Central China
Center for Nuclear Theory
华中核理论中心

EIC Physics

- based on some selected topics

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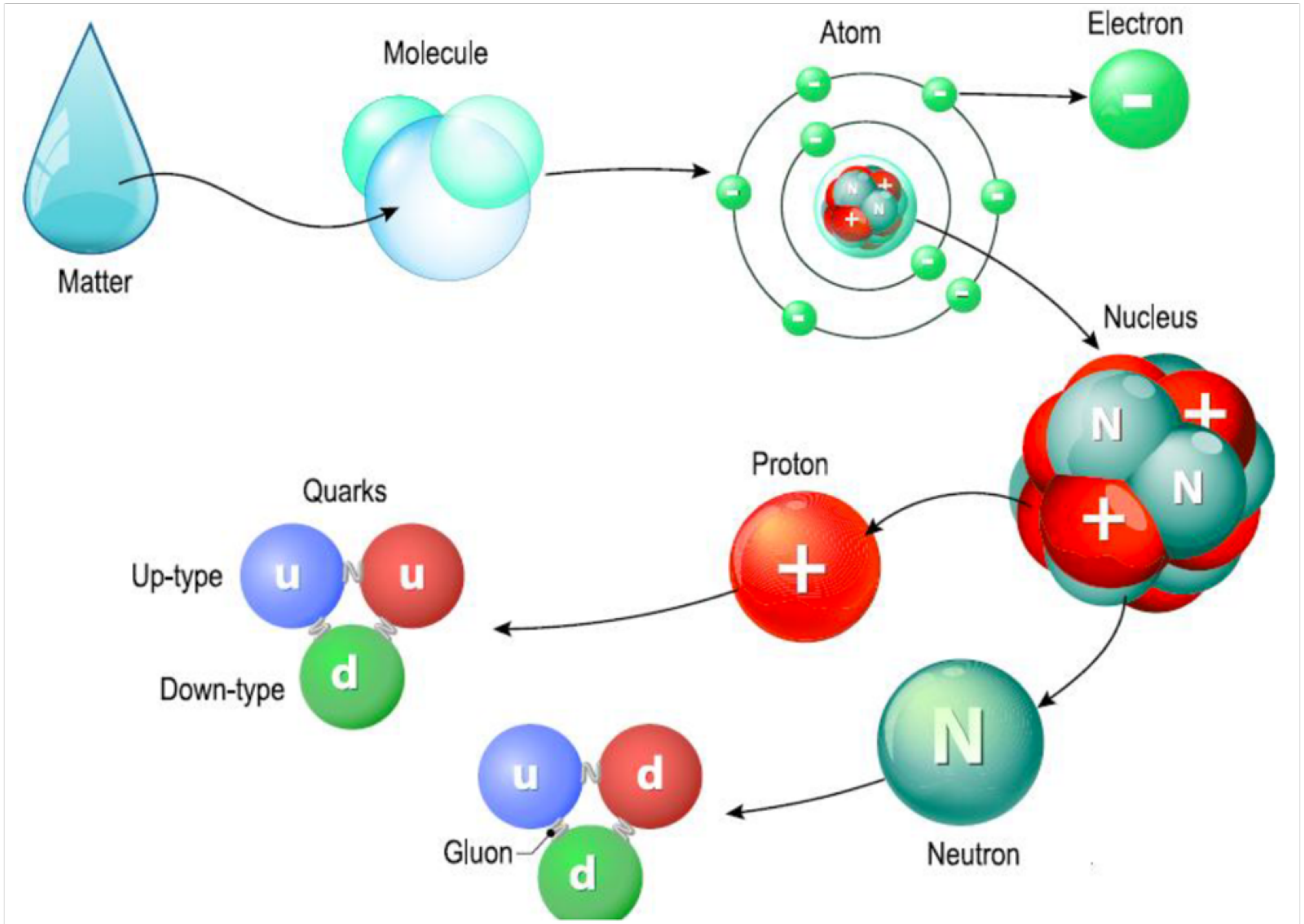
Wuhan, 2025.5.17-18

The mystery of our visible matter



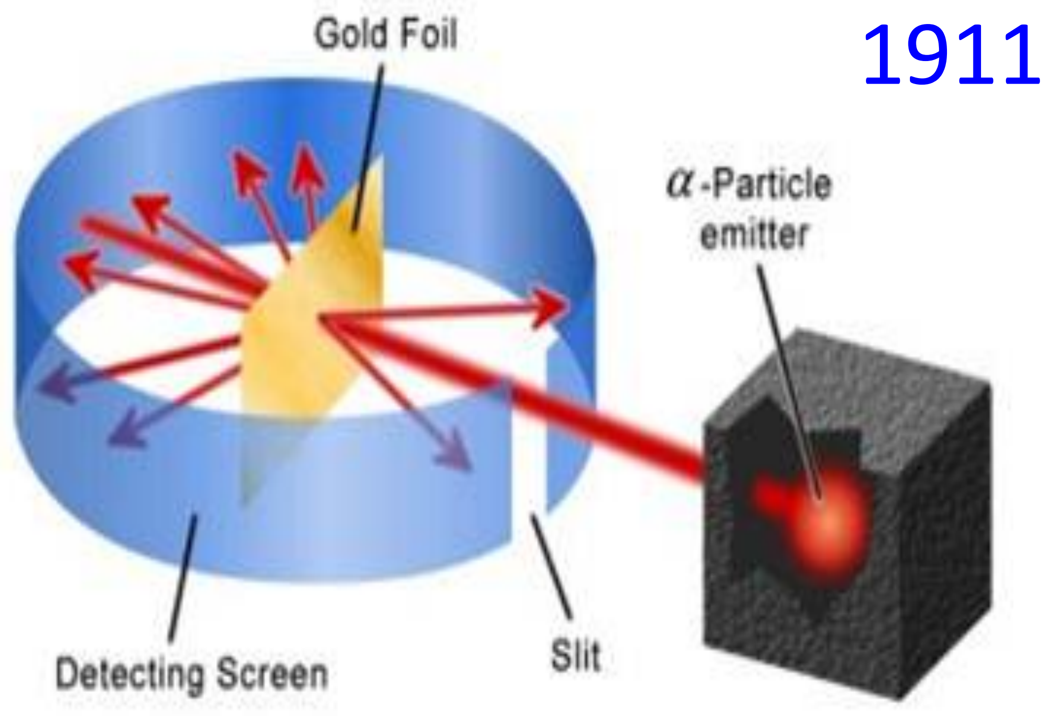
Nuclear Femtography: search for answers to the most fundamental structure at Fermi scale!

Nucleon partonic structure

✦ Revolution in our view of nuclear structure

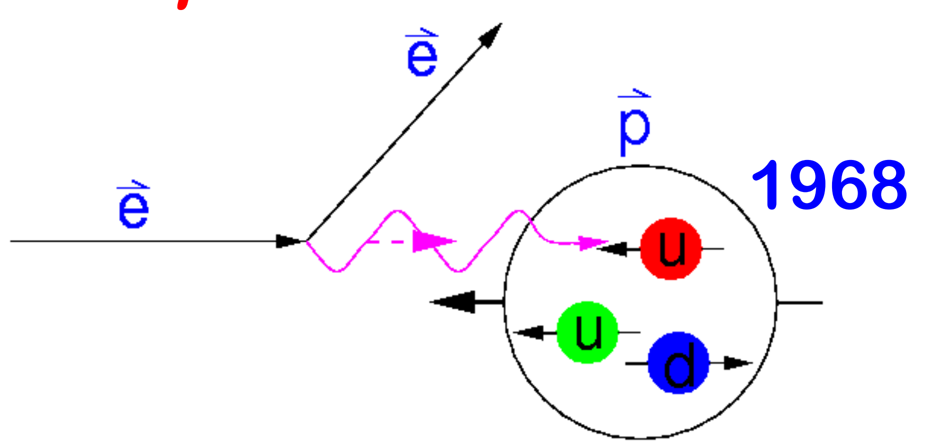
- Atom: Dalton 1803
- Nucleus: Rutherford 1911
- Proton: Rutherford 1919
- Neutron: Chadwick 1932
- Quark model: Gell-Mann and Zweig 1964
- Parton model: Feynman 1969
- …

1911



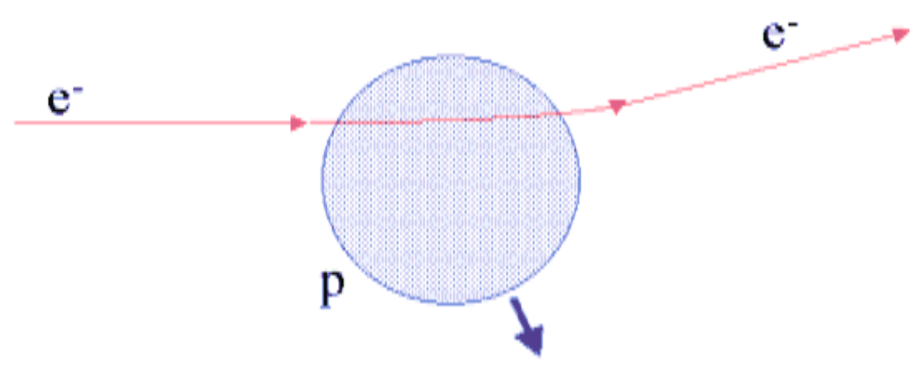
Rutherford scattering

e + *p* → e + *X*

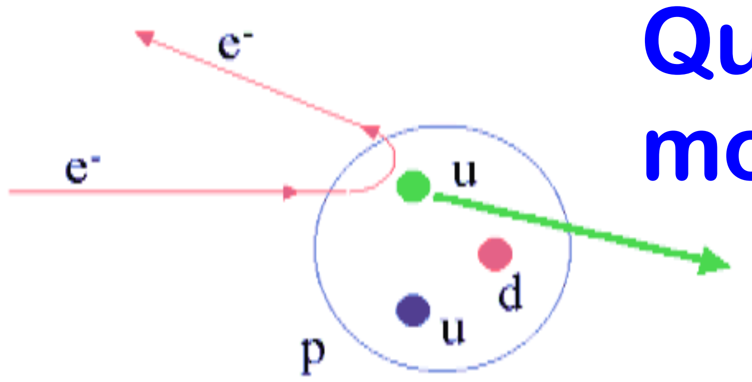


Modern Rutherford scattering

◆ If proton "charge cloud":



◆ If proton contains point charges, some of time see:



Quark model

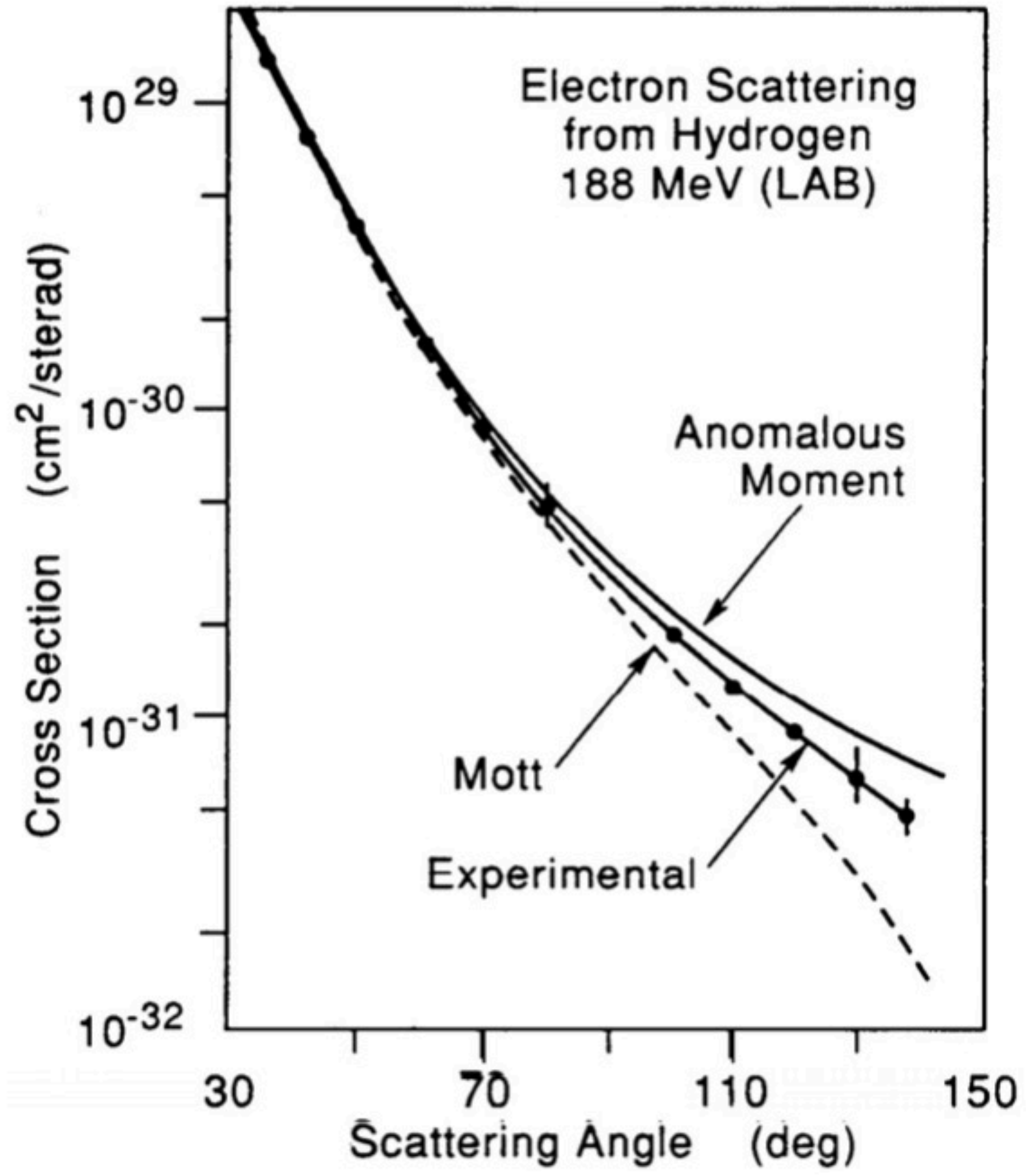
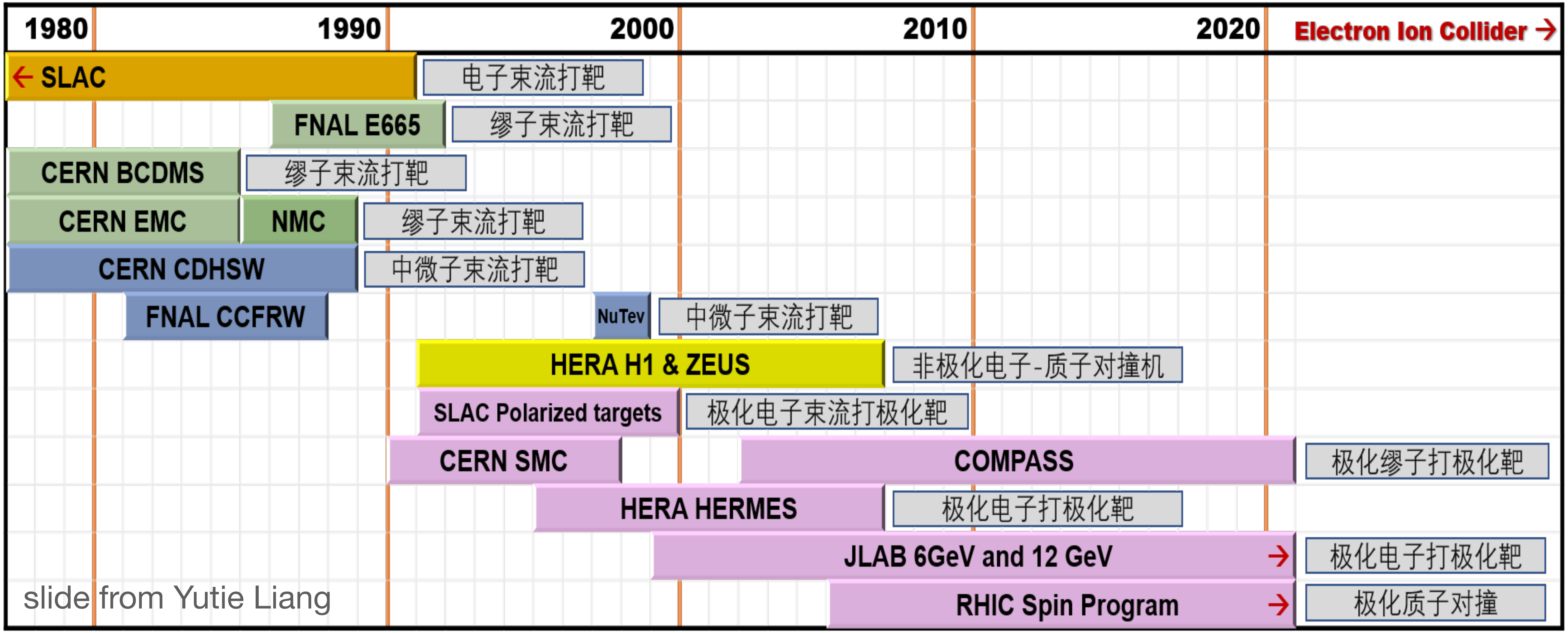


Fig. 5. Elastic electron scattering cross sections from hydrogen compared with the Mott scattering formula (electrons scattered from a particle with unit charge and no magnetic moment) and with the Rosenbluth cross section for a point proton with an anomalous magnetic moment. The data falls between the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

Birth of QCD !

The existing experiments for nucleon structure



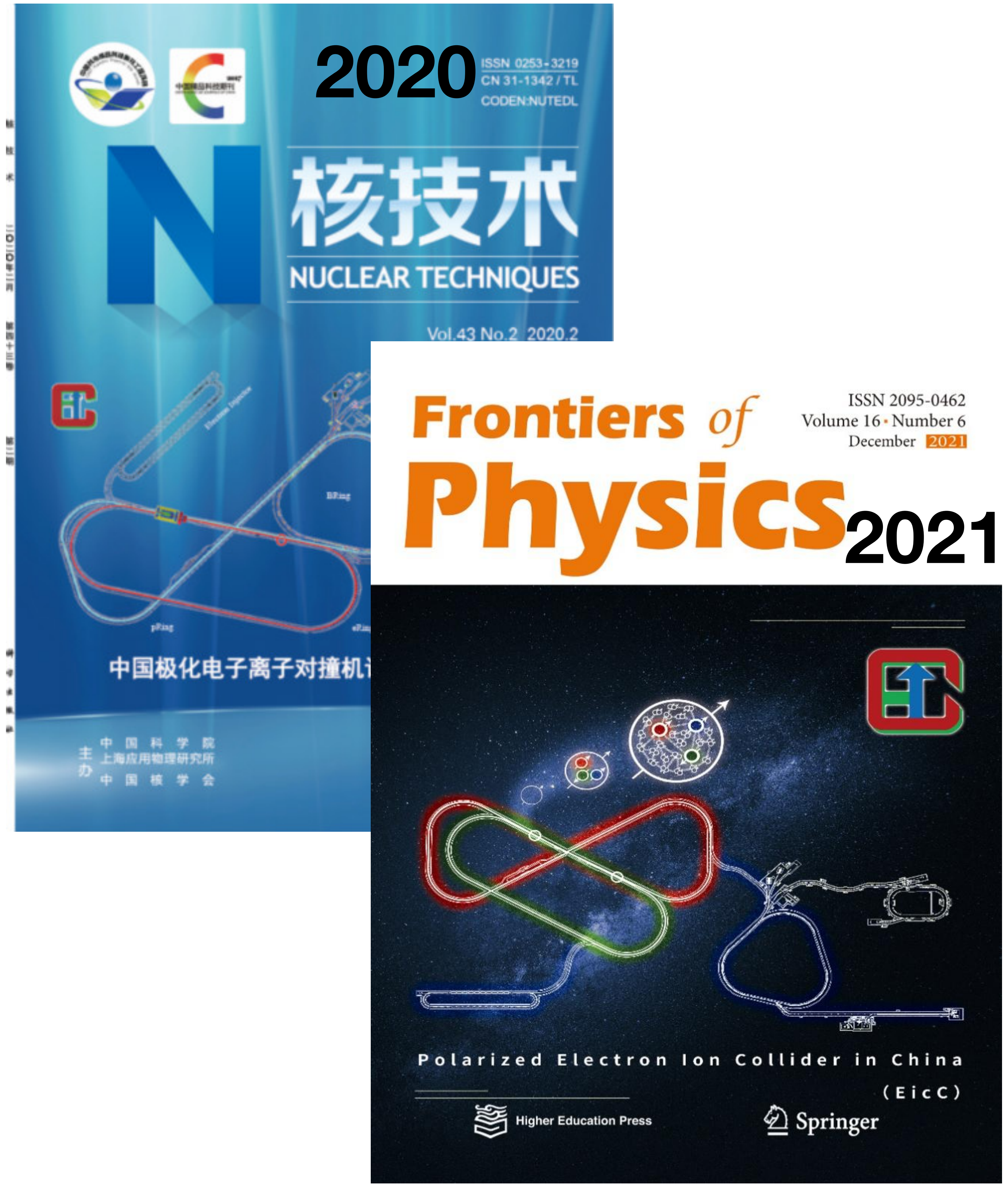
Electron Ion Colliders -> the next generation facility specifically for nucleon structure!

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

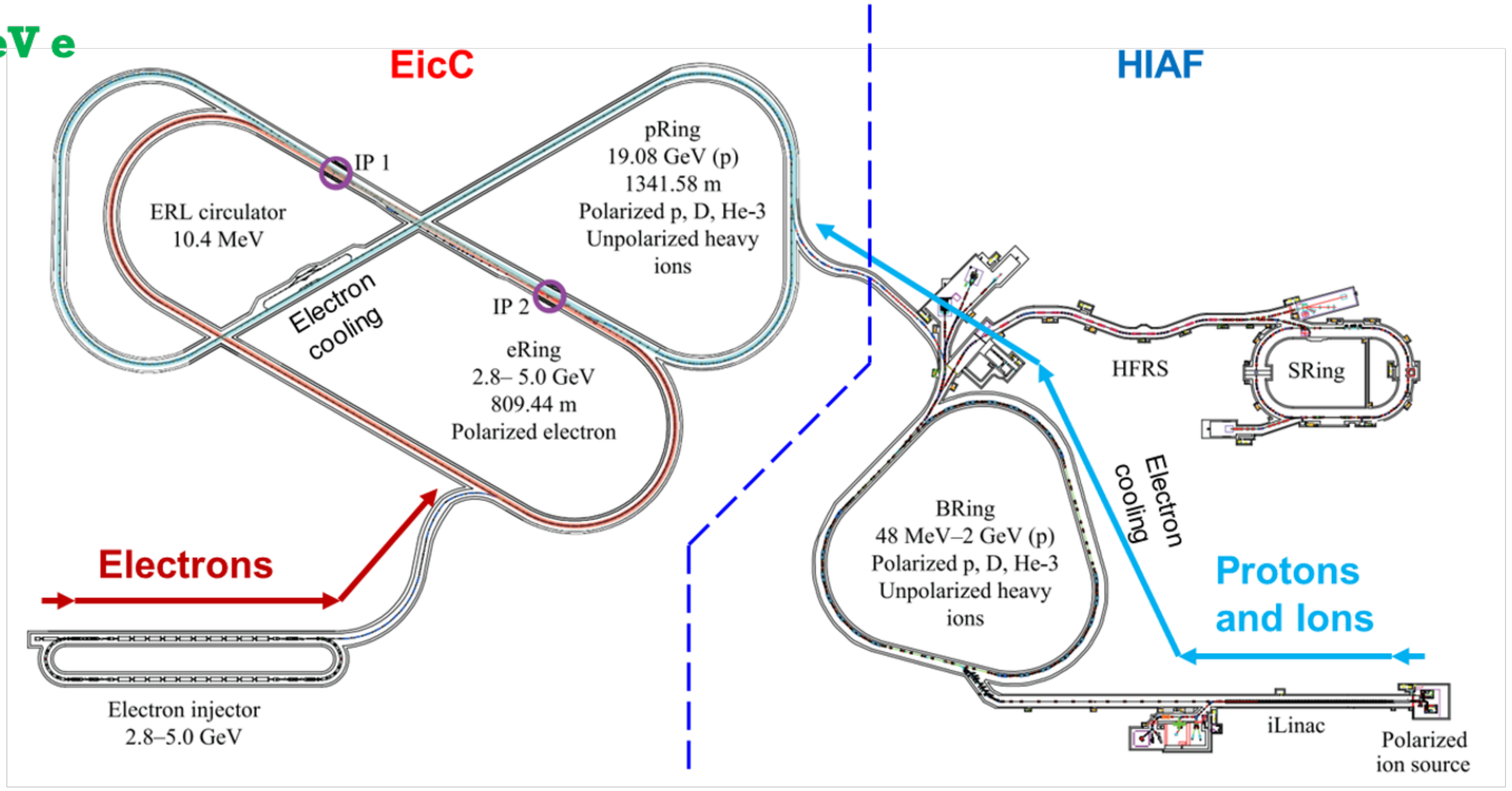
2025 European Particle Physics Strategy (2503.18208)

Electron Ion Collider in China (EicC)



- **20 GeV p + 3.5 GeV e**
- $\sqrt{S}$: **16.7GeV**
- **High Lumi.:**

  2-4 x10^{33} $cm^{-2}s^{-1}$
- **Polarized beams**



HIAF under construction

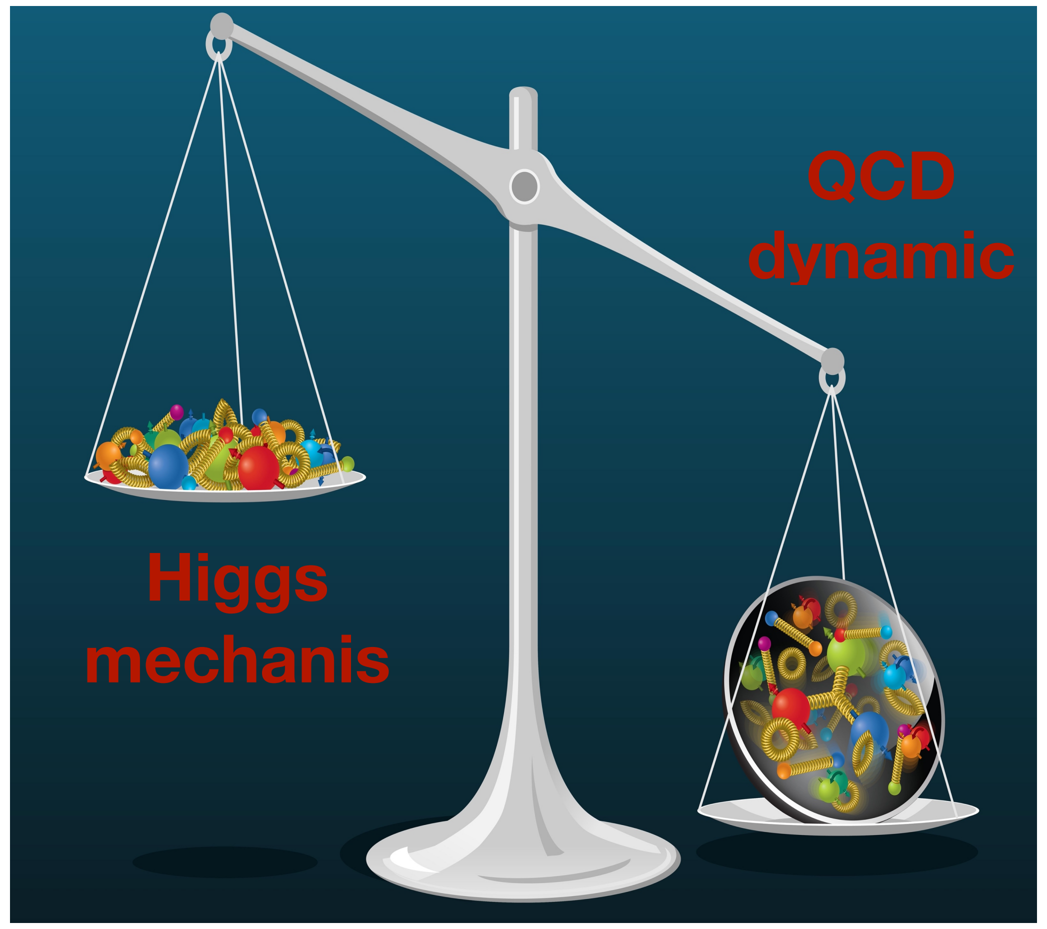
EIC in China

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

a nuclear facility proposed to be built in Huizhou, China

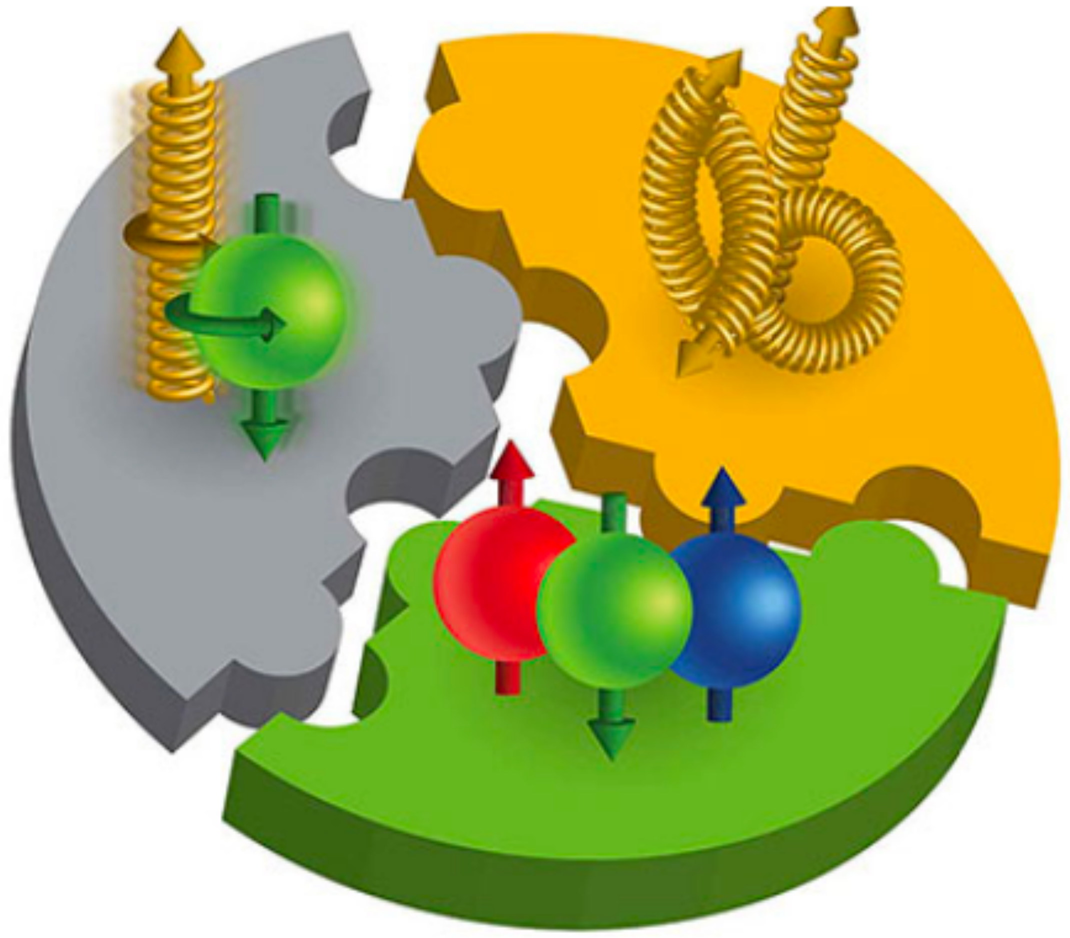

Wuhan
Huizhou

Science Pillars for EICs



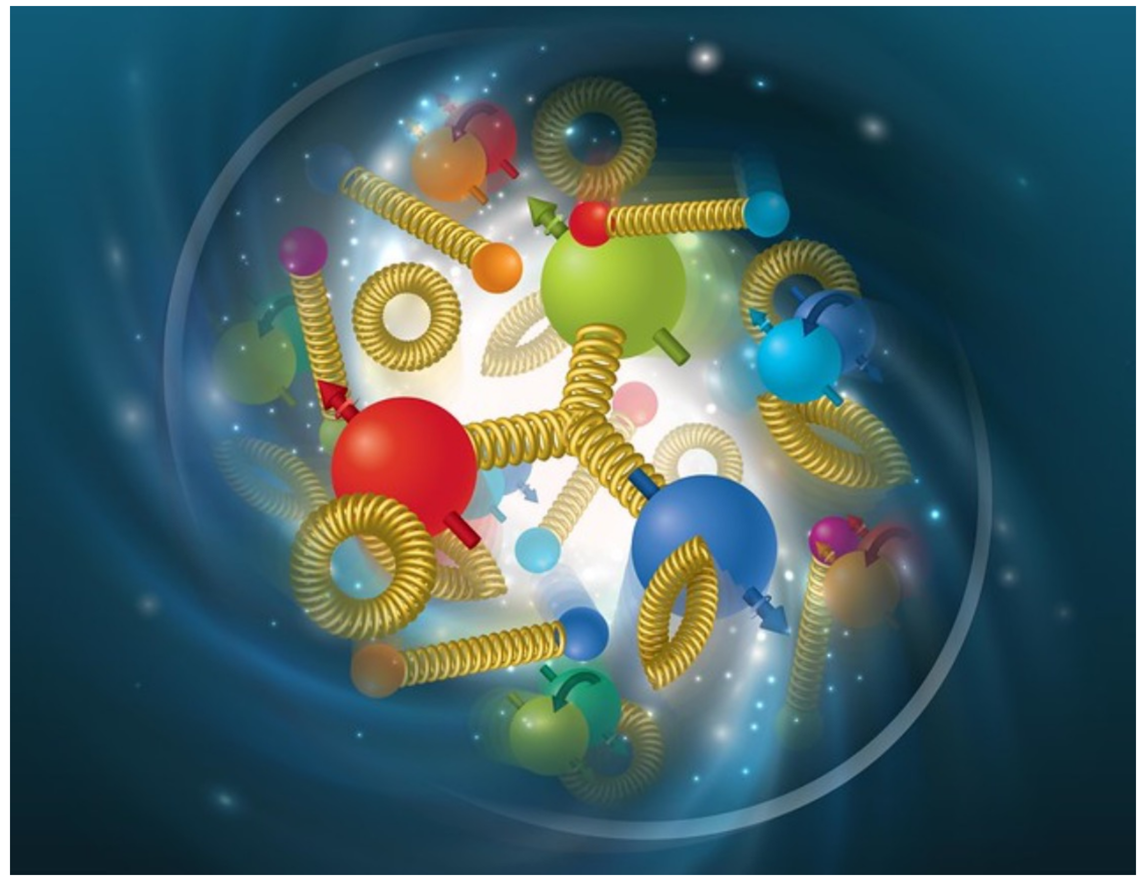
The proton mass decomposition

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



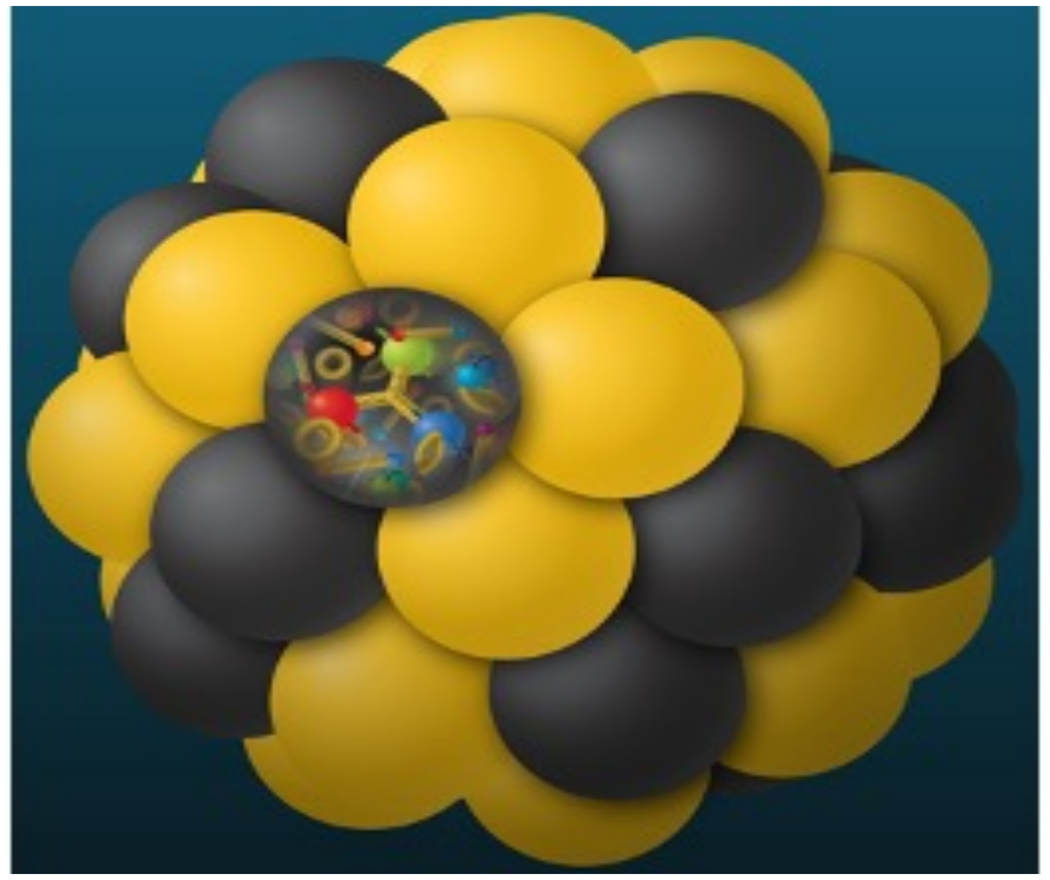
The origin of proton spin

- 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



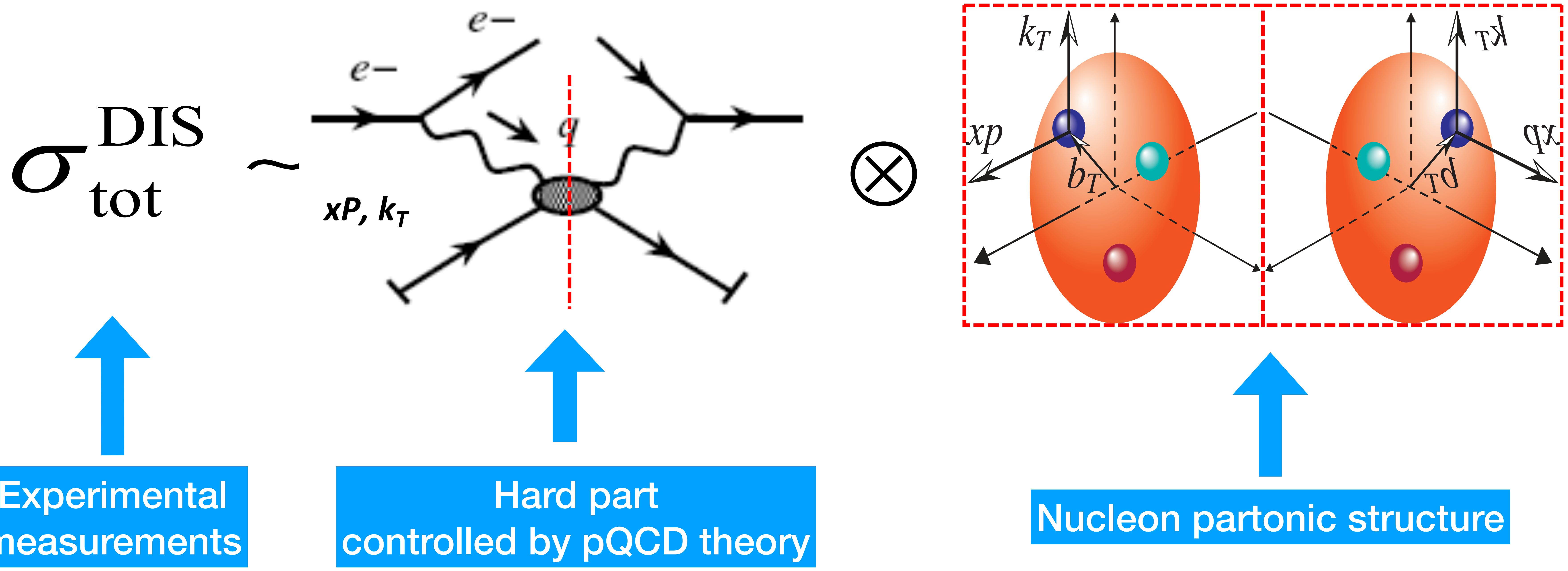
Confined partonic/ hadronic states in nucleus

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

How to probe the nucleon partonic structure?

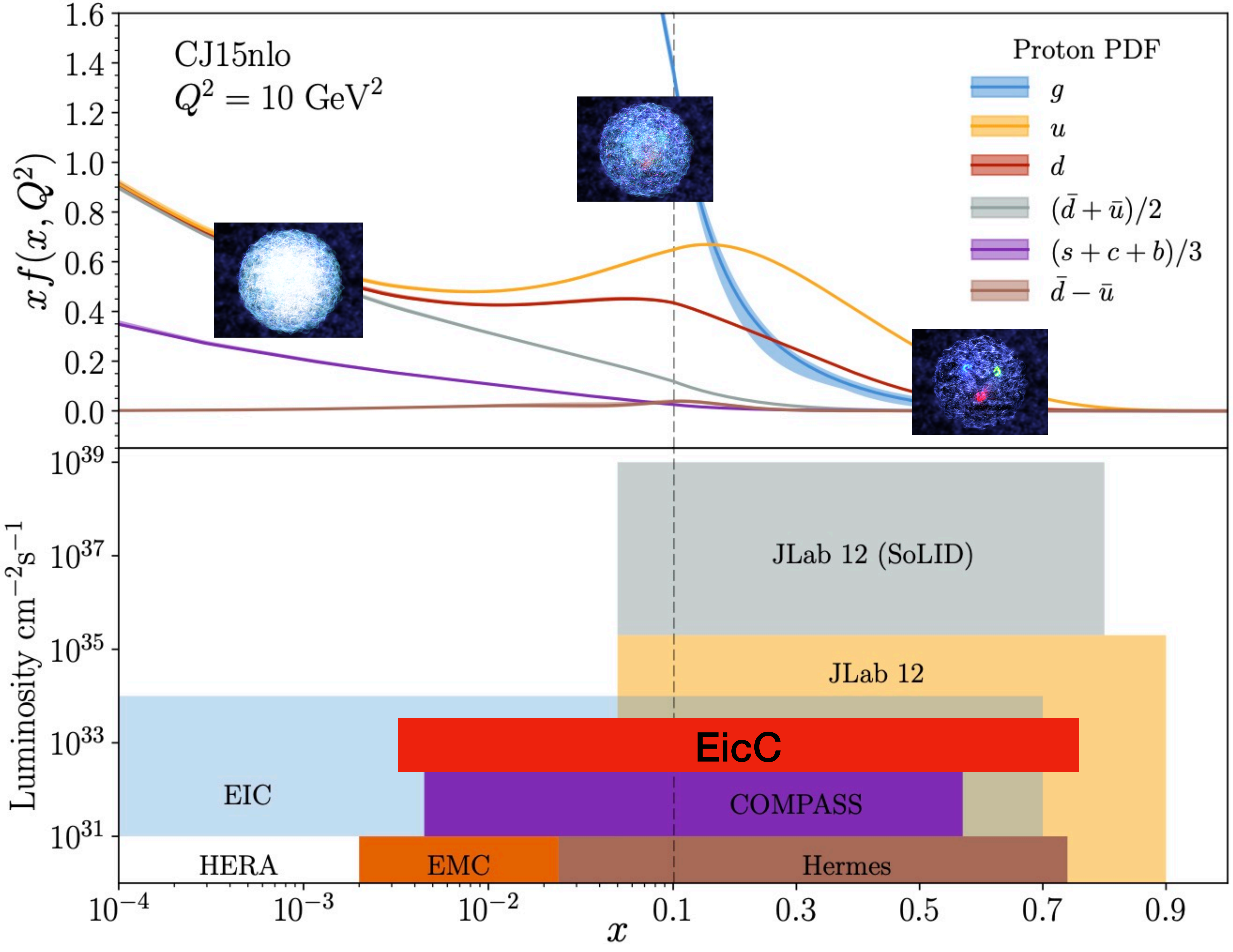
✦ Indispensable joint efforts from experiments and QCD theory

QCD factorization theorem

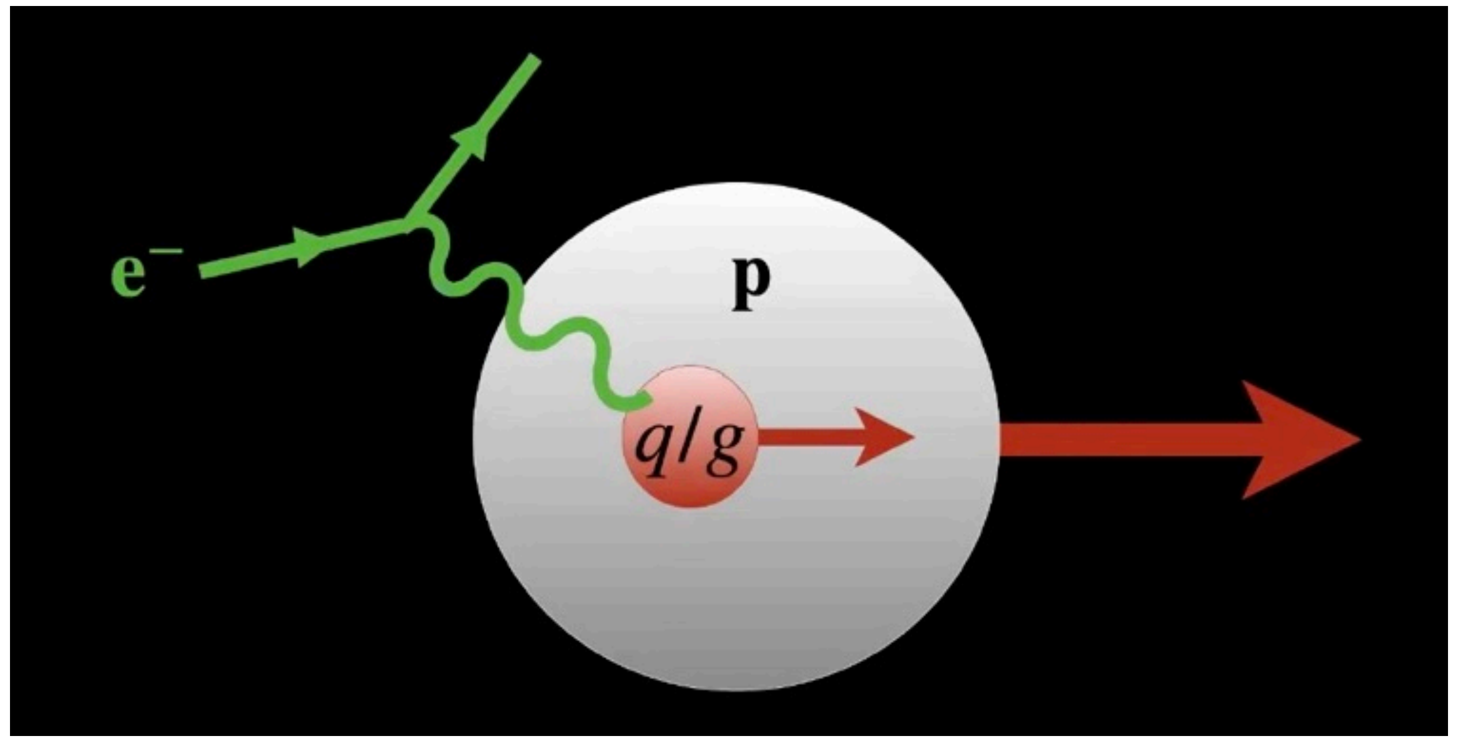


- **Uncertainty principle: we can't precisely determine the position and momentum of a parton at the same time**
- **We can determine the probability of seeing a parton in proton with specific characteristics - PDF**

Proton interior in 1-dimension



Prog. Part. Nucl. Phys. 127 (2022) 103985

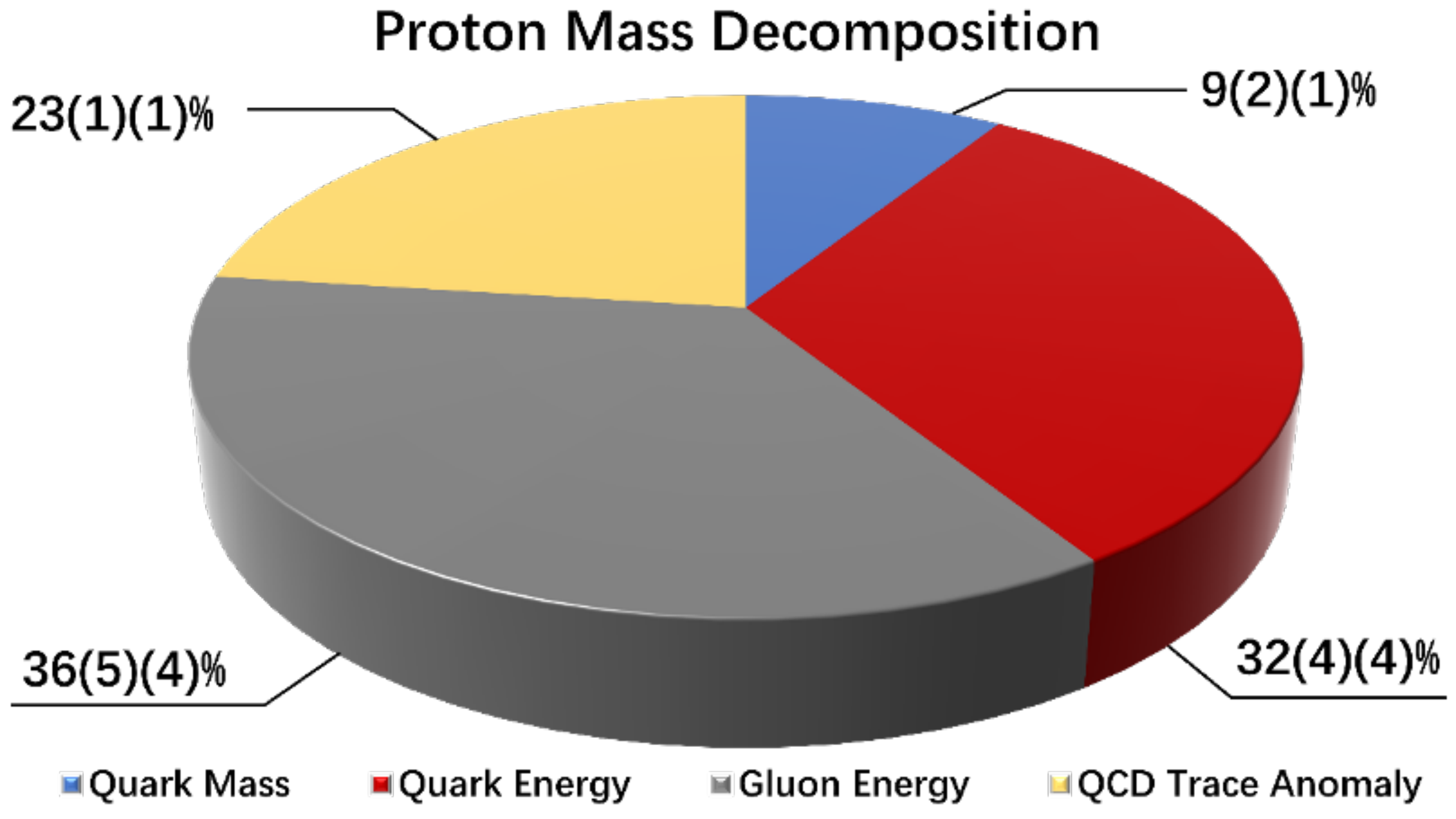


- ✦ There is no still picture for nucleon structure
- ✦ The x-dependence can not be predicted in theory, it can be only accessed in experiment
- ✦ There is no single machine can map out the full partonic structure of proton!

Proton mass

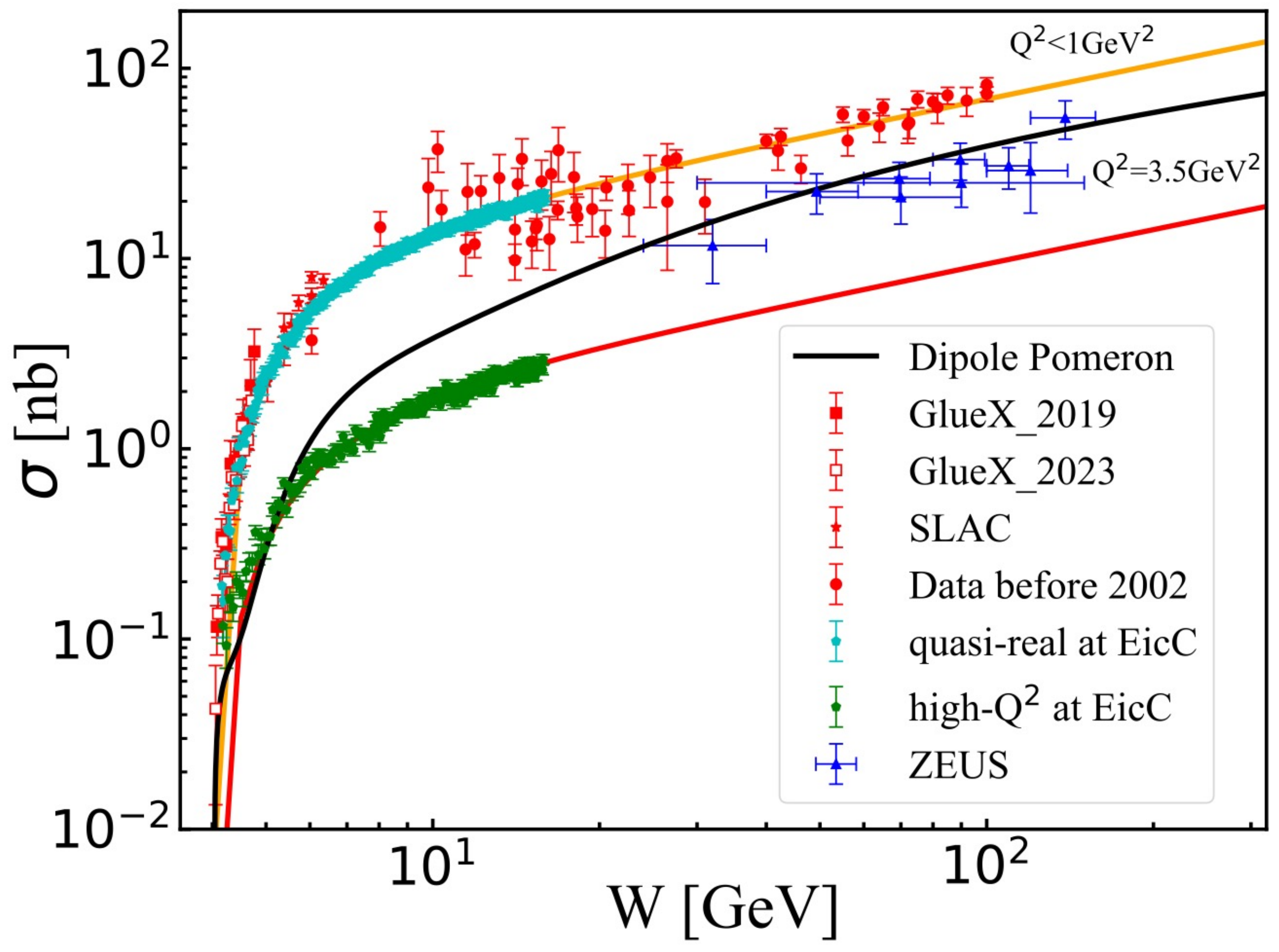
✦ The origin of proton mass

Phys. Rev. Lett. 121 (2018) 21, 212001

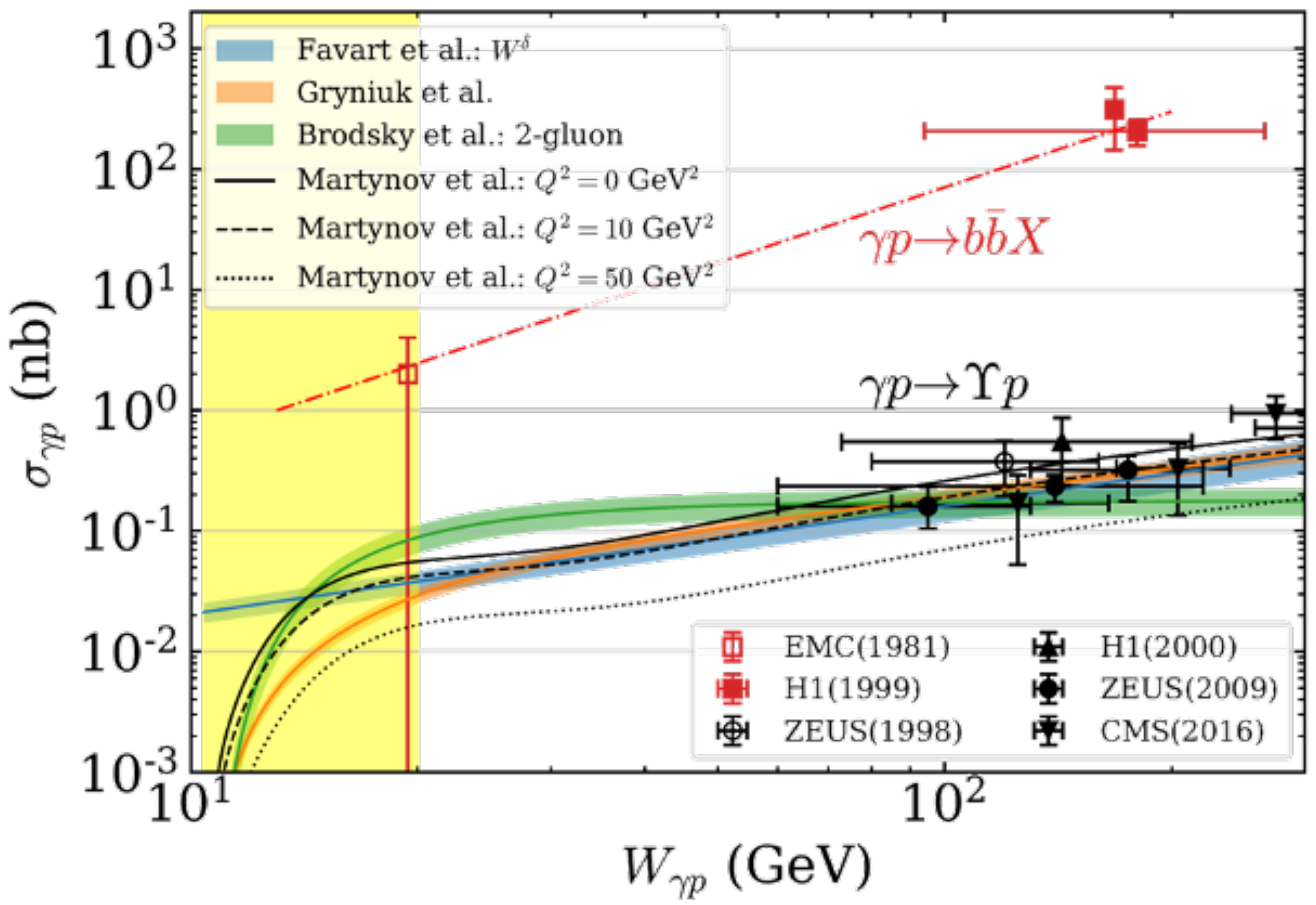


$$M = M_q + M_m + M_g + M_a$$

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 ?

Kharzeev et al, Proc. Int. Sch. Phys. Fermi 130 (1996) 105; Eur. Phys. J. C 9 (1999) 459-462
Sun, Tong, Yuan, Phys. Lett. B 822 (2021), 136655; Phys. Rev. D 105 (2022), 054032

Proton spin

✦ Naive parton model —> spin crises

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

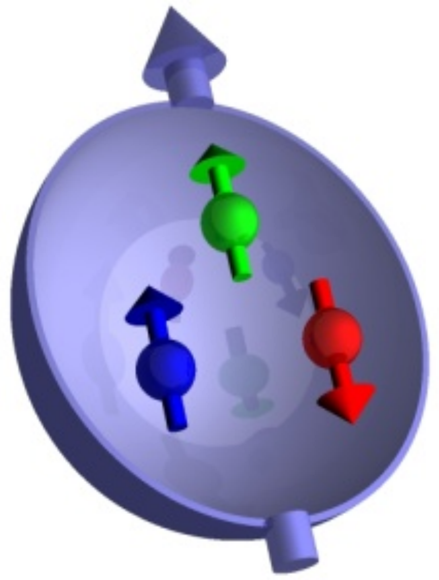
proton spin 1/2 is consistent with naive parton model, but contradict with experiments.

✦ Proton spin decomposition

Jaffe, Manohar; Ji

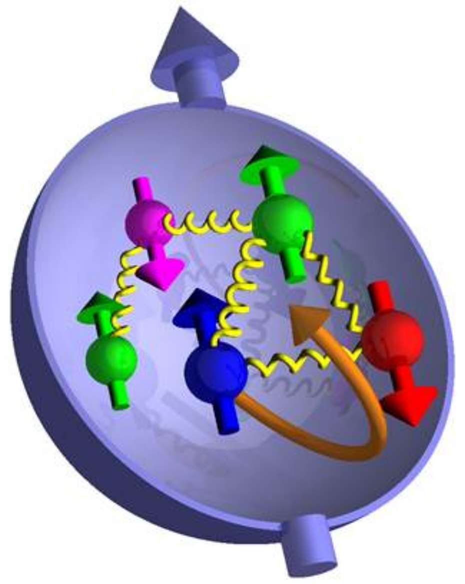
$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}|J^z_{QCD}|P,\frac{1}{2}\right\rangle = \frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2) + \int_0^1 dx\Delta G(x,Q^2) + \int_0^1 dx(\sum_q L^z_q + L^z_g)$$

total quark spin



gluon spin

angular momentum



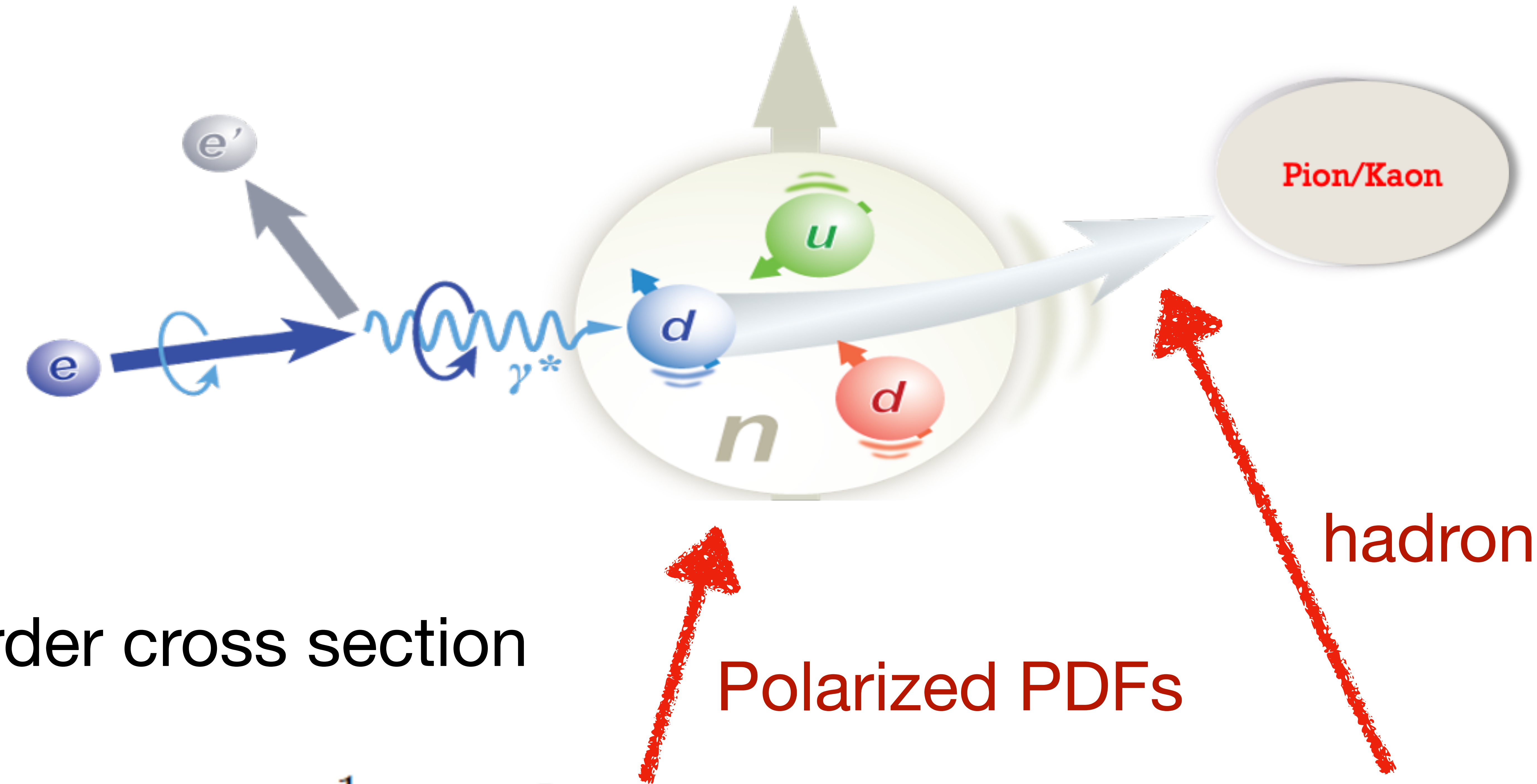
Quark ~ 30%

gluon ~ 40%

Orbital angular momentum?

Pin down the proton spin in future EICs

✦ Polarized structure function measurement g_1



- Leading order cross section

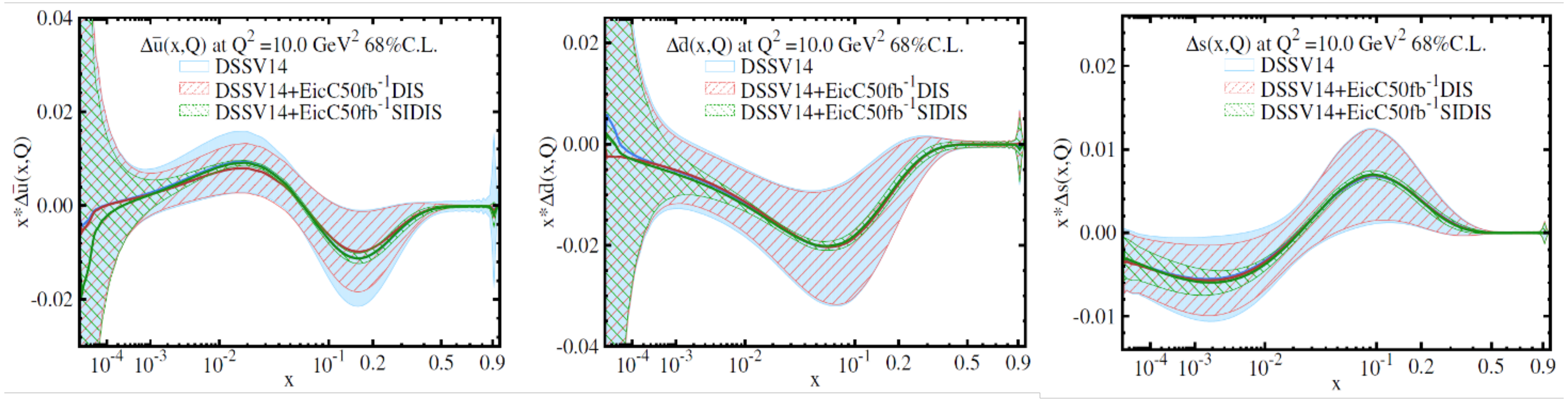
$$g_1^h(x, Q^2, z) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q(x, Q^2) D_q^h(z, Q^2) + \Delta \bar{q}(x, Q^2) D_{\bar{q}}^h(z, Q^2)\right]$$

Extracted nucleon structure information: polarized PDFs (helicity distribution)

Pin down the proton spin in EIC&EicC

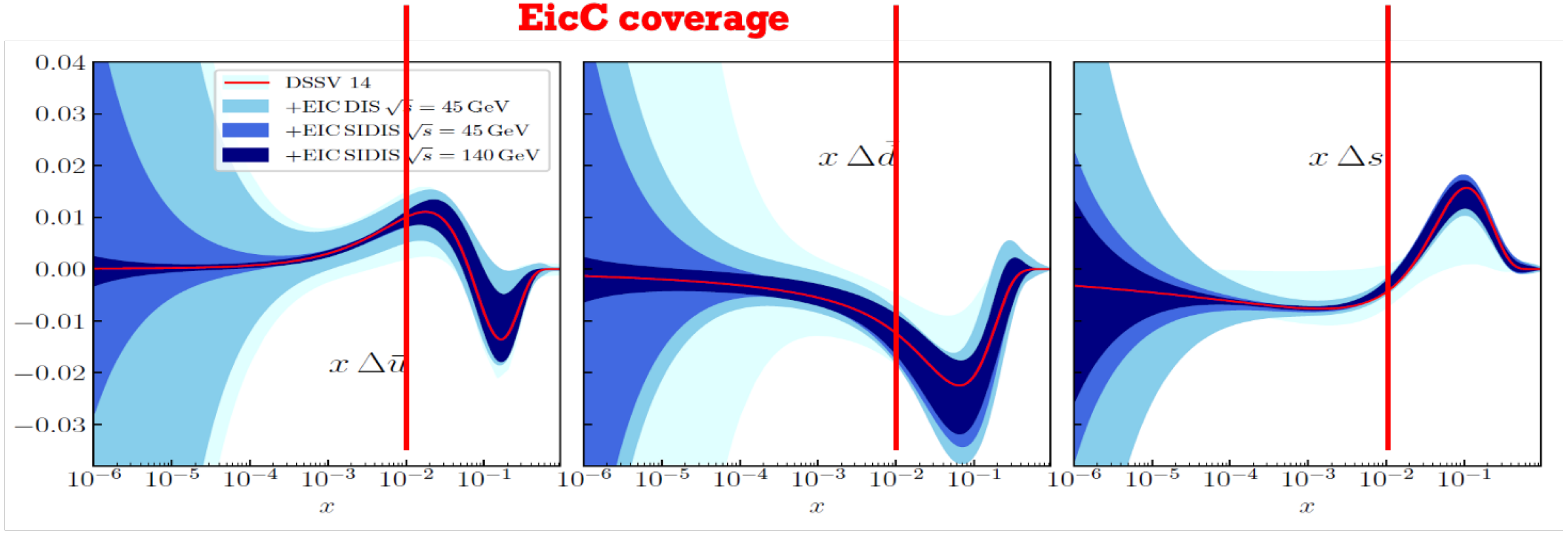
✦ SIDIS for flavor decomposition

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



EicC white paper

EicC coverage

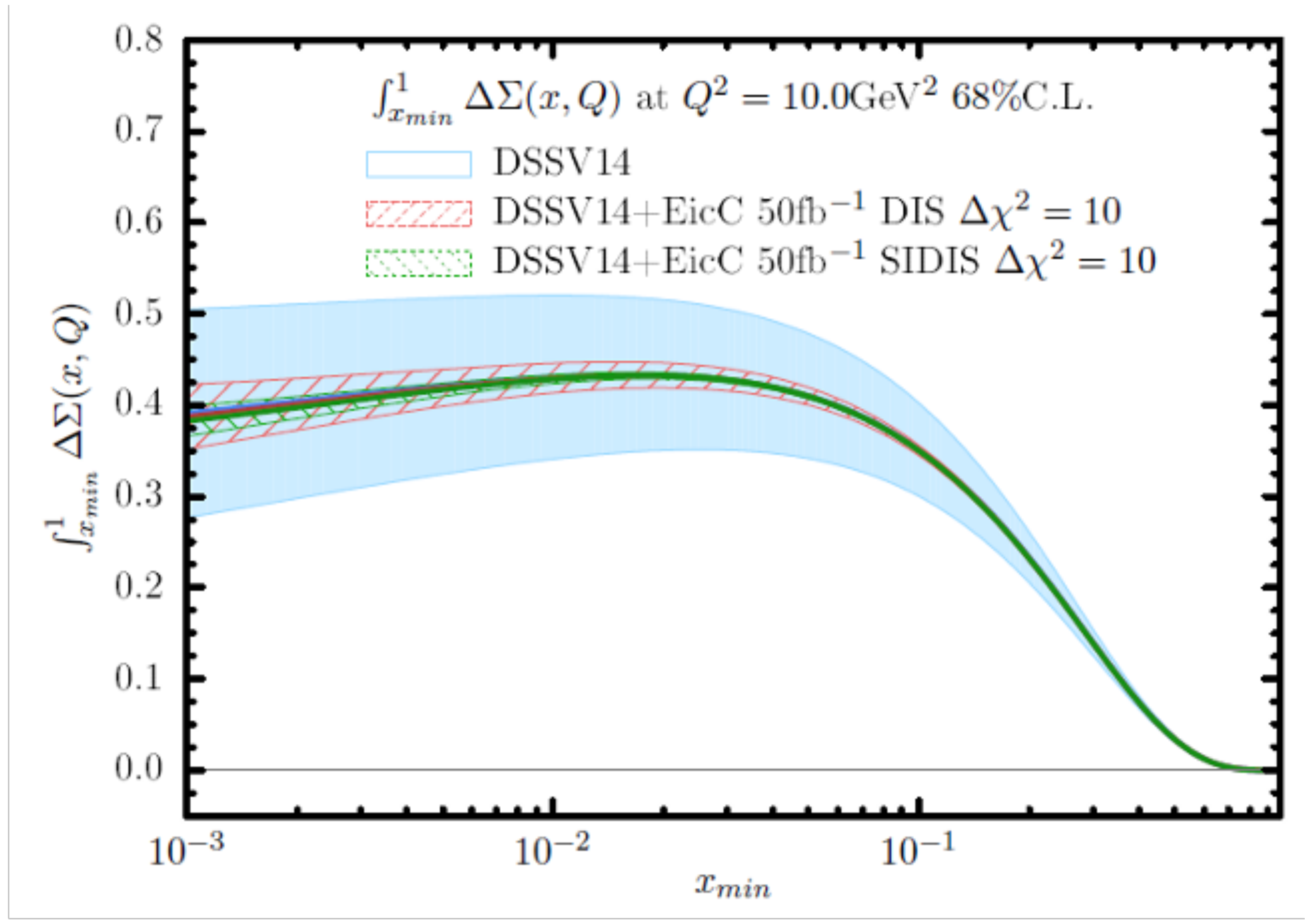


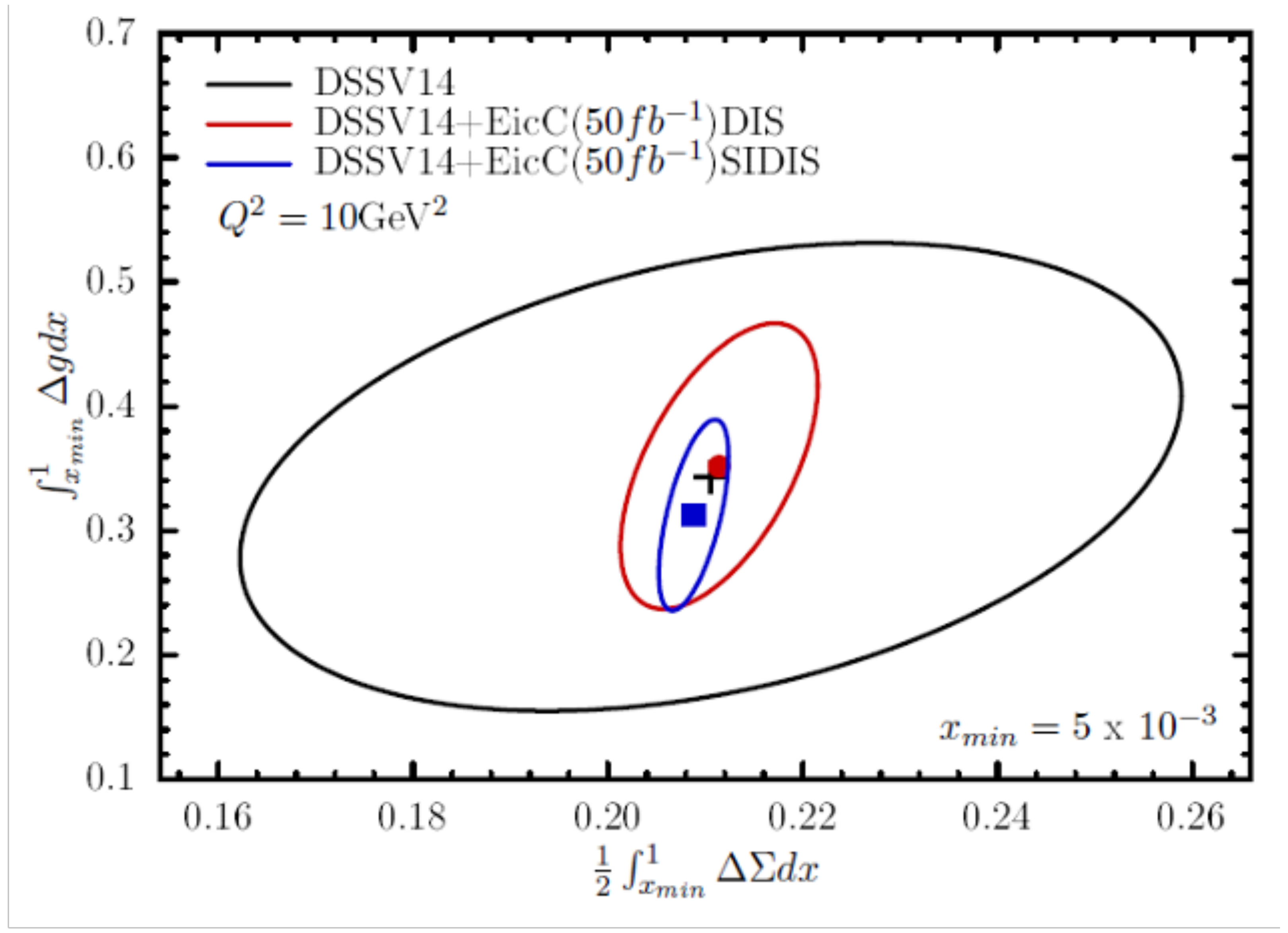
EIC Yellow Report

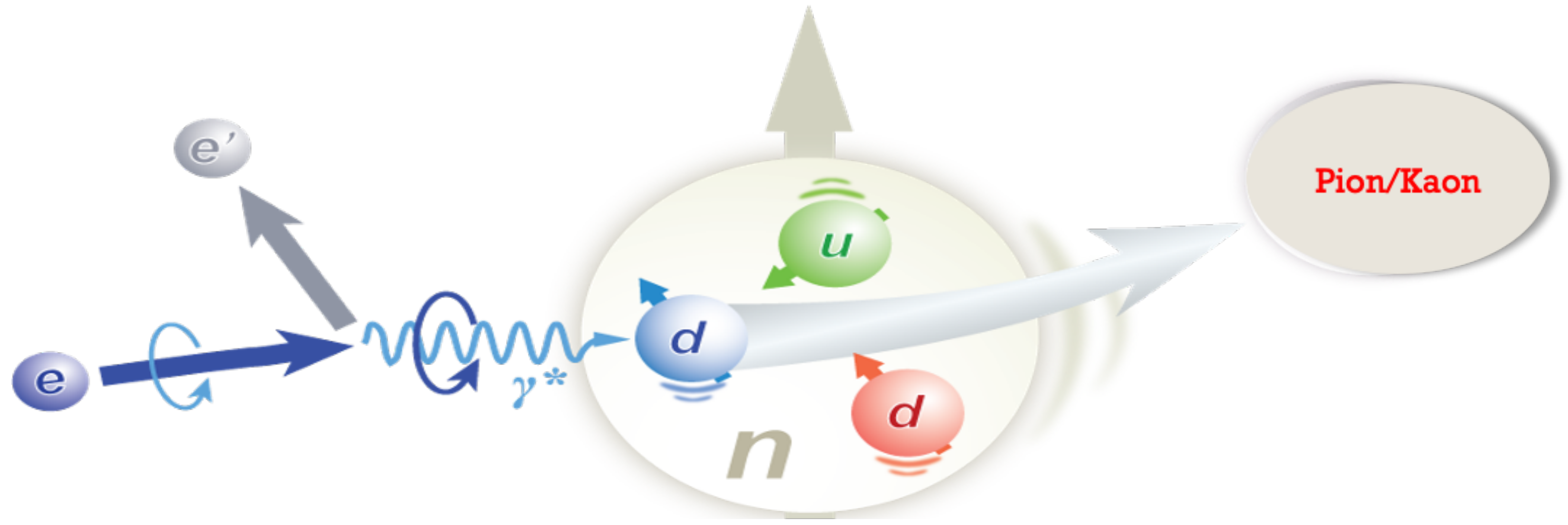
Pin down the proton spin in EIC&EicC

✦ Parton spin contribution to proton spin

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







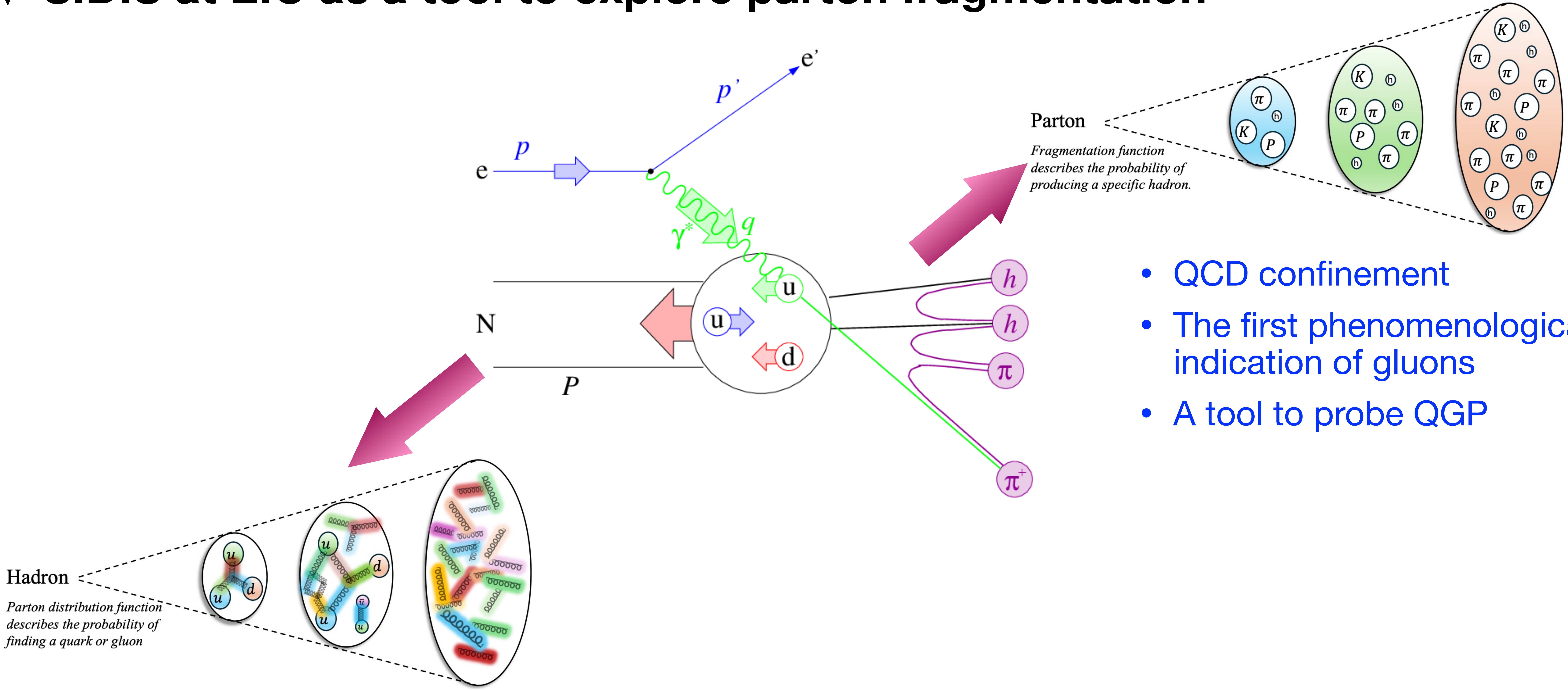
$$g_1^h(x,Q^2,z) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q(x,Q^2) D_q^h(z,Q^2) + \Delta\bar{q}(x,Q^2) D_{\bar{q}}^h(z,Q^2)\right]$$

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



- QCD confinement
- The first phenomenological indication of gluons
- A tool to probe QGP

FF global fitting panorama

✦ Joint efforts from experiments & theory in extracting FFs

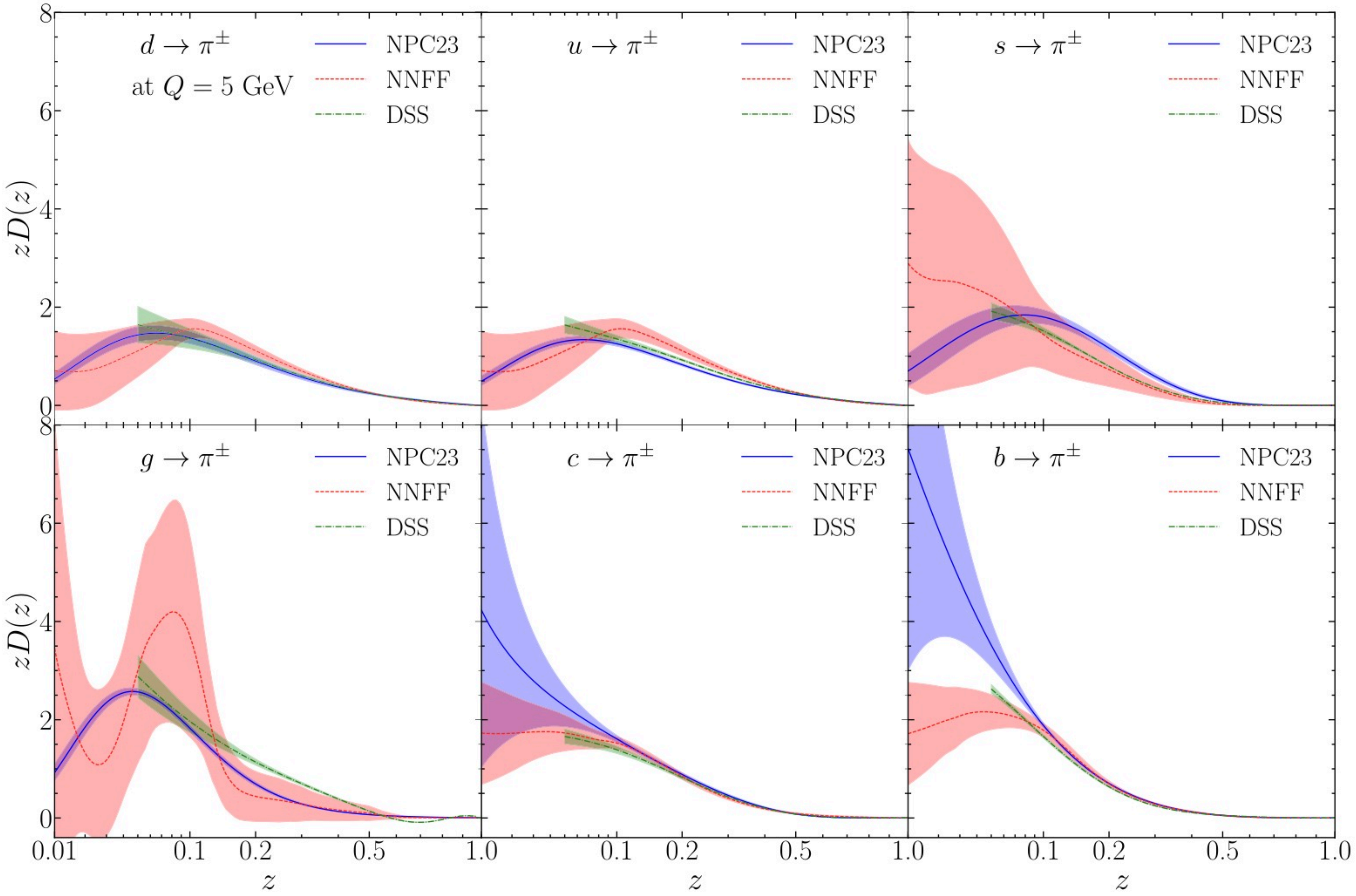
FFs Collab.	NPC	DSS	NNFF	JAM	HKNS	MAPFF
SIA	✔	✔	✔	✔	✔	✔
SIDIS	✔	✔	✘	✘	✘	✔
pp incl. hadron	✔	✔	✘	✘	✘	✘
pp hadron in jet	✔	✘	✘	✘	✘	✘
stat. treatment	Hessian	Hessian	Monte Carlo	Monte Carlo	Hessian	Monte Carlo
parametrization	standard	standard	neural network	standard	standard	neural network
hadron species	$\pi^\pm, K^\pm, p/\bar{p}$ 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)*

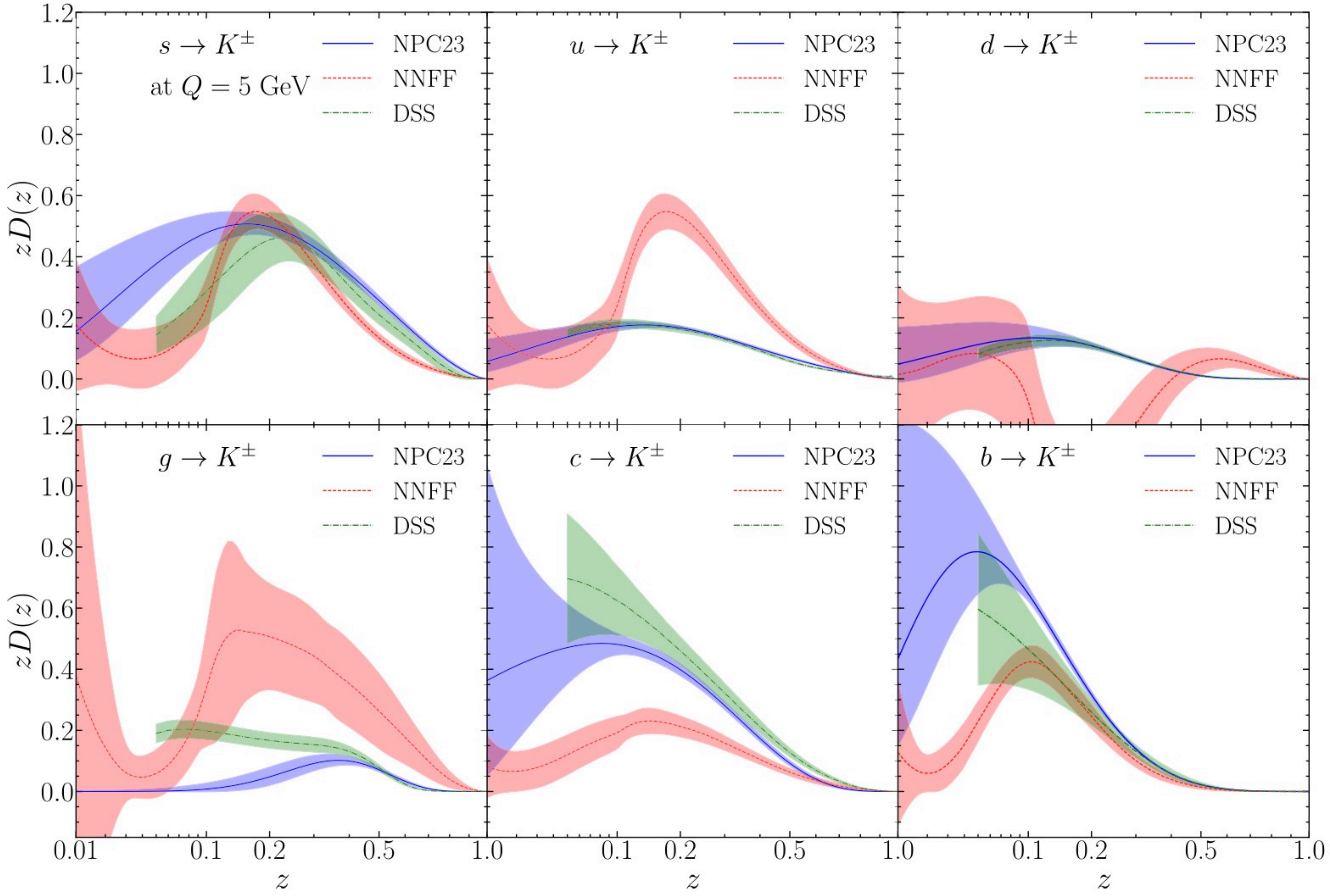
NPC: the most precise and complete FFs to date!

New efforts from NPC（SJTU & SCNU & IMP）

✦ **NPC23 vs. others**

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





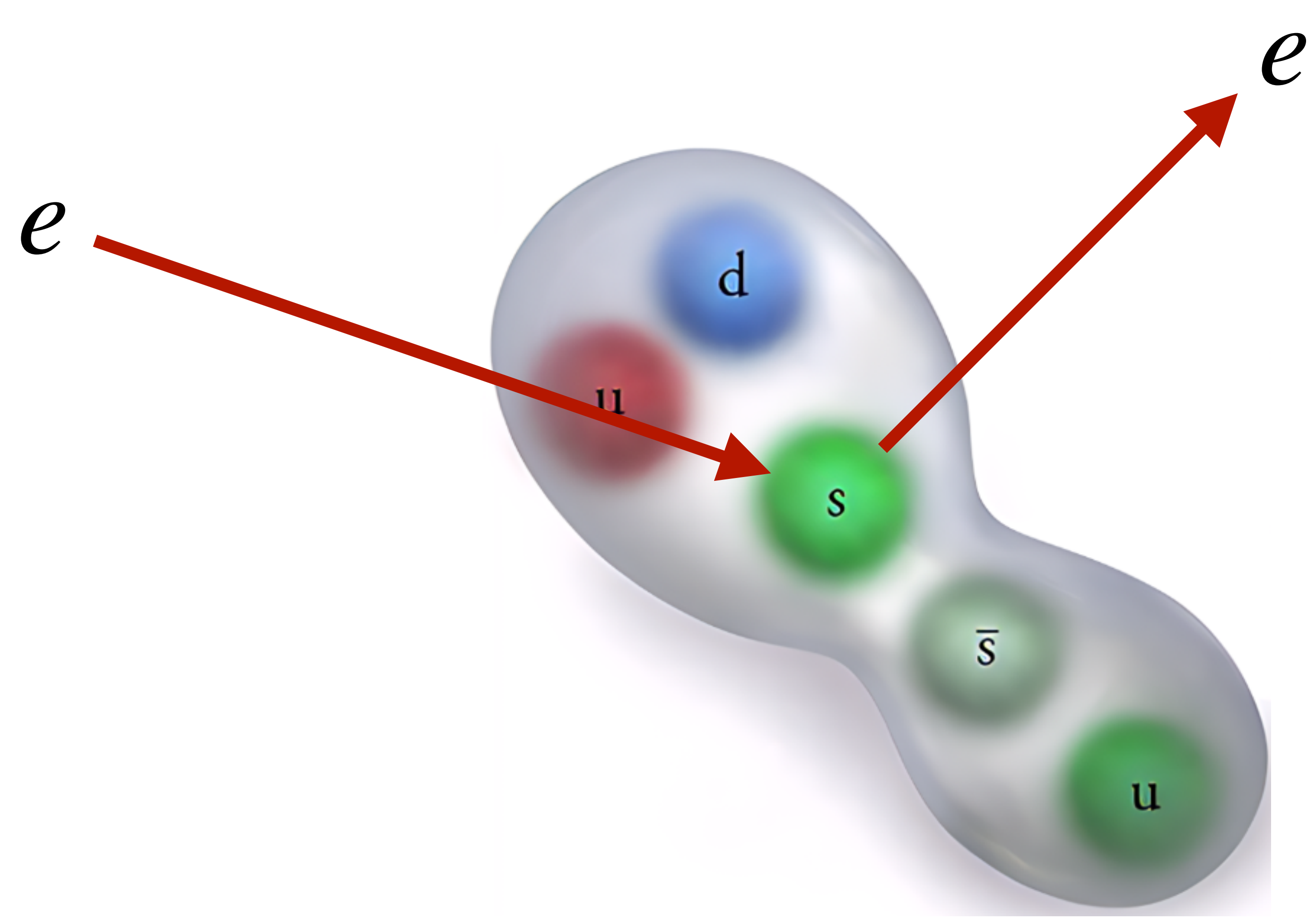
126 Hessian error FFs are all available in LHAPDF

- 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

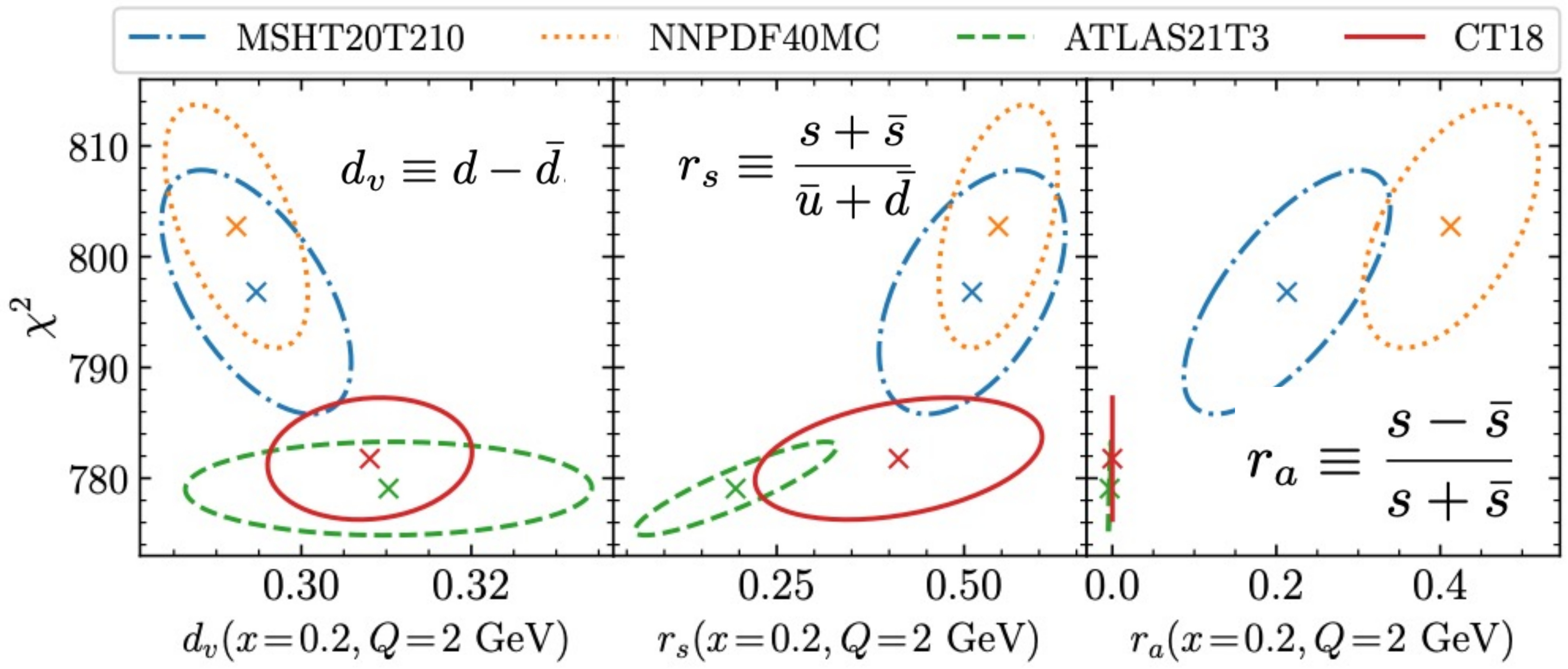
Gao, Shen, **HX**, Zhao, Zhou, arXiv:2502.17837



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

The puzzle of strange quark asymmetry:

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



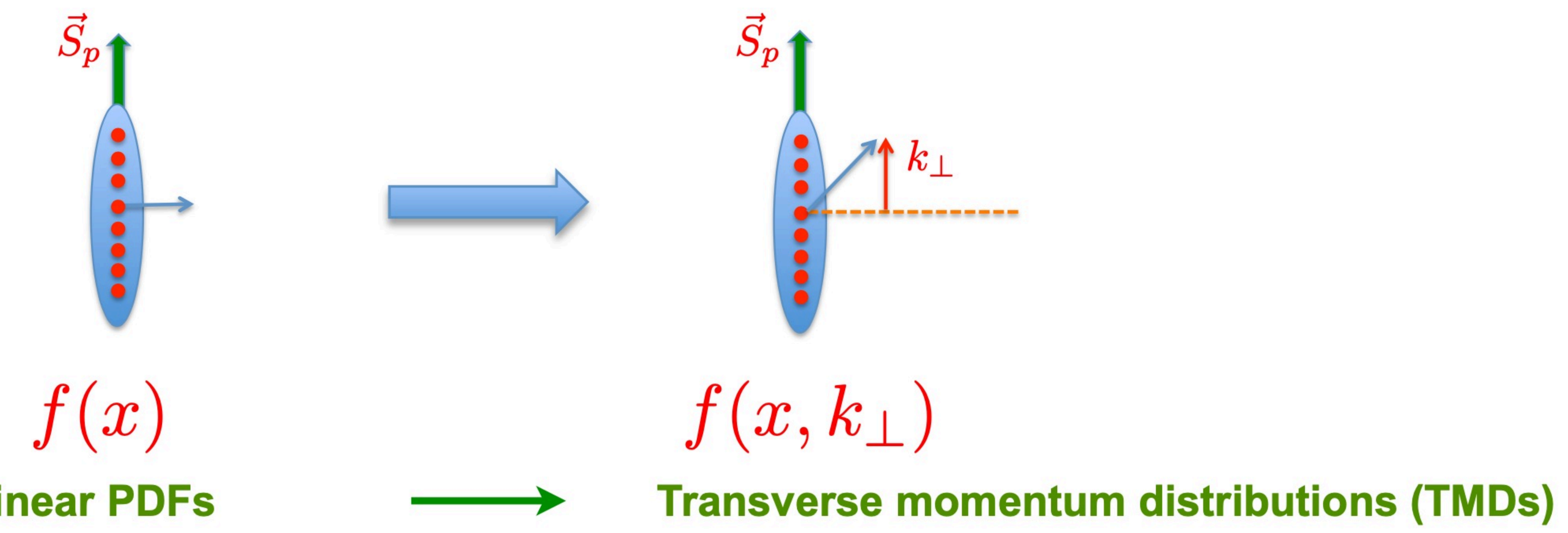
	$d_v(x=0.2, Q=2\text{GeV})$	$r_s(x=0.2, Q=2\text{GeV})$	$r_a(x=0.2, Q=2\text{GeV})$
NNPDF4.0	0.2924 ± 0.0084	0.547 ± 0.079	0.408 ± 0.107
NNPDF4.0(reweighting)	0.3021 ± 0.0069	0.438 ± 0.066	0.281 ± 0.086
MSHT20	0.295 ± 0.011	0.511 ± 0.124	0.213 ± 0.126
MSHT20(profiling)	0.298 ± 0.011	0.481 ± 0.121	0.167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

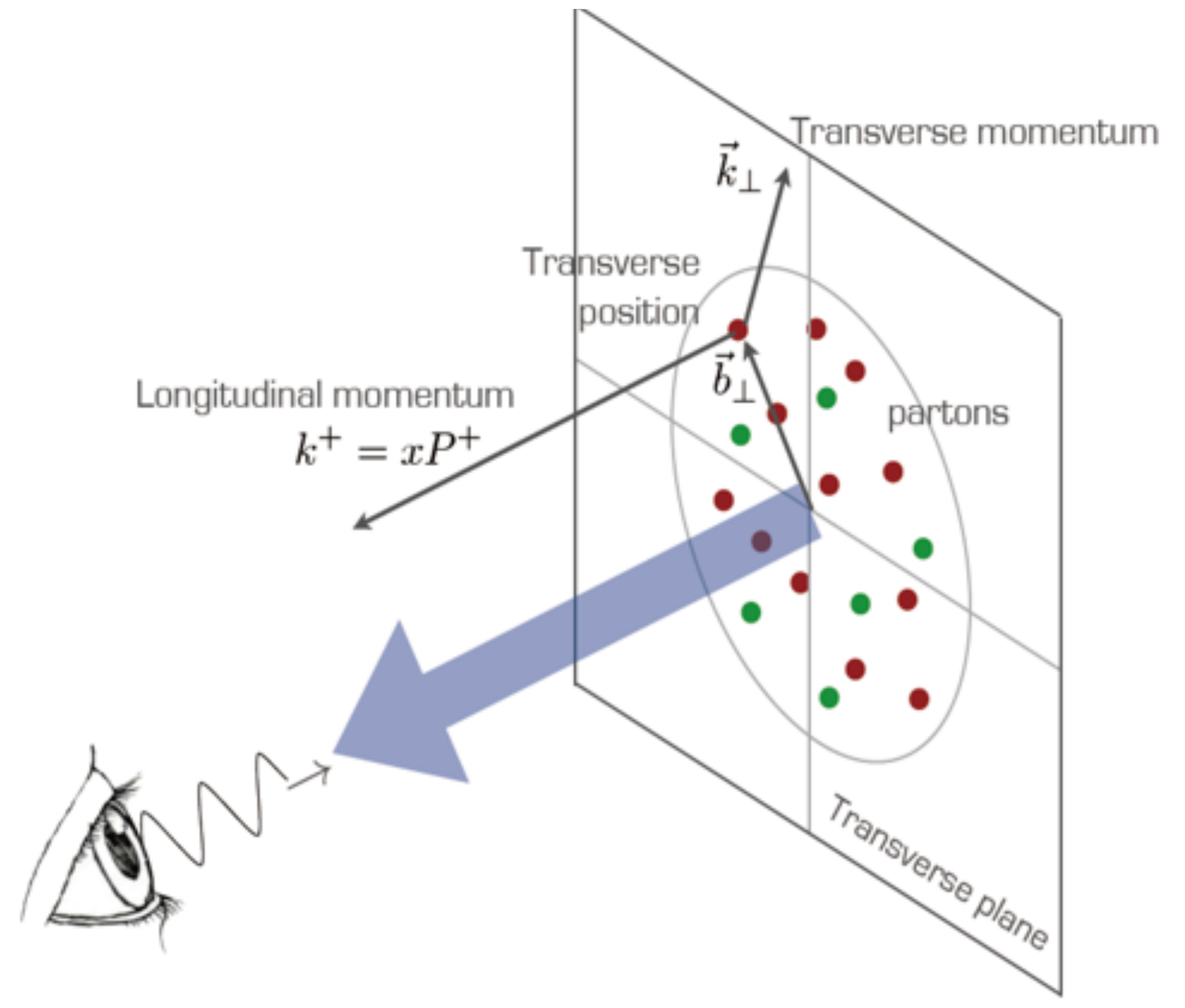
- The impact of NPC FFs on the state-of-the-art PDFs at NNLO
- Preference of reduced asymmetry in the strange quark PDFs

Nucleon partonic structure - 3D imaging

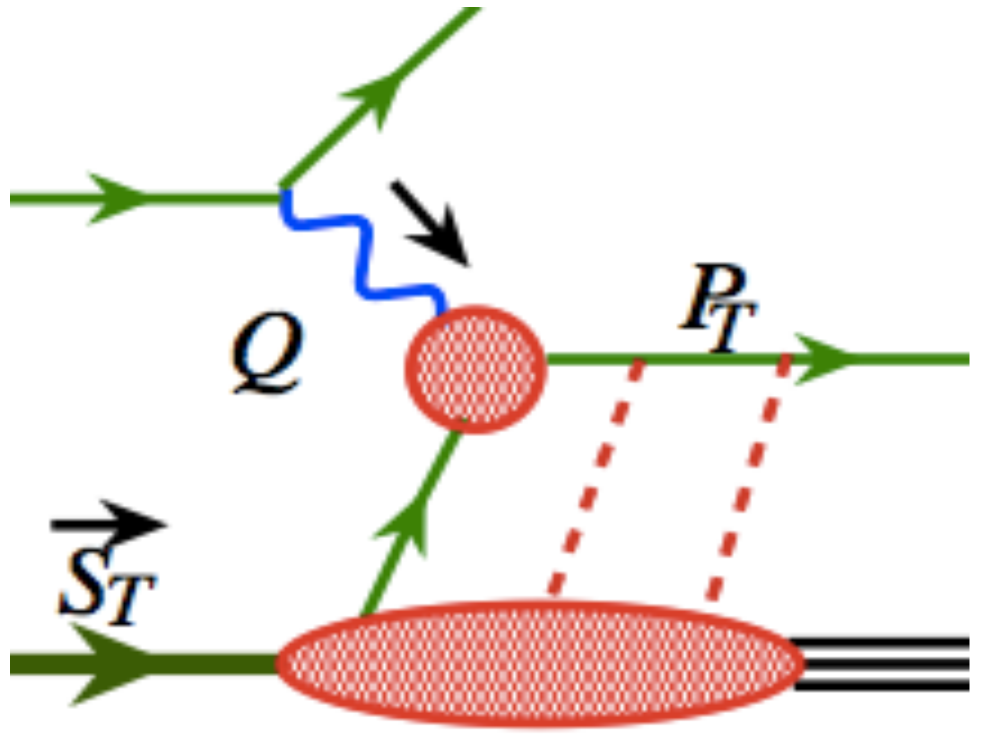
Nucleon partonic structure - 3D imaging

✦ Transverse momentum dependent PDFs (TMDs)





- 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

Nucleon partonic structure - 3D imaging

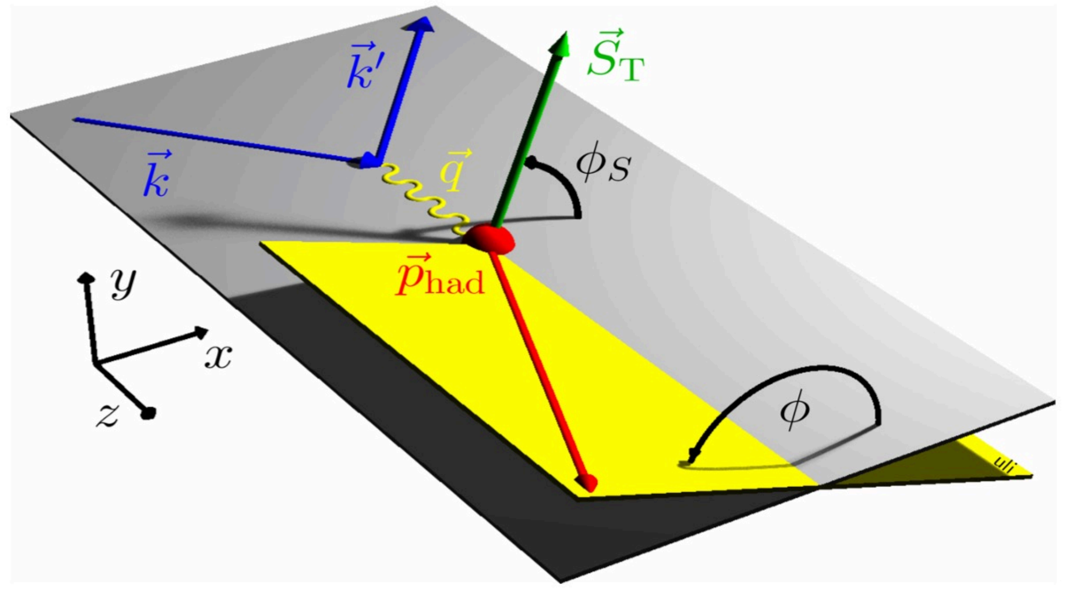
TMDs: explore the flavor-spin-motion correlation

Nucleon Polarization		Quark Polarization		
		Unpolarized	Longitudinally pol.	Transversely pol.
	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**

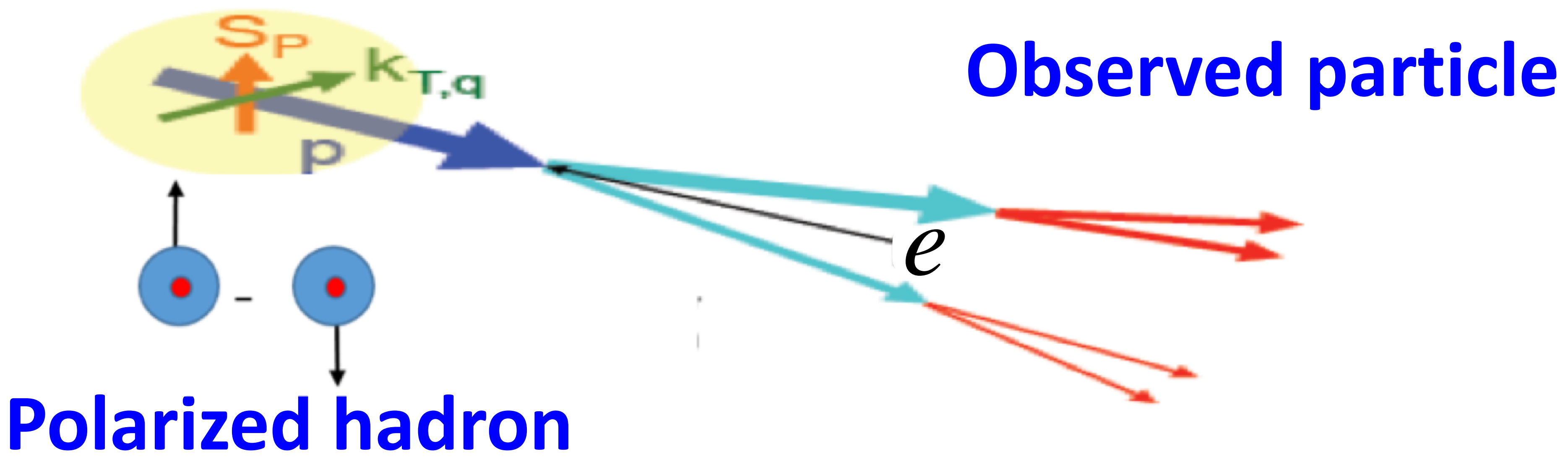
Nucleon partonic structure - 3D imaging

✦ SSA: transverse polarized proton + unpolarized electron

$$A_{UT}(\phi_h,\phi_s)=\frac{1}{S_T}\frac{d\sigma(\phi_h,\phi_s)-d\sigma(\phi_h,\phi_s+\pi)}{d\sigma(\phi_h,\phi_s)+d\sigma(\phi_h,\phi_s+\pi)}$$
$$=A_{UT}^{Collins}\sin(\phi_h+\phi_s)+A_{UT}^{Sivers}\sin(\phi_h-\phi_s)+A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_s)$$



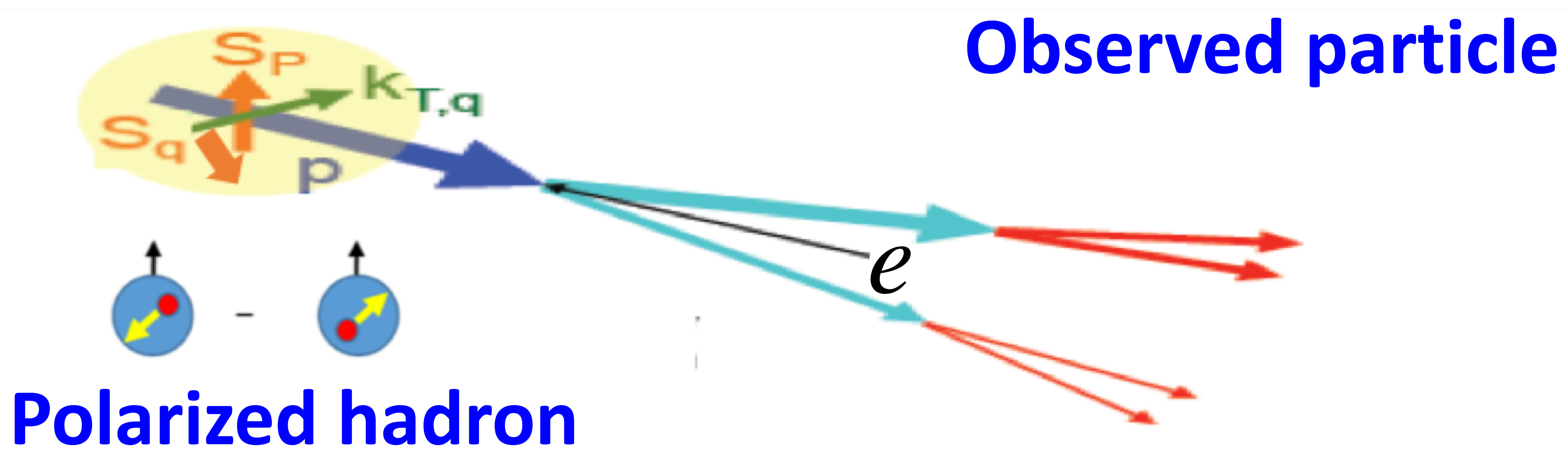
✦ Quantum correlation between proton spin and parton motion



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

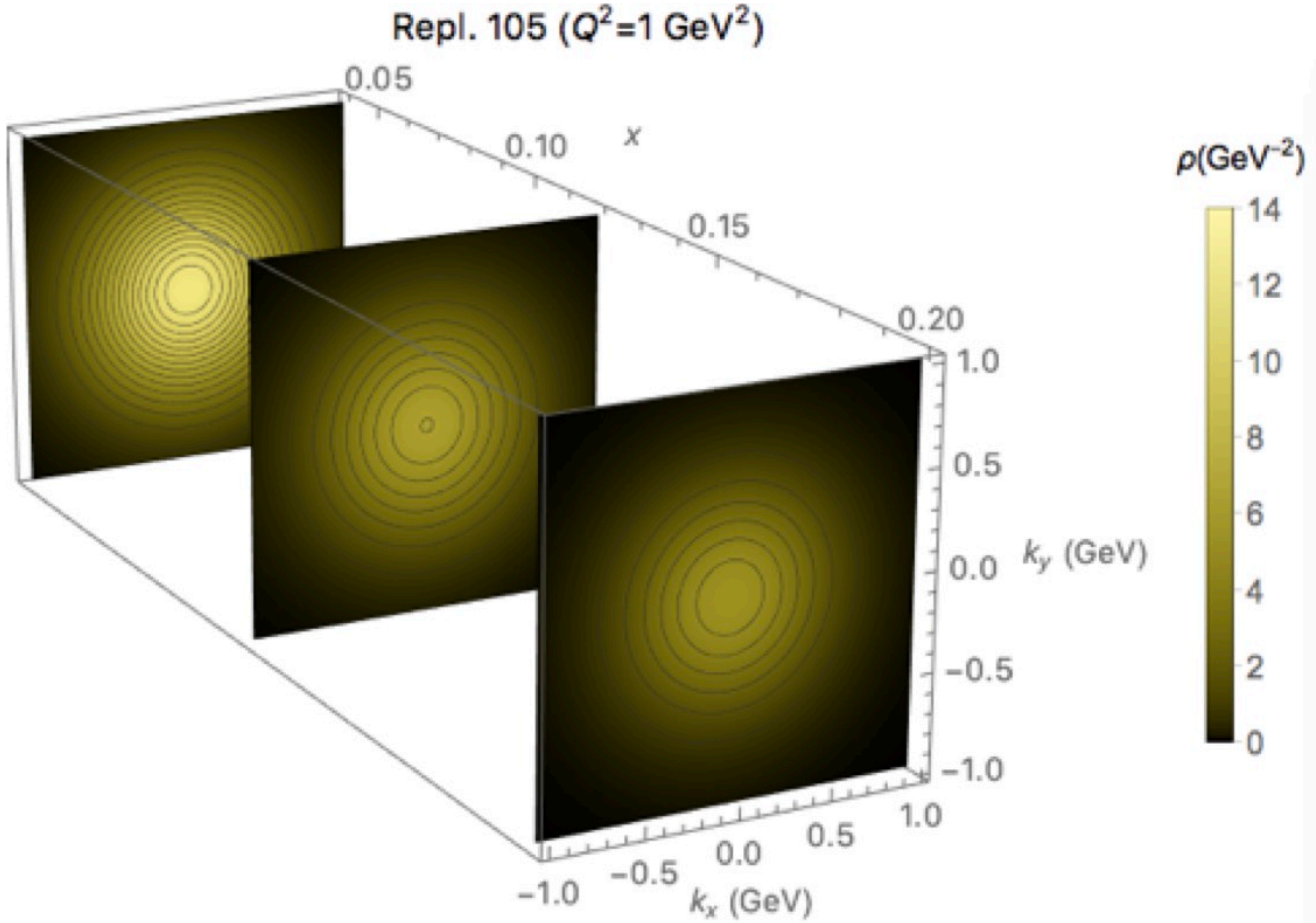


Pretzelosity function $h_{1T}^{\perp}$: proton spin and parton spin influence parton's transverse motion

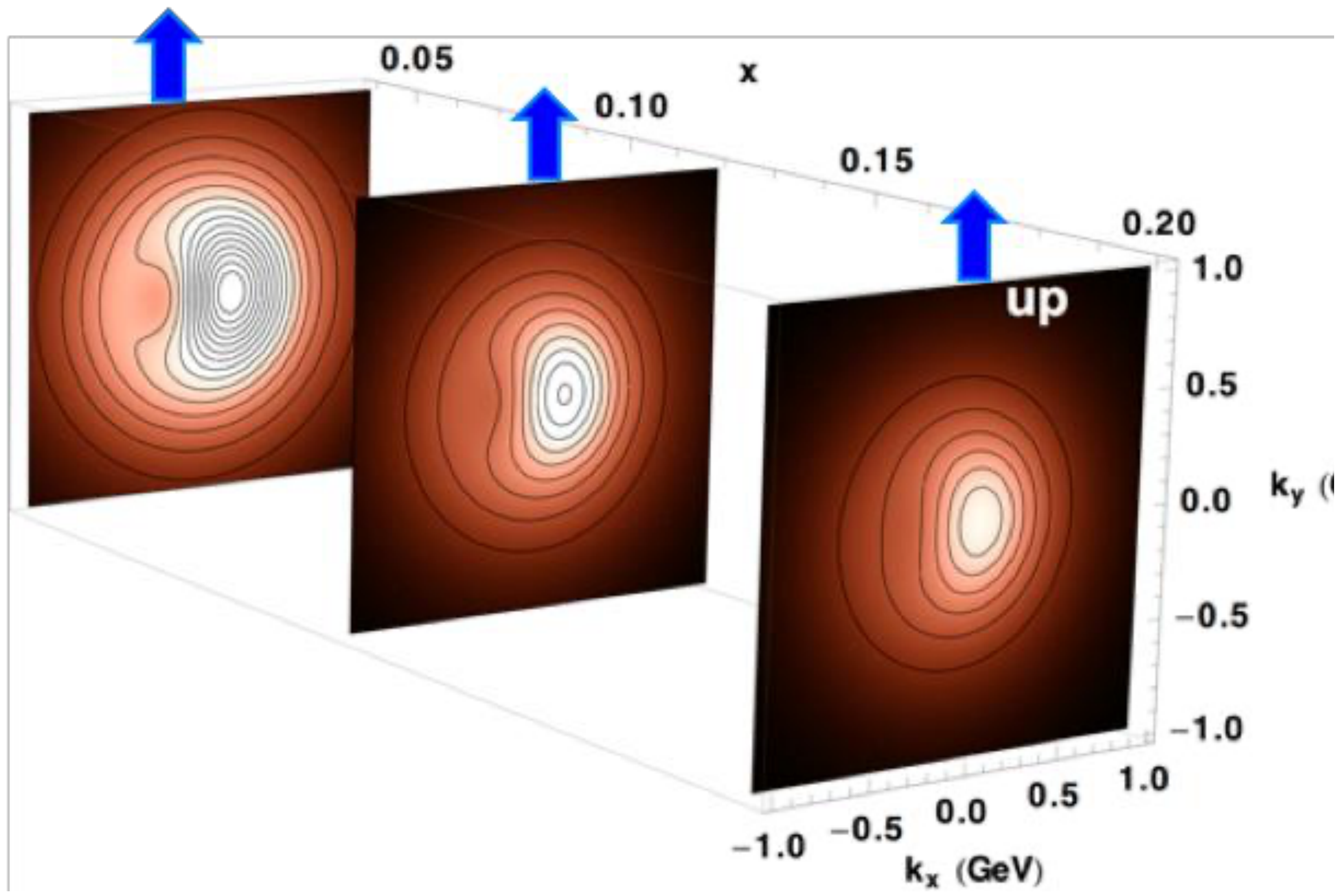
$$A_{UT}^{Pretzelosity}\propto\left\langle\sin(3\phi_h-\phi_S)\right\rangle_{UT}\propto h_{1T}^{\perp}\otimes H_1^{\perp}$$

Nucleon partonic structure - 3D imaging

Unpolarized proton



Transversely polarized proton

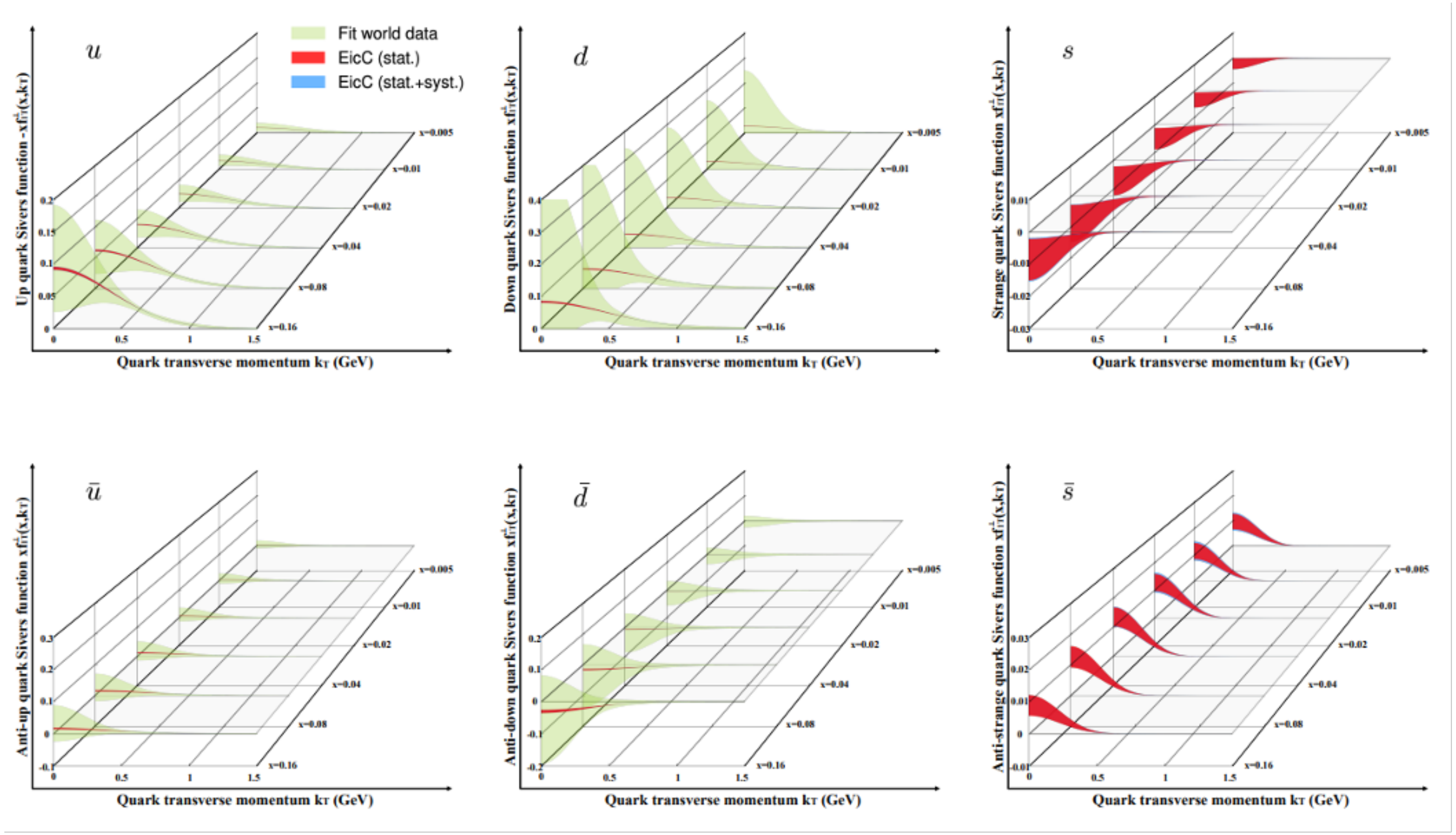


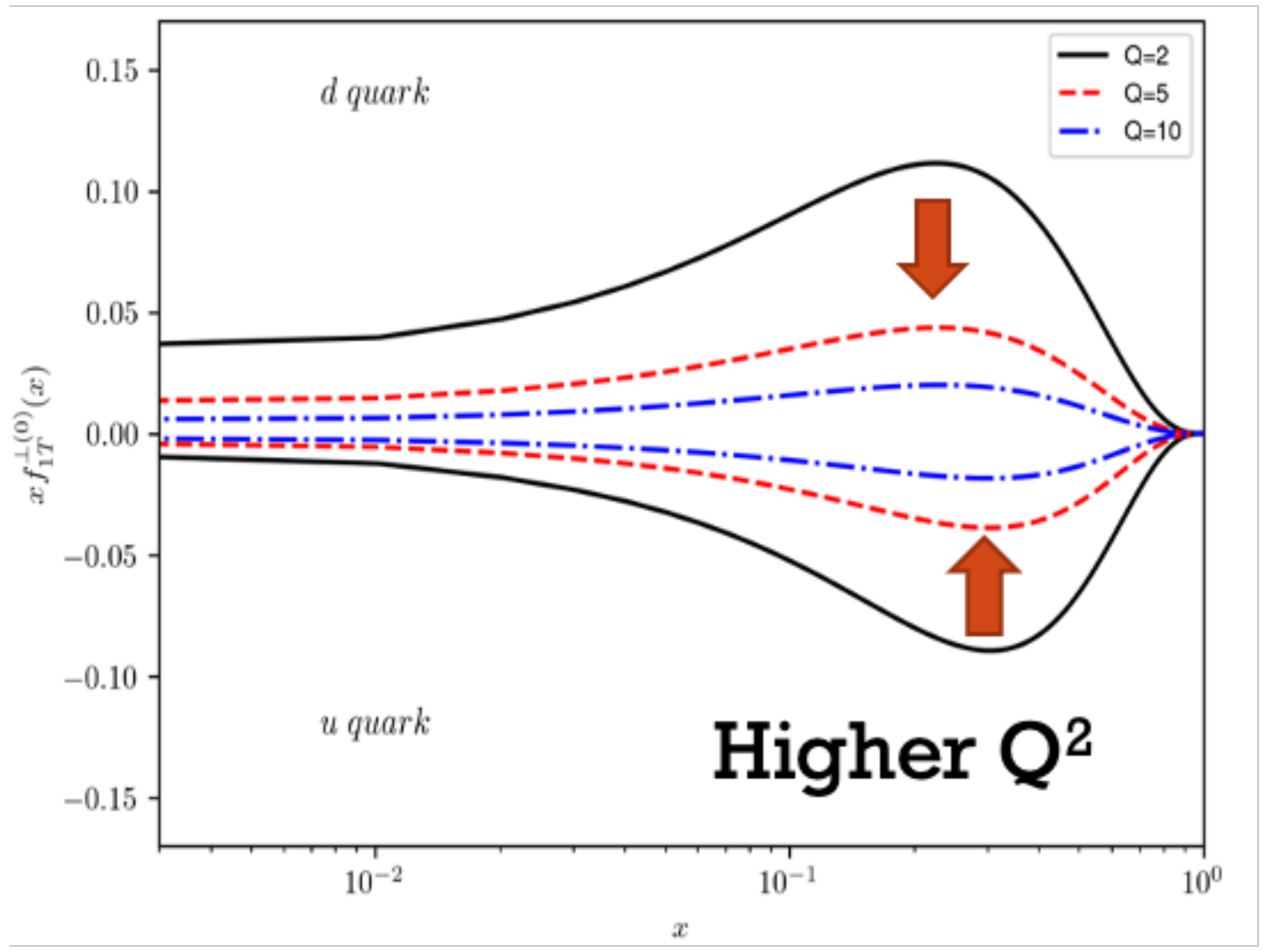
By Andrea Signori

Transversely polarized quark distribution is distorted!

Nucleon 3D imaging at EicC - Sivers effect

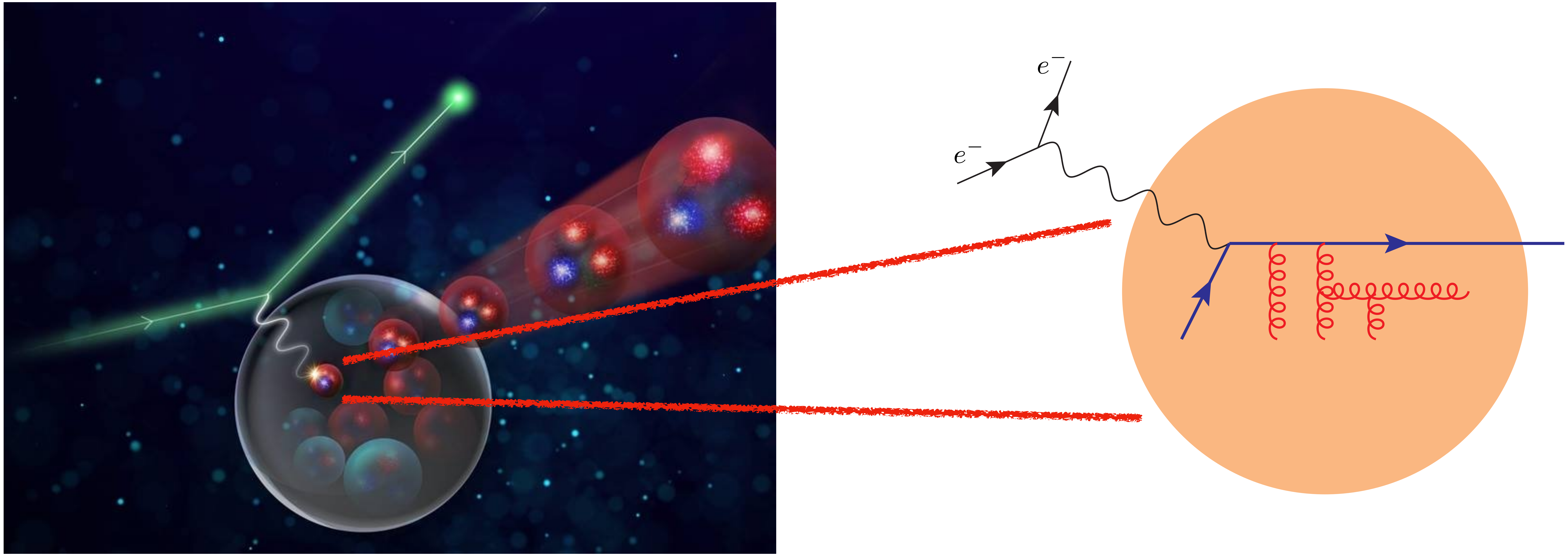
Zeng, Liu, Sun, Zhao, PRD, 2023





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

What if the nucleon is bounded in nucleus?



Initial state

Nuclear partonic structure

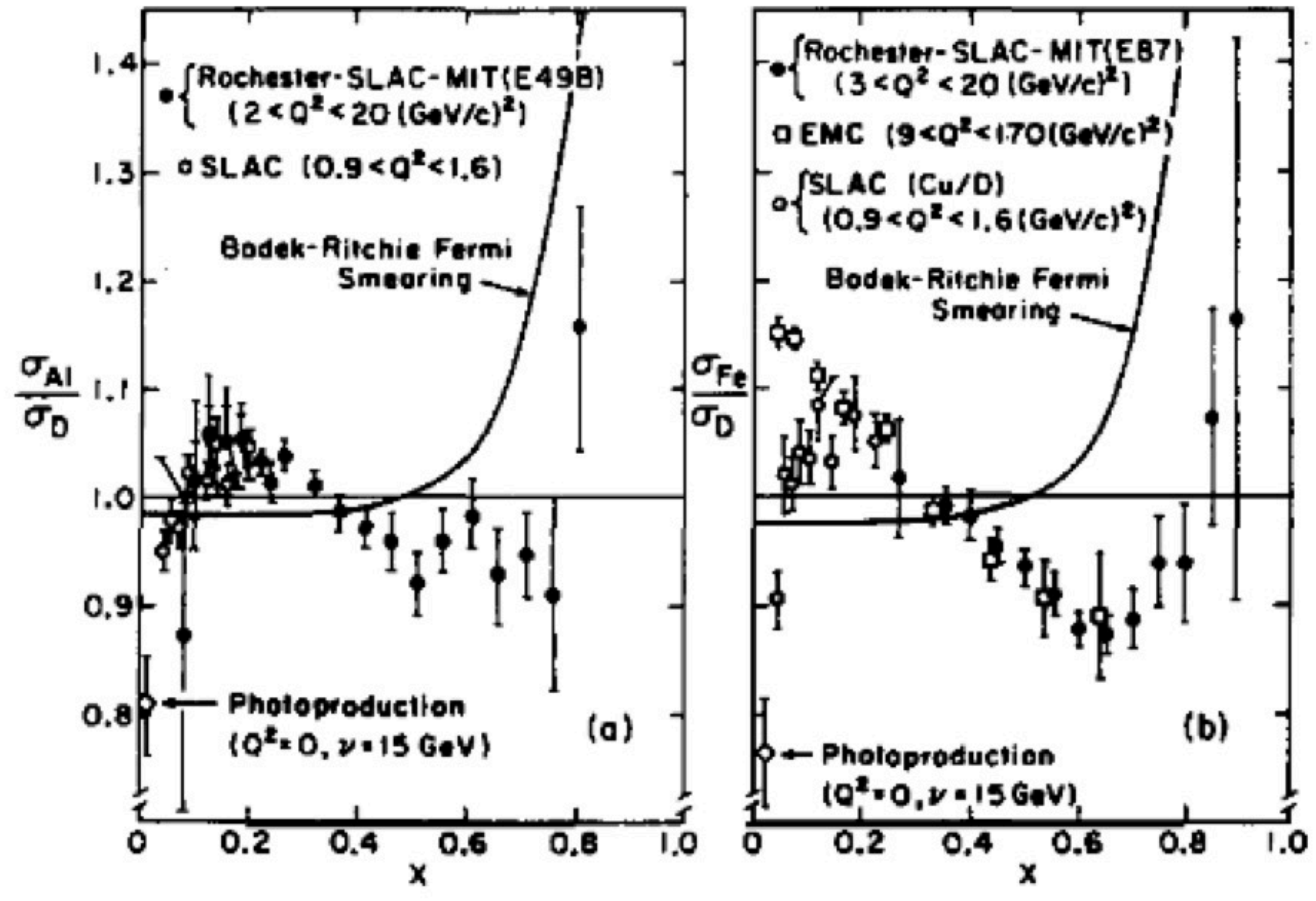
Final state

Parton propagating in nuclear medium

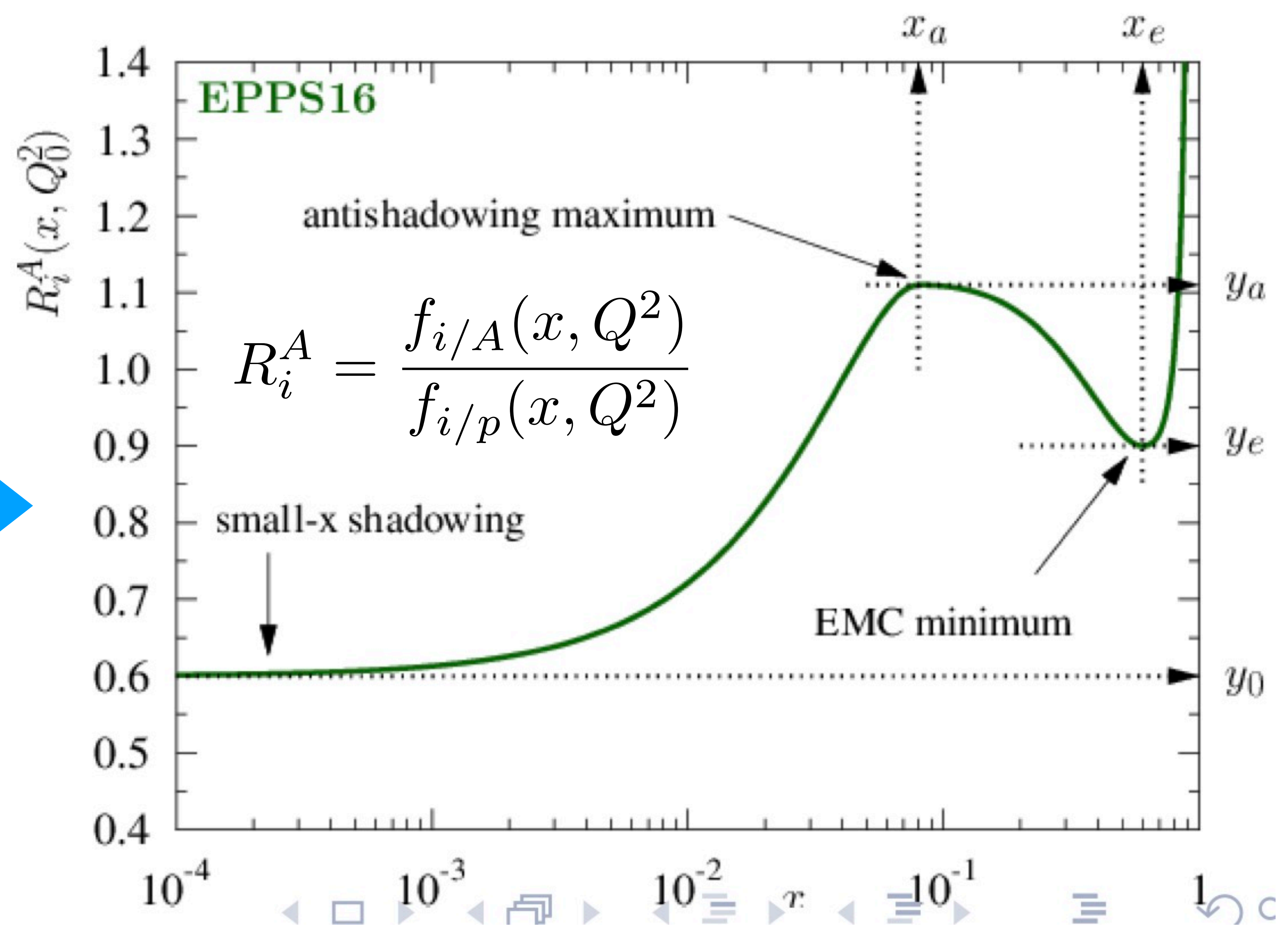
Two mechanisms leading to nontrivial nuclear effects

- One-dimensional nuclear partonic structure

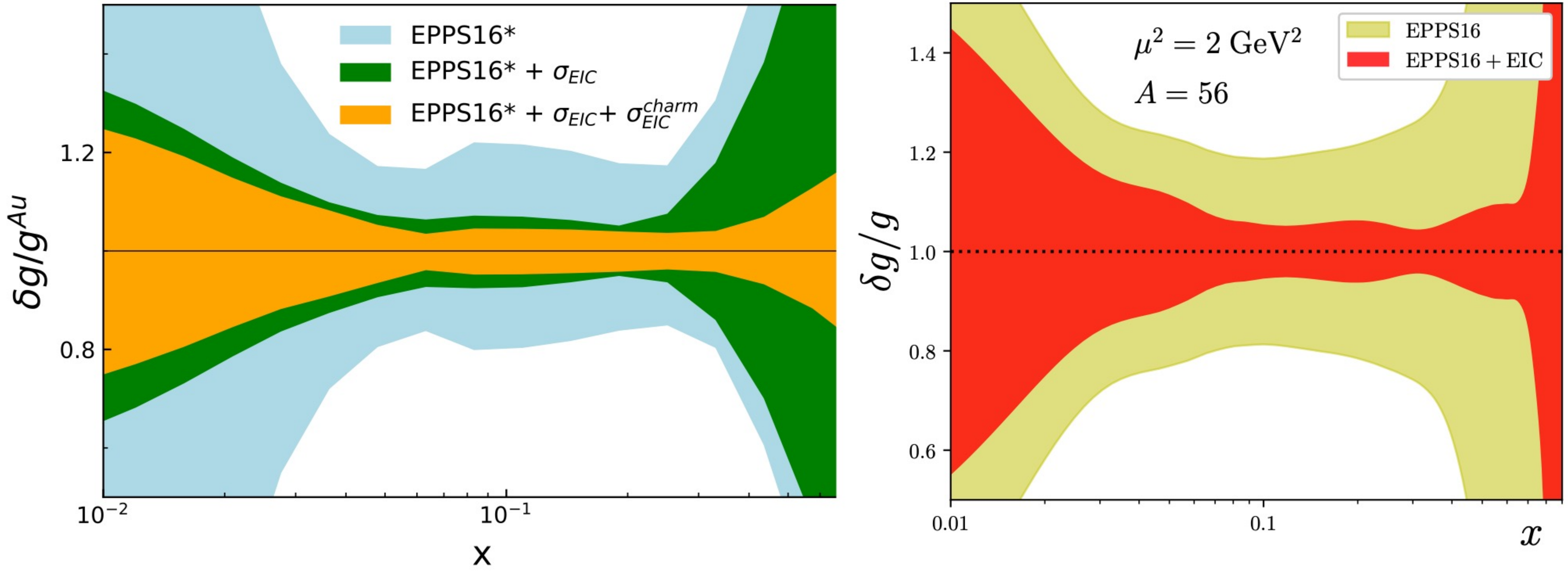
Four Decades of the EMC Effect



EMC Collaboration, 1983



- One-dimensional nuclear partonic structure - impact of EIC

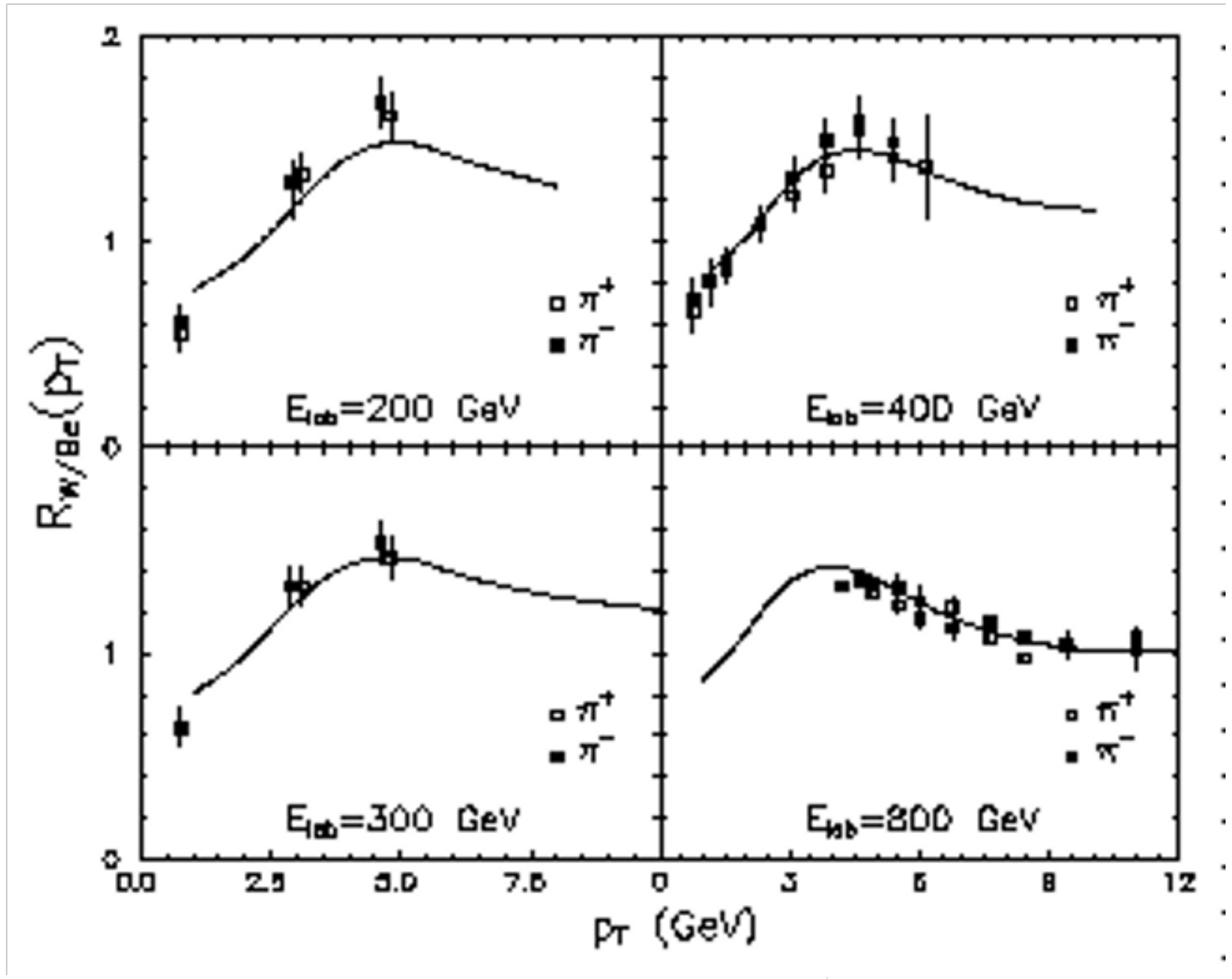


EIC Yellow Report

“Old” and long standing problems of nuclear partonic structure

- Three-dimensional nuclear partonic structure

Cronin effect （50 years）

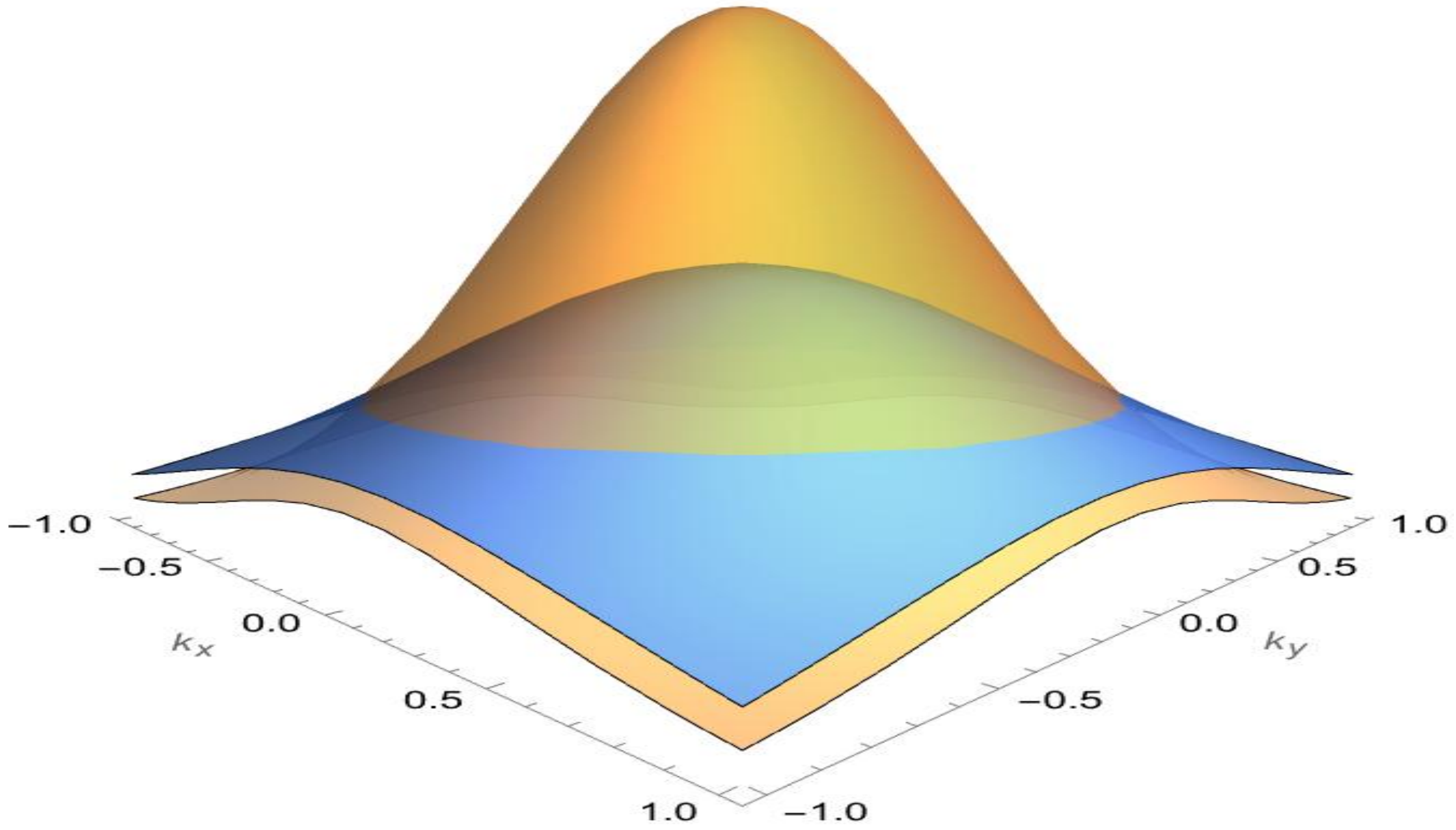


$$p + A \to \text{hadron(p)} + X \qquad R(p_T) = \frac{B}{A}\frac{d\sigma_{pA}/d^2p_T}{d\sigma_{pB}/d^2p_T}$$

E100 Collaboration, PRD 11, 3105（1975）

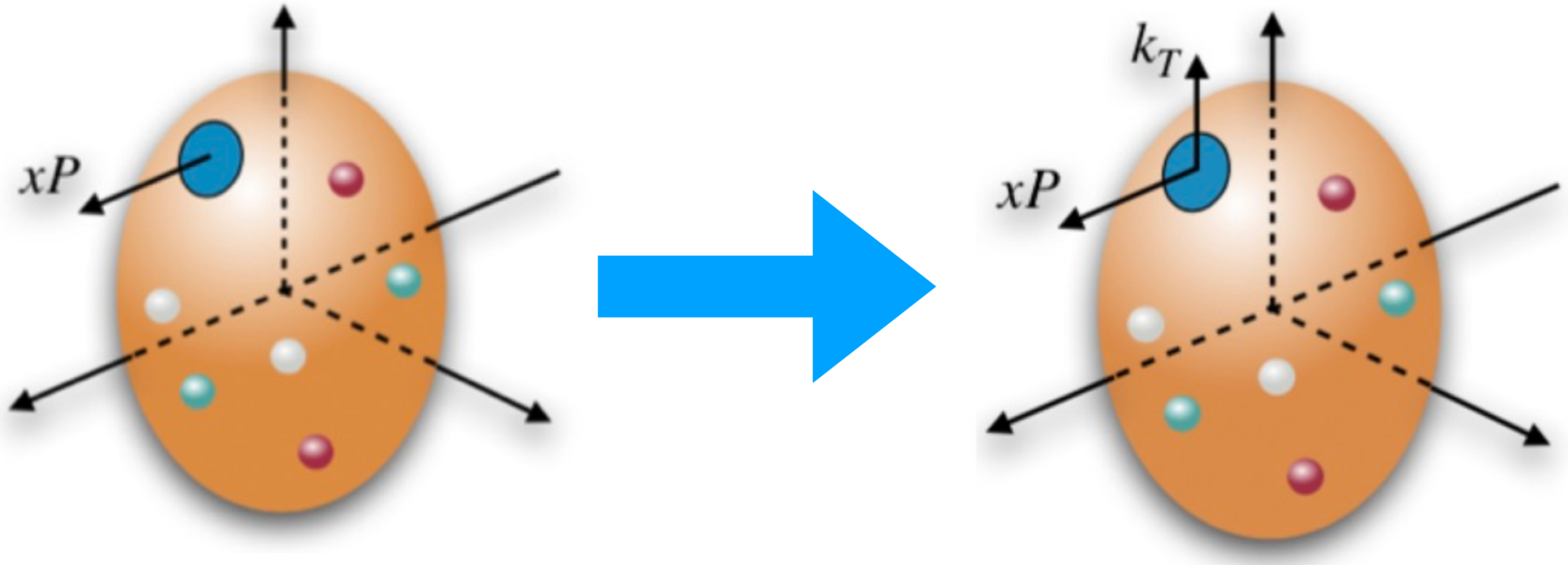
- Naive Gaussian model

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



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

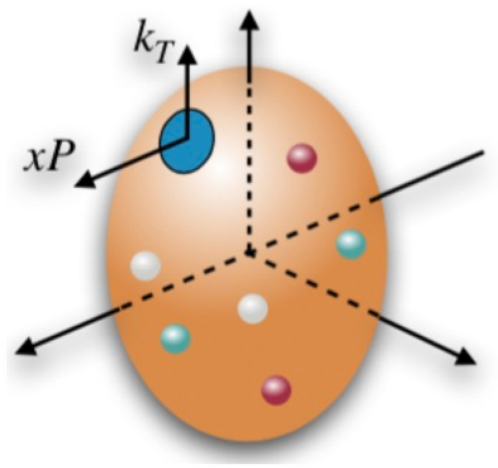
- TMD factorization in nuclear medium

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

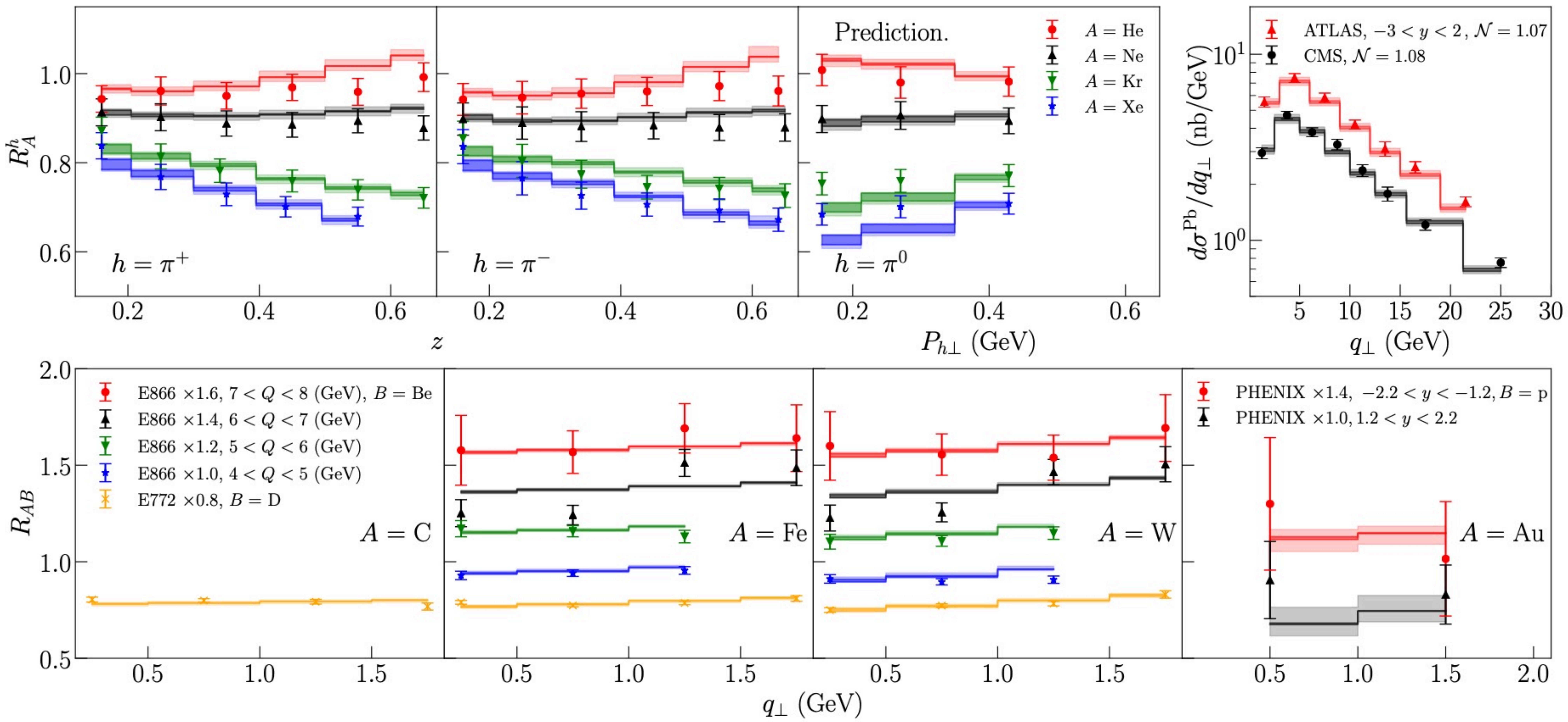
$$f_{q/n}^A(x,b;Q) = \left[C_{q\leftarrow i}\otimes f_{i/n}^A\right](x,\mu_{b_*})\exp\left\{-S_{\text{pert}}(\mu_{b_*},Q) - S_{\text{NP}}^f(b,Q,A)\right\}$$

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

nuclear 3D imaging - global extraction from world data



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

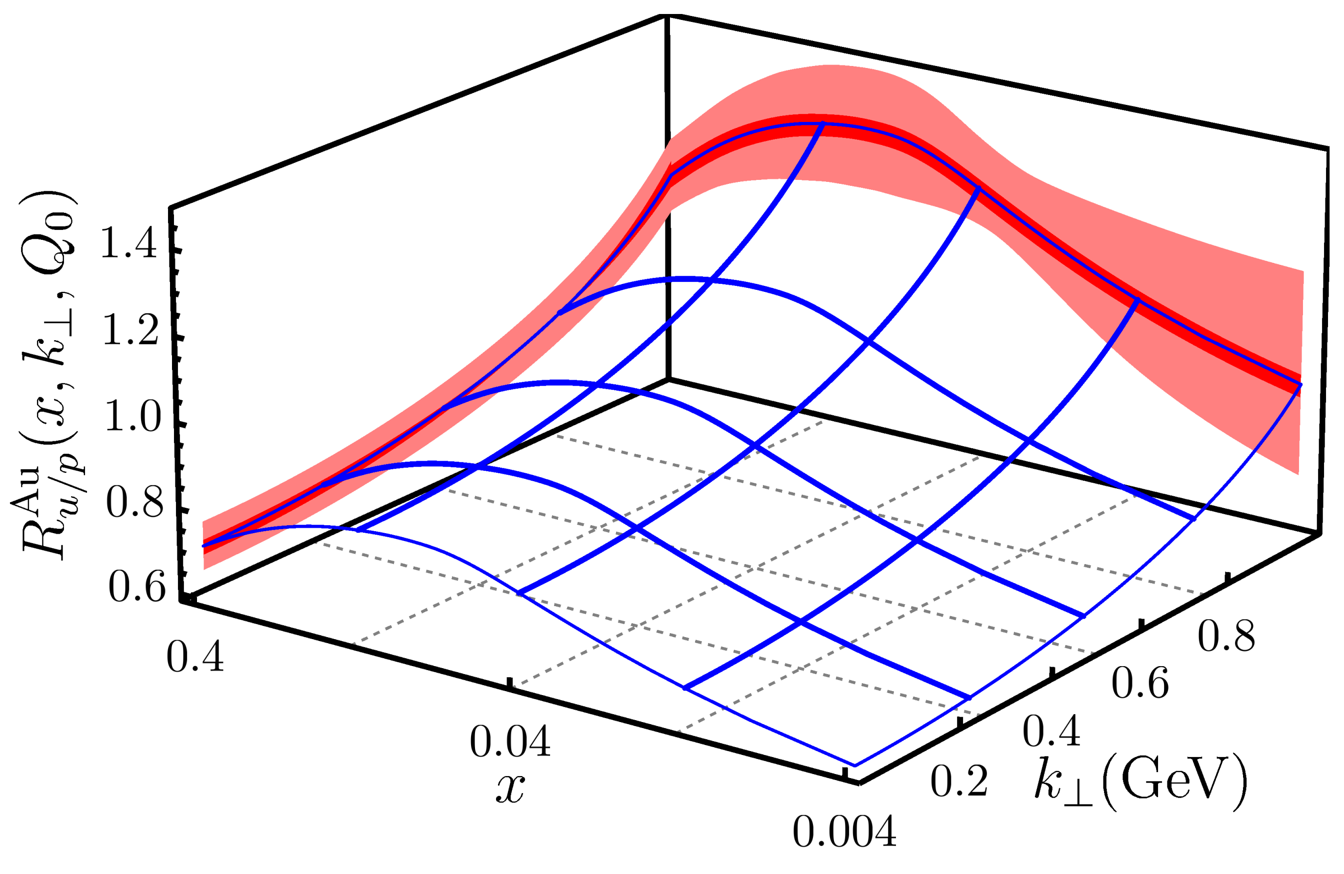


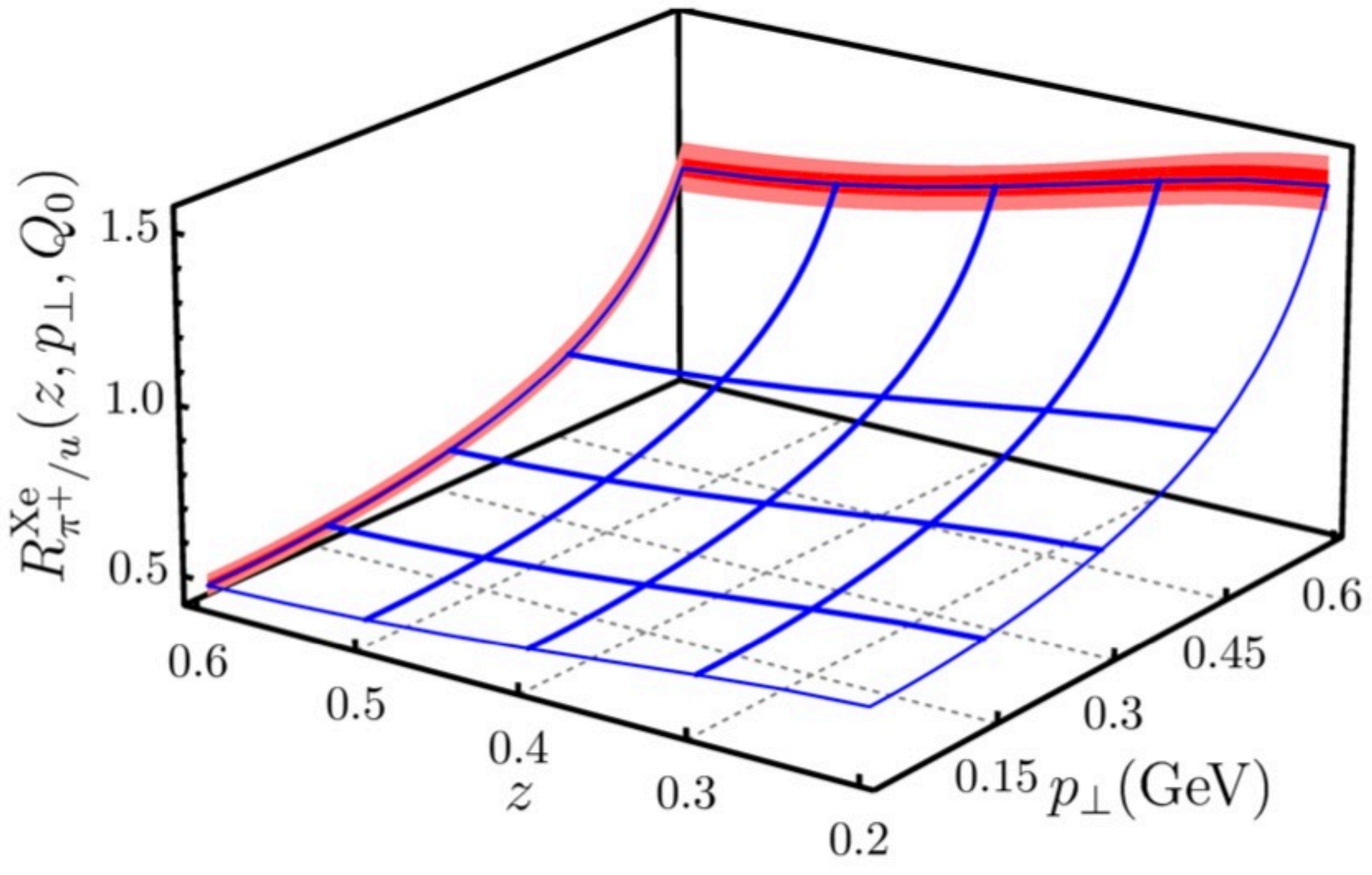
Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

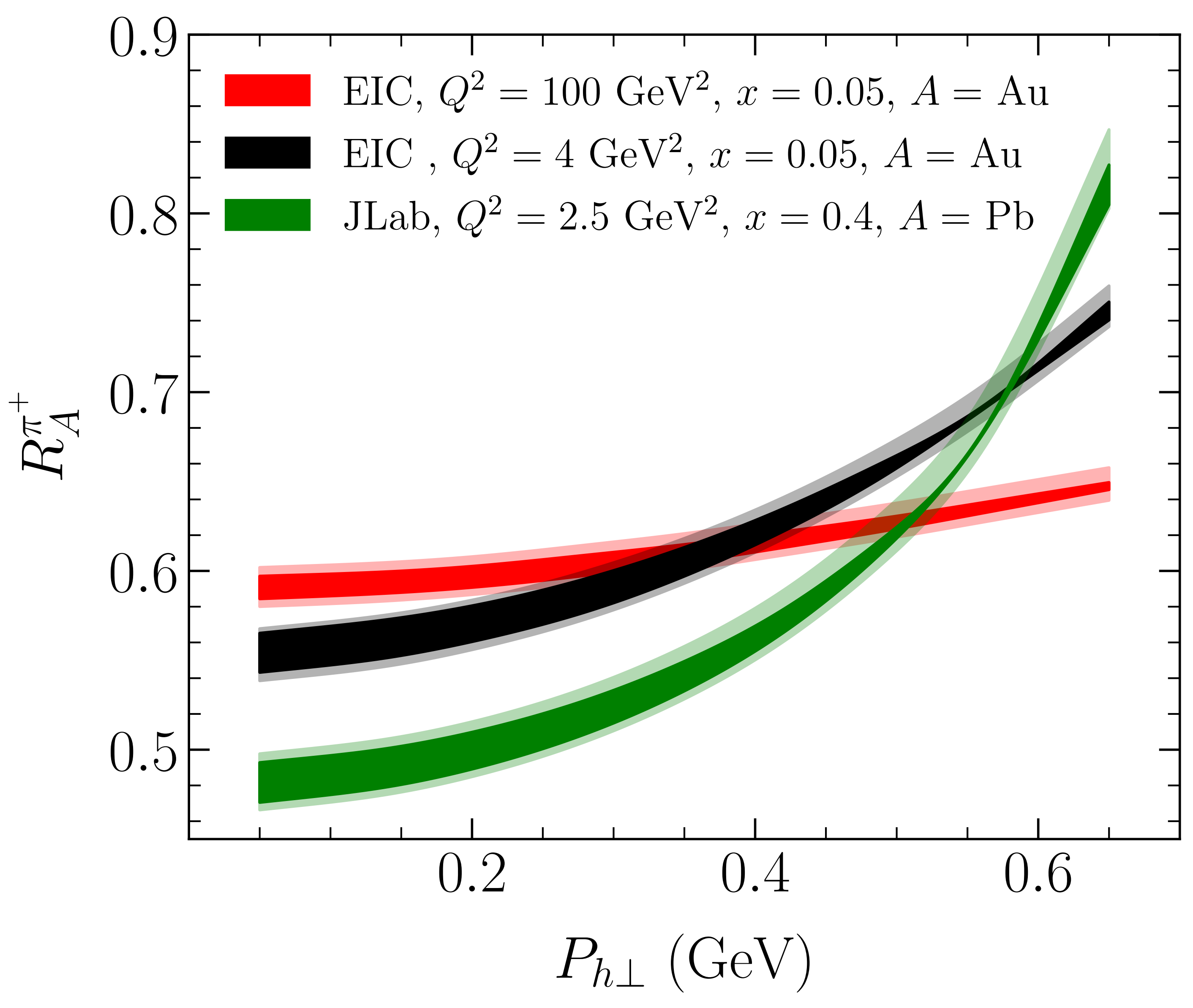
Three-dimension imaging in nuclei

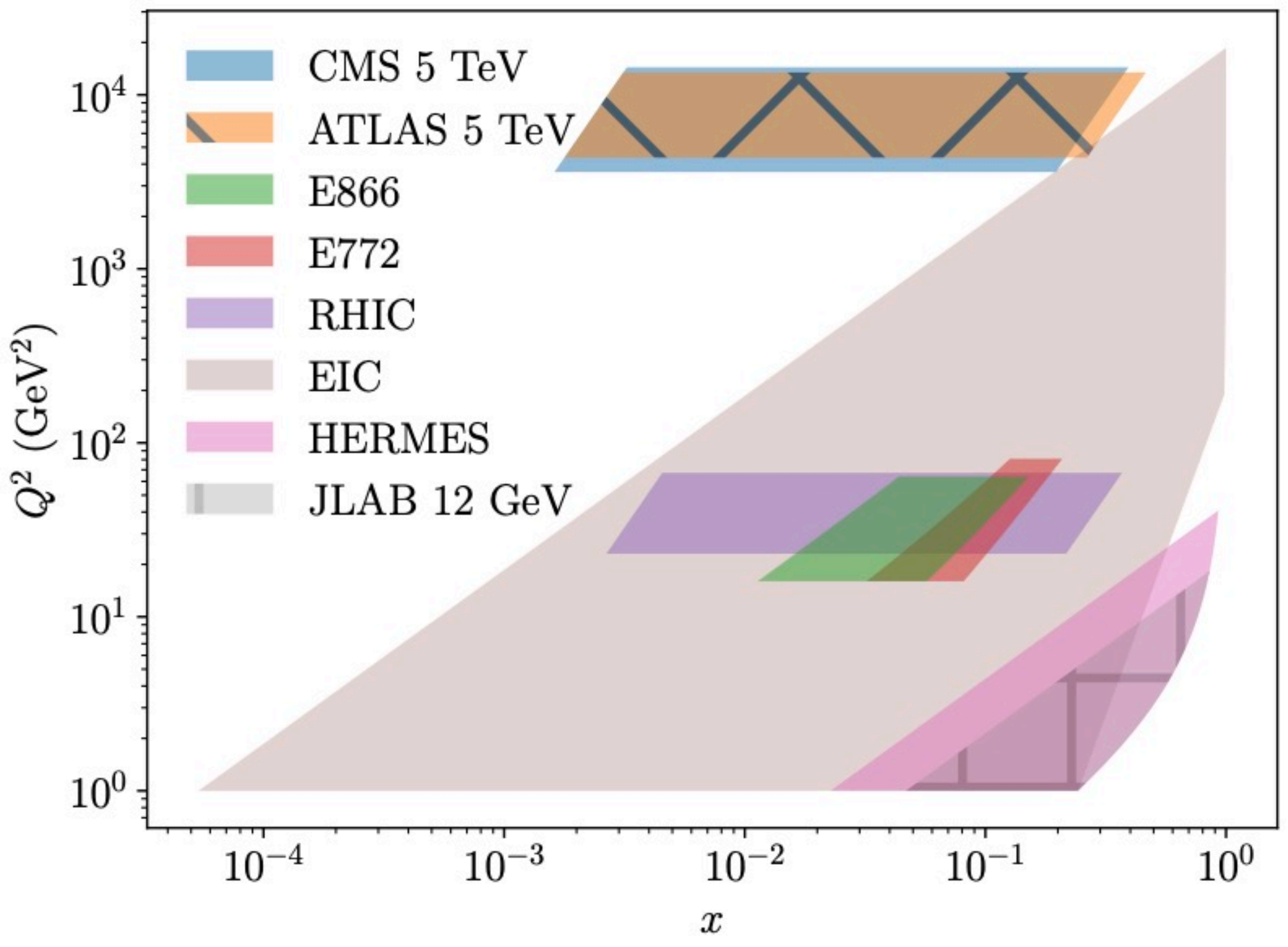
$$R_{u/p}^{\mathrm{Au}}(x, k_\perp, Q_0) = \frac{f_{u/p}^{\mathrm{Au}}(x, k_\perp, Q_0)}{f_{u/p}(x, k_\perp, Q_0)}$$

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







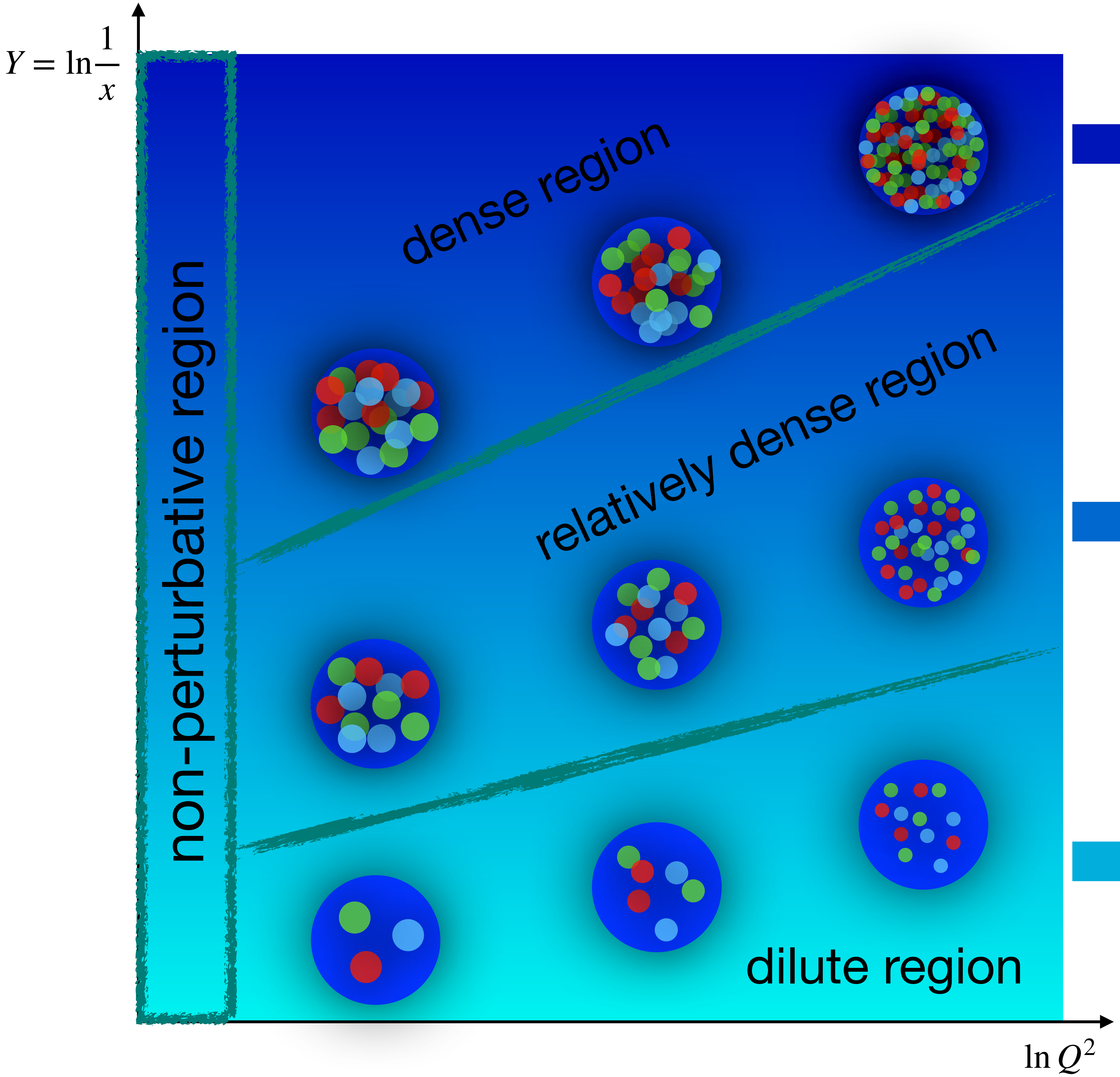


- First time quantitative determination of nuclear TMDs
- Identification of transverse momentum broadening in nuclei

Alrashed, Anderle, Kang, Terry, **HX**, 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 $\lambda \sim 1/xp \gg L \sim A^{1/3}$

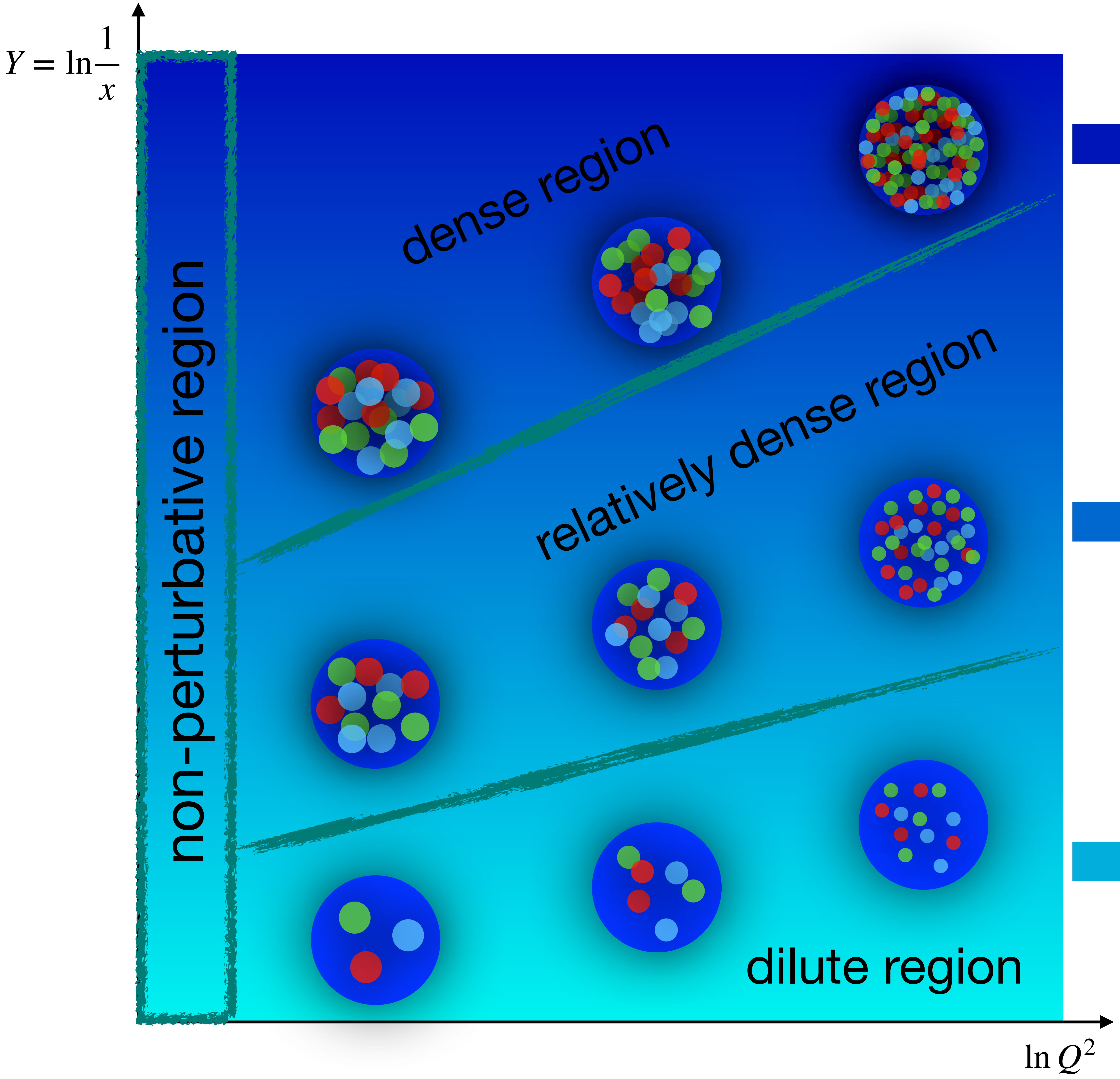
Relatively dense region: $x \lesssim \mathcal{O}(1)$

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)

McLerran, Venugopalan, 1994

Wilson lines, BK/JIMWLK evolution

See review: Gelis, Iancu, Venugopalan, 2003

High-twist formalism

Multi-parton correlation, DGLAP-type evoluti

Qiu, Stermann, PRD, 1991

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

Leading twist collinear factorization

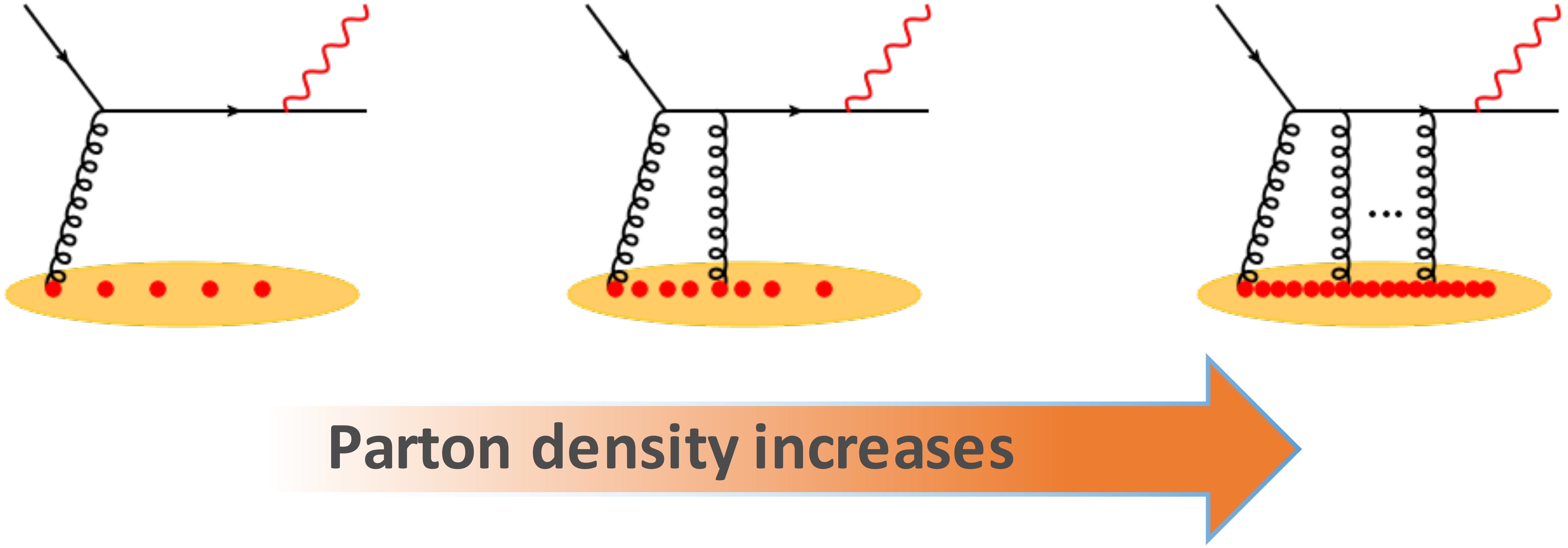
PDF, DGLAP evolution

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



$$d\sigma \sim \frac{1}{p_{\gamma\perp}^4}\left[A + B\frac{\langle k_\perp^2\rangle}{p_{\gamma\perp}^2} + C\frac{\langle k_\perp^2\rangle^2}{p_{\gamma\perp}^4}\cdots\right] \longrightarrow \textbf{CGC}$$

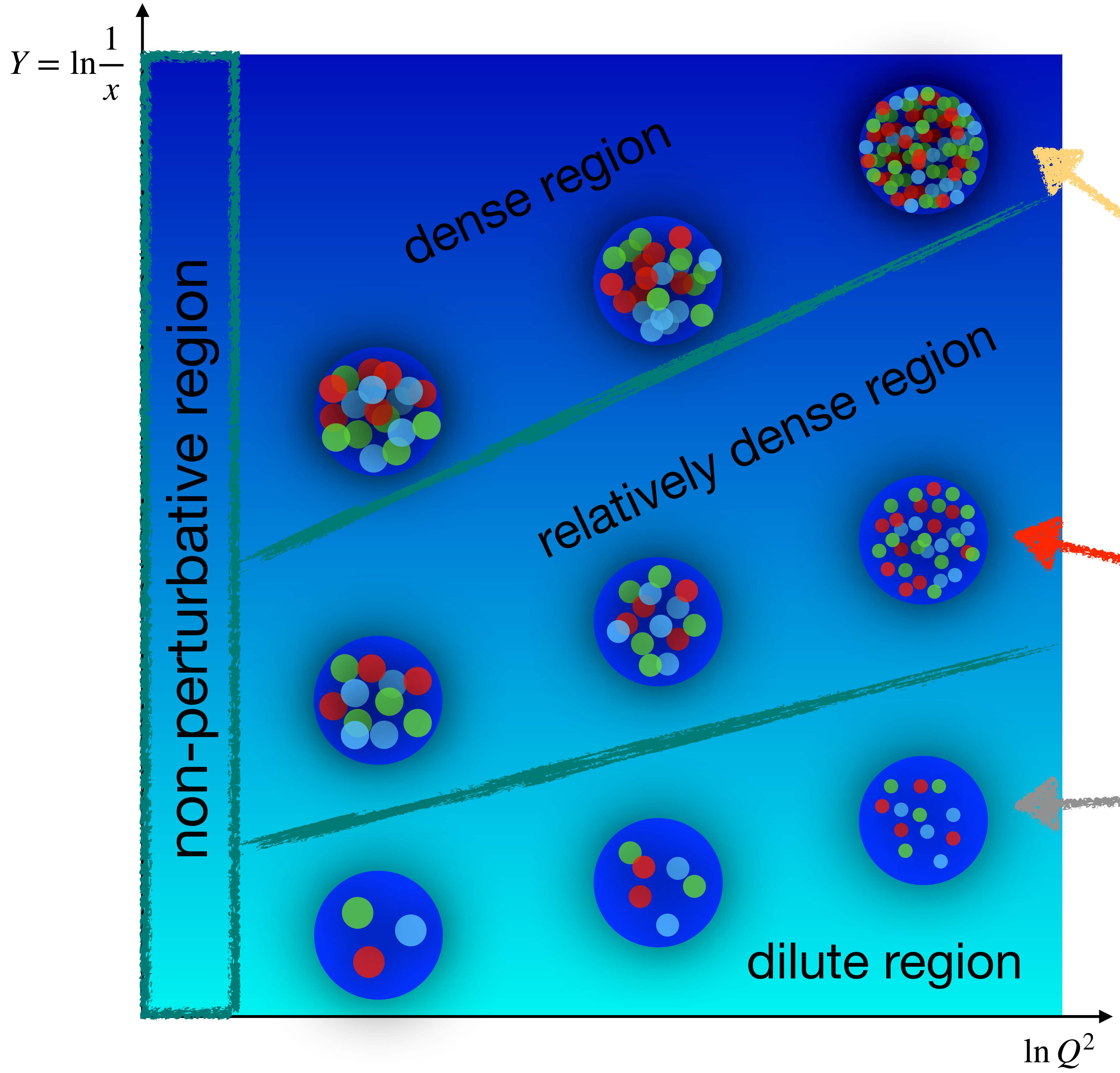
$\langle k_\perp^2\rangle \sim Q_s^2 \propto A^{1/3}x^{-\lambda}$

leading twist (twist-2)

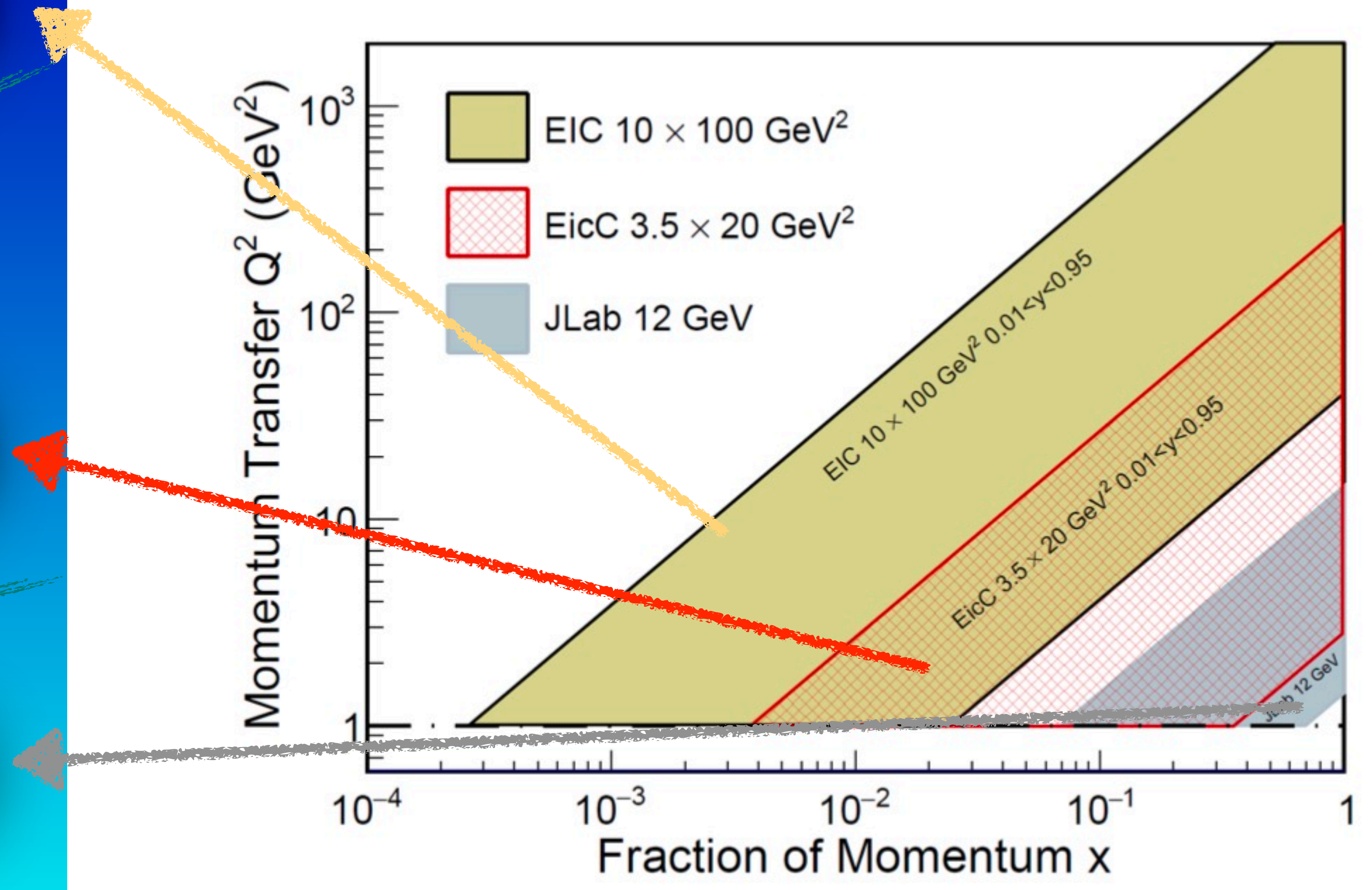
Higher twist (twist-4 and twist-6)

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

Nuclear partonic structure from dilute to dense region



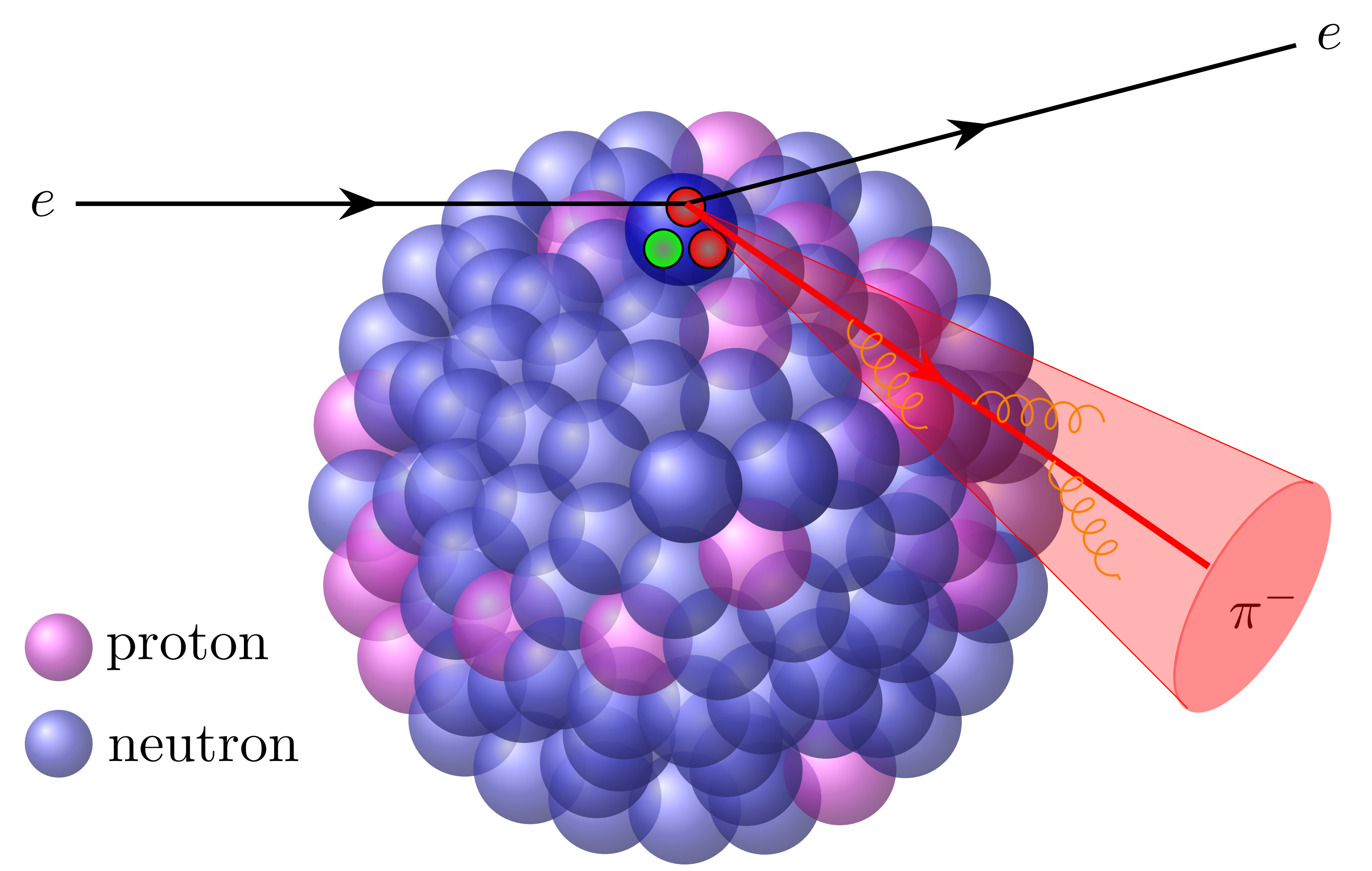
Fu, Kang, Salazar, Wang, **HX**, PRL, 2025

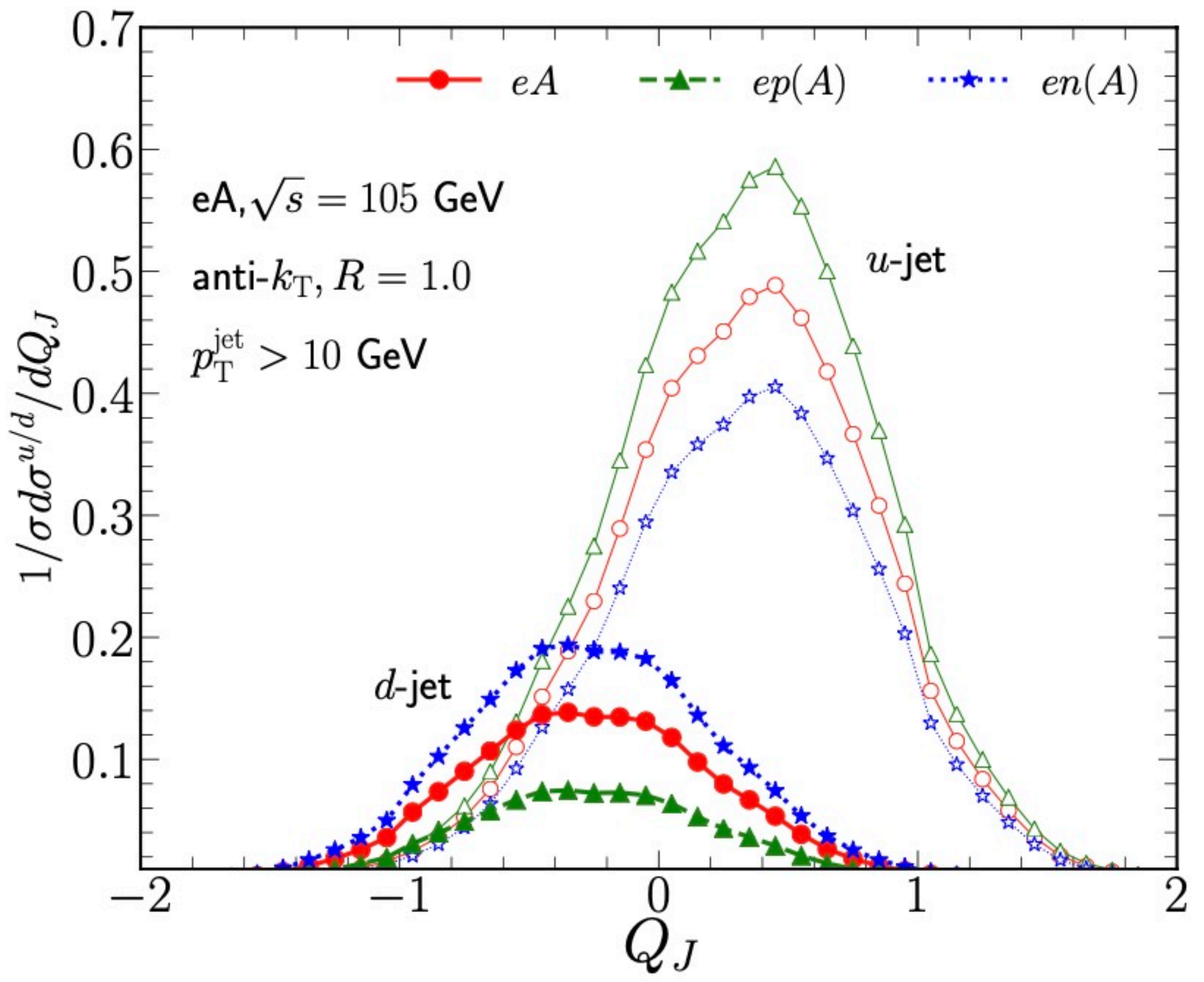


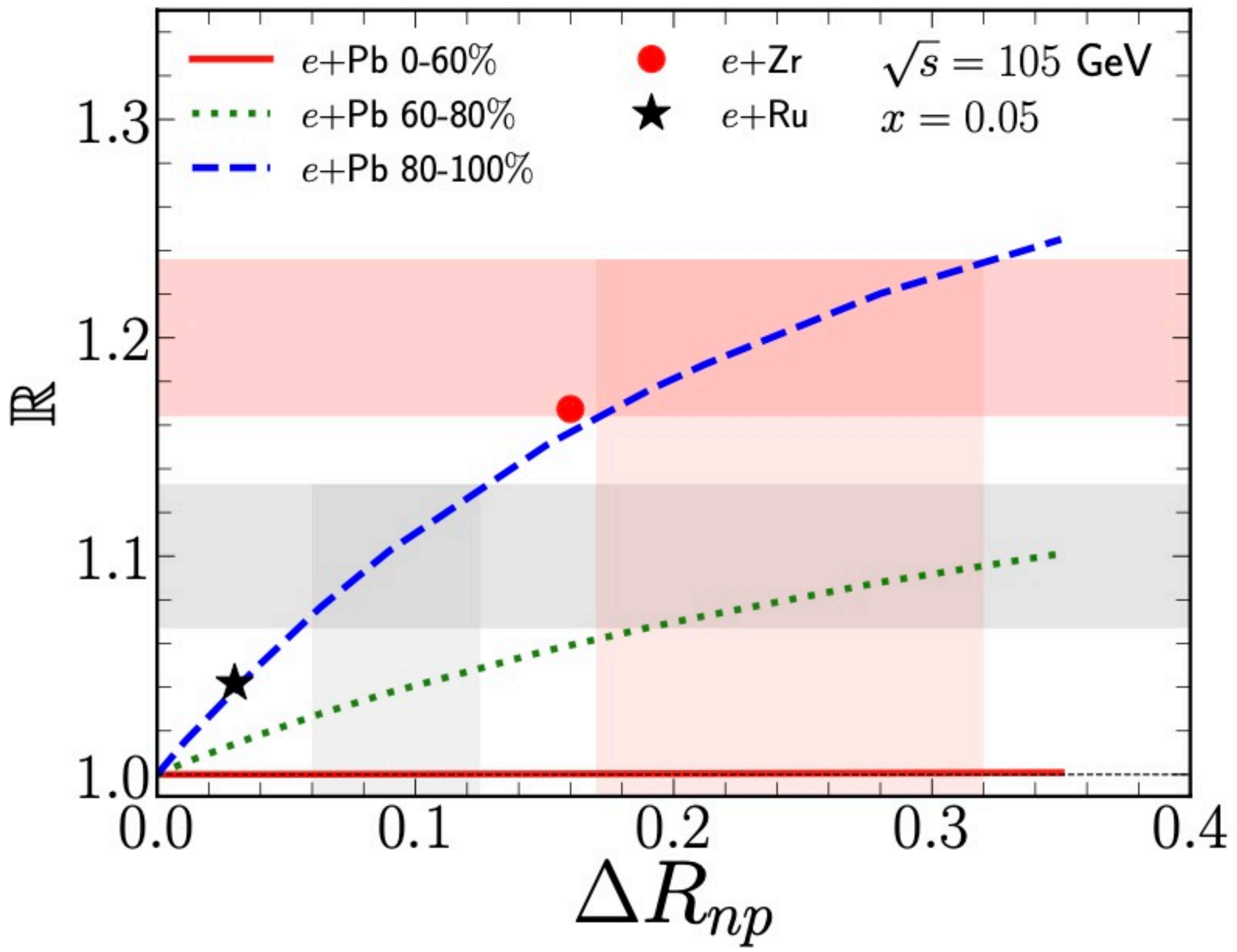
Mapping out the QCD phase diagram for nuclei with worldwide efforts using a unified theoretical framework!

Bridging EIC to low energy nuclear structure

✦ Linking physics phenomena at both low and high collision energies







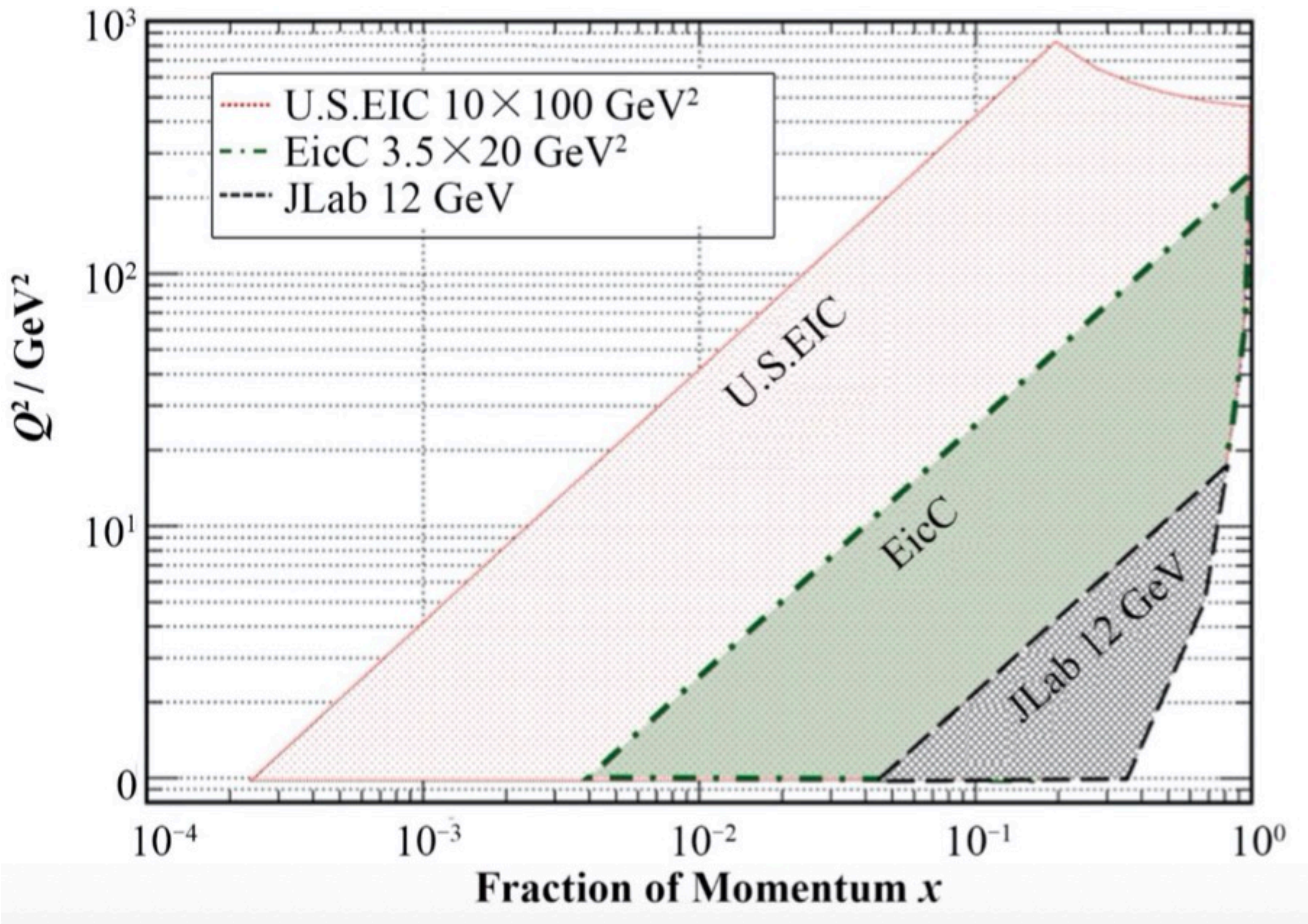
Zhang, Wang, **HX**, to appear soon

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

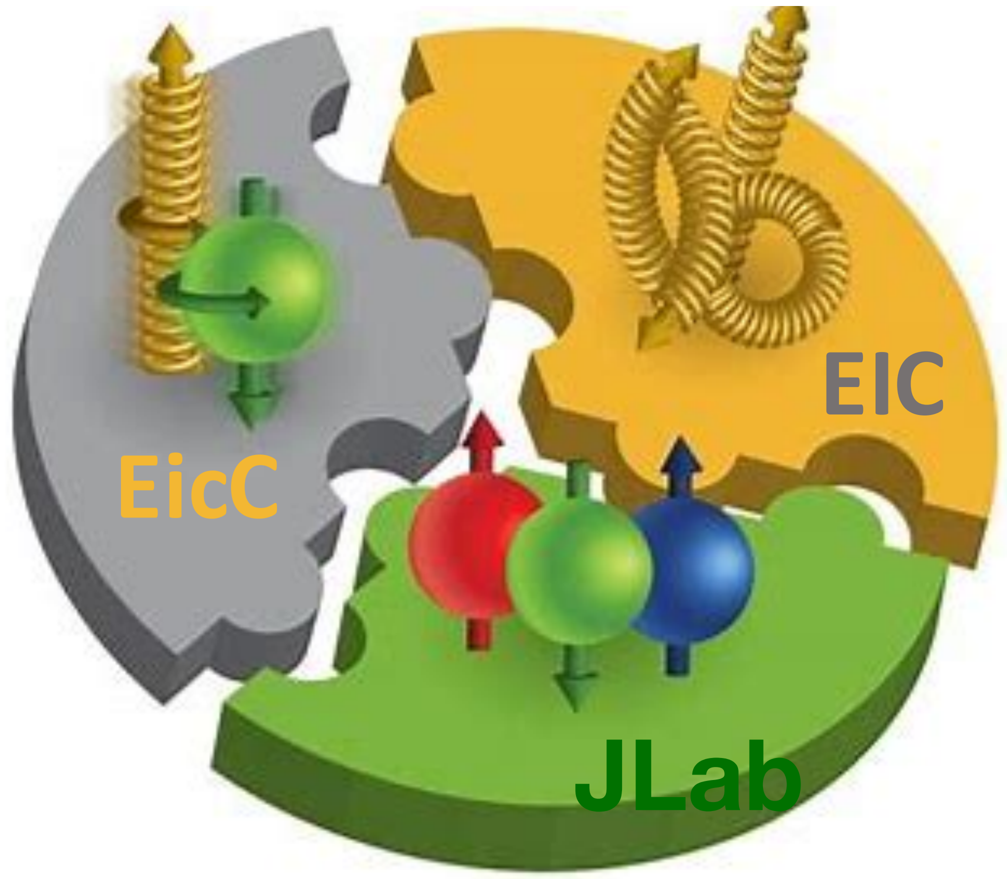
- Jet charge distribution in eA DIS: a novel probe for high precision determination of neutron skin thickness

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！



Congratulations to C3NT!