Physics at Electron-Ion Colliders

Hongxi Xing
邢 宏 喜

Institute of Quantum Matter
South China Normal University

Outline

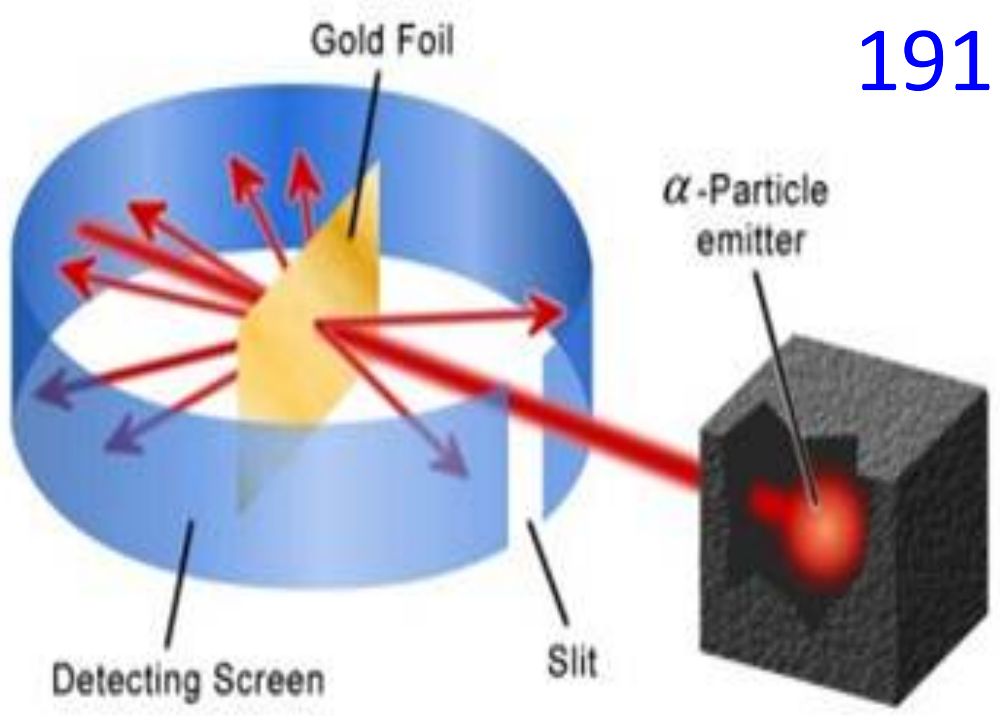
- ✦ Introduction to Electron-Ion Colliders
- ✦ Selected topics for EIC physics:
  - proton spin decomposition
  - proton 3D tomography
  - nuclear effects
- ✦ Summary and outlook

Nucleon partonic structure

✦ Revolution in our view of nuclear structure

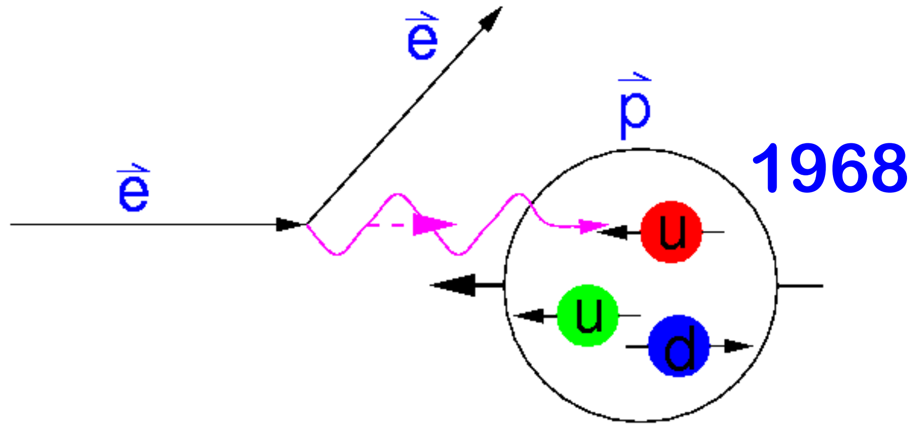
- Atom: Dalton 1803
- Nucleus: Rutherford 1911
- Proton: Rutherford 1919
- Neutron: Chadwick 1932
- Quark model: Gell-Mann and Zweig 1964
- Parton model: Feynman 1969
- …

1911



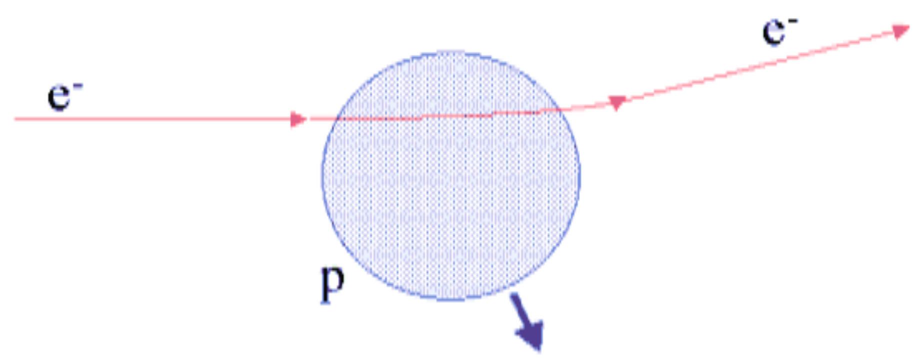
Rutherford scattering

e + *p* ➔ e + *X*

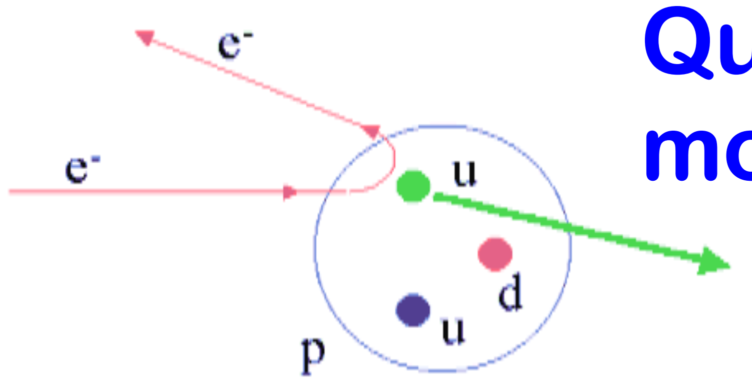


Modern Rutherford scattering

◆ If proton "charge cloud":



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



Quark model

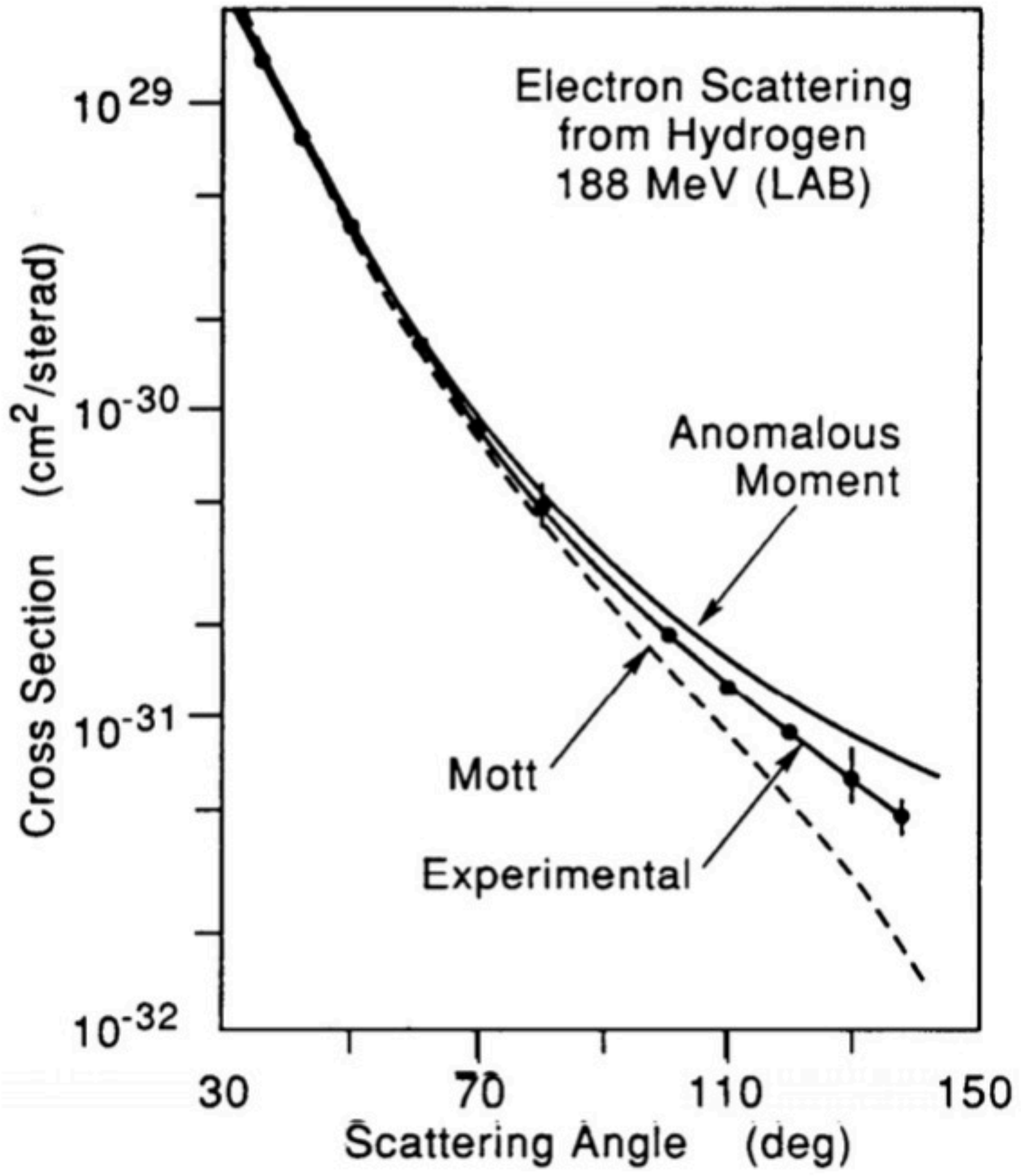


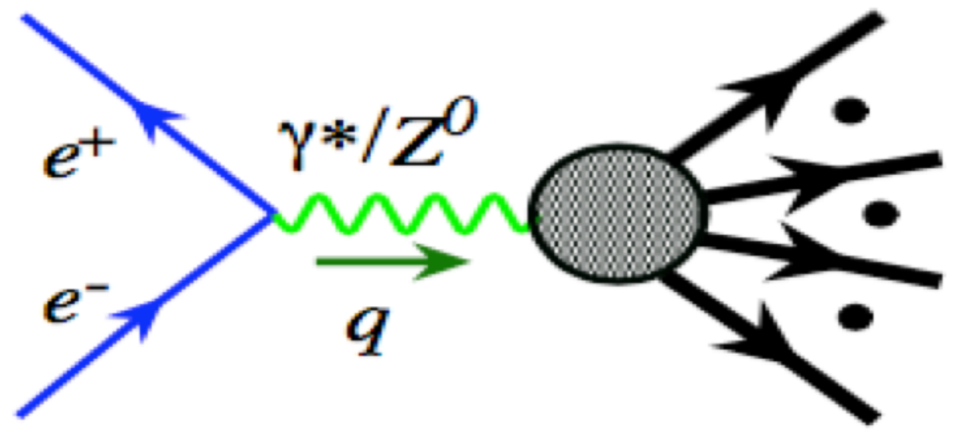
Fig. 5. Elastic electron scattering cross sections from hydrogen compared with the Mott scattering formula (electrons scattered from a particle with unit charge and no magnetic moment) and with the Rosenbluth cross section for a point proton with an anomalous magnetic moment. The data falls between the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

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

How to probe the nucleon partonic structure?

✦ Indispensable joint efforts from experiments and QCD theory

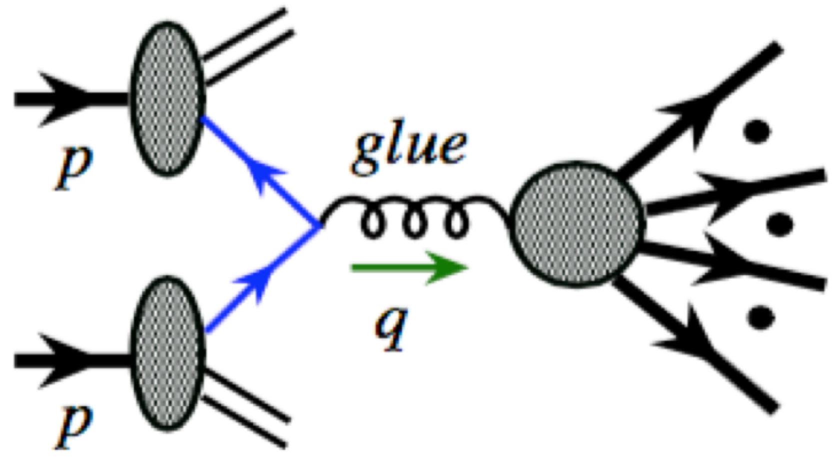
Lepton-lepton colliders



BEPC, SuperKEKB

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

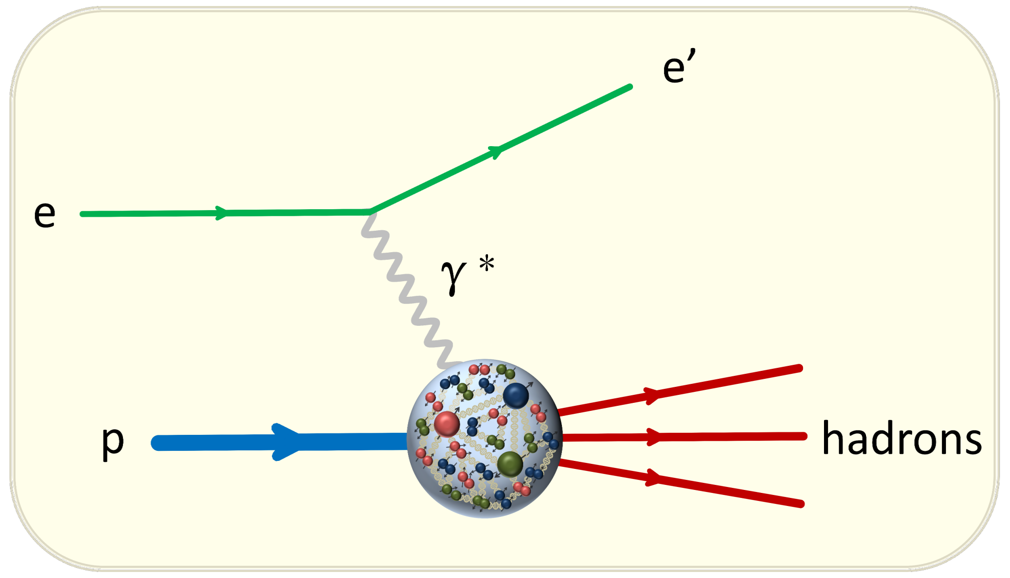
Hadron-hadron colliders



RHIC, LHC

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

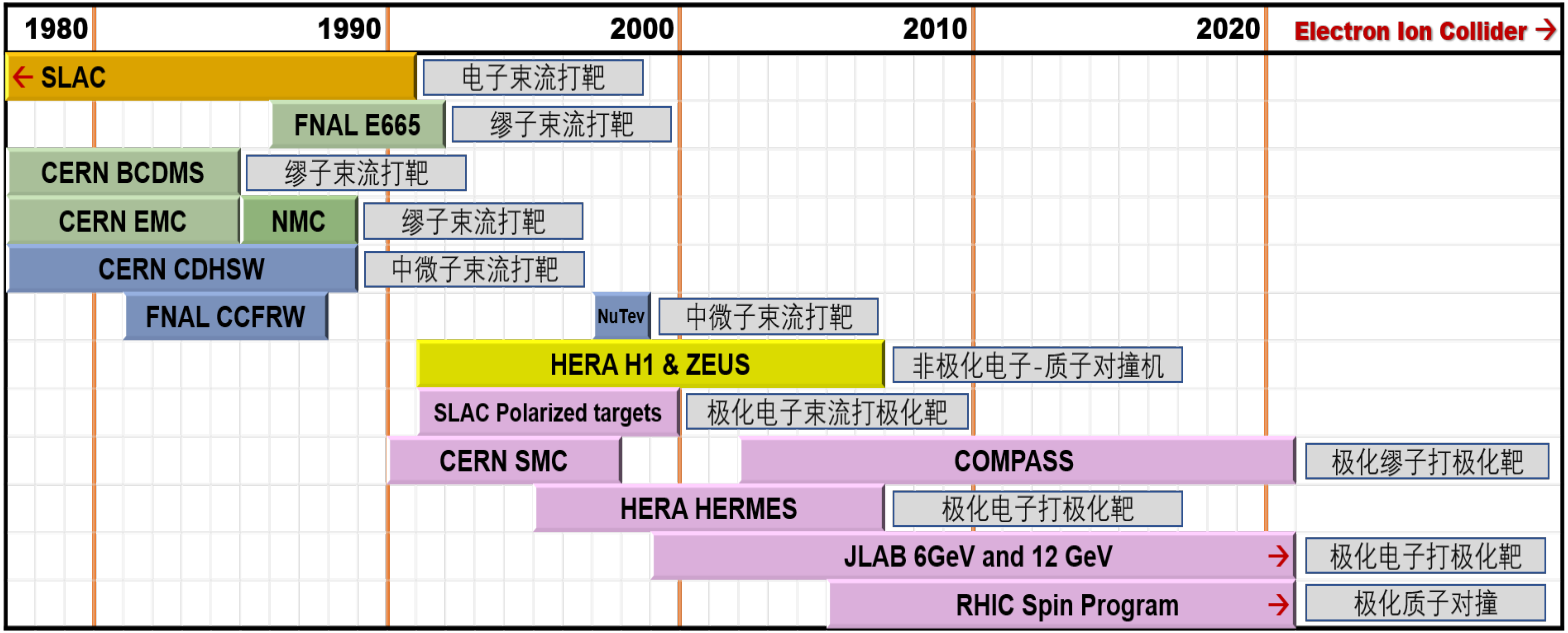
lepton-hadron colliders



HERA, JLab

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

The modern experiments for nucleon structure



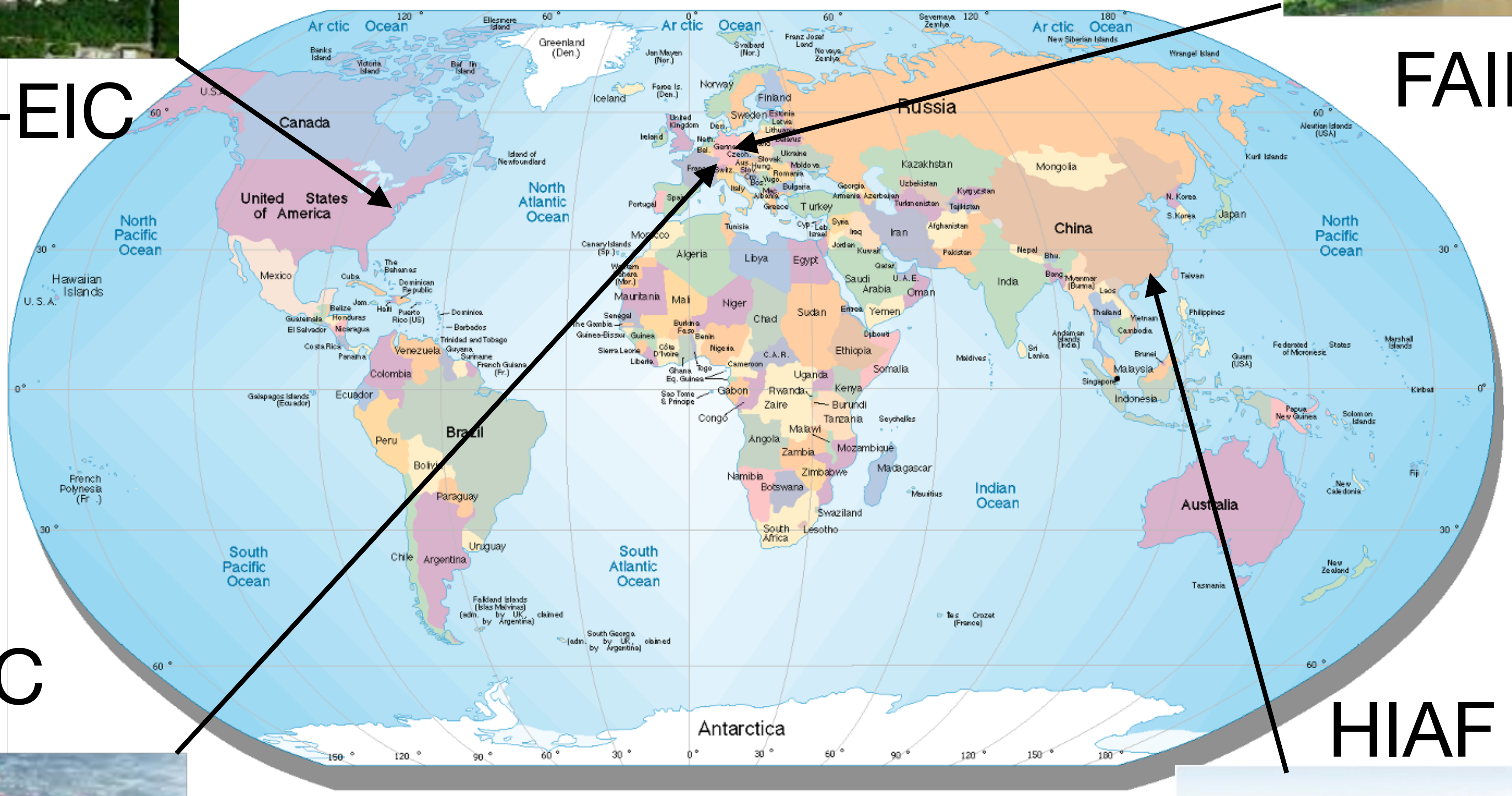
Electron Ion Colliders -> the next generation facility specifically for nucleon structure!

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

电子－离子对撞机 (EIC)

质心能量~100 GeV

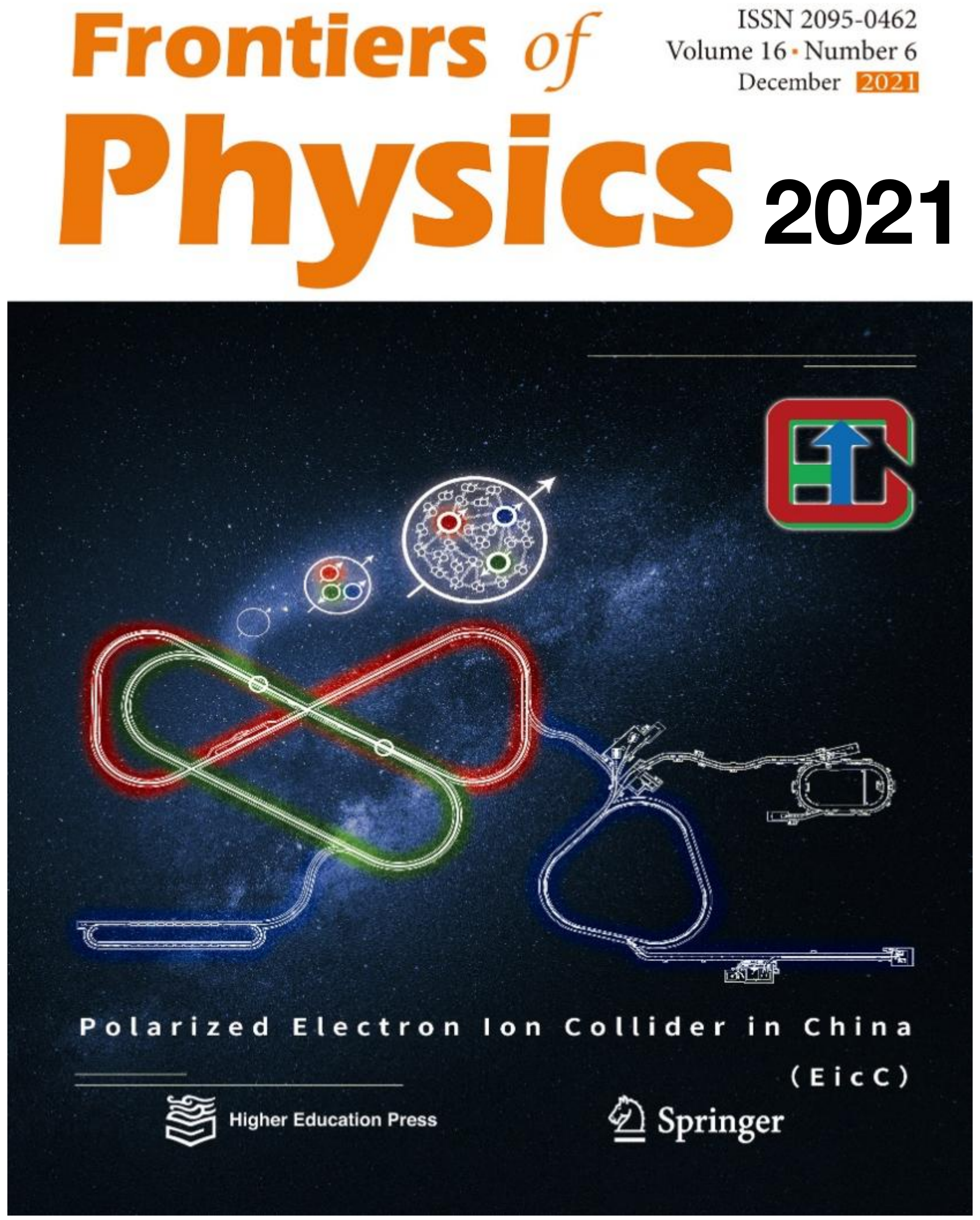
2005: 领域内开始讨论
2007, 2015: 美国核科学长程计划
2015: EIC 白皮书
2018: 美国科学院重申EIC物理重要性
2019.12：**EIC 立项**
2020: EIC 黄皮书和概念设计
2021: EIC 探测器方案建议书
2030: 计划开始运行

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

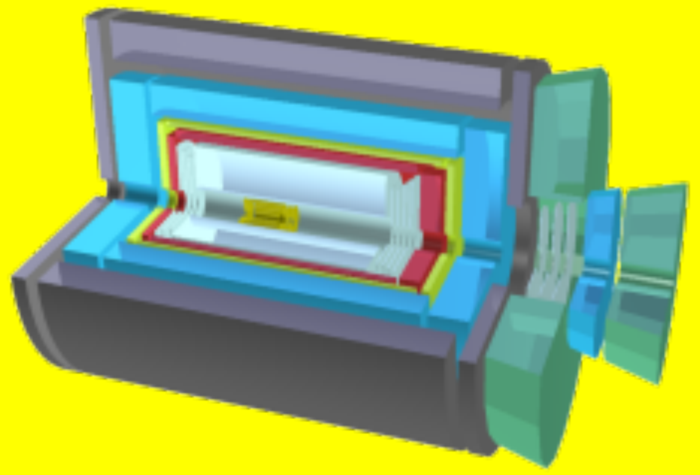
Time evolution of EicC



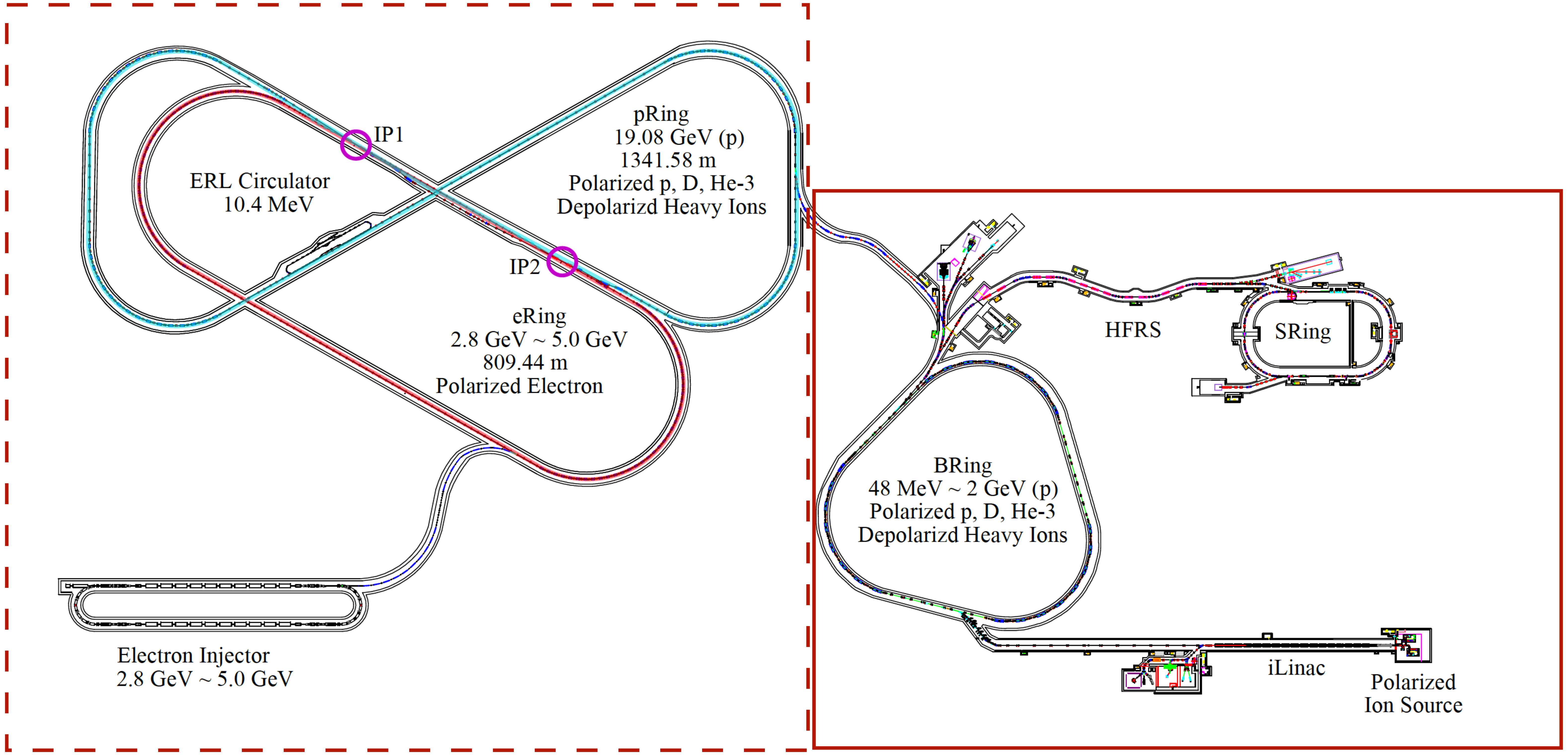
中国电子 – 离子对撞机 (EicC)

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

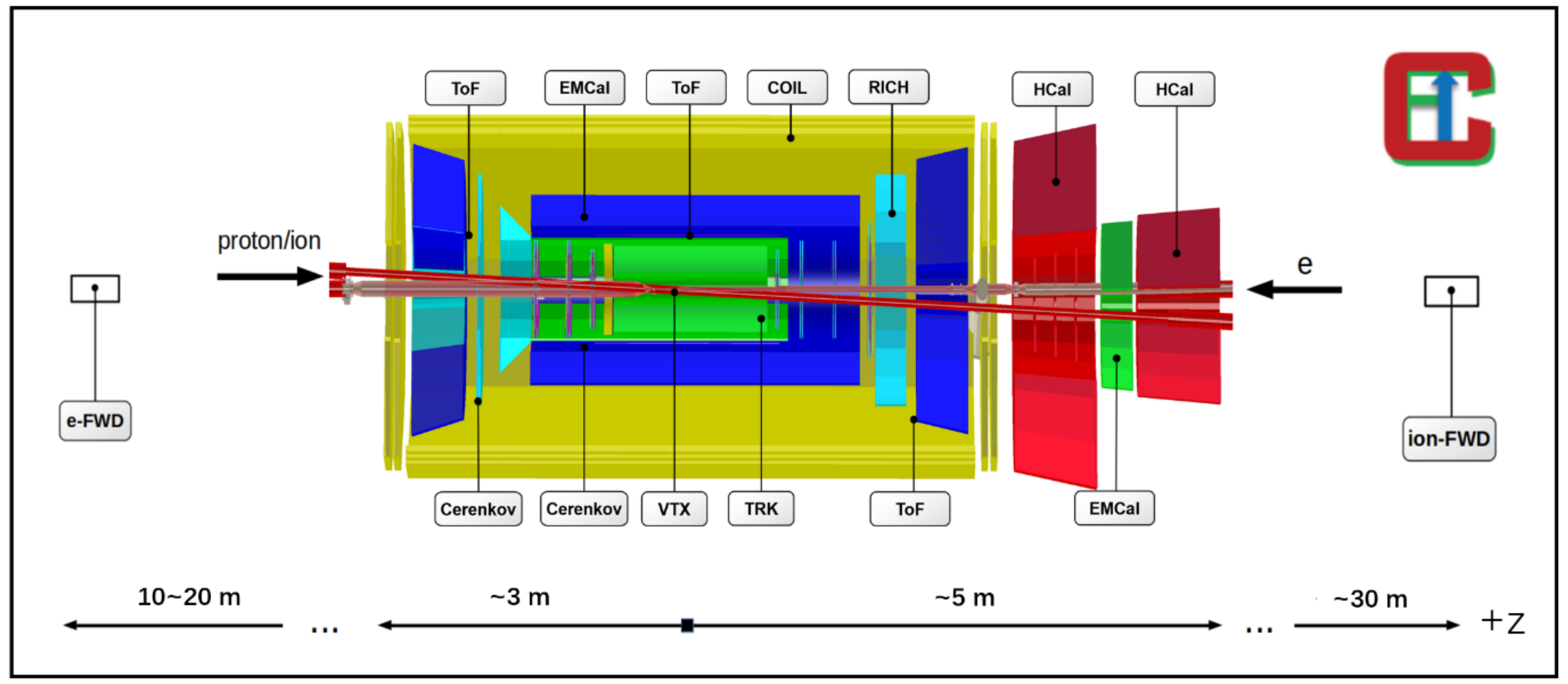


Electron-Ion Collider in China (EicC)



Need to be built for the EicC

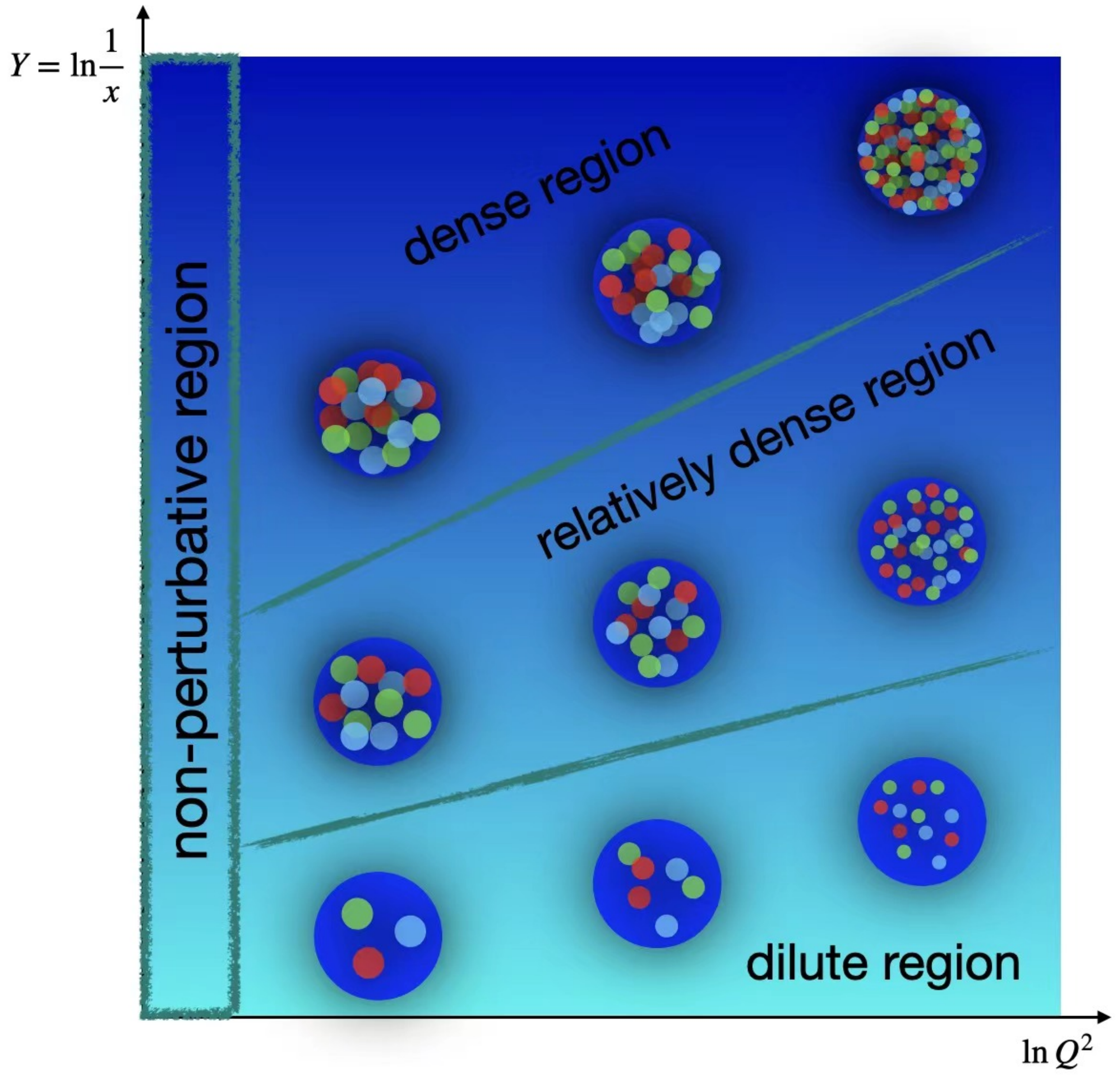
HIAF under construction



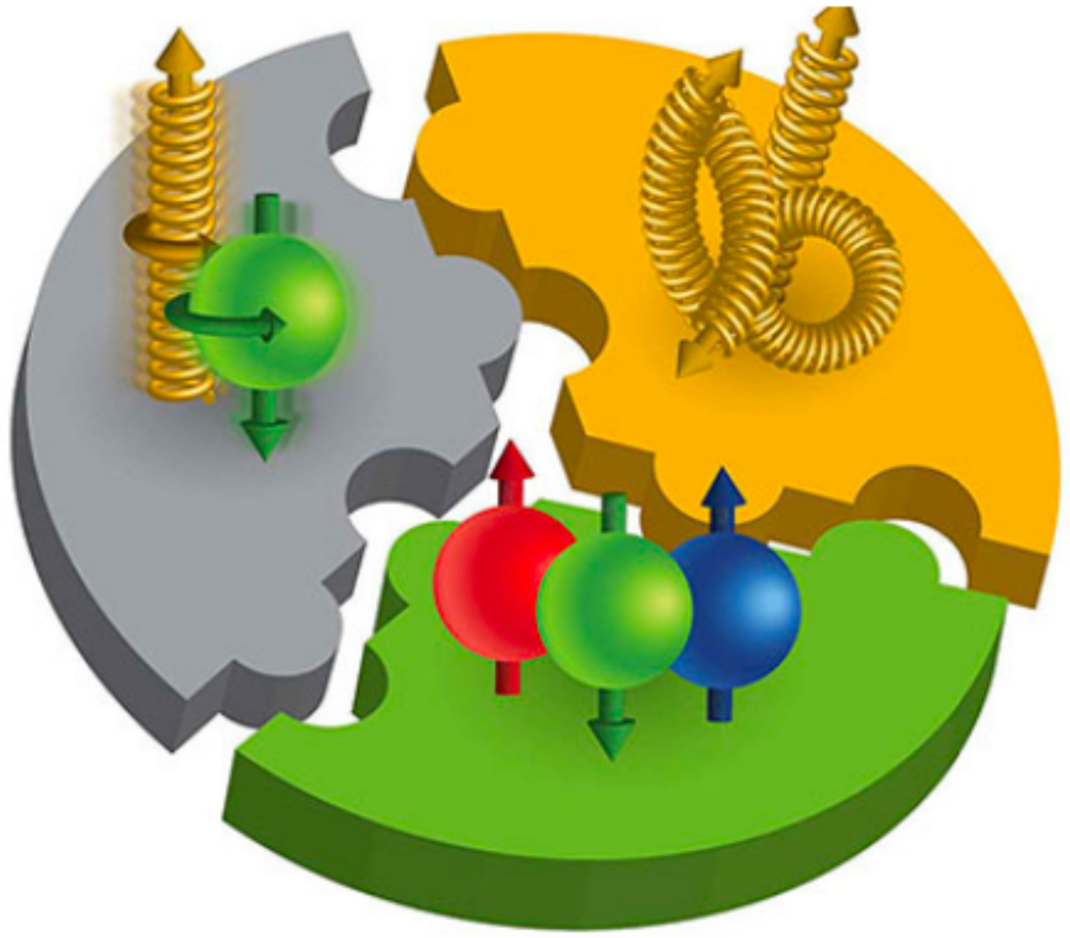
主要参加研究单位：
中科院近物所、理论所、高能所、国科大、科大、清华、北大、山大、华中师大、华南师大；
美国Jlab、UVa、UCLA

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

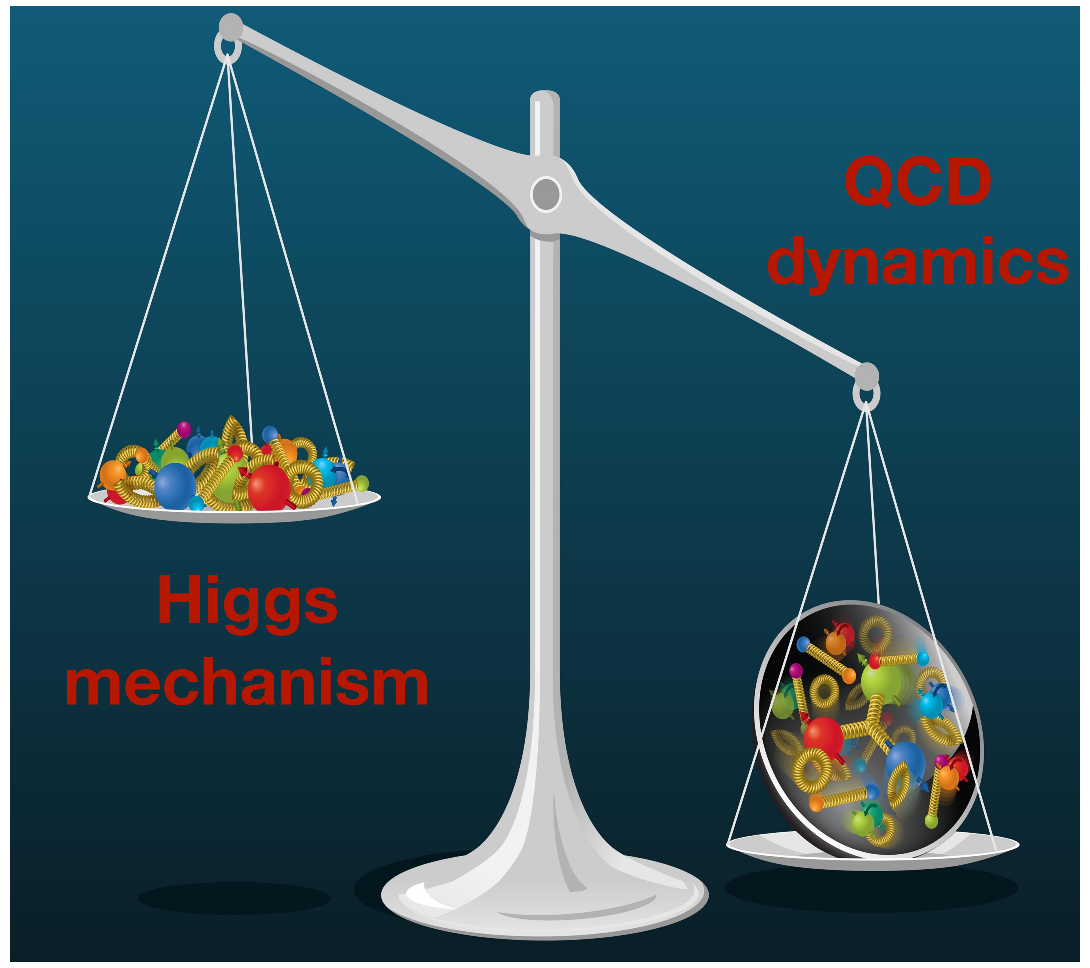
Scientific goals at EIC worldwide



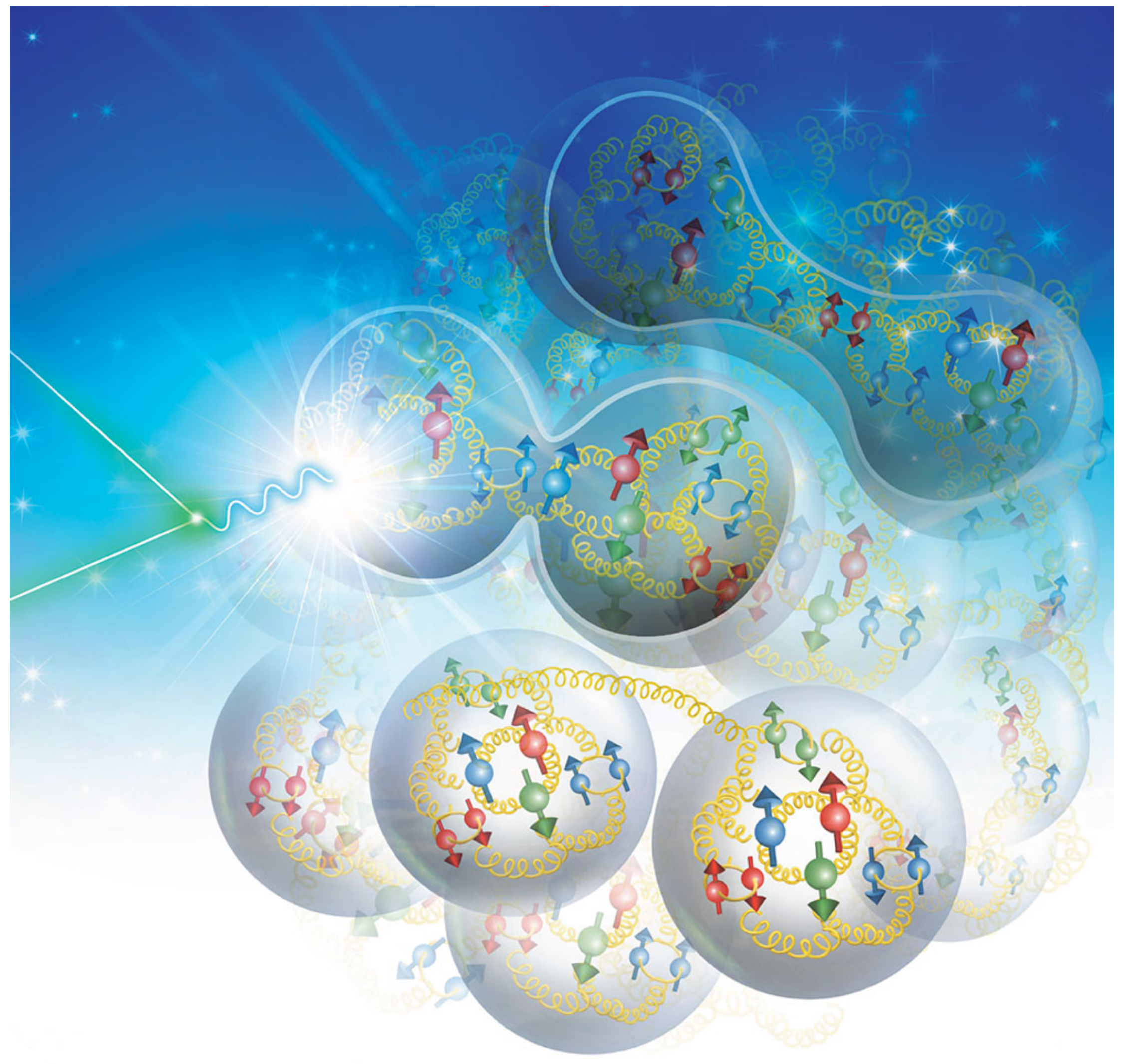
The energy momentum distribution of partons in nucleon/nuclei



The origin of proton spin

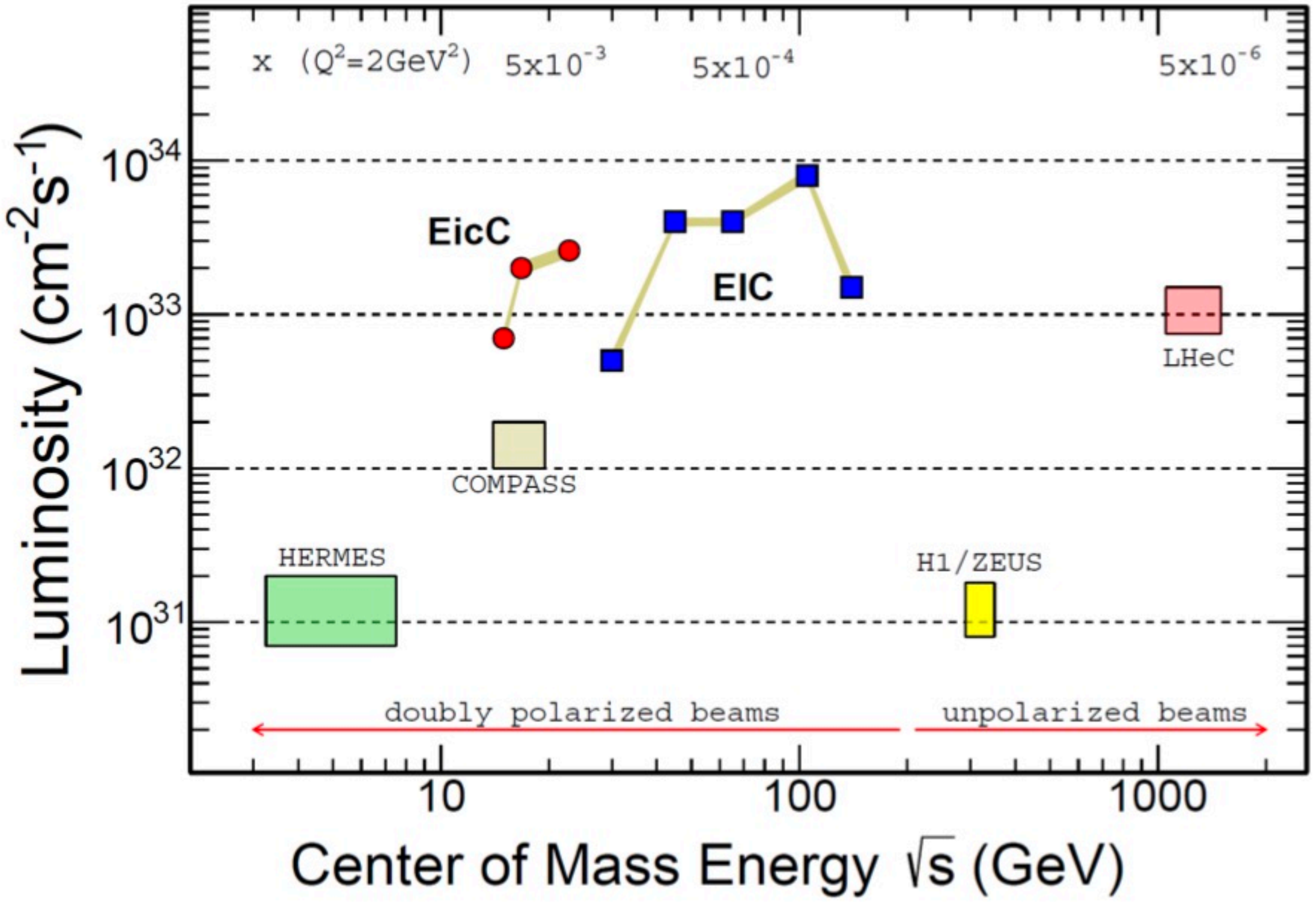


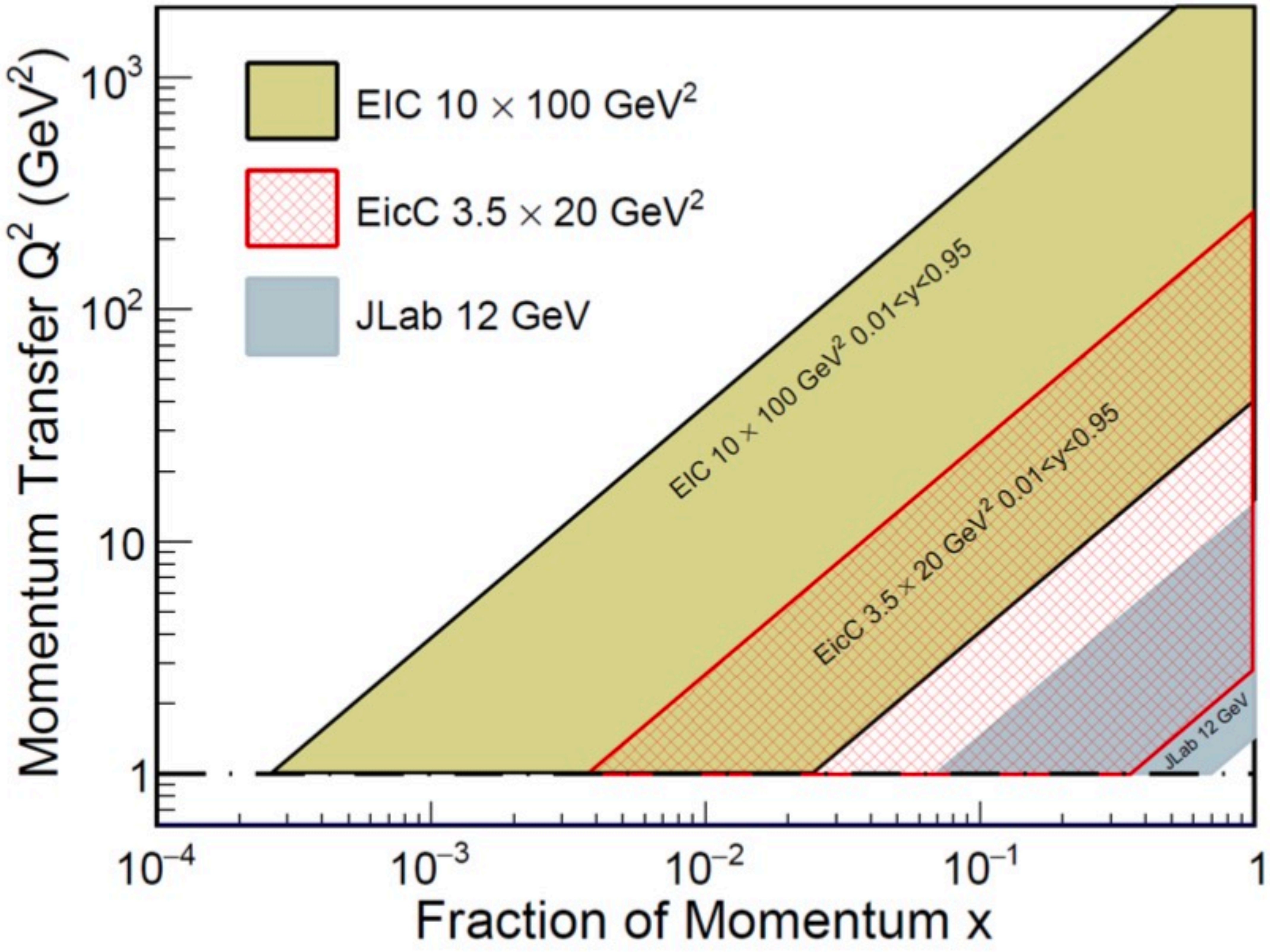
The origin of proton mass



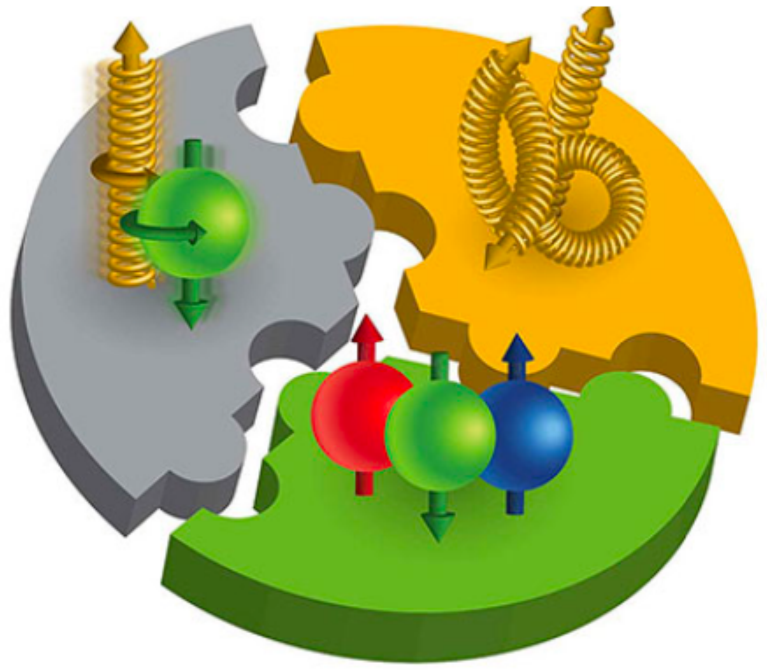
nuclear effects

Complementarity between EIC and EicC





Mapping out the nucleon structure via EICs worldwide

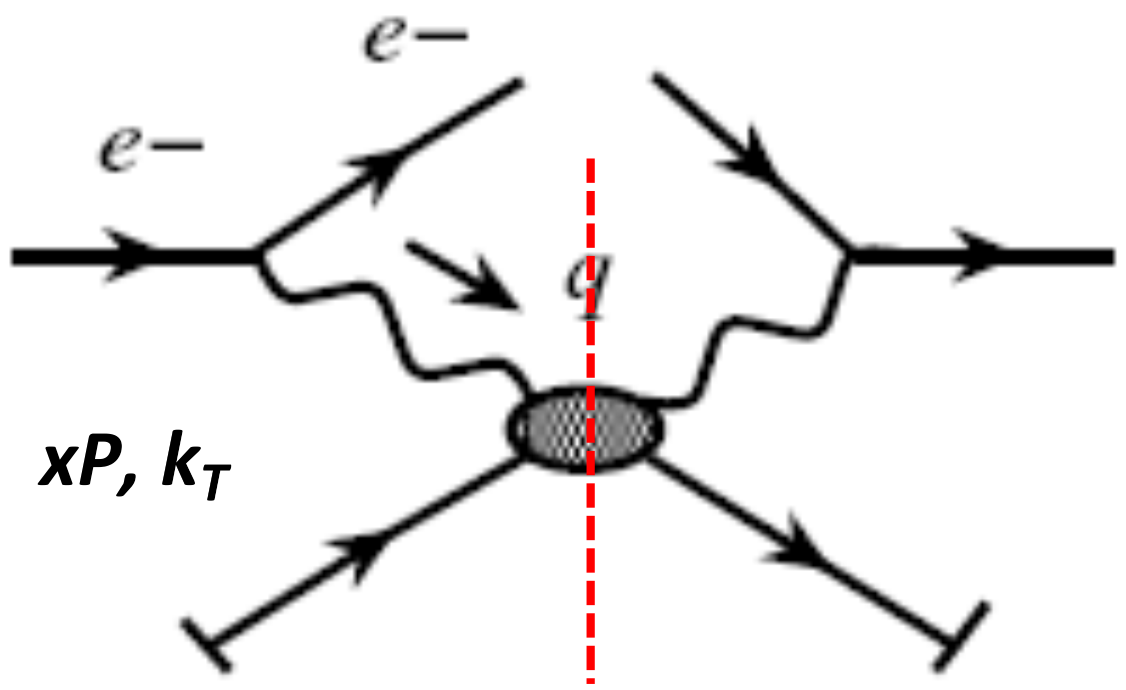


How to probe the nucleon partonic structure?

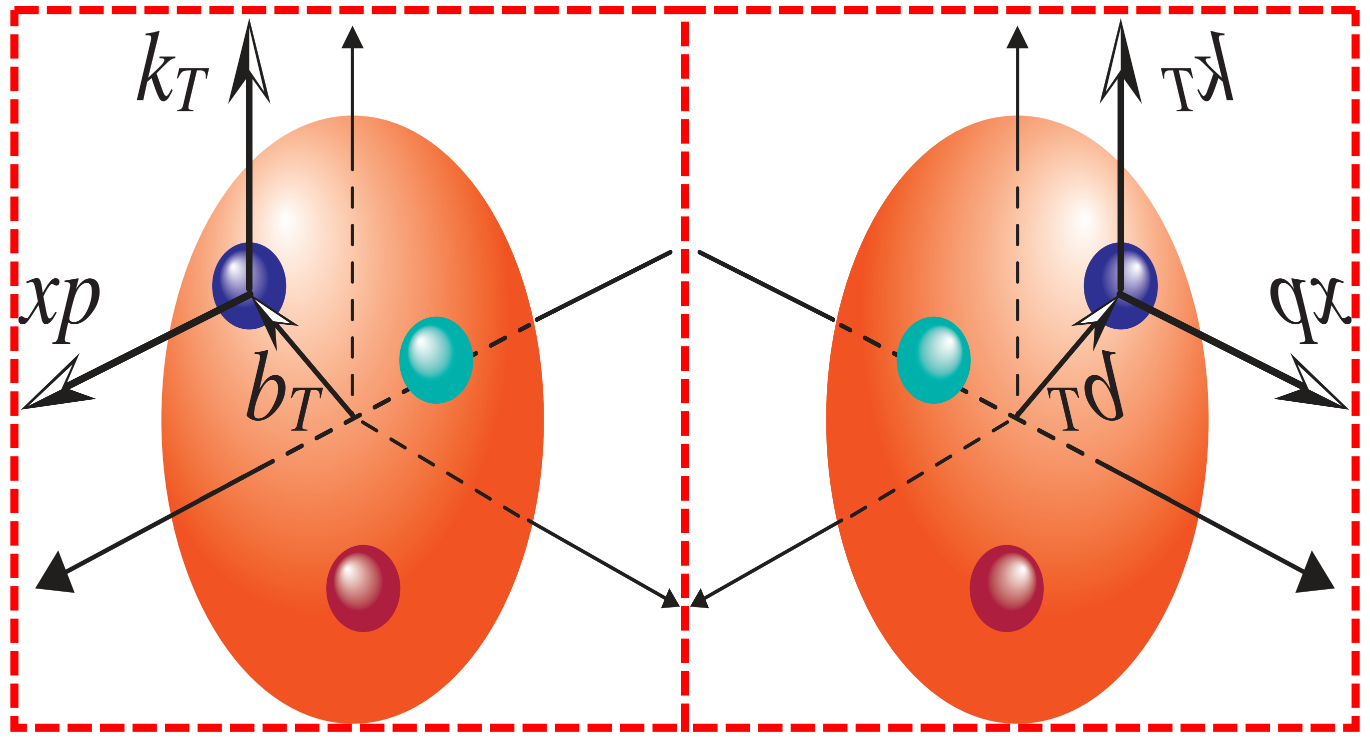
✦ Indispensable joint efforts from experiments and QCD theory

QCD factorization theorem

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



$$\otimes$$



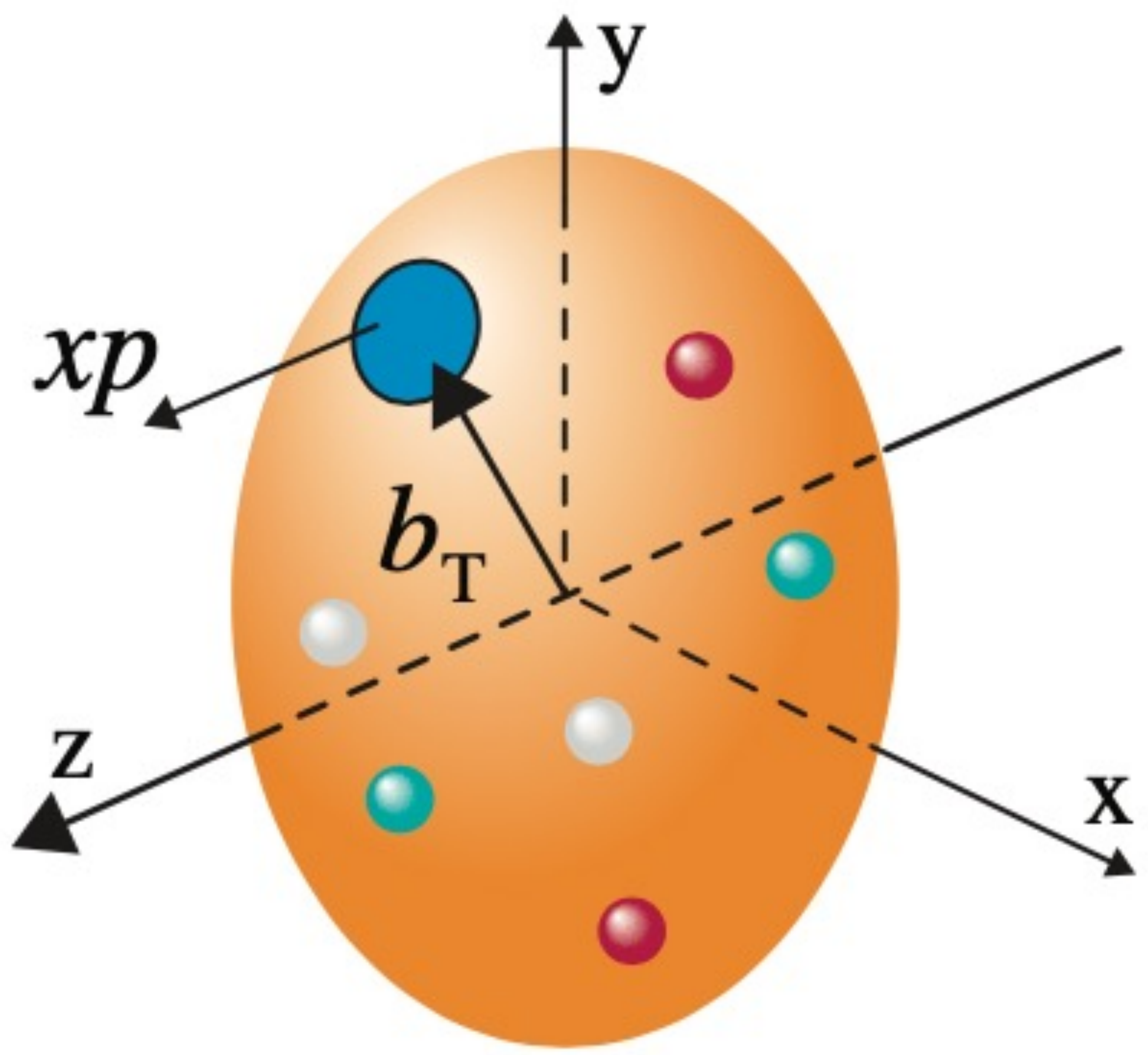
Experimental measurements

Hard part controlled by pQCD theory

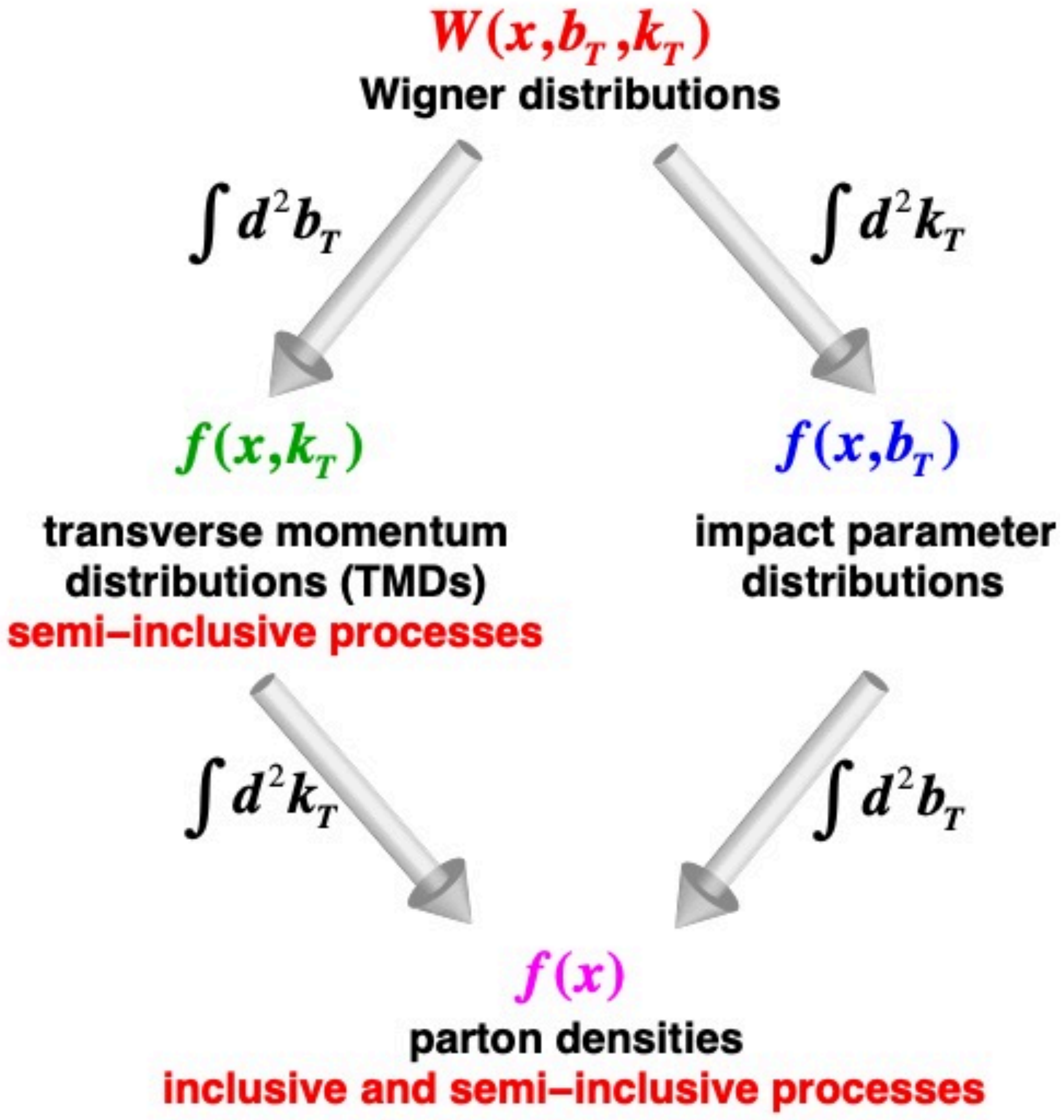
Nucleon partonic structure

Nucleon partonic structure - momentum distribution

✦ Multi-dimensional view of nucleon partonic structure



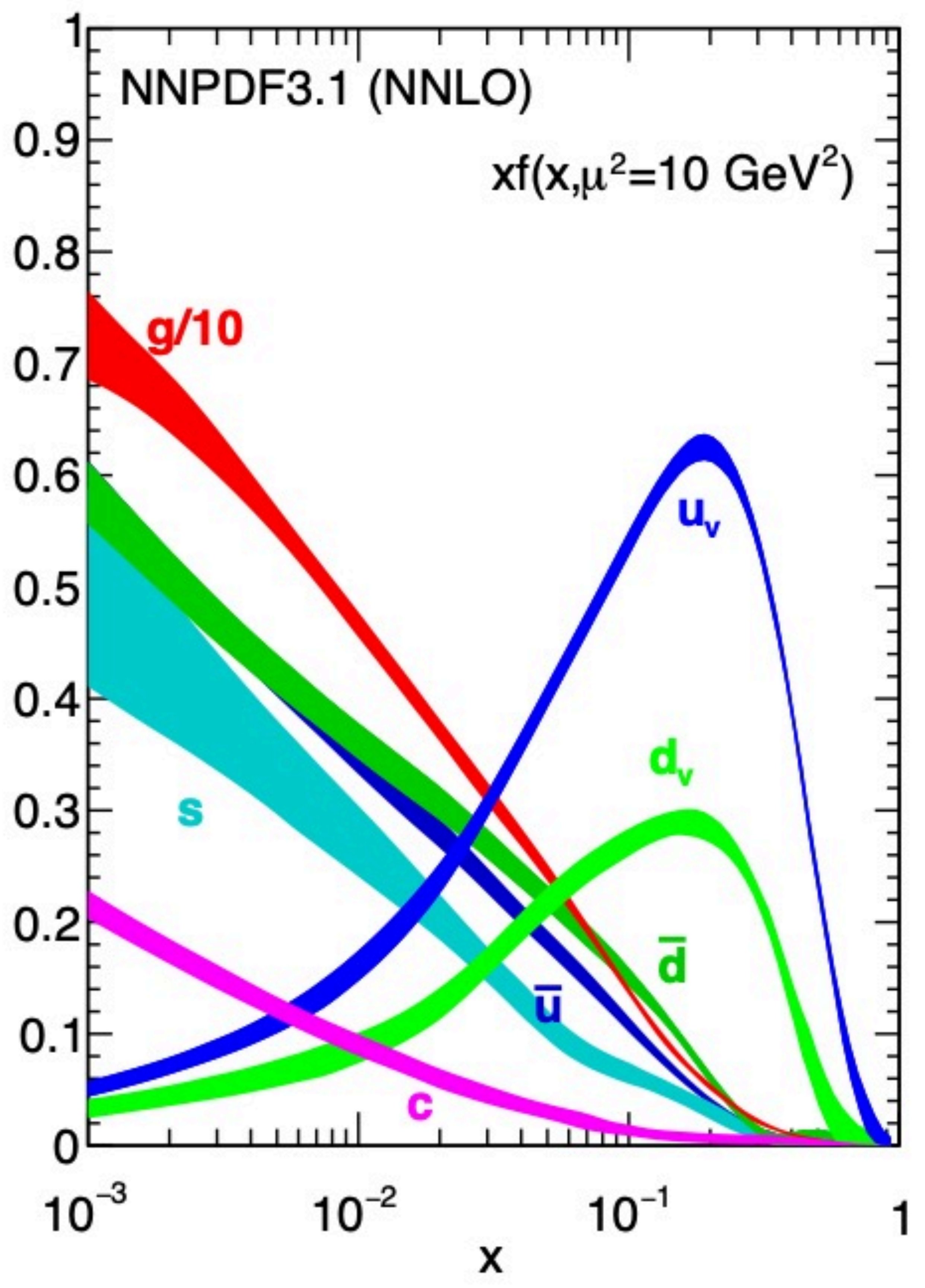
Wigner distribution
5D view



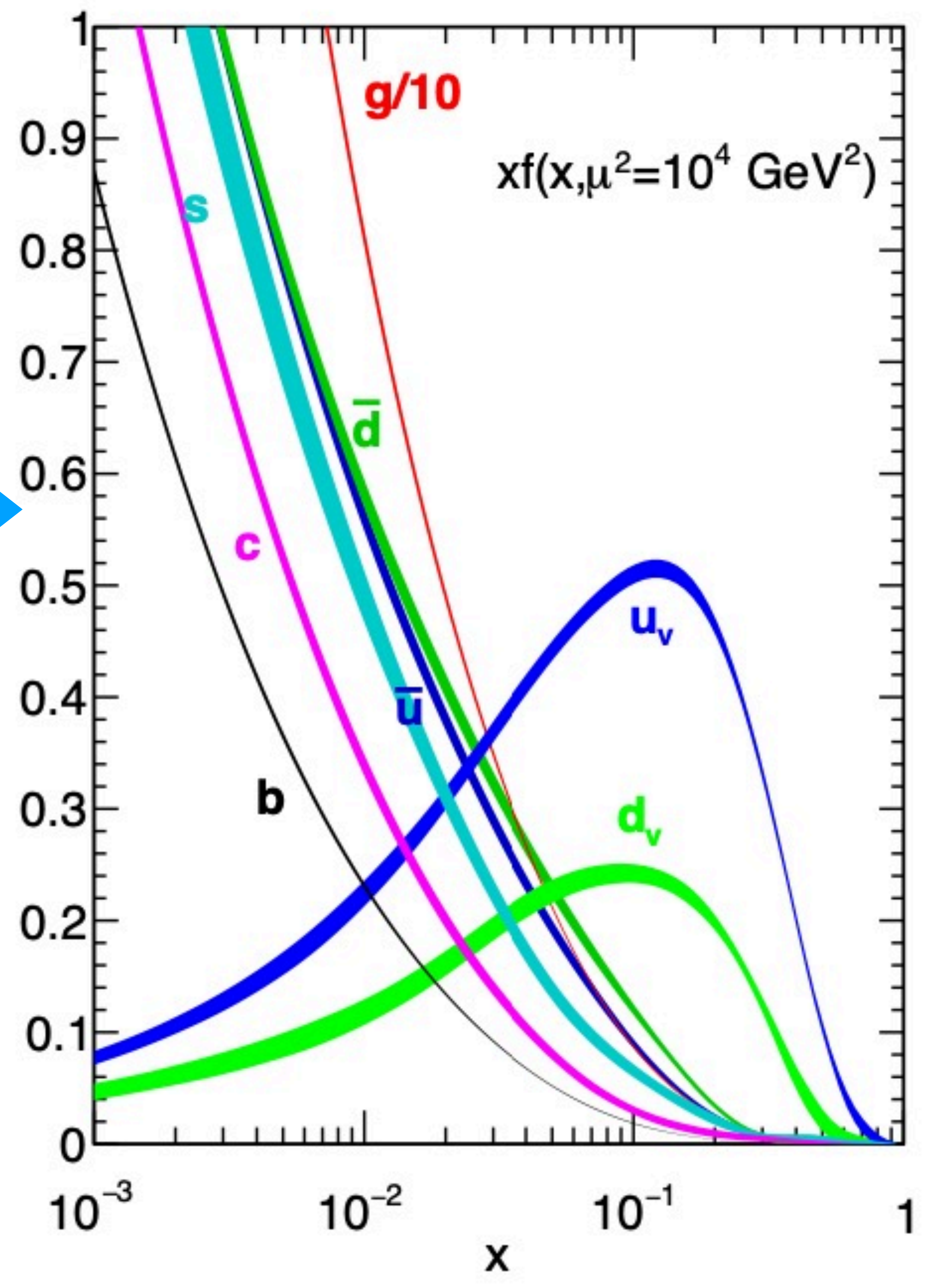
Nucleon structure: quantum probability, there is no still picture for partons inside nucleon.

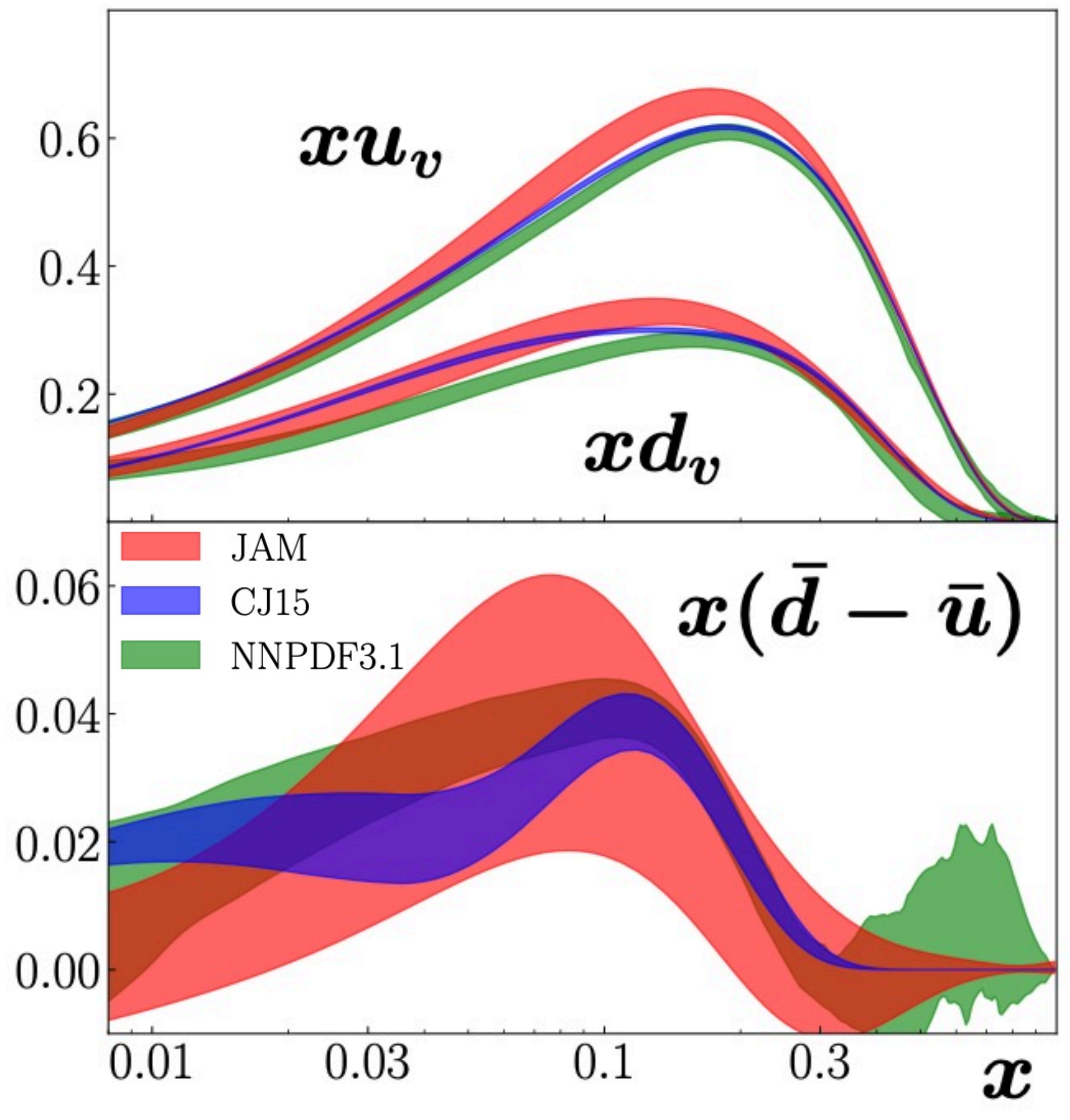
QCD global analysis of world data - nucleon 1D structure

✦ Current knowledge about proton PDFs



NNPDF:1706.00428





JAM 20, arXiv:2101.04664

Nucleon partonic structure - spin configuration

✦ Naive parton model

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

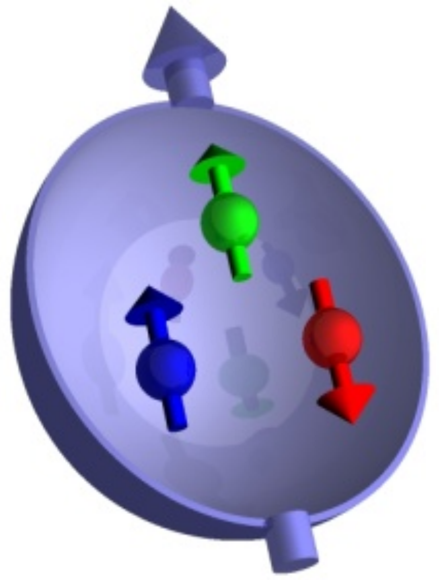
proton spin 1/2 is consistent with naive parton model, but contradict with experiments.

✦ Proton spin decomposition

Jaffe, Manohar; Ji

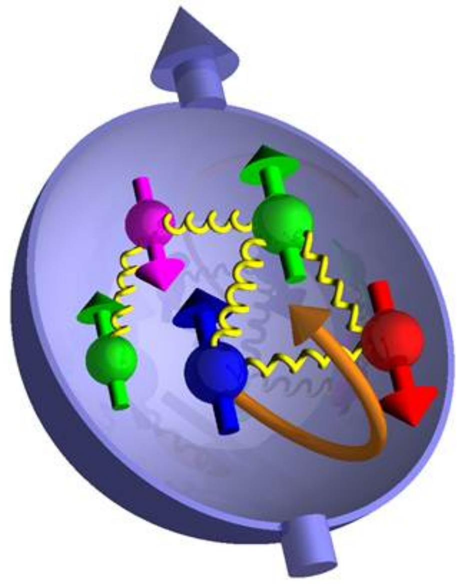
$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}|J^z_{QCD}|P,\frac{1}{2}\right\rangle = \frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2) + \int_0^1 dx\Delta G(x,Q^2) + \int_0^1 dx(\sum_q L_q^z + L_g^z)$$

total quark spin



gluon spin

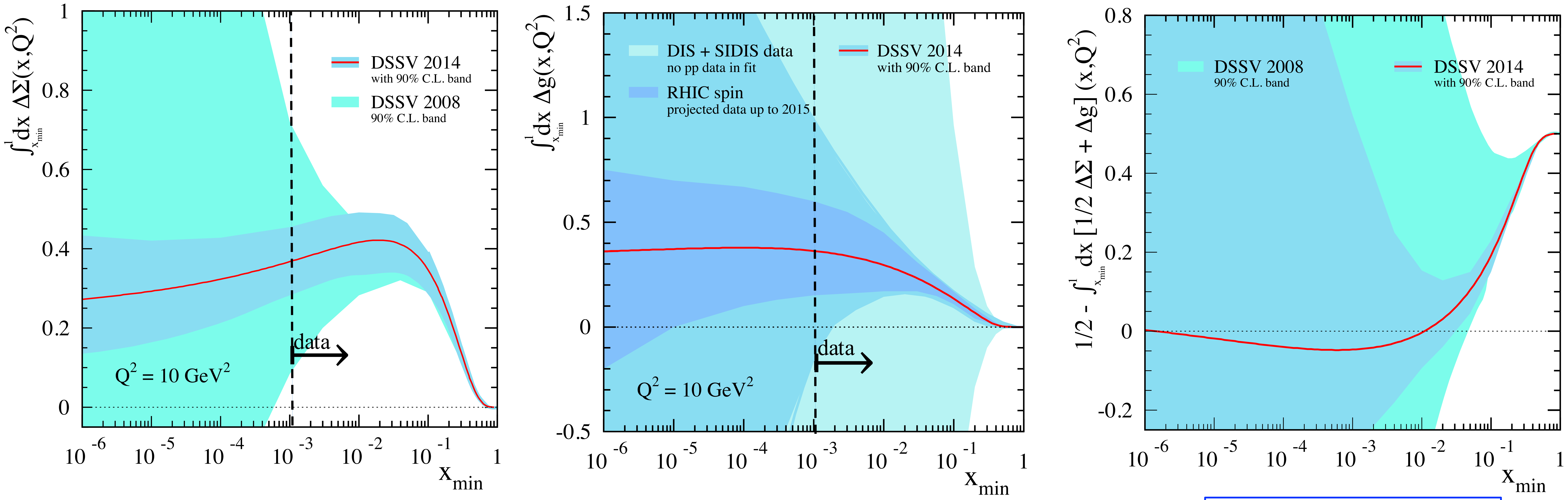
angular momentum



- 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%

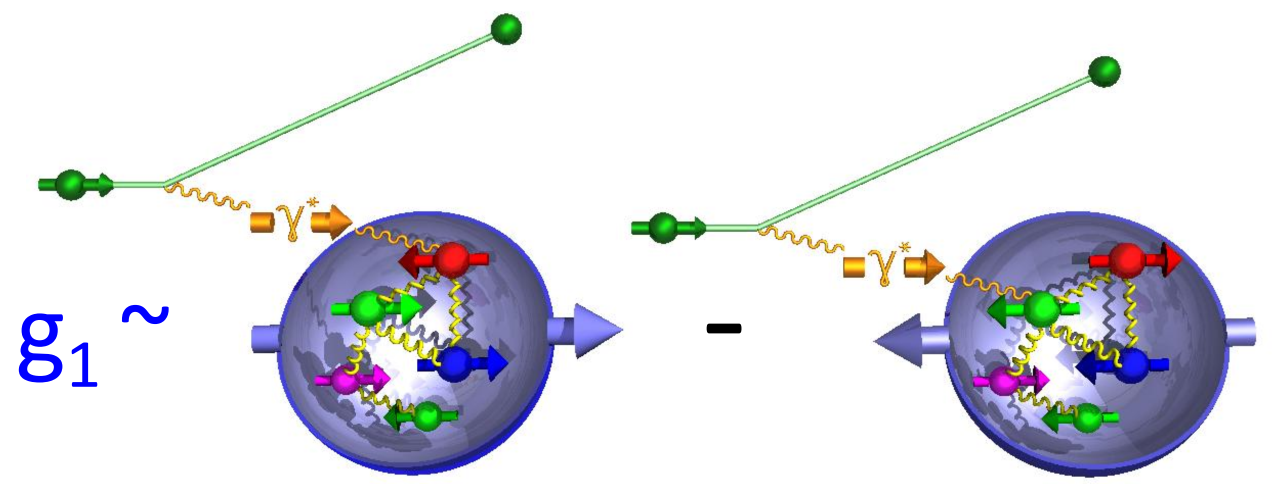
Orbital angular momentum ?

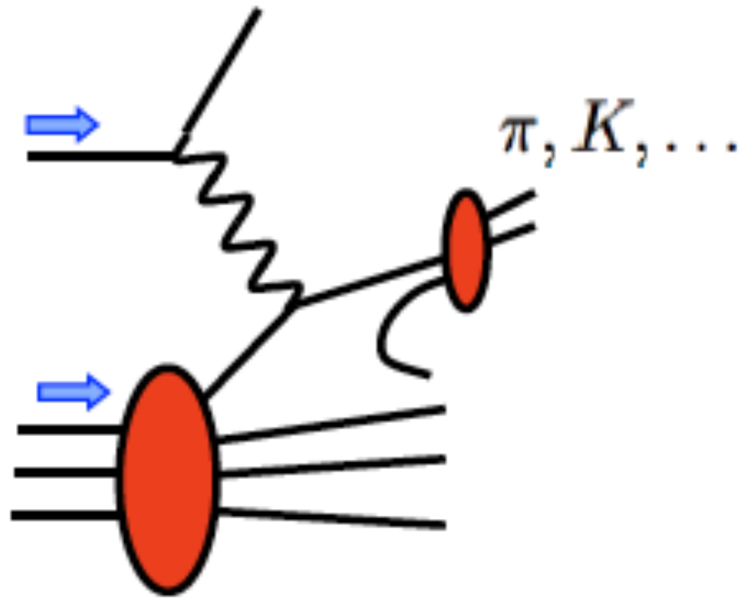
It is more than the number ½ ! It is the interplay between the intrinsic properties and interactions of quarks and gluons

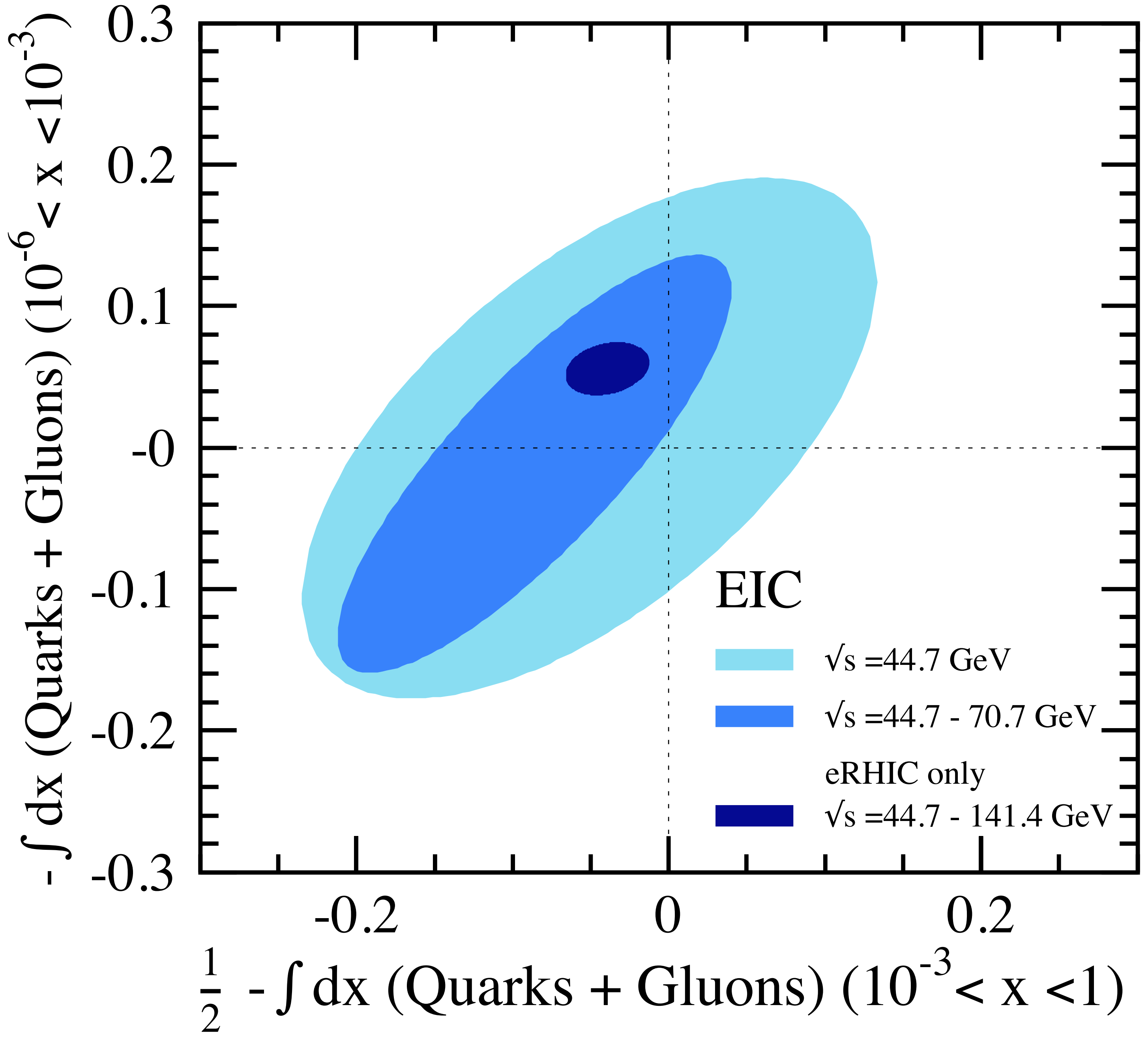
What can we do in future to pin down the proton spin?

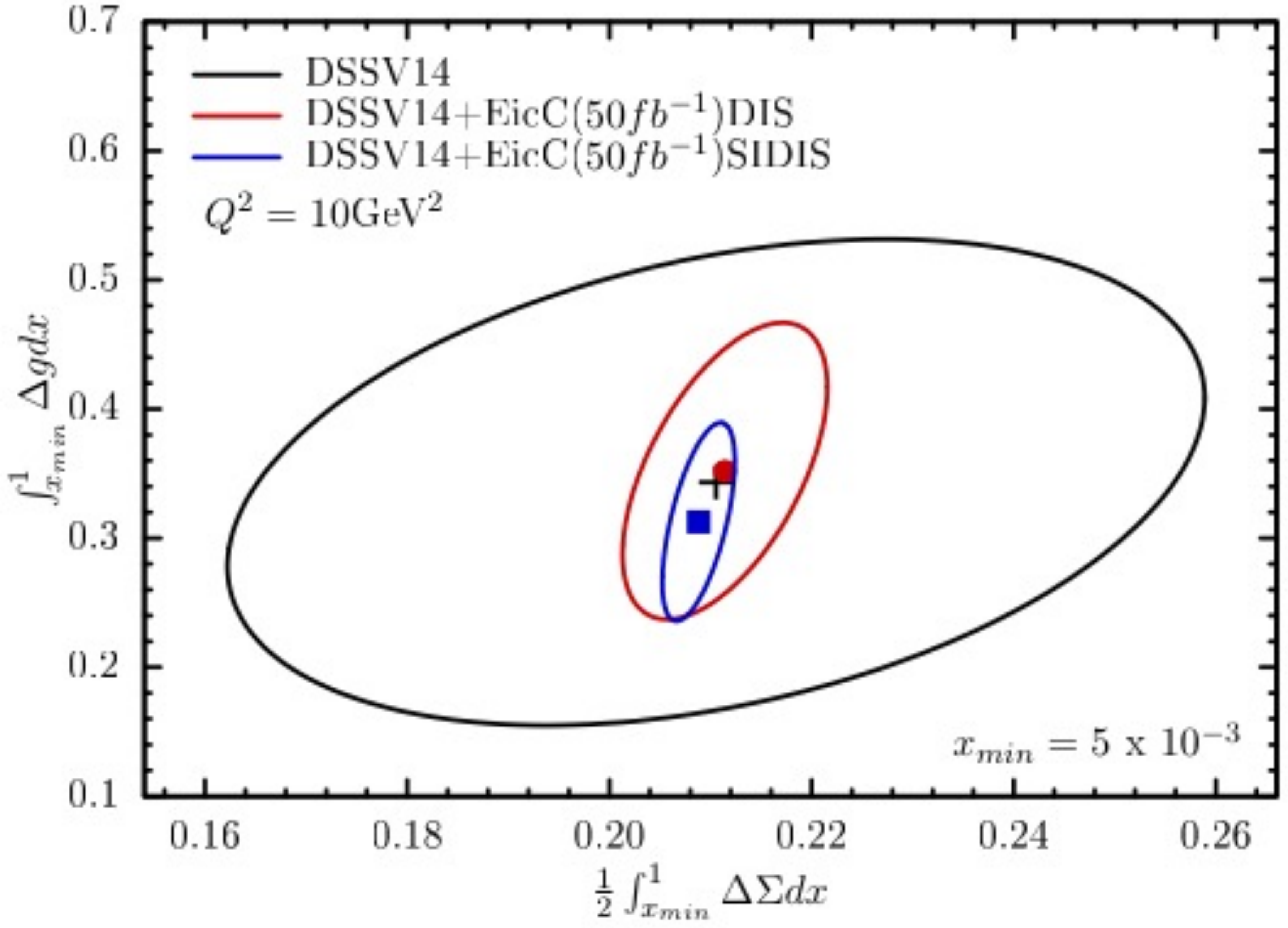
✦ Flip the proton spin

Anderle, Hou, Yuan, **HX**, Zhao, JHEP 2021
Anderle et al, PRD 2021

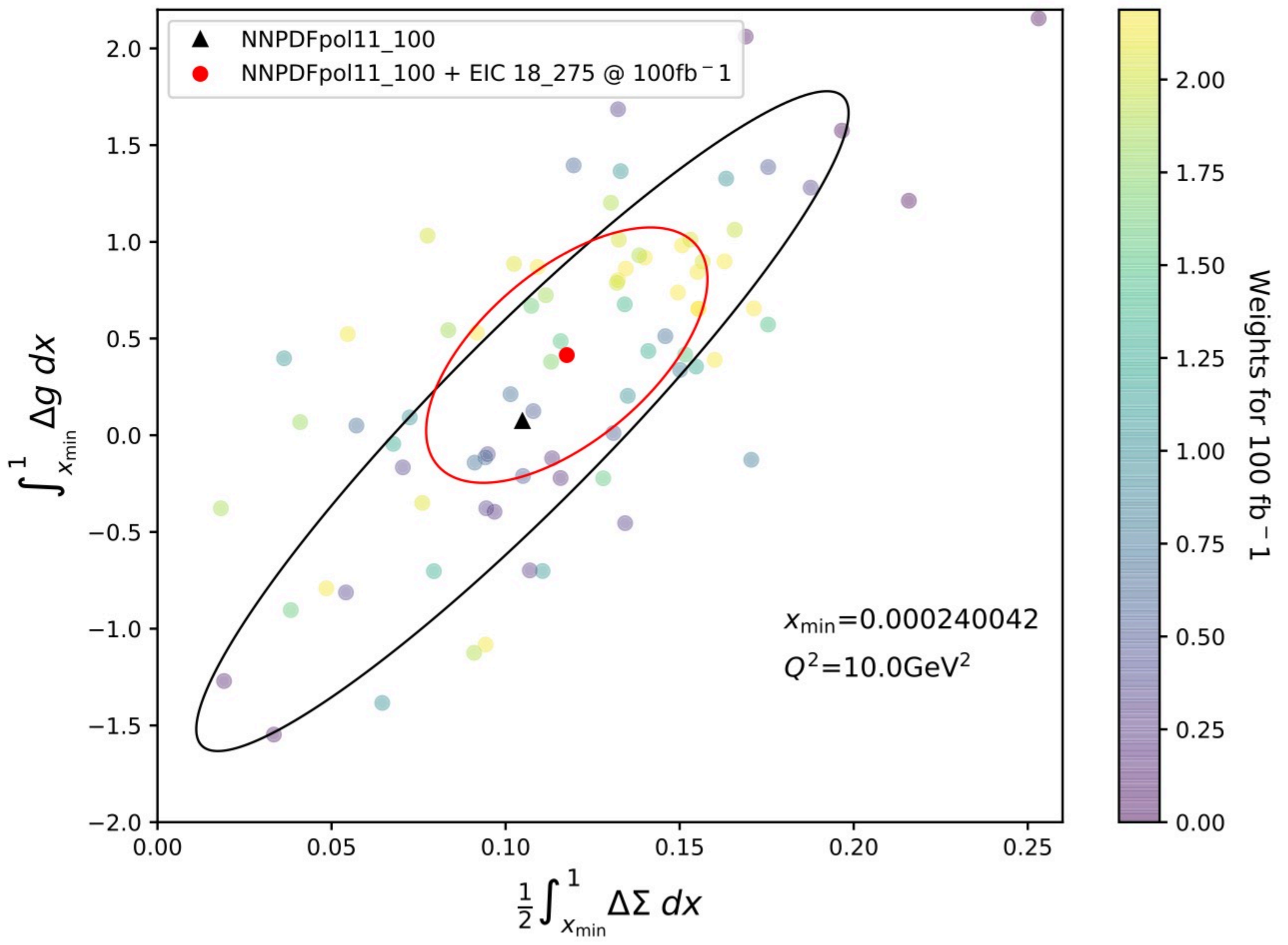








Light flavor hadron production

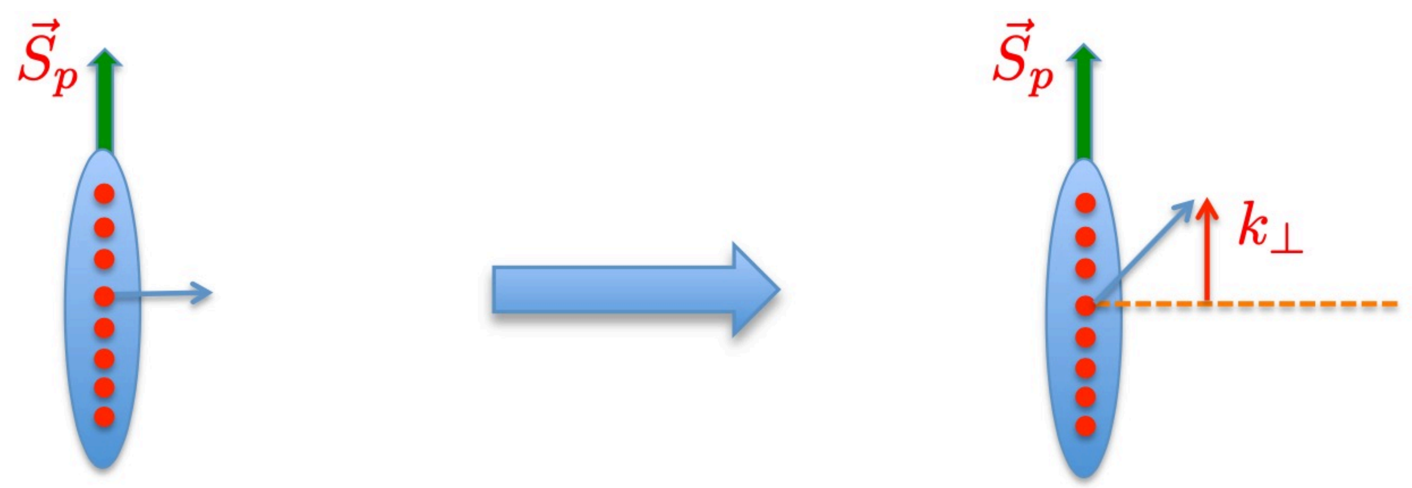


Heavy flavor production

The power of future EIC and EicC for proton spin

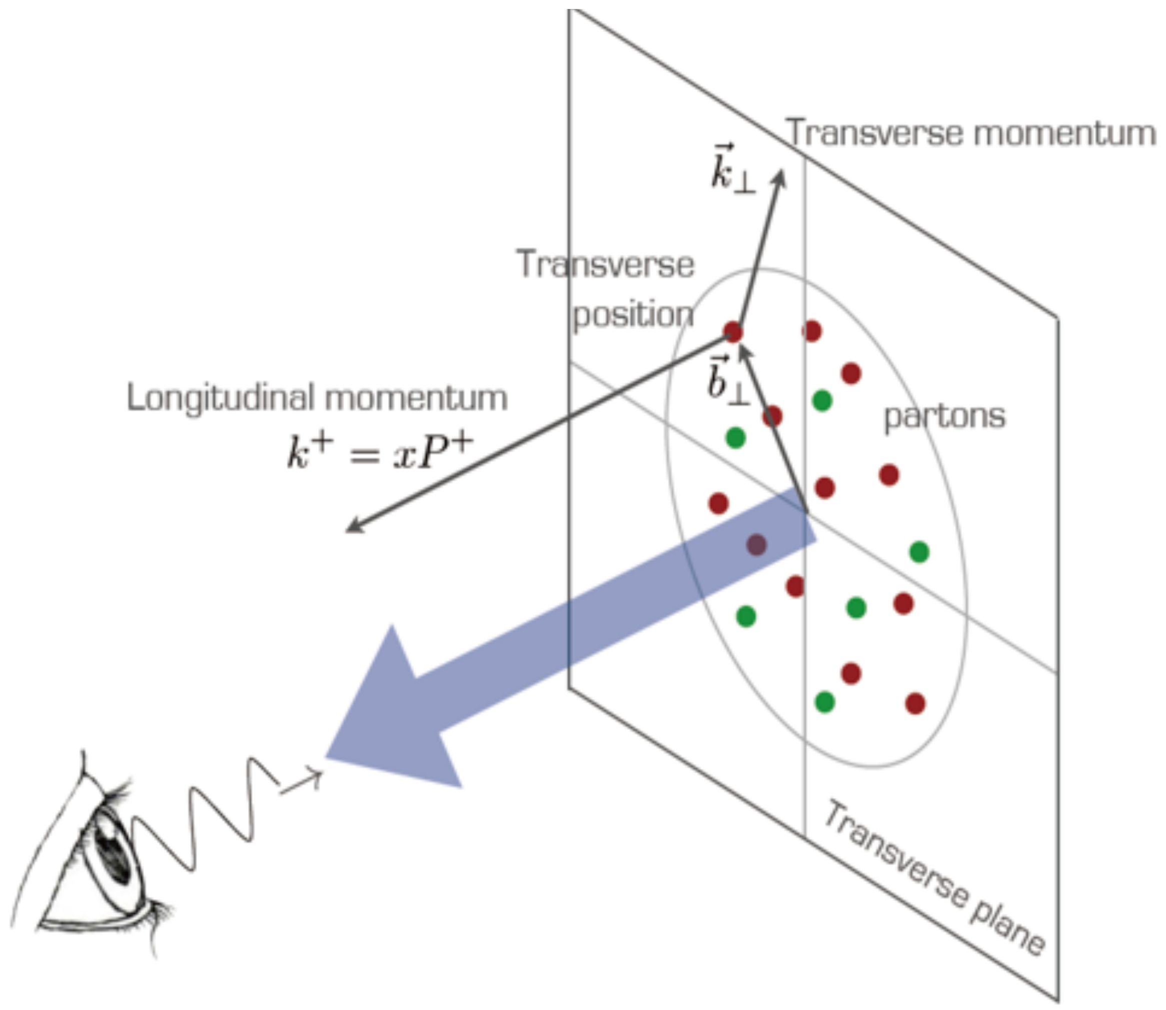
Nucleon partonic structure - 3D imaging

✦ Transverse momentum dependent PDFs (TMDs)

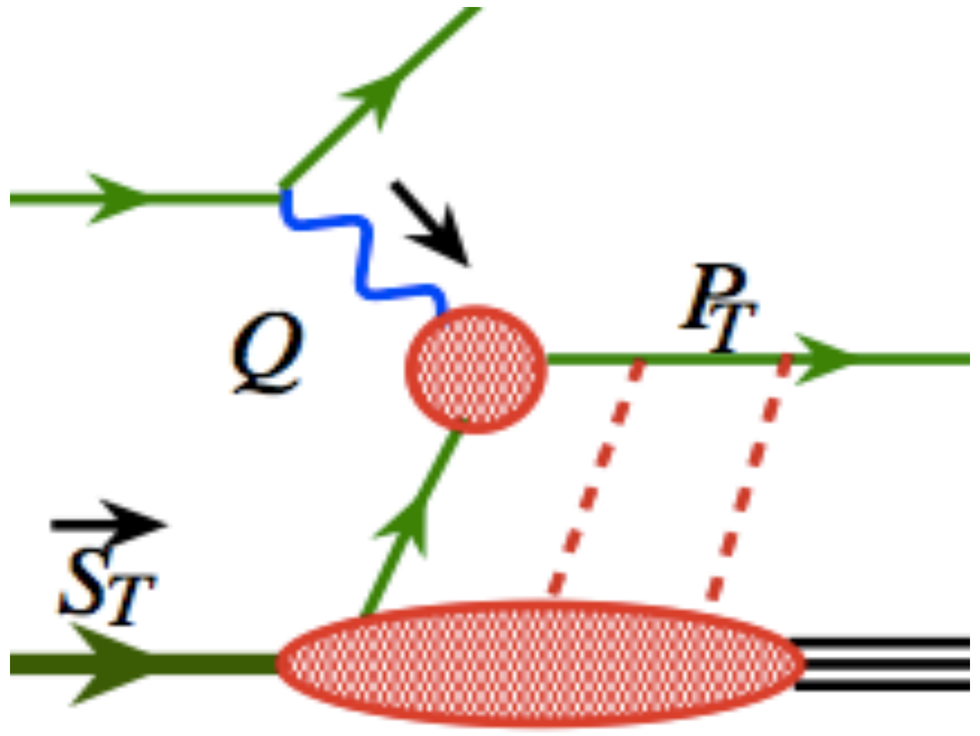


$f(x)$ $\quad$ $f(x, k_\perp)$

Collinear PDFs $\longrightarrow$ **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$_T$

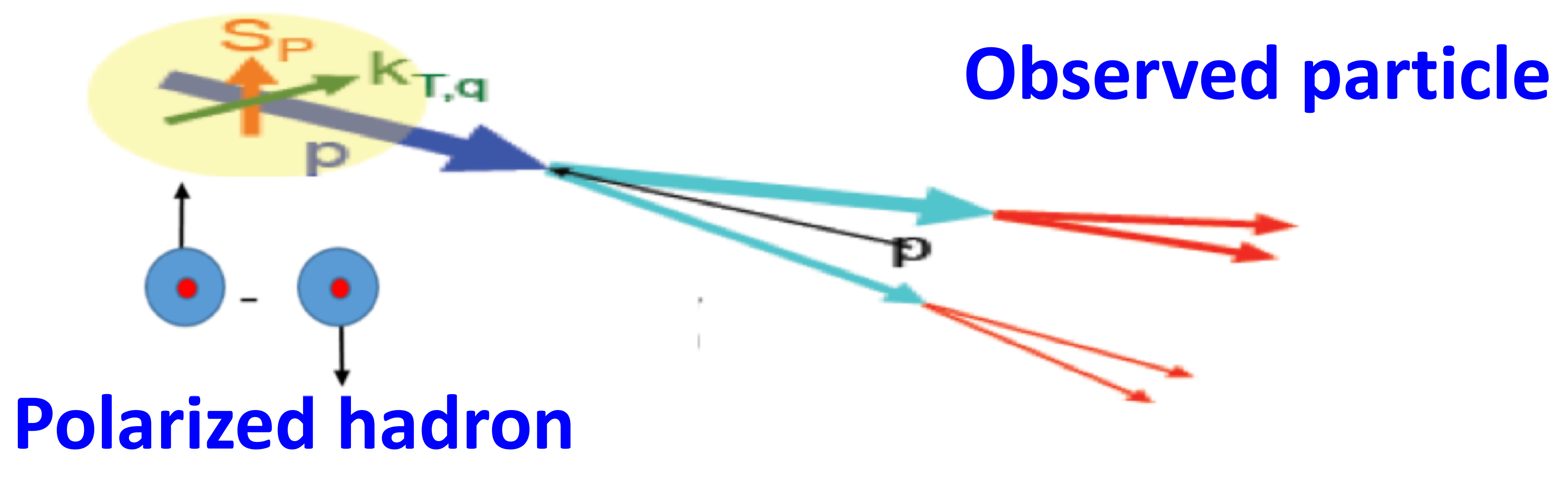
Nucleon partonic structure - 3D imaging

TMDs: explore the flavor-spin-motion correlation

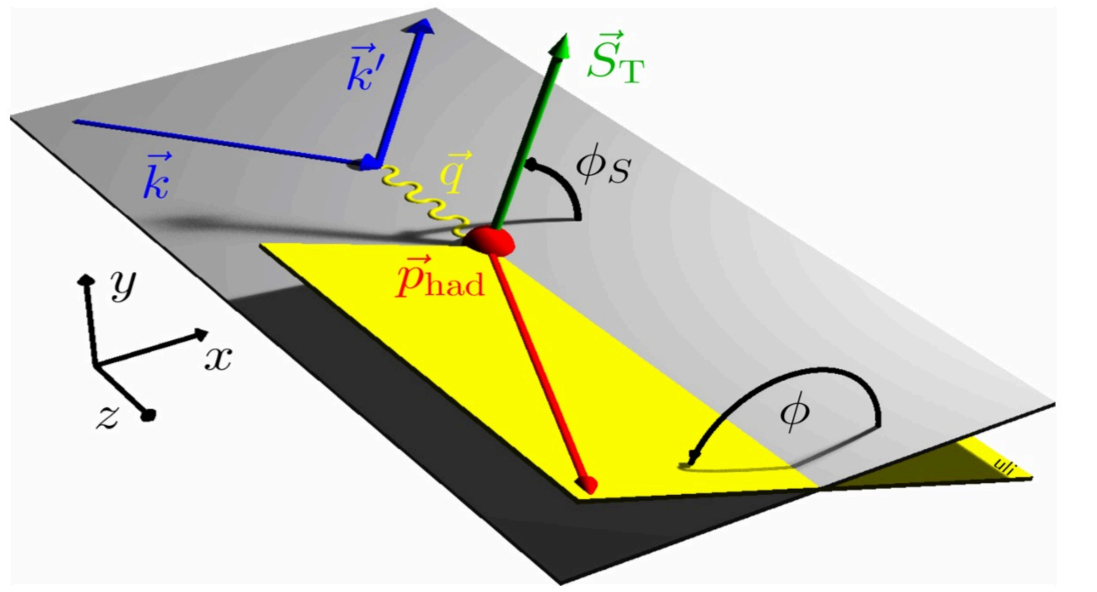
TMDs		Quark polarization		
		Unpolarized (U)	Longitudinally polarized (L)	Transversely polarized (T)
Nucleon polarization	U	f_1 Unpolarized		$h_1^{\perp}$ Boer–Mulders
	L		g_{1L} Helicity	$h_{1L}^{\perp}$ Longi-transversity
	T	$f_{1T}^{\perp}$ Sivers	g_{1T} Trans-helicity	h_1 Transversity $h_{1T}^{\perp}$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

Nucleon partonic structure - 3D imaging

✦ Quantum correlation between proton spin and parton motion

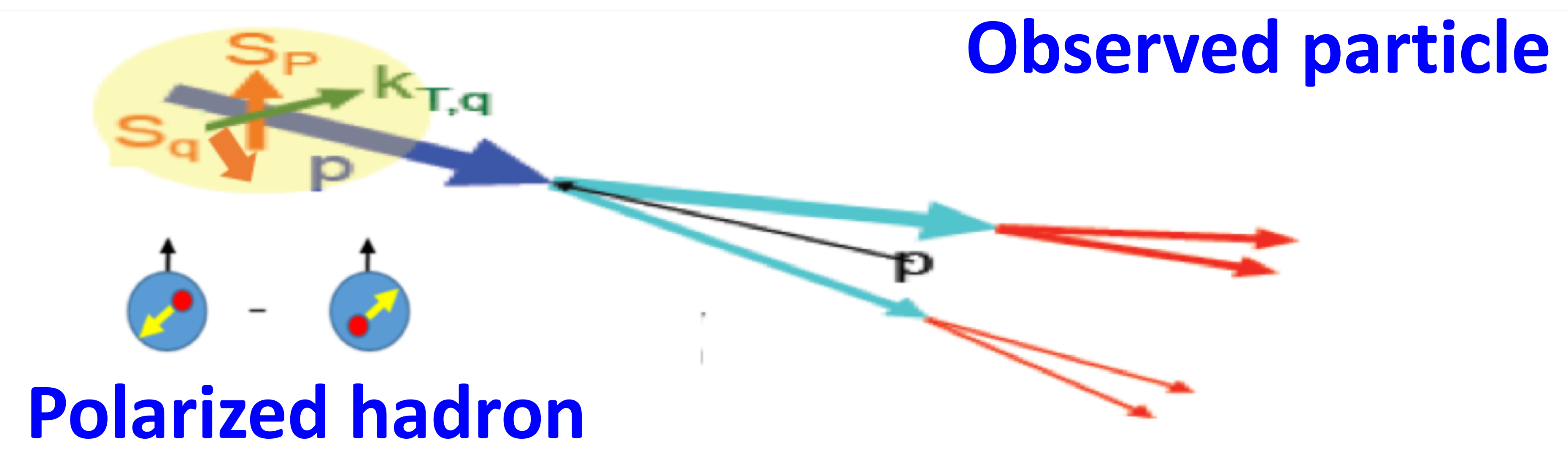


Sivers function $f_{1T}^{\perp}$: proton spin influences parton's transverse motion



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

✦ Quantum correlation between proton spin and parton spin



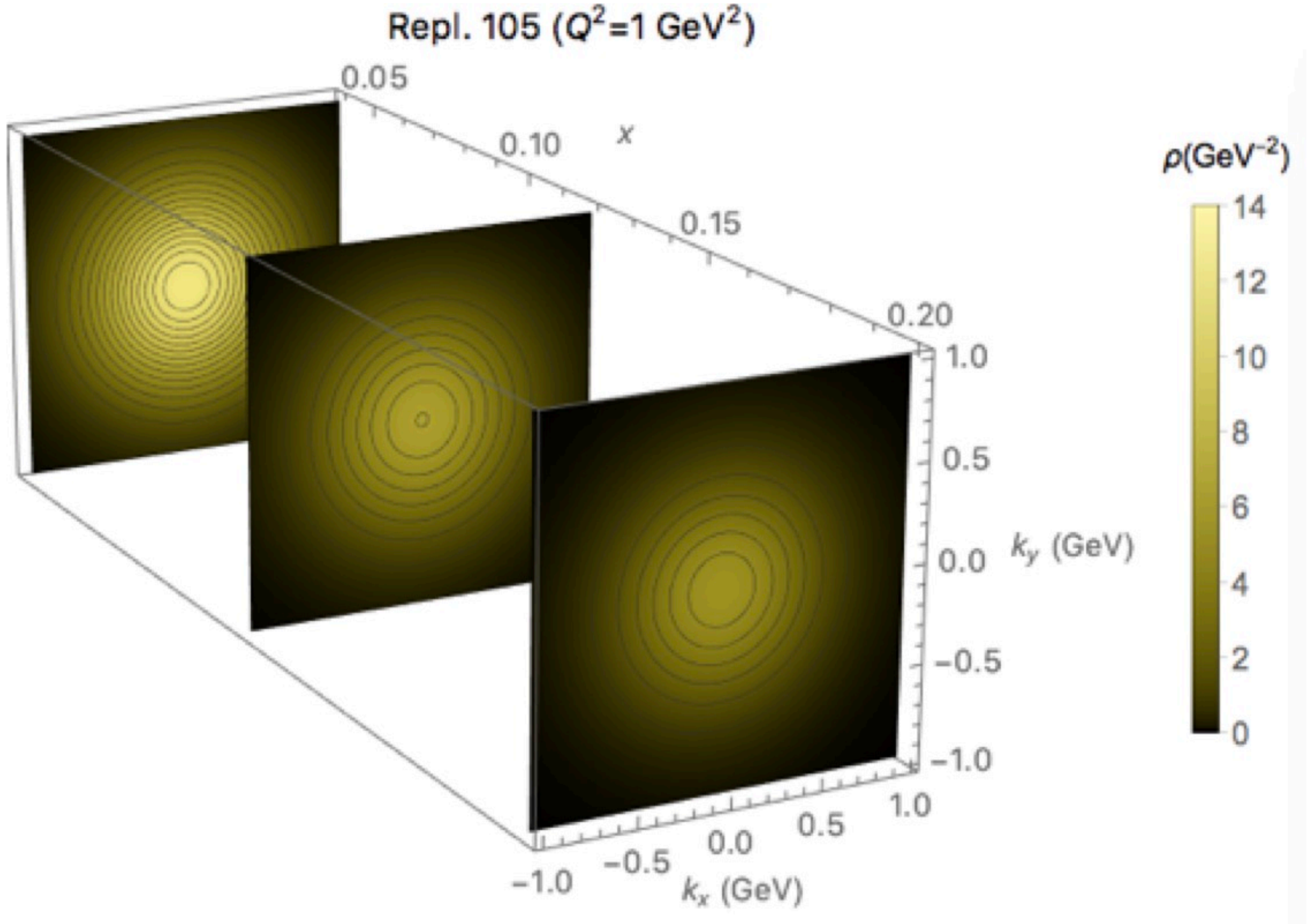
Pretzelosity function $h_{1T}^{\perp}$: proton spin and parton spin influence parton's transverse motion

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

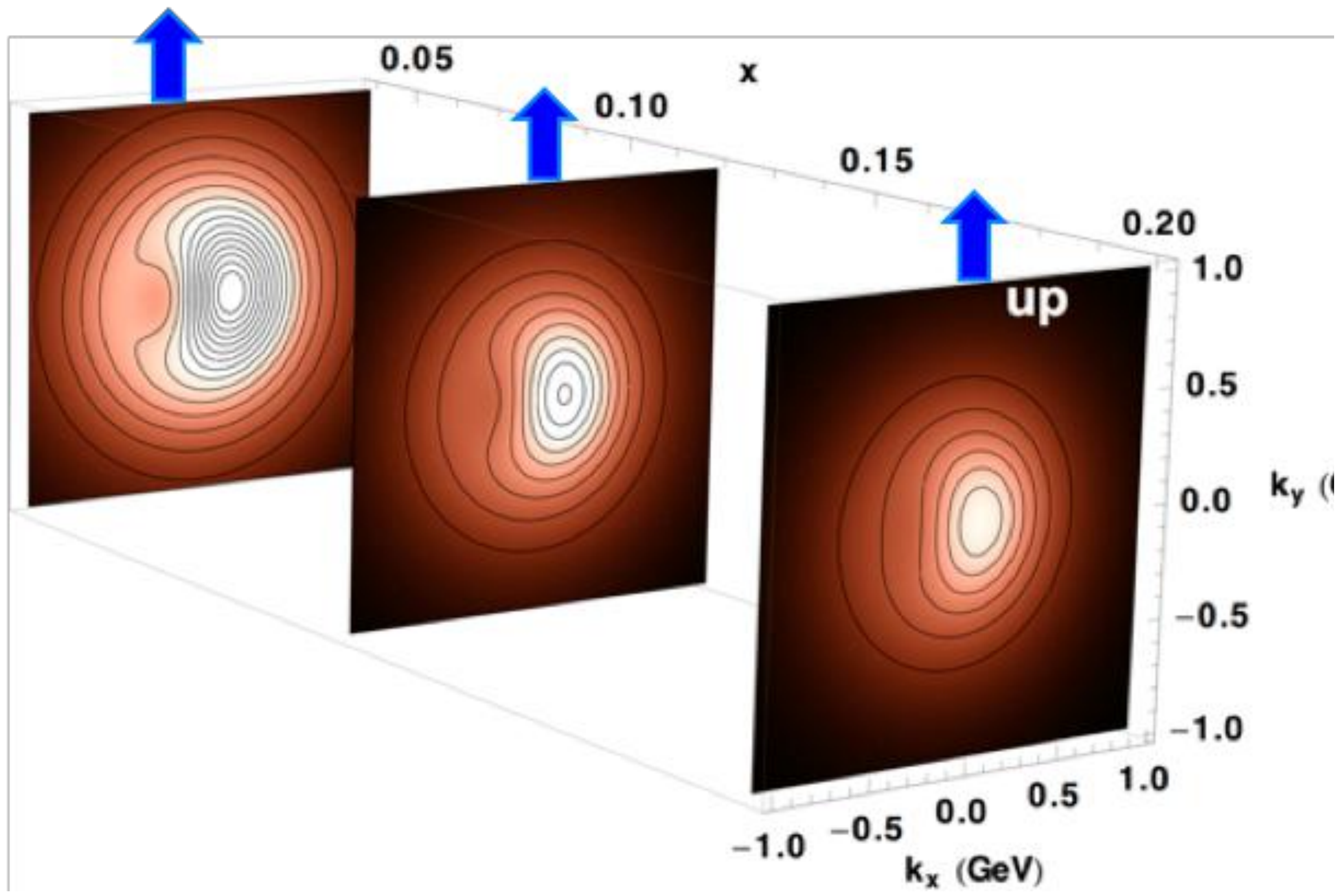
Nucleon partonic structure - 3D imaging

By Andrea Signori

Unpolarized proton



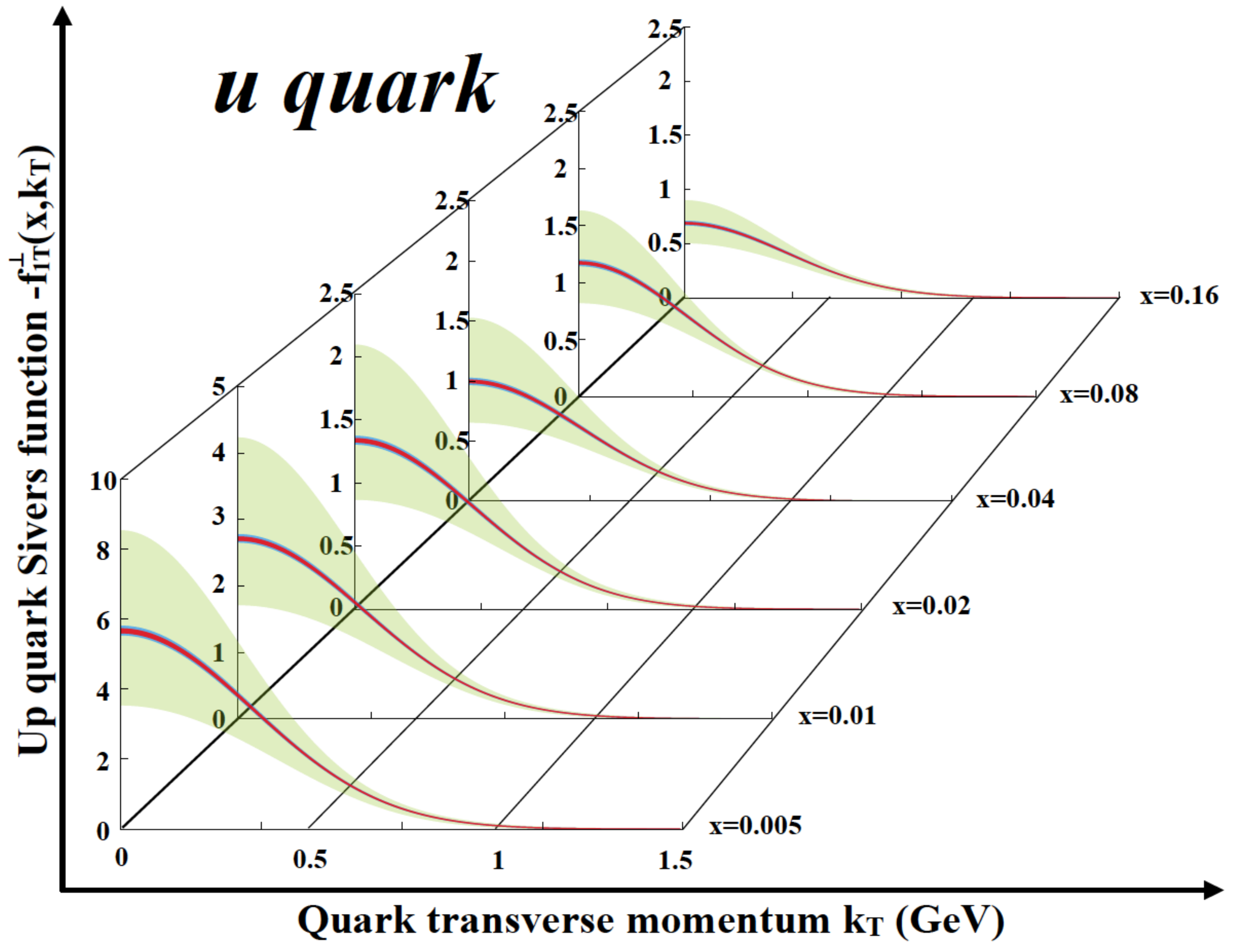
Transversely polarized proton

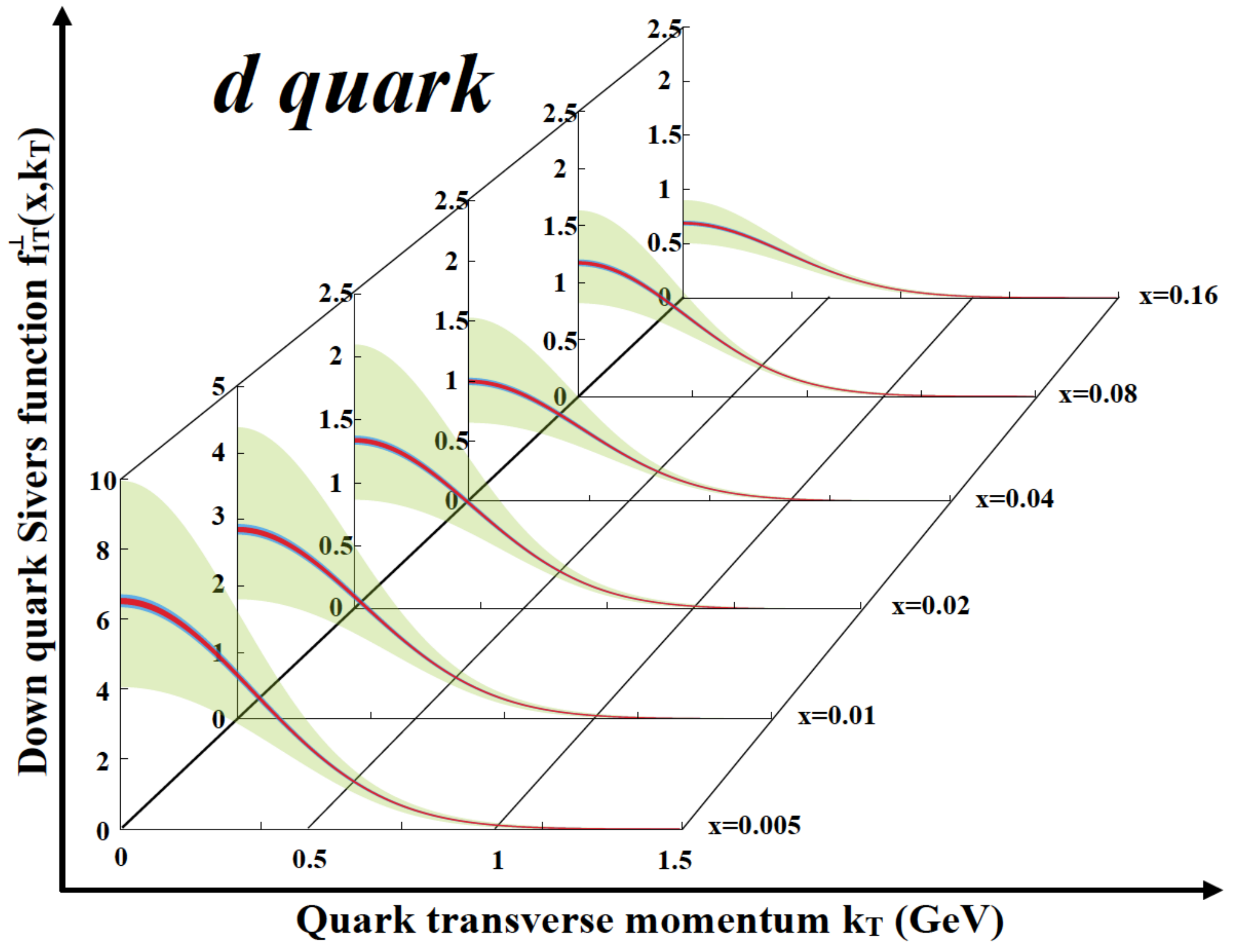


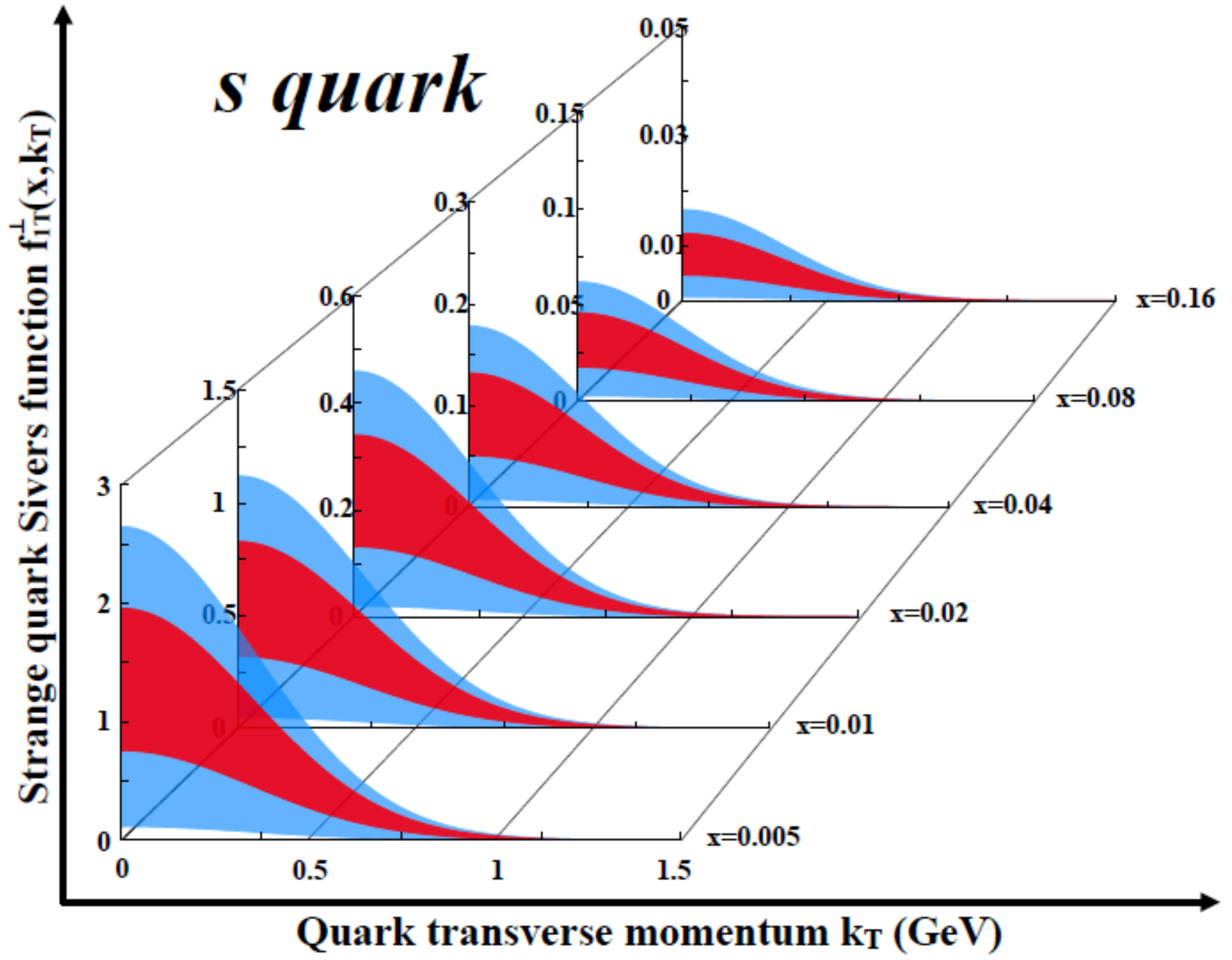
Transversely polarized quark distribution is distorted!

Nucleon 3D imaging at EicC - Sivers effect

from EicC white paper

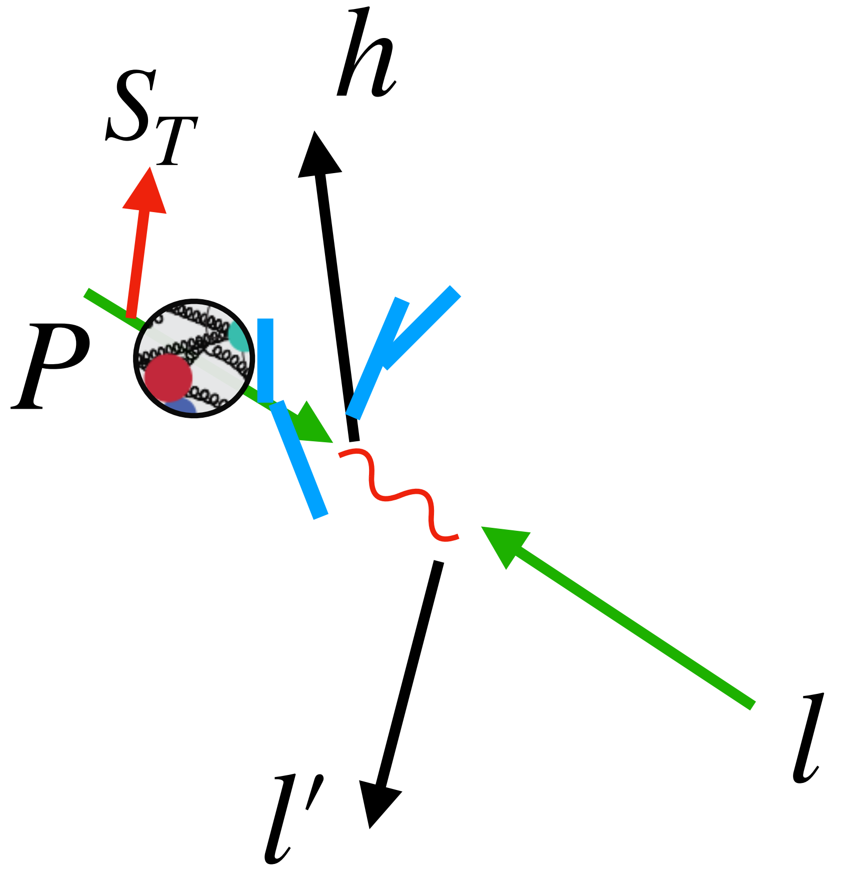




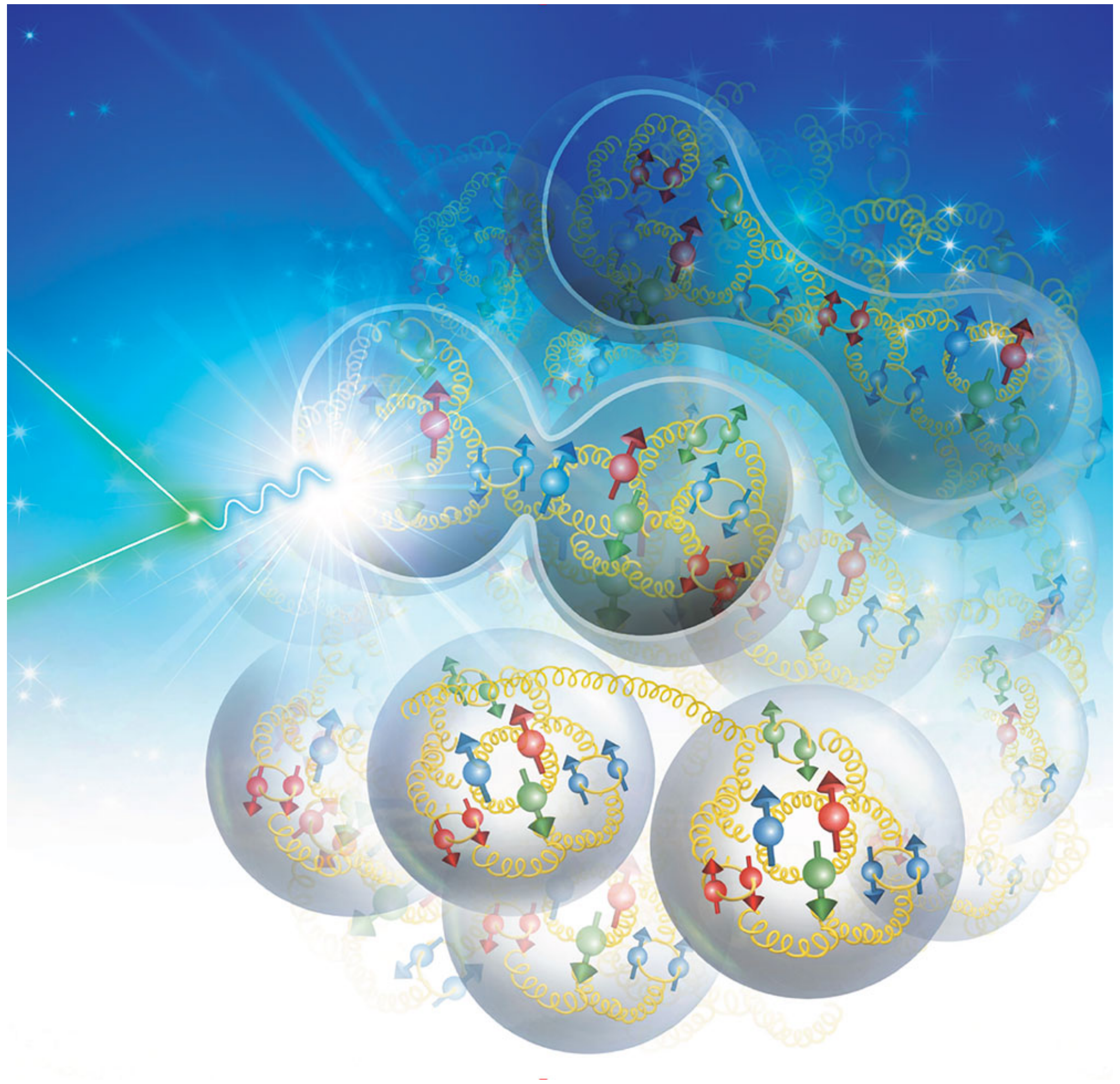


LO analysis of EicC projection

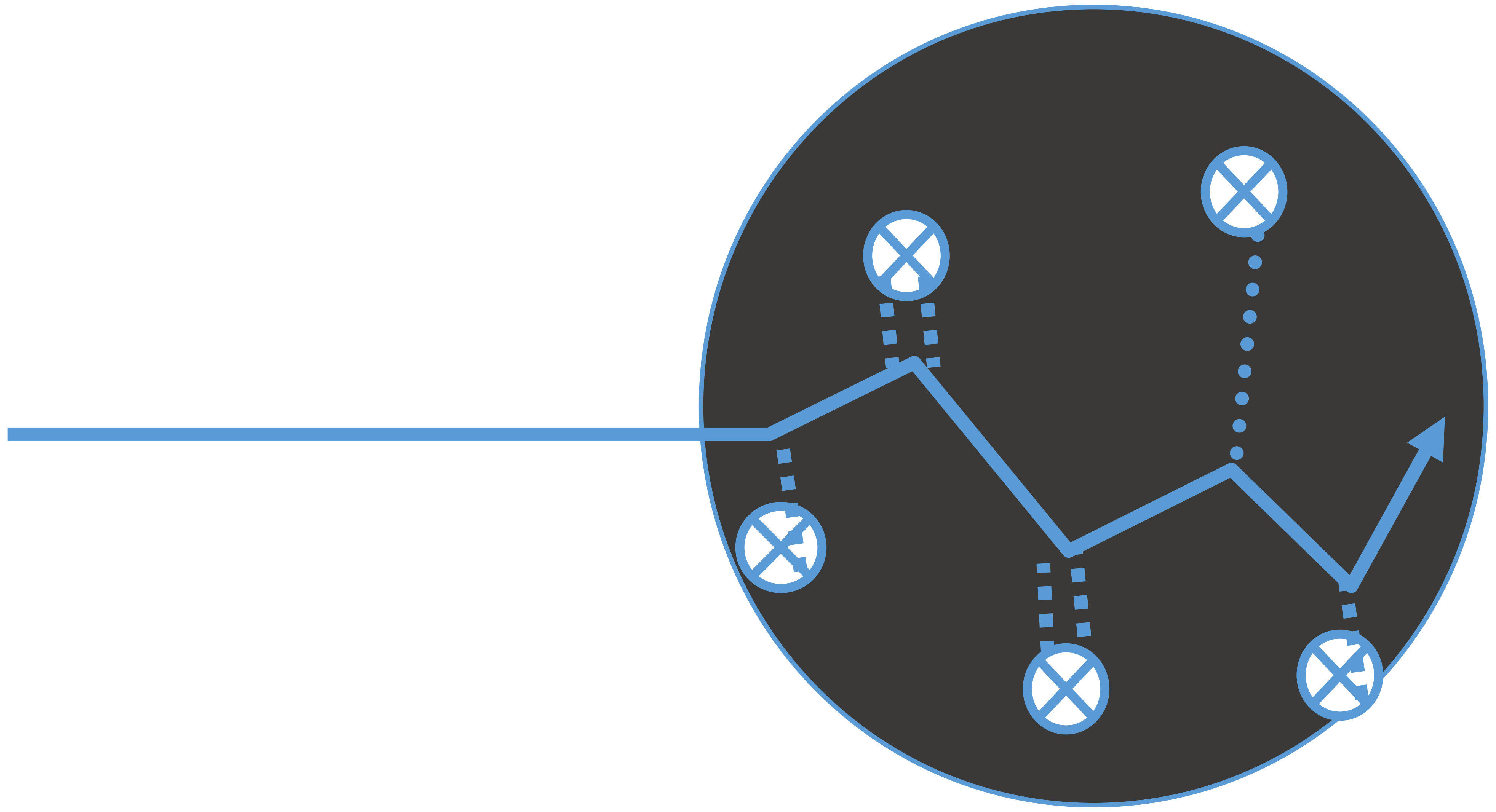
- Pion(+/-), Kaon(+/-)
- ep: 3.5 GeV x 20 GeV
- eHe-3: 3.5 GeV x 40 GeV
- Lumi: ep 50 fb^{-1}, eHe-3 50 fb^{-1}
- Stat. Error vs Sys. Error



What if the nucleon is bounded in nucleus?



Nuclear partonic structure

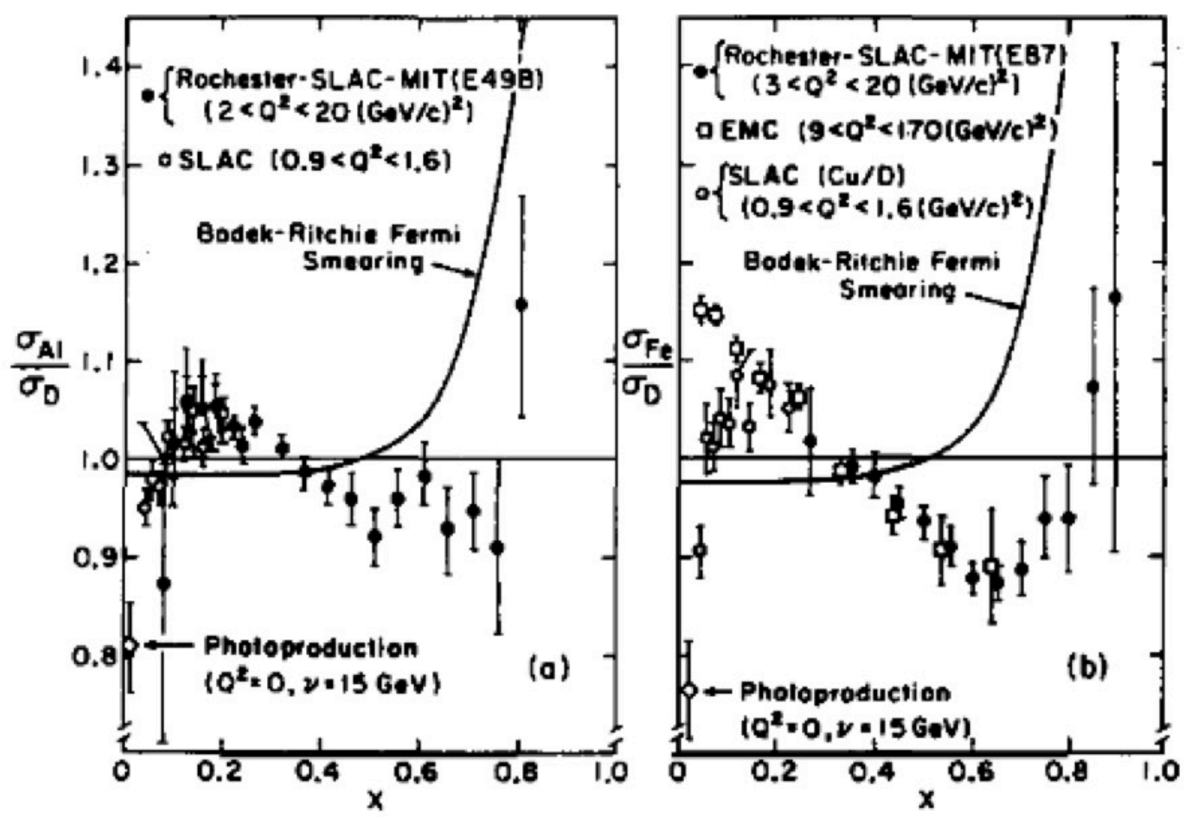


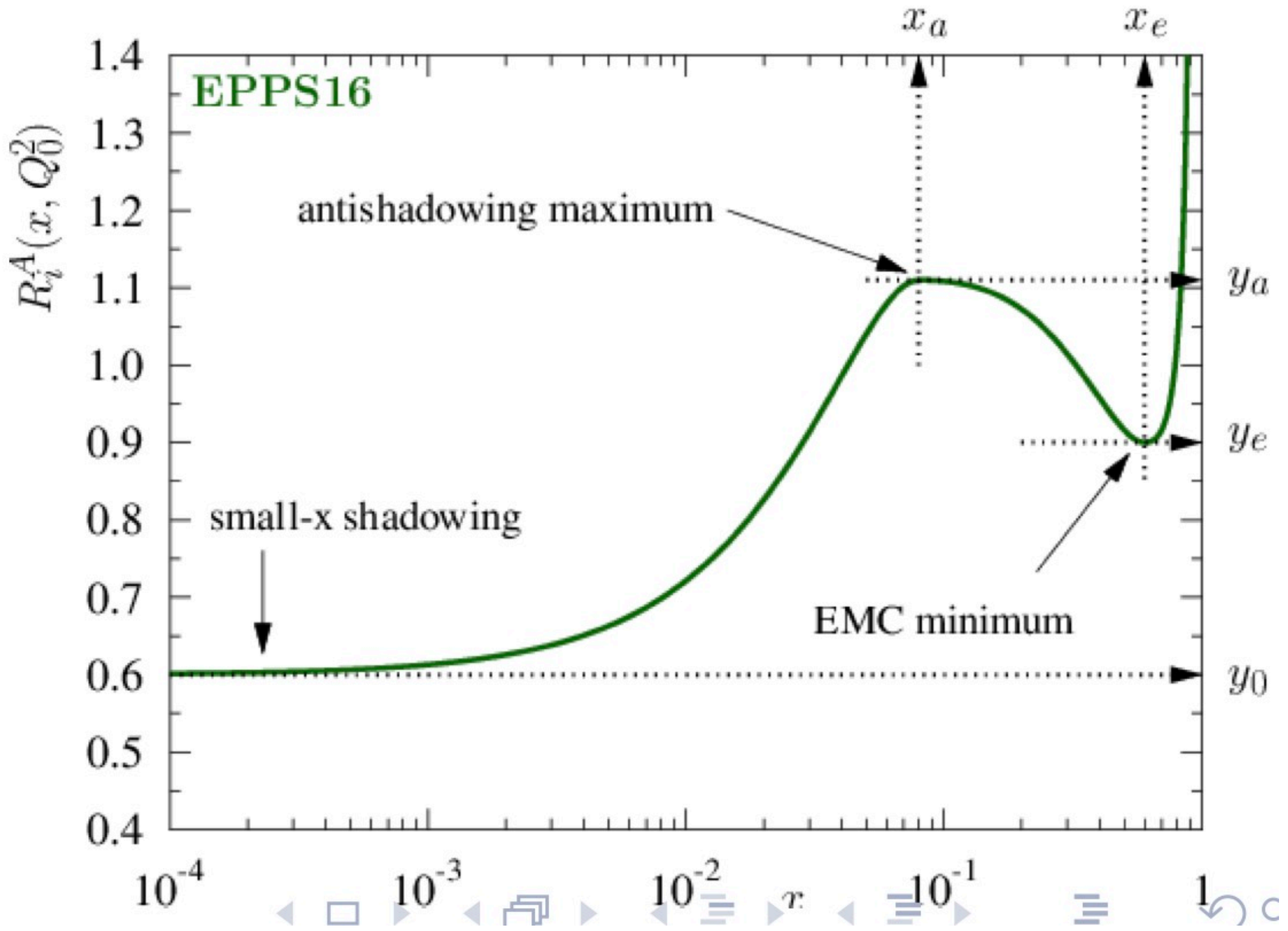
Parton propagating in nuclear medium

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

- Nuclear partonic structure

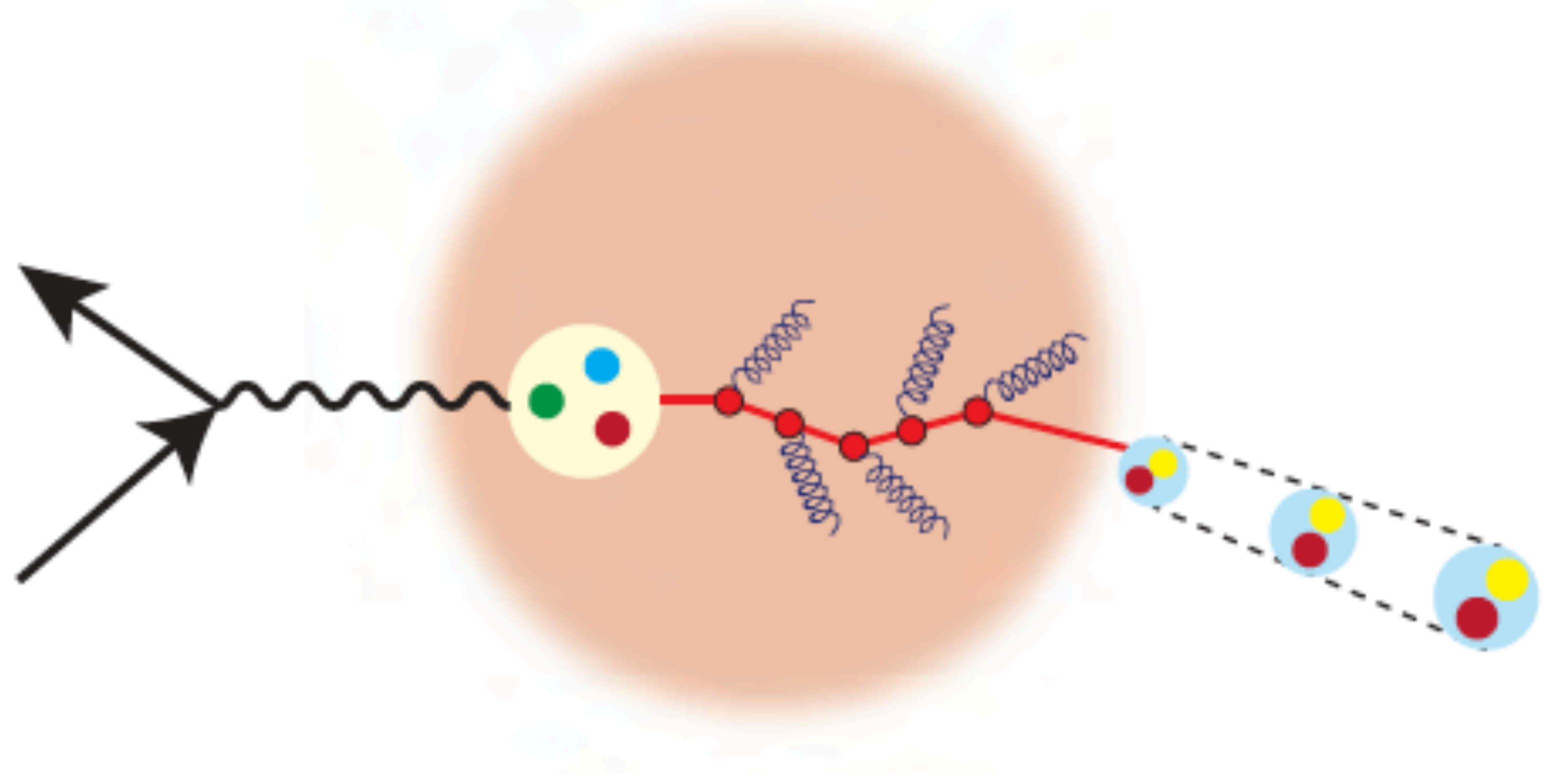
Four Decades of the EMC Effect

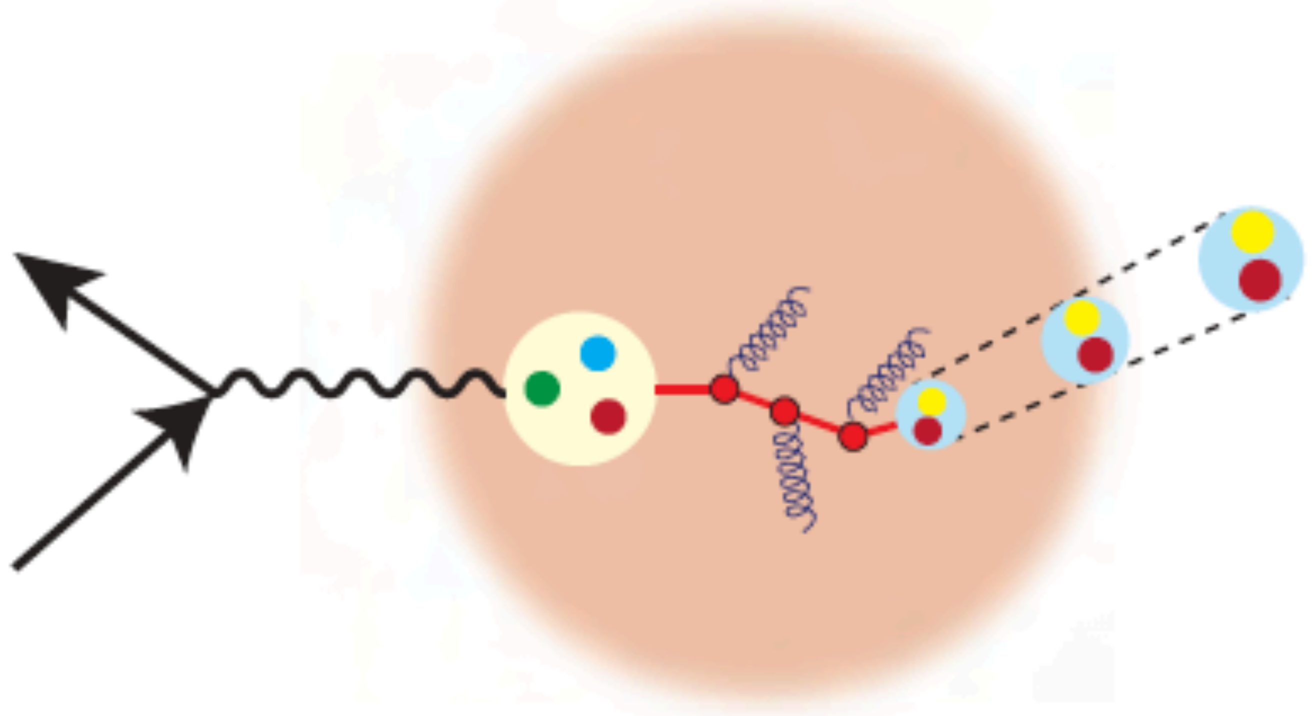




$$R_i^A = \frac{f_{i/A}(x,Q^2)}{f_{i/p}(x,Q^2)}$$

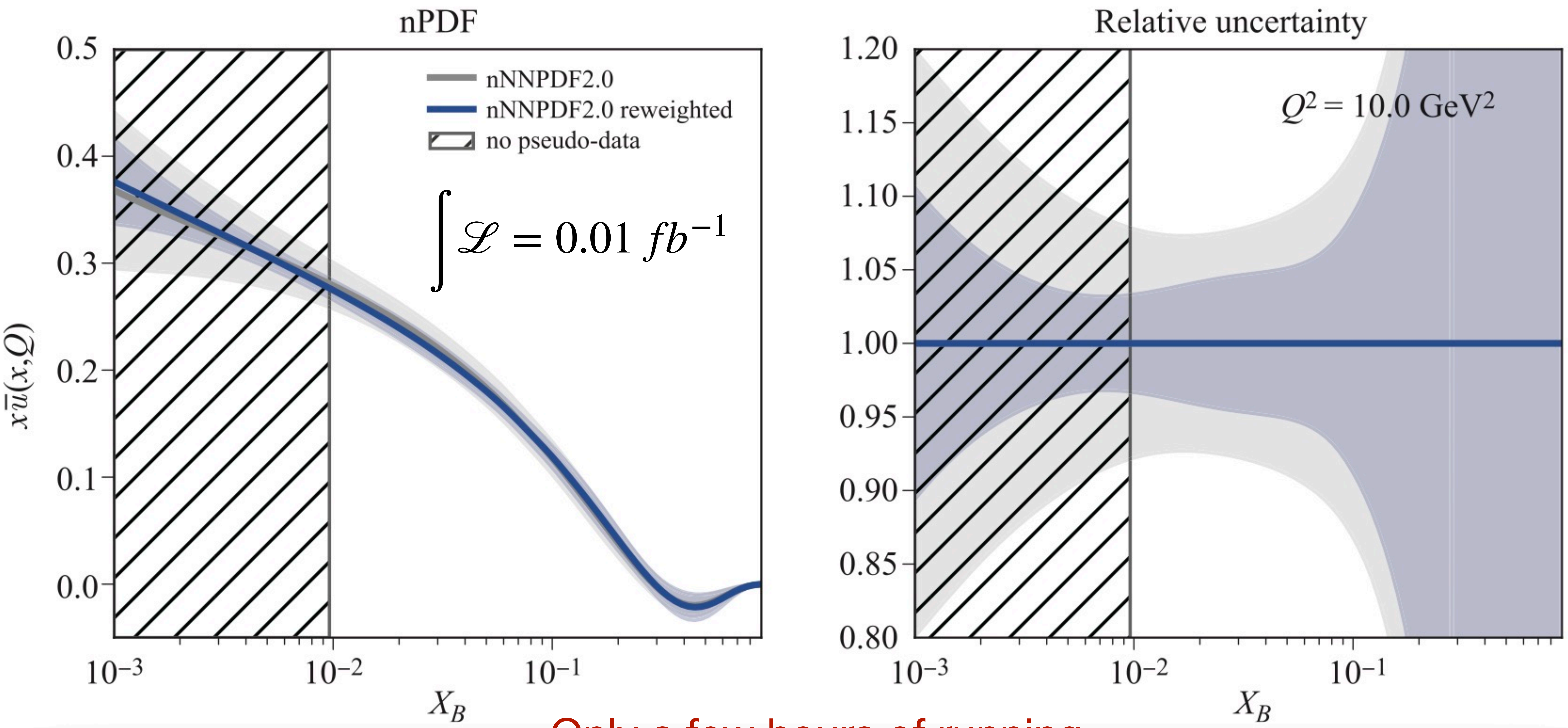
- Quark gluon propagation in nuclear medium





Power of EicC for nuclear partonic structure - 1D

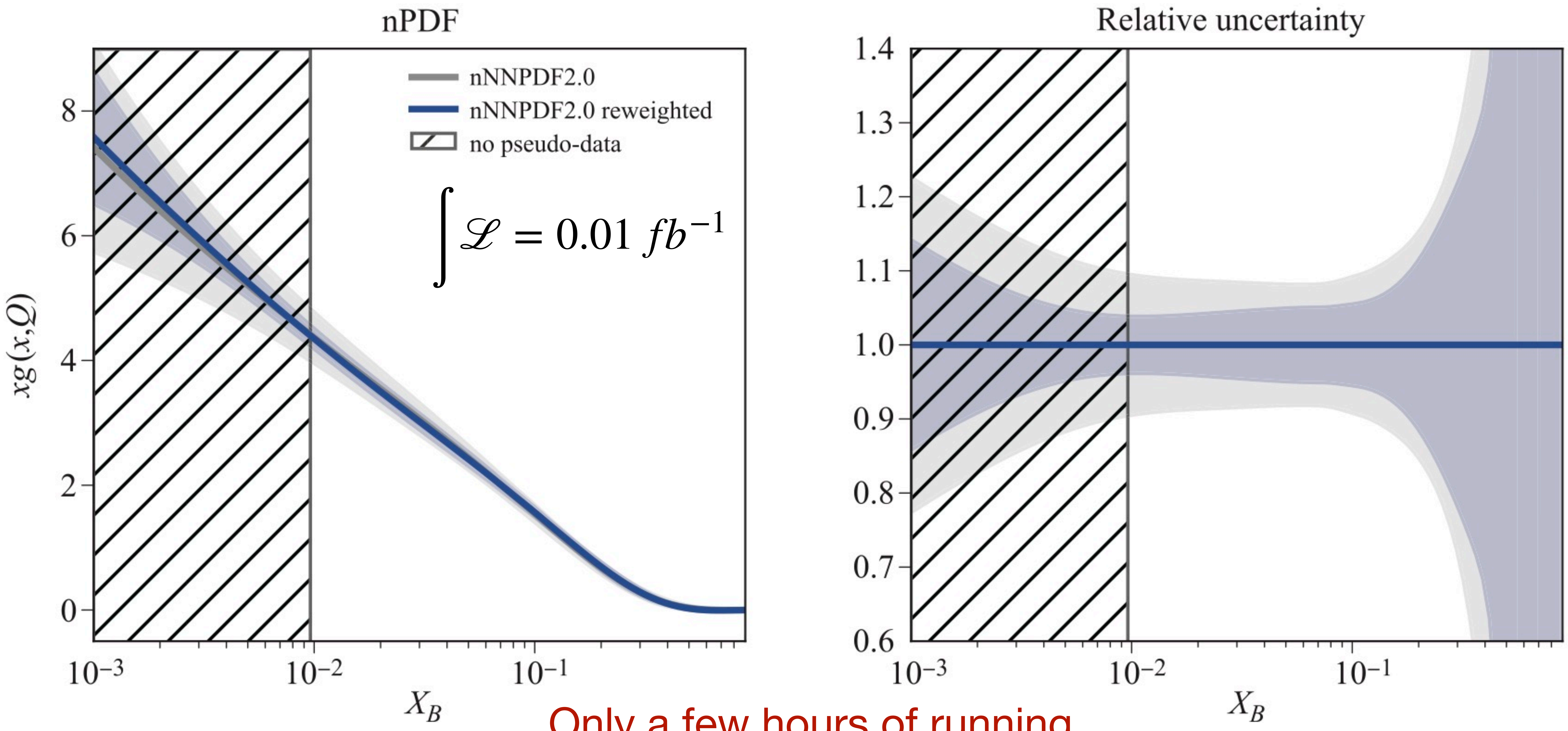
- Nuclear partonic structure - nuclear quark distribution



Only a few hours of running

Power of EicC for nuclear partonic structure - 1D

- Nuclear partonic structure - nuclear gluon distribution

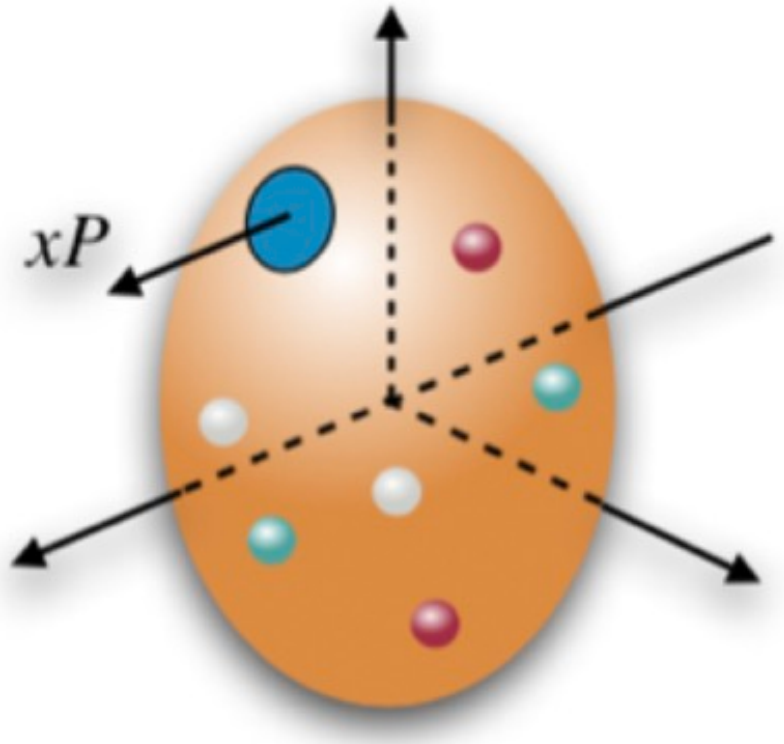


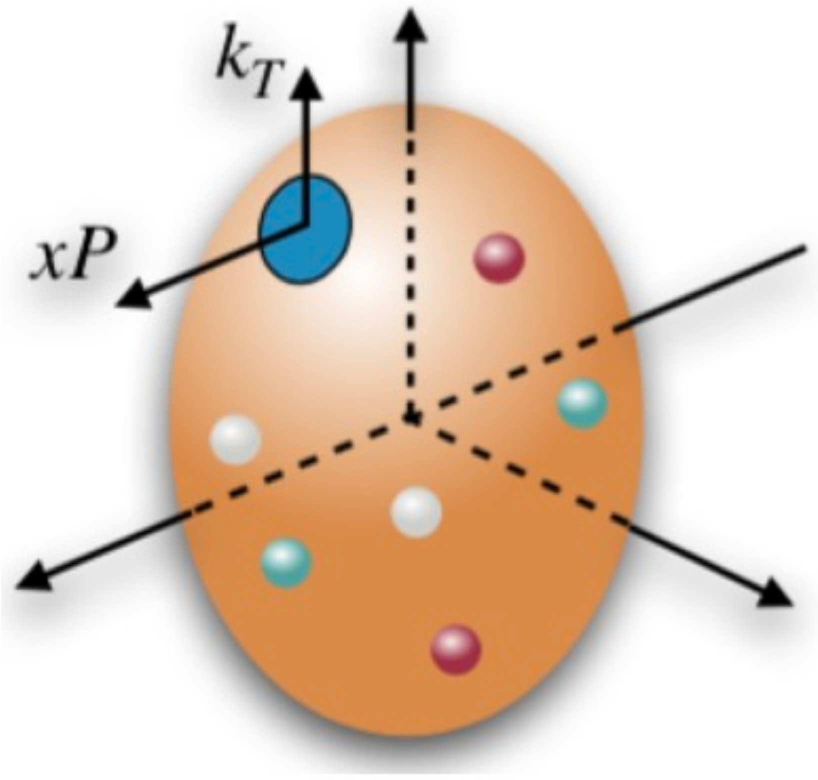
Only a few hours of running

Nuclear partonic structure - 3D

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

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



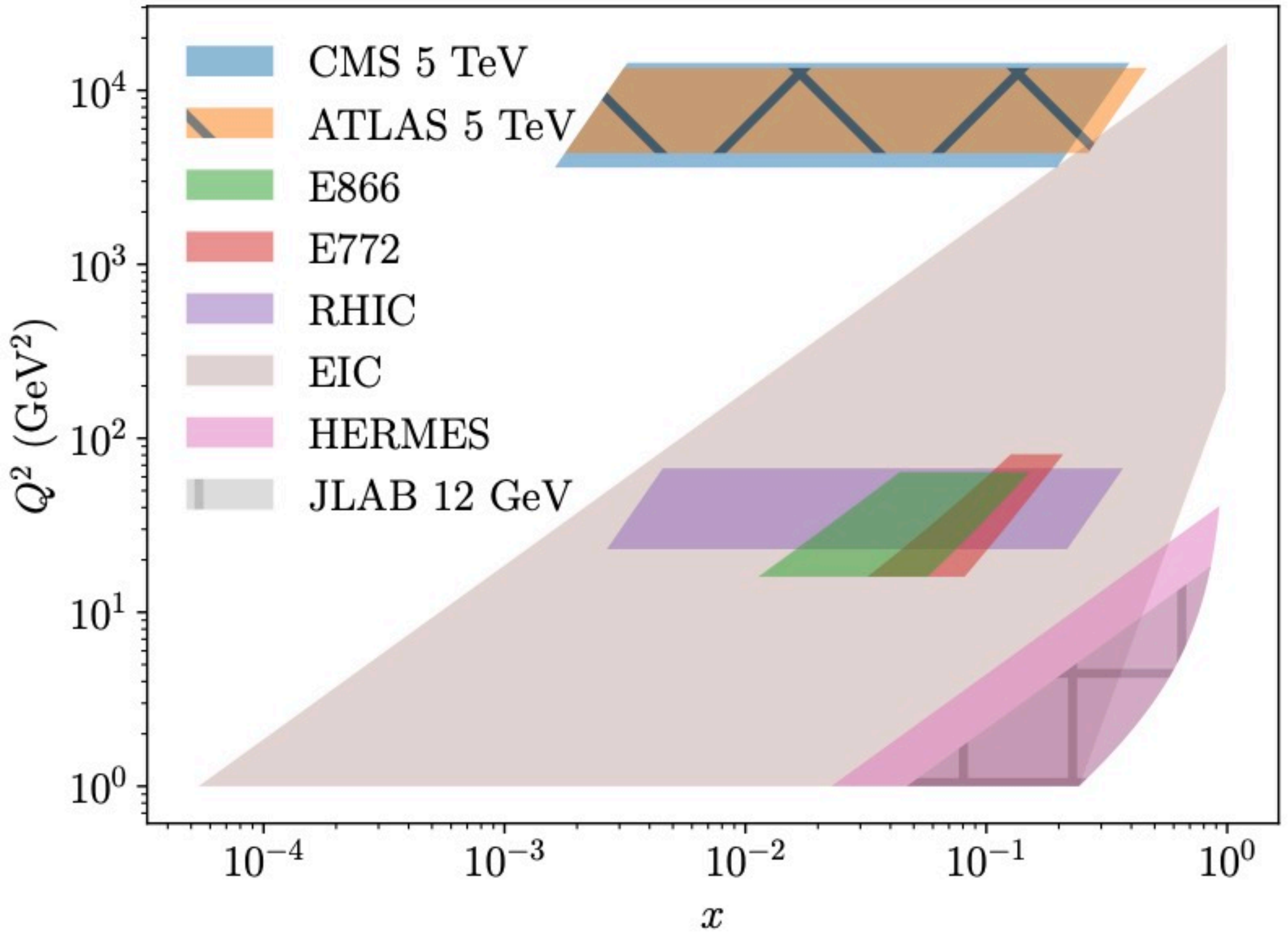


Drell-Yan Measurements

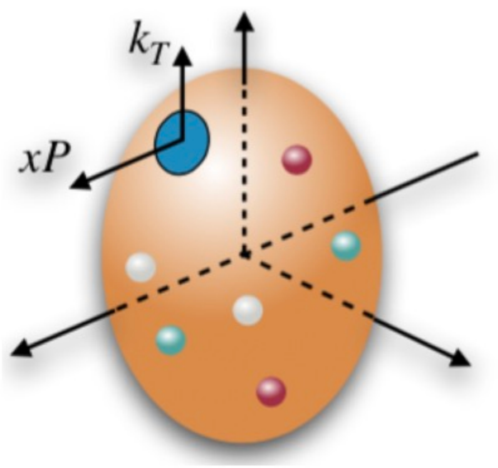
- $R_{\mathrm{AB}} = \frac{d\sigma_A}{dq_\perp} \Big/ \frac{d\sigma_B}{dq_\perp}$
  -E866
  -E772
  -Prelim. RHIC
- $d\sigma/dq_\perp$ (p Pb)
  ATLAS
  CMS

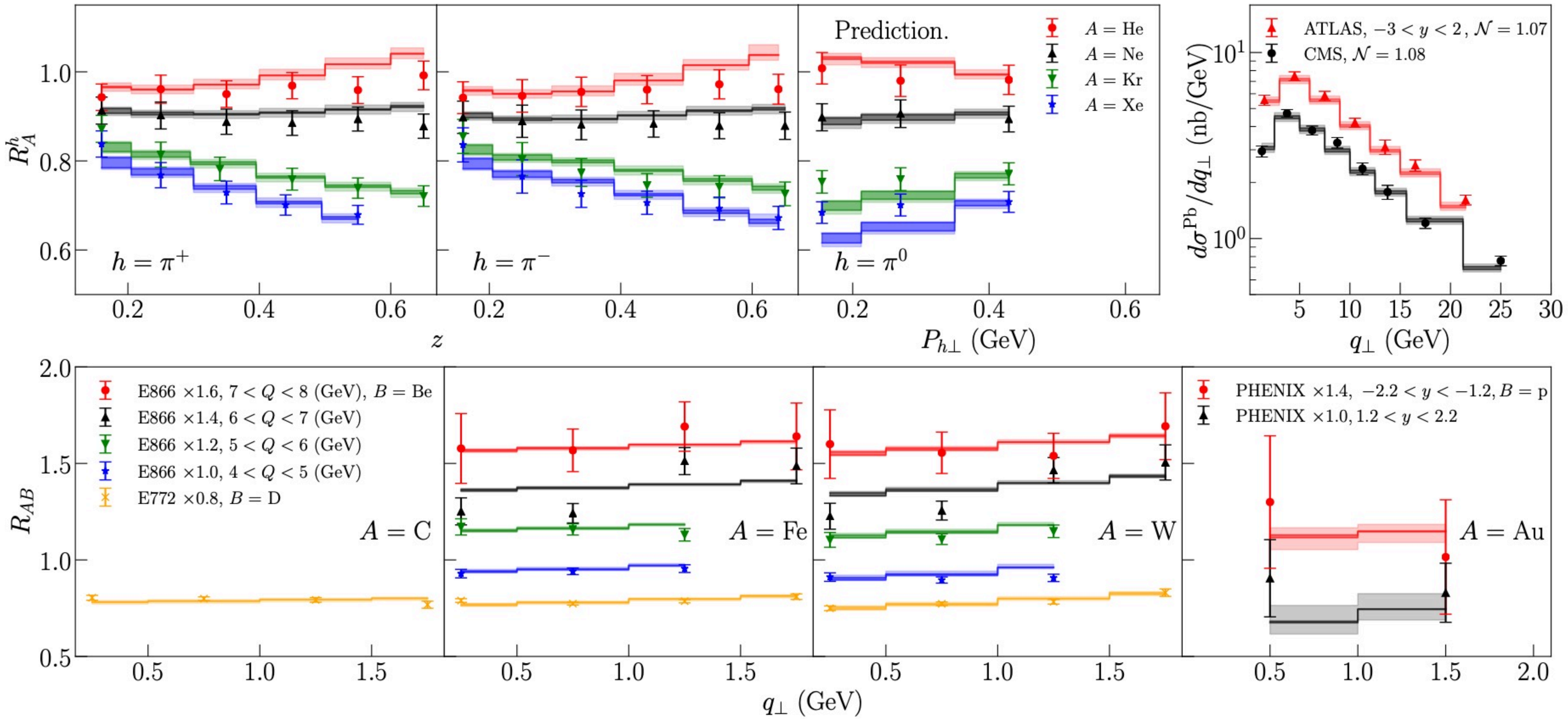
SIDIS Measurements

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



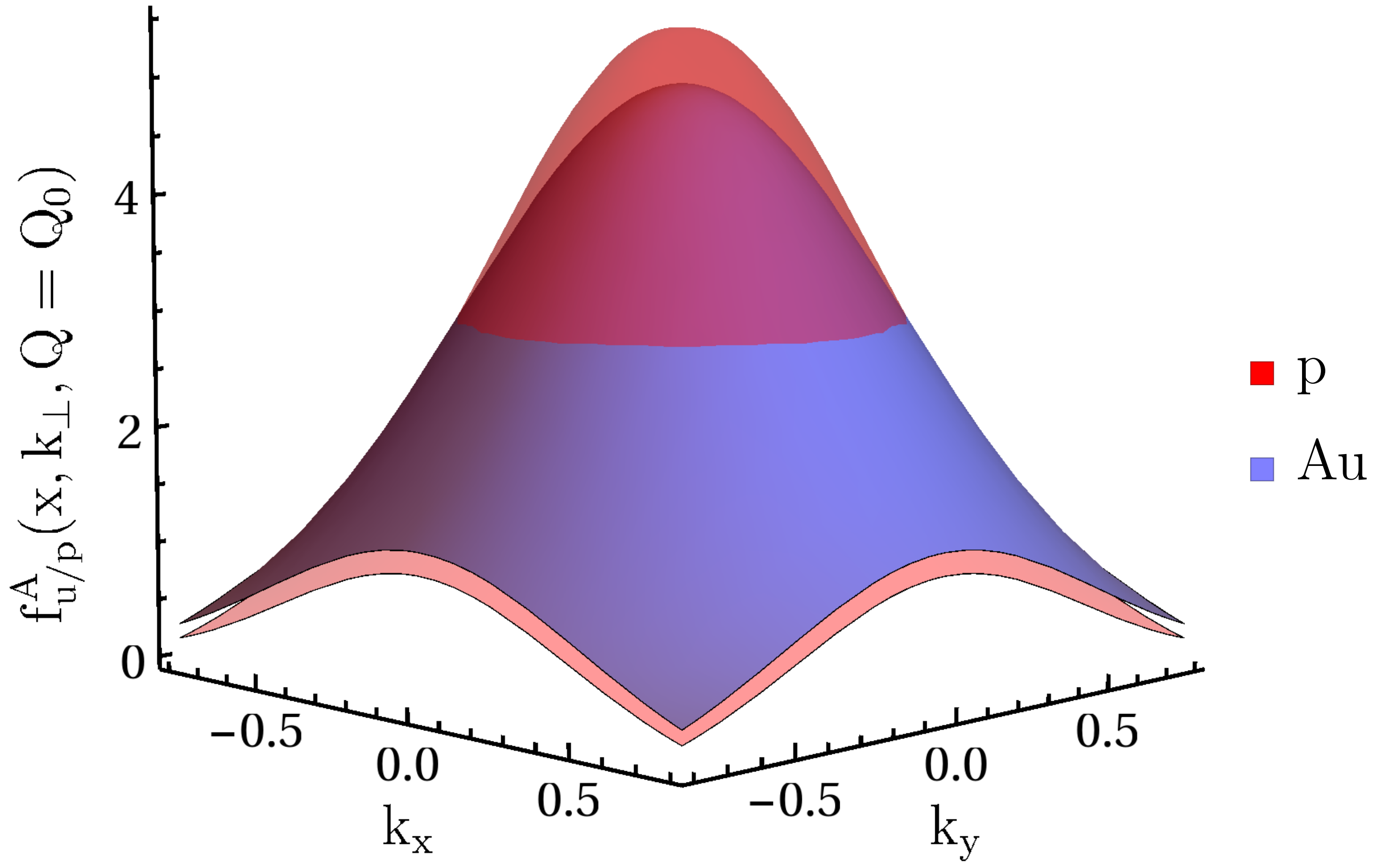
nuclear 3D imaging - global extraction from world data

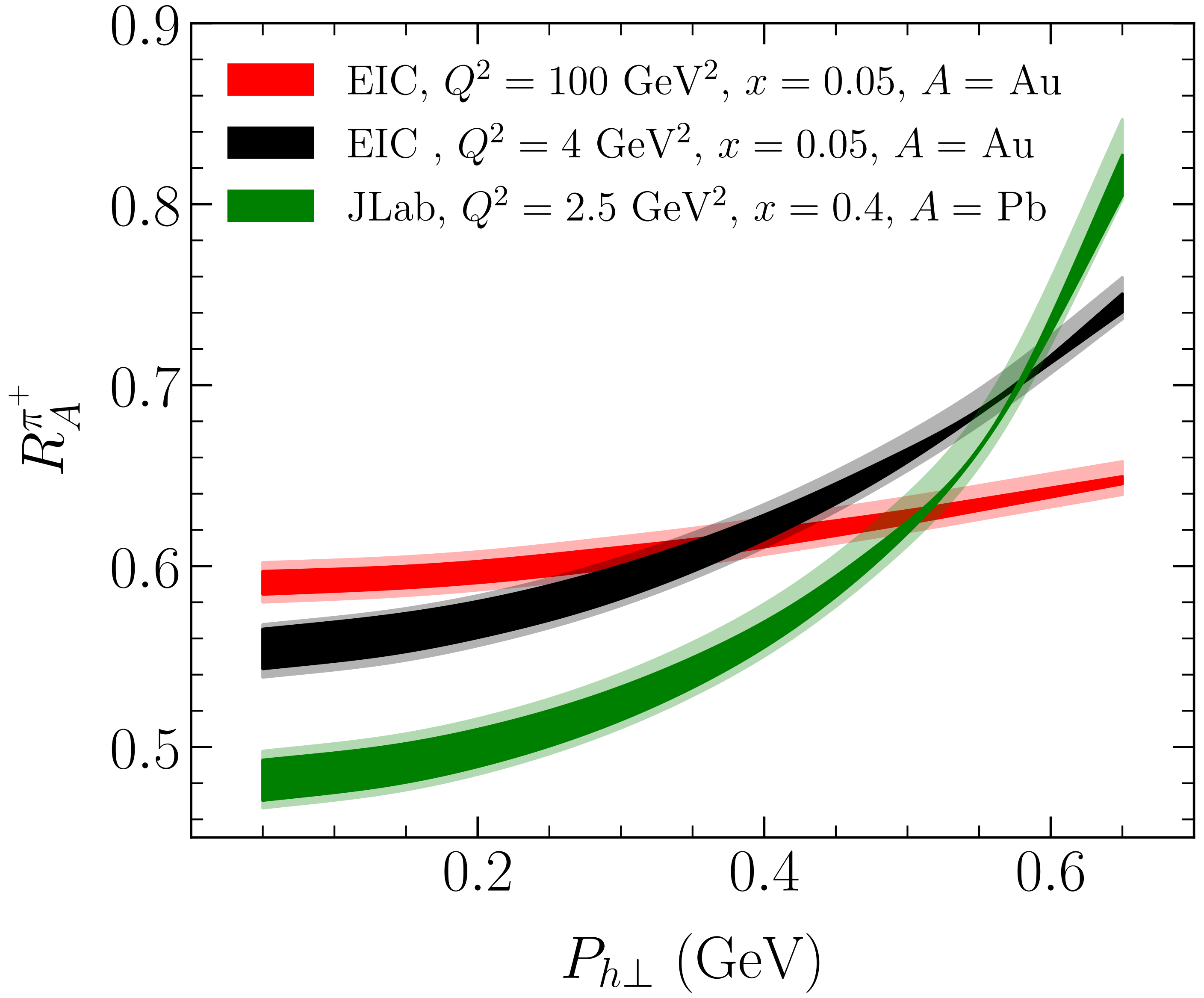




Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

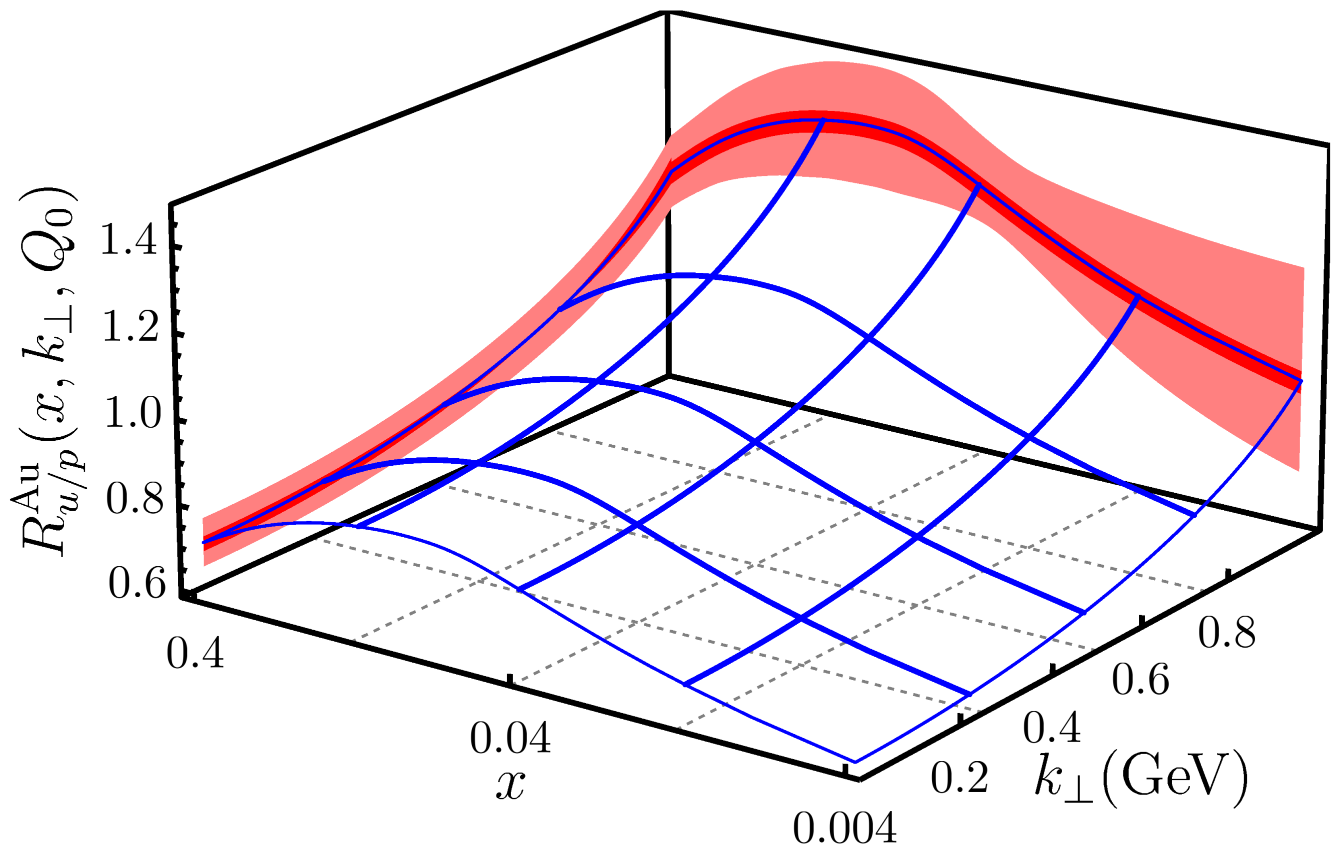
Three-dimension imaging in nuclei

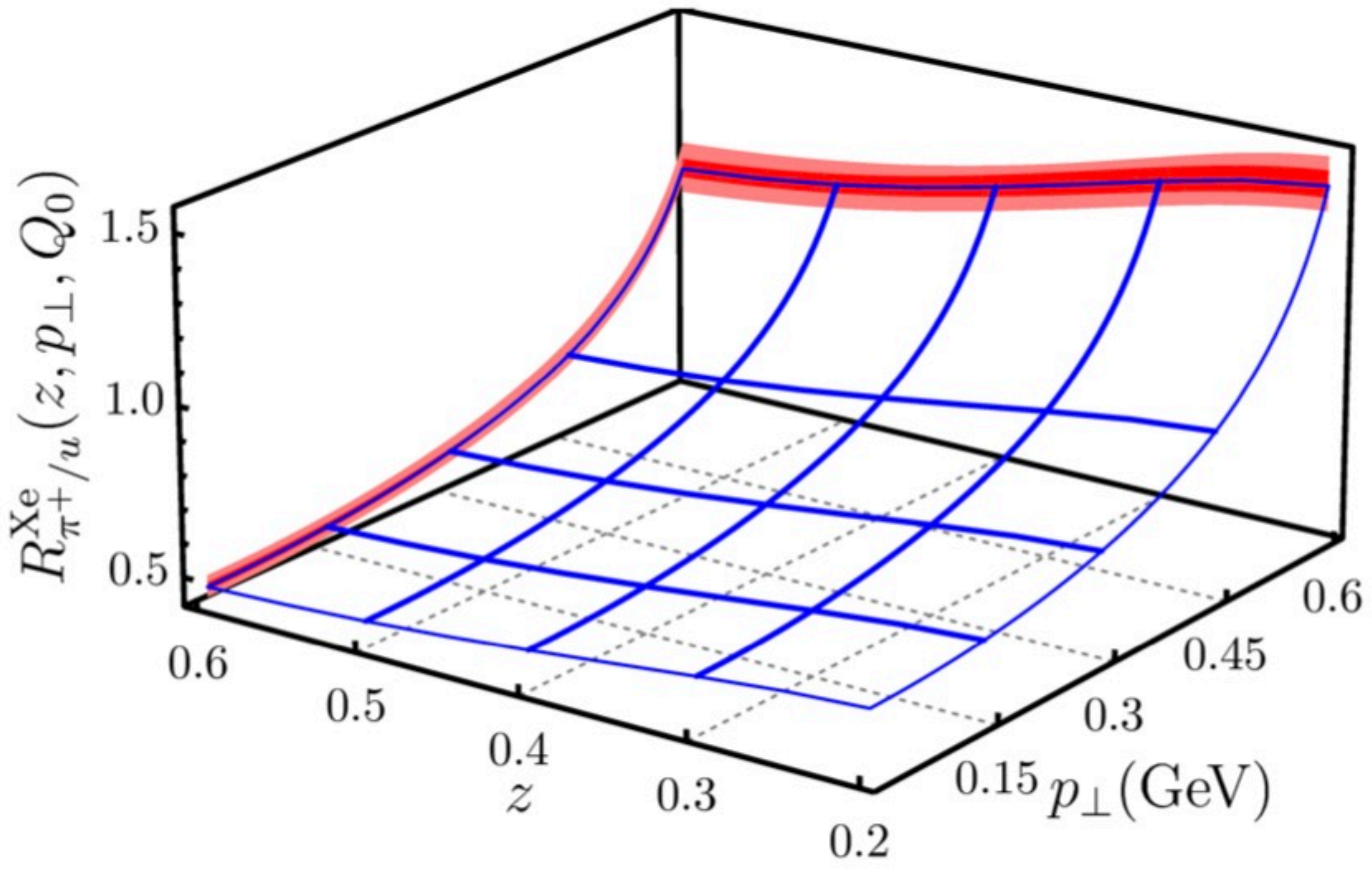




Alrashed, Anderle, Kang, Terry, **HX**
arXiv:2107.12401

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





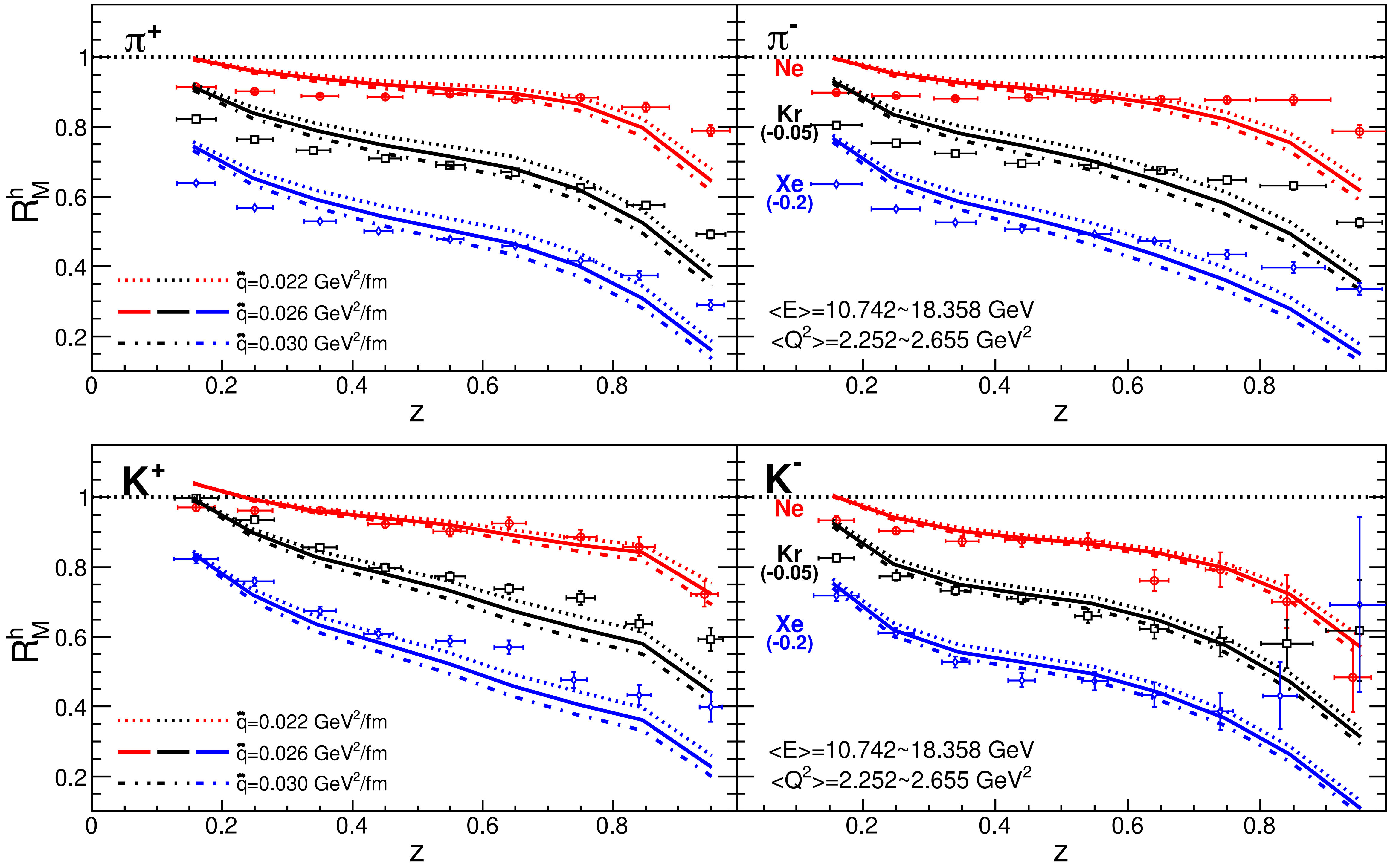
$$R^{\mathrm{Au}}_{u/p}(x, k_\perp, Q_0) = \frac{f^{\mathrm{Au}}_{u/p}(x, k_\perp, Q_0)}{f_{u/p}(x, k_\perp, Q_0)}$$

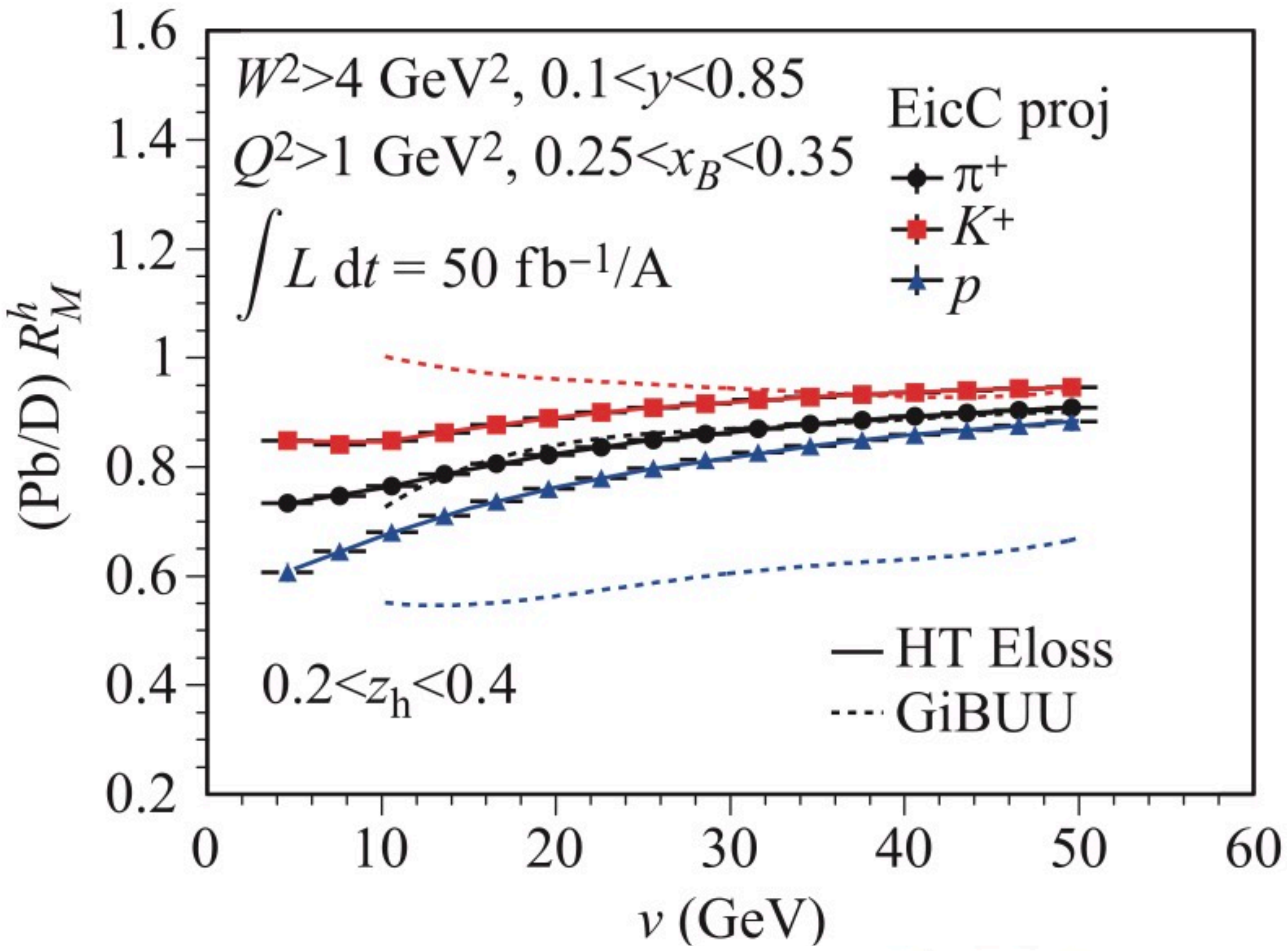
$$\mathcal{R}^{\mathrm{Xe}}_{\pi^+/u}(z, p_\perp, Q_0) = \frac{D^{\mathrm{Xe}}_{\pi^+/u}(z, p_\perp, Q_0)}{D_{\pi^+/u}(z, p_\perp, Q_0)}$$

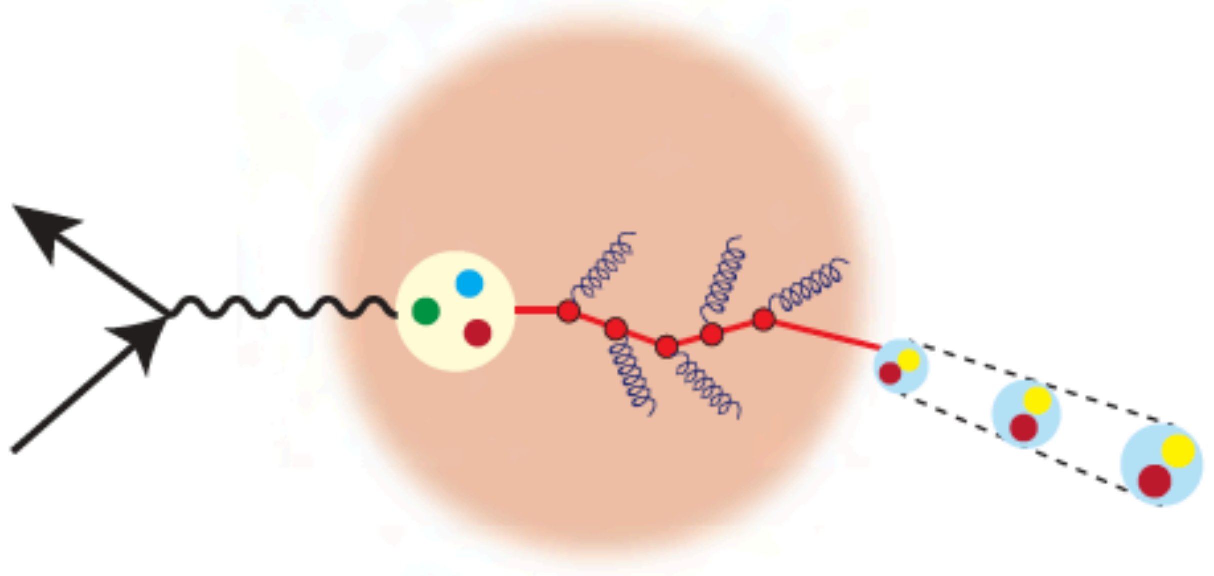
EicC for parton propagation in nuclear medium

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

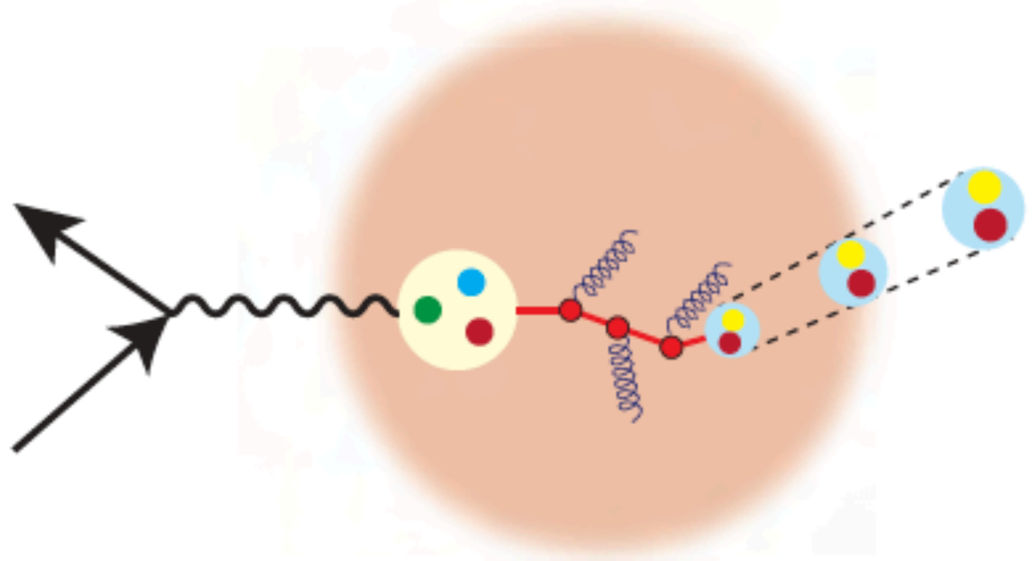
NLO + ELoss





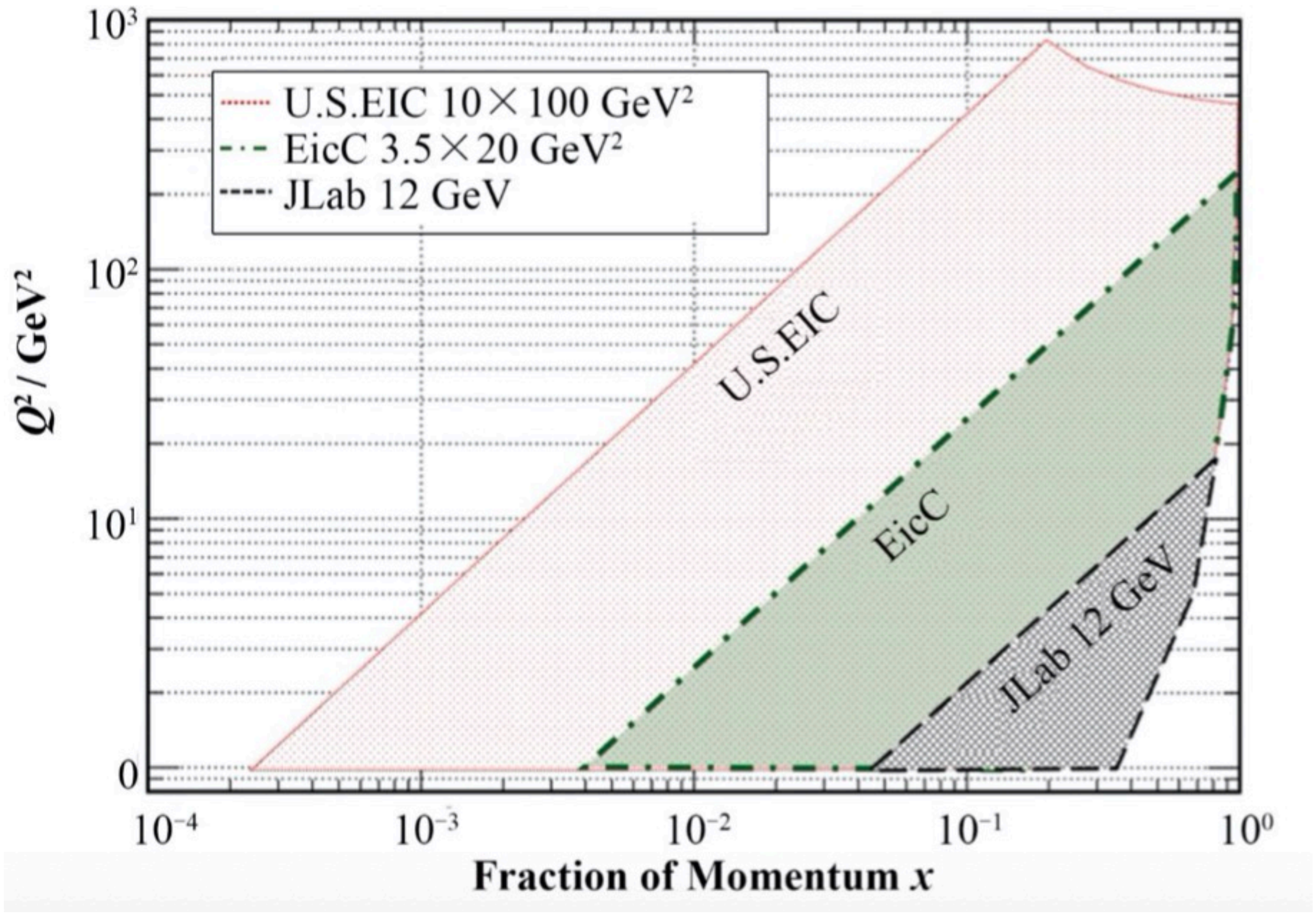


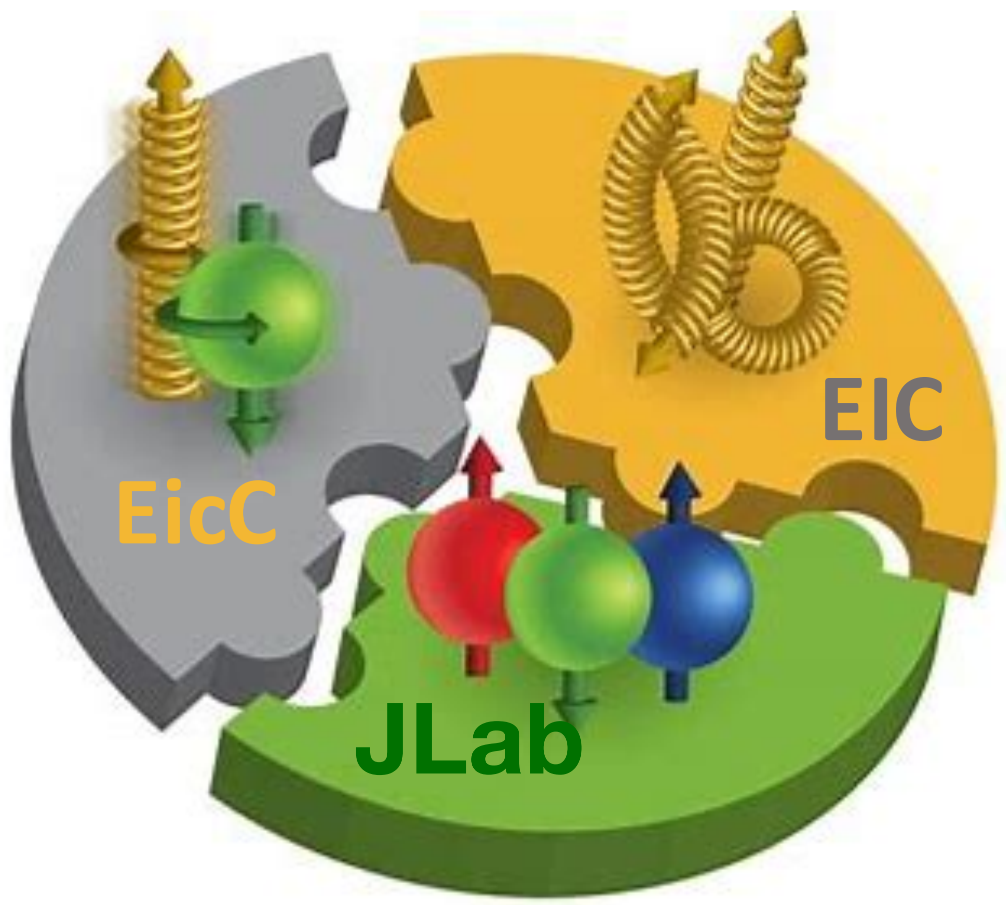
From HERMES to EicC



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**





Advertisements

EicC email list:

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

The 3rd EicC CDR workshop

22-24 August 2022
Shandong University (Qingdao)
Asia/Shanghai timezone

- Overview
- Scientific Programme
- Timetable
- Contribution List
- Author index
- Registration
  - Registration Form
- List of registrants

! ! ! NOTICE : Due to the arising Covid-19 situation in some cities, we decide to postpone our 3rd EicC CDR workshop in Qingdao. We still keep the plan of having a meeting in person and will inform you the new dates when the situation is better.

Lepton scattering is an established ideal tool for studying inner structure of small particles such as nucleons as well as nuclei. As a future high energy nuclear physics project, an Electron-ion collider in China (EicC) has been proposed. It will be constructed based on an upgraded heavy-ion accelerator, High Intensity heavy-ion Accelerator Facility (HIAF) which is currently under construction, together with a new electron ring. In 2021, the EicC white paper (English version) has been released and published in Frontiers of Physics. After reaching this milestone of the EicC project, the EicC working group has been moving forward towards the Conceptual Design Report (CDR).

We will have the 3rd EicC CDR workshop during July 25-27, 2022 in Qingdao, with the goal of reviewing the progress towards EicC CDR. The workshop will be hosted by Shandong University at Qingdao. Please register by June 30, to help us with the hotel reservation. The Covid-19 related information will be updated in advance. Hope to see you all in person in Qingdao this summer.