EIC Physics
- a view point from EicC

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原子核结构与相对论重离子碰撞前沿交叉研讨会

2023.7.31-8.6

Outline

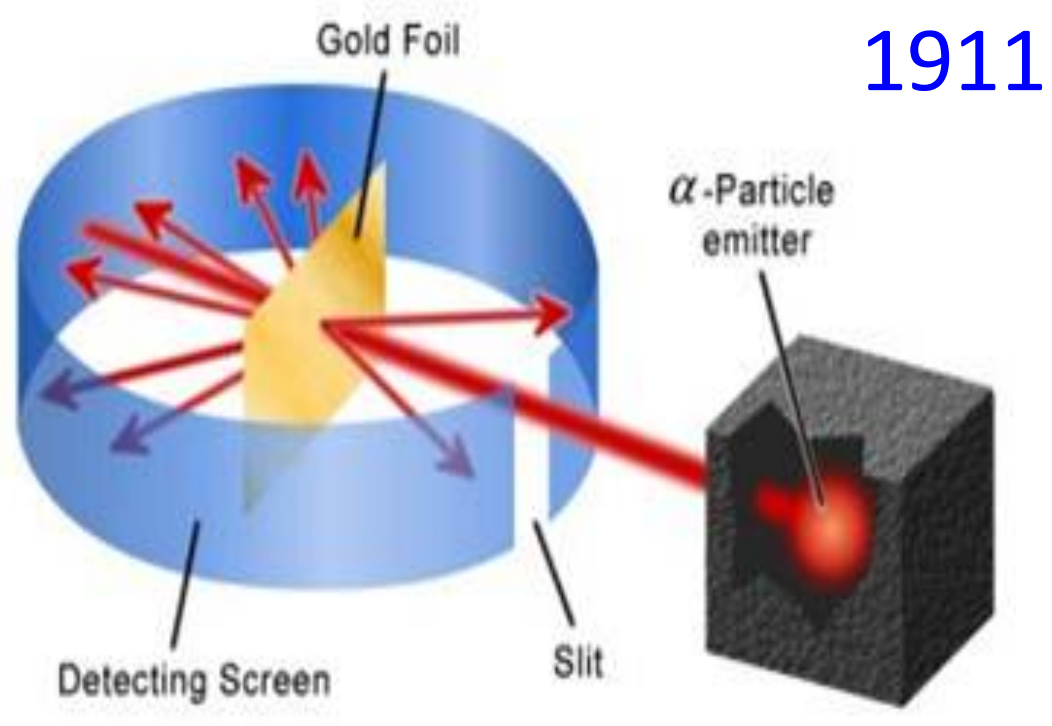
- ✦ Introduction to Electron Ion Colliders
- ✦ Selected topics for nucleon/nucleus structure
  - proton 1D structure
  - proton 3D structure
  - nuclear effects
- ✦ Summary

Nucleon partonic structure

✦ Revolution in our view of nuclear structure

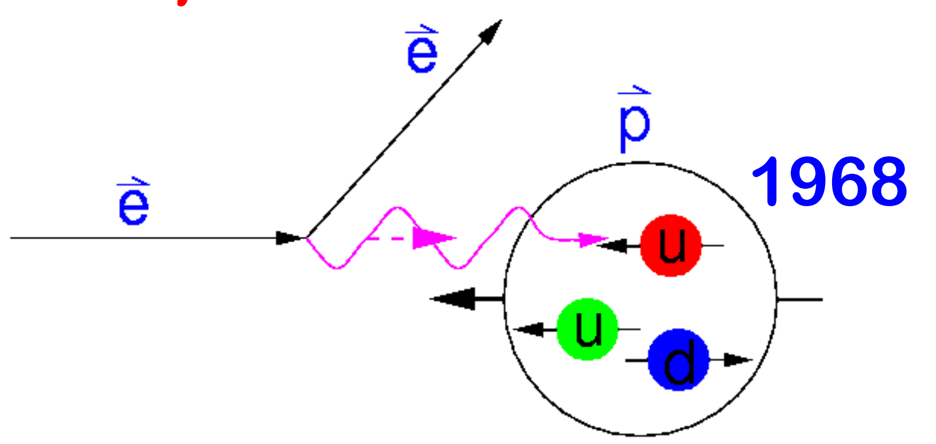
- Atom: Dalton 1803
- Nucleus: Rutherford 1911
- Proton: Rutherford 1919
- Neutron: Chadwick 1932
- Quark model: Gell-Mann and Zweig 1964
- Parton model: Feynman 1969
- …

1911

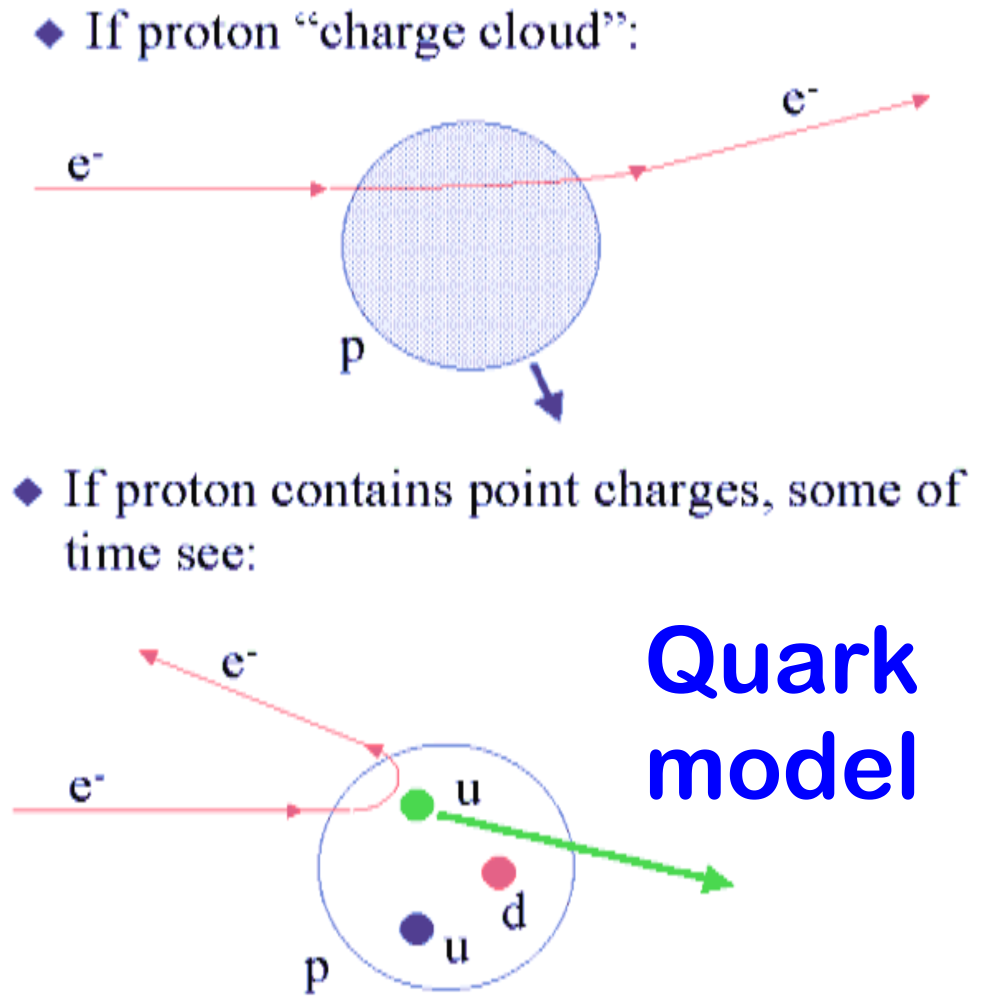


Rutherford scattering

e + *p* ➔ e + *X*



Modern Rutherford scattering



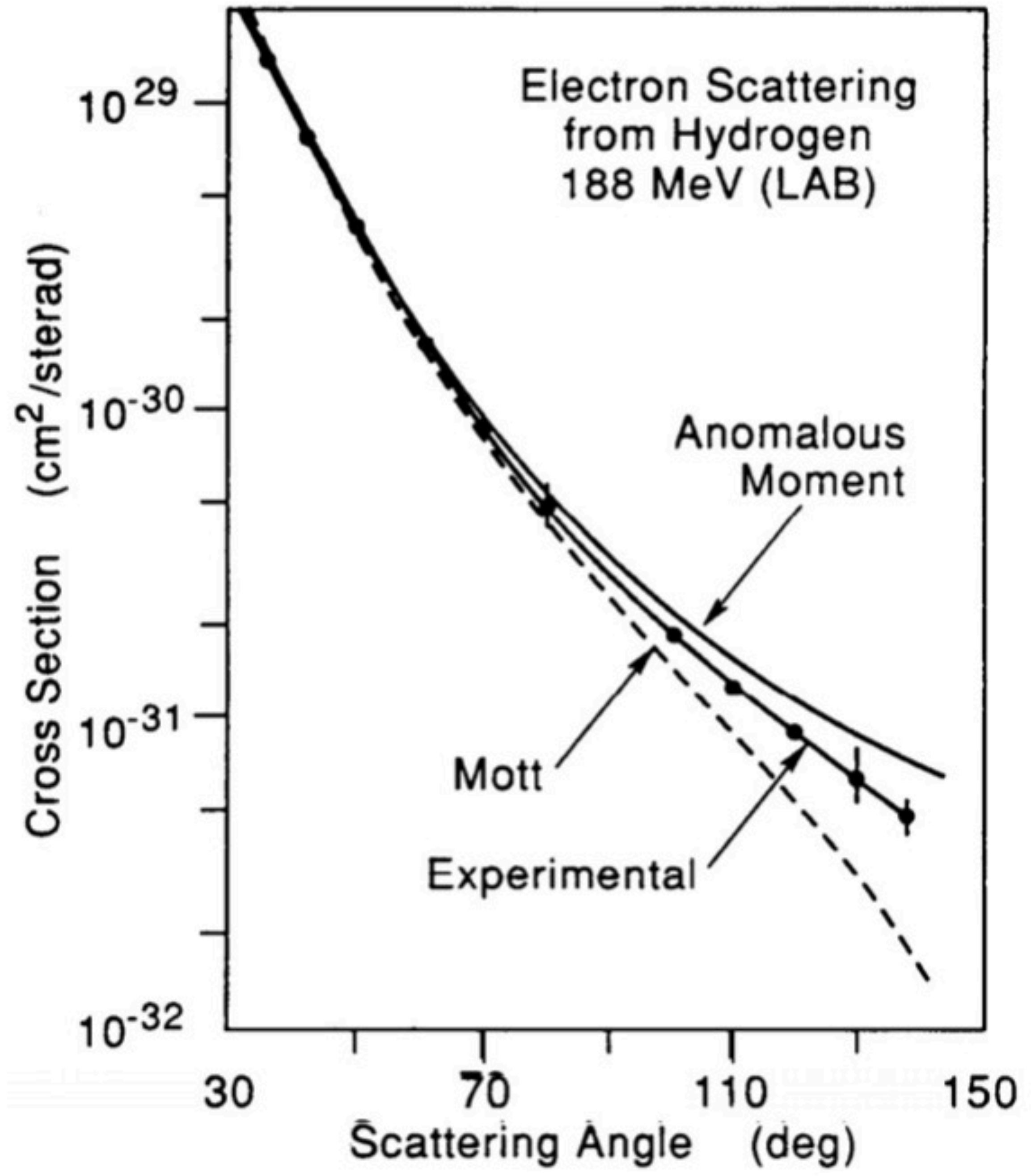
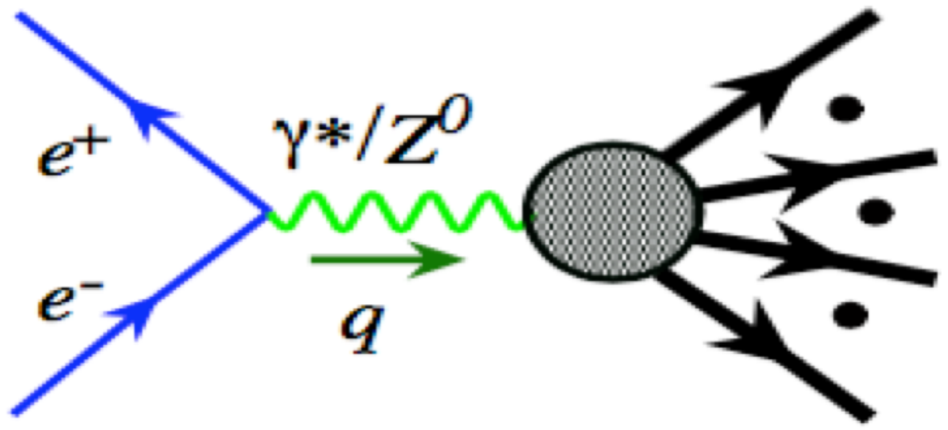


Fig. 5. Elastic electron scattering cross sections from hydrogen compared with the Mott scattering formula (electrons scattered from a particle with unit charge and no magnetic moment) and with the Rosenbluth cross section for a point proton with an anomalous magnetic moment. The data falls between the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

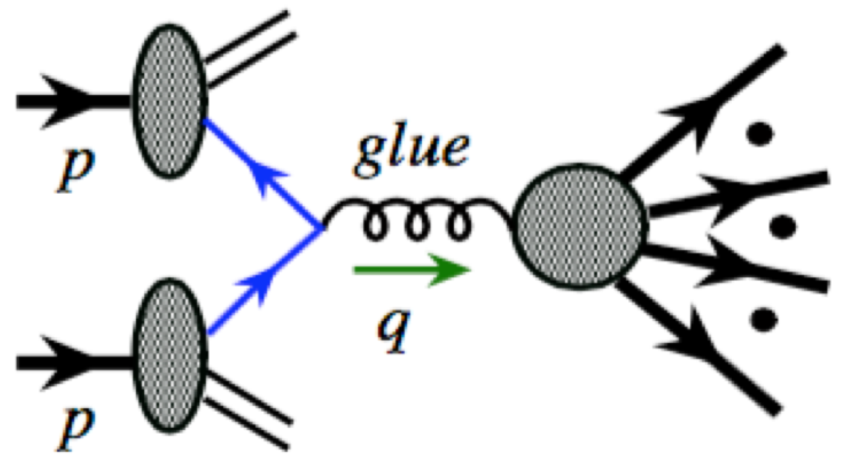
Lepton-lepton colliders



BEPC, SuperKEKB

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

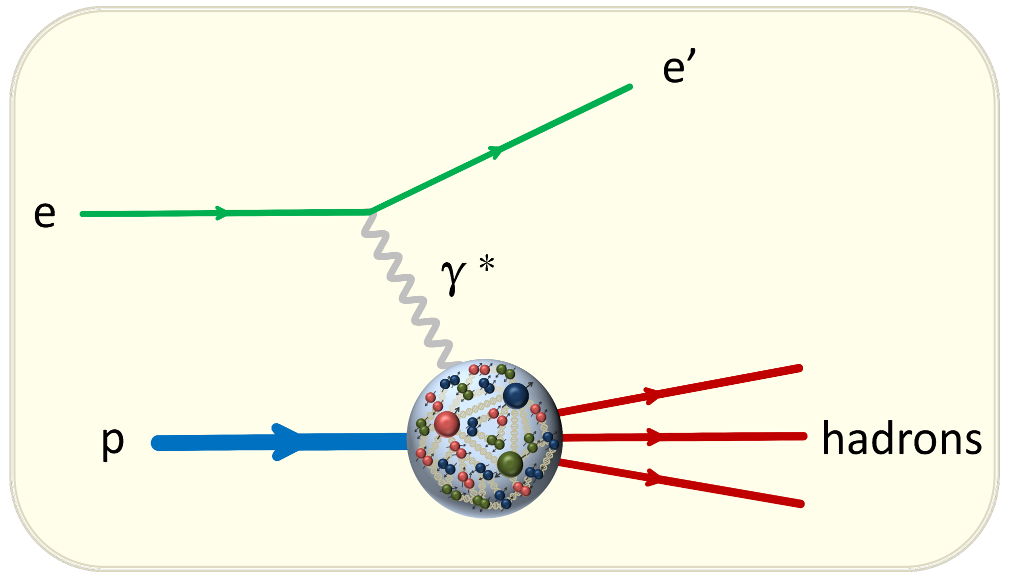
Hadron-hadron colliders



RHIC, LHC

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

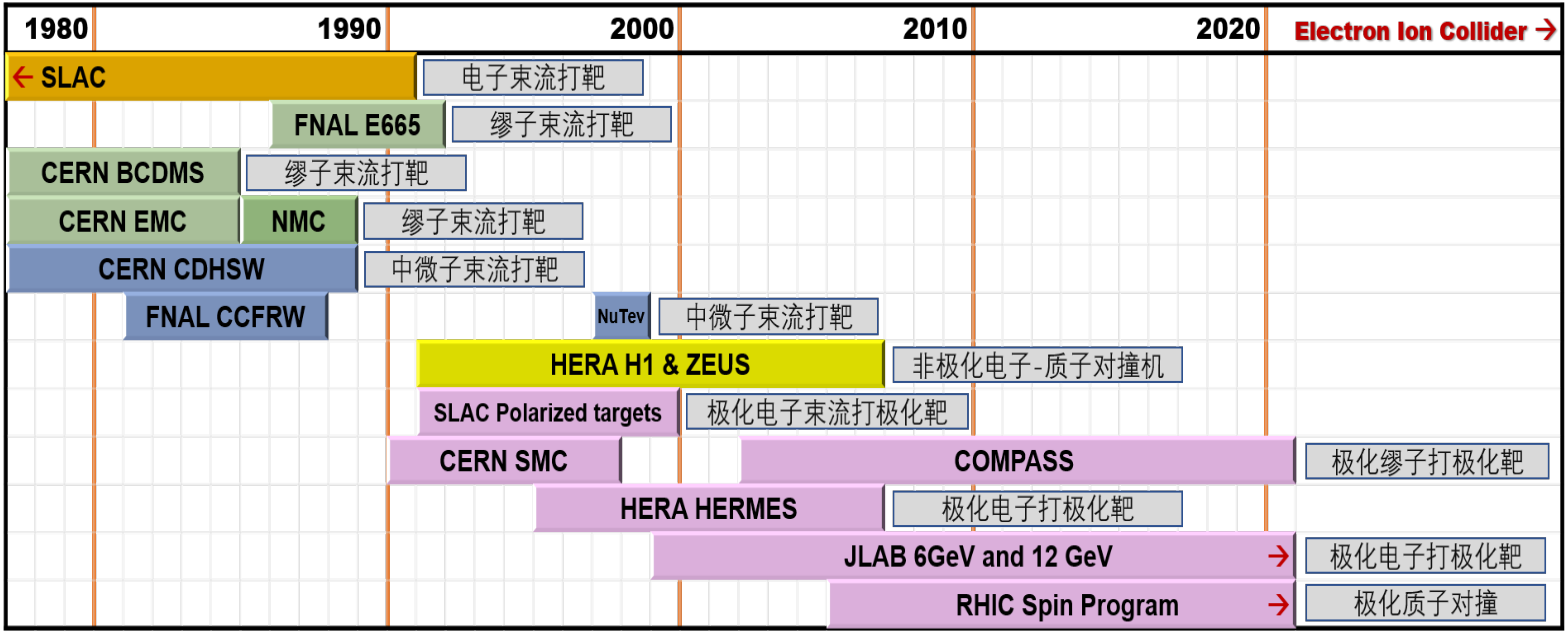
lepton-hadron colliders



HERA, JLab

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

The modern experiments for nucleon structure



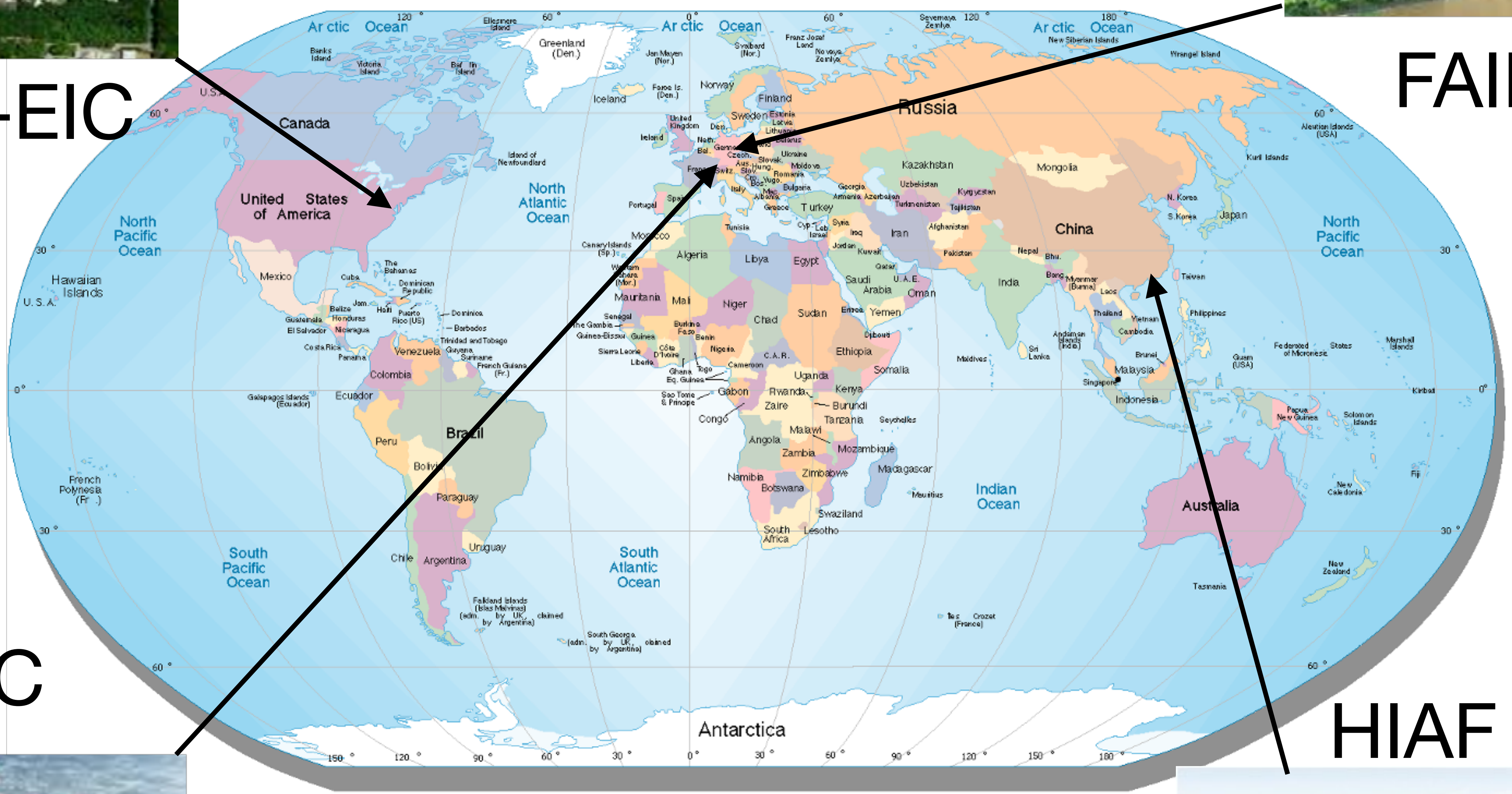
Electron Ion Colliders -> the next generation facility specifically for nucleon structure!

slide from Yutie Liang

Proposed Electron-ion colliders

RHIC ➔ US-EIC

FAIR ➔ ENC

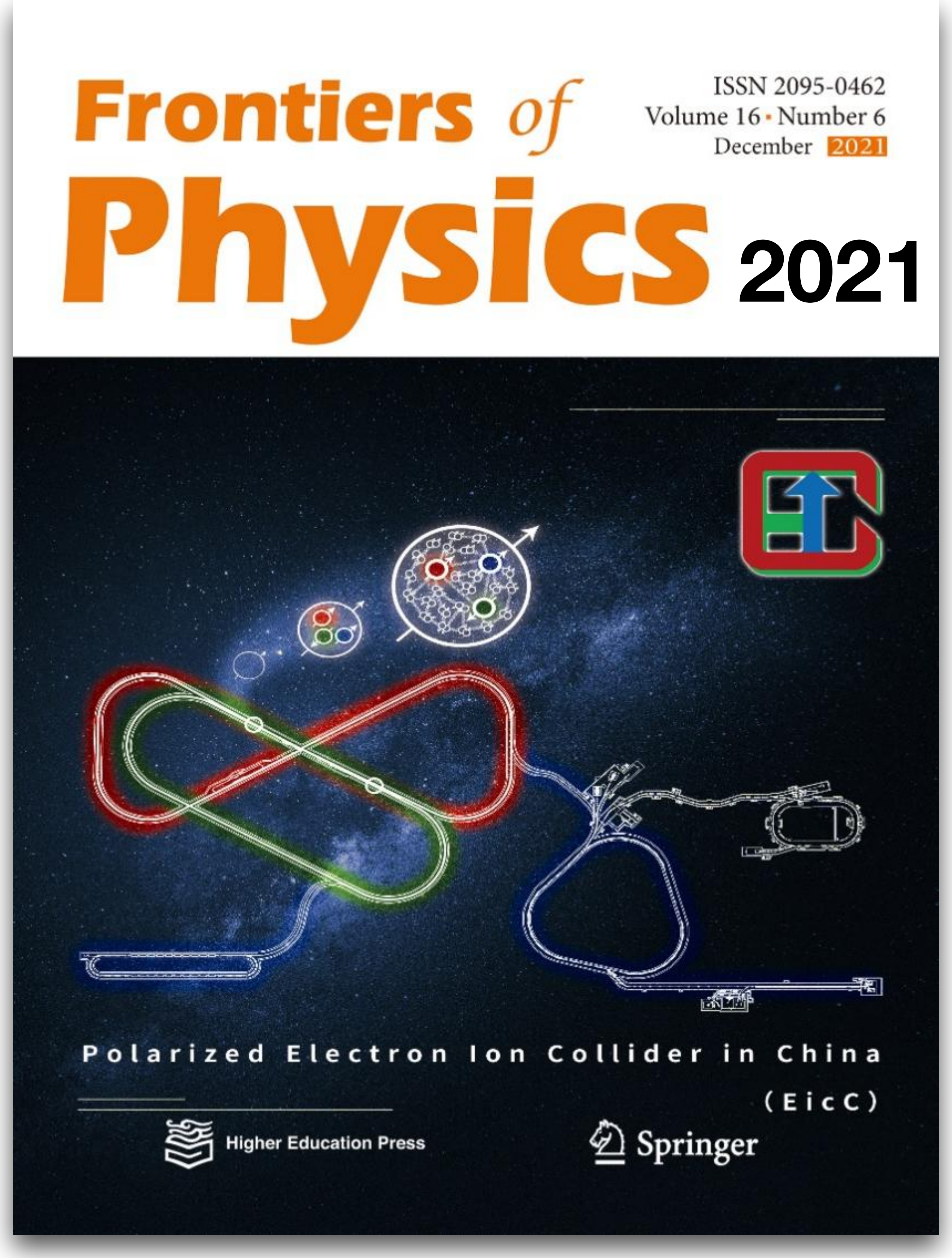


LHC ➔ LHeC

HIAF ➔ **EicC**

slide from Jinlong Zhang

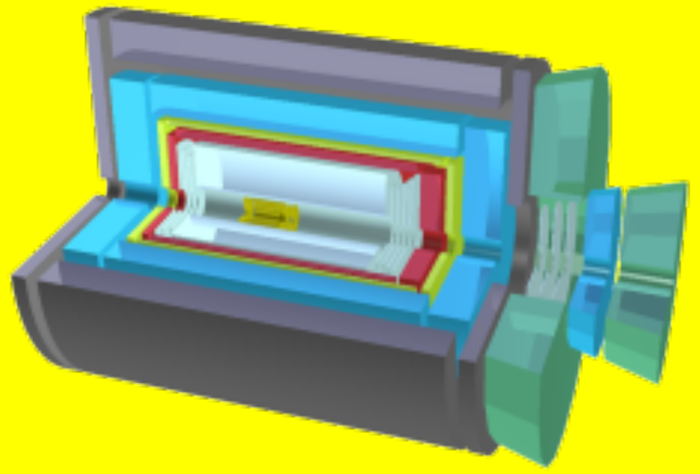
Time evolution of EicC



中国电子 – 离子对撞机 (EicC)

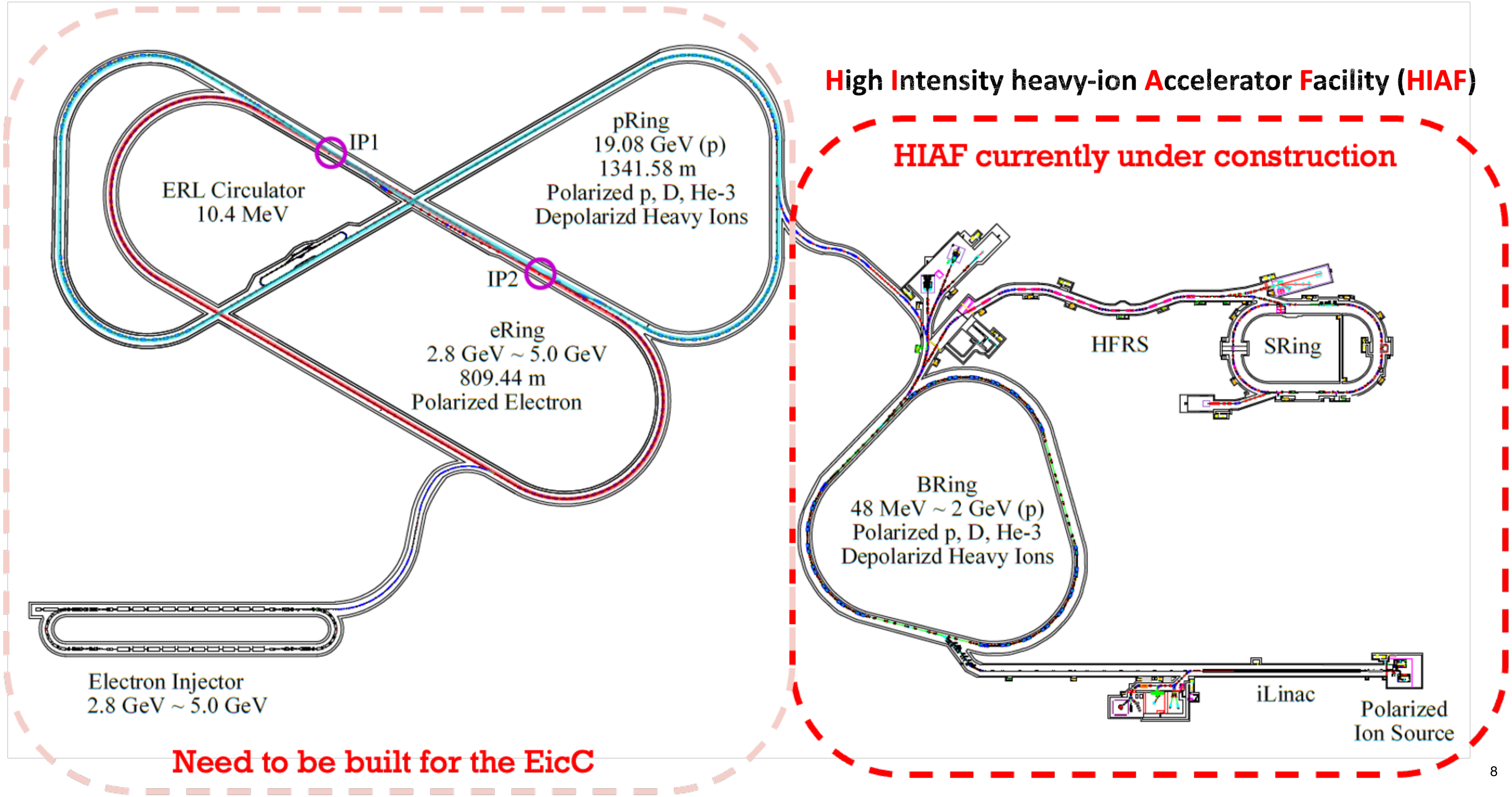
2012: 领域内开始讨论
2020.2, 2021.6:白皮书 (中文, 英文)
2021-2023: 概念设计研究

参与单位： ~ 45

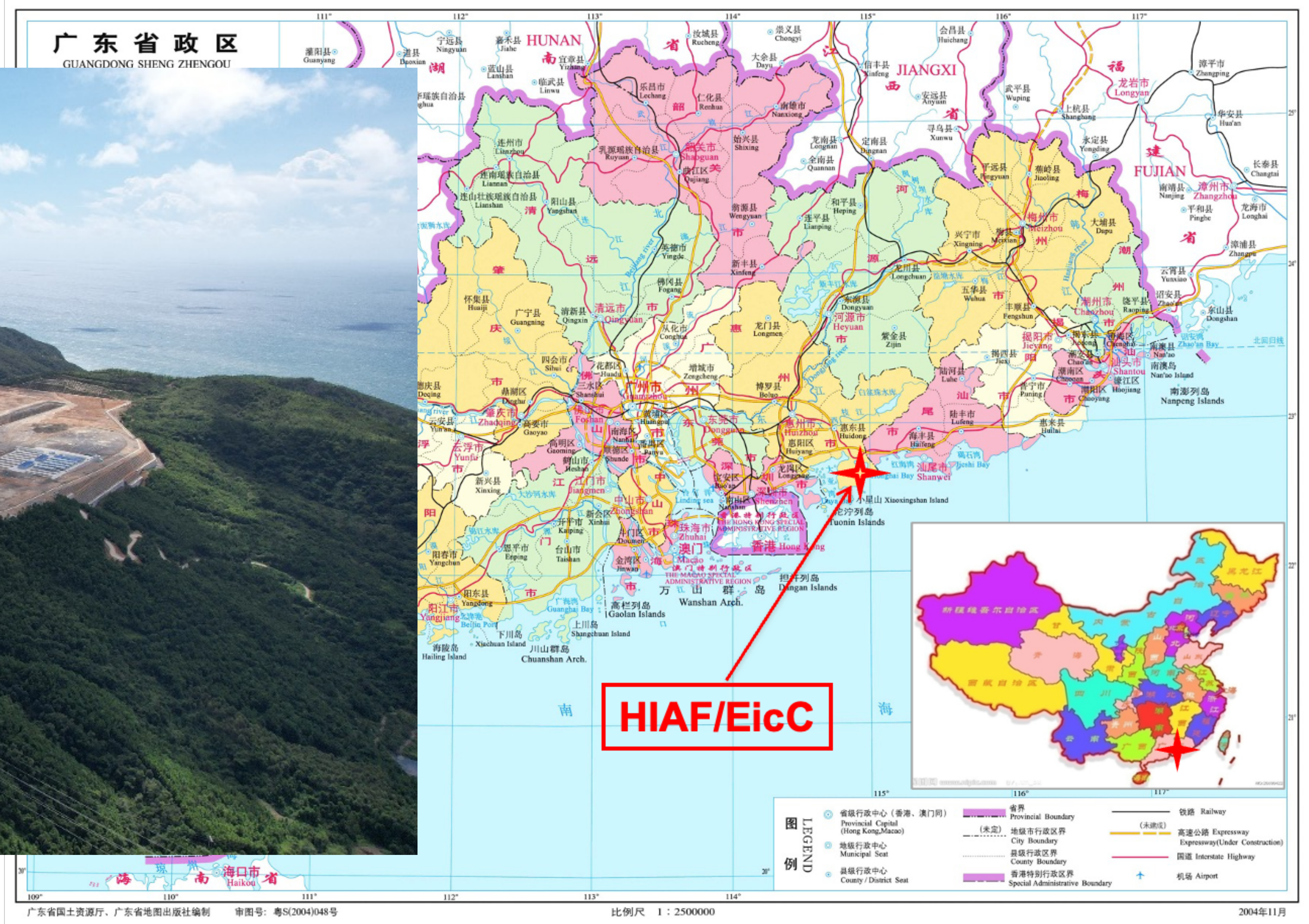


Electron Ion Collider in China, EicC

Electron-Ion Collider in China (EicC)



Electron-Ion Collider in China (EicC)

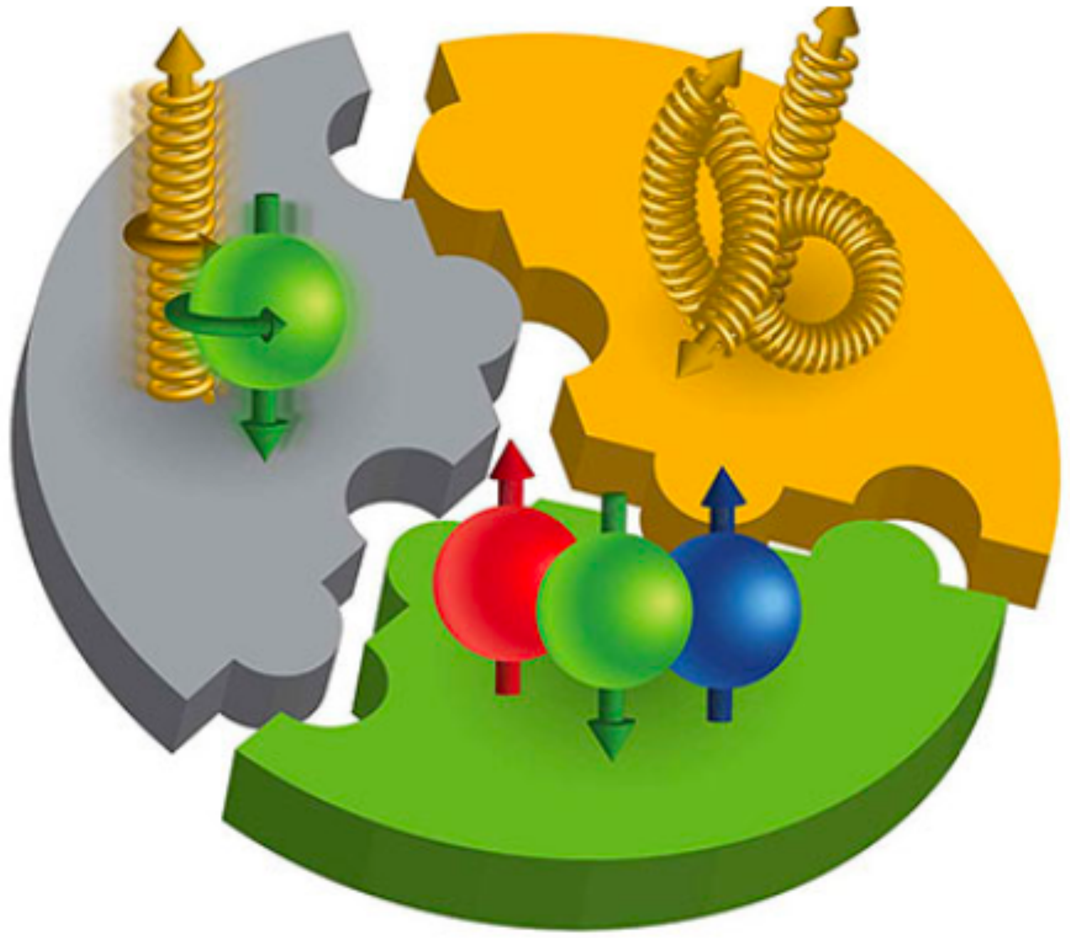


HIAF under construction

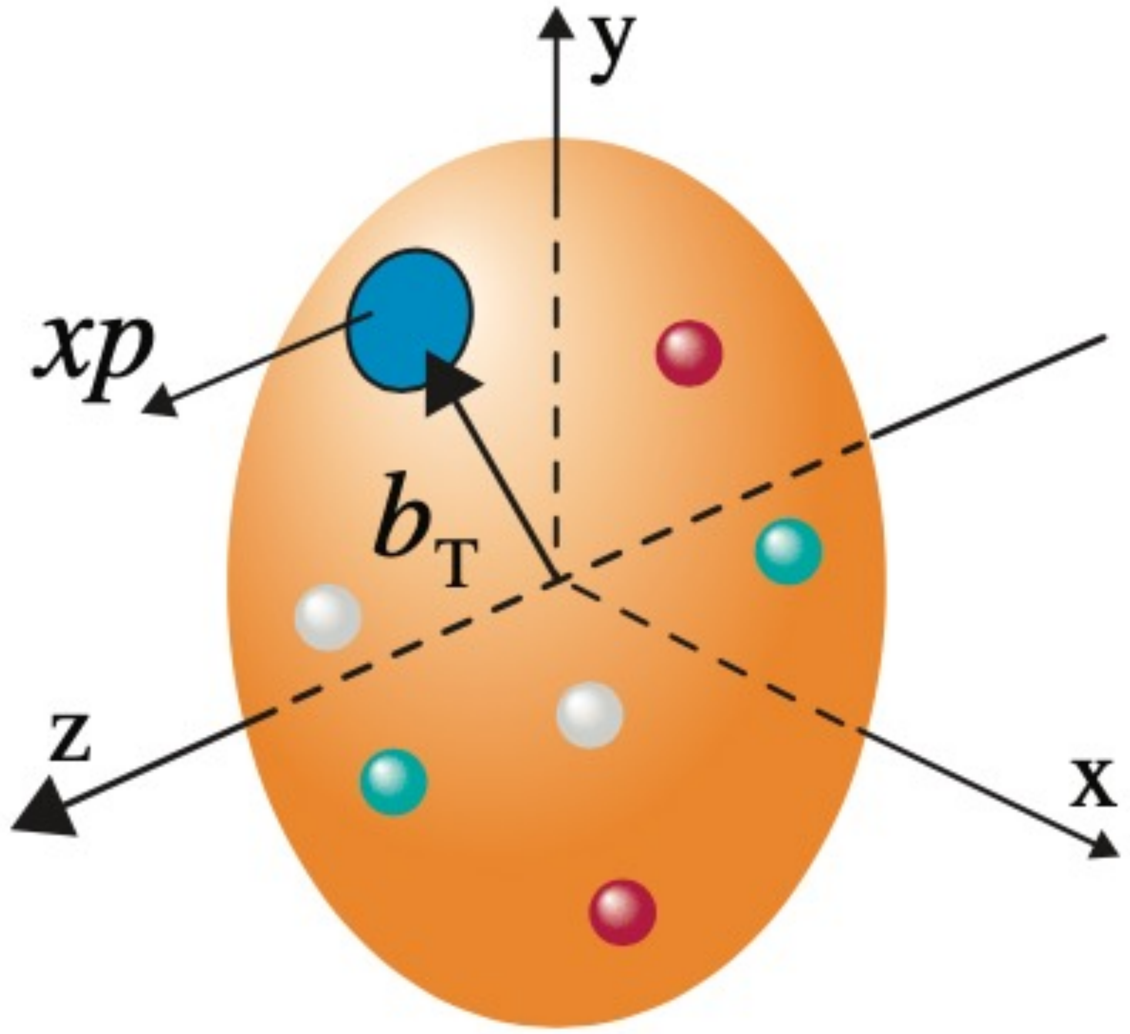
EIC in China

a nuclear facility proposed to be built in Huizhou, China

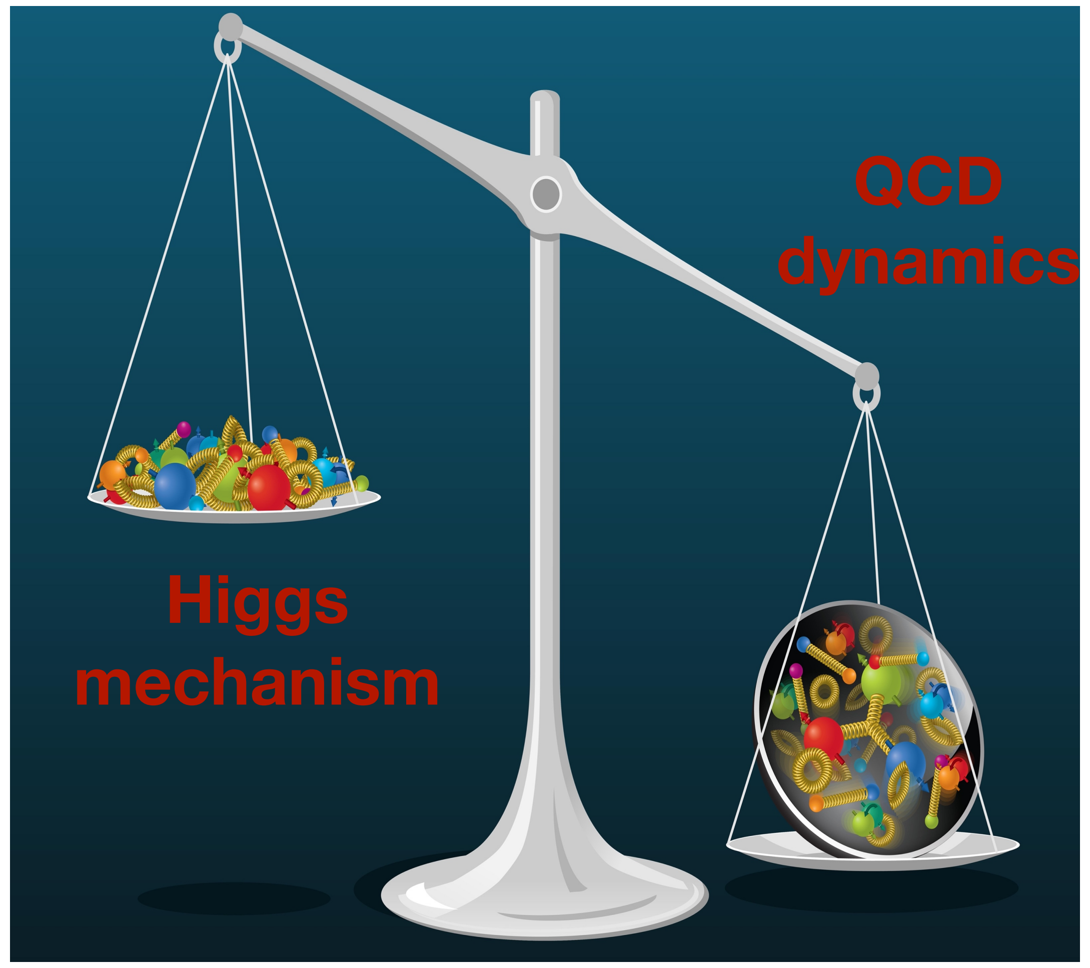
Scientific goals at EICs



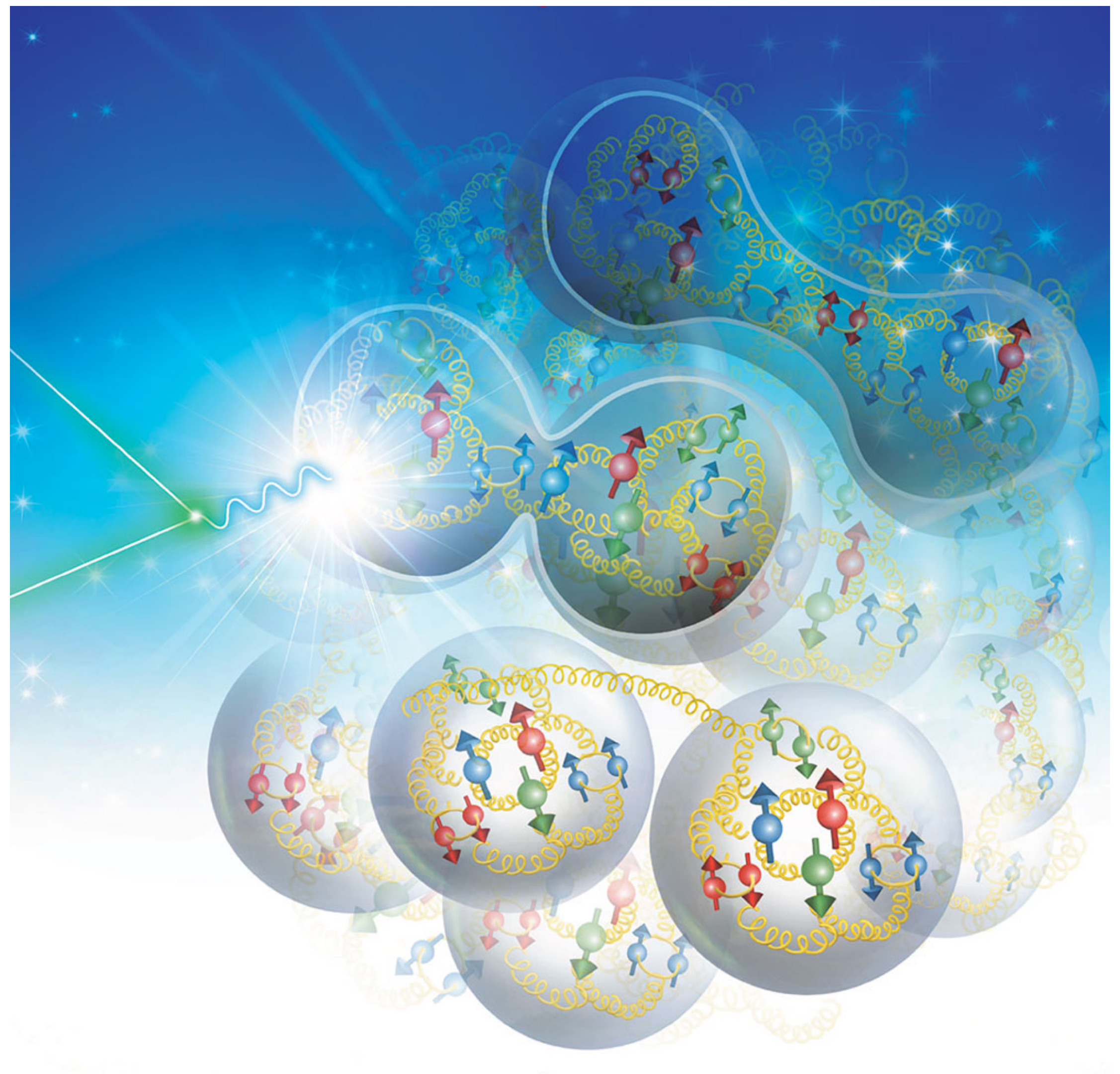
The origin of proton spin



Nucleon 3D imaging

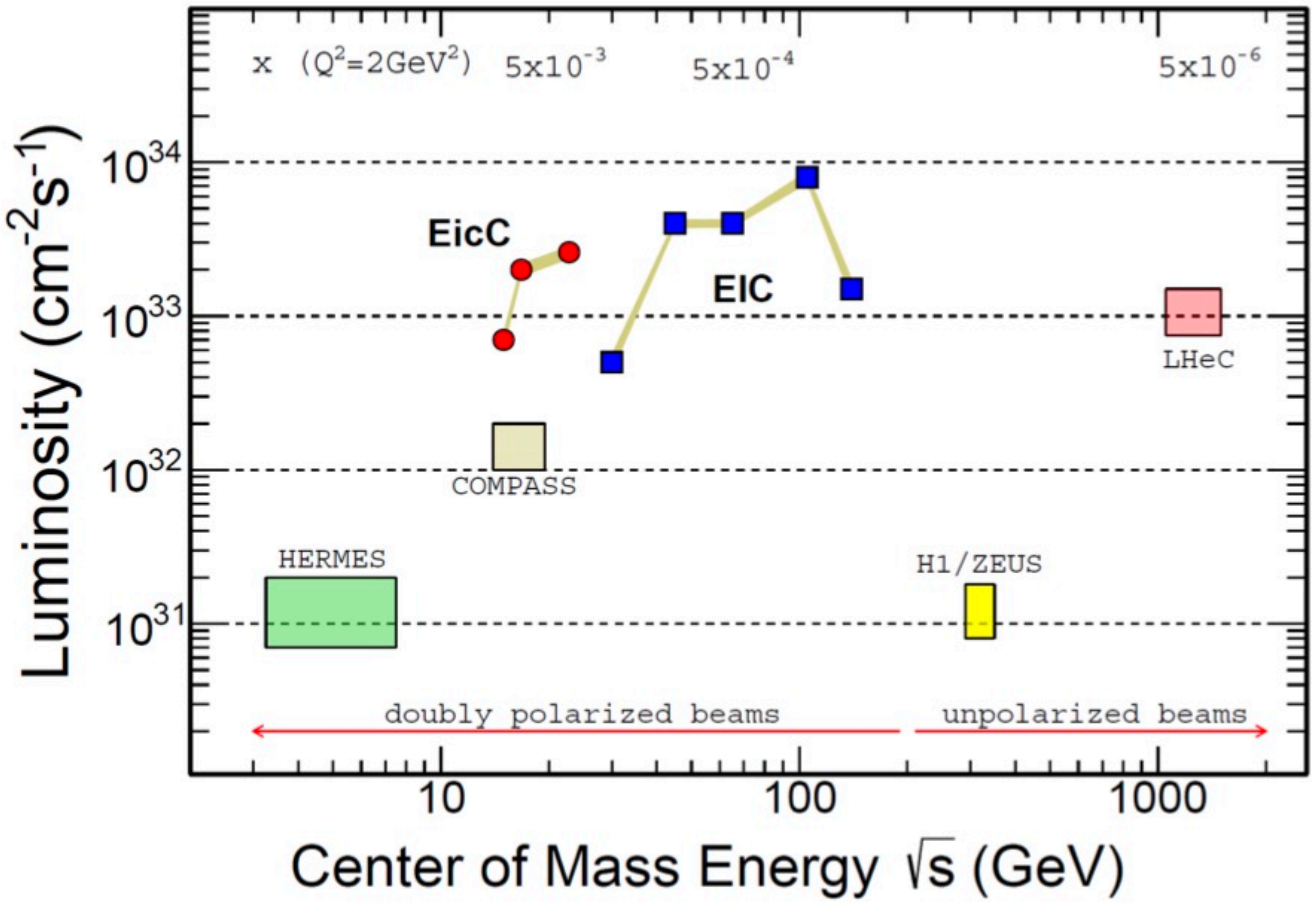


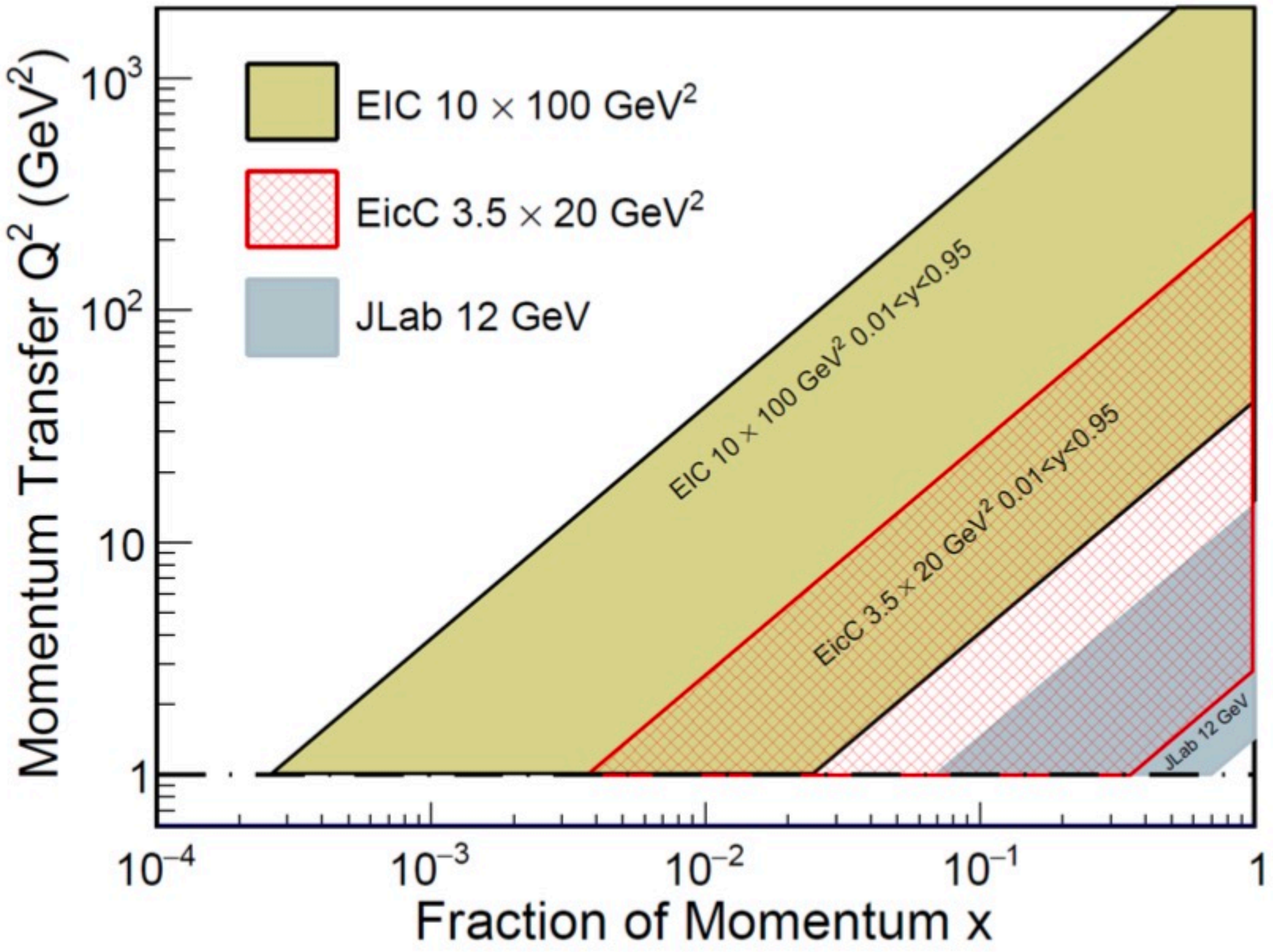
The origin of proton mass



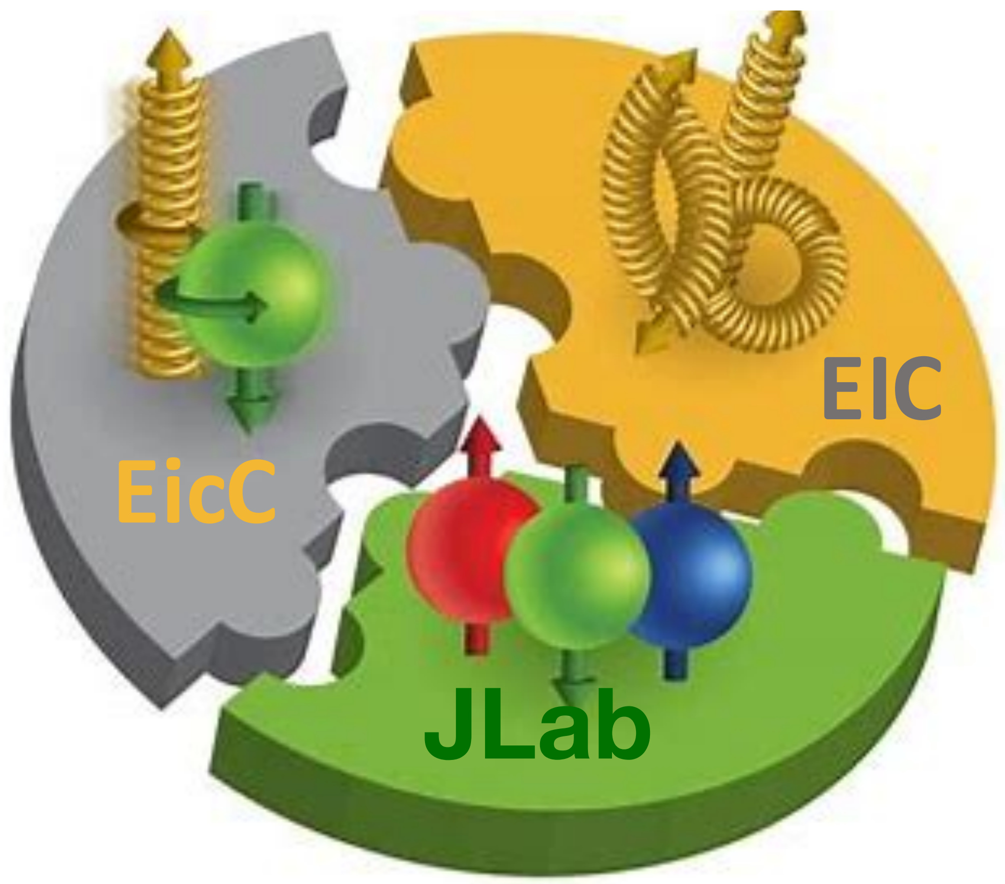
nuclear effects

Complementarity between EIC and EicC





Mapping out the nucleon structure
via EICs worldwide

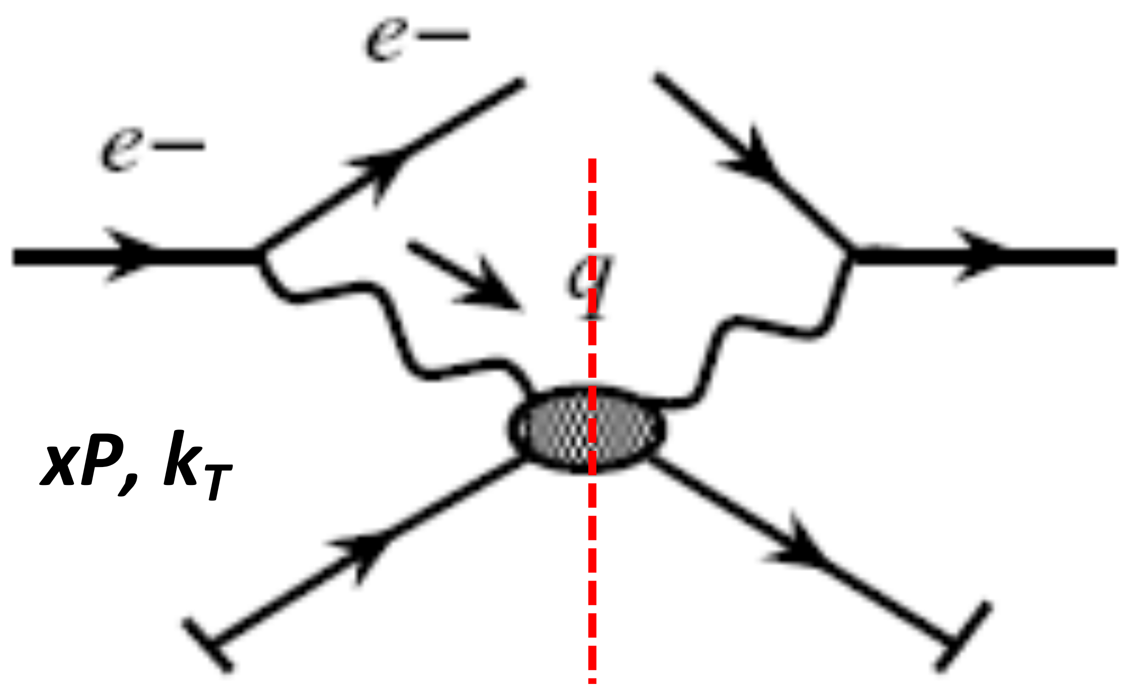


How to probe the nucleon partonic structure?

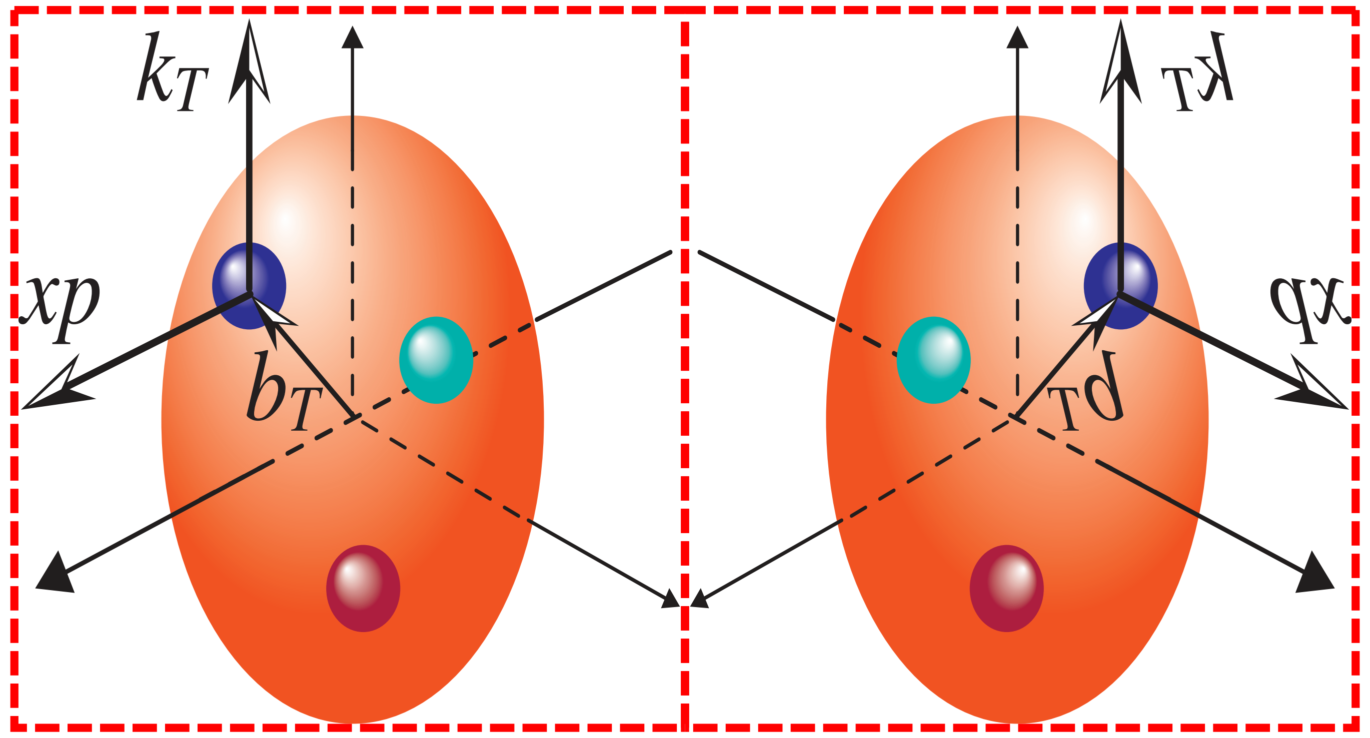
✦ Indispensable joint efforts from experiments and QCD theory

QCD factorization theorem

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



$\otimes$



Experimental measurements

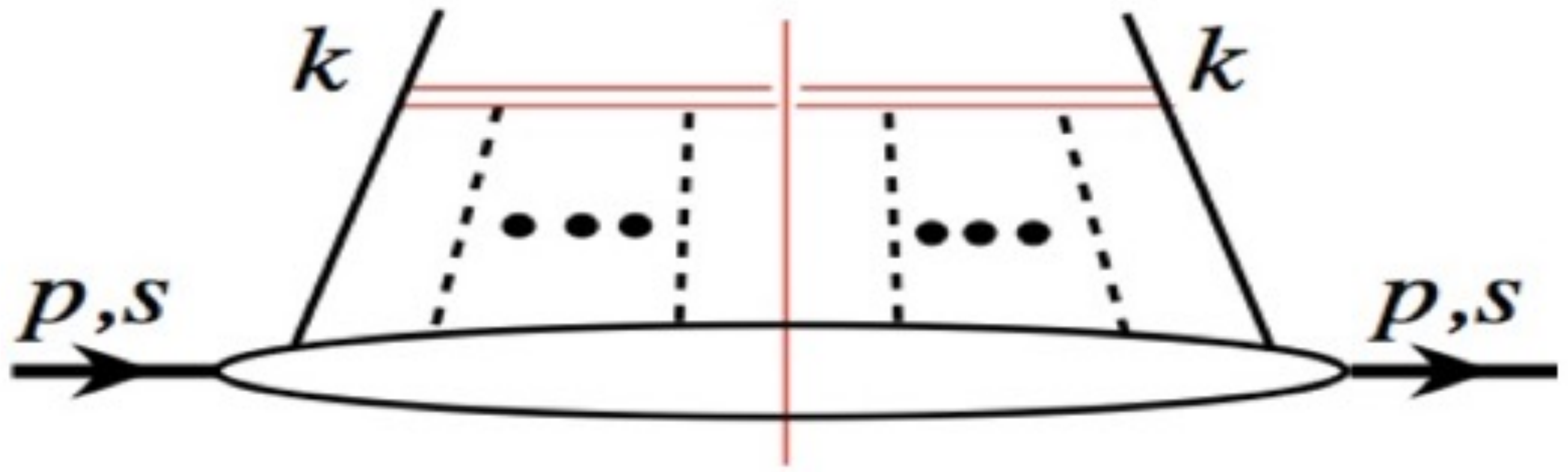
Hard part controlled by pQCD theory

Nucleon partonic structure

1D momentum distribution: Parton distribution functions (PDFs)

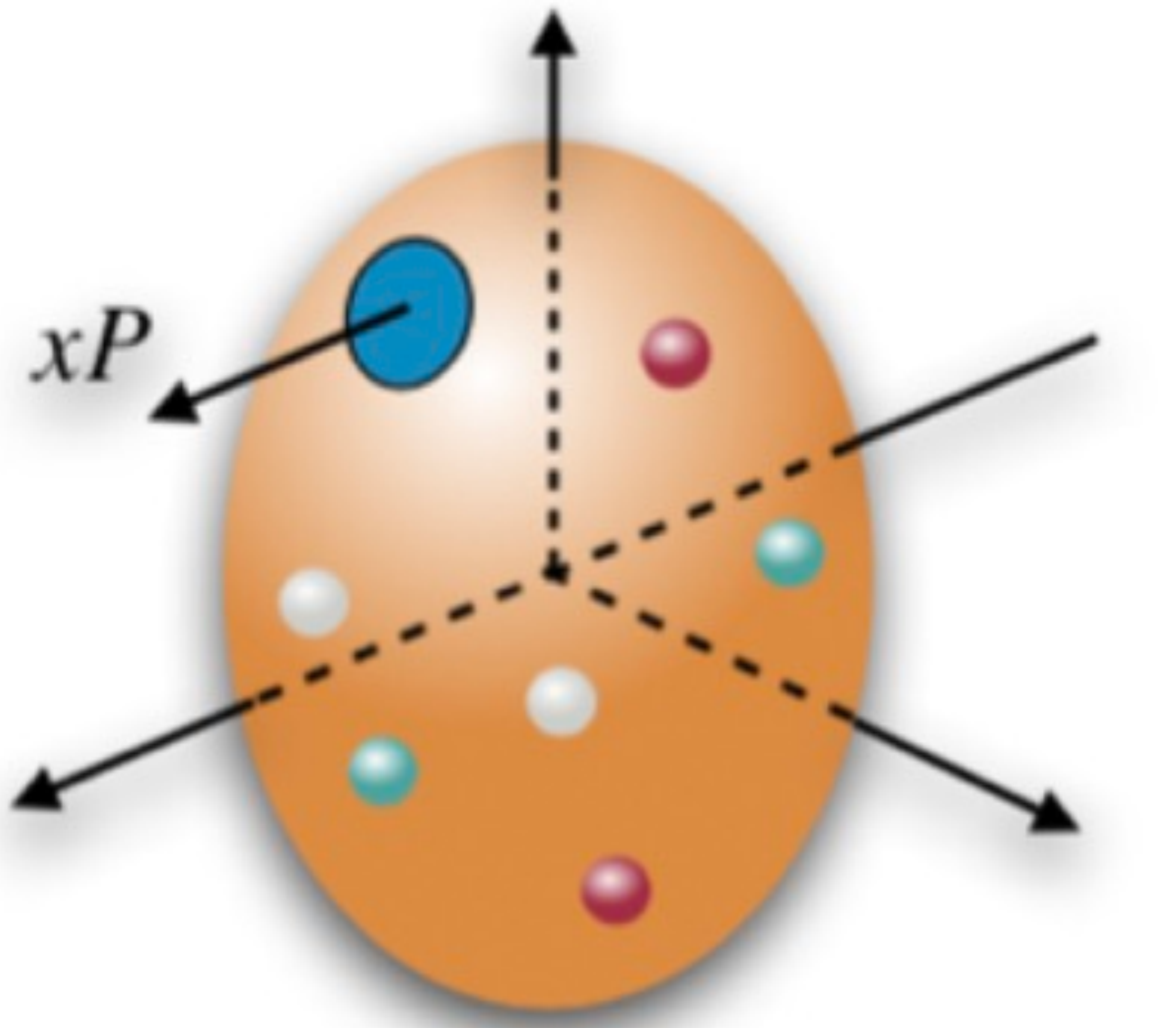
✦ Operator definition of quark PDF

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



- 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 $\sum_{a=q,g} \int_0^1 dx x f_{a/p}(x) = 1$

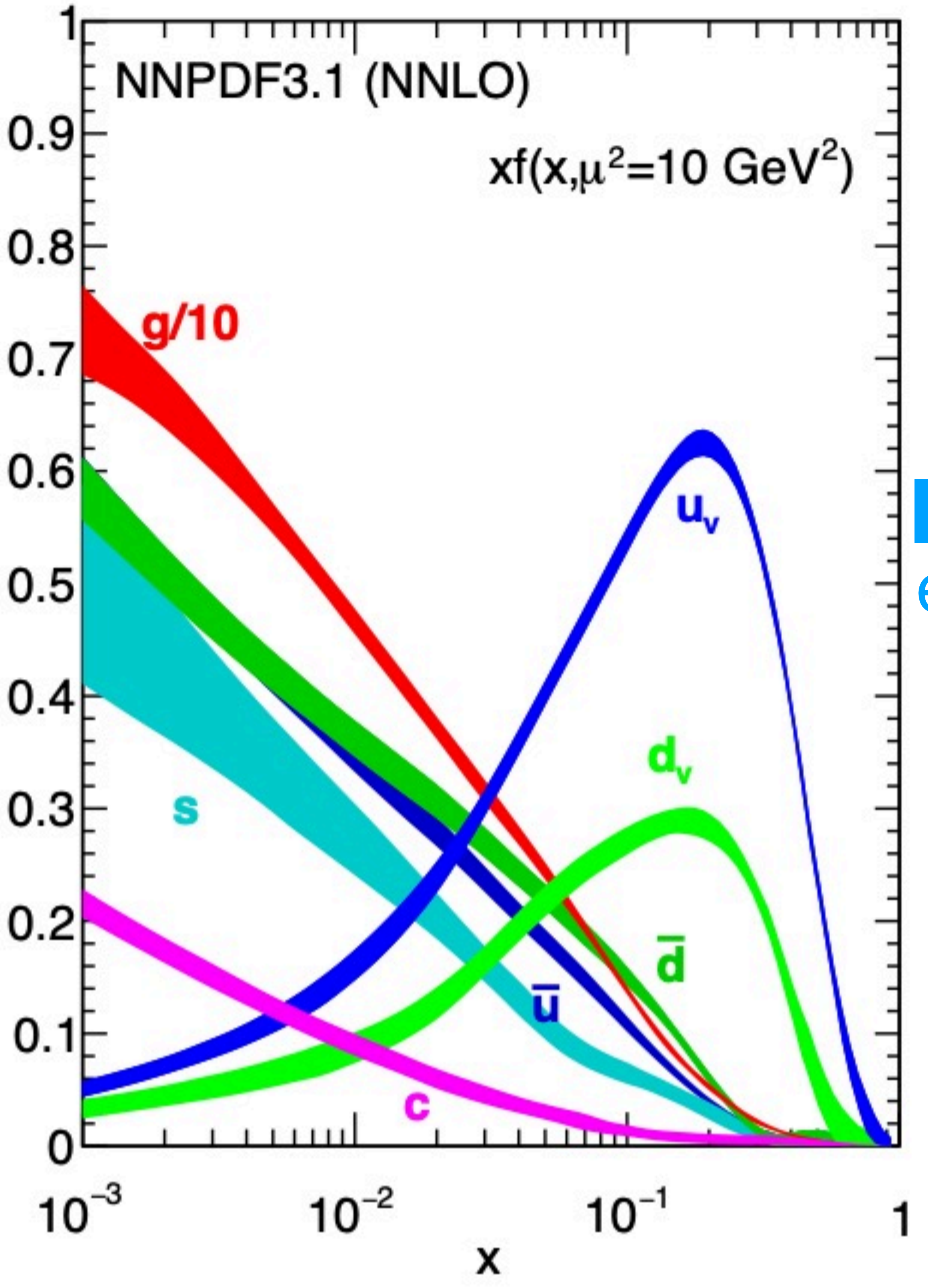
Parton distribution functions

- ✦ 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)

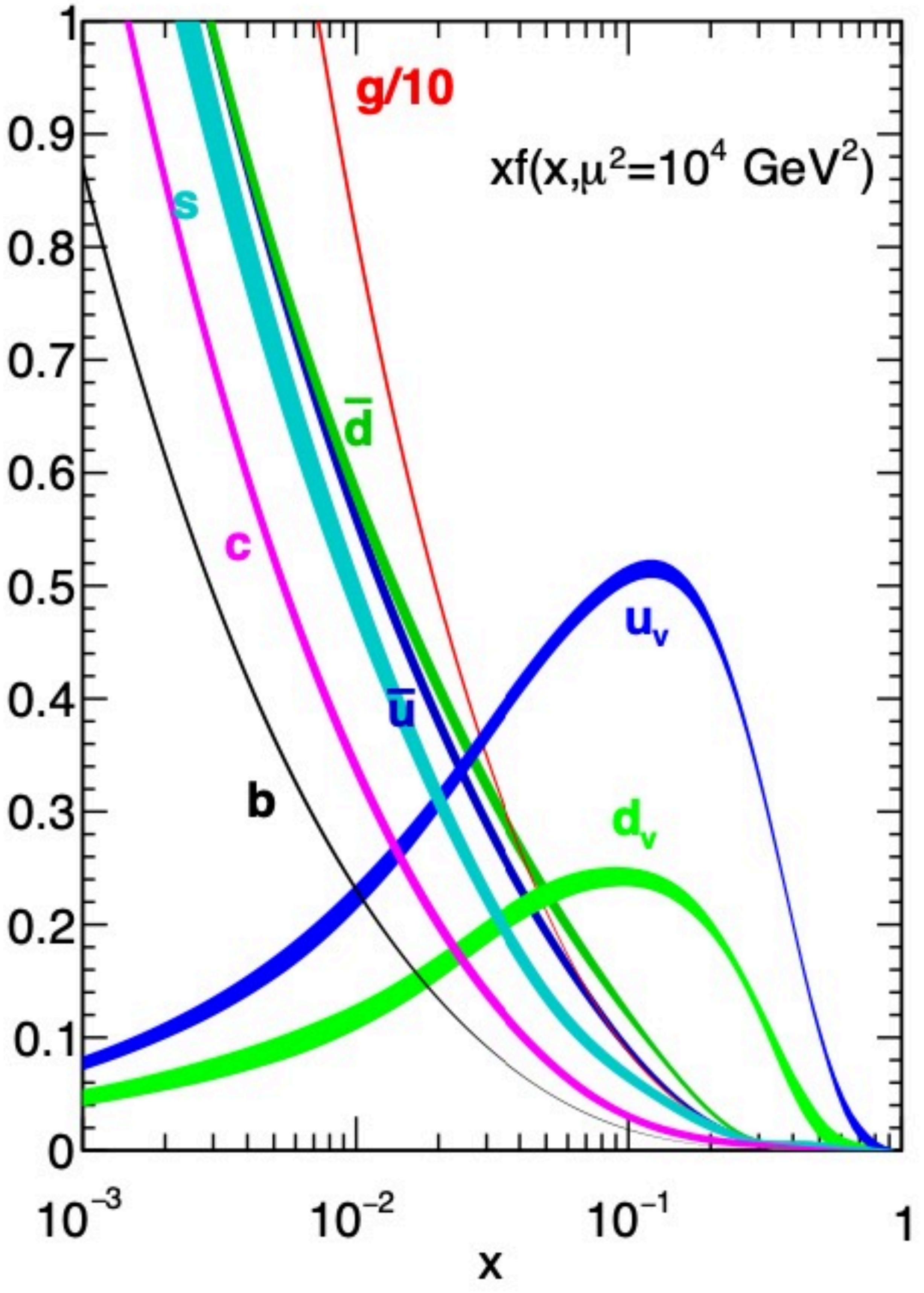
QCD global analysis of world data

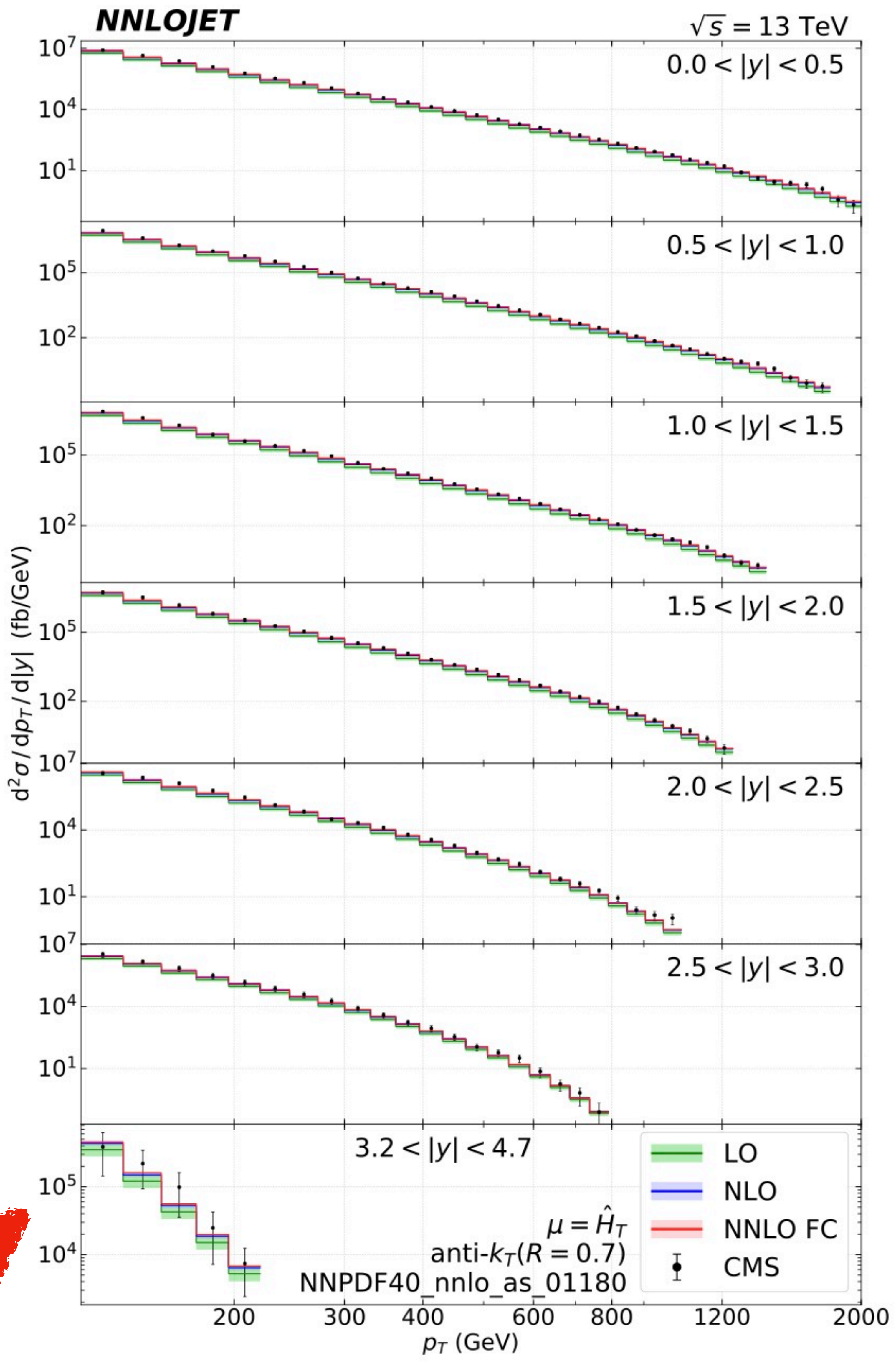
✦ Current knowledge about proton PDFs



NNPDF:1706.00428

QCD evolution





Predictive power of pQCD

X. Chen et al, JHEP, 2022

Nucleon partonic structure - spin configuration

✦ Naive parton model

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

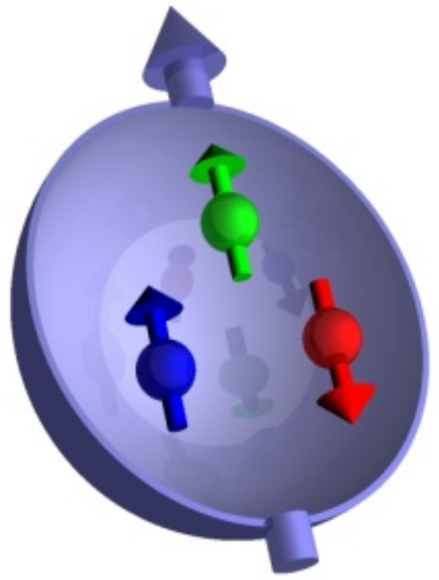
proton spin 1/2 is consistent with naive parton model, but contradict with experiments.

✦ Proton spin decomposition

Jaffe, Manohar; Ji

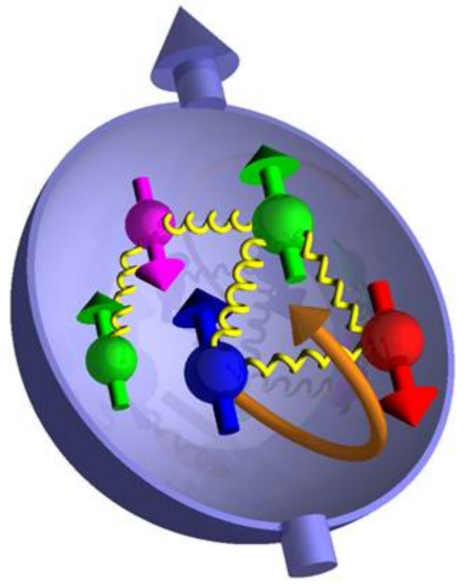
$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}|J^z_{QCD}|P,\frac{1}{2}\right\rangle = \frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2)+\int_0^1 dx\Delta G(x,Q^2)+\int_0^1 dx\Big(\sum_q L_q^z + L_g^z\Big)$$

total quark spin



gluon spin

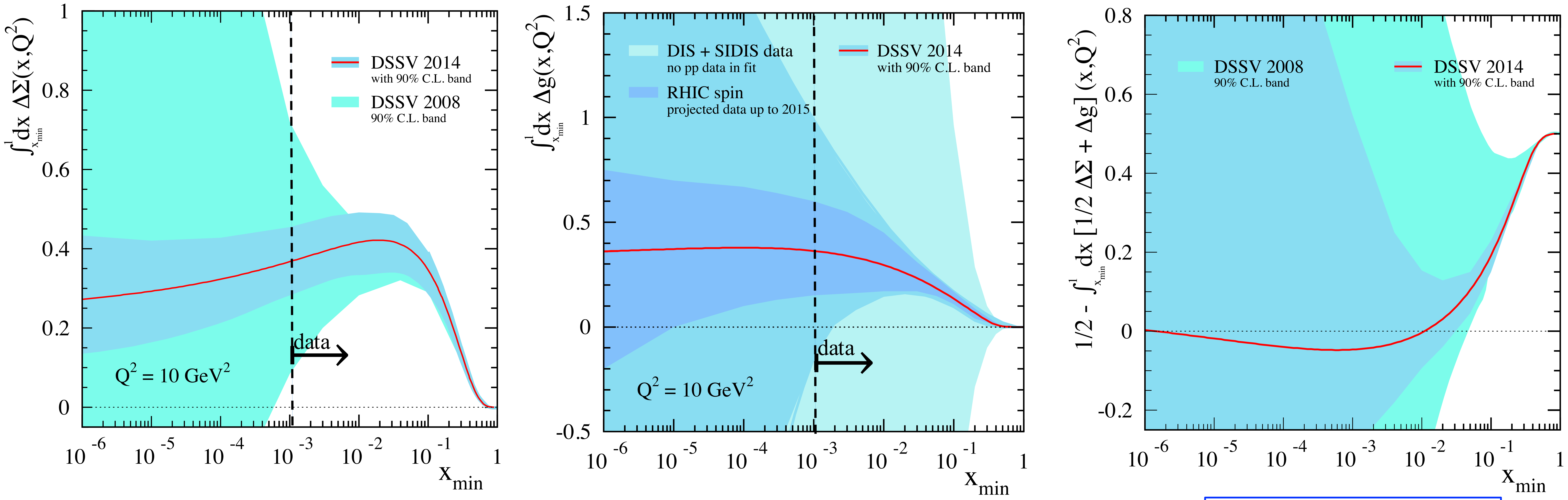
angular momentum



- 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%

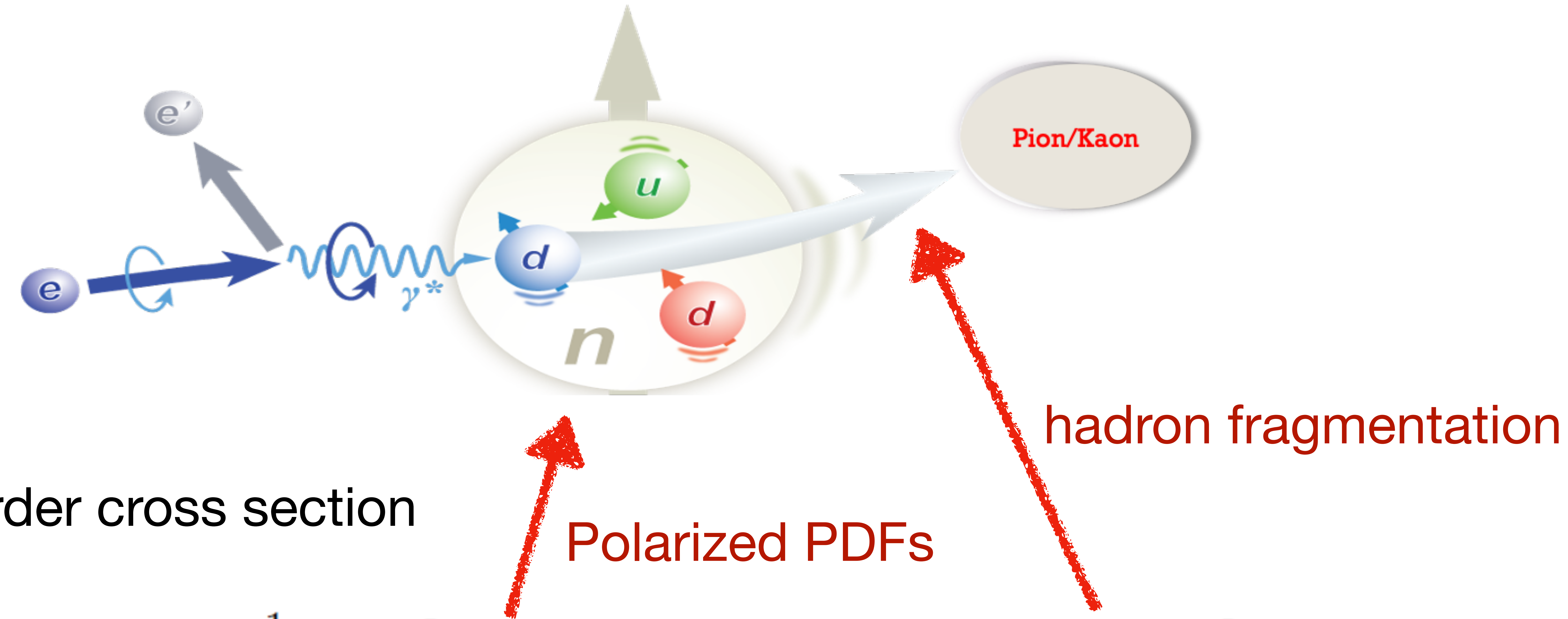
Gluon ~ 40%

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



- Leading order cross section

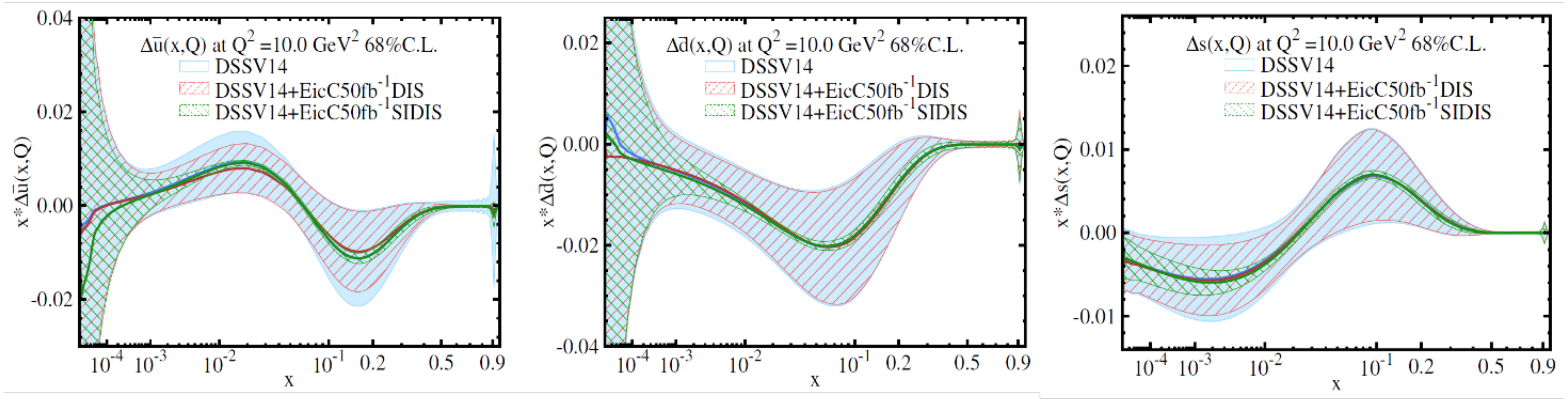
$$g_1^h(x,Q^2,z) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q(x,Q^2) D_q^h(z,Q^2) + \Delta\bar{q}(x,Q^2) D_{\bar{q}}^h(z,Q^2)\right]$$

Extracted nucleon structure information: polarized PDFs (helicity distribution)

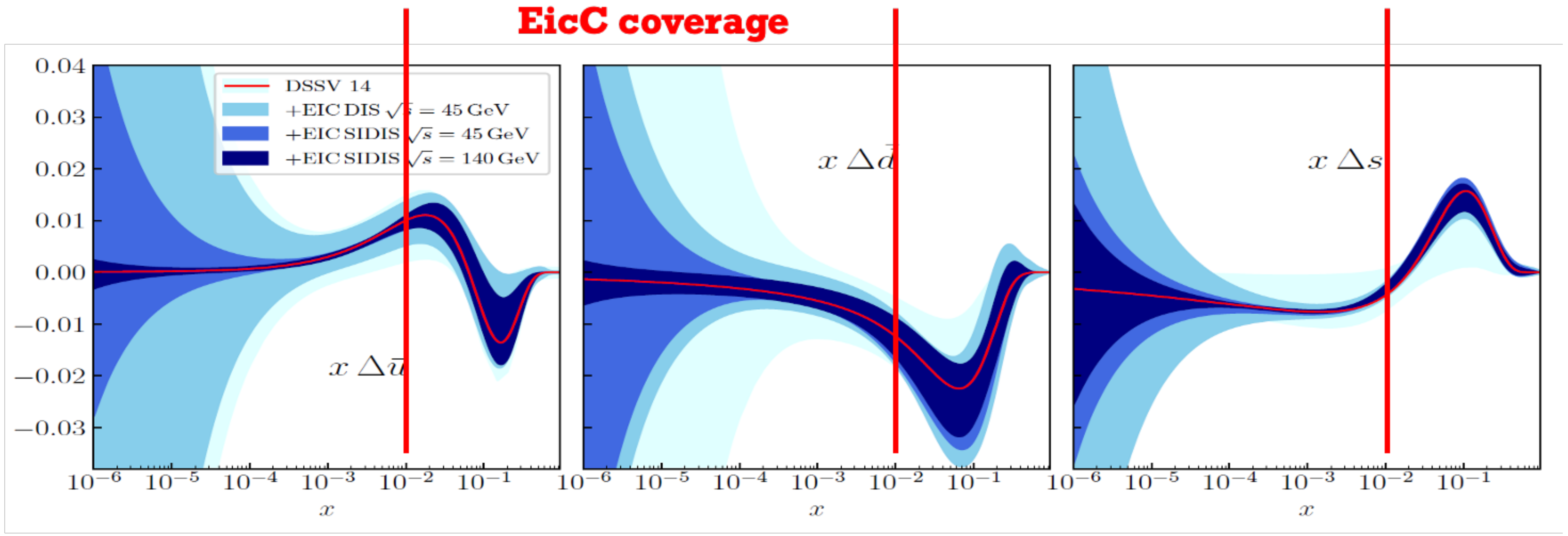
What can we do in future to pin down the proton spin?

✦ SIDIS for flavor decomposition

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



EicC white paper

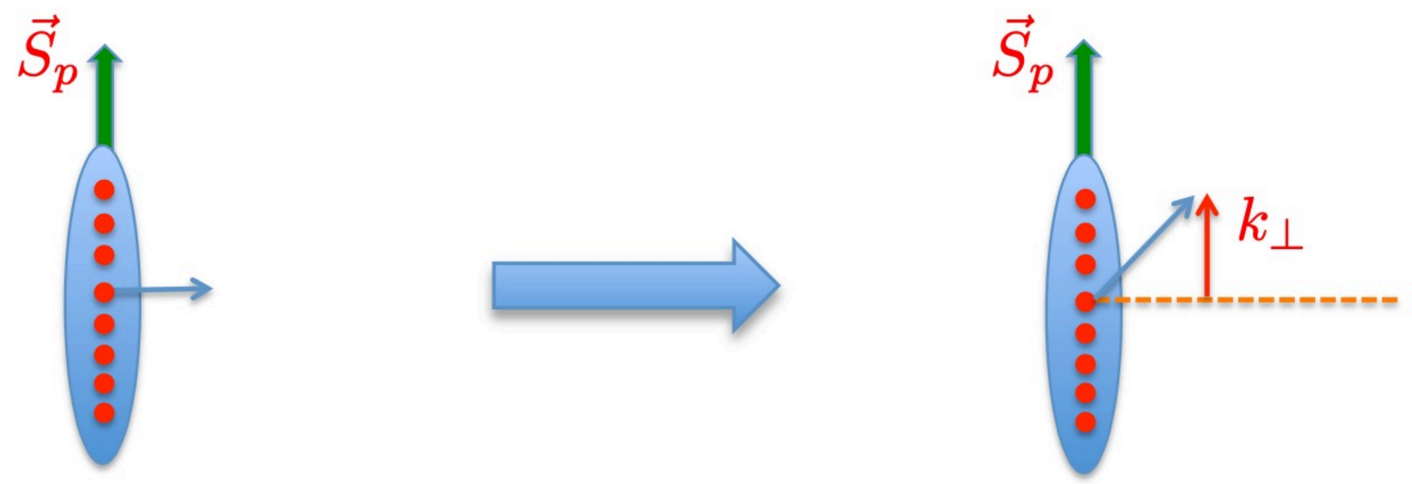


EIC Yellow Report

Nucleon partonic structure - 3D imaging

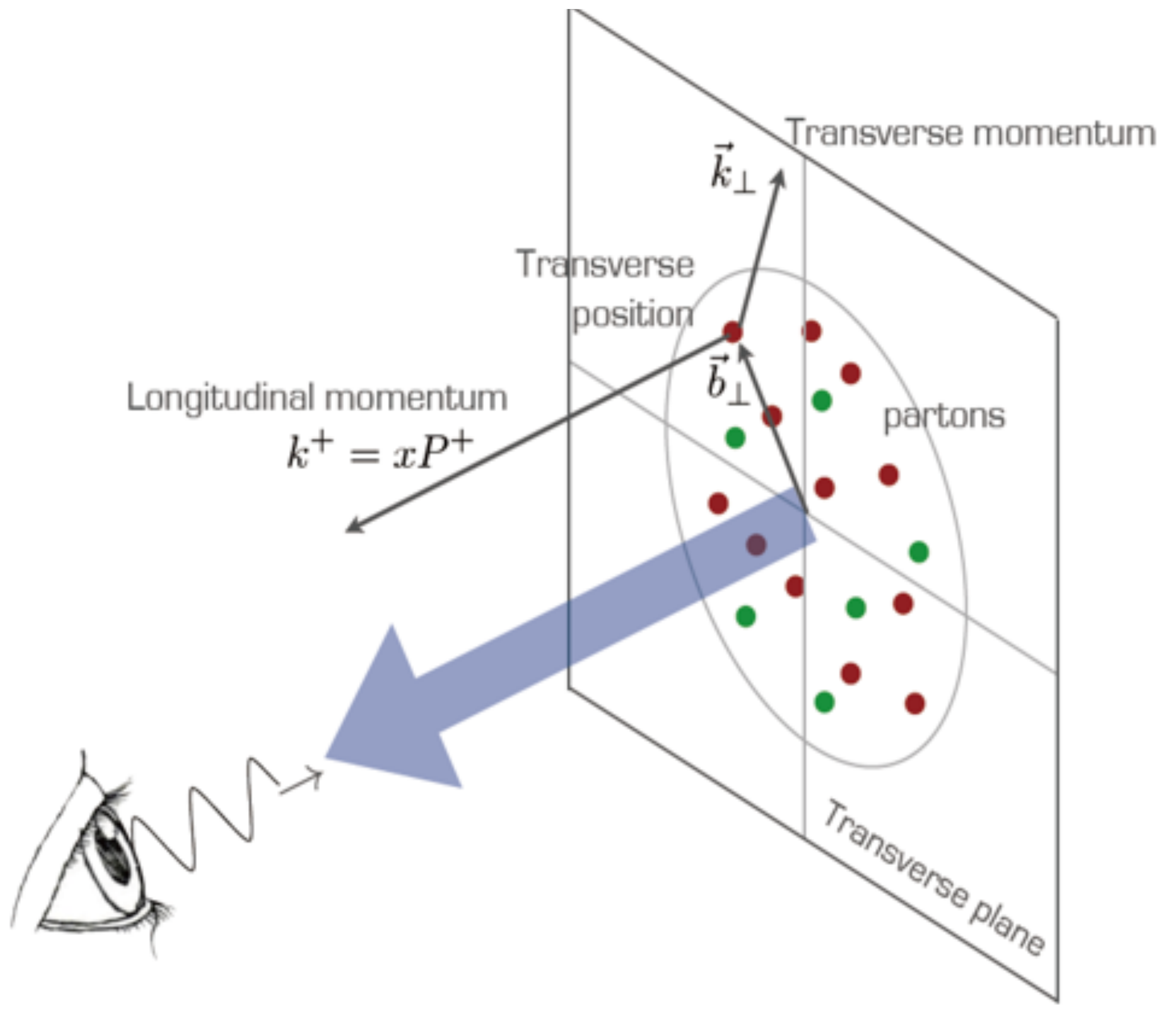
Nucleon partonic structure - 3D imaging

✦ Transverse momentum dependent PDFs (TMDs)

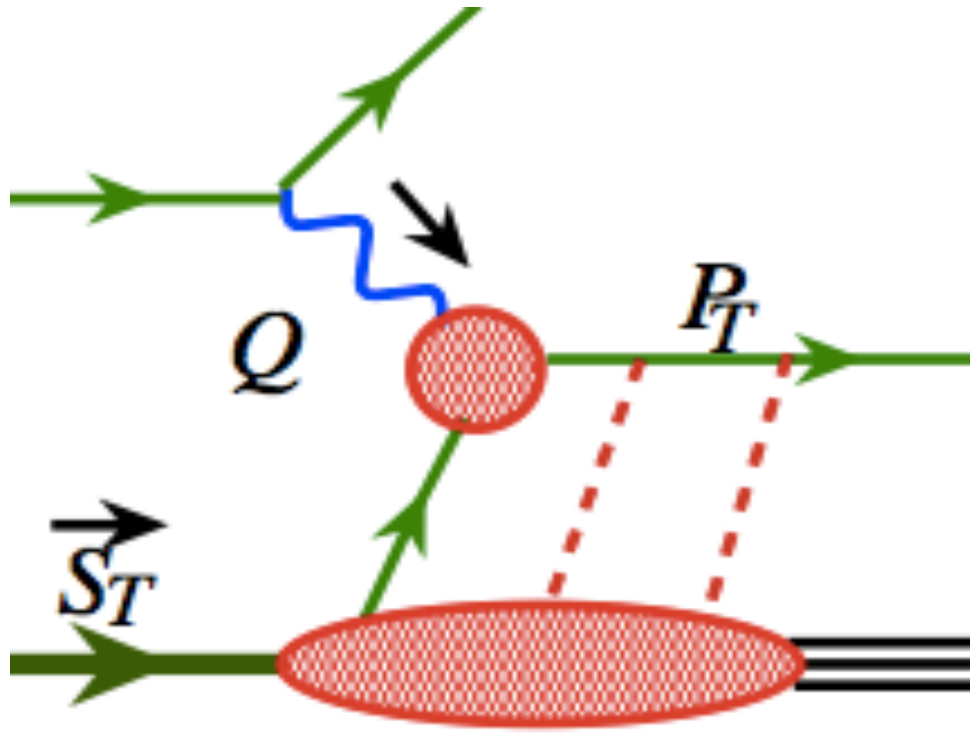


$f(x)$ $\qquad$ $f(x, k_\perp)$

Collinear PDFs ⟶ **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

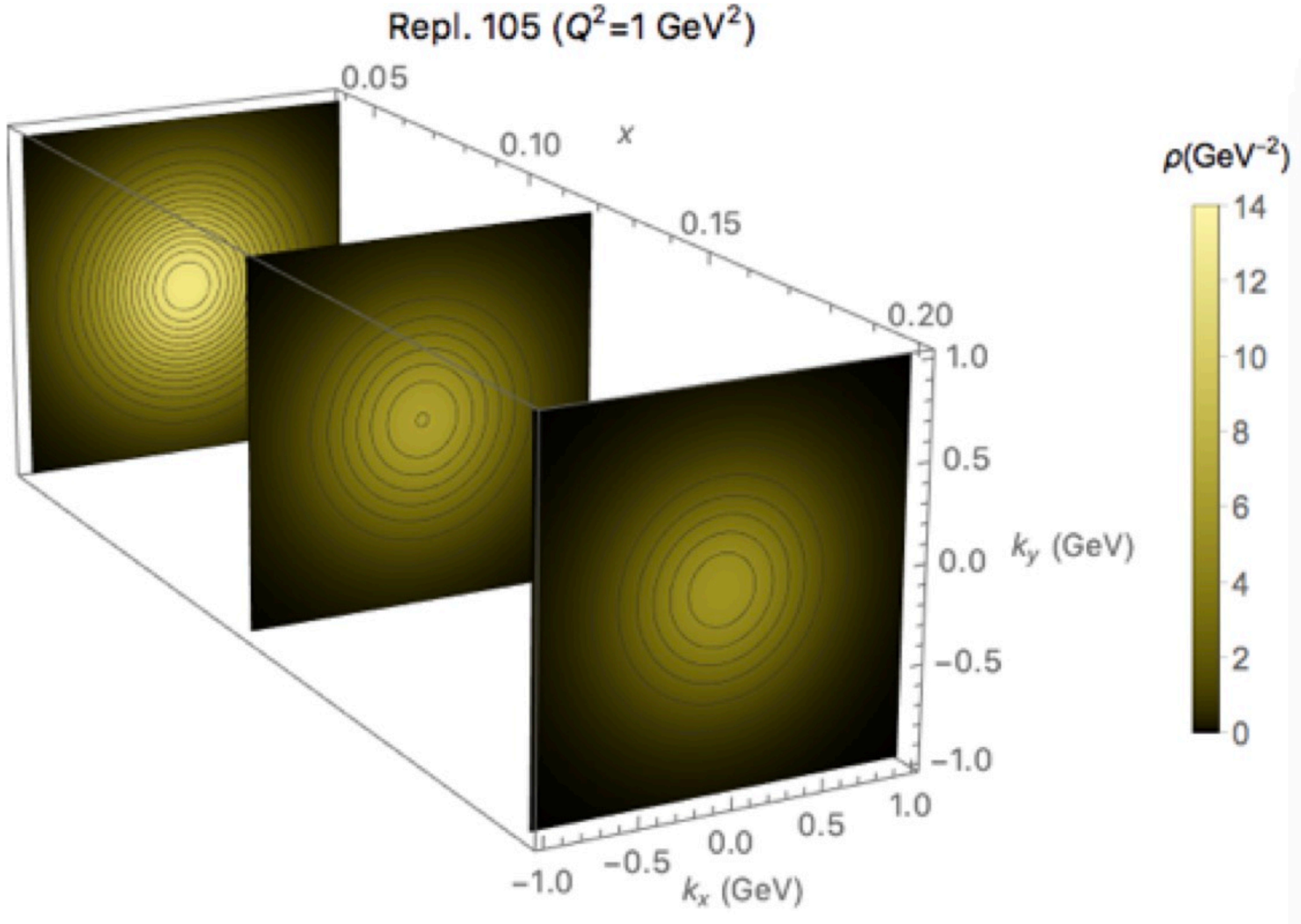
		Quark polarization		
		Unpolarized (U)	**Longitudinally Polarized (L)**	**Transversely Polarized (T)**
Nucleon Polarization	**U**	f_1 =		$h_1^{\perp}$ = − Boer-Mulders
	L		g_1 = − Helicity	$h_{1L}^{\perp}$ = − Worm Gear
	T	$f_{1T}^{\perp}$ = − Sivers	g_{1T} = − Worm Gear	h_1 = − Transversity $h_{1T}^{\perp}$ = − Pretzelosity

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

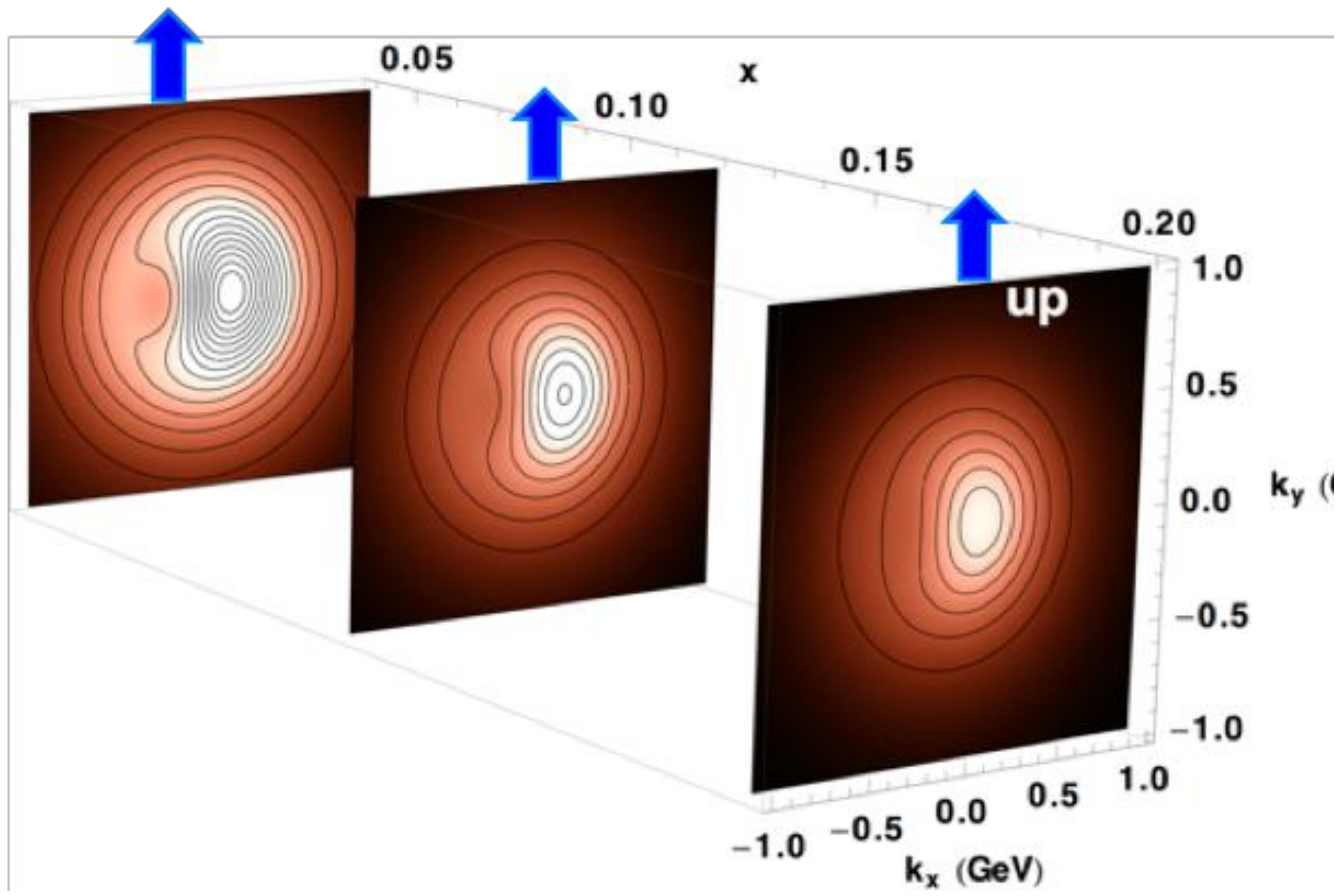
Nucleon partonic structure - 3D imaging

By Andrea Signori

Unpolarized proton



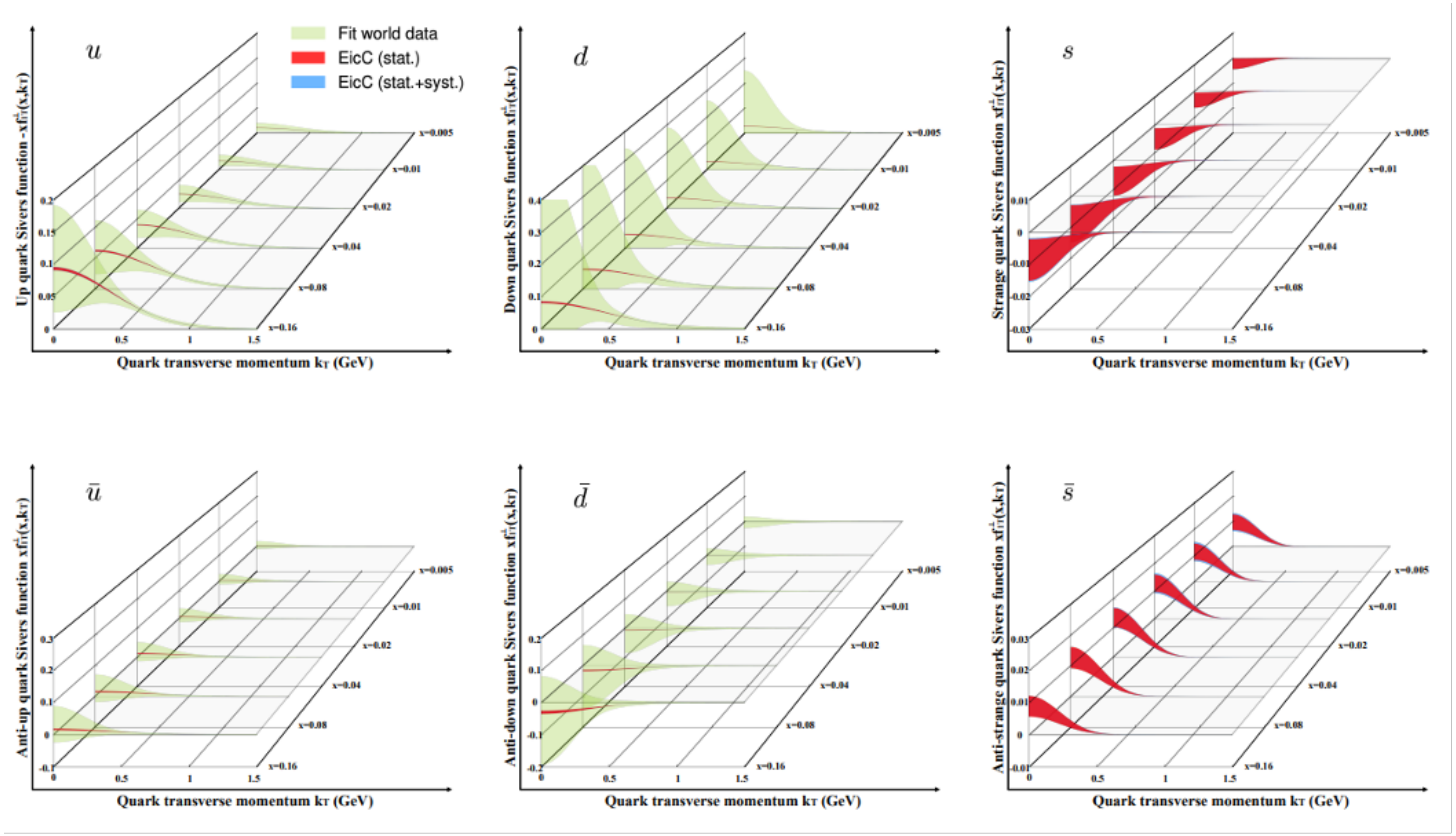
Transversely polarized proton



Transversely polarized quark distribution is distorted!

Nucleon 3D imaging at EicC - Sivers effect

Liu, Zhao, Zheng, 2023



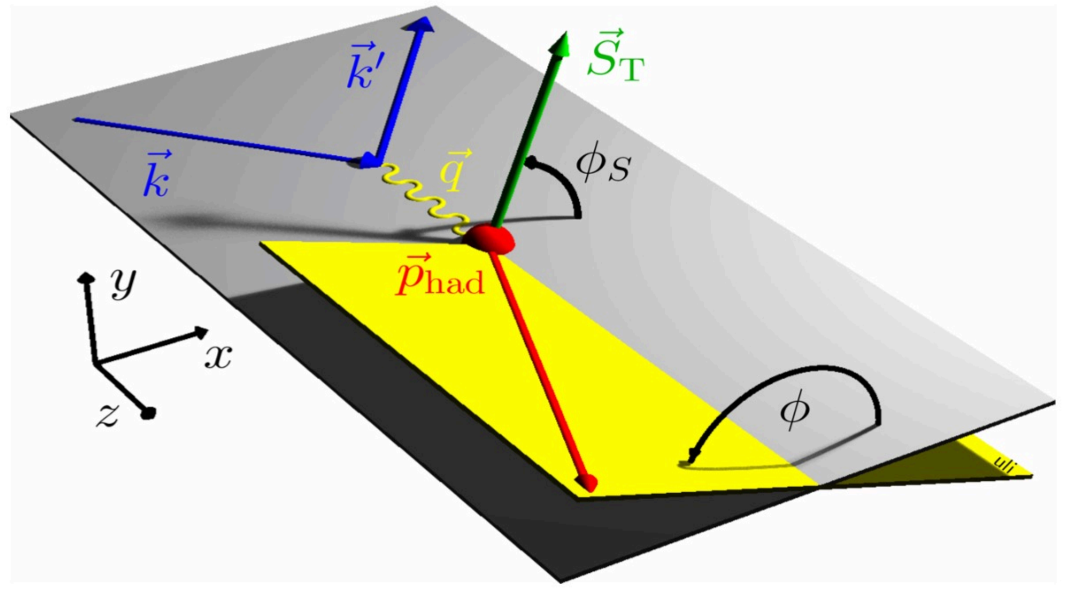
u/d Sivers EicC vs world data

LO analysis

EicC SIDS data:

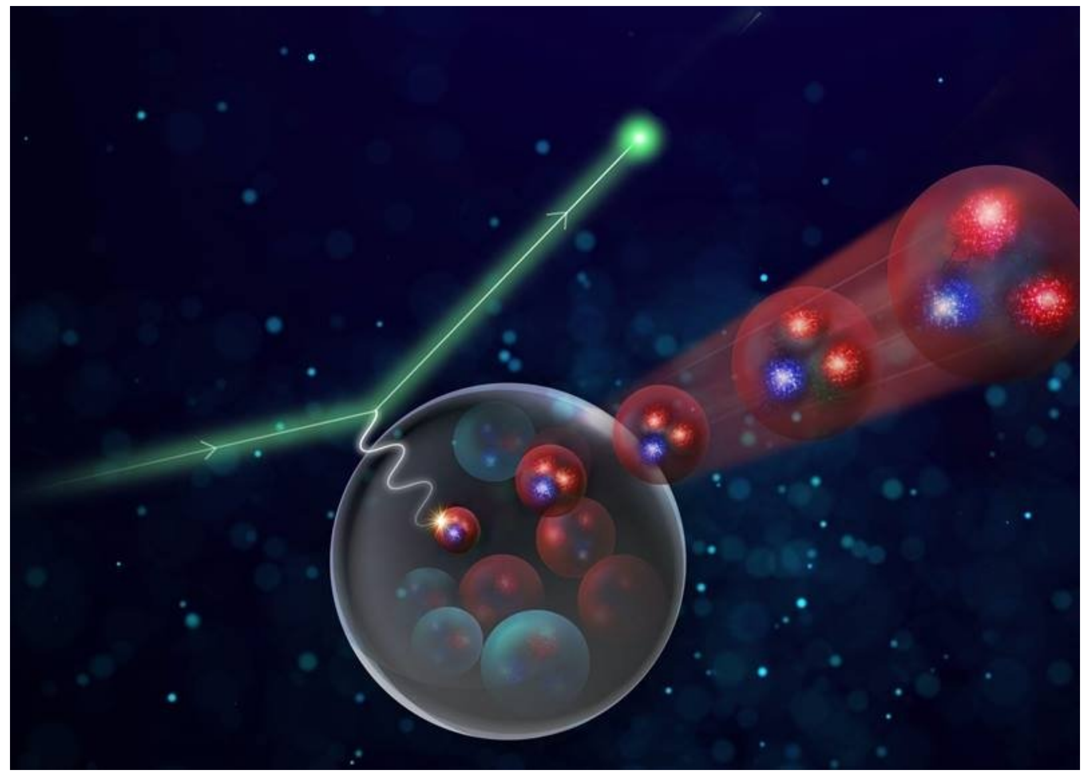
- Pion(+/-), Kaon(+/-)
- ep: 3.5 GeV X 20 GeV
- eHe-3: 3.5 GeV X 40 GeV
- Pol.: e(80%), p(70%), He-3(70%)
- Lumi: ep 50 fb^{-1}, eHe-3 50 fb^{-1}

EicC, precise measurements.

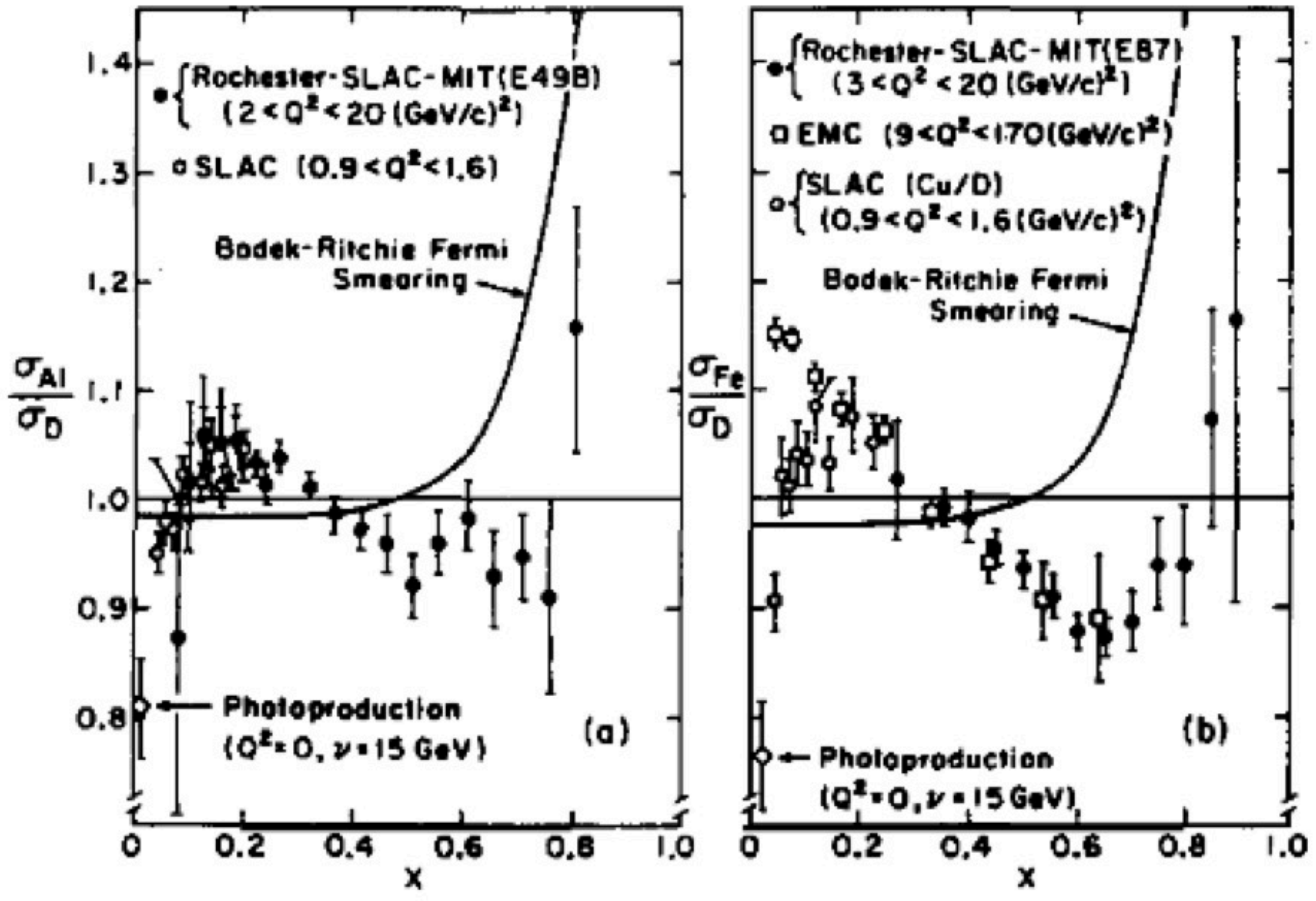


“Old” and long standing problems of nuclear partonic structure

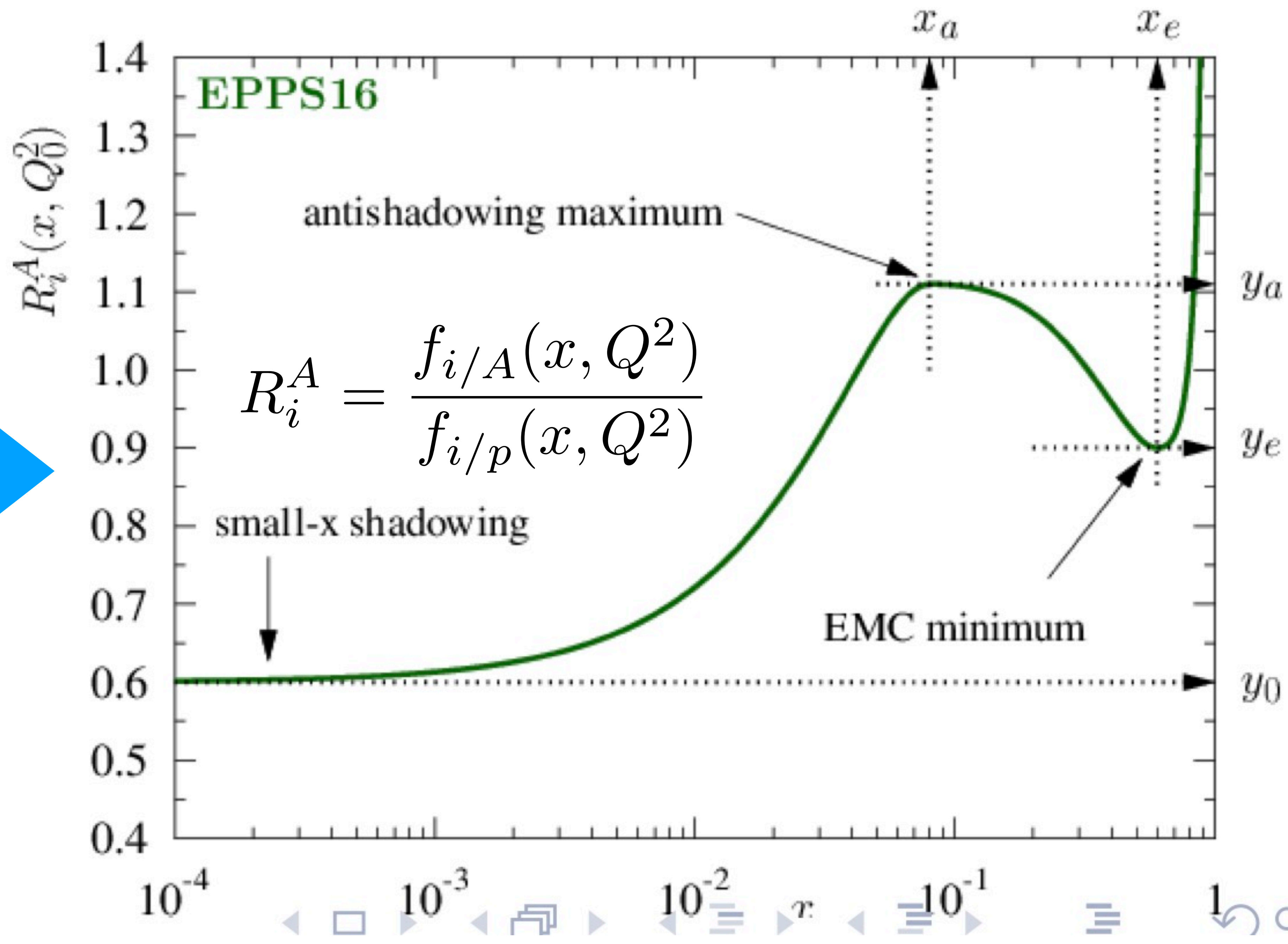
✦ One-dimensional nuclear partonic structure



Four Decades of the EMC Effect

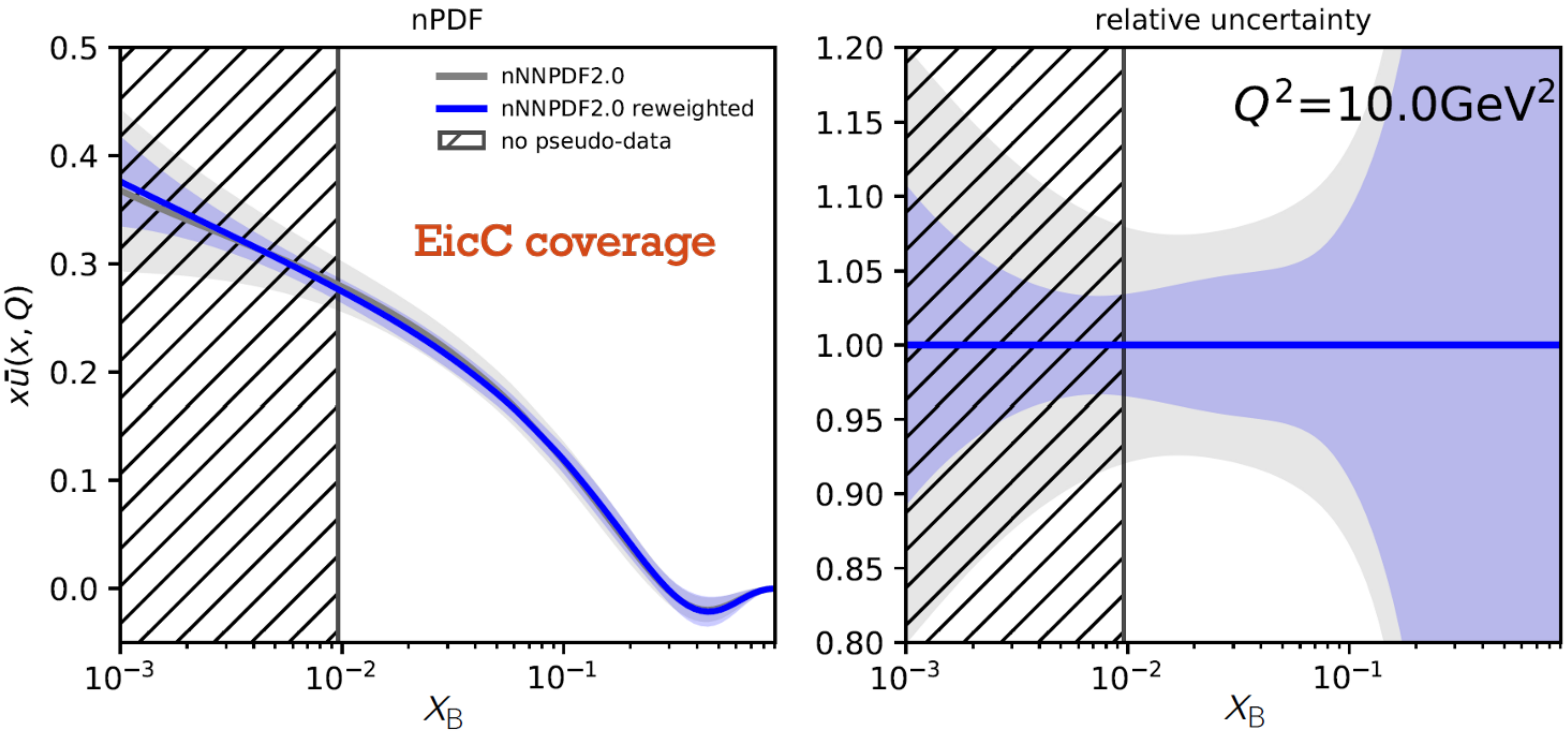


EMC Collaboration, 1983



Power of EicC for nuclear partonic structure - 1D

✦ Nuclear partonic structure - nuclear quark distribution

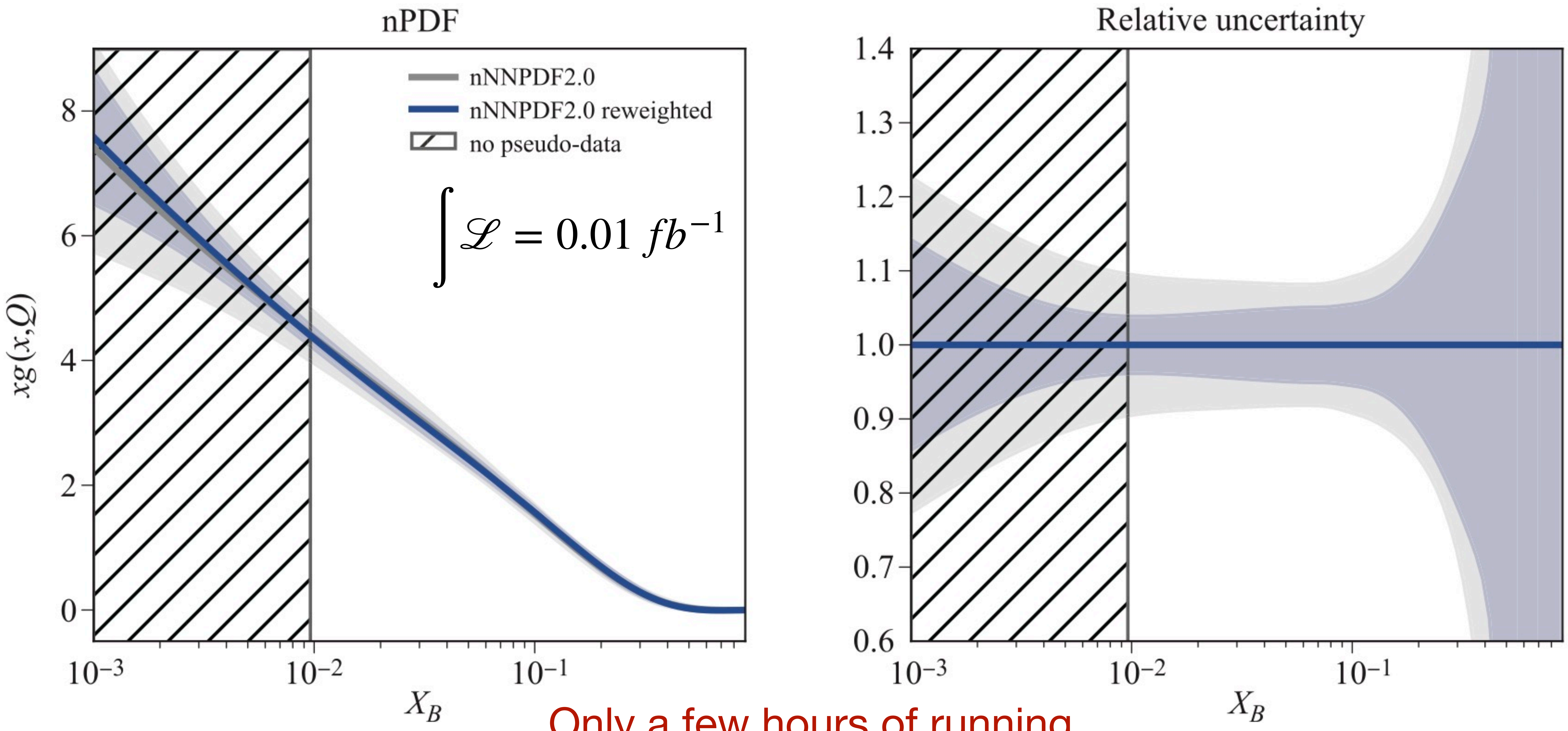


$$\int \mathscr{L} = 0.01\ fb^{-1}$$

Only a few hours of running

Power of EicC for nuclear partonic structure - 1D

✦ Nuclear partonic structure - nuclear gluon distribution

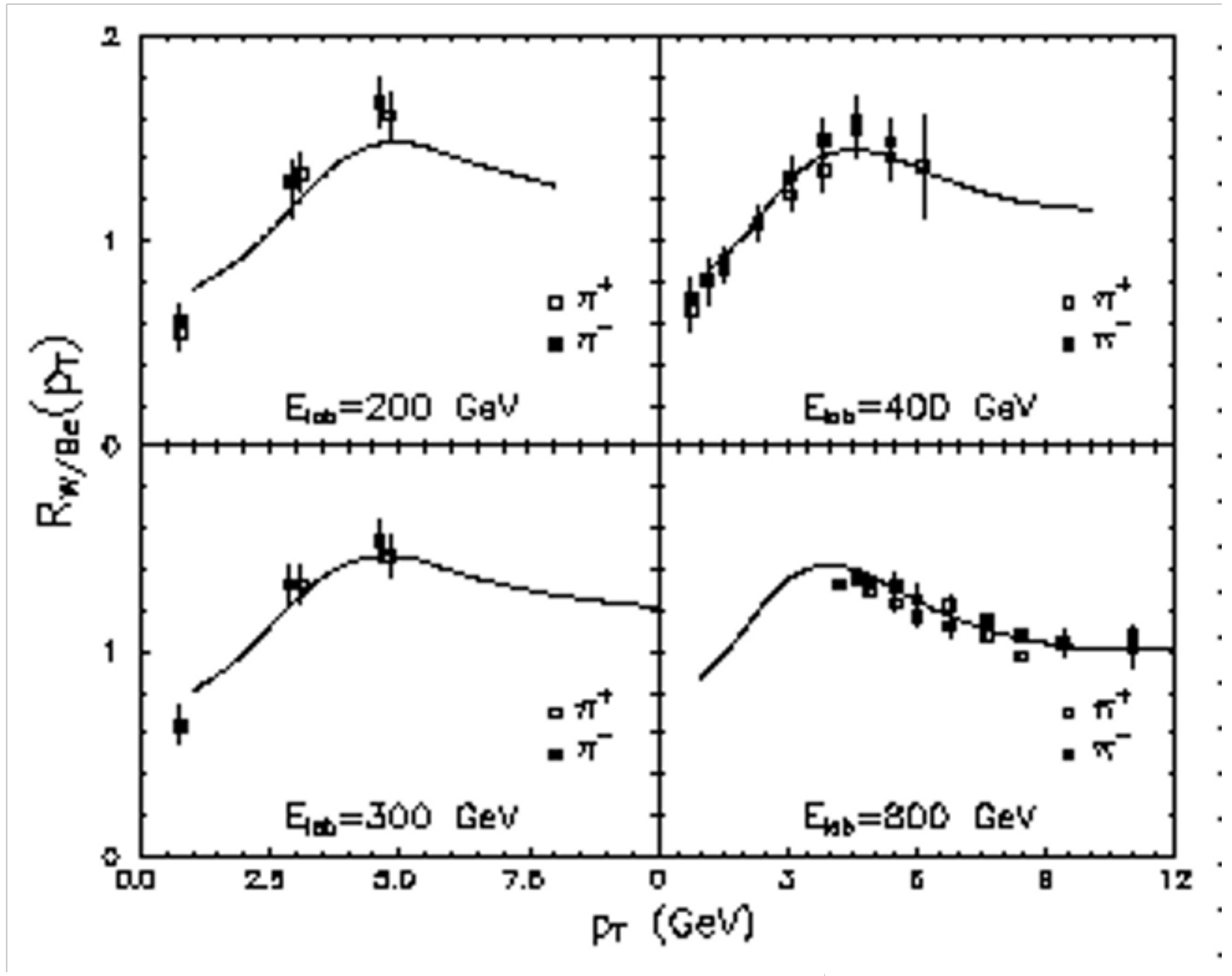


Only a few hours of running

“Old” and long standing problems of nuclear partonic structure

✦ Three-dimensional nuclear partonic structure

Cronin effect

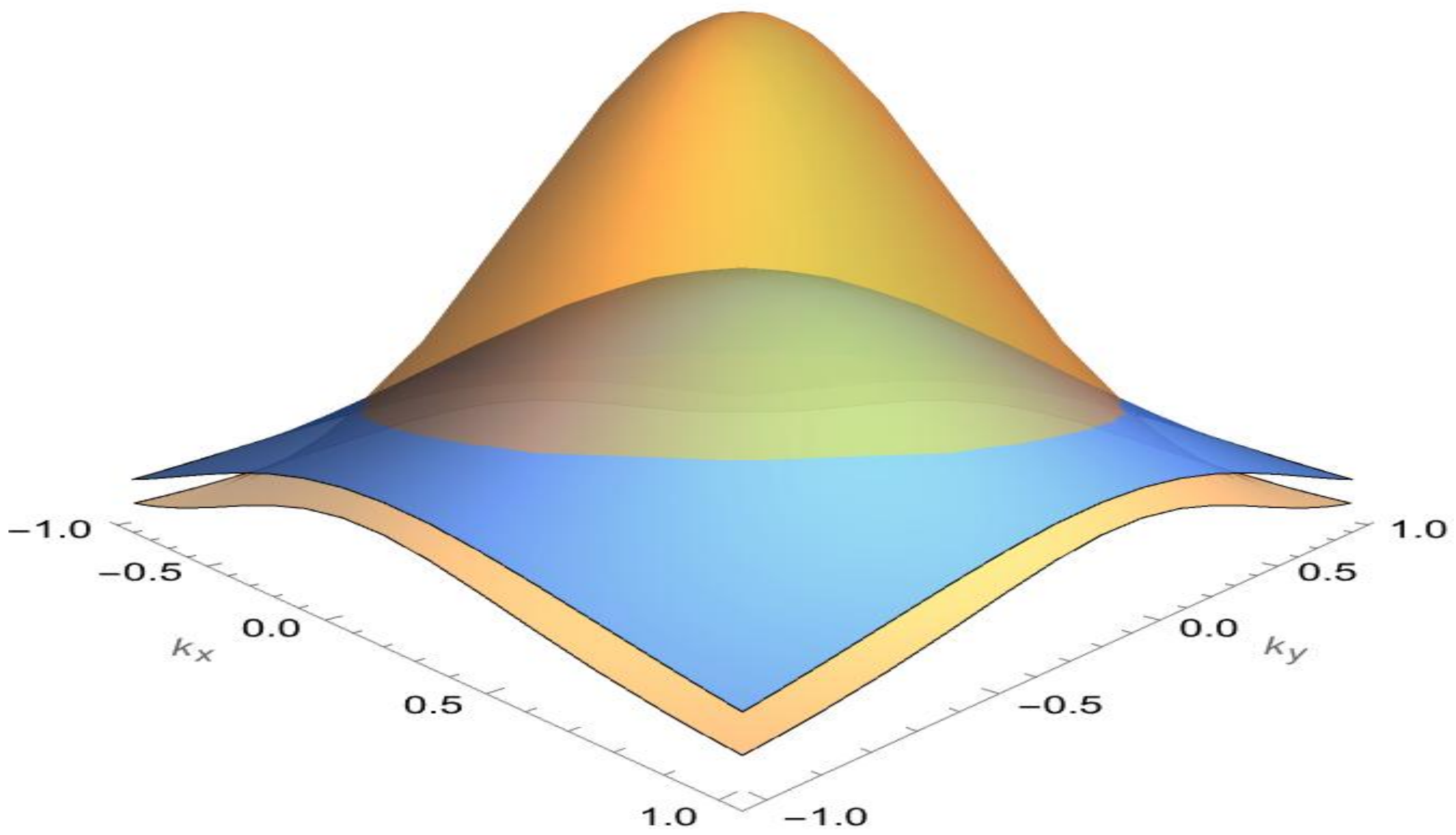


$$p + A \to \text{hadron(p)} + X \qquad R(p_T) = \frac{B}{A}\frac{d\sigma_{pA}/d^2p_T}{d\sigma_{pB}/d^2p_T}$$

E100 Collaboration, PRD 11, 3105 (1975)

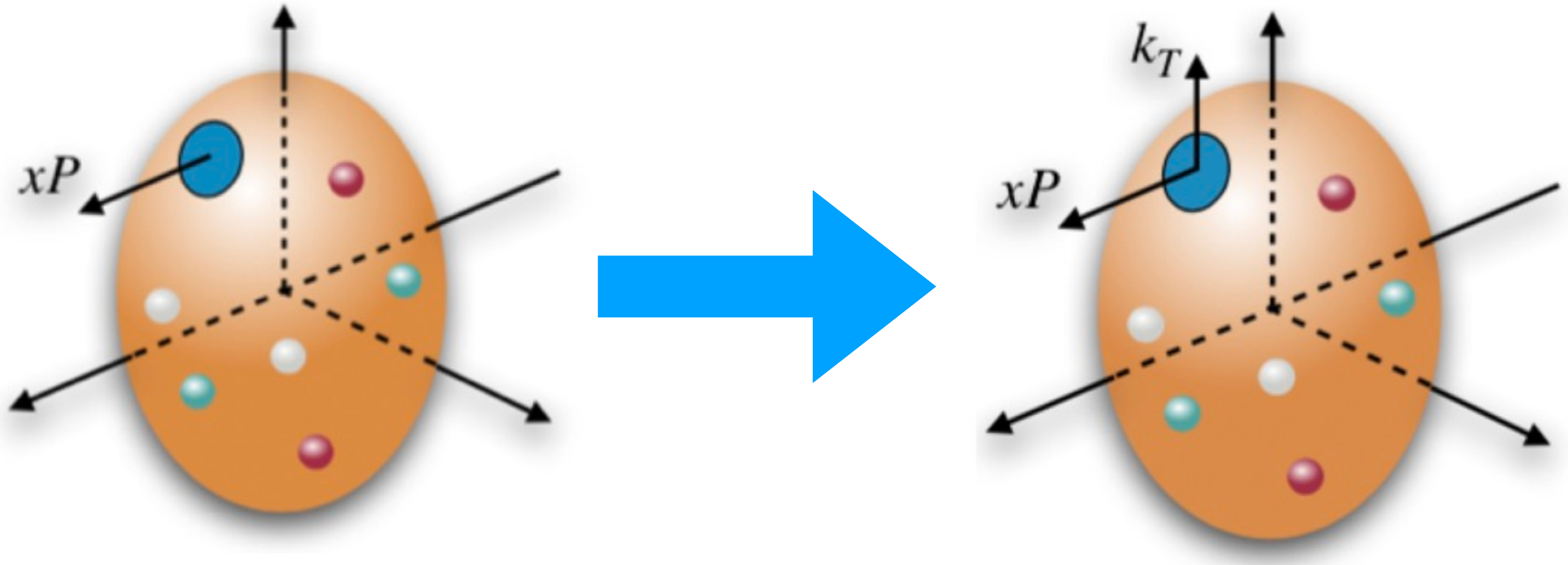
- Naive Gaussian model

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



Nuclear 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

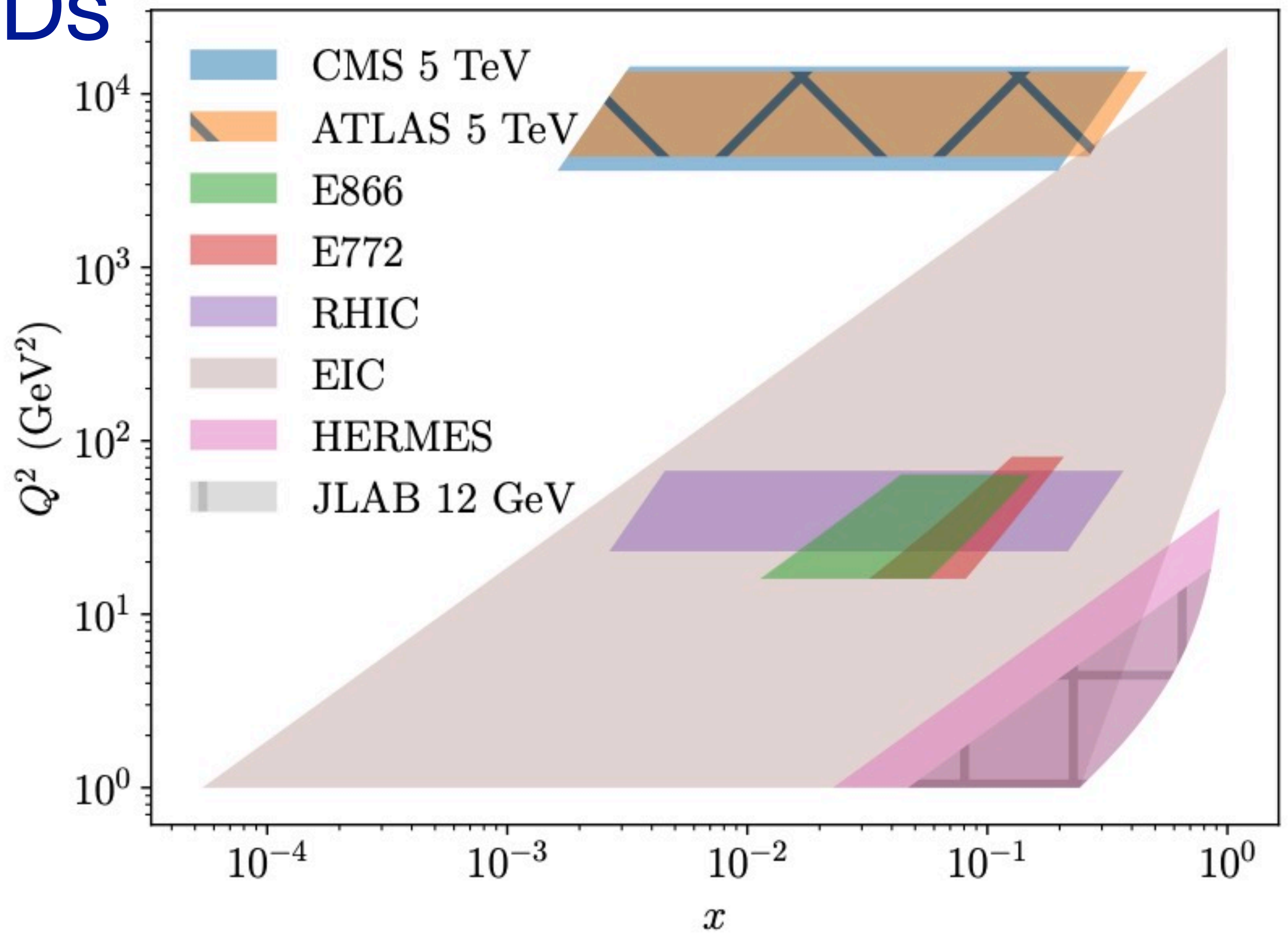
✦Two scale processes are necessary for TMDs

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

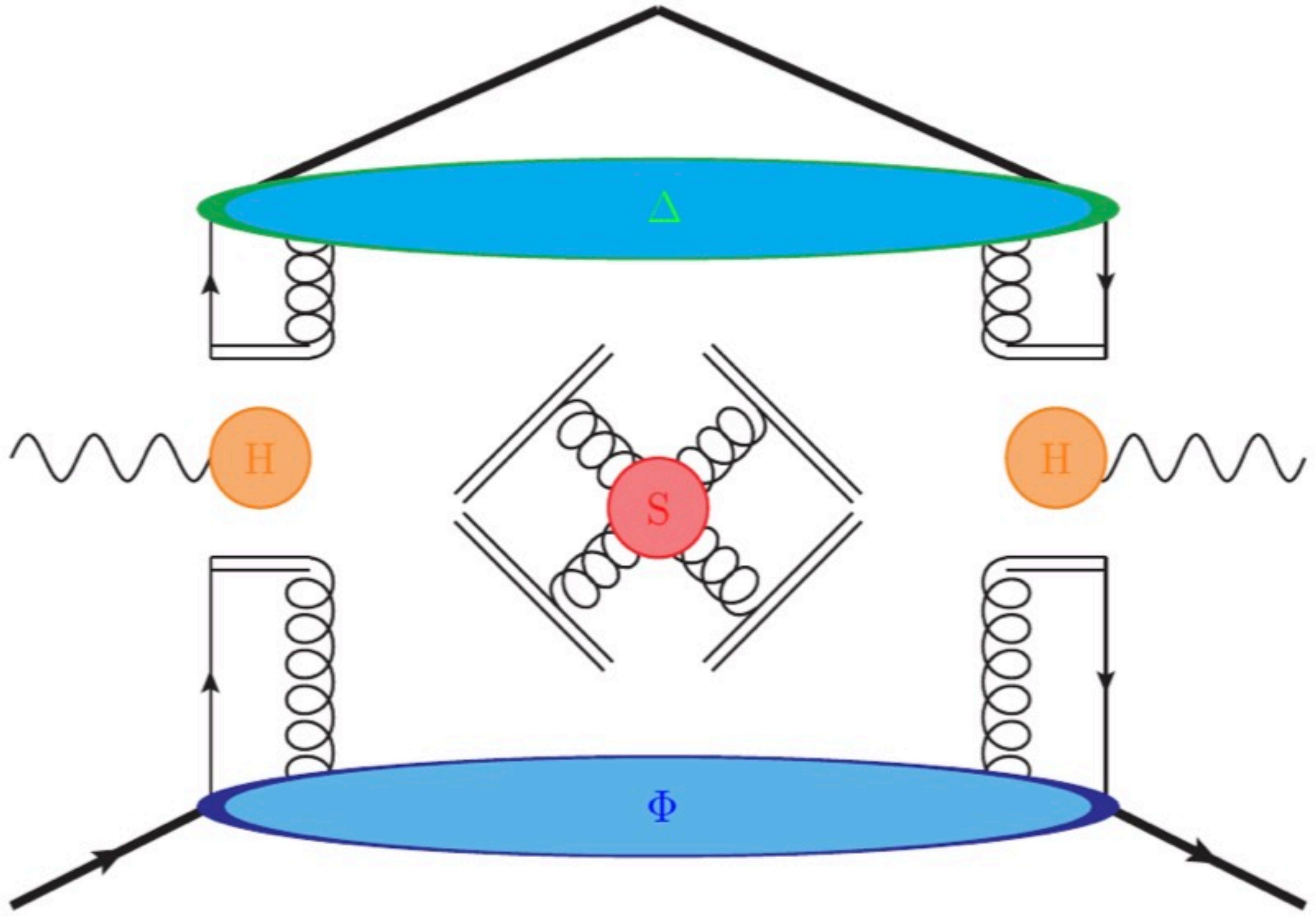
- Multiplicity ratio $R_h^A = M_h^A / M_h^D$.
  -HERMES 2007
  -Prelim. JLab
  -Planned JLab
  -Possible EIC.



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

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

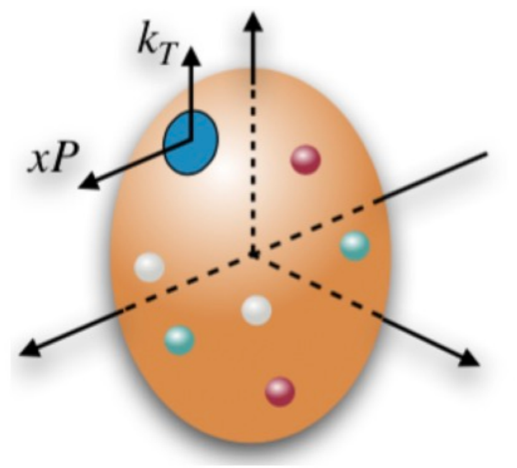
$$D_{h/q}^A(z,b;Q) = \frac{1}{z^2}\left[\hat{C}_{i\leftarrow q}\otimes D_{h/i}^A\right](z,\mu_{b_*})\exp\left\{-S_{\rm pert}(\mu_{b_*},Q) - S_{\rm NP}^D(b,z,Q,A)\right\}$$

Non-perturbative parametrization

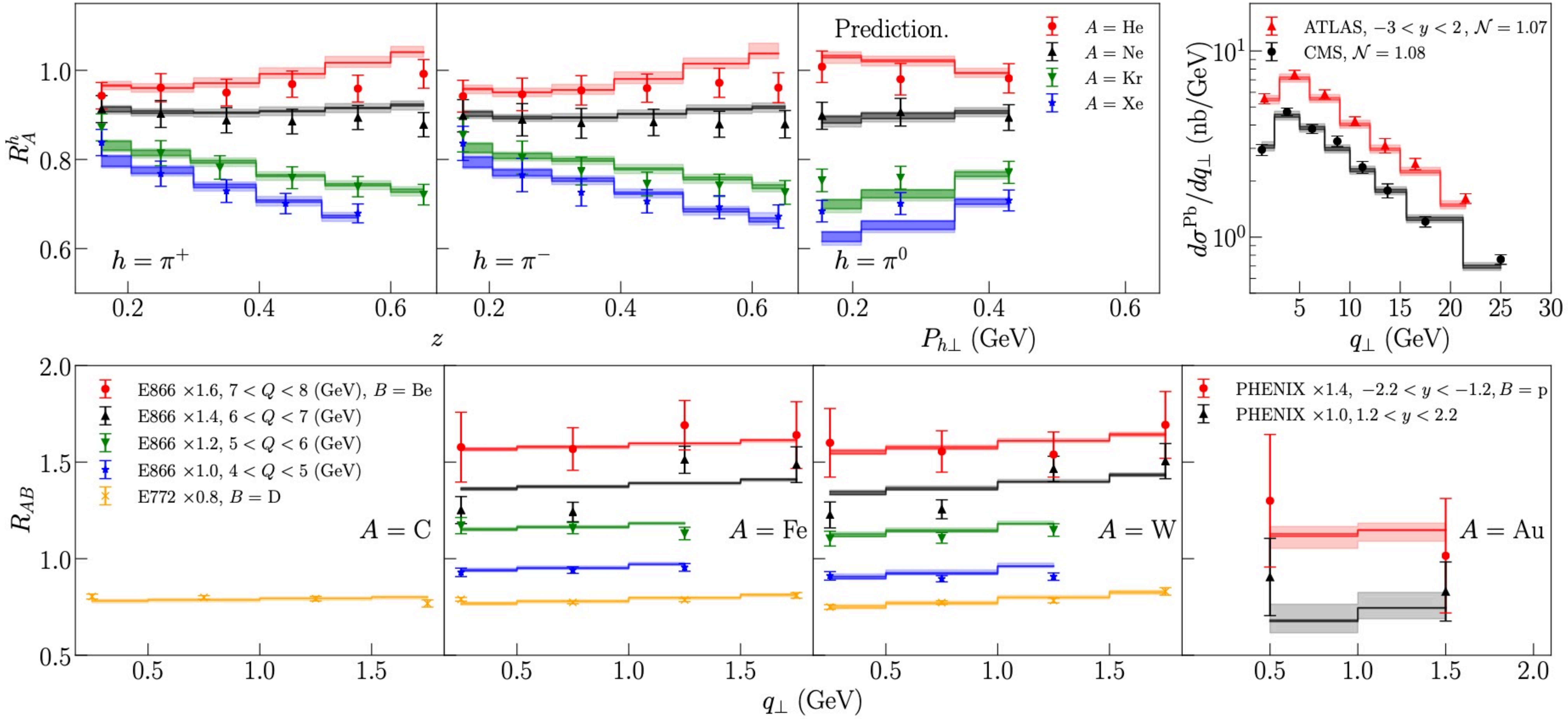
$$S_{\rm NP}^f(b,Q,A) = S_{\rm NP}^f(b,Q) + a_N\left(A^{1/3}-1\right)b^2$$

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

nuclear 3D imaging - global extraction from world data



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

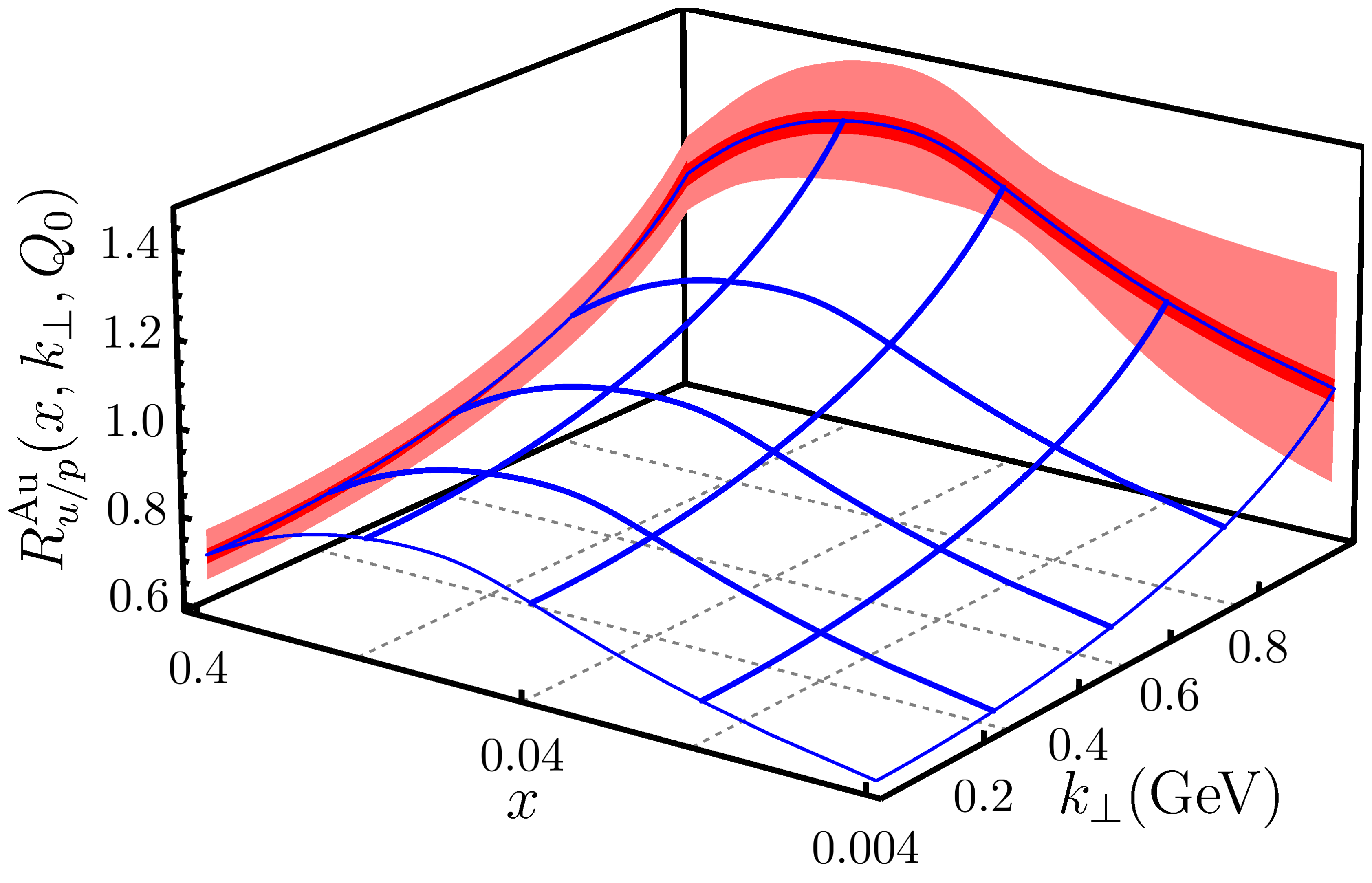


Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

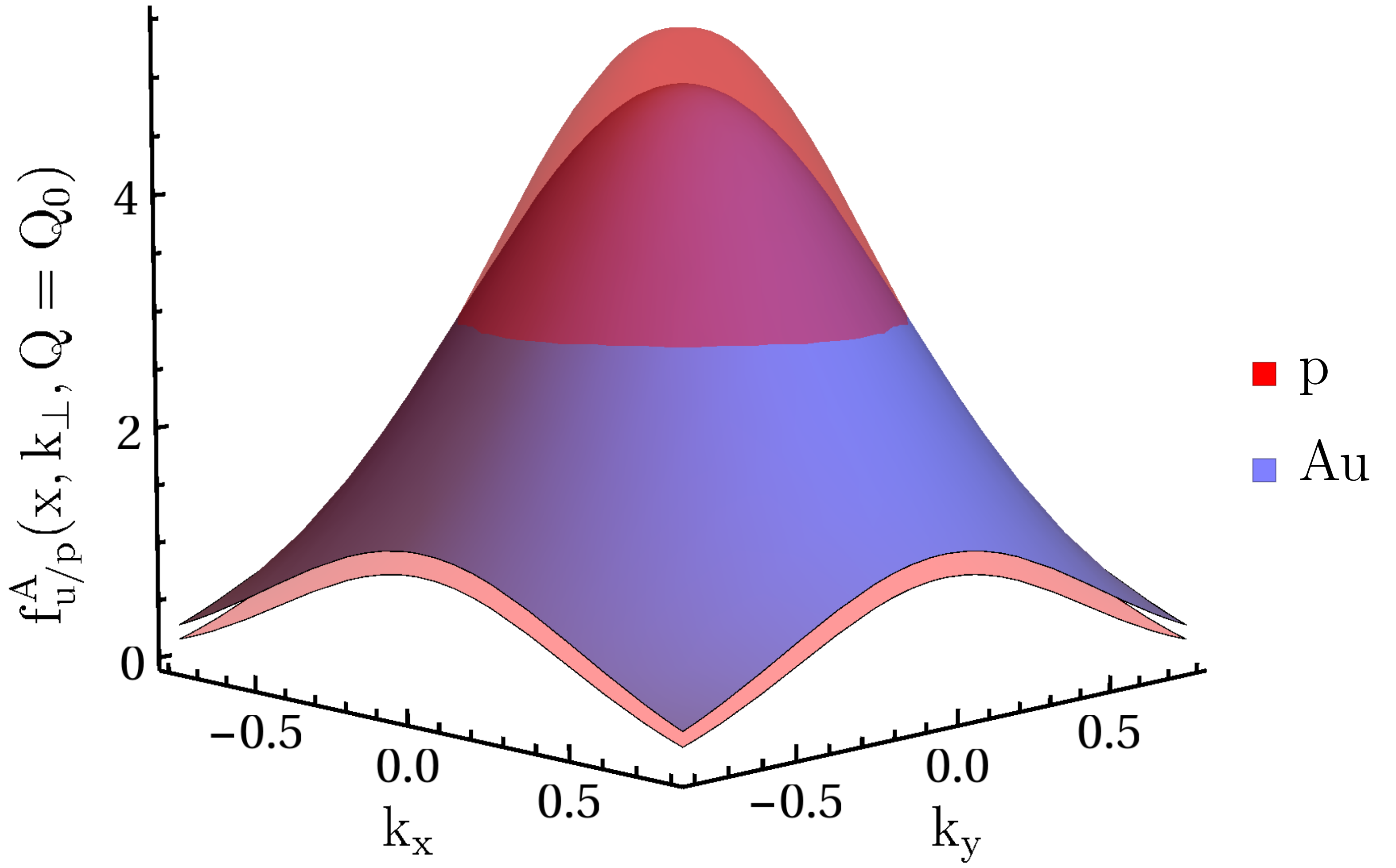
Three-dimension imaging in nuclei

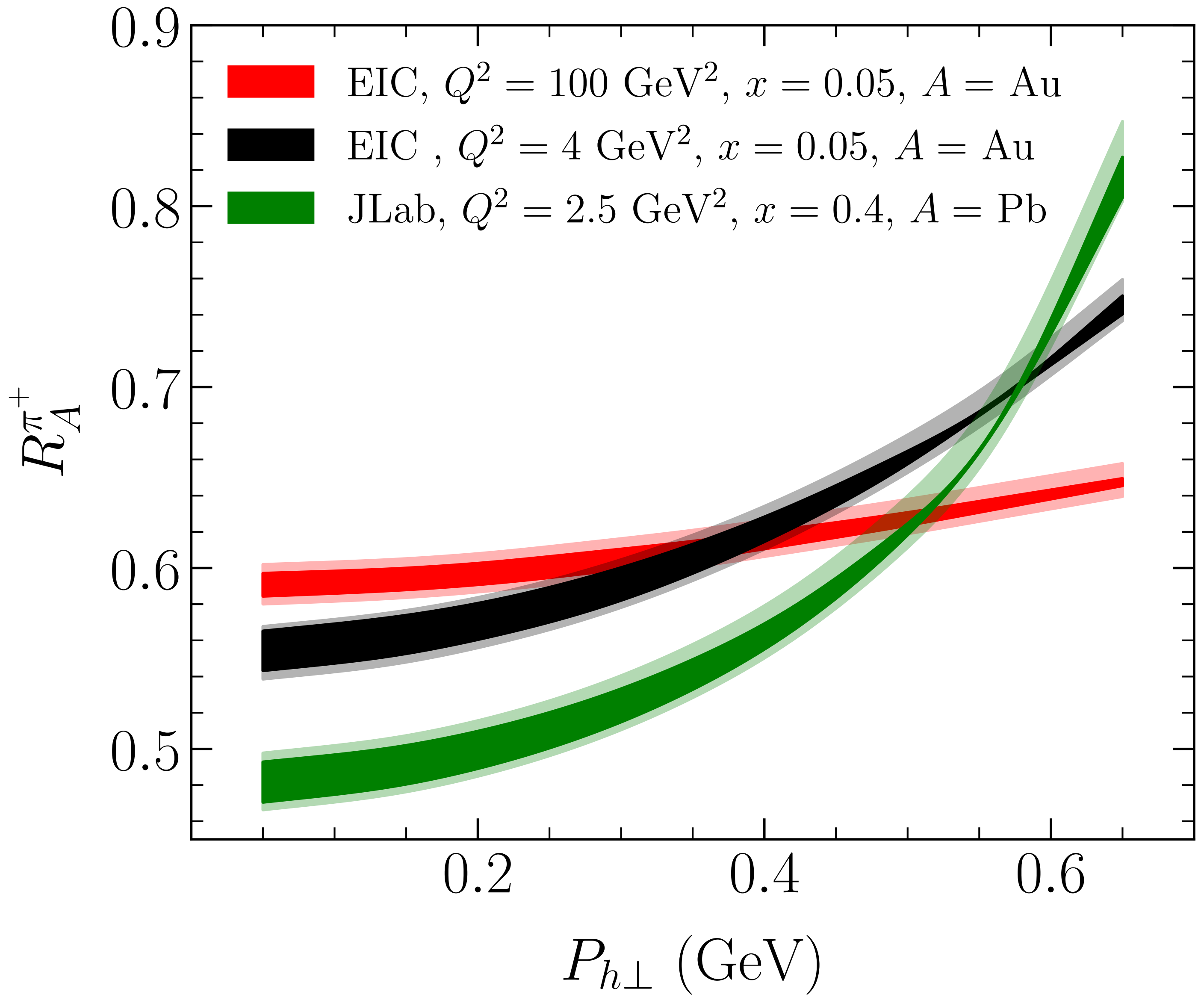
✦ Three-dimensional nuclear partonic structure

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



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



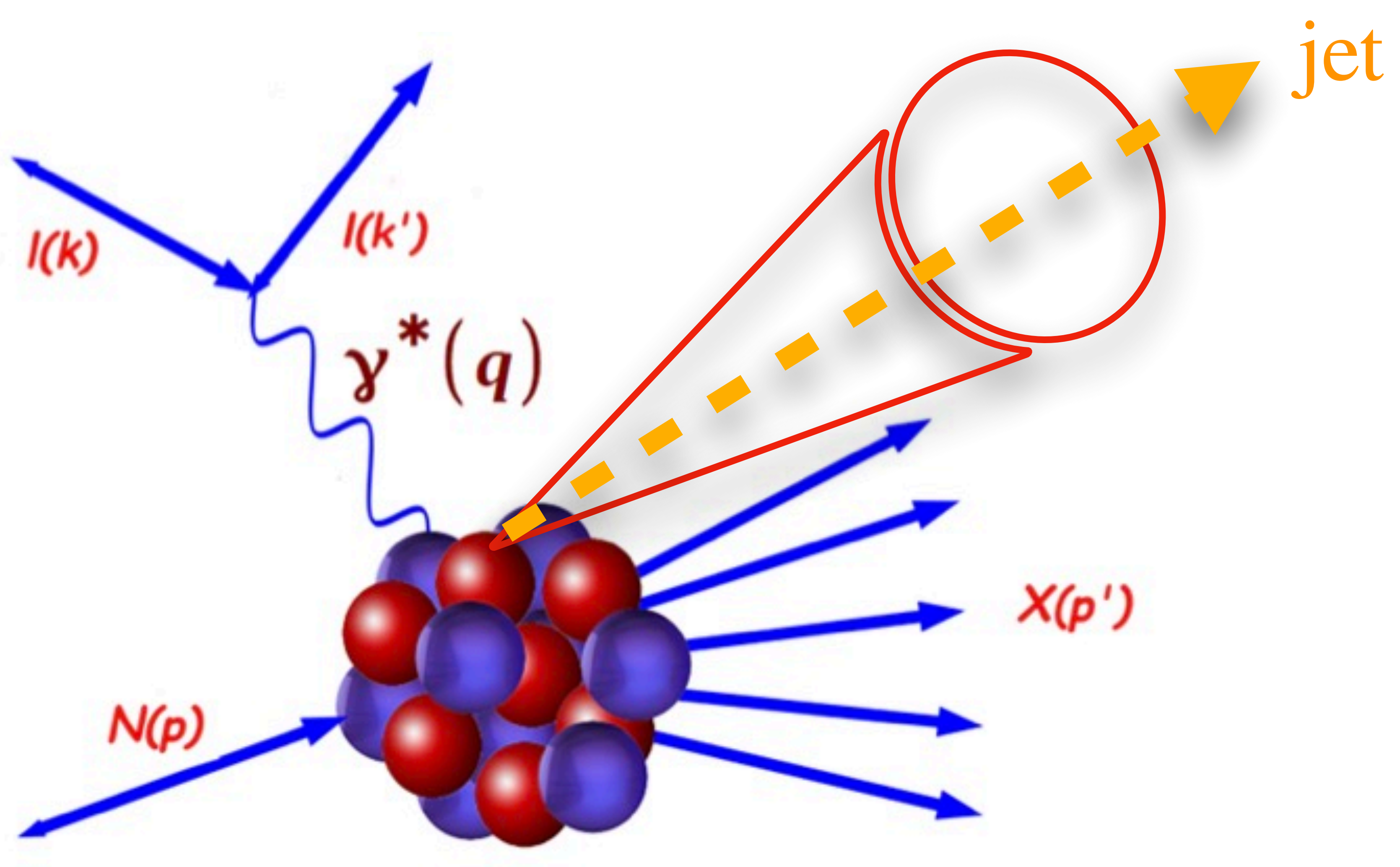


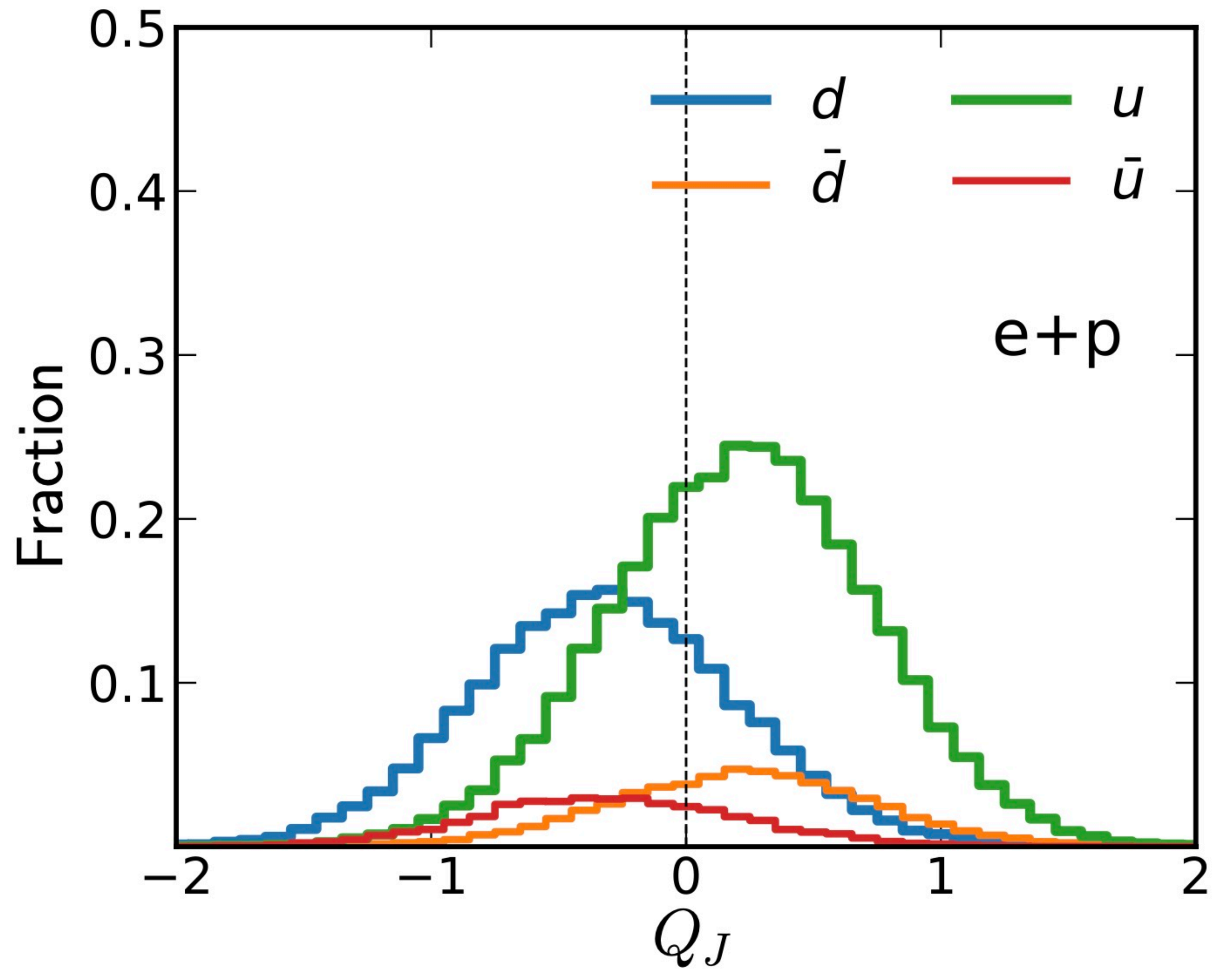
- First time quantitative determination of nuclear TMDs
- Identification of transverse momentum broadening in nuclei

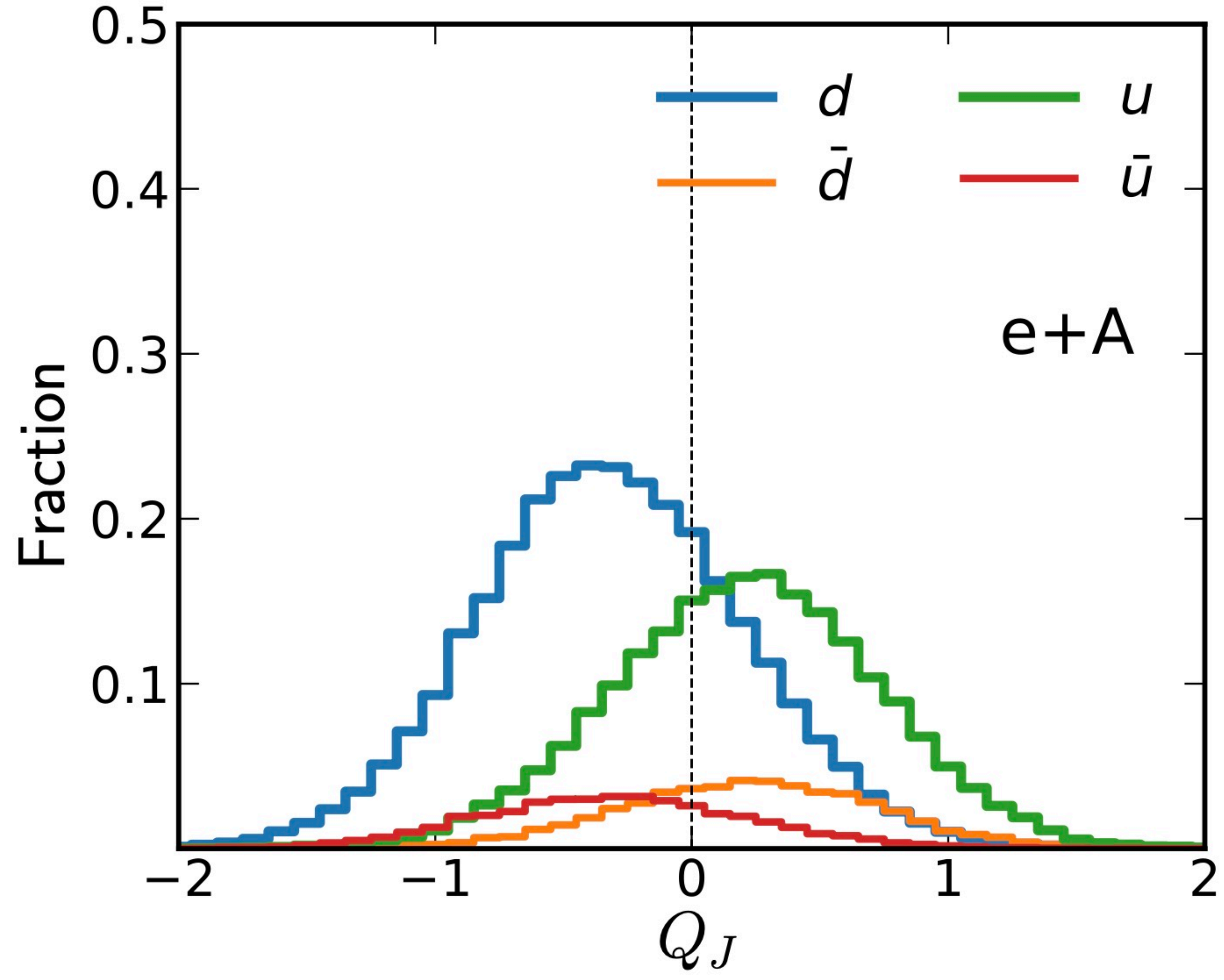
Hard probe of neutron skin at EIC

✦ Jet charge distribution in eA collisions

$$Q_J = \sum_i \left(\frac{p_{i,T}}{p_J}\right)^\kappa Q_i$$

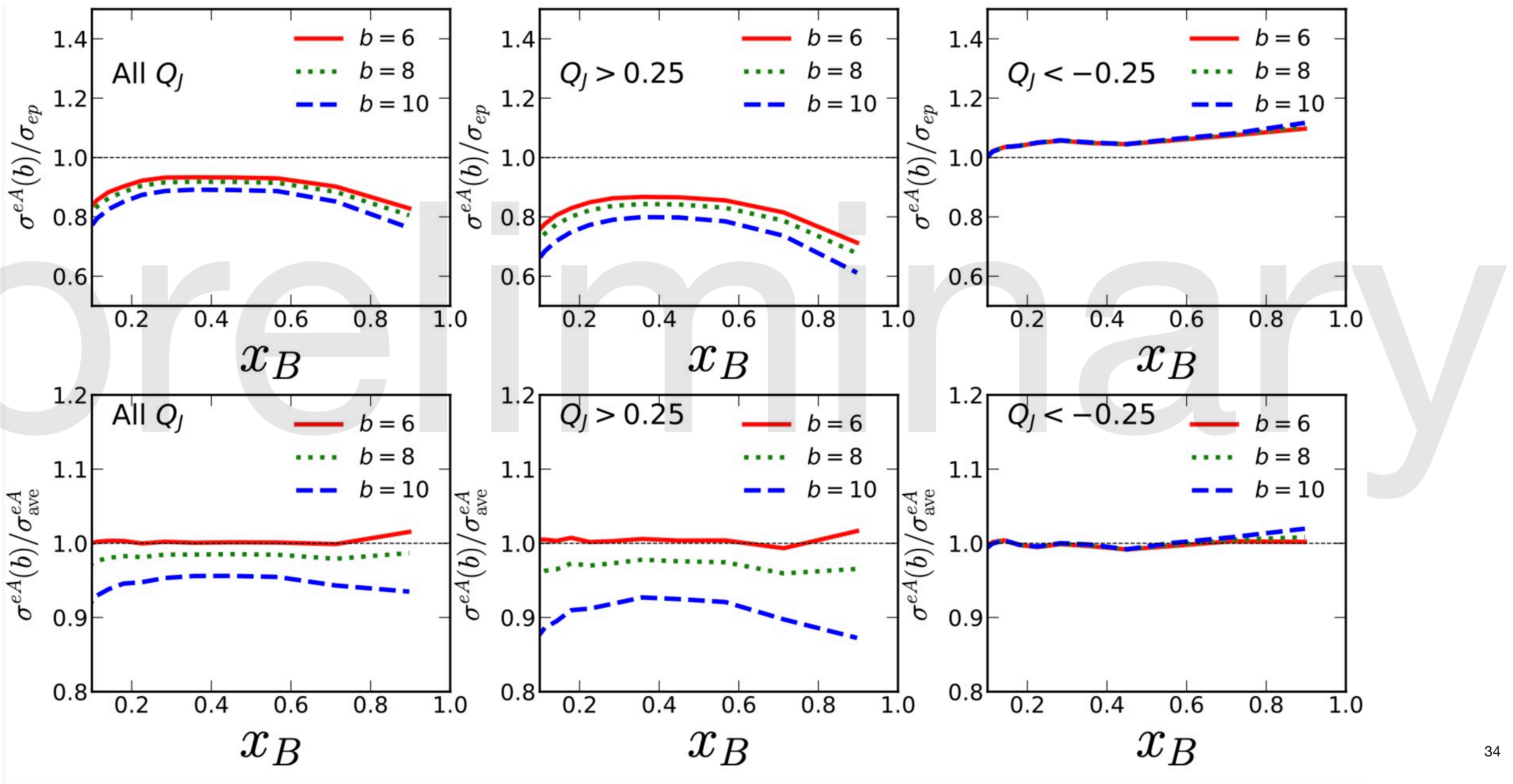






Hard probe of neutron skin at EIC

✦ Jet charge distribution in eA collisions



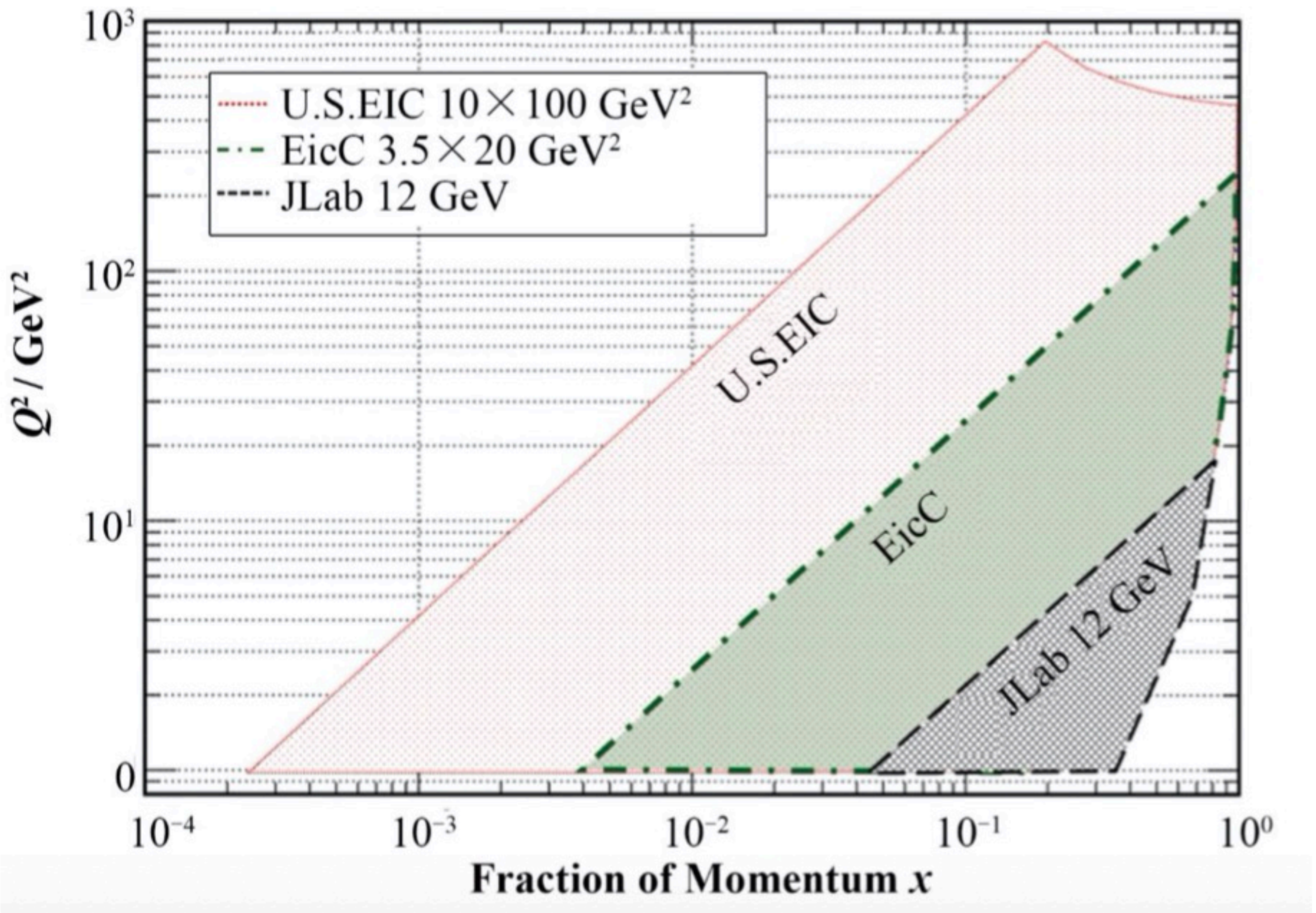
Summary

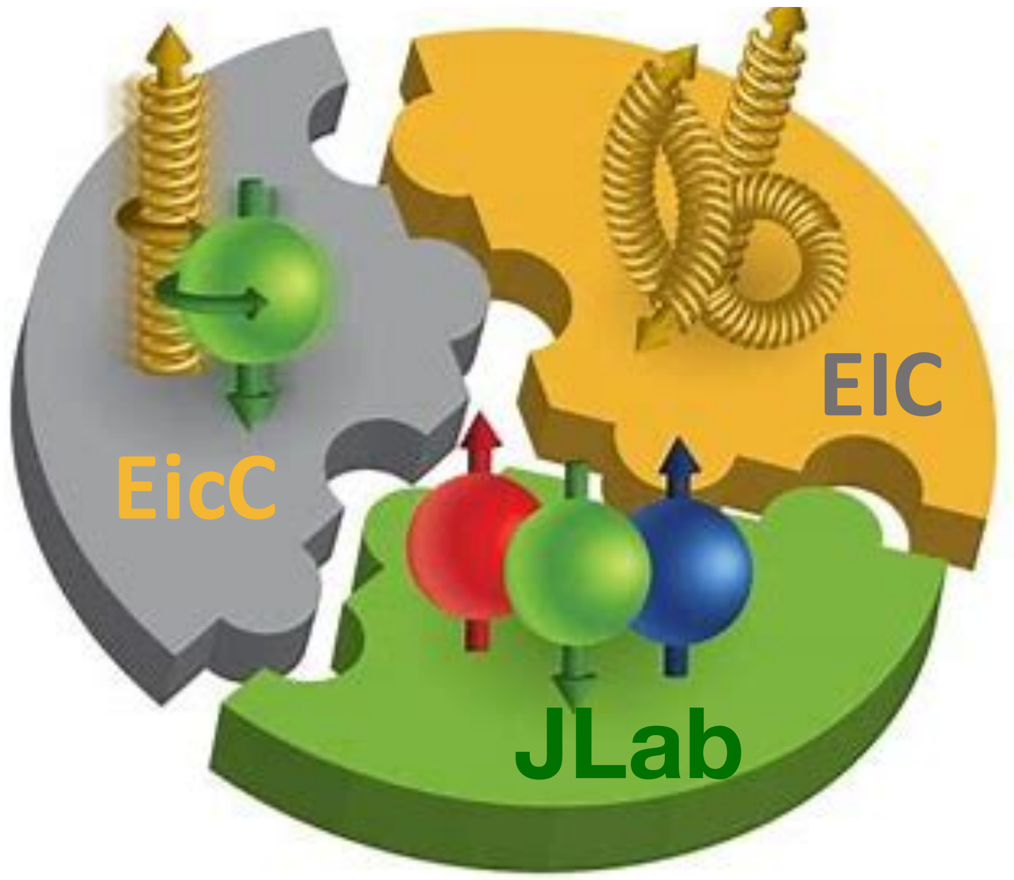
✦**EICs are the ultimate machines to explore the inner world of proton/nuclei at fm scale**

- Proton 1-D and 3-D imaging
- Proton spin
- 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**





EicC团队/组织

Accelerator: 刘杰、冒立军、杨建成

- EicC Accelerators 刘杰、申国栋、杨建成
- Ion Sources 孙良亭
- Ion Machine 常铭轩、申国栋、王磊
- Electron Machine 张子民、赵贺
- Polarization 李民祥、申国栋
- Cooling 马伏、冒立军、赵贺
- IR 刘杰
- Common System 王儒亮、郑亚军

Physics: 肖博文、邢宏喜、赵宇翔、周剑

- Inclusive 张金龙、林德旭、高俊、刘晓辉
- SIDIS 杨帅、李昕、赵宇翔、刘天博、肖博文、邢宏喜
- Heavy Flavor 张一飞、王亚平、郭爱强、邢宏喜、孙鹏、周剑
- Exclusive 熊伟志、梁羽铁、郭奉坤、曹须、吴佳俊

Detector: 刘建北、徐庆华、赵宇翔

- Tracking 郭爱强、王亚平、赵承心
- PID 李昕、杨帅、叶志鸿
- Calorimetry 林德旭、林挺、王义、王晓冬
- IR+Magnet 郭爱强、张金龙
- Luminosity and polarimetry 勾伯兴、张金龙
- Far-Forward detector 林挺、郭爱强、梁羽铁、熊伟志
- DAQ 陈凯、刘国明
- Simulations 梁羽铁、张一飞

Software (EicCRoot): 梁羽铁

Computing: 南方核科学计算中心(广州)

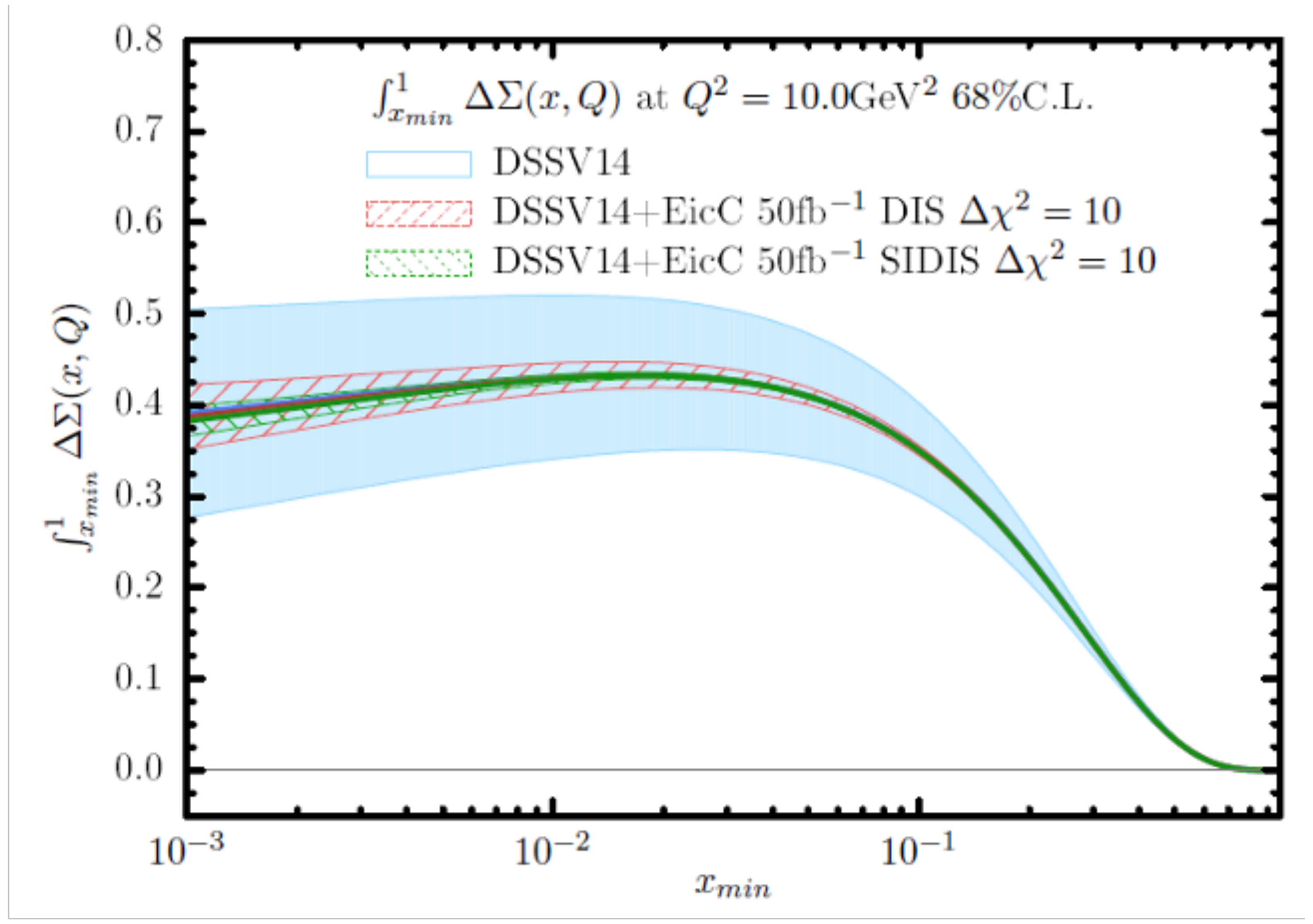
Platform: 南方核科学理论研究中心(惠州)

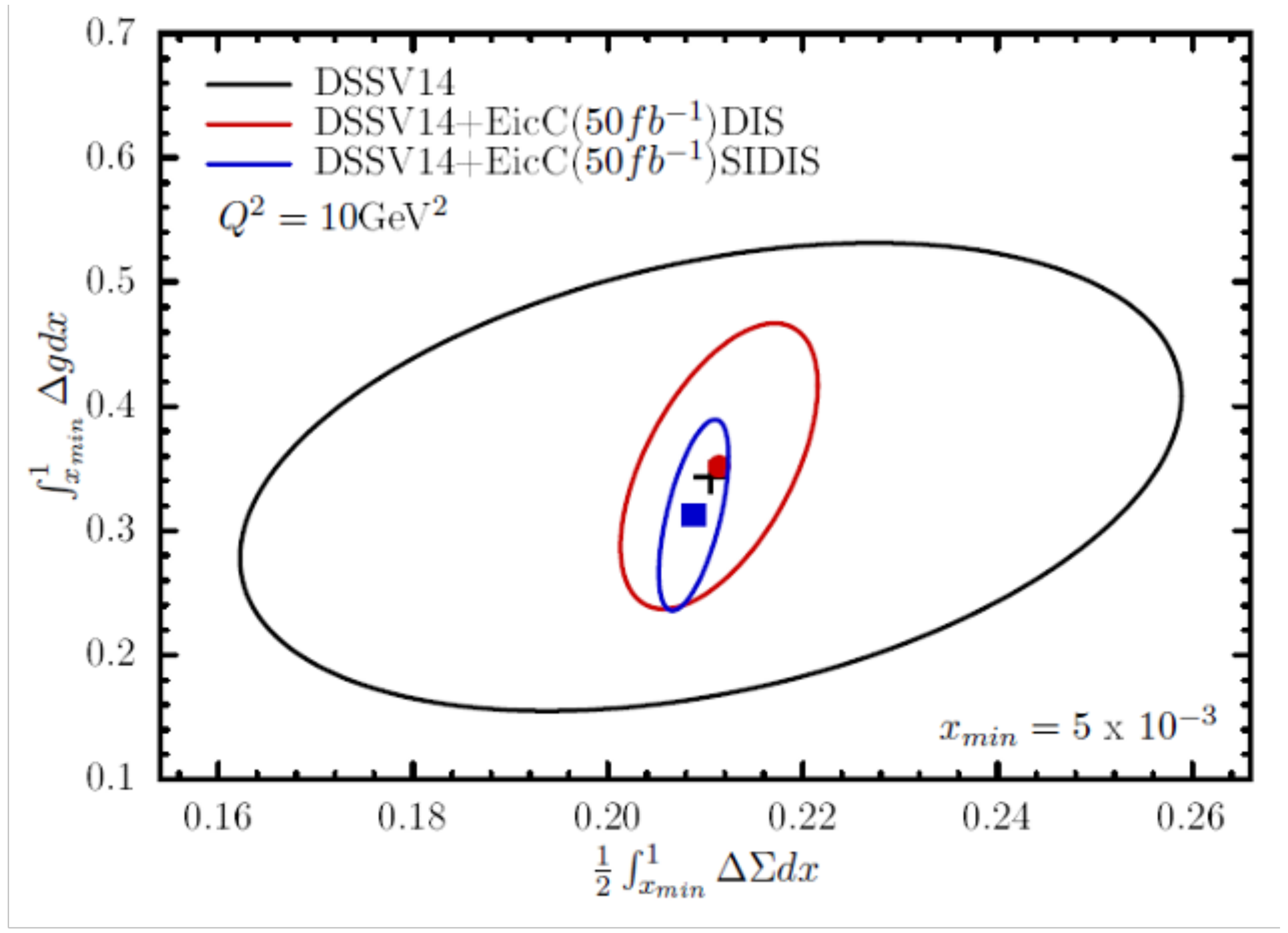
Thanks and you are more than welcome to join EicC!

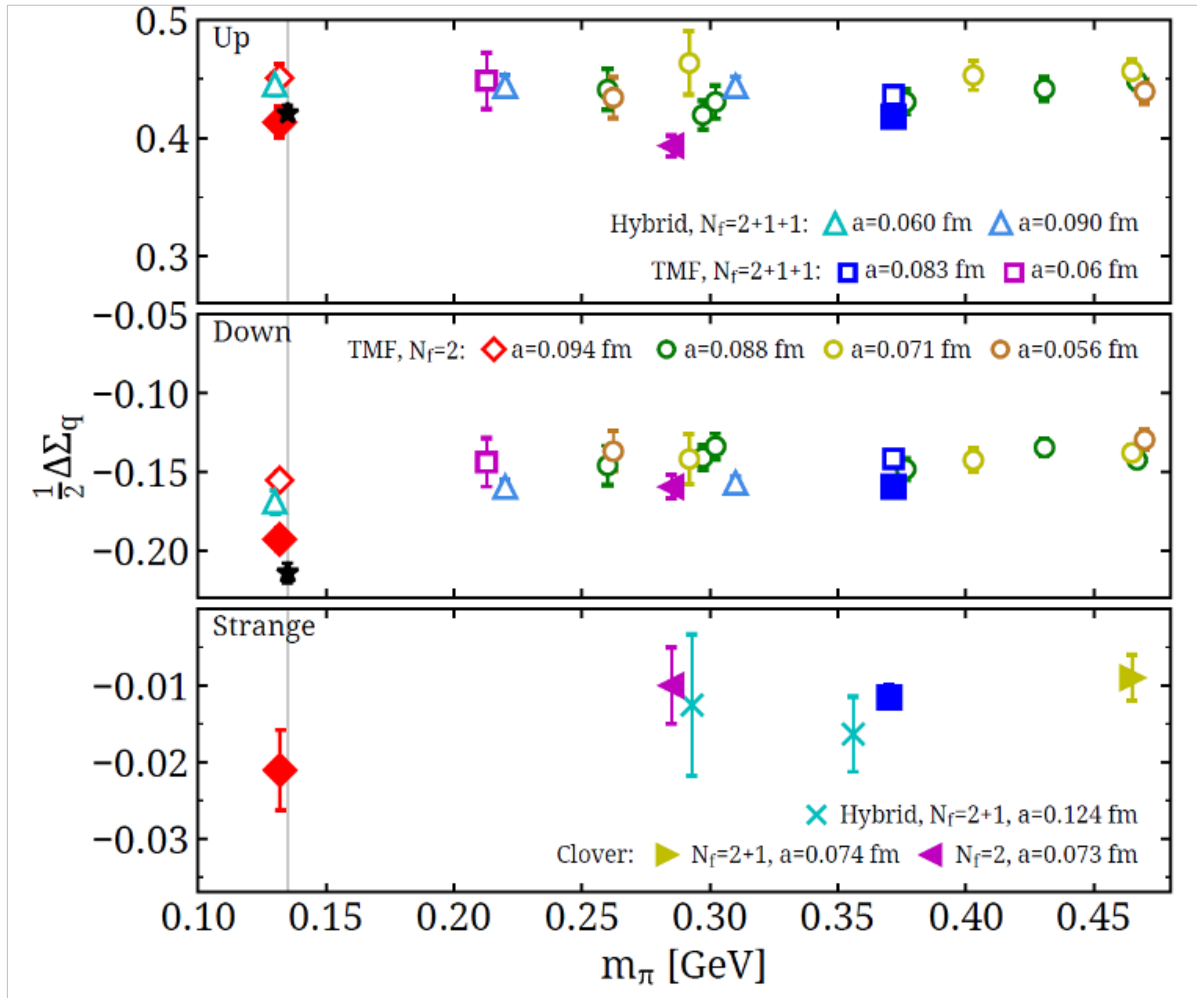
What can we do in future to pin down the proton spin?

✦ 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