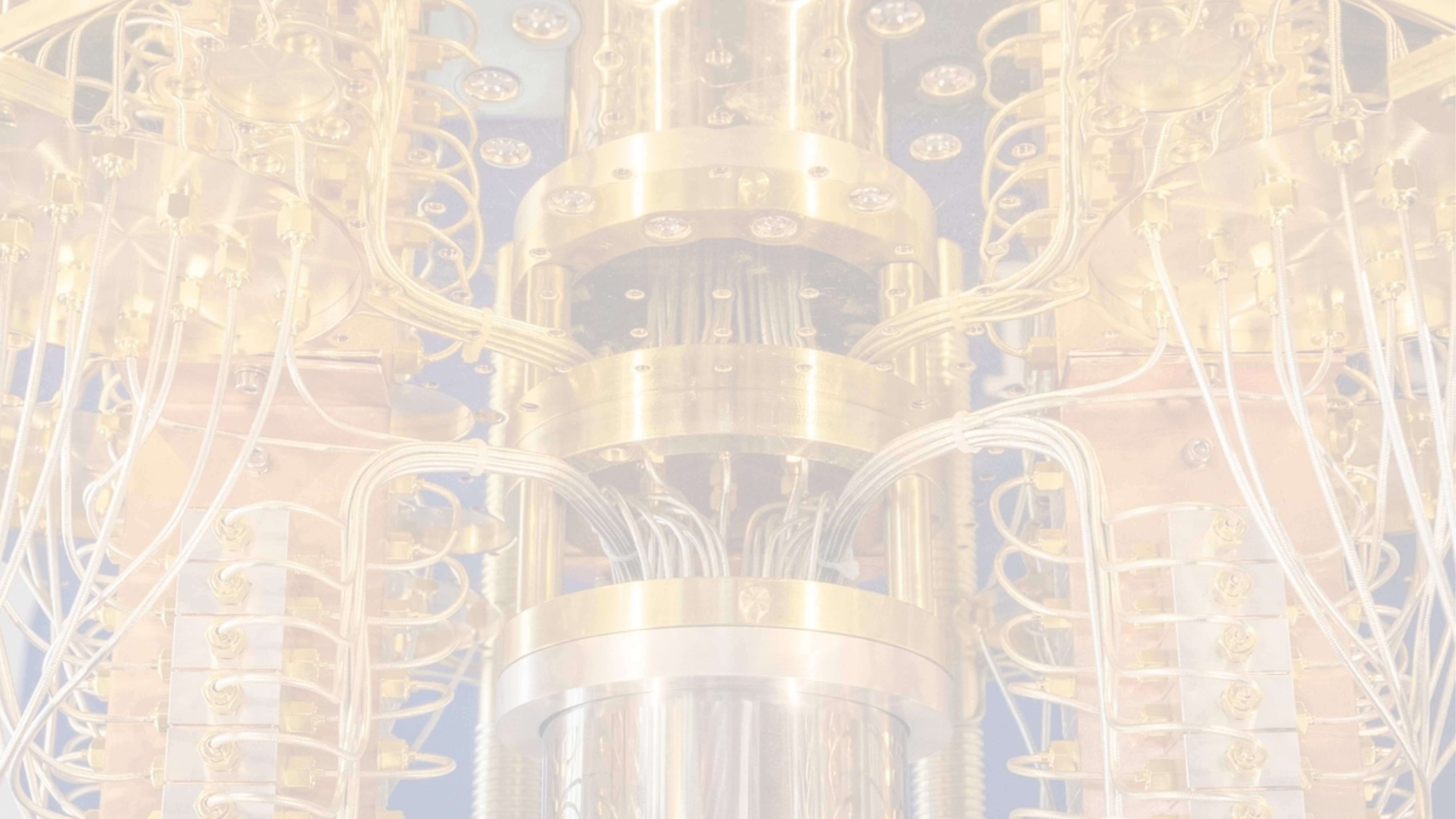
Exploring Hadronic Structure: From Large Facilities to Quantum Machines

Hongxi Xing

South China Normal University

IOPP Colloquium，2026.5.19



Outline

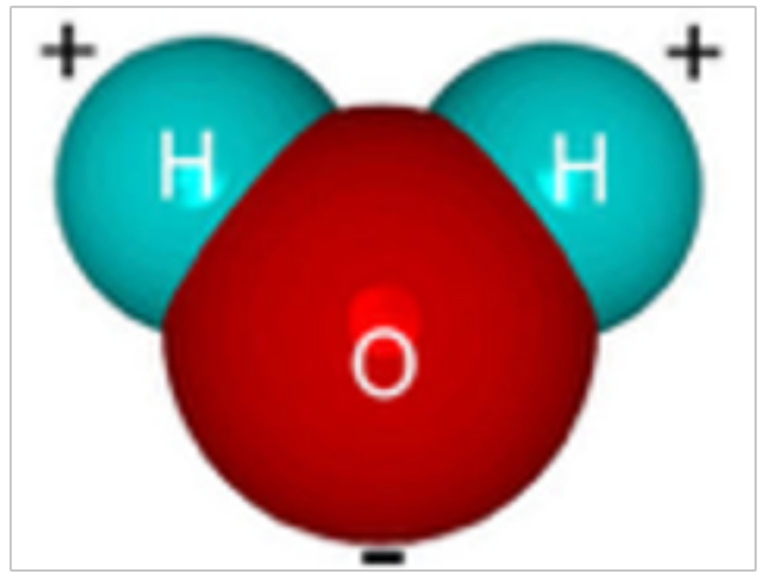
- Introduction
- Nucleon partonic structure - PDFs
- Parton fragmentation to hadrons - FFs
- Nucleon structure @ quantum computer

What are we made of ?

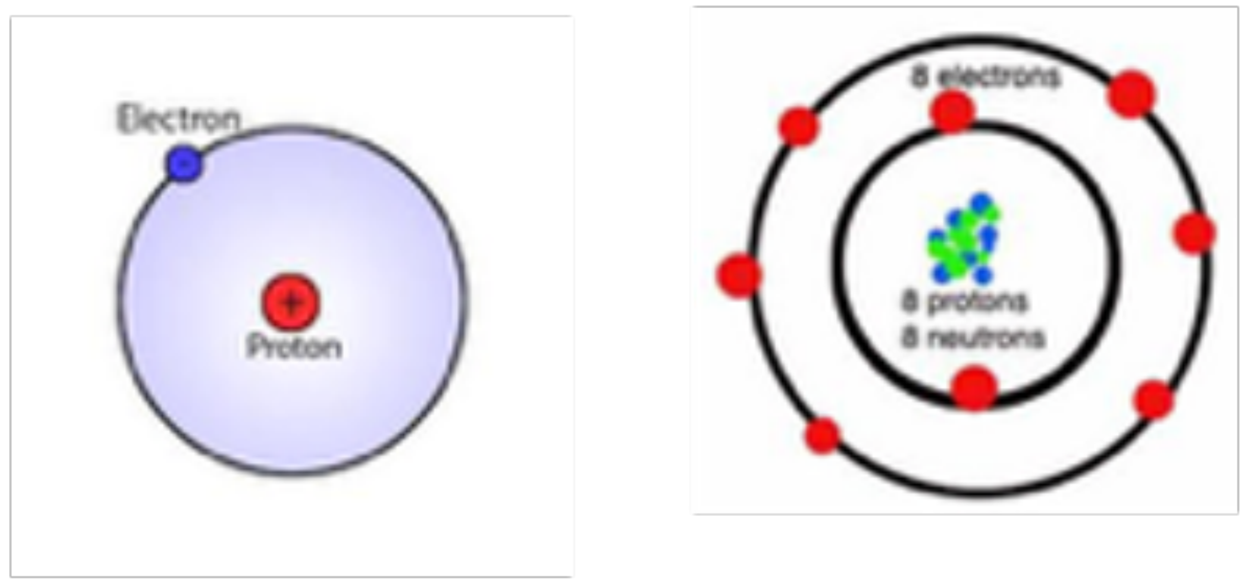
The physical world has a hierarchy of structures.

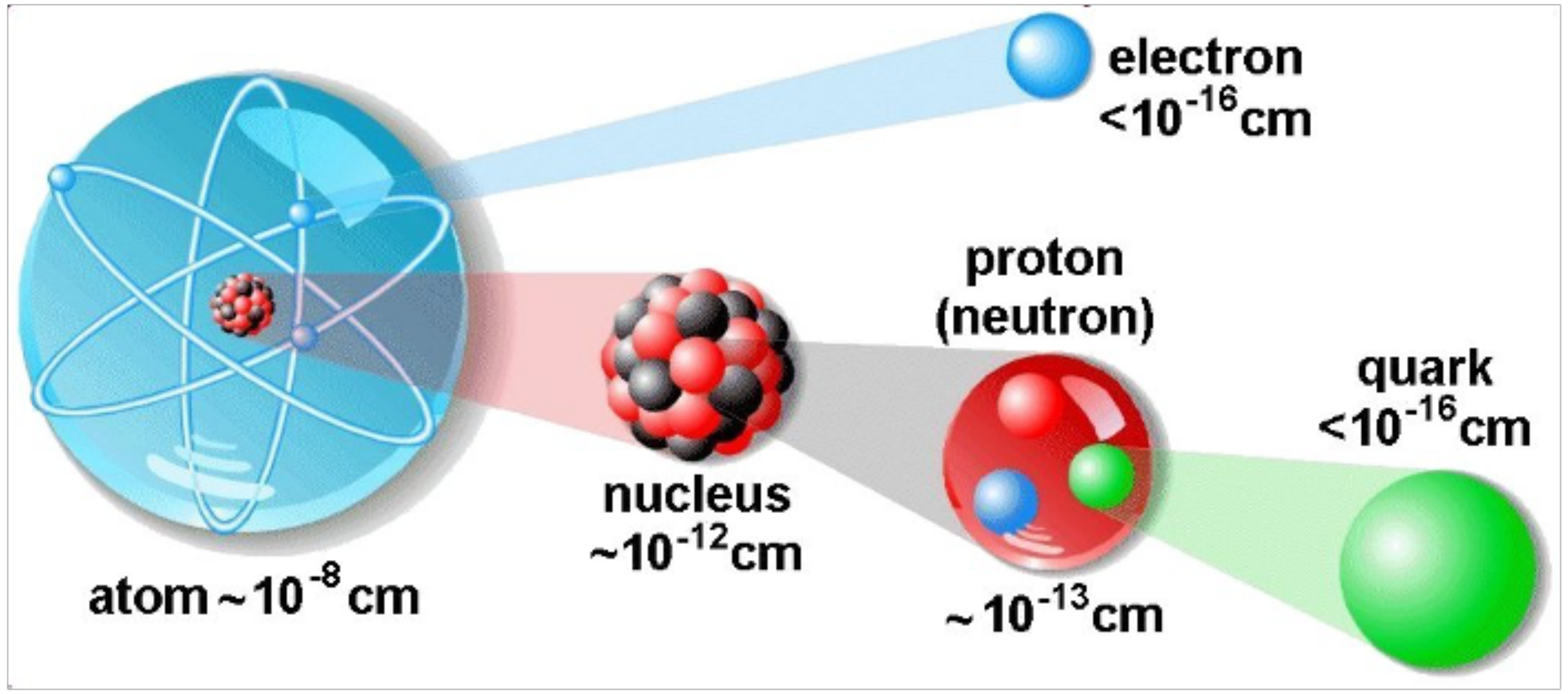
water

molecule



atom

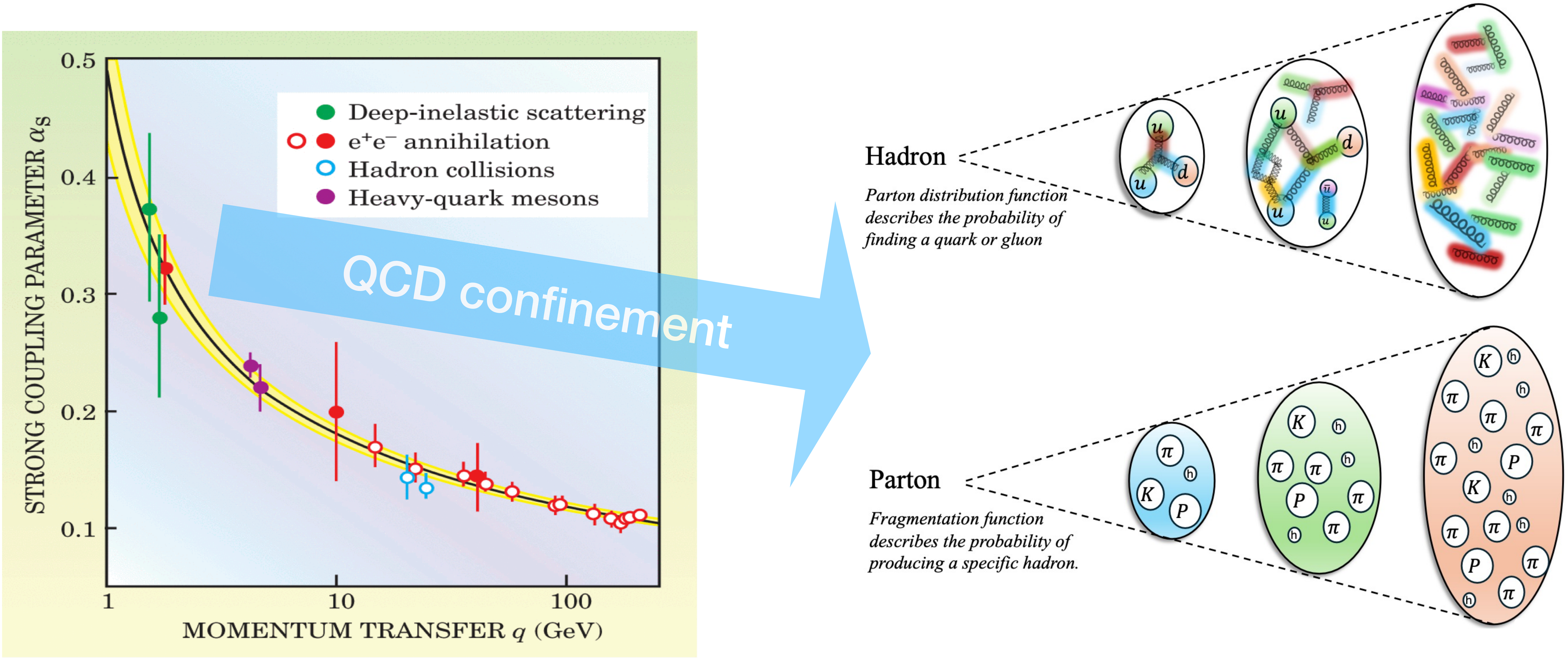




hadron

QCD confinement

✦ QCD as the fundamental theory of strong interaction



Hadron

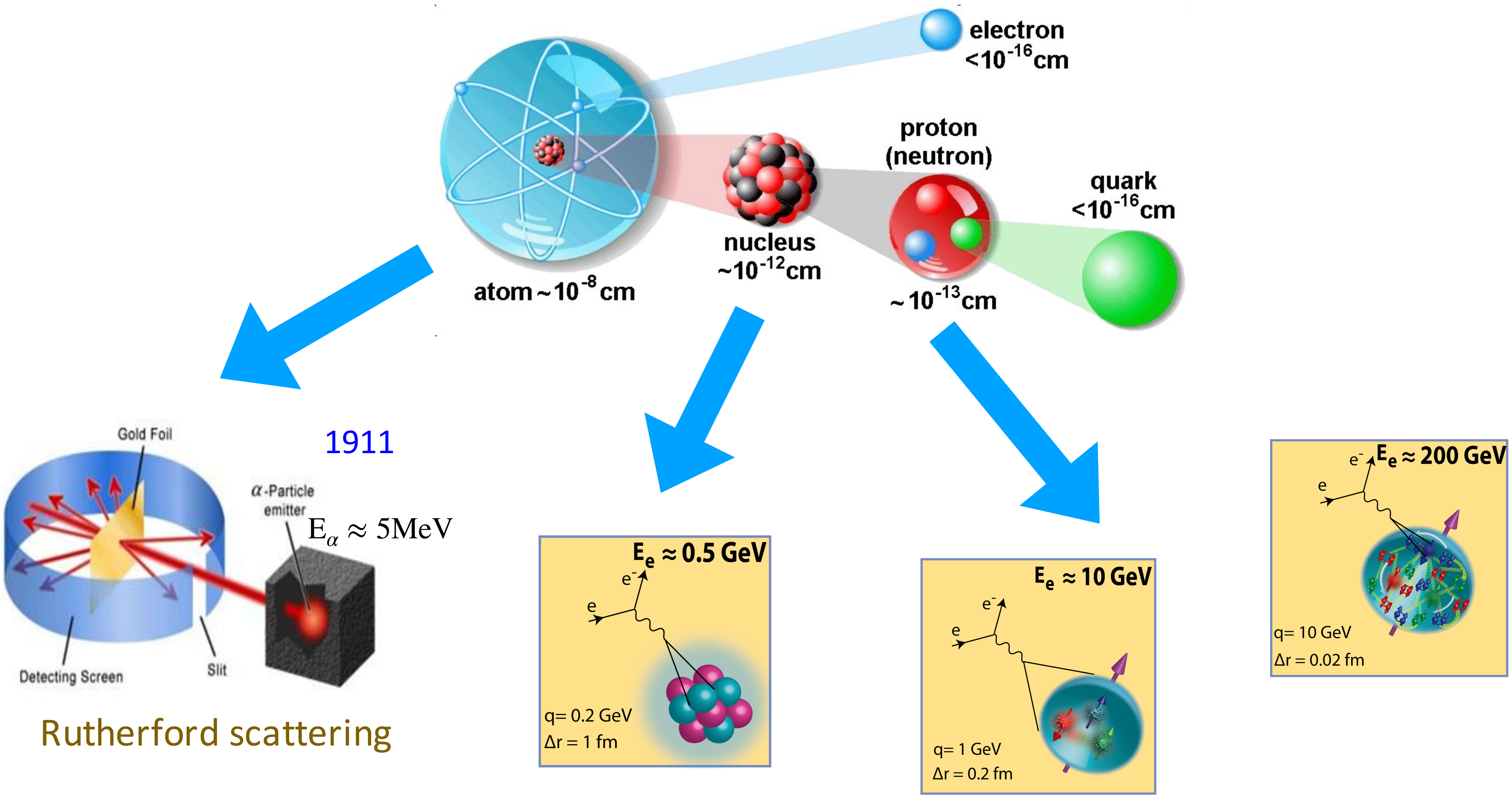
Parton distribution function describes the probability of finding a quark or gluon

Parton

Fragmentation function describes the probability of producing a specific hadron.

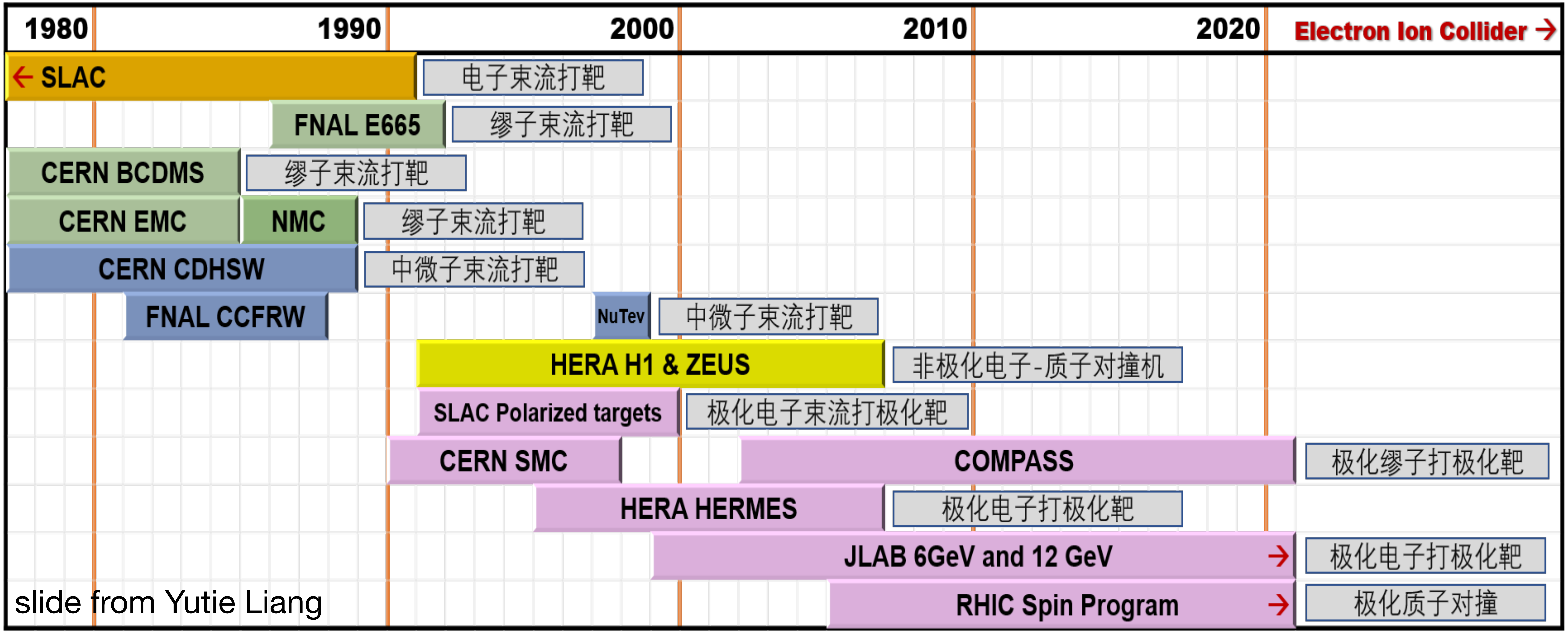
Figure taking from PRL 134,111902

Probing nuclear structure at different energy scales



scattering: a fundamental tool to explore the nuclear structure!

Worldwide experiments for nucleon structure



← SLAC 电子束流打靶

FNAL E665 缪子束流打靶

CERN BCDMS 缪子束流打靶

CERN EMC NMC 缪子束流打靶

CERN CDHSW 中微子束流打靶

FNAL CCFRW NuTev 中微子束流打靶

HERA H1 & ZEUS 非极化电子-质子对撞机

SLAC Polarized targets 极化电子束流打极化靶

CERN SMC COMPASS 极化缪子打极化靶

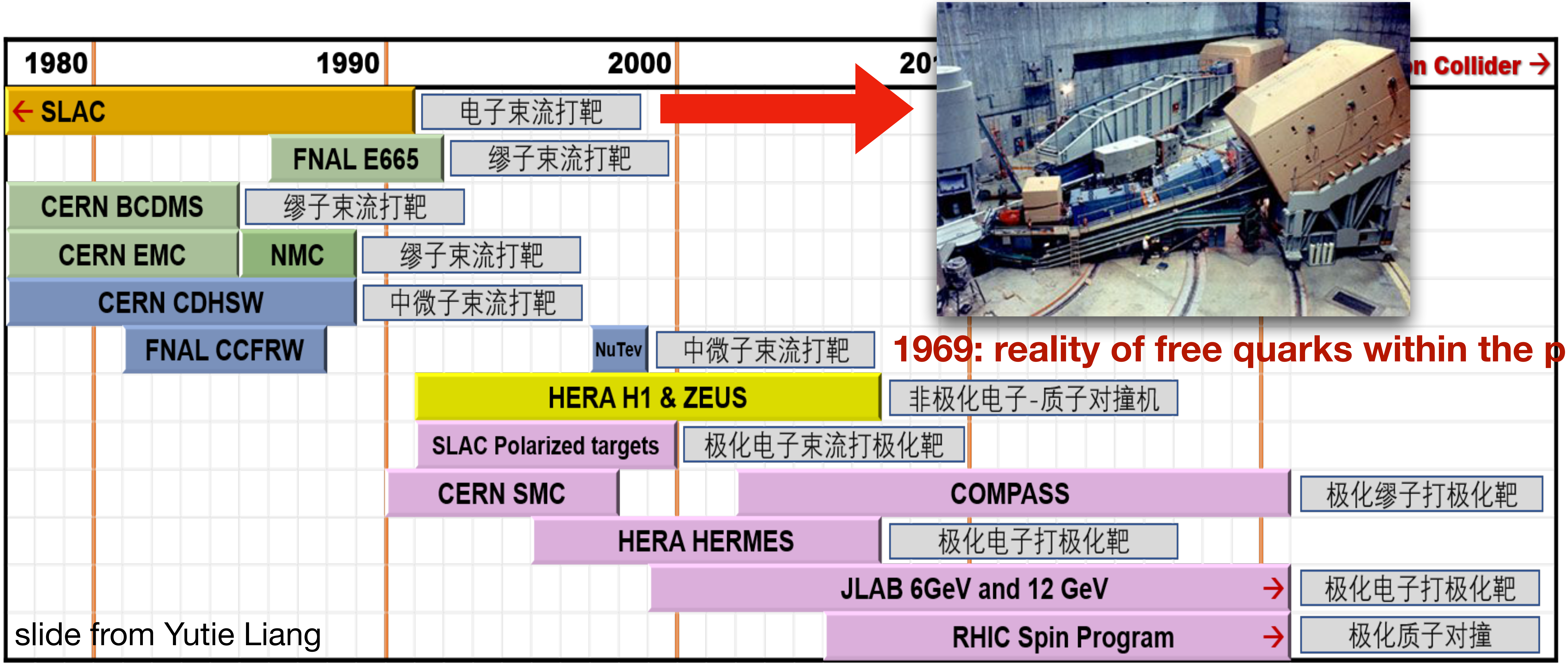
HERA HERMES 极化电子打极化靶

JLAB 6GeV and 12 GeV → 极化电子打极化靶

RHIC Spin Program → 极化质子对撞

slide from Yutie Liang

Worldwide experiments for nucleon structure



1969: reality of free quarks within the proton

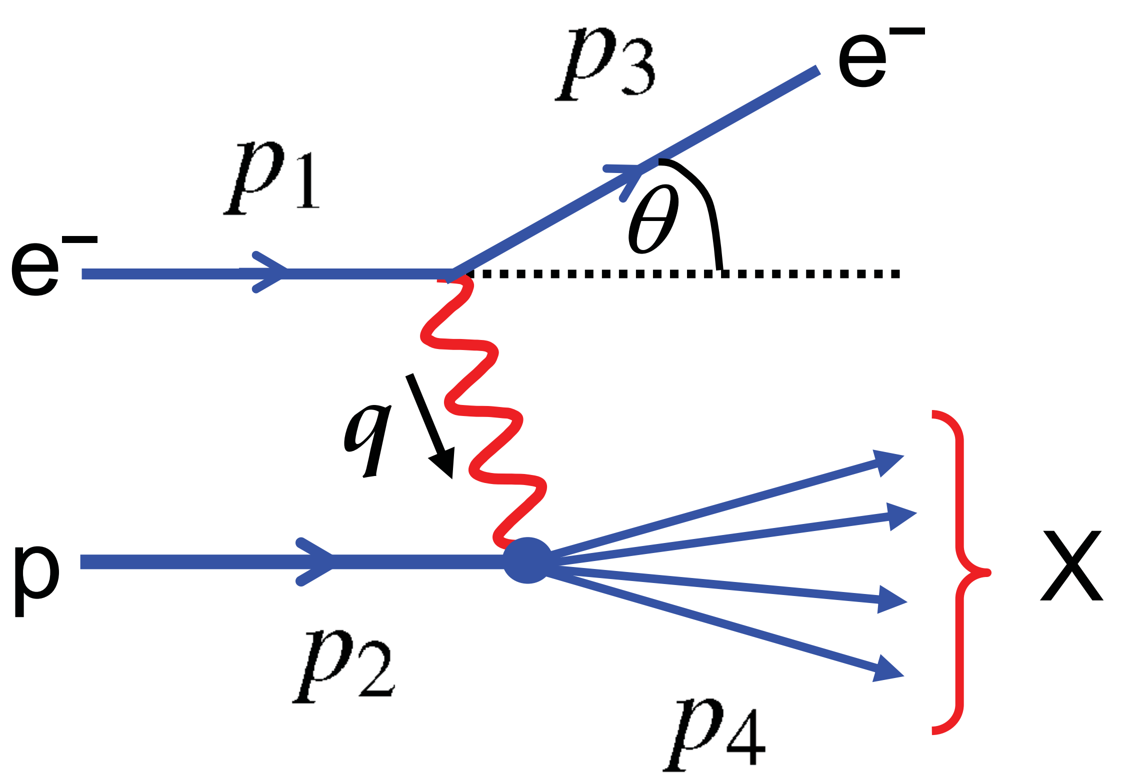
slide from Yutie Liang

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

Revolution of our view of hadron structure

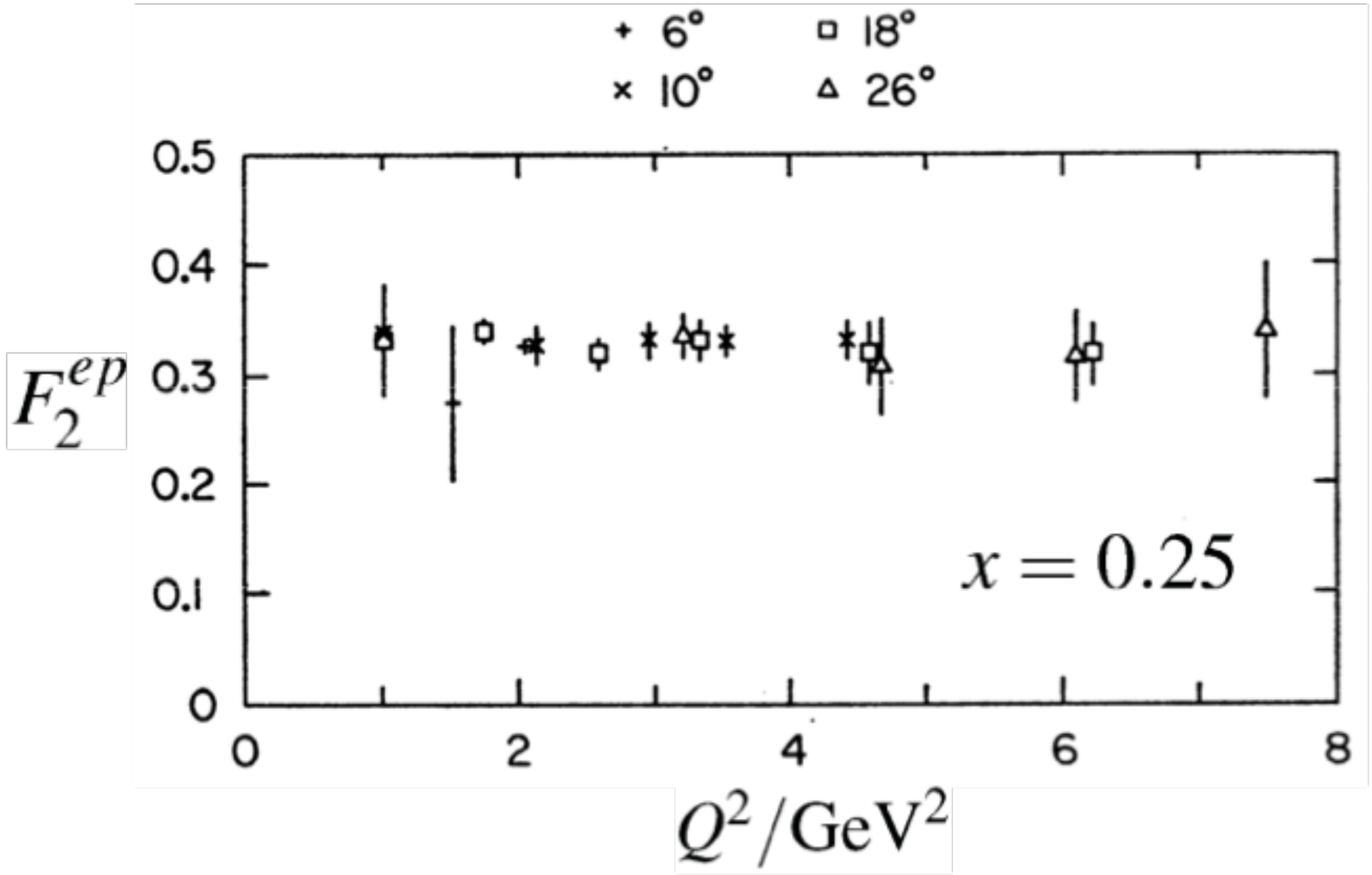
❑ Deep inelastic scattering

$$\boxed{\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]}$$



$$Q^2 = -q^2 \qquad x = \frac{Q^2}{2p\cdot q} \qquad y = \frac{p\cdot q}{p\cdot \ell}$$

❑ The famous Bjorken scaling



J.T.Friedman + H.W.Kendall, Ann. Rev. Nucl. Sci. 22 (1972) 203

- The independence of the structure functions on Q^2
- It is strongly suggestive of scattering from point-like constituents within the proton

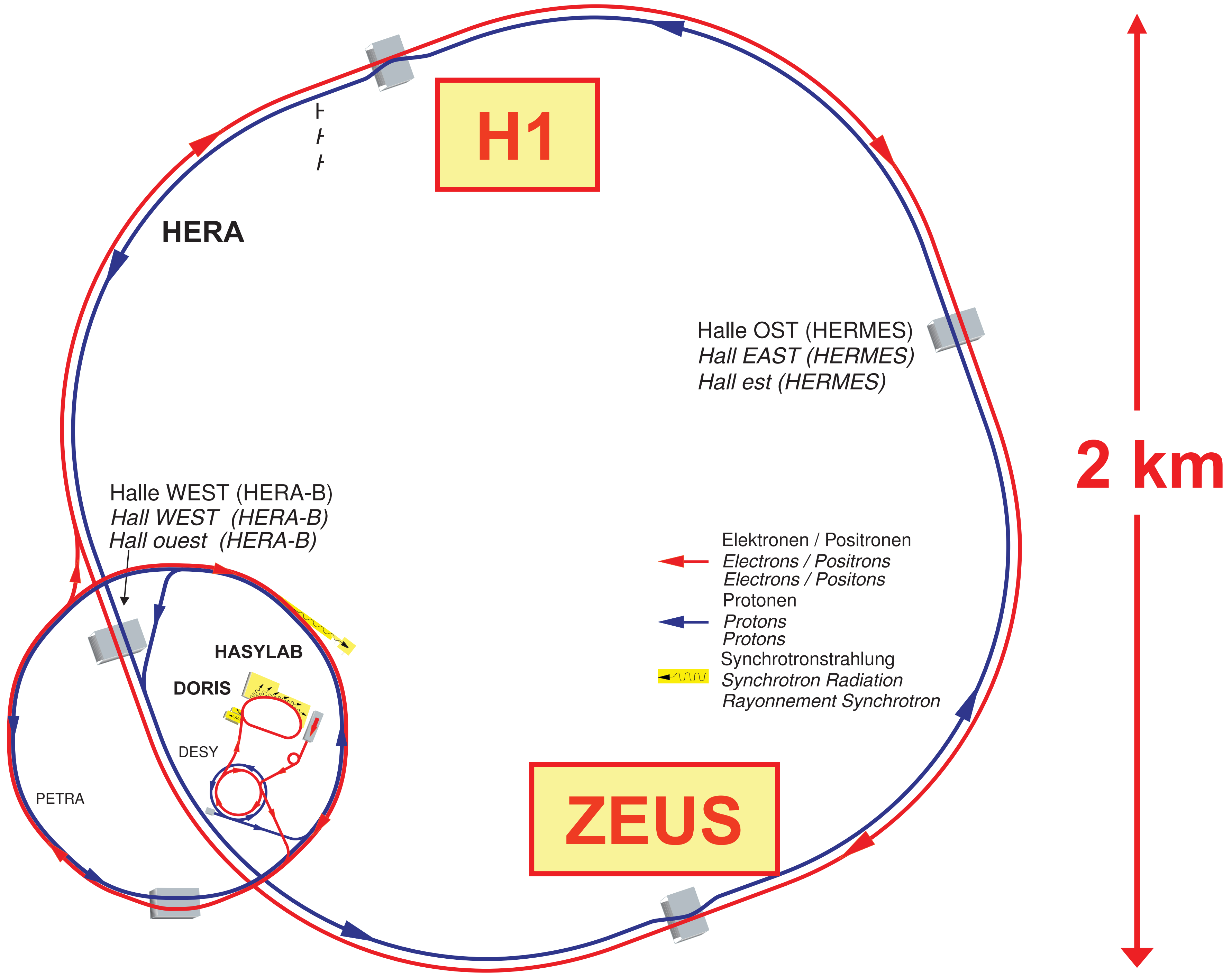
Revolution of our view of hadron structure

❑ With higher collision energies – HERA ep collider (1991-2007)

★ **DESY (Deutsches Elektronen-Synchroton) Laboratory, Hamburg, Germany**

$e^{\pm}$ **27.5 GeV** → ← **820 GeV** p

$\sqrt{s} = 300$ **GeV**

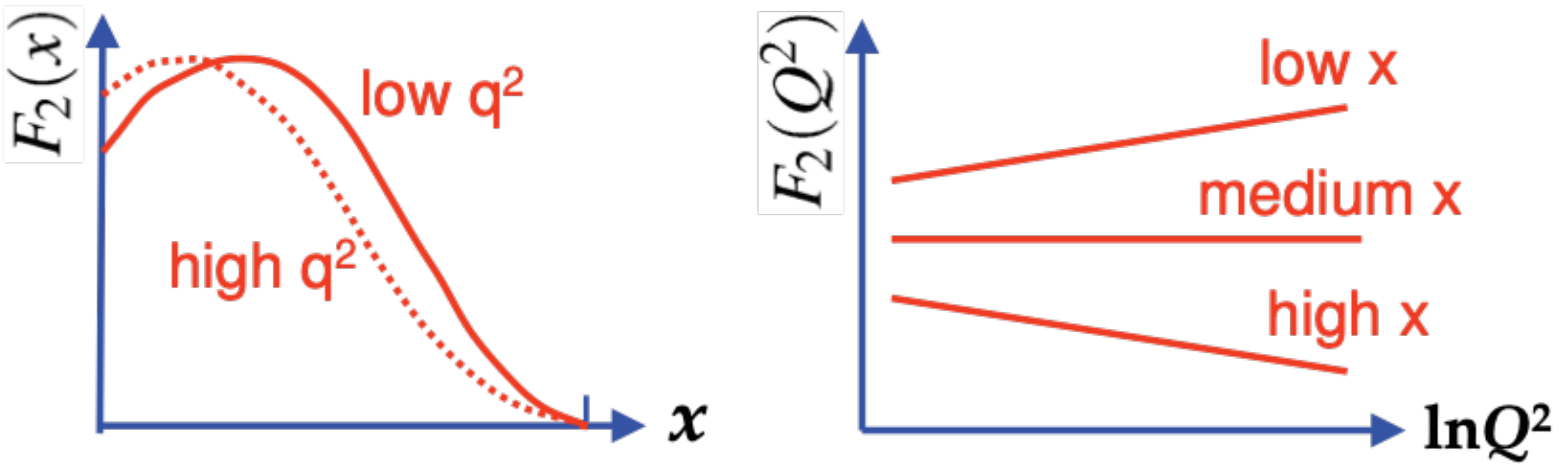


★ **Two large experiments : H1 and ZEUS**

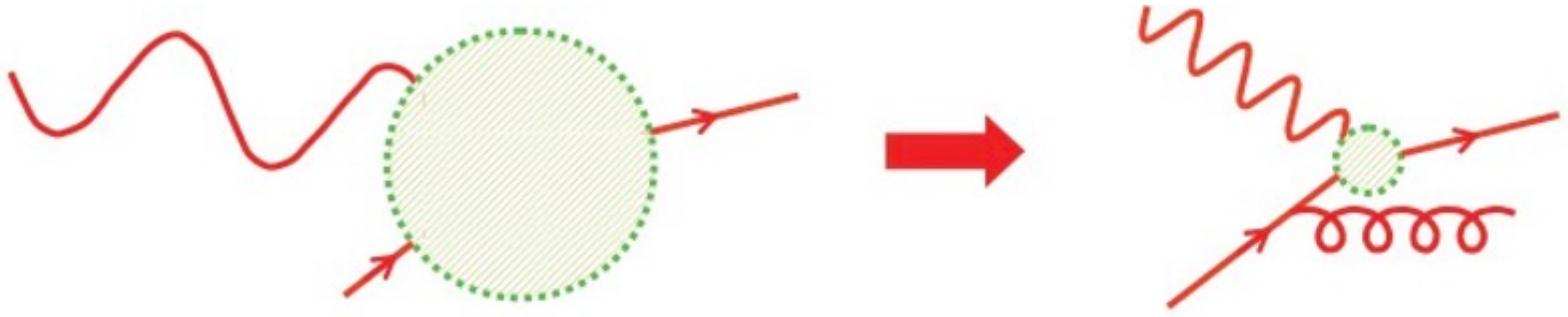
★ **Probe proton at very high Q^2 and very low x**

Revolution of our view of hadron structure

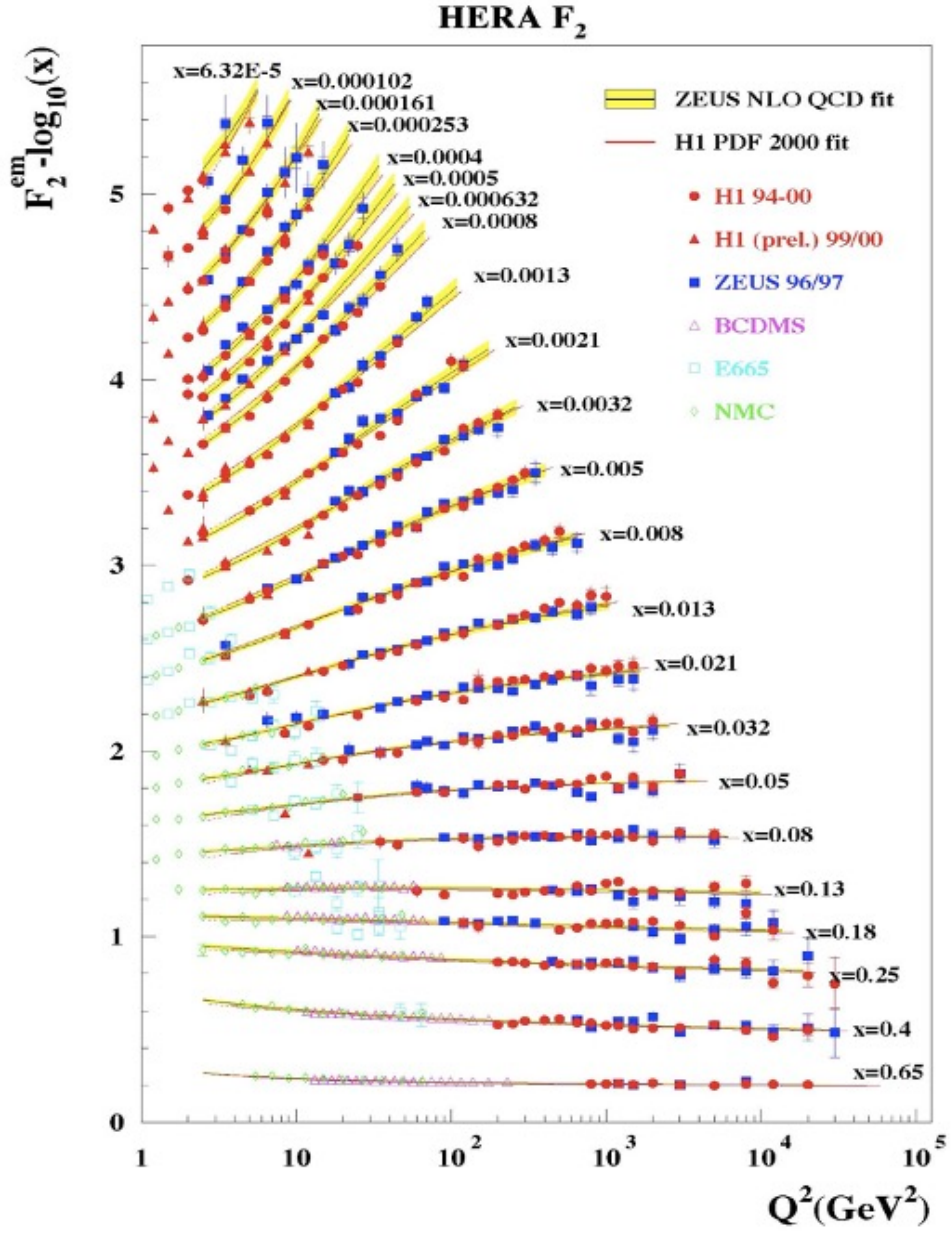
❑ Bjorken scaling violation



- Higher Q^2 (= shorter wave length) can resolve finer structure
- Quark is sharing momentum with gluon

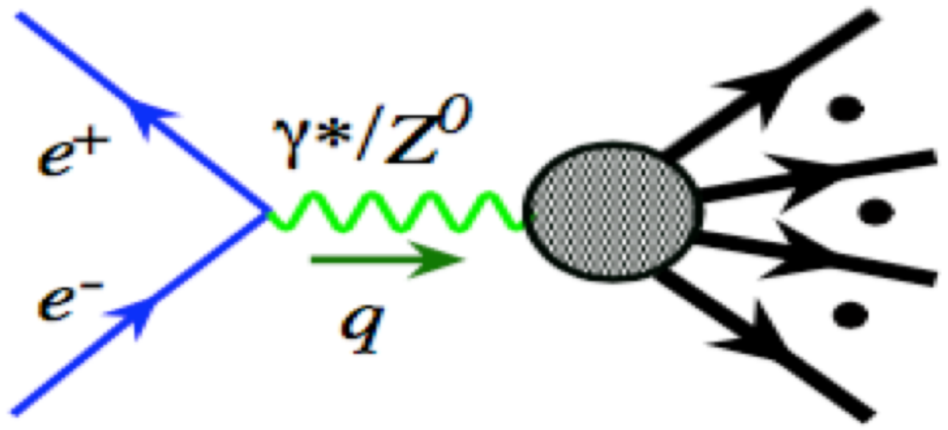


The quantum world does not like constants!



Modern facilities to probe the nucleon partonic structure

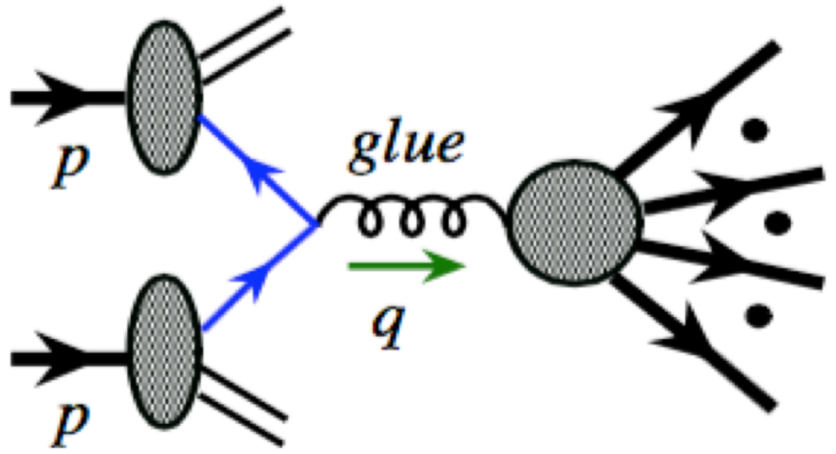
Lepton-lepton colliders



BEPC, SuperKEKB

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

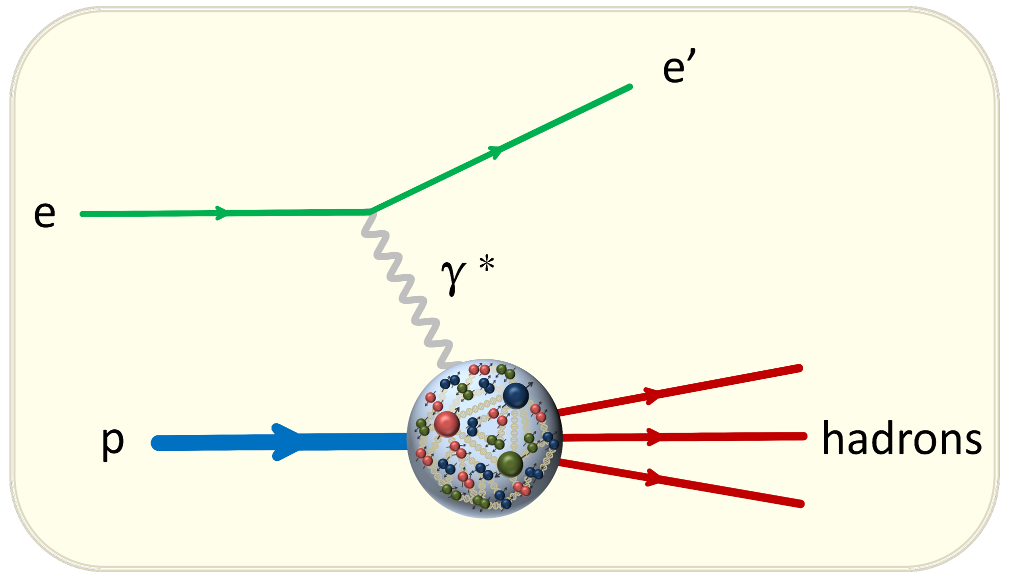
Hadron-hadron colliders



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

Modern view of proton structure

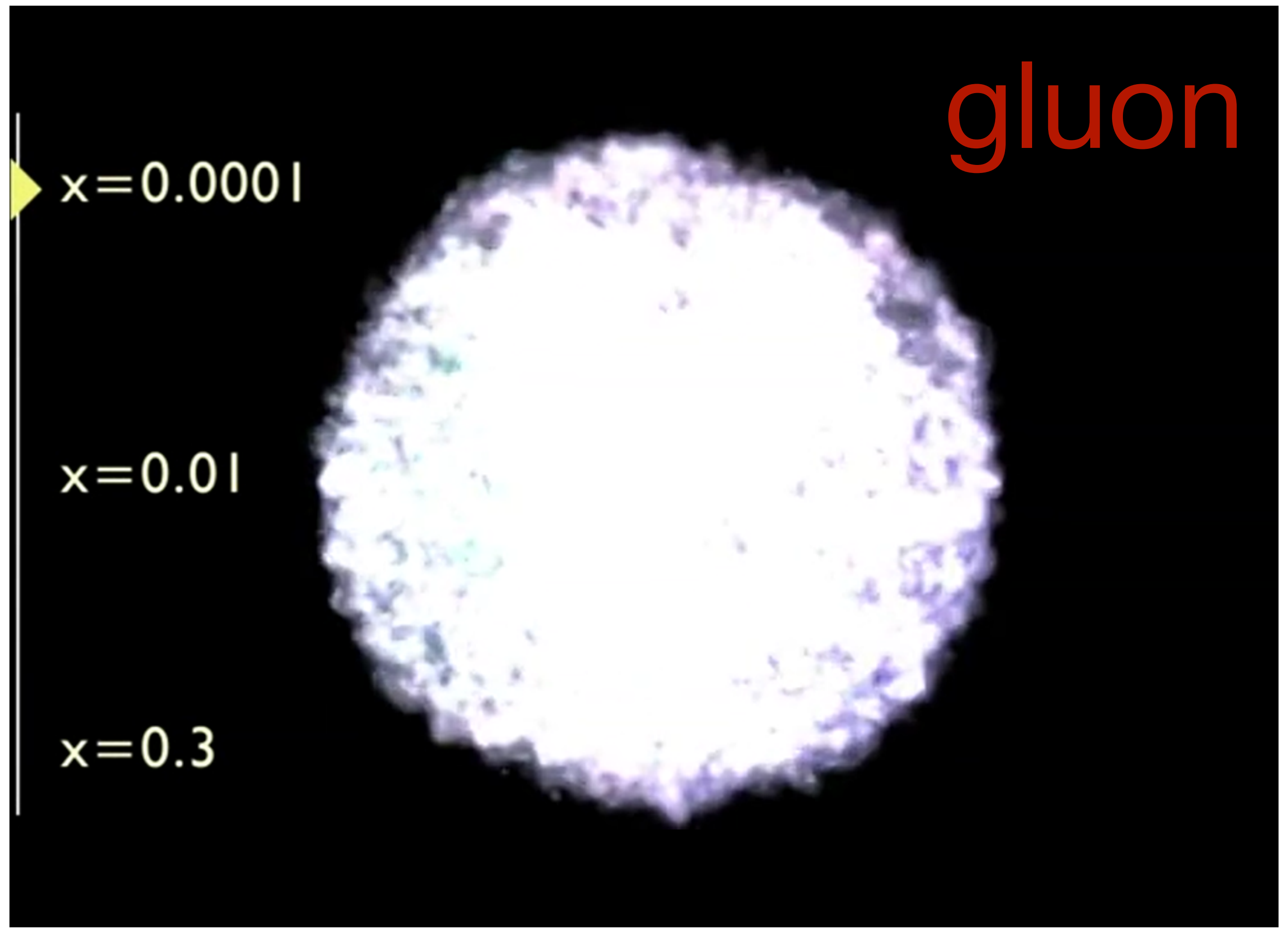
- Extract proton PDFs（1D）from world data

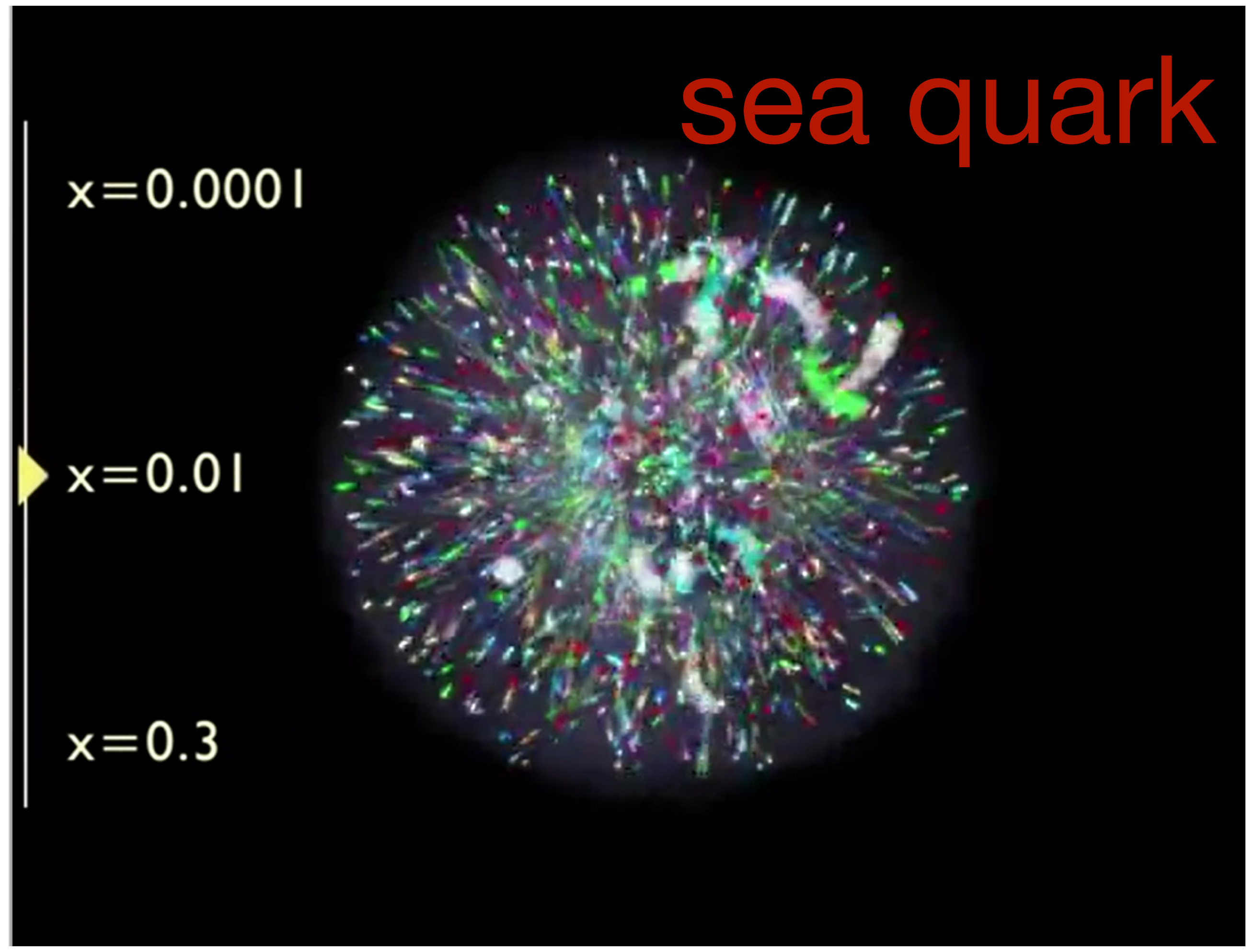
EIC user group

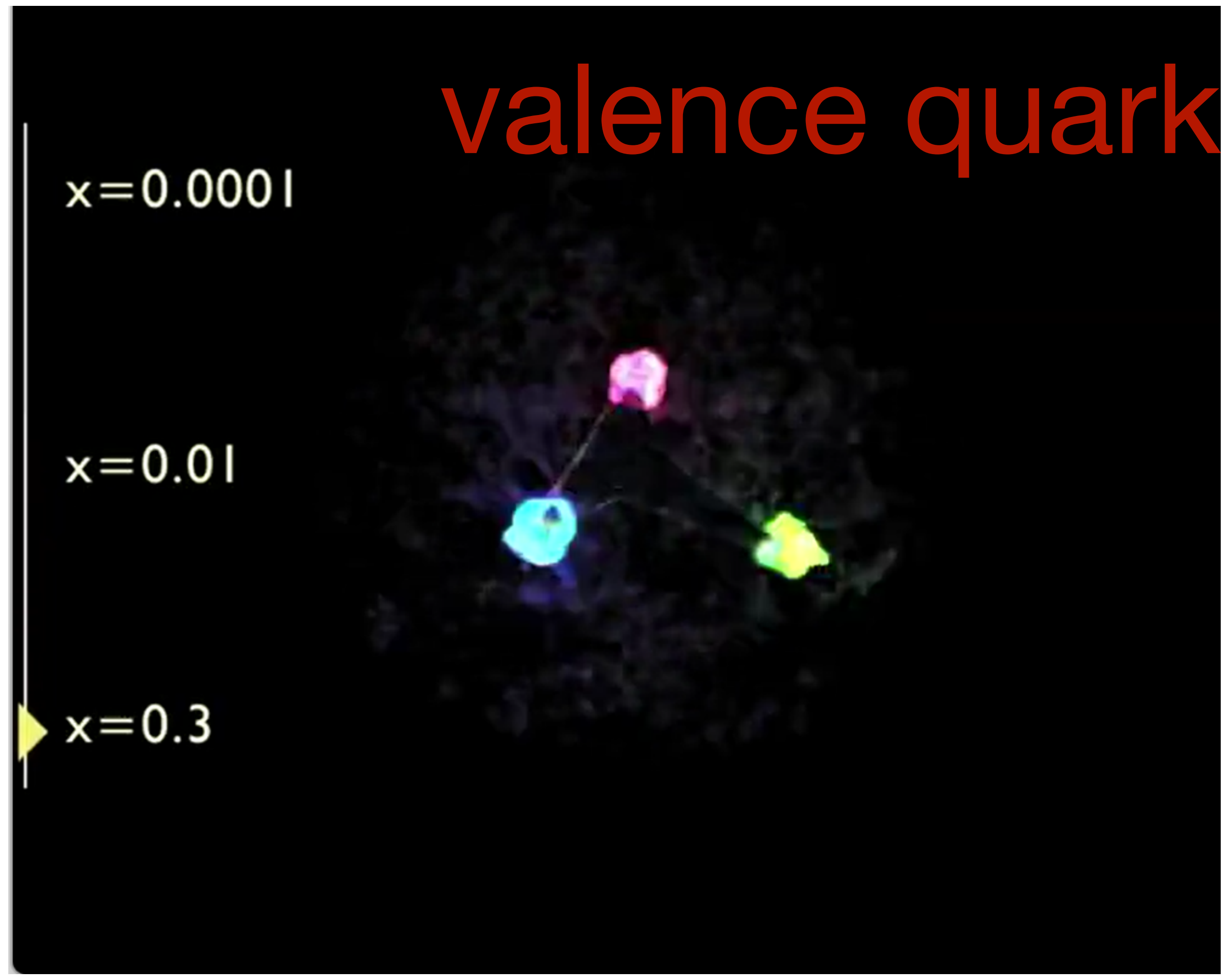
Modern view of proton structure

- ✦ Extract proton PDFs（1D）from world data

EIC user group





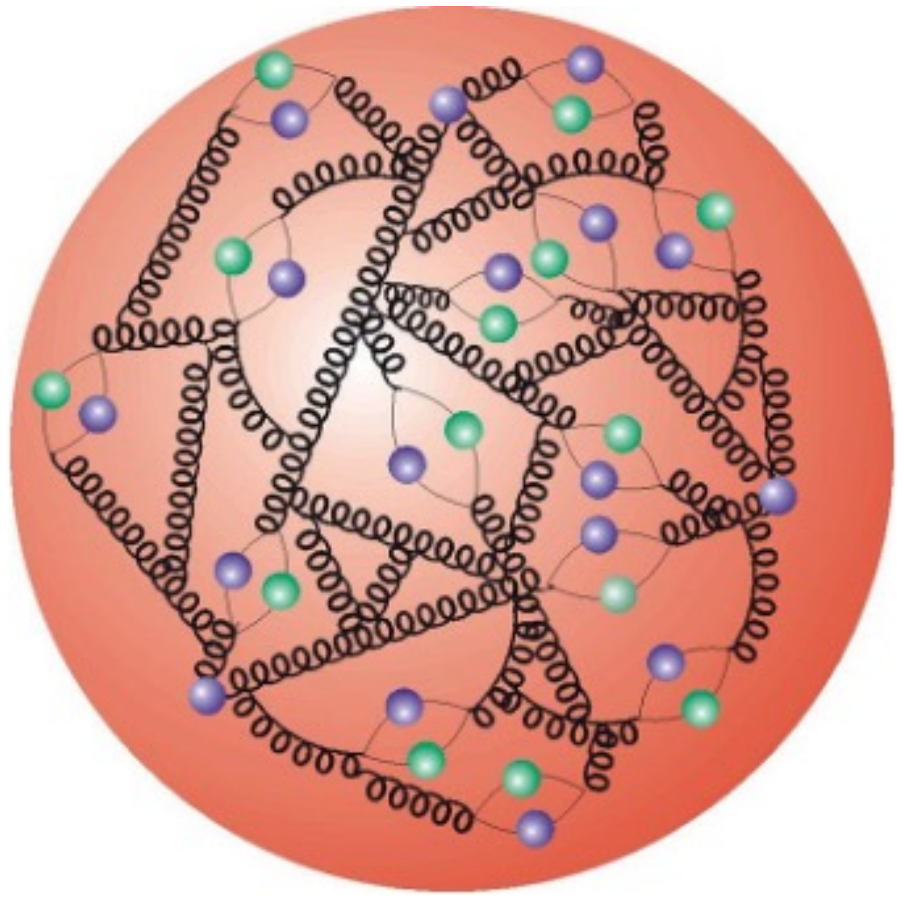


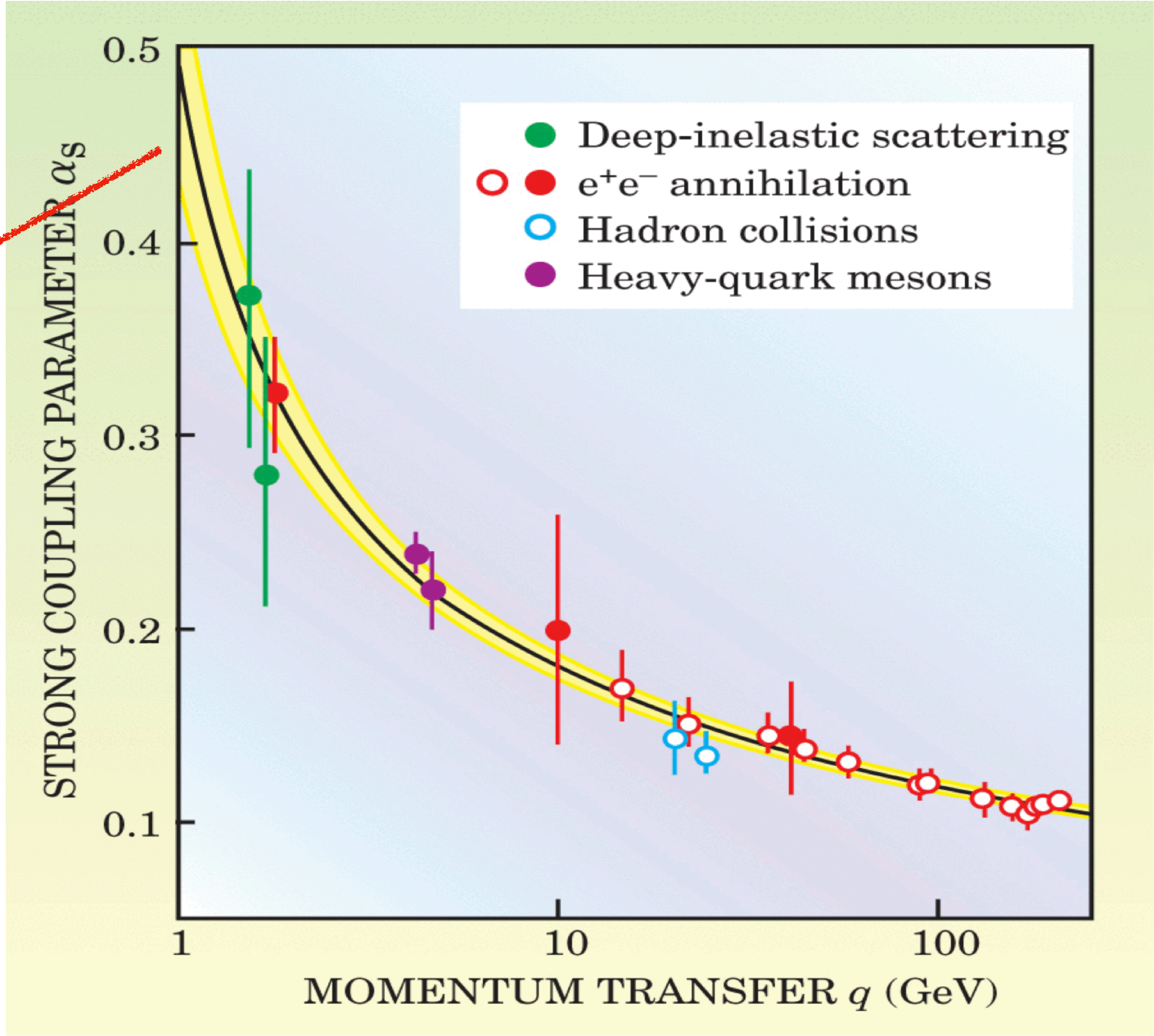
How to probe the nucleon partonic structure?

✦ No way to directly see the parton - color confinement

$$\mathcal{L} = \overline{\Psi}_c(i\gamma^\mu\partial_\mu - m)\Psi_c + g\,\overline{\Psi}_c\gamma^\mu T_a\Psi_c G^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$G^a_{\mu\nu} \equiv \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - \boxed{g f_{abc} G^b_\mu G^c_\nu}$$





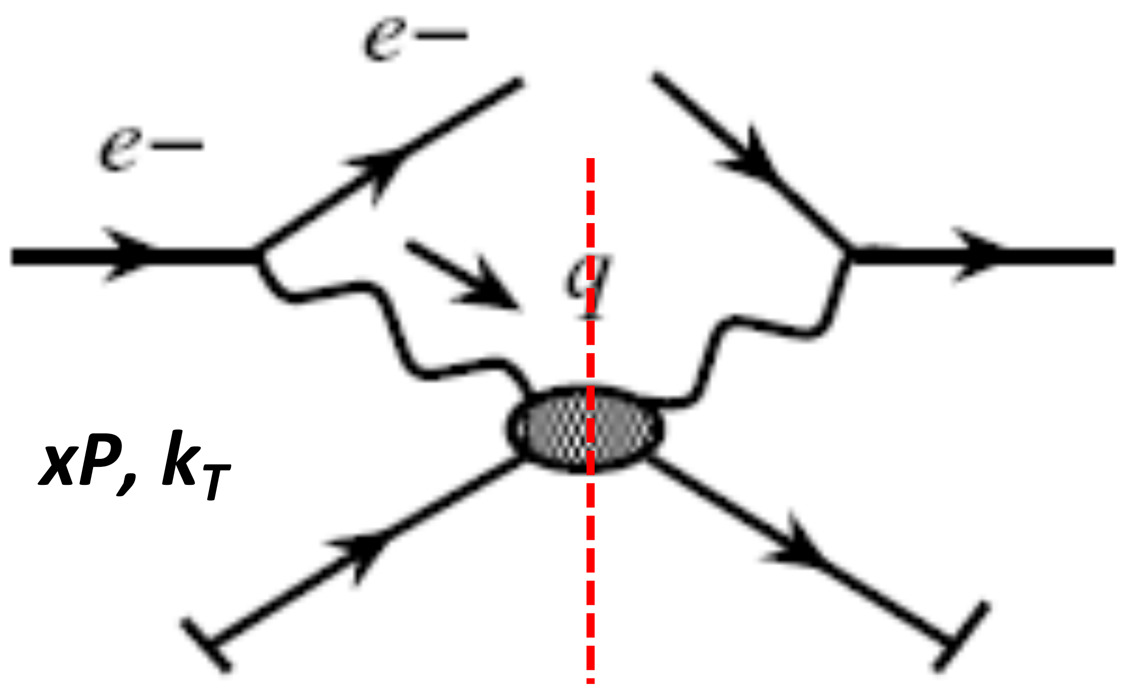
$$f_{q/p}(x) = \int_{-\infty}^{\infty} \frac{dy^-}{2\pi} e^{ixp^+y^-} \langle p\,|\,\bar{\psi}(0)\frac{\gamma^+}{2}\mathscr{W}(0,y^-)\psi(y^-)\,|\,p\rangle$$

How to probe the nucleon partonic structure?

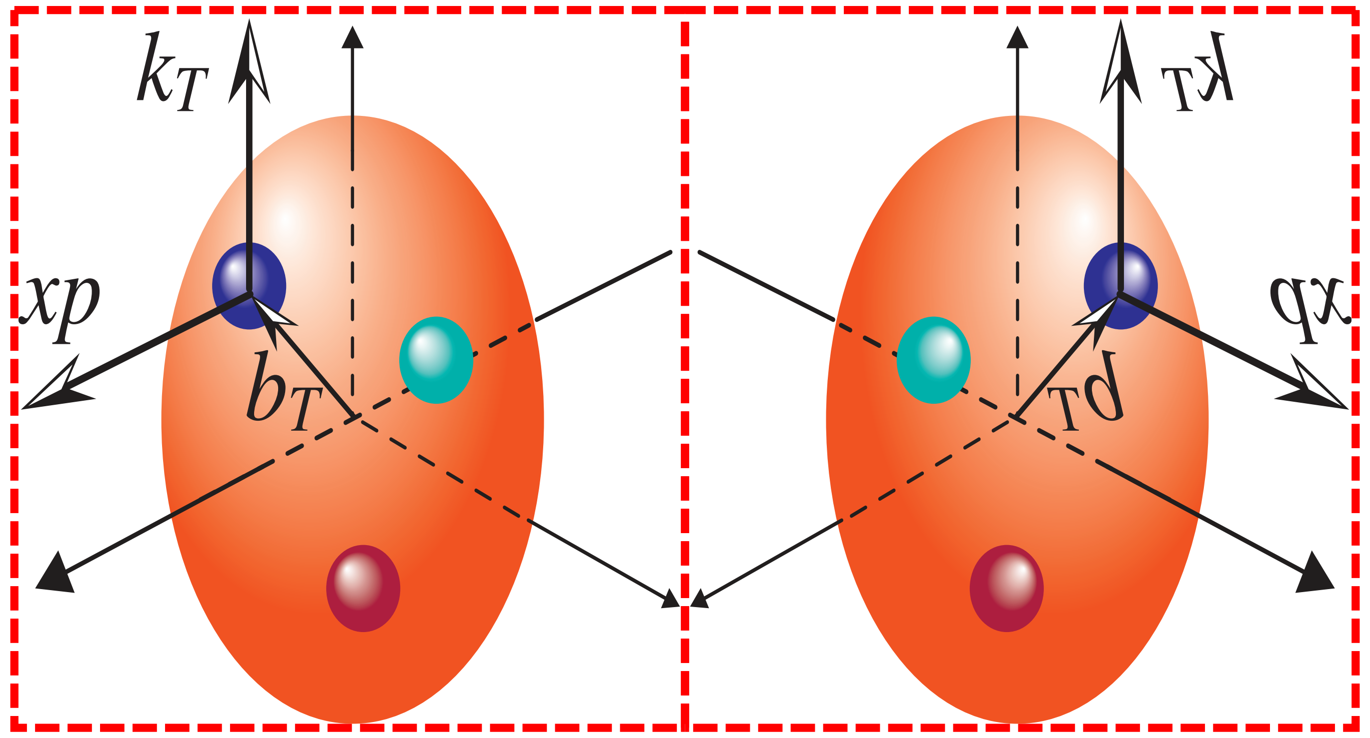
- Indispensable joint efforts from experiments and QCD theory

QCD factorization theorem

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



$\otimes$



Experimental measurements

Hard part controlled by pQCD theory

Nucleon partonic structure

实验

理论

计算

Methodology for global extraction of PDFs

Fitting Framework

Construction of χ^2_{global} from χ^2_n

PDF Parametrization

χ^2_n Construction

Generation of Theory Data

PDFs Evolution

Coefficient functions

Experimental Data

Minimization of χ^2_{global}

Hessian Matrix

Constructed sampling the χ^2_{global} function

Best fit

Uncertainties

PDF eigen vectors set using Hessian Method

MC Sampling of parameter space: new parameters introduced

理论

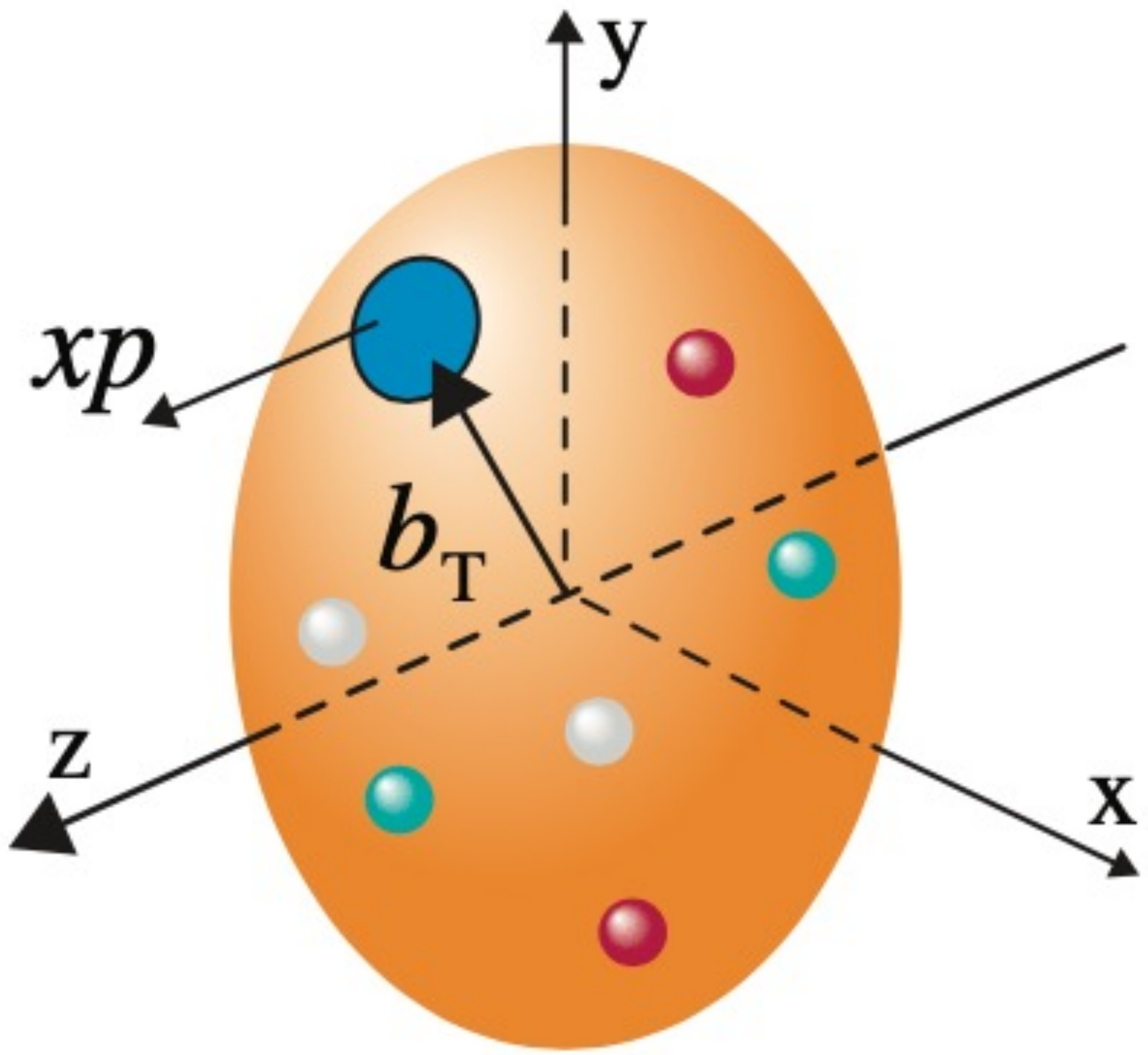
+

计算

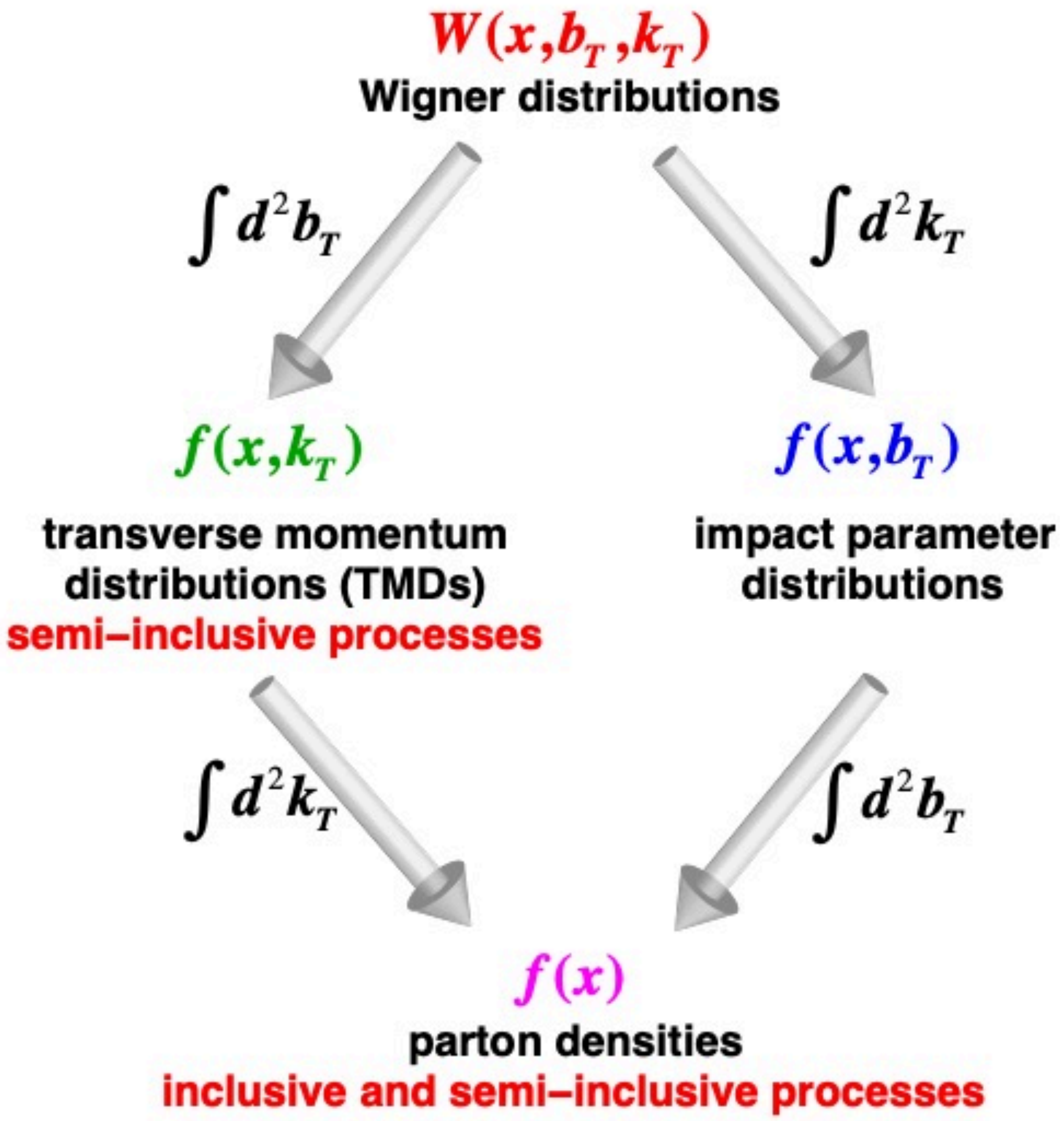
+

实验

Multi-dimensional view of nucleon structure



Wigner distribution
5D view



$W(x,b_T,k_T)$
Wigner distributions

$\int d^2b_T$

$\int d^2k_T$

$f(x,k_T)$
transverse momentum distributions (TMDs)
semi–inclusive processes

$f(x,b_T)$
impact parameter distributions

$\int d^2k_T$

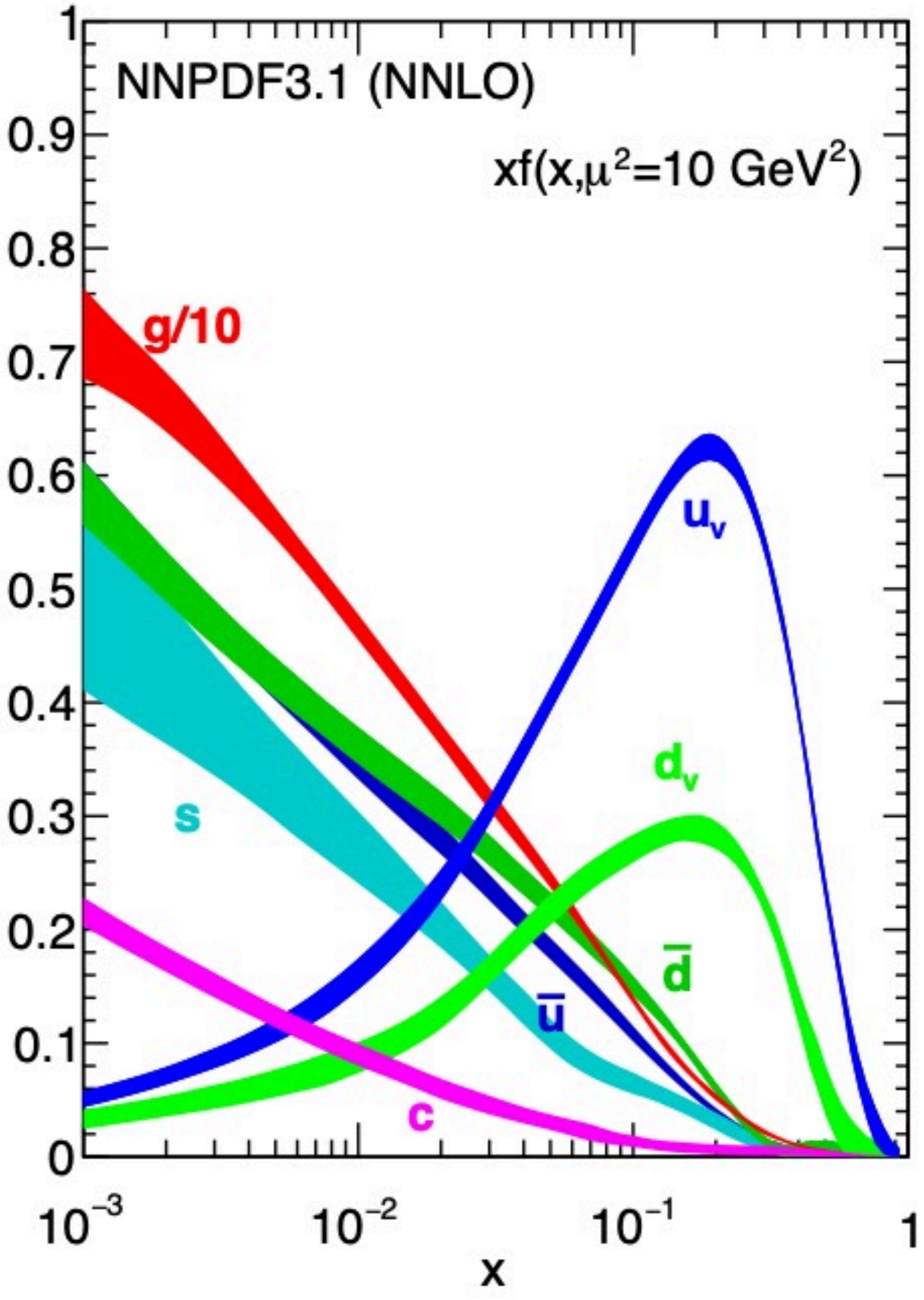
$\int d^2b_T$

$f(x)$
parton densities
inclusive and semi–inclusive processes

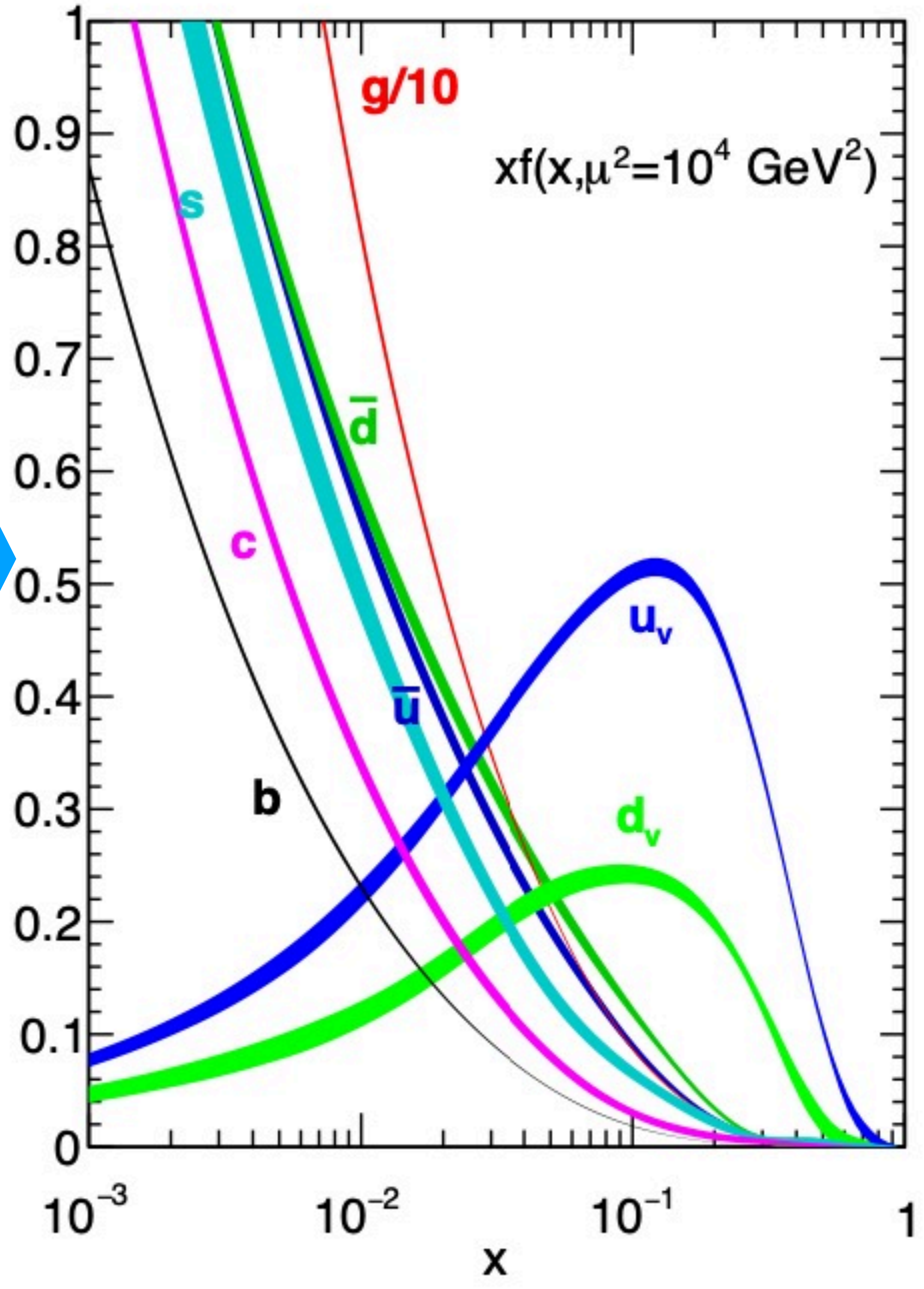
Many more remains to be answered: proton mass, proton spin, 3D structure …

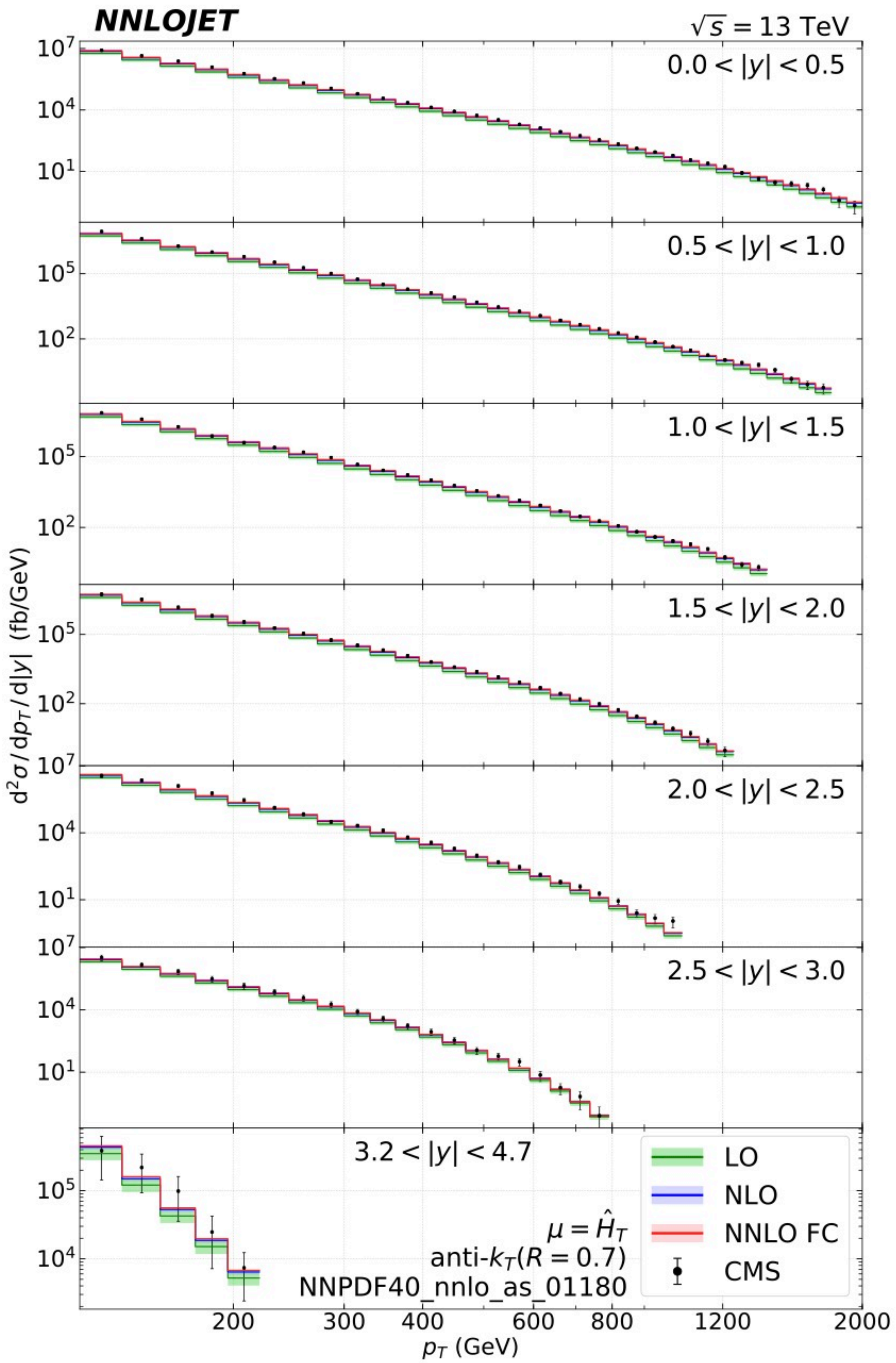
Predictive power of pQCD

- QCD evolution of nucleon 1D structure



DGLAP

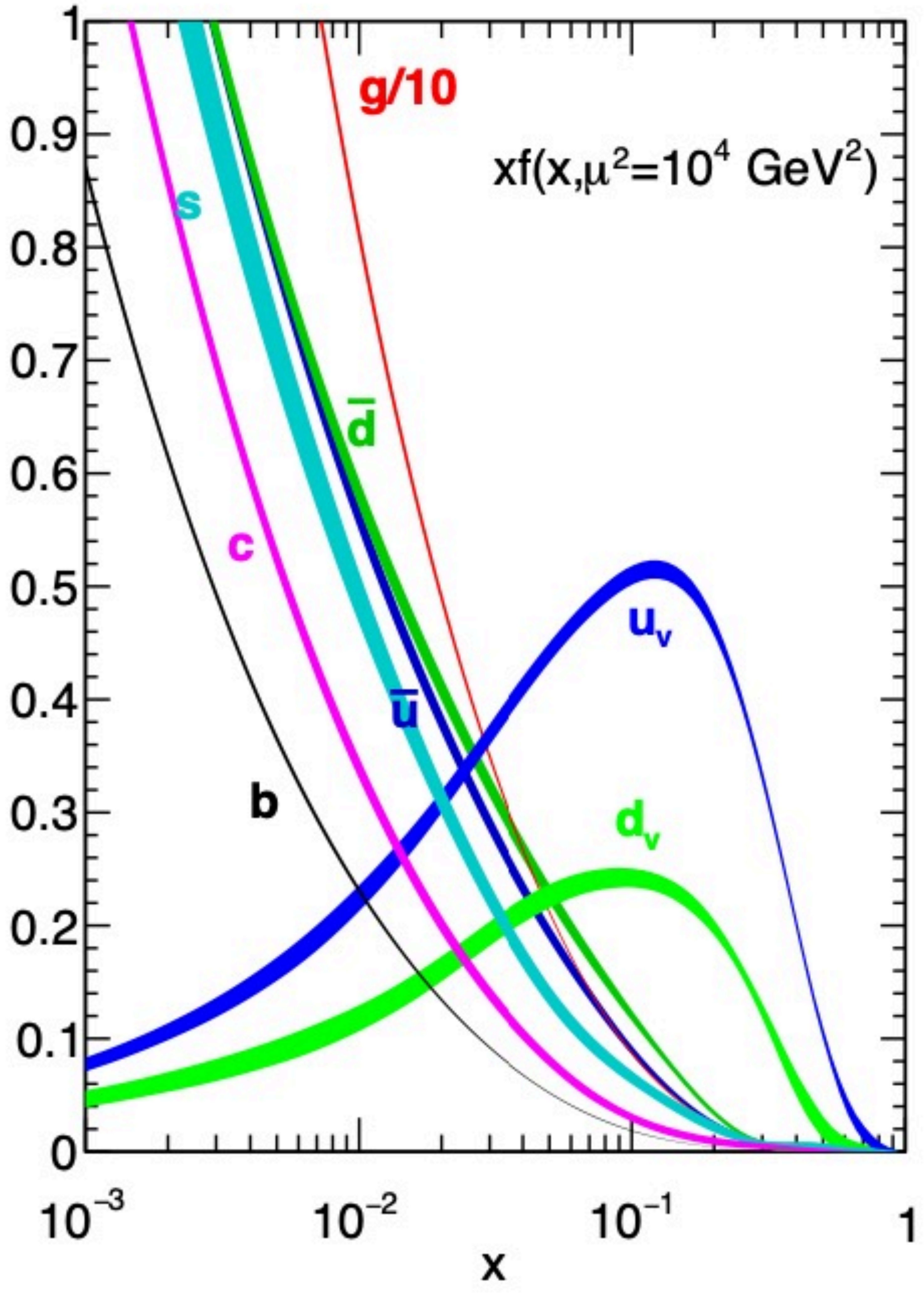


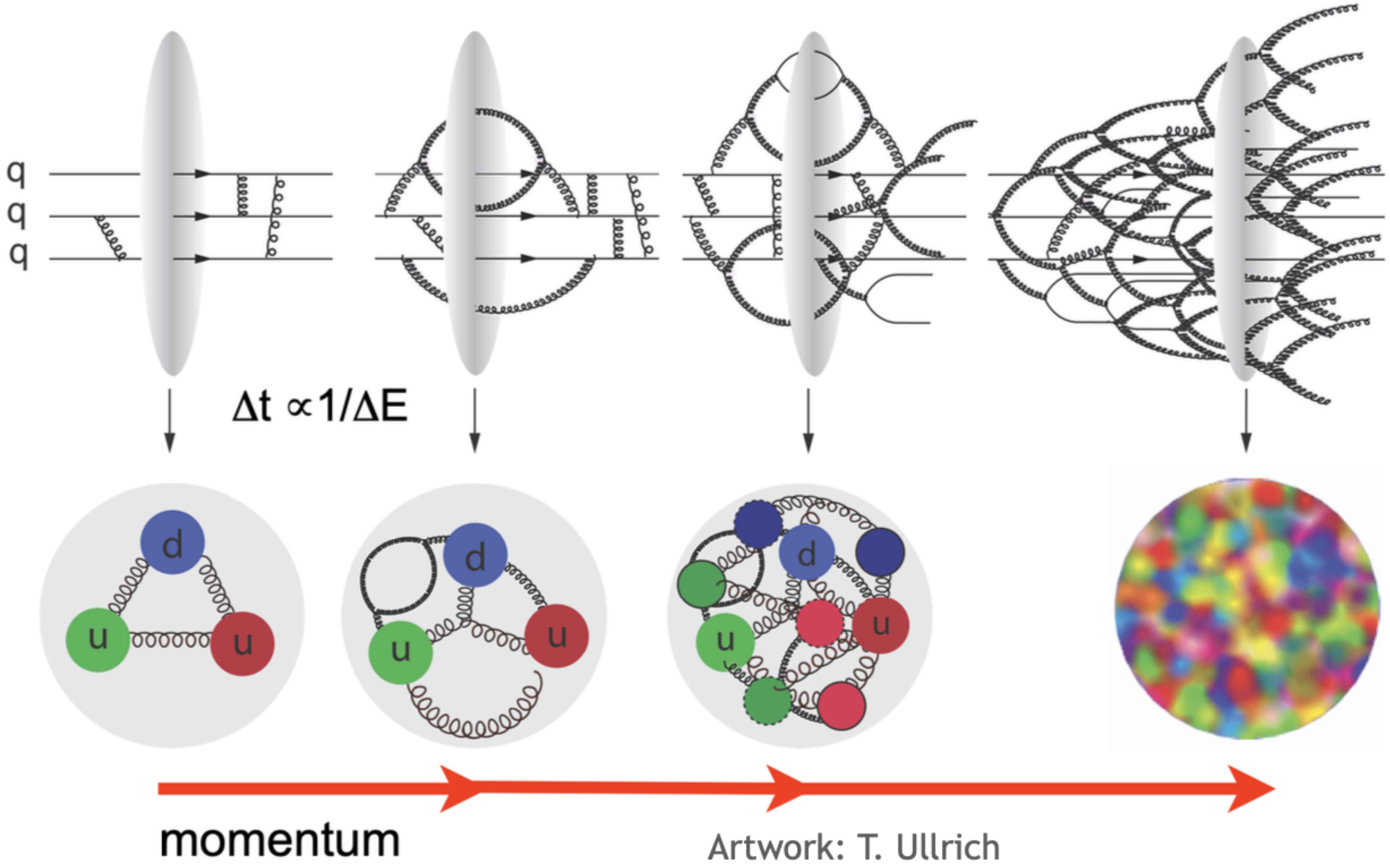


X. Chen et al, JHEP, 2022

There is no still picture for partons inside nucleon!

Anatomy of nuclear matter at high-energies





Artwork: T. Ullrich

Proposed Electron-ion colliders

RHIC ➔ US-EIC

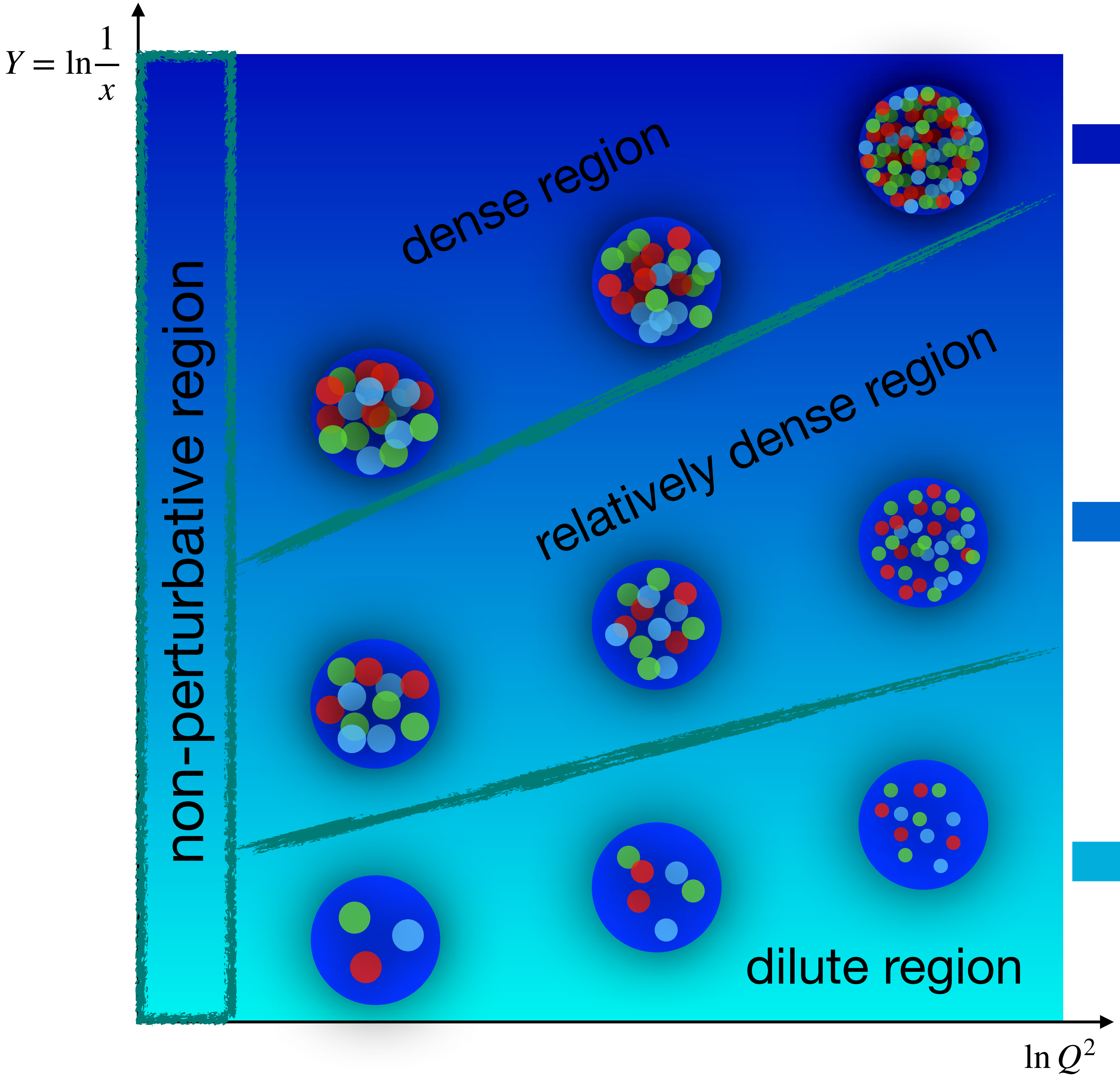
FAIR ➔ ENC

LHC ➔ LHeC

HIAF ➔ **EicC**

slide from Jinlong Zhang

QCD "phase diagram" for nuclei



Dense region: $x \ll \mathcal{O}(1)$

Probing length $\lambda \sim 1/xp \gg L \sim A^{1/3}$

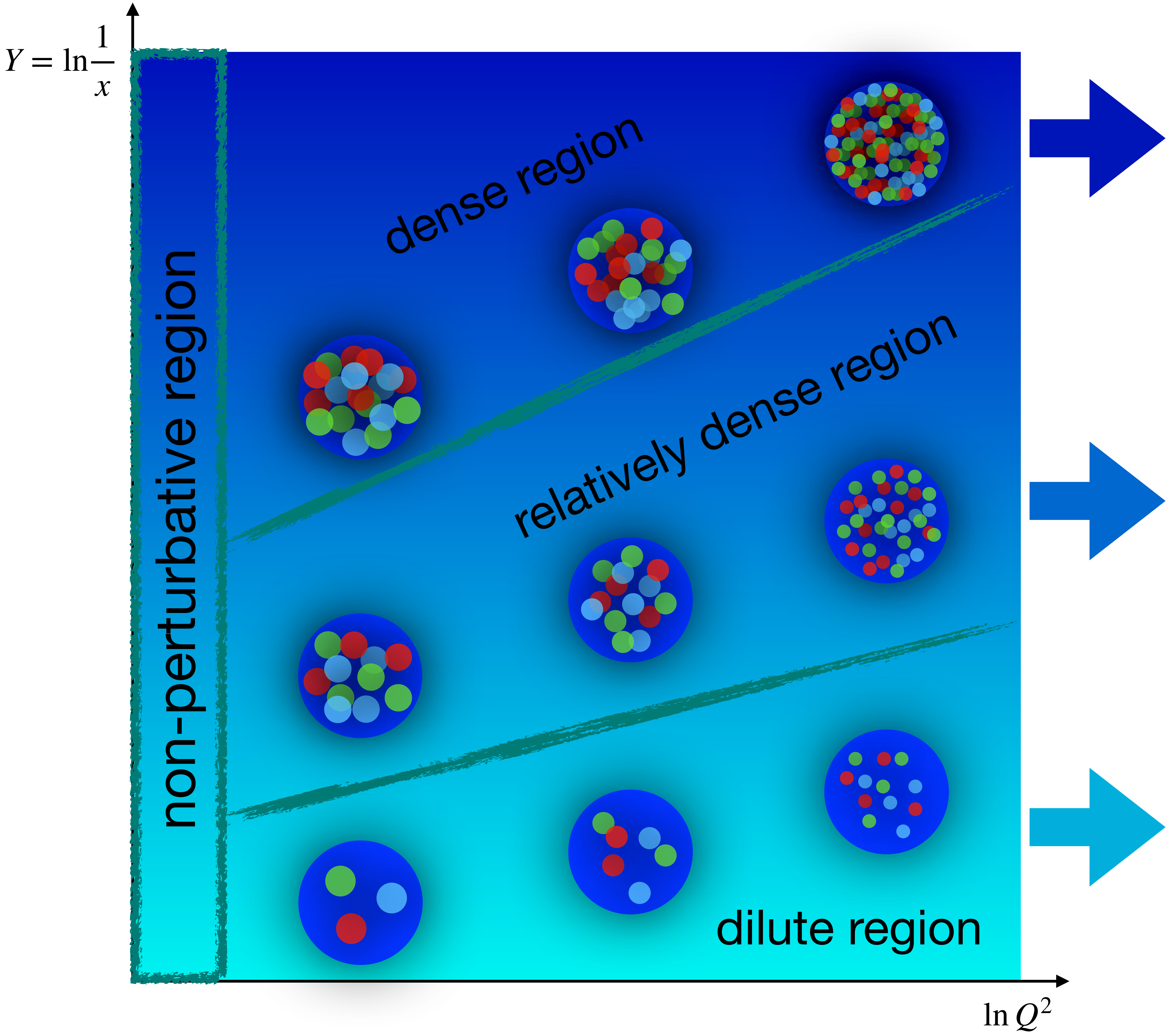
Relatively dense region: $x \lesssim \mathcal{O}(1)$

Probing length $\lambda \sim 1/xp \lesssim L \sim A^{1/3}$

Dilute region: $x \sim \mathcal{O}(1)$

Probing length $\lambda \sim 1/xp \ll L \sim A^{1/3}$

QCD factorization from dilute to dense region



Color Glass Condensate (CGC)

Wilson lines, nonlinear BK/JIMWLK evolution

See review: Gelis, Iancu, Venugopalan, 2003

High-twist formalism

Multi-parton correlation, DGLAP-type evolution

Qiu, Stermann, 1991

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

Leading twist collinear factorization

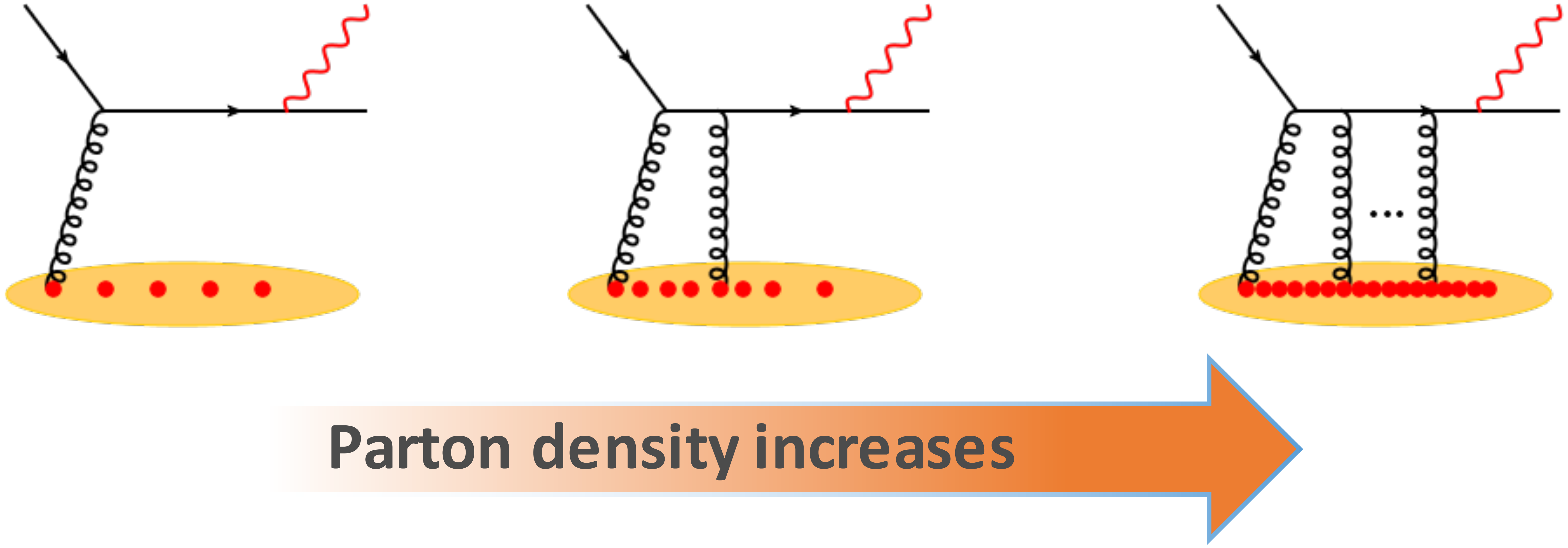
PDF, DGLAP evolution

Collins, Soper, 1981

CGC meets twist expansion

- Take direct photon production as an example to prove the matching of CGC and HT

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



$$\mathrm{d}\sigma \sim \frac{1}{p_{\gamma\perp}^4}\left[\underset{\substack{\uparrow\\ \text{leading twist}\\ \text{(twist-2)}}}{A} + \underbrace{B\frac{\langle k_\perp^2\rangle}{p_{\gamma\perp}^2} + C\frac{\langle k_\perp^2\rangle^2}{p_{\gamma\perp}^4}}_{\substack{\text{Higher twist}\\ \text{(twist-4 and twist-6)}}}\cdots\right] \longrightarrow \text{CGC}$$

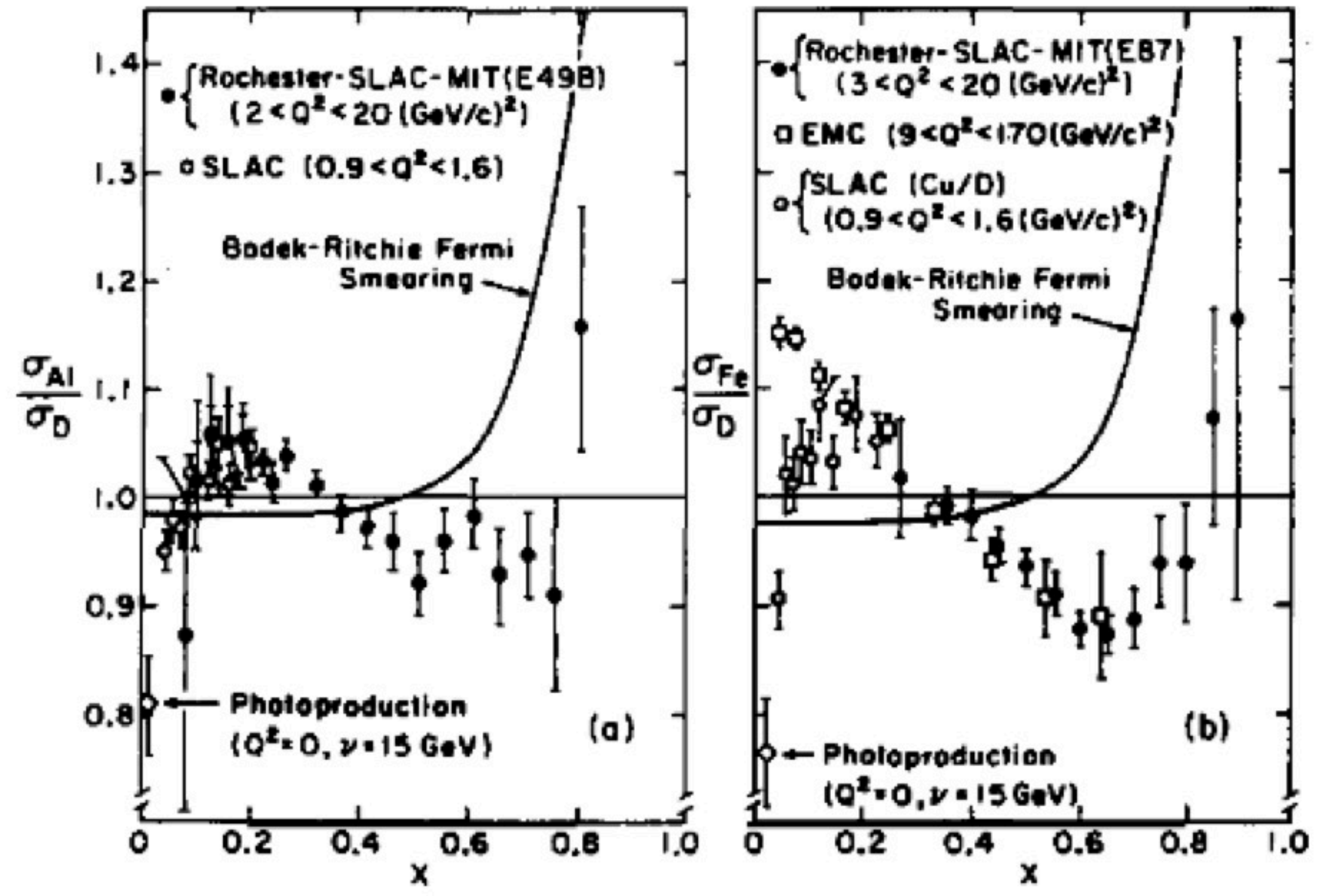
$\langle k_\perp^2\rangle \sim Q_s^2 \propto A^{1/3}x^{-\lambda}$

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

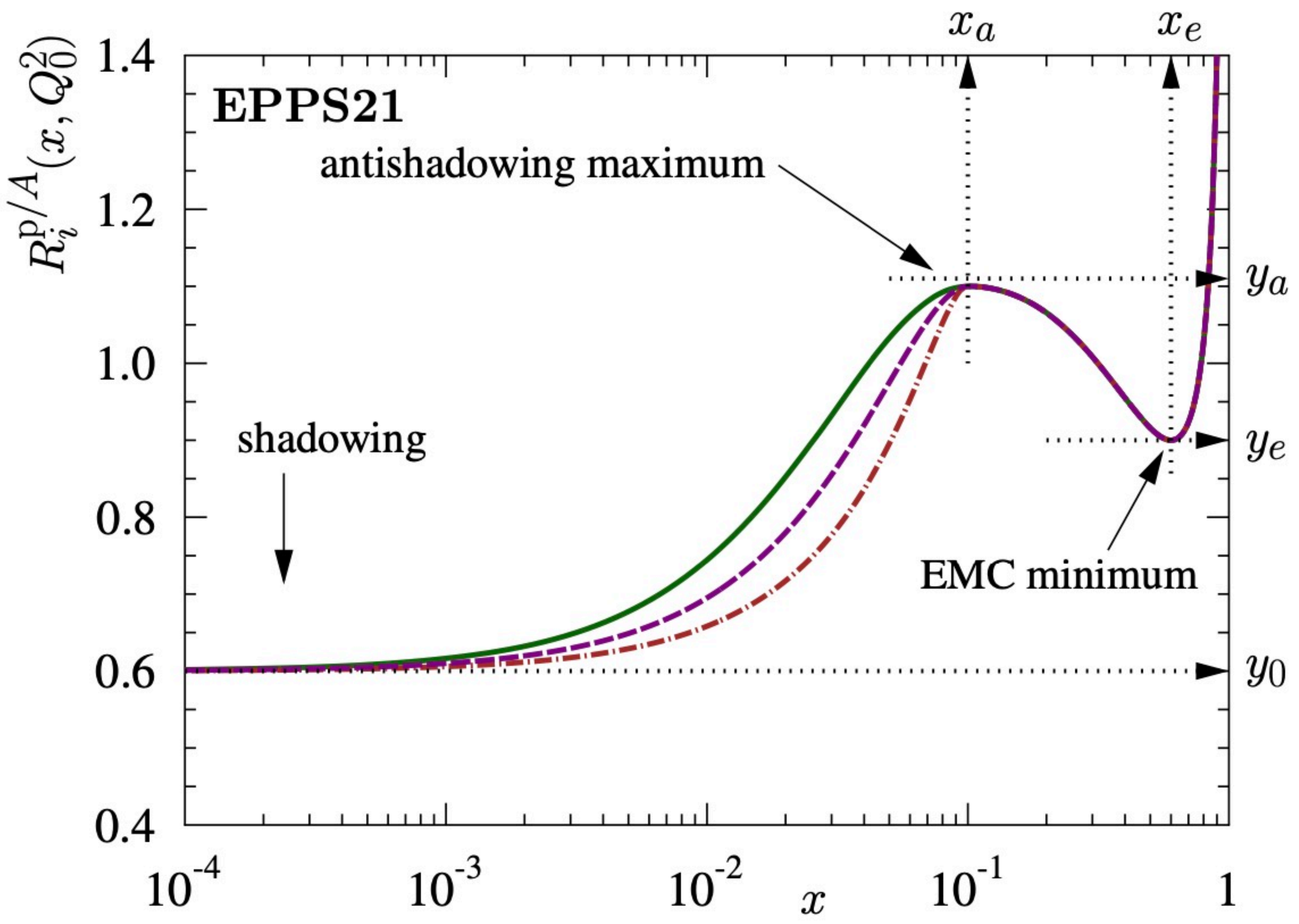
Long standing problems of nuclear partonic structure

✦ One-dimensional nuclear partonic structure

Four Decades of the EMC Effect



EMC Collaboration, 1983

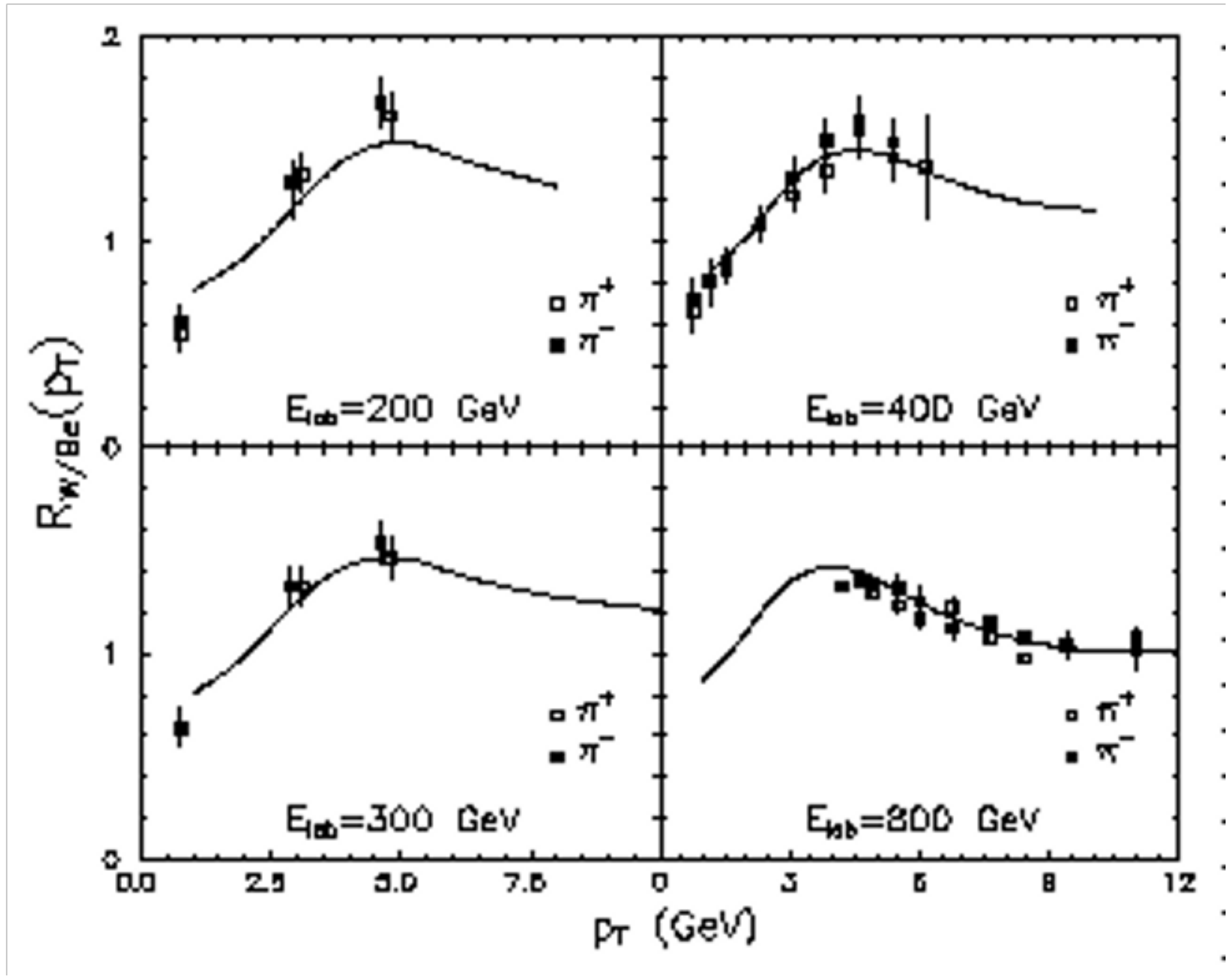


$$R_i^A = \frac{f_{i/A}(x,Q^2)}{f_{i/p}(x,Q^2)}$$

Long standing problems of nuclear partonic structure

✦ Three-dimensional nuclear partonic structure

Cronin effect

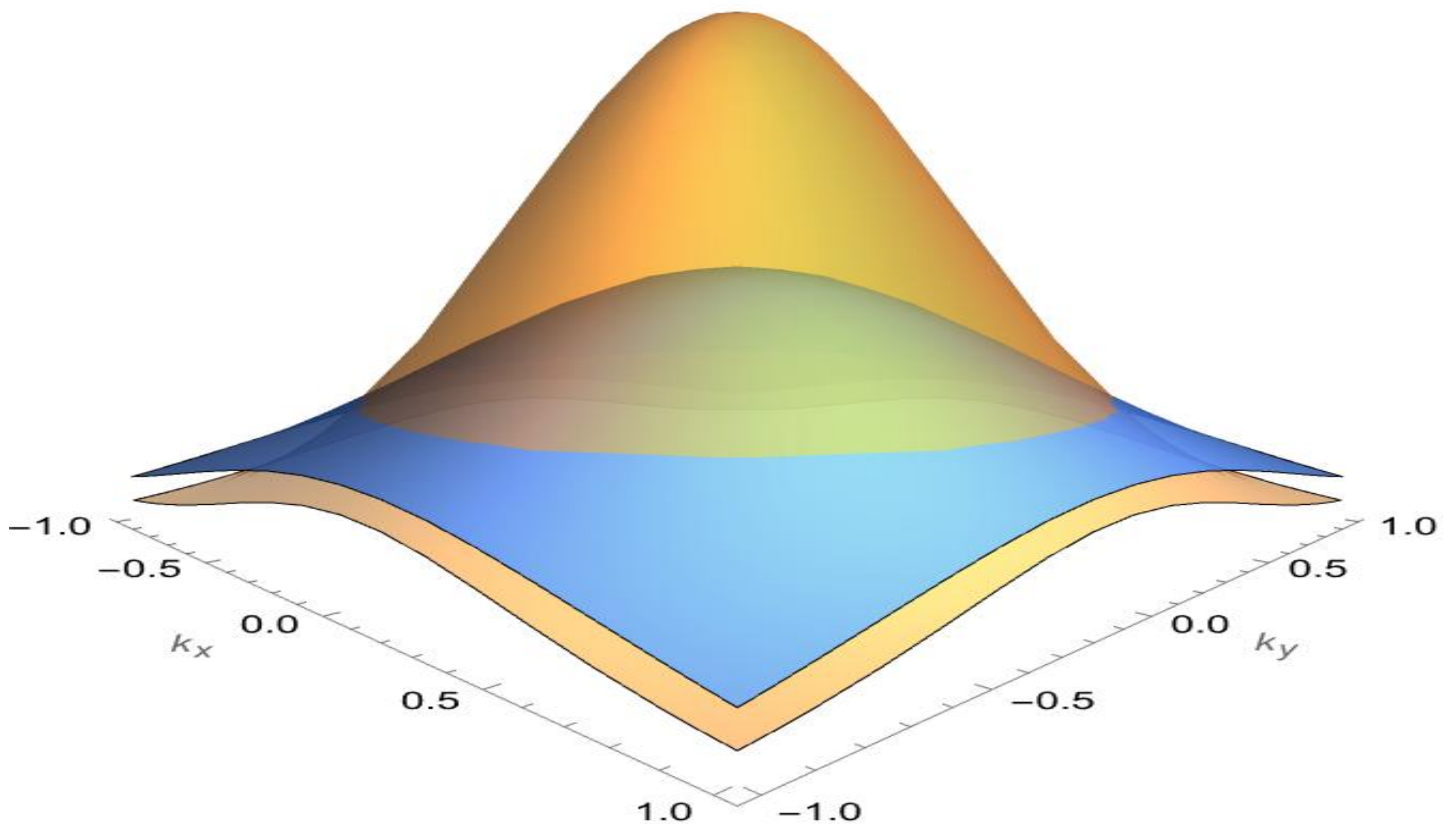


$$p + A \to \text{hadron(p)} + X$$

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

E100 Collaboration, PRD 11, 3105（1975）

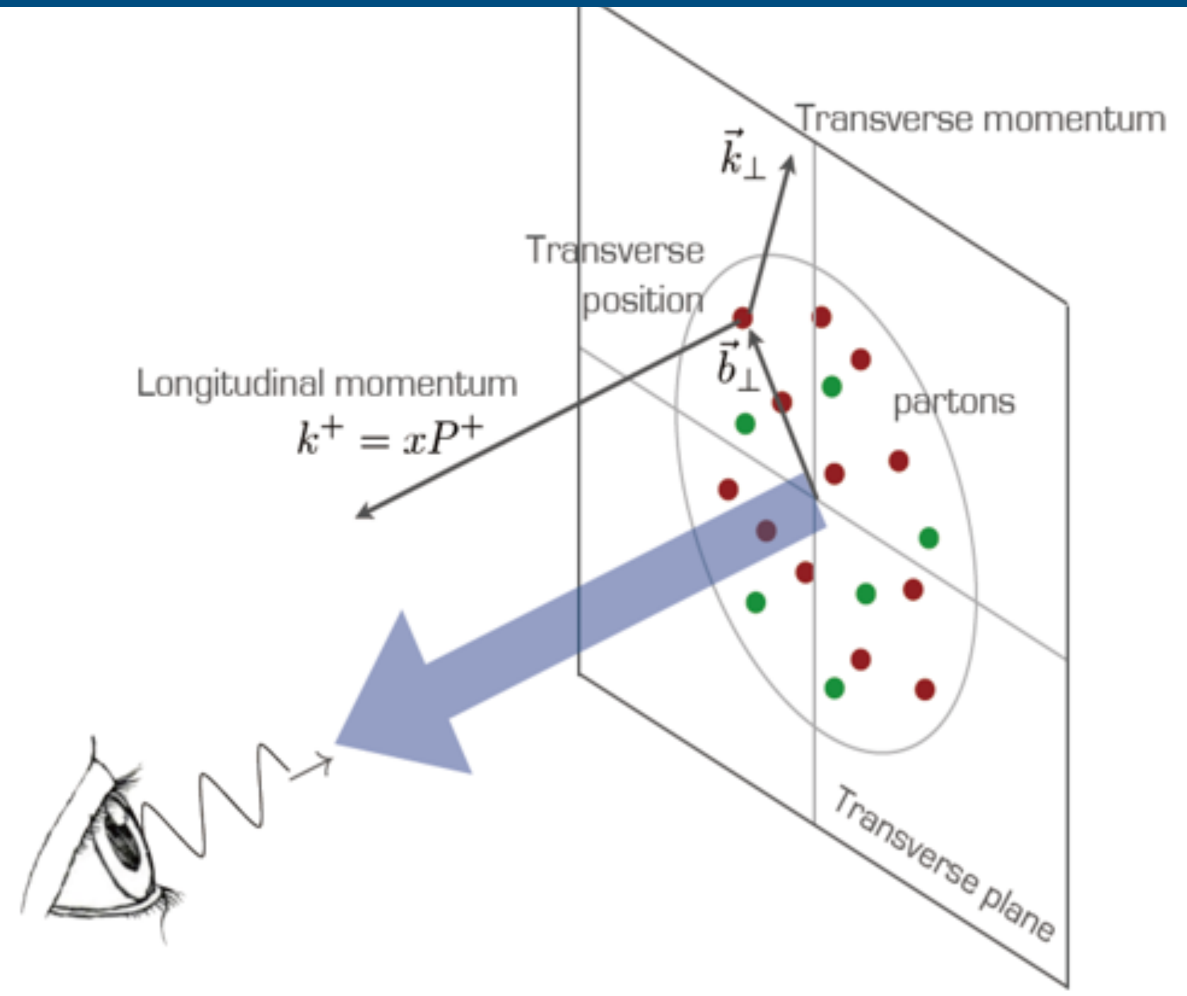
- Naive Gaussian model

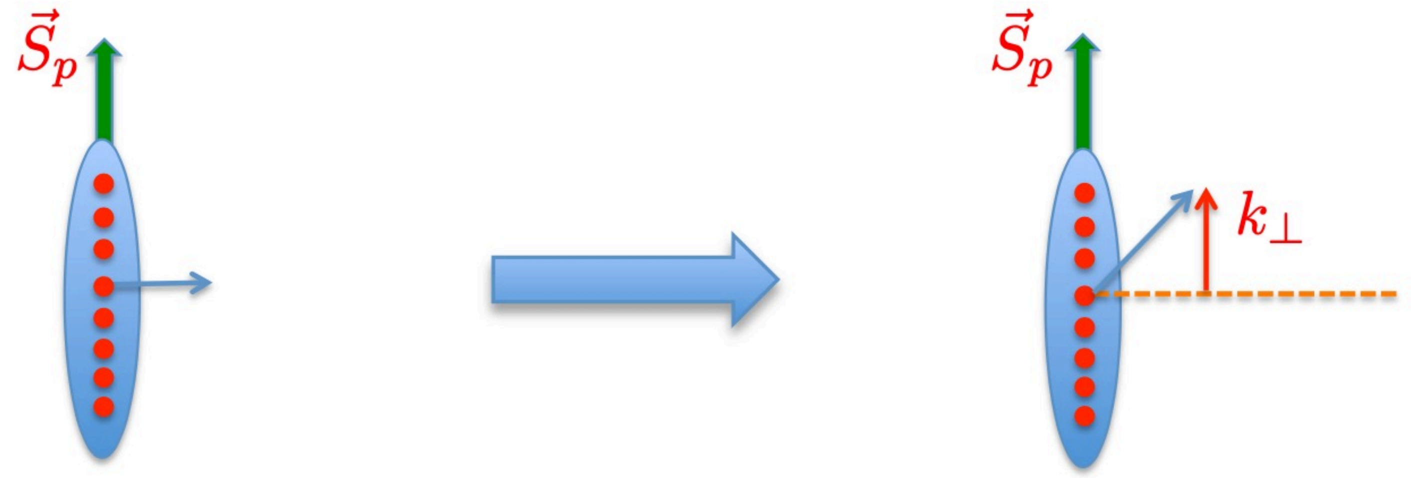


$$F_{i/p}(x, k_T) = f_{i/p}(x)\frac{e^{-k_T^2/\langle k_T^2\rangle}}{\pi\langle k_T^2\rangle}, \qquad \langle k_T^2\rangle_A \to \langle k_T^2\rangle_p + \left\langle \frac{2\mu^2 L}{\lambda} \right\rangle \xi^2$$

Global analysis of nuclear TMD

✦ Transverse momentum dependent PDFs (TMDs)

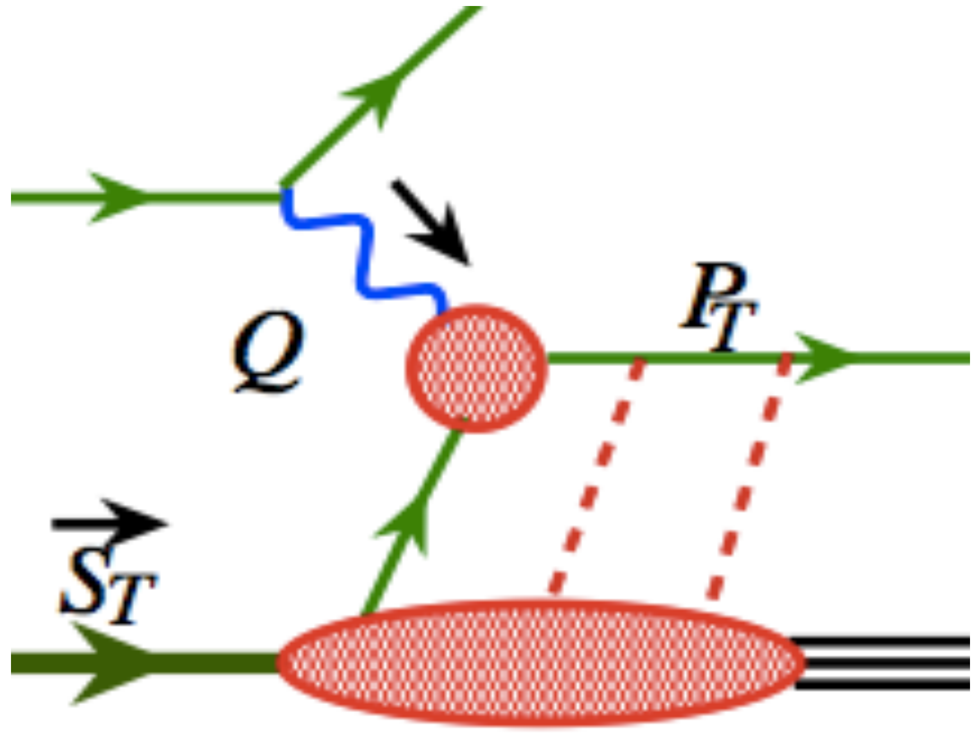




$f(x)$ $f(x, k_\perp)$

Collinear PDFs → **Transverse momentum distributions (TMDs)**

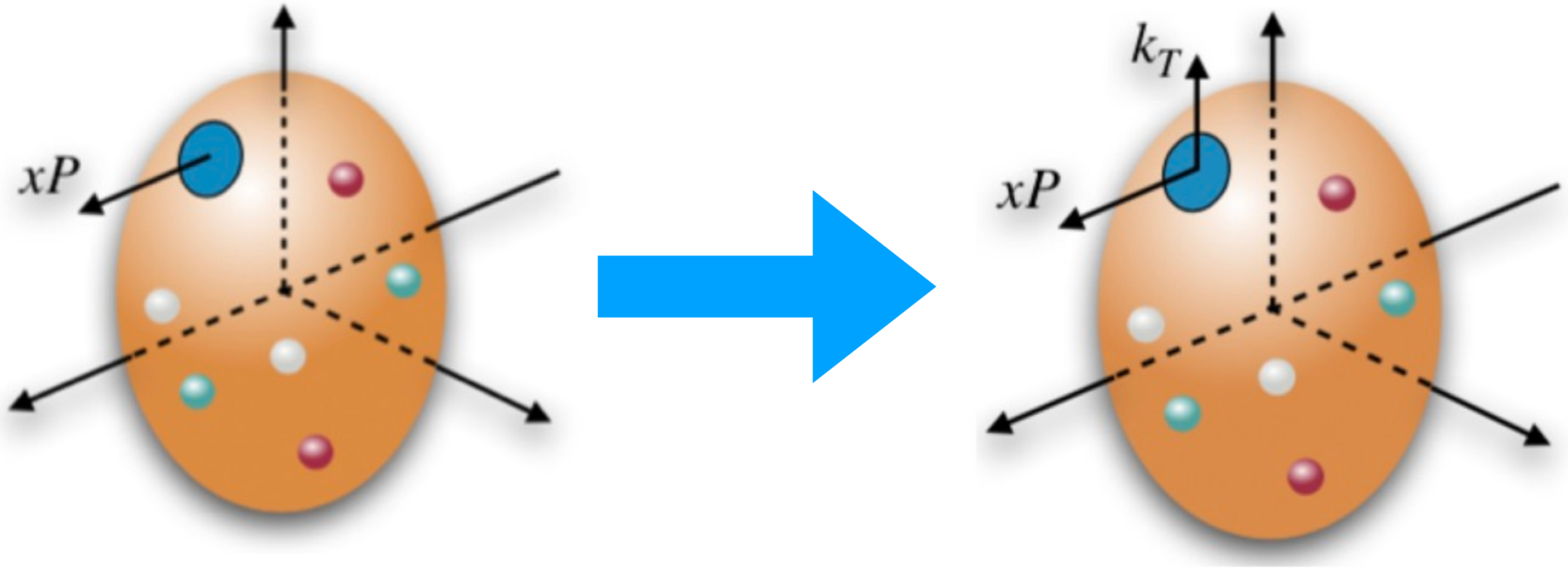
- Probing nucleon 3D structure requires two momentum scales
- Hard scale $Q_1 \gg 1/fm$ localizes the probes (particle nature of quarks/gluons)
- Soft scale $Q_2 \sim 1/fm$ accesses the transverse motion of quarks/gluons



SIDIS: Q>>P_T

Global analysis of nuclear TMD

✦ From collinear (1D) to TMD (3D)



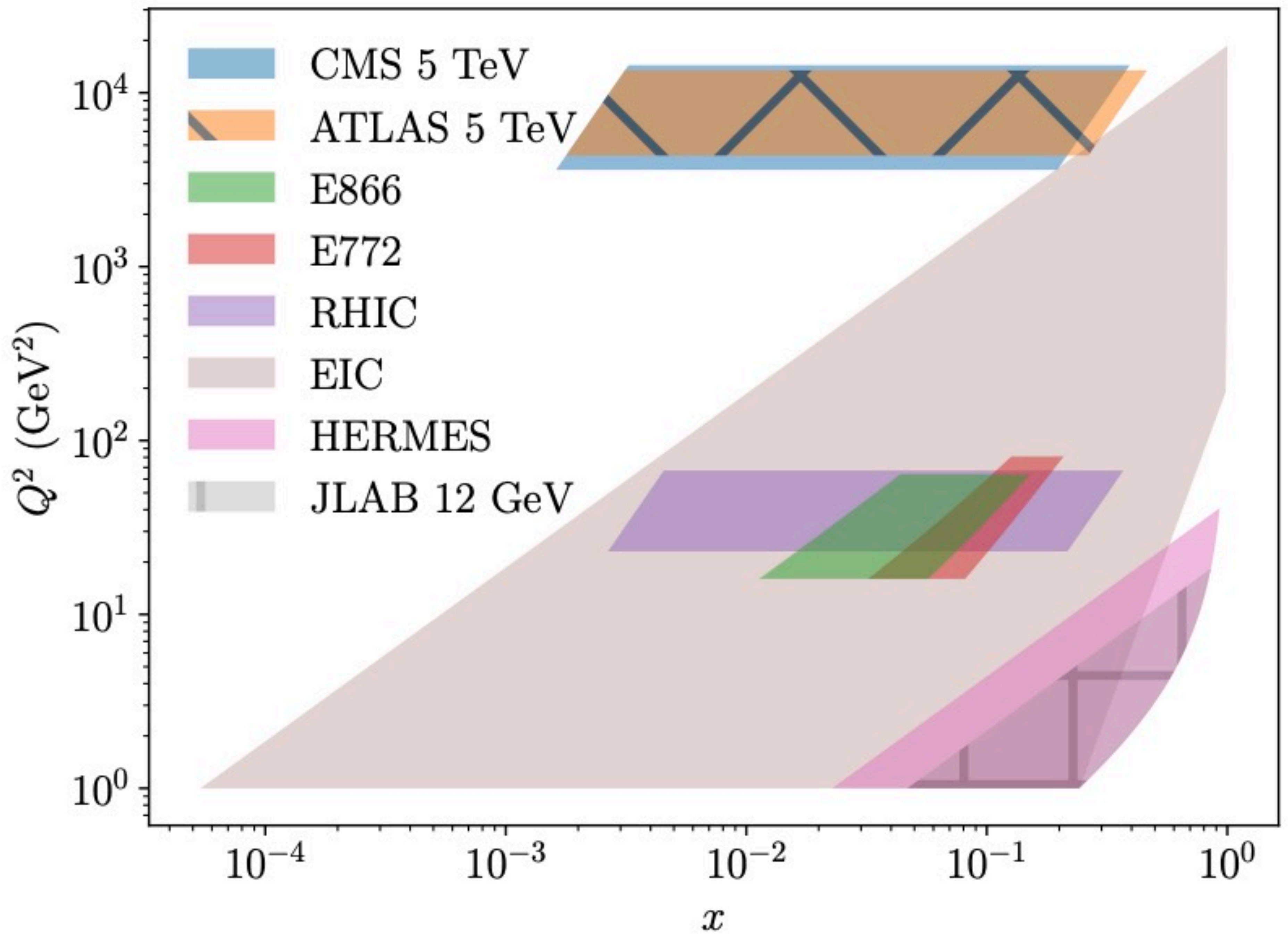
Collaboration	Process	Baseline	Nuclei	N_{dat}	χ^2
HERMES [36]	SIDIS (π)	D	Ne, Kr, Xe	27	16.3
RHIC [44]	DY	p	Au	4	2.0
E772 [42]	DY	D	C, Fe, W	16	20.1
E866 [43]	DY	Be	Fe, W	28	43.3
CMS [45]	γ^*/Z	NA	Pb	8	9.7
ATLAS [46]	γ^*/Z	NA	Pb	7	13.1
Total				90	105.2

Drell-Yan Measurements

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

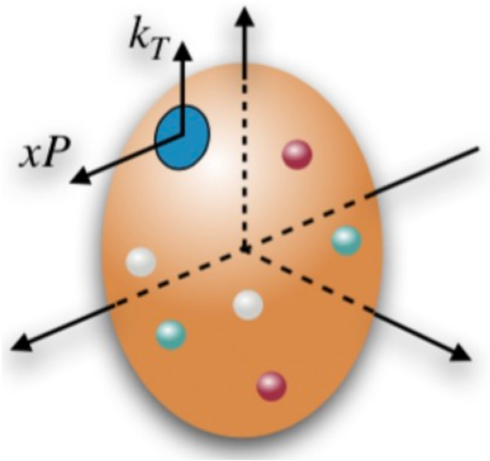
SIDIS Measurements

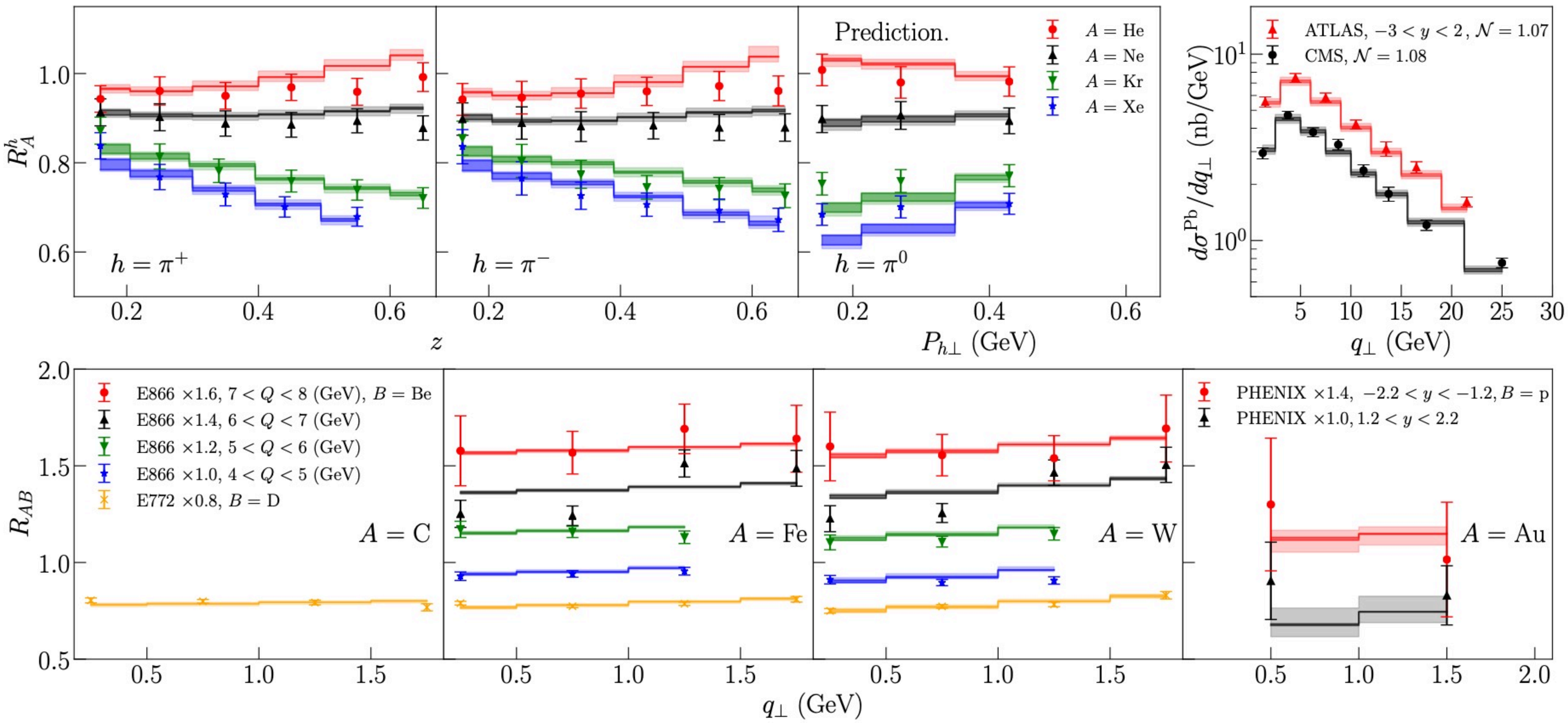
- Multiplicity ratio $R_h^A = M_h^A / M_h^D$.
  -HERMES 2007
  -Prelim. JLab
  -Planned JLab
  -Possible EIC.



Global analysis of nuclear TMD

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



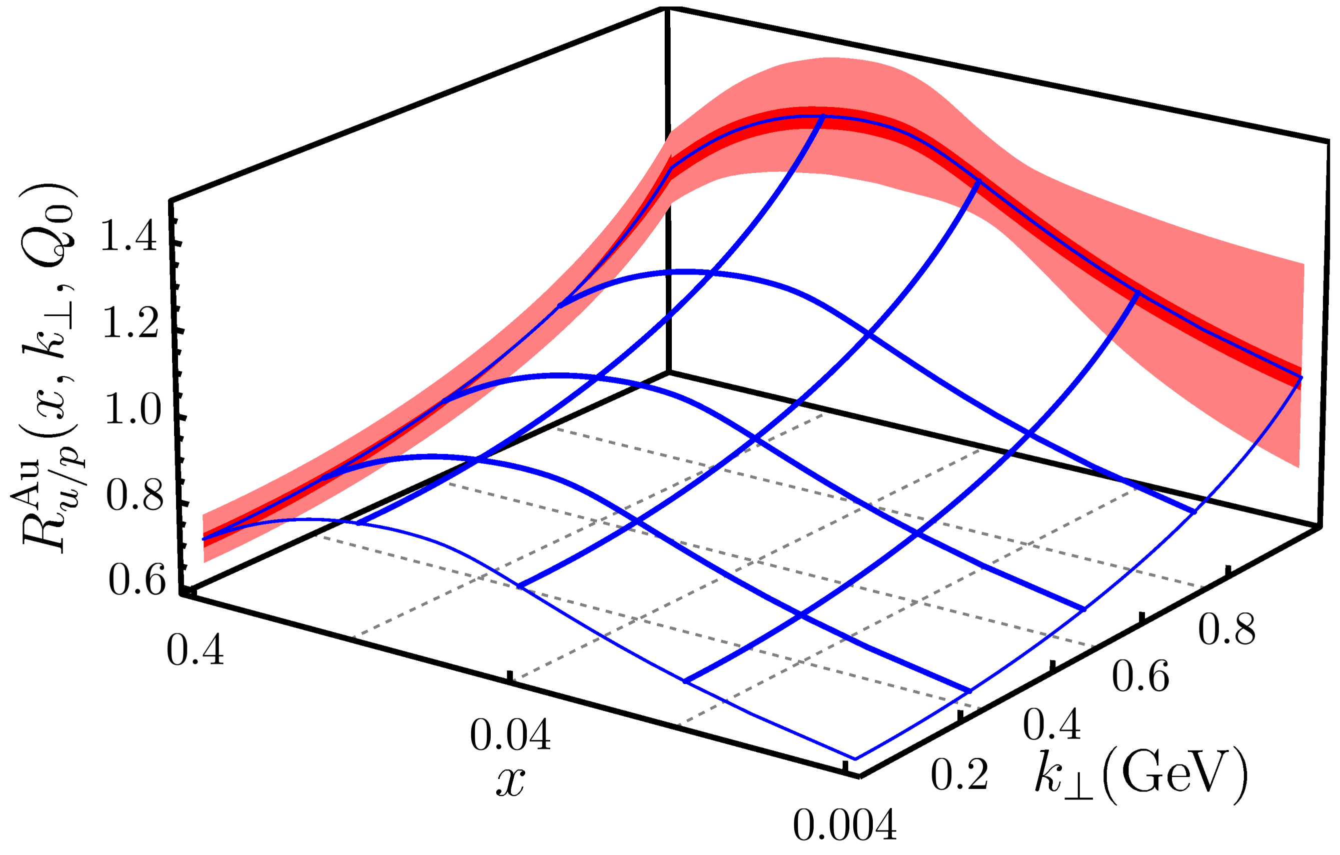


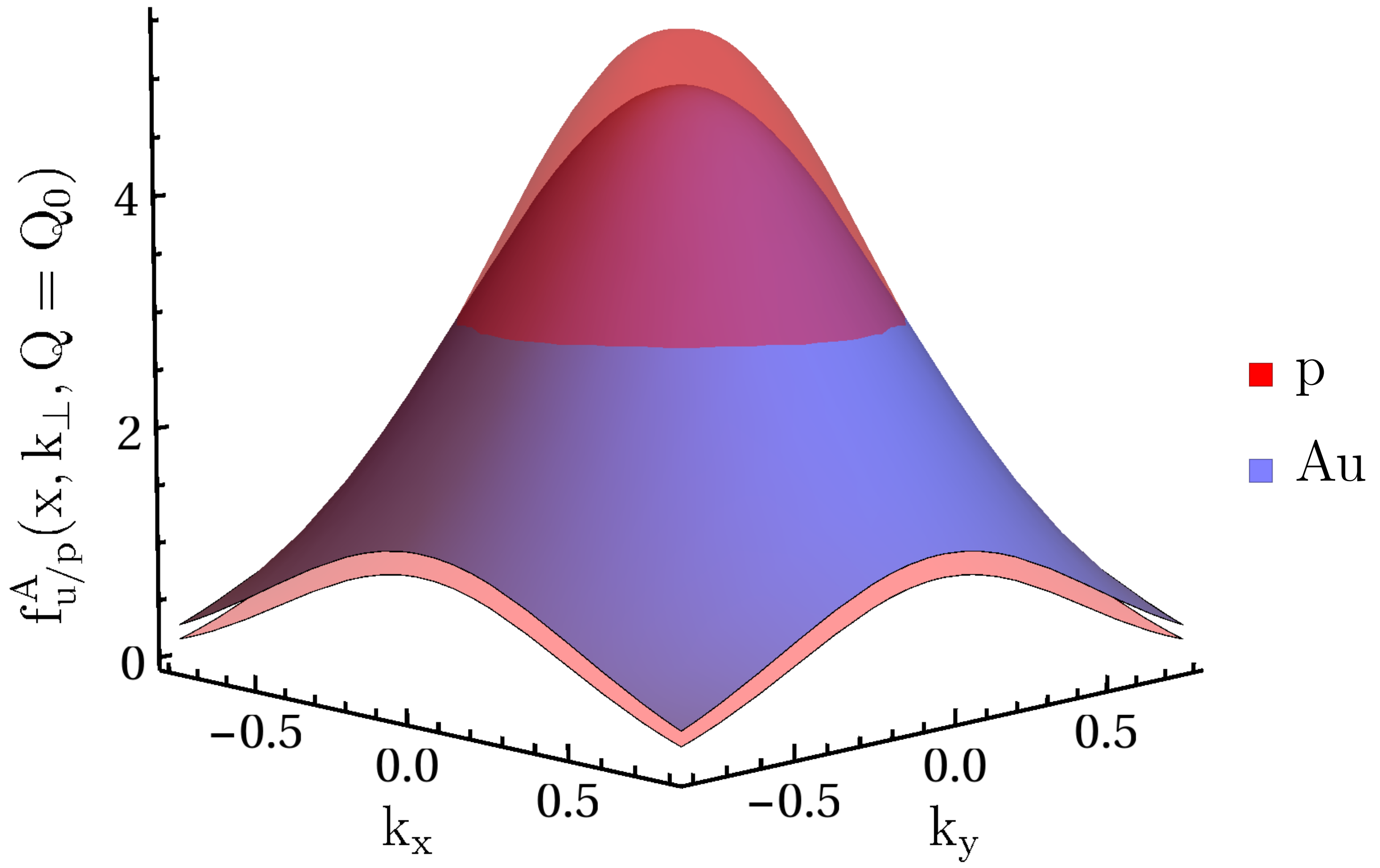
Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

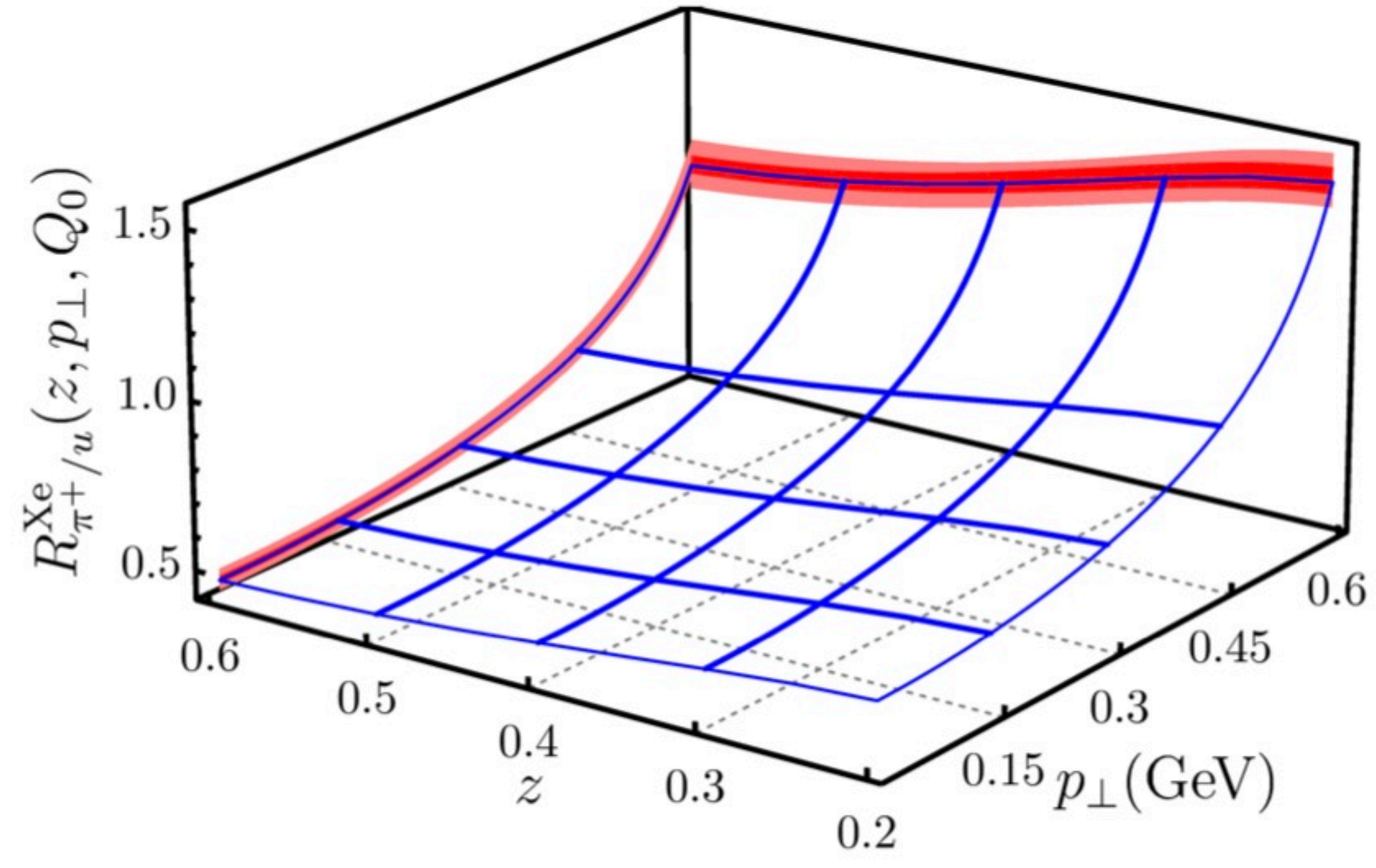
Three-dimension imaging in nuclei

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

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







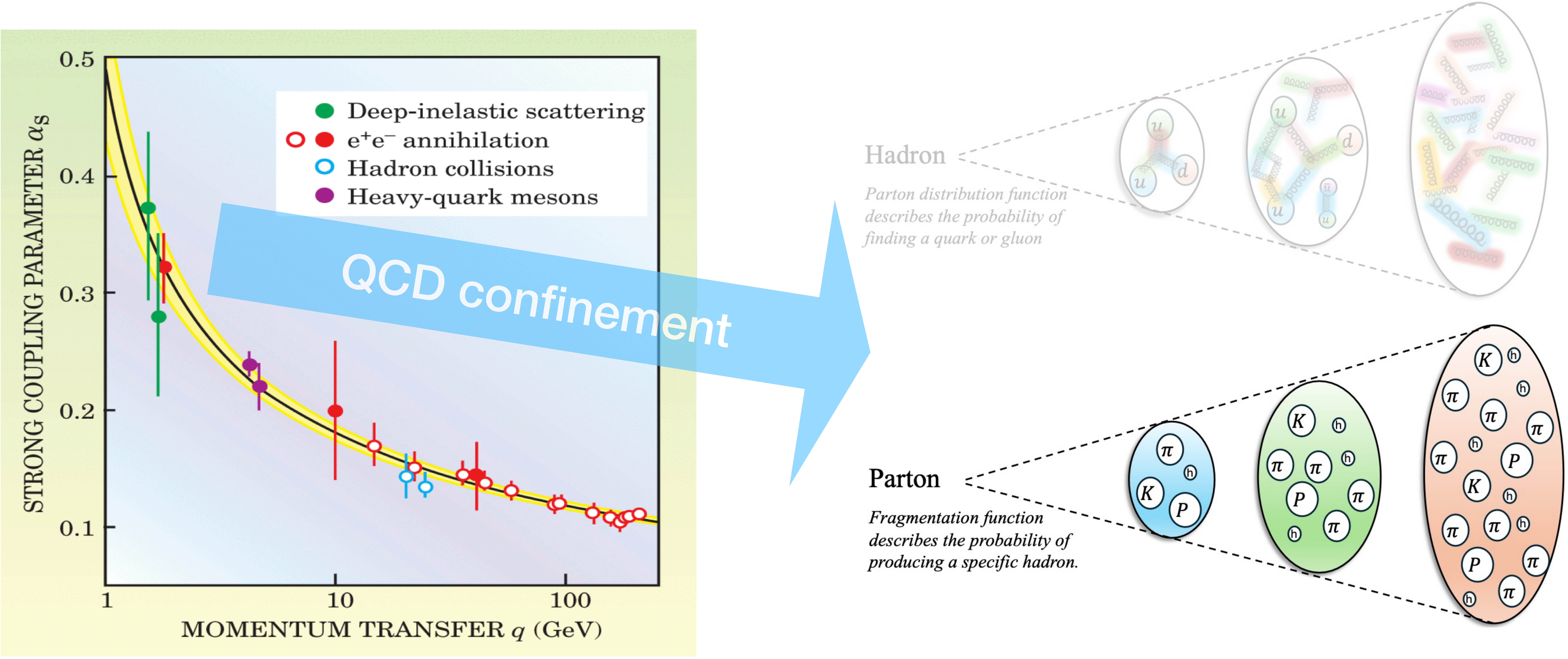
- **First time quantitative determination of nuclear TMDs**
- **Identification of transverse momentum broadening in nuclei**

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

Alrashed, Kang, Terry, **HX**, Zhang, 2312.09226

QCD confinement

✦ QCD as the fundamental theory of strong interaction



Parton distribution function describes the probability of finding a quark or gluon

Fragmentation function describes the probability of producing a specific hadron.

Figure taking from PRL 134,111902

QCD confinement - FF as a proxy of hadronization

✦ First validating QCD via FFs - “discovery” of gluon!

- The first propose of FFs

INCLUSIVE PROCESSES AT HIGH TRANSVERSE MOMENTUM†

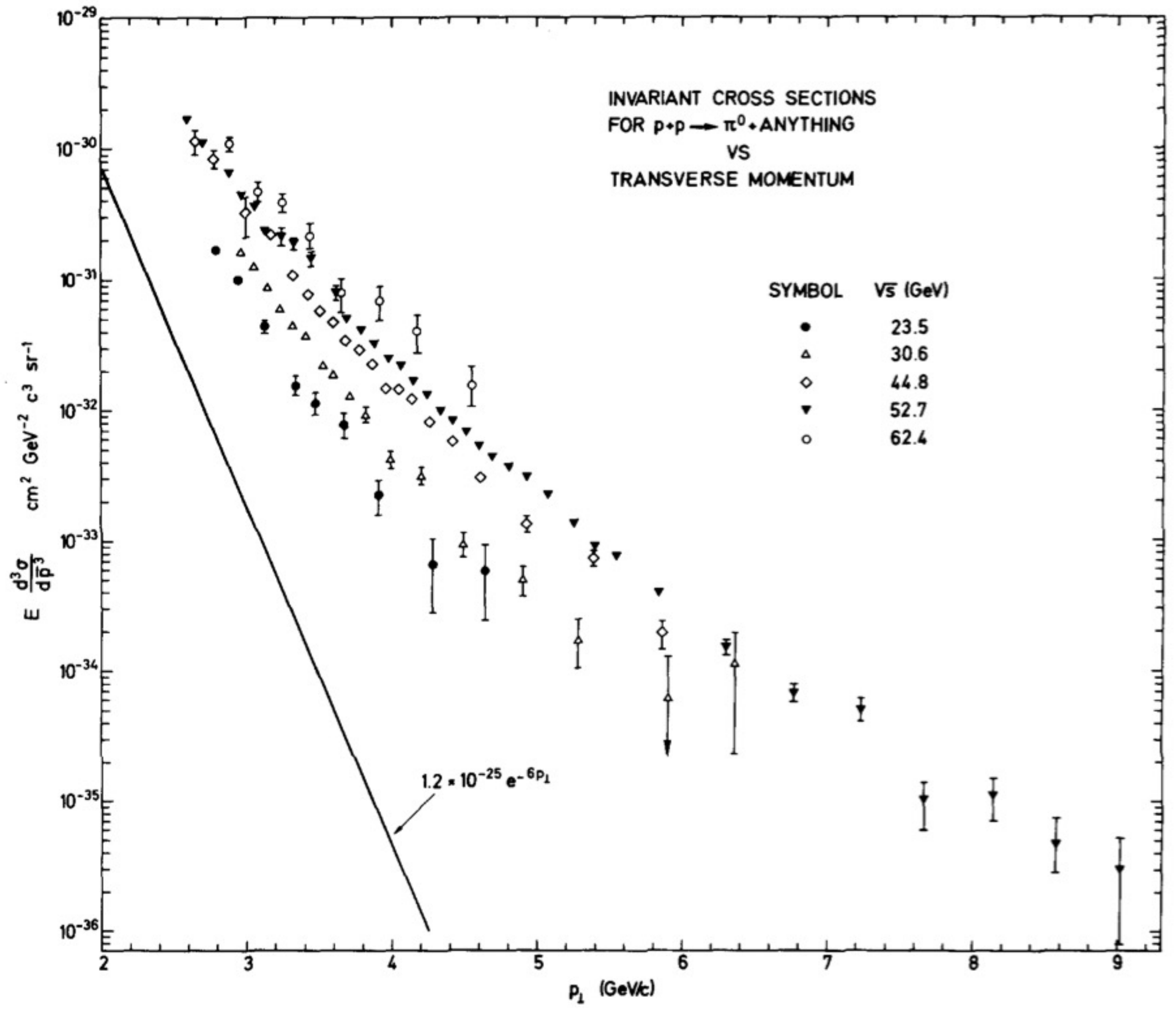
S. M. Berman, J. D. Bjorken and J. B. Kogut
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

ABSTRACT

We calculate the distribution of secondary particles C in processes A + B → C +
anything at … m p_T far in
excess of … deep-
inelastic el… lepton (ℓ),
photon (γ), … a scaling
behavior, … behavior
even for A, … easing
p_T, implyi… produced
in 400 GeV … ceeds
8 GeV/c. … colliding-
beam exper… n (or
neutrino processes). Among the processes discussed in some detail are ℓℓ → h, γγ → h, ℓh → h, γh → h, γh → ℓ, as well as hh → ℓ, hh → γ, hh → W, and W → h, where W is the conjectured weak-interaction intermediate boson. The basis of the calculation is an extension of the parton model. The new ingredient necessary to calculate the processes of interest is the inclusive probability for finding a hadron emerging from a parton struck in a deep-inelastic collision. This probability is taken to have a form similar to that generally presumed for finding a parton in an energetic hadron. We study the dependence of our conclusions on the validity of the

Berman, Bjorken, Kogut, PRD (1971)

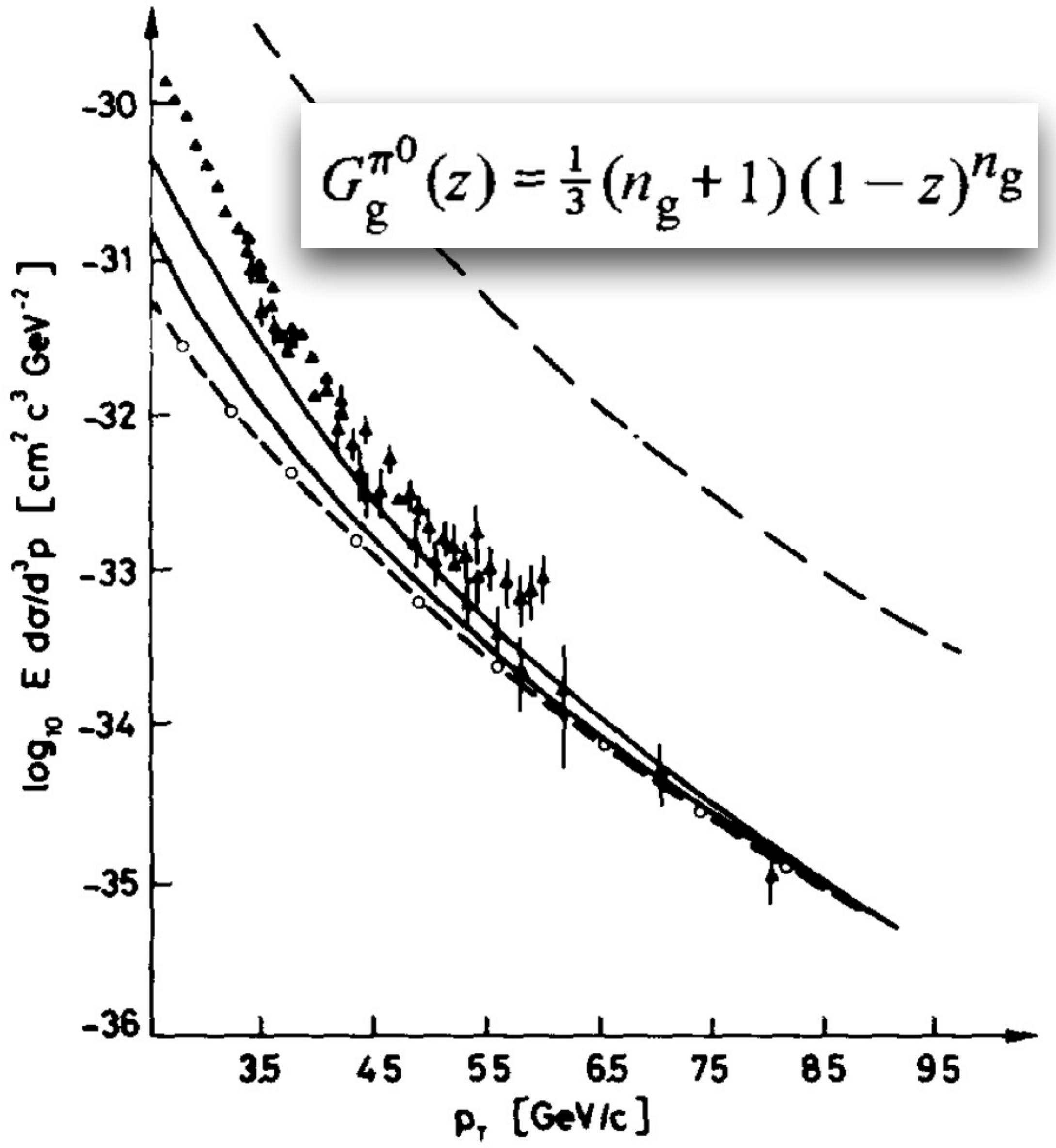
- **The first phenomenological indication of gluons**



CERN-ISR, PLB, 1973

Cahalan, Geer, Kogut, Susskind, PRD (1975)

EARLIER THAN
Gluon discover by
3-jet events in e^+e^- (TASSO, 1979)



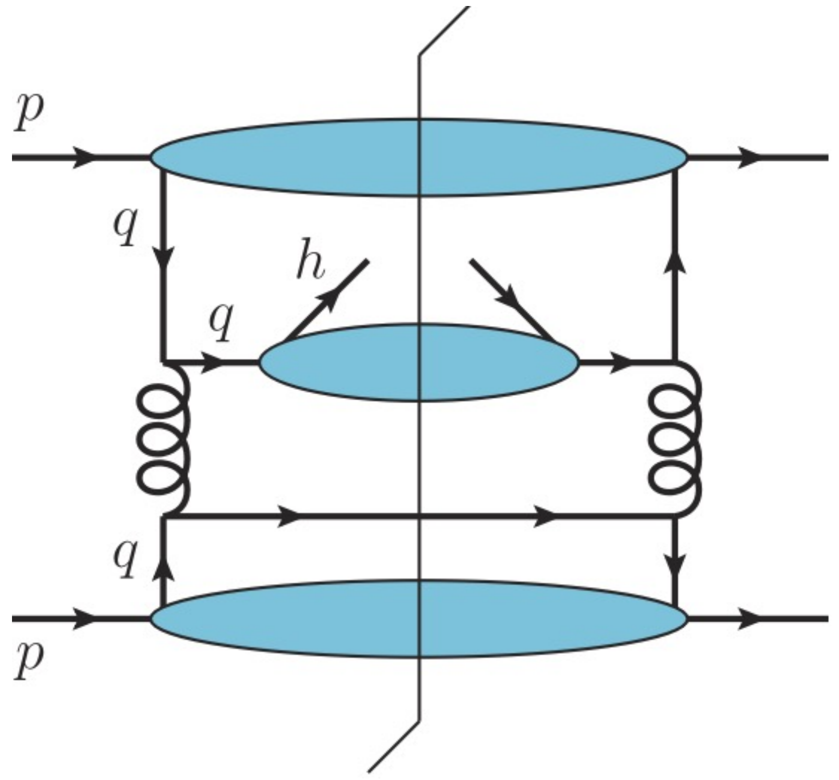
$$G_g^{\pi^0}(z) = \frac{1}{3}(n_g + 1)(1 - z)^{n_g}$$

Fig. 2 Predictions for π^0 (solid curves) and total jet (dash-dot curve) inclusive cross-sections in pp interactions at $\sqrt{s} = 62.4$ GeV, $\theta = 90°$. The two solid curves correspond to $n_g = 1$ (upper) and $n_g = 3$ in eq. (4). The quark-quark scattering contribution alone is given by the dash-open circle curve. The points are single pion data from ref. [9].

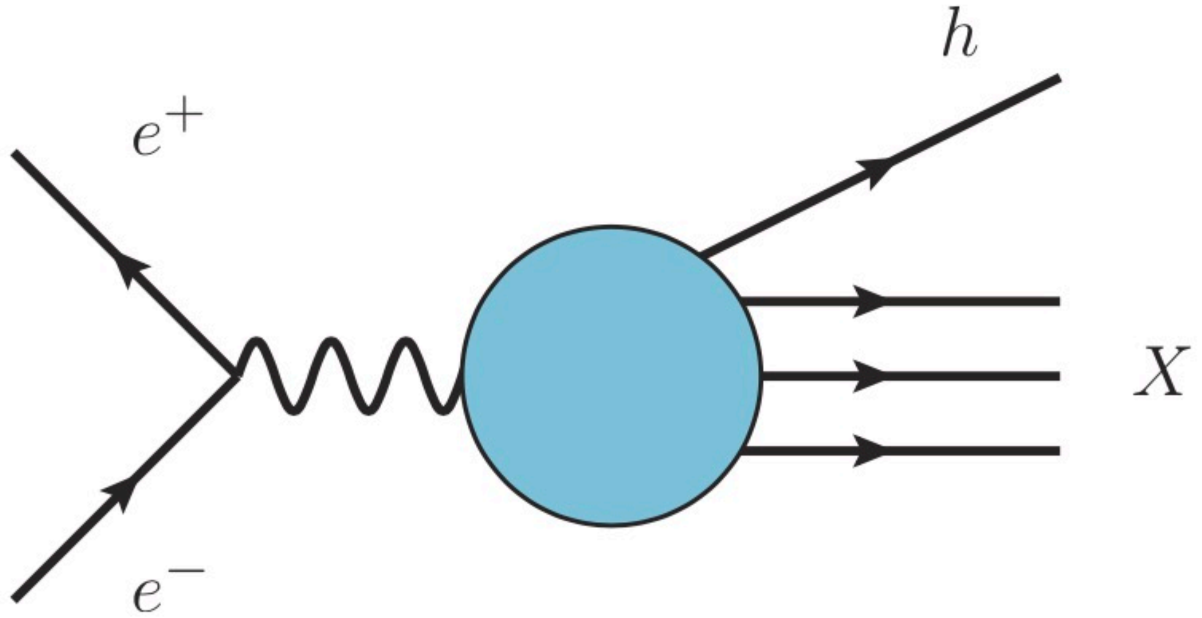
Cambridge, Kripfganz, Ranft, PLB (1977)
Cutler, Sivers, PRD (1978)
Owens, Reya, Gluck, PRD (1978)

QCD factorization for hadron production

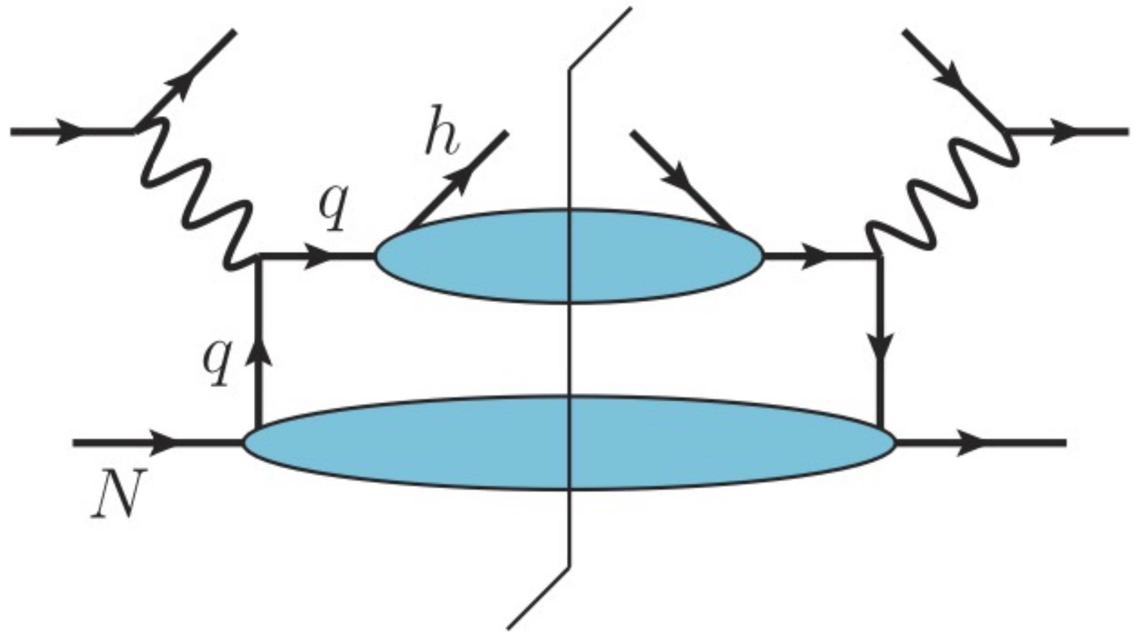
✦ **Access to FFs in pp, e^+e^- and ep collisions: universality of FFs**



RHIC, LHC



BEPC, SuperKEKB



HERA, JLab, EIC/EicC

- **Factorization requires large momentum transfer** $Q \gg \Lambda_{QCD}$

$$\sigma^{pp\to hX} = f_{i/p} \otimes f_{j/p} \otimes \hat{\sigma}_{ij\to k} \otimes D_{k\to h}$$

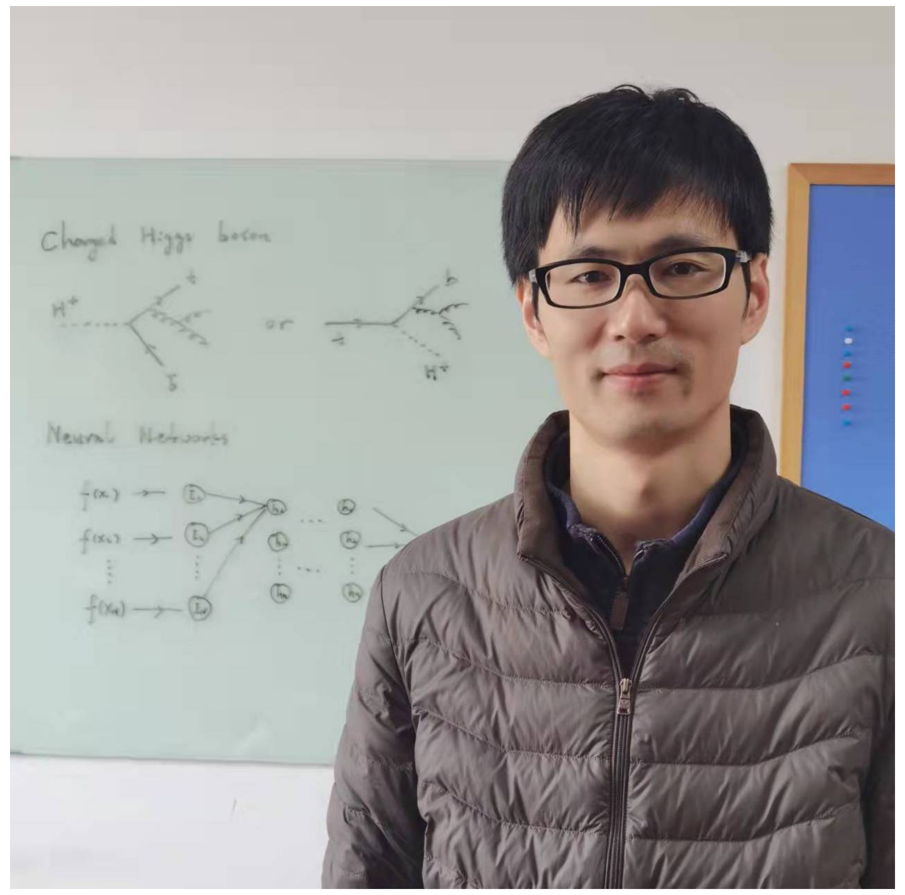
experimental measurement

global extraction

pQCD

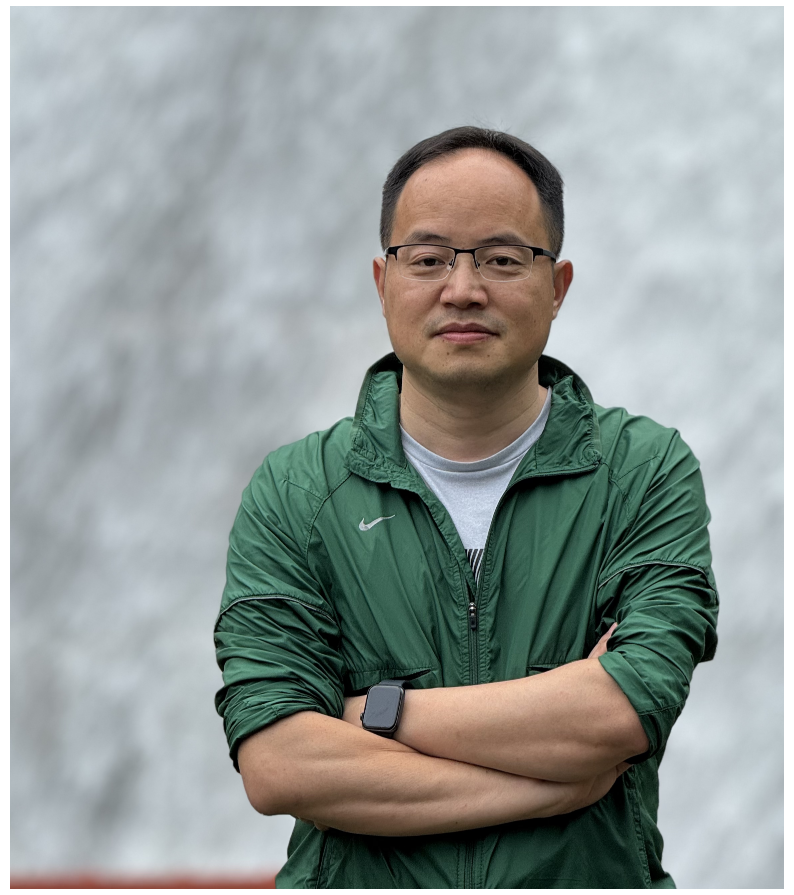
global extraction

Non-perturbative Physics Collaboration (NPC)



Jun Gao

SJTU

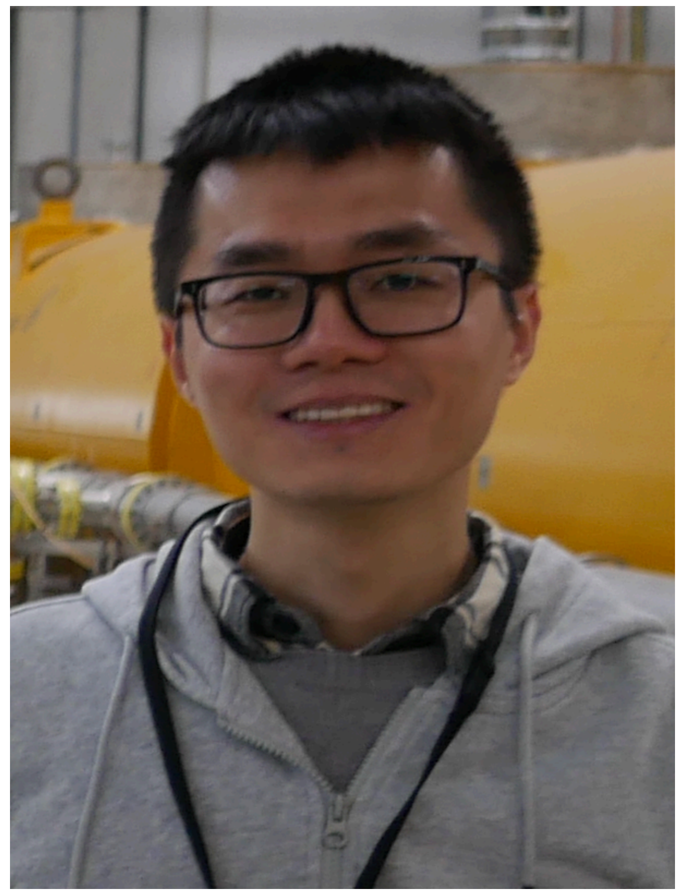


Hongxi Xing

SCNU

Yuxiang Zhao

IMP



Xiaomin Shen

IMP

Yiyu Zhou

IMP

Mengyang Li

SJTU

Chongyang Liu

SJTU

FF global fitting panorama

✦ **Joint efforts from experiments & theory in extracting FFs**

FFs Collab.	**NPC**	**DSS**	**NNFF**	**JAM**	**HKNS**	**MAPFF**
SIA	✓	✓	✓	✓	✓	✓
SIDIS	✓	✓	✗	✗	✗	✓
pp incl. hadron	✓	✓	✗	✗	✗	✗
pp hadron in jet	✓	✗	✗	✗	✗	✗
stat. treatment	Hessian	Hessian	Monte Carlo	Monte Carlo	Hessian	Monte Carlo
parametrization	standard	standard	neural network	standard	standard	neural network
hadron species	$\pi^{\pm}, K^{\pm}, p/\bar{p}$ η, k_s^0, Λ	$\pi^{\pm}, K^{\pm}, p/\bar{p}$	$\pi^{\pm}, K^{\pm}, p/\bar{p}$	$\pi^{\pm}, K^{\pm}$	$\pi^{\pm}, K^{\pm}, p/\bar{p}$	$\pi^{\pm}, K^{\pm}$
pQCD order	NLO/NNLO	NLO	NNLO	NLO	NLO	Approx. NNLO
latest update	*PRL 132, 261903 (2024)* *PRD 110, 114019 (2024)*	*PRD 95, 094019 (2017)* *PRD 105, L031502 (2022)*	*EPJC 77, 516 (2017)* *EPJC 78, 651 (2018)*	*PRD 94, 114004 (2016)*	*PTEP 2016, 113B04 (2016)*	*PLB 834, 137456 (2022)*

NPC: the most precise and complete FFs to date!

New efforts from NPC

✦ **NPC23 vs. others**

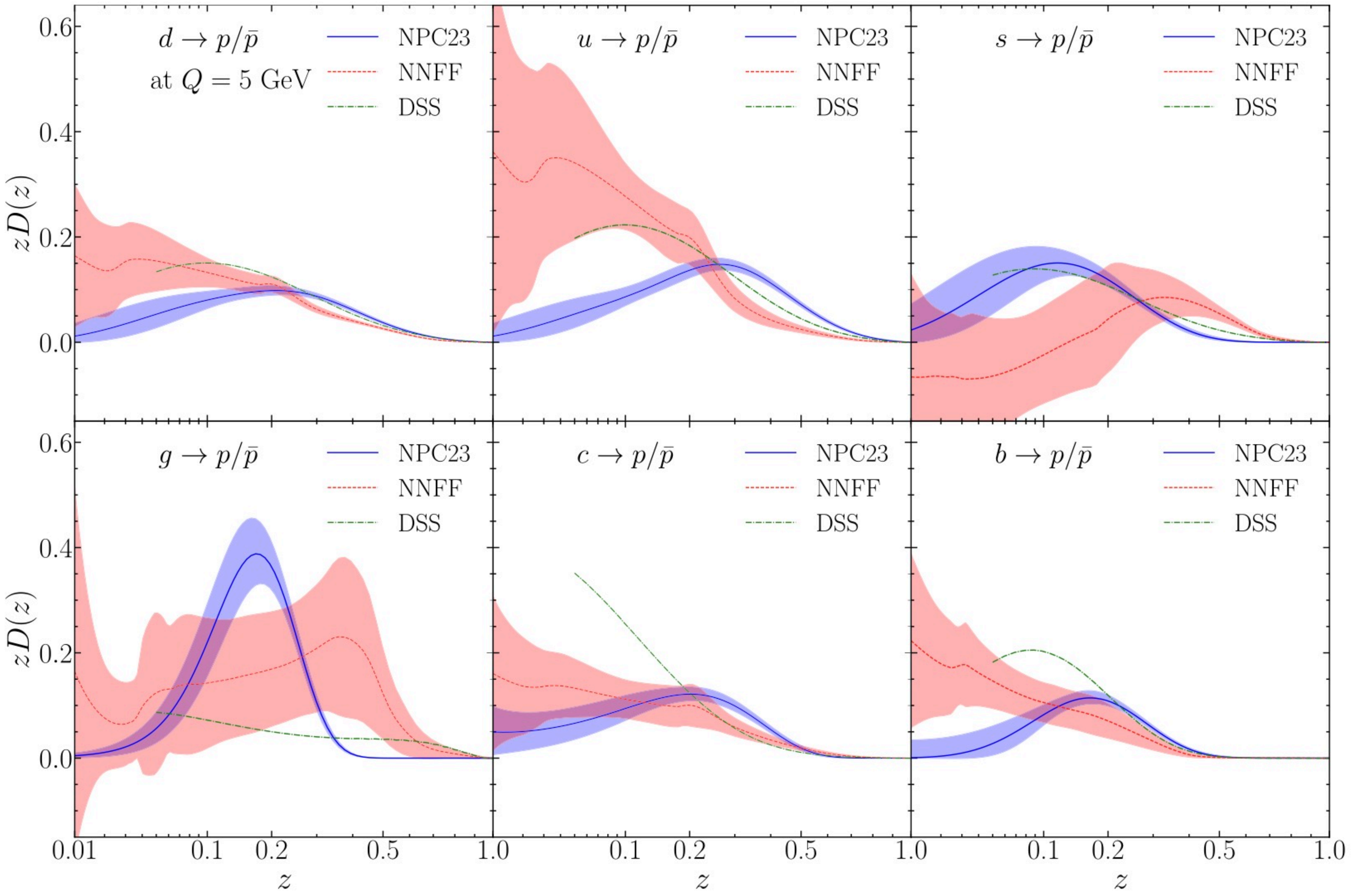
Gao, Liu, Shen, **HX**, Zhao, PRD Editor's suggestion
Gao, Liu, Shen, **HX**, Zhao, PRL, 2024, 2025

- General agreement for u/d quark to pion
- Discrepancies for FFs to kaon/proton and gluon FFs

New efforts from NPC

✦ NPC23 vs. others

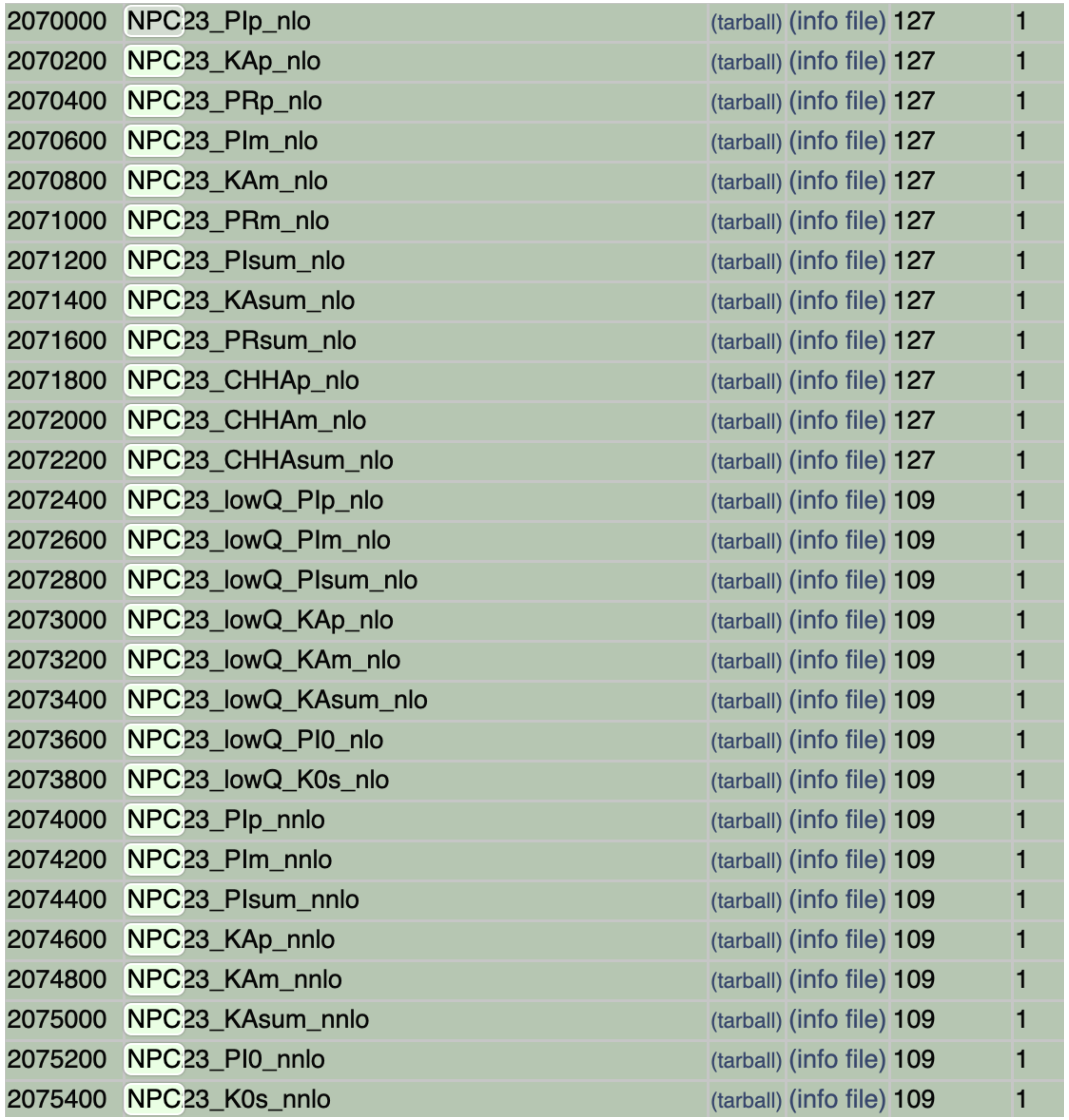
Gao, Liu, Shen, **HX**, Zhao, PRD Editor's suggestion
Gao, Liu, Shen, **HX**, Zhao, PRL, 2024, 2025



- FFs are universal, why they look different?
  - Different selections of experimental data (kinematic cut)
  - Different parametrization for FFs at initial scale, NNFF unbiased? DSS biased?
  - Everything else is the same

More measurements are needed to further constrain the FFs!

New efforts from NPC



2070000	NPC23_PIp_nlo	(tarball)	(info file)	127	1
2070200	NPC23_KAp_nlo	(tarball)	(info file)	127	1
2070400	NPC23_PRp_nlo	(tarball)	(info file)	127	1
2070600	NPC23_PIm_nlo	(tarball)	(info file)	127	1
2070800	NPC23_KAm_nlo	(tarball)	(info file)	127	1
2071000	NPC23_PRm_nlo	(tarball)	(info file)	127	1
2071200	NPC23_PIsum_nlo	(tarball)	(info file)	127	1
2071400	NPC23_KAsum_nlo	(tarball)	(info file)	127	1
2071600	NPC23_PRsum_nlo	(tarball)	(info file)	127	1
2071800	NPC23_CHHAp_nlo	(tarball)	(info file)	127	1
2072000	NPC23_CHHAm_nlo	(tarball)	(info file)	127	1
2072200	NPC23_CHHAsum_nlo	(tarball)	(info file)	127	1
2072400	NPC23_lowQ_PIp_nlo	(tarball)	(info file)	109	1
2072600	NPC23_lowQ_PIm_nlo	(tarball)	(info file)	109	1
2072800	NPC23_lowQ_PIsum_nlo	(tarball)	(info file)	109	1
2073000	NPC23_lowQ_KAp_nlo	(tarball)	(info file)	109	1
2073200	NPC23_lowQ_KAm_nlo	(tarball)	(info file)	109	1
2073400	NPC23_lowQ_KAsum_nlo	(tarball)	(info file)	109	1
2073600	NPC23_lowQ_PI0_nlo	(tarball)	(info file)	109	1
2073800	NPC23_lowQ_K0s_nlo	(tarball)	(info file)	109	1
2074000	NPC23_PIp_nnlo	(tarball)	(info file)	109	1
2074200	NPC23_PIm_nnlo	(tarball)	(info file)	109	1
2074400	NPC23_PIsum_nnlo	(tarball)	(info file)	109	1
2074600	NPC23_KAp_nnlo	(tarball)	(info file)	109	1
2074800	NPC23_KAm_nnlo	(tarball)	(info file)	109	1
2075000	NPC23_KAsum_nnlo	(tarball)	(info file)	109	1
2075200	NPC23_PI0_nnlo	(tarball)	(info file)	109	1
2075400	NPC23_K0s_nnlo	(tarball)	(info file)	109	1

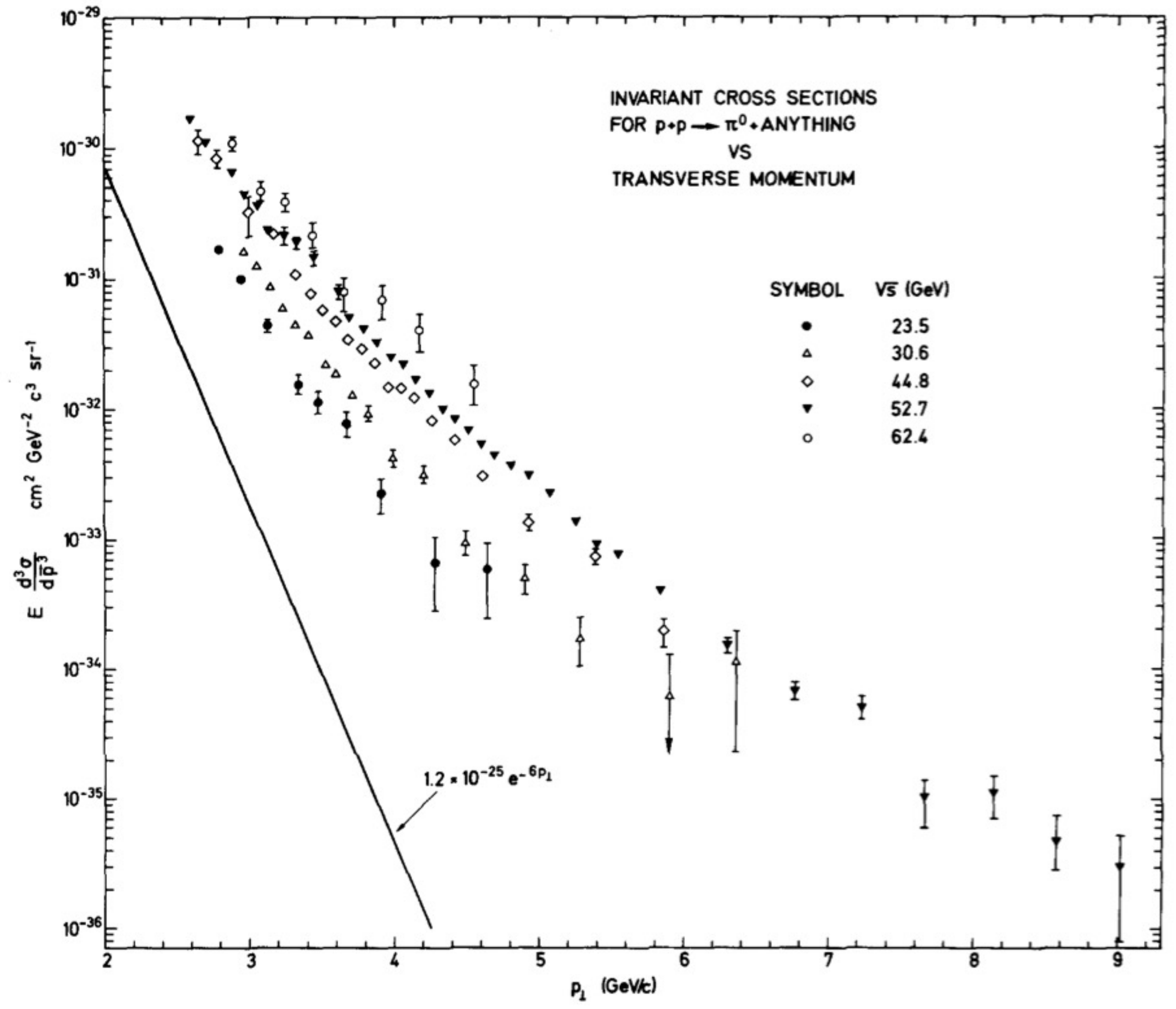
126/108 Hessian error FFs for charged π, k, p at NLO/NNLO are all available in LHAPDF

Probe hadronization via FFs

✦ Jet fragmentation function -> gluon hadronization

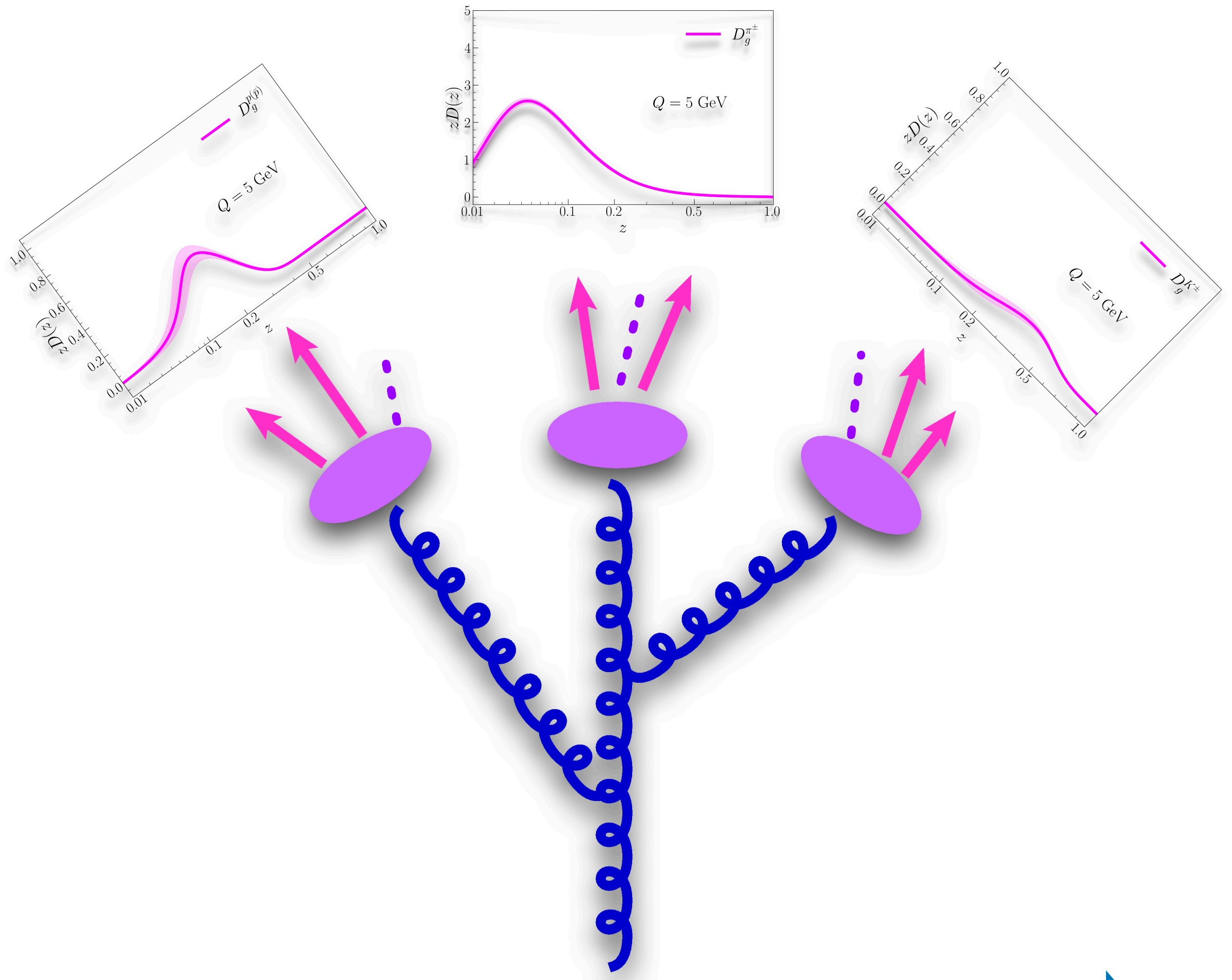
NPC23, PRL, 2024

- **The first phenomenological indication of gluons**

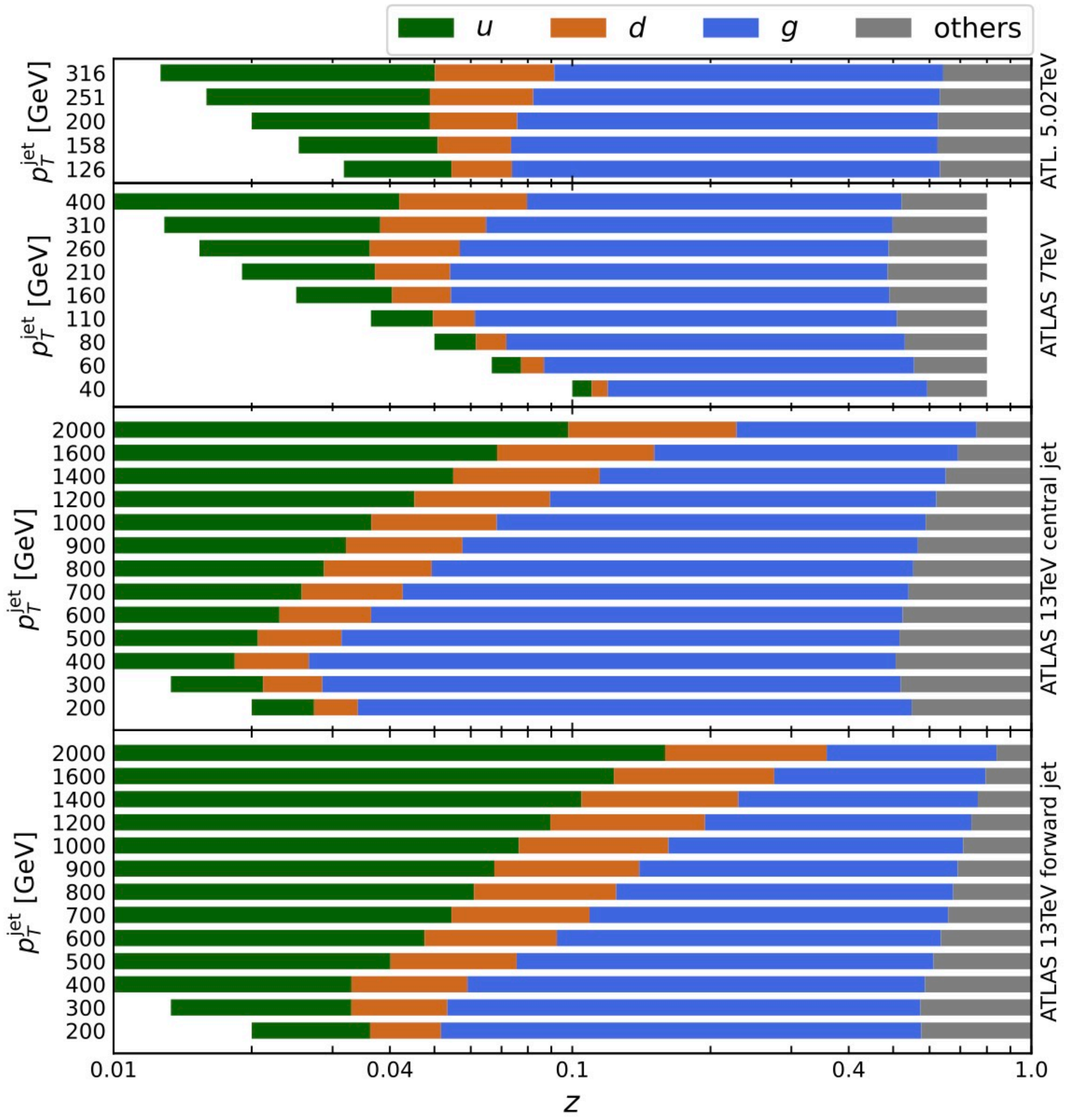


CERN-ISR, PLB, 1973

Cahalan, Geer, Kogut, Susskind, PRD (1975)



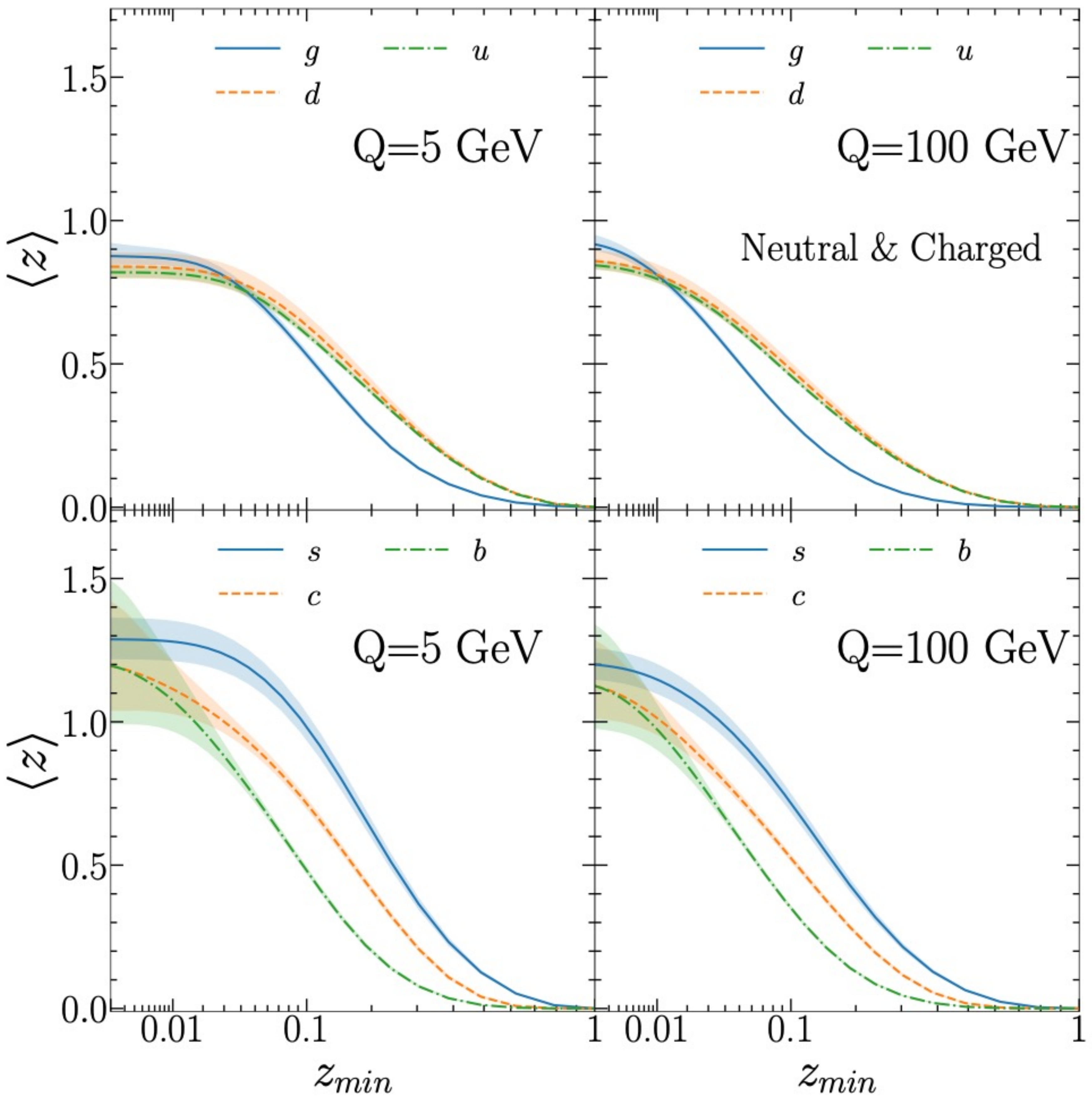
- **The most accurate determination of gluon FF**

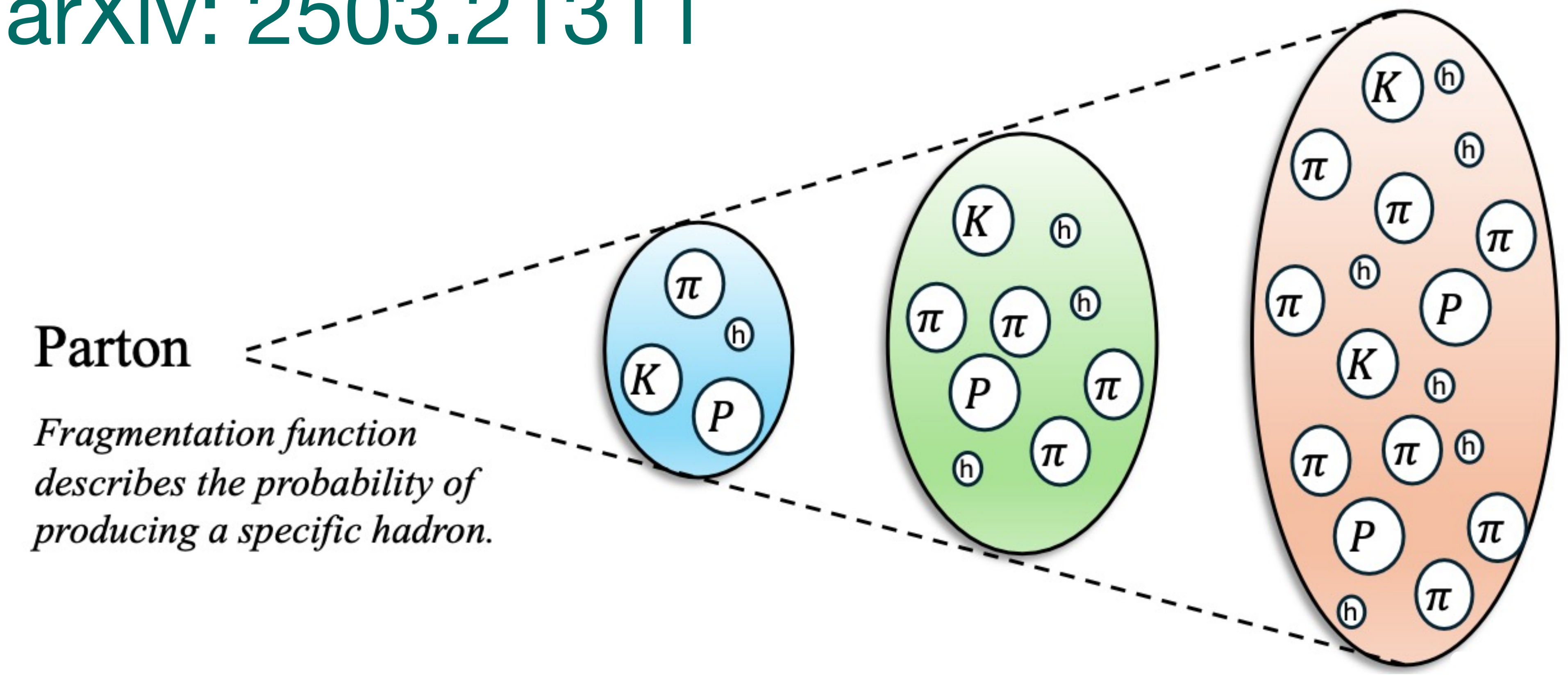


Validating QCD sum rule via FFs

✦ Test of QCD momentum sum rule

Gao, Liu, Li, Shen, **HX**, Zhao, Zhou, arXiv: 2503.21311





Momentum sum rule: $\sum_h \int_0^1 dz z D_i^h(z, Q) = 1$

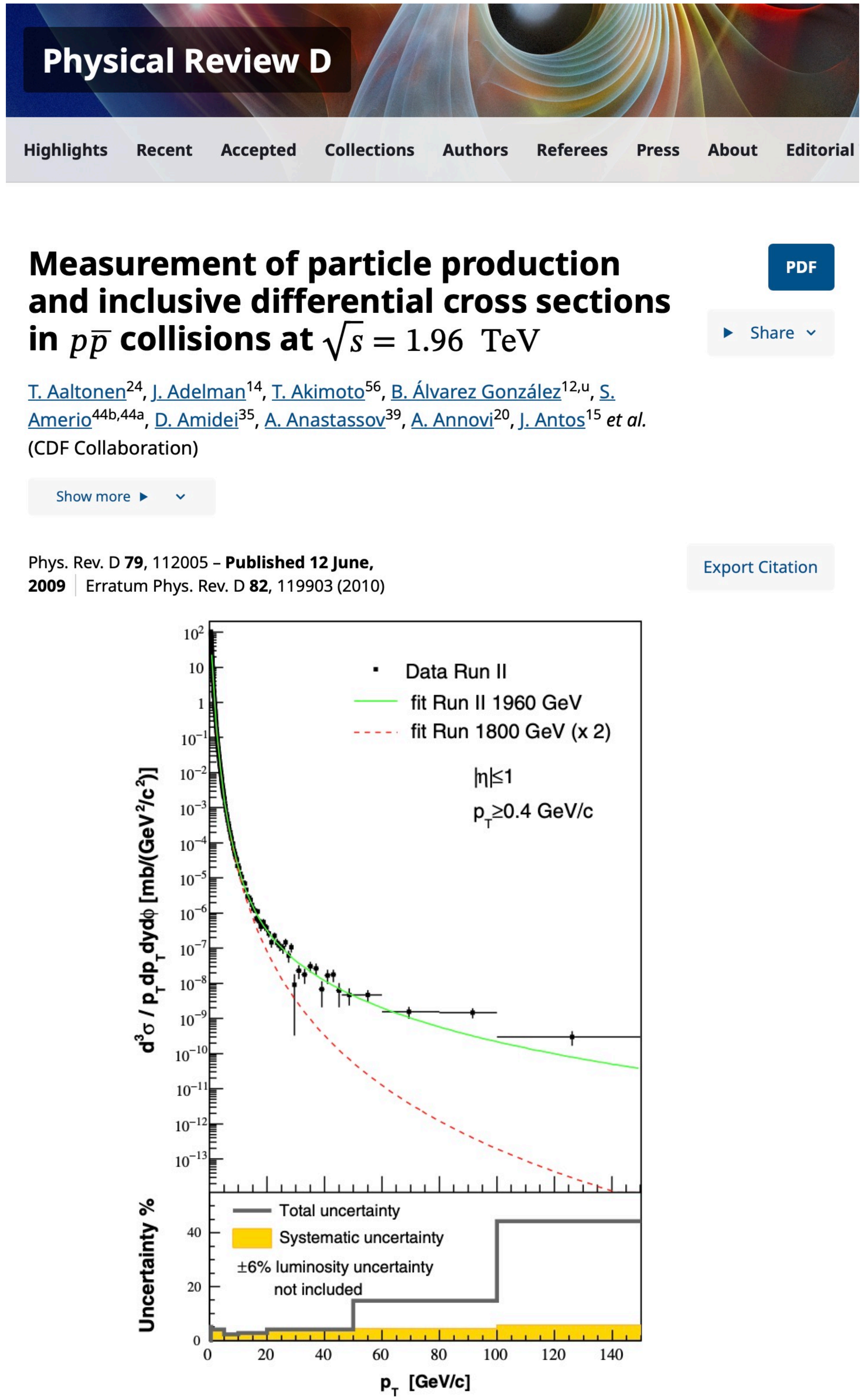
Momentum sum rule test with finite z-cut:

$$\langle z \rangle_i^h = \sum_h \int_{z_{min}}^1 dz z D_i^h(z, Q)$$

- Strange quark is always strange: violation of momentum sum rule?
- Need more advanced experimental techniques to isolate feed-down contributions from short-lived strange hadrons

Do we really trust QCD factorization?

✦ A fail story to criticize QCD factorization

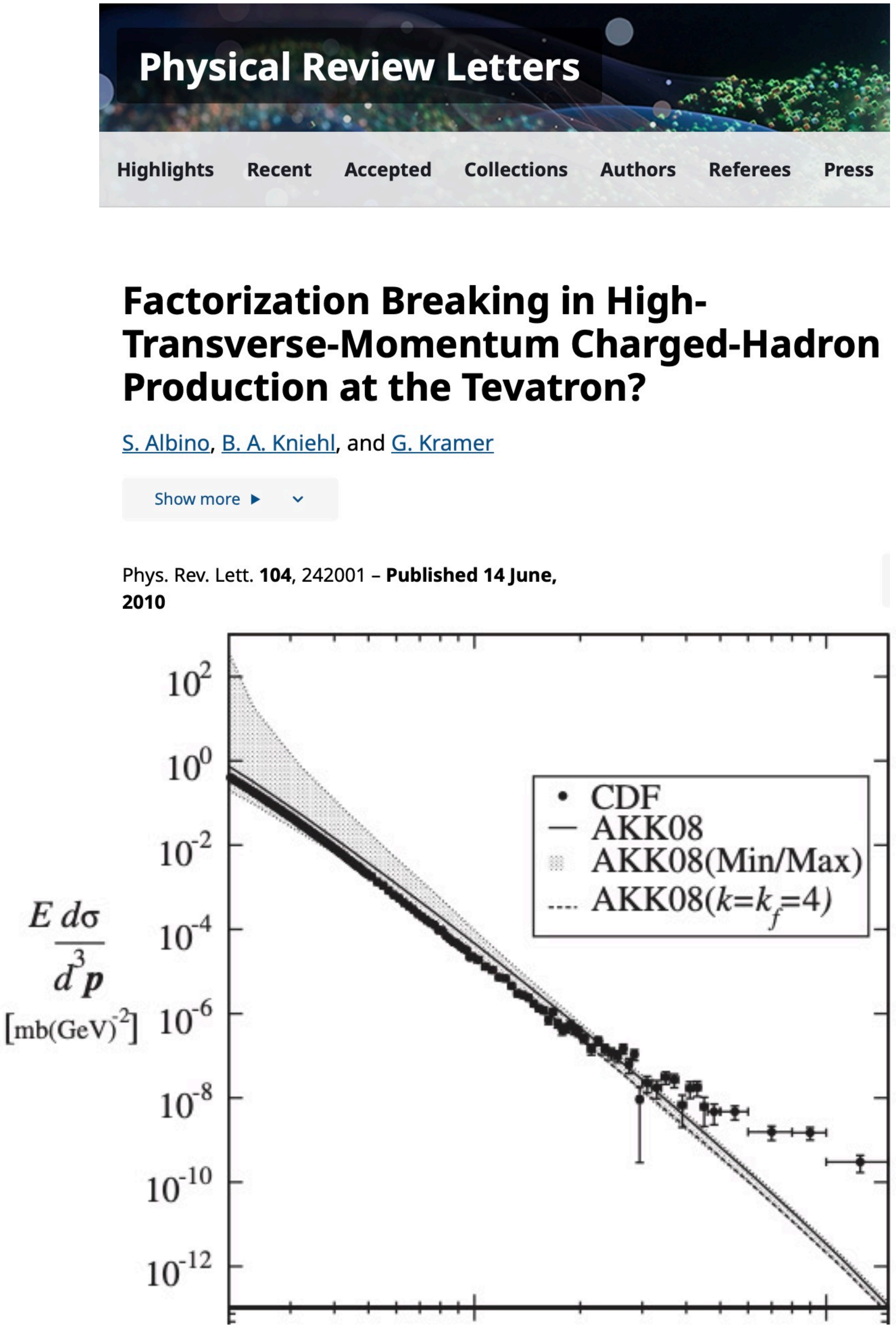


Physical Review D

Measurement of particle production and inclusive differential cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen[24], J. Adelman[14], T. Akimoto[56], B. Álvarez González[12,u], S. Amerio[44b,44a], D. Amidei[35], A. Anastassov[39], A. Annovi[20], J. Antos[15] *et al.* (CDF Collaboration)

Phys. Rev. D **79**, 112005 – **Published 12 June, 2009** | Erratum Phys. Rev. D **82**, 119903 (2010)

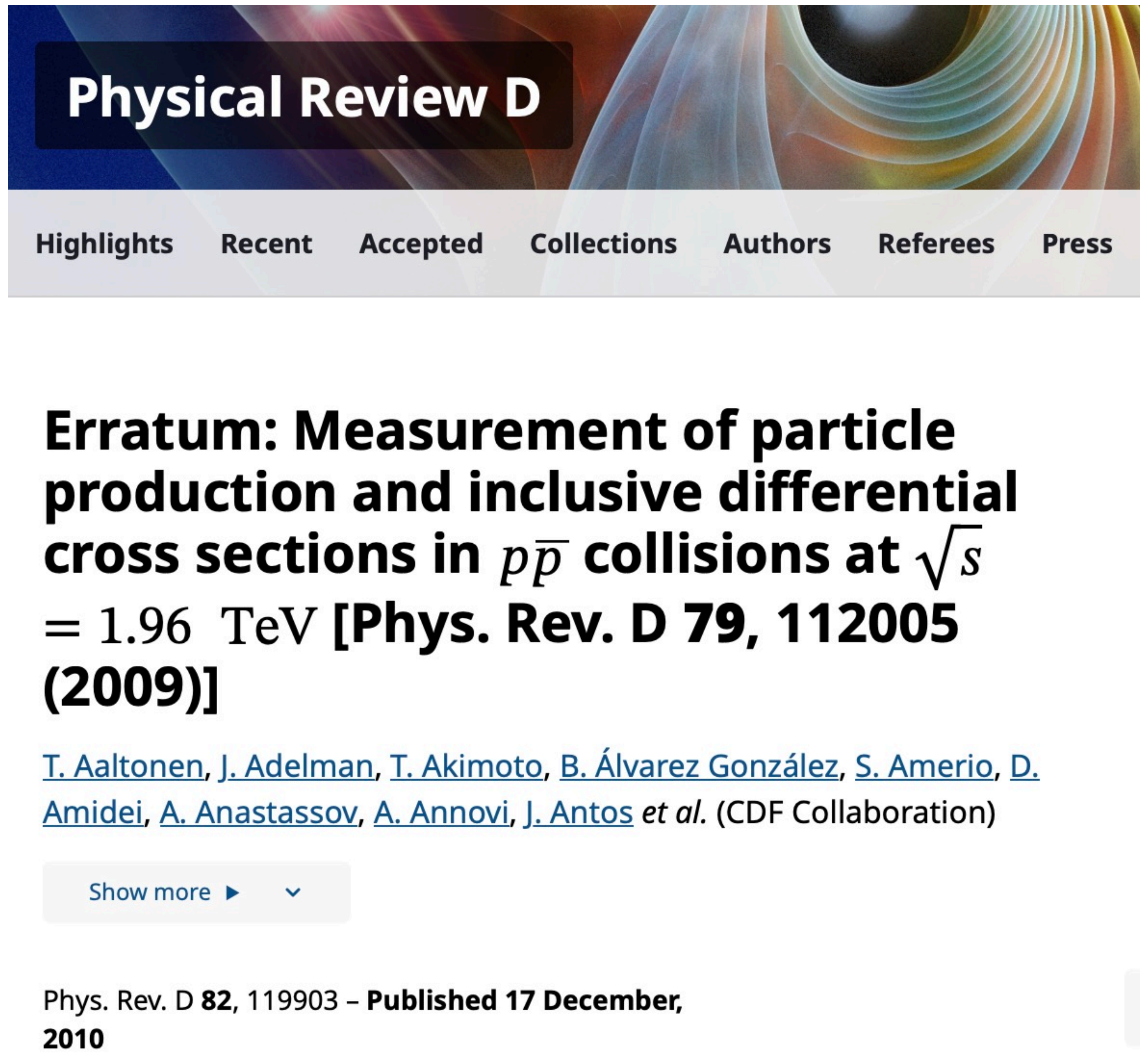


Physical Review Letters

Factorization Breaking in High-Transverse-Momentum Charged-Hadron Production at the Tevatron?

S. Albino, B. A. Kniehl, and G. Kramer

Phys. Rev. Lett. **104**, 242001 – **Published 14 June, 2010**



Physical Review D

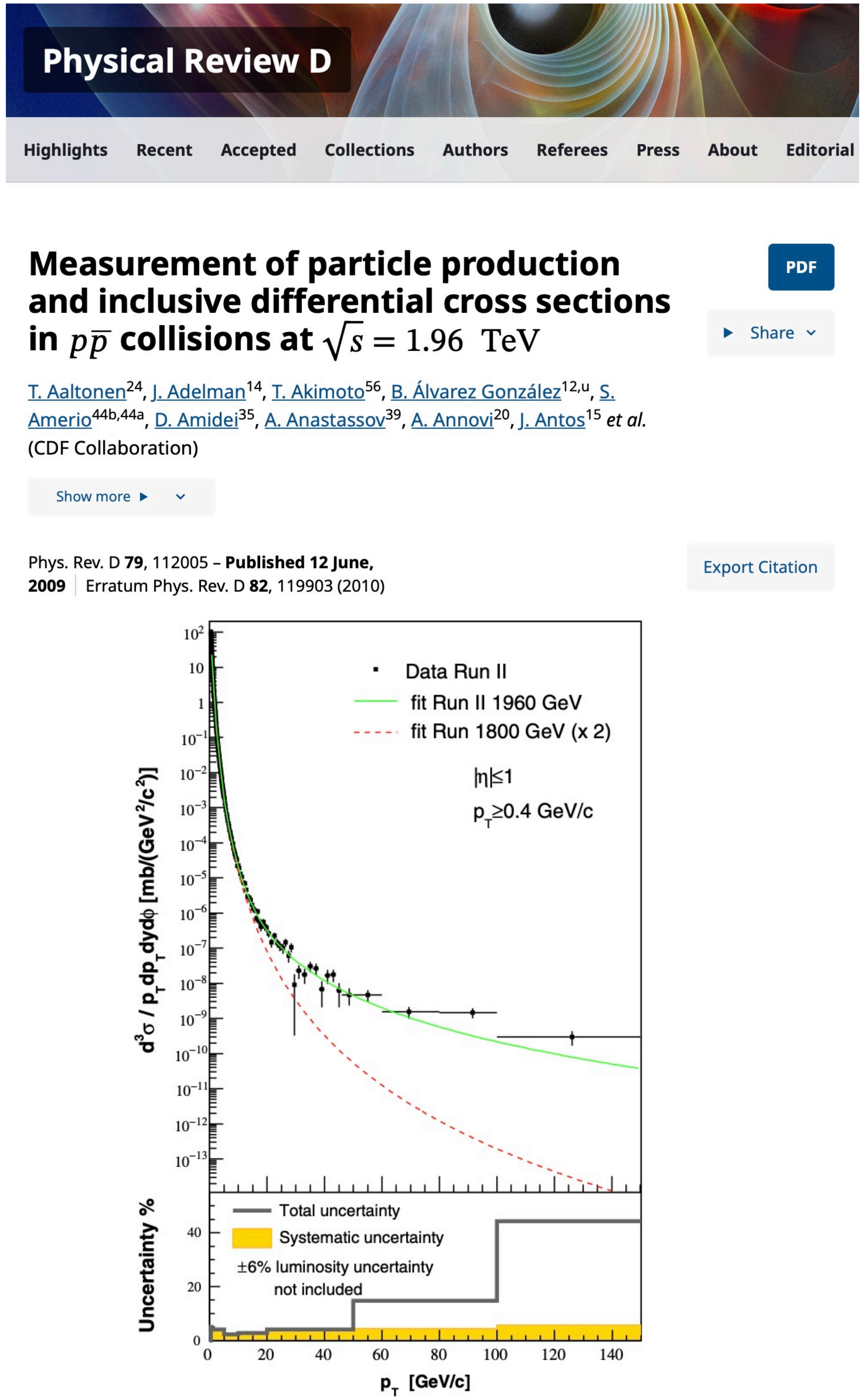
Erratum: Measurement of particle production and inclusive differential cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [Phys. Rev. D 79, 112005 (2009)]

T. Aaltonen, J. Adelman, T. Akimoto, B. Álvarez González, S. Amerio, D. Amidei, A. Anastassov, A. Annovi, J. Antos *et al.* (CDF Collaboration)

Phys. Rev. D **82**, 119903 – **Published 17 December, 2010**

The reported excess of high p_T prompt charged particles over pythia predictions was found to be largely due to mismeasured tracks …

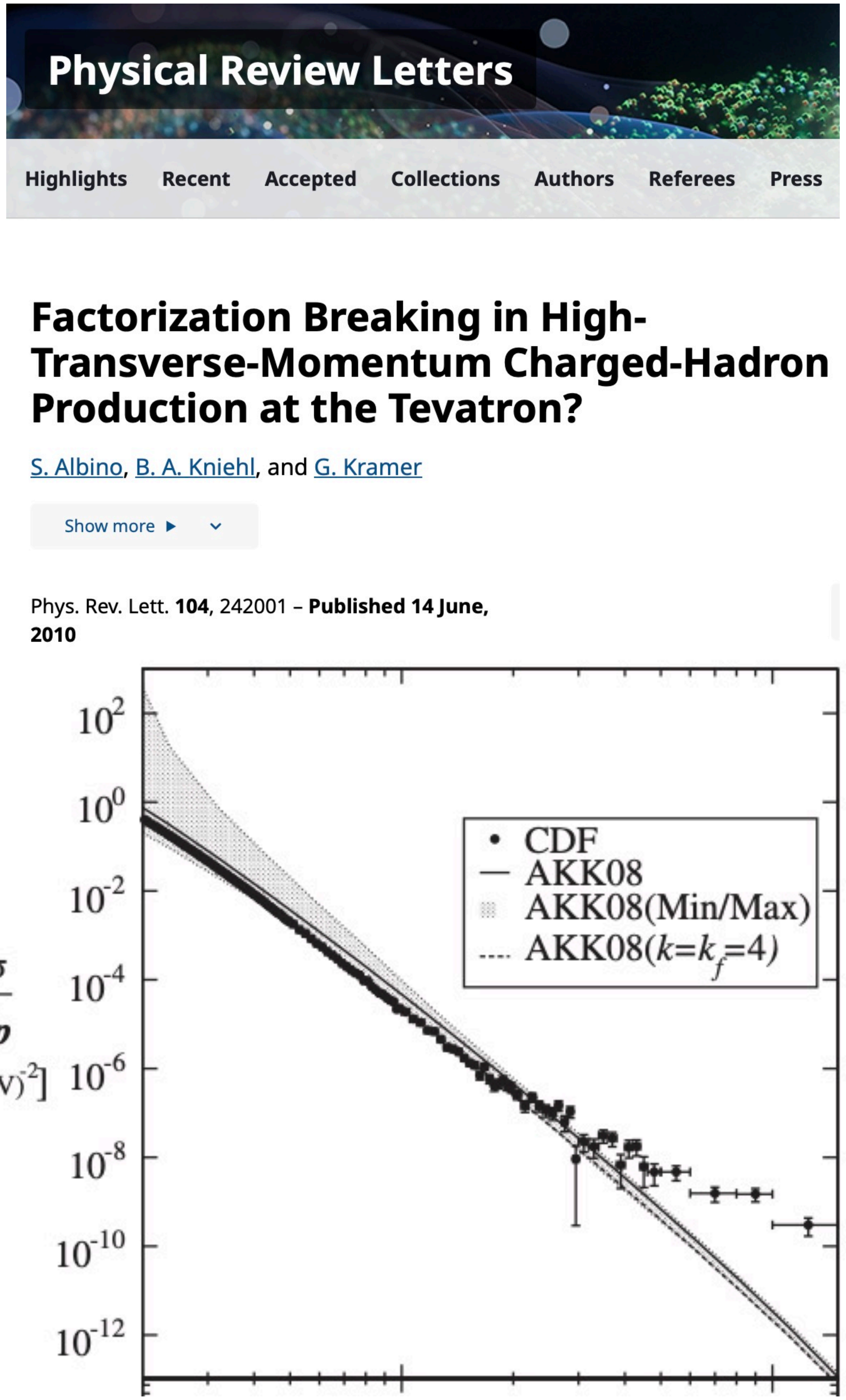
A successful story to believe pQCD prediction



Measurement of particle production and inclusive differential cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\ \mathrm{TeV}$

T. Aaltonen[24], J. Adelman[14], T. Akimoto[56], B. Álvarez González[12,u], S. Amerio[44b,44a], D. Amidei[35], A. Anastassov[39], A. Annovi[20], J. Antos[15] *et al.*
(CDF Collaboration)

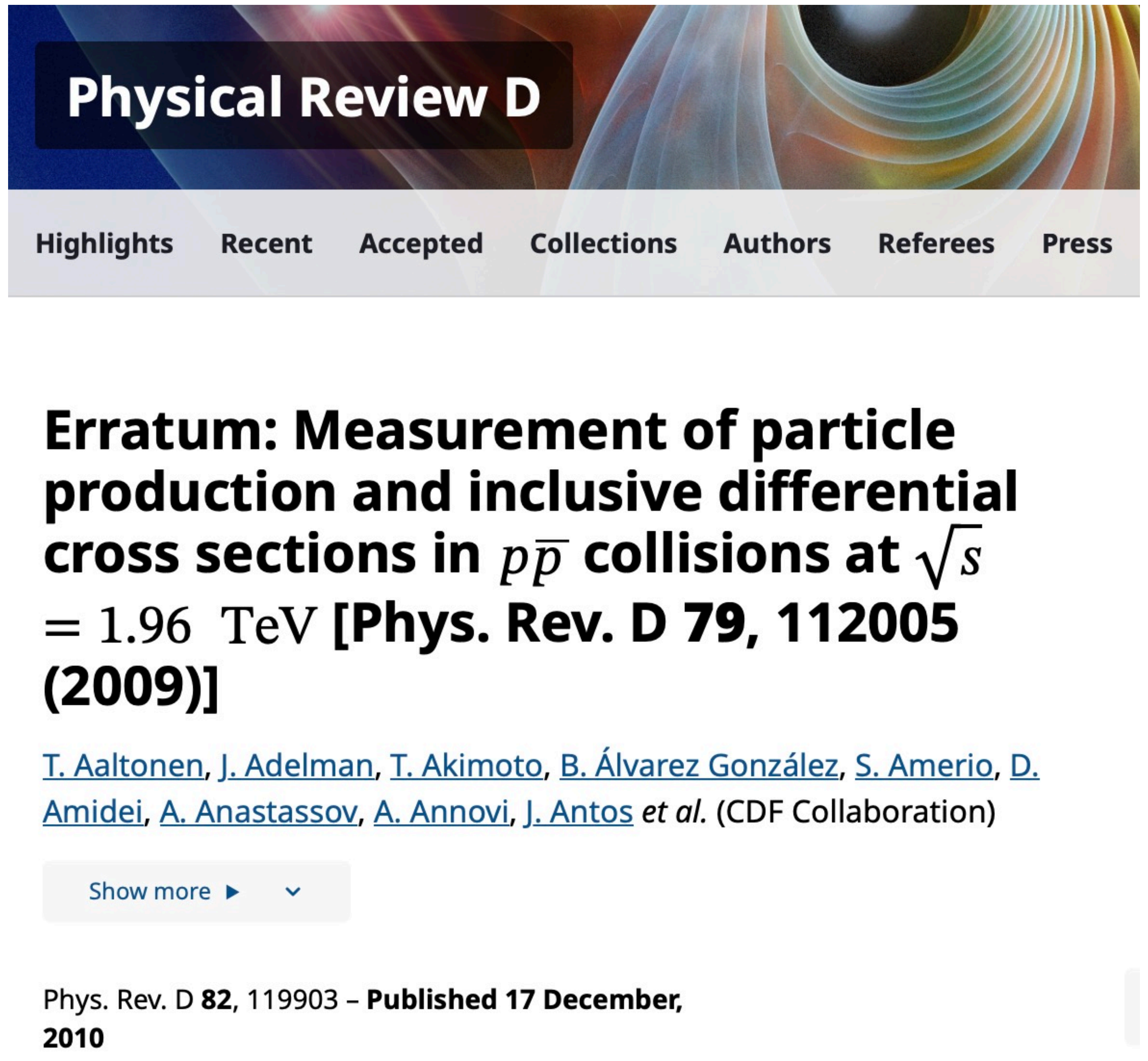
Phys. Rev. D **79**, 112005 – **Published 12 June, 2009** | Erratum Phys. Rev. D **82**, 119903 (2010)



Factorization Breaking in High-Transverse-Momentum Charged-Hadron Production at the Tevatron?

S. Albino, B. A. Kniehl, and G. Kramer

Phys. Rev. Lett. **104**, 242001 – **Published 14 June, 2010**



Erratum: Measurement of particle production and inclusive differential cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\ \mathrm{TeV}$ [Phys. Rev. D 79, 112005 (2009)]

T. Aaltonen, J. Adelman, T. Akimoto, B. Álvarez González, S. Amerio, D. Amidei, A. Anastassov, A. Annovi, J. Antos *et al.* (CDF Collaboration)

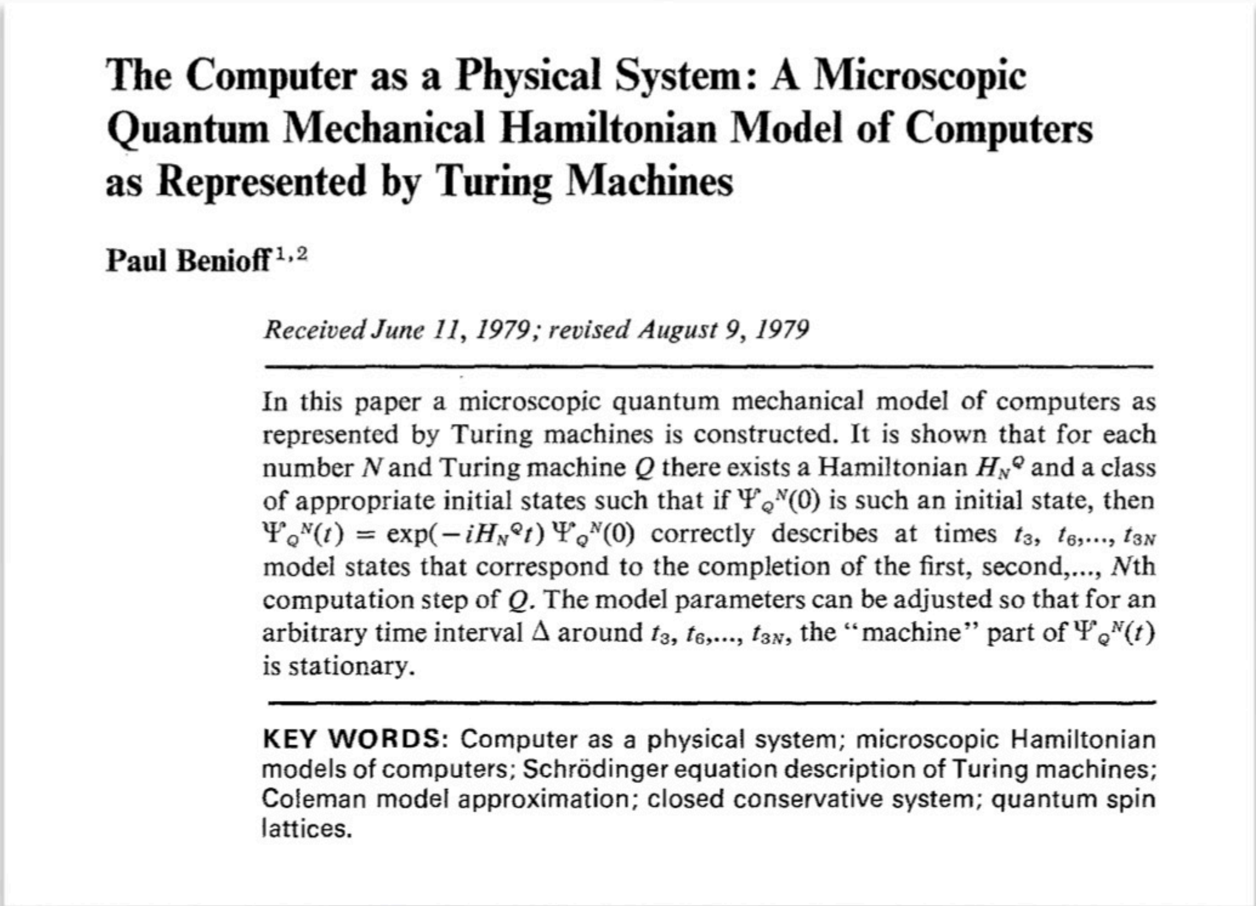
Phys. Rev. D **82**, 119903 – **Published 17 December, 2010**

The reported excess of high p_T prompt charged particles over pythia predictions was found to be largely due to mismeasured tracks …

Can we simulate particle collisions from first principles?

Quantum computing

✦ A bit history



The Computer as a Physical System: A Microscopic Quantum Mechanical Hamiltonian Model of Computers as Represented by Turing Machines

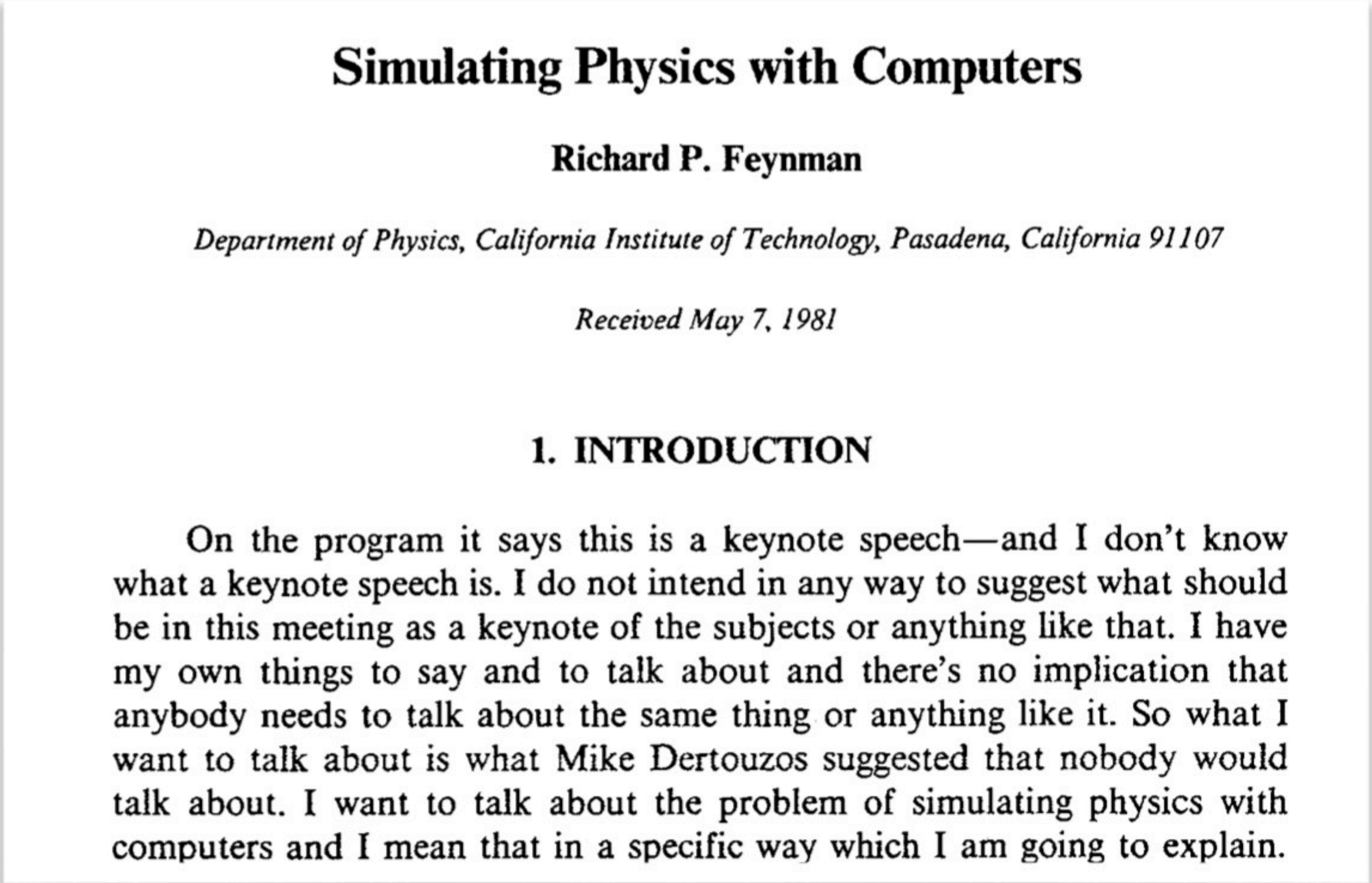
Paul Benioff[1,2]

Received June 11, 1979; revised August 9, 1979

In this paper a microscopic quantum mechanical model of computers as represented by Turing machines is constructed. It is shown that for each number N and Turing machine Q there exists a Hamiltonian $H_N{}^Q$ and a class of appropriate initial states such that if $\Psi_Q{}^N(0)$ is such an initial state, then $\Psi_Q{}^N(t) = \exp(-iH_N{}^Q t)\,\Psi_Q{}^N(0)$ correctly describes at times $t_3, t_6, \ldots, t_{3N}$ model states that correspond to the completion of the first, second,..., Nth computation step of Q. The model parameters can be adjusted so that for an arbitrary time interval Δ around $t_3, t_6, \ldots, t_{3N}$, the "machine" part of $\Psi_Q{}^N(t)$ is stationary.

KEY WORDS: Computer as a physical system; microscopic Hamiltonian models of computers; Schrödinger equation description of Turing machines; Coleman model approximation; closed conservative system; quantum spin lattices.

P. Benioff, 1979



Simulating Physics with Computers

Richard P. Feynman

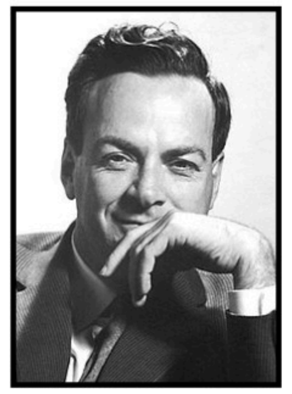
Department of Physics, California Institute of Technology, Pasadena, California 91107

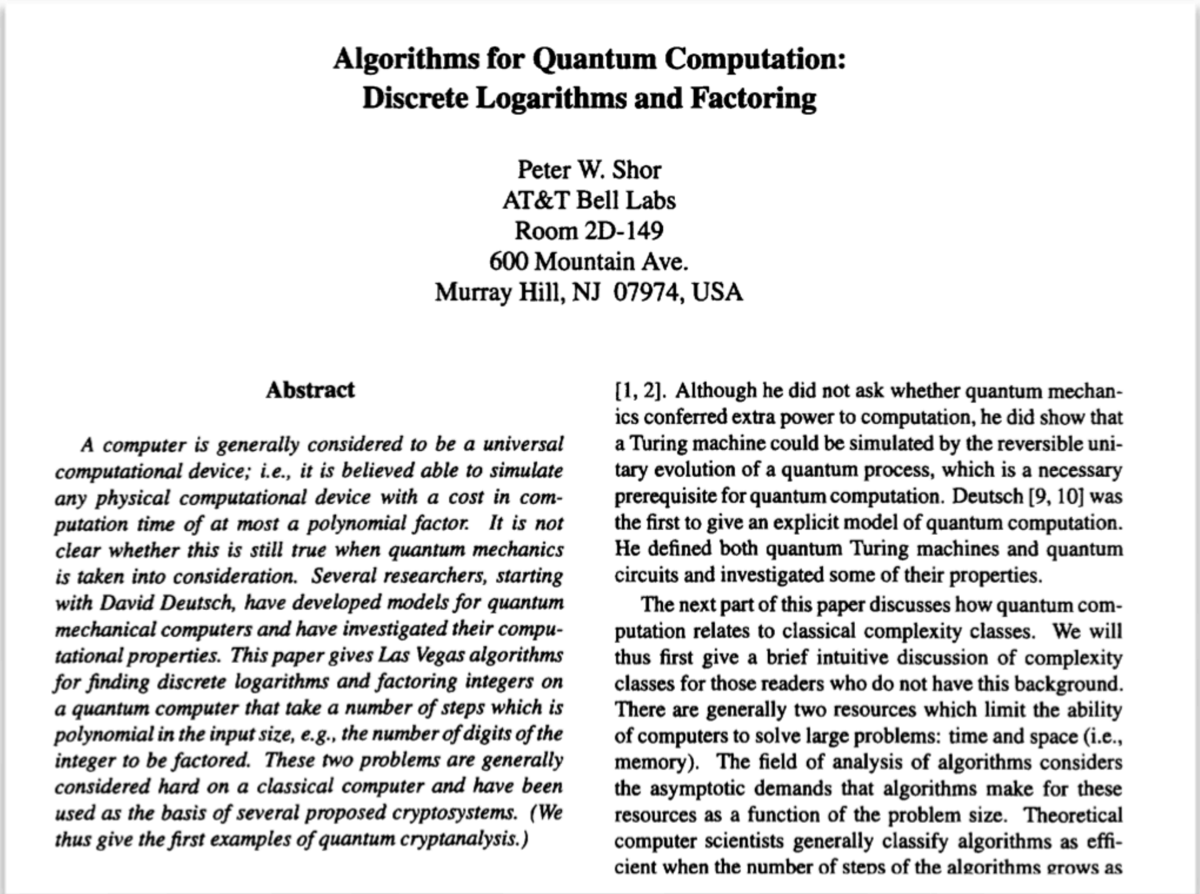
Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain.

R. Feynman, 1981





Algorithms for Quantum Computation: Discrete Logarithms and Factoring

Peter W. Shor
AT&T Bell Labs
Room 2D-149
600 Mountain Ave.
Murray Hill, NJ 07974, USA

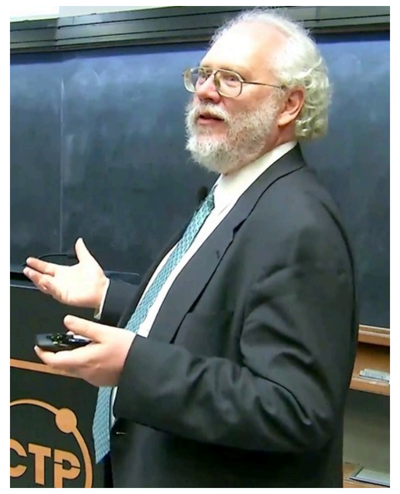
Abstract

A computer is generally considered to be a universal computational device; i.e., it is believed able to simulate any physical computational device with a cost in computation time of at most a polynomial factor. It is not clear whether this is still true when quantum mechanics is taken into consideration. Several researchers, starting with David Deutsch, have developed models for quantum mechanical computers and have investigated their computational properties. This paper gives Las Vegas algorithms for finding discrete logarithms and factoring integers on a quantum computer that take a number of steps which is polynomial in the input size, e.g., the number of digits of the integer to be factored. These two problems are generally considered hard on a classical computer and have been used as the basis of several proposed cryptosystems. (We thus give the first examples of quantum cryptanalysis.)

[1, 2]. Although he did not ask whether quantum mechanics conferred extra power to computation, he did show that a Turing machine could be simulated by the reversible unitary evolution of a quantum process, which is a necessary prerequisite for quantum computation. Deutsch [9, 10] was the first to give an explicit model of quantum computation. He defined both quantum Turing machines and quantum circuits and investigated some of their properties.

The next part of this paper discusses how quantum computation relates to classical complexity classes. We will thus first give a brief intuitive discussion of complexity classes for those readers who do not have this background. There are generally two resources which limit the ability of computers to solve large problems: time and space (i.e., memory). The field of analysis of algorithms considers the asymptotic demands that algorithms make for these resources as a function of the problem size. Theoretical computer scientists generally classify algorithms as efficient when the number of steps of the algorithms grows as

P. Shor, 1994



IBM Q System One (2019), the first circuit-based commercial quantum computer

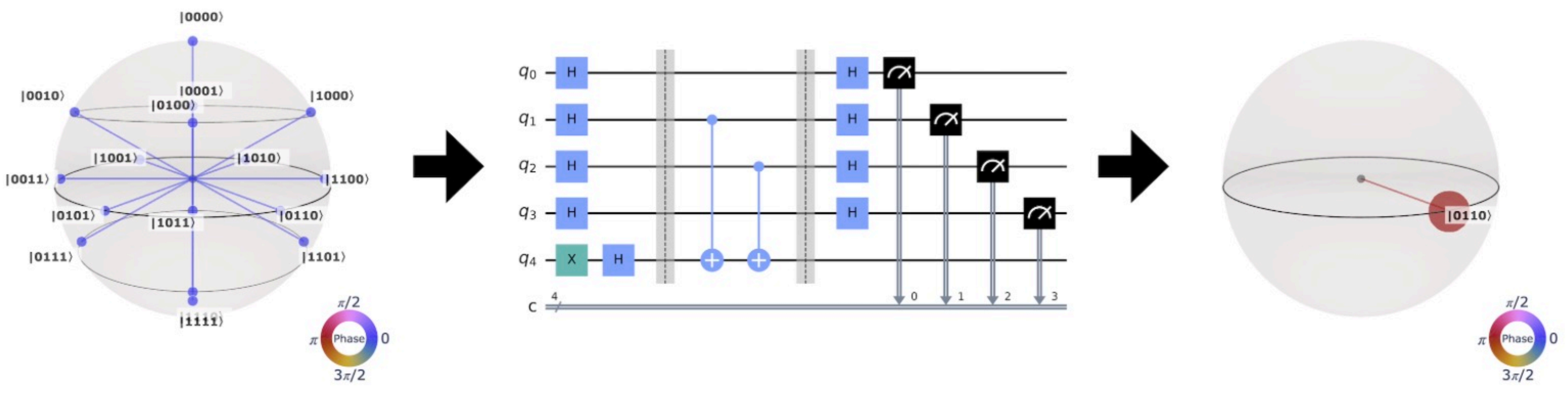
"... and if you want to make a simulation of nature, you'd better make it quantum mechanical, ..."

—Feynman

Quantum computing

https://qiskit.org/

Quantum circuit



Superposition of all possibilities

Computation driven interference

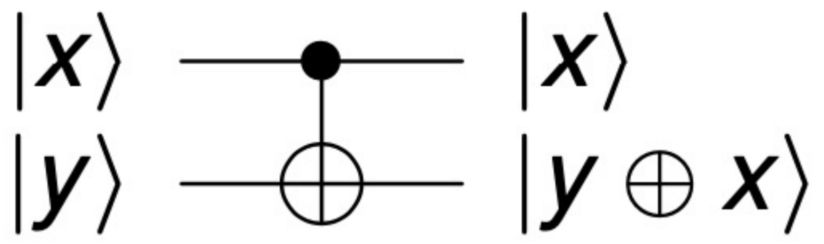
Solution

✦ Building blocks of quantum computing

- Qubit: takes infinitely many different values $|\psi\rangle := \alpha\,|0\rangle + \beta\,|1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$
- Quantum gate: unitary operators (X、Y、Z、CNOT)

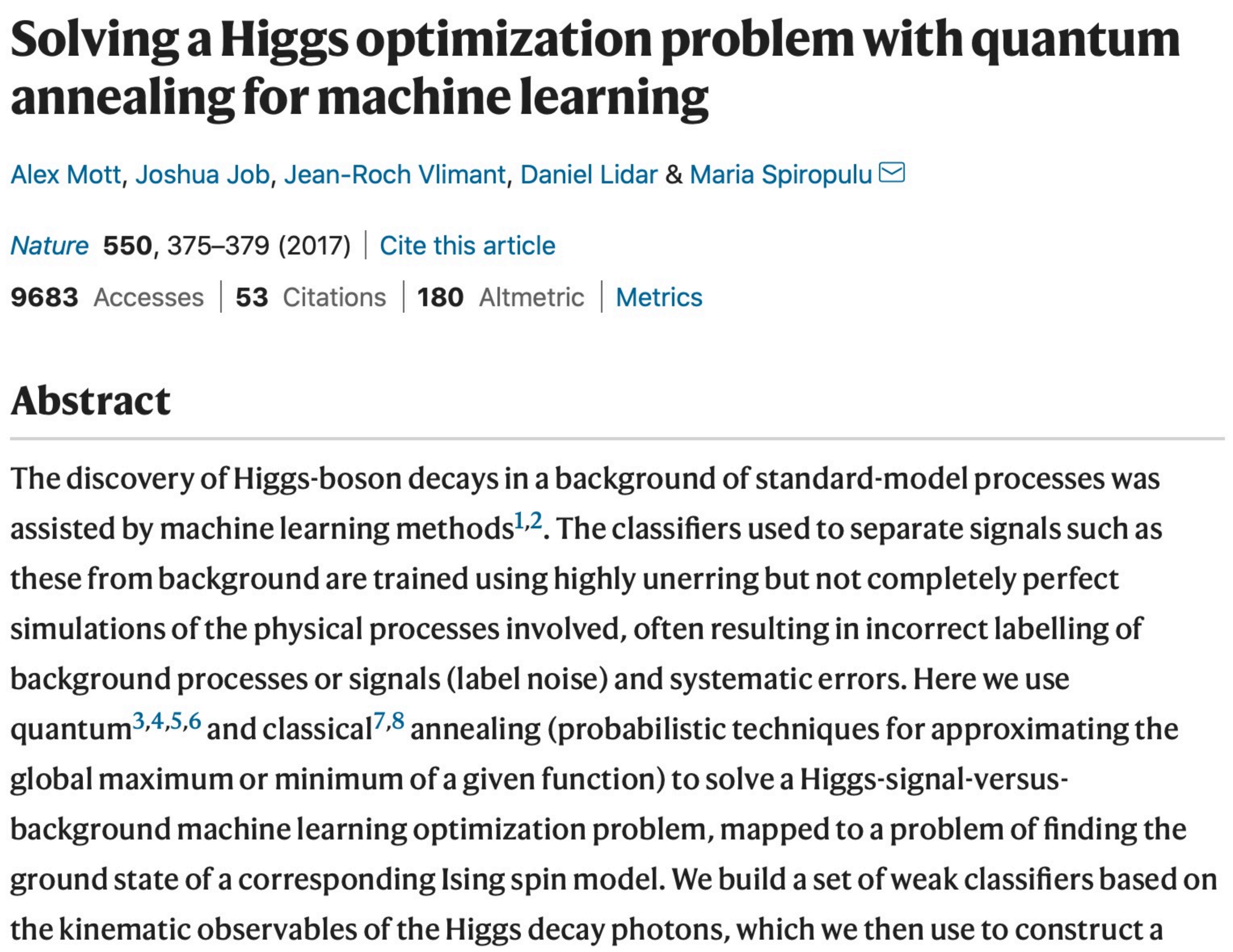
$\alpha\,|0\rangle + \beta\,|1\rangle \; -\boxed{X}- \; \beta\,|0\rangle + \alpha\,|1\rangle$

$|0\rangle \; -\boxed{H}- \; \frac{|0\rangle+|1\rangle}{\sqrt{2}}$



- Measurements: Hermitian

Increasing interest using quantum computing



Solving a Higgs optimization problem with quantum annealing for machine learning

Alex Mott, Joshua Job, Jean-Roch Vlimant, Daniel Lidar & Maria Spiropulu

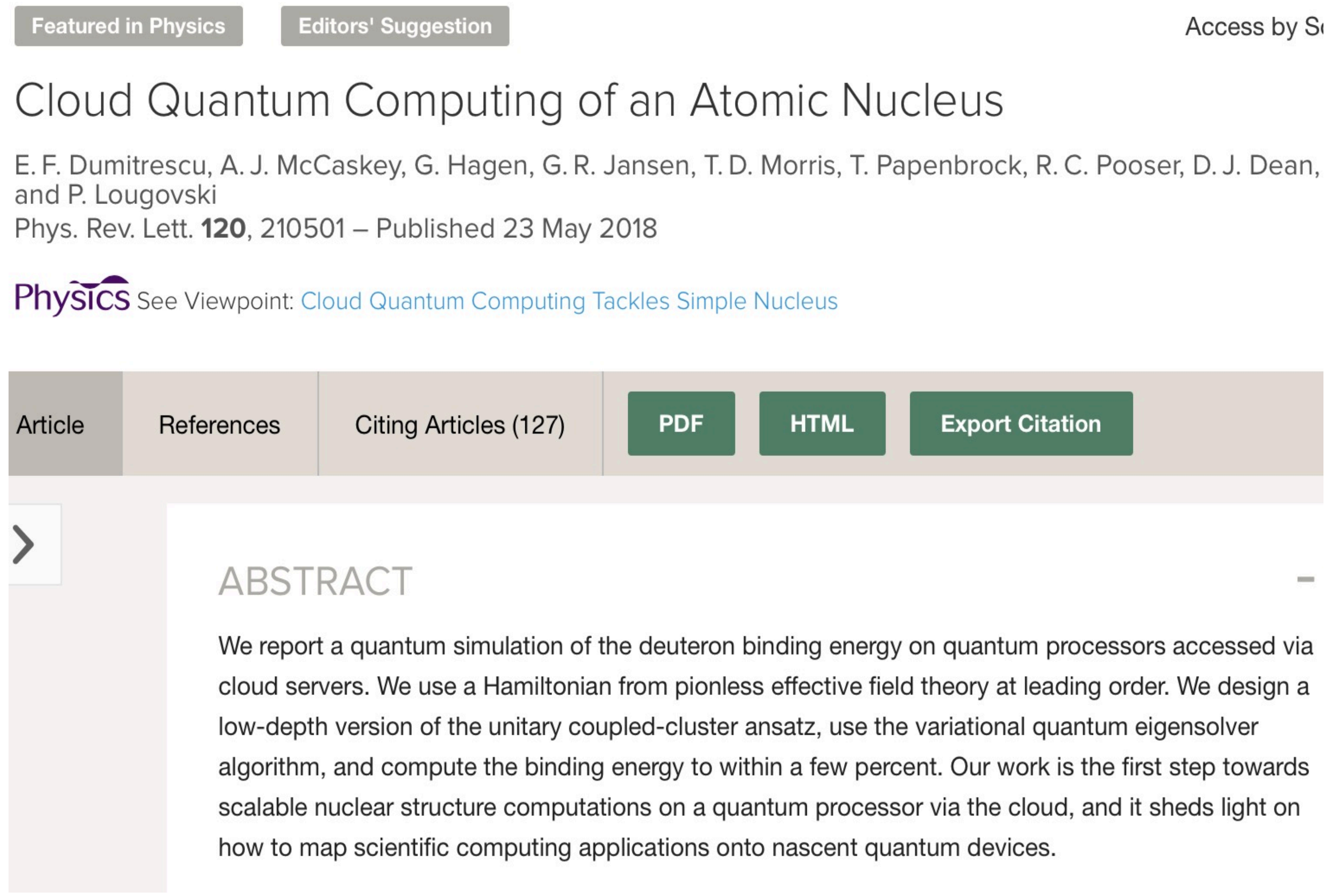
Nature **550**, 375–379 (2017) | Cite this article

9683 Accesses | **53** Citations | **180** Altmetric | Metrics

Abstract

The discovery of Higgs-boson decays in a background of standard-model processes was assisted by machine learning methods[1,2]. The classifiers used to separate signals such as these from background are trained using highly unerring but not completely perfect simulations of the physical processes involved, often resulting in incorrect labelling of background processes or signals (label noise) and systematic errors. Here we use quantum[3,4,5,6] and classical[7,8] annealing (probabilistic techniques for approximating the global maximum or minimum of a given function) to solve a Higgs-signal-versus-background machine learning optimization problem, mapped to a problem of finding the ground state of a corresponding Ising spin model. We build a set of weak classifiers based on the kinematic observables of the Higgs decay photons, which we then use to construct a

---



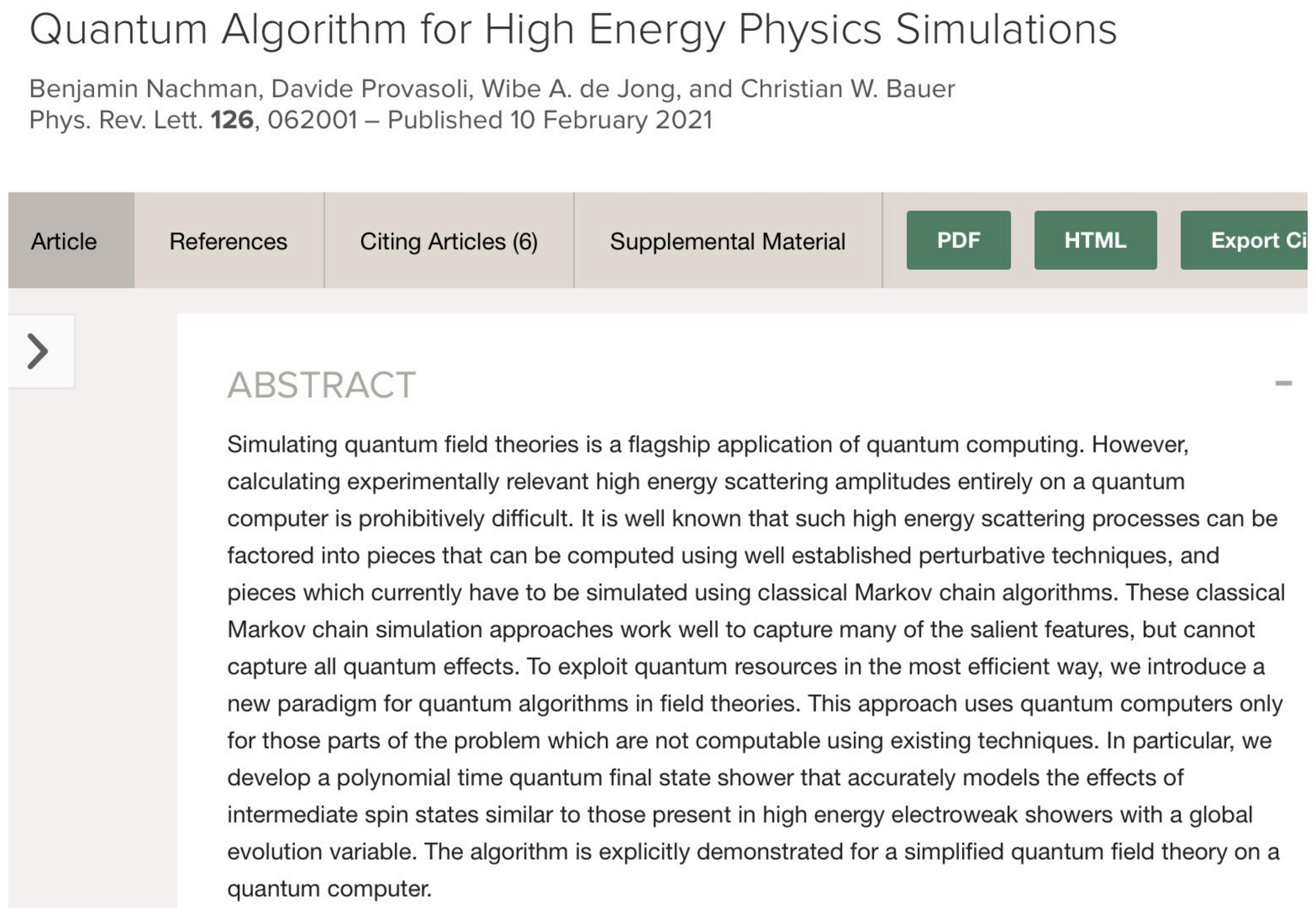
Cloud Quantum Computing of an Atomic Nucleus

E. F. Dumitrescu, A. J. McCaskey, G. Hagen, G. R. Jansen, T. D. Morris, T. Papenbrock, R. C. Pooser, D. J. Dean, and P. Lougovski
Phys. Rev. Lett. **120**, 210501 – Published 23 May 2018

Physics See Viewpoint: Cloud Quantum Computing Tackles Simple Nucleus

ABSTRACT

We report a quantum simulation of the deuteron binding energy on quantum processors accessed via cloud servers. We use a Hamiltonian from pionless effective field theory at leading order. We design a low-depth version of the unitary coupled-cluster ansatz, use the variational quantum eigensolver algorithm, and compute the binding energy to within a few percent. Our work is the first step towards scalable nuclear structure computations on a quantum processor via the cloud, and it sheds light on how to map scientific computing applications onto nascent quantum devices.

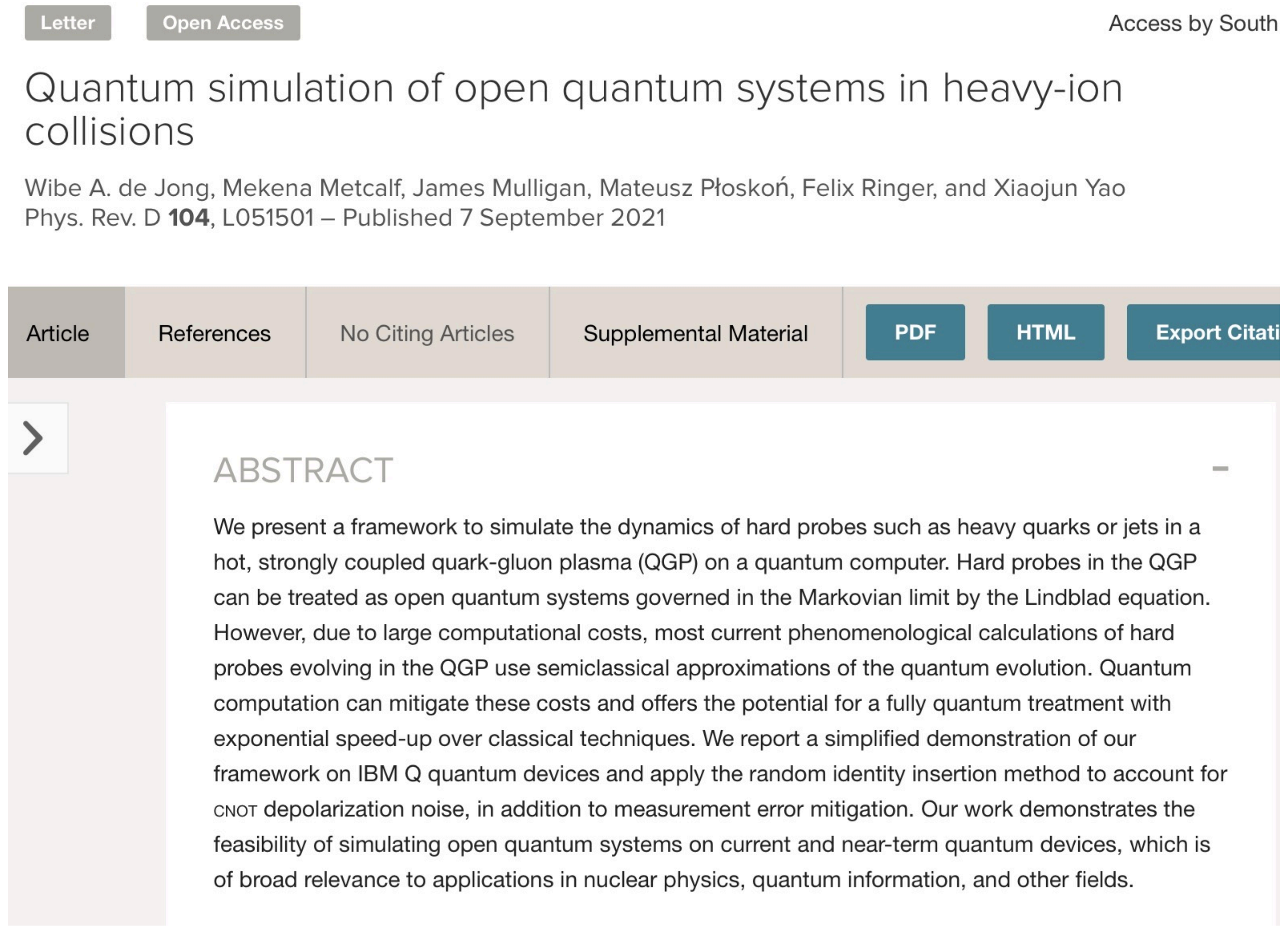


Quantum Algorithm for High Energy Physics Simulations

Benjamin Nachman, Davide Provasoli, Wibe A. de Jong, and Christian W. Bauer
Phys. Rev. Lett. **126**, 062001 – Published 10 February 2021

ABSTRACT

Simulating quantum field theories is a flagship application of quantum computing. However, calculating experimentally relevant high energy scattering amplitudes entirely on a quantum computer is prohibitively difficult. It is well known that such high energy scattering processes can be factored into pieces that can be computed using well established perturbative techniques, and pieces which currently have to be simulated using classical Markov chain algorithms. These classical Markov chain simulation approaches work well to capture many of the salient features, but cannot capture all quantum effects. To exploit quantum resources in the most efficient way, we introduce a new paradigm for quantum algorithms in field theories. This approach uses quantum computers only for those parts of the problem which are not computable using existing techniques. In particular, we develop a polynomial time quantum final state shower that accurately models the effects of intermediate spin states similar to those present in high energy electroweak showers with a global evolution variable. The algorithm is explicitly demonstrated for a simplified quantum field theory on a quantum computer.

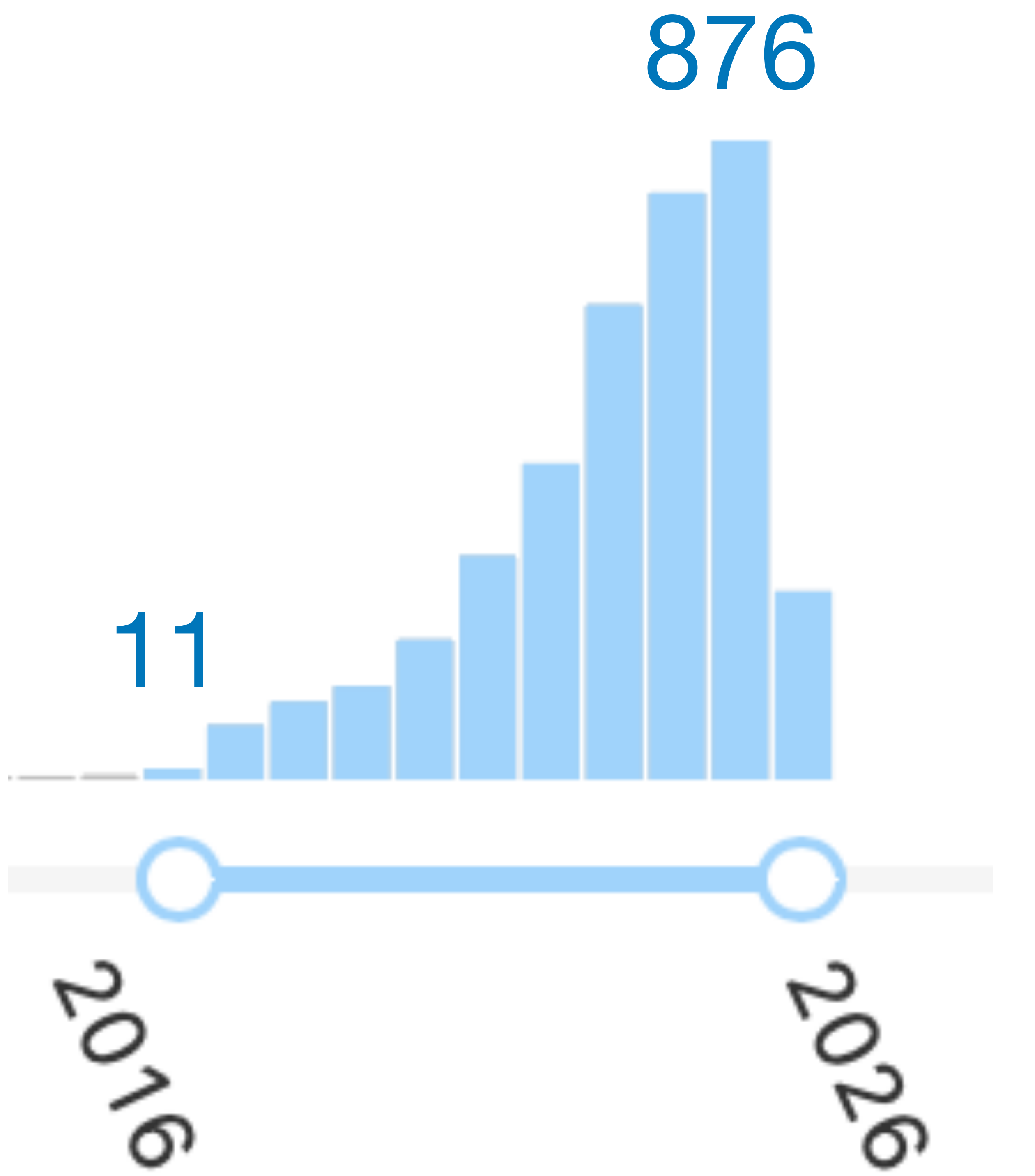


Quantum simulation of open quantum systems in heavy-ion collisions

Wibe A. de Jong, Mekena Metcalf, James Mulligan, Mateusz Płoskoń, Felix Ringer, and Xiaojun Yao
Phys. Rev. D **104**, L051501 – Published 7 September 2021

ABSTRACT

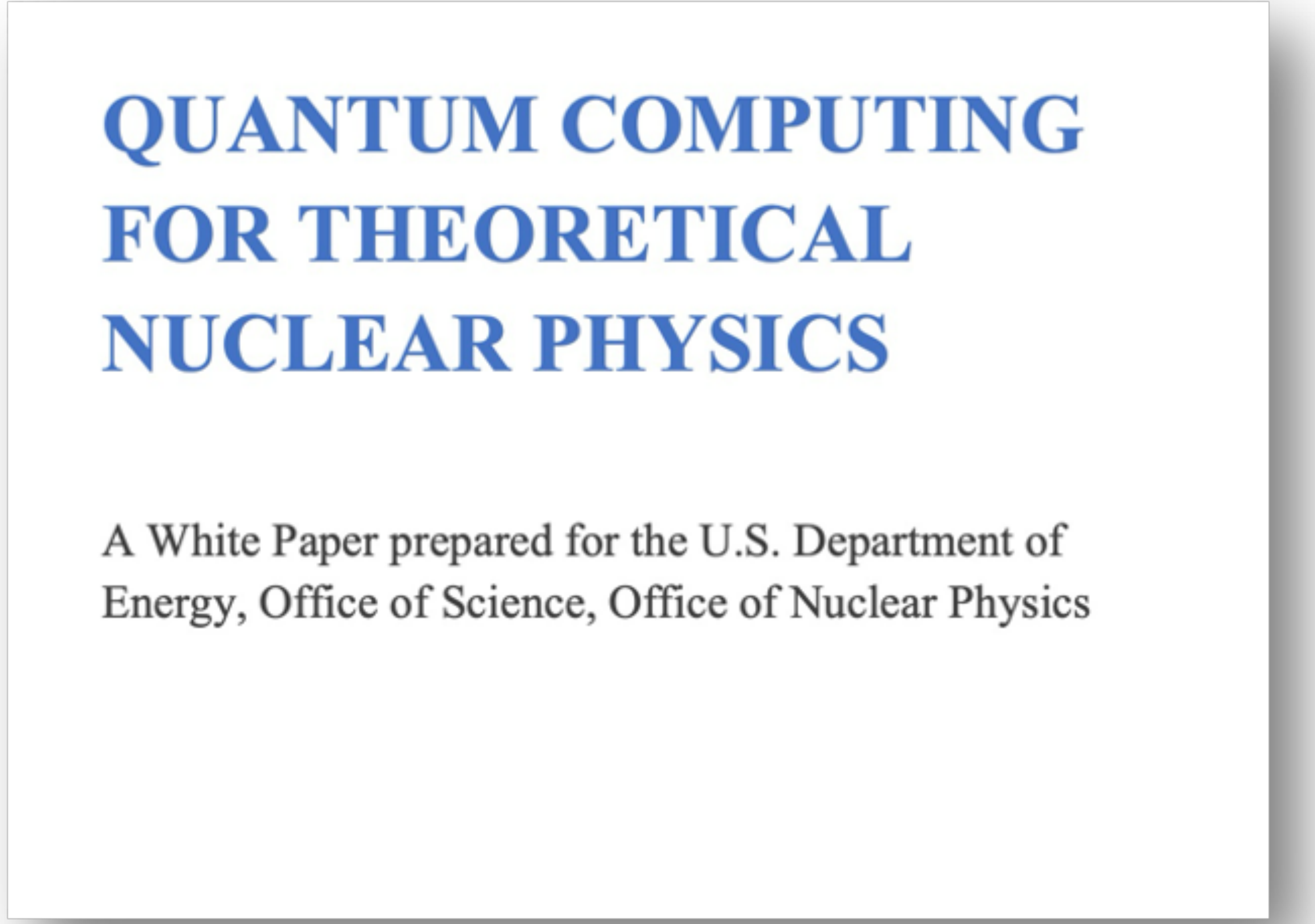
We present a framework to simulate the dynamics of hard probes such as heavy quarks or jets in a hot, strongly coupled quark-gluon plasma (QGP) on a quantum computer. Hard probes in the QGP can be treated as open quantum systems governed in the Markovian limit by the Lindblad equation. However, due to large computational costs, most current phenomenological calculations of hard probes evolving in the QGP use semiclassical approximations of the quantum evolution. Quantum computation can mitigate these costs and offers the potential for a fully quantum treatment with exponential speed-up over classical techniques. We report a simplified demonstration of our framework on IBM Q quantum devices and apply the random identity insertion method to account for CNOT depolarization noise, in addition to measurement error mitigation. Our work demonstrates the feasibility of simulating open quantum systems on current and near-term quantum devices, which is of broad relevance to applications in nuclear physics, quantum information, and other fields.



Inspire:

find t quantum computing and date>2016

Community-wide efforts

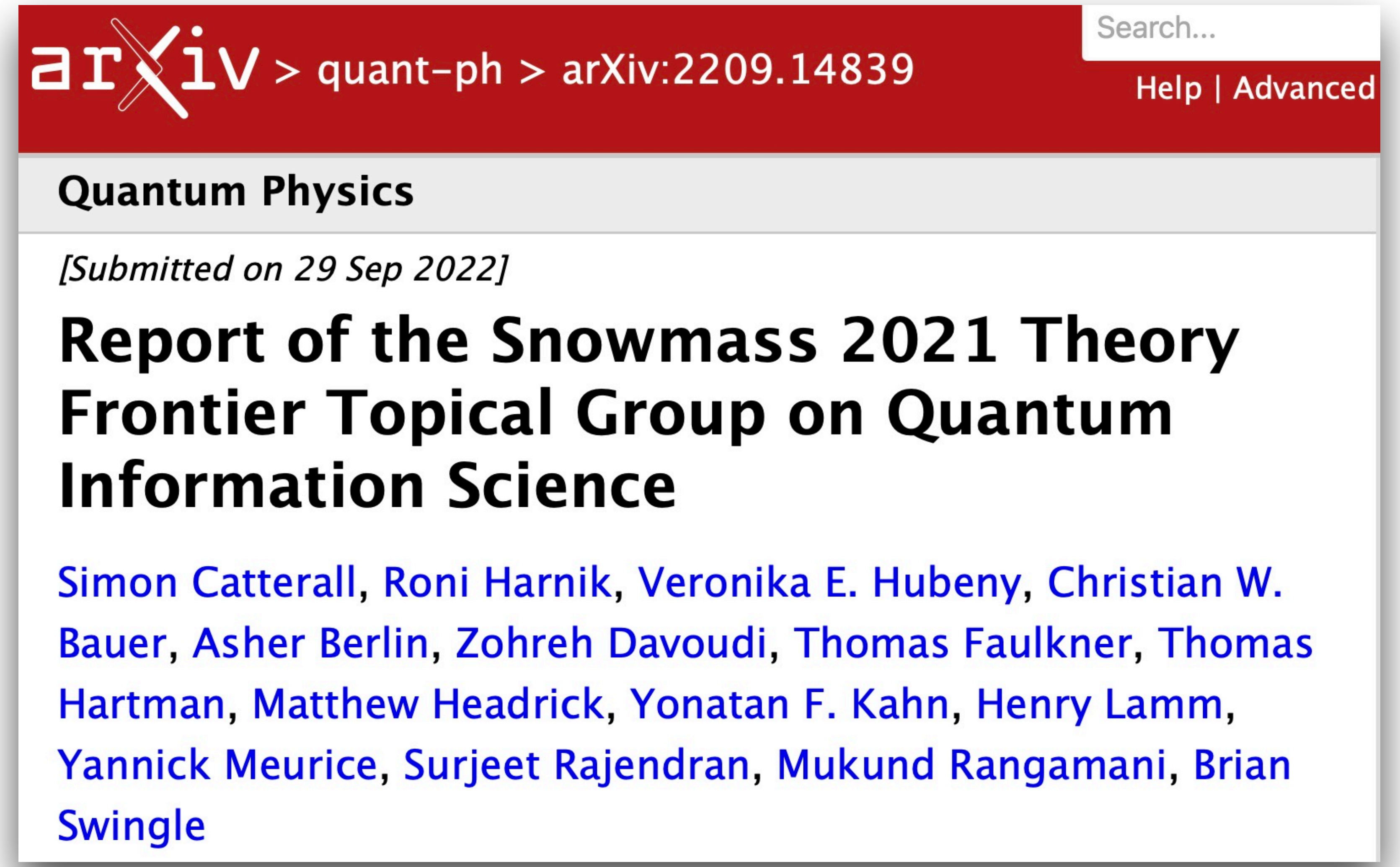


QUANTUM COMPUTING FOR THEORETICAL NUCLEAR PHYSICS

A White Paper prepared for the U.S. Department of Energy, Office of Science, Office of Nuclear Physics

Opportunities for Nuclear Physics & Quantum Information Science

Quantum support vector machines for Higgs boson classification

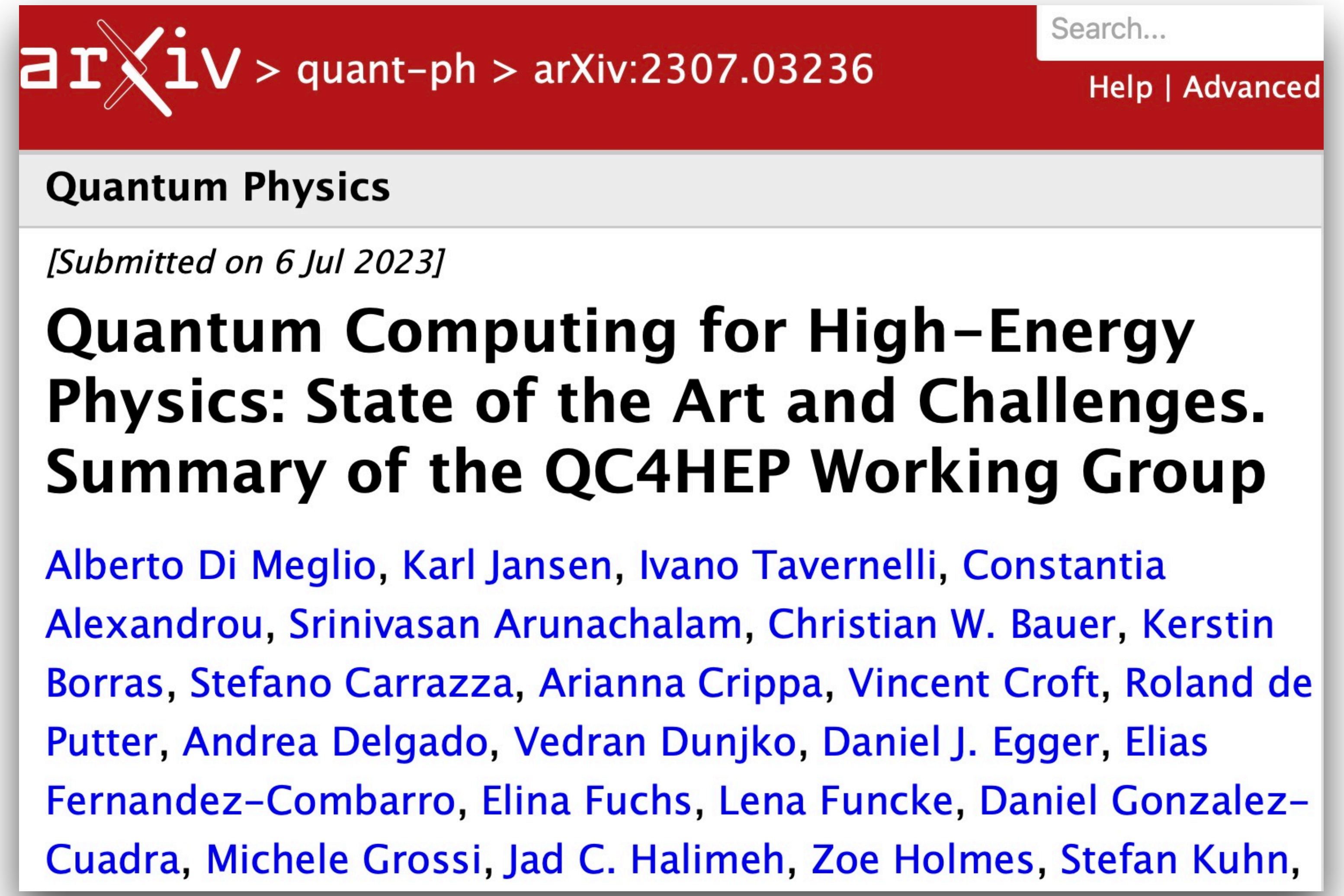


Quantum Physics

[Submitted on 29 Sep 2022]

Report of the Snowmass 2021 Theory Frontier Topical Group on Quantum Information Science

Simon Catterall, Roni Harnik, Veronika E. Hubeny, Christian W. Bauer, Asher Berlin, Zohreh Davoudi, Thomas Faulkner, Thomas Hartman, Matthew Headrick, Yonatan F. Kahn, Henry Lamm, Yannick Meurice, Surjeet Rajendran, Mukund Rangamani, Brian Swingle

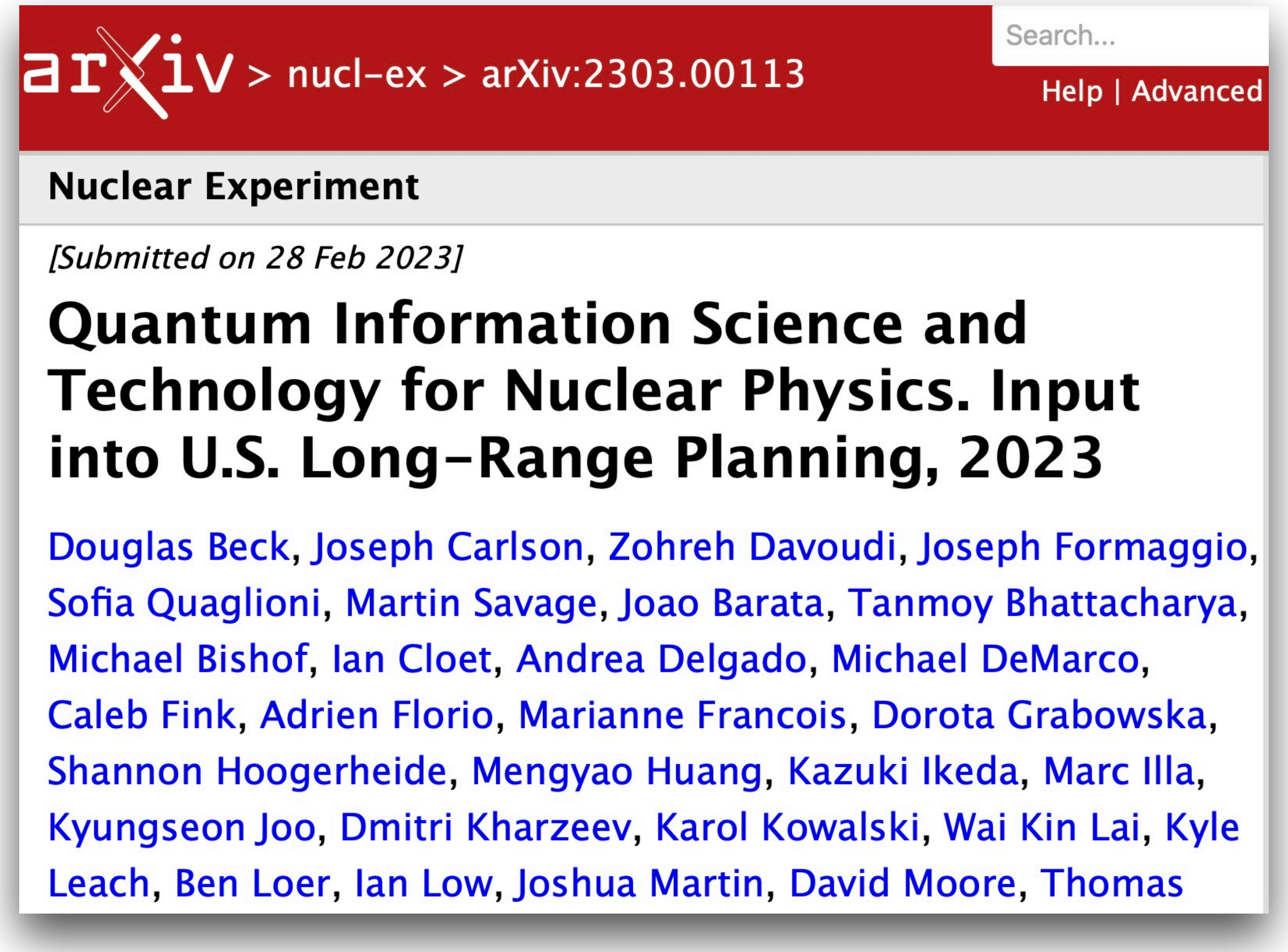


Quantum Physics

[Submitted on 6 Jul 2023]

Quantum Computing for High-Energy Physics: State of the Art and Challenges. Summary of the QC4HEP Working Group

Alberto Di Meglio, Karl Jansen, Ivano Tavernelli, Constantia Alexandrou, Srinivasan Arunachalam, Christian W. Bauer, Kerstin Borras, Stefano Carrazza, Arianna Crippa, Vincent Croft, Roland de Putter, Andrea Delgado, Vedran Dunjko, Daniel J. Egger, Elias Fernandez-Combarro, Elina Fuchs, Lena Funcke, Daniel Gonzalez-Cuadra, Michele Grossi, Jad C. Halimeh, Zoe Holmes, Stefan Kuhn,



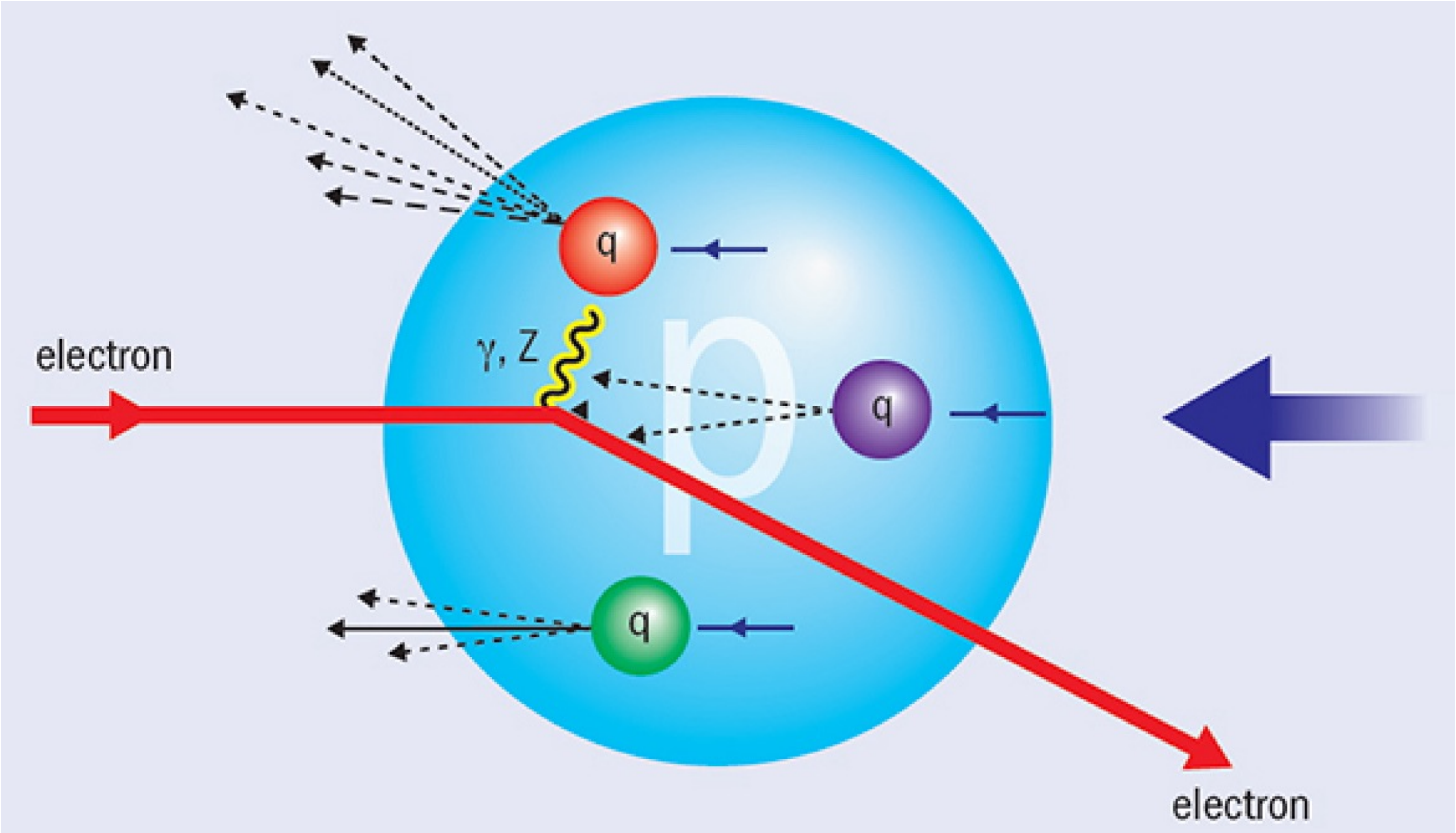
Nuclear Experiment

[Submitted on 28 Feb 2023]

Quantum Information Science and Technology for Nuclear Physics. Input into U.S. Long-Range Planning, 2023

Douglas Beck, Joseph Carlson, Zohreh Davoudi, Joseph Formaggio, Sofia Quaglioni, Martin Savage, Joao Barata, Tanmoy Bhattacharya, Michael Bishof, Ian Cloet, Andrea Delgado, Michael DeMarco, Caleb Fink, Adrien Florio, Marianne Francois, Dorota Grabowska, Shannon Hoogerheide, Mengyao Huang, Kazuki Ikeda, Marc Illa, Kyungseon Joo, Dmitri Kharzeev, Karol Kowalski, Wai Kin Lai, Kyle Leach, Ben Loer, Ian Low, Joshua Martin, David Moore, Thomas

First principle calculation on lattice



- ✦ Electron-proton collisions

$$|\langle X(T)\,|\,U(T,-T)\,|\,ep\ (-T)\rangle|^2$$

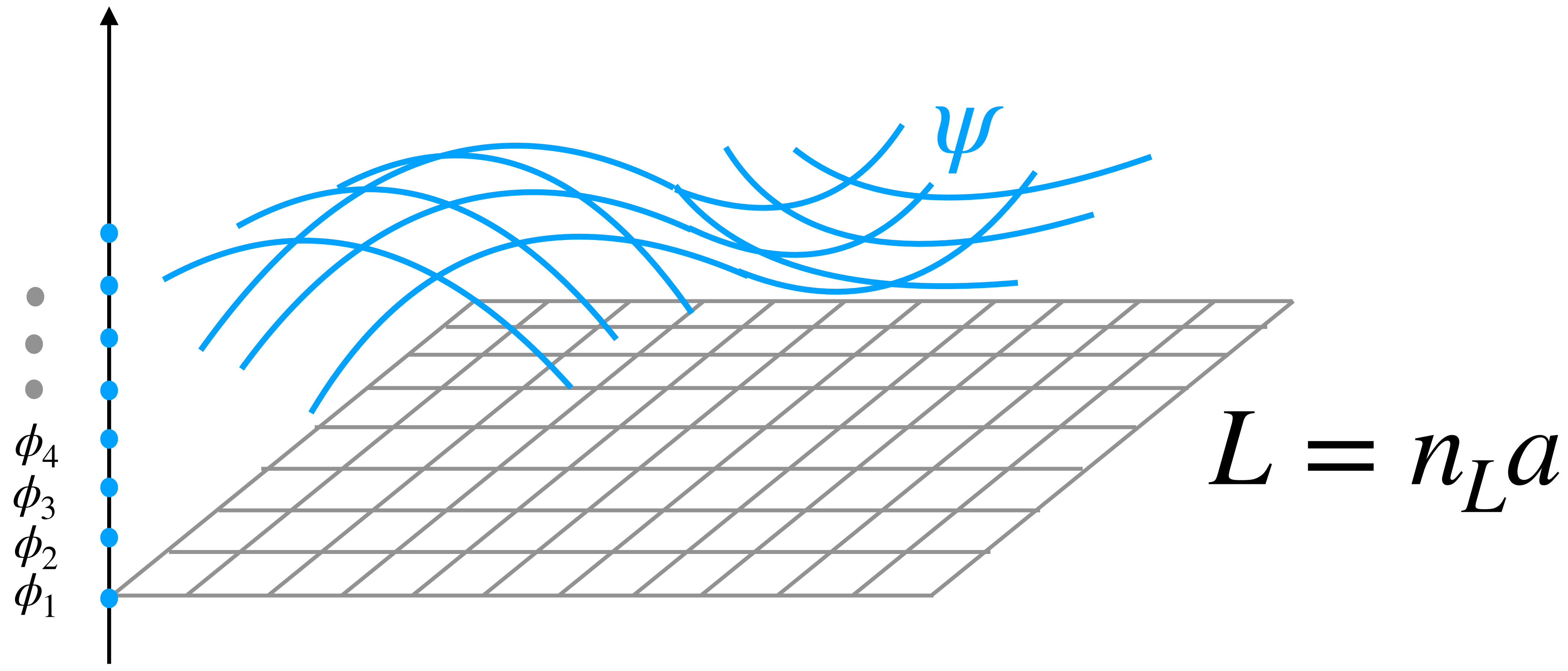
- ✦ Key steps
  - Prepare initial states from the distance past $(-T)$
  - Evolve these states from the distance past to time T, $U(T,-T) \rightarrow e^{-iH(\psi)T}$
  - Perform measurement in final state

However, the Hilbert space in quantum field theory is infinite …

First principle calculation on lattice

✦ Digitize field ϕ at discrete points x

$$|\langle X(T)|U(T,-T)|ep\ (-T)\rangle|^2$$



- Hilbert space dimension: $n_H = (n_\phi)^{n_L{}^d}$

n_ϕ : # of digitized field values

n_L : # of lattice points per dimension

d : # of dimensions

- Energy range can be described by lattice

$$(n_L a)^{-1} \lesssim E \lesssim a^{-1}$$

Full energy range of LHC: $100\text{MeV} \lesssim E \lesssim 13\text{TeV}$

$$n_L^d \sim 10^{15}$$

Assume 5 bit digitization: $n_\phi = 2^5 = 32$

Dimension of Hilbert space: $n_H = 32^{10^{15}} \sim \infty$

First principle calculation on lattice

✦ Digitize field ϕ at discrete points x

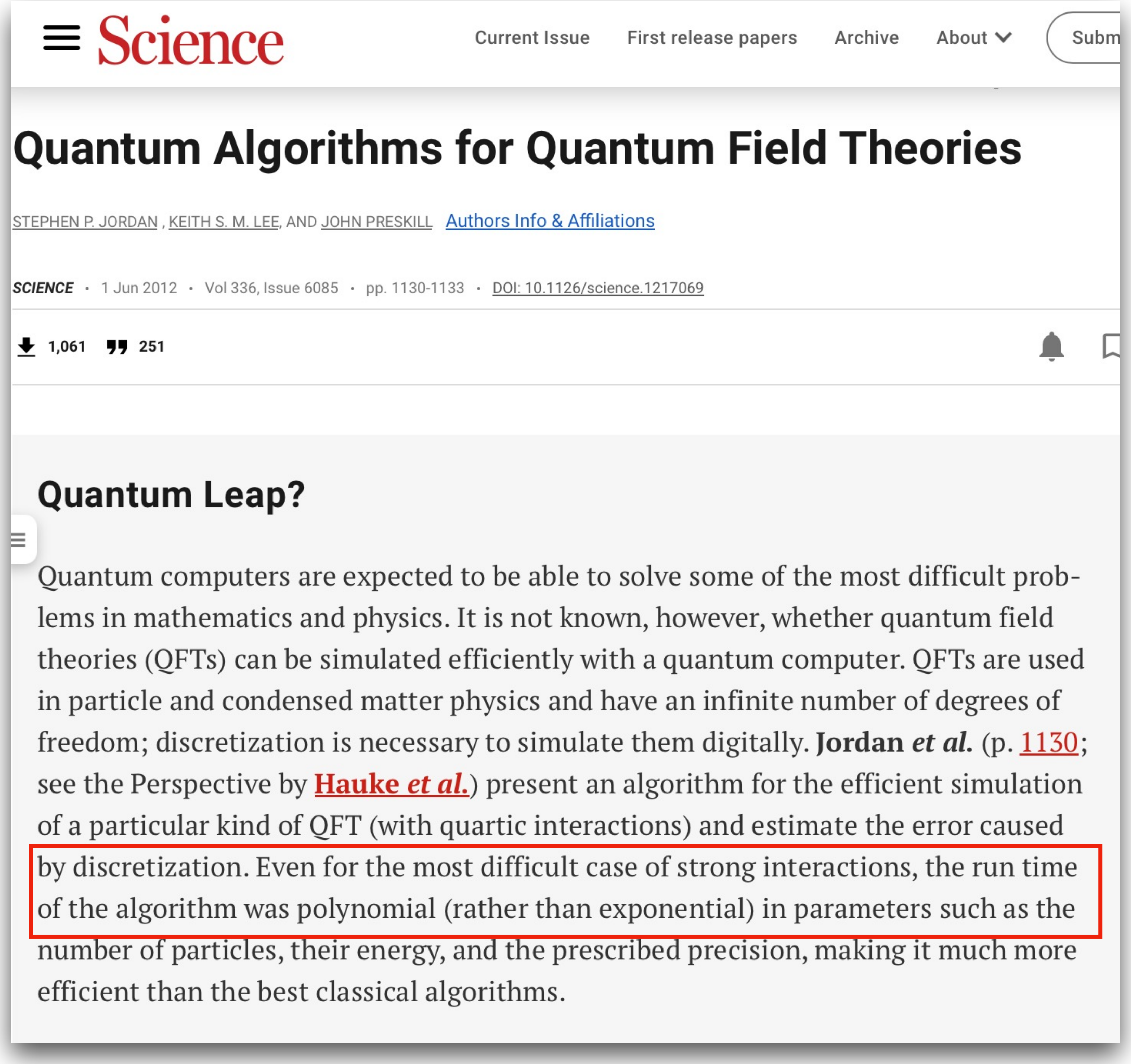
$$|\langle X(T)\,|\,U(T,-T)\,|\,ep\ (-T)\rangle|^2$$

- Hilbert space dimension: $n_H = (n_\phi)^{{n_L}^d}$

Quantum computing: encoding in qubits

$$n_q = \ln_2 n_H = n_L^D \ln_2 n_\phi$$

For LHC: $n_q = 5 \times 10^{15}$



Quantum Algorithms for Quantum Field Theories

STEPHEN P. JORDAN, KEITH S. M. LEE, AND JOHN PRESKILL Authors Info & Affiliations

SCIENCE • 1 Jun 2012 • Vol 336, Issue 6085 • pp. 1130-1133 • DOI: 10.1126/science.1217069

Quantum Leap?

Quantum computers are expected to be able to solve some of the most difficult problems in mathematics and physics. It is not known, however, whether quantum field theories (QFTs) can be simulated efficiently with a quantum computer. QFTs are used in particle and condensed matter physics and have an infinite number of degrees of freedom; discretization is necessary to simulate them digitally. **Jordan *et al.*** (p. 1130; see the Perspective by **Hauke *et al.***) present an algorithm for the efficient simulation of a particular kind of QFT (with quartic interactions) and estimate the error caused by discretization. Even for the most difficult case of strong interactions, the run time of the algorithm was polynomial (rather than exponential) in parameters such as the number of particles, their energy, and the prescribed precision, making it much more efficient than the best classical algorithms.

Way beyond NISQ ear in quantum computing!

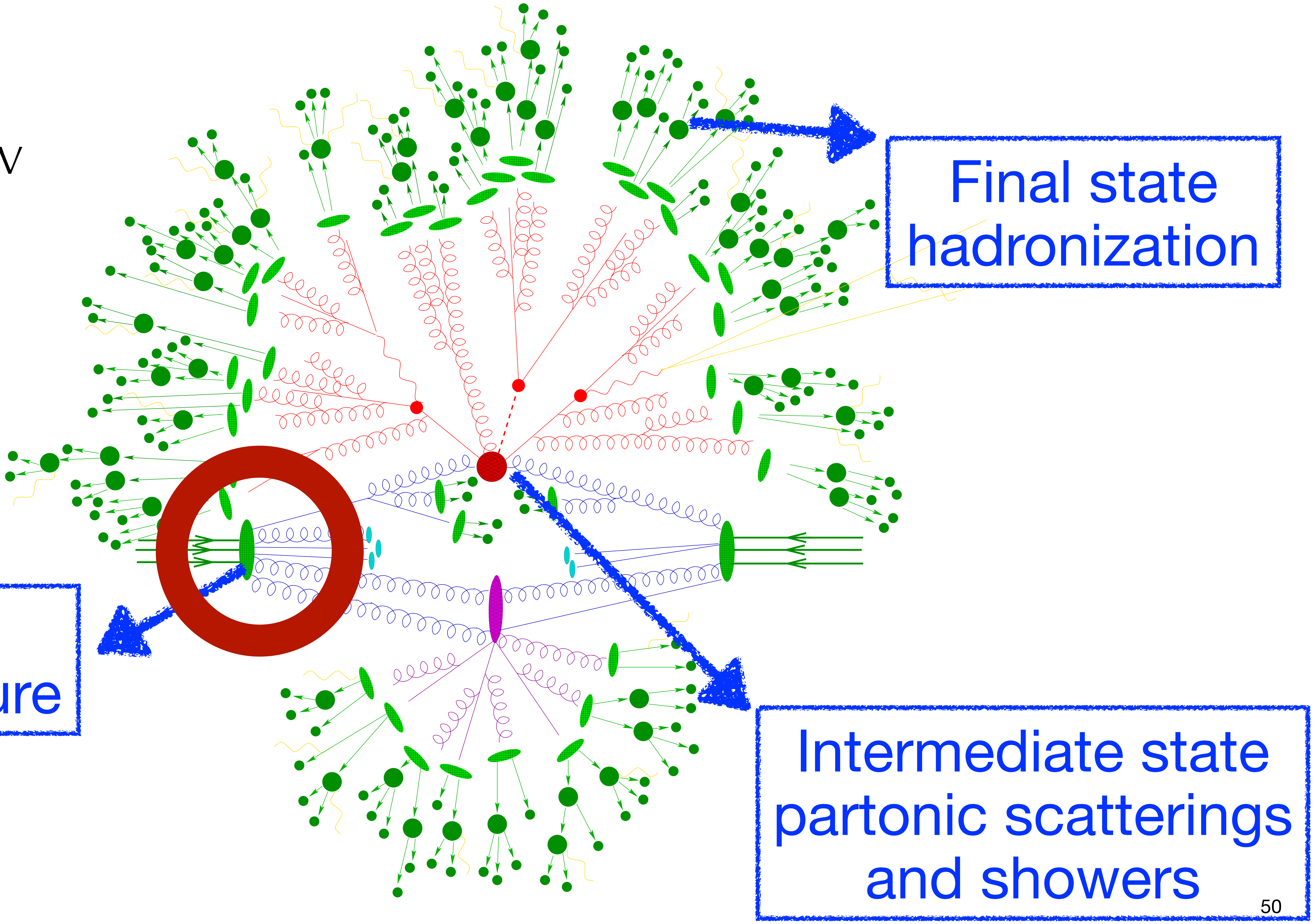
First principle calculation on lattice

Bauer, Freytsis, Nachman, PRL 2021

For the hadron: $100\text{MeV} \lesssim E \lesssim 1\text{GeV}$

$n_L^D \sim 10^3$

# of qubits: $n_q = 5 \times 10^3$



Final state hadronization

Initial state hadron structure

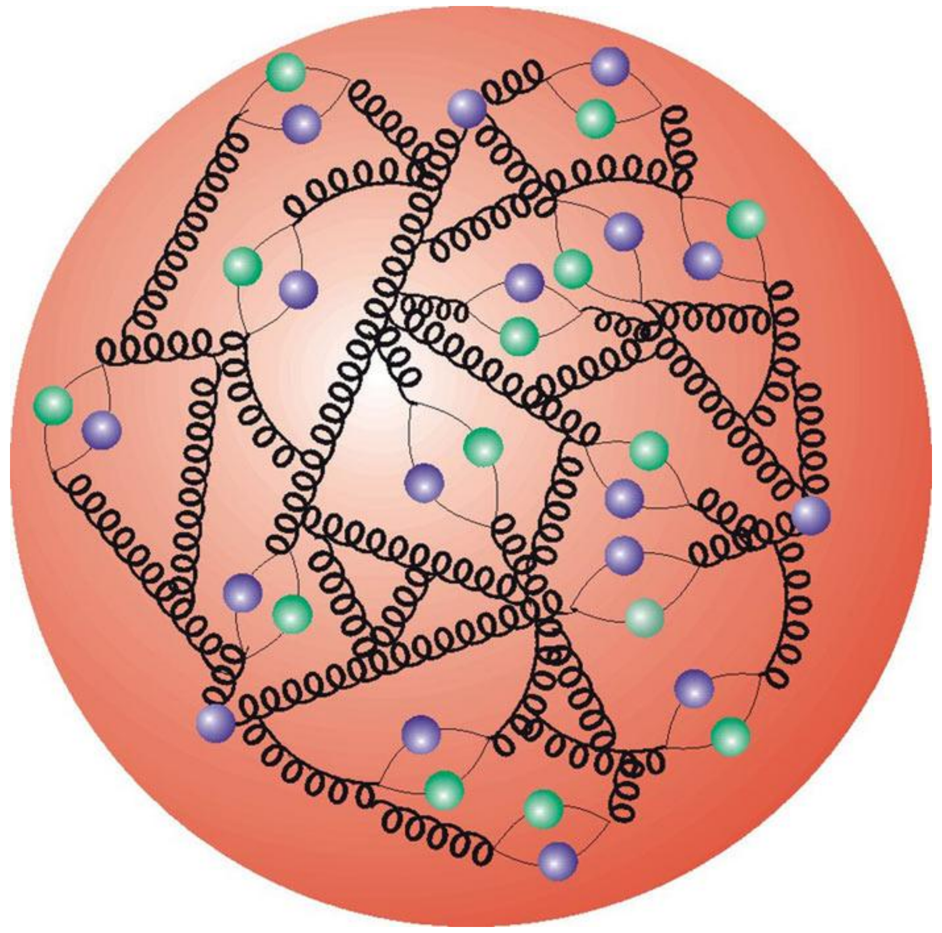
Intermediate state partonic scatterings and showers

Simulate hadron structure on quantum computer

✦ Operator definition of quark PDF

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

$$y^- = (t - y_3)/\sqrt{2}$$



✦ PDFs are extremely challenge to simulate directly in Euclidean lattice calculation, due to multidimensional oscillating integral.

✦ QC can naturally simulate real-time dynamics.

✦ We are far from QCD Quantum Supremacy, start from a toy model for proof of concept study

Simulate hadron structure on quantum computer

✦ A toy model - 1+1D NJL (Gross, Neveu, 1974), no gauge field

$$\mathcal{L} = \bar{\psi}_\alpha(i\gamma^\mu\partial_\mu - m_\alpha)\psi_\alpha + g(\bar{\psi}_\alpha\psi_\alpha)^2$$

$$f(x) = \int dz^- e^{-ixM_h z^-}\langle h|\bar{\psi}(z^-)\gamma^+\psi(0)|h\rangle = \int dz^- e^{-ixM_h z^-}\boxed{\langle h|}\boxed{e^{iHz}\bar{\psi}(0,-z)e^{-iHz}\gamma^+\psi(0)}\boxed{|h\rangle}$$

✦ Challenges in quantum computing

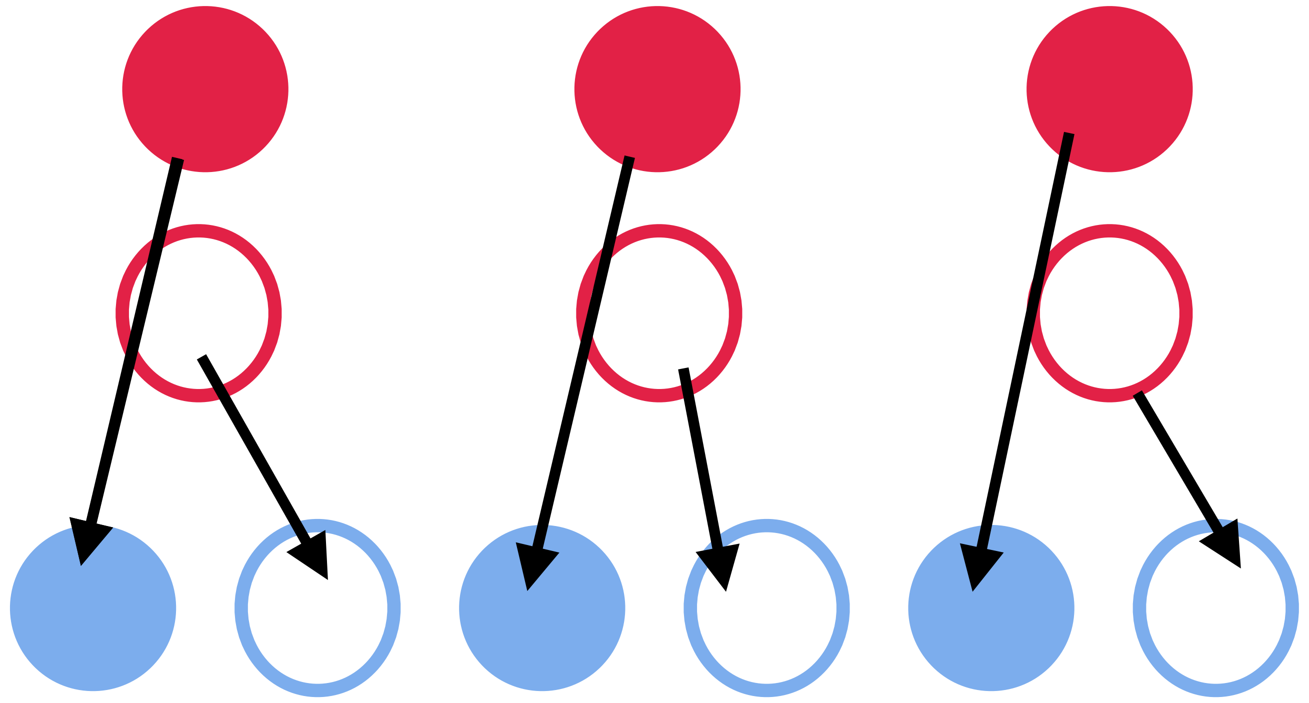
- Map QFT to qubits+gates system
- Prepare the external hadronic state $|h\rangle$
- Evaluate the real-time dynamical correlation function
- Measurement of final observable

Simulate hadron structure on quantum computer

✦ Quantum field to qubits+gates

$$\mathscr{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + g(\bar{\psi}\psi)^2$$

- Discretization: staggered fermion, put different fermion components, flavors on different sites



$$\psi = \begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} \to \begin{pmatrix}\phi_{2n}\\ \phi_{2n+1}\end{pmatrix}$$

- Jordan-Wigner transformation

$$\phi_n = \prod_{i<n} Z_i (X + iY)_n$$

- Discretized PDF:

$$f(x) \to \sum_{i,j}\sum_{z} \frac{1}{4\pi} e^{-ixM_h z}\langle h \,|\, e^{iHz}\phi^\dagger_{-2z+i} e^{-iHz}\phi_j \,|\, h\rangle$$

$$H = H_1 + H_2 + H_3 + H_4 \qquad H_1 = \sum_{n=\text{even}} \frac{1}{4}\left[X_n Y_{n+1} - Y_n X_{n+1}\right]$$

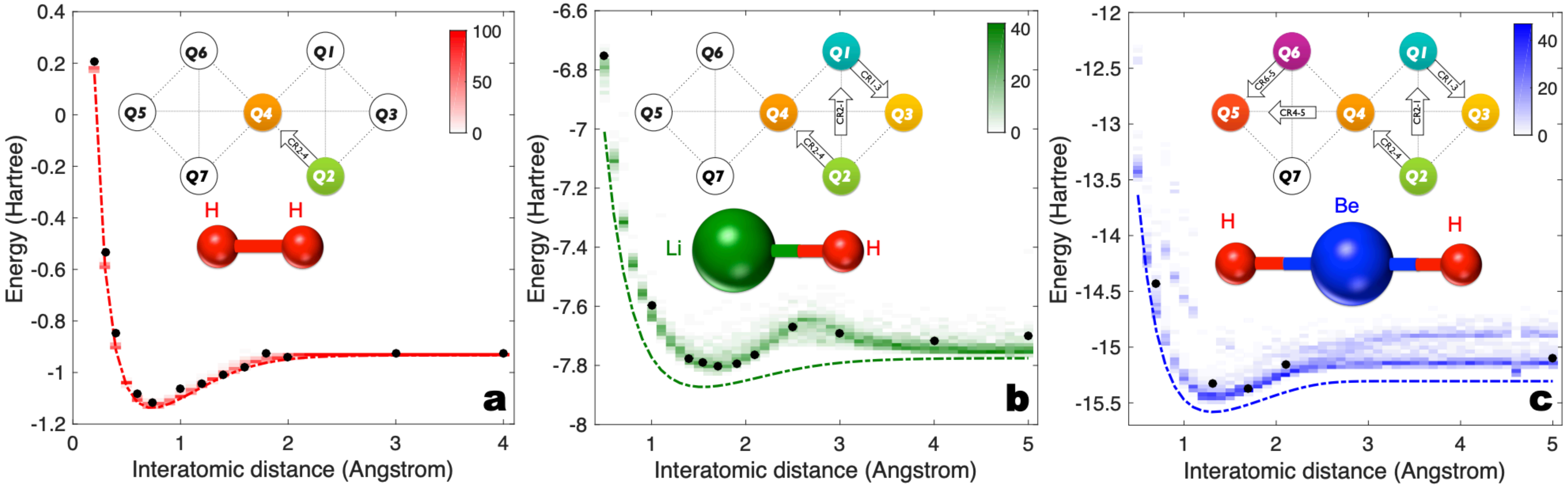
Simulate hadron structure on quantum computer

✦ Hadron state preparation - VQE

- Hadron states are the eigenstates of the Hamiltonian with certain quantum numbers.
- Prepare the state by variational quantum eigensolver (VQE) 2103.08505 + …
- VQE is a hybrid method involves both classical and quantum computers

Potential energy surfaces

Nature 549, 242 (2017)



show its power in quantum chemistry

Simulate hadron structure on quantum computer

✦ Hadron state preparation - VQE

Li et al (QuNu), PRD (letter, 2022)

1. For a giving quantum number l and first k excited states, construct a trial hadronic state $|\psi_{lk}\rangle$

2. Divide $H = H_1 + H_2 + H_3 + H_4$

$$U(\theta) \equiv \prod_{i=1}^{p} \prod_{j=1}^{n} \exp(i\,\theta_{ij} H_j)$$

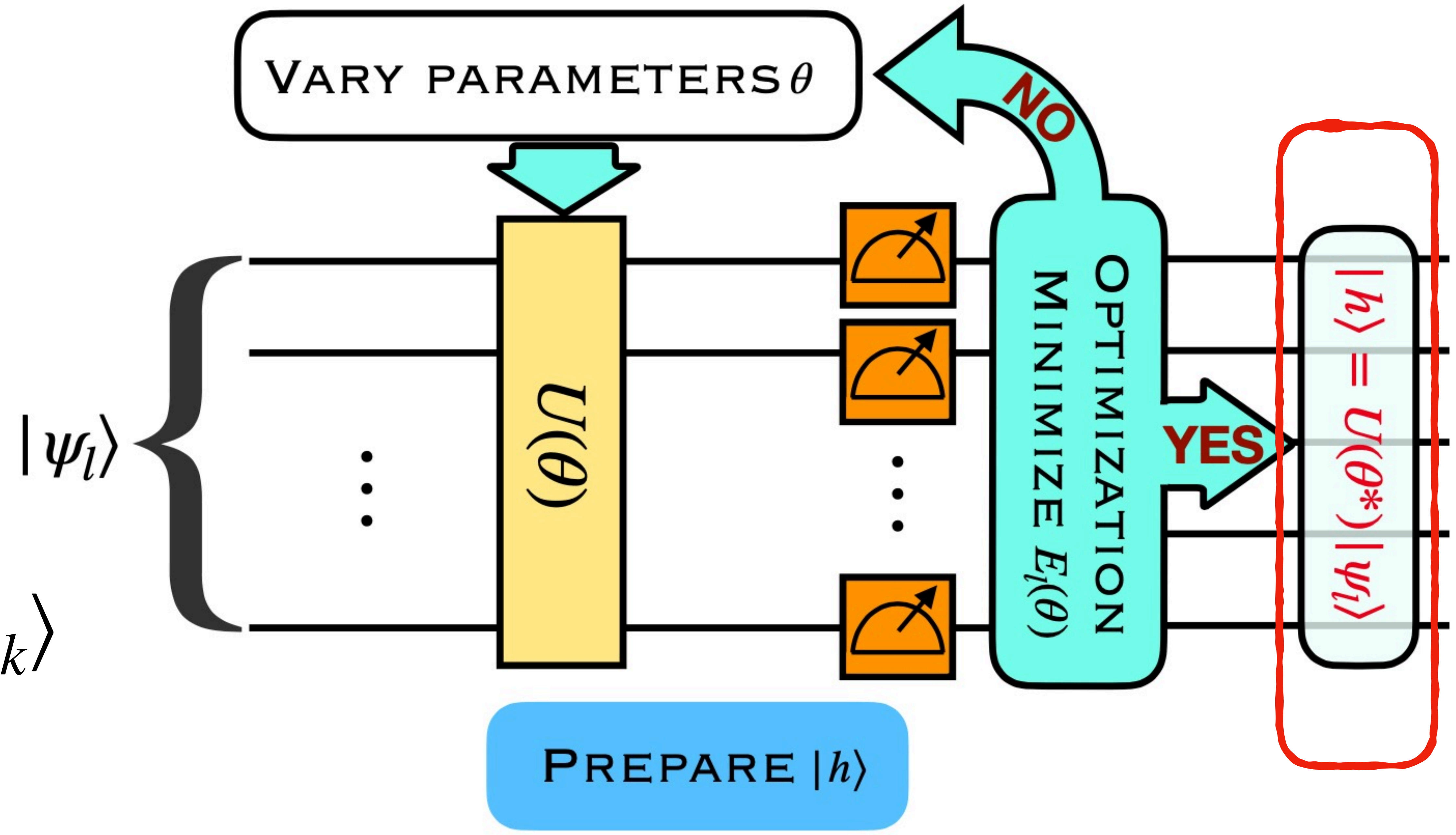
3. Generate the trial state: $|\psi_{lk}(\theta)\rangle = U(\theta)|\psi_{lk}\rangle$

4. Measure the loss function:

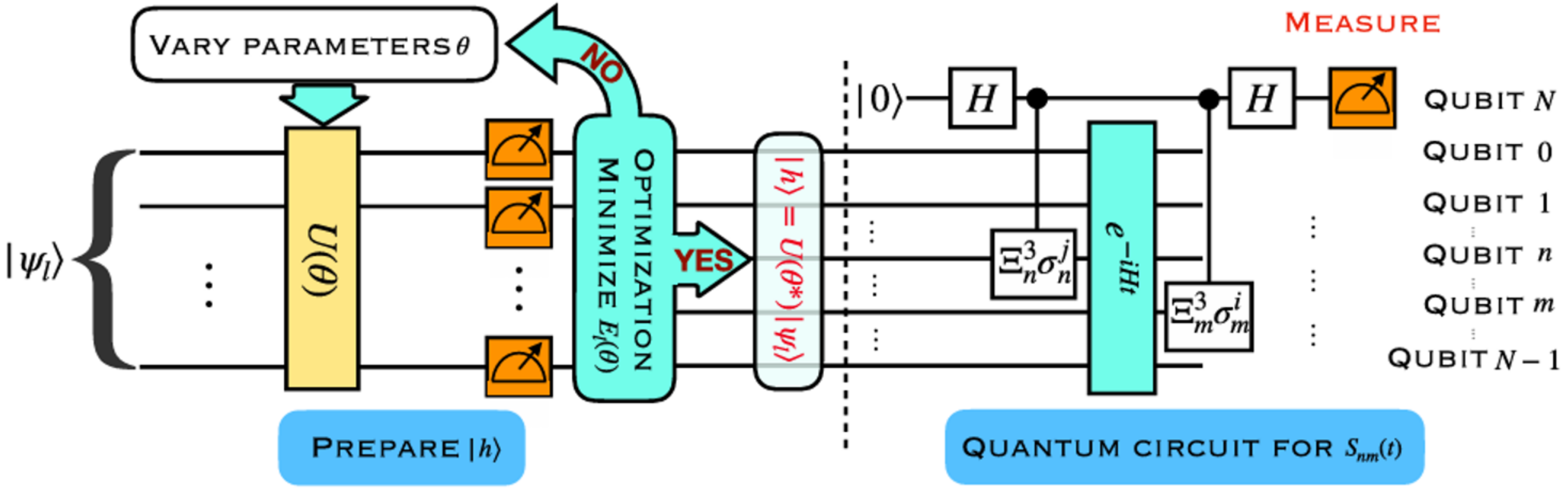
$$E_l(\theta) = \sum_{i=1}^{k} w_{li} \langle \psi_{li}(\theta) | H | \psi_{li}(\theta) \rangle$$

5. Optimize the parameters θ^* on classical machine

6. Generate the hadron state $|h\rangle = U(\theta^*)|\psi_{lk}\rangle$



Quantum circuit for hadron structure



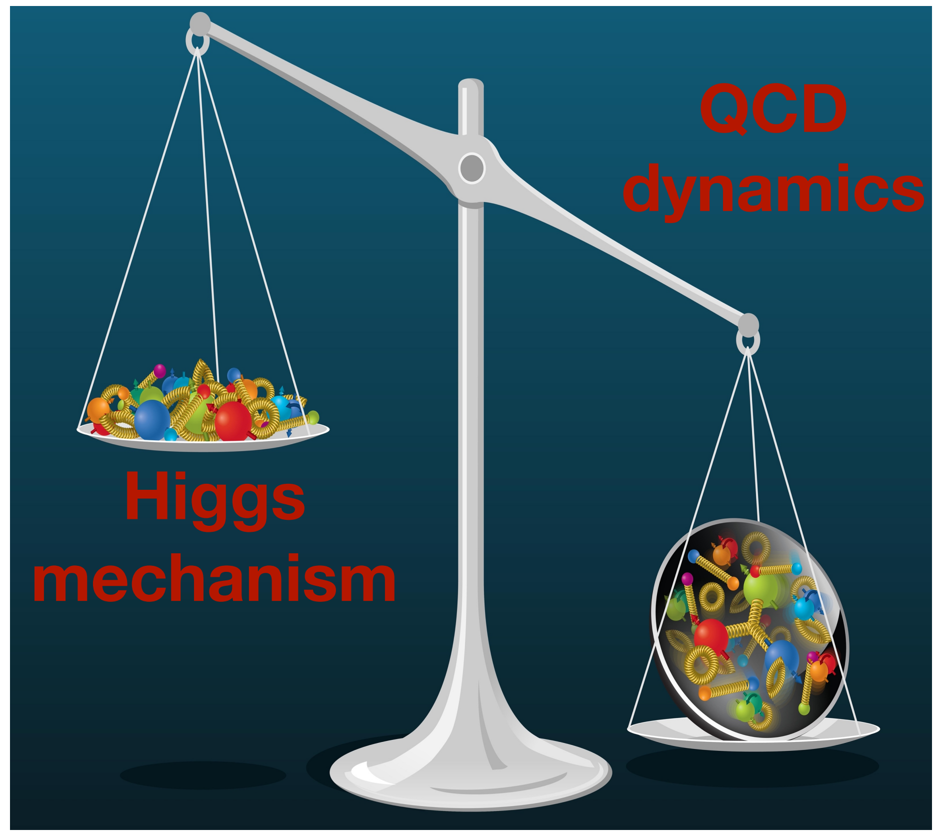
Hadron mass on quantum computer

✦ Measurement of hadron mass $M_h = \langle h|H|h\rangle - \langle\Omega|H|\Omega\rangle$

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

$N = 12$

$ma = 0.2$



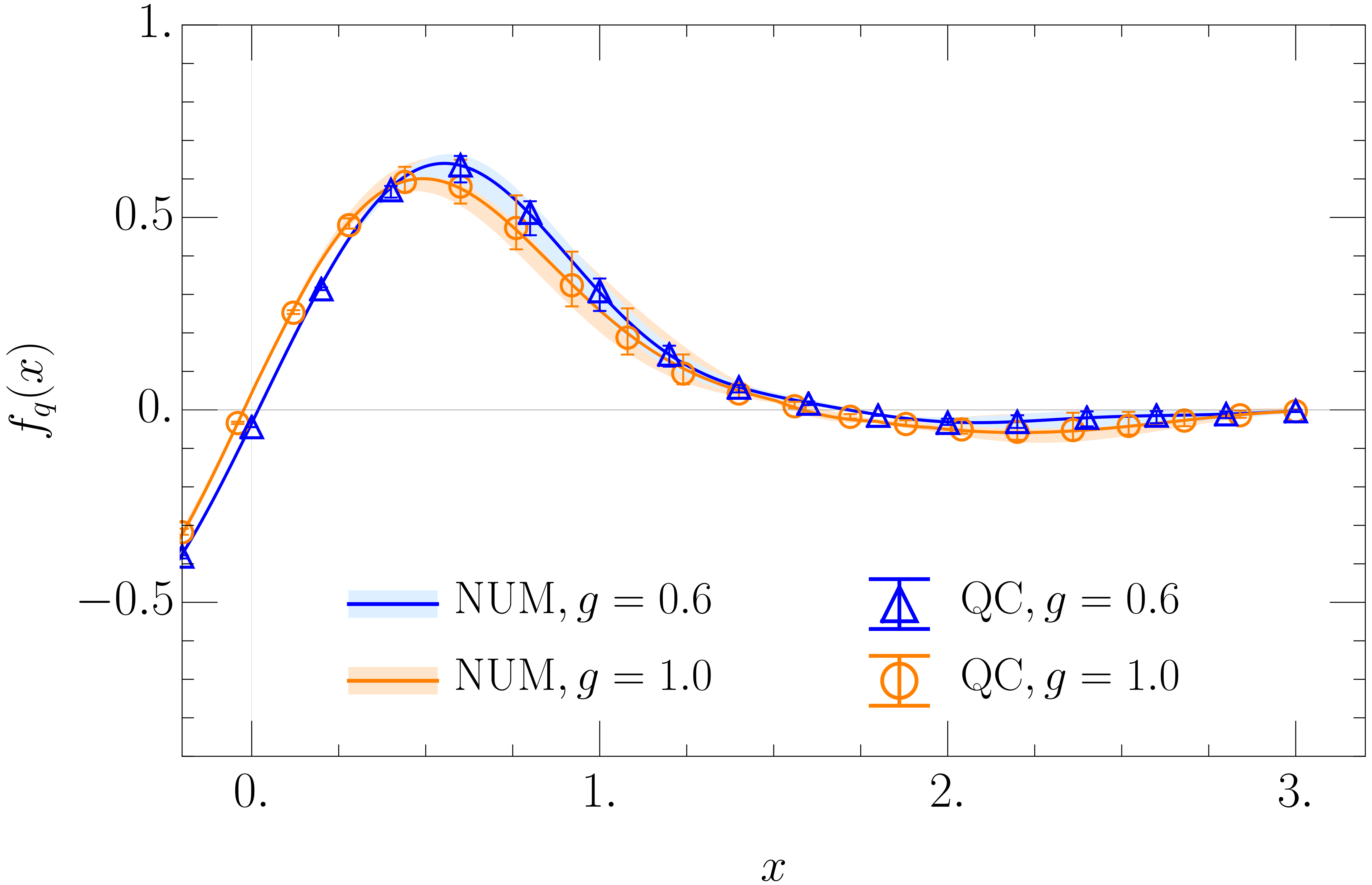
- Considering the current limitations of using real quantum devices, the results are generated using a classical simulation of the quantum circuit
- Measure the mass of the lowest-lying ud-like hadron in NJL model with 2 flavors, QAOA has good accuracy
- For small quark mass, the dominant contribution comes from the interaction rather than the quark masses
- For $ma = 0.8$, the quark masses are dominant

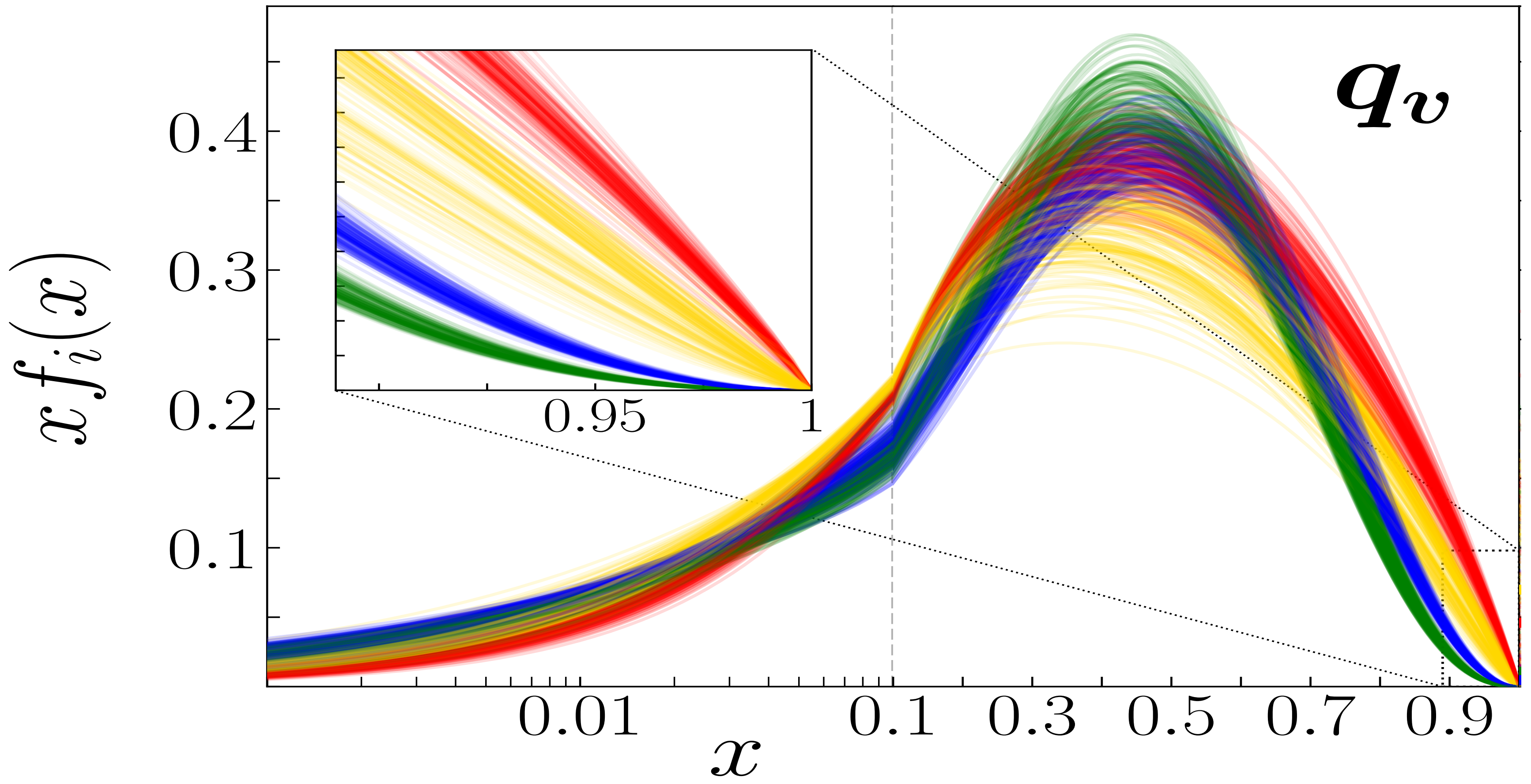
PDF on quantum computer

Li et al (QuNu), PRD (letter, 2022)

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

- Good agreement between quantum computing 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



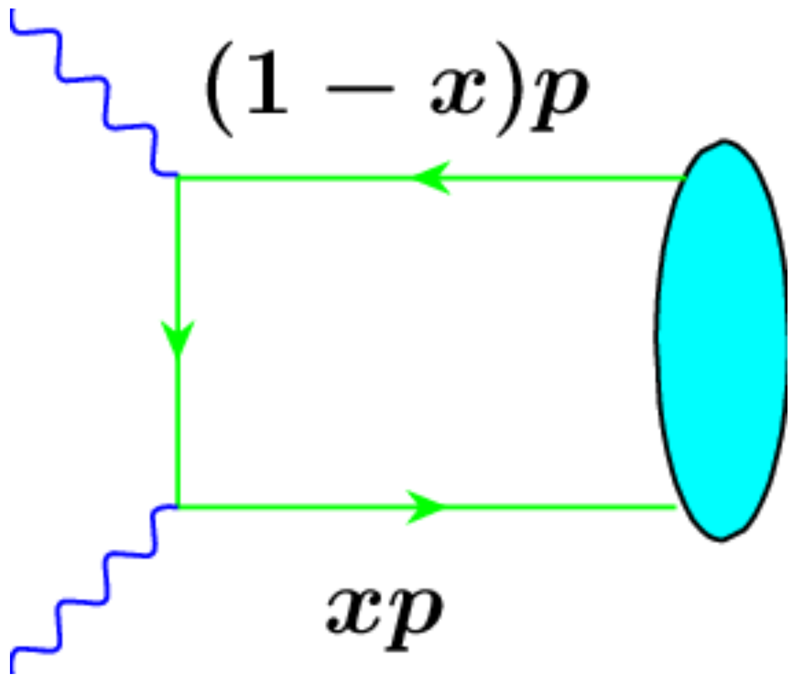


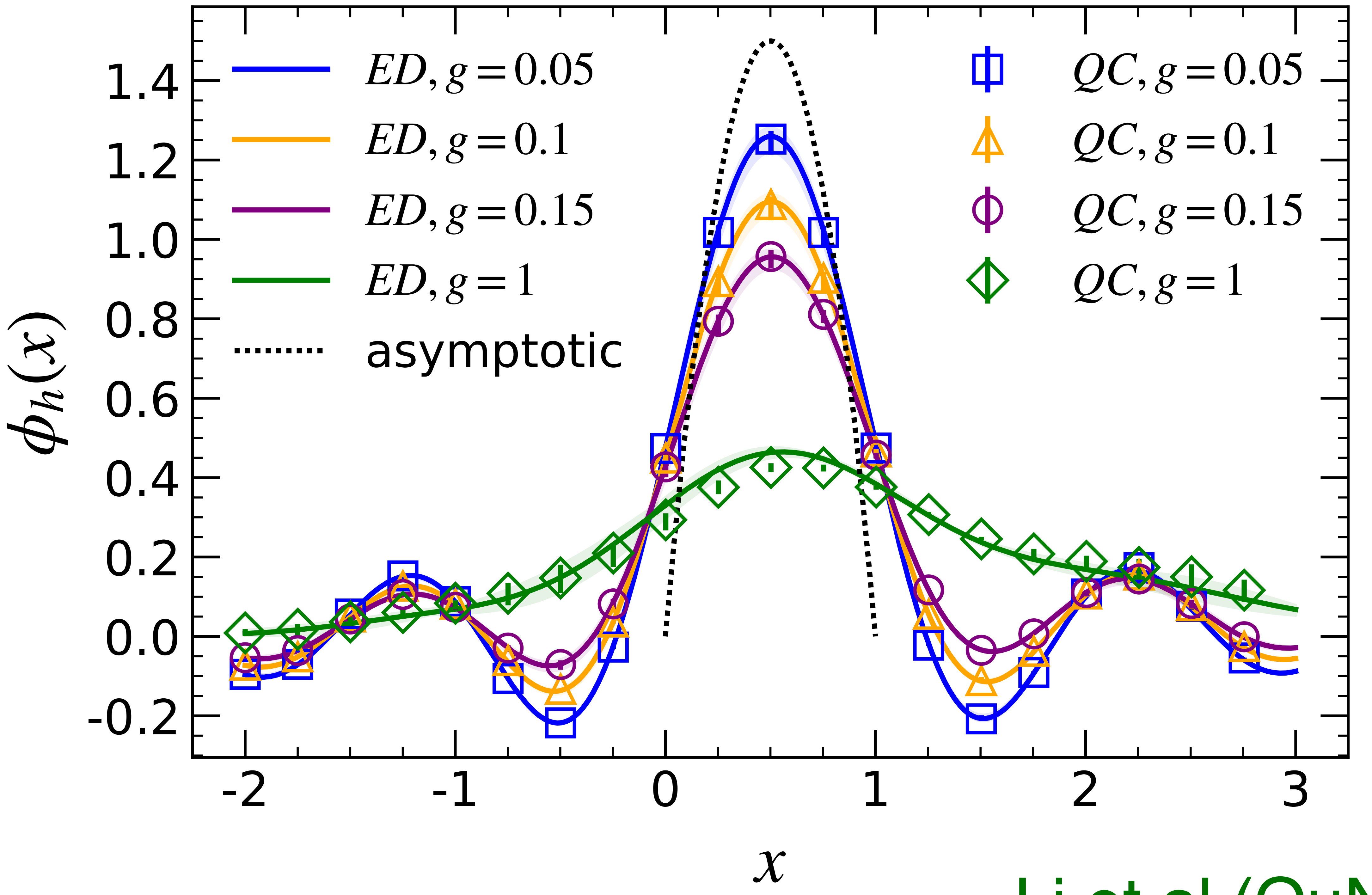
JAM Collaboration, PRL, 2021

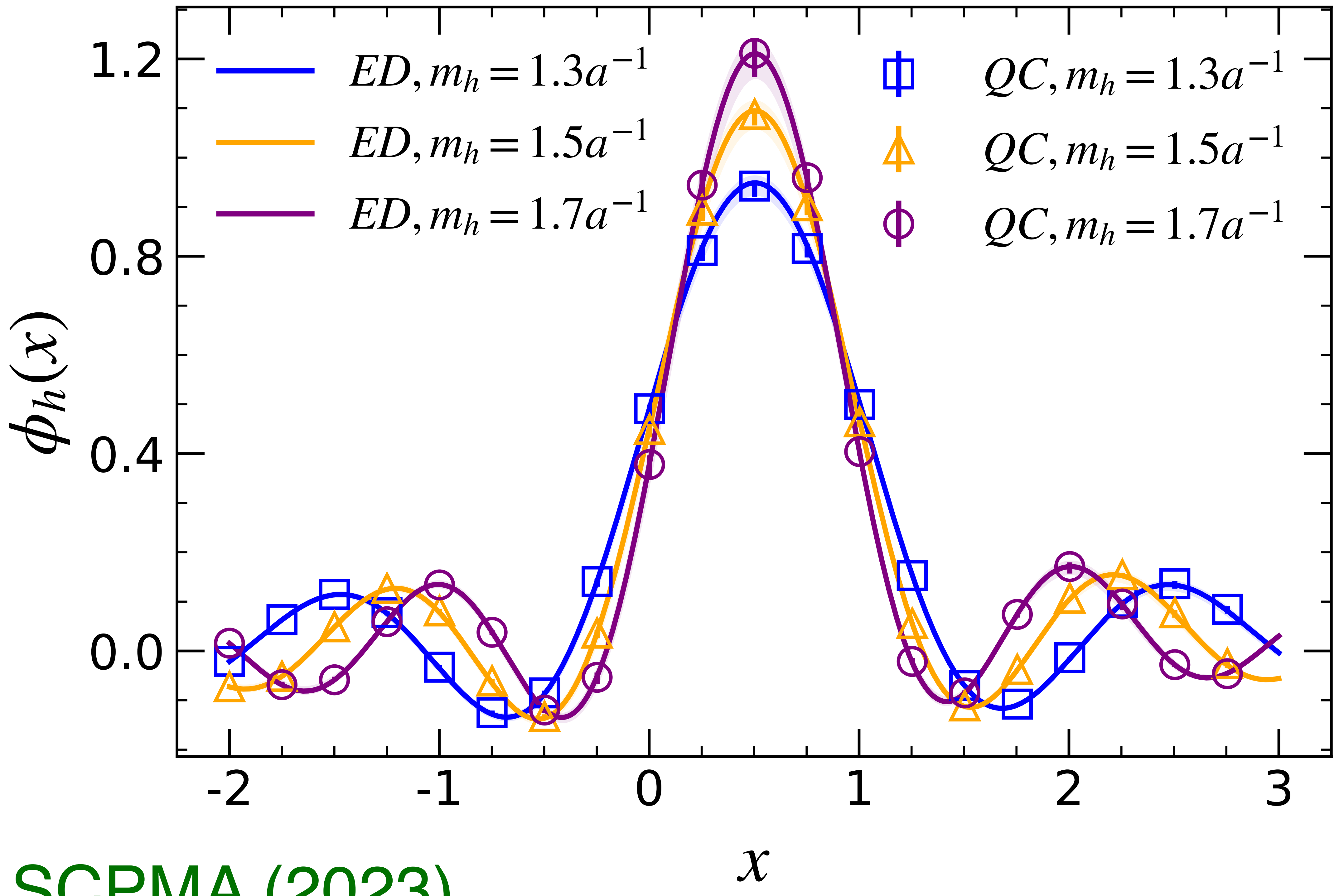
Exclusive hadronization on quantum computer

- ✦ light cone distribution amplitude - the formation/decay of a hadron

$$\phi(x) = \frac{1}{f}\int dz e^{-i(x-1)n\cdot Pz}\langle\Omega\,|\,\bar{\psi}(zn)\gamma^{+}\psi(0)\,|\,h(P)\rangle$$







Li et al (QuNu), SCPMA (2023)

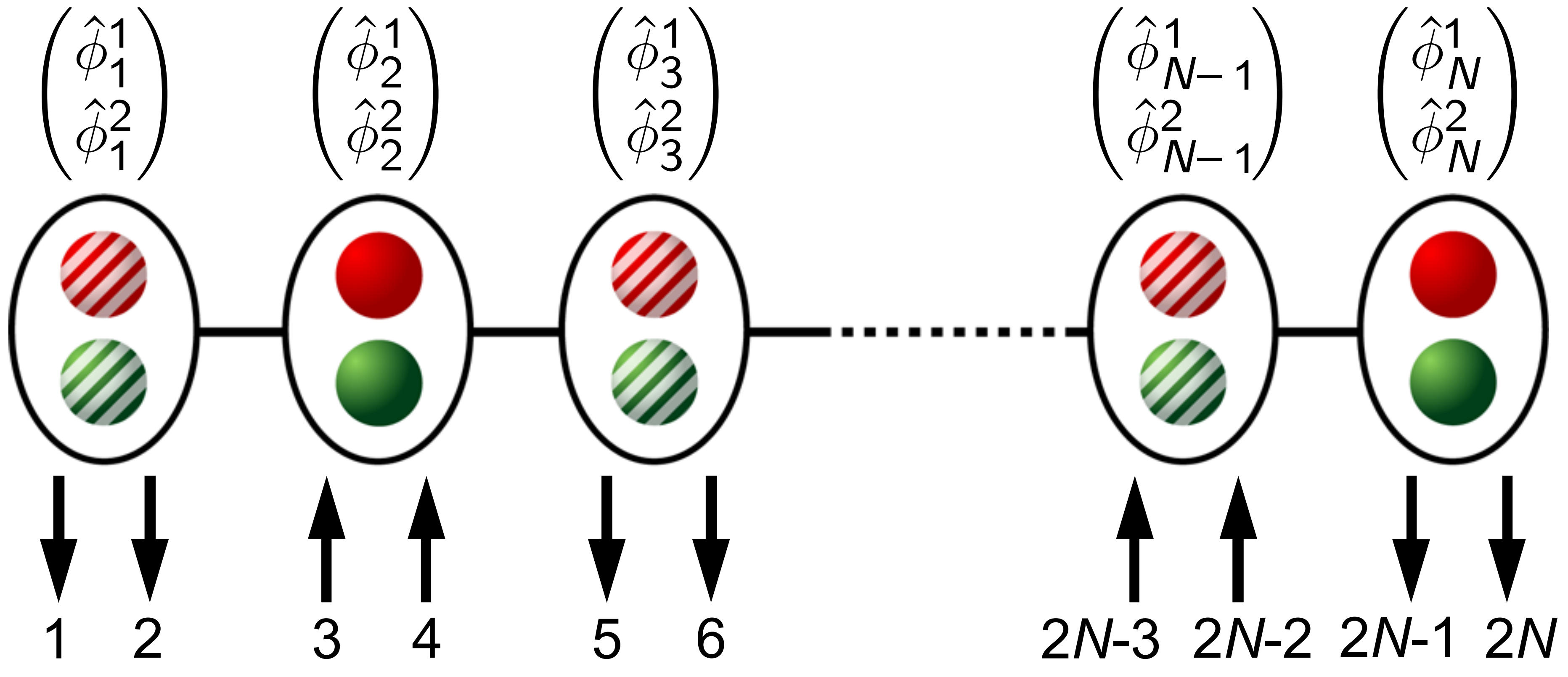
SU(2) on quantum computer

- SU(2) Hamiltonian

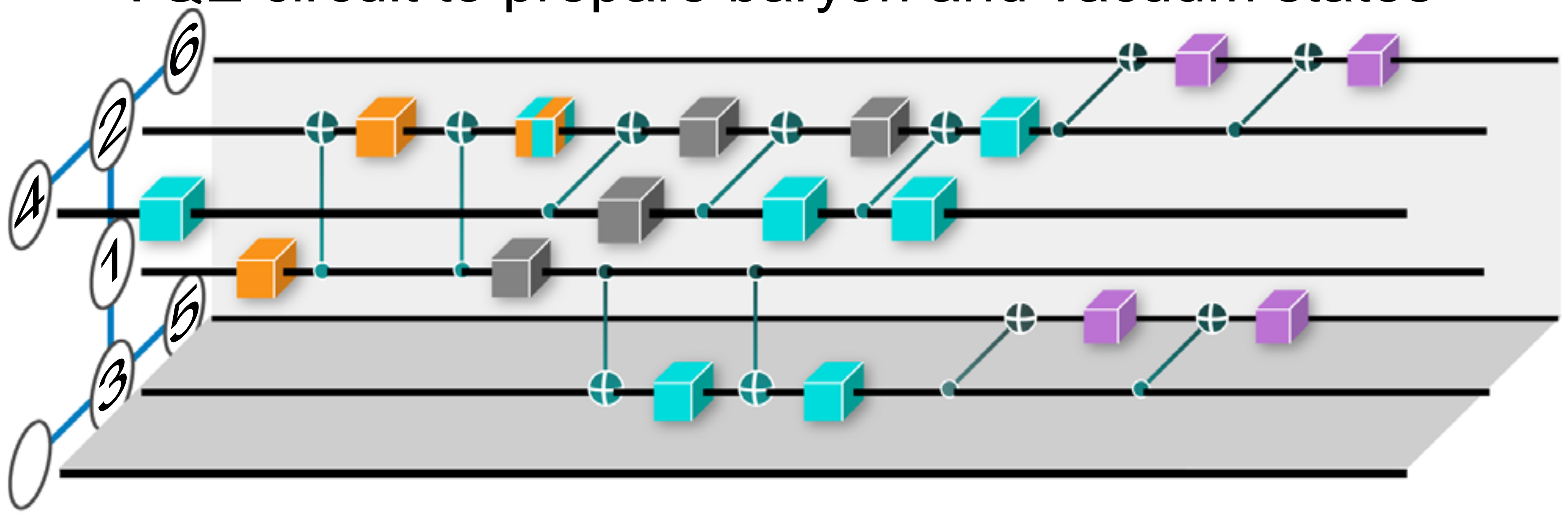
Atas et al, Nature Commun. 2021

$$\hat{H}_l = \frac{1}{2a_l}\sum_{n=1}^{N-1}\left(\hat{\phi}_n^\dagger \hat{U}_n \hat{\phi}_{n+1} + \text{H.C.}\right) + m\sum_{n=1}^{N}(-1)^n \hat{\phi}_n^\dagger \hat{\phi}_n + \frac{a_l g^2}{2}\sum_{n=1}^{N-1}\hat{\boldsymbol{L}}_n^2$$

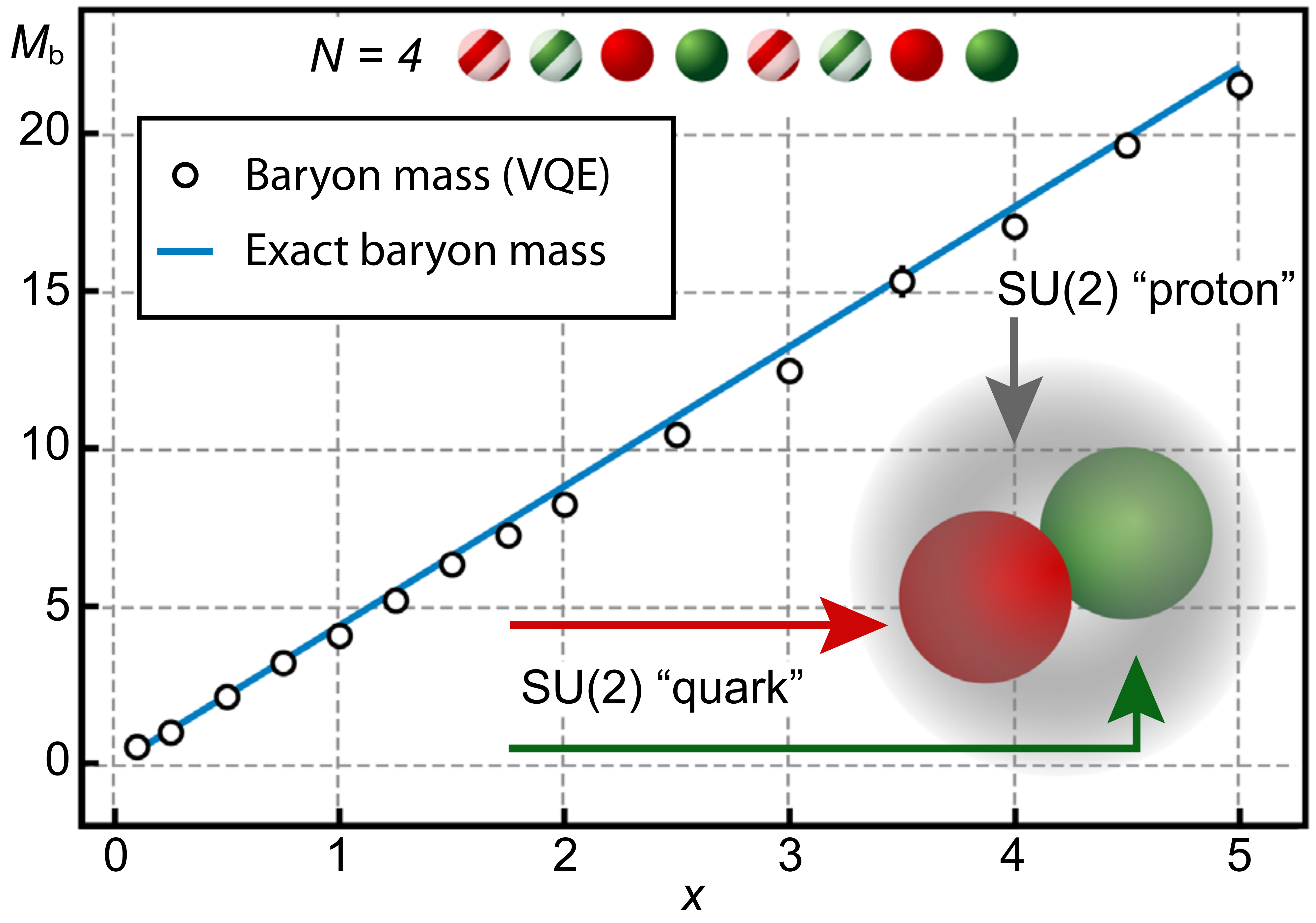
a Spatial lattice and qubit encoding



a VQE circuit to prepare baryon and vacuum states



b VQE preparation of the baryon mass



Recent progress on quantum computing for HEP

✦ Schwinger model for PDF

Chen et al, 2506.16829; Grieninger et al, PRD 2026, Banuls et al, PRD 2026, Kang et al, JHEP 2025

✦ Global fitting for PDF

Salinas et al, PRD 2021

✦ Scattering amplitude

Ikeda et al, 2512.18062; Chawdhry et al, 2507.07194; Davoudi et al, 2505.20408; Li et al, PRD 2024

✦ Heavy ion physics

Qian HP2024 talk

✦ Review articles

Fang et al, SCPMA 2025; Bauer et al, PRX Quantum 2023 …

Thanks for your attention!