Electron Ion Physics - a view point from EicC

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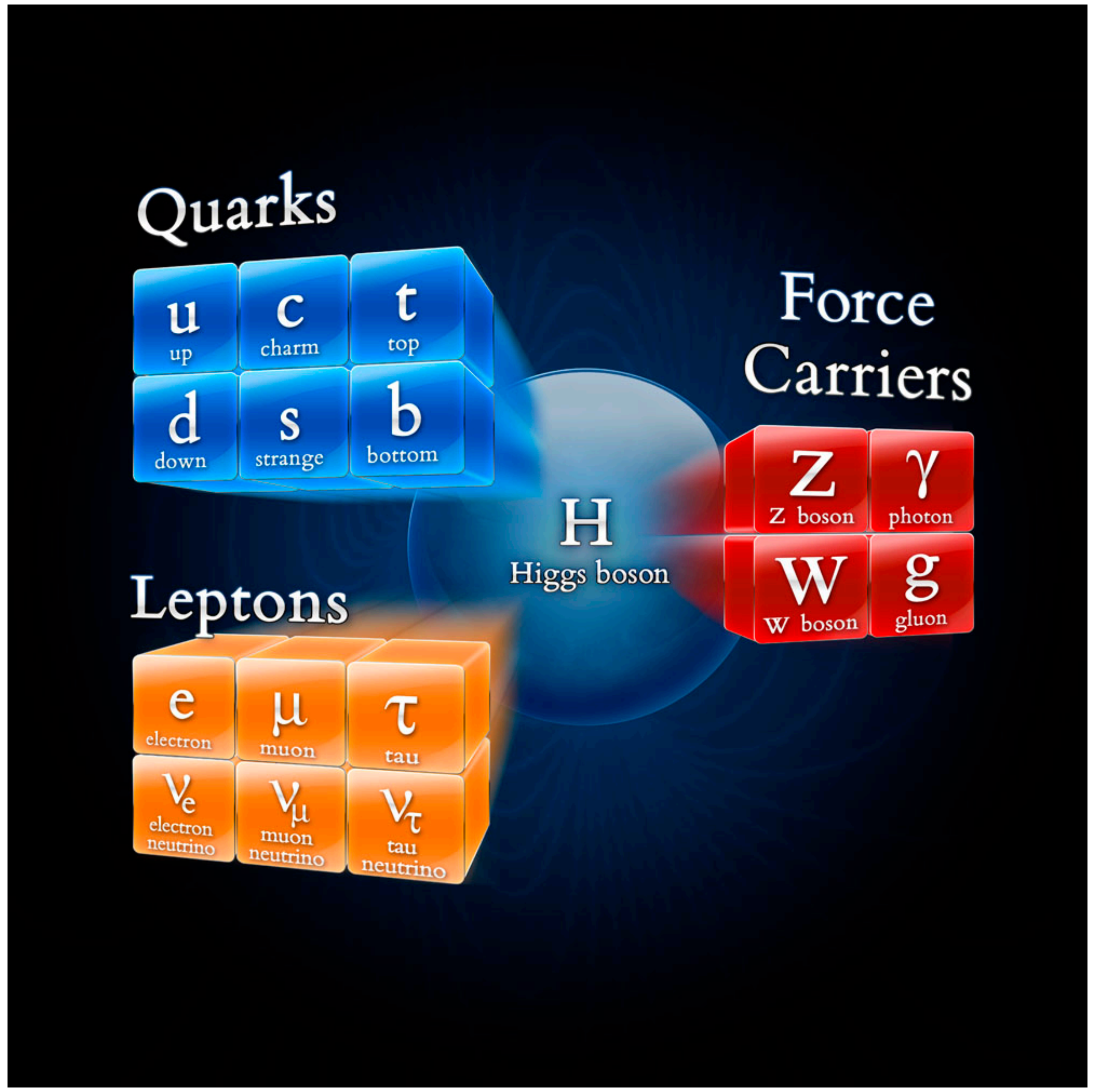
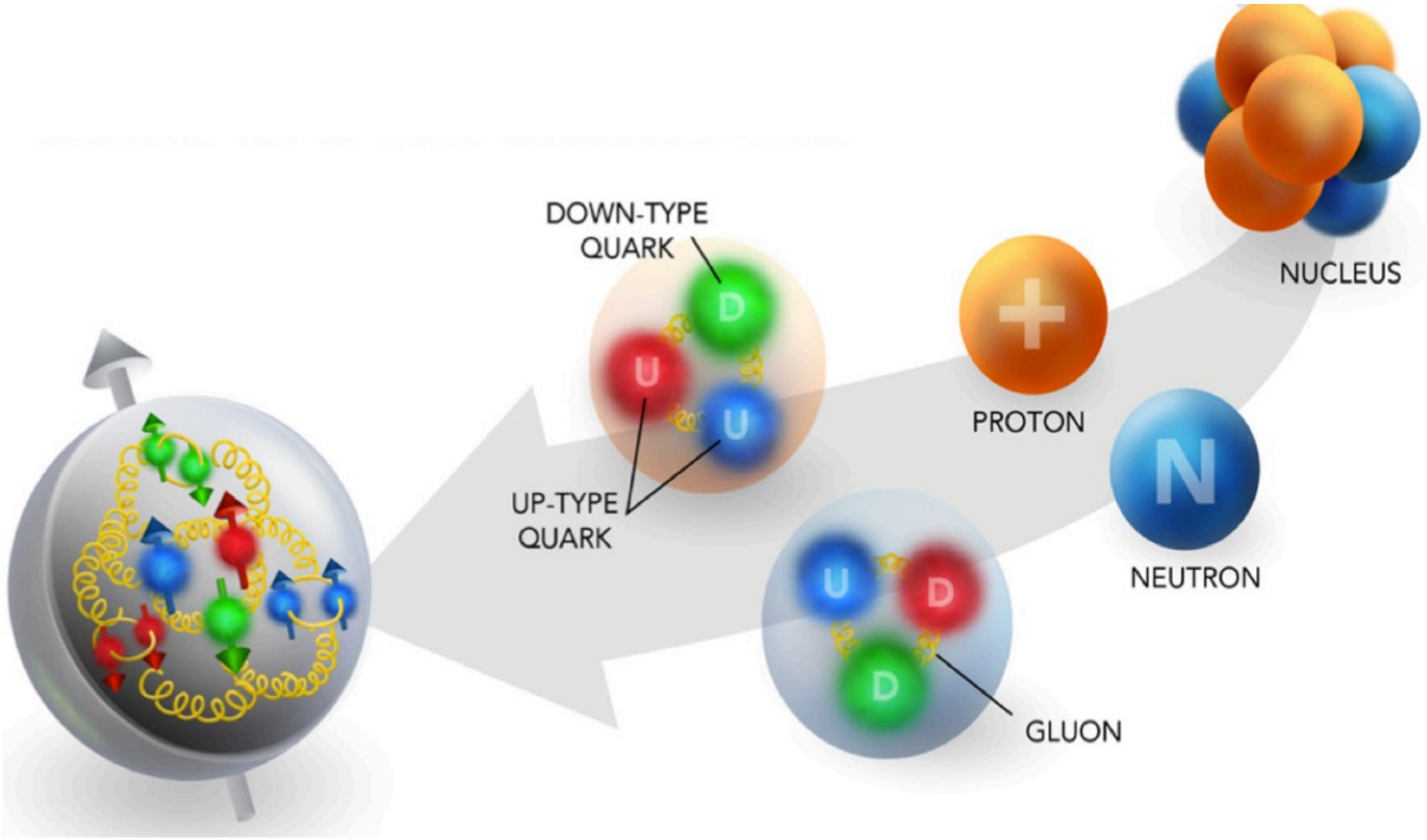
Outline

- ✦ Introduction to Electron Ion Colliders
- ✦ Selected topics for nucleon/nucleus structure
  - proton 1D structure
  - proton 3D structure
  - nuclear effects
- ✦ Summary

What holds us together?

standard model



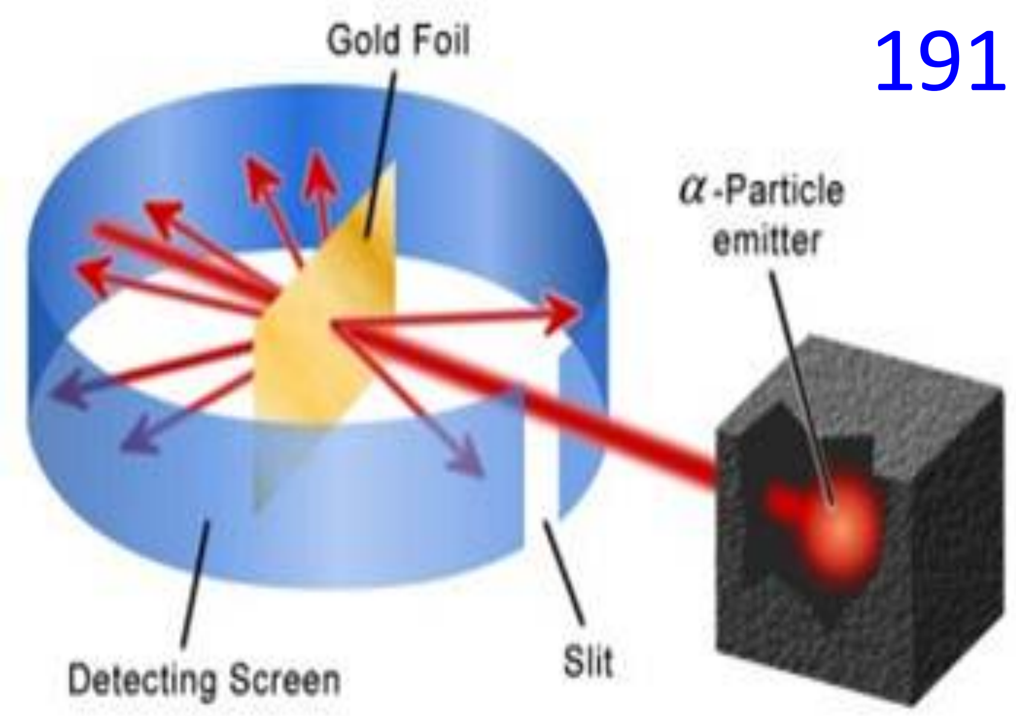


Nuclear Femtography: search for answers to the most fundamental structure at Fermi scale!

Nucleon partonic structure

✦ Revolution in our view of nuclear structure

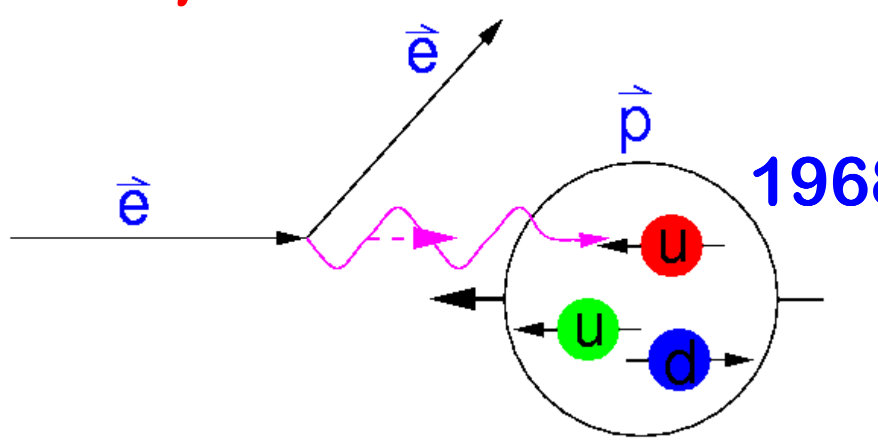
- Atom: Dalton 1803
- Nucleus: Rutherford 1911
- Proton: Rutherford 1919
- Neutron: Chadwick 1932
- Quark model: Gell-Mann and Zweig 1964
- Parton model: Feynman 1969
- …



1911

Rutherford scattering

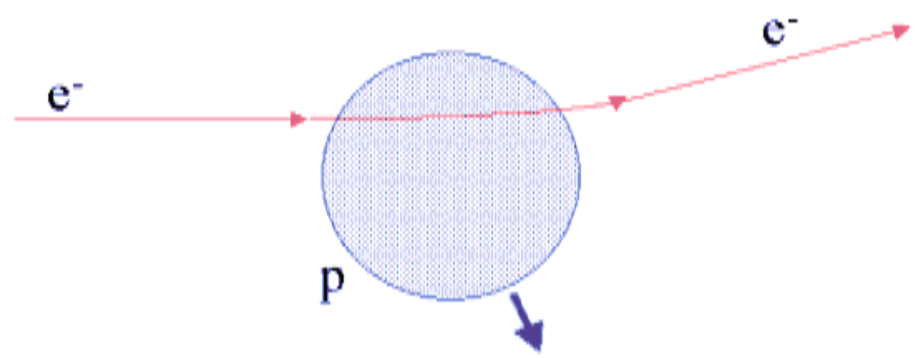
e + *p* ➔ e + *X*



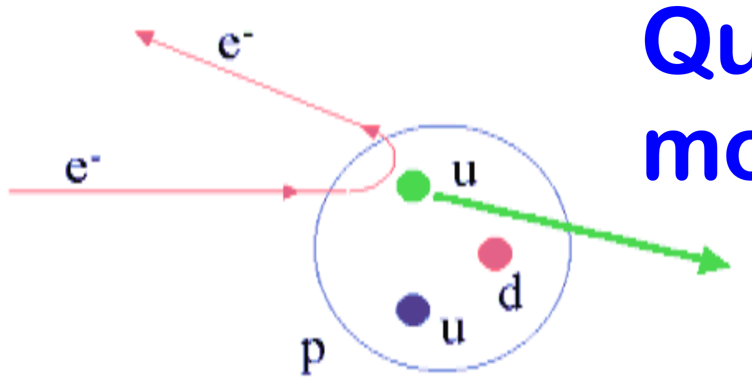
1968

Modern Rutherford scattering

◆ If proton "charge cloud":



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



Quark model

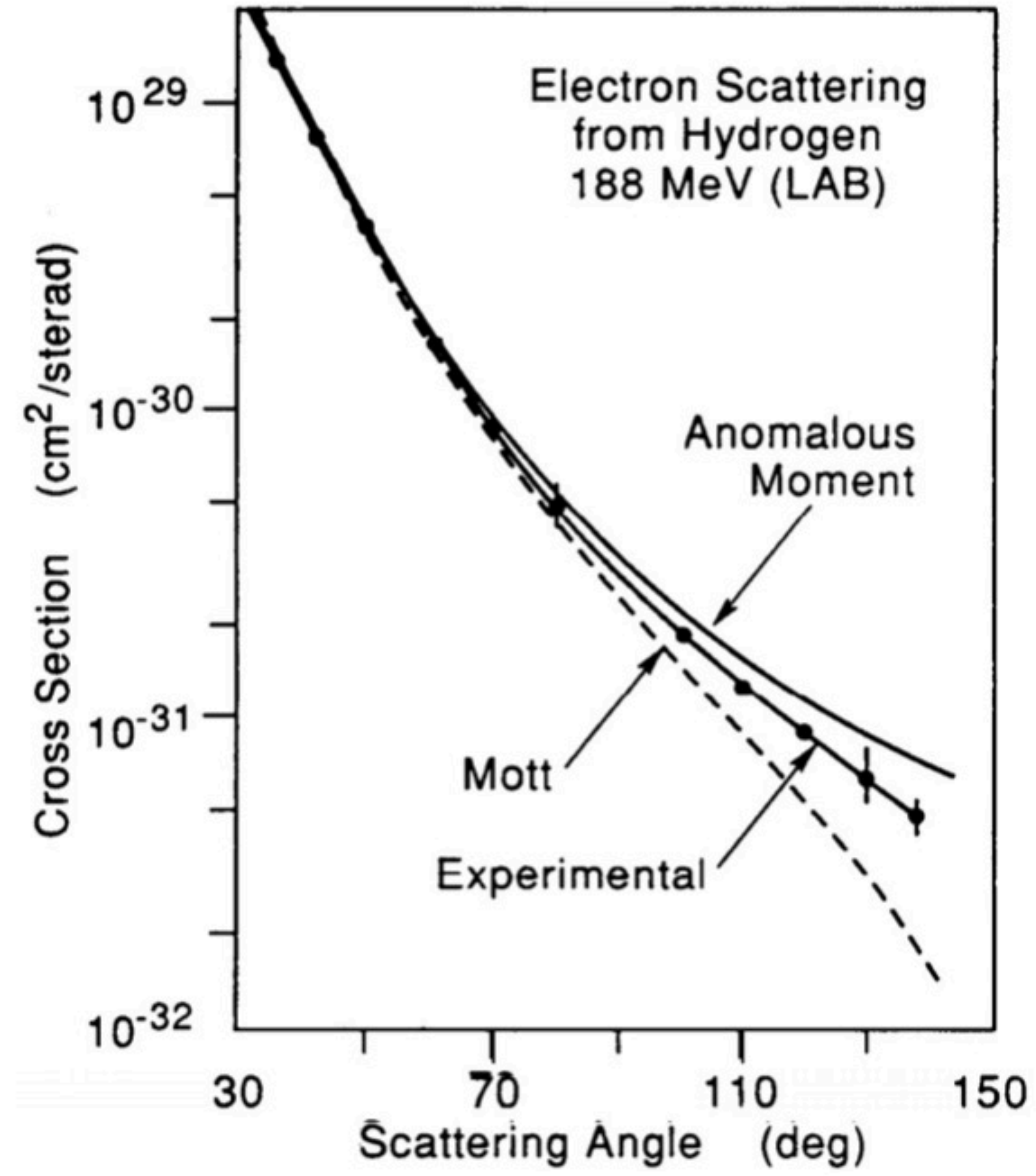
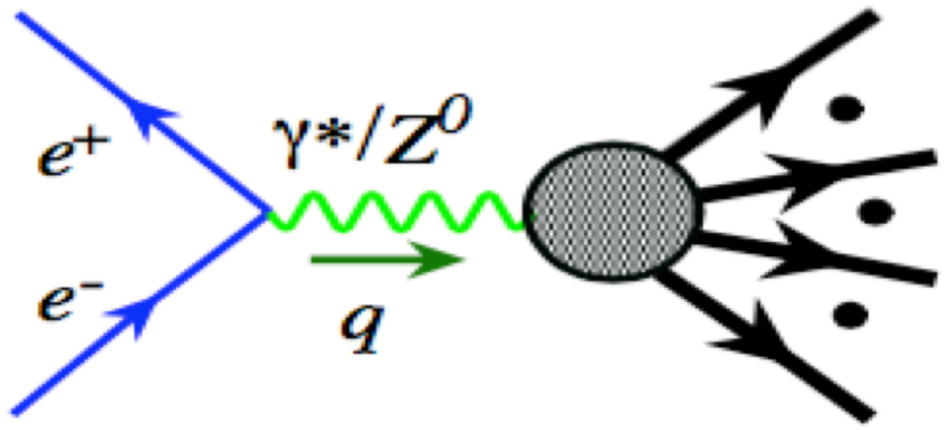


Fig. 5. Elastic electron scattering cross sections from hydrogen compared with the Mott scattering formula (electrons scattered from a particle with unit charge and no magnetic moment) and with the Rosenbluth cross section for a point proton with an anomalous magnetic moment. The data falls between the 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 !

Modern machines to probe the nucleon partonic structure

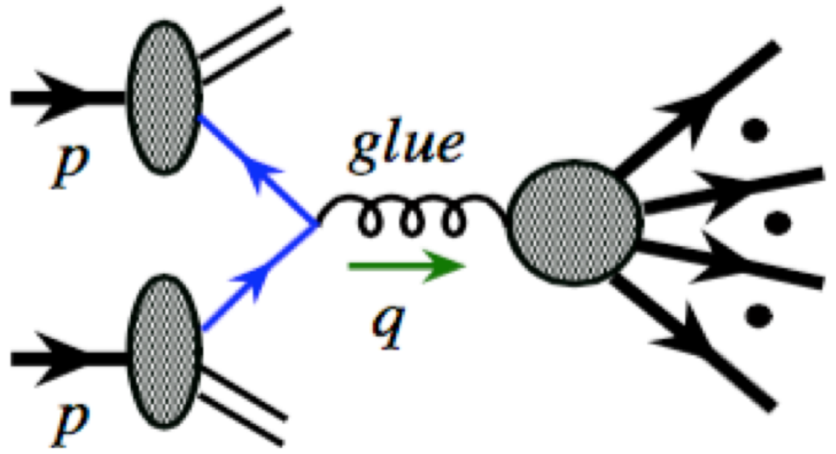
Lepton-lepton colliders



BEPC, SuperKEKB

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

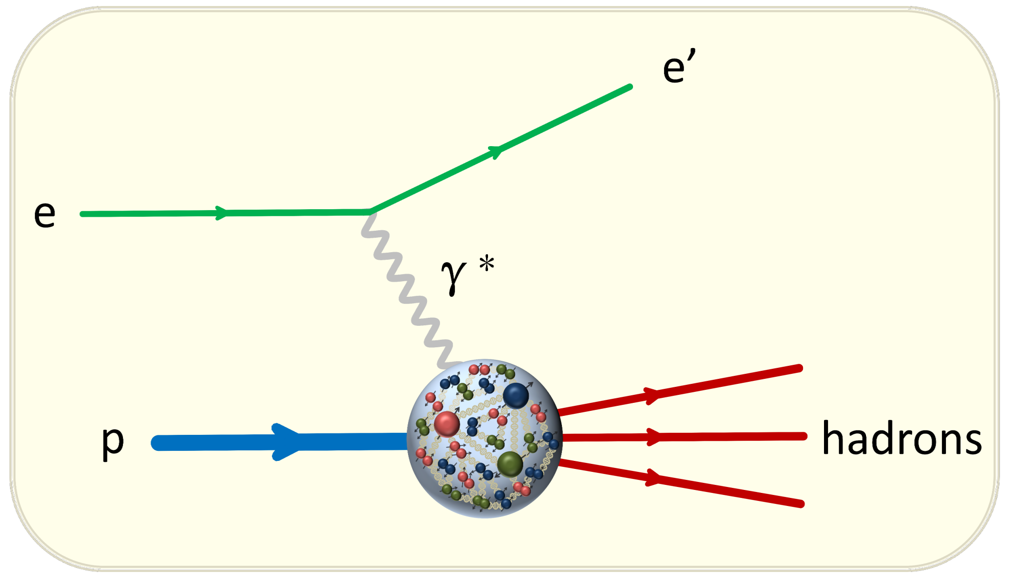
Hadron-hadron colliders



RHIC, LHC

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

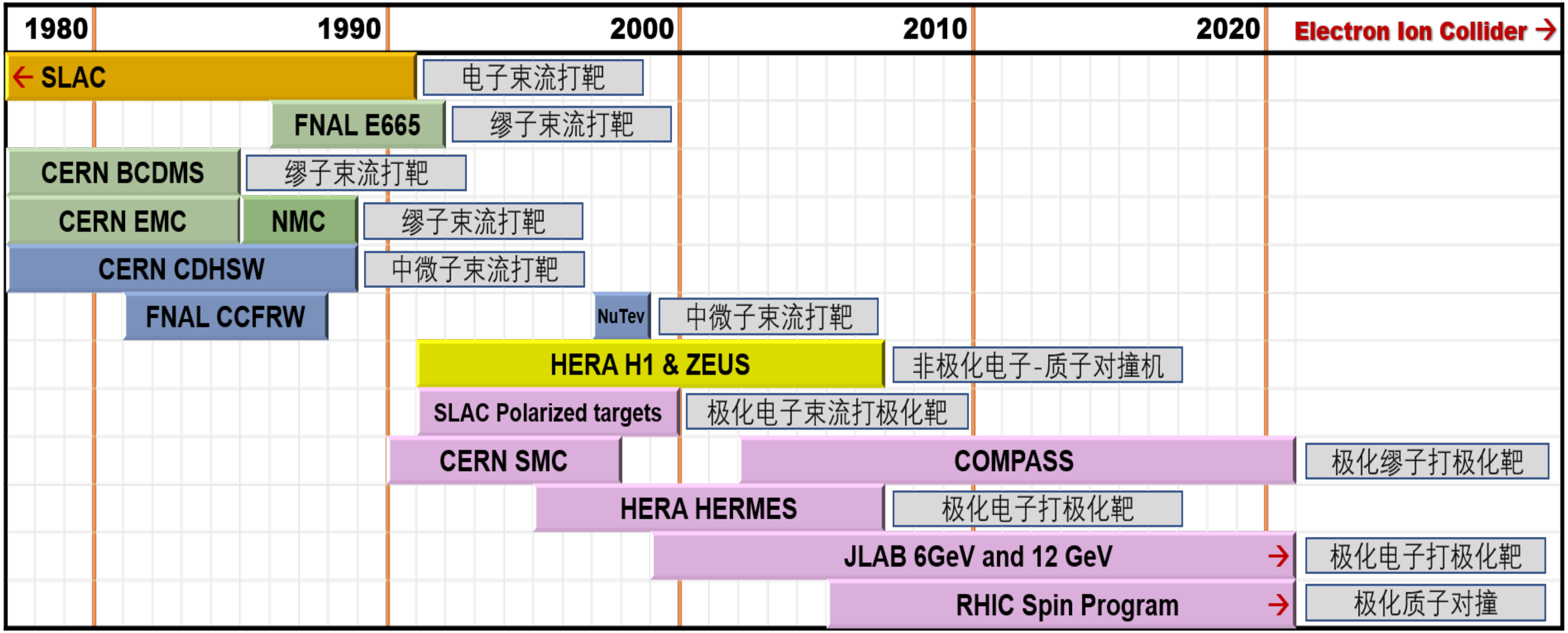
lepton-hadron colliders



HERA, JLab

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

The modern experiments for nucleon structure



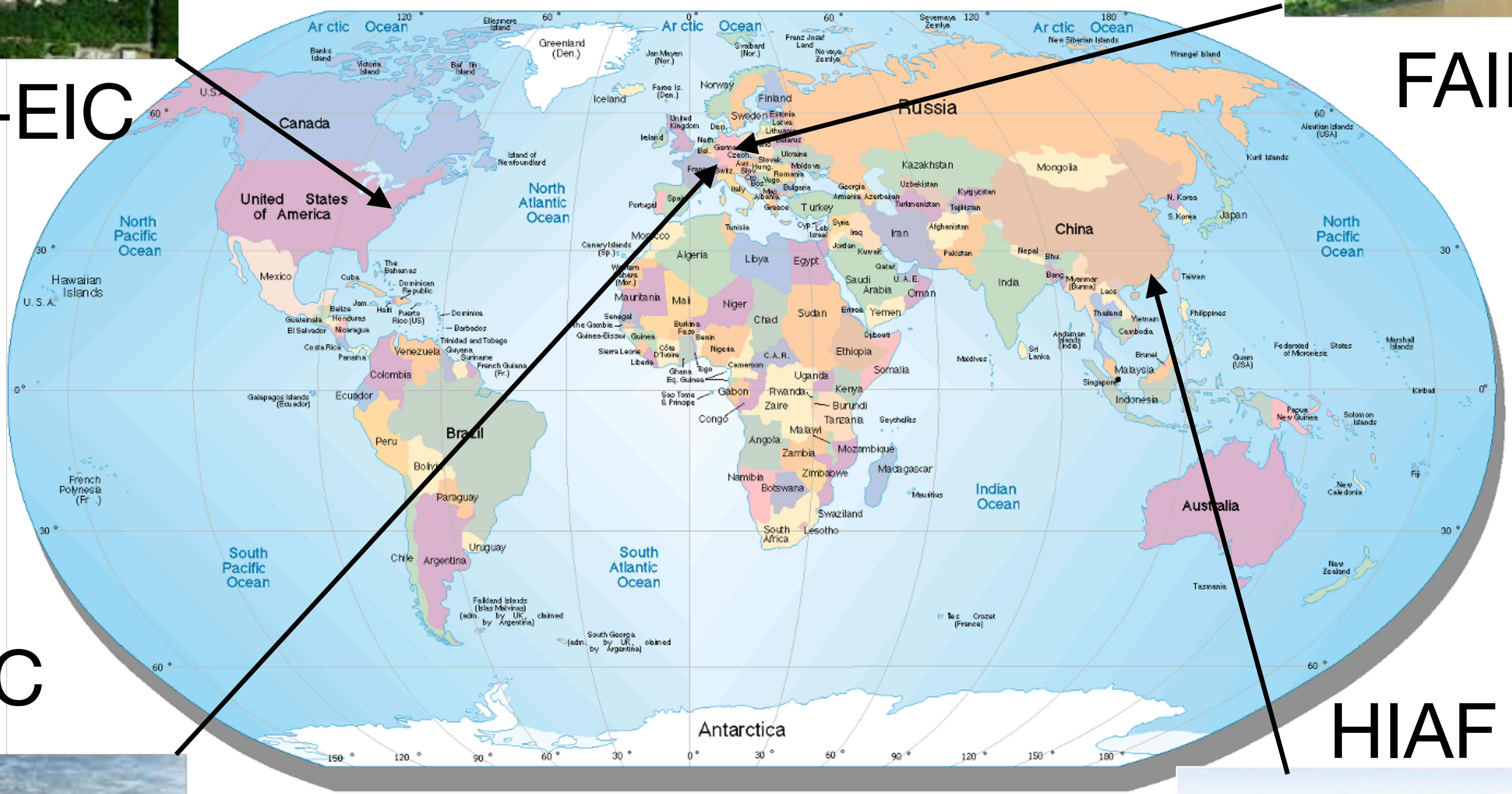
Electron Ion Colliders -> the next generation facility specifically for nucleon structure!

slide from Yutie Liang

Proposed Electron-ion colliders

RHIC ➔ US-EIC

FAIR ➔ ENC



LHC ➔ LHeC

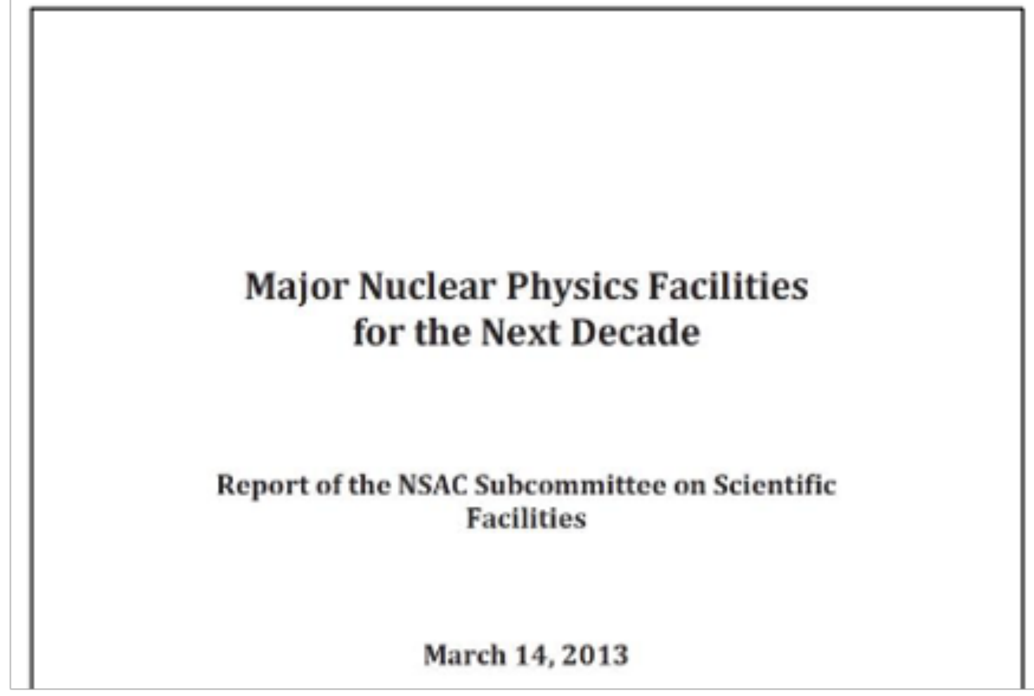
HIAF ➔ **EicC**

slide from Jinlong Zhang

Time evolution of US EIC

2002 Long Range Plan in the US

The Electron-Ion Collider (EIC). The EIC is a new accelerator concept that has been proposed to extend our understanding of the structure of matter in terms of its quark and gluon constituents. Two classes of


Major Nuclear Physics Facilities
for the Next Decade

Report of the NSAC Subcommittee on Scientific Facilities

March 14, 2013

The 2013 NSAC *Subcommittee on Future Facilities* identified an Electron-Ion Collider as ***absolutely central*** to the nuclear science program of the next decade.

- Gluons…generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain…. These can only be answered with a powerful new electron ion collider (EIC). ***We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.***

2020:CD-0

Approved project!

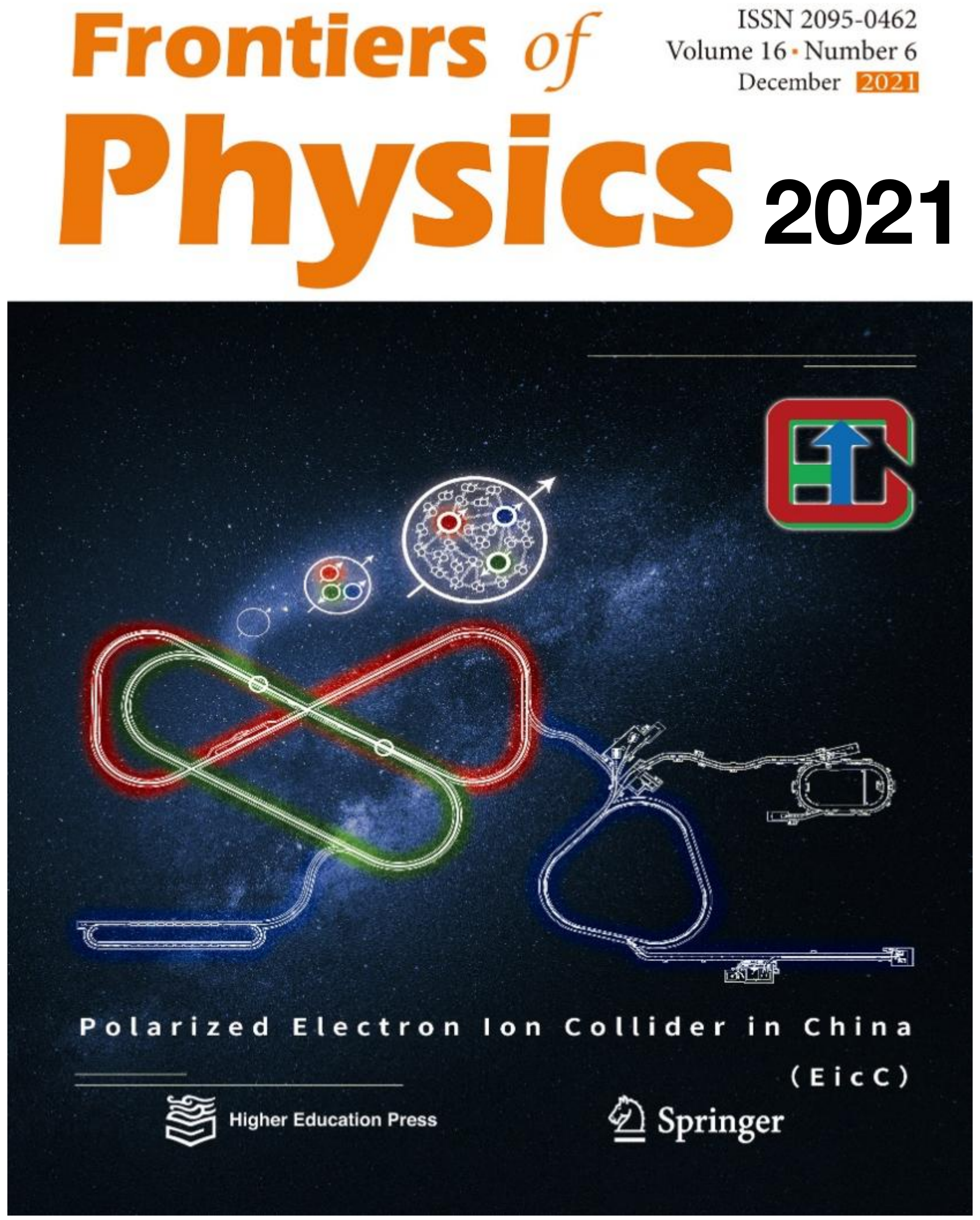
2021:CD-1

~2030:operation

Time evolution of EicC

2020

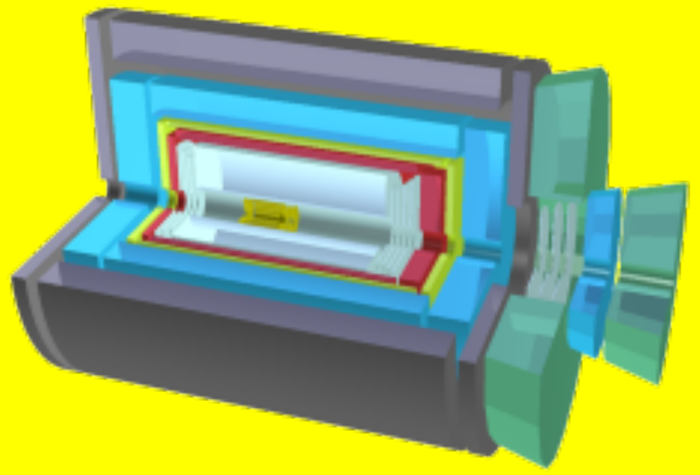
2021



中国电子 – 离子对撞机 (EicC)

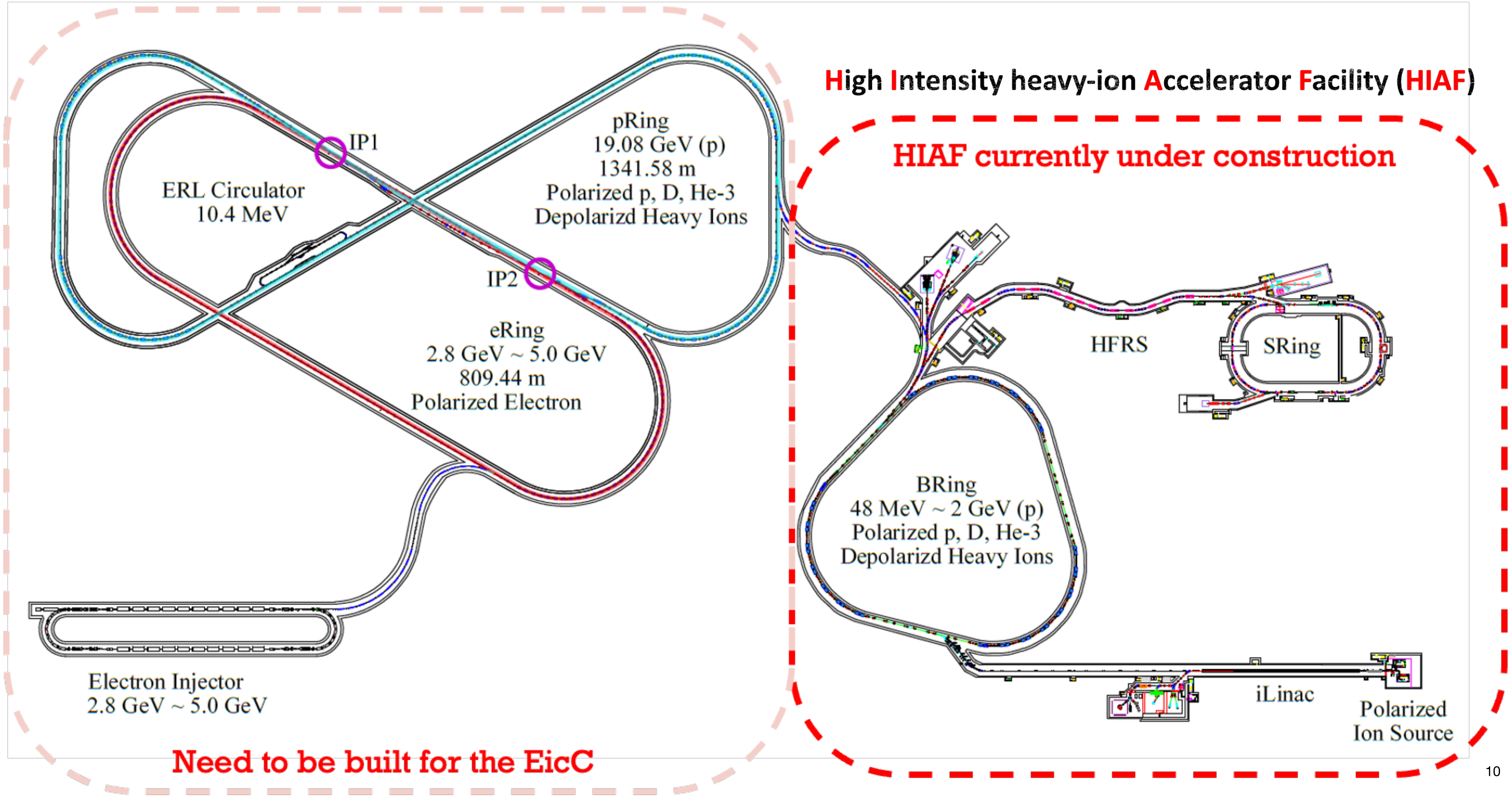
2012: 领域内开始讨论
2020.2, 2021.6:白皮书 (中文, 英文)
2021-2023: 概念设计研究

参与单位： ~ 45

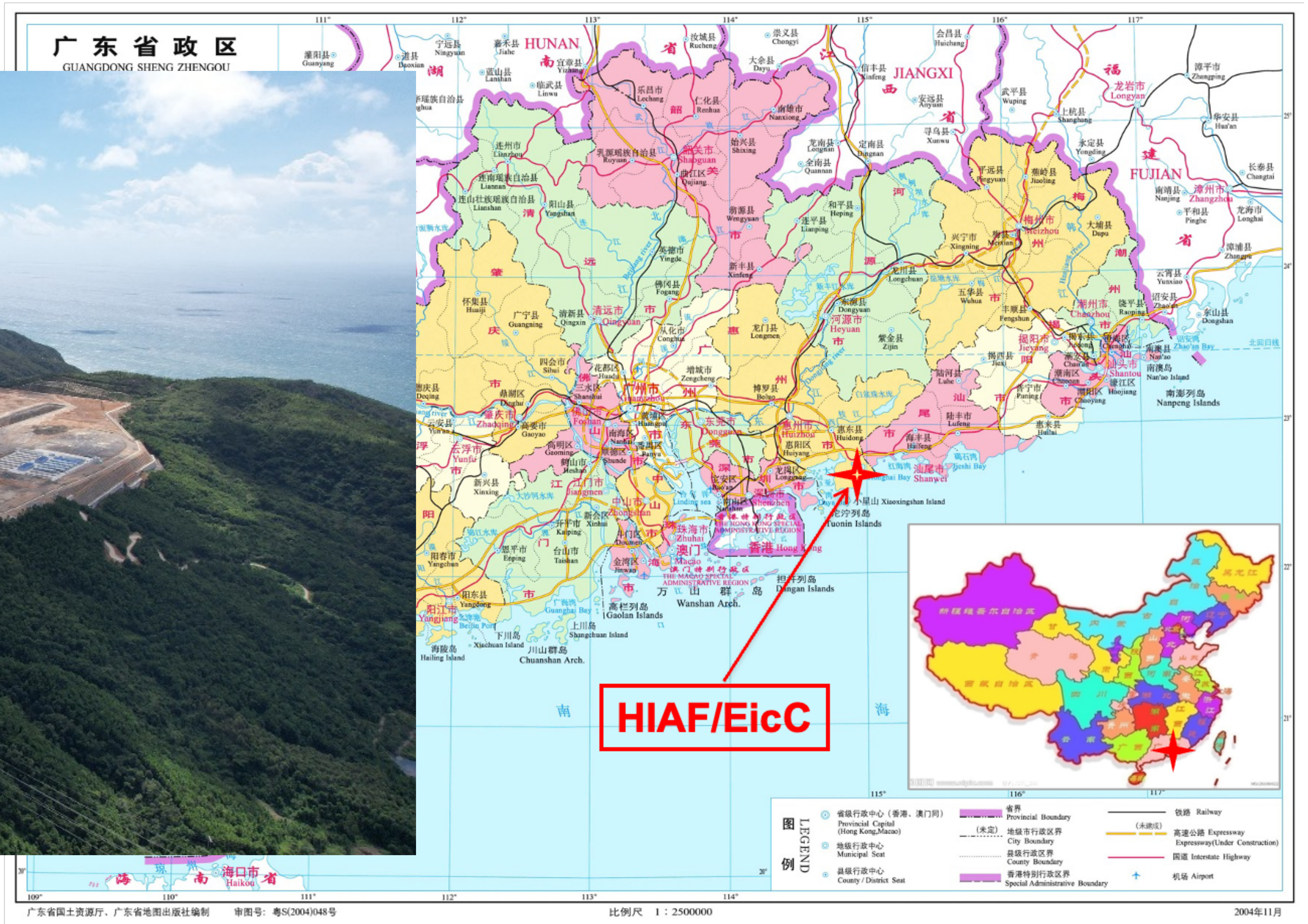


Electron Ion Collider in China, EicC

Electron-Ion Collider in China (EicC)



Electron-Ion Collider in China (EicC)

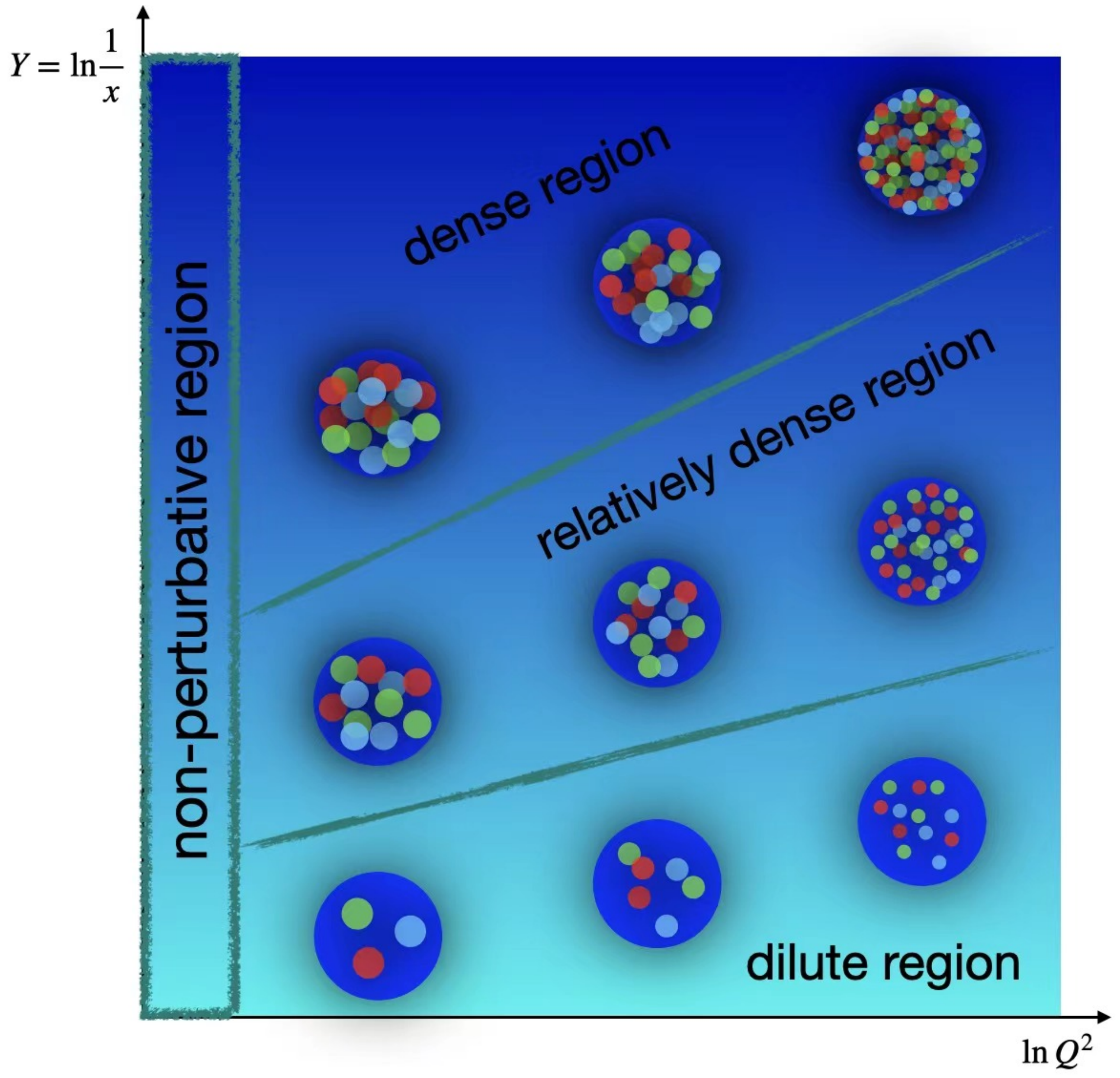


HIAF under construction

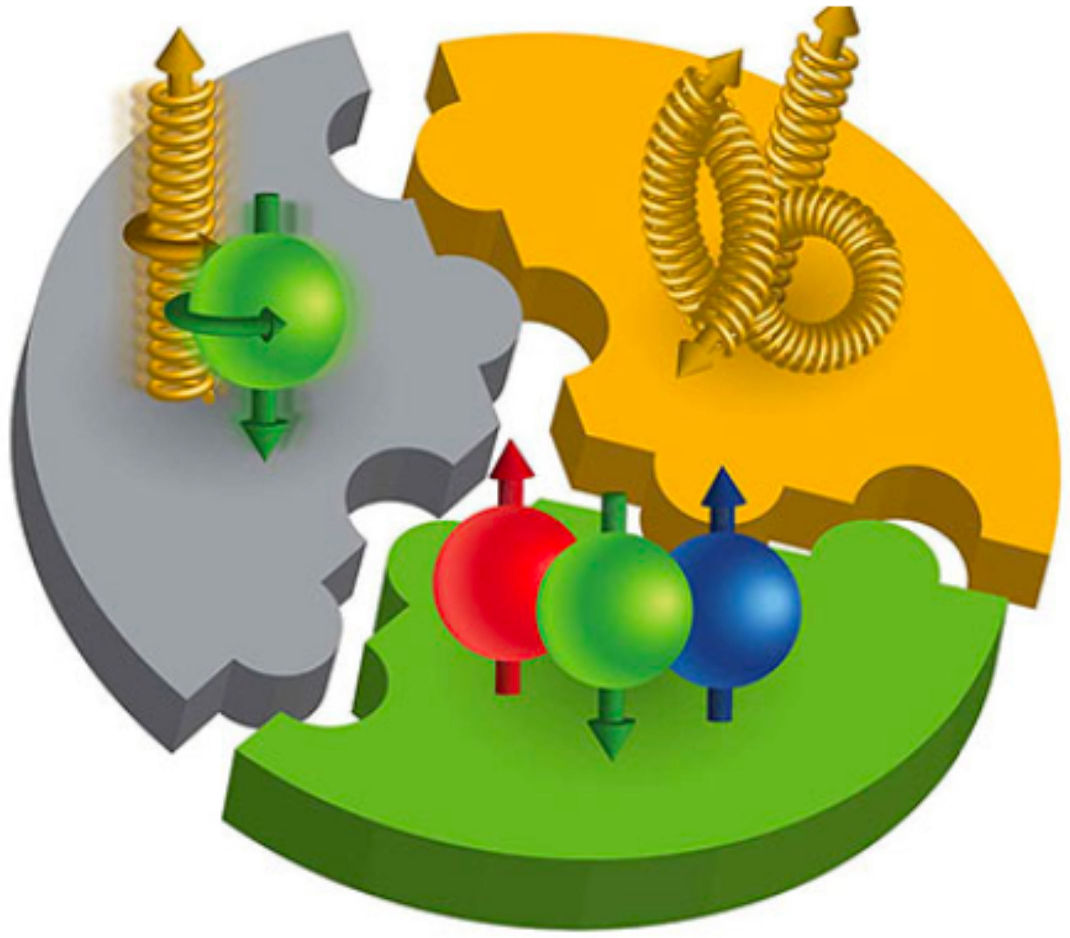
EIC in China

a nuclear facility proposed to be built in Huizhou, China

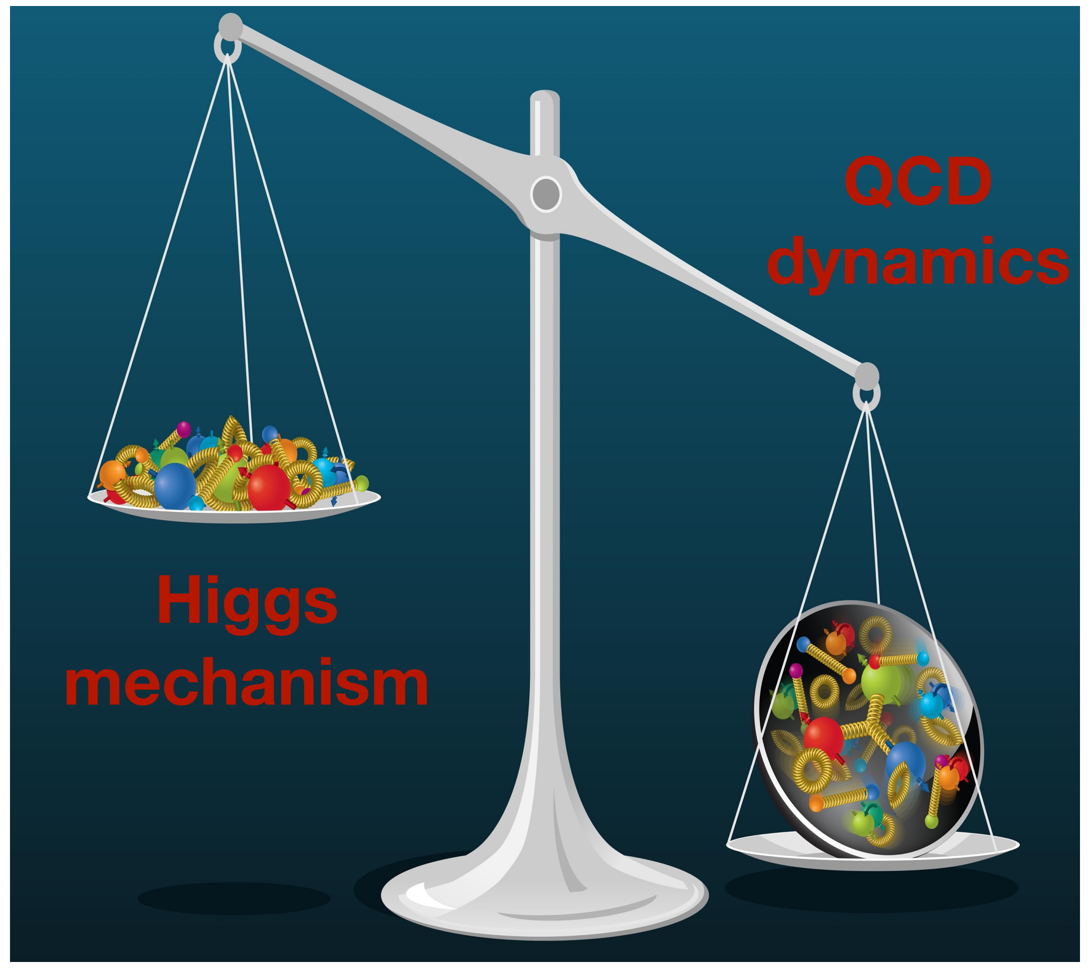
Scientific goals at EICs



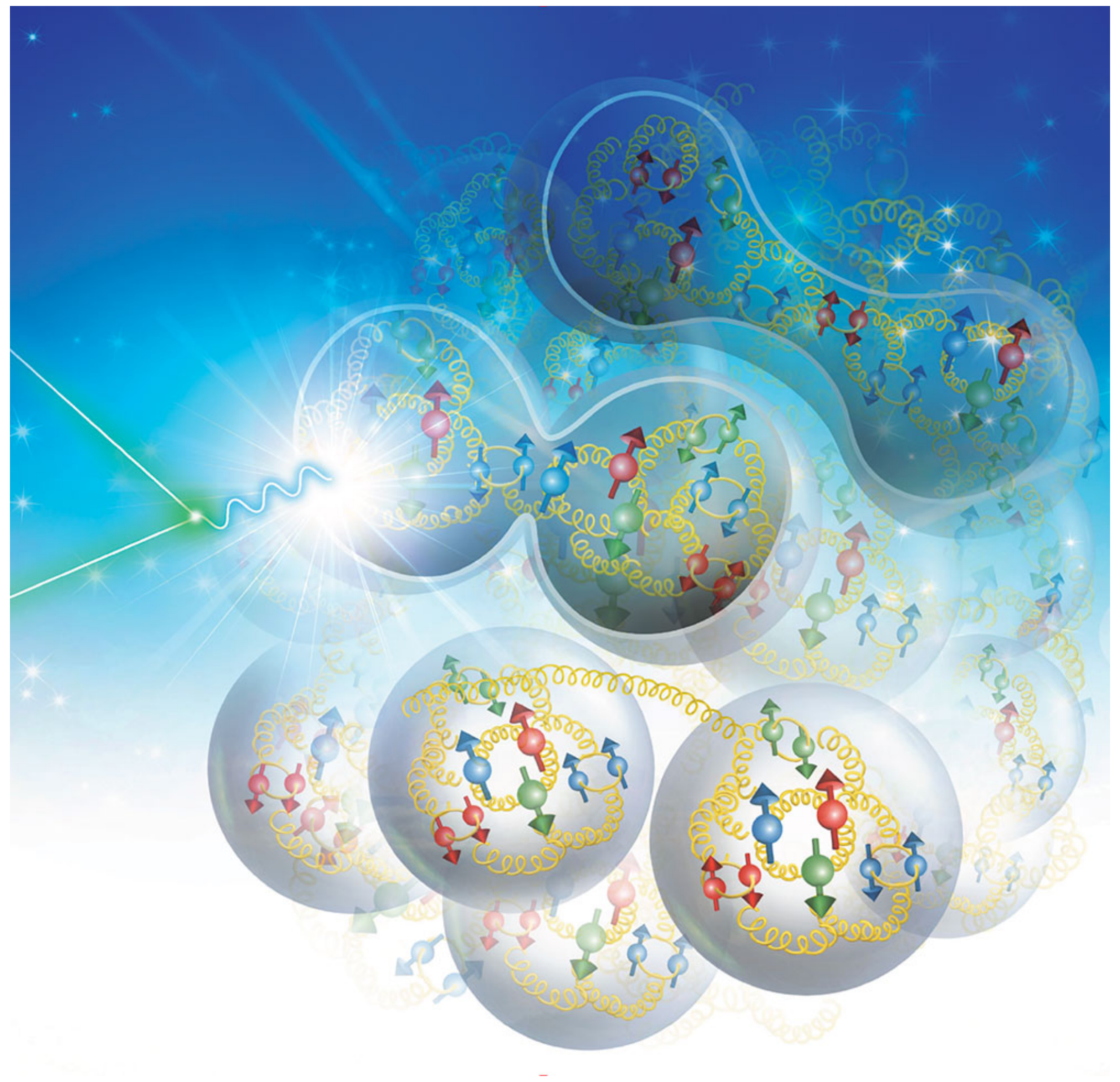
The energy momentum distribution of partons in nucleon/nuclei



The origin of proton spin

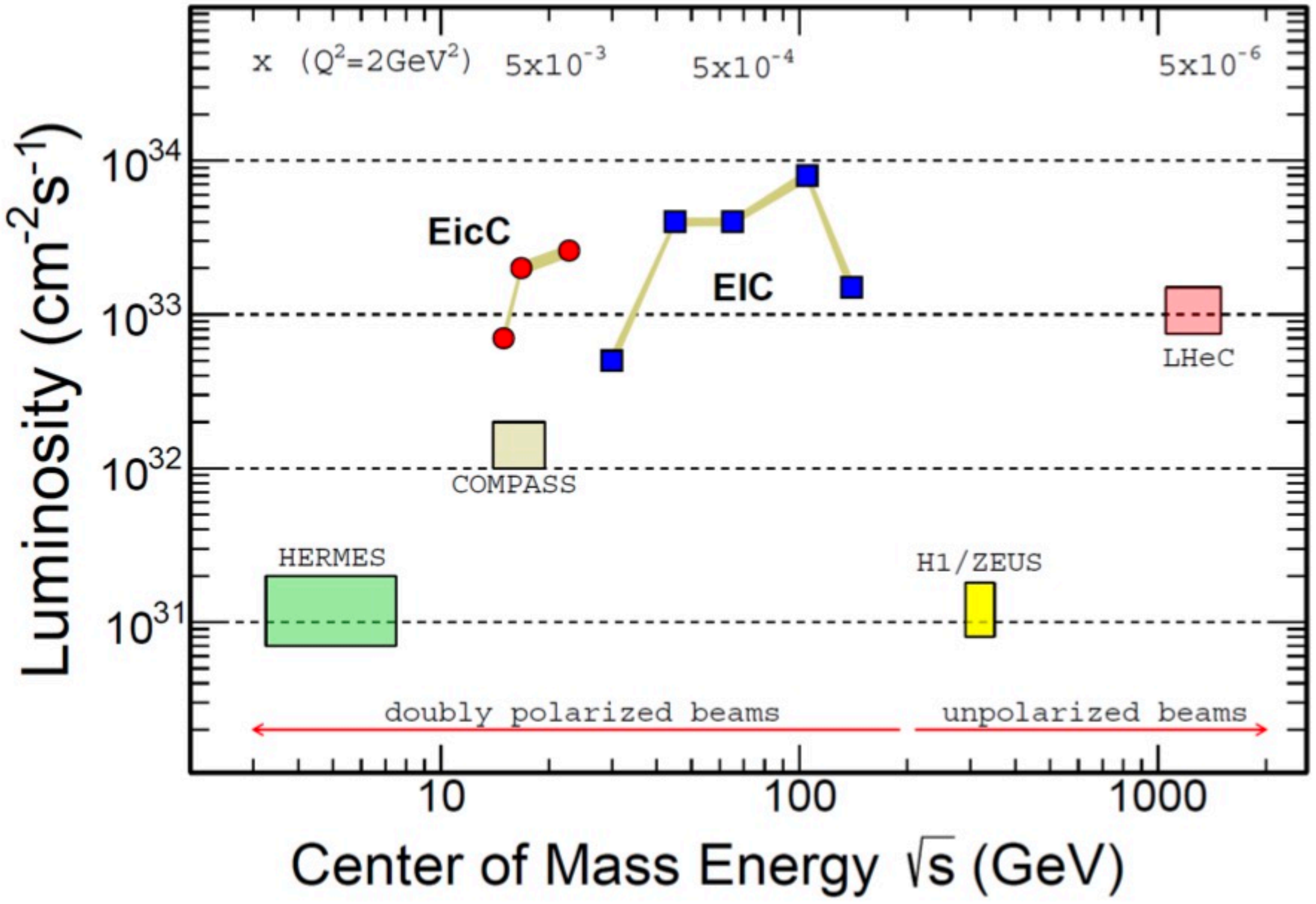


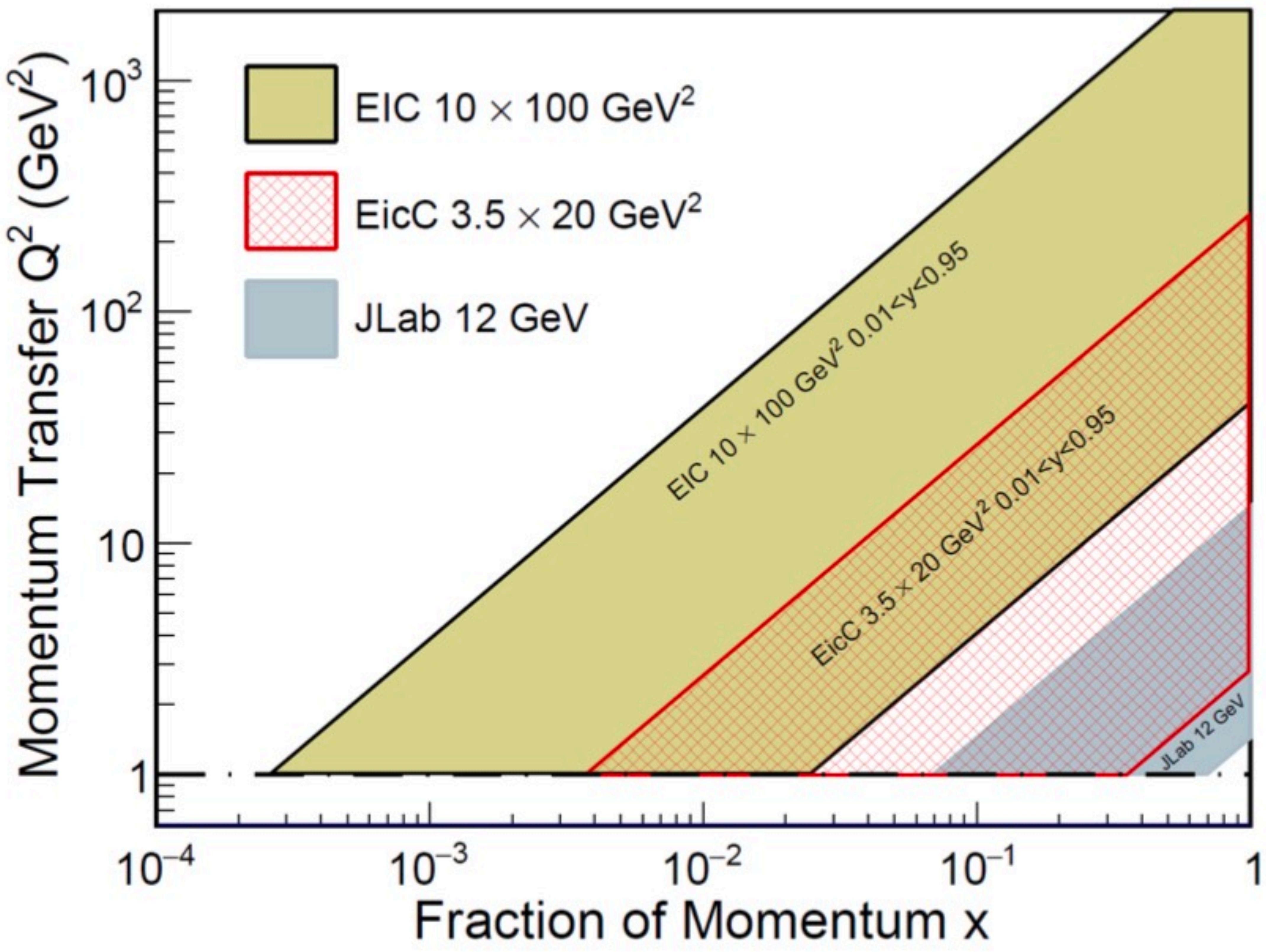
The origin of proton mass



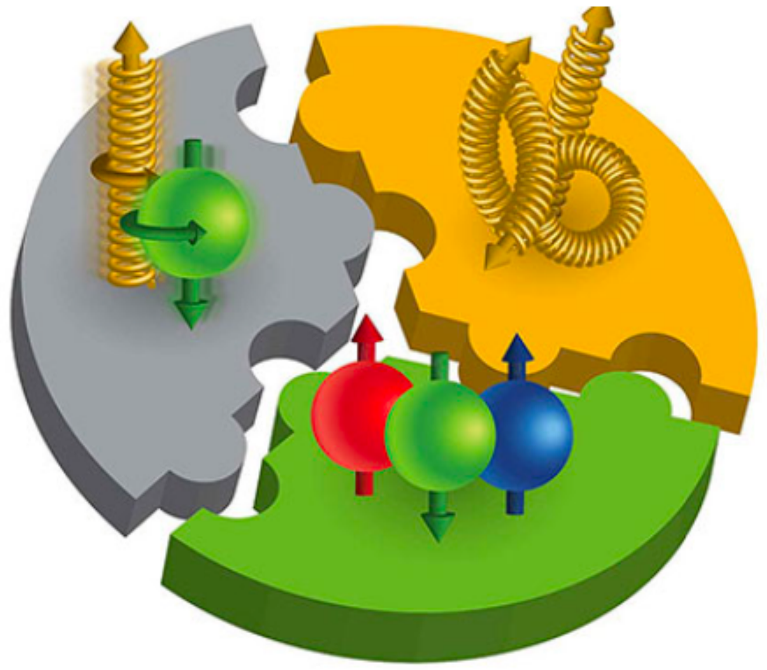
nuclear effects

Complementarity between EIC and EicC





Mapping out the nucleon structure via EICs worldwide

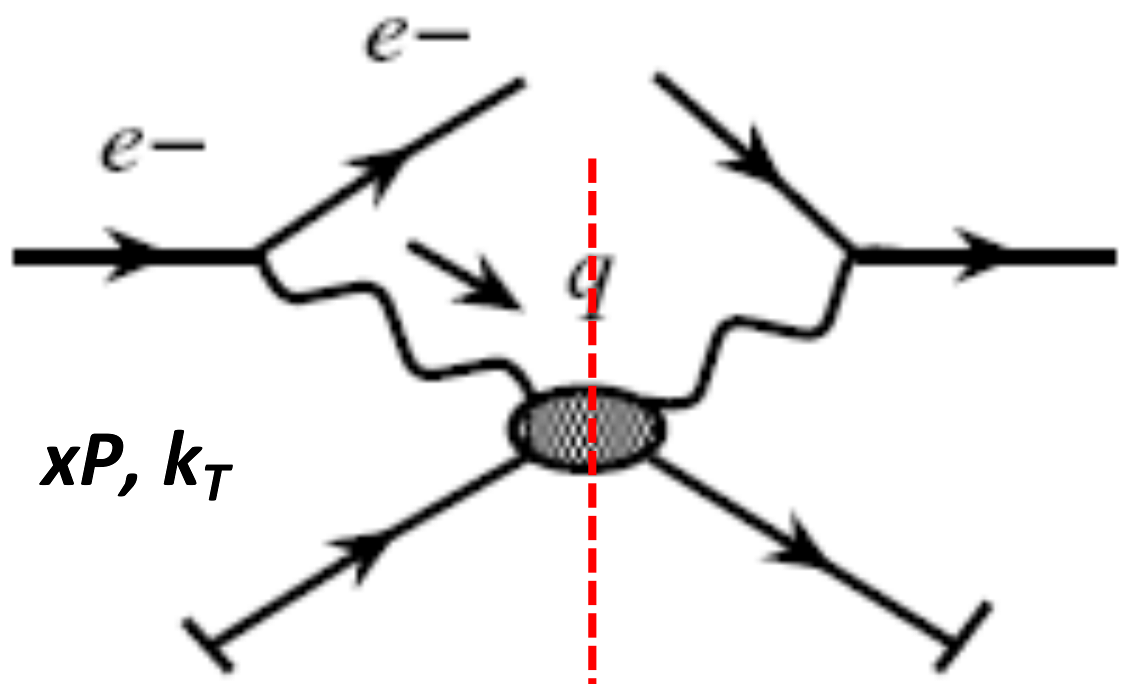


How to probe the nucleon partonic structure?

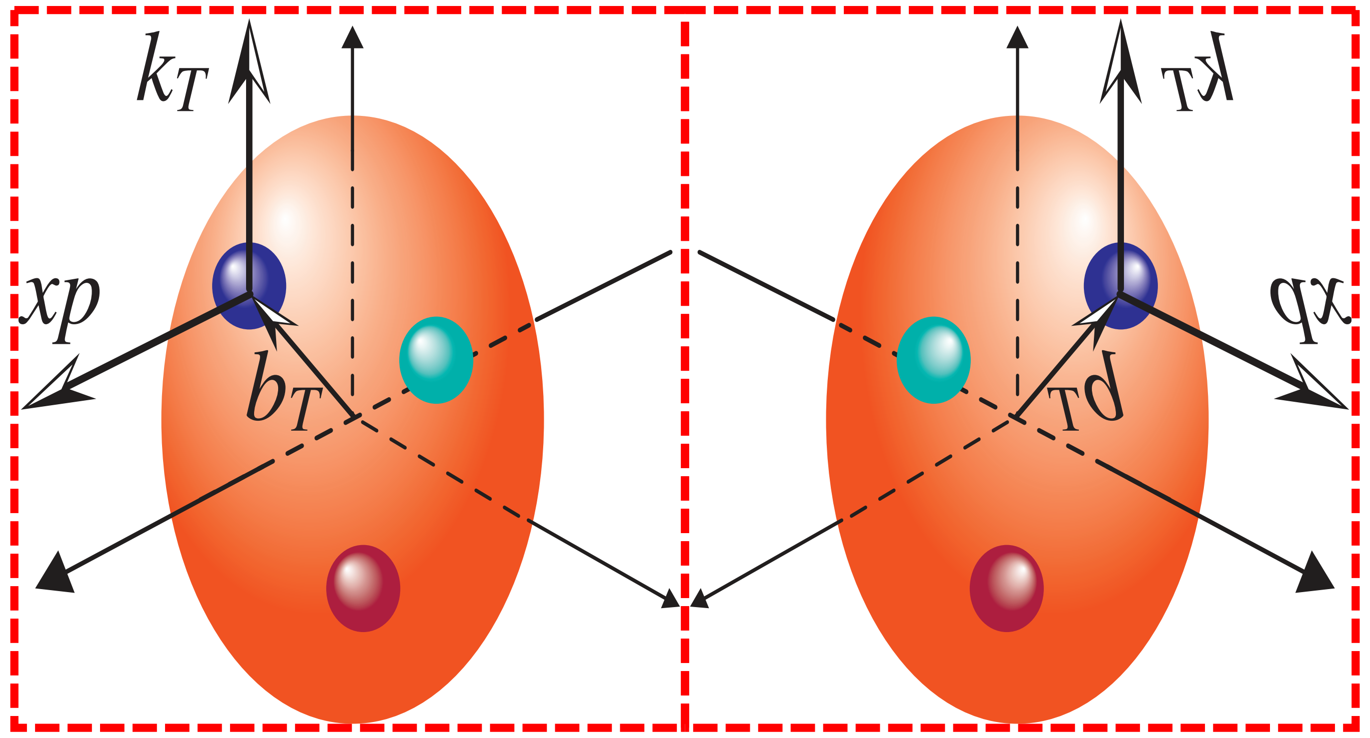
✦ Indispensable joint efforts from experiments and QCD theory

QCD factorization theorem

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



$\otimes$



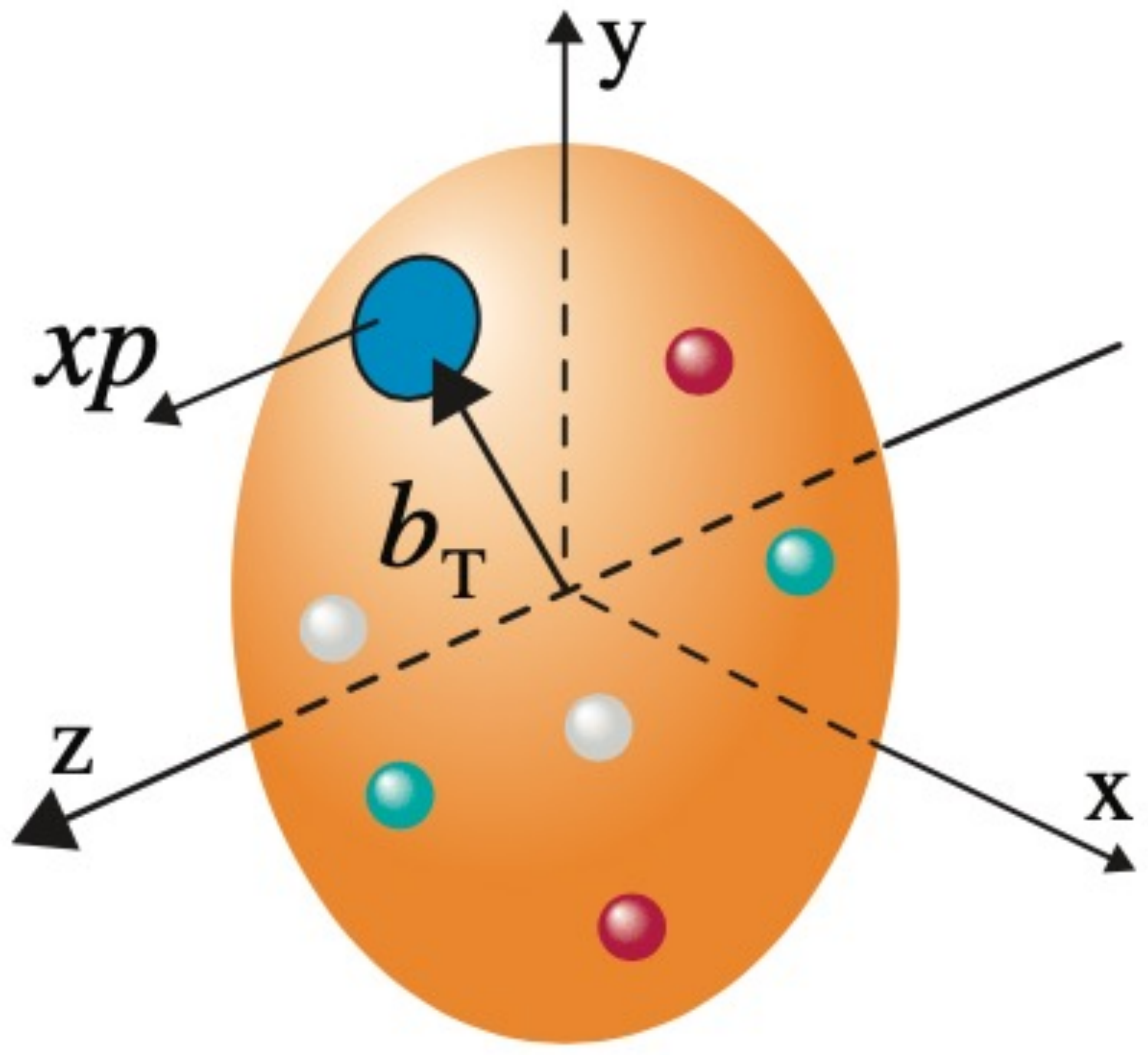
Experimental measurements

Hard part controlled by pQCD theory

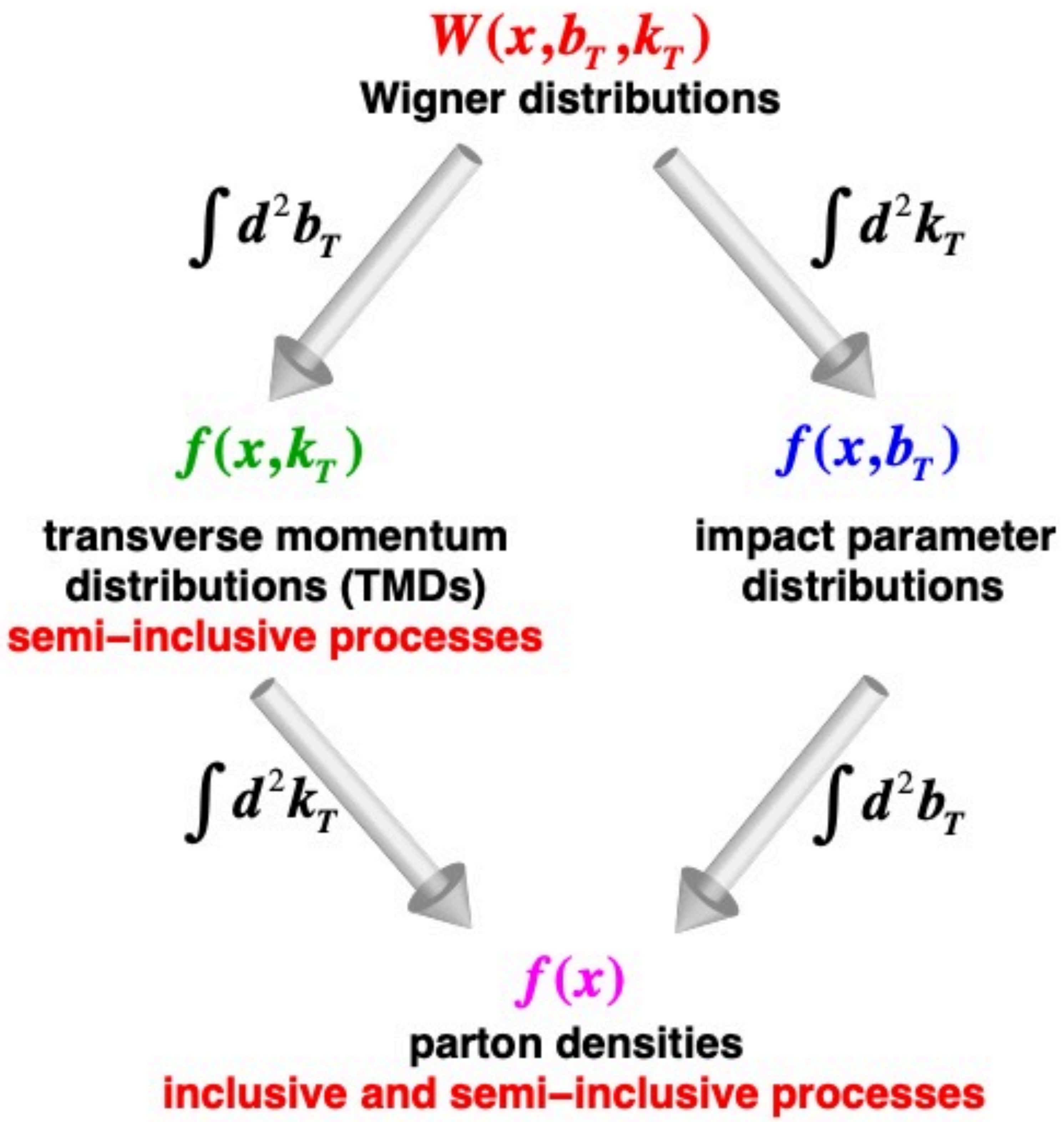
Nucleon partonic structure

Nucleon partonic structure - momentum distribution

- ✦ Multi-dimensional view of nucleon partonic structure



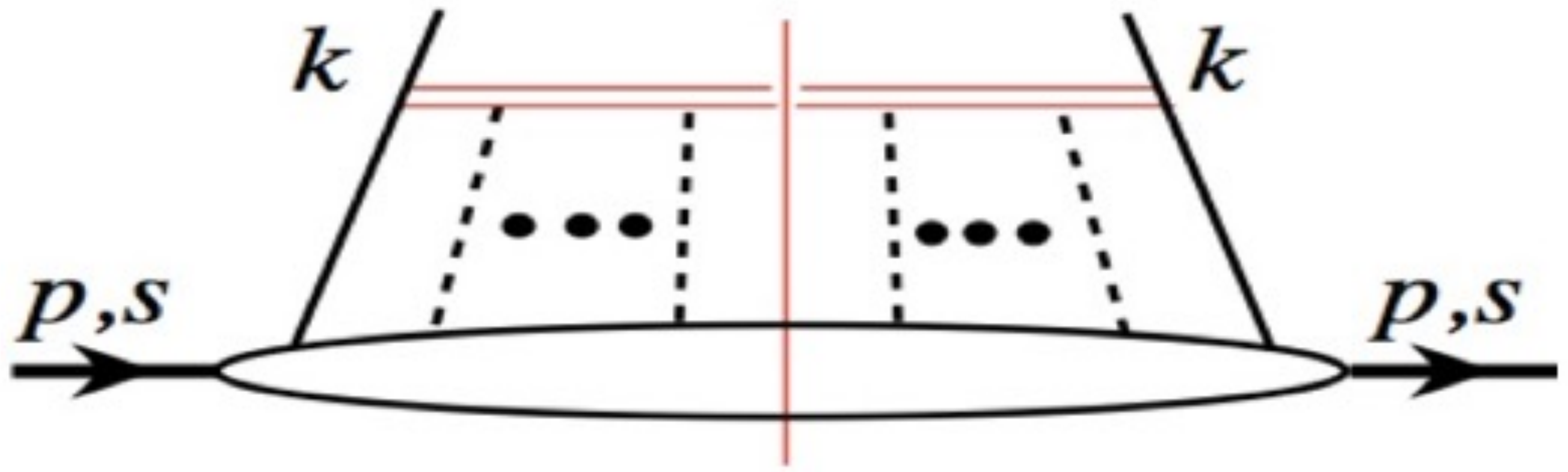
Wigner distribution
5D view



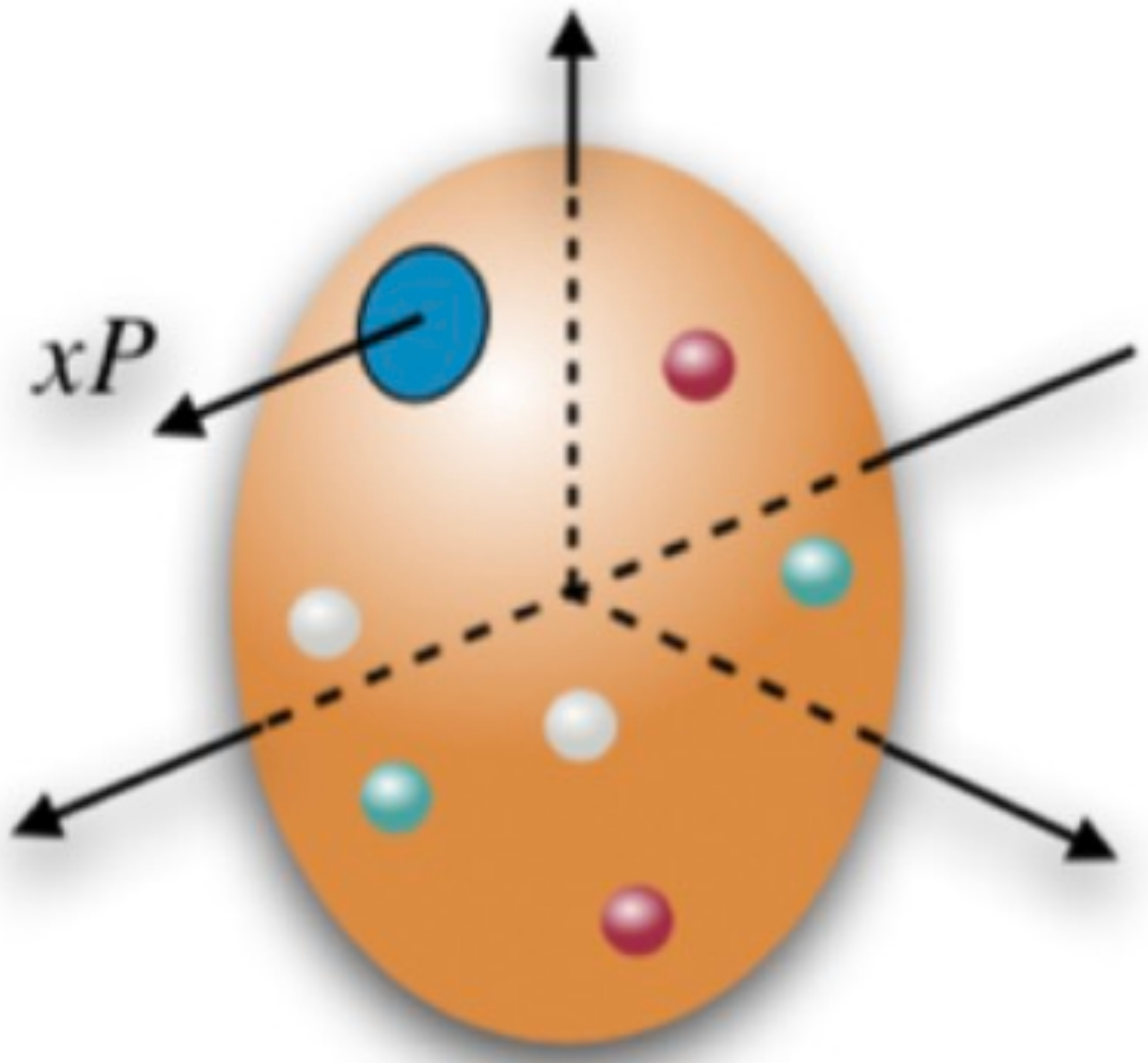
1D momentum distribution: Parton distribution functions (PDFs)

✦ Operator definition of quark PDF

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



- Light cone momentum fraction: $x = k^+/p^+$
- Wilson line to ensure gauge invariance
  $\mathscr{W}(0,y^-) = \mathscr{P} e^{-ig \int_0^{y^-} d\eta^- A^+(\eta^-)}$



✦ Probability interpretation

- The probability density of finding a parton inside a proton
- Satisfies energy conservation $\sum_{a=q,g} \int_0^1 dx x f_{a/p}(x) = 1$

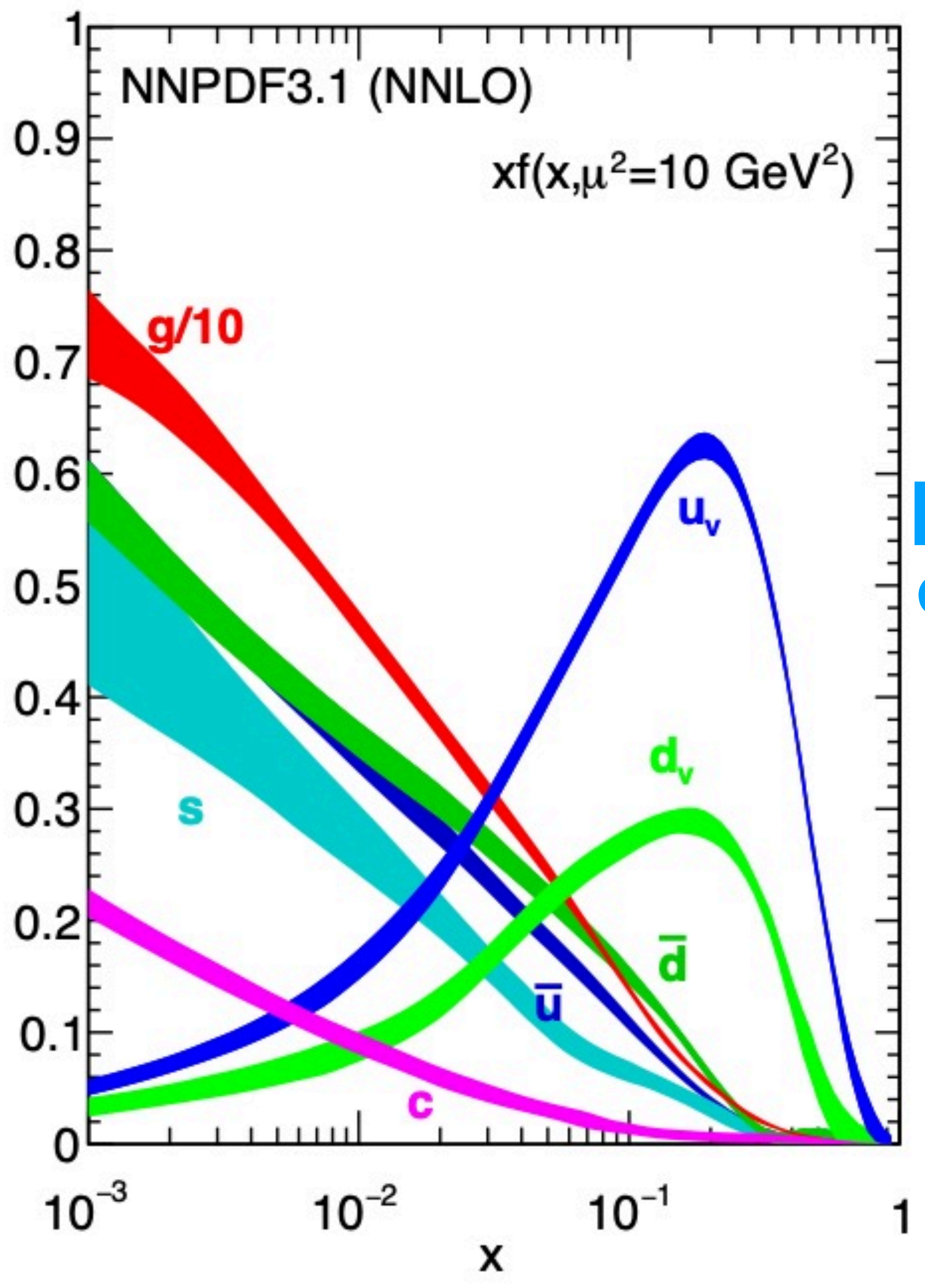
Parton distribution functions

- ✦ PDFs are key ingredient in high energy and nuclear physics
  - Understand the fundamental structure of QCD bound states (JLab, EIC, EicC…)
  - Provide essential baseline for hard probes in heavy ion collisions (RHIC, LHC)
  - Precision test of standard model (LHC)
  - Compute backgrounds in searches for BSM physics (LHC)

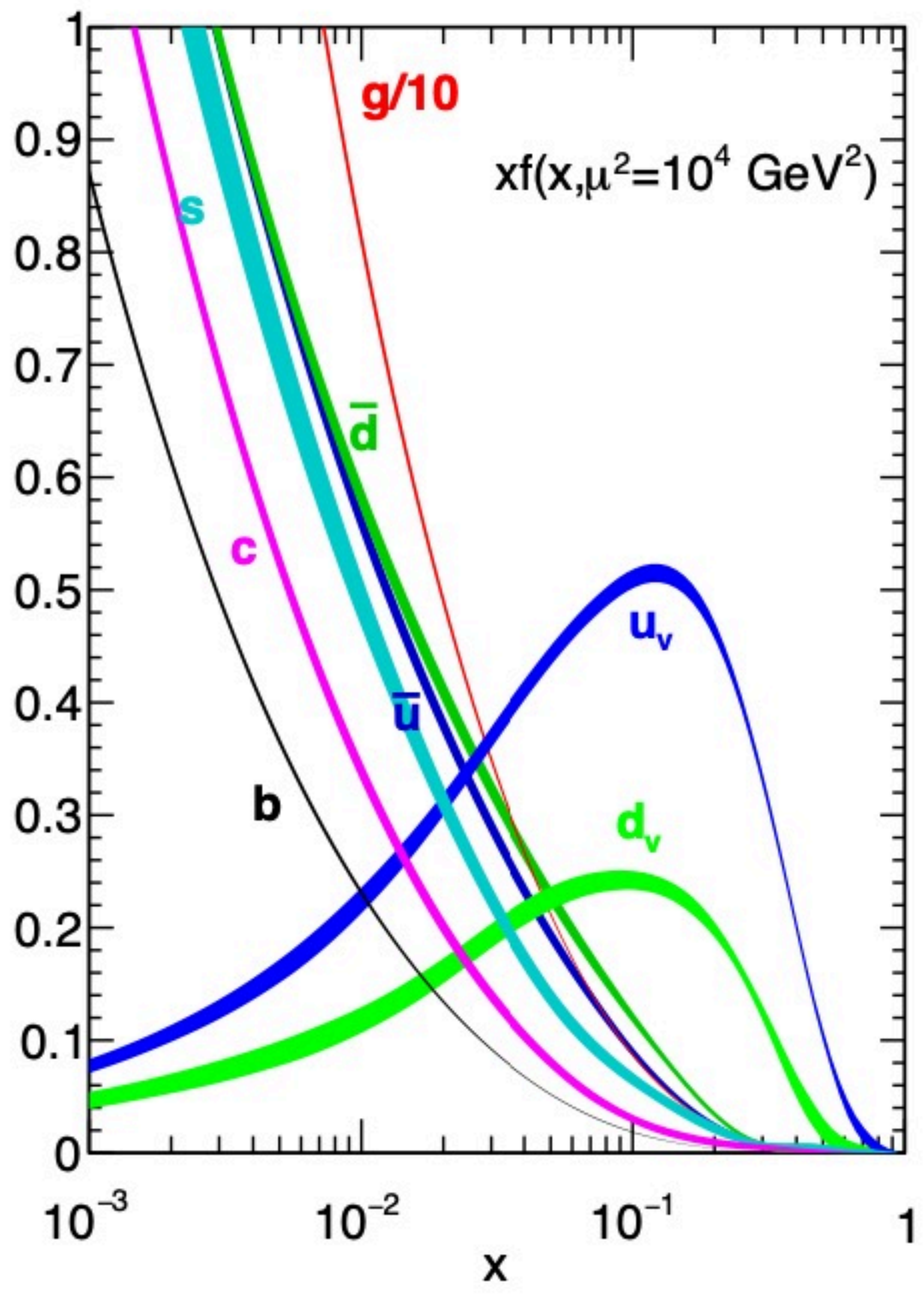
- ✦ Methods to obtain and understand PDFs
  - Nonperturbative models (DSE, χEFT, LFQ, Ads/CFT …)
  - QCD global analysis (measurements + pQCD)
  - Lattice QCD (lattice QFT + high performance computing)
  - Quantum information science (quantum computing)

QCD global analysis of world data

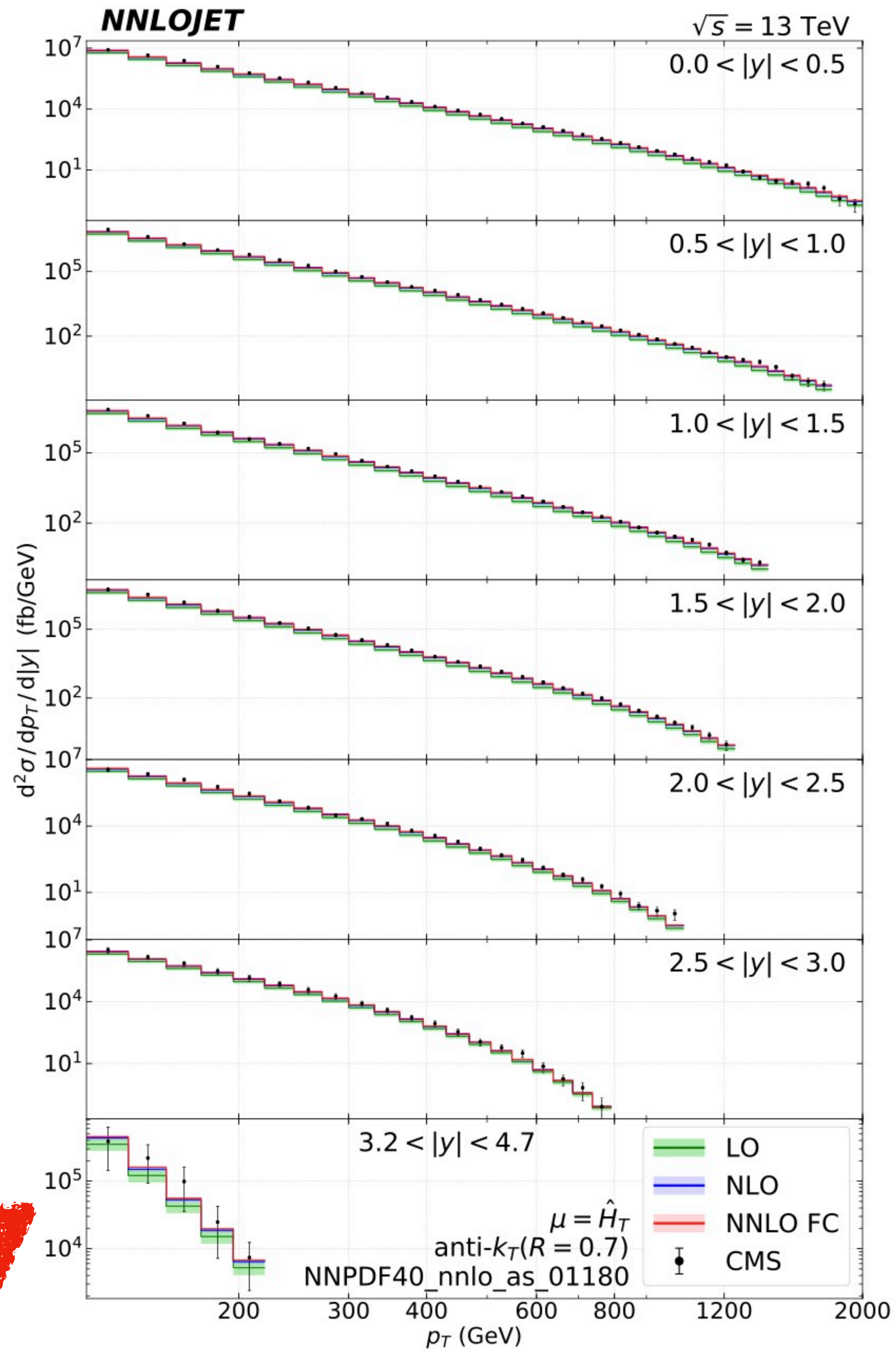
✦ Current knowledge about proton PDFs



QCD evolution



NNPDF:1706.00428



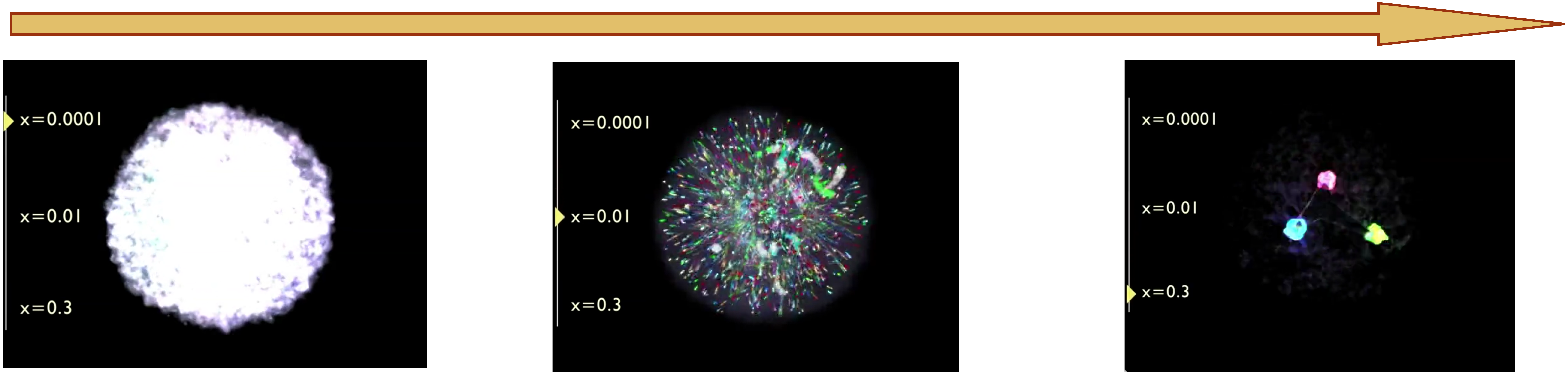
Predictive power of pQCD

X. Chen et al, JHEP, 2022

QCD global analysis of world data

✦ Current knowledge about proton PDFs

See video at: http://eicug.org/



gluon   sea   valence

Nucleon structure: quantum probability, there is no still picture for partons inside nucleon.

PDFs on lattice

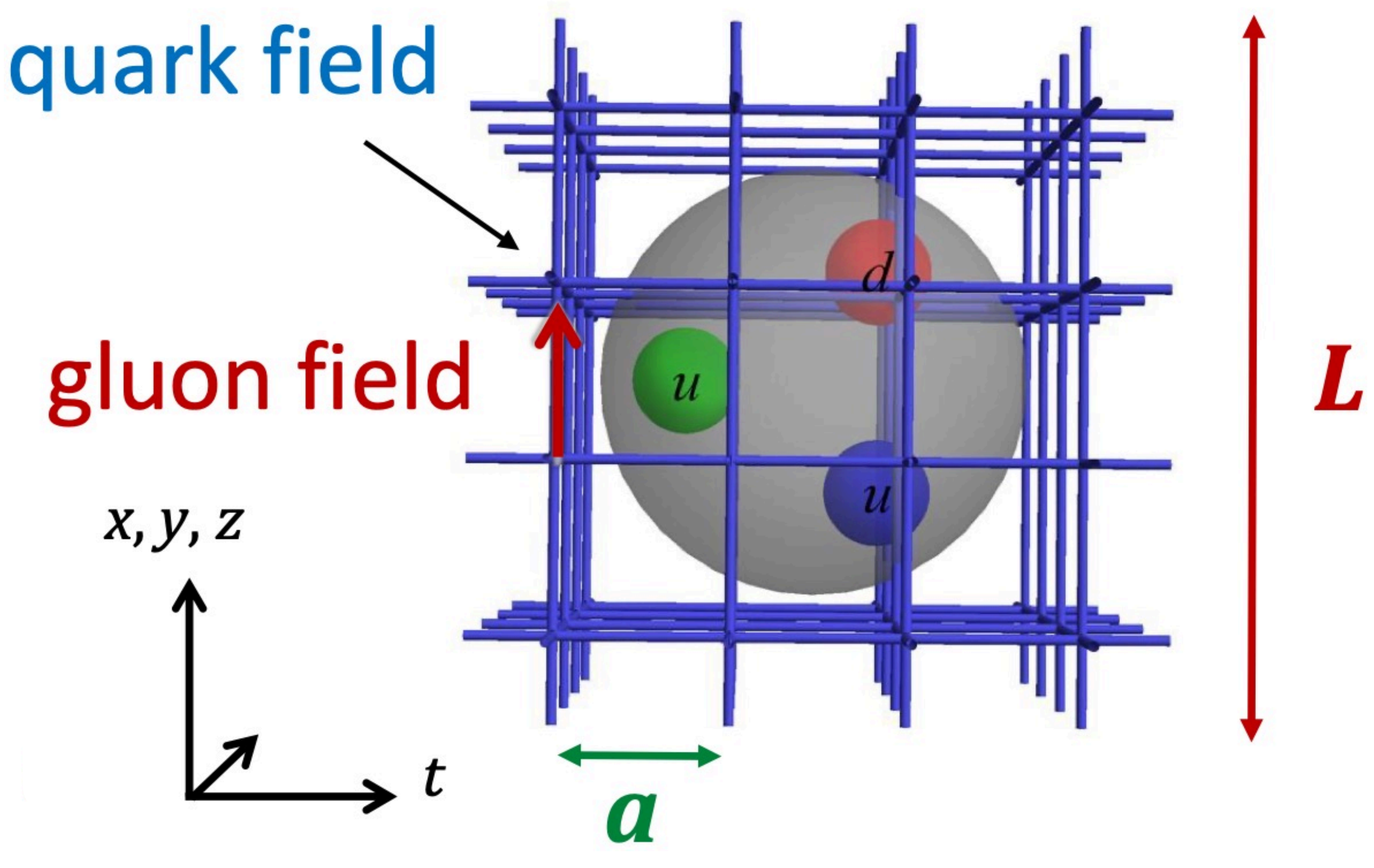
- ✦ Traditional lattice calculation: using OPE to provide moments

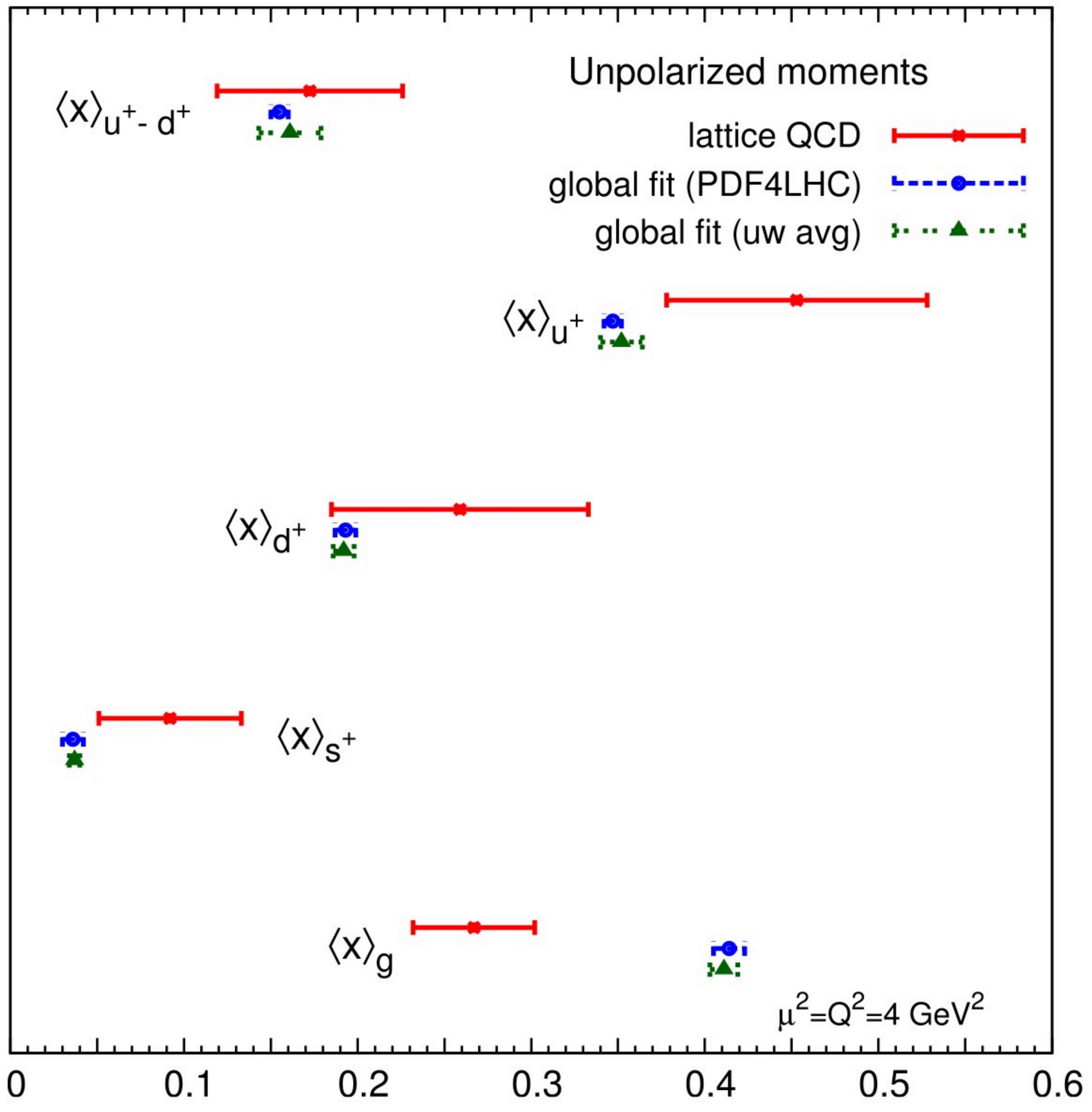
$$\langle x^{n-1}\rangle = \int_{-1}^{1} dx x^{n-1} f_{q/p}(x)$$

  - PDFs can not be directly calculated on lattice
  - Lattice results are not compatible with their global-fit counterparts

- ✦ New strategies in lattice calculation - finite boost parton distribution
  - quasi-PDF using LaMET (Ji, 13)
  - Pseudo-PDF (Radyushkin, 17)
  - Lattice cross-section (Ma and Qiu, 14, 17)
  - …

Progress in Particle and Nuclear Physics 100 (2018) 107–160

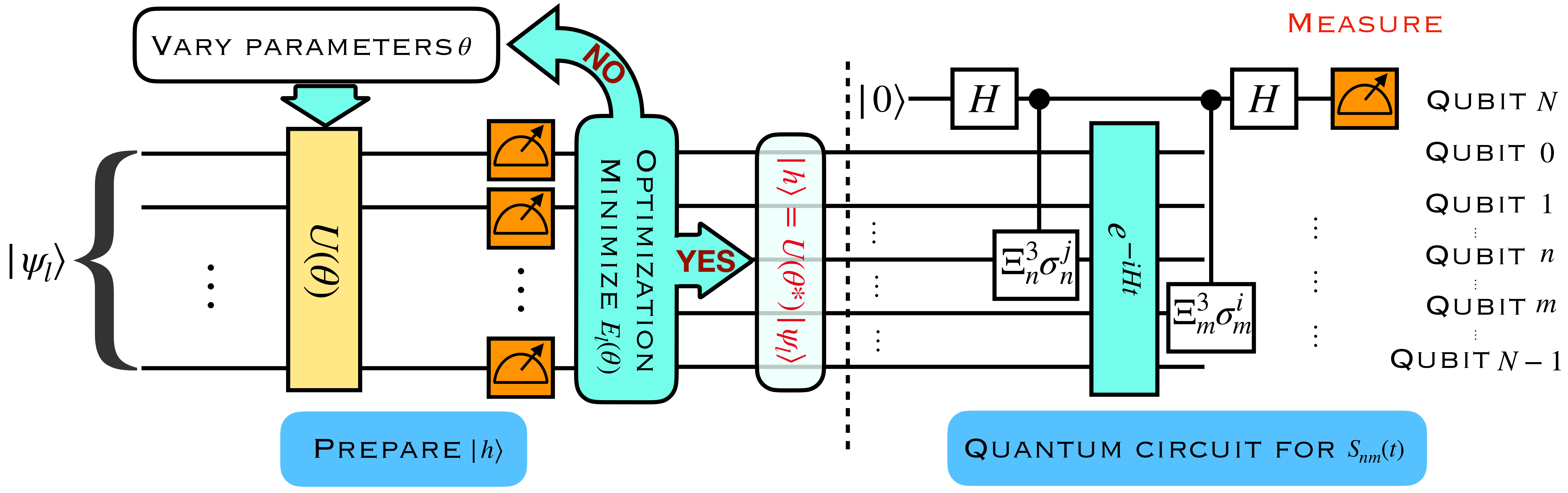




1D collinear PDFs from Quantum computing

✦ Strategies in our quantum computing

QuNu Collab. PRD(L) 2022



1. Map quantum field to qubits

$$f_{q/h}(x) = \int \frac{dz}{4\pi} e^{-ixM_h z} \langle h | e^{iHt} \bar{\psi}(0,-z) e^{-iHt} \gamma^{+} \psi(0,0) | h \rangle$$

2. Prepare the initial hadronic state

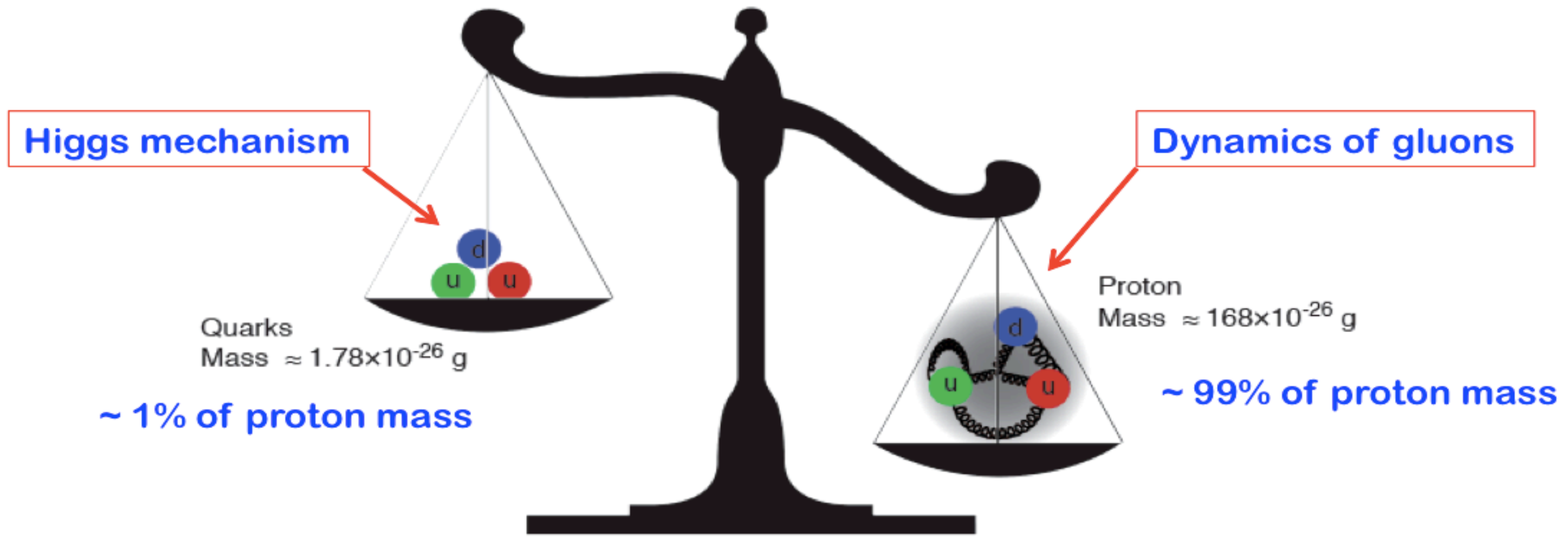
3. Evaluate the real-time dynamical correlation function

4. Measurement of relevant observable

Numerical results from quantum computing in NJL model

✦ Measurement of hadron mass

g	0.2	0.4	0.6	0.8	1.0
$M_{h,\mathrm{QC}}a$	1.002	1.810	2.674	3.534	4.352
$M_{h,\mathrm{NUM}}a$	1.001	1.801	2.659	3.509	4.342



$$M_h = \langle h|H|h\rangle - \langle\Omega|H|\Omega\rangle$$

$$ma = 0.2 \qquad N = 12$$

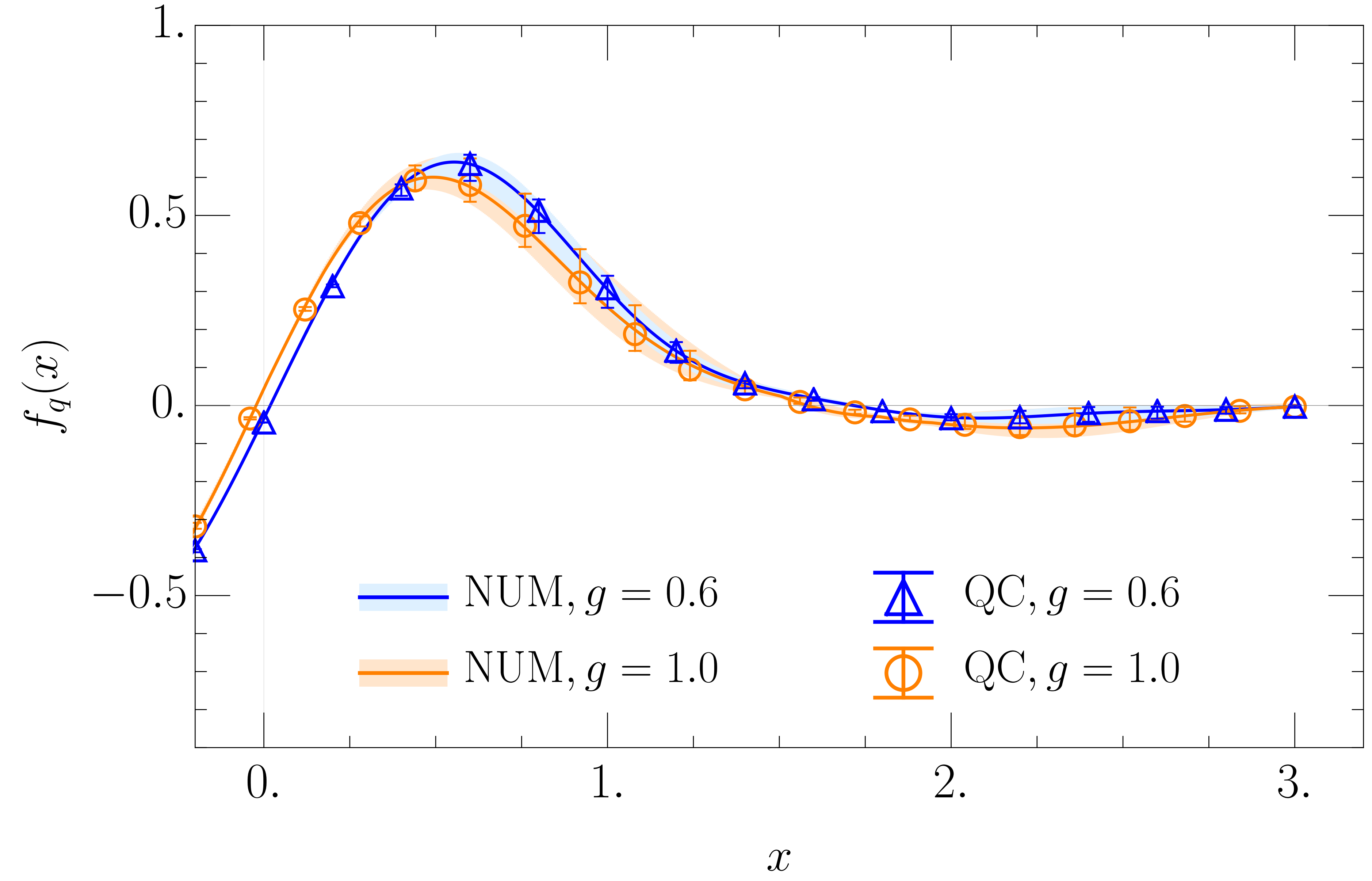
- Considering the current limitations of using real quantum devices, the results are generated using a classical simulation of the quantum circuit
- Measure the mass of the lowest-lying ud-like hadron in NJL model with 2 flavors
- QCD dynamics generates majority of the hadron mass

Numerical results from quantum computing

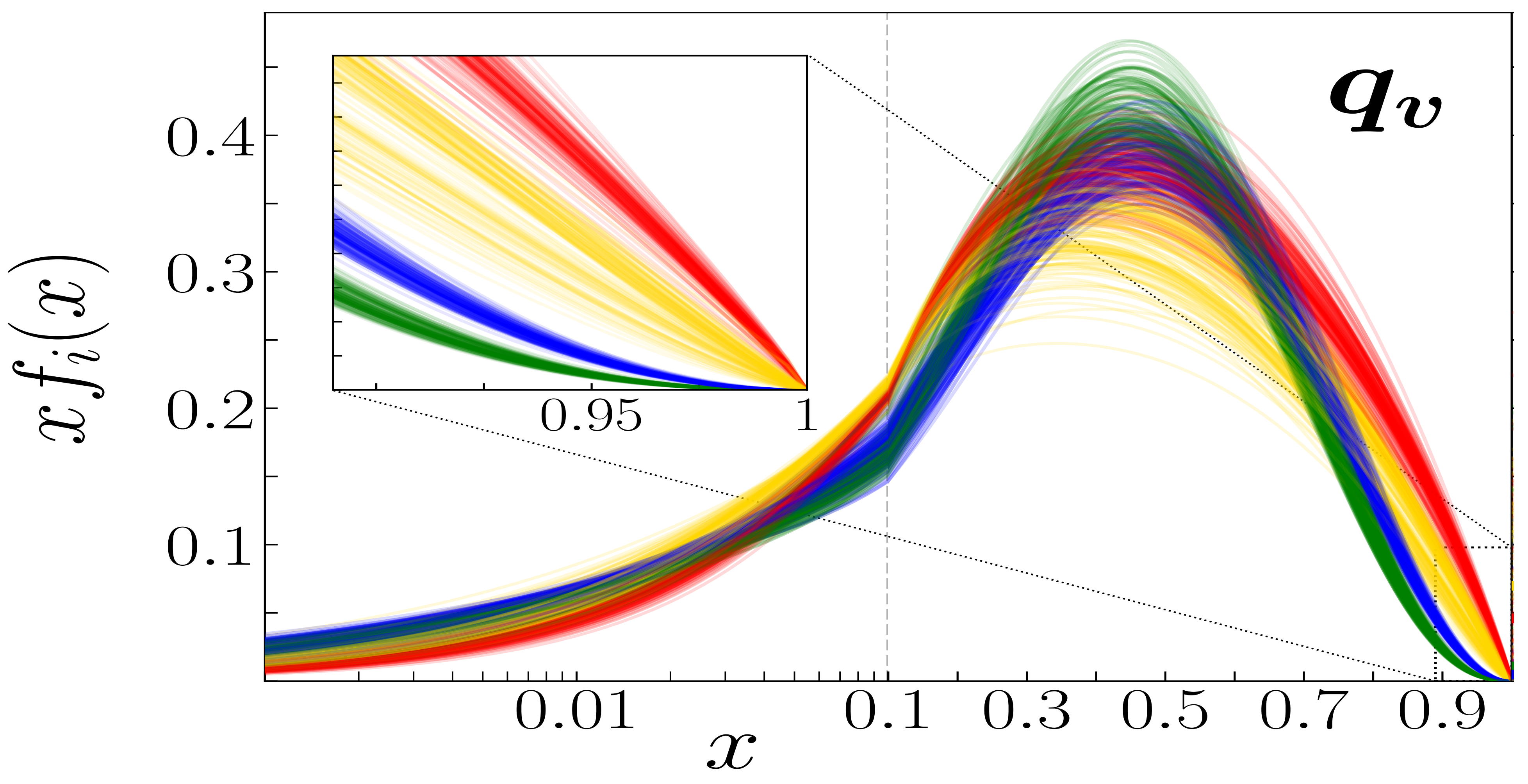
QuNu Collab. PRD(L) 2022

✦ quark PDF of the lowest-lying zero-charge hadron

- Good agreement between quantum computation and numerical diagonalization
- The non-vanishing contributions in the $x > 1$ are partly due to the finite volume effect
- We observe the expected peak around $x = 0.5$ and qualitative agreement with pion PDFs



JAM Collaboration, PRL, 2021



Nucleon partonic structure - spin configuration

✦ Naive parton model

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

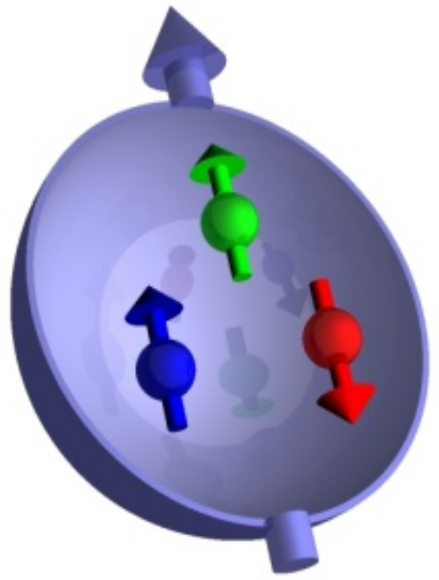
proton spin 1/2 is consistent with naive parton model, but contradict with experiments.

✦ Proton spin decomposition

Jaffe, Manohar; Ji

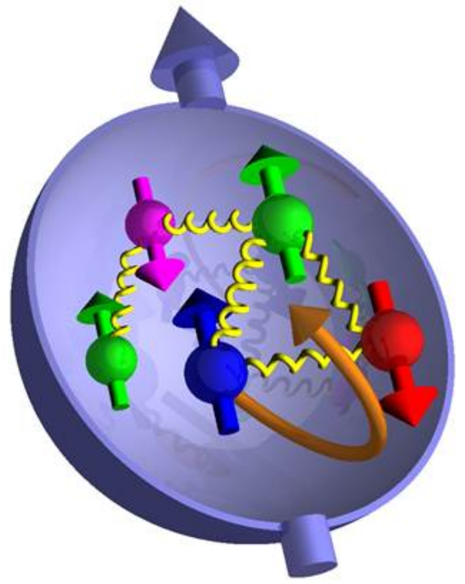
$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}|J^z_{QCD}|P,\frac{1}{2}\right\rangle = \frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2) + \int_0^1 dx\Delta G(x,Q^2) + \int_0^1 dx(\sum_q L_q^z + L_g^z)$$

total quark spin



gluon spin

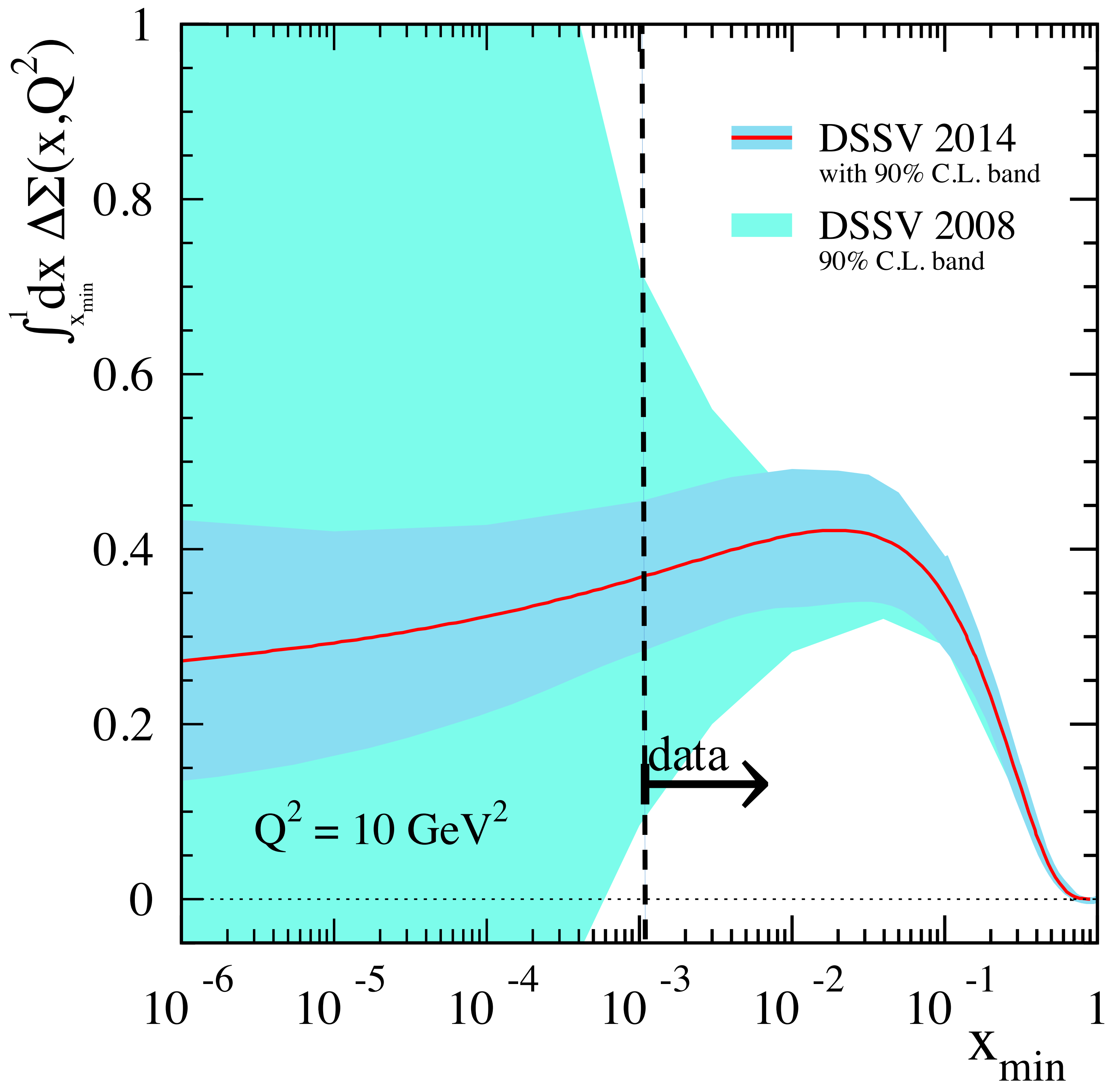
angular momentum



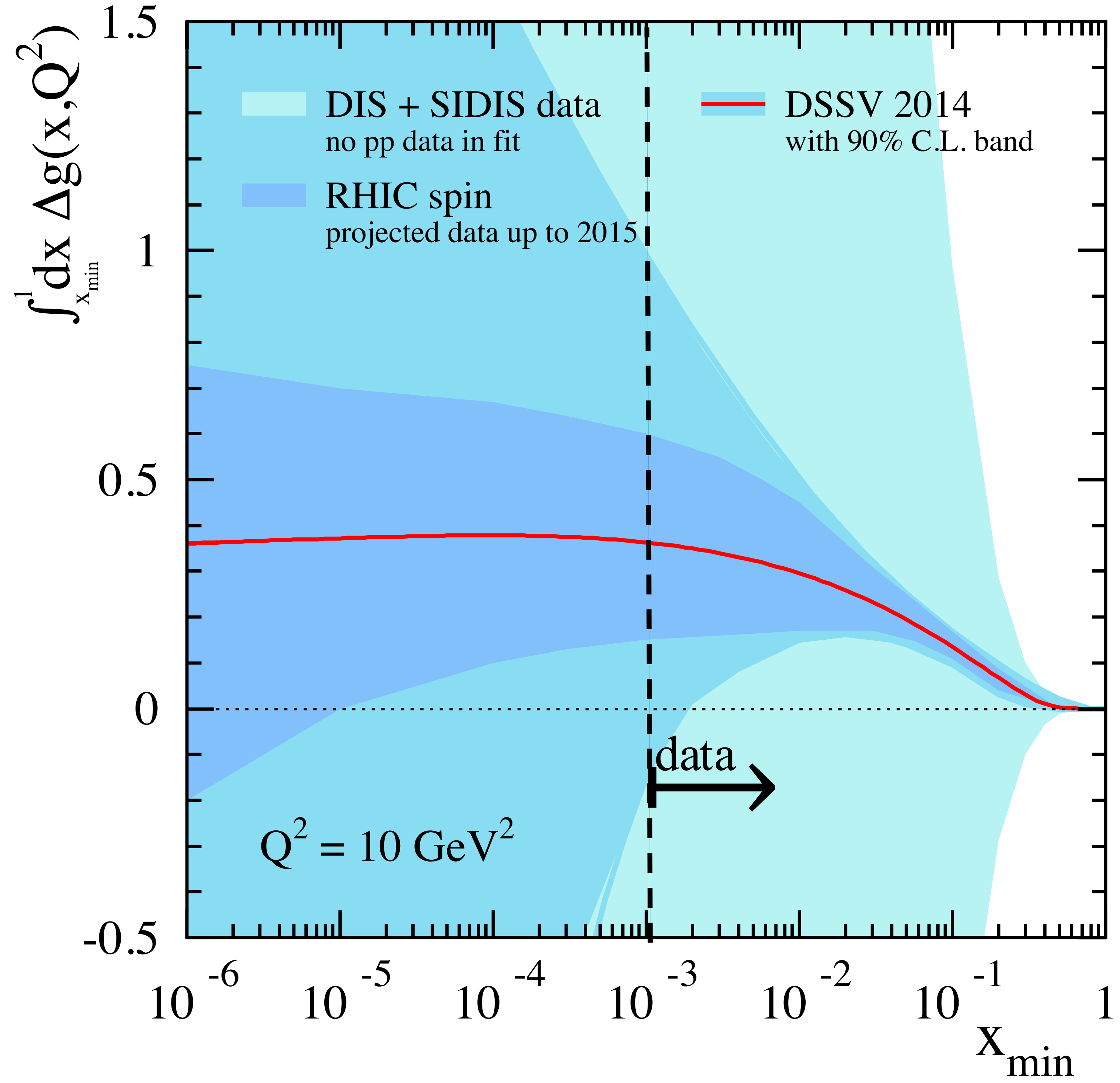
- Spin is one of the fundamental properties of matter
- We don't know yet how the spin of proton arises in terms of its quarks and gluons - spin crises.

what do we know about the proton spin?

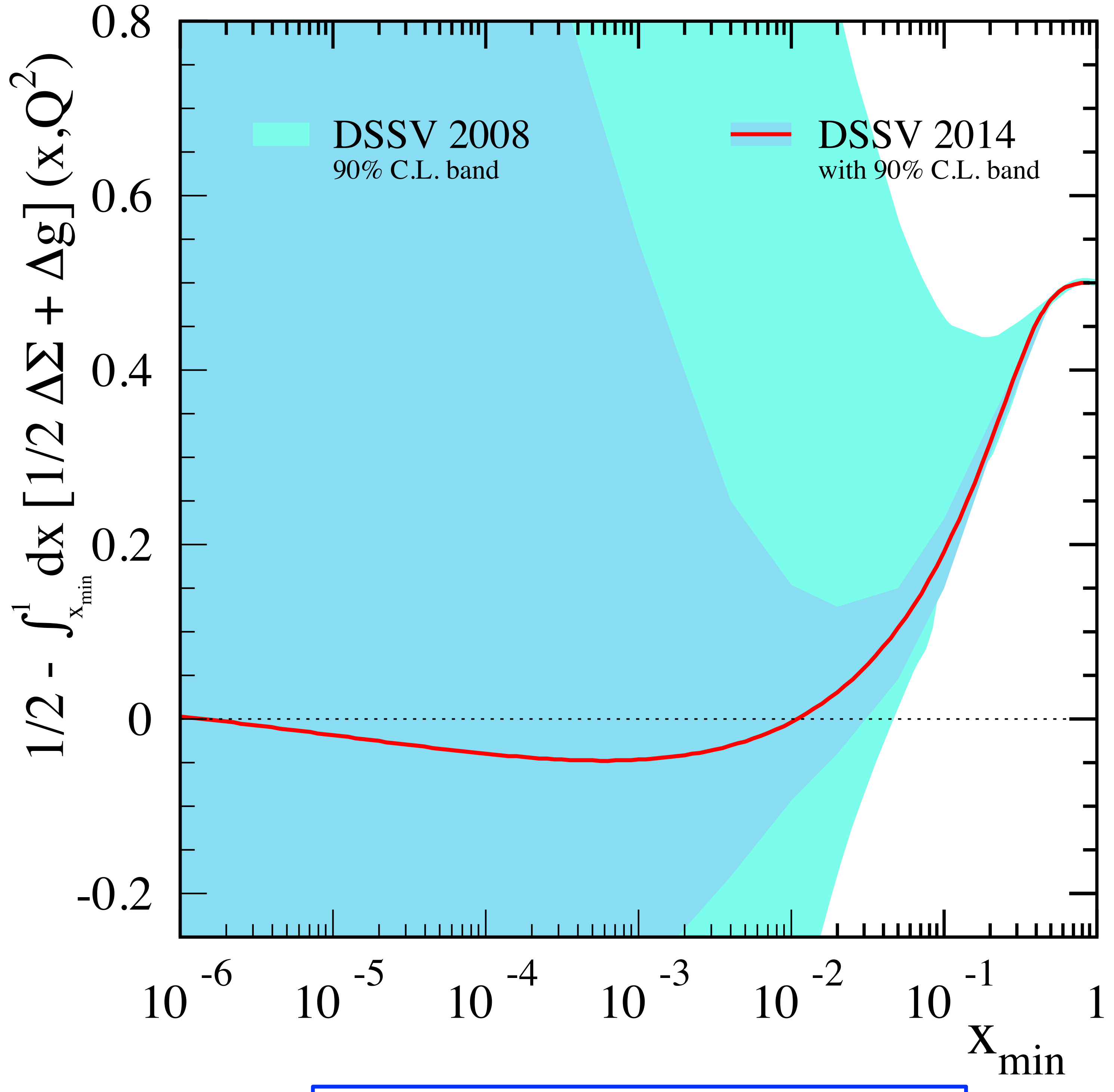
✦ Current knowledge about proton spin decomposition from world data



Quarks ~ 30%



Gluon ~ 40%

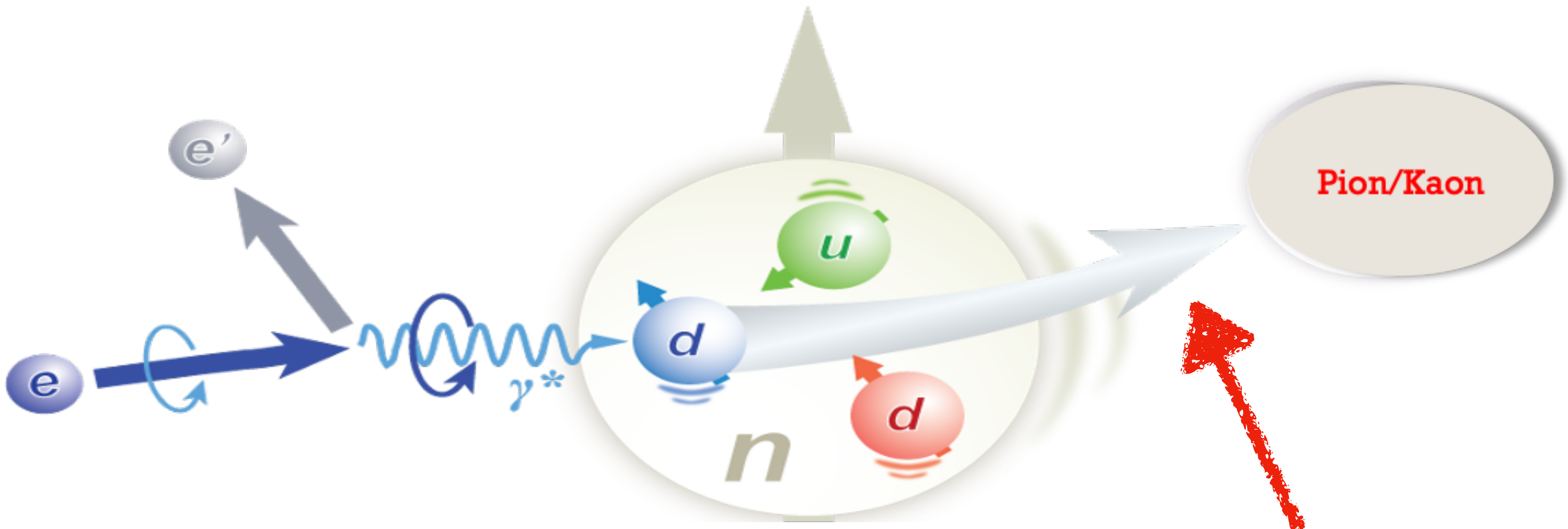


Orbital angular momentum ?

It is more than the number ½ ! It is the interplay between the intrinsic properties and interactions of quarks and gluons

What can we do in future to pin down the proton spin?

✦ Polarized structure function measurement g_1



hadron fragmentation

- Leading order cross section

Polarized PDFs

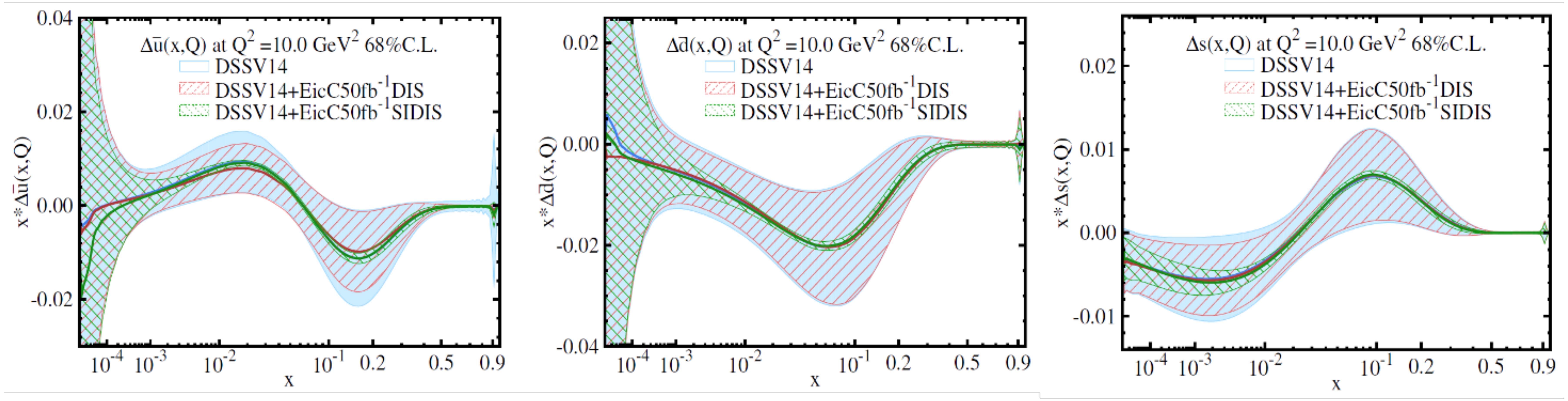
$$g_1^h(x,Q^2,z) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q(x,Q^2) D_q^h(z,Q^2) + \Delta\bar{q}(x,Q^2) D_{\bar{q}}^h(z,Q^2)\right]$$

Extracted nucleon structure information: polarized PDFs (helicity distribution)

What can we do in future to pin down the proton spin?

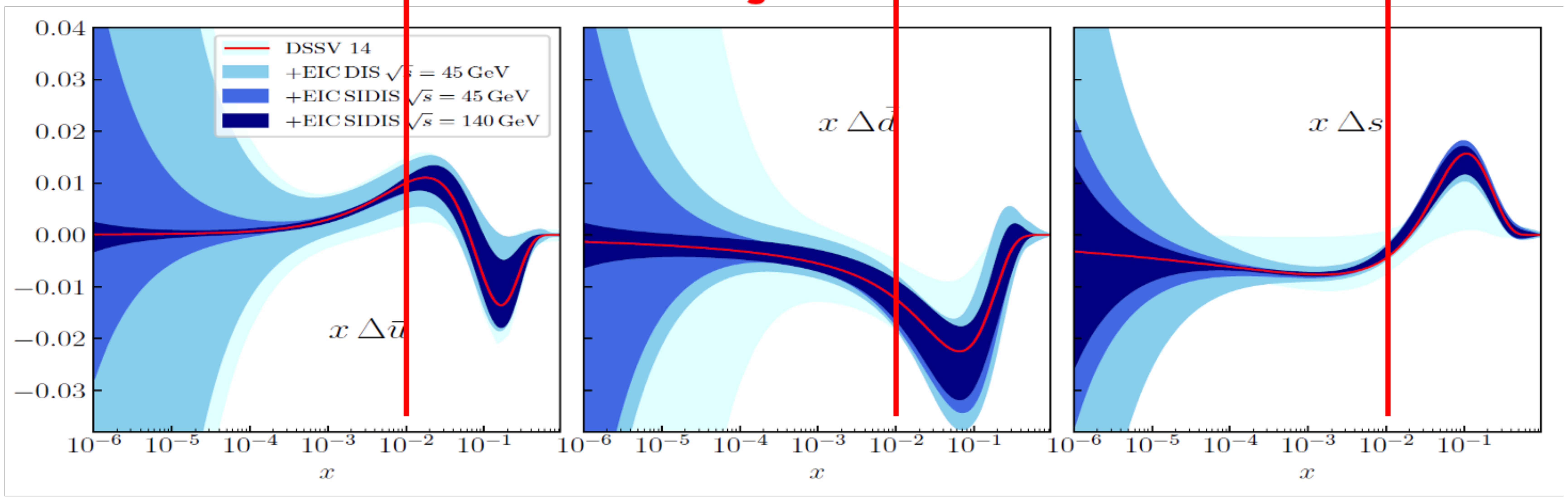
✦ SIDIS for flavor decomposition

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



EicC white paper

EicC coverage

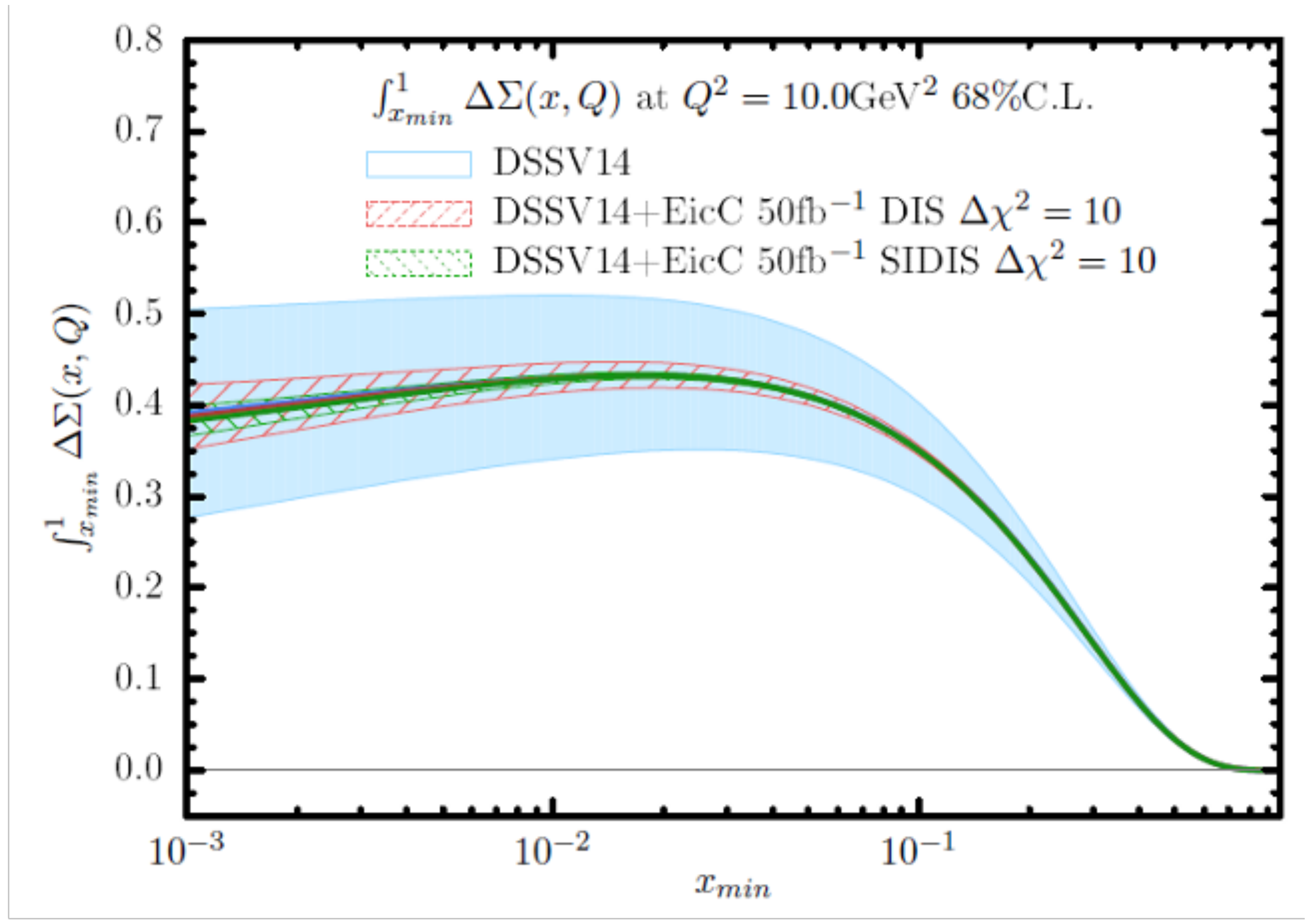


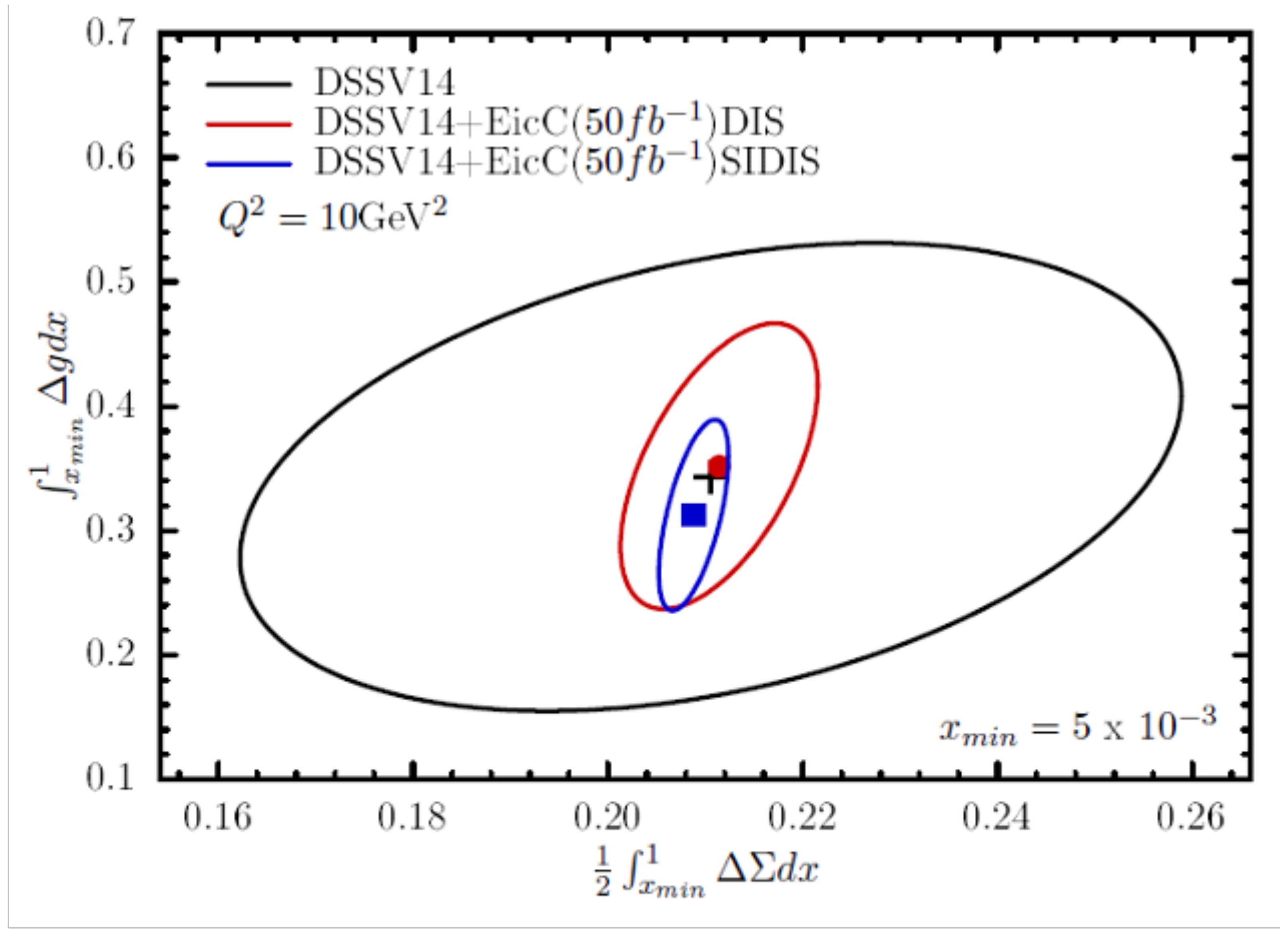
EIC Yellow Report

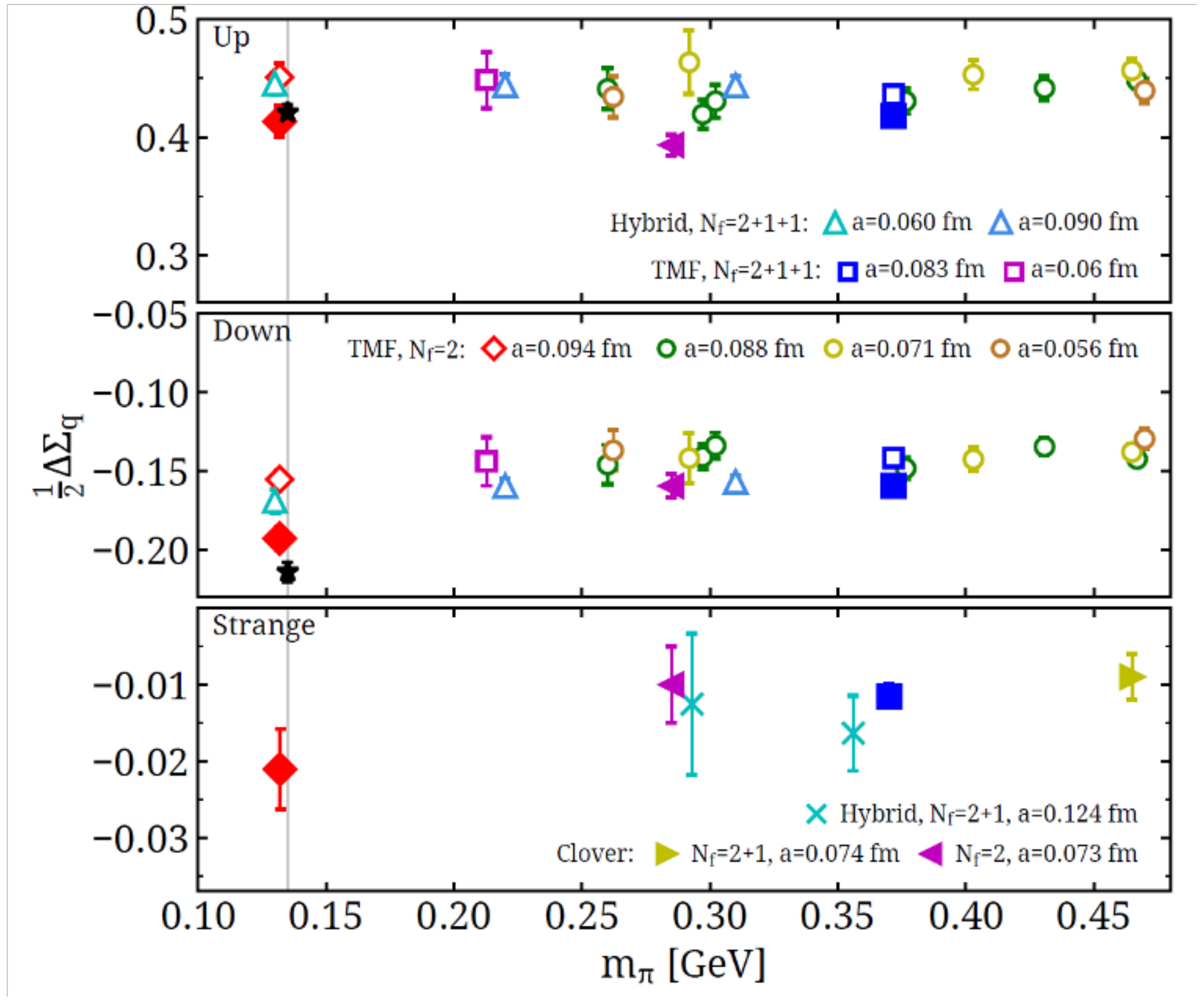
What can we do in future to pin down the proton spin?

✦ Parton spin contribution to proton spin

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







The power of EicC for proton spin!

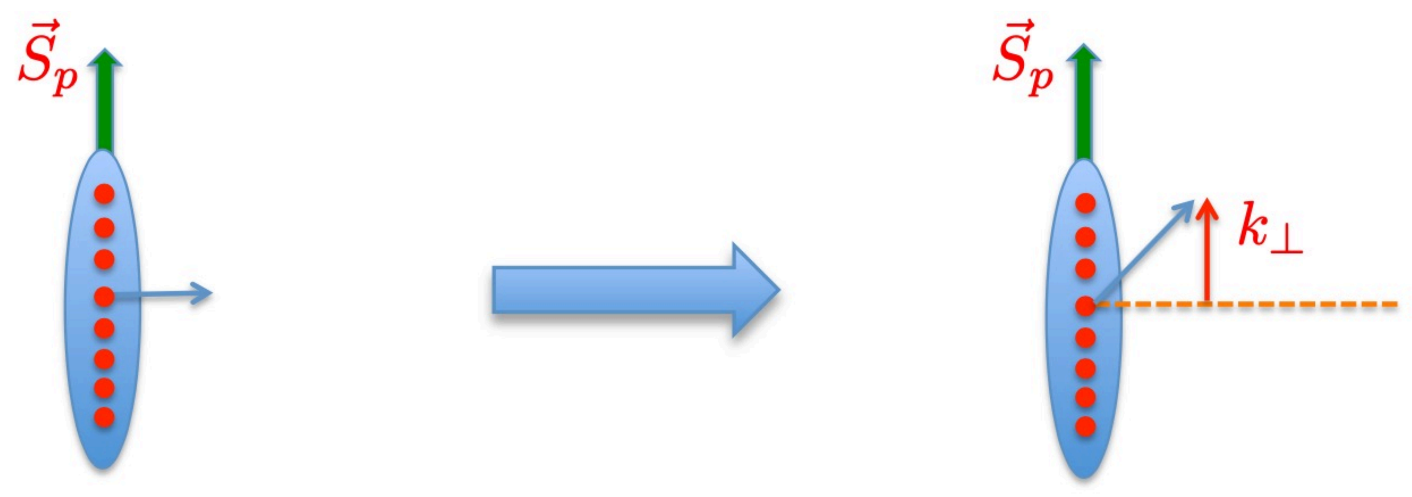
Lattice QCD simulations

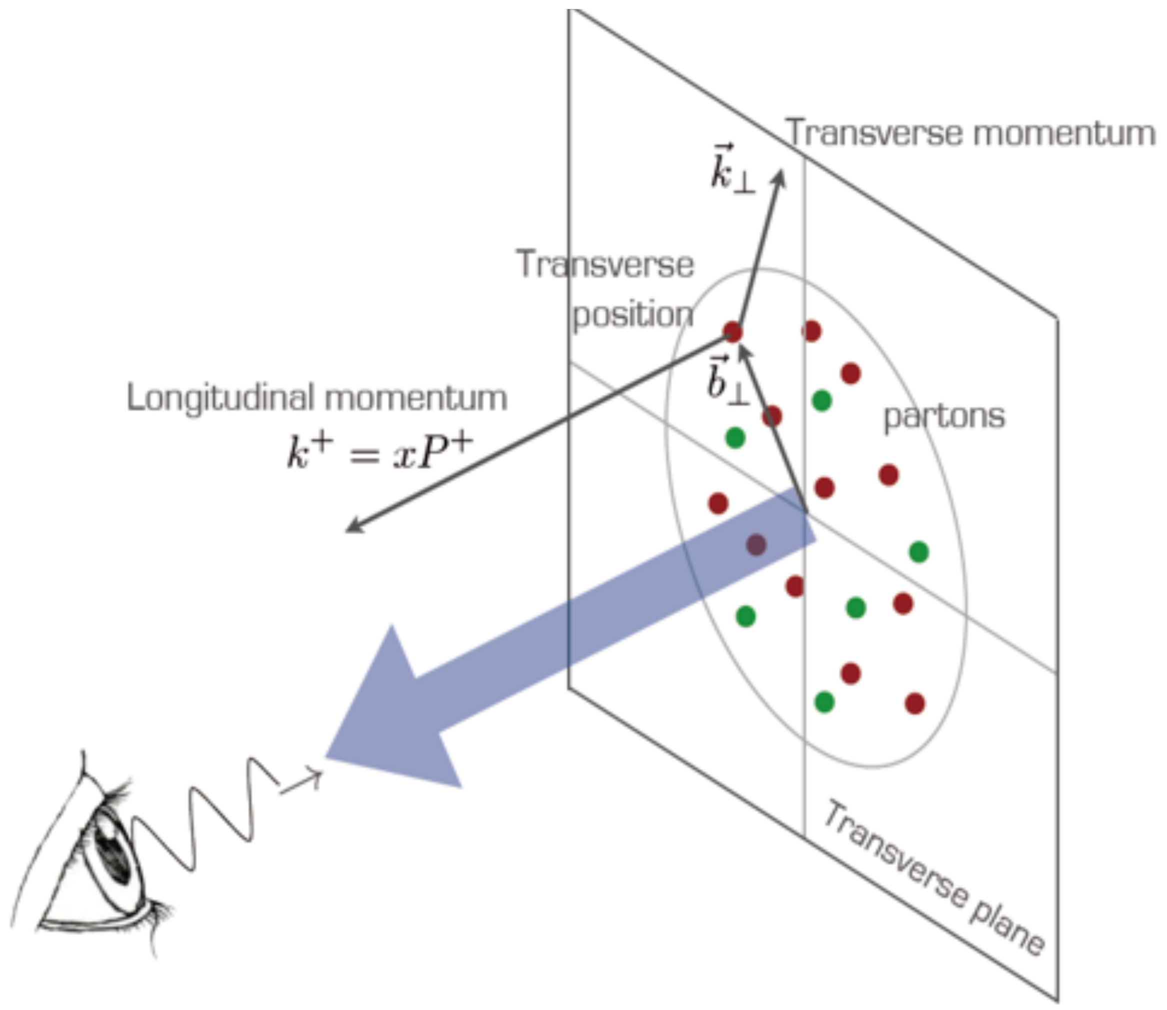
PRL119.142002, 2017

Nucleon partonic structure - 3D imaging

Nucleon partonic structure - 3D imaging

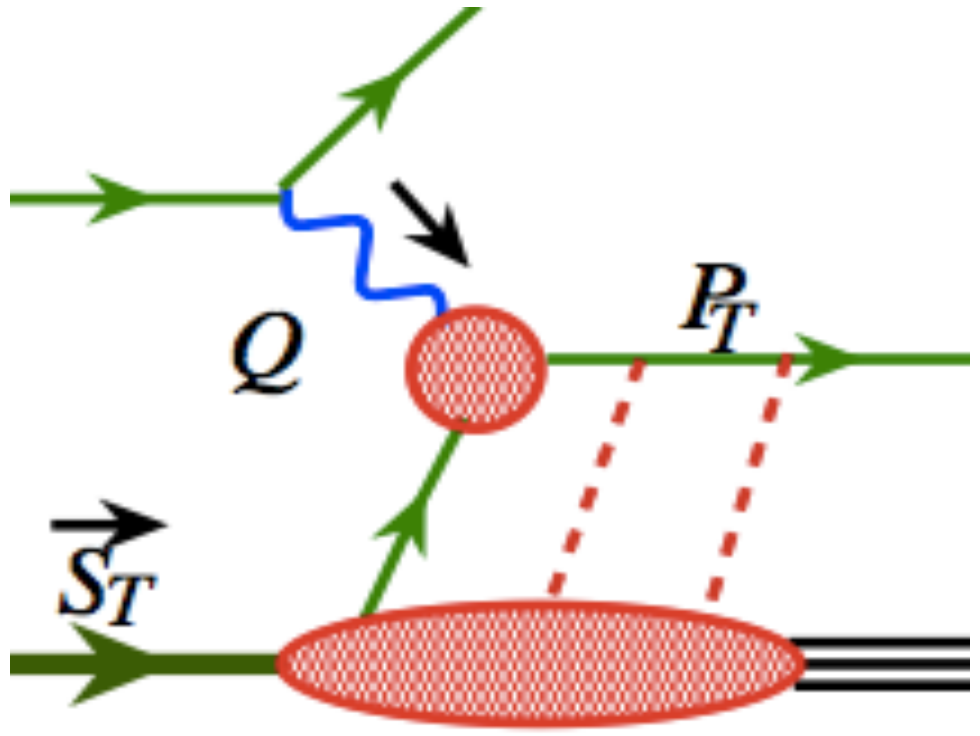
✦ Transverse momentum dependent PDFs (TMDs)





$f(x)$ — Collinear PDFs → $f(x, k_\perp)$ — Transverse momentum distributions (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 (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	$f_1 =$		$h_1^{\perp} =$ Boer-Mulders
L		$g_1 =$ Helicity	$h_{1L}^{\perp} =$ Worm Gear
T	$f_{1T}^{\perp} =$ Sivers	$g_{1T} =$ Worm Gear	$h_1 =$ Transversity $h_{1T}^{\perp} =$ Pretzelosity

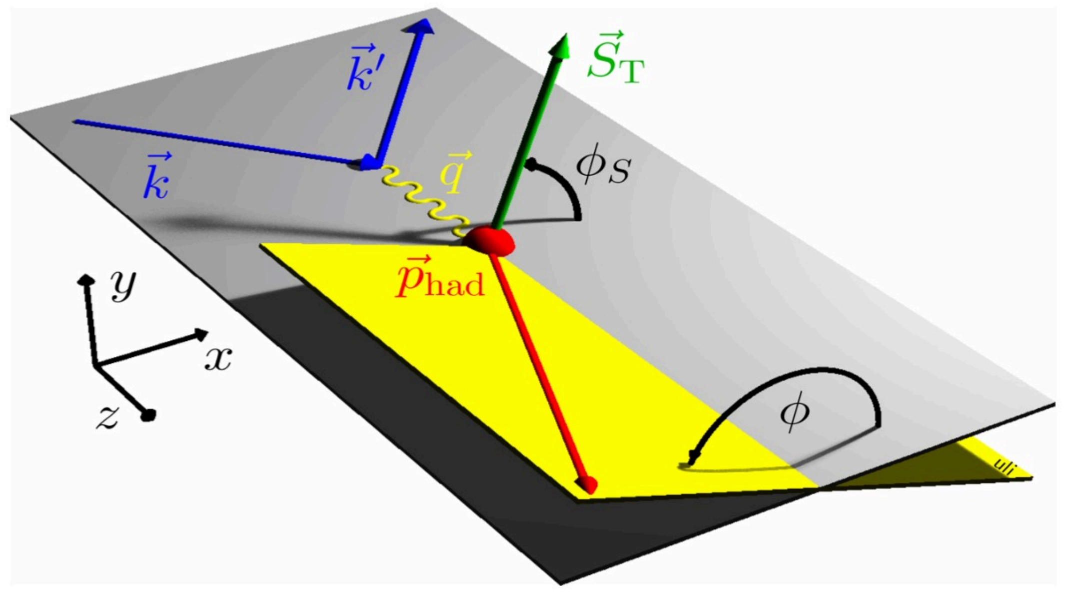
Nucleon Spin *Quark Spin* **Survive the k_T integration, yield 1D pdfs**

Nucleon partonic structure - single transverse spin asymmetry

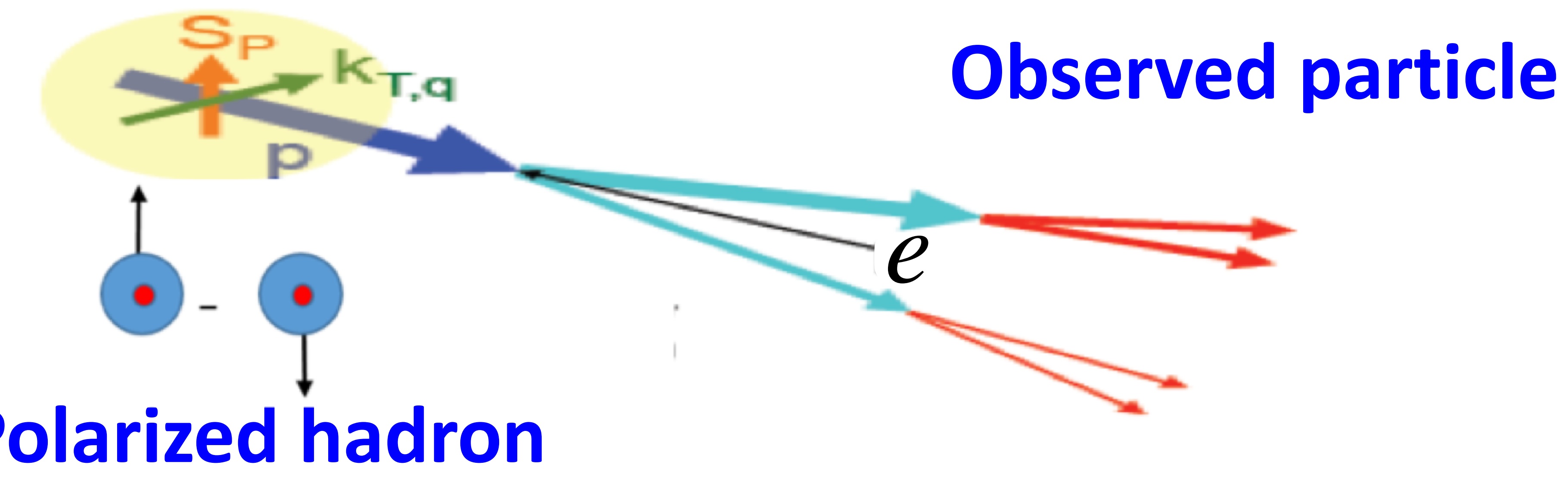
✦ Transverse polarized proton + unpolarized electron

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

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



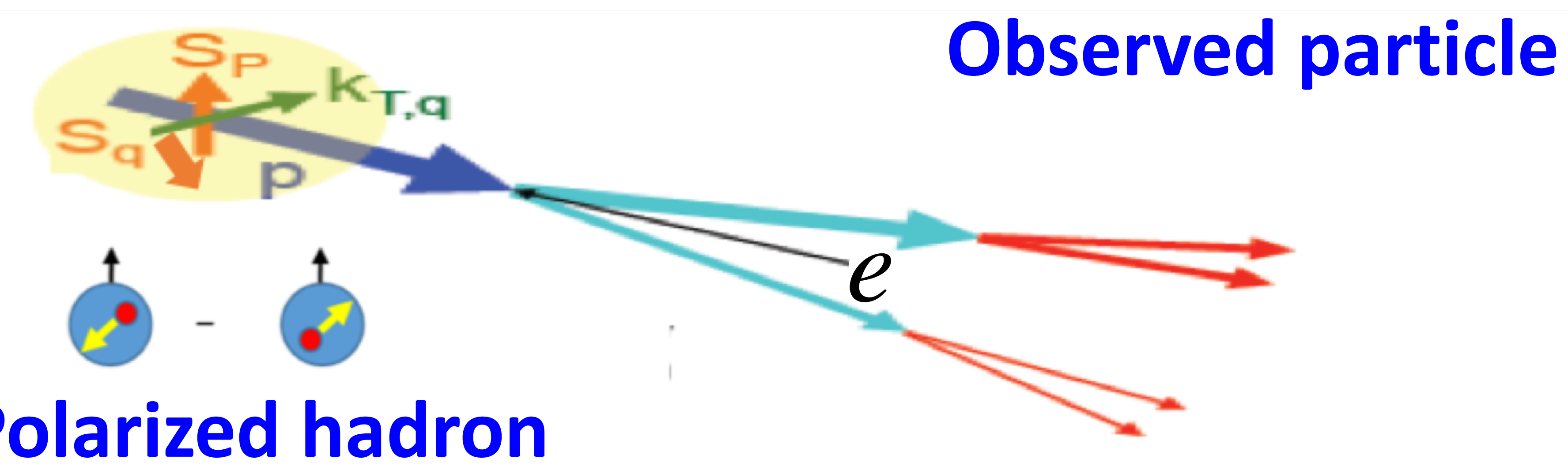
✦ Quantum correlation between proton spin and parton motion



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



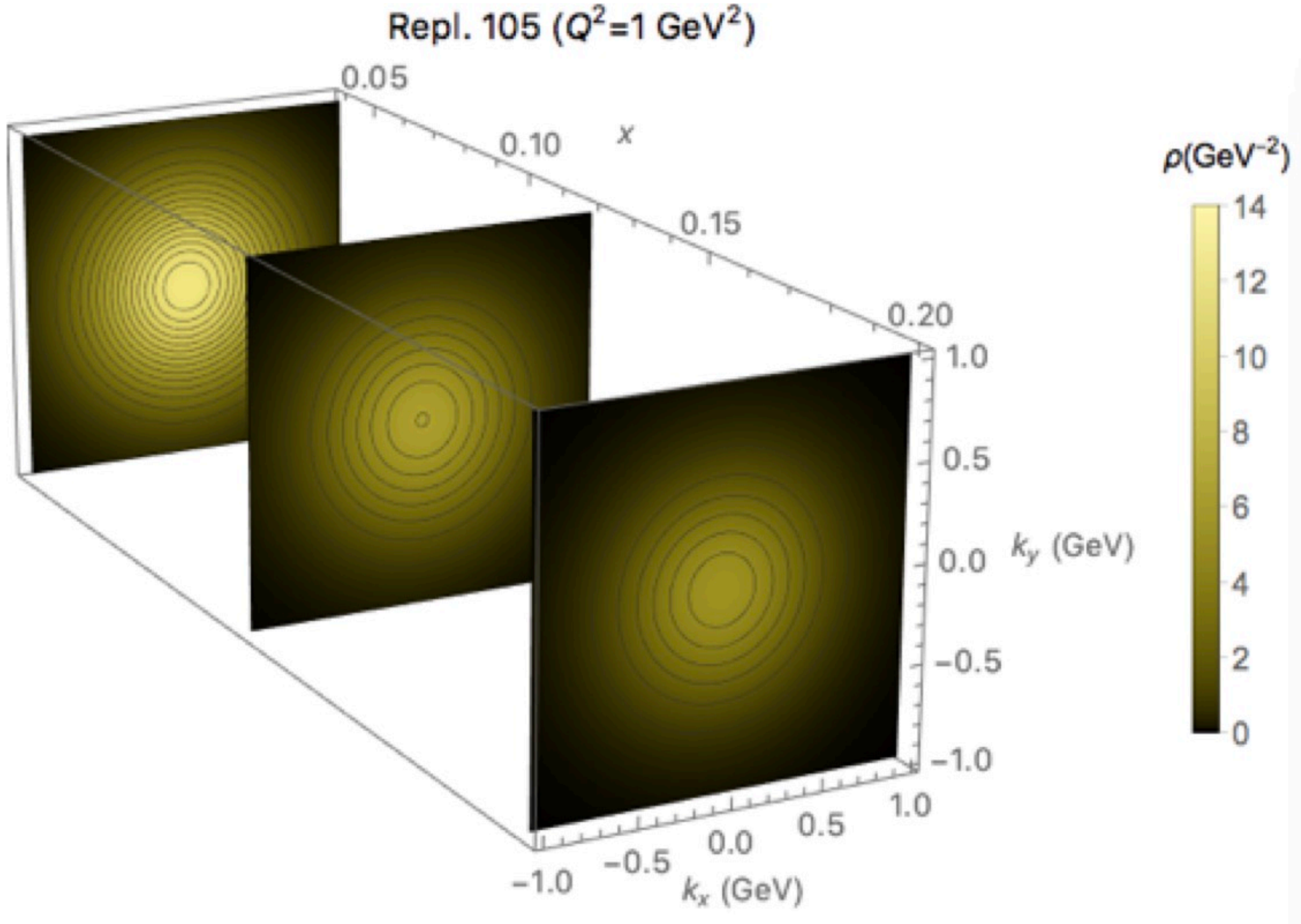
Pretzelosity function $h_{1T}^{\perp}$: proton spin and parton spin influence parton's transverse motion

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

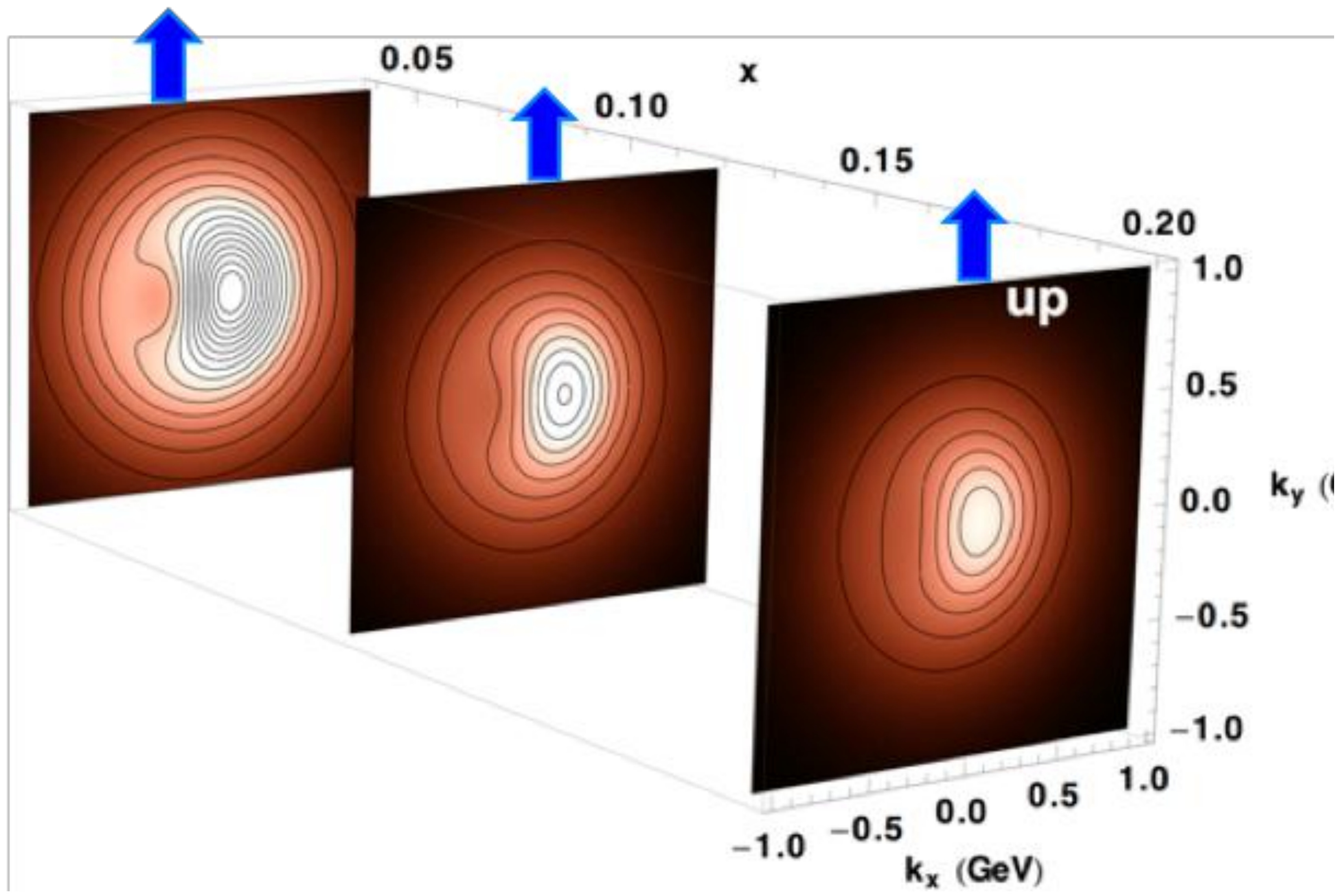
Nucleon partonic structure - 3D imaging

By Andrea Signori

Unpolarized proton



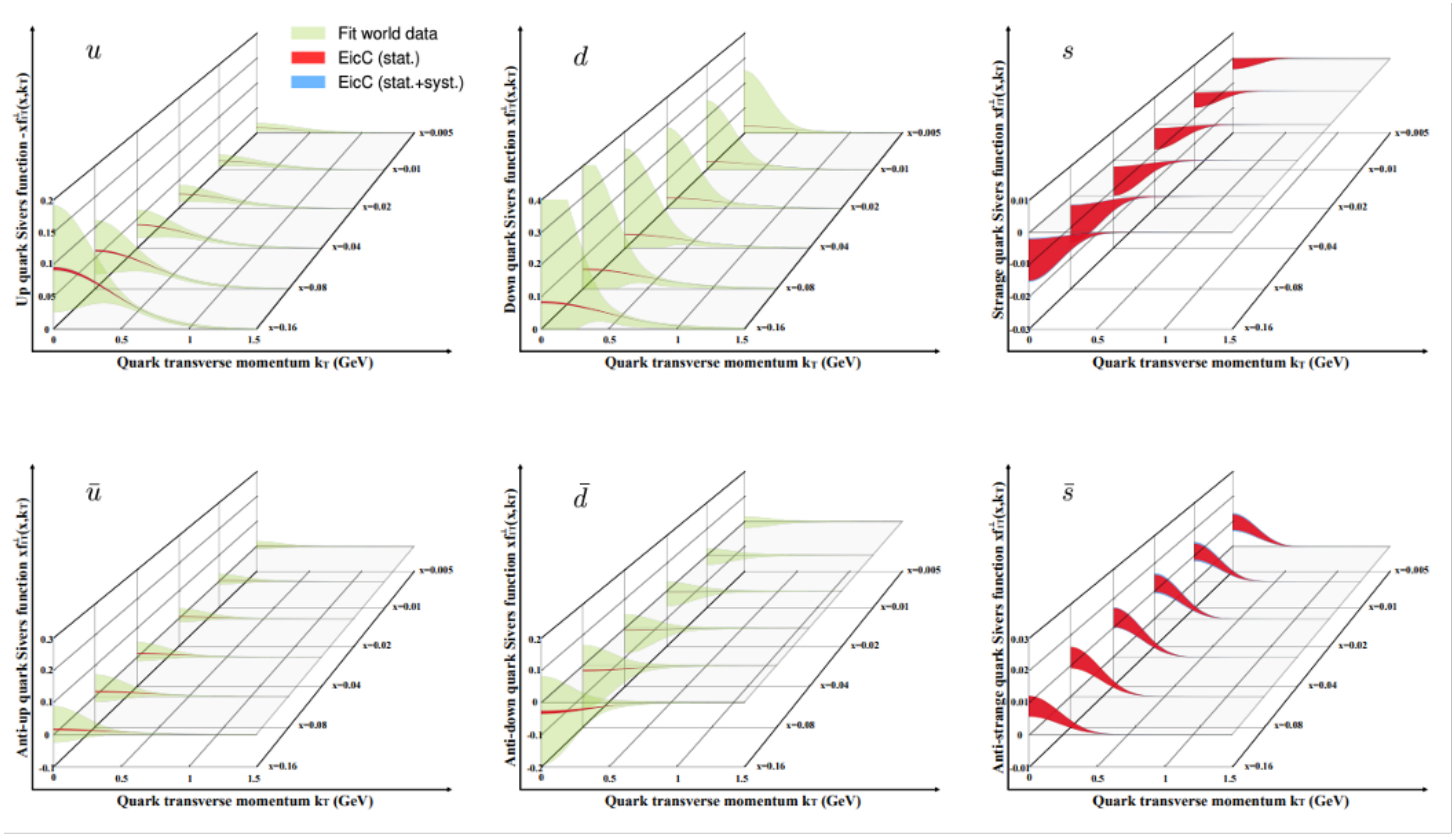
Transversely polarized proton



Transversely polarized quark distribution is distorted!

Nucleon 3D imaging at EicC - Sivers effect

Liu, Zhao, Zheng, 2023



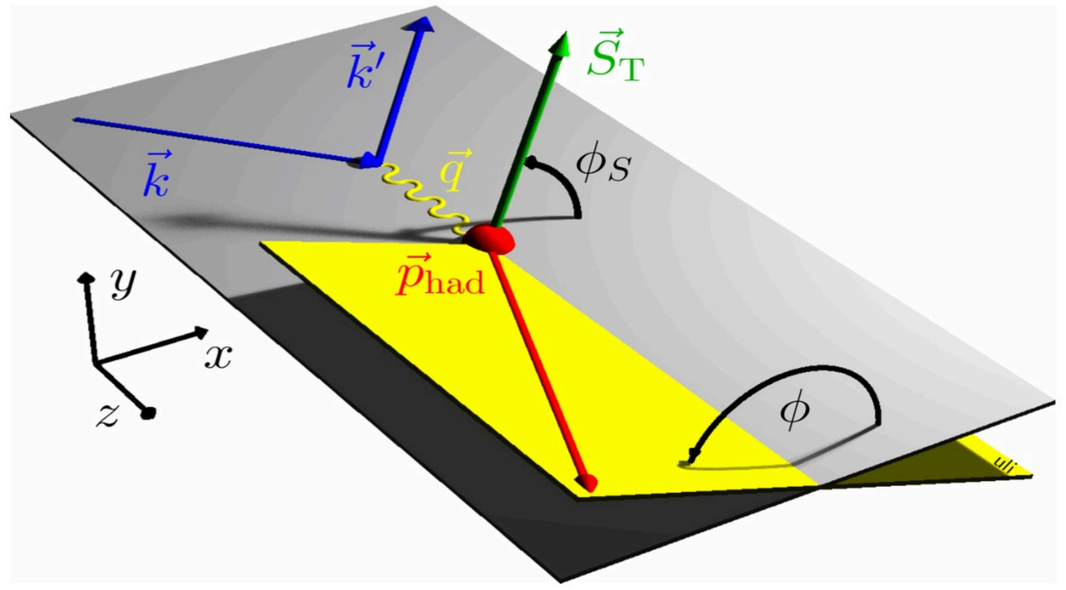
u/d Sivers EicC vs world data

LO analysis

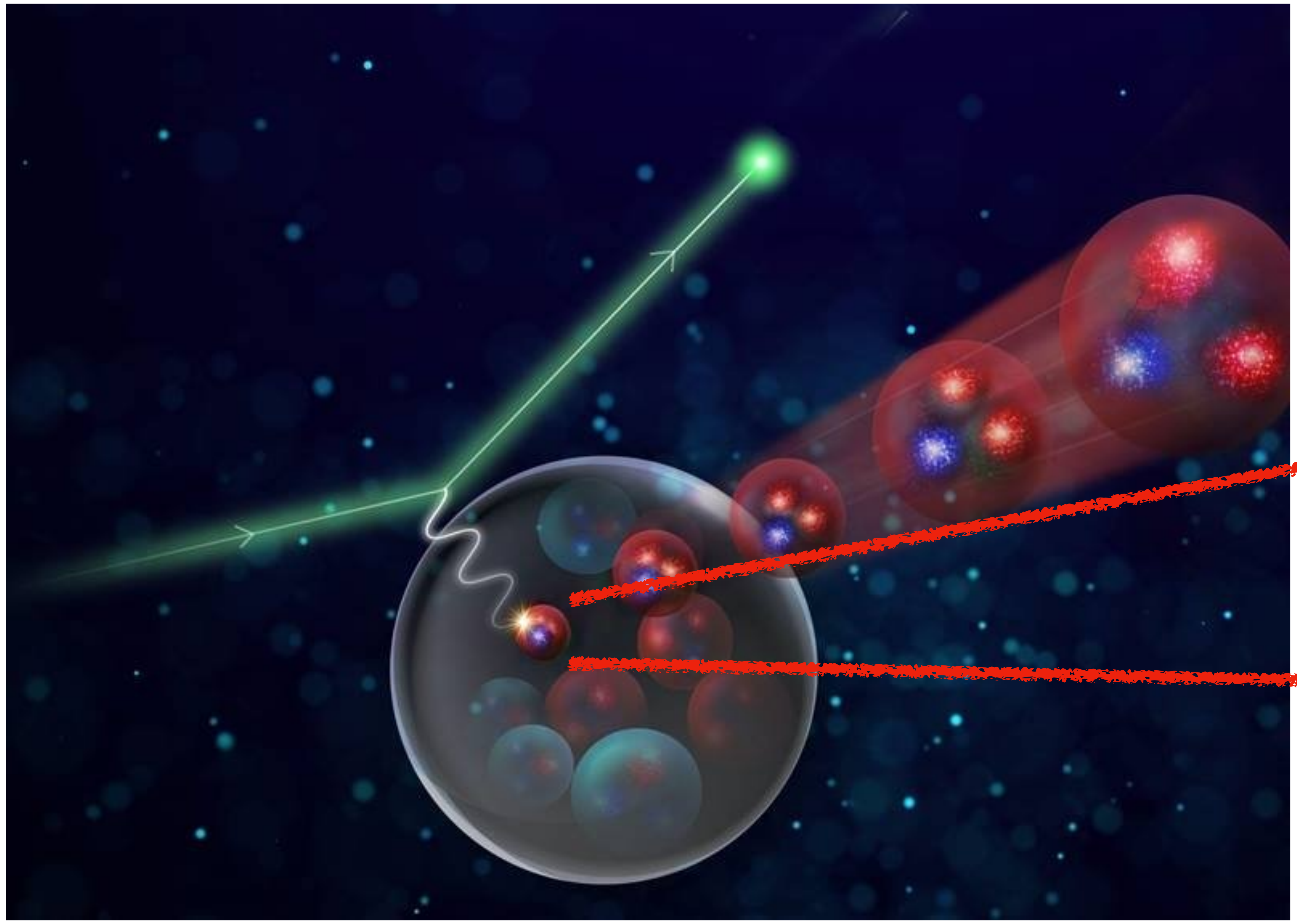
EicC SIDS data:

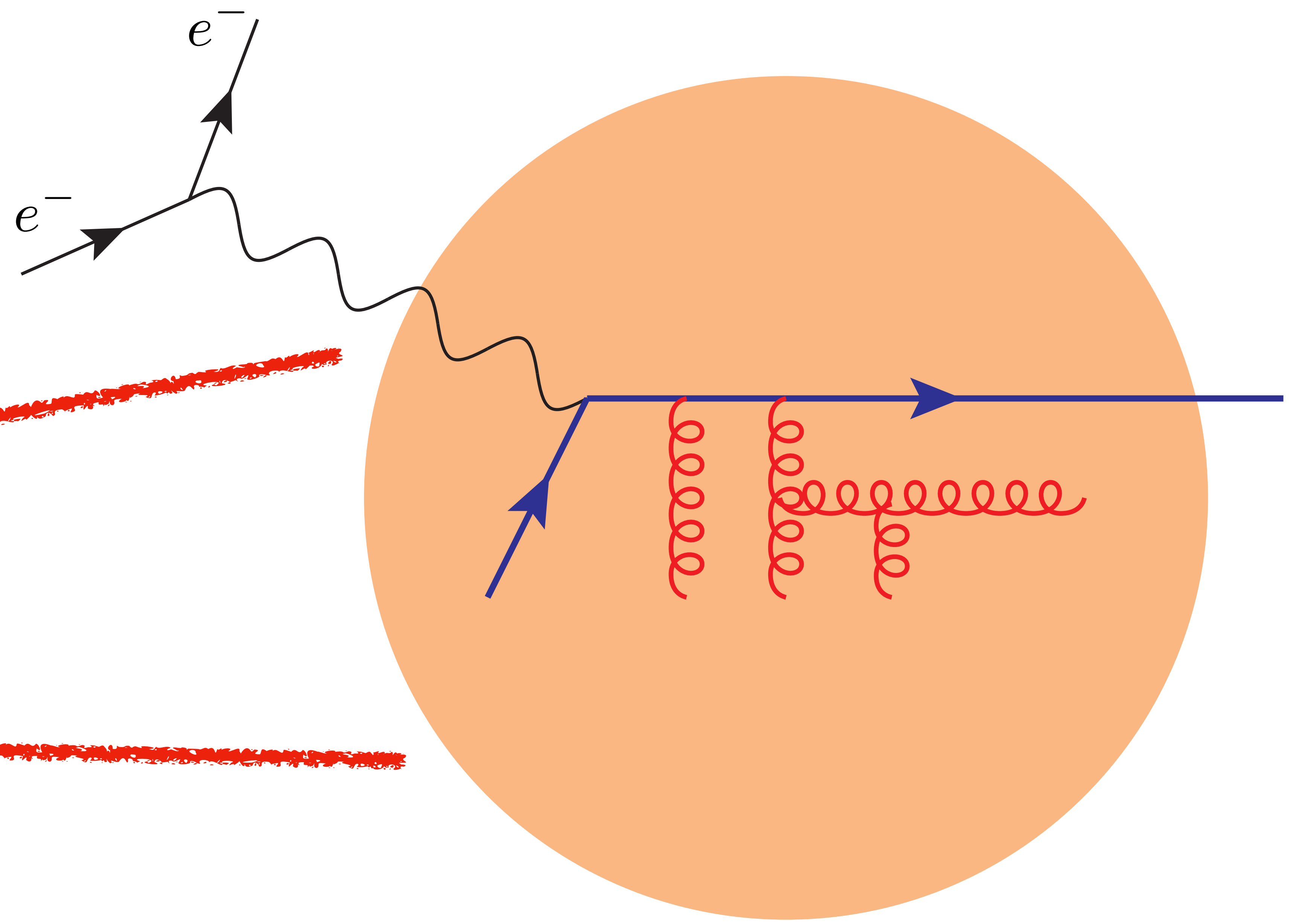
- **Pion(+/-), Kaon(+/-)**
- **ep: 3.5 GeV X 20 GeV**
- **eHe-3: 3.5 GeV X 40 GeV**
- **Pol.: e(80%), p(70%), He-3(70%)**
- **Lumi: ep 50 fb^{-1}, eHe-3 50 fb^{-1}**

EicC, precise measurements.



What if the nucleon is bounded in nucleus?





Initial state
Nuclear partonic structure

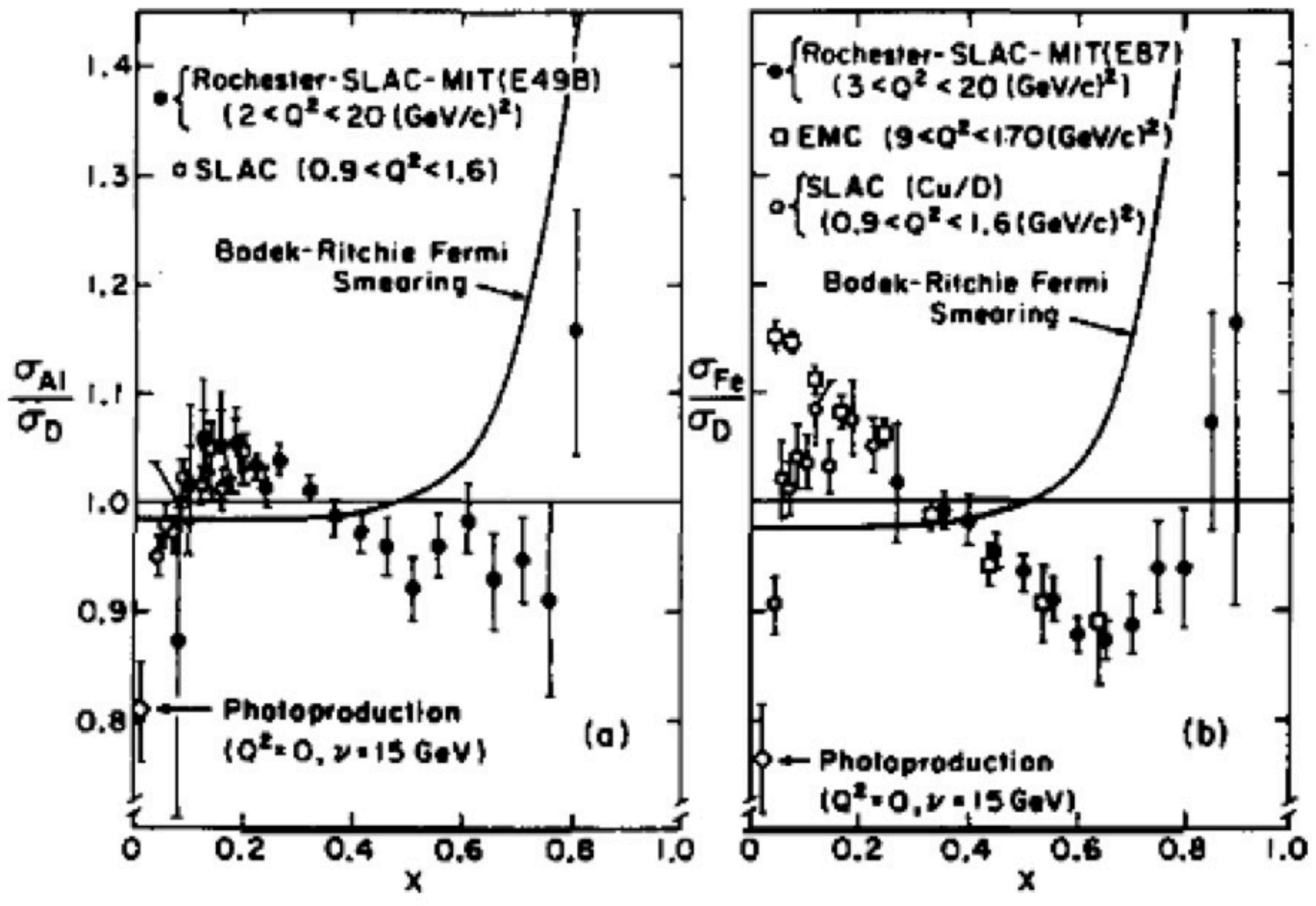
Final state
Parton propagating in nuclear medium

Two mechanisms leading to nontrivial nuclear effects.

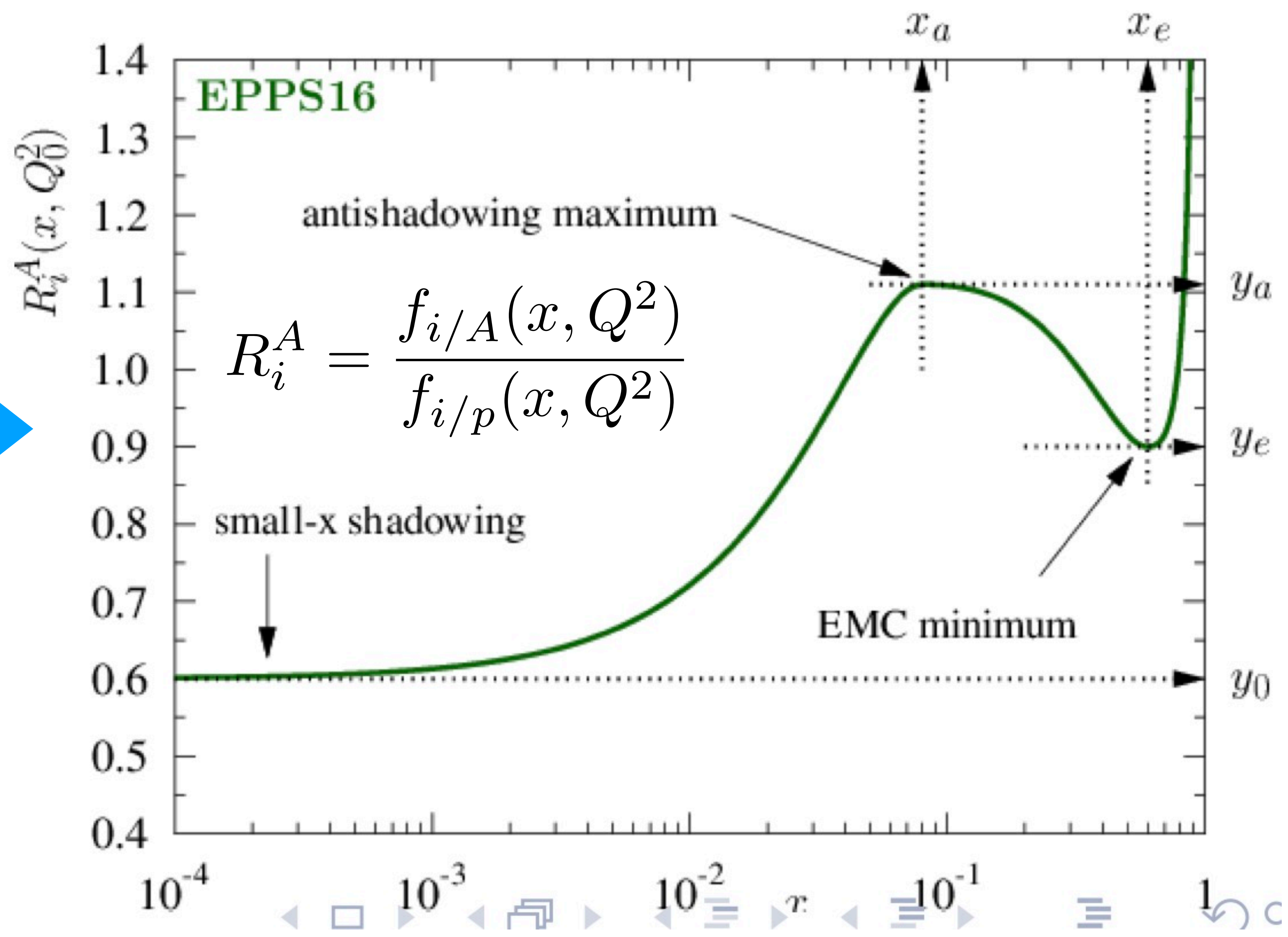
"Old" and long standing problems of nuclear partonic structure

- One-dimensional nuclear partonic structure

Four Decades of the EMC Effect

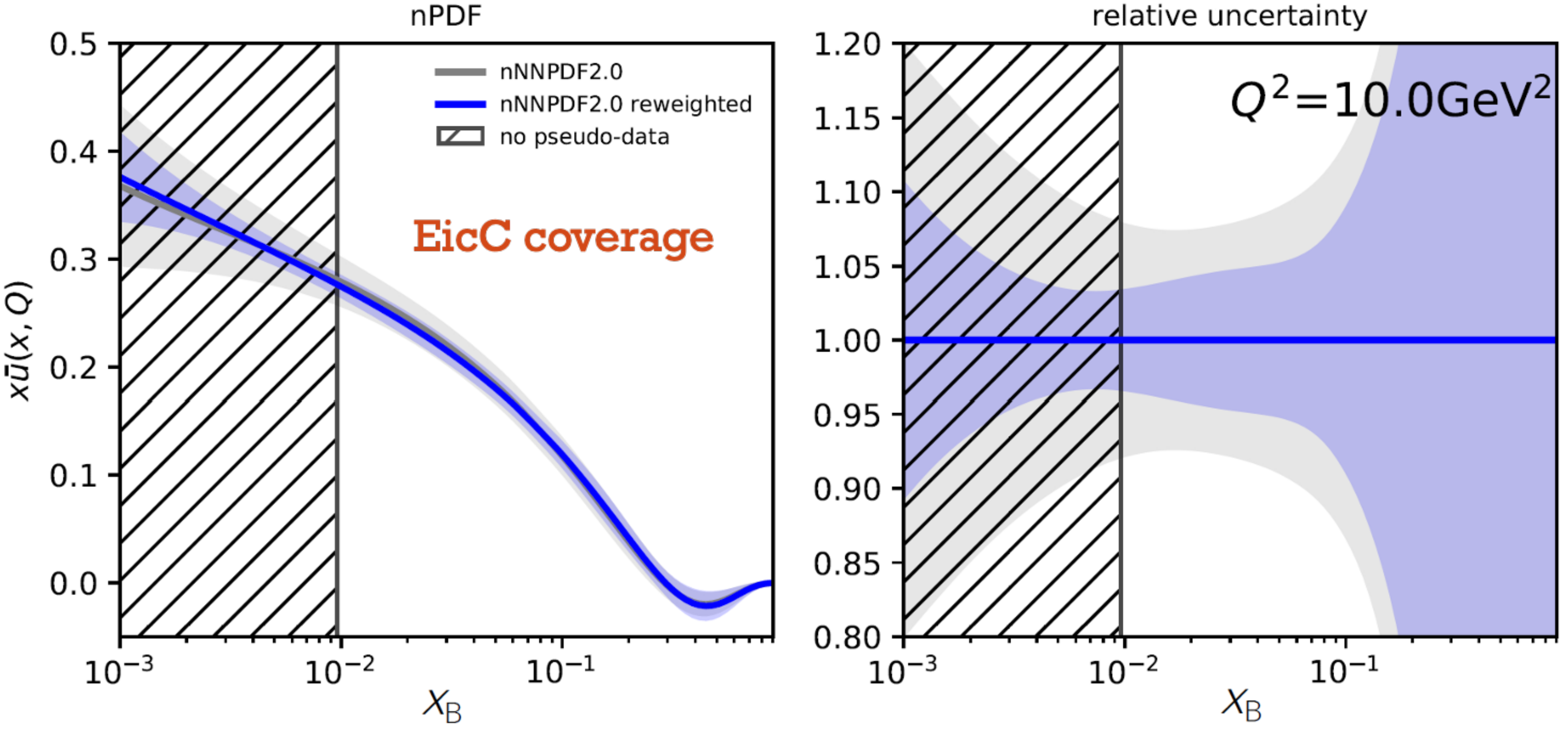


EMC Collaboration, 1983



Power of EicC for nuclear partonic structure - 1D

- Nuclear partonic structure - nuclear quark distribution

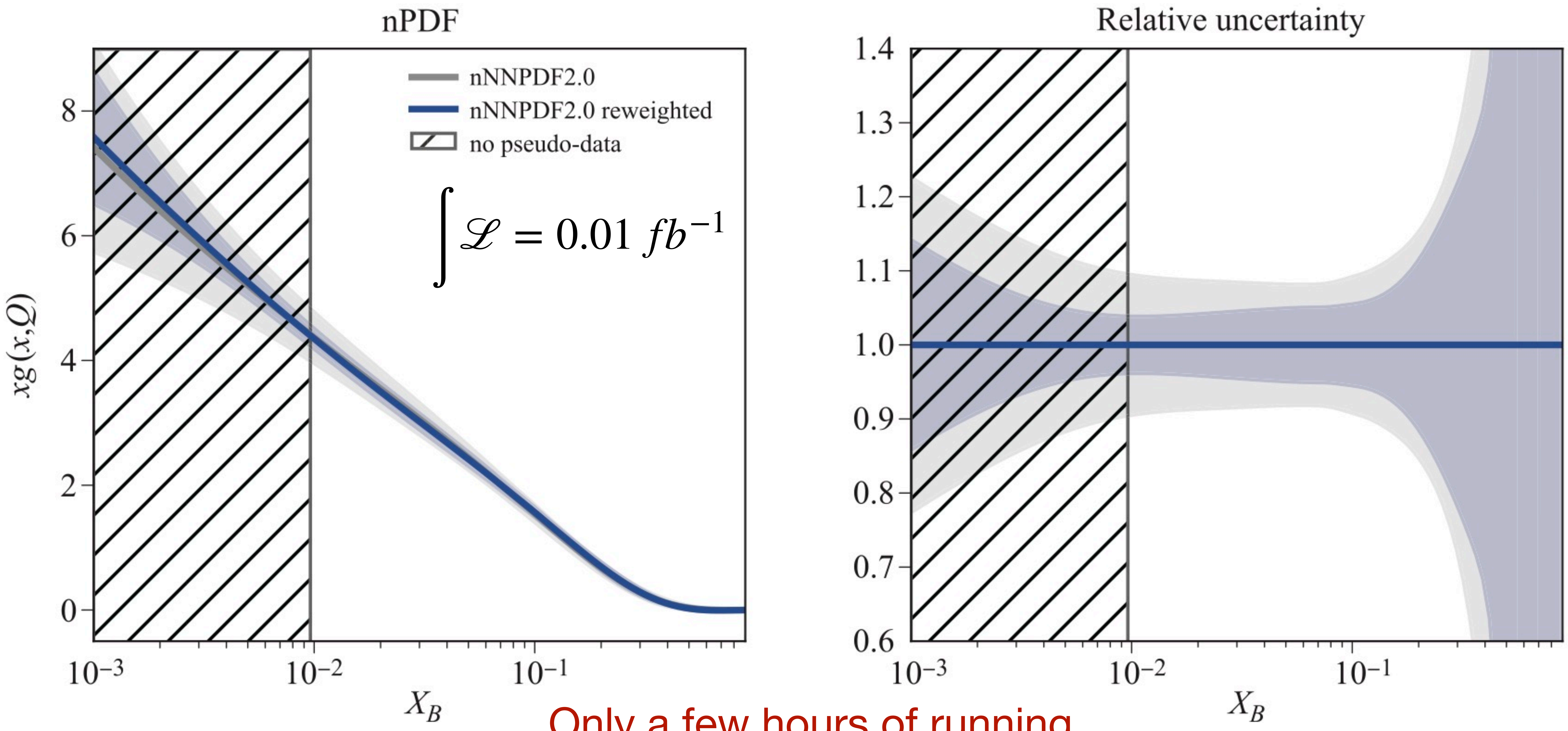


$$\int \mathscr{L} = 0.01\ fb^{-1}$$

Only a few hours of running

Power of EicC for nuclear partonic structure - 1D

- Nuclear partonic structure - nuclear gluon distribution

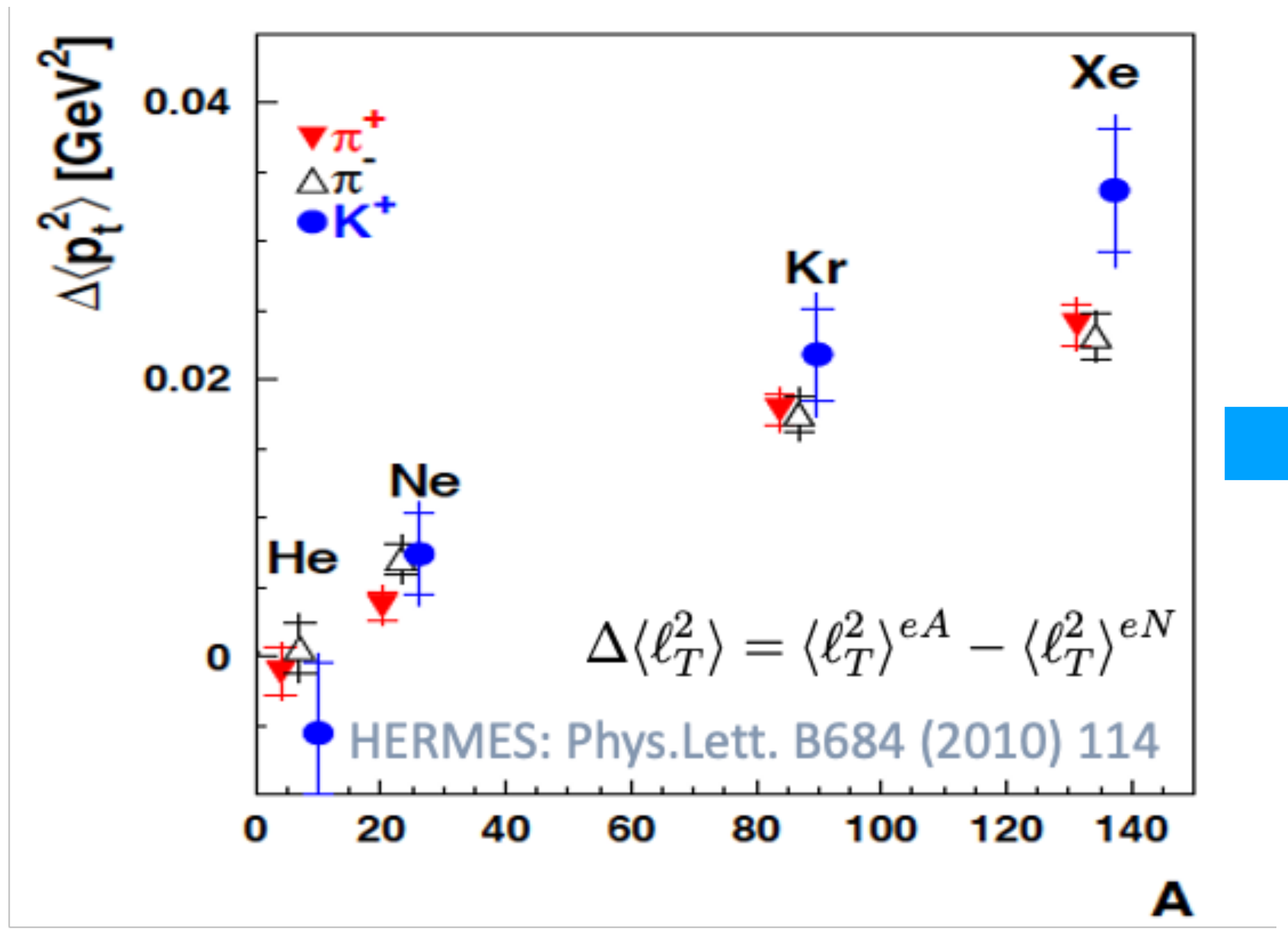


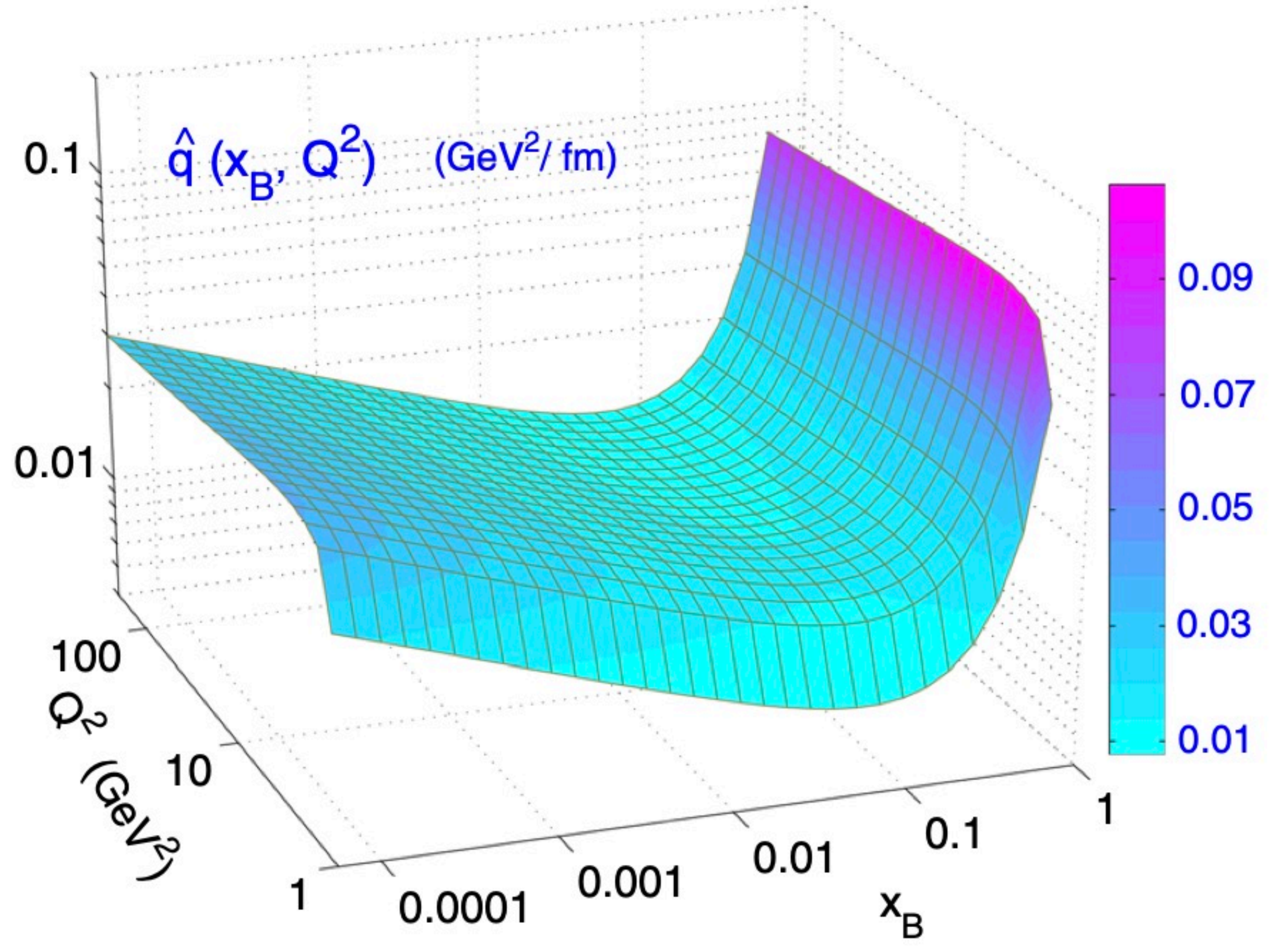
Only a few hours of running

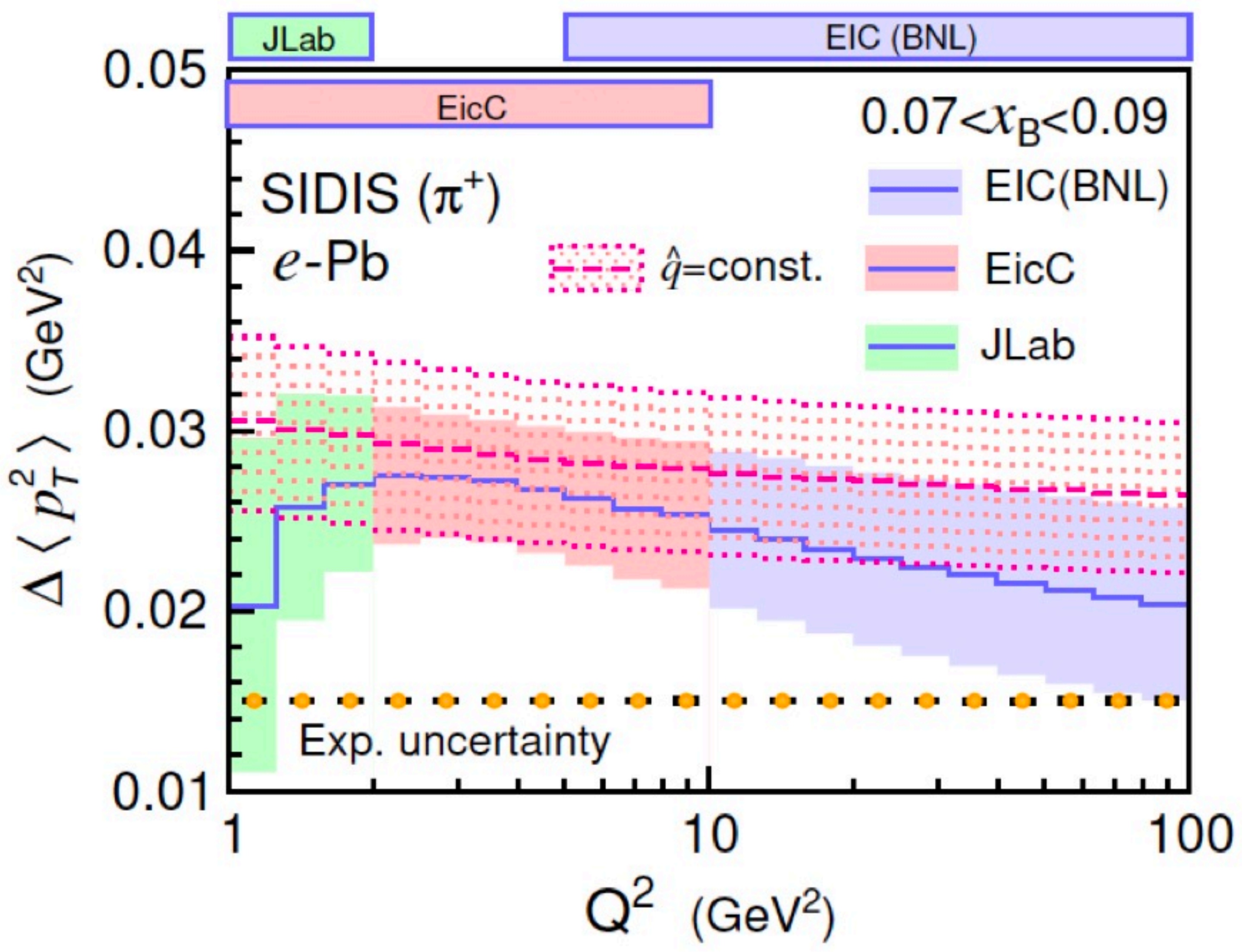
Nuclear partonic structure: jet transport parameter

SIDIS off nucleus

Peng Ru's talk, Wednesday







$\hat{q}$: jet transport parameter

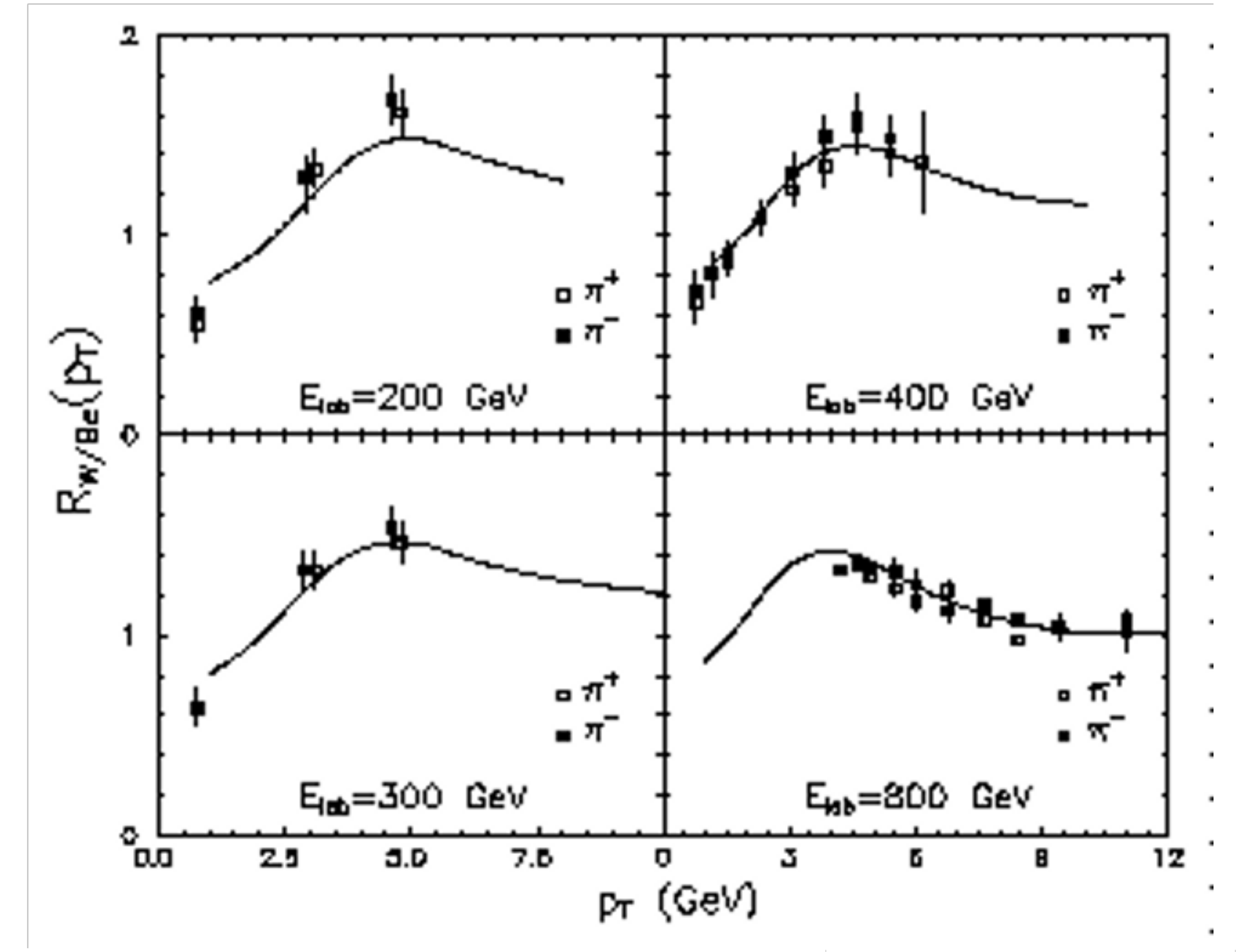
$$T_{qg}(x_B, 0, 0, \mu^2) \approx \frac{N_c}{4\pi^2\alpha_s} f_{q/A}(x_B, \mu^2) \int dy^- \hat{q}(\mu^2, y^-)$$

The nuclear partonic structure can never be a still picture, future EICs can precisely study the QCD evolution of jet transport parameter!

“Old” and long standing problems of nuclear partonic structure

- Three-dimensional nuclear partonic structure

Cronin effect



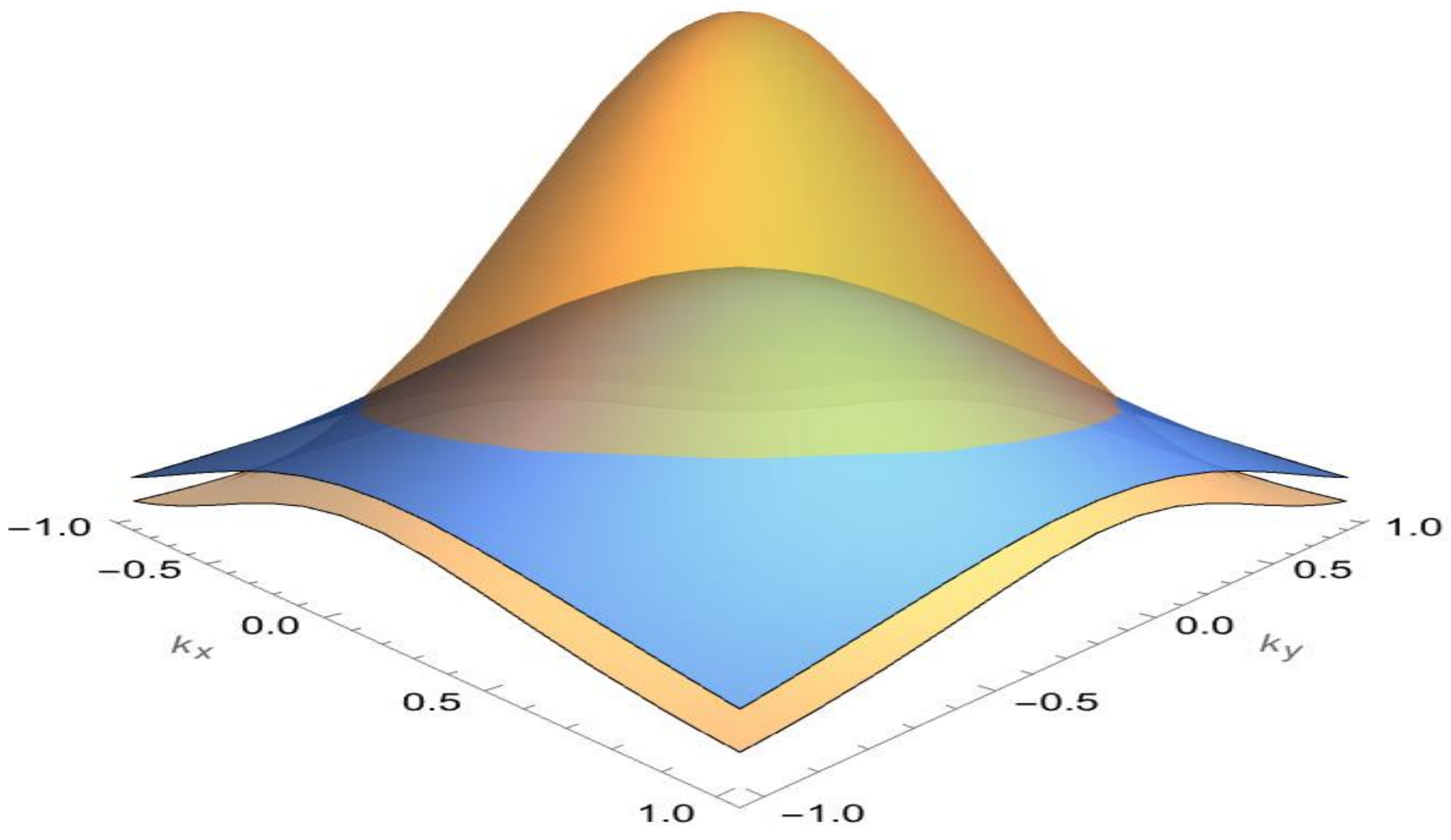
$$p + A \to \text{hadron(p)} + X$$

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

E100 Collaboration, PRD 11, 3105 (1975)

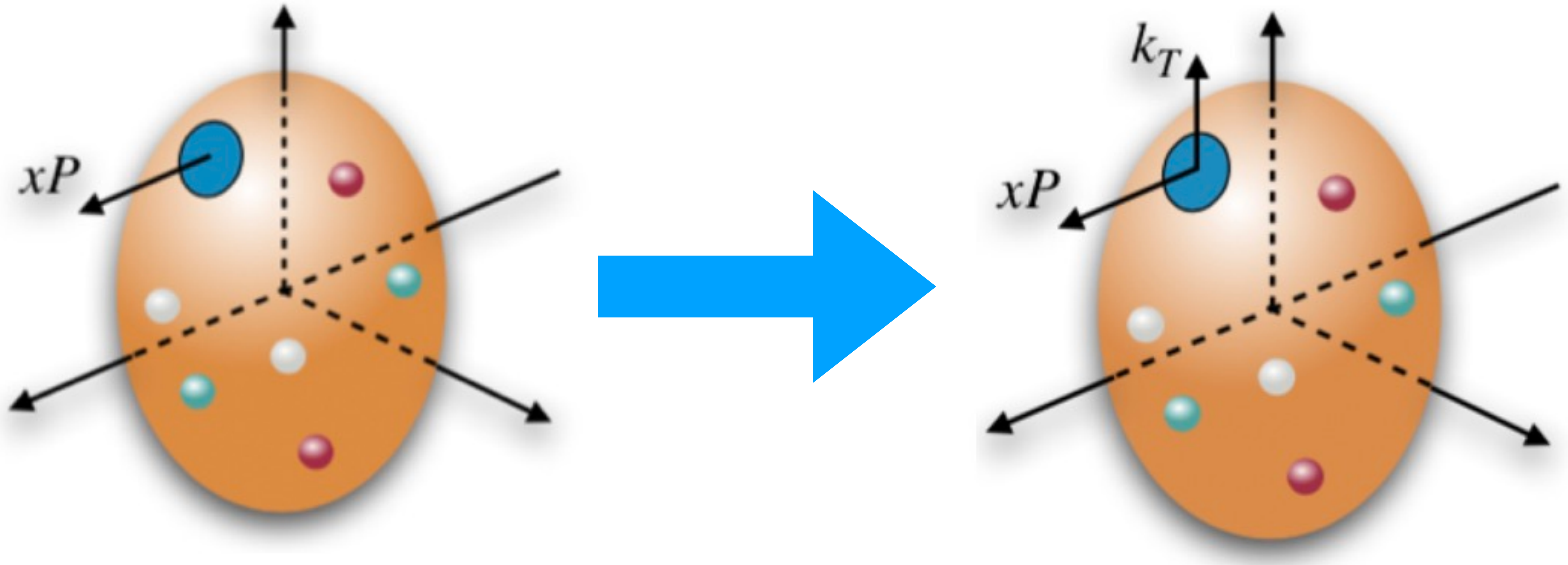
- Naive Gaussian model

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



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

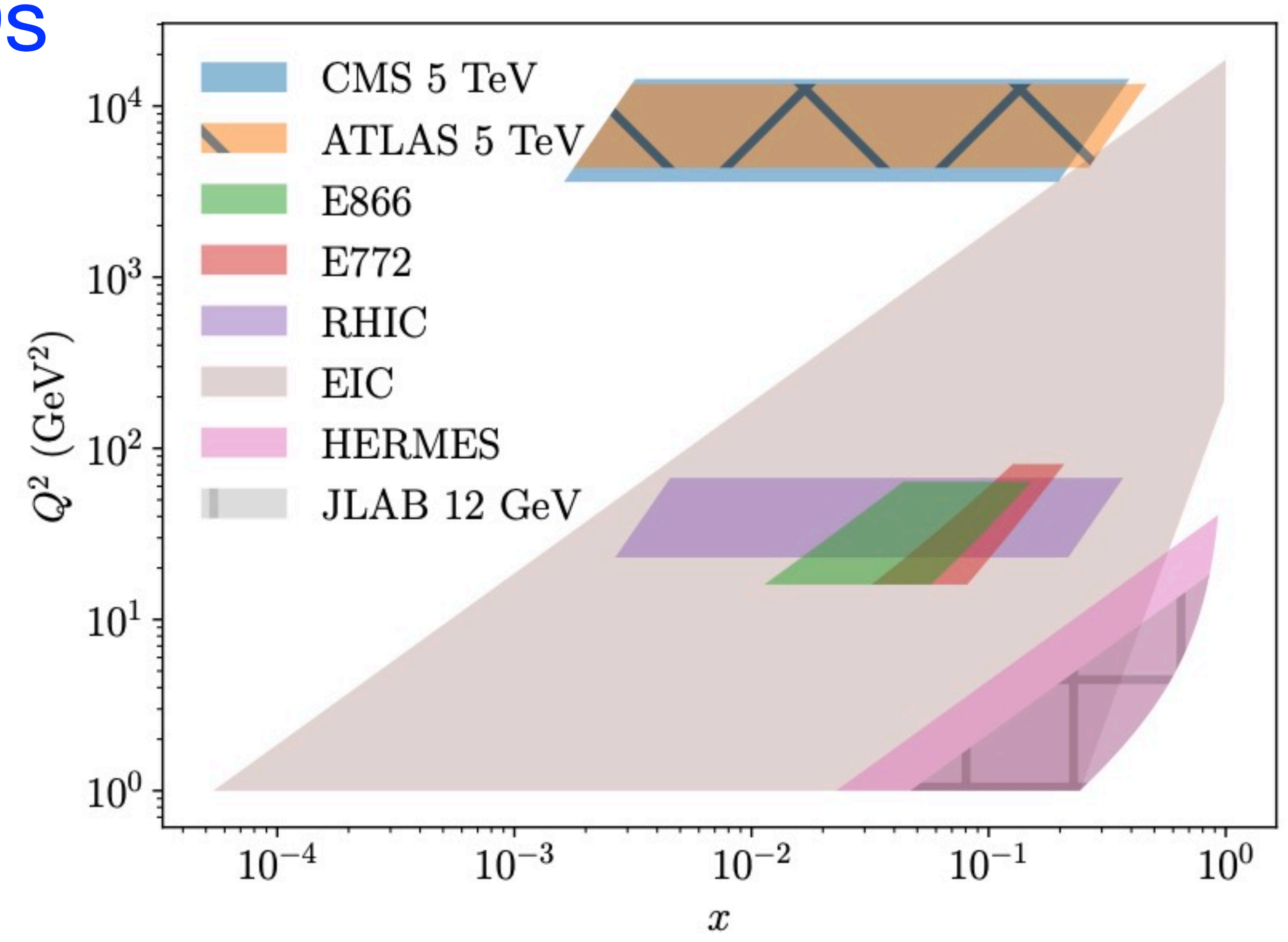
- Two scale processes are necessary for TMDs

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.



Nuclear partonic structure - 3D imaging

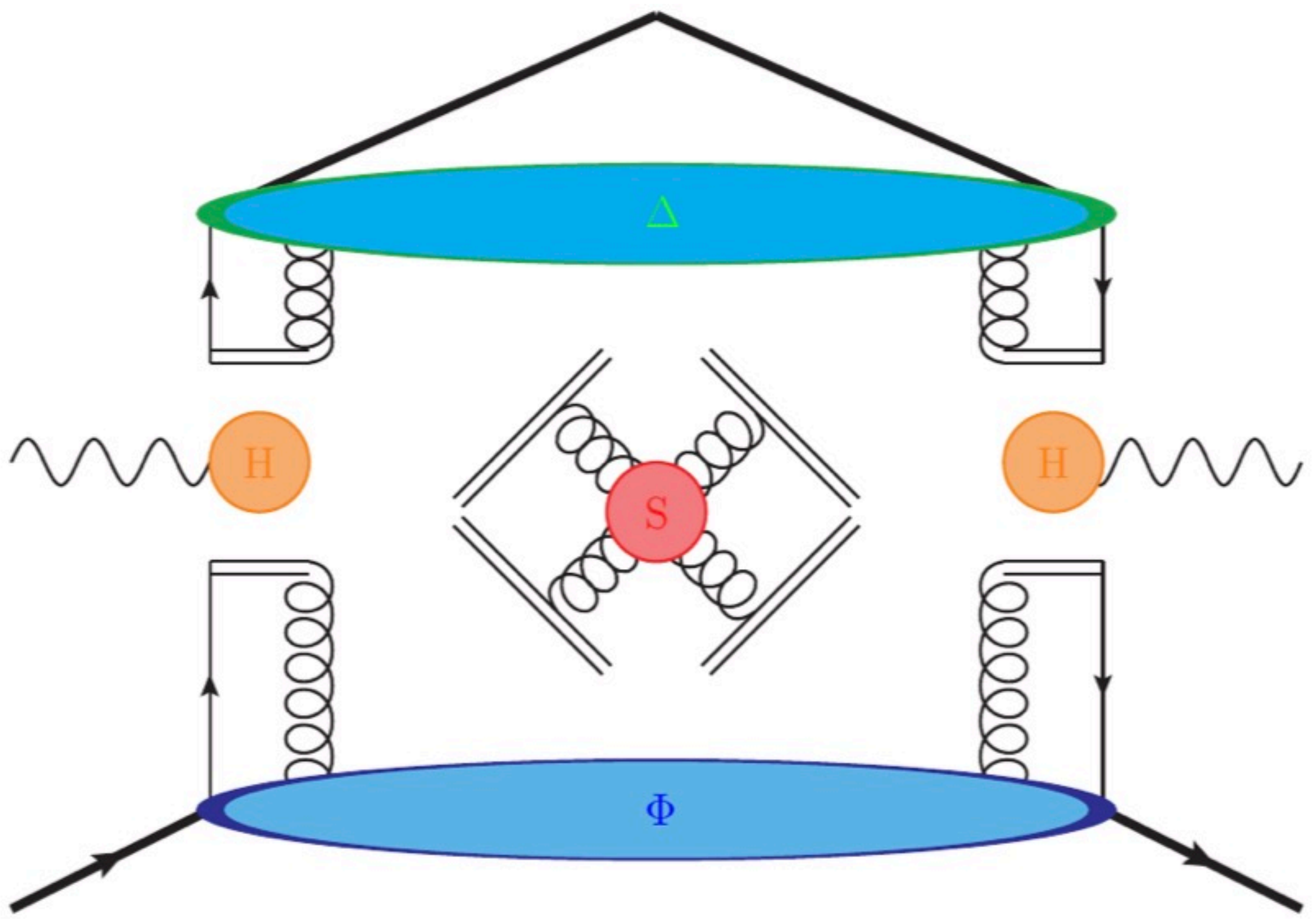
- TMD factorization for cross section

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

- 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

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

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

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

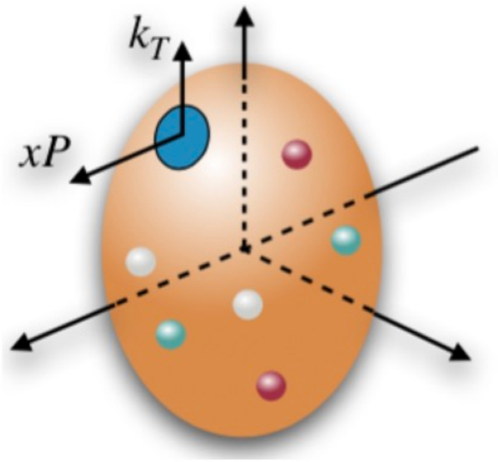
Work at NLO+NNLL for the TMDs.

Non-perturbative parametrization

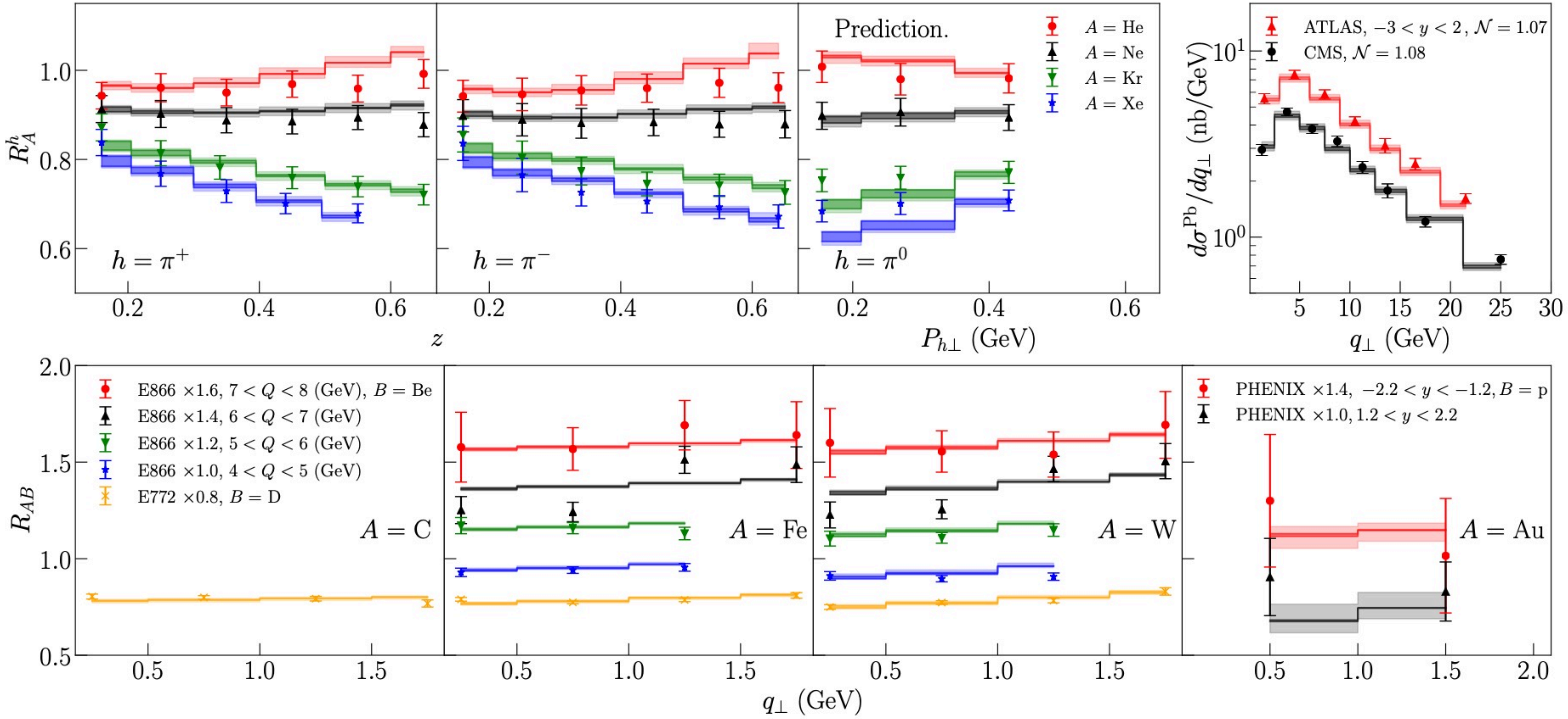
$$S^f_{\rm NP}(b,Q,A) = S^f_{\rm NP}(b,Q) + a_N\left(A^{1/3}-1\right)b^2$$

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

nuclear 3D imaging - global extraction from world data



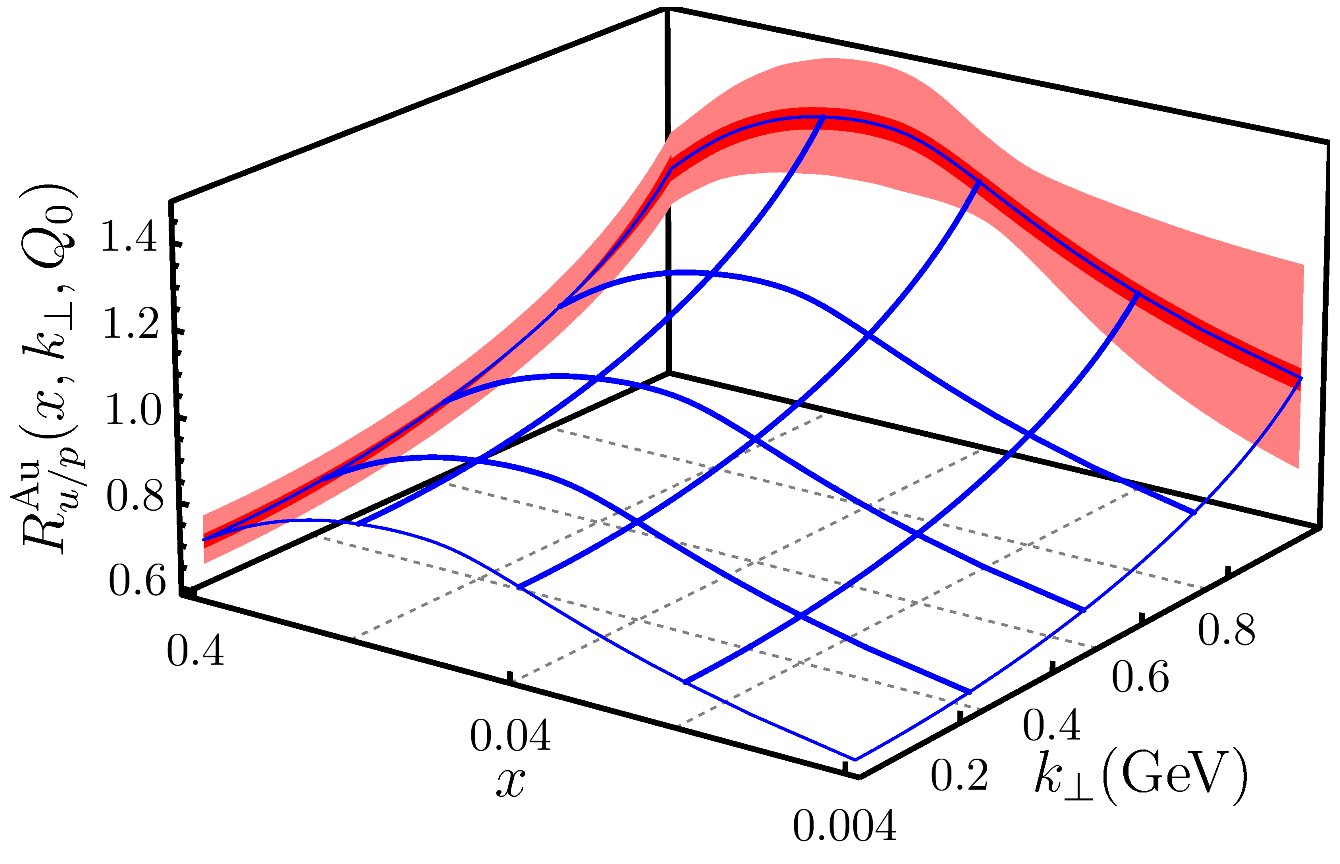
Alrashed, Anderle, Kang, Terry, **HX**, PRL 2022



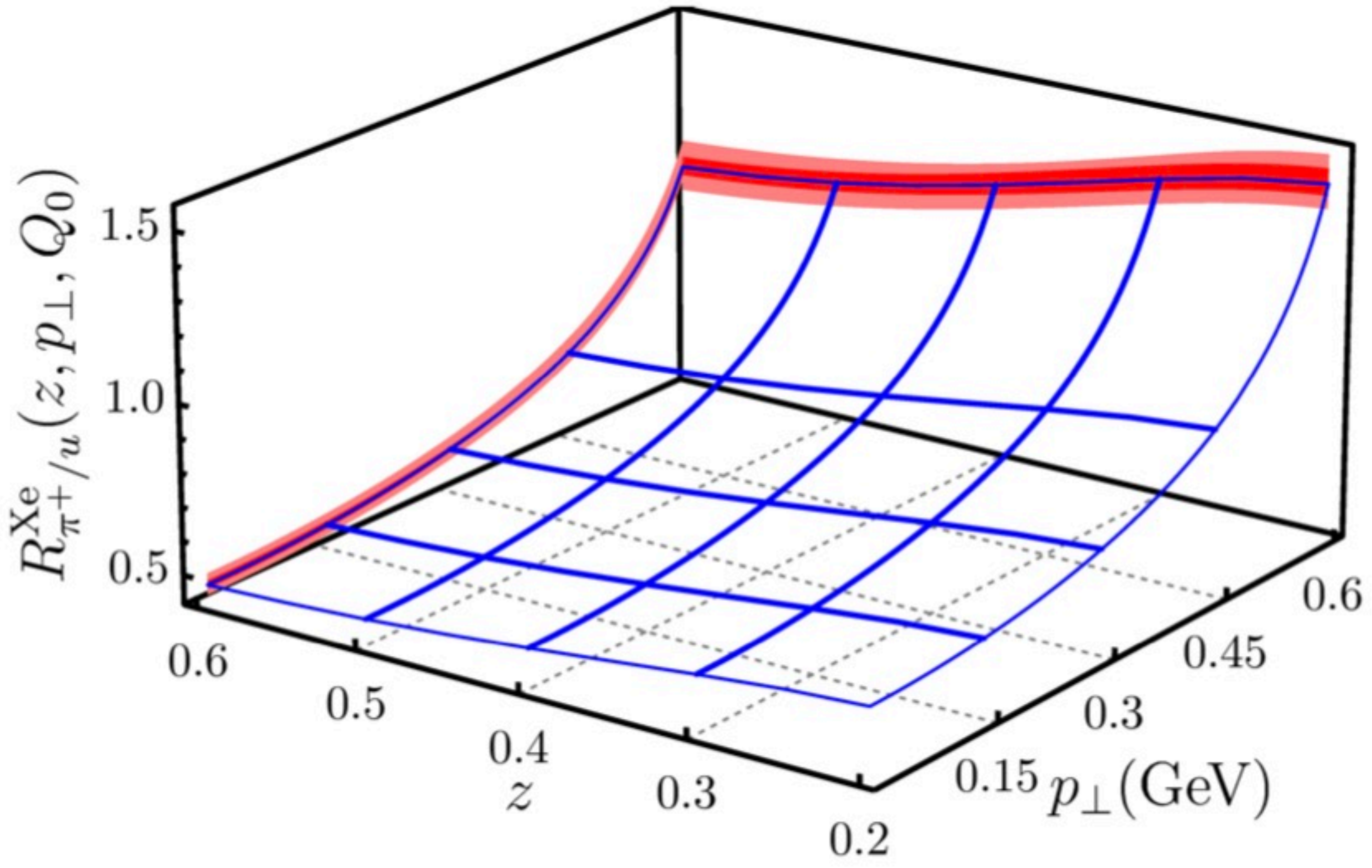
Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

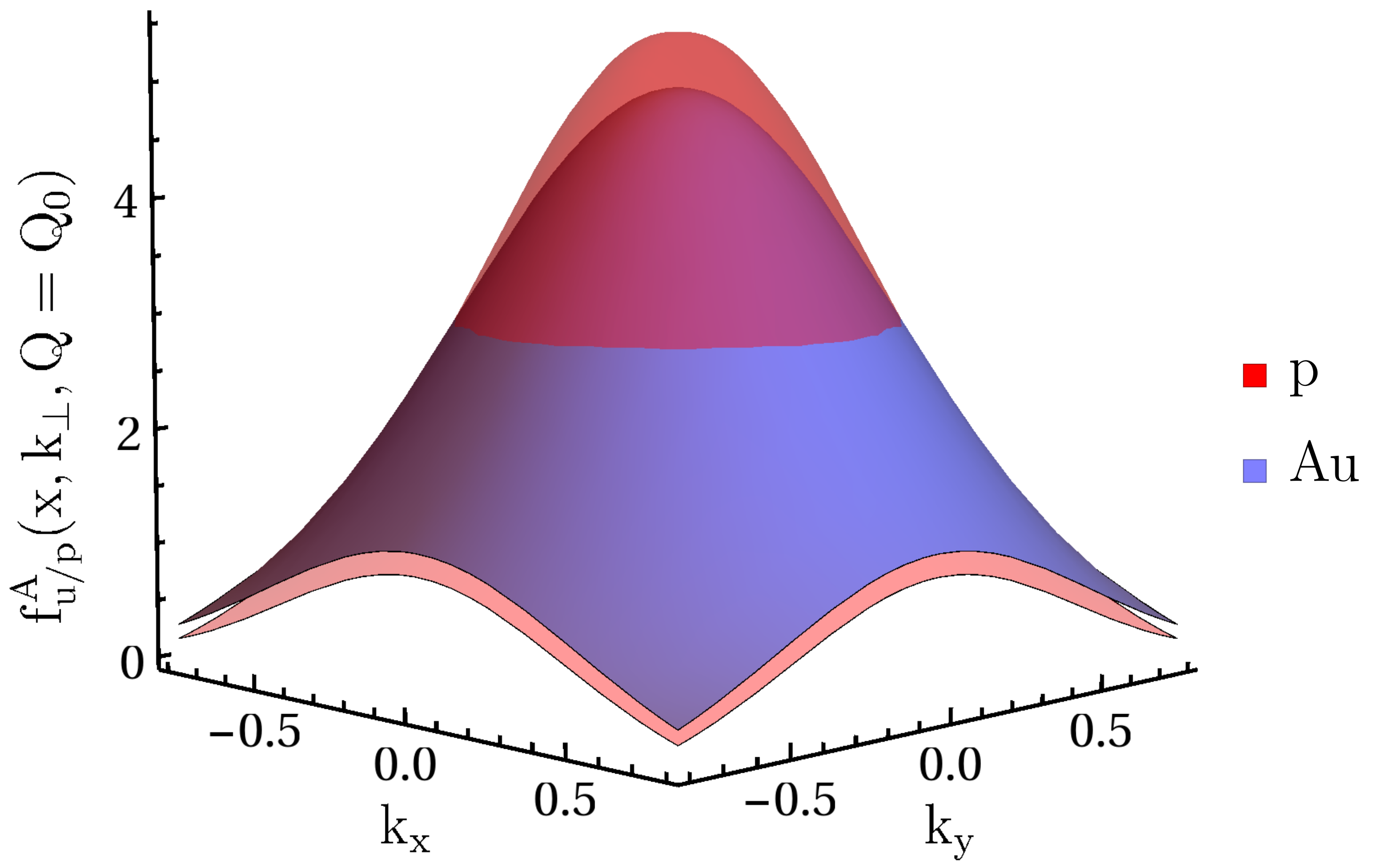
Three-dimension imaging in nuclei

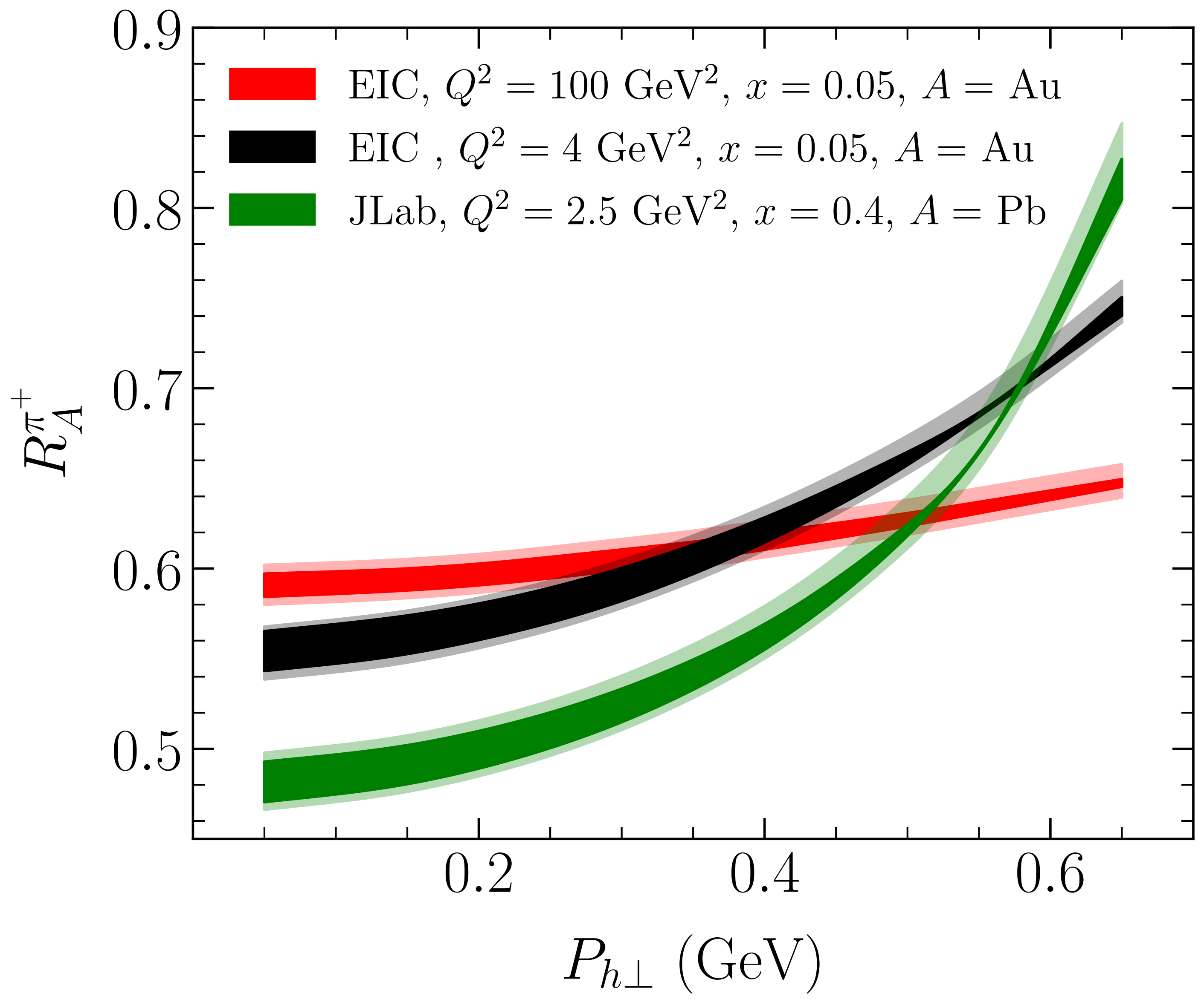
$$R^{\mathrm{Au}}_{u/p}(x,k_\perp,Q_0)=\frac{f^{\mathrm{Au}}_{u/p}(x,k_\perp,Q_0)}{f_{u/p}(x,k_\perp,Q_0)}$$



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





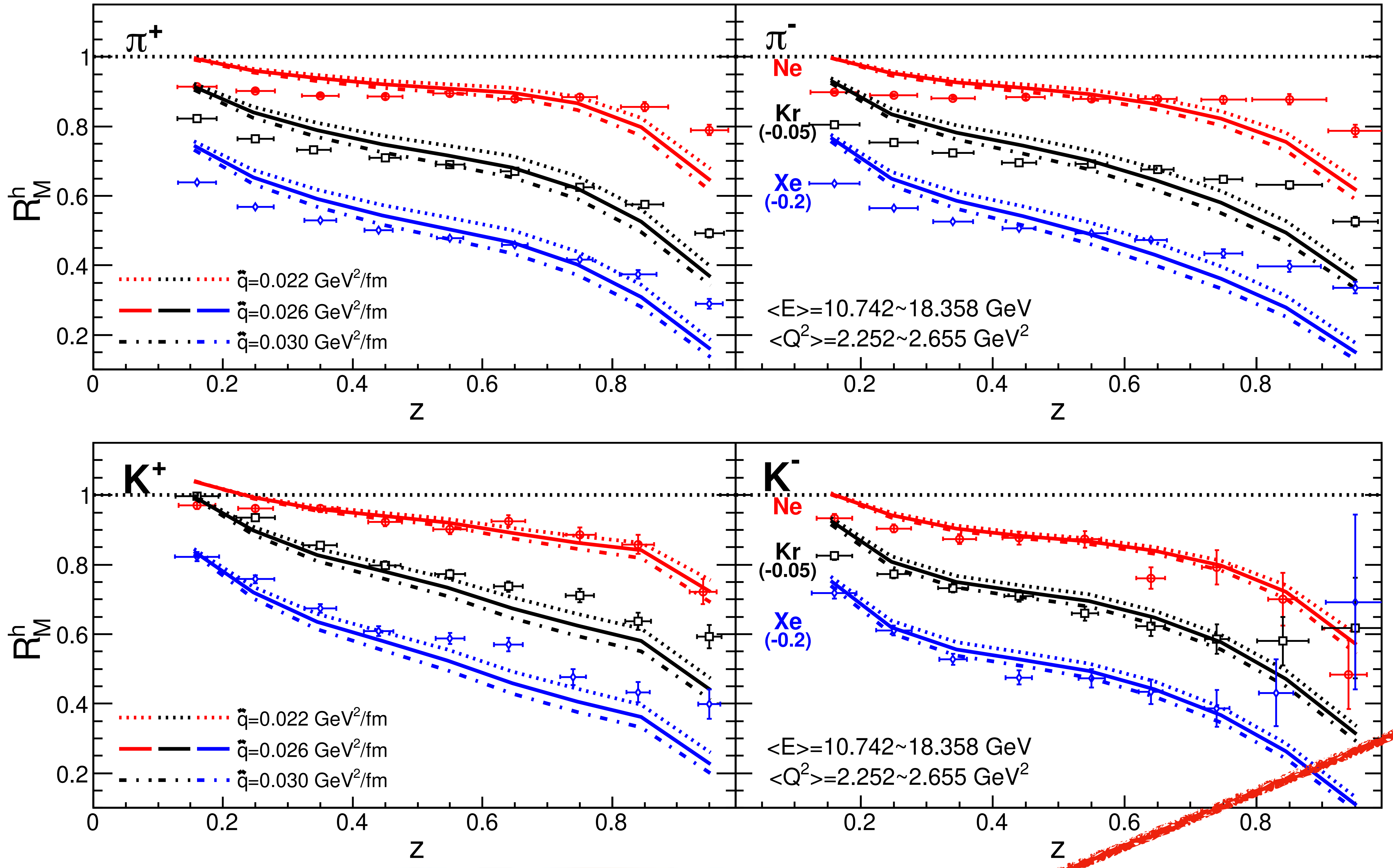


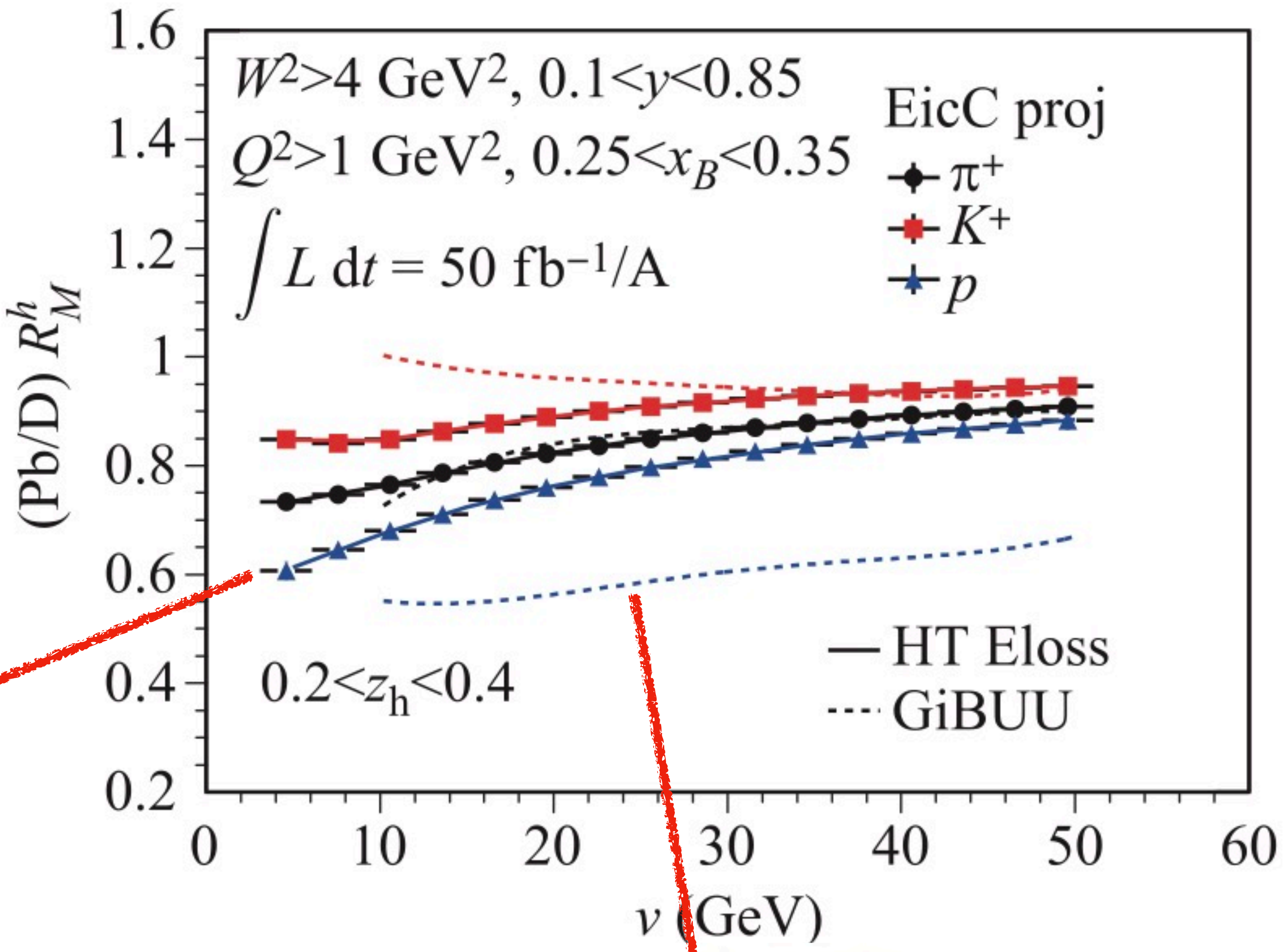
- First time quantitative determination of nuclear TMDs
- Identification of transverse momentum broadening in nuclei

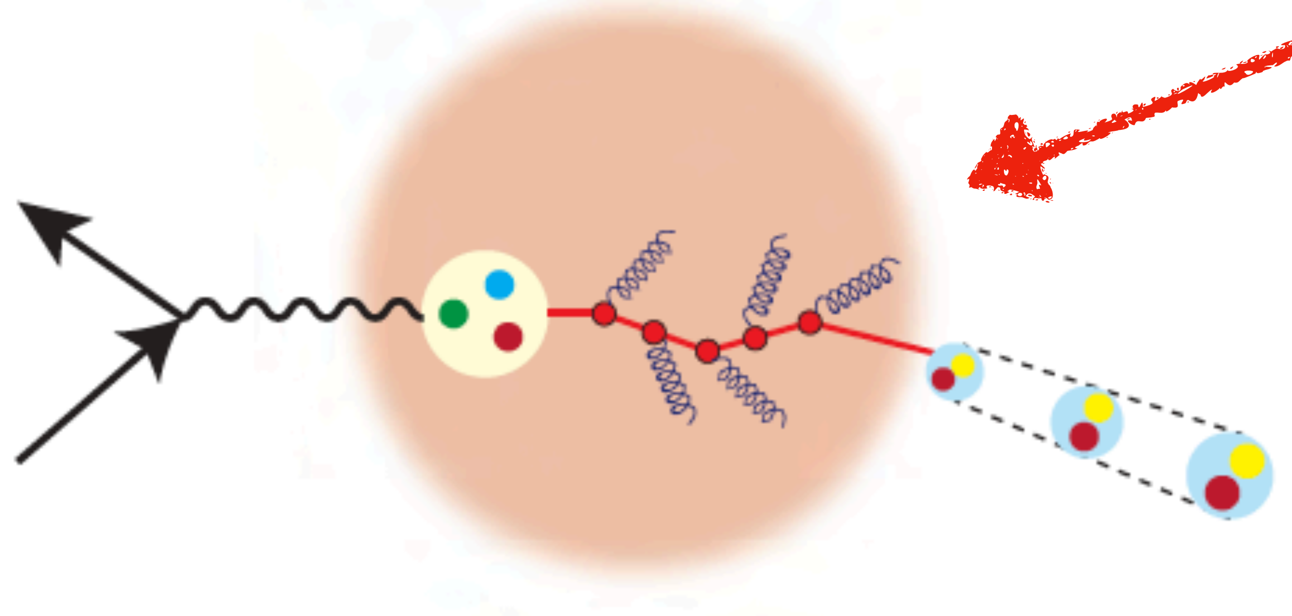
Parton propagation in nuclear medium

- energy loss vs. hadronization

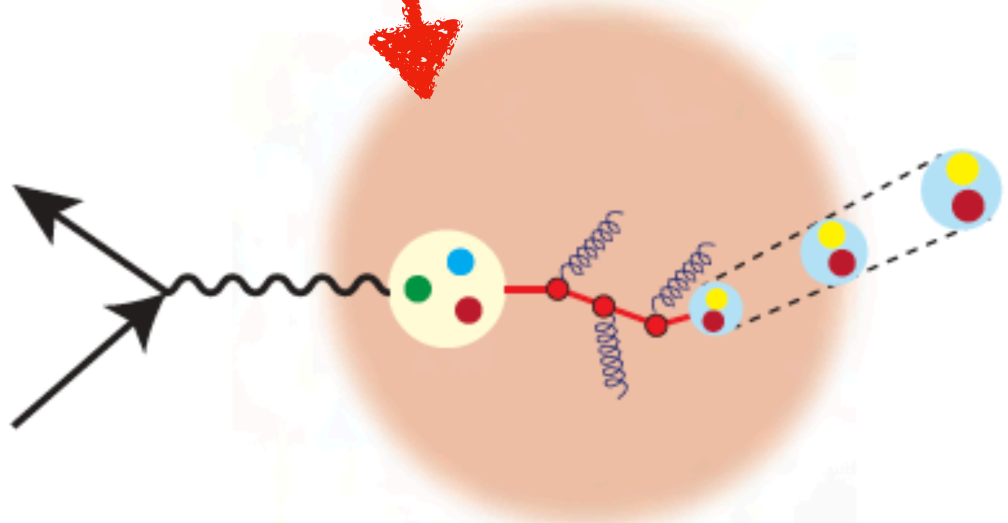
NLO + ELoss







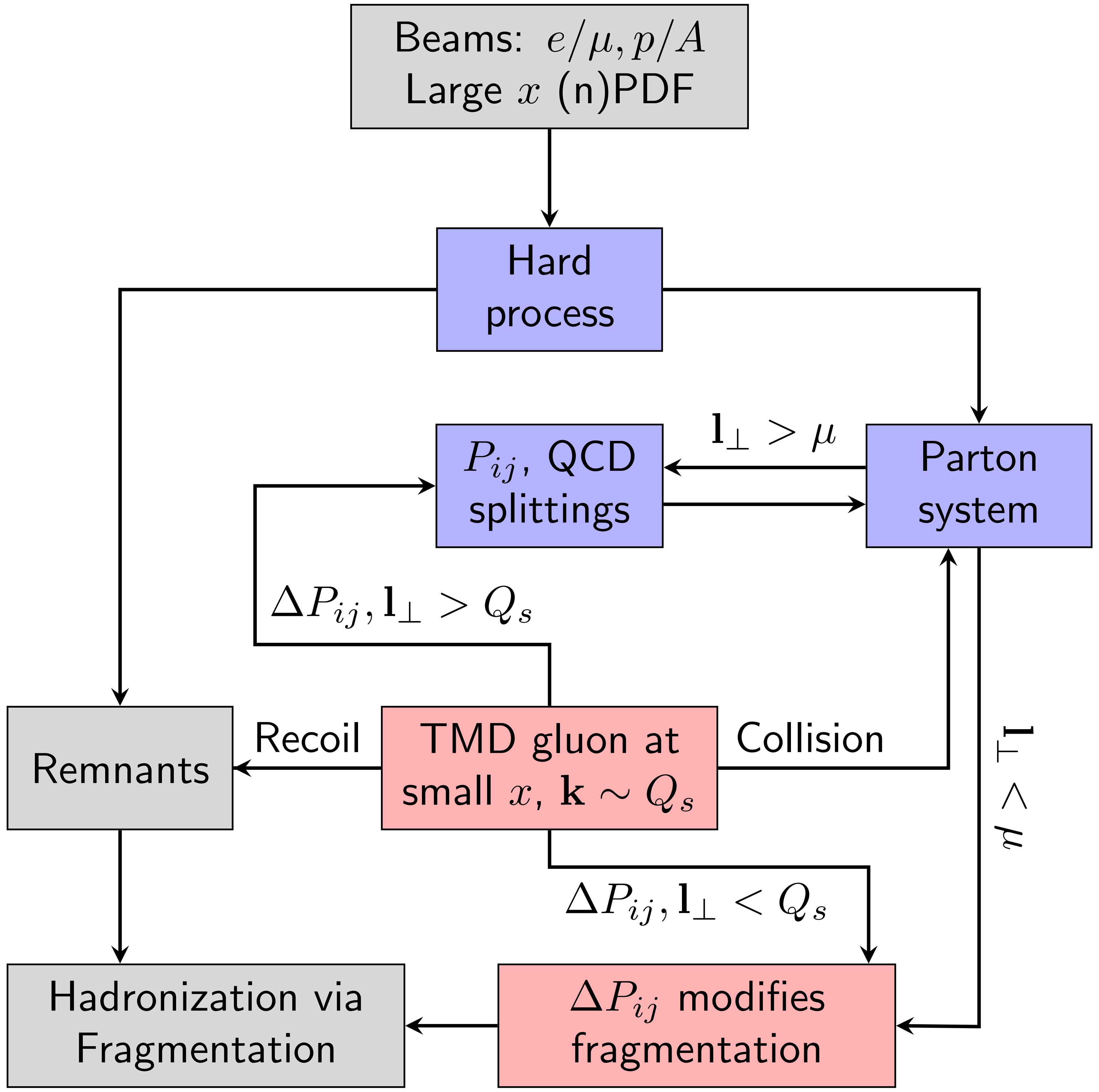
From HERMES to EicC

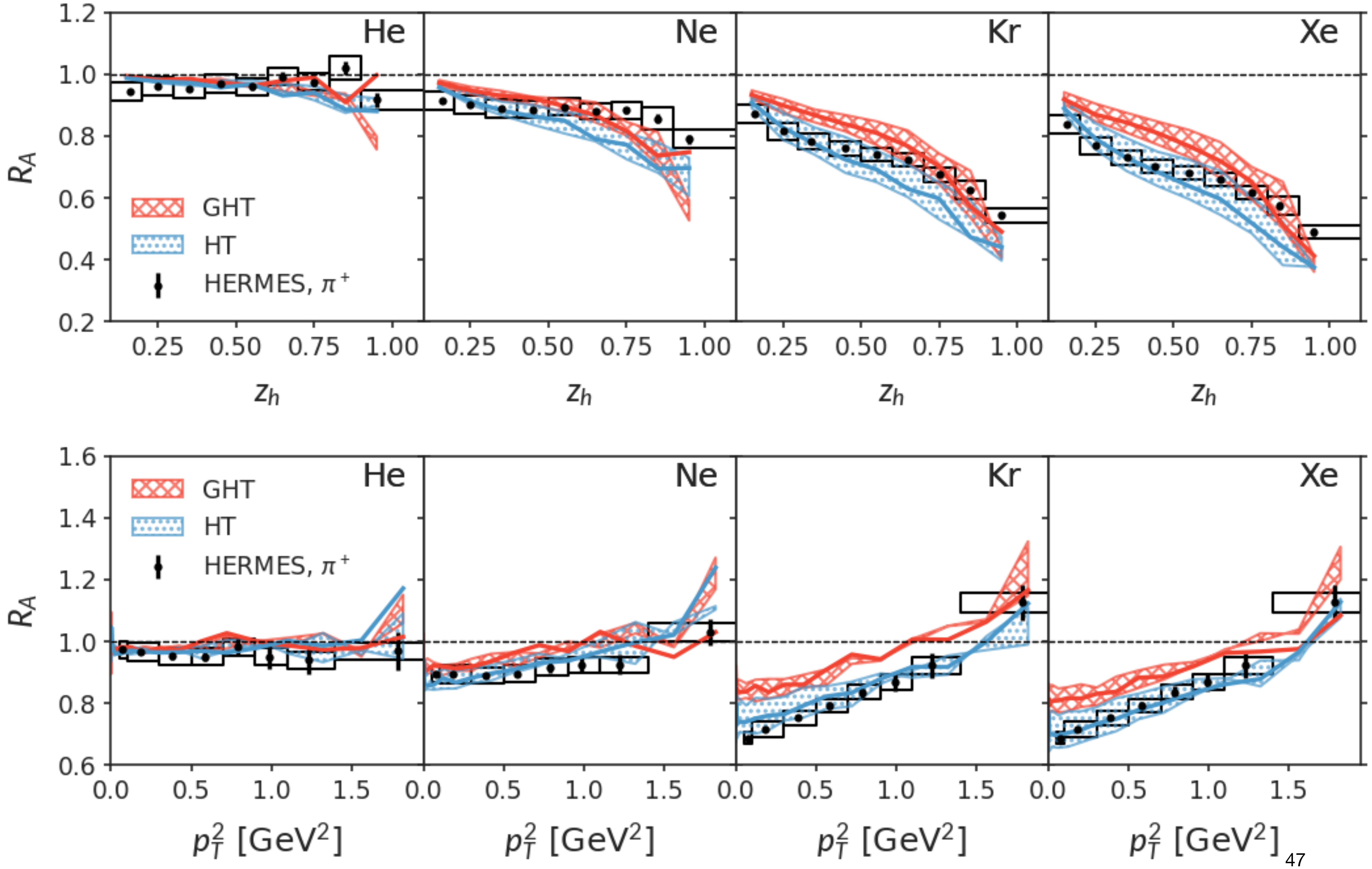


Parton propagation in cold nuclear medium

- eHIJING: an Event Generator for Jet Tomography in EIC

Ke, Zhang, Xing, Wang, 2304.10779





Parton propagation in cold nuclear medium

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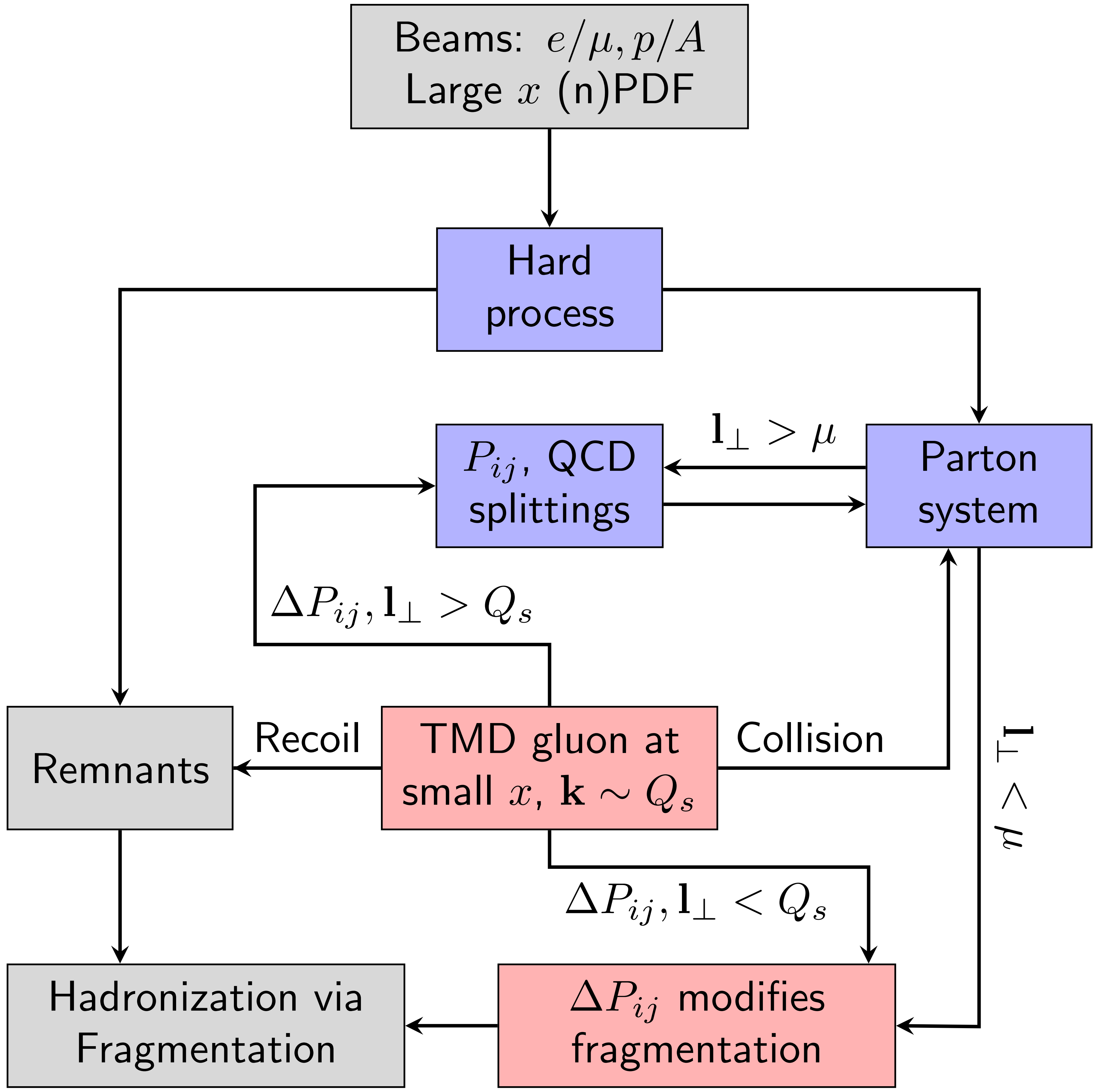
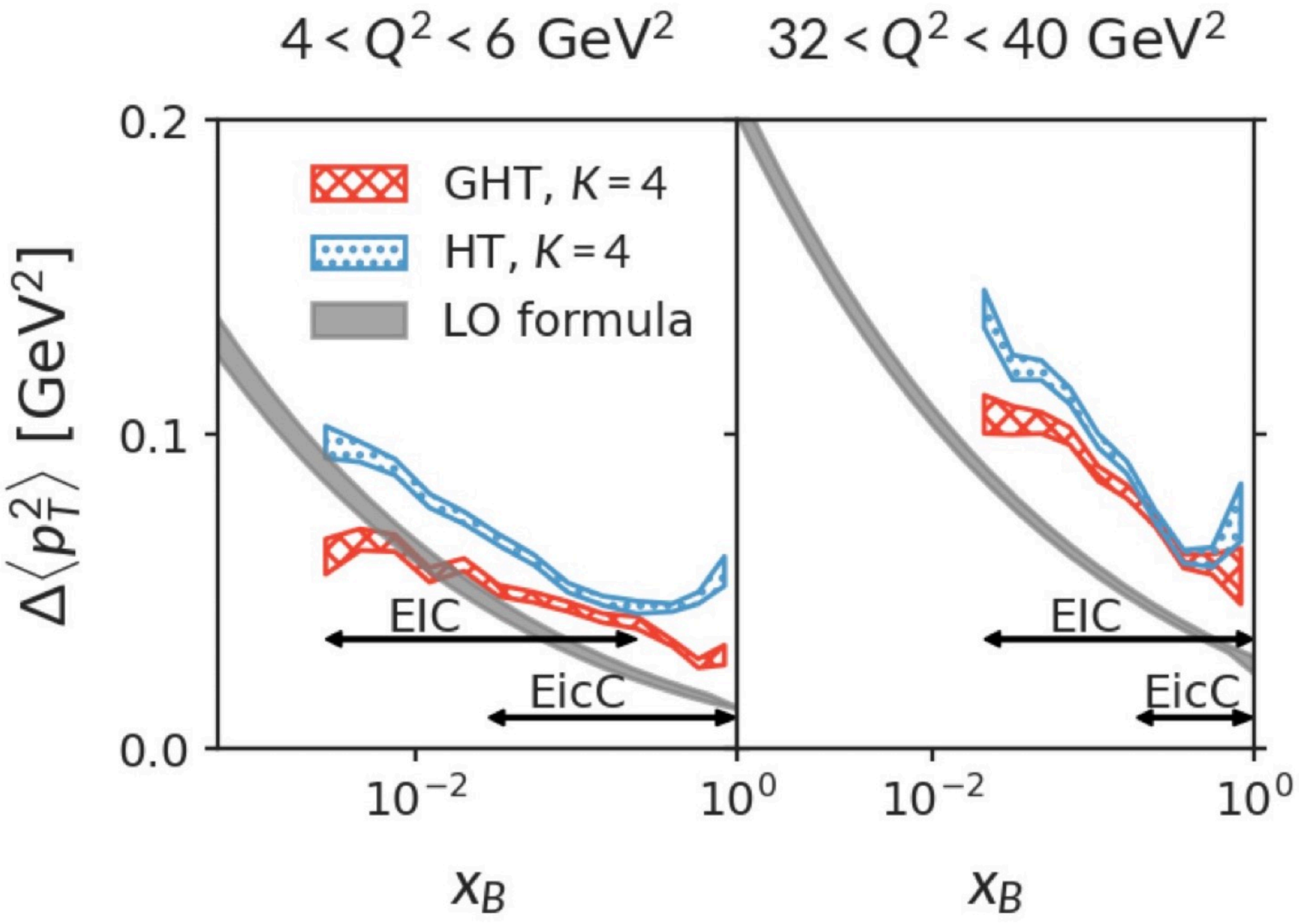
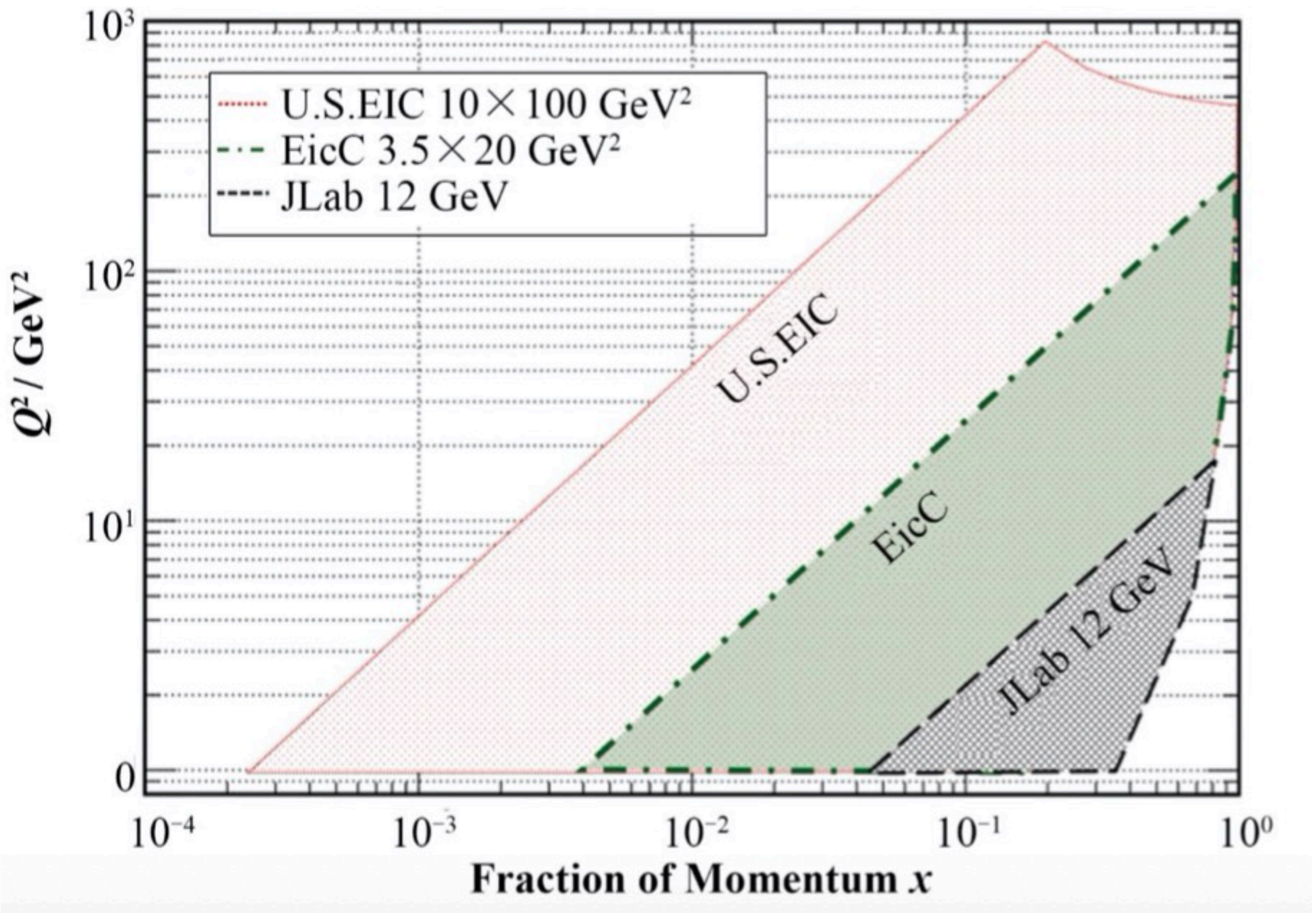
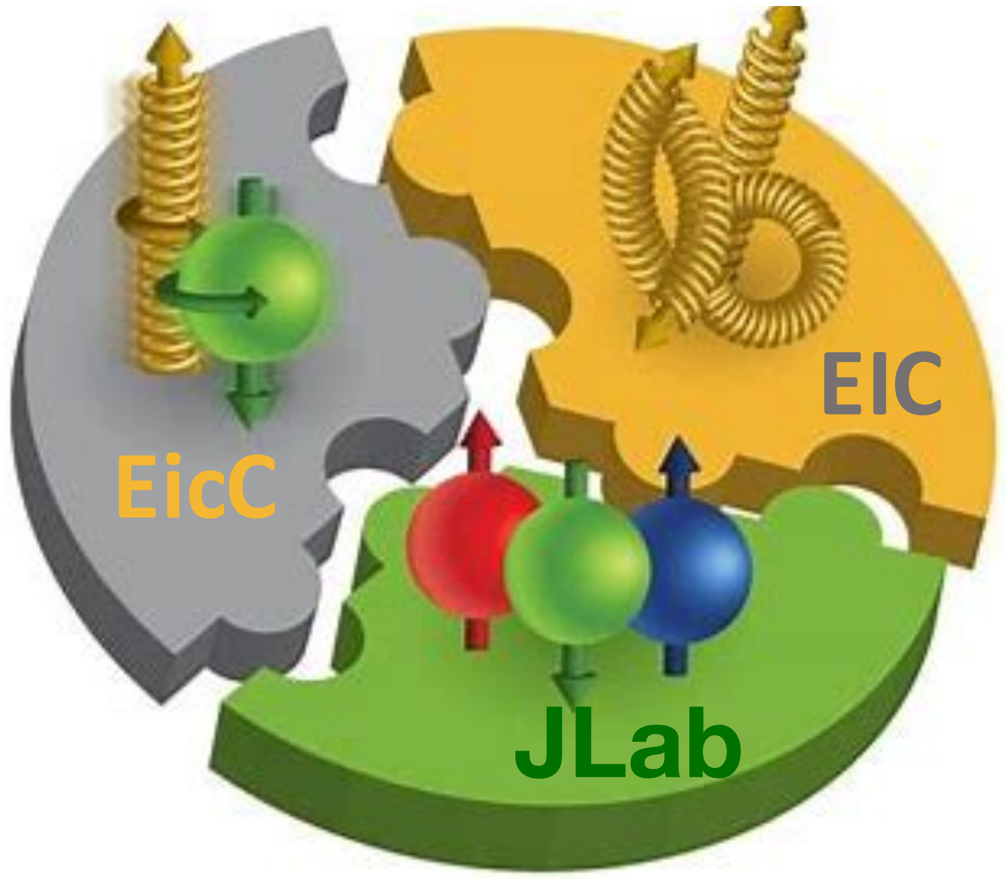




Summary

- **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. Nuclear effects
- **Many more topics are not covered, such as gluon saturation, proton mass, GPDs, exotic states, detector R&D …**
- **EIC、EicC、JLab are complementary to each other**





Thanks and you are more than welcome to join EicC!