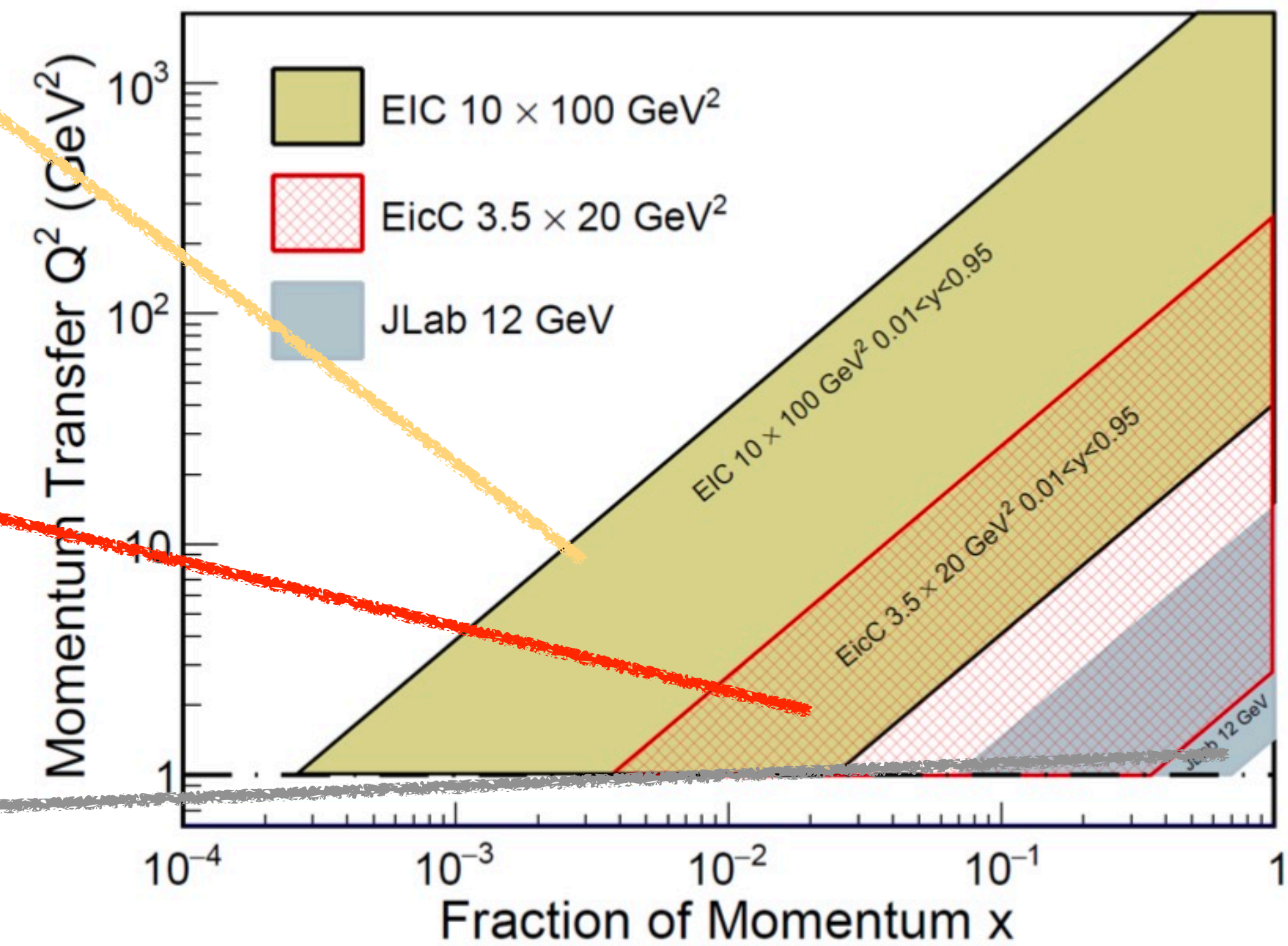
CGC

establish a unified picture for dilute-dense dynamics in QCD medium

Nuclear partonic structure from dilute to dense region



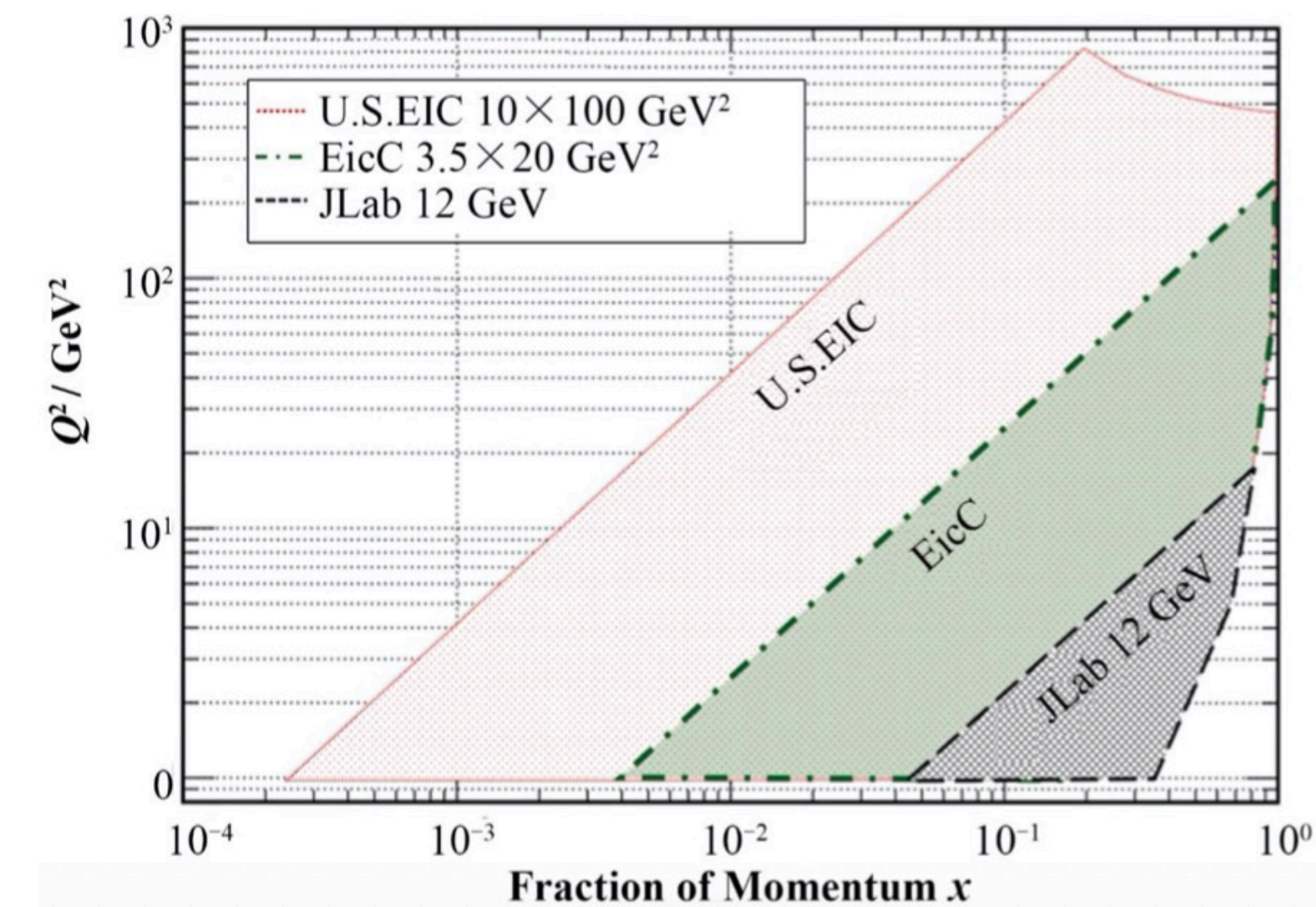
Fu, Kang, Salazar, Wang, **HX**, PRL, 2025



Mapping out the QCD phase diagram for nuclei with worldwide efforts using a unified theoretical framework!

Summary

- **EICs are the ultimate machines to explore the inner world of proton/nuclei at fm scale**
 1. Proton 1-D and 3-D imaging
 2. Proton spin
 3. Parton fragmentation
 4. Nuclear effects
- **Many more topics are not covered, such as GPDs, exotic states ...**
- **EIC、EicC、JLab are complementary to each other**



谢谢!

