

第二届 微扰量子场论研讨会

杭州 2022年8月22-24日

会议组织者：
朱华星（浙江大学）
杨李林（浙江大学）
高俊（上海交通大学）
李钊（中科院高能所）
王健（山东大学）



Physics at Electron-Ion Colliders

Hongxi Xing

邢宏喜



Institute of Quantum Matter
South China Normal University



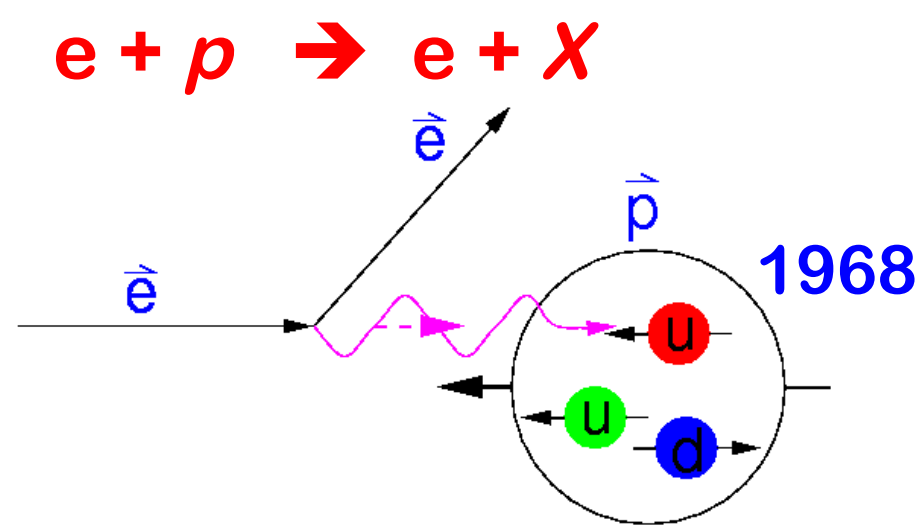
Outline

- ◆ Introduction to Electron-Ion Colliders
- ◆ Selected topics for EIC physics:
 - proton spin decomposition
 - proton 3D tomography
 - nuclear effects
- ◆ Summary and outlook

Nucleon partonic structure

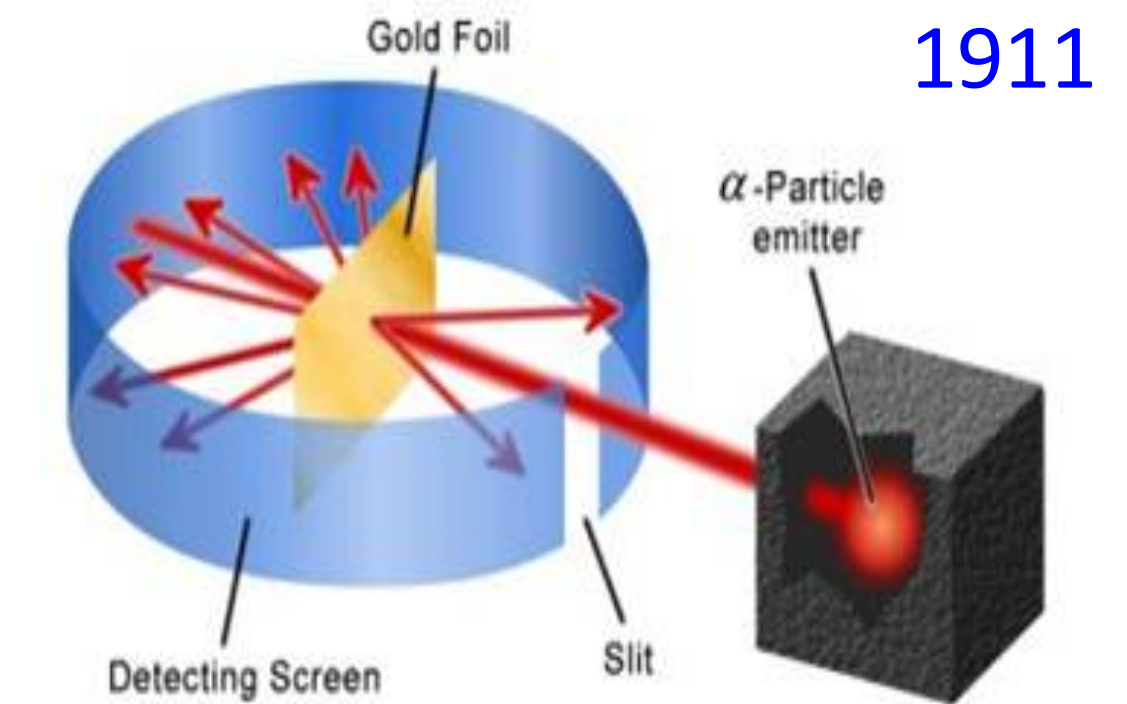
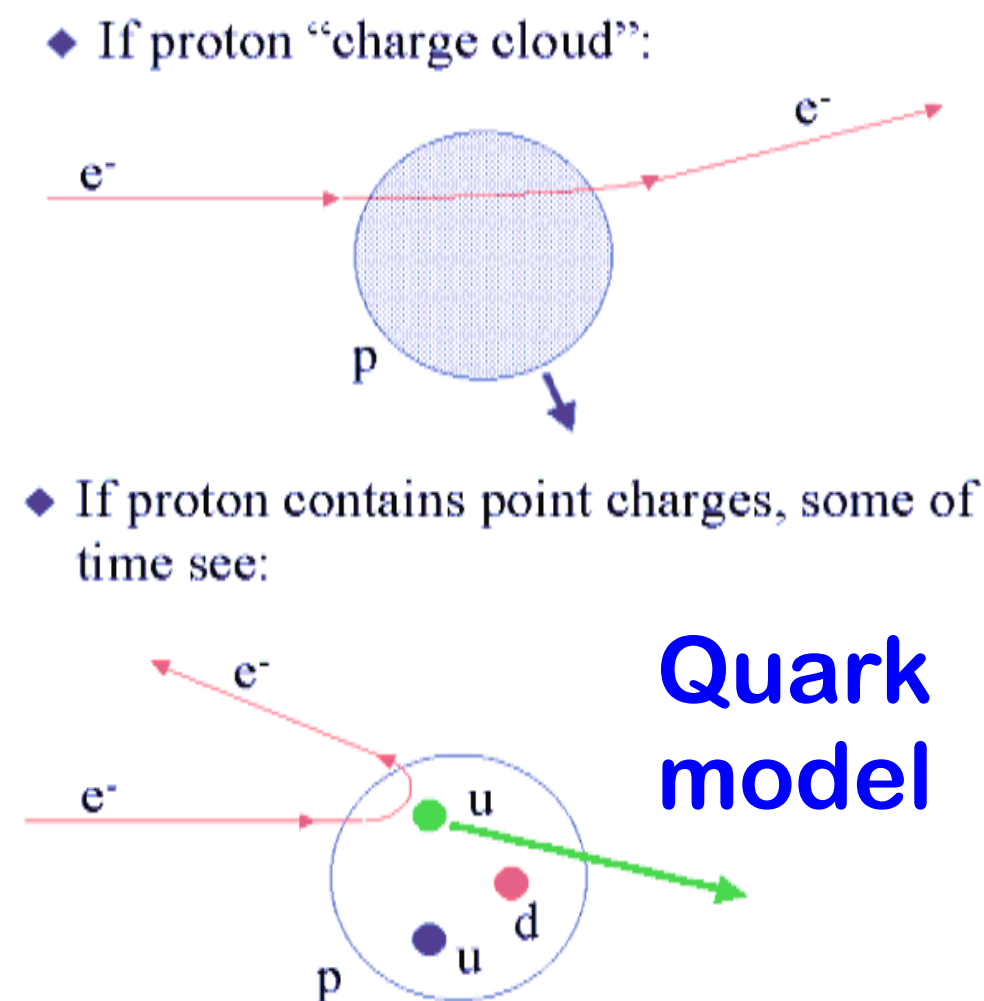
♦ Revolution in our view of nuclear structure

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



Modern Rutherford scattering

- partons/quarks - moving relativistically
- Quantum fluctuation - parton number is not fixed
- Birth of QCD



Rutherford scattering

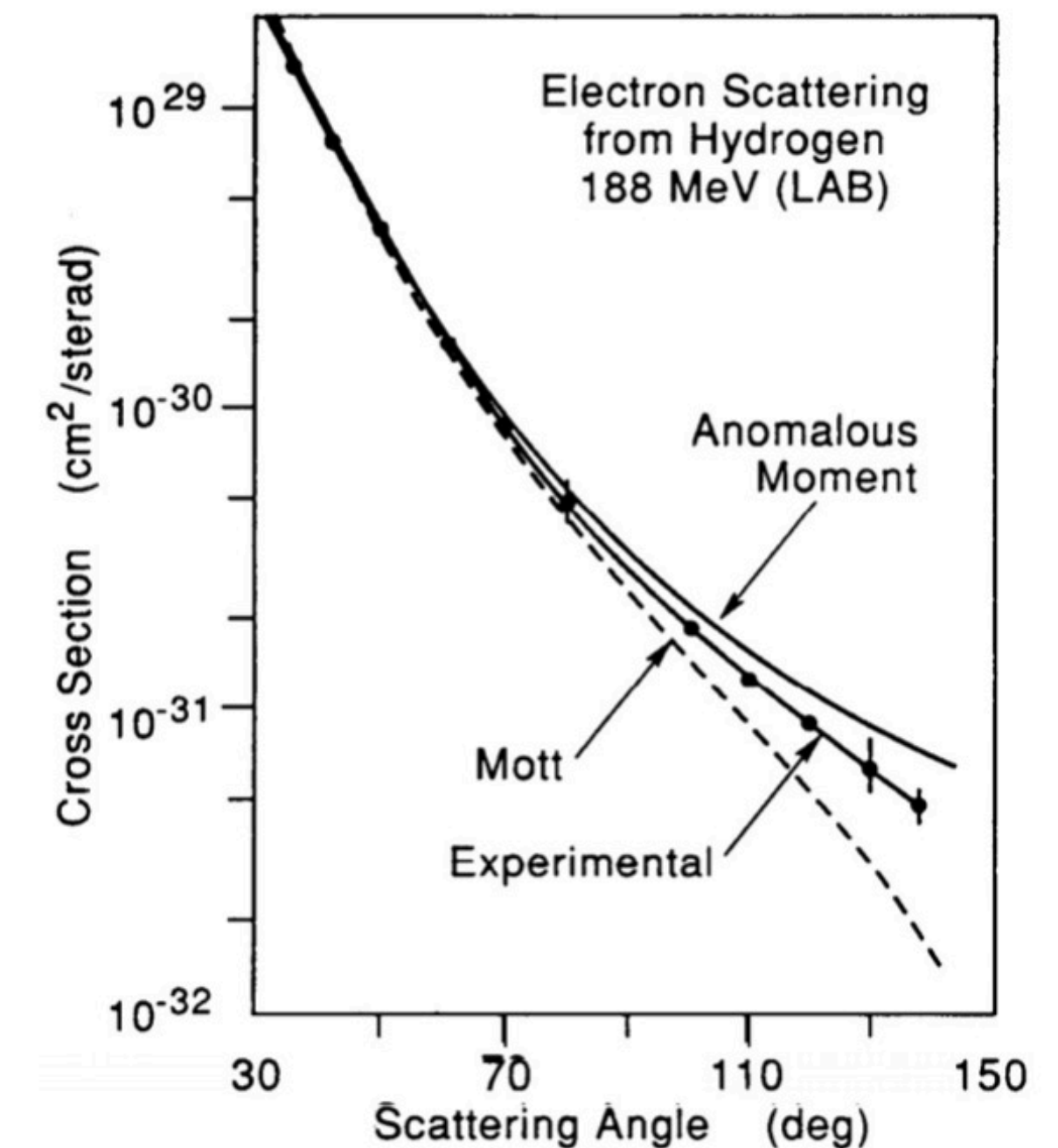
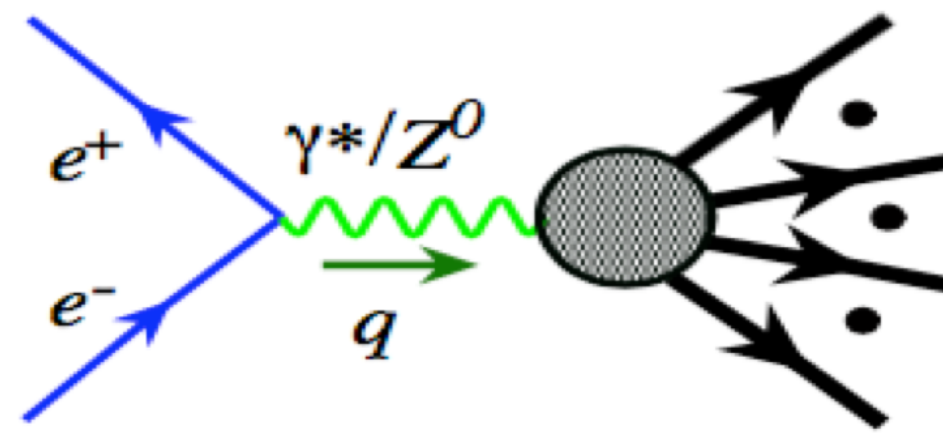


Fig. 5. Elastic electron scattering cross sections from hydrogen compared with the Mott scattering formula (electrons scattered from a particle with unit charge and no magnetic moment) and with the Rosenbluth cross section for a point proton with an anomalous magnetic moment. The data falls between the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

How to probe the nucleon partonic structure?

◆ Indispensable joint efforts from experiments and QCD theory

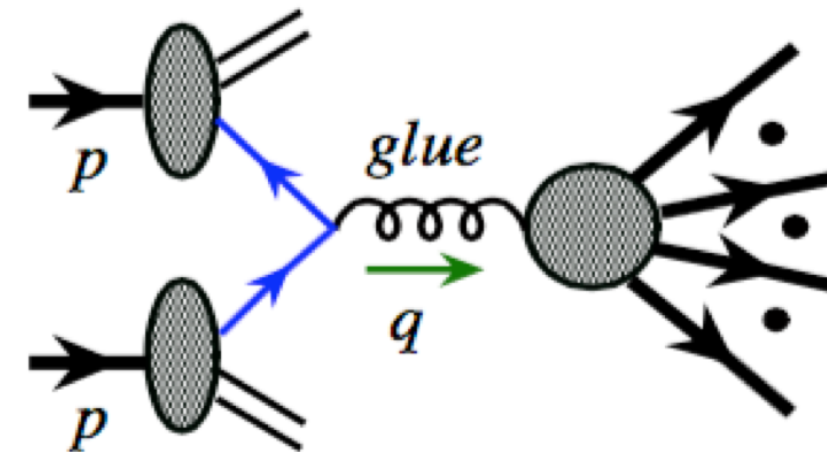
Lepton-lepton colliders



BEPC, SuperKEKB

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

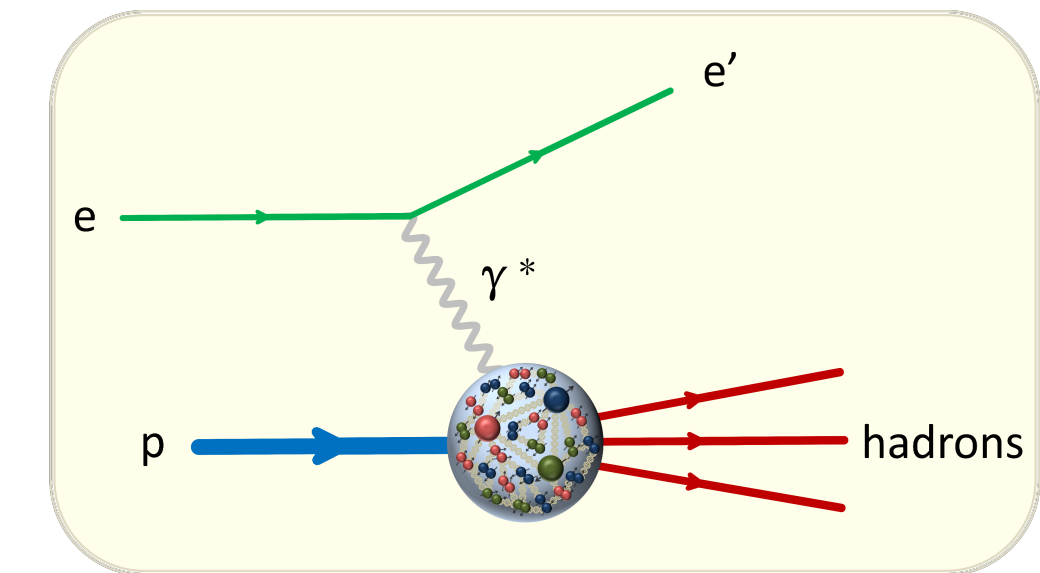
Hadron-hadron colliders



RHIC, LHC

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

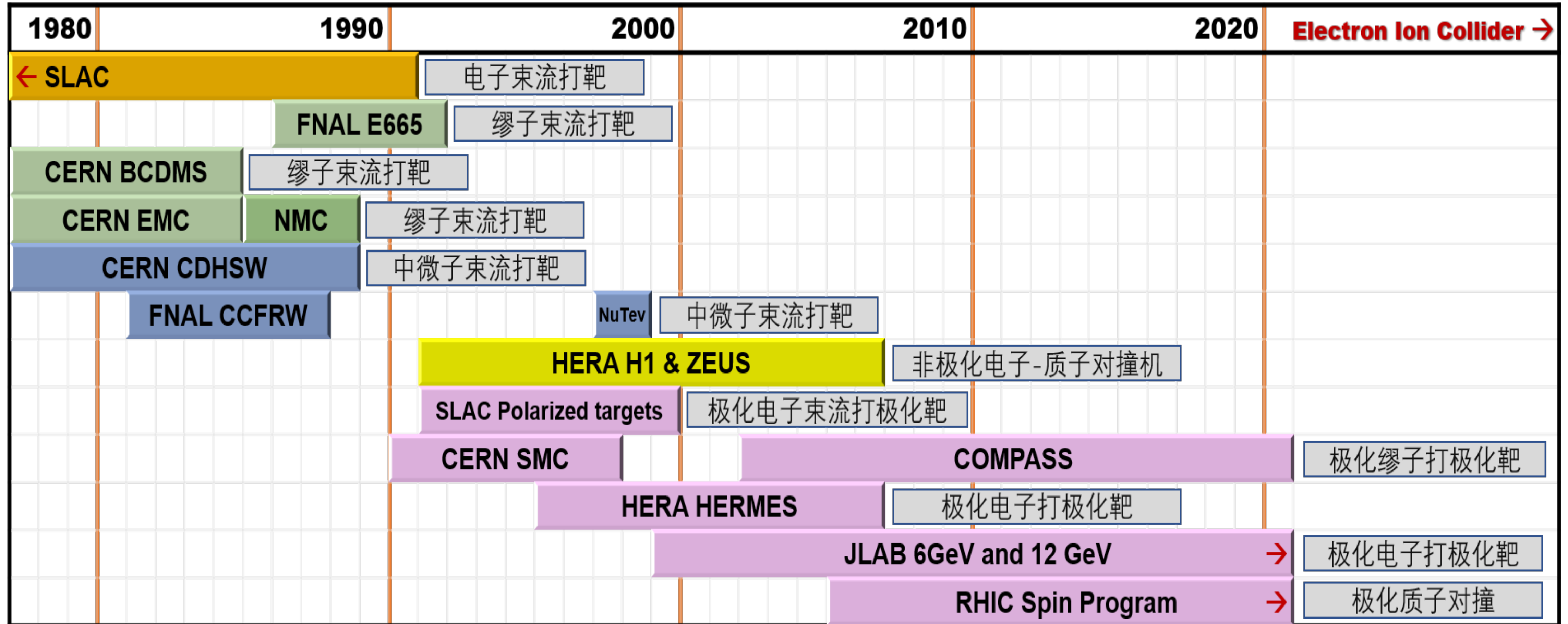
lepton-hadron colliders



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!

Proposed Electron-ion colliders



RHIC → US-EIC



FAIR → ENC



LHC → LHeC



HIAF → **EicC**



Time evolution of US EIC



电子 – 离子对撞机 (EIC)

质心能量~100 GeV

2005: 领域内开始讨论

2007, 2015: 美国核科学长程计划

2015: EIC 白皮书

2018: 美国科学院重申EIC物理重要性

2019.12: **EIC 立项**

2020: EIC 黄皮书和概念设计

2021: EIC 探测器方案建议书

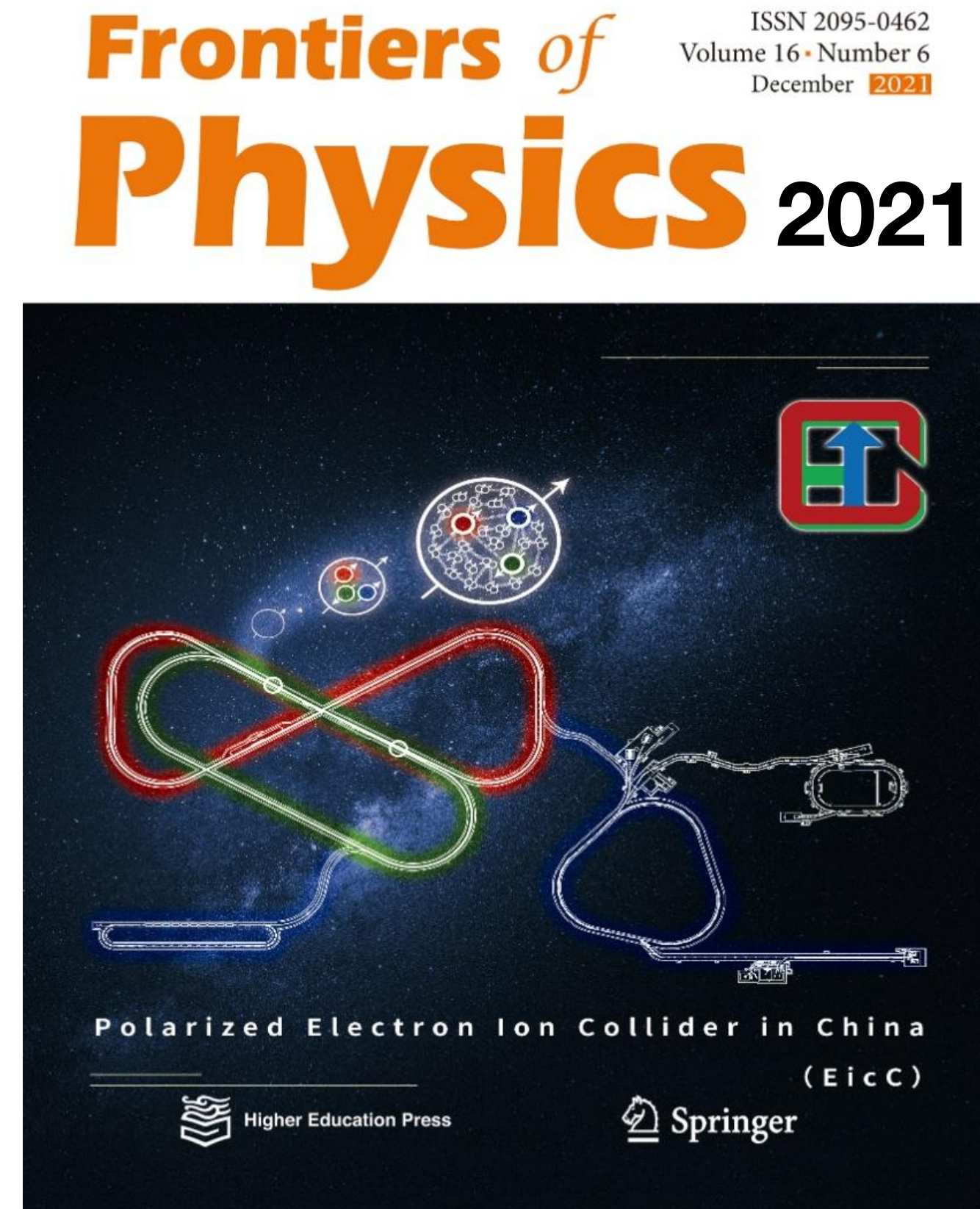
2030: 计划开始运行

高能核物理、粒子物理重要方向

1200 研究人员, 230 单位, 31 国家

美国国家实验室: ANL, BNL
LANL, LBNL, ORNL

Time evolution of EicC



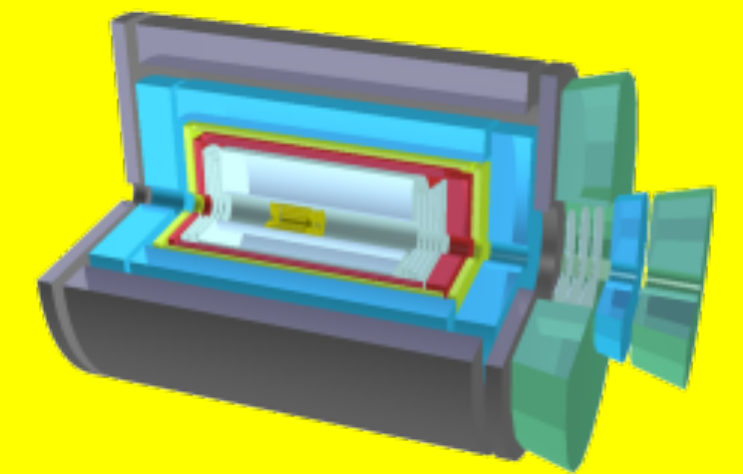
中国电子 – 离子对撞机 (EicC)

2012: 领域内开始讨论

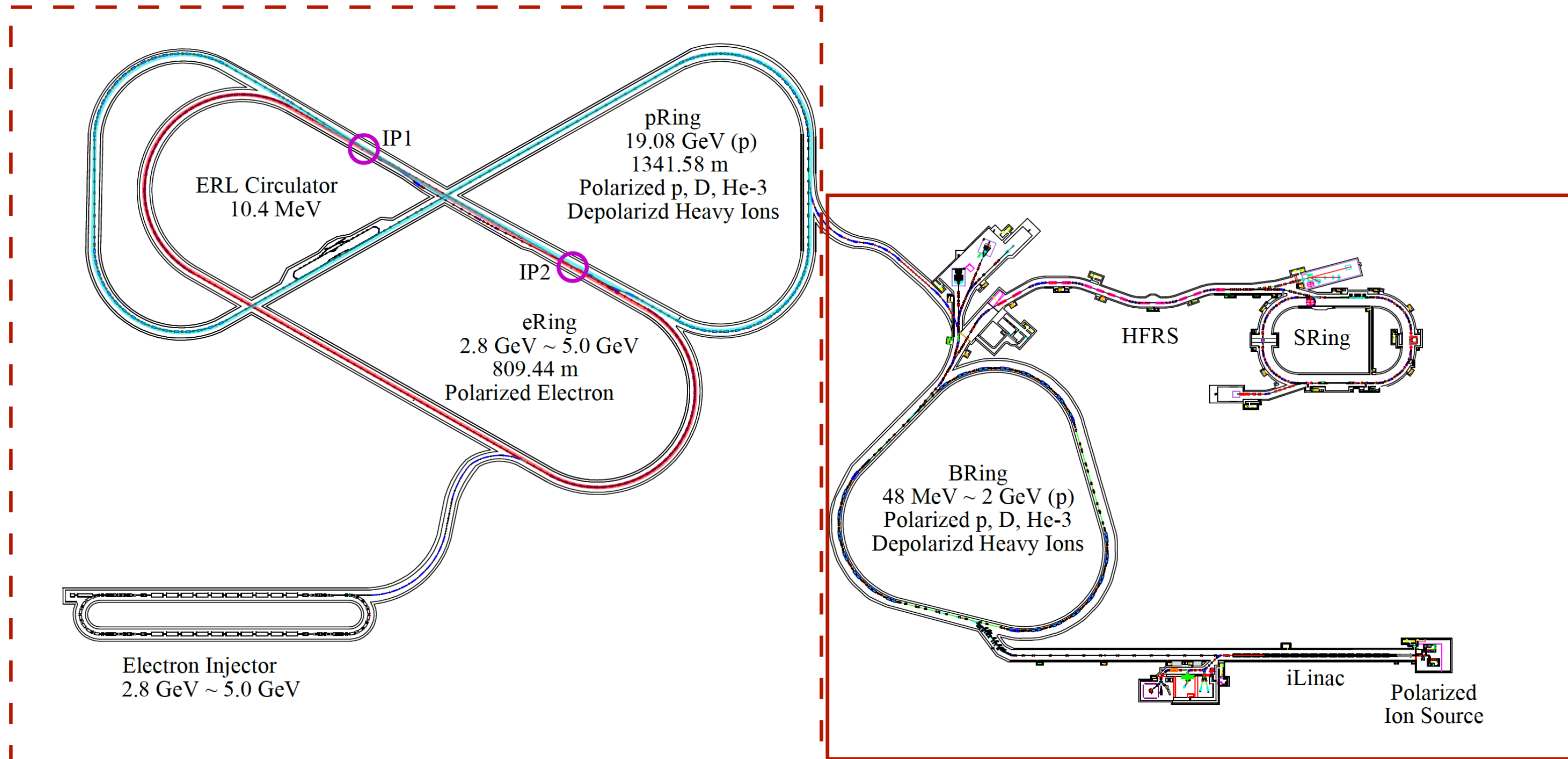
2020.2, 2021.6: 白皮书 (中文, 英文)

2021-2023: 概念设计研究

参与单位: ~ 45



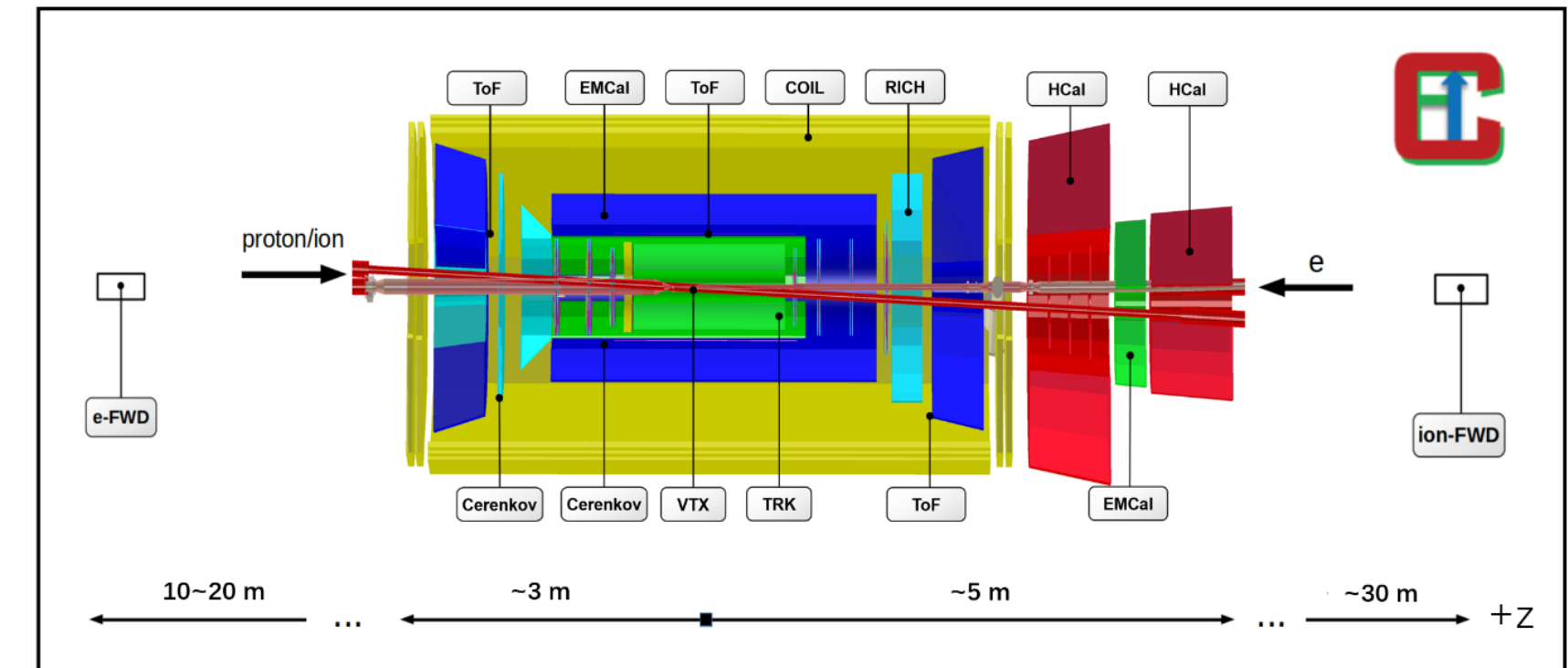
Electron-Ion Collider in China (EicC)



Need to be built for the EicC

HIAF under construction

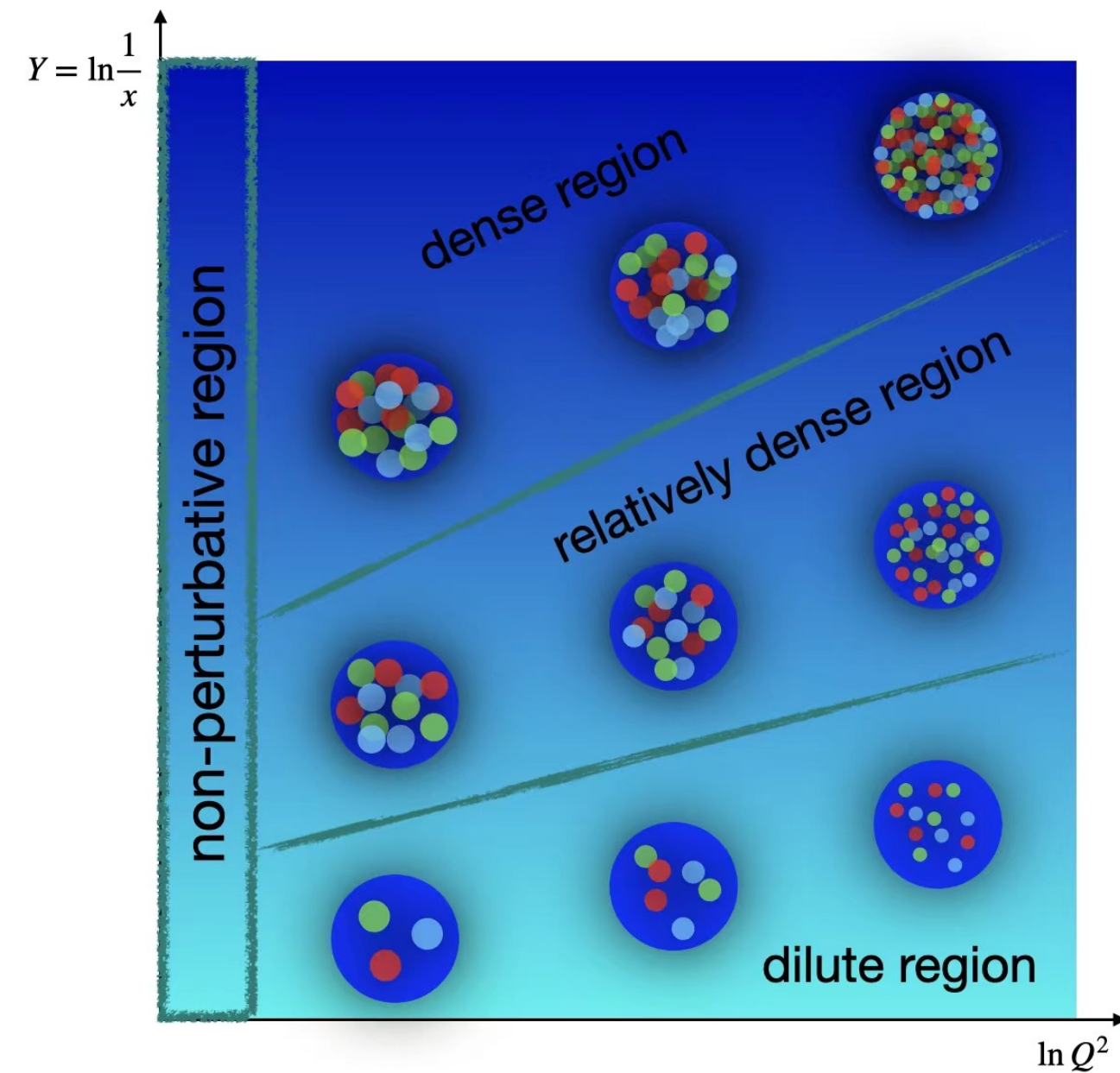
- Polarized electron injector + racetrack eRing + Figure 8 pRing
- 2 interaction regions
- 3.5 GeV (e) x 20 GeV (p)



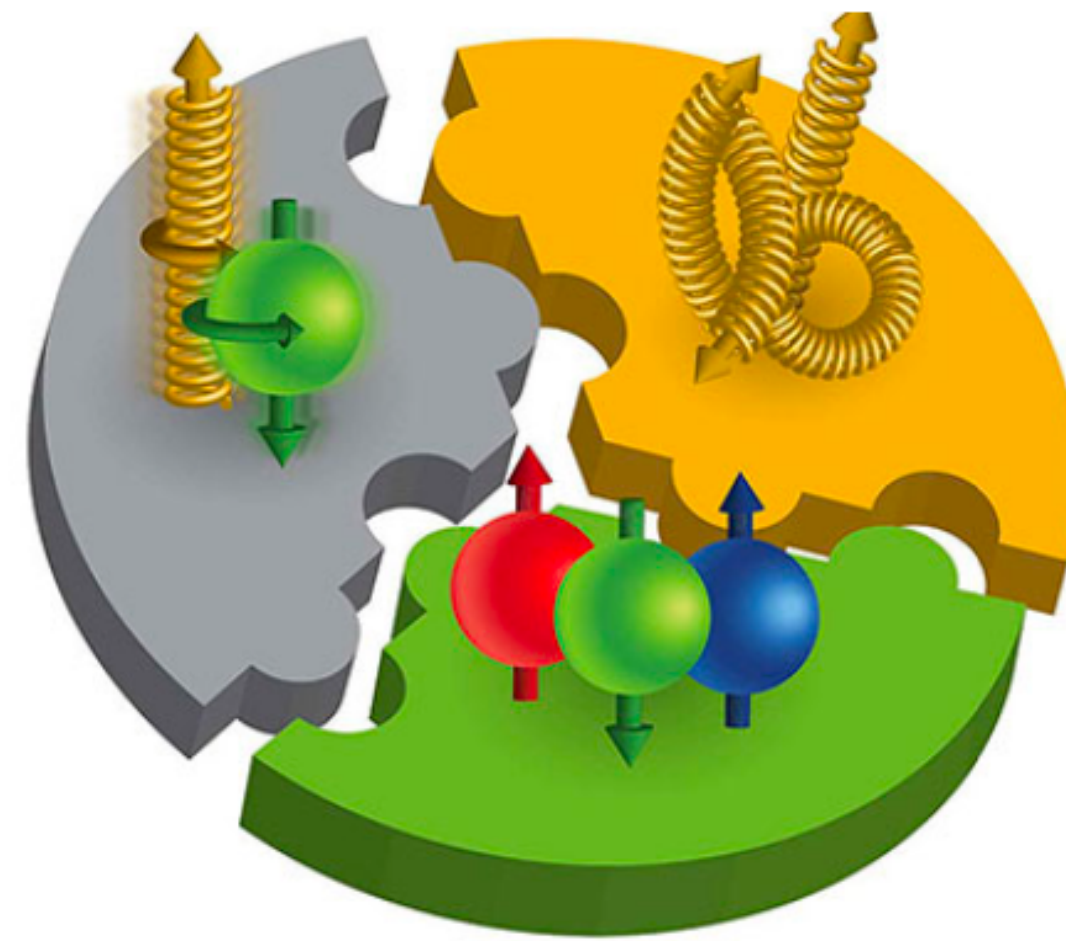
主要参加研究单位:

中科院近物所、理论所、高能所、
国科大、科大、清华、北大、山
大、华中师大、**华南师大**;
美国Jlab、UVa、UCLA

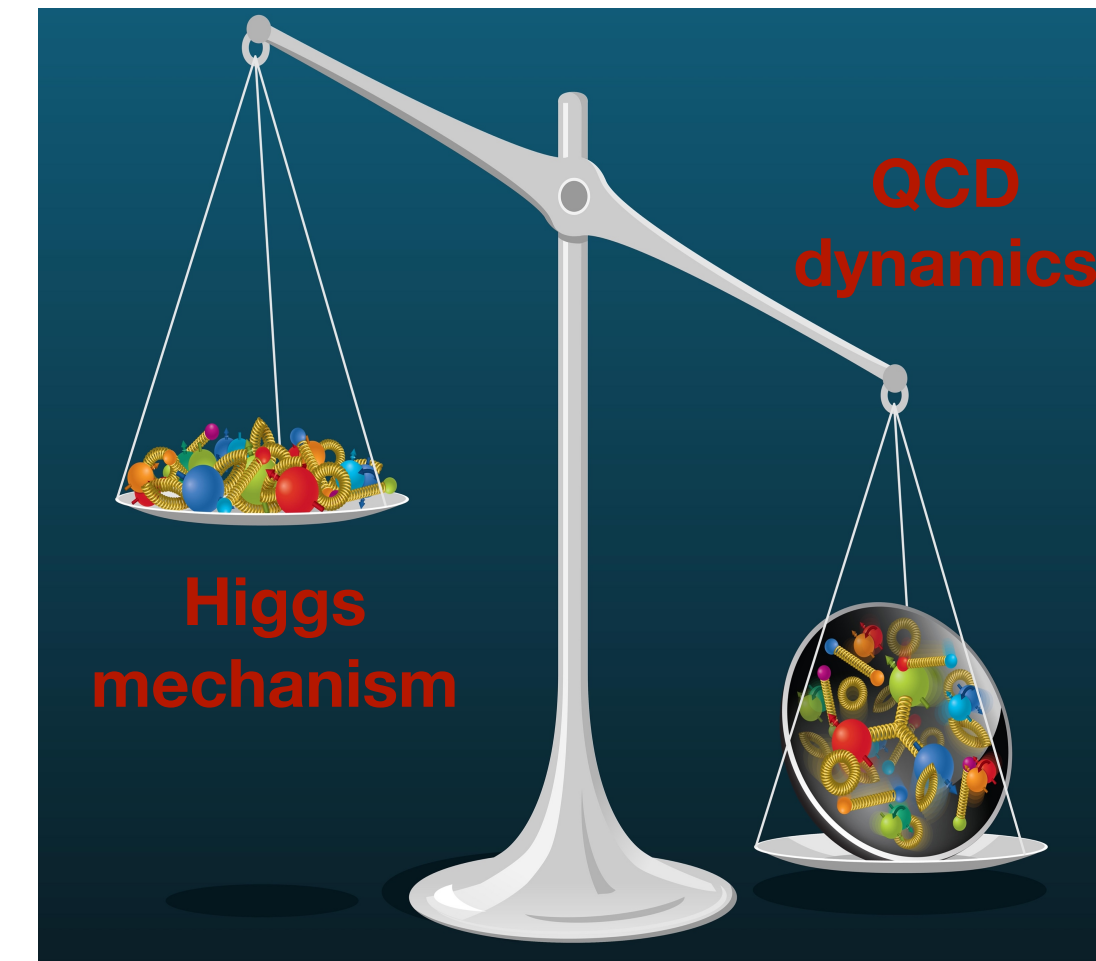
Scientific goals at EIC worldwide



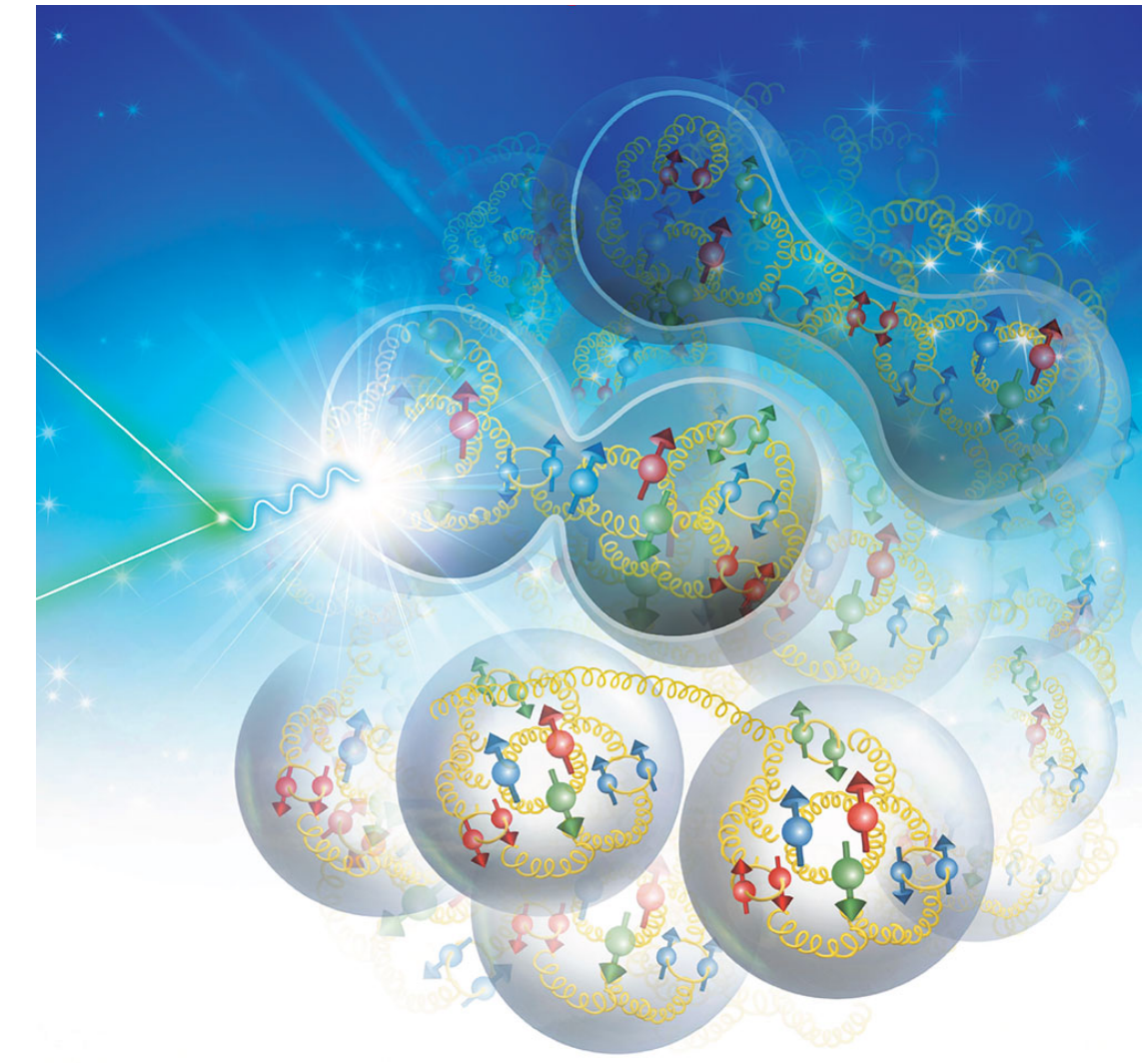
The energy momentum distribution of partons in nucleon/nuclei



The origin of proton spin

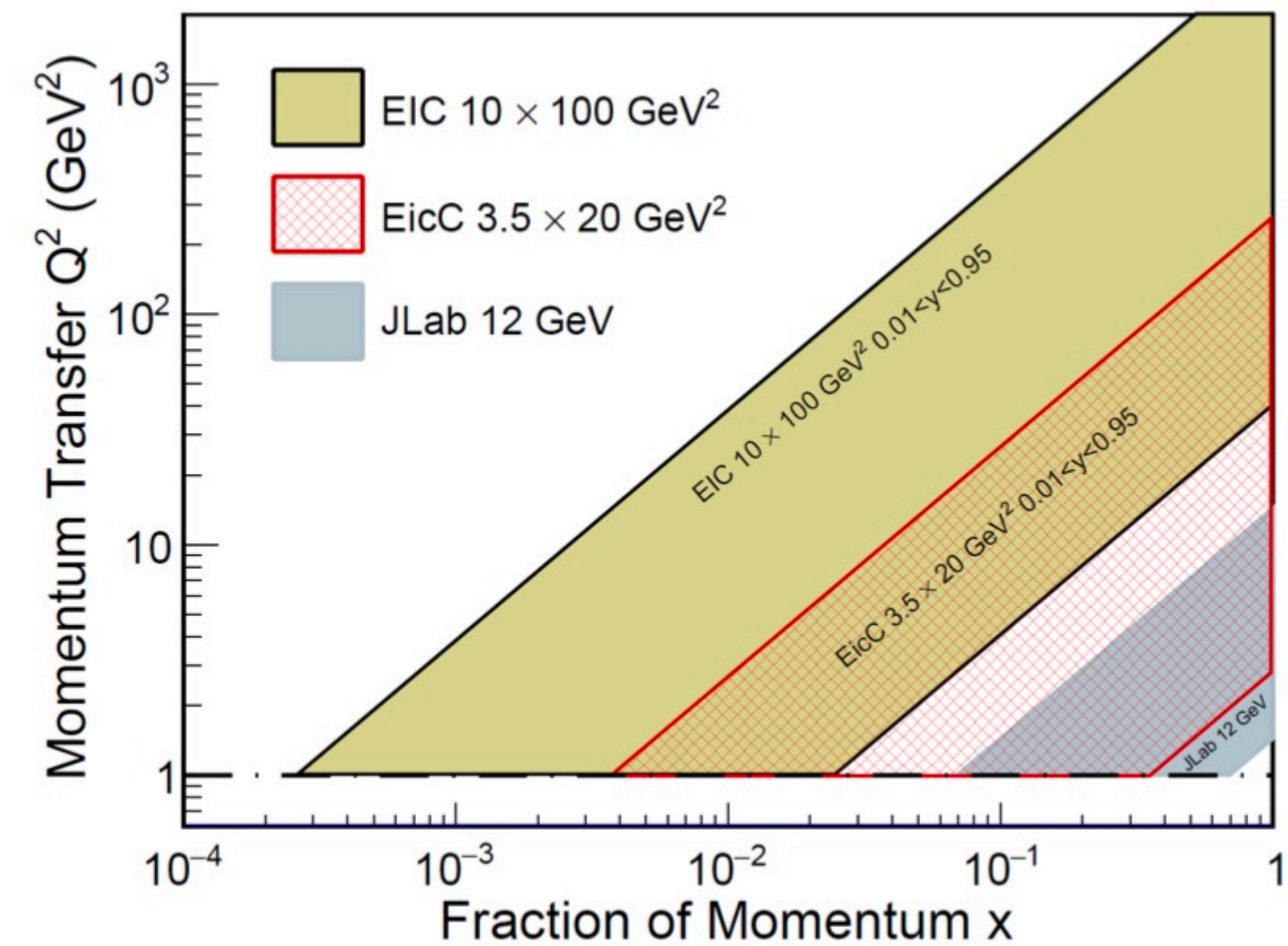
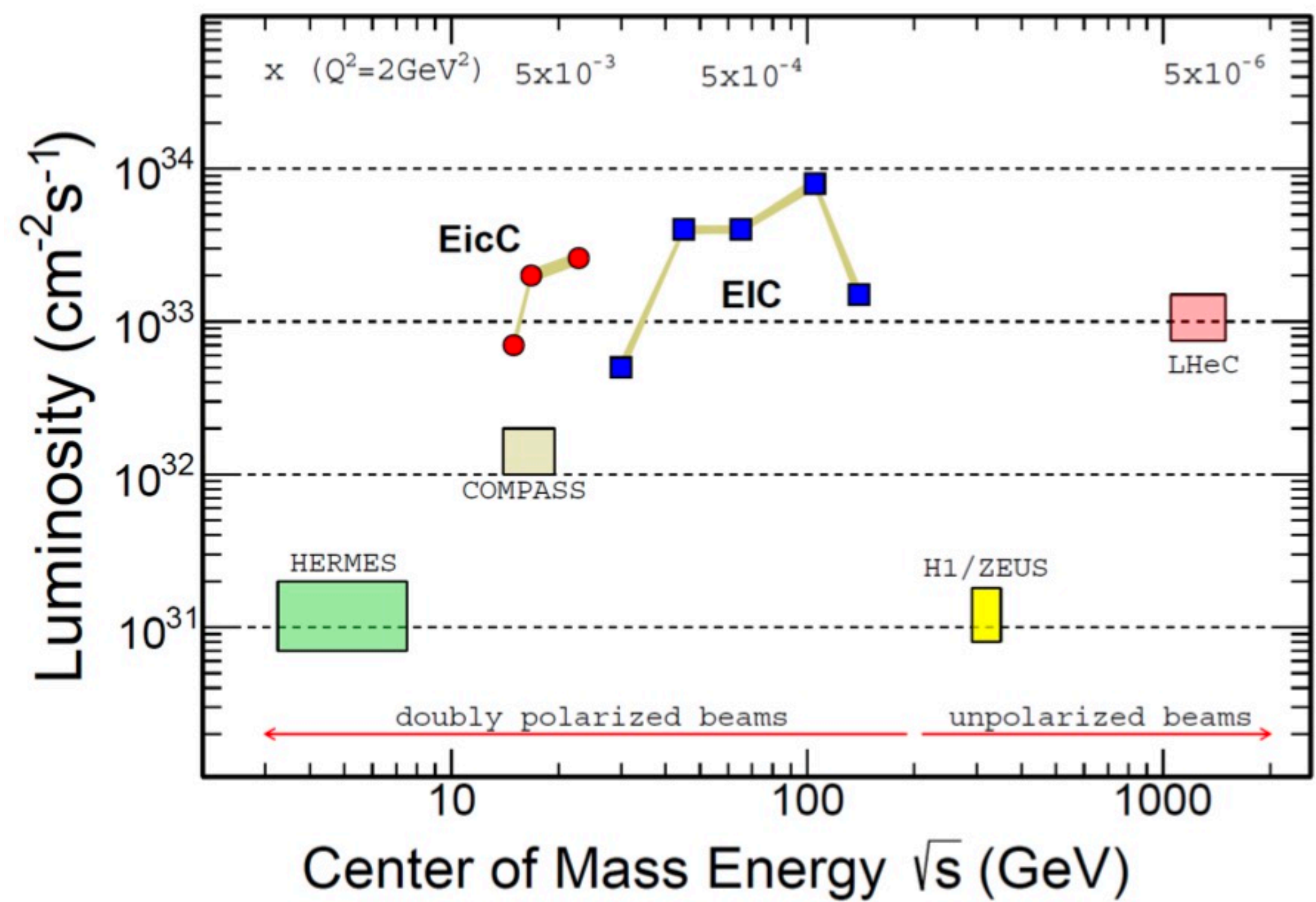


The origin of proton mass

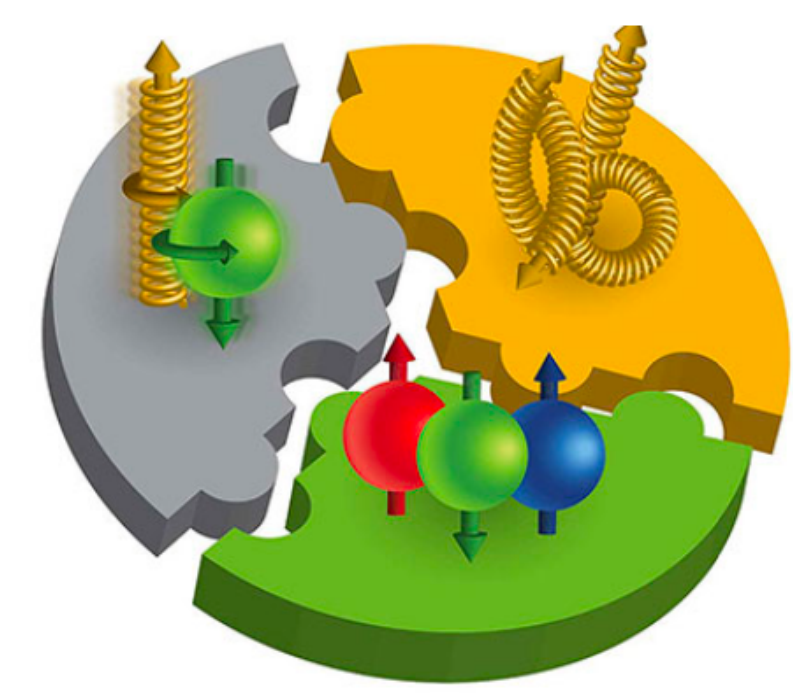


nuclear effects

Complementarity between EIC and EicC



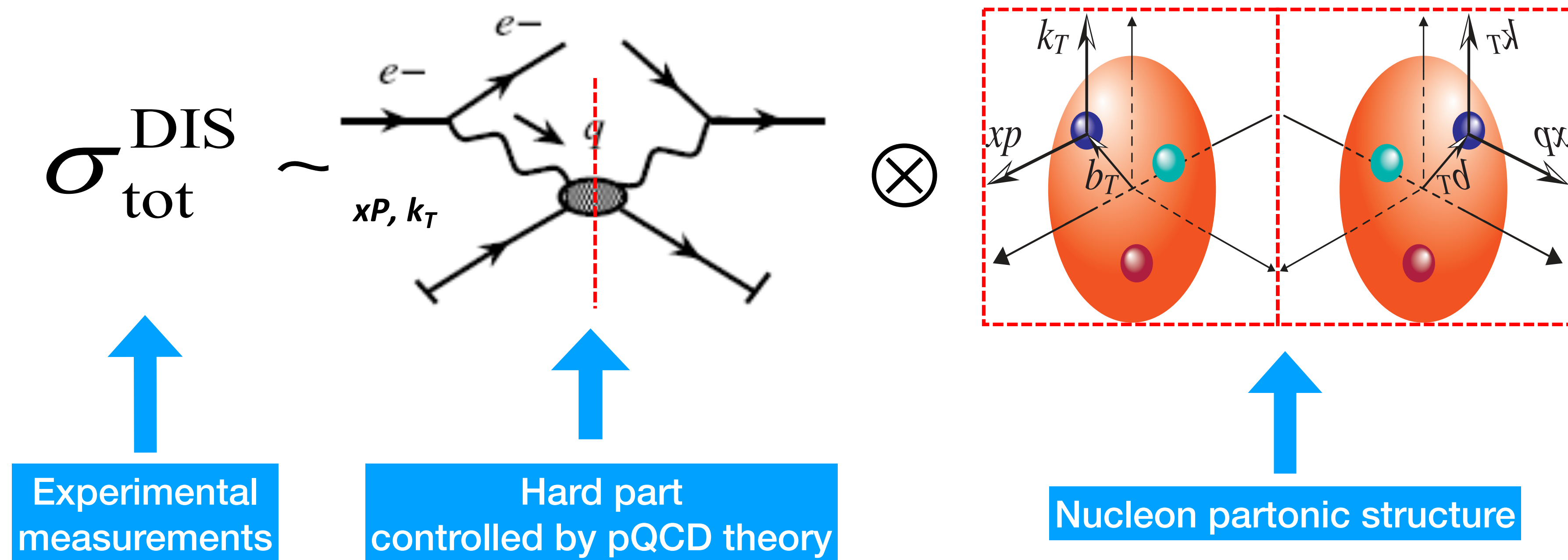
Mapping out the nucleon structure
via EICs worldwide



How to probe the nucleon partonic structure?

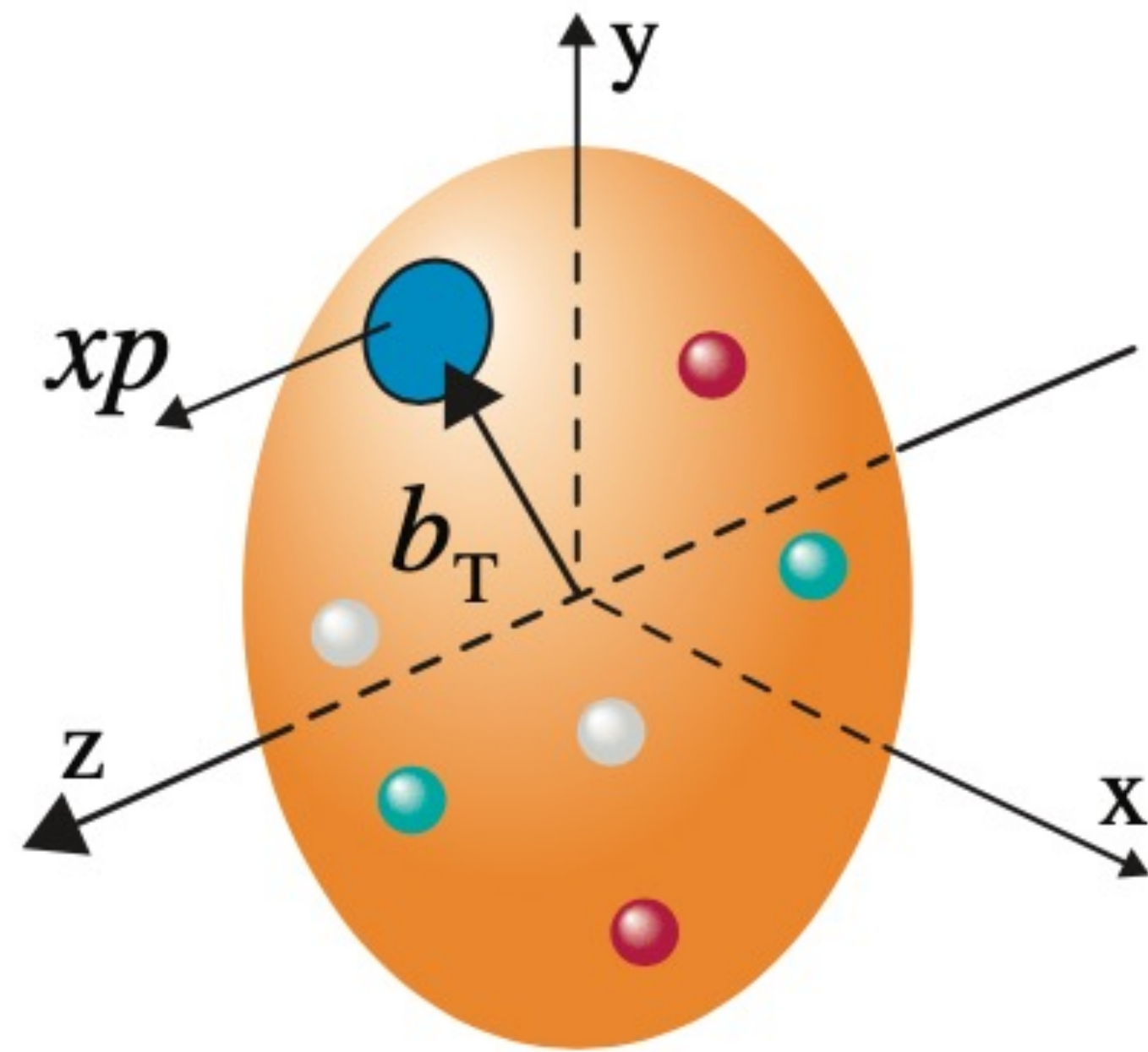
- ◆ Indispensable joint efforts from experiments and QCD theory

QCD factorization theorem

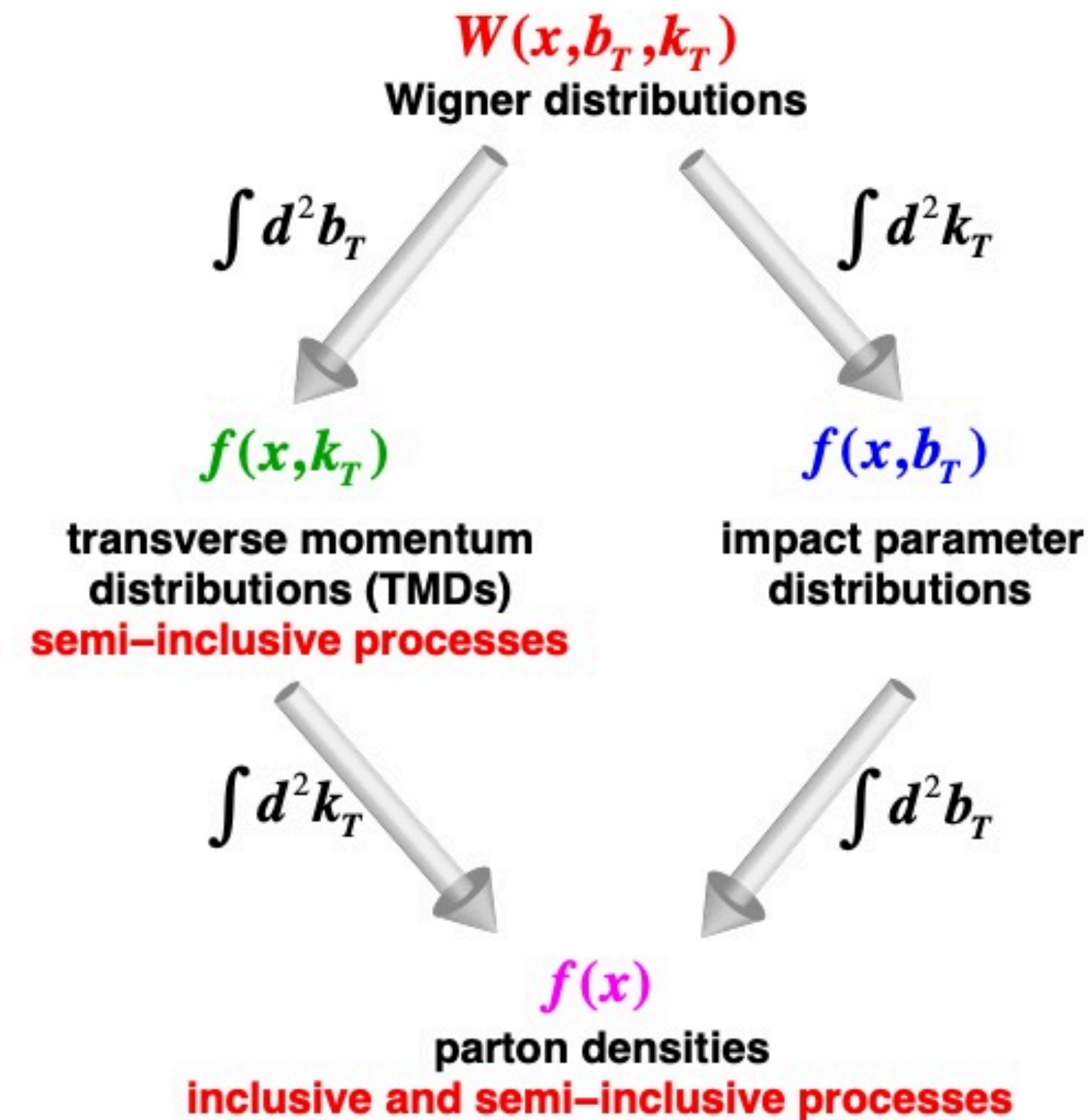


Nucleon partonic structure - momentum distribution

◆ Multi-dimensional view of nucleon partonic structure



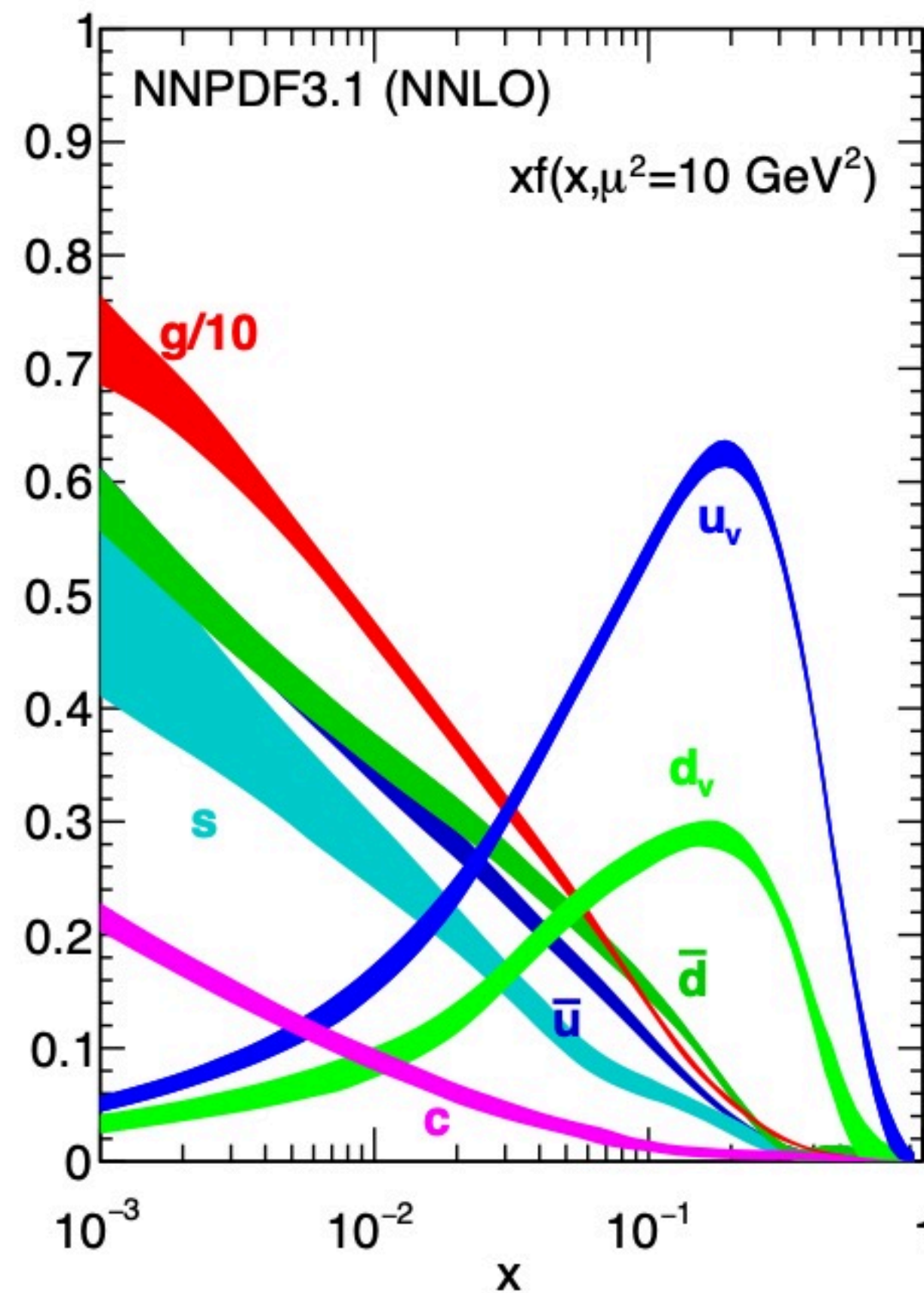
Wigner distribution
5D view



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

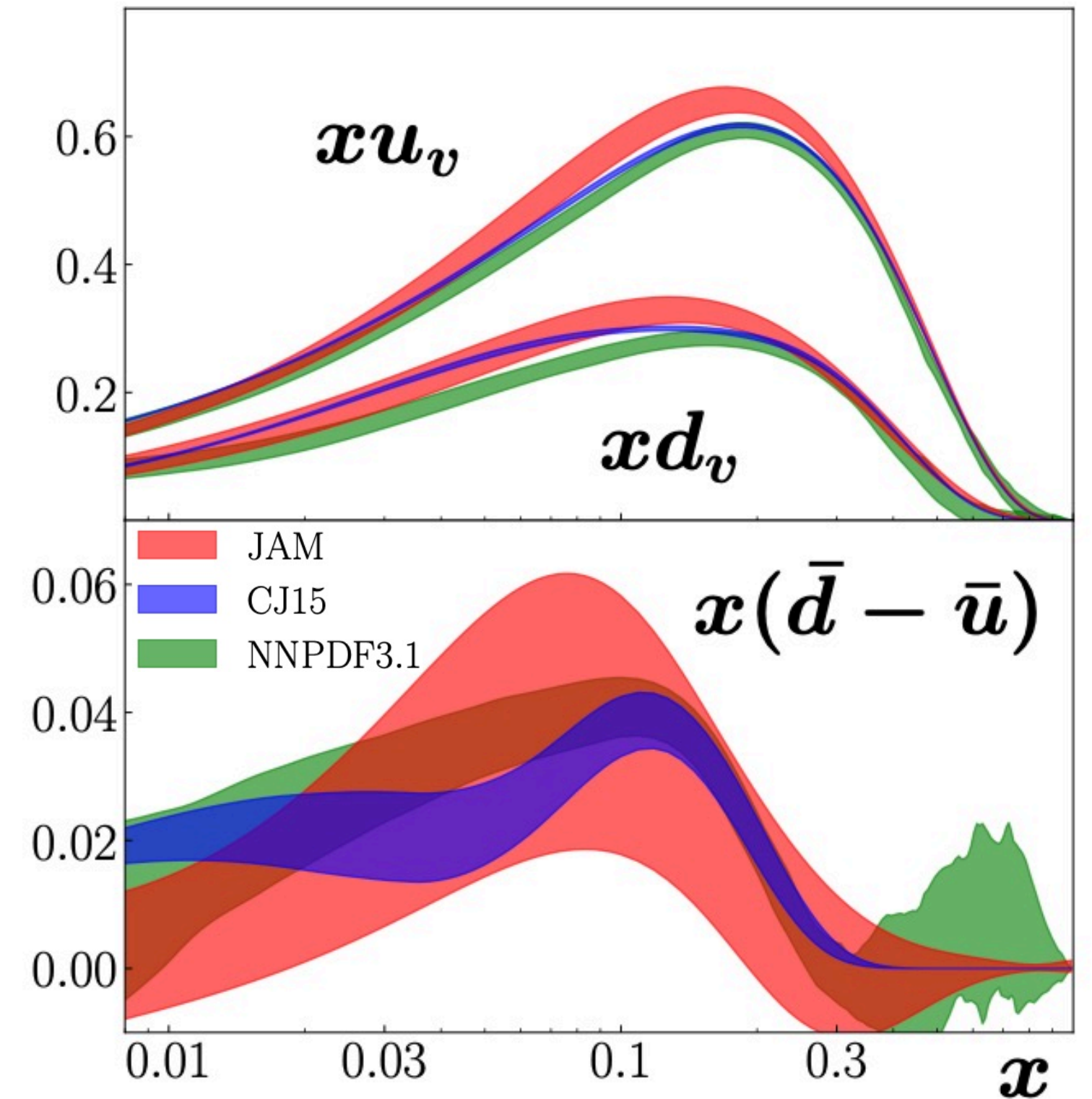
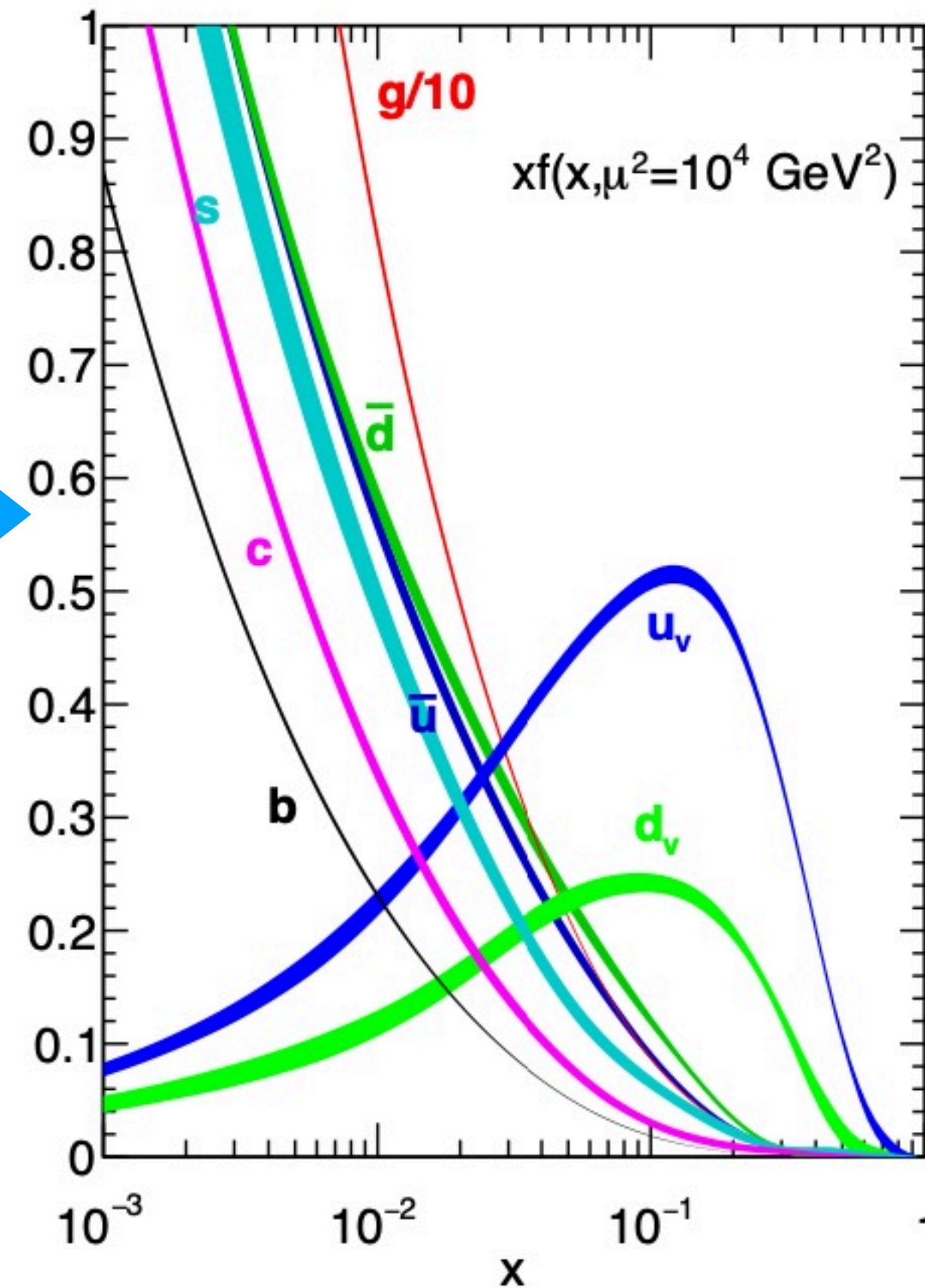
QCD global analysis of world data - nucleon 1D structure

◆ Current knowledge about proton PDFs



NNPDF:1706.00428

QCD
prediction



JAM 20, arXiv:2101.04664

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

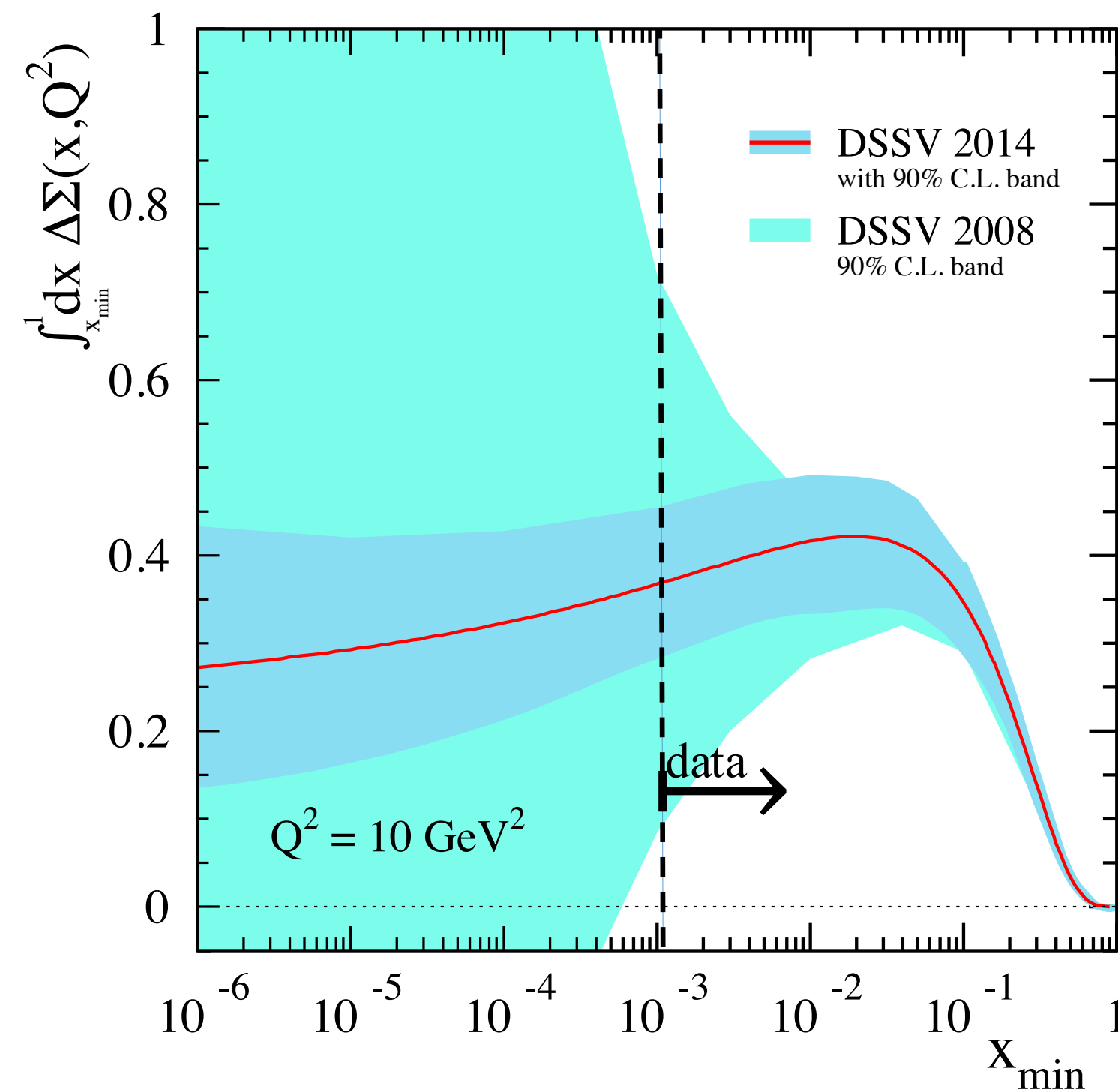
$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} \left| J_{QCD}^z \right| P, \frac{1}{2} \right\rangle = \frac{1}{2} \int_0^1 dx \Delta \Sigma(x, Q^2) + \int_0^1 dx \Delta G(x, Q^2) + \int_0^1 dx \left(\sum_q L_q^z + L_g^z \right)$$



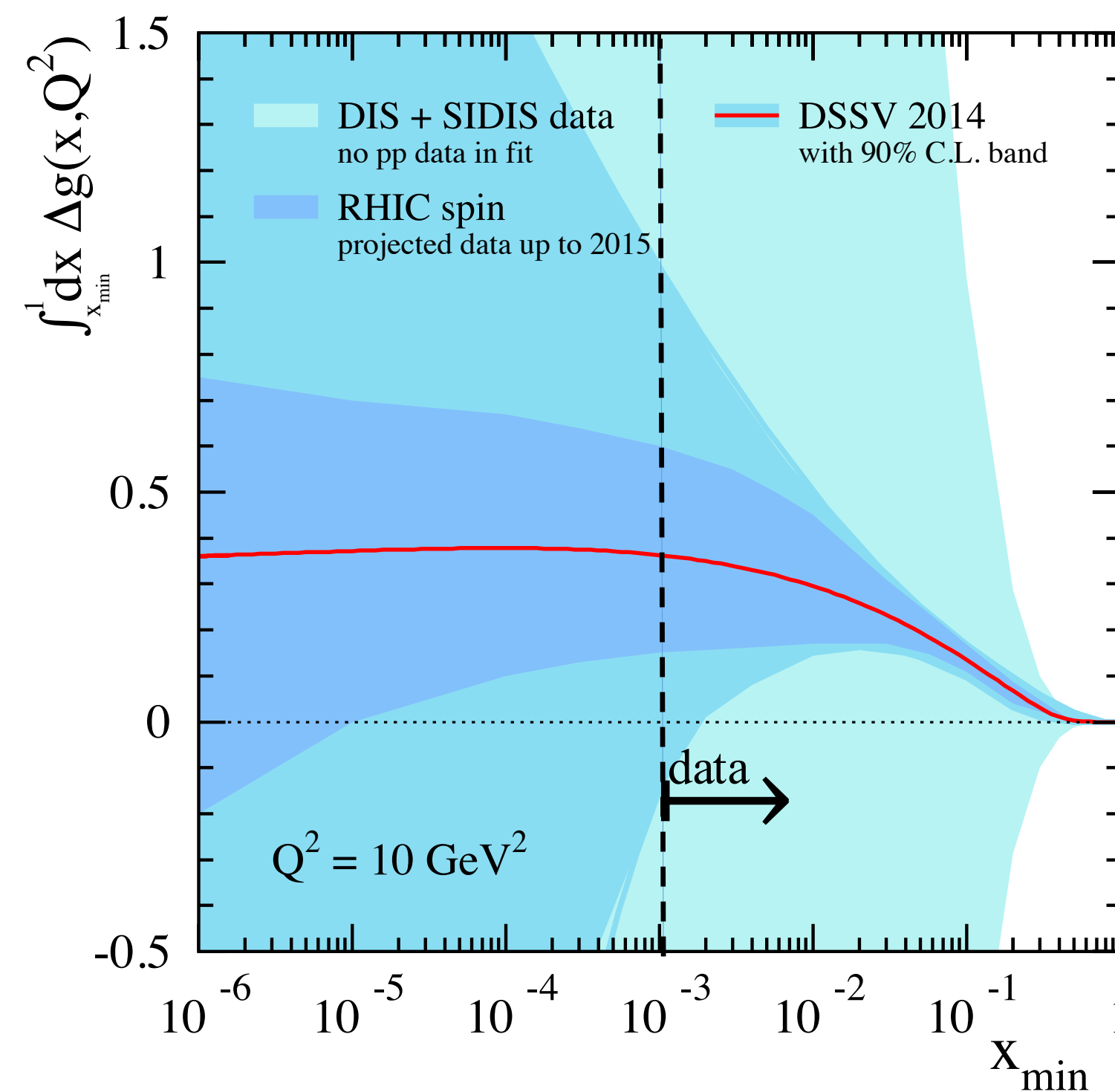
- Spin is one of the fundamental properties of matter
- We don't know yet how the spin of proton arises in terms of its quarks and gluons - spin crises.

what do we know about the proton spin?

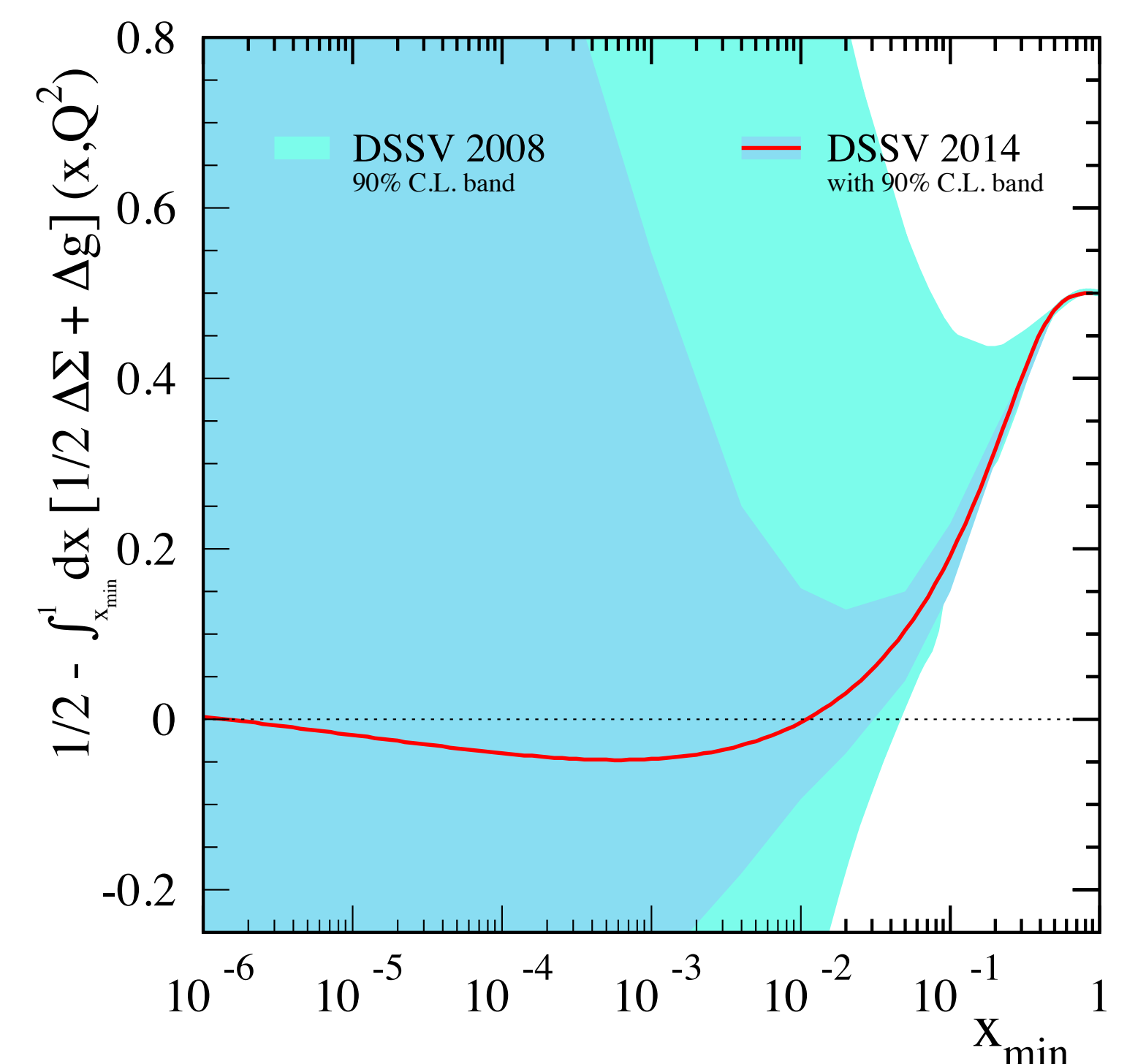
◆ Current knowledge about proton spin decomposition from world data



Quarks ~ 30%



Gluon ~ 40%



Orbital angular momentum ?

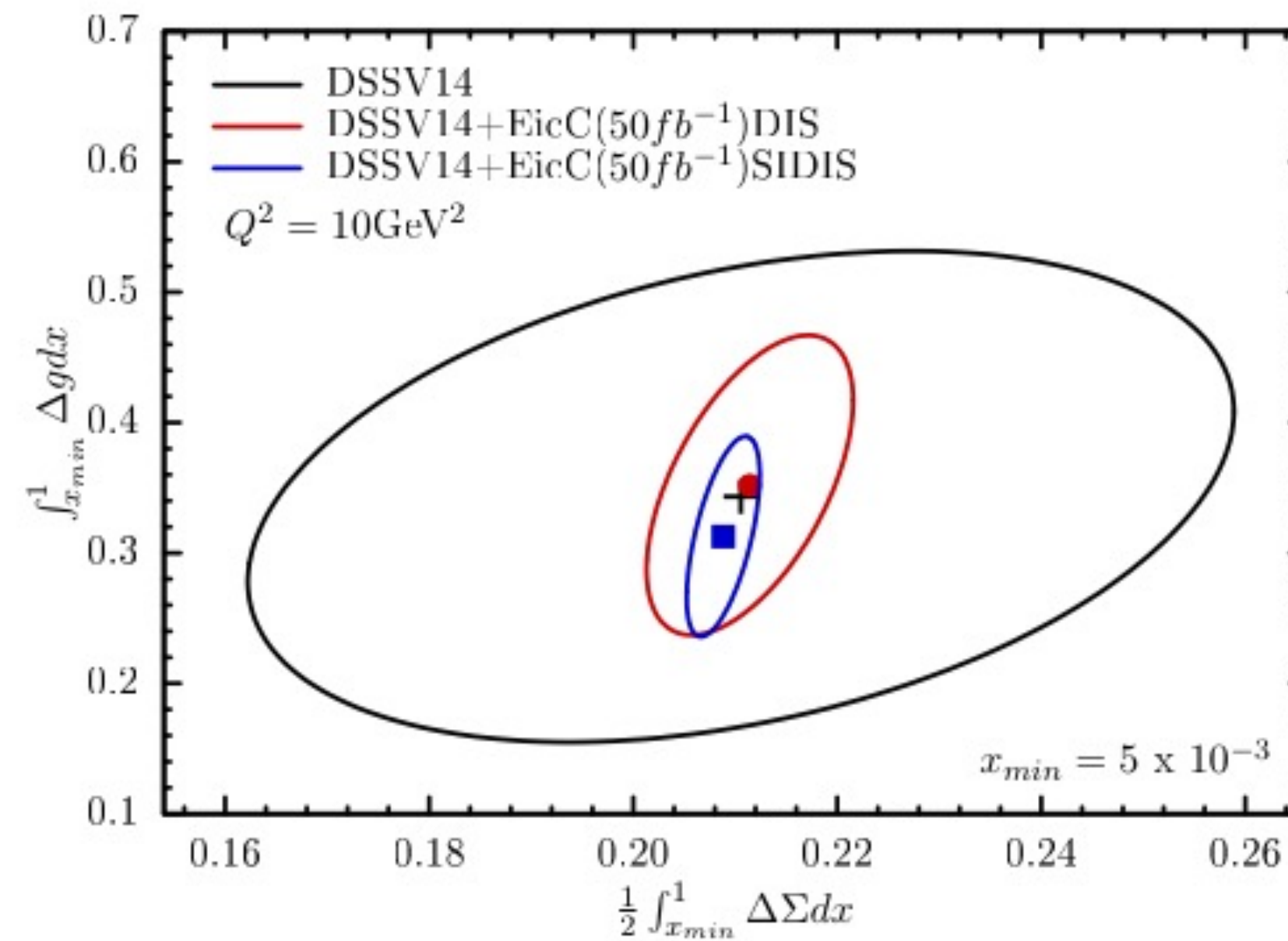
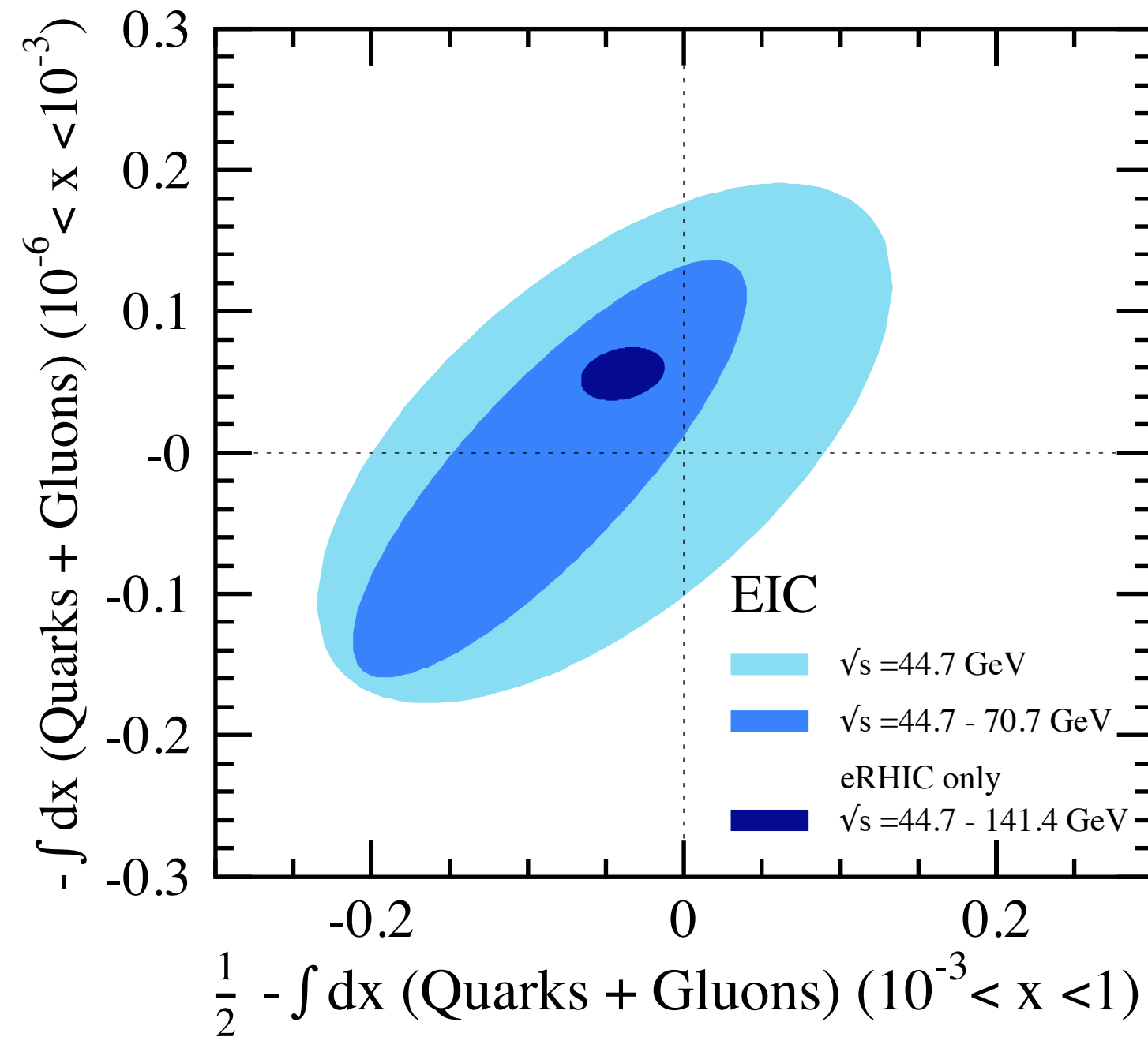
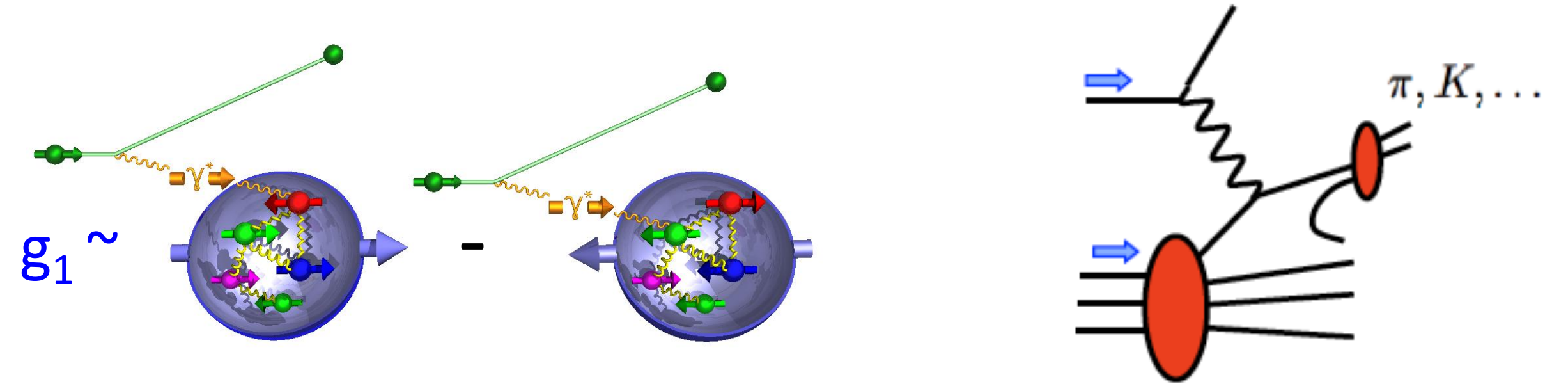
It is more than the number $\frac{1}{2}$! It is the interplay between the intrinsic properties and interactions of quarks and gluons

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

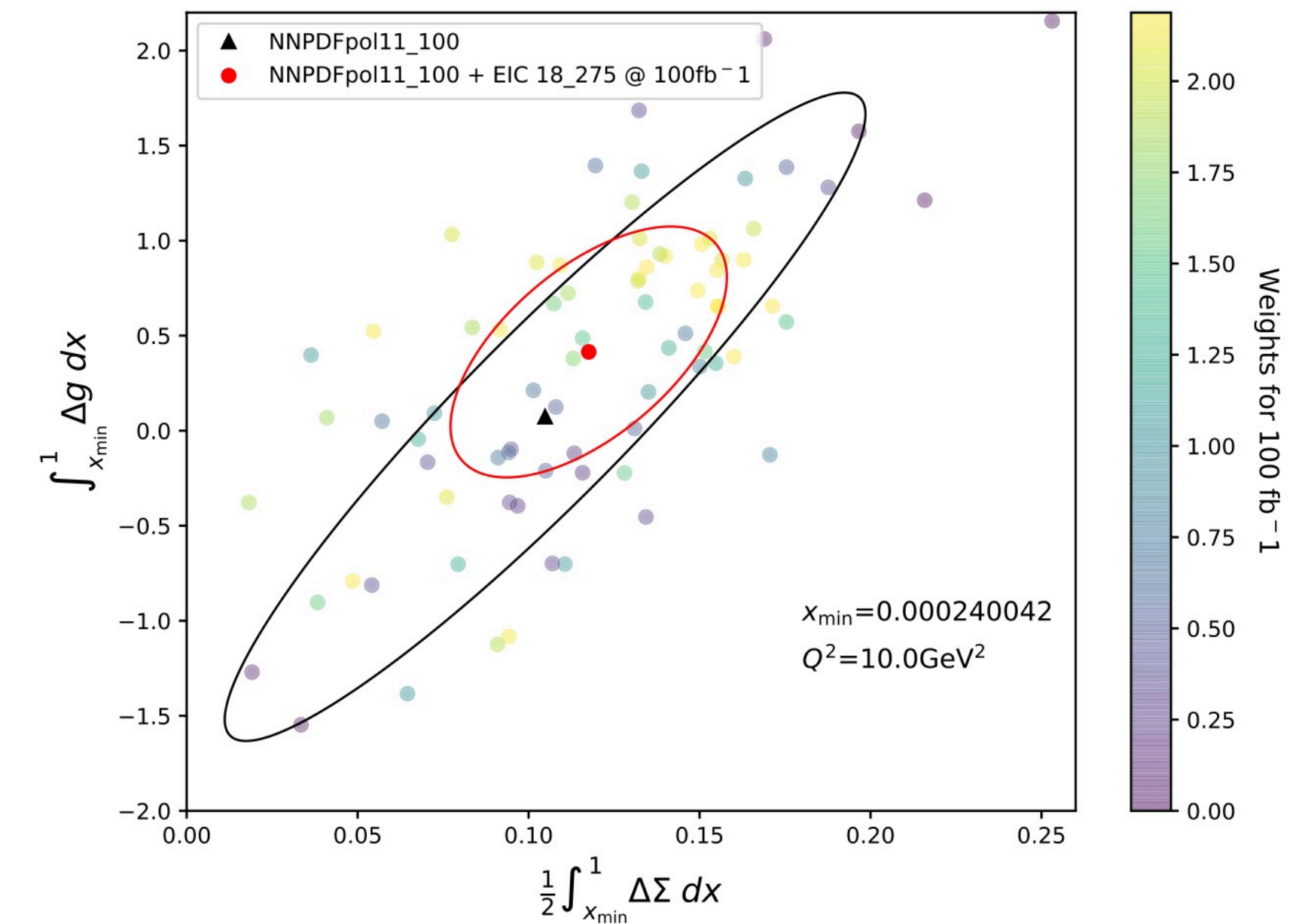
◆ Flip the proton spin

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

Anderle et al, PRD 2021



Light flavor hadron production

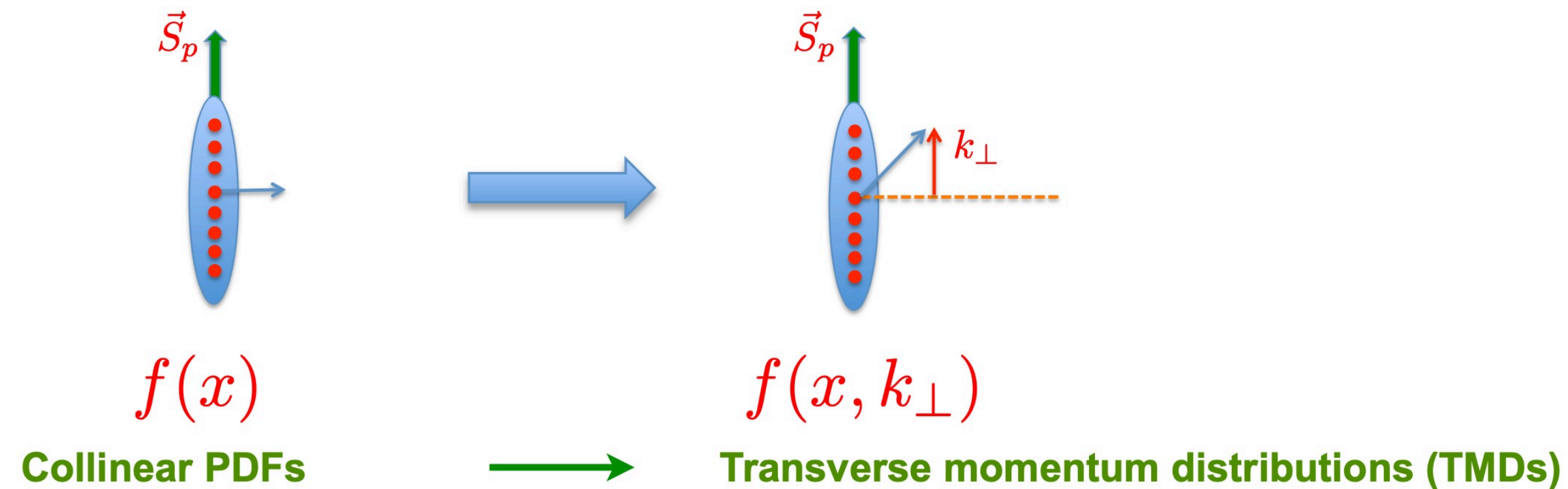


Heavy flavor production

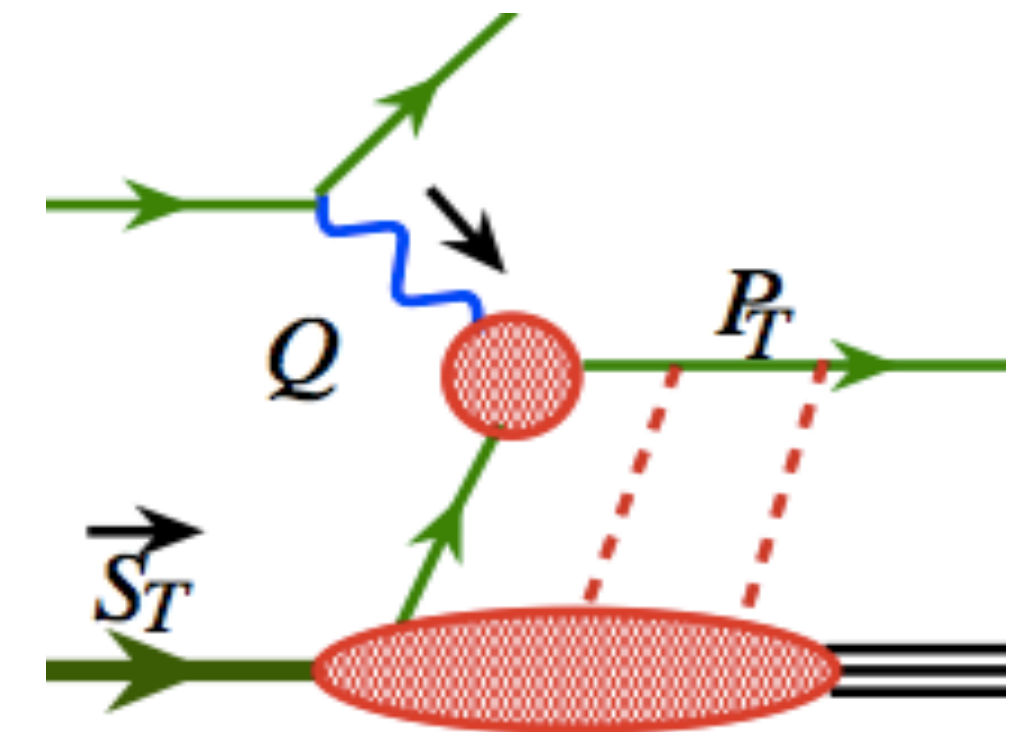
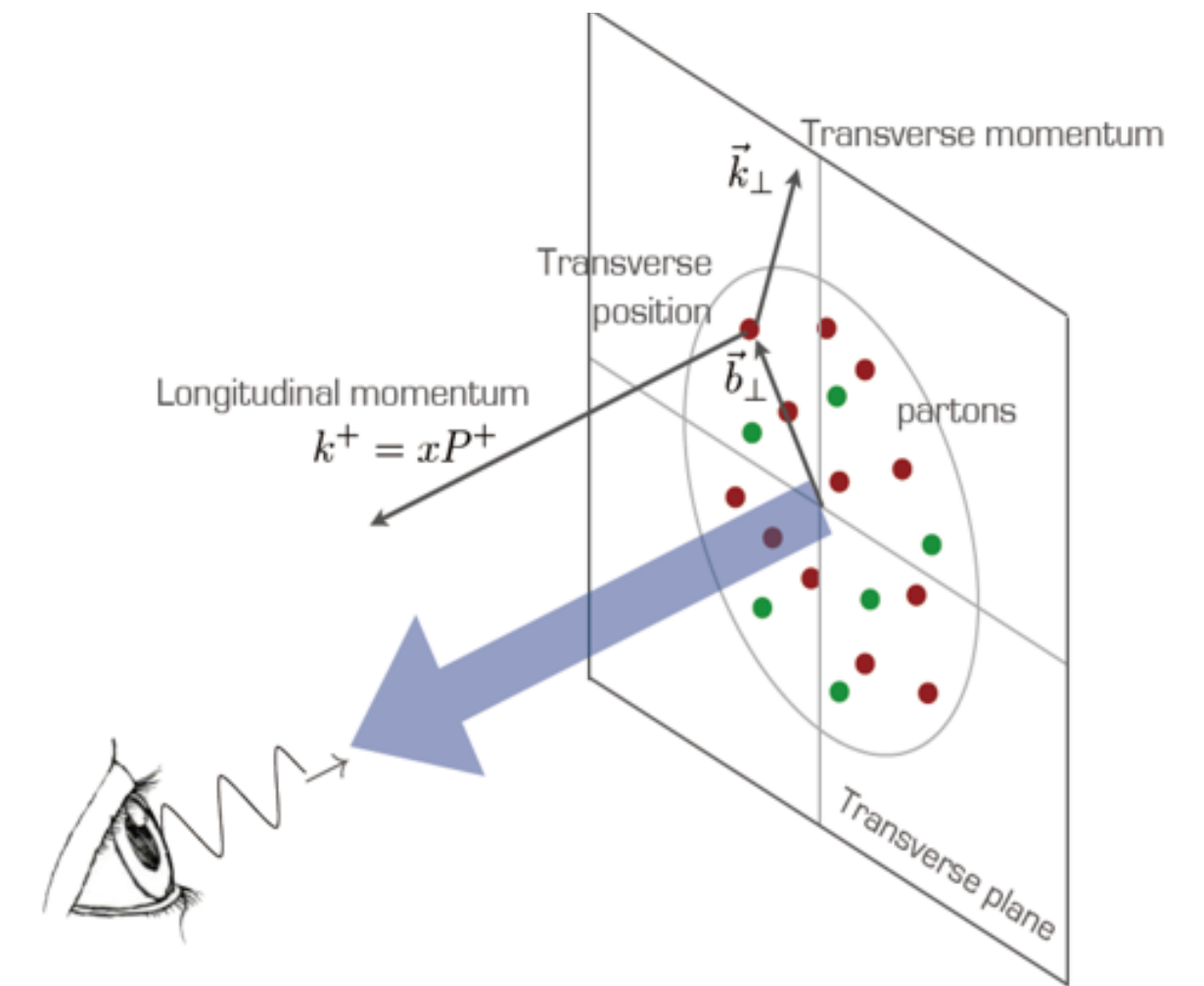
The power of future EIC and EicC for proton spin

Nucleon partonic structure - 3D imaging

◆ Transverse momentum dependent PDFs (TMDs)



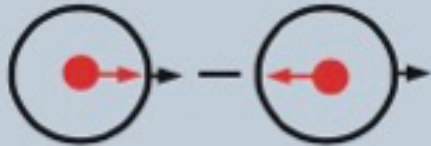
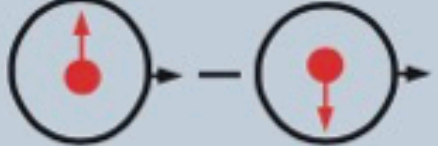
- Probing nucleon 3D structure requires two momentum scales
- Hard scale $Q_1 \gg 1/fm$ localizes the probes (particle nature of quarks/gluons)
- Soft scale $Q_2 \sim 1/fm$ accesses the transverse motion of quarks/gluons



SIDIS: $Q \gg P_T$

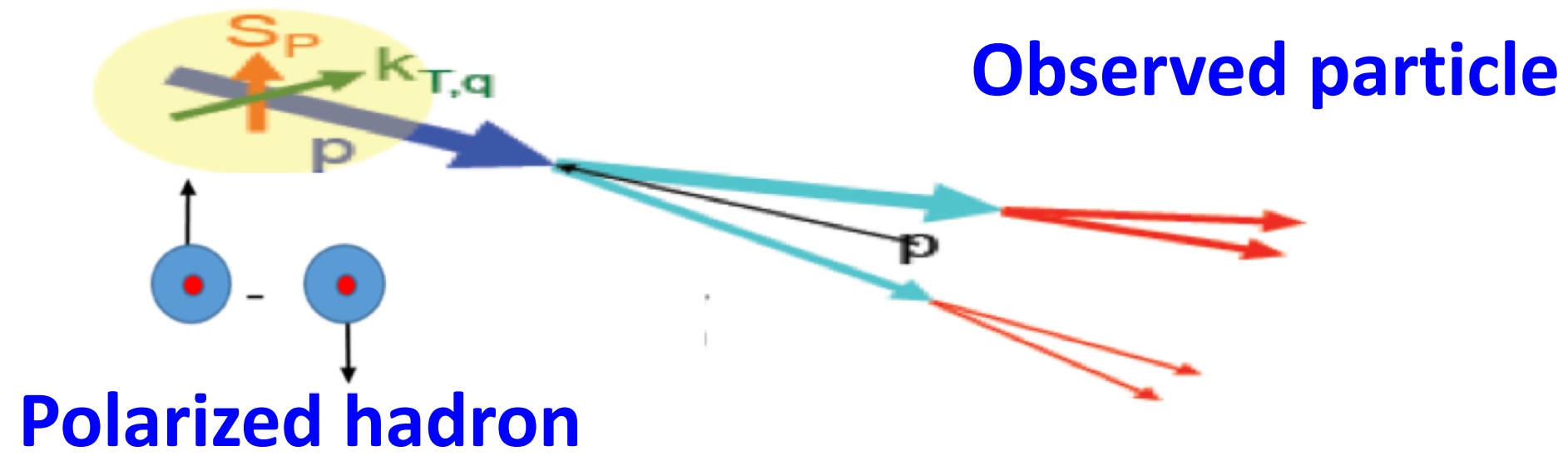
Nucleon partonic structure - 3D imaging

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

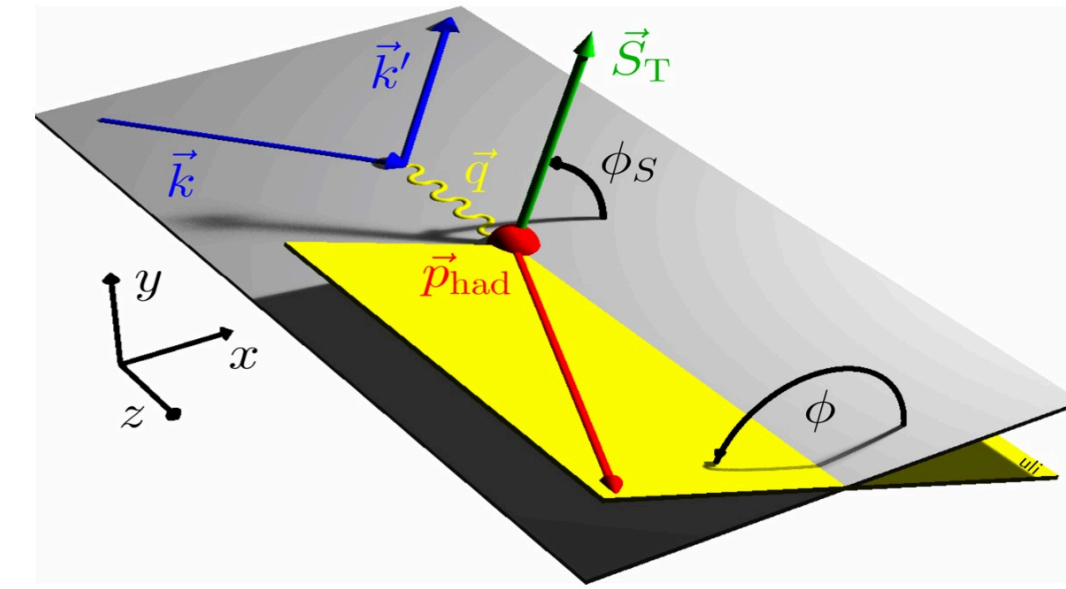
Nucleon partonic structure - 3D imaging

◆ Quantum correlation between proton spin and parton motion

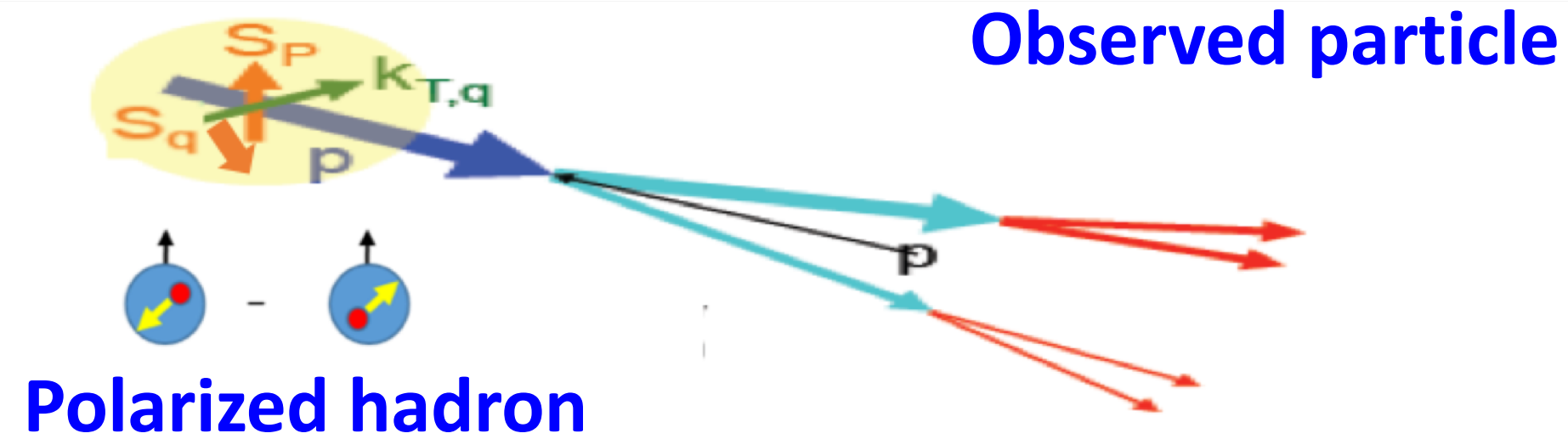


Sivers function $f_{1T}^\perp$: proton spin influences parton's transverse motion

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



◆ Quantum correlation between proton spin and parton spin



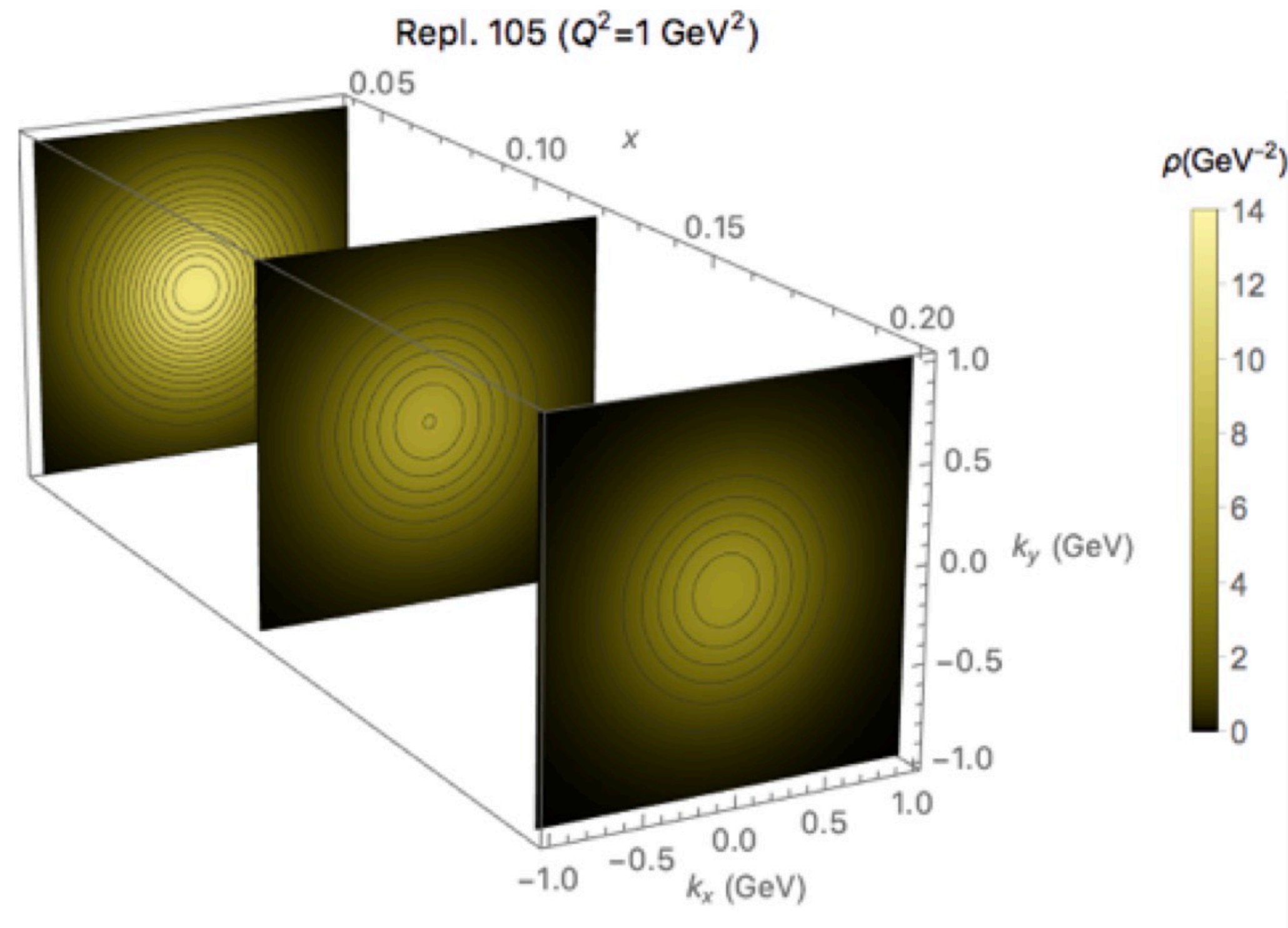
Pretzelosity function $h_{1T}^\perp$: proton spin and parton spin influence parton's transverse motion

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

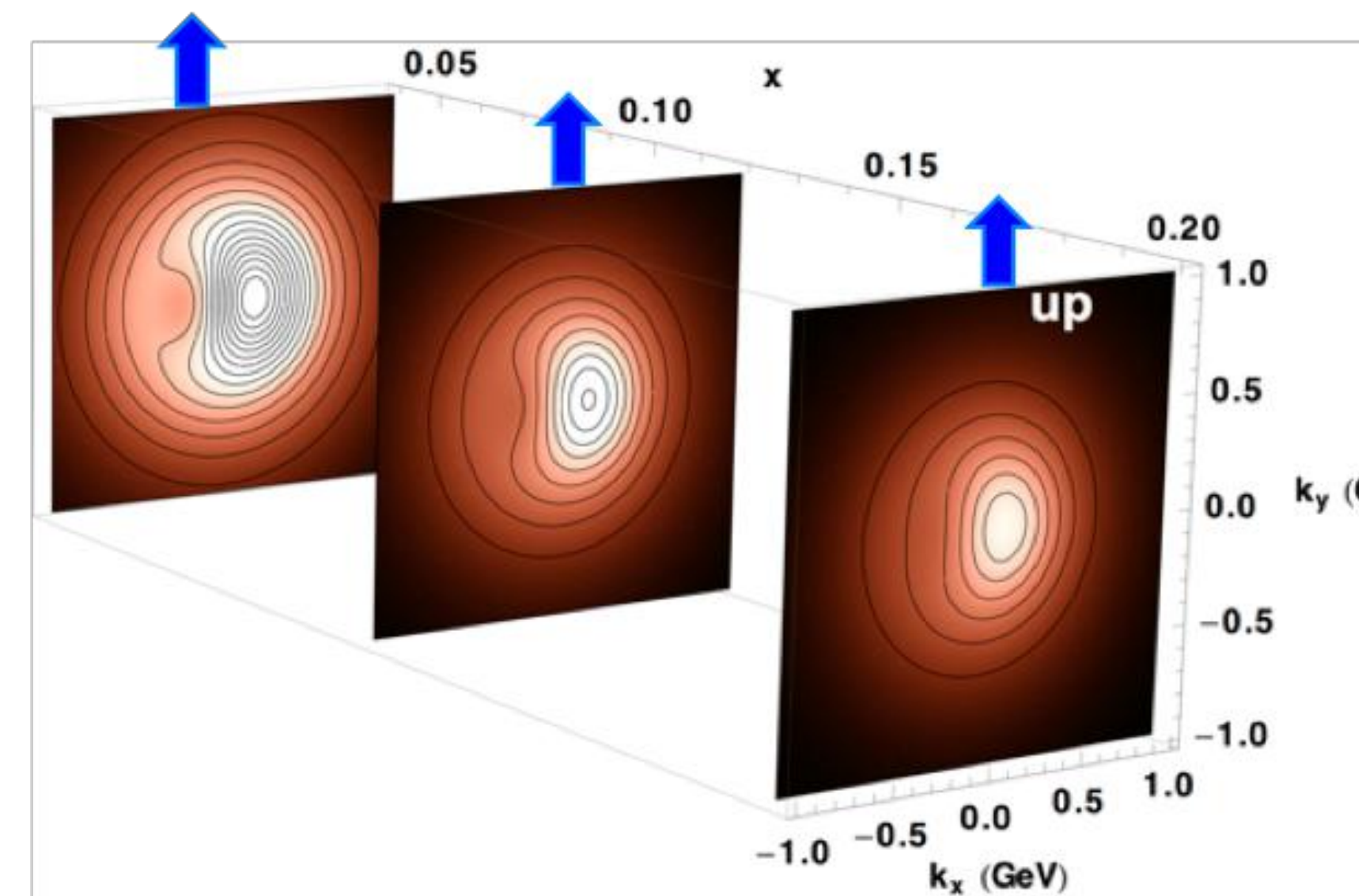
Nucleon partonic structure - 3D imaging

By Andrea Signori

Unpolarized proton



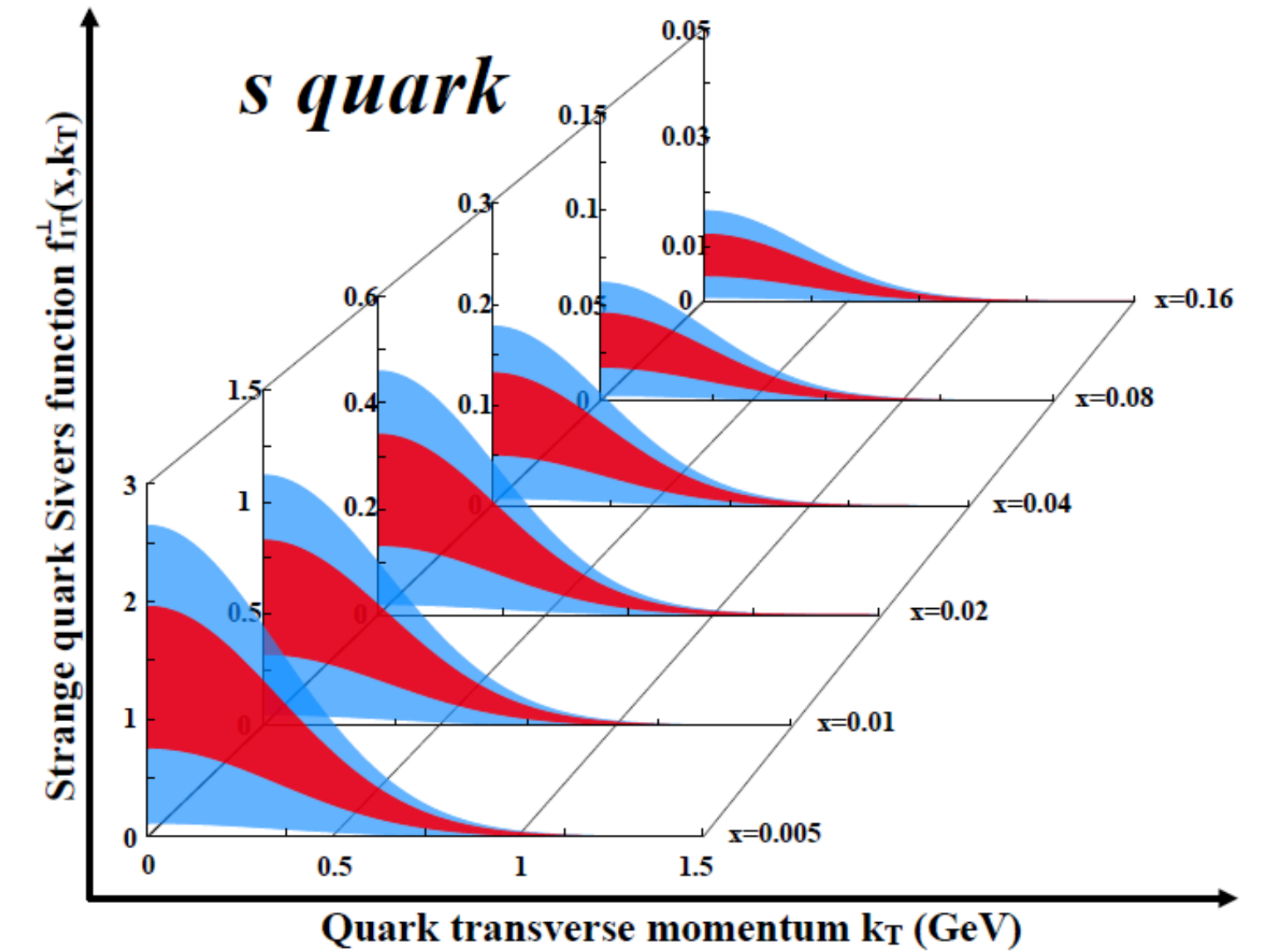
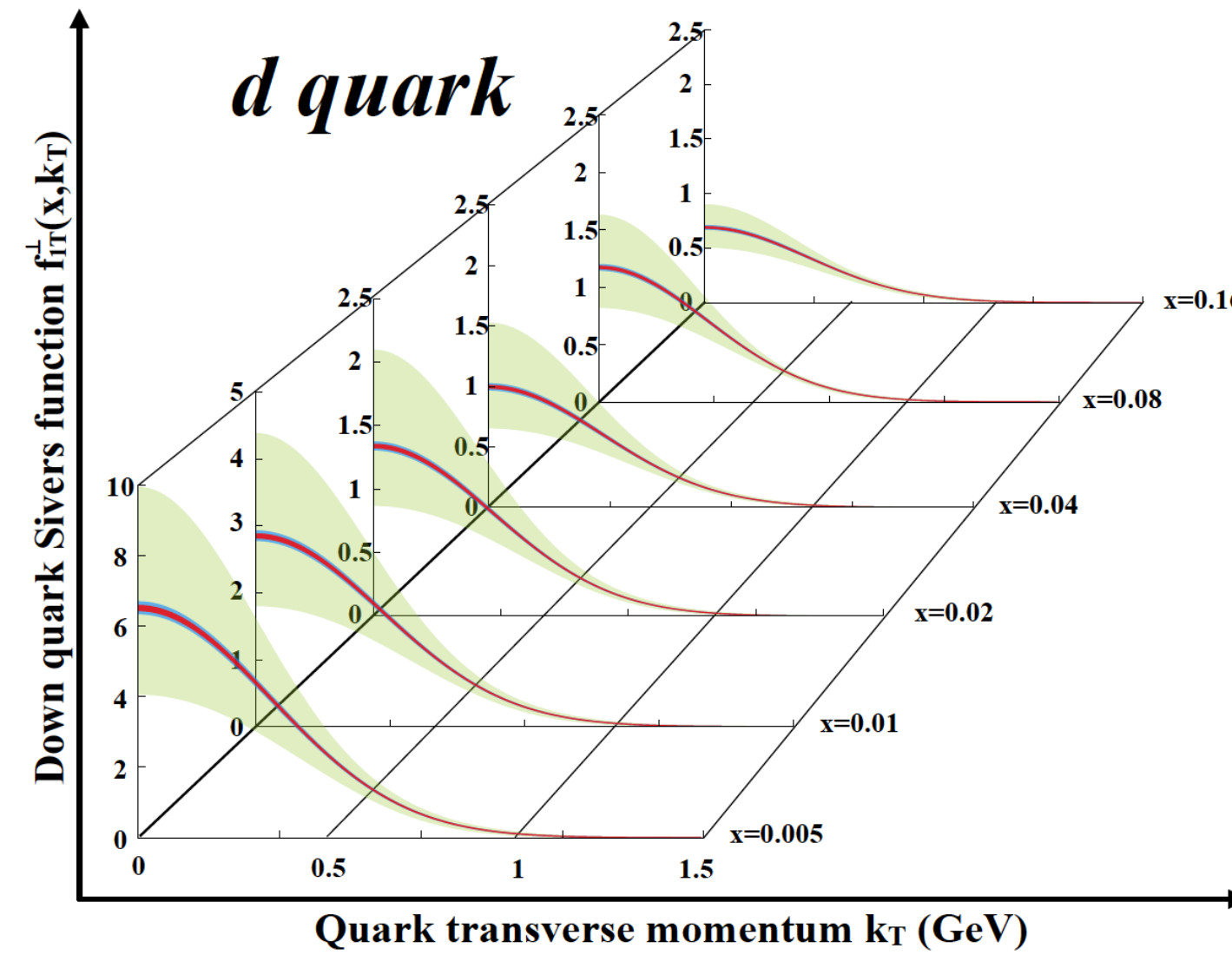
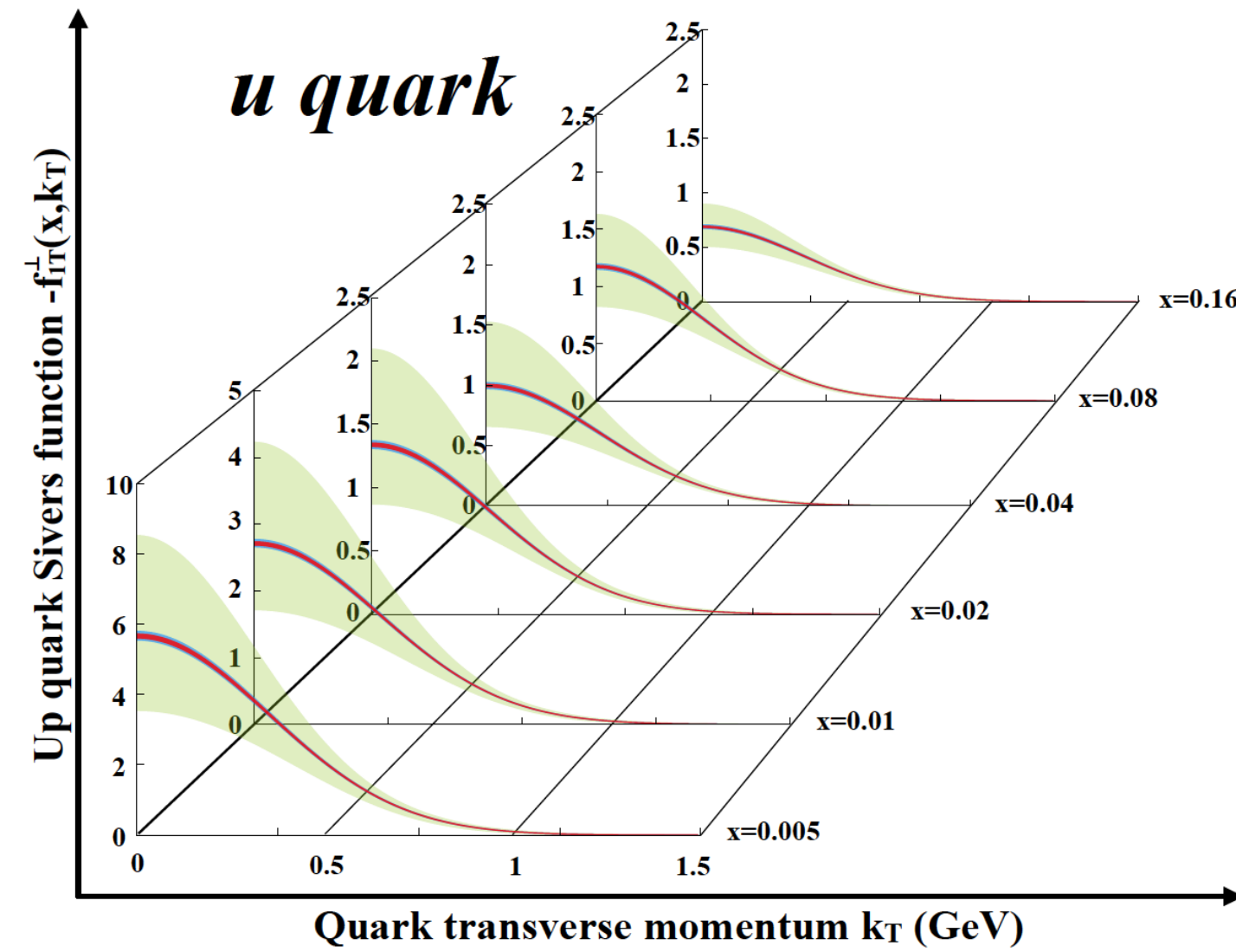
Transversely polarized proton



Transversely polarized quark distribution is distorted!

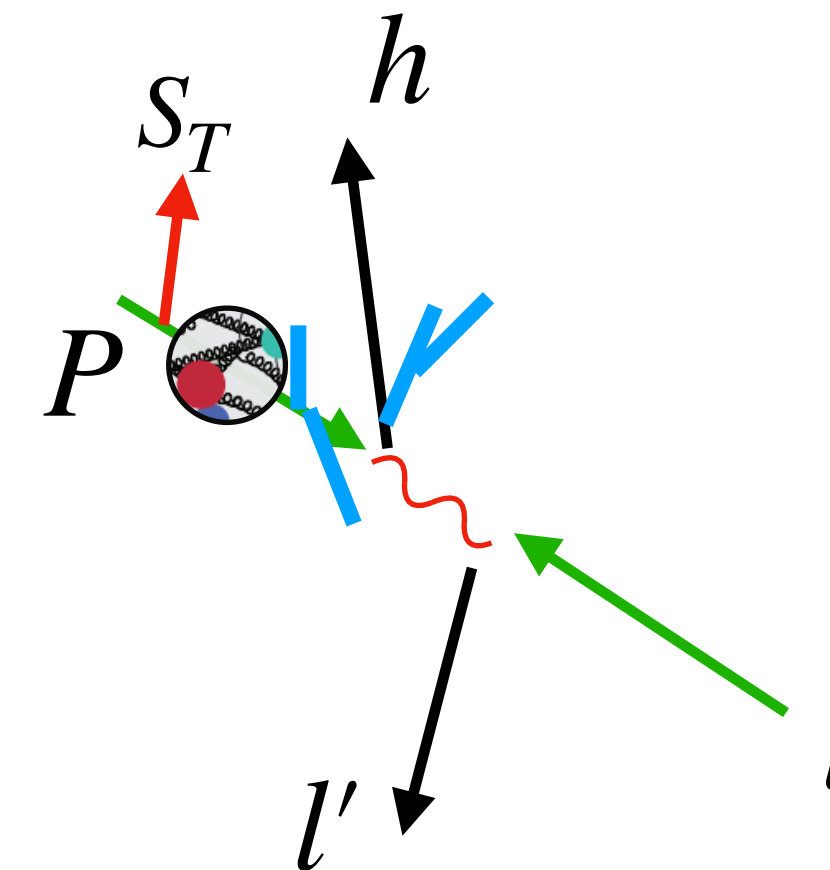
Nucleon 3D imaging at EicC - Sivers effect

from EicC white paper

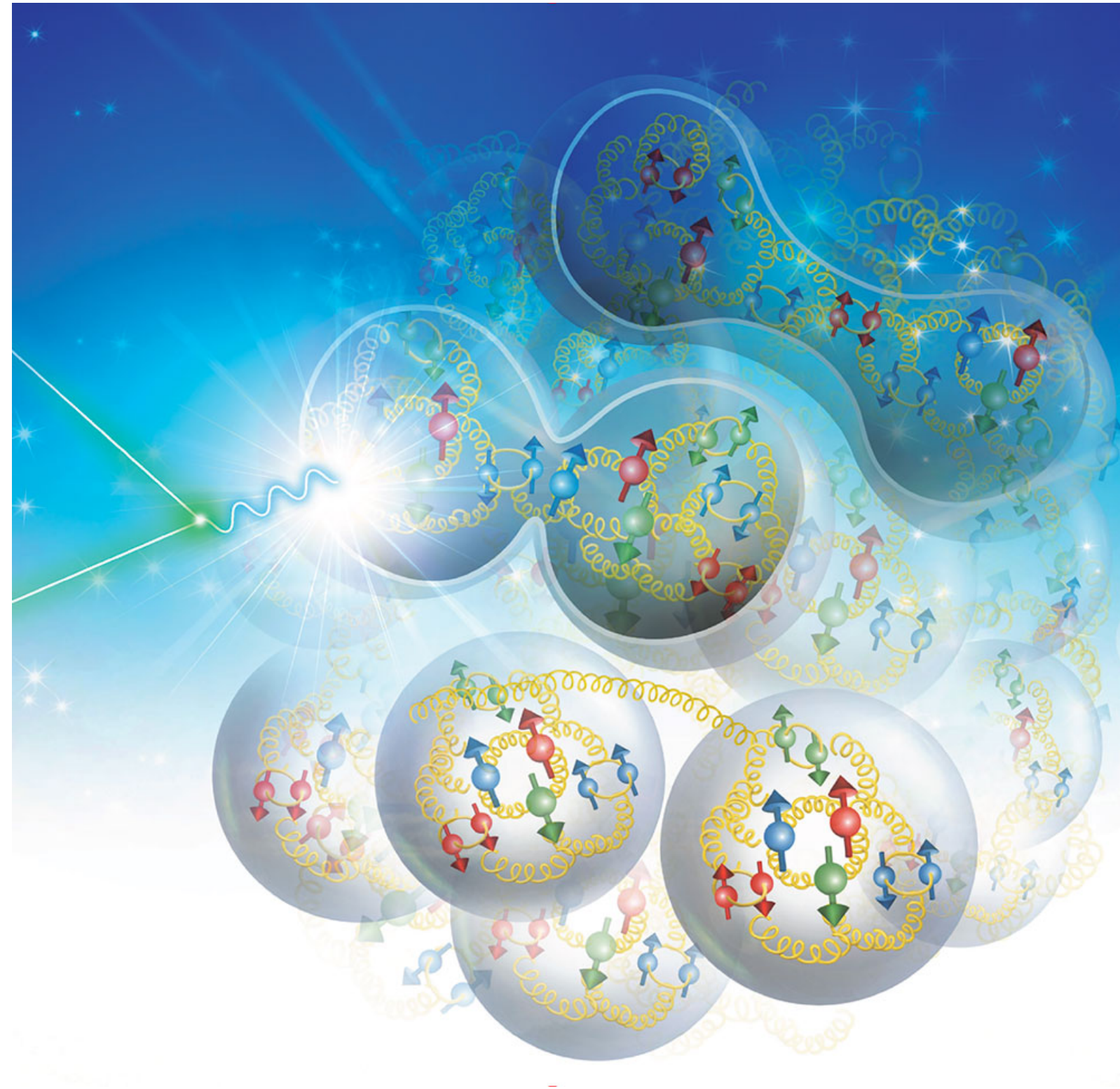


LO analysis of EicC projection

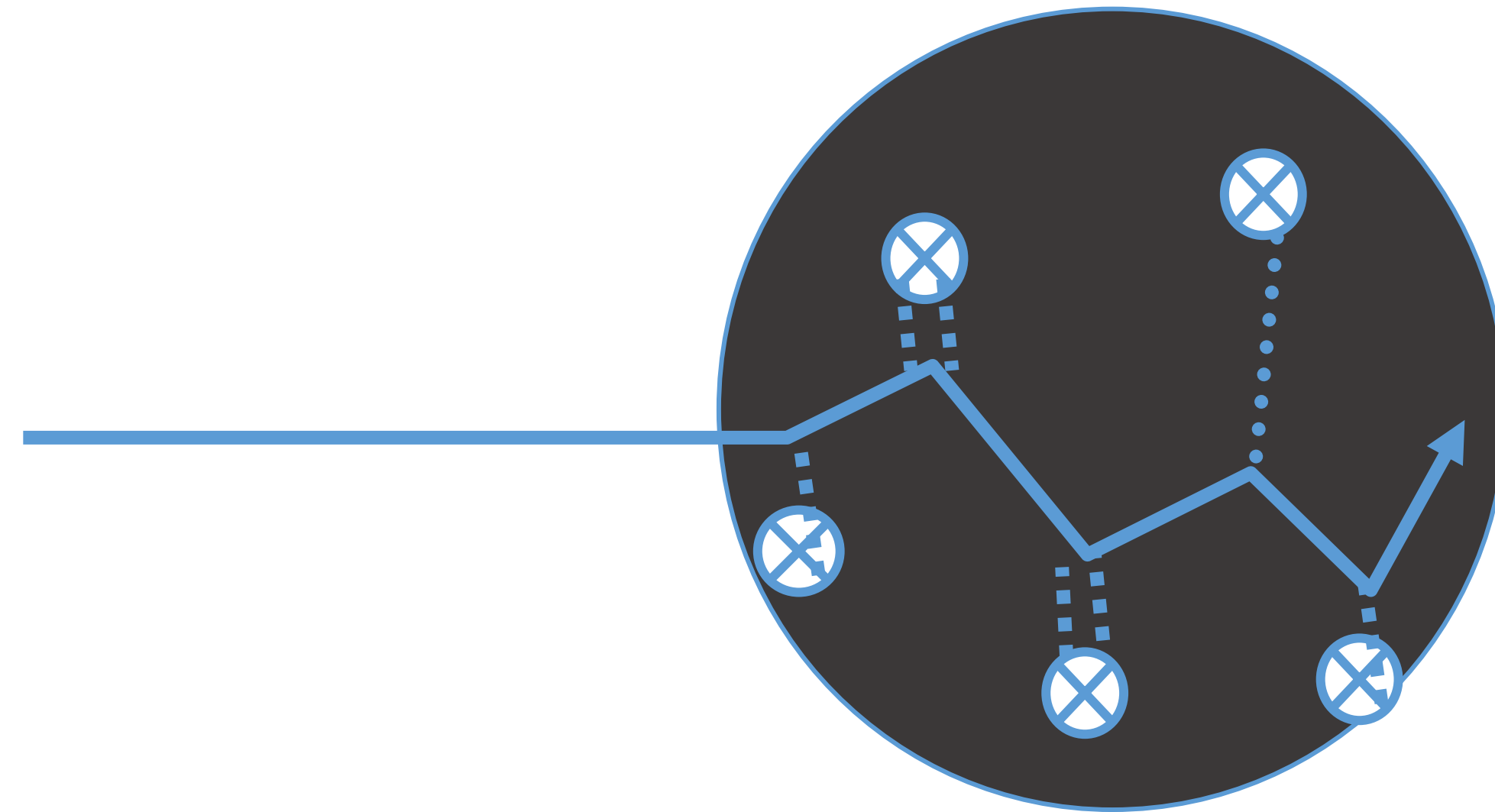
- Pion(+/-), Kaon(+/-)
- ep: 3.5 GeV x 20 GeV
- eHe-3: 3.5 GeV x 40 GeV
- Lumi: ep 50 fb⁻¹, eHe-3 50 fb⁻¹
- **Stat. Error** vs **Sys. Error**



What if the nucleon is bounded in nucleus?



Nuclear partonic structure

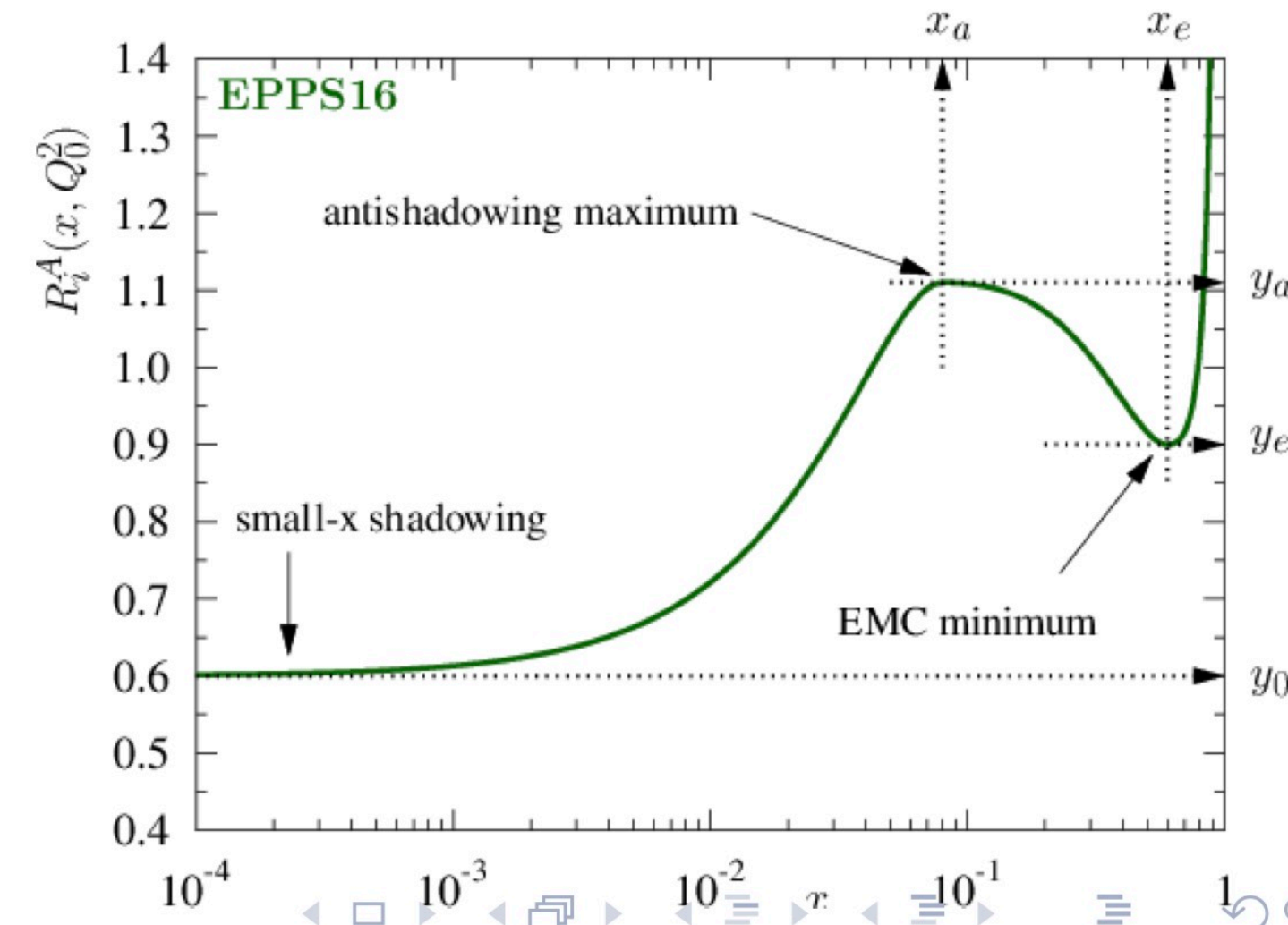
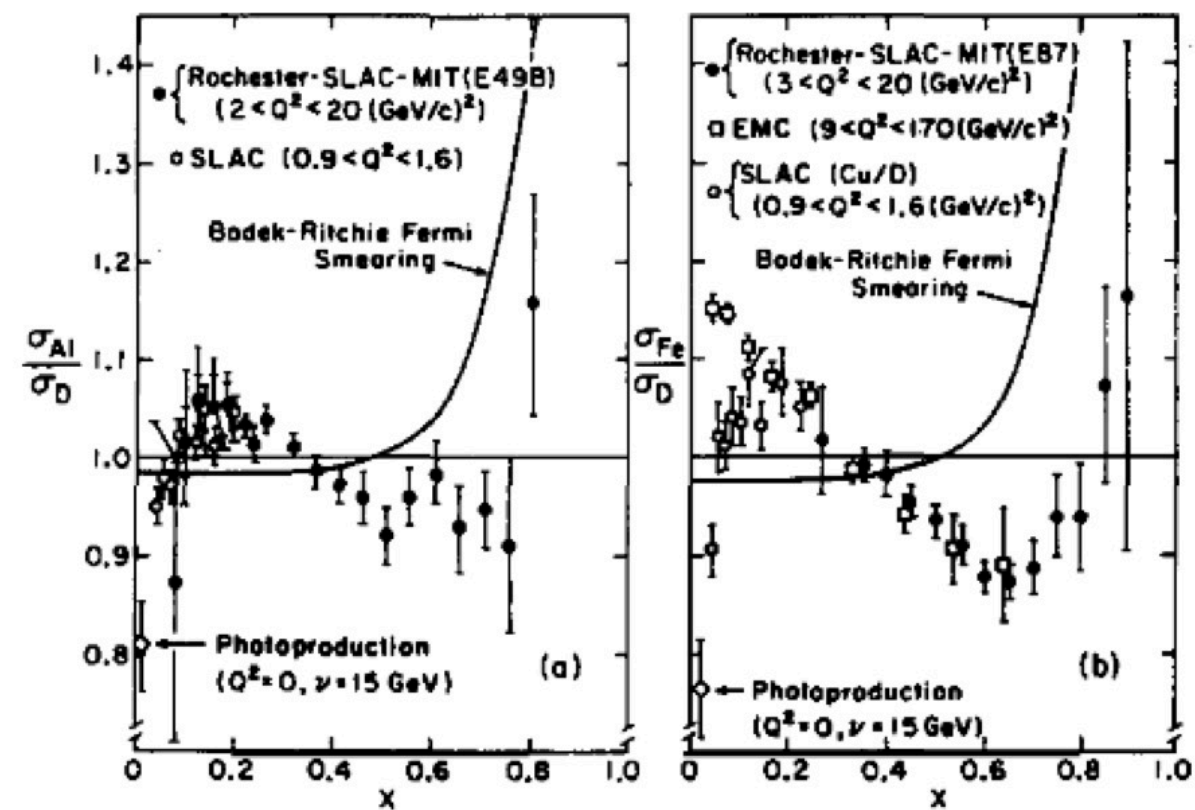


Parton propagating in nuclear medium

“Old” and long standing problems for cold nuclear matter effect

- Nuclear partonic structure

Four Decades of the EMC Effect



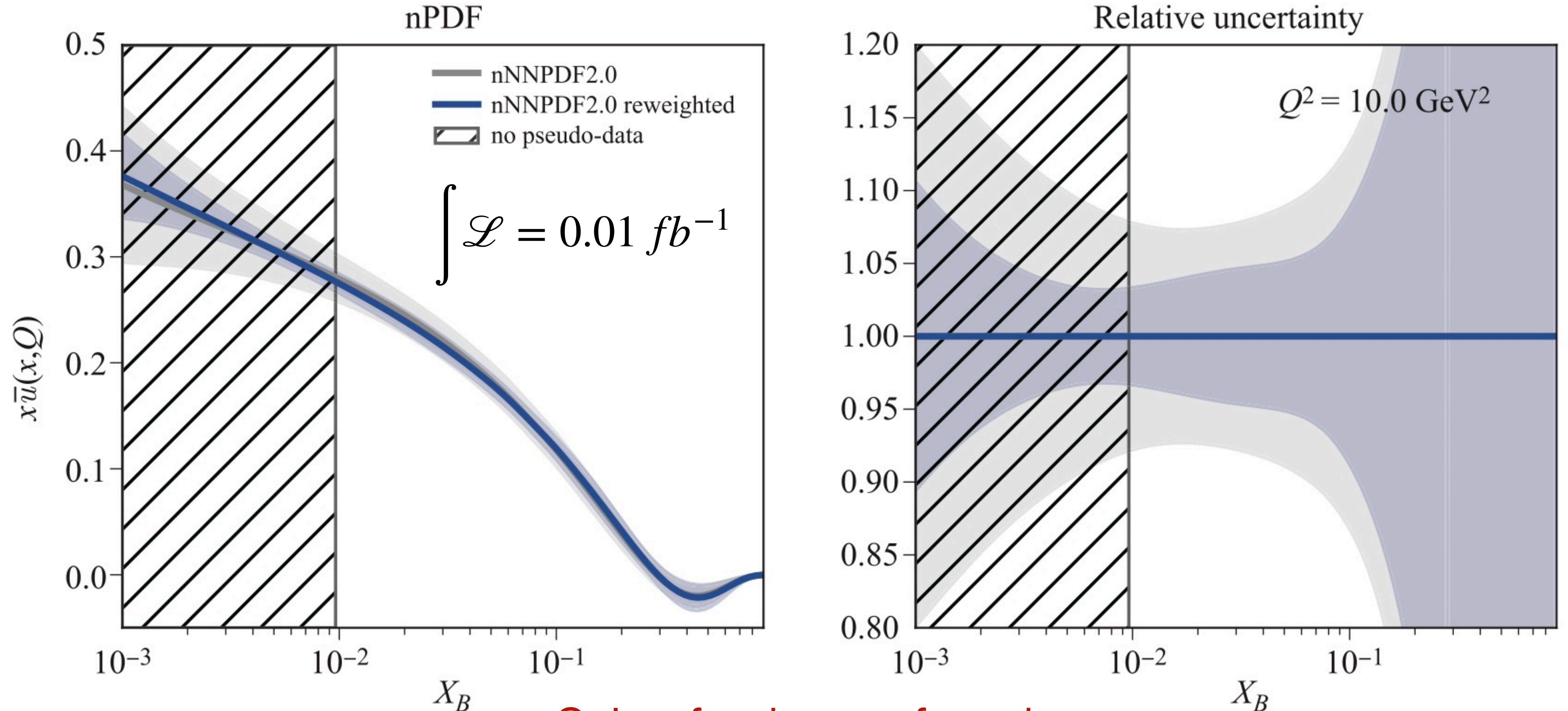
$$R_i^A = \frac{f_{i/A}(x, Q^2)}{f_{i/p}(x, Q^2)}$$

- Quark gluon propagation in nuclear medium



Power of EicC for nuclear partonic structure - 1D

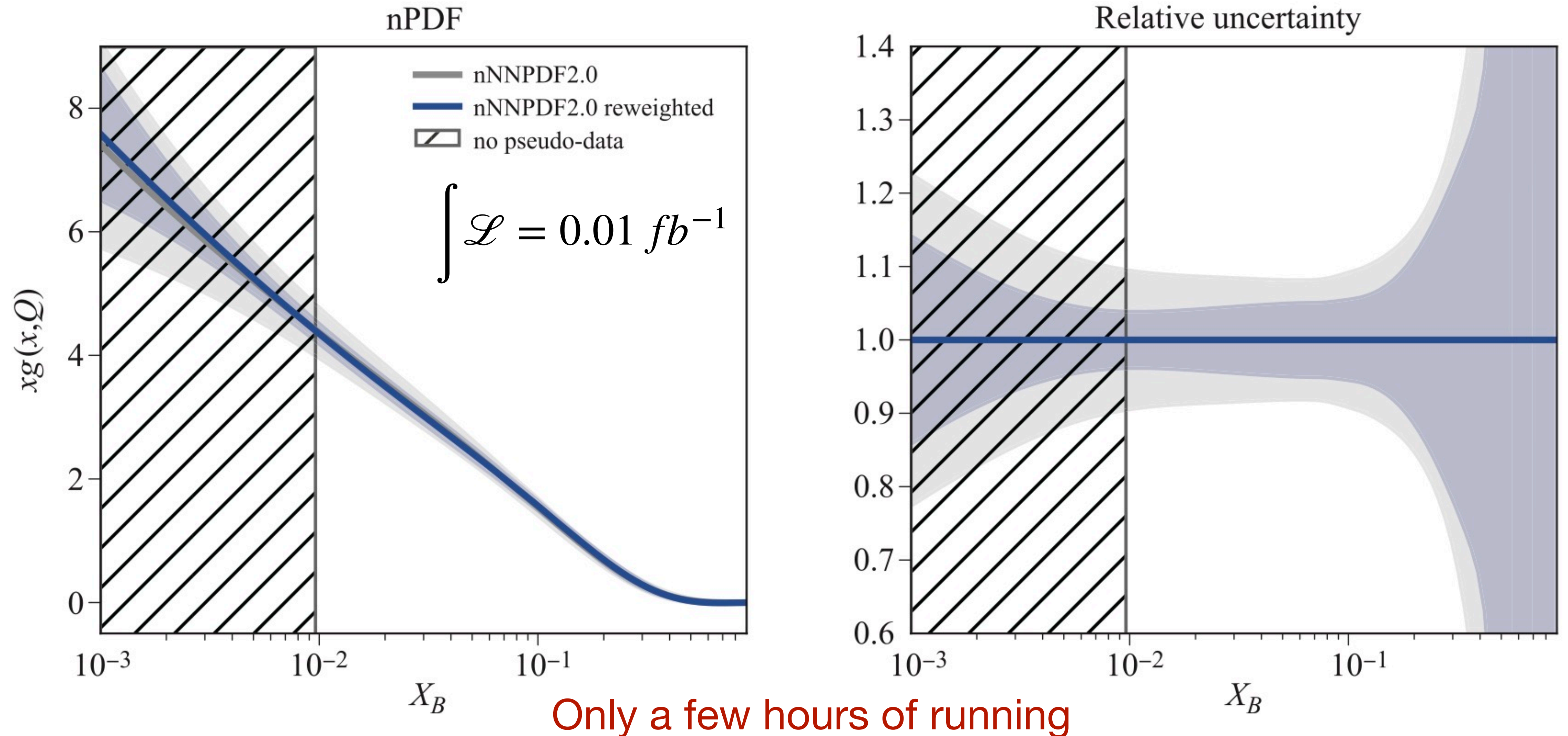
- Nuclear partonic structure - nuclear quark distribution



Only a few hours of running

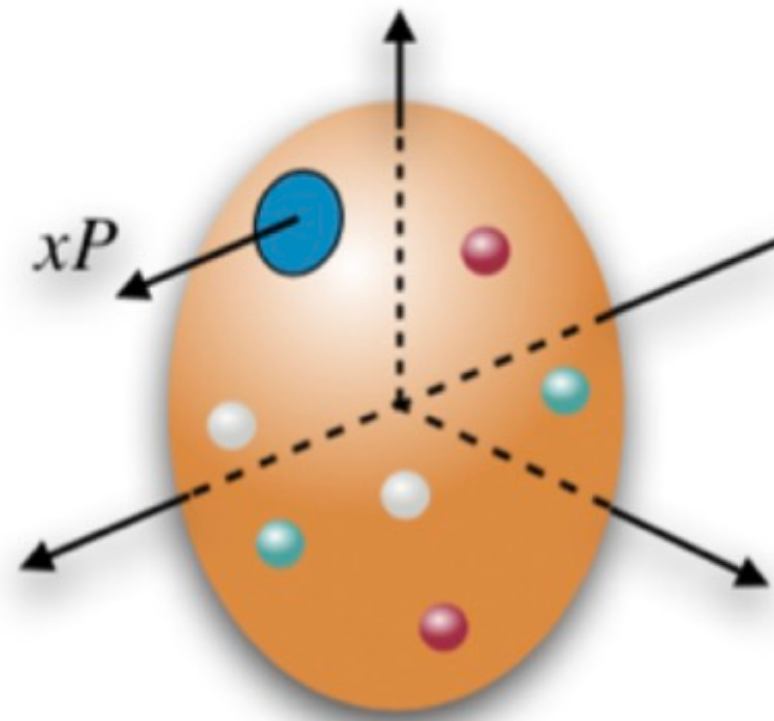
Power of EicC for nuclear partonic structure - 1D

- Nuclear partonic structure - nuclear gluon distribution

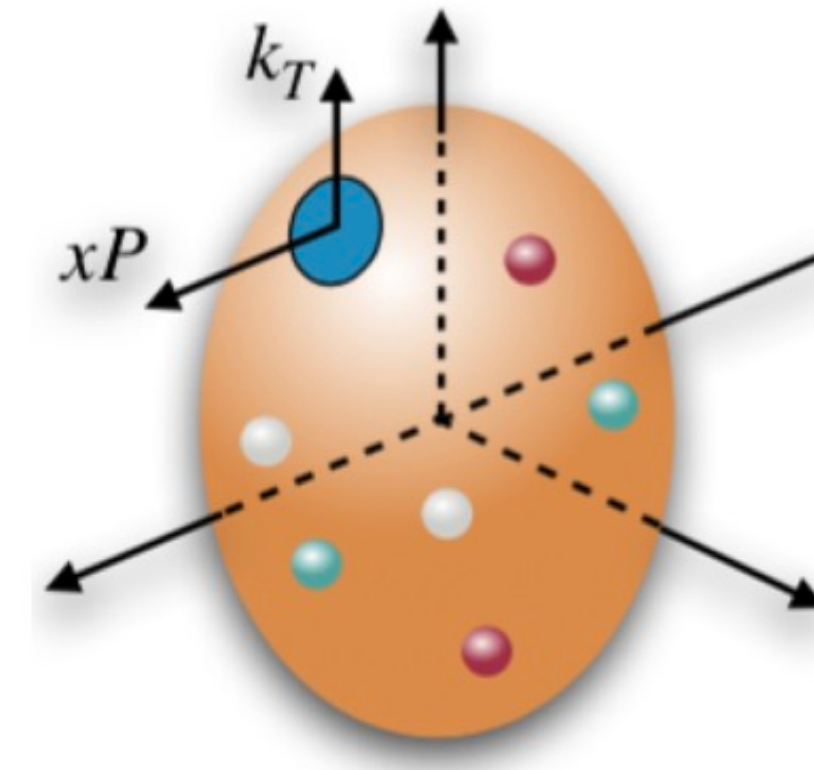


Nuclear partonic structure - 3D

- From collinear (1D) to TMD (3D)



Alrashed, Anderle, Kang, Terry, **HX**
arXiv:2107.12401

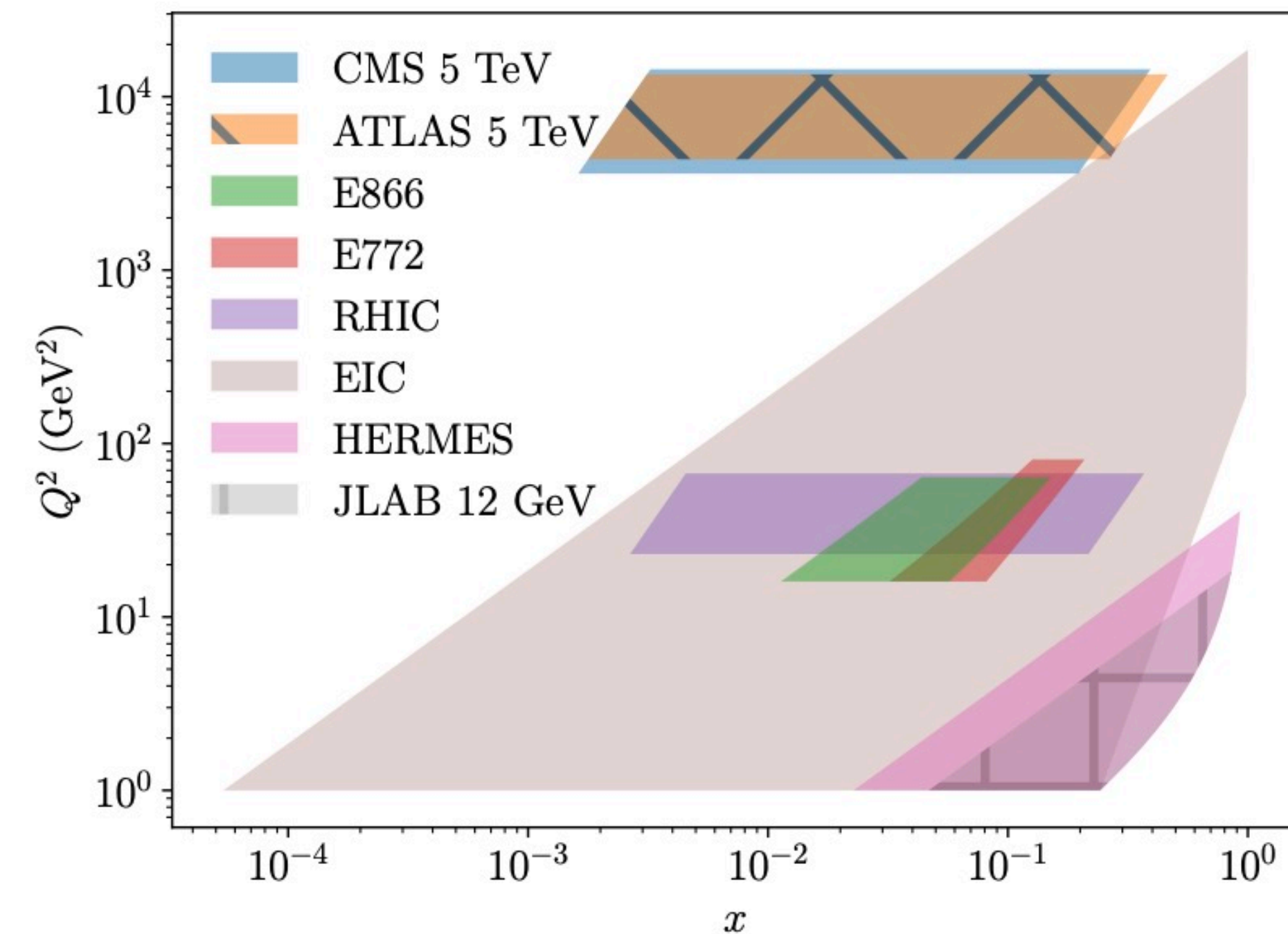


Drell-Yan Measurements

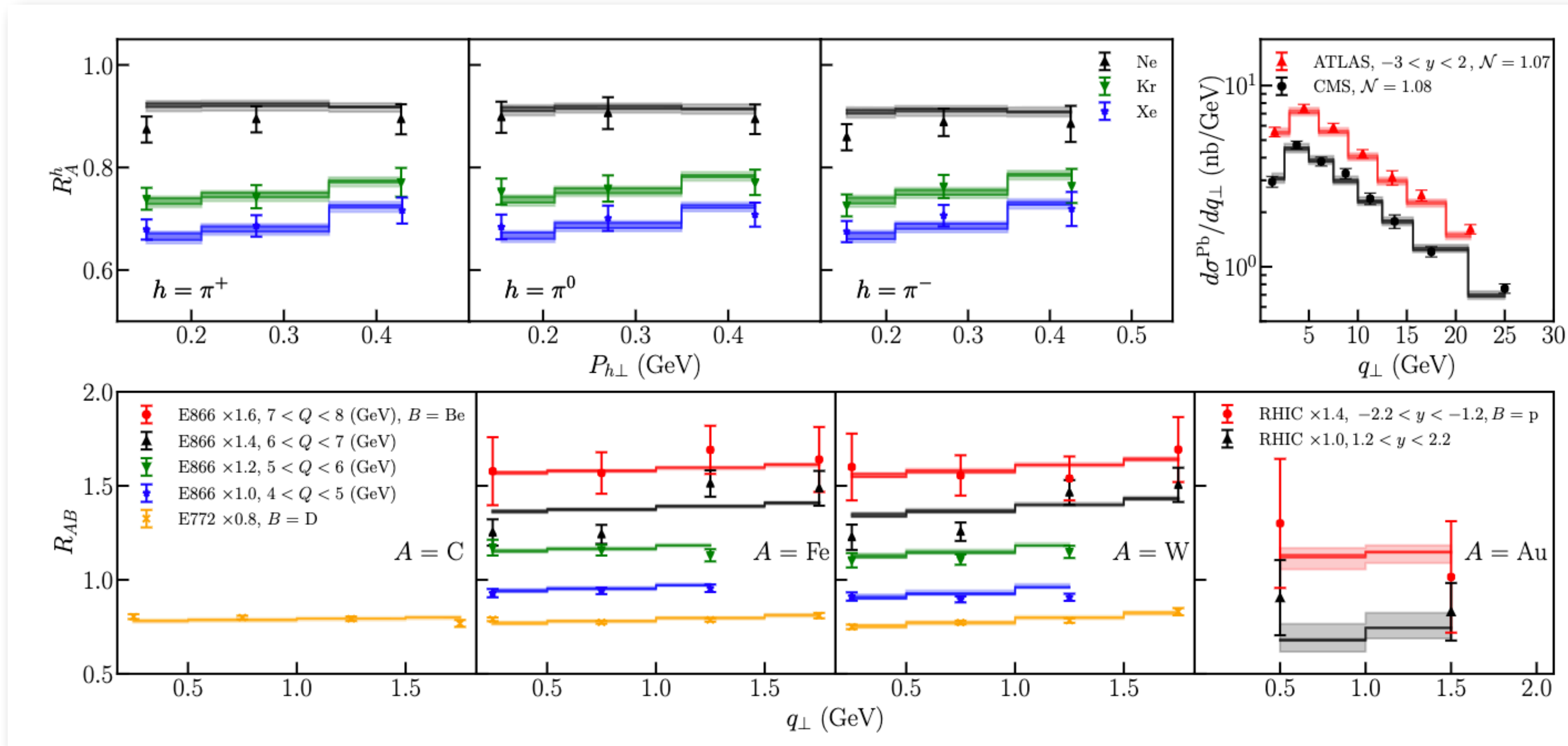
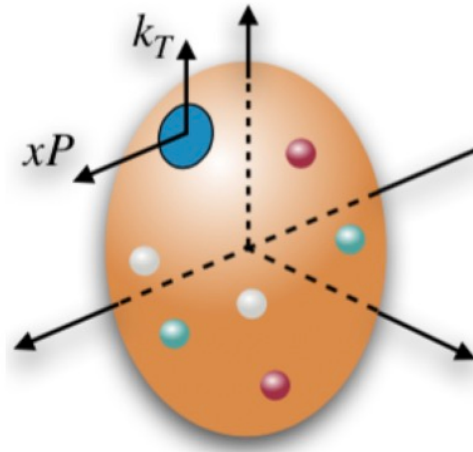
- $R_{AB} = \frac{d\sigma_A}{dq_\perp} / \frac{d\sigma_B}{dq_\perp}$
 - E866
 - E772
 - Prelim. RHIC
- $d\sigma/dq_\perp$ (p Pb)
 - ATLAS
 - CMS

SIDIS Measurements

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

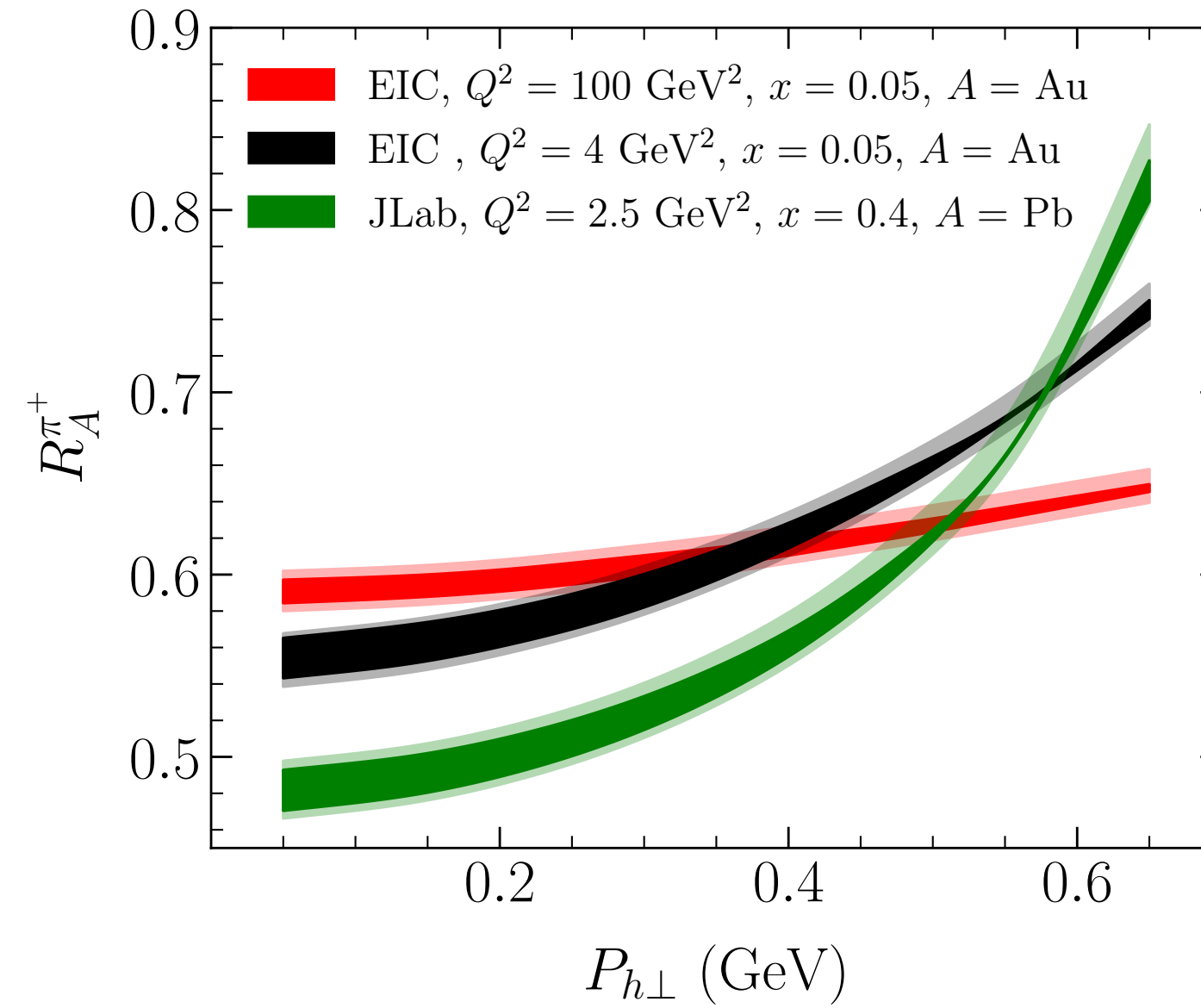
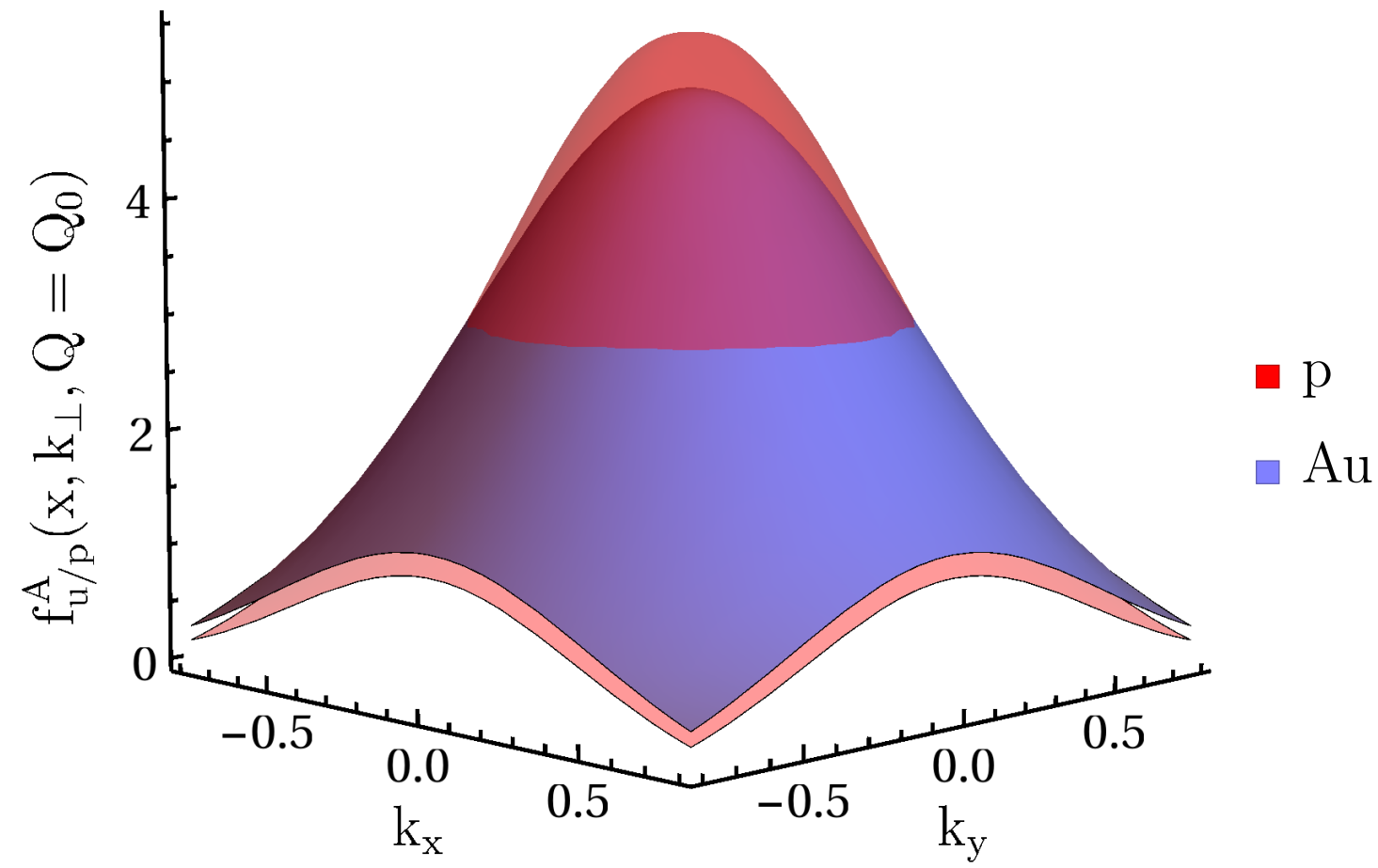


nuclear 3D imaging - global extraction from world data

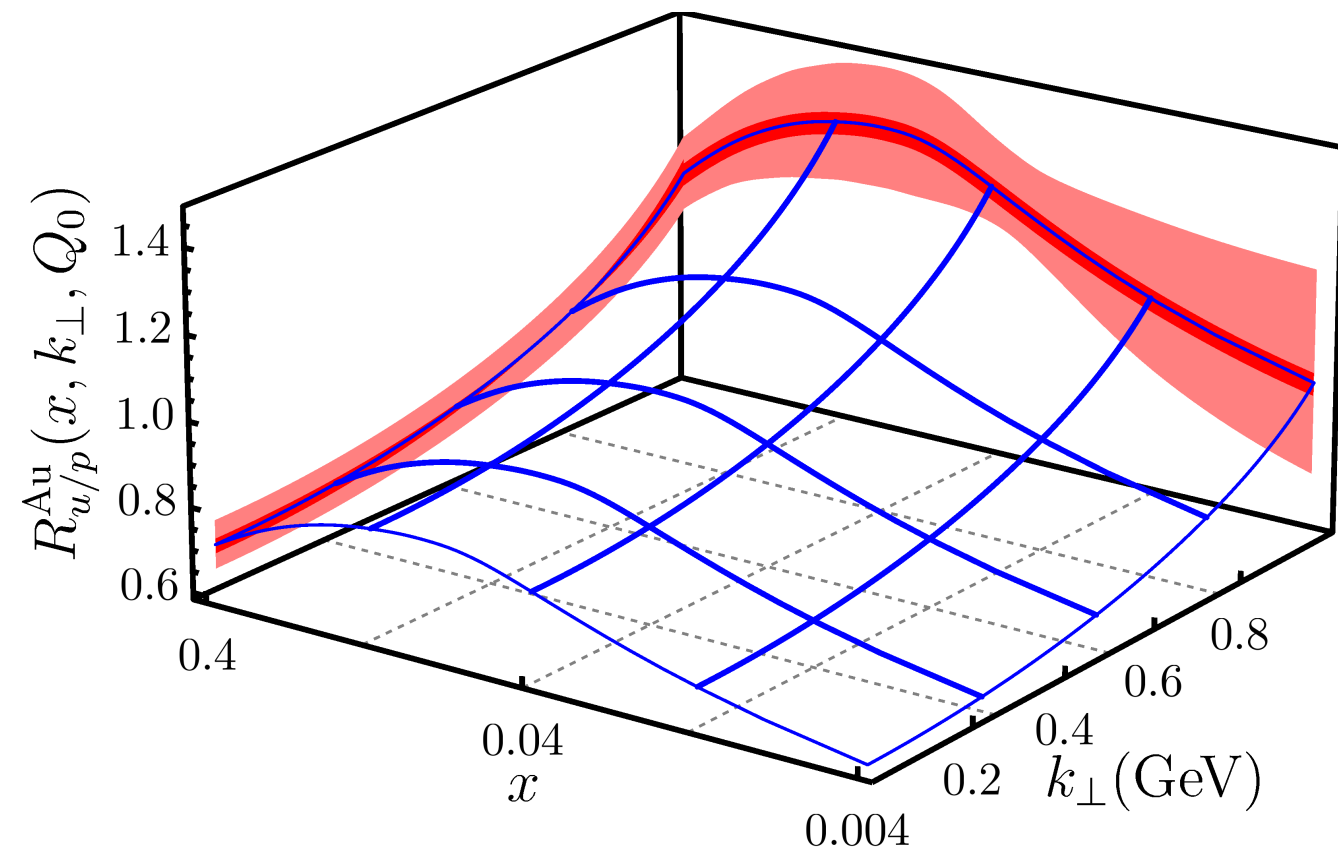


Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

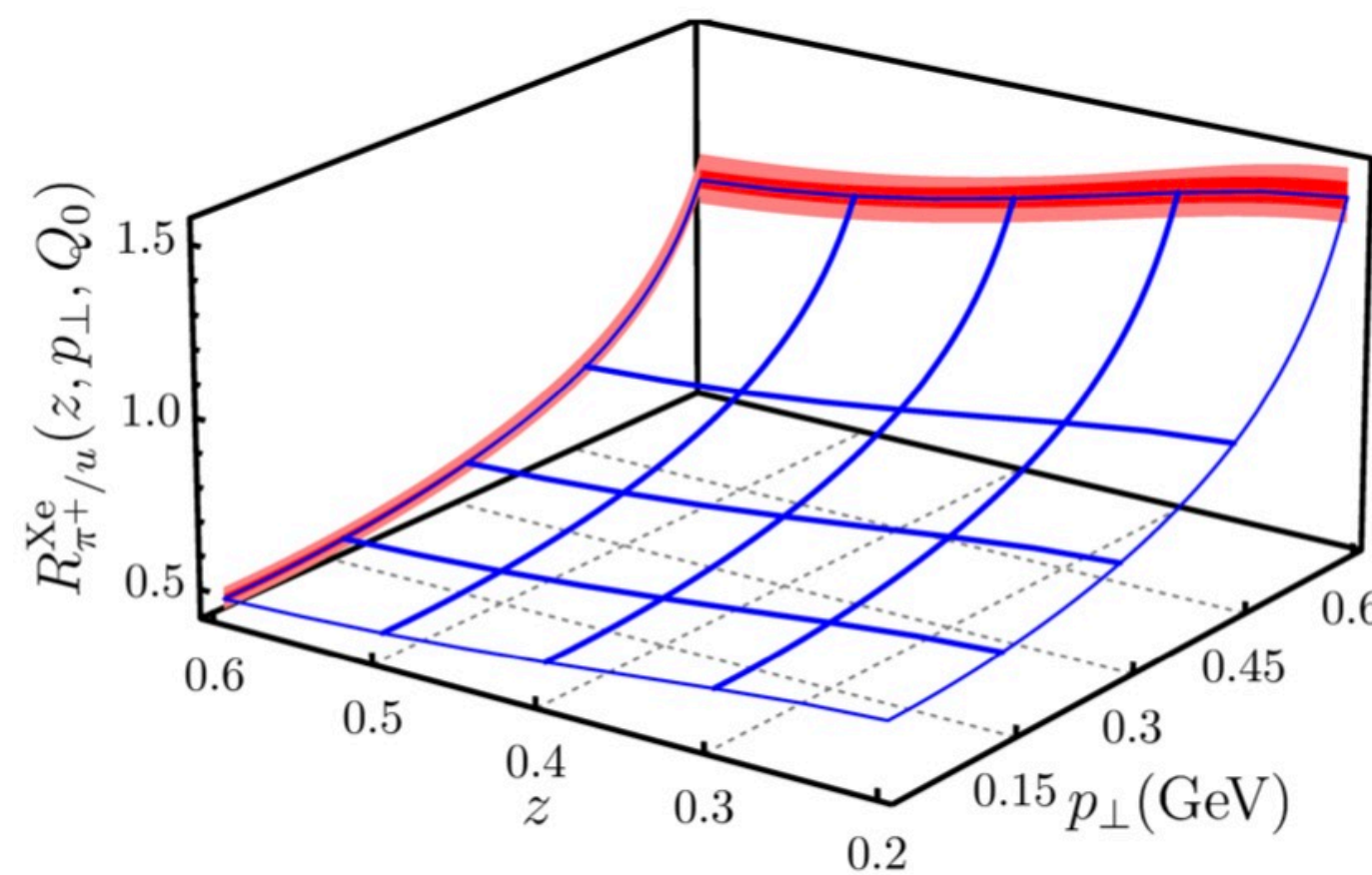
Three-dimension imaging in nuclei



Alrashed, Anderle, Kang, Terry, **HX**
arXiv:2107.12401



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



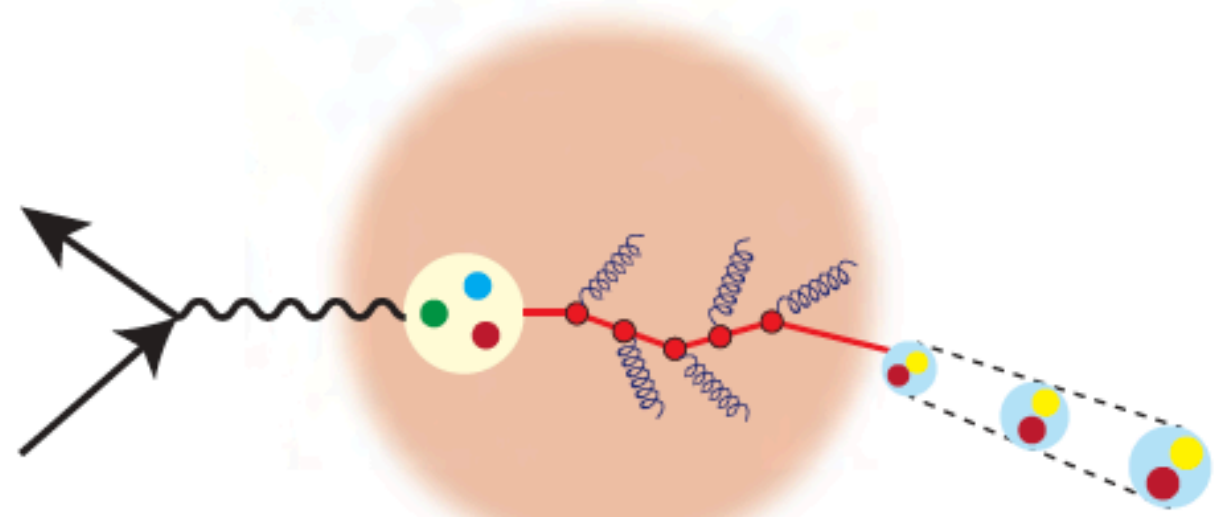
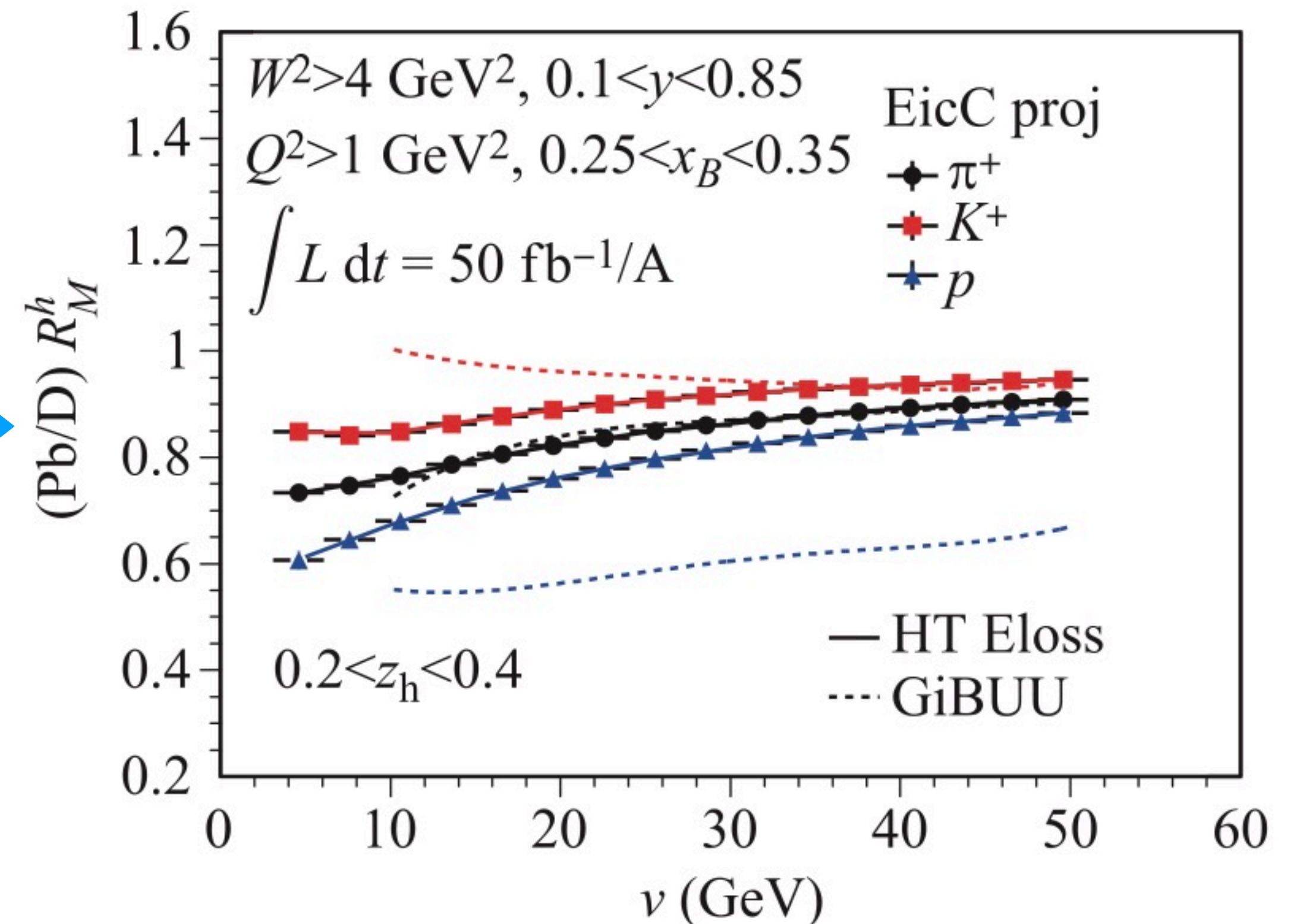
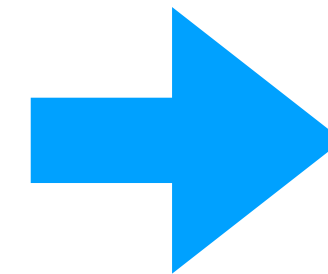
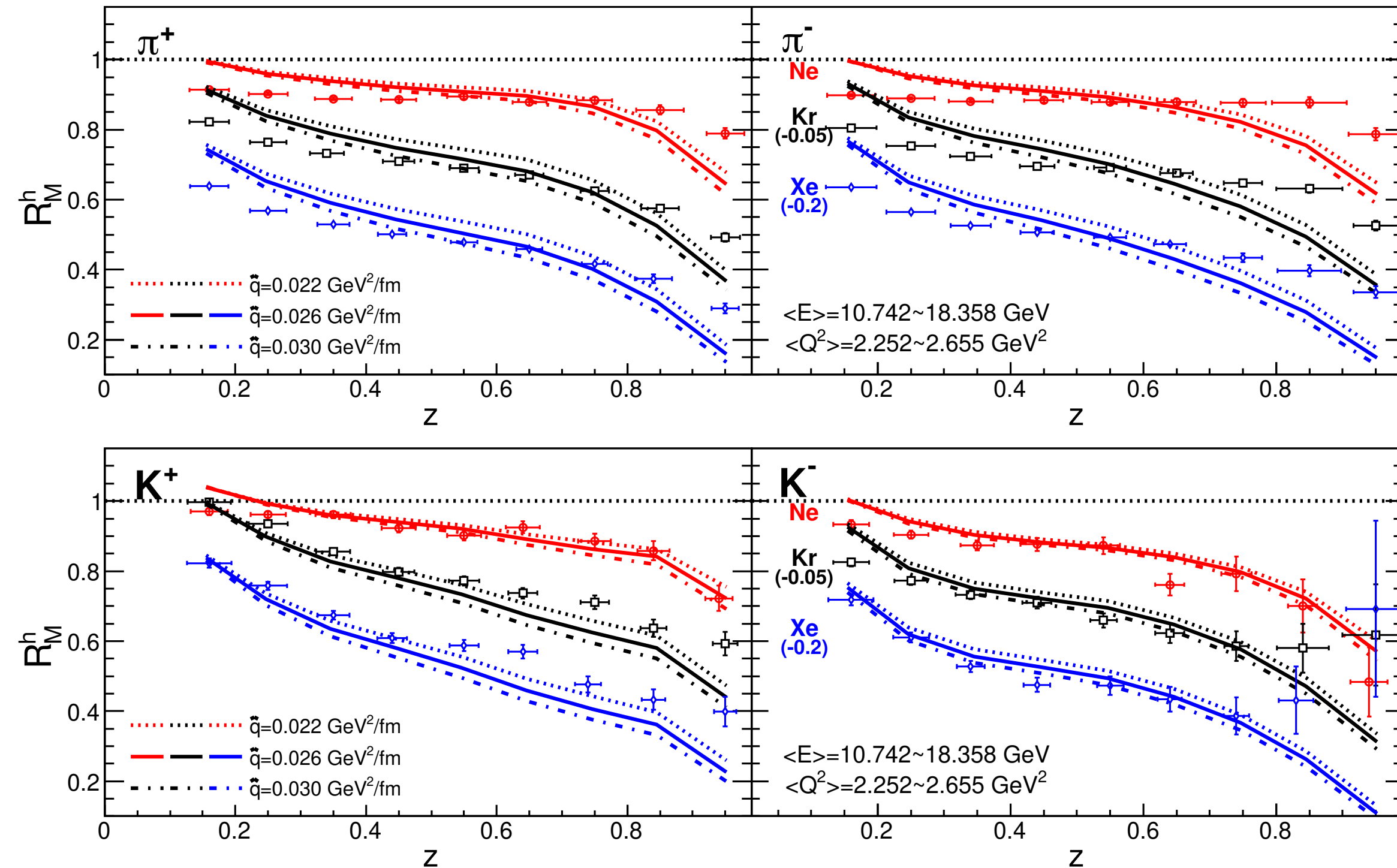
$$\mathcal{R}_{\pi^+/u}^{\text{Xe}}(z, p_{\perp}, Q_0) = \frac{D_{\pi^+/u}^{\text{Xe}}(z, p_{\perp}, Q_0)}{D_{\pi^+/u}(z, p_{\perp}, Q_0)}$$

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

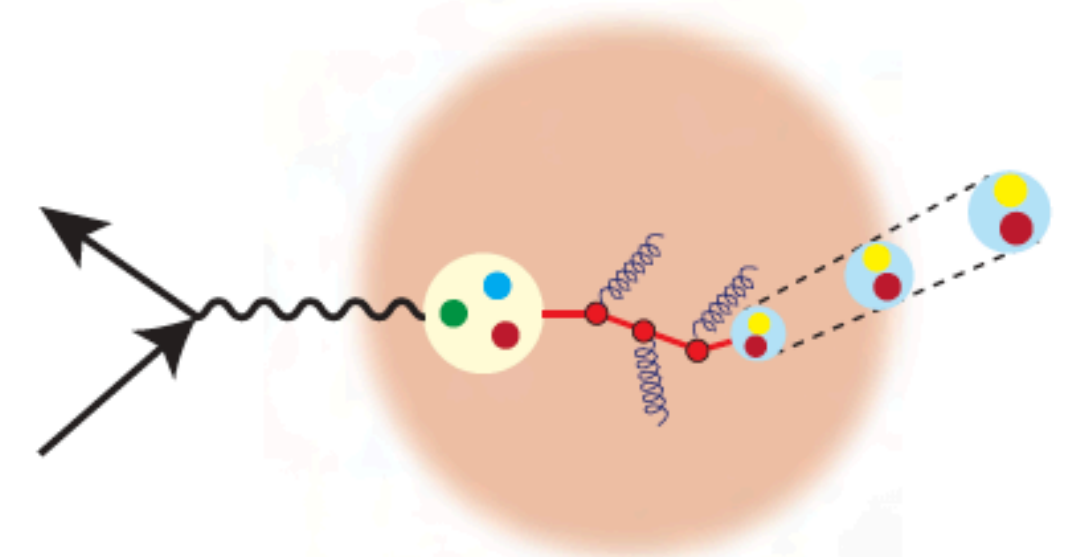
EicC for parton propagation in nuclear medium

- Quark-gluon propagation in nuclear medium - energy loss vs. hadronization

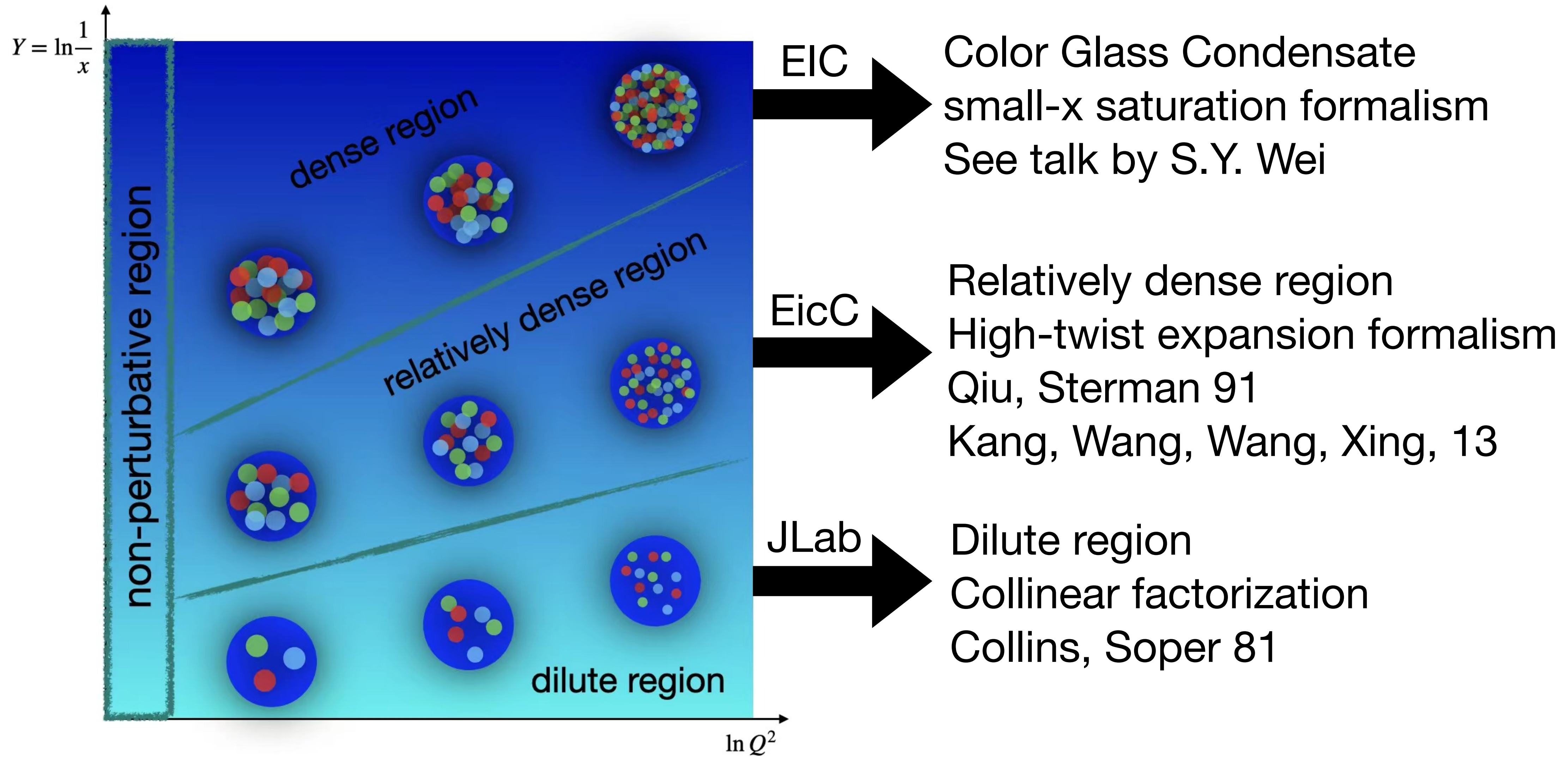
NLO + ELoss



From HERMES to EicC



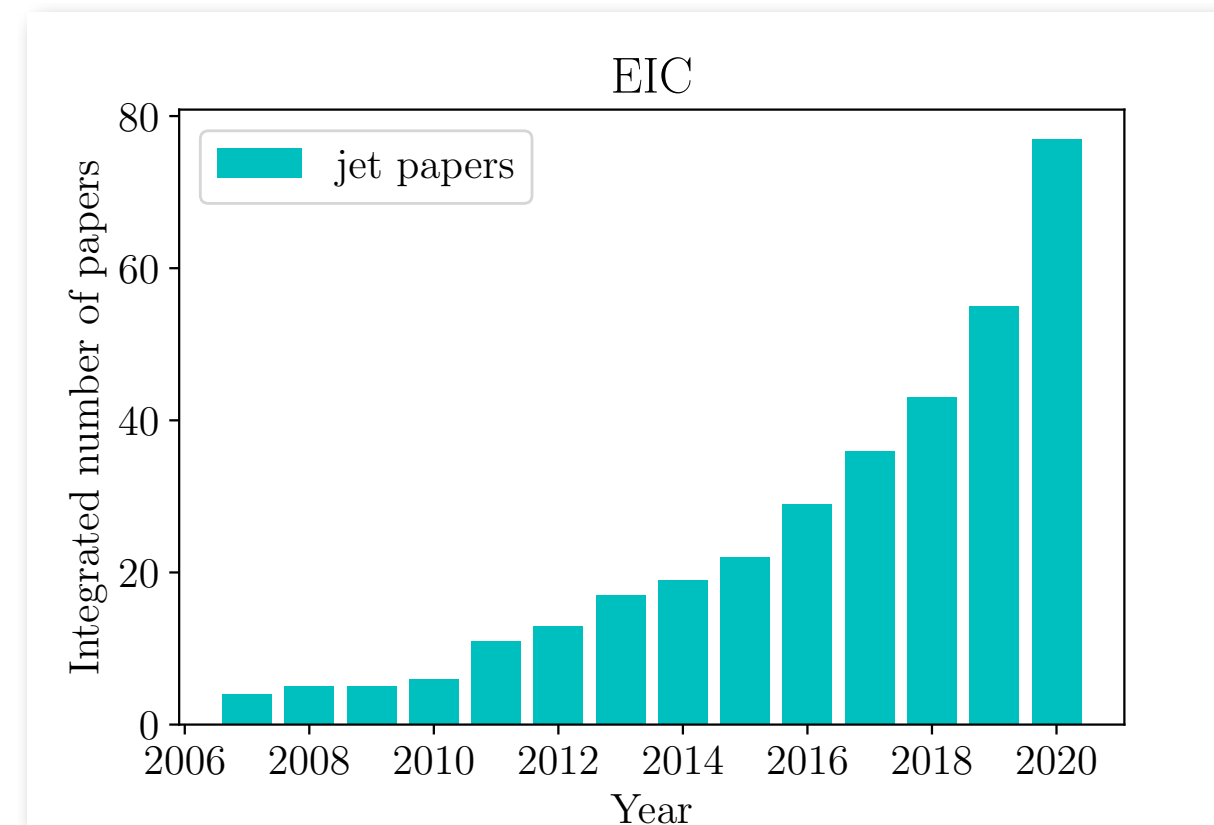
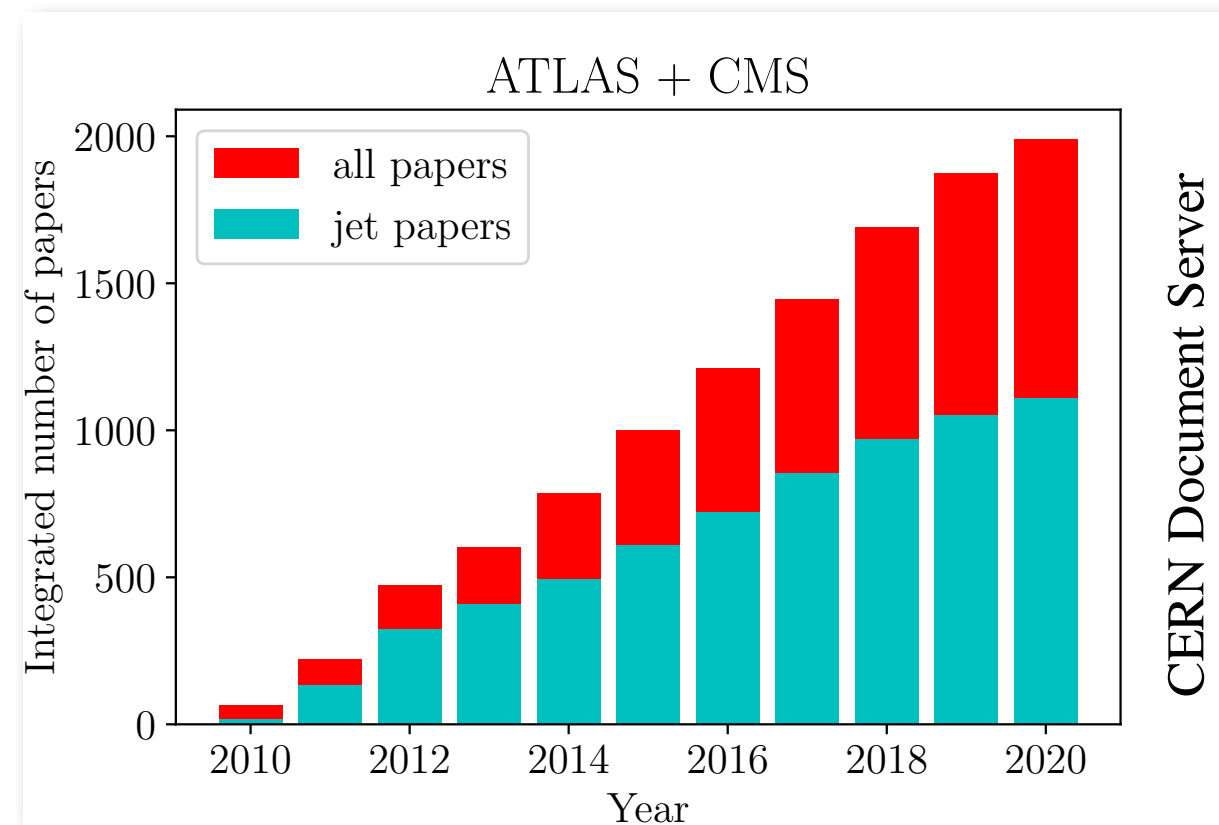
From dilute to dense QCD dynamics in nuclear medium



Matching CGC and high-twist!
Fu, Kang, Salazar, Wang, HX, in preparation

Connections to HEP

- JET physics



Liu, Ringer, Vogelsang, Yuan, PRL 19

Kang, Liu, Mantry, Shao, PRL 20

Hatta, Xiao, Yuan, Zhou, PRL 21

Liu, HX, 2104.03328, 2021

Li, Vitev, PRL 21

...

- Call for high precisions

NLO SIDIS at high twist, Kang, Vitev, **HX**, PRD 13, Kang, Wang, Wang, **HX**, PRL 14

Jet production at NLO in longitudinal polarized DIS, Boughezal, Petriello, **HX**, PRD 2018

Jet production at N3LO, Gehrmann, Huss, Niehues, Vogt, Walker, PLB 2018

Jet production at N3LO, Currie, Gehrmann, Glover, Huss, Niehues, JHEP 2018

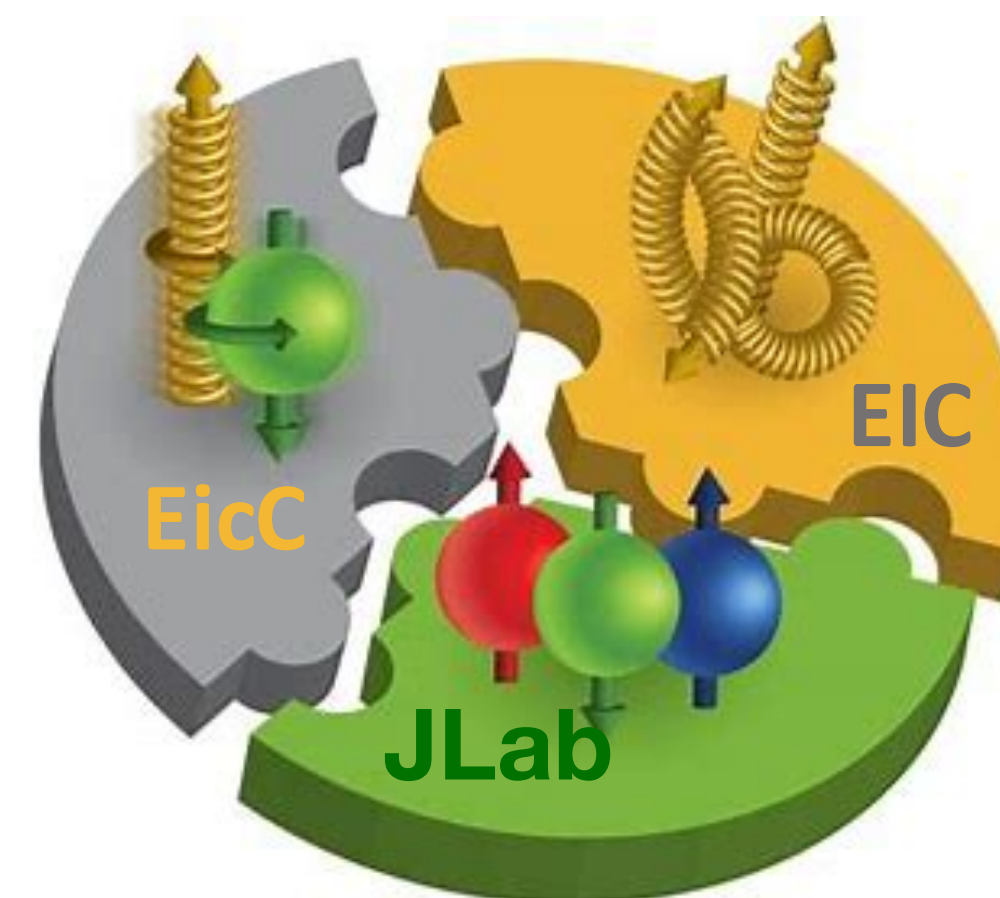
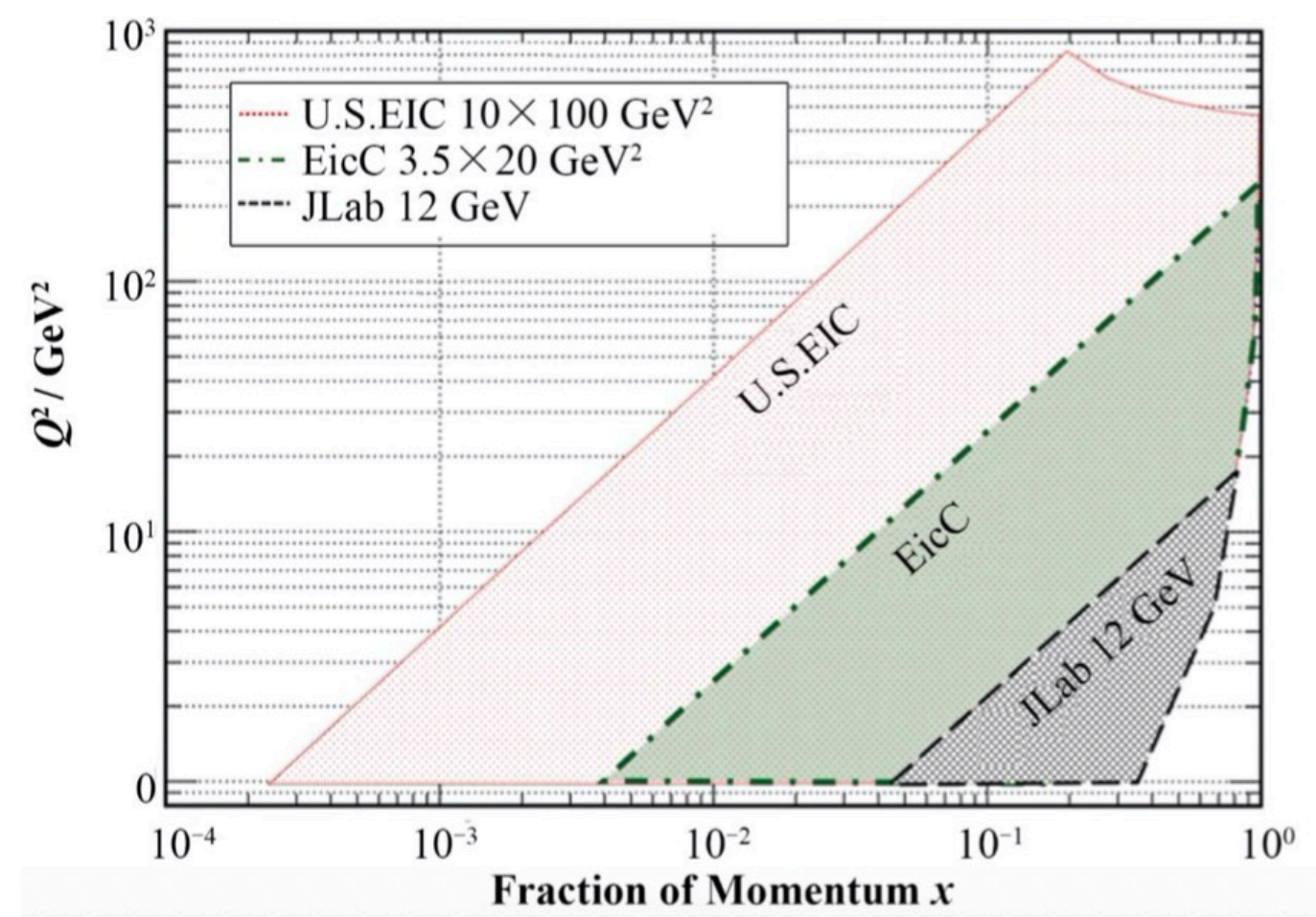
Jet production at NNLO in longitudinal polarized DIS, Borsa, Florian, Pedron, PRL 2020

Massive Charged current DIS, Berger, Gao, Li, Liu, Zhu, PRL 16; Gao, JHEP 18

Polarized DIS, SIDIS ...

Summary

- **EicC is one of the ultimate machines to explore the inner world of proton at fm scale**
 1. Proton 1-D 3-D imaging
 2. Proton spin
 3. Nuclear effect
- **EIC、EicC、JLab are complementary to each other**



Advertisement

EicC email list:

http://lists.ustc.edu.cn/sympa/subscribe/eicc_member?previous_action=info

The 3rd EicC CDR workshop

23-26 September 2022
Shandong University (Qingdao)
Asia/Shanghai timezone

Overview

Scientific Programme

Timetable

Contribution List

Author index

Registration

Update: After discussion, we decided the new date for our 3rd EicC CDR workshop in Qingdao: September 23-25, 2022. September 23 will be the arrival day, and September 26 is the leaving day. We kindly ask you to modify the registration information in particular the arrival/departure date by the end of August 31, to help us reserve the hotel room.

We hope to see you all in Qingdao!