Exploring hadronic structure from large facility to small quantum machine

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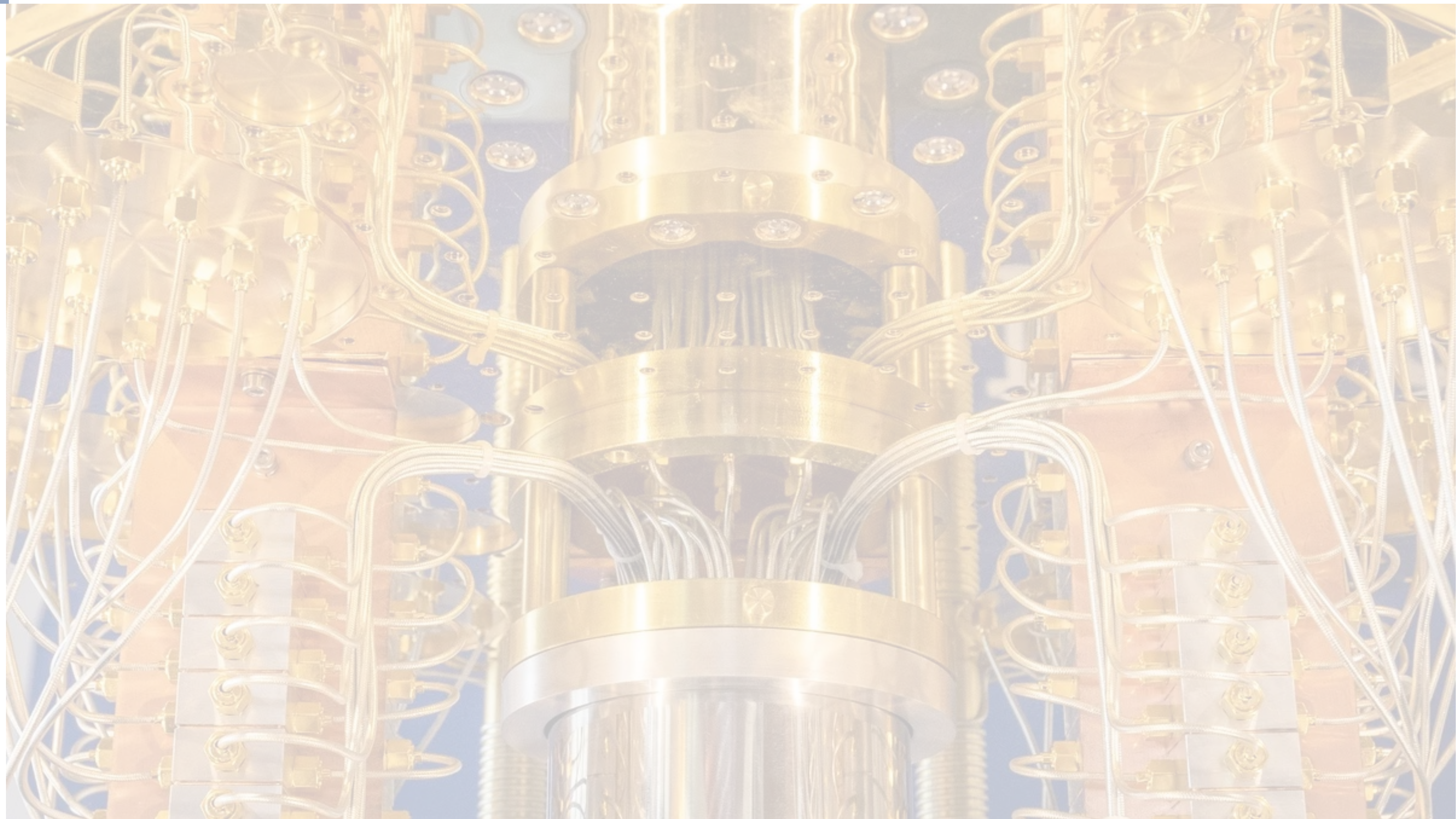
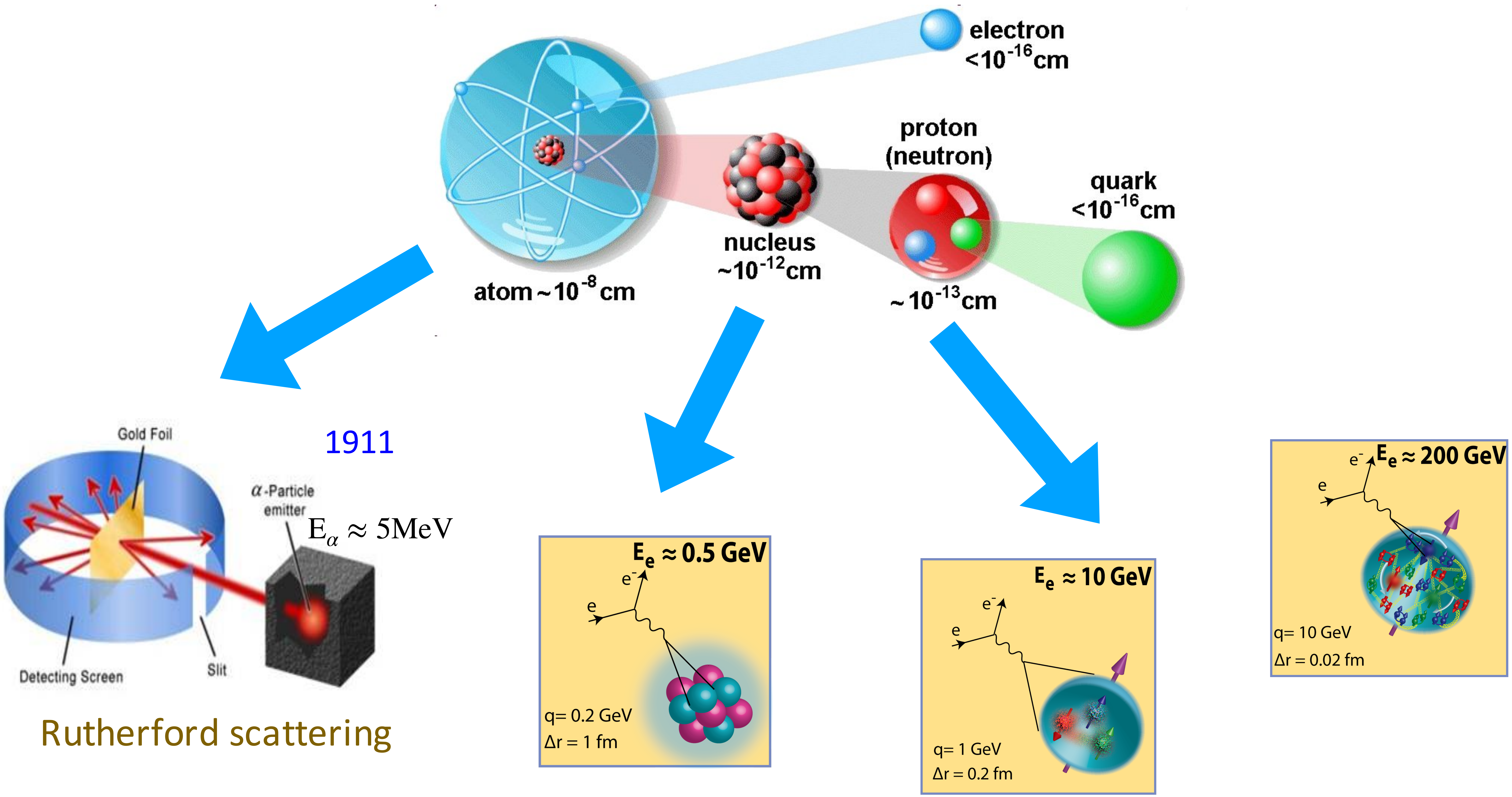


Outline

- ✦ Introduction
- ✦ Nucleon structure @ EicC
- ✦ Nucleon structure @ quantum computer

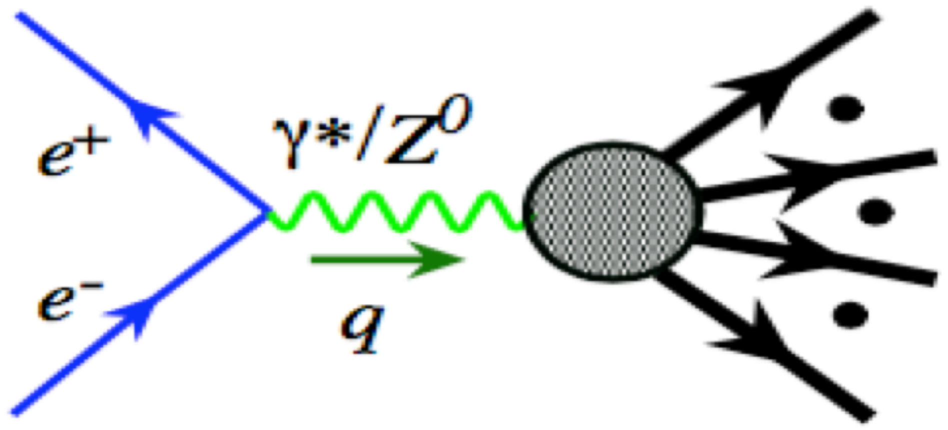
Probing nuclear structure at different energy scales



scattering: a fundamental tool to explore the nuclear structure!

Modern facilities to probe the nucleon partonic structure

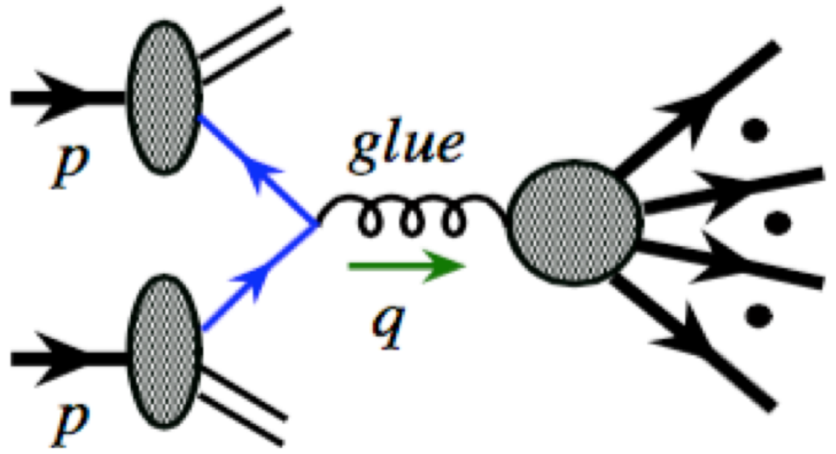
Lepton-lepton colliders



BEPC, SuperKEKB

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

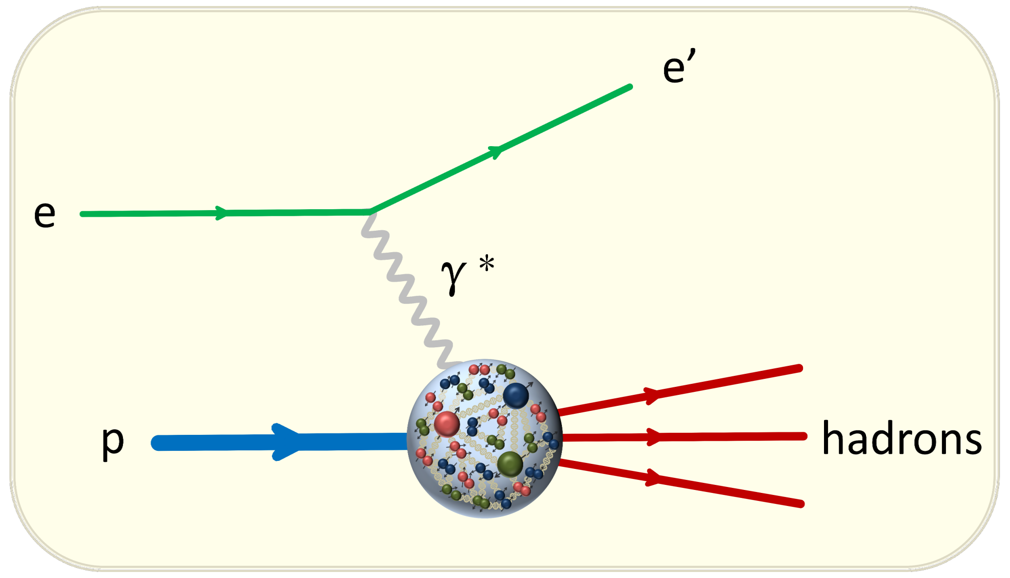
Hadron-hadron colliders



RHIC, LHC

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

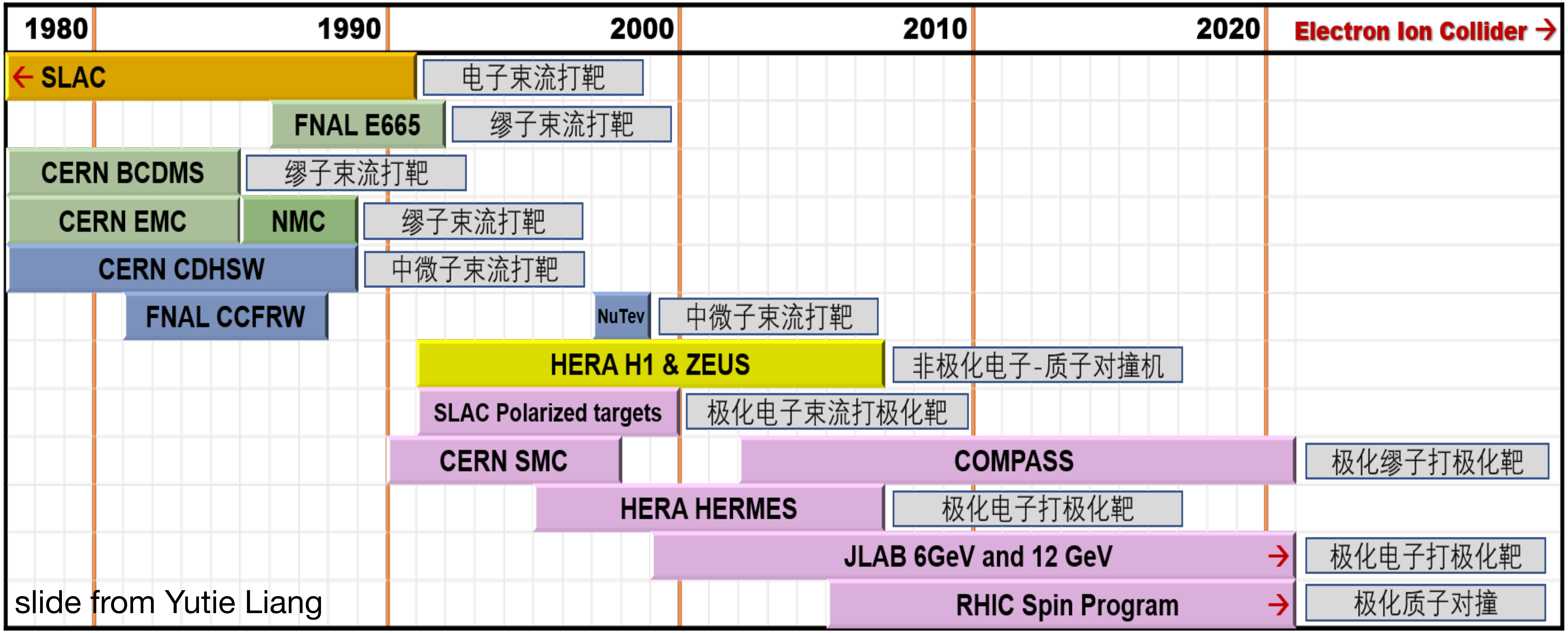
lepton-hadron colliders



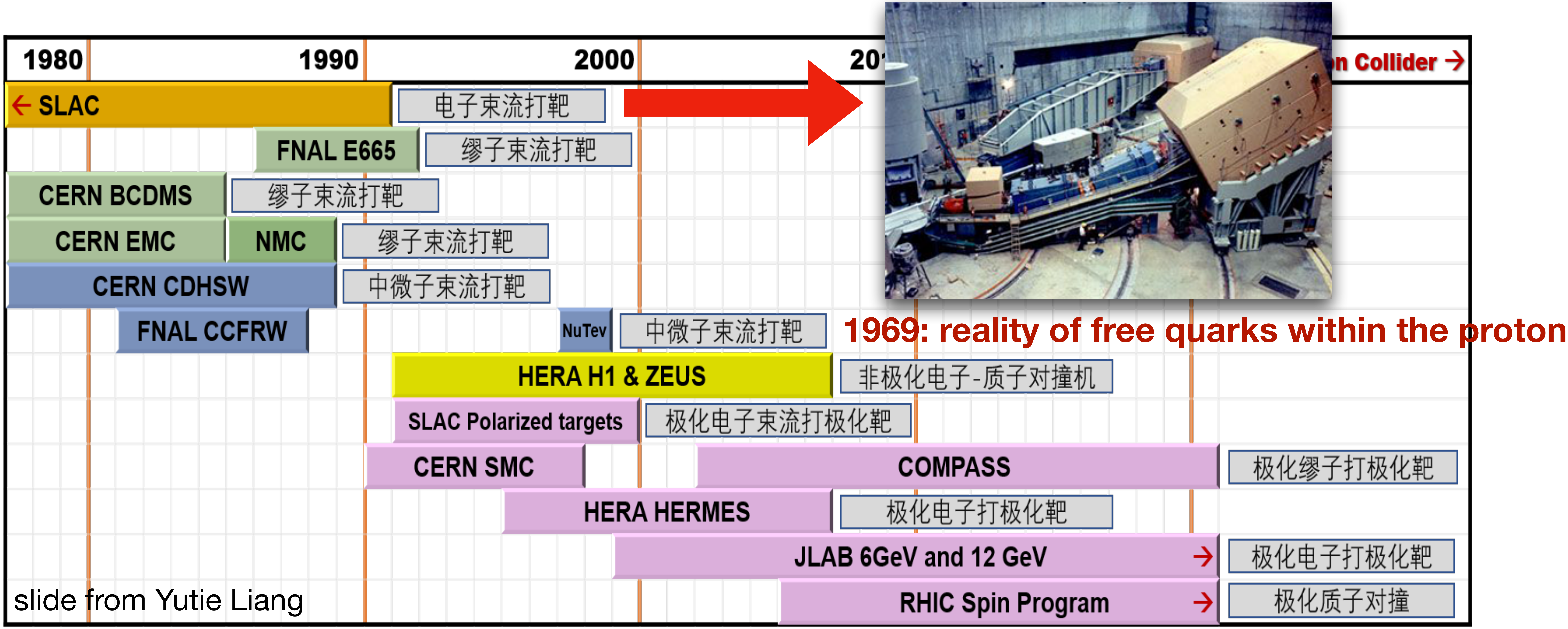
HERA, JLab

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

The modern experiments for nucleon structure



The modern experiments for nucleon structure



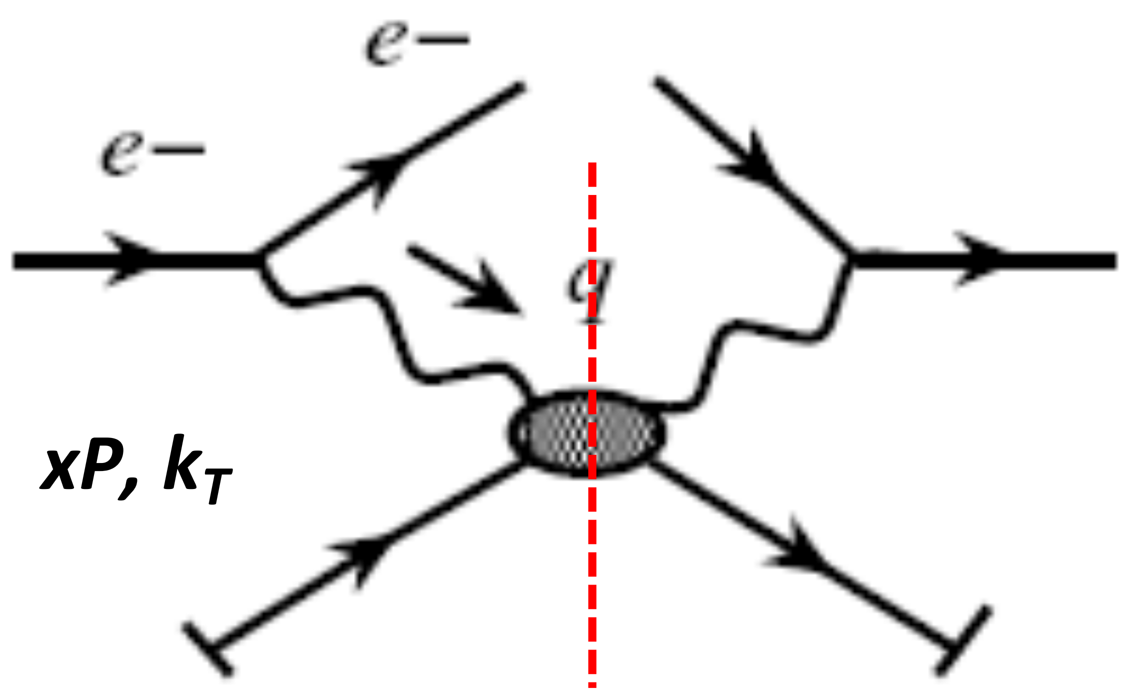
Electron Ion Colliders -> the next generation facility specifically for nucleon structure!

How to probe the nucleon partonic structure?

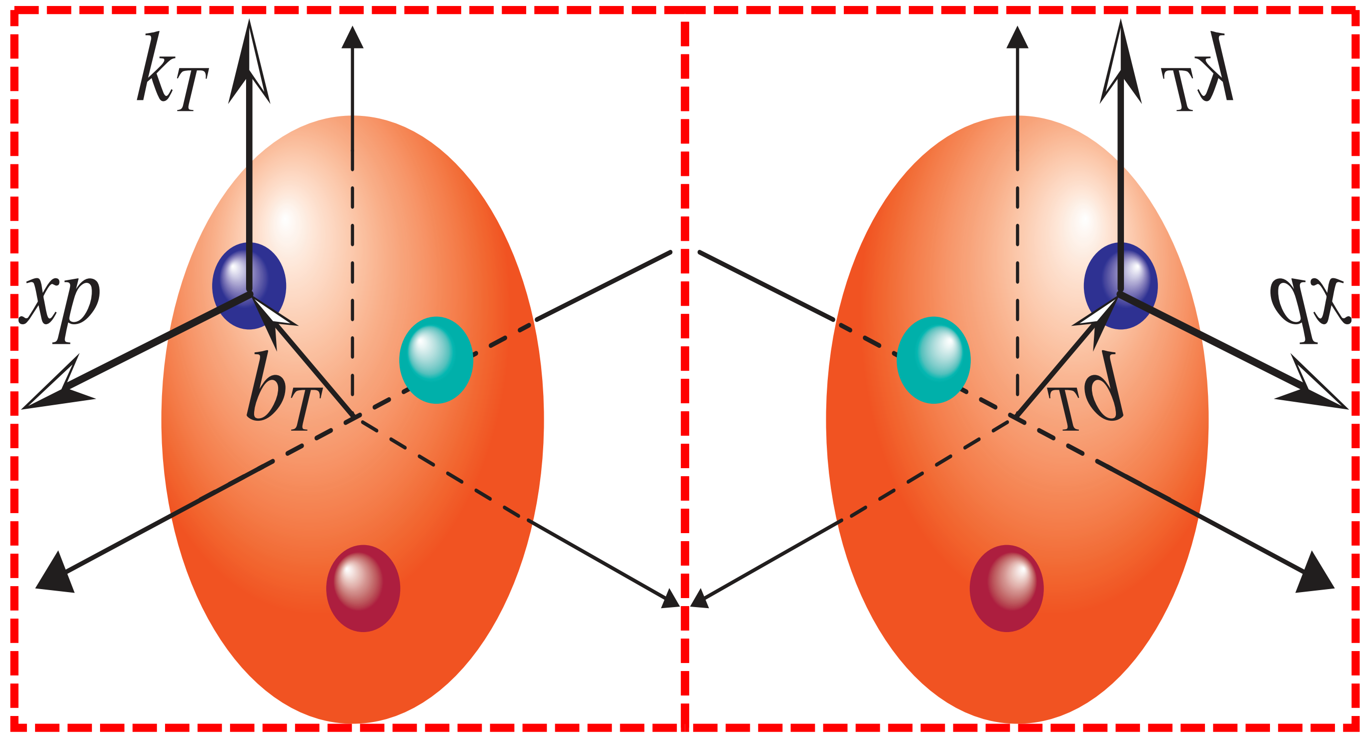
✦ Indispensable joint efforts from experiments and QCD theory

QCD factorization theorem

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



$\otimes$



Experimental measurements

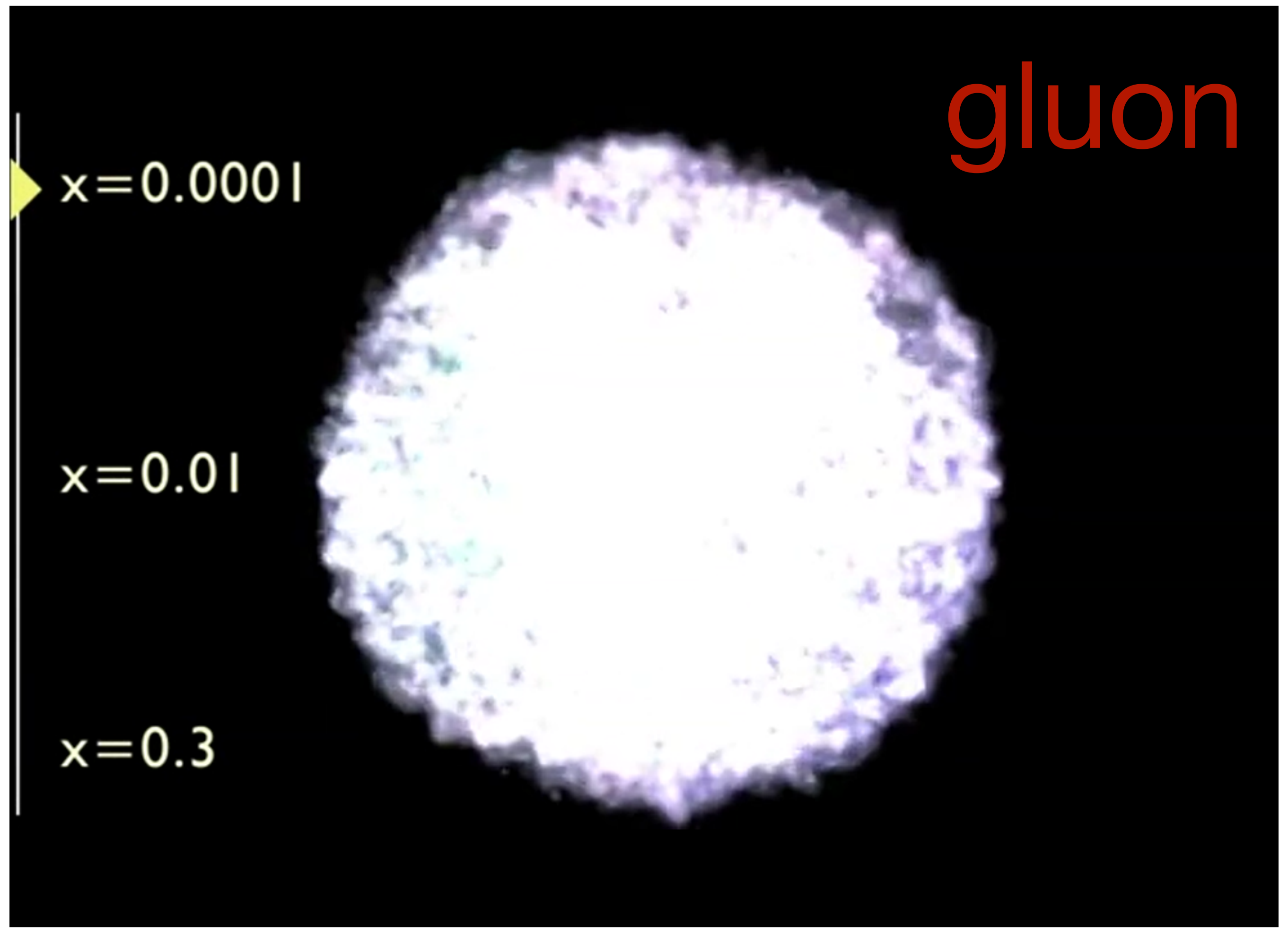
Hard part controlled by pQCD theory

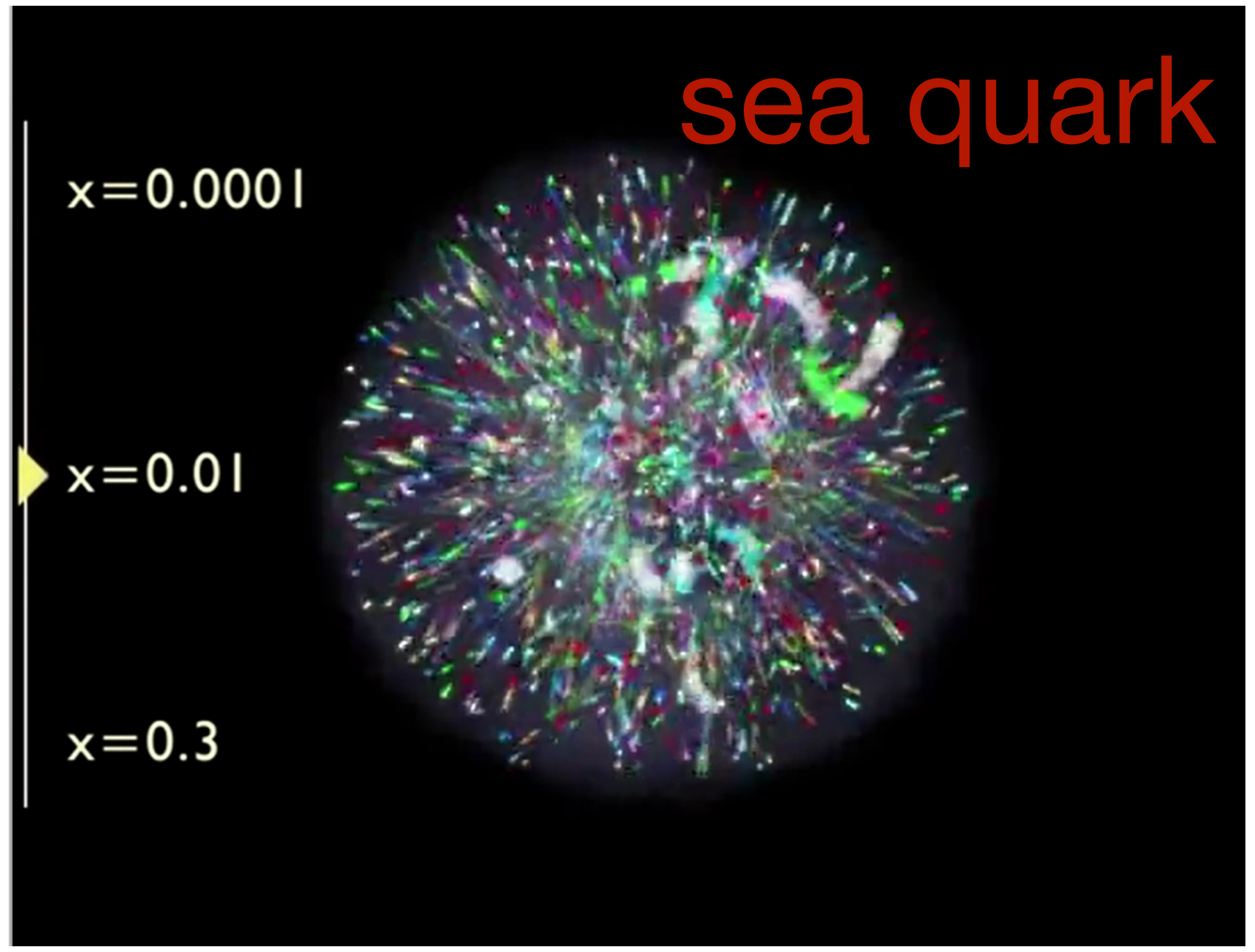
Nucleon partonic structure

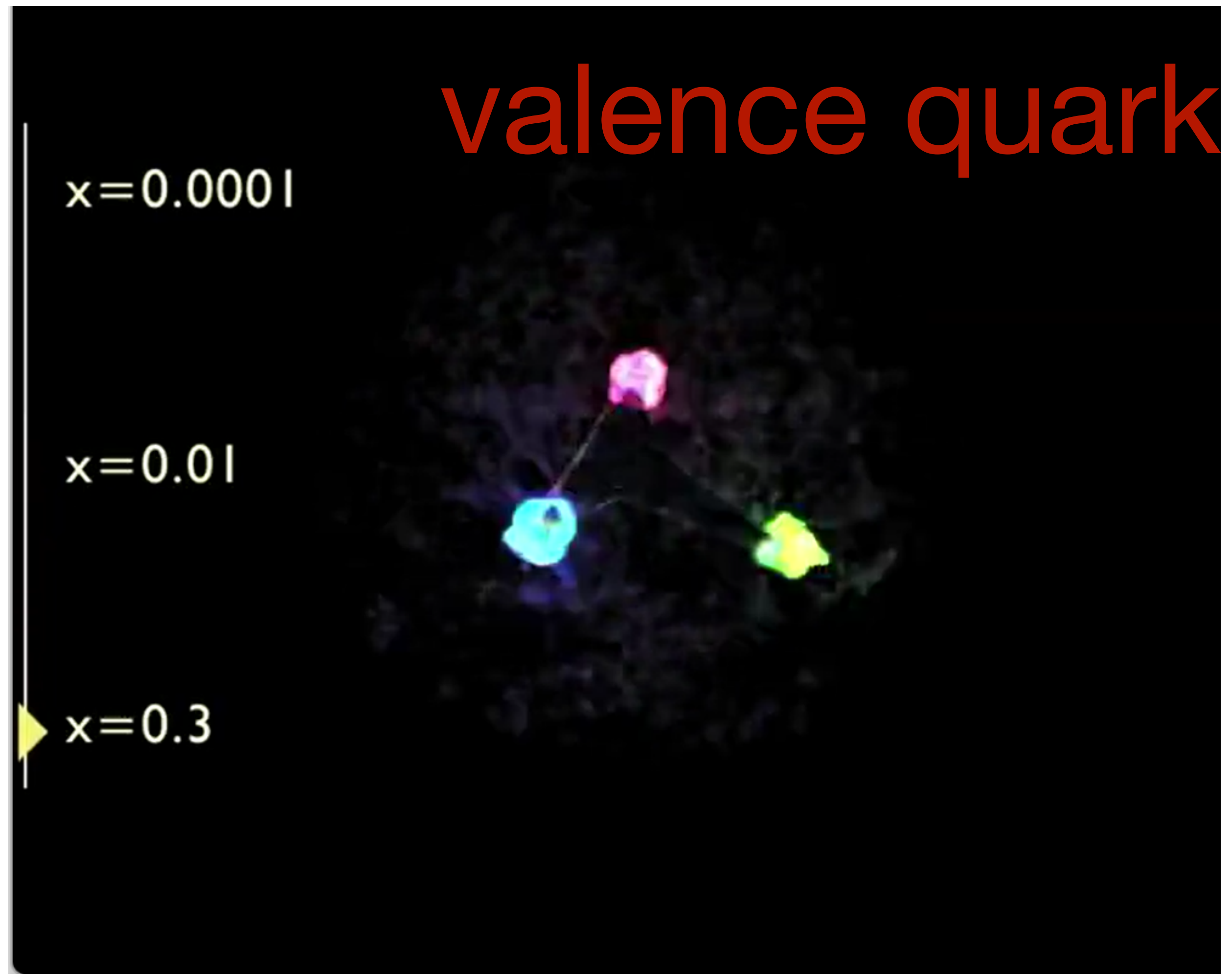
The benefits from hadronic scattering

✦ Extract proton PDFs（1D）from world data

EIC user group

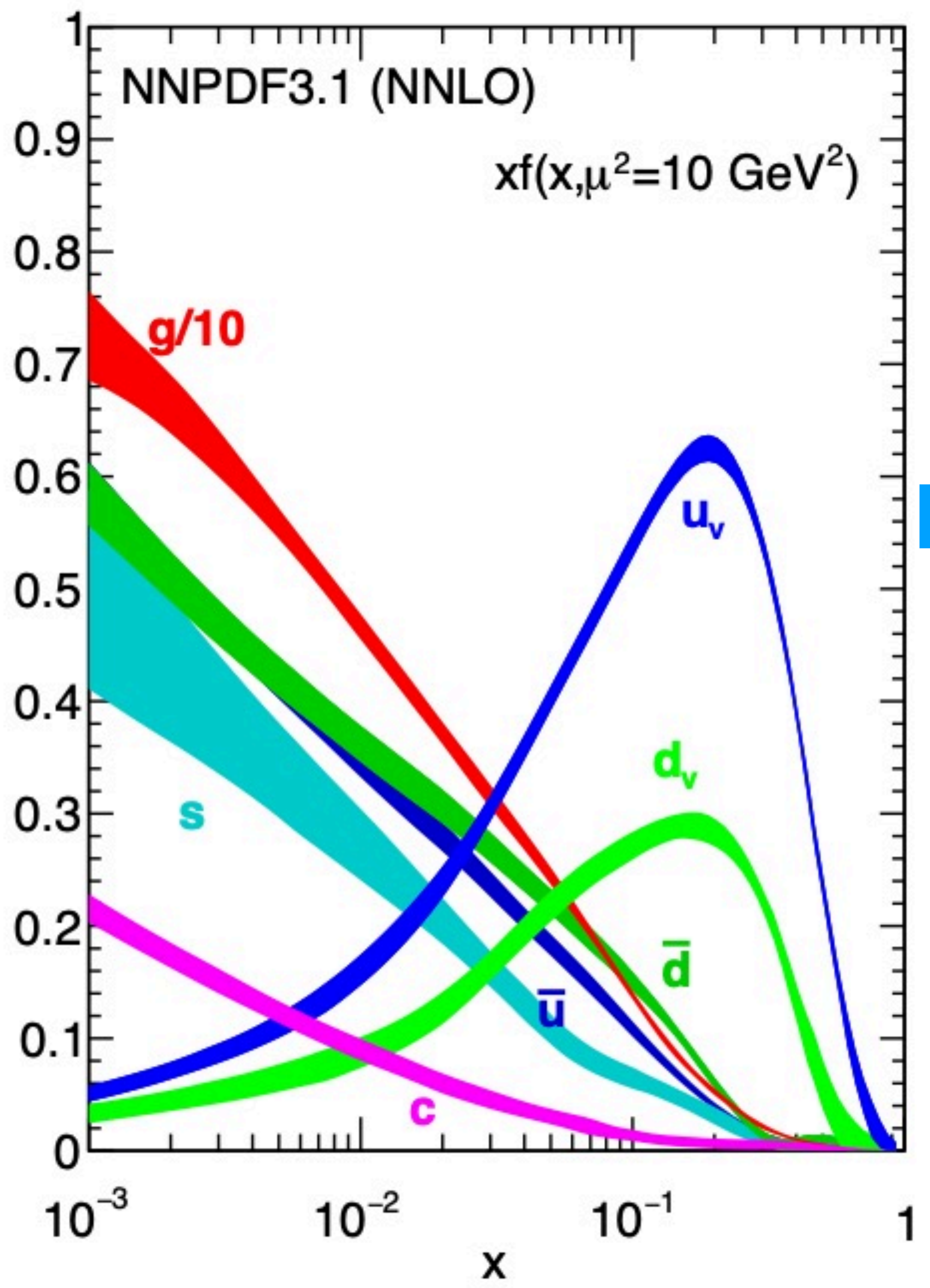


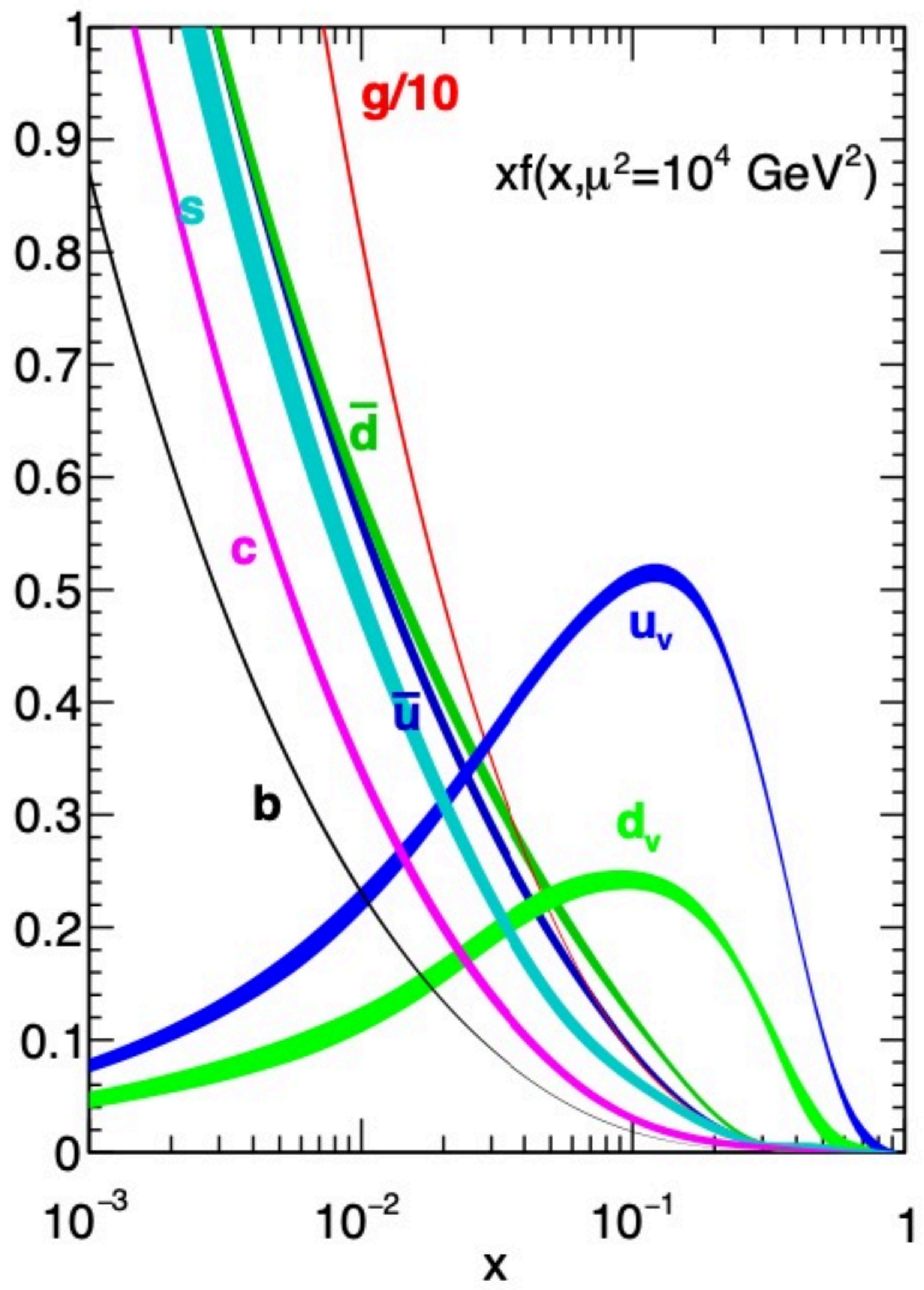


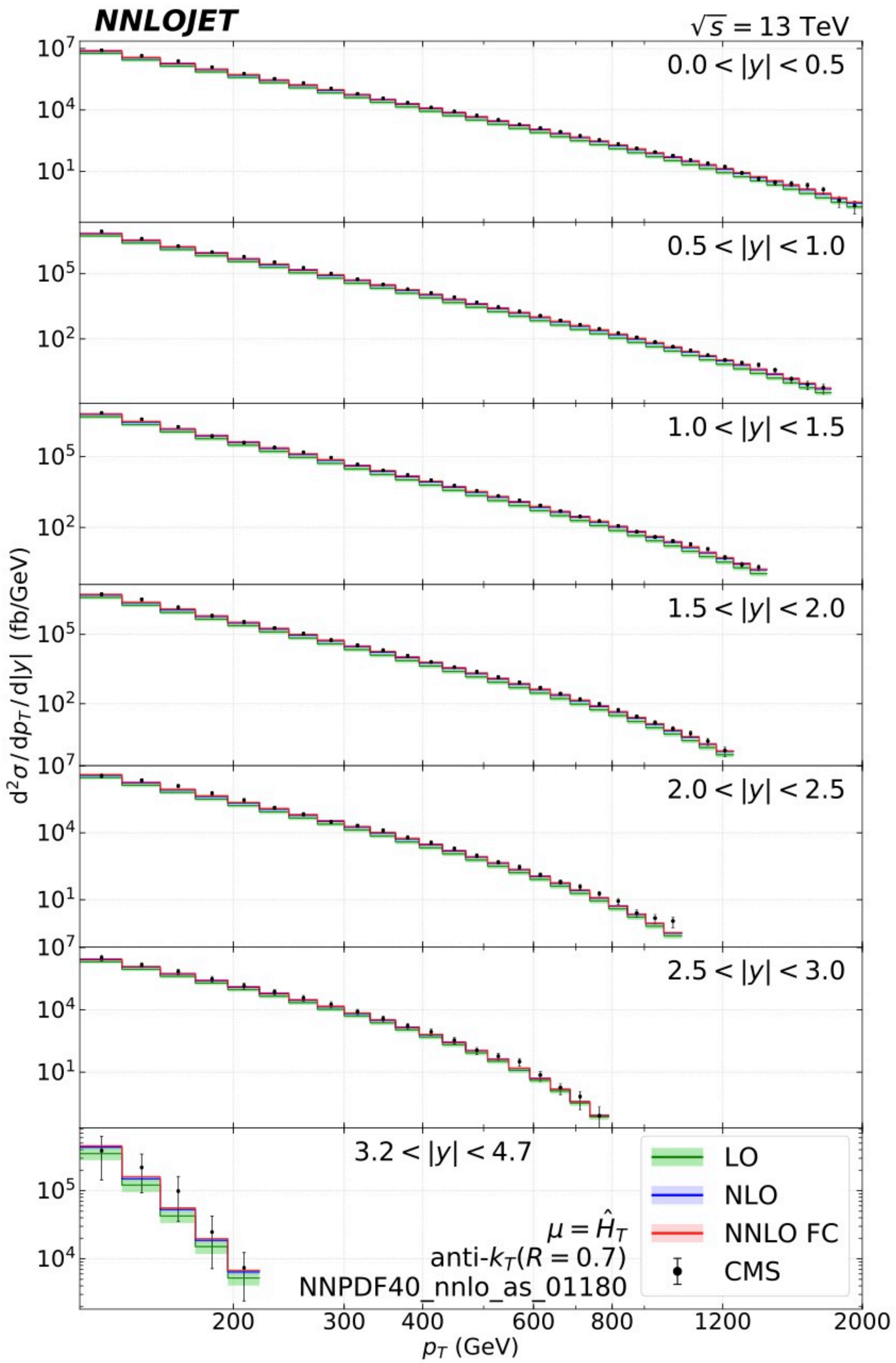


The benefits from hadronic scattering

✦ QCD evolution of nucleon 1D structure





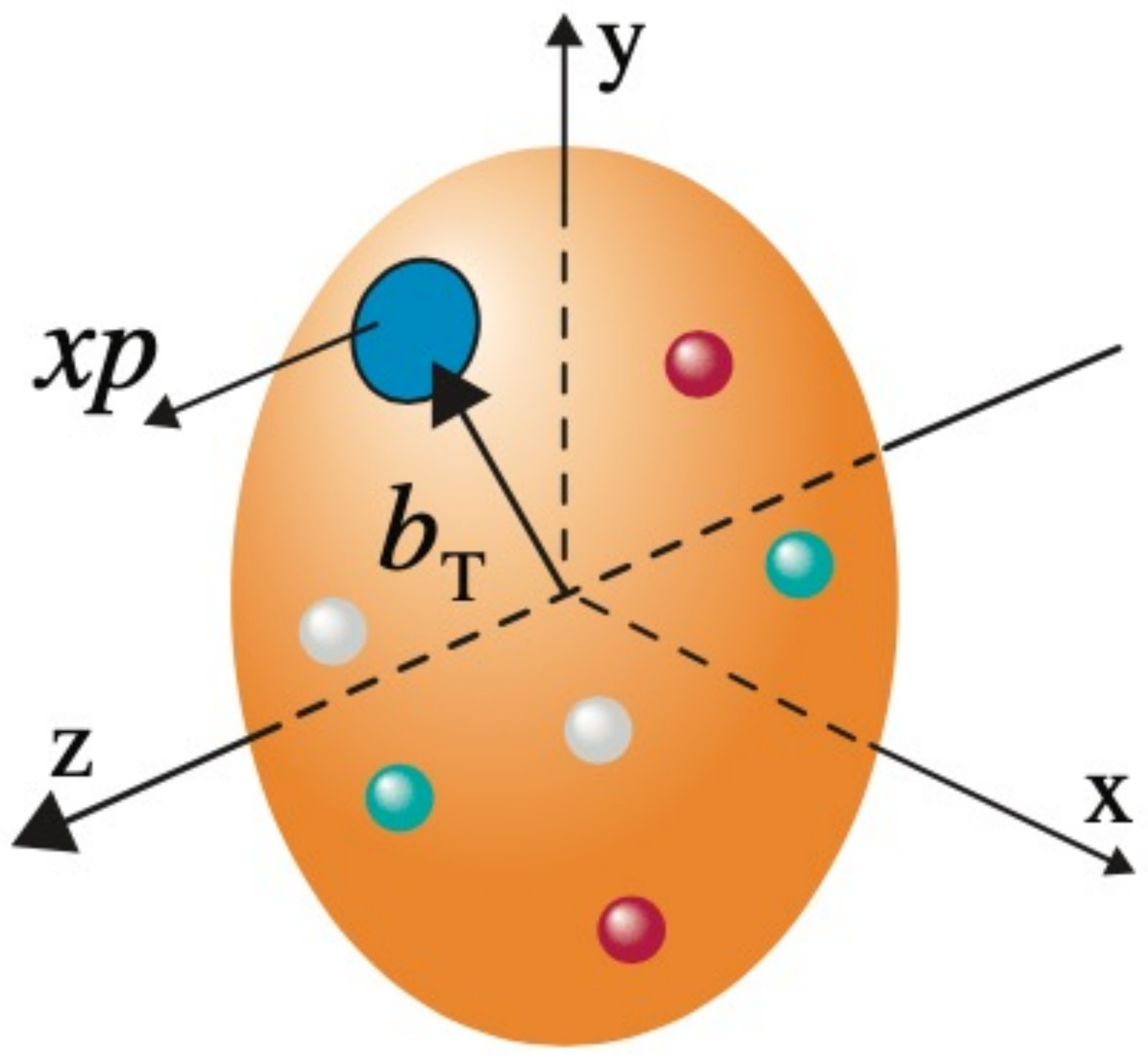


There is no still picture for partons inside nucleon!

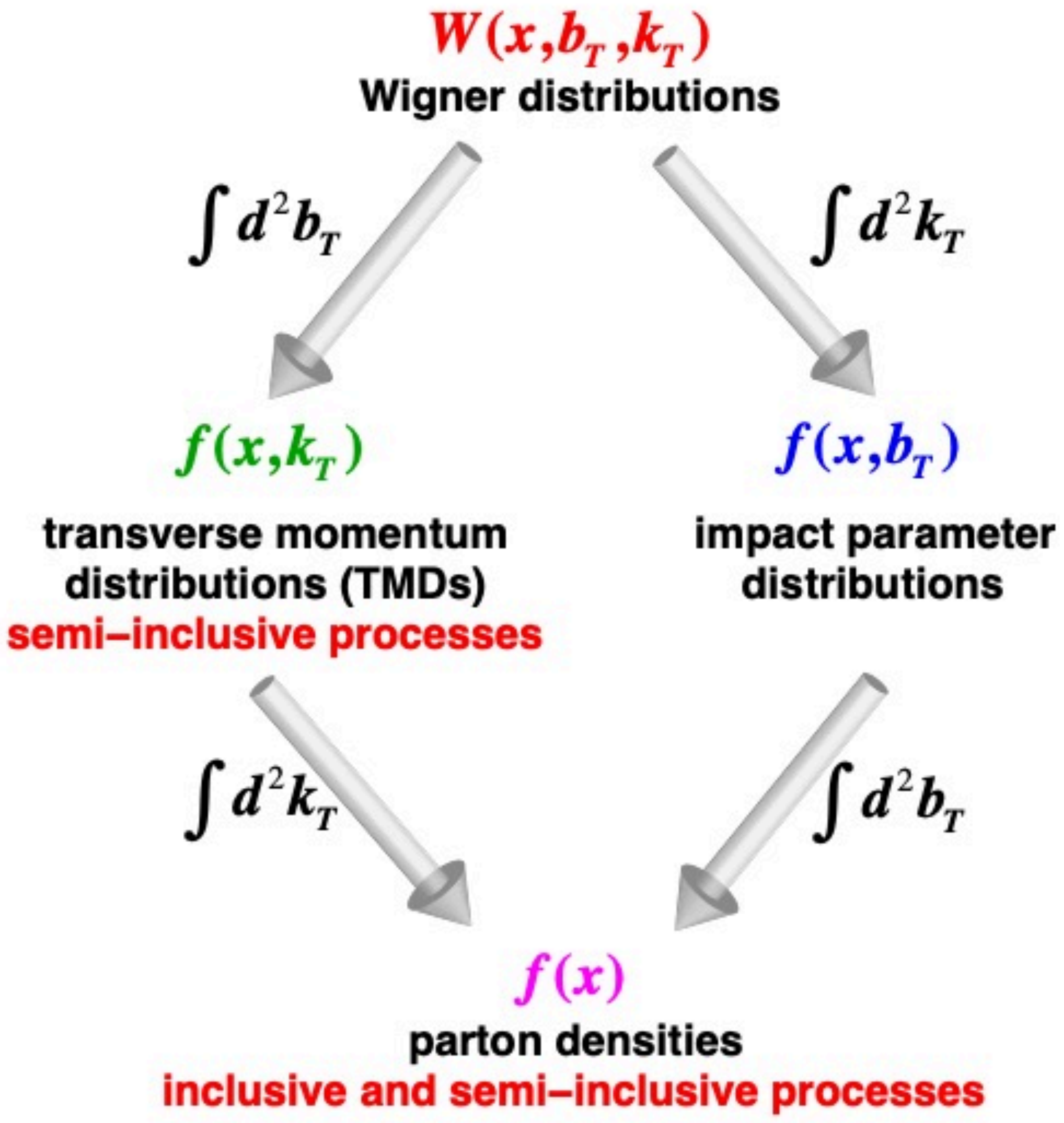
X. Chen et al, JHEP, 2022

Nucleon partonic structure - momentum distribution

- ✦ Multi-dimensional view of nucleon partonic structure



Wigner distribution
5D view

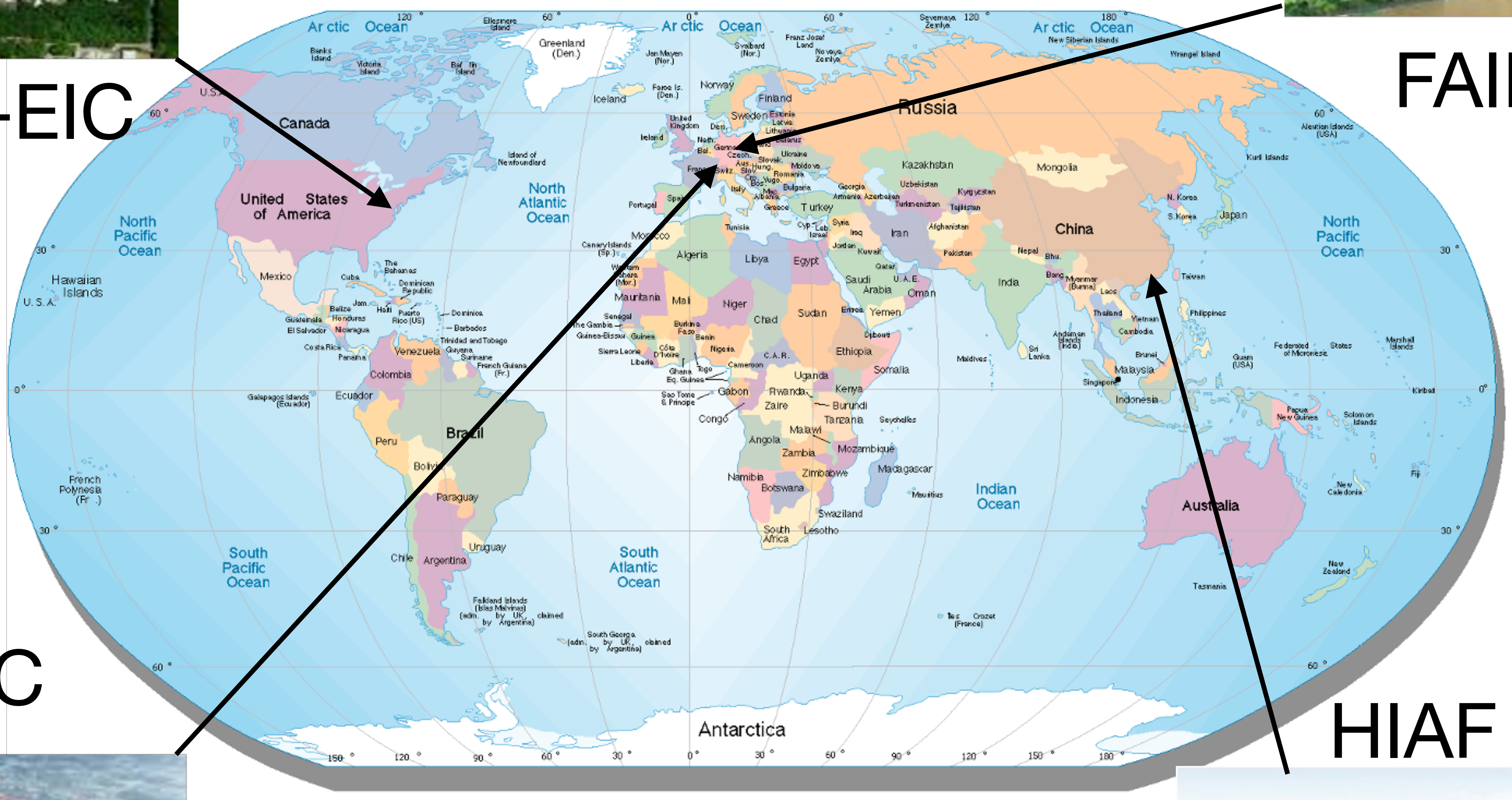


Many more remains to be answered: proton mass, proton spin, 3D structure …

Proposed Electron-ion colliders

RHIC ➔ US-EIC

FAIR ➔ ENC



LHC ➔ LHeC

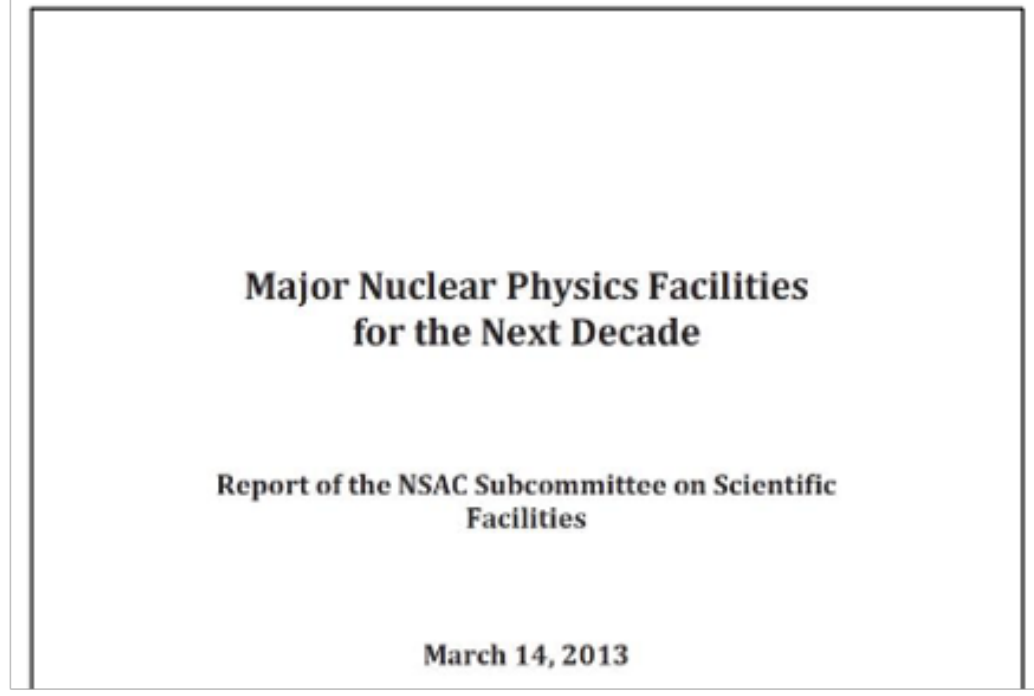
HIAF ➔ **EicC**

slide from Jinlong Zhang

Time evolution of US EIC

2002 Long Range Plan in the US

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



Major Nuclear Physics Facilities
for the Next Decade

Report of the NSAC Subcommittee on Scientific Facilities

March 14, 2013

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

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

2020:CD-0
Approved project!

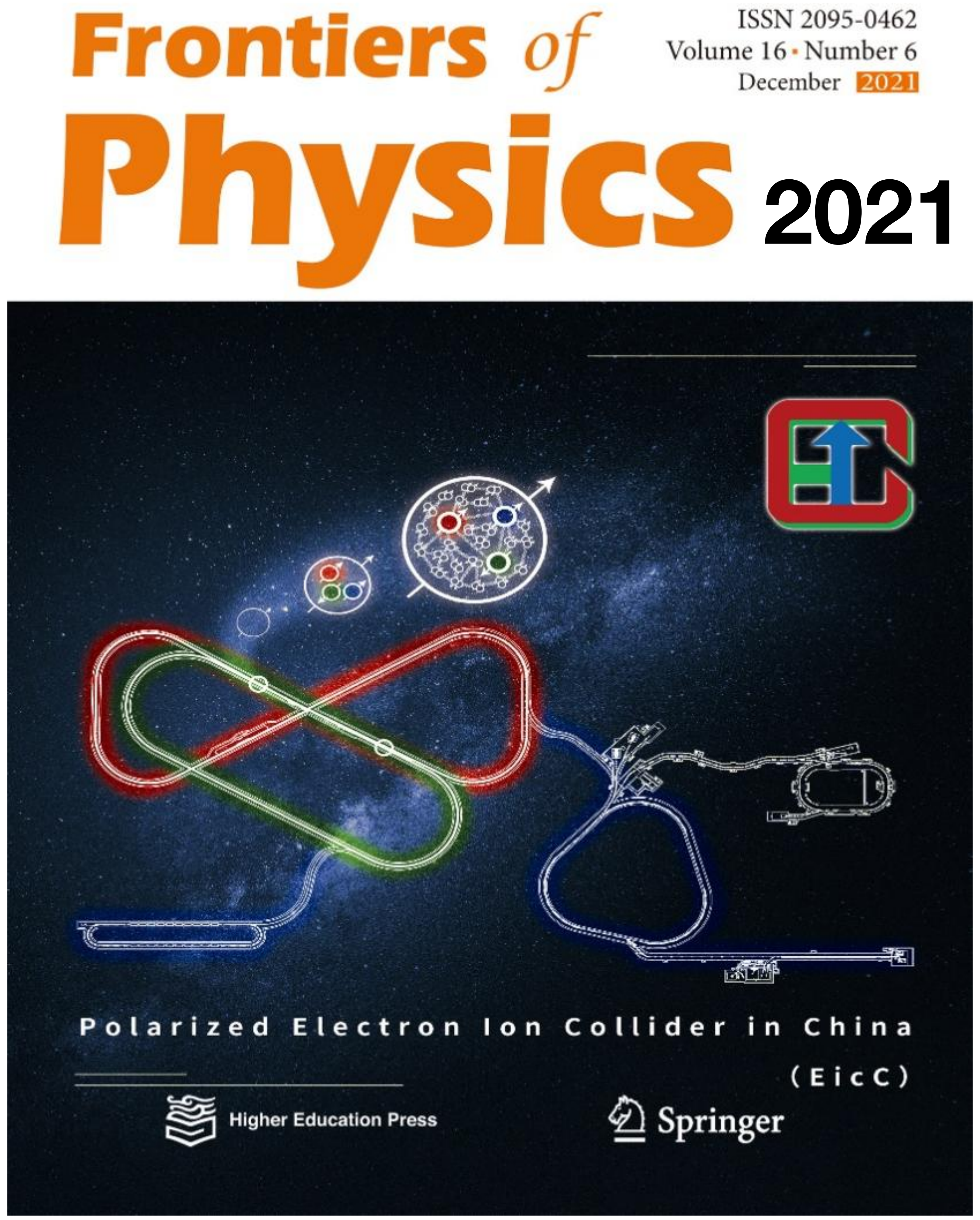
2021:CD-1

~2030:operation

Time evolution of EicC

2020

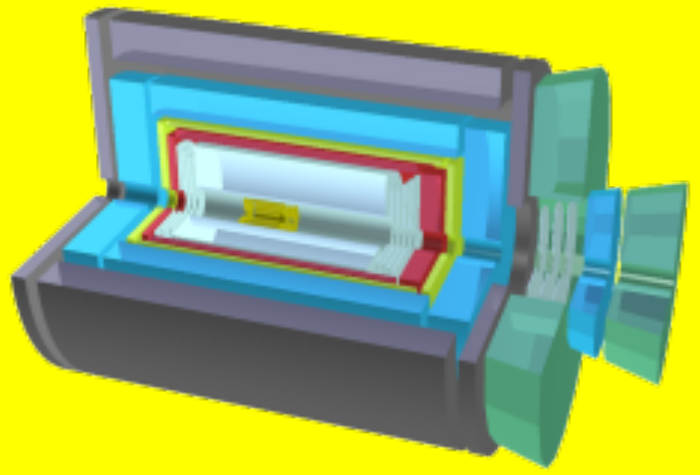
2021



中国电子 – 离子对撞机 (EicC)

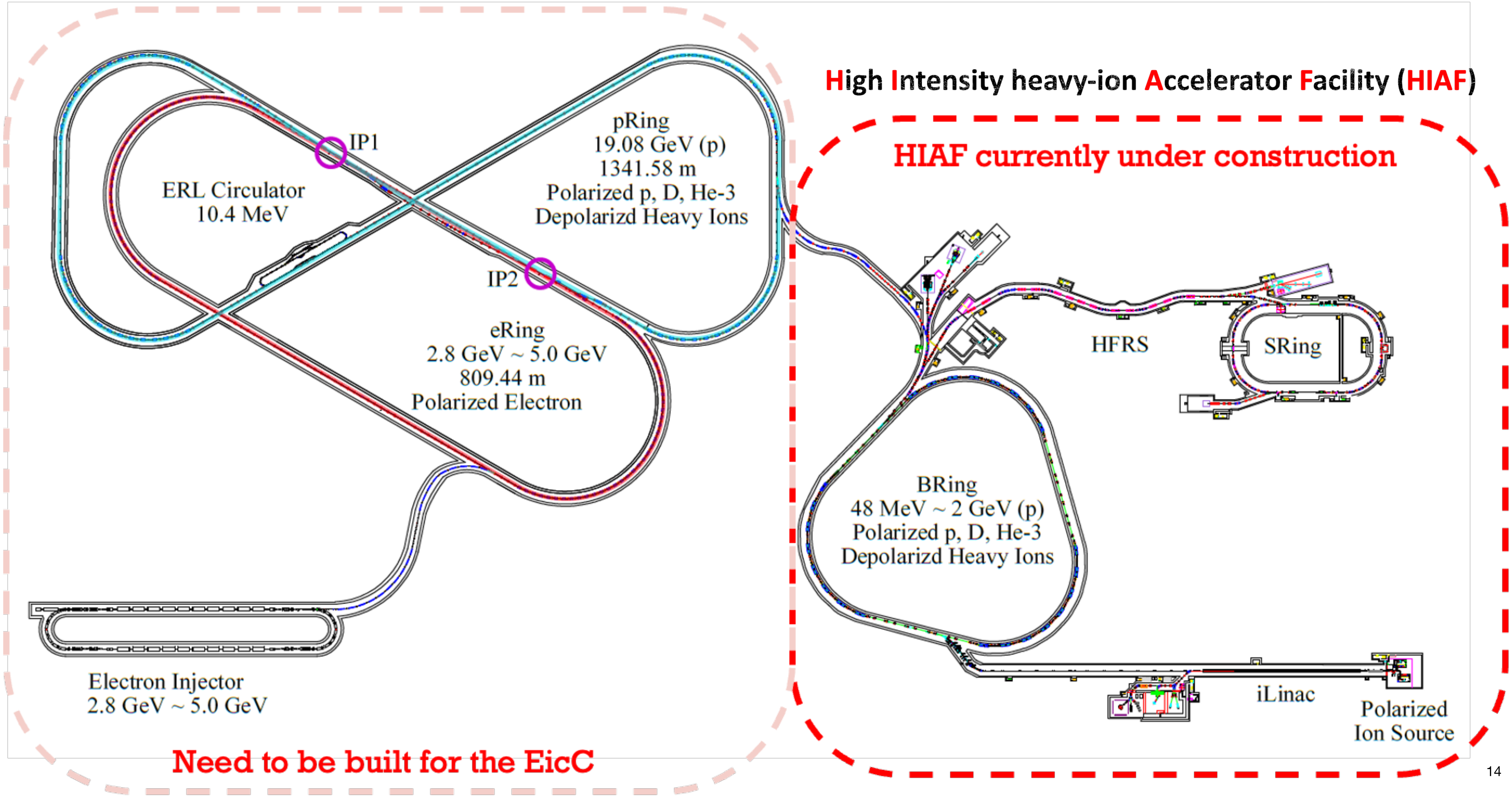
2012: 领域内开始讨论
2020.2, 2021.6:白皮书 (中文, 英文)
2021-2023: 概念设计研究

参与单位： ~ 45

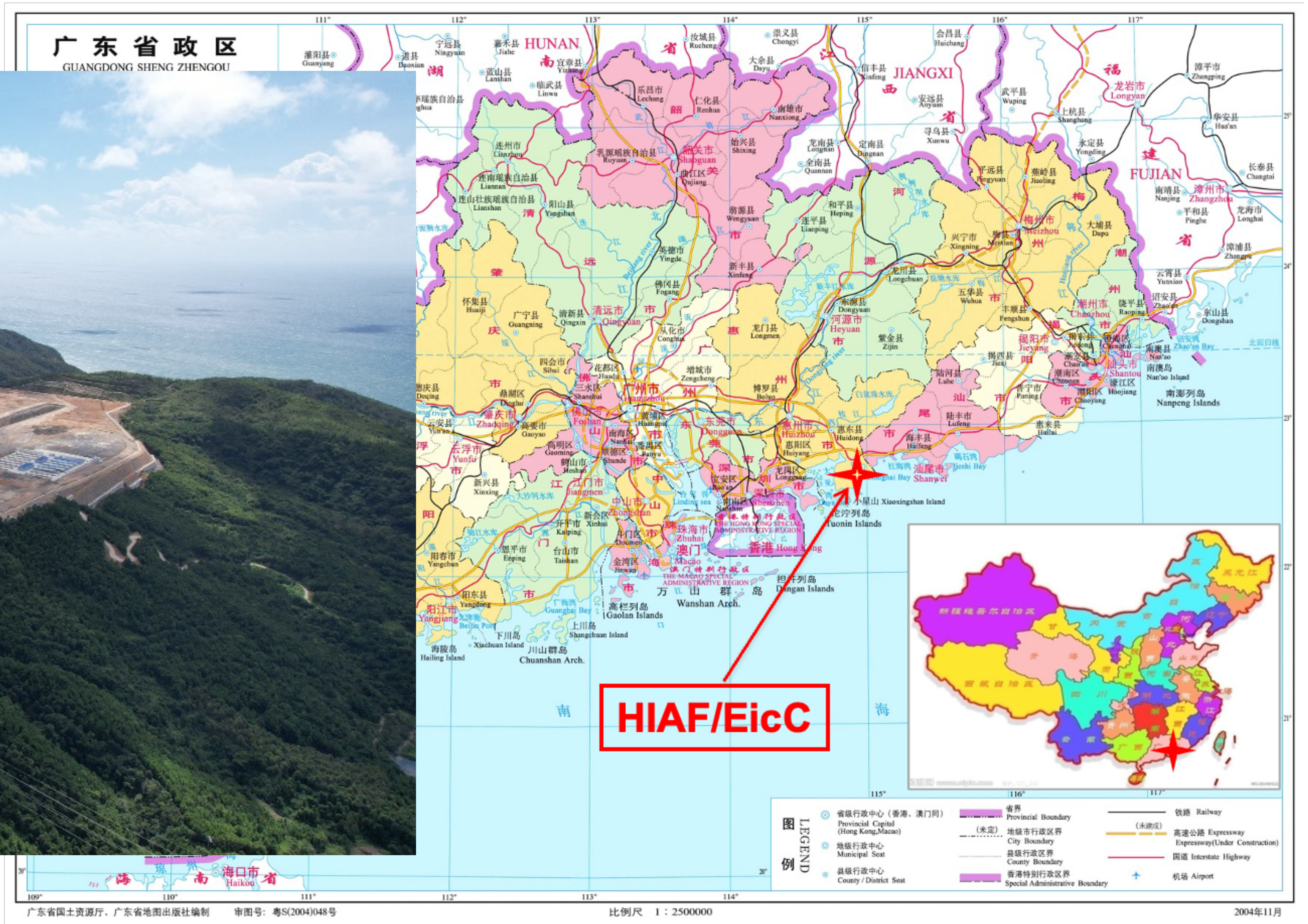


Electron **I**on **C**ollider in **C**hina, EicC

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

Nucleon partonic structure - spin configuration

✦ Naive parton model

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

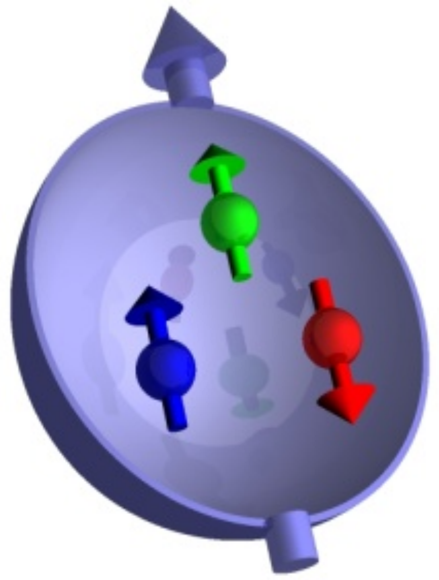
proton spin 1/2 is consistent with naive parton model, but contradict with experiments.

✦ Proton spin decomposition

Jaffe, Manohar; Ji

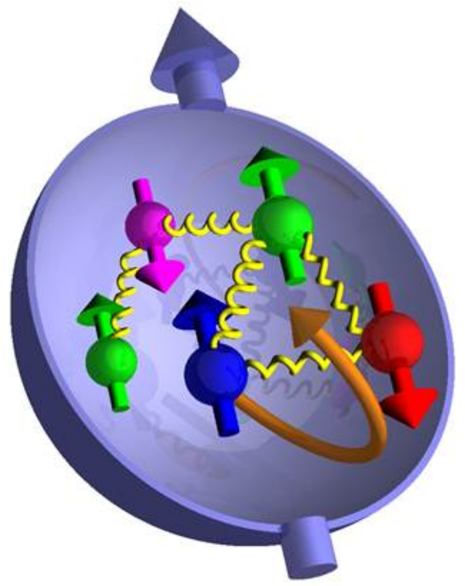
$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}|J^z_{QCD}|P,\frac{1}{2}\right\rangle = \frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2) + \int_0^1 dx\Delta G(x,Q^2) + \int_0^1 dx(\sum_q L_q^z + L_g^z)$$

total quark spin



gluon spin

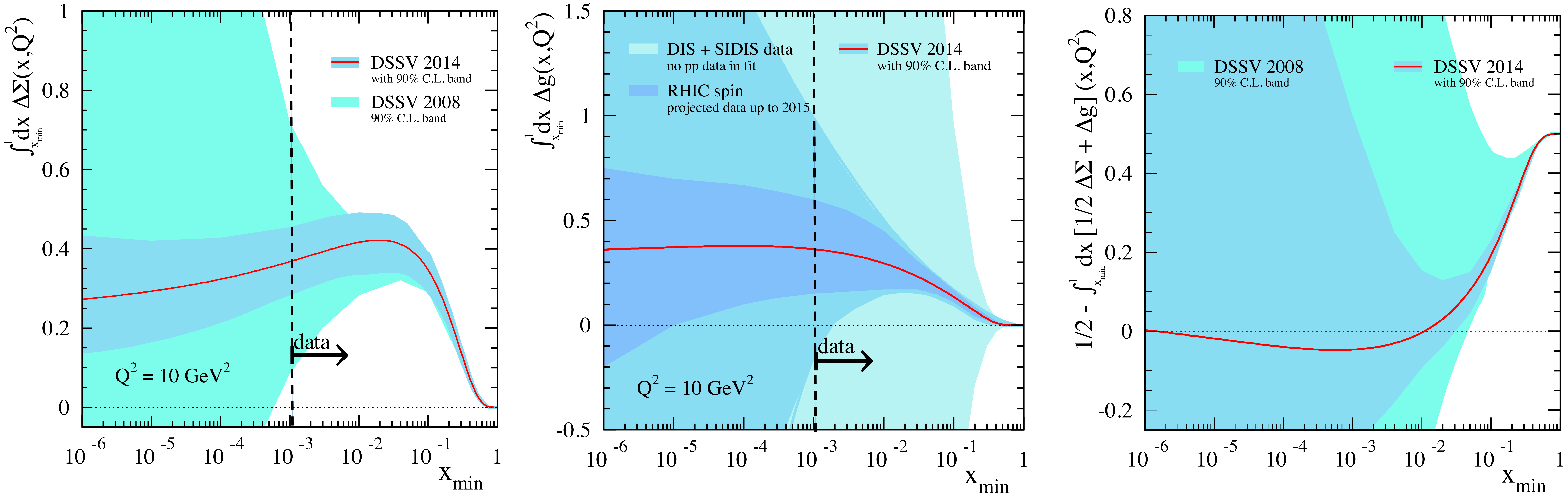
angular momentum



We don’t know yet how the spin of the 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%

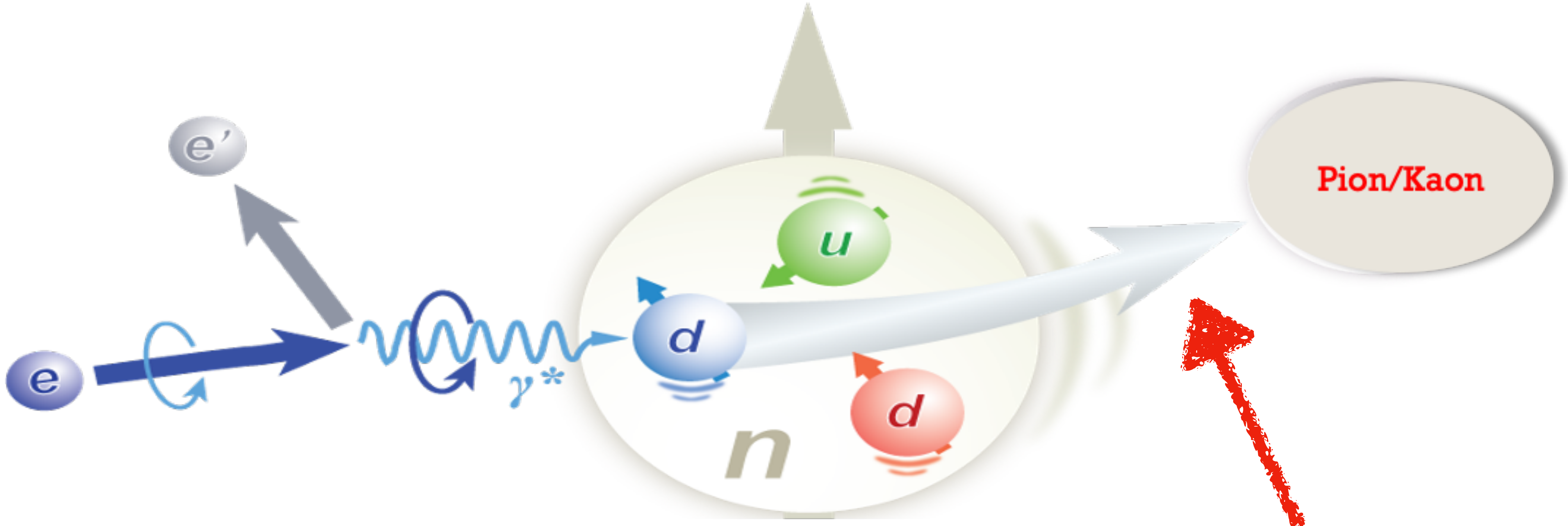
Gluons ~ 30%

Orbital angular momentum ?

It is more than the number 1/2 → the interplay between the intrinsic properties and interactions of quarks and gluons

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

✦ Polarized structure function measurement g_1



hadron fragmentation

- Leading order cross section

Polarized PDFs

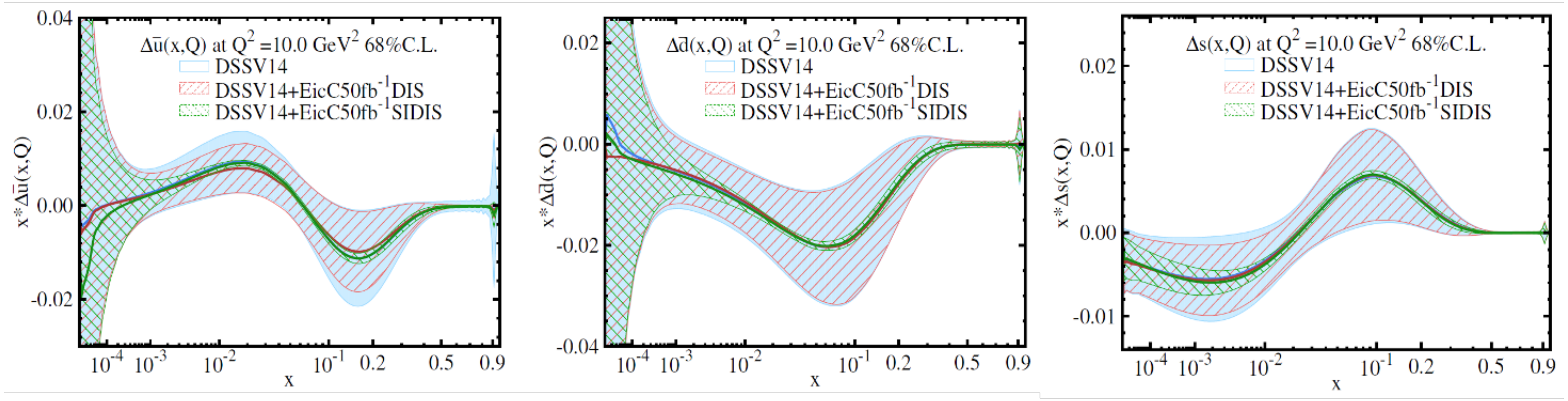
$$g_1^h(x,Q^2,z) = \frac{1}{2}\sum_q e_q^2\left[\Delta q(x,Q^2)D_q^h(z,Q^2) + \Delta\bar{q}(x,Q^2)D_{\bar{q}}^h(z,Q^2)\right]$$

Extract longitudinal polarized PDFs (helicity distribution)

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

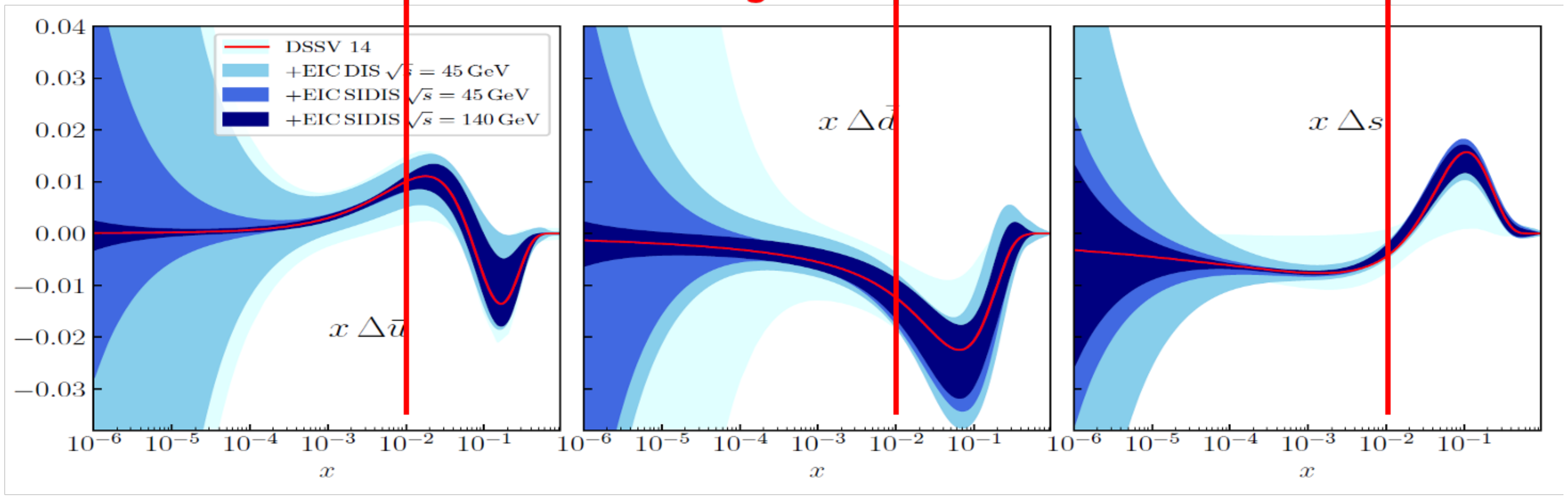
✦ SIDIS for flavor decomposition

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



EicC white paper

EicC coverage

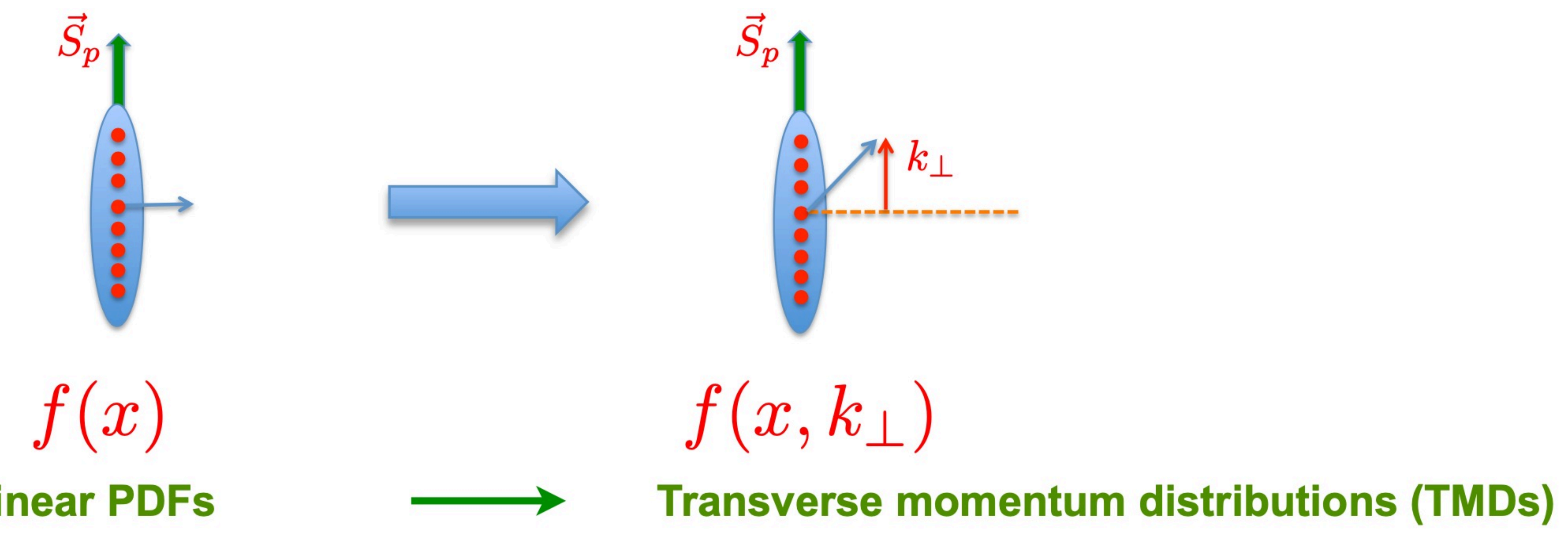


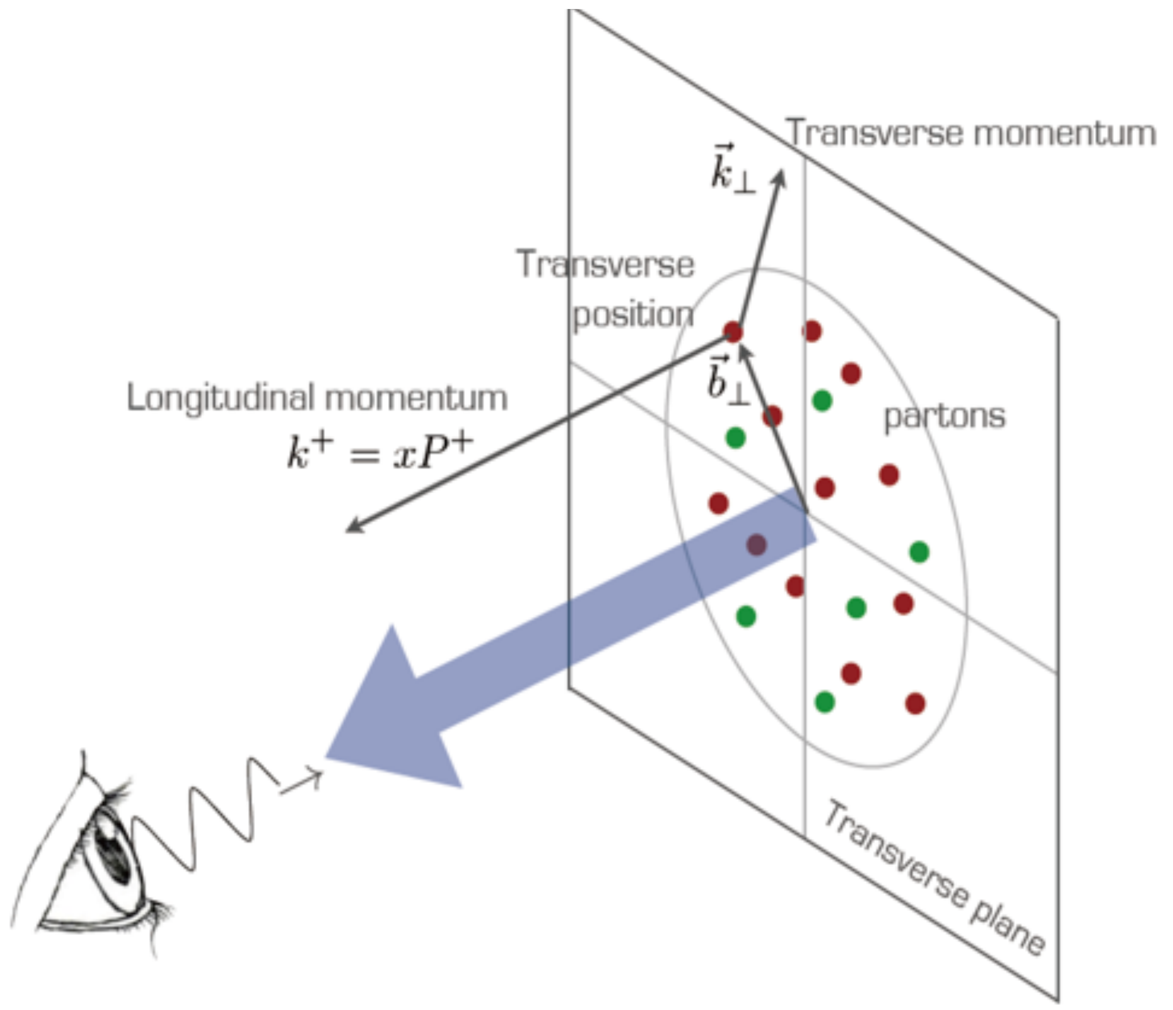
EIC Yellow Report

Nucleon partonic structure - 3D imaging

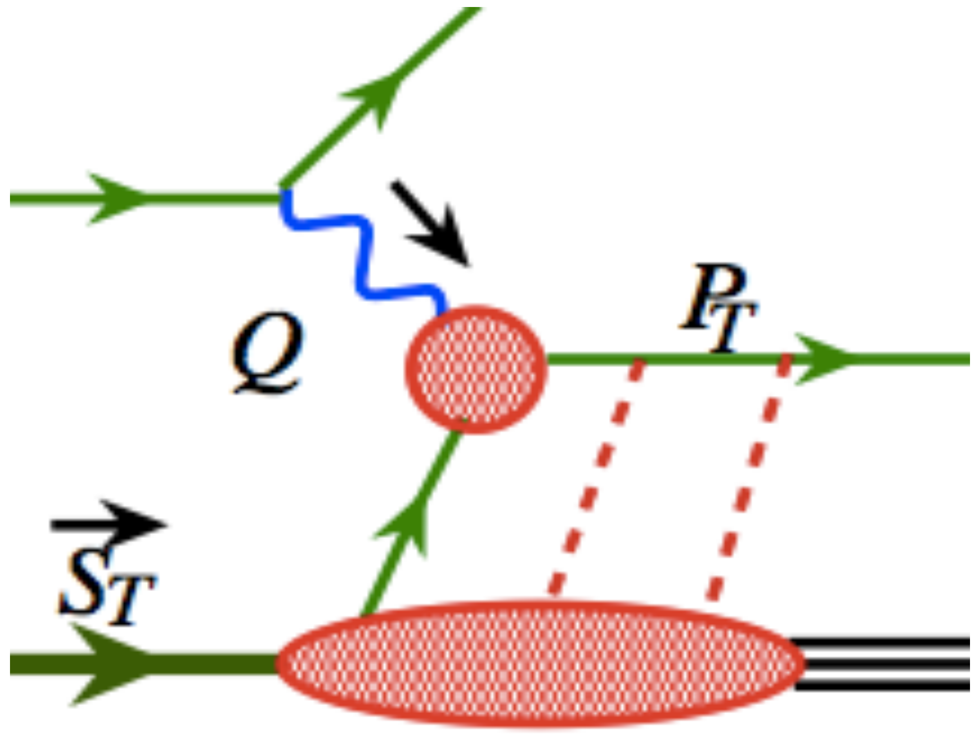
Nucleon partonic structure - 3D imaging

✦ Transverse momentum dependent PDFs (TMDs)





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



SIDIS: Q>>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

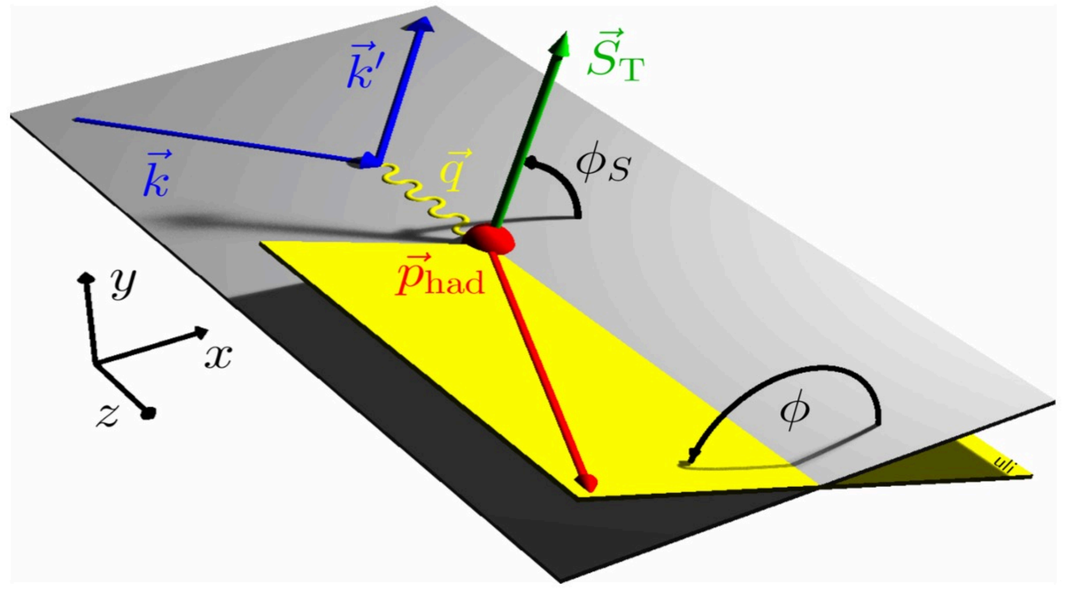
Nucleon Spin *Quark Spin* **Survive the k_T integration, yield 1D pdfs**

Nucleon partonic structure - single transverse spin asymmetry

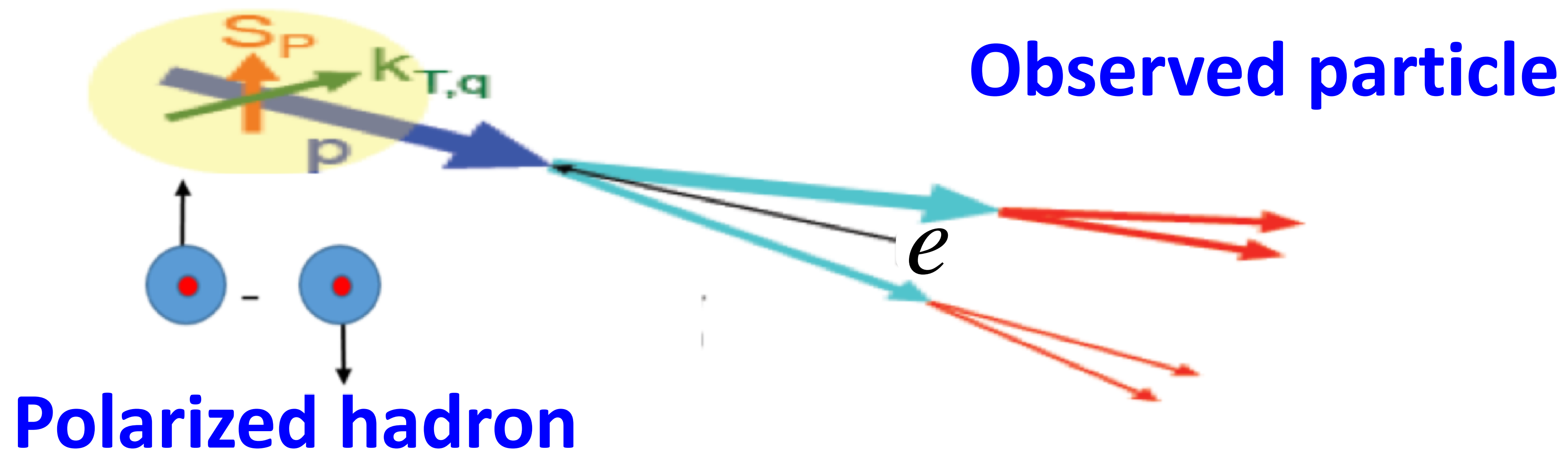
✦ Transverse polarized proton + unpolarized electron

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

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



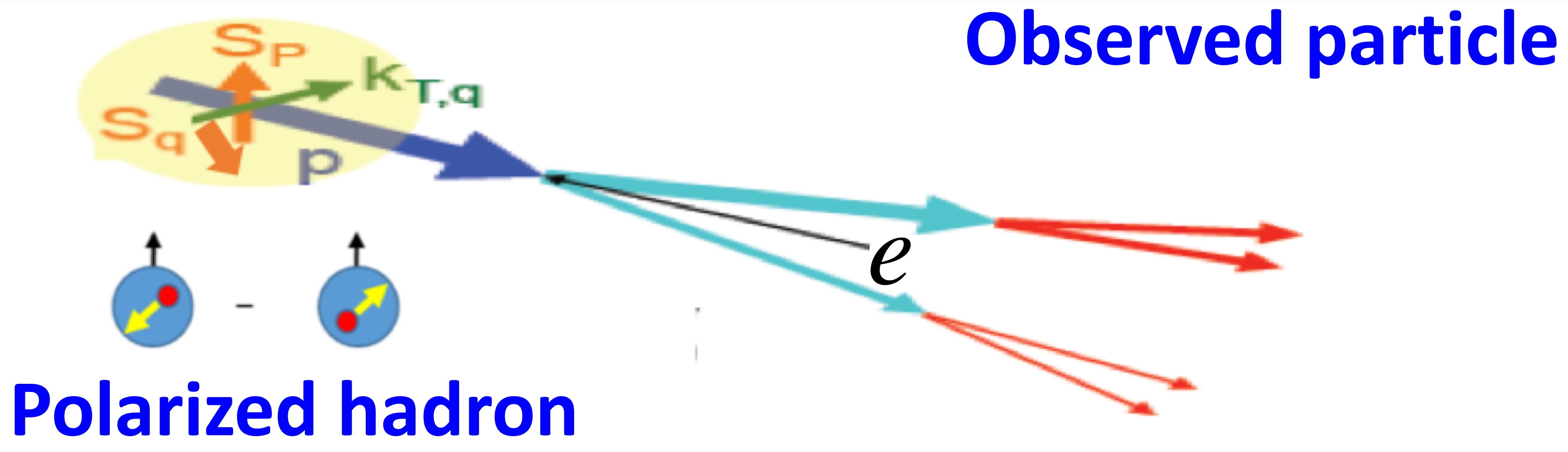
✦ Quantum correlation between proton spin and parton motion



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

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

✦ Quantum correlation between proton spin and parton spin



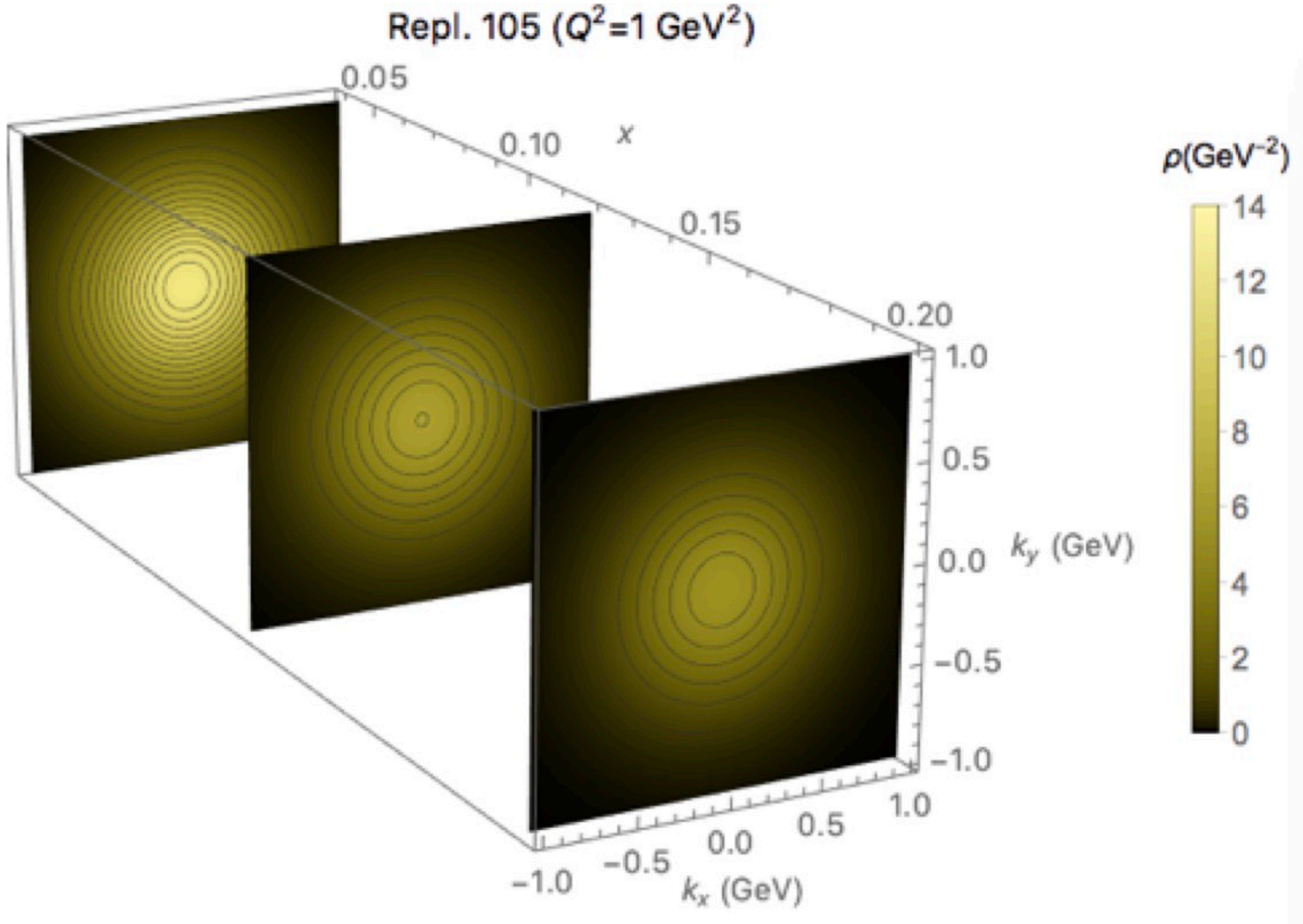
Pretzelosity function $h_{1T}^{\perp}$: proton spin and parton spin influence parton's transverse motion

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

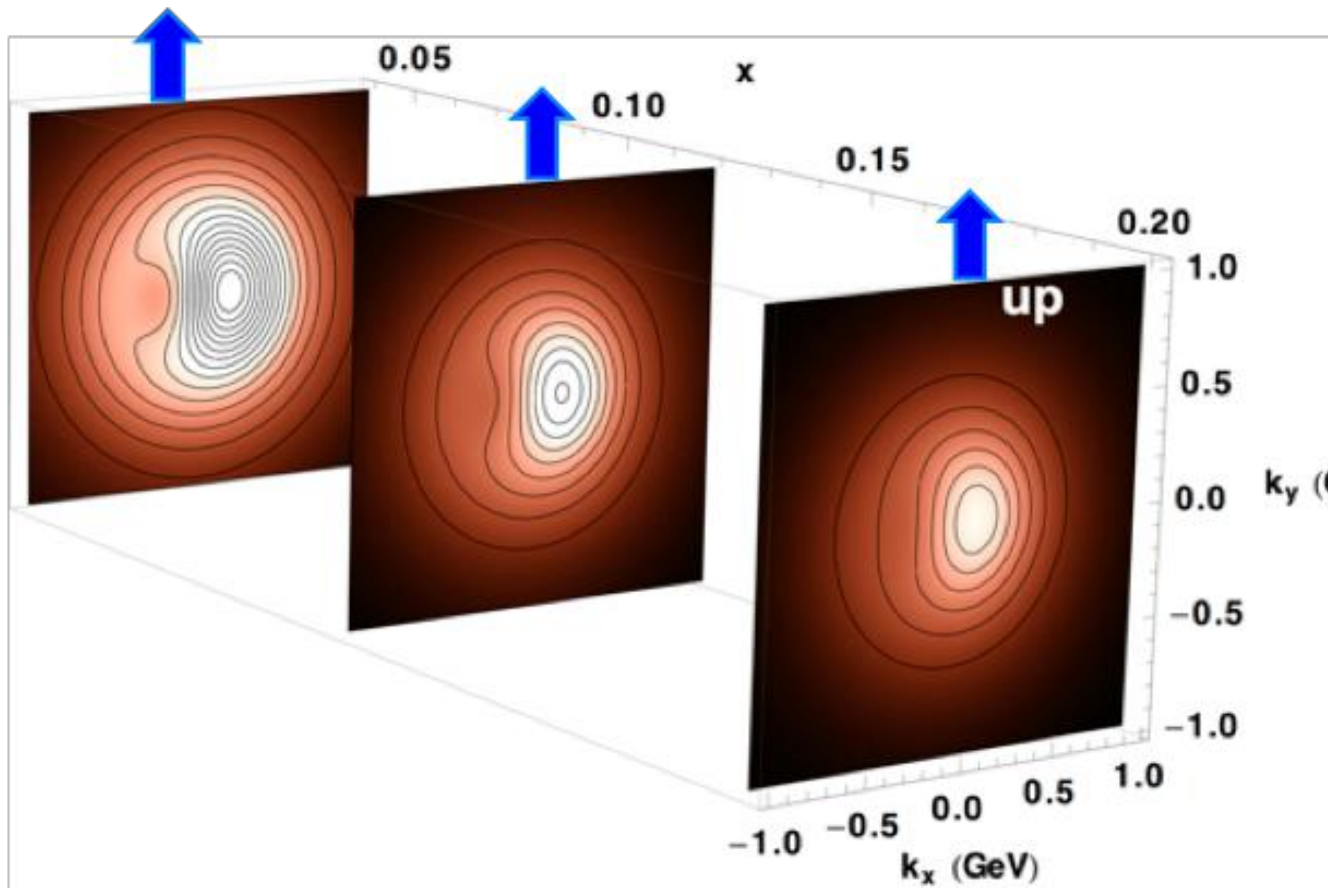
Nucleon partonic structure - 3D imaging

By Andrea Signori

Unpolarized proton



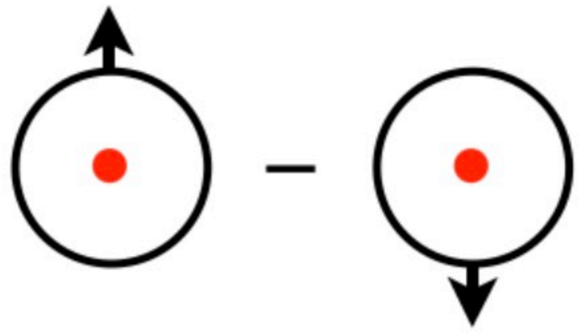
Transversely polarized proton

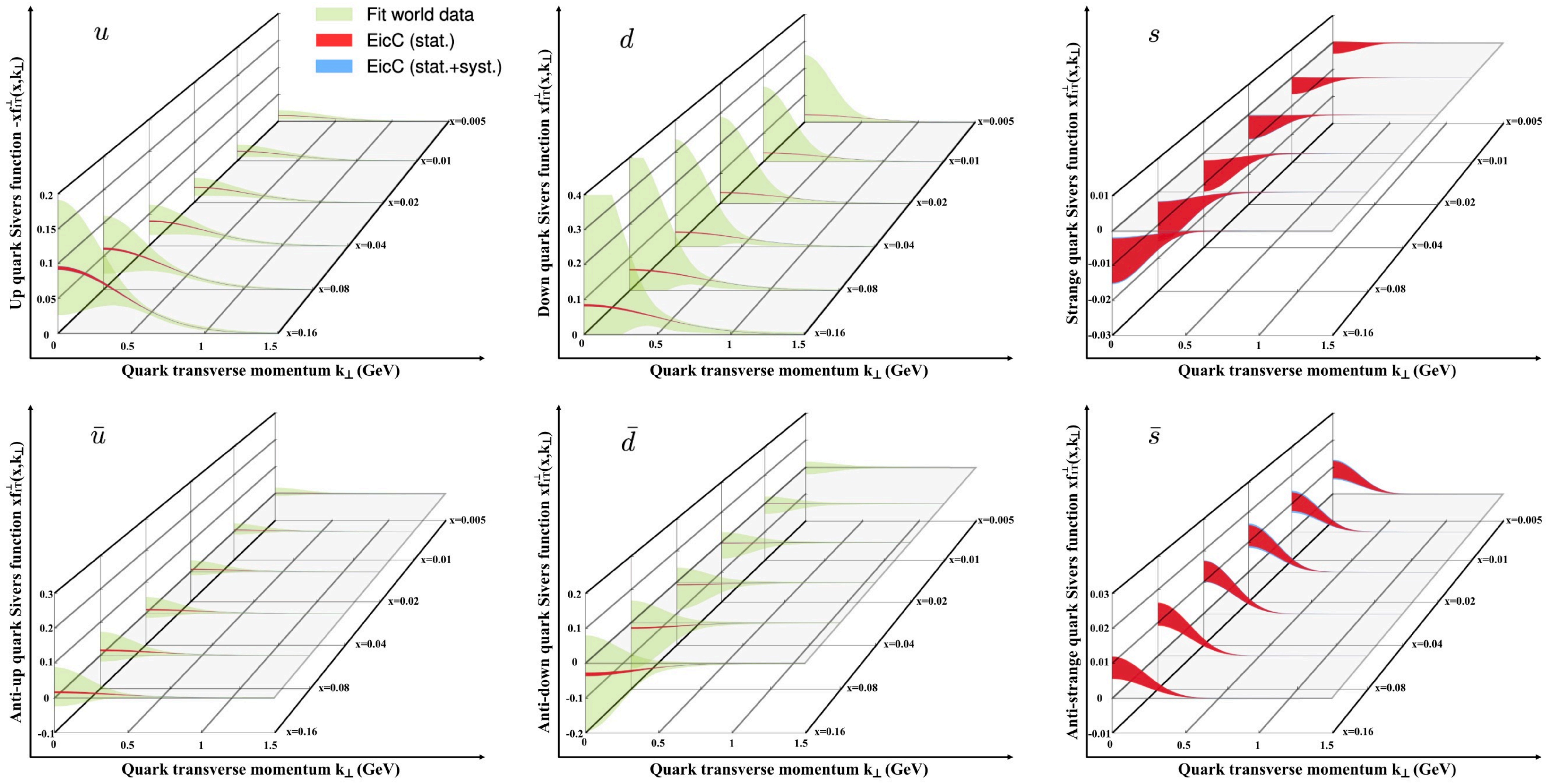


Transversely polarized quark distribution is distorted!

Nucleon 3D imaging at EicC - Sivers effect

$$f_{1T}^{\perp}(x, \mathbf{k}_{\perp})$$





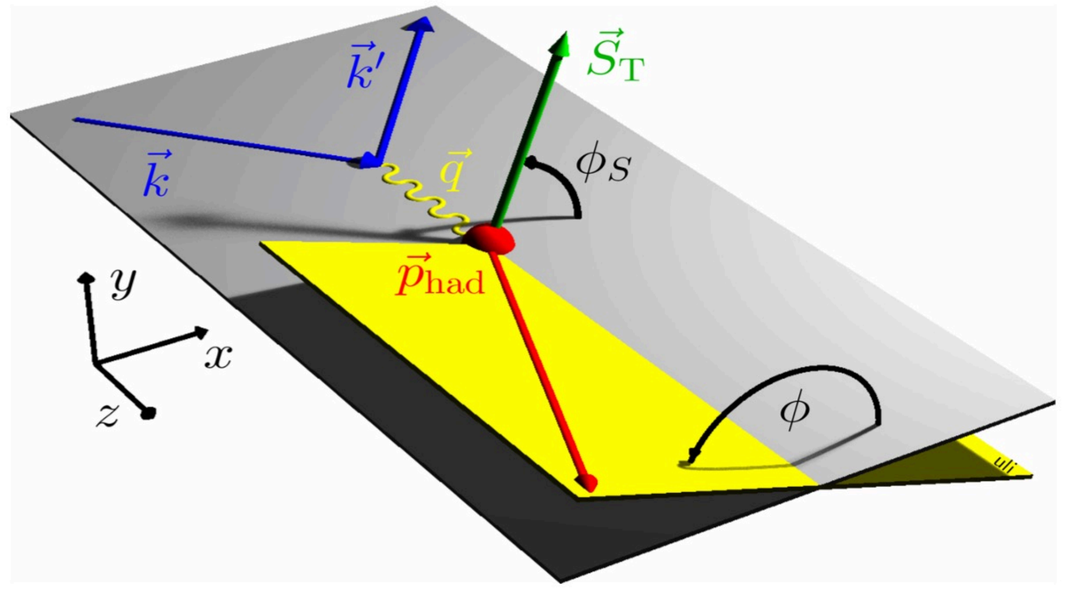
u/d Sivers EicC vs world data

LO analysis

EicC SIDS data:

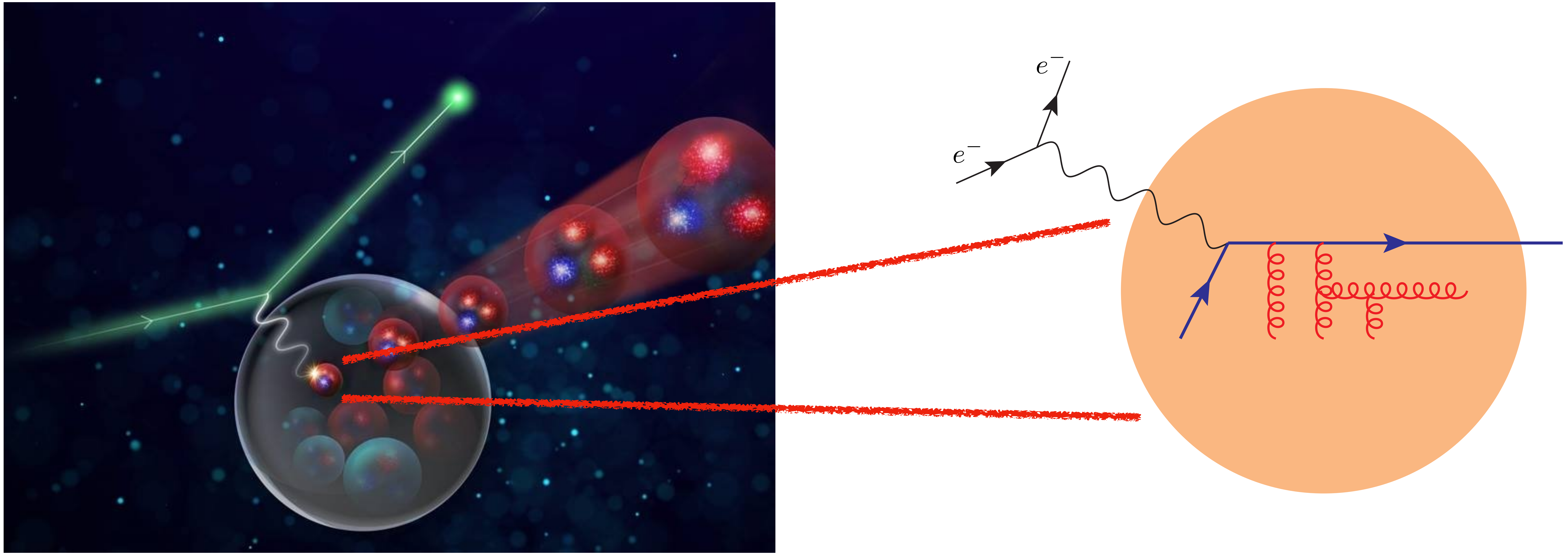
- Pion(+/-), Kaon(+/-)
- ep: 3.5 GeV X 20 GeV
- eHe-3: 3.5 GeV X 40 GeV
- Pol.: e(80%), p(70%), He-3(70%)
- Lumi: ep 50 fb^{-1}, eHe-3 50 fb^{-1}

EicC, precise measurements.



C. Zeng, T. Liu, P. Sun, Y. Zhao, Phys. Rev. D 106 (2022) 094039

What if the nucleon is bounded in nucleus?



Initial state
Nuclear partonic structure

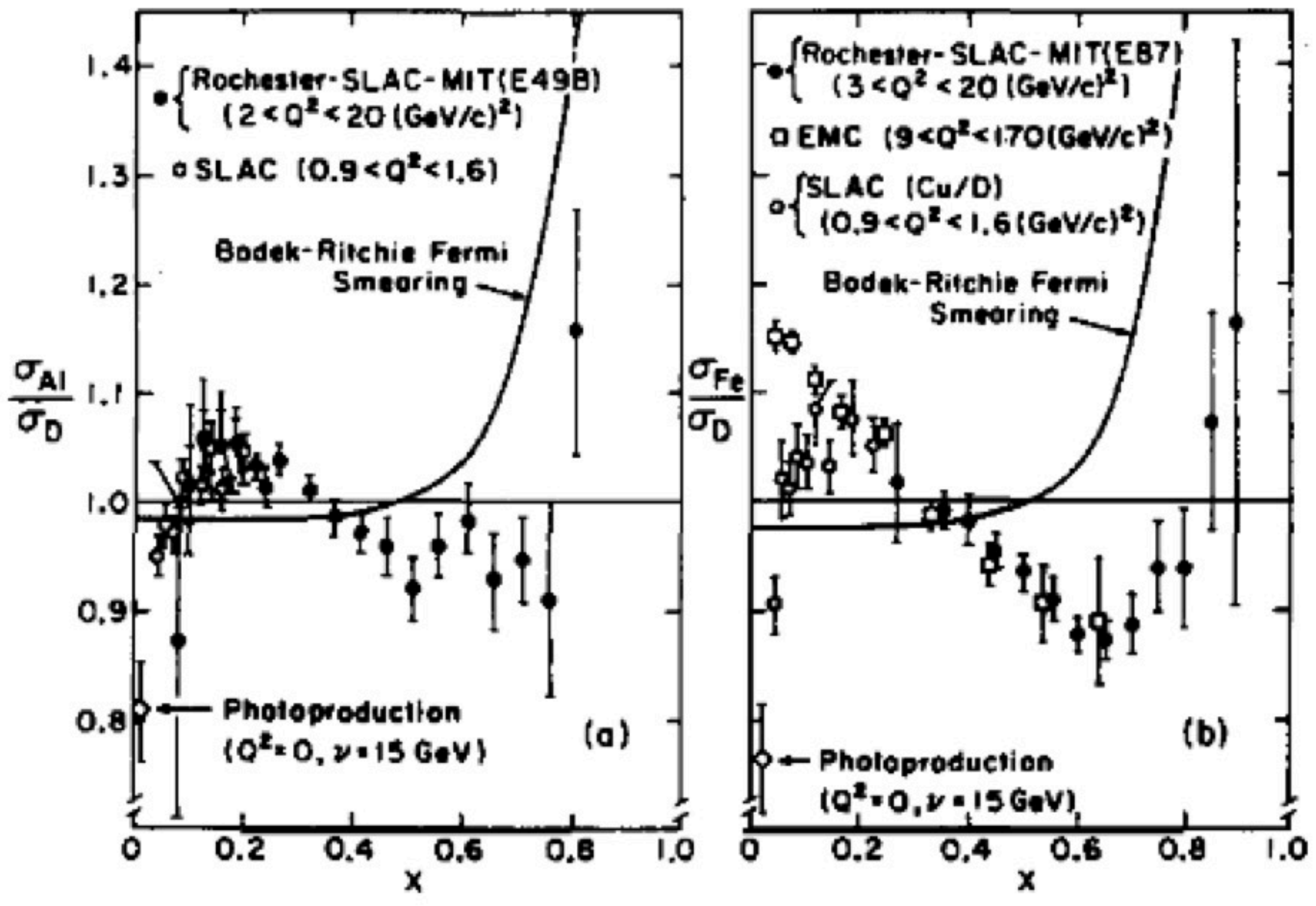
Final state
Parton propagating in nuclear medium

Two mechanisms to nontrivial nuclear effects.

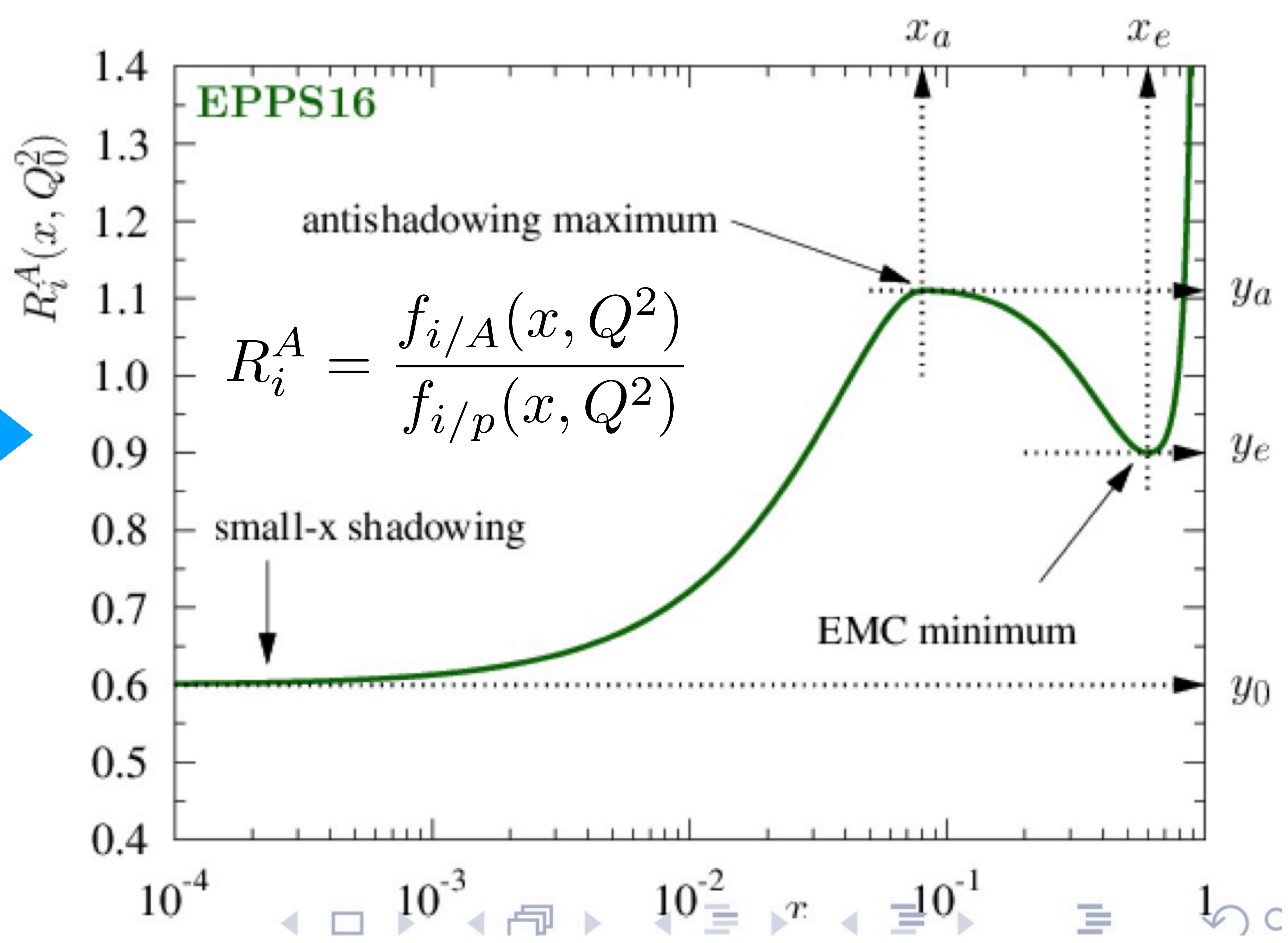
“Old” and long standing problems of nuclear partonic structure

- One-dimensional nuclear partonic structure

Four Decades of the EMC Effect

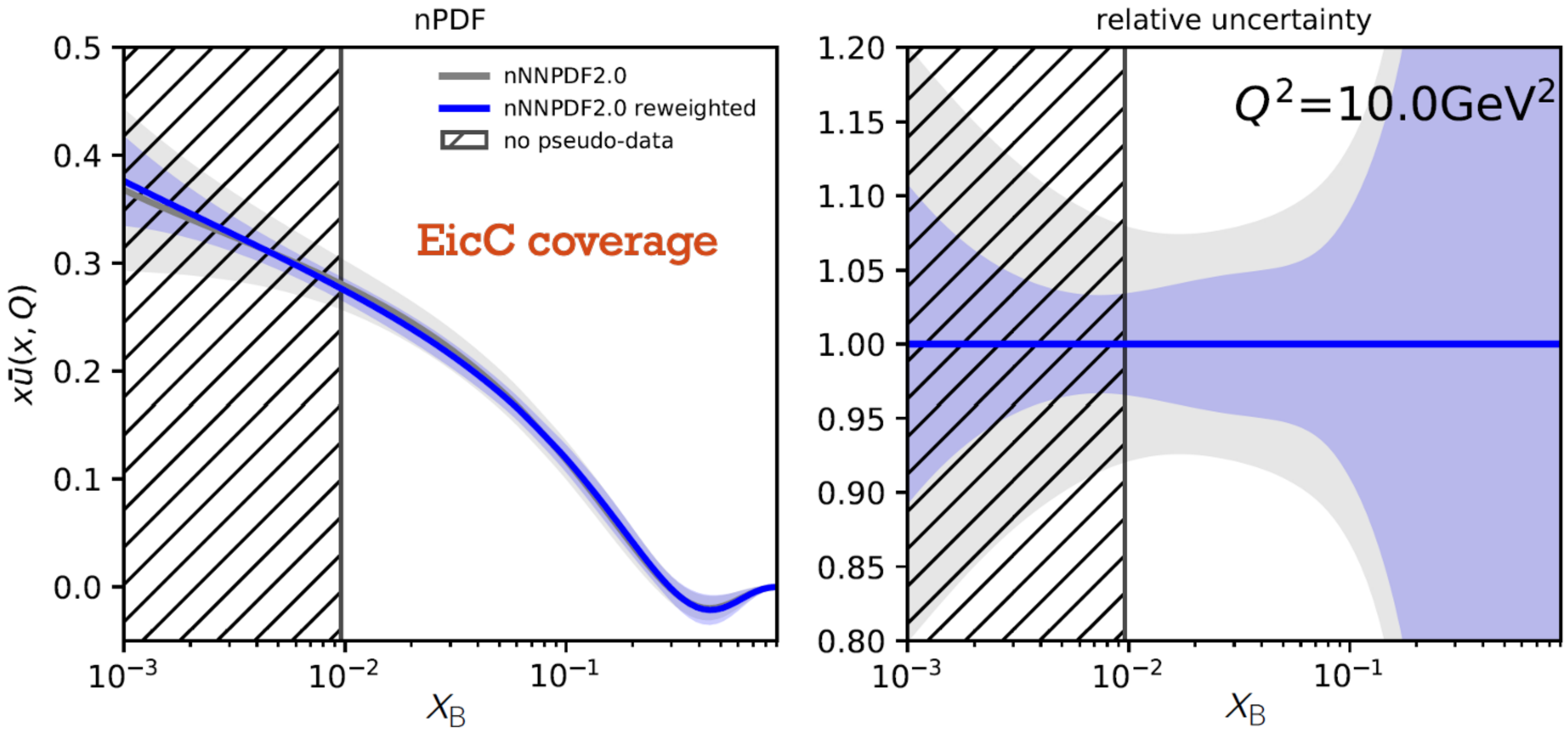


EMC Collaboration, 1983



Power of EicC for nuclear partonic structure - 1D

- Nuclear partonic structure - nuclear quark distribution



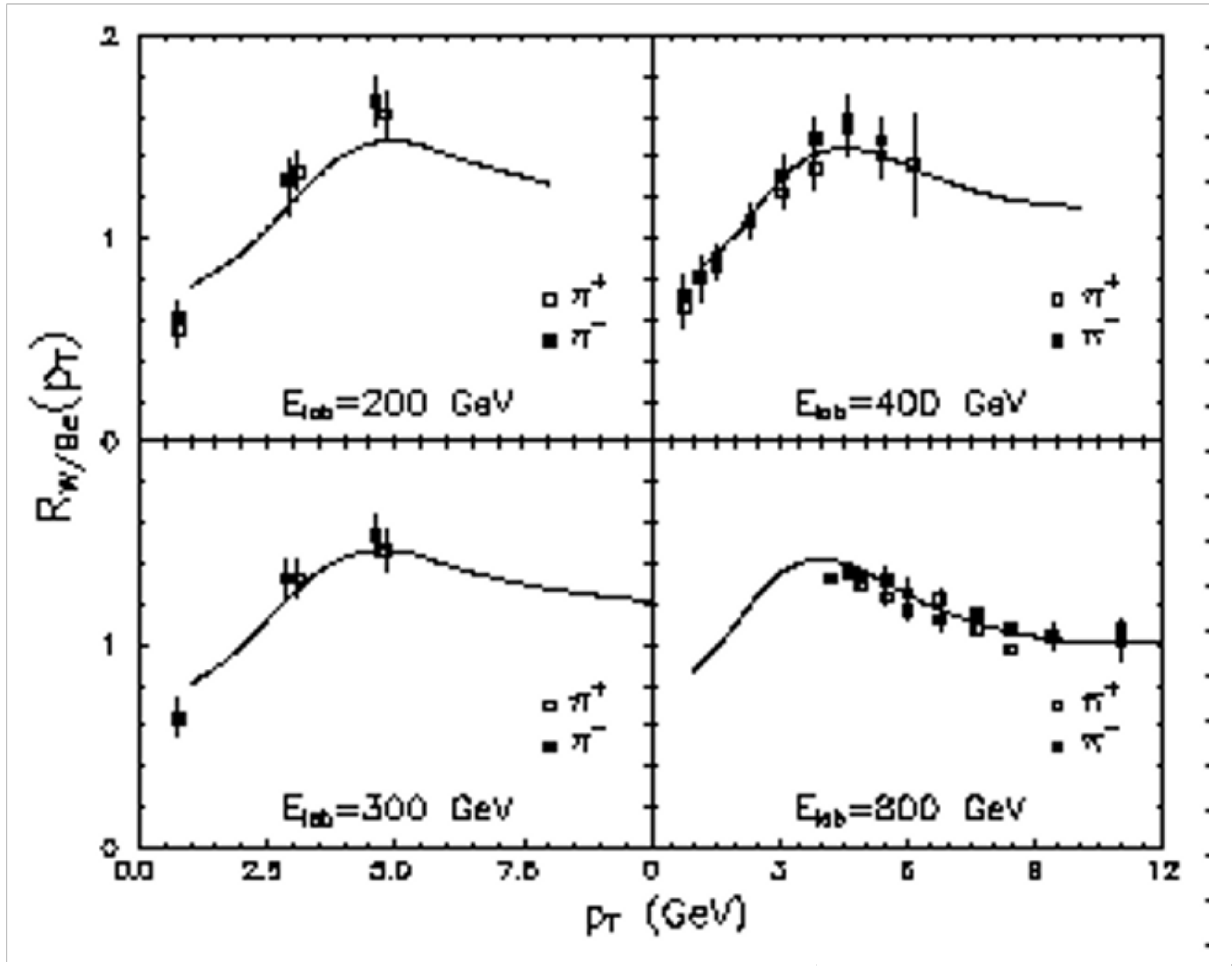
$$\int \mathscr{L} = 0.01\ fb^{-1}$$

Only a few hours of running

“Old” and long standing problems of nuclear partonic structure

- Three-dimensional nuclear partonic structure

Cronin effect



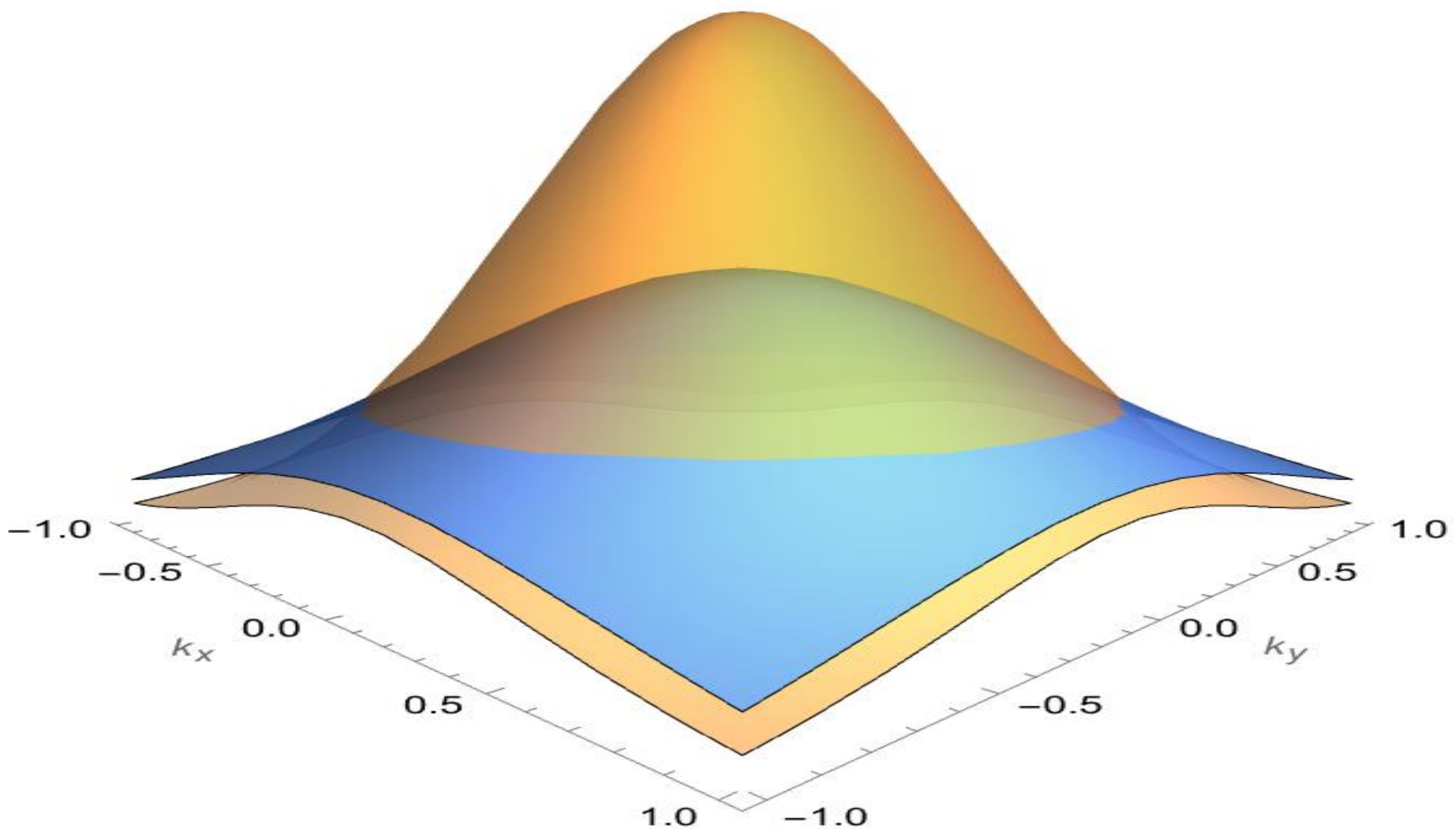
$$p + A \to \text{hadron(p)} + X$$

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

E100 Collaboration, PRD 11, 3105 (1975)

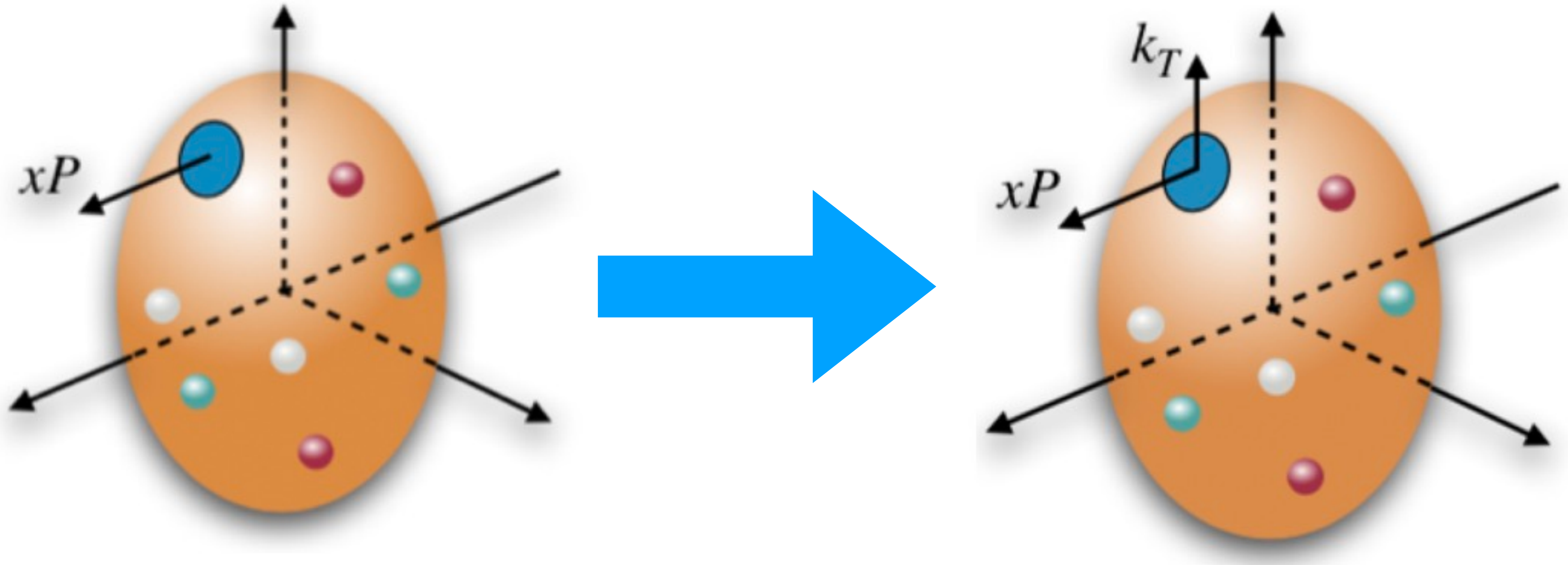
- Naive Gaussian model

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



Nuclear partonic structure - 3D

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



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

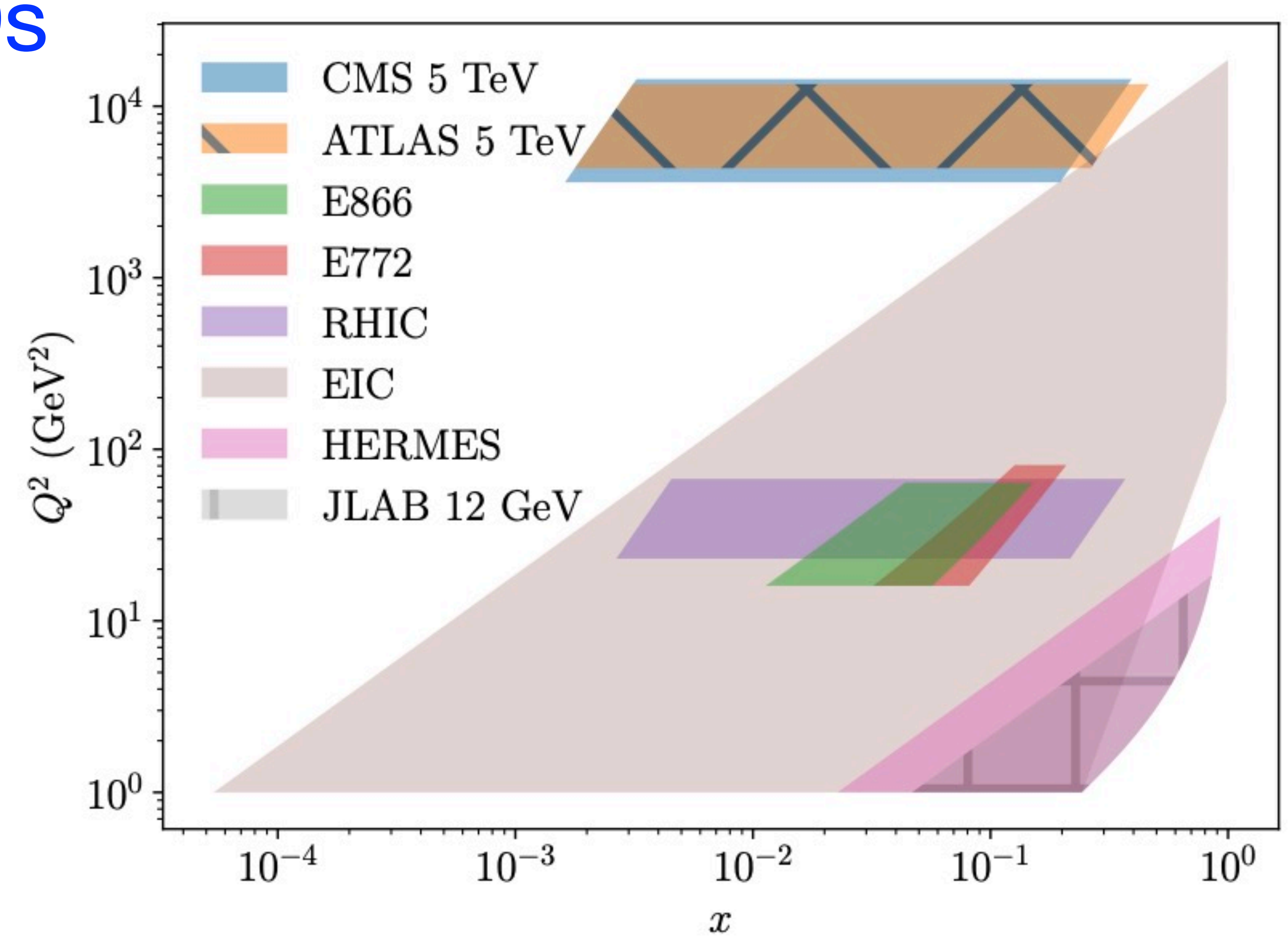
- Two scale processes are necessary for TMDs

Drell-Yan Measurements

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

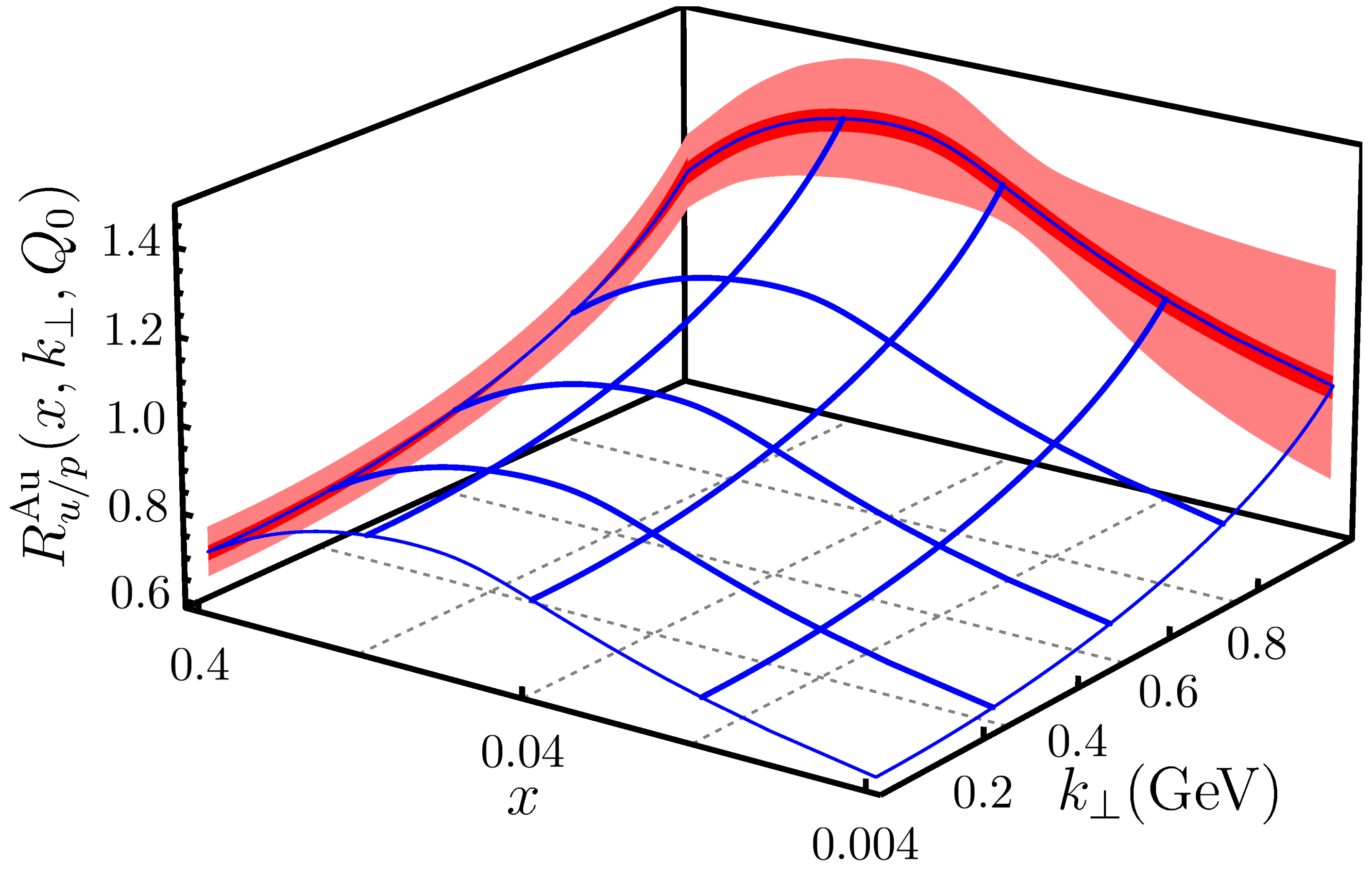
SIDIS Measurements

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

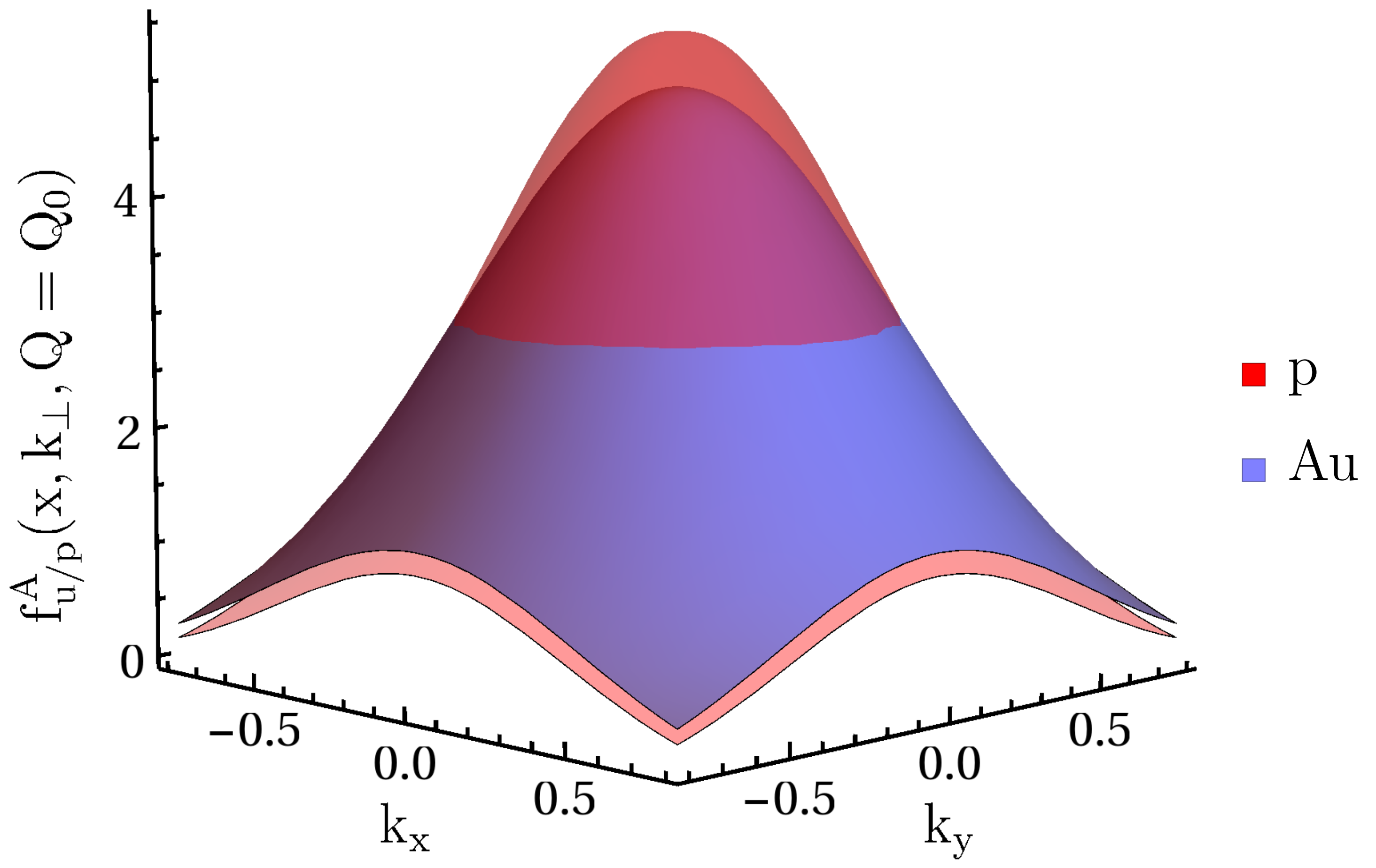


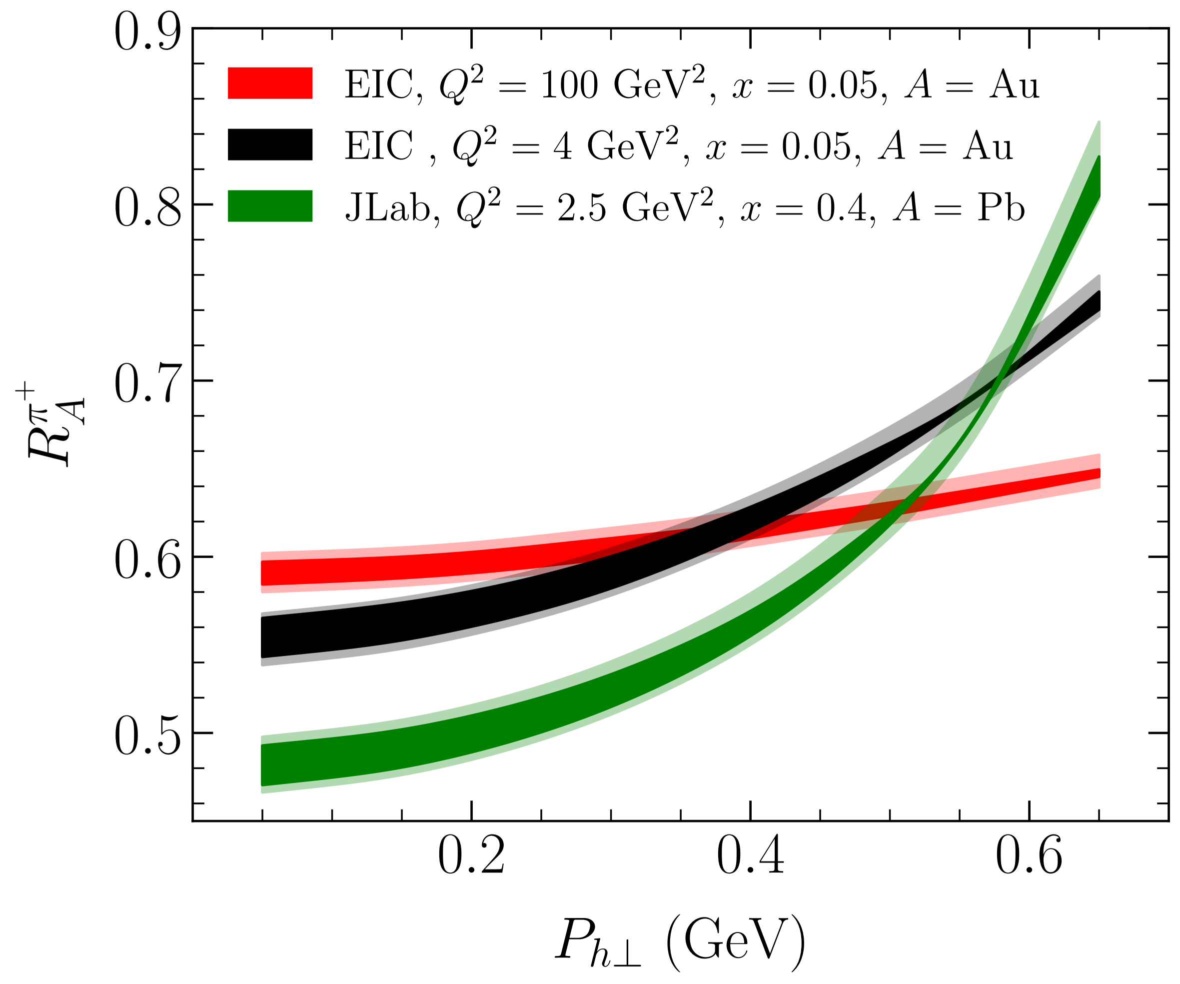
Three-dimension imaging in nuclei

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

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

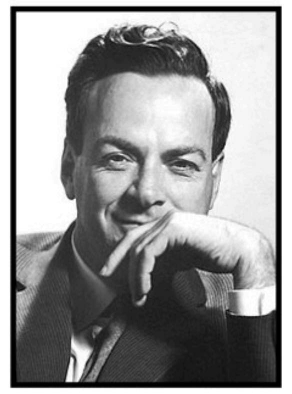
Department of Physics, California Institute of Technology, Pasadena, California 91107

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

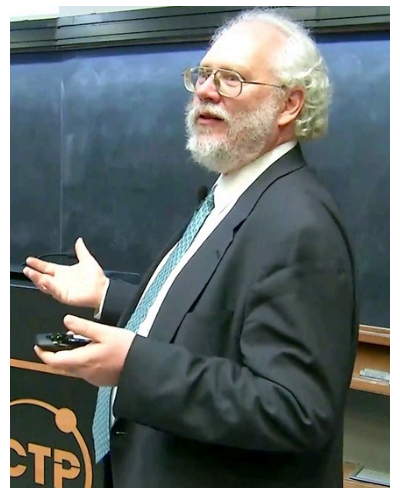
Abstract

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



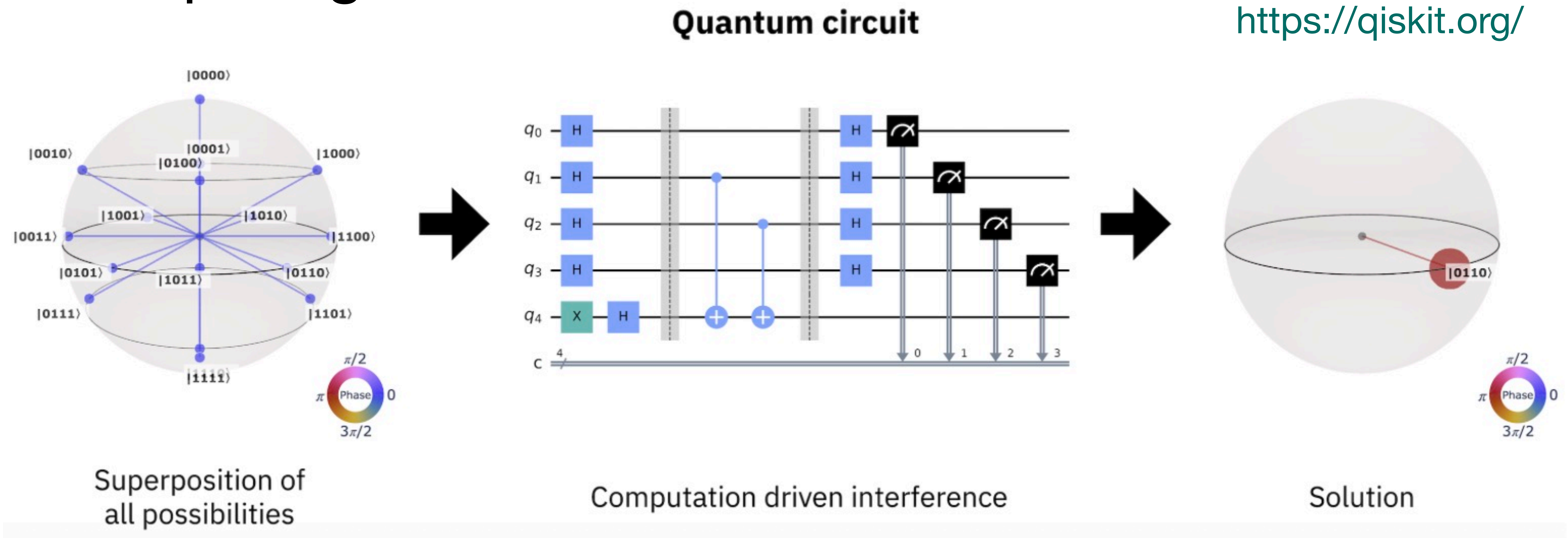
IBM Q System One (2019), the first circuit-based commercial quantum computer

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

—Feynman

Quantum computing

https://qiskit.org/



✦ 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)

$\alpha\,|0\rangle + \beta\,|1\rangle$ —[X]— $\beta\,|0\rangle + \alpha\,|1\rangle$ $\qquad$ $|0\rangle$ —[H]— $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$ $\qquad$ $|x\rangle \to |x\rangle$, $|y\rangle \to |y \oplus x\rangle$

- Measurements: Hermitian

Increasing interest in HEP and NP 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

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Cloud Quantum Computing of an Atomic Nucleus

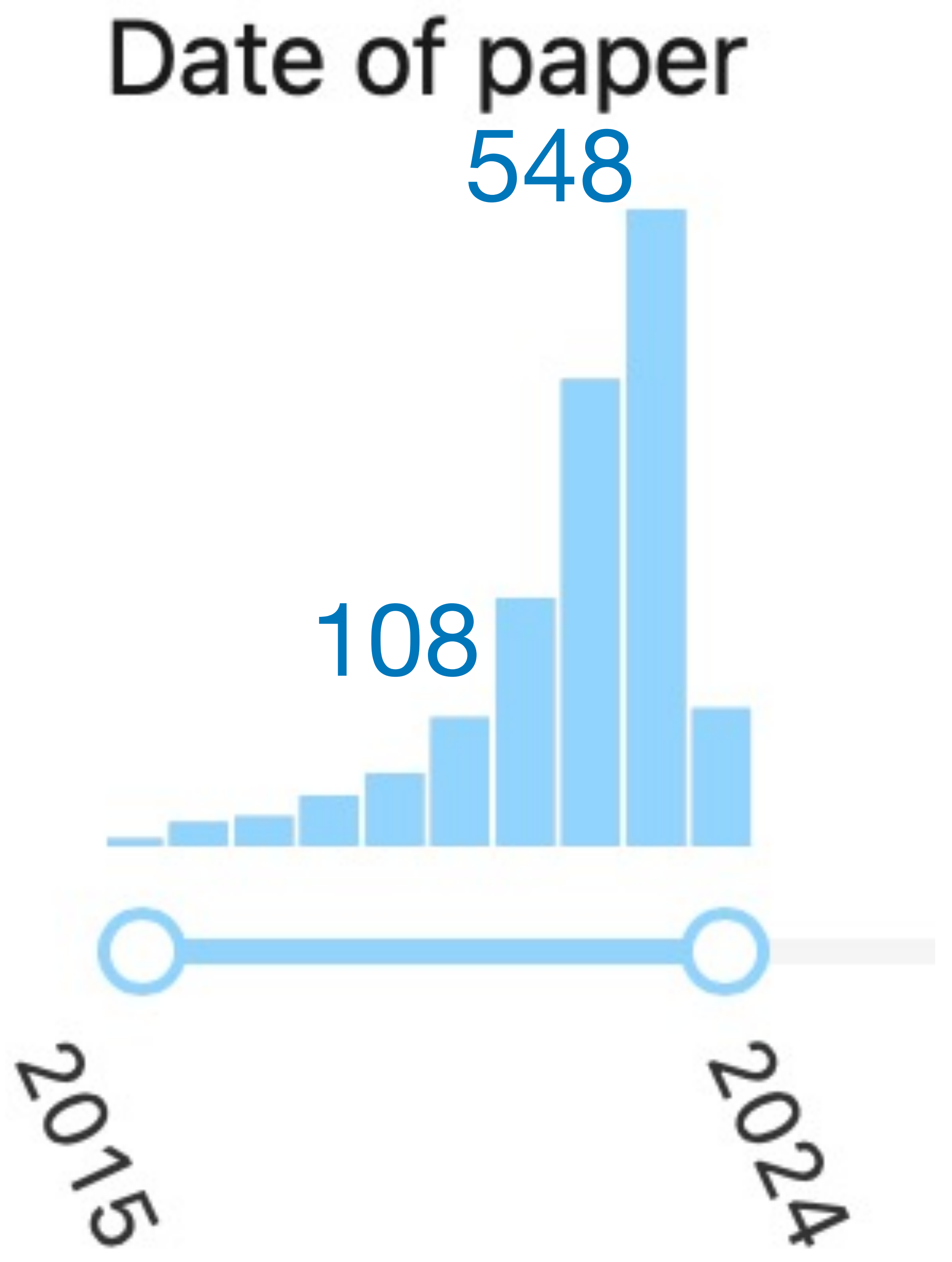
E. F. Dumitrescu, A. J. McCaskey, G. Hagen, G. R. Jansen, T. D. Morris, T. Papenbrock, R. C. Pooser, D. J. Dean, and P. Lougovski
Phys. Rev. Lett. **120**, 210501 – Published 23 May 2018

Physics See Viewpoint: Cloud Quantum Computing Tackles Simple Nucleus

Article | References | Citing Articles (127) | PDF | HTML | Export Citation

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

Article | References | Citing Articles (6) | Supplemental Material | PDF | HTML | Export Ci

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.

Letter | Open Access | Access by South

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

Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citati

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.

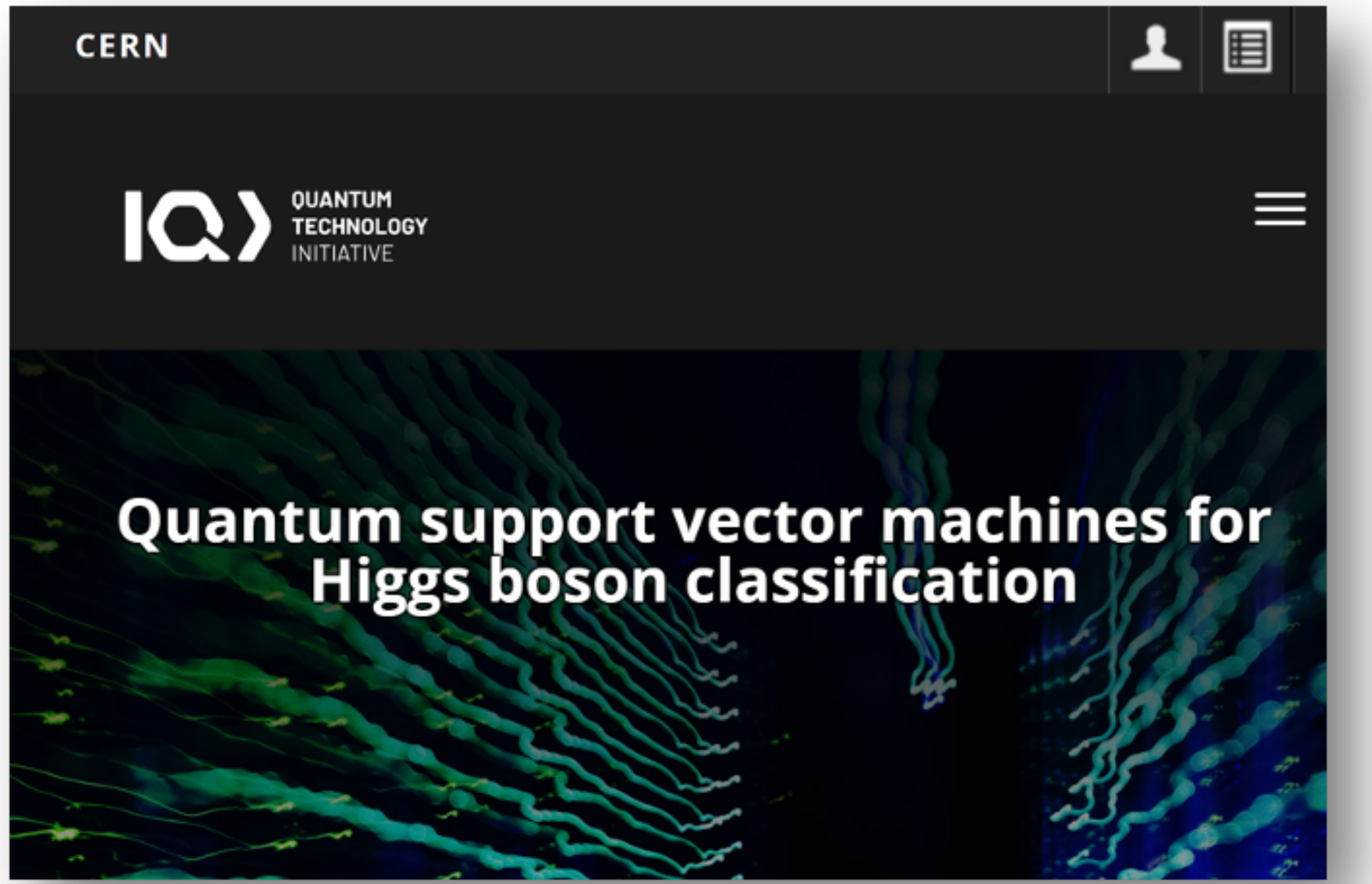
Inspire:

find t quantum computing and date>2015

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



arXiv > quant-ph > arXiv:2209.14839

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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

arXiv > quant-ph > arXiv:2307.03236

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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,

arXiv > nucl-ex > arXiv:2303.00113

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Nuclear Experiment

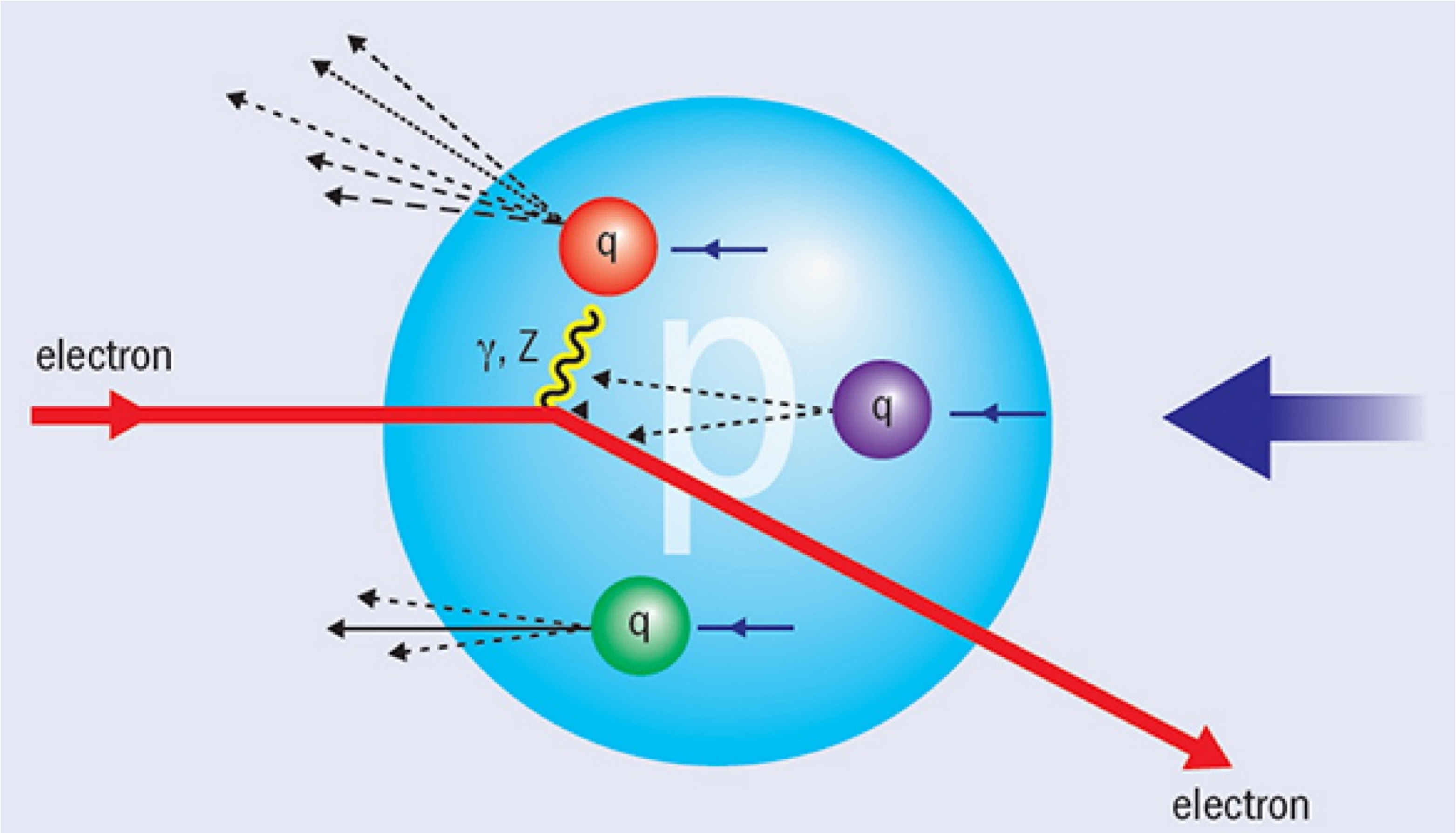
[Submitted on 28 Feb 2023]

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

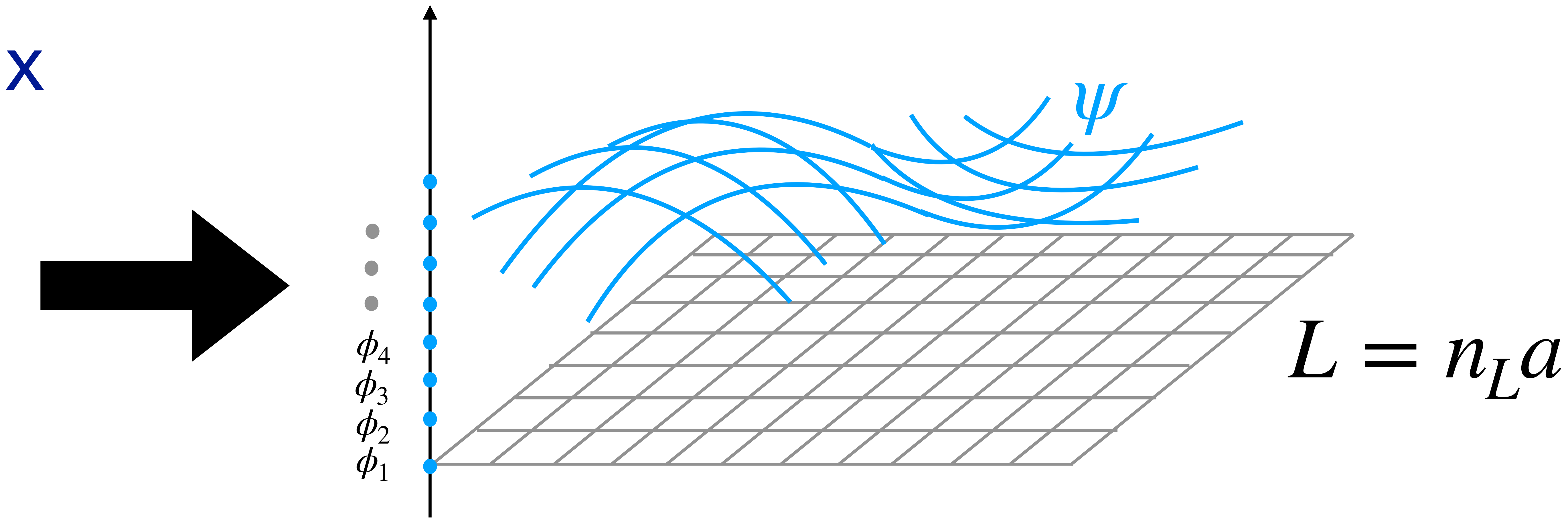
- Prepare initial states from the distance past $(-T)$
- Evolve these states from the distance past to time T , $U(T,-T) \to e^{-iH(\psi)T}$
- Perform measurement in final state

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: $100\text{MeV} \lesssim E \lesssim 13\text{TeV}$

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

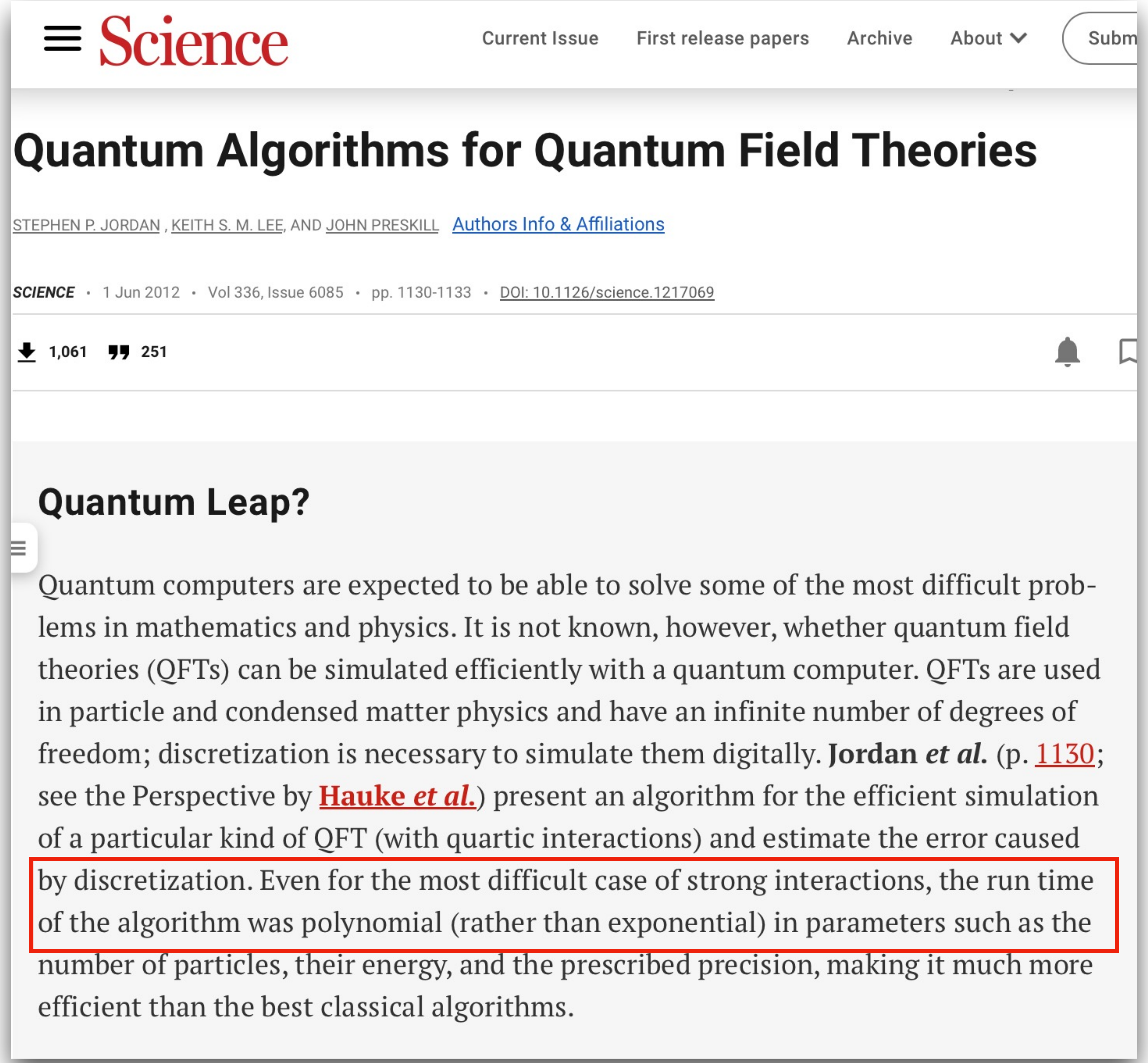
  Assume 5 bit digitization: $n_\phi = 2^5 = 32$

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

First principle calculation on lattice

✦ Digitize field ϕ at discrete points x

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



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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

1,061 251

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.

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

Way beyond NISQ ear in quantum computing!

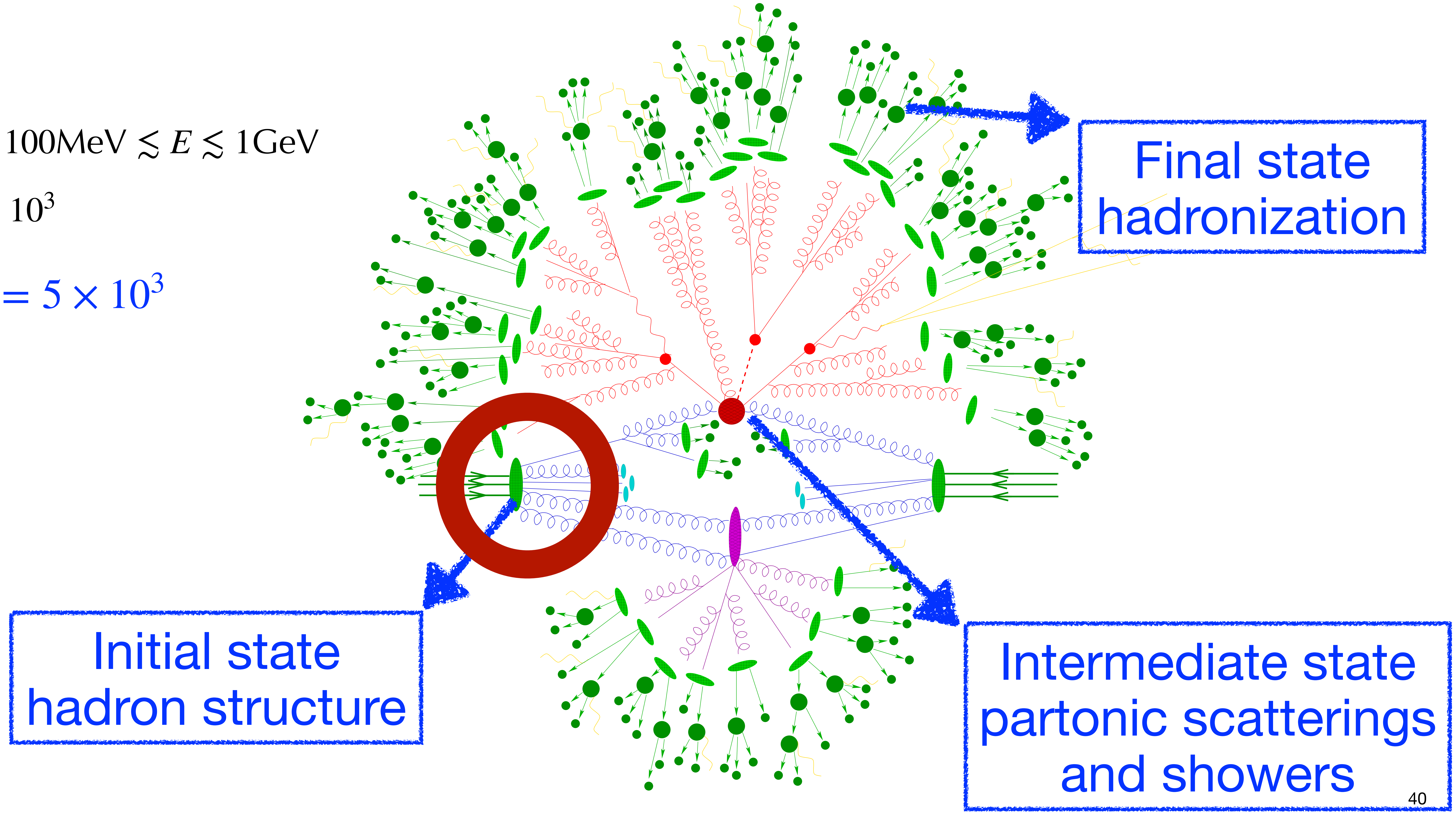
Quantum simulation using EFT

Bauer, Freytsis, Nachman, PRL 2021

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

$n_L^D \sim 10^3$

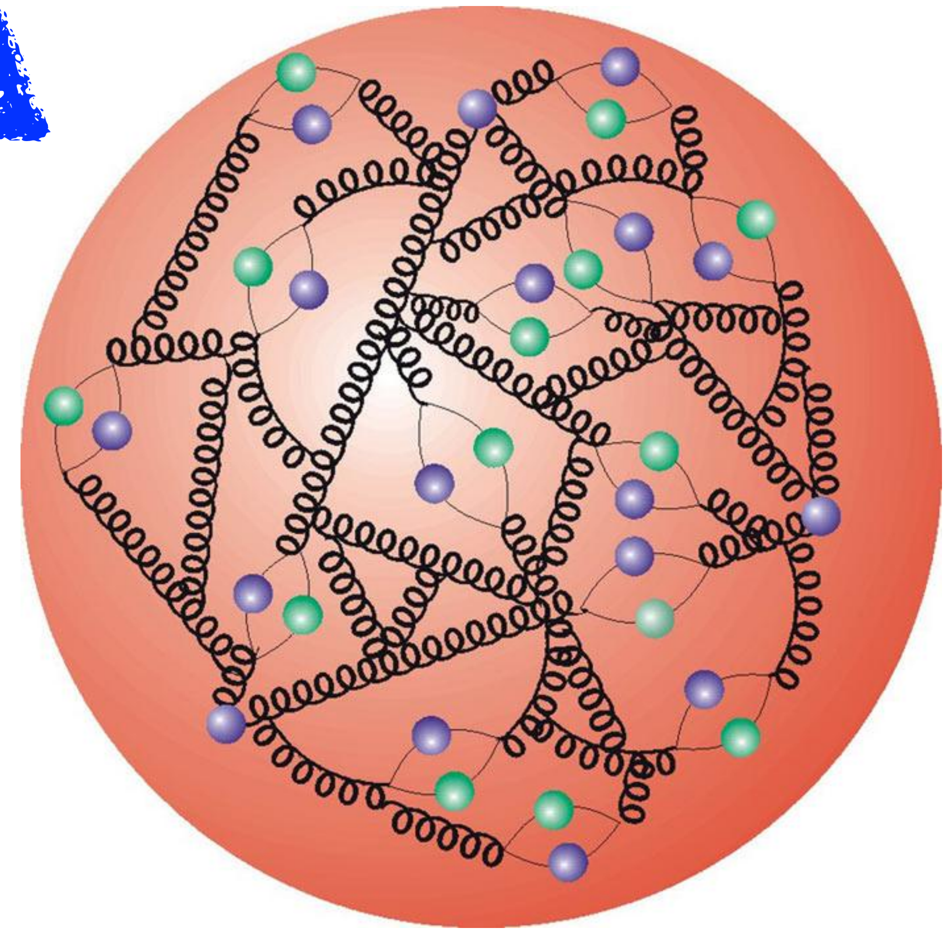
# of qubits: $n_q = 5 \times 10^3$



Simulate hadron partonic structure on quantum computer

✦ Operator definition of quark PDF

$$\sigma \sim f_A \otimes H \otimes D$$



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

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

real time correlation function

✦ 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 partonic structure on quantum computer

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

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

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

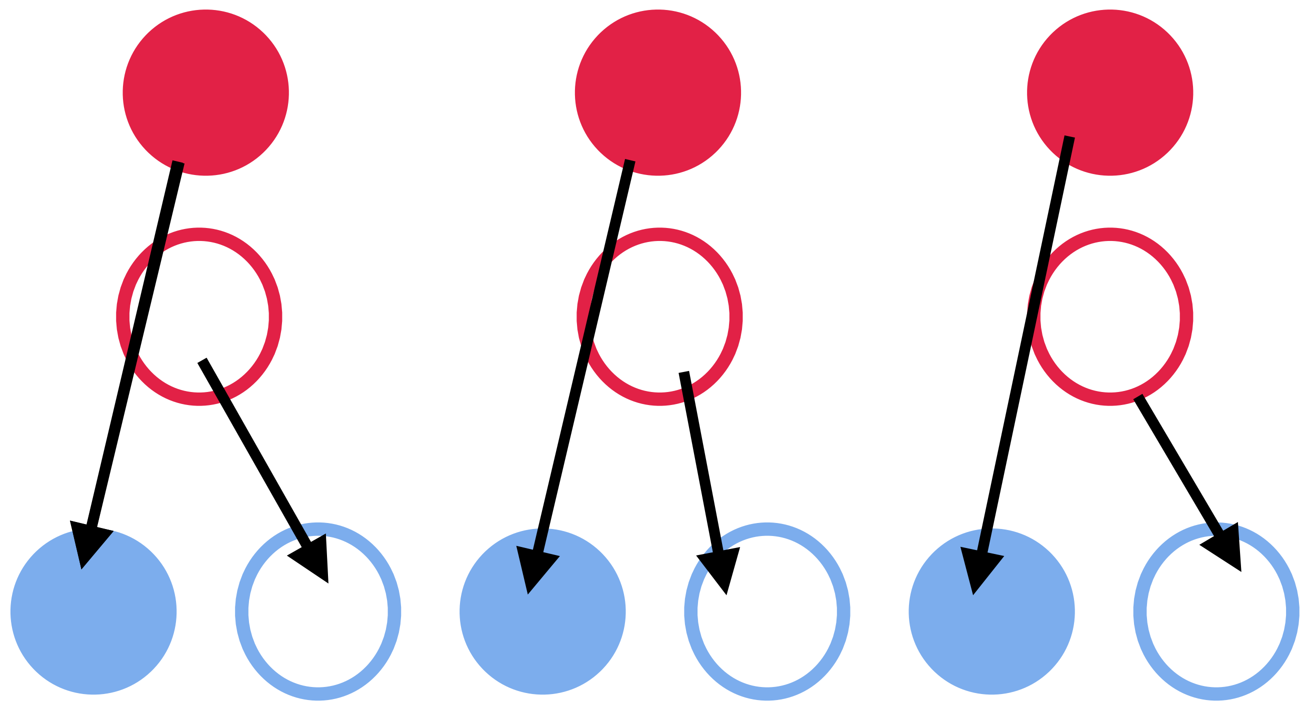
✦ Challenges in quantum computing

- 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 partonic 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:

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

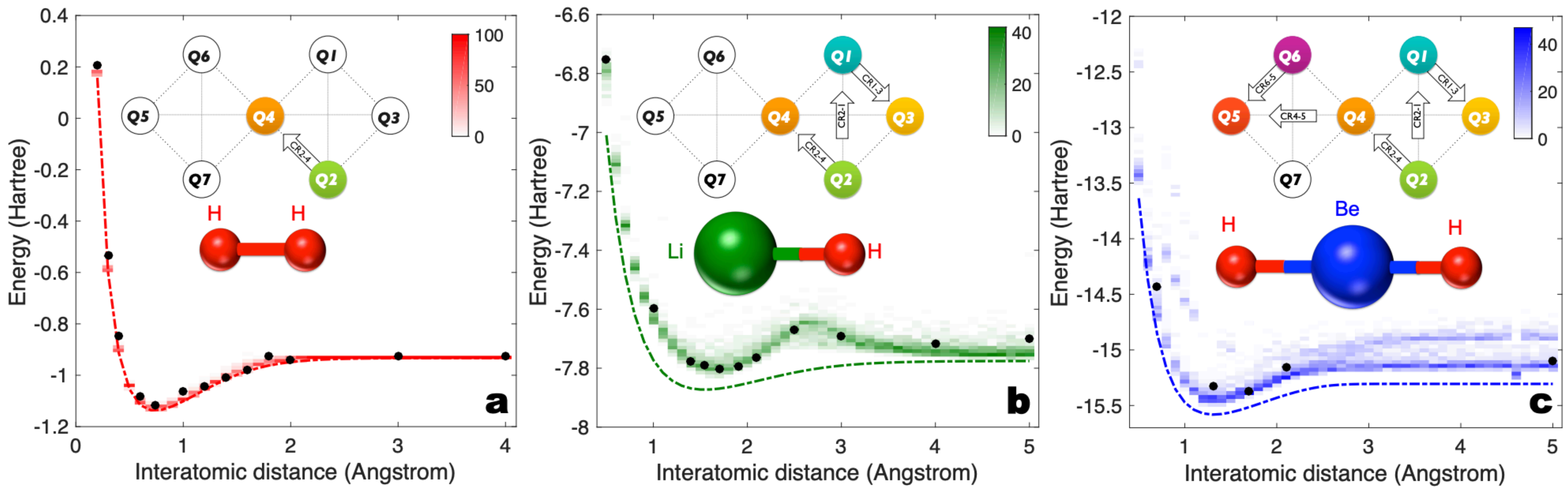
$$H = H_1 + H_2 + H_3 + H_4 \qquad H_1 = \sum_{n=\text{even}} \frac{1}{4} \left[X_n Y_{n+1} - Y_n X_{n+1} \right]$$

Simulate hadron partonic 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)



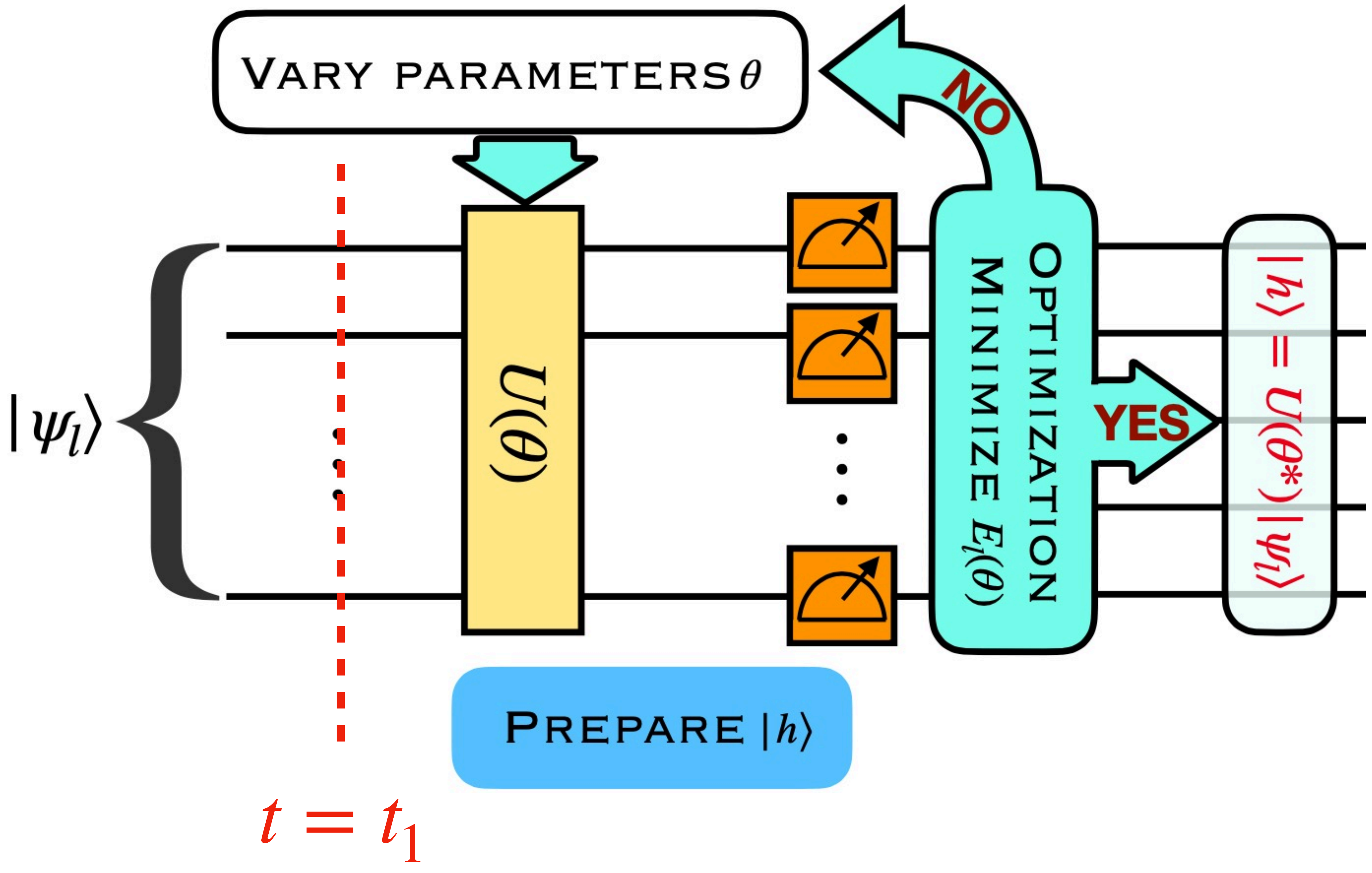
show its power in quantum chemistry

Simulate hadron partonic 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 $|\psi_{lk}\rangle$



Simulate hadron partonic structure on quantum computer

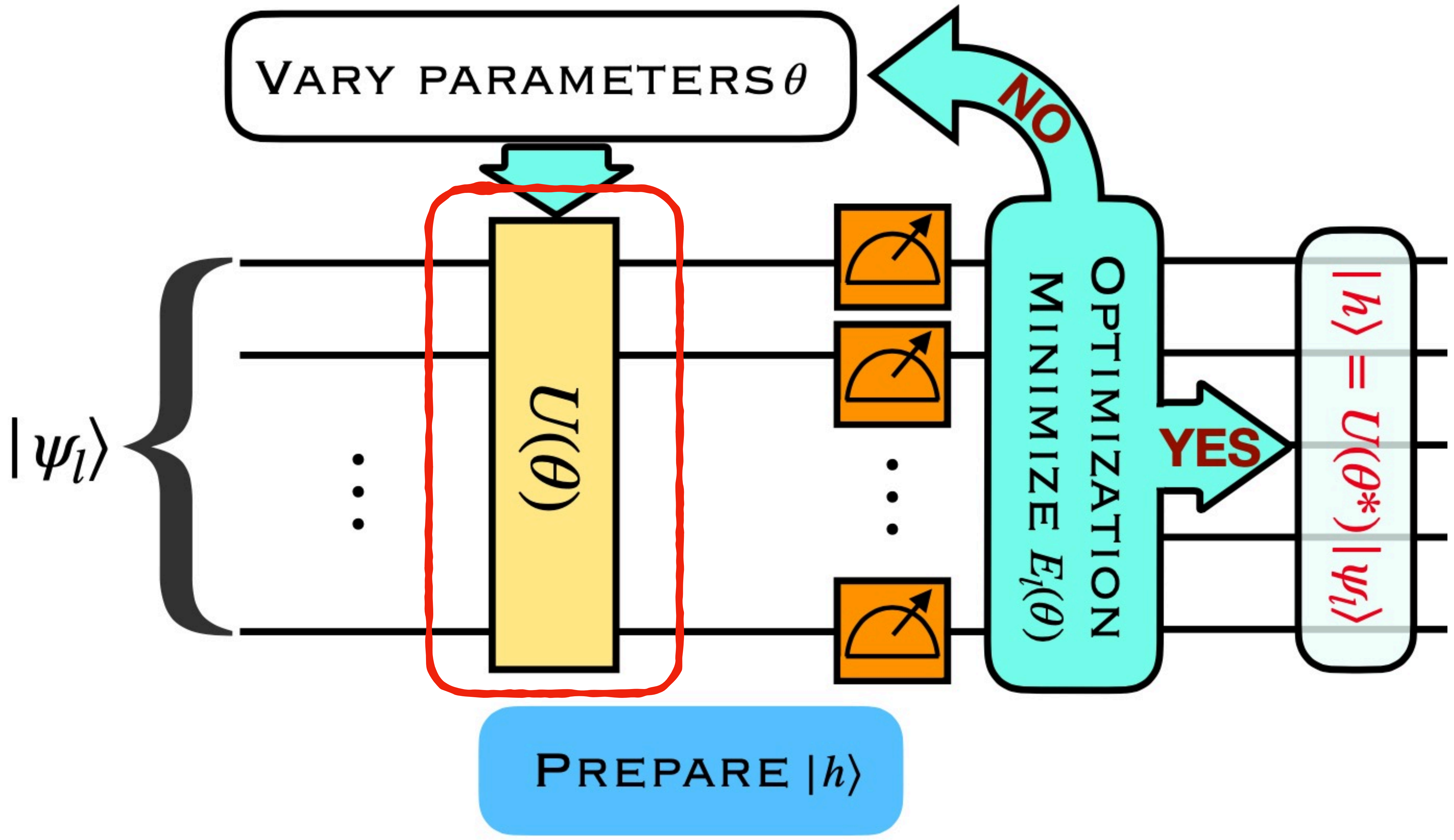
✦ Hadron state preparation - VQE

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 $H = H_1 + H_2 + H_3 + H_4$

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



Simulate hadron partonic structure on quantum computer

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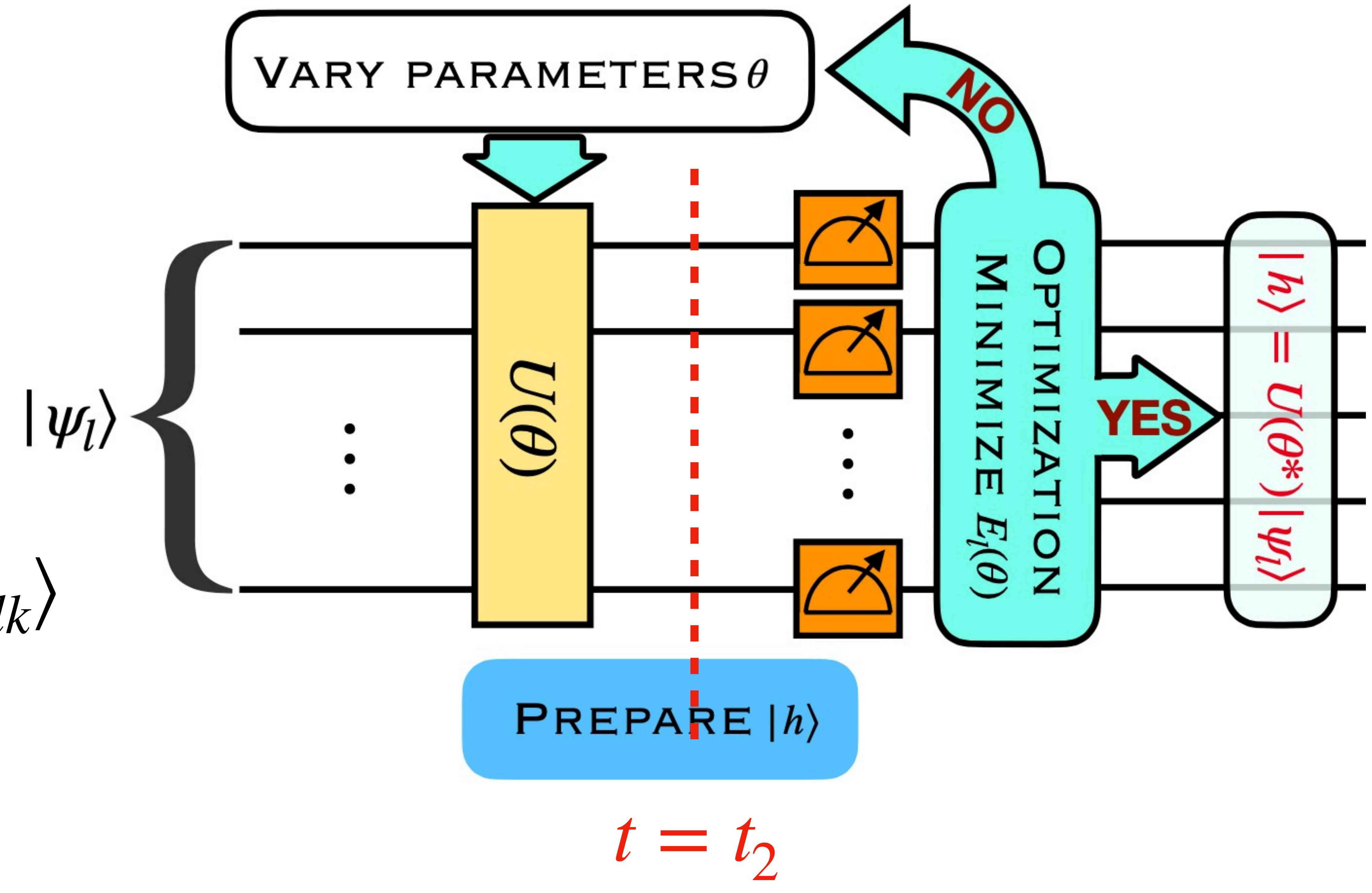
$$U(\theta) \equiv \prod_{i=1}^{p} \prod_{j=1}^{n} \exp(i\,\theta_{ij} H_j)$$

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



Simulate hadron partonic structure on quantum computer

✦ Hadron state preparation - VQE

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

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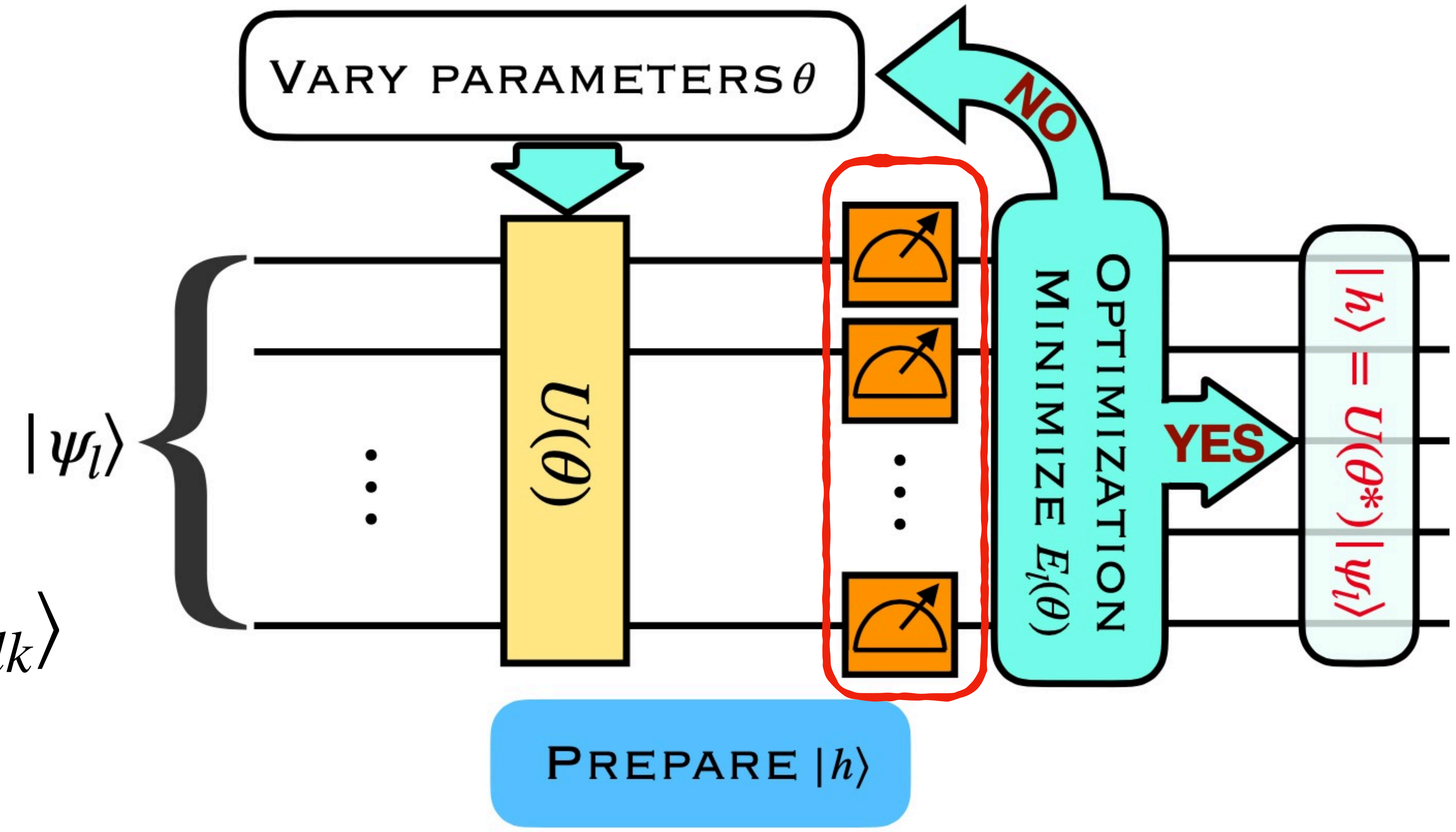
$$U(\theta) \equiv \prod_{i=1}^{p} \prod_{j=1}^{n} \exp(i\,\theta_{ij} H_j)$$

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

4. Measure the loss function:

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



Simulate hadron partonic structure on quantum computer

✦ Hadron state preparation - VQE

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

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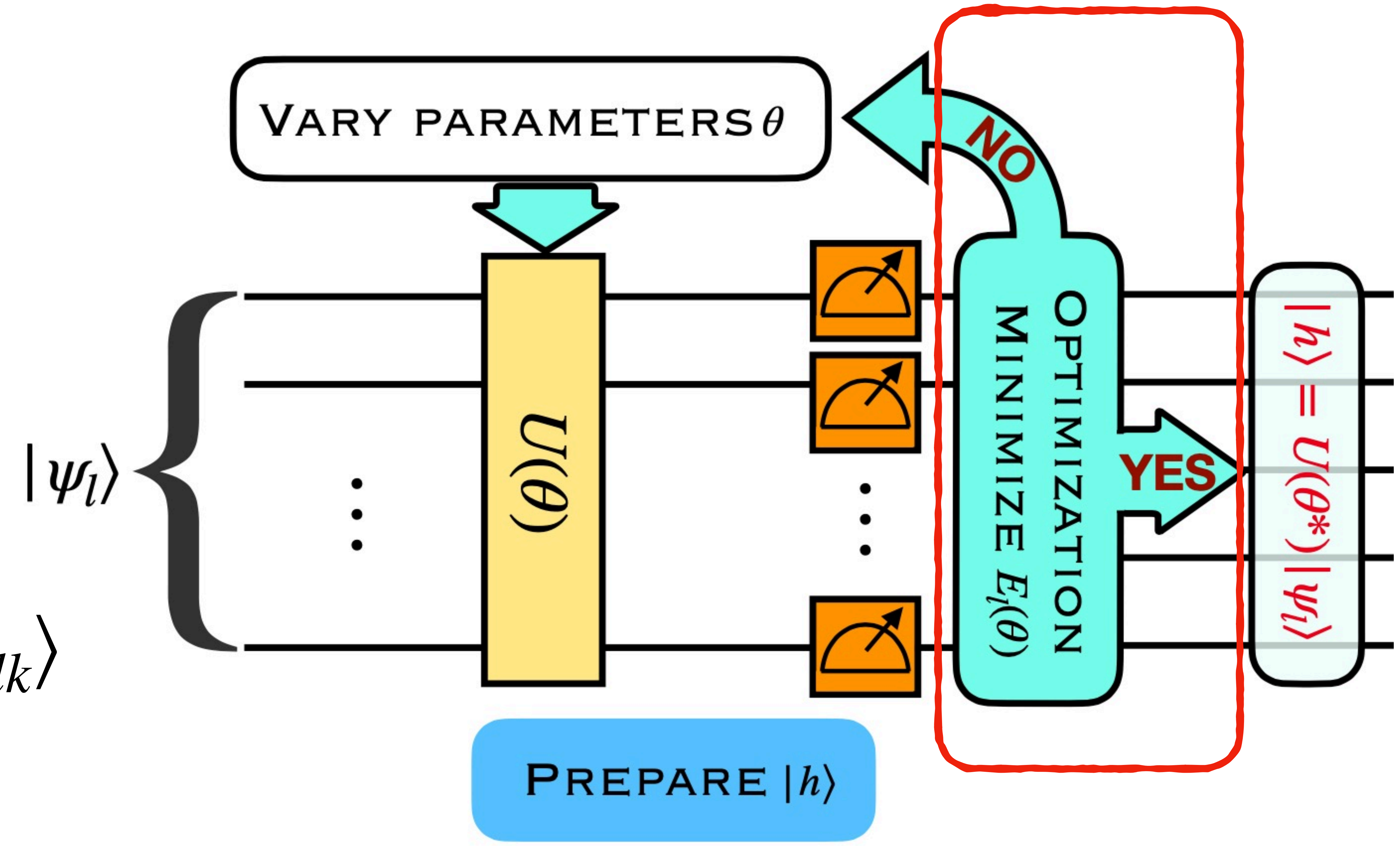
$$U(\theta) \equiv \prod_{i=1}^{p} \prod_{j=1}^{n} \exp(i\,\theta_{ij} H_j)$$

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



Simulate hadron partonic 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 $H = H_1 + H_2 + H_3 + H_4$

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

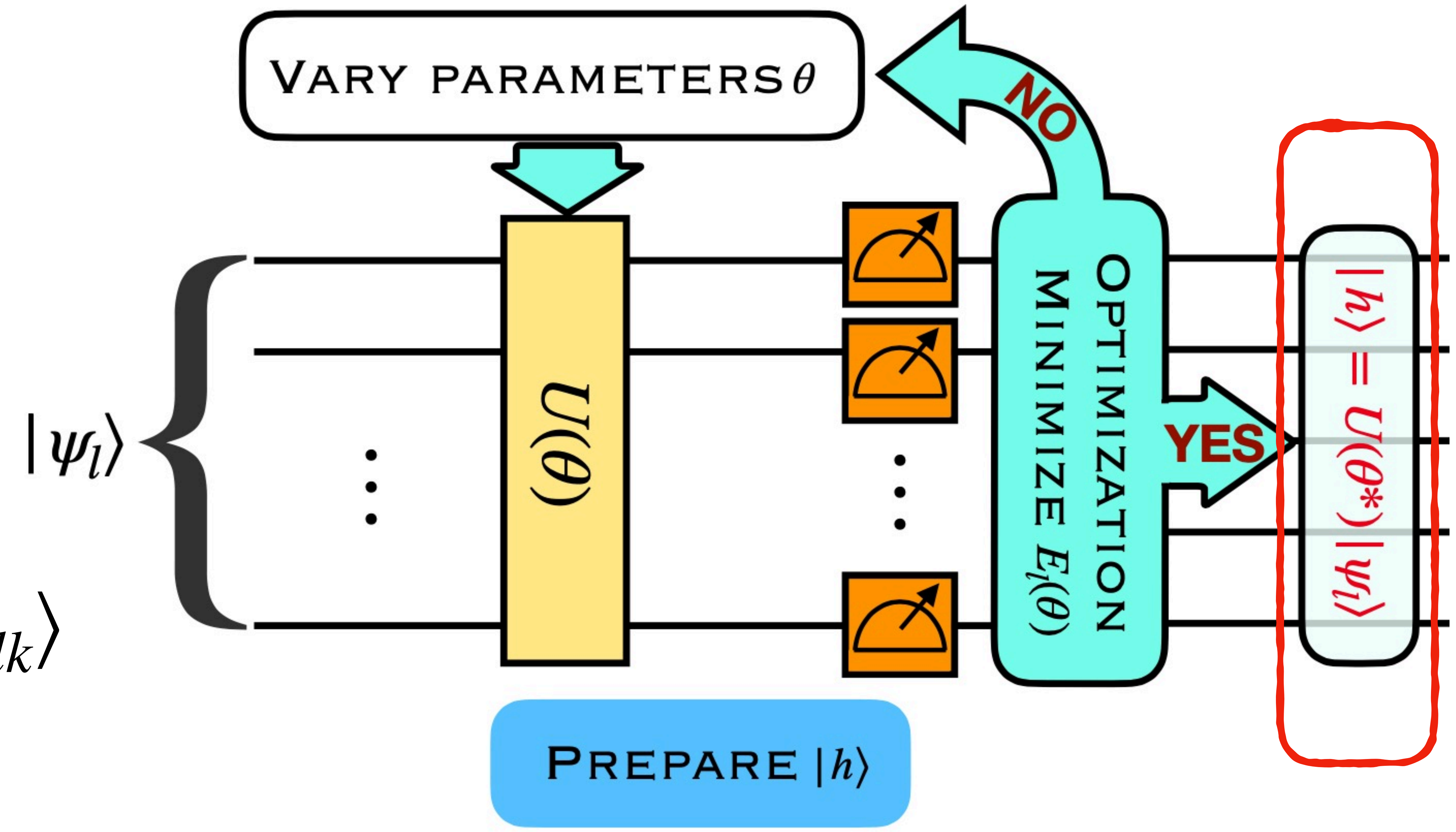
3. Generate the trial state: $|\psi_{lk}(\theta)\rangle = U(\theta)|\psi_{lk}\rangle$

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 $|h\rangle = U(\theta^*)|\psi_{lk}\rangle$



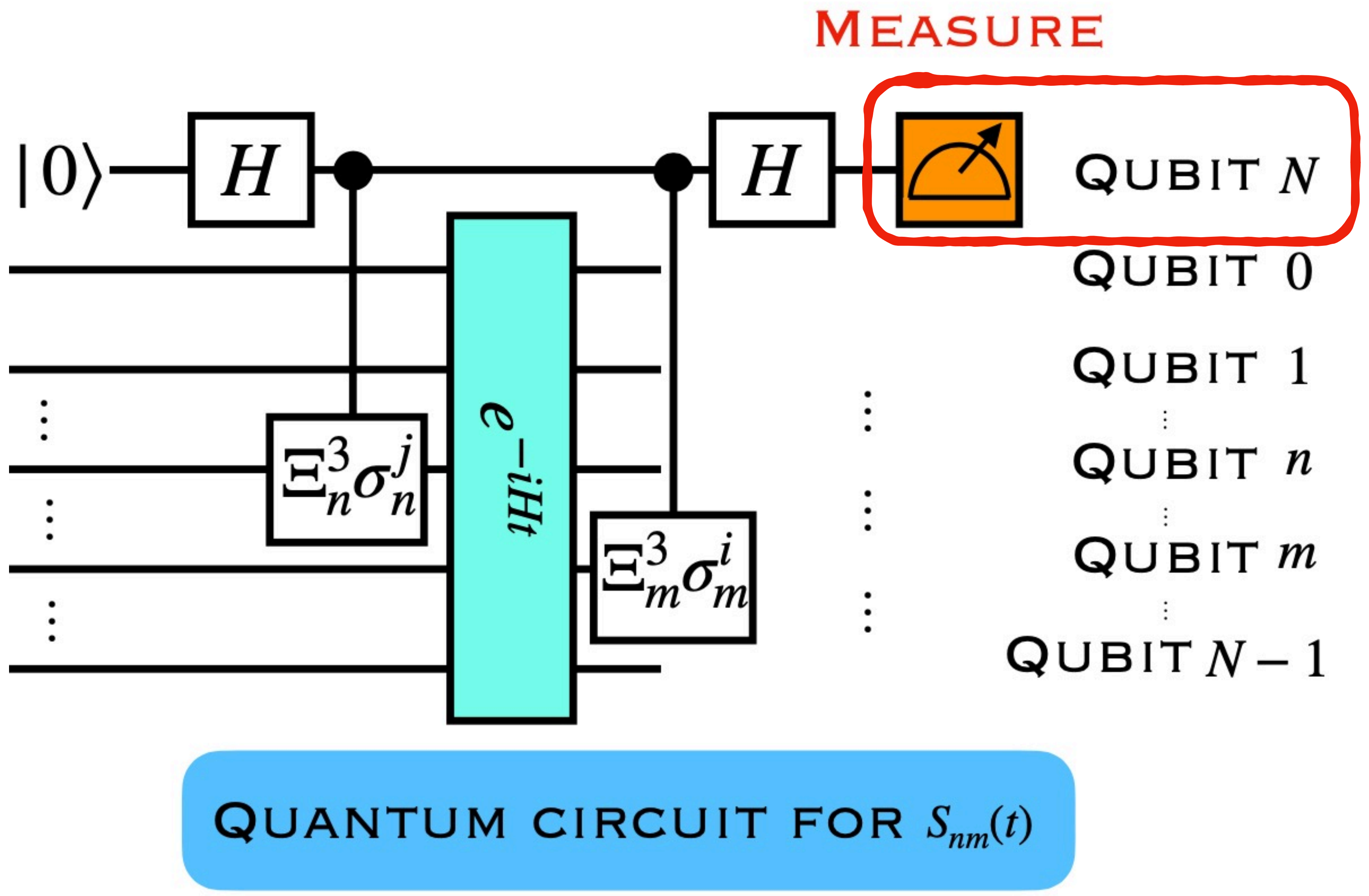
Simulate hadron partonic structure on quantum computer

✦ Evaluate the real-time dynamical correlation function

$$S_{mn}(t) = \langle h \,|\, e^{iHt} \Xi^3_m \sigma^i_m e^{-iHt} \Xi^3_n \sigma^j_n \,|\, h \rangle$$

PDFs can be written as a sum of such correlation functions

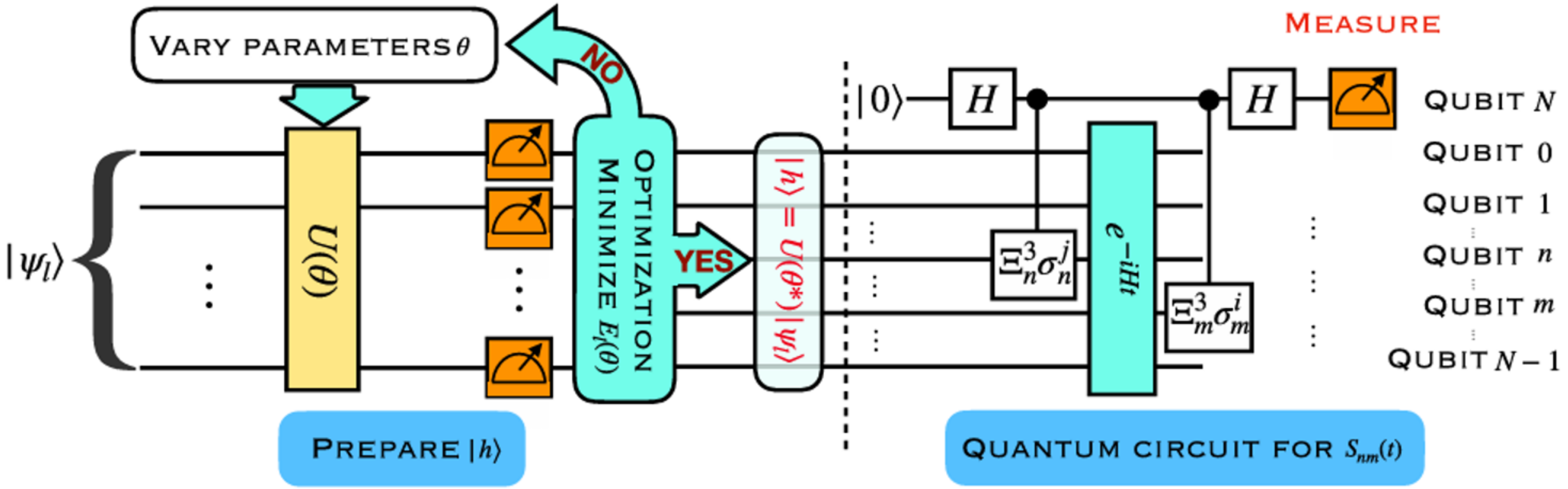
✦ Measure the observable with one auxiliary qubit



Measure the ancillary qubit on X (Y) basis to get the real (imaginary) part of $S_{mn}(t)$

Pedernales et al, PRL. 113, 020505 (2014)

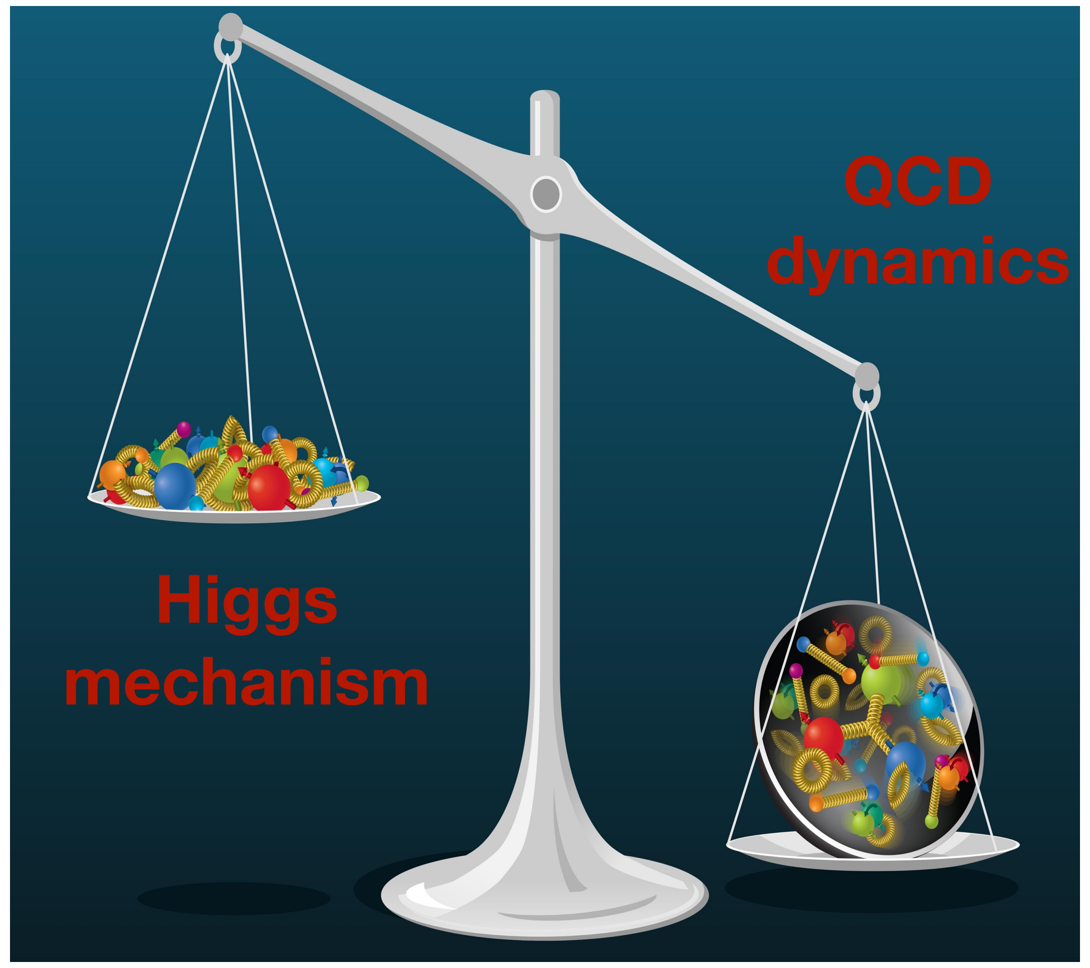
Simulate hadron partonic structure on quantum computer



Numerical results from quantum computing

✦ 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

Numerical results from quantum computing

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

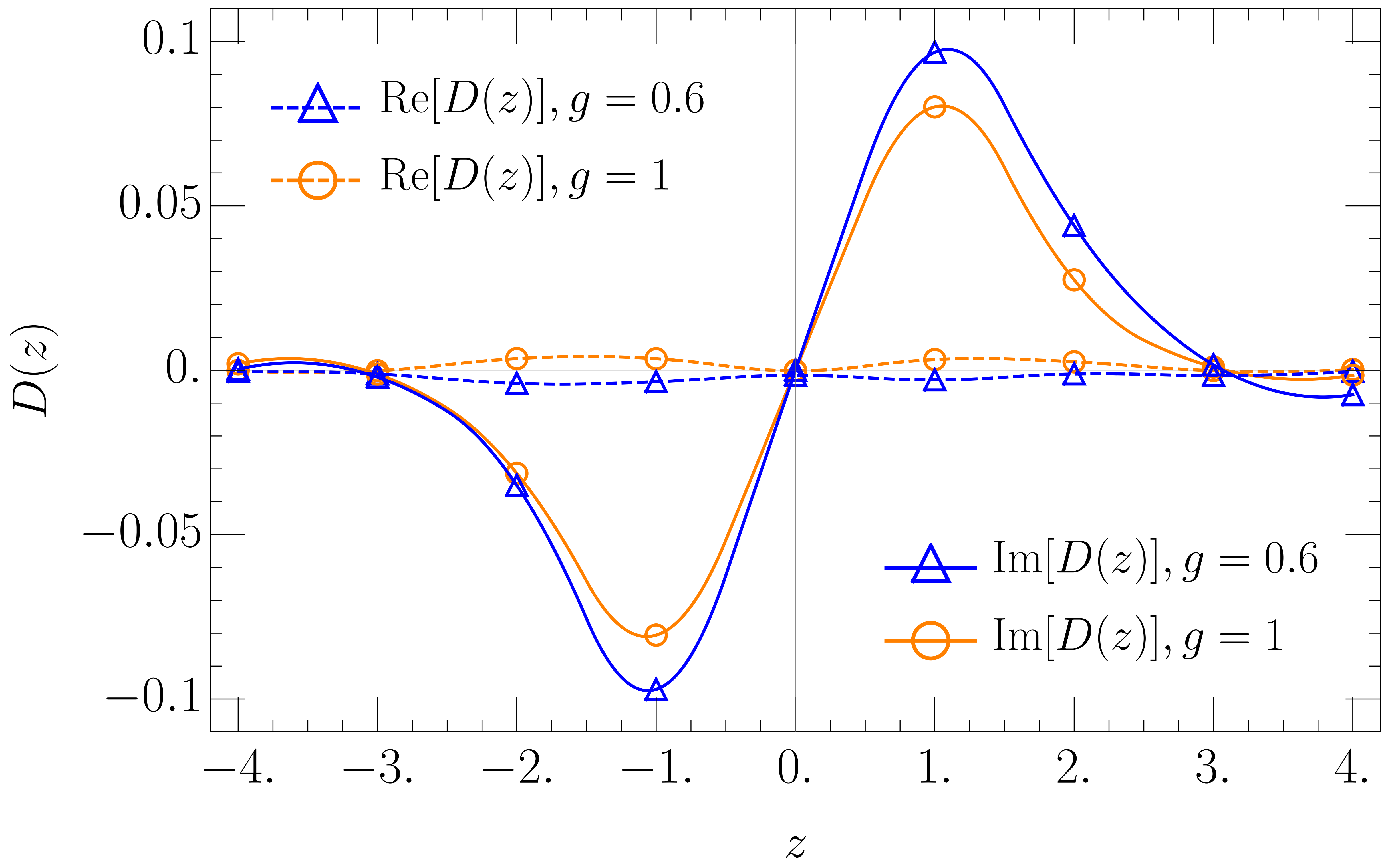
- quark PDF in position space

$$ma = 0.8 \qquad N = 18 \qquad n_f = 1$$

- The real part is consistent with 0

$$f_q(x) = f_{\bar{q}}(x) = -f_q(-x)$$

- The bound state behavior

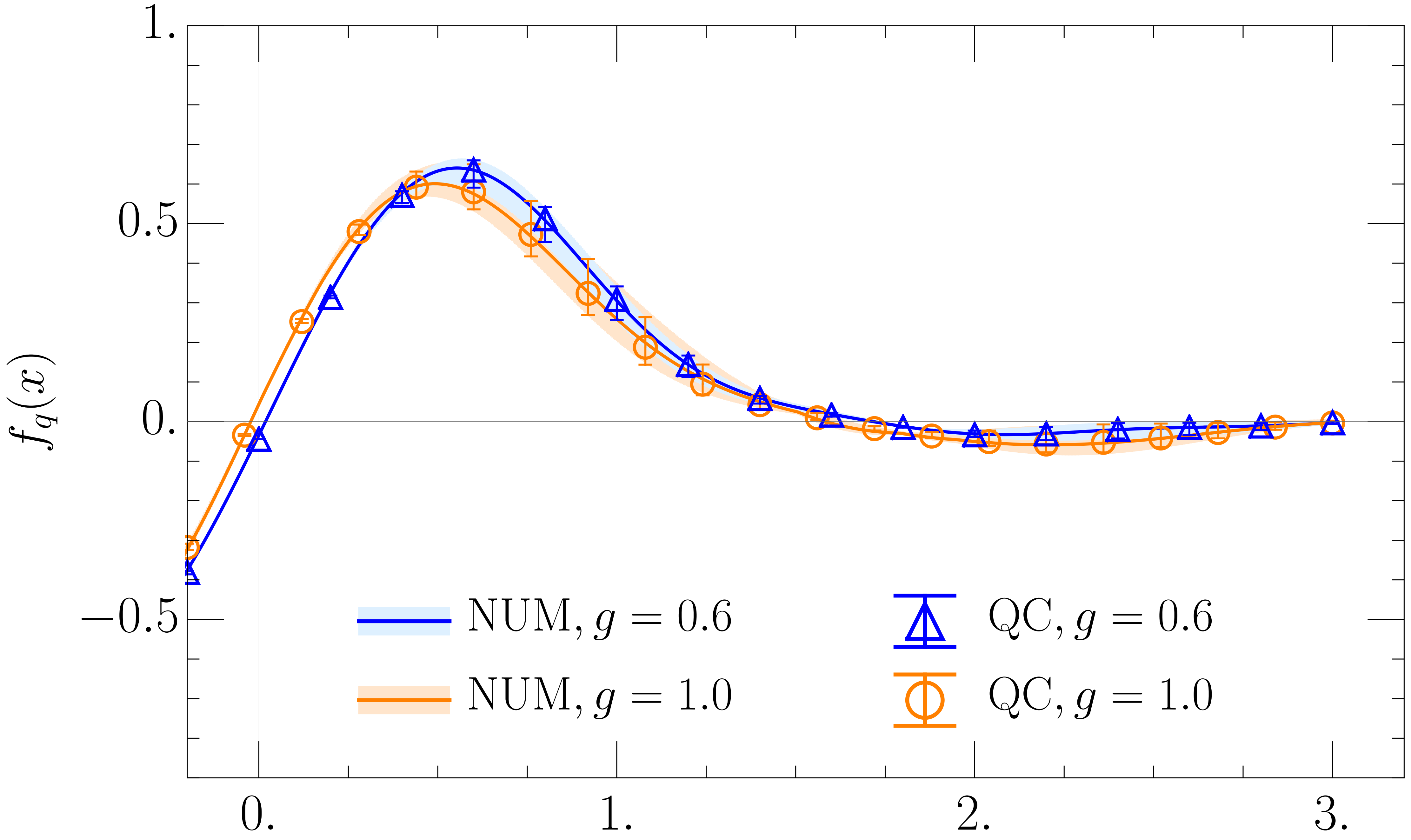


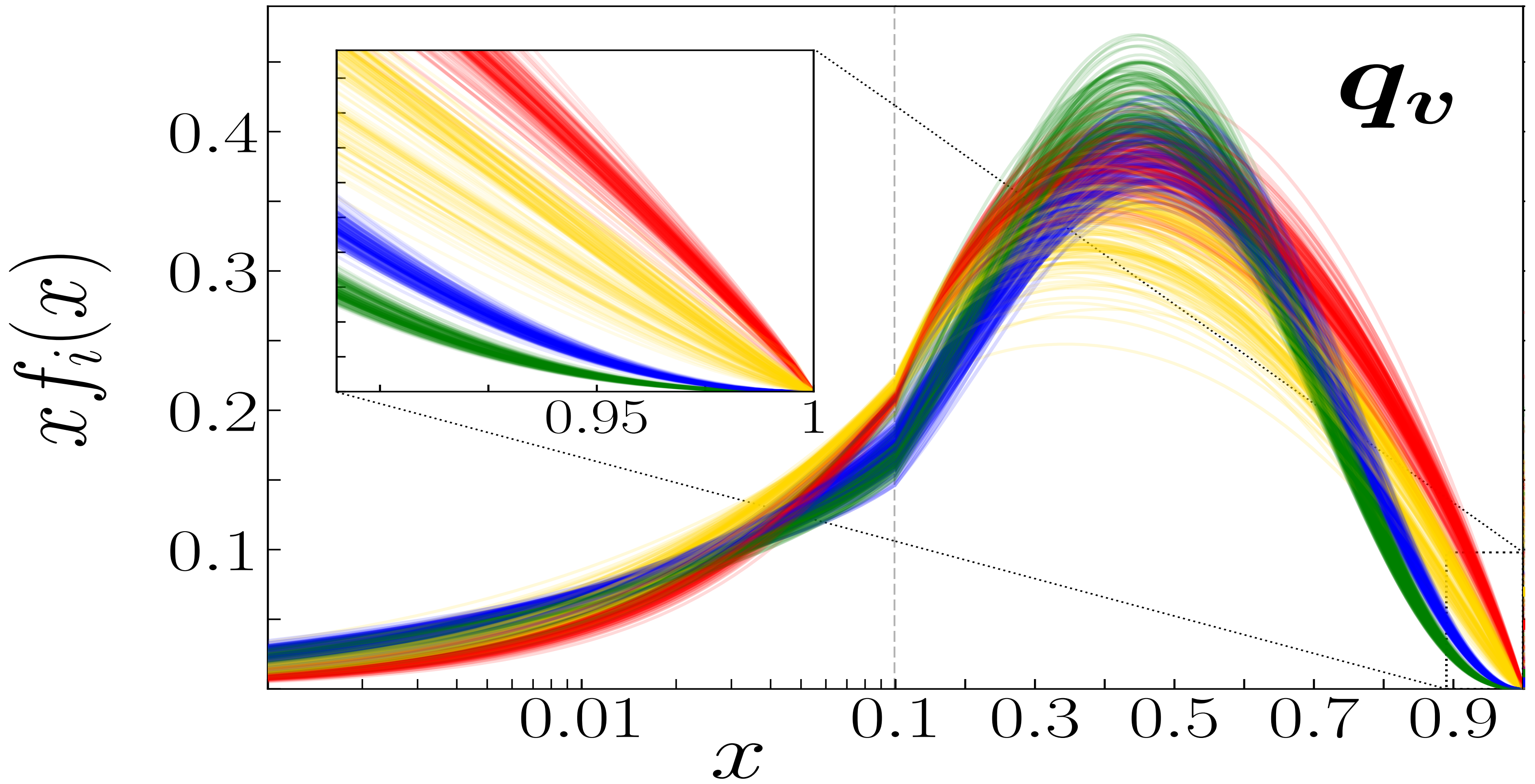
Numerical results from quantum computing

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





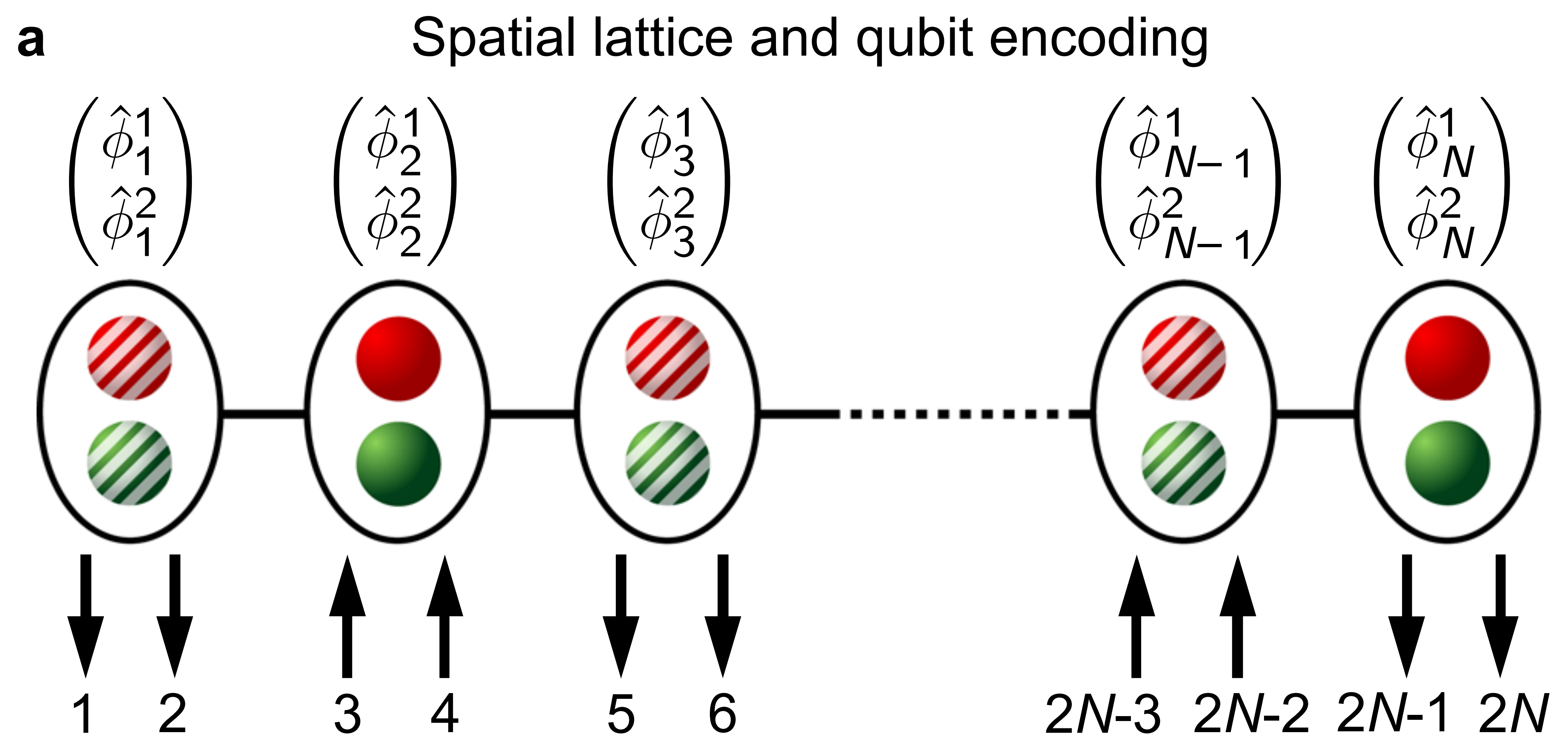
JAM Collaboration, PRL, 2021

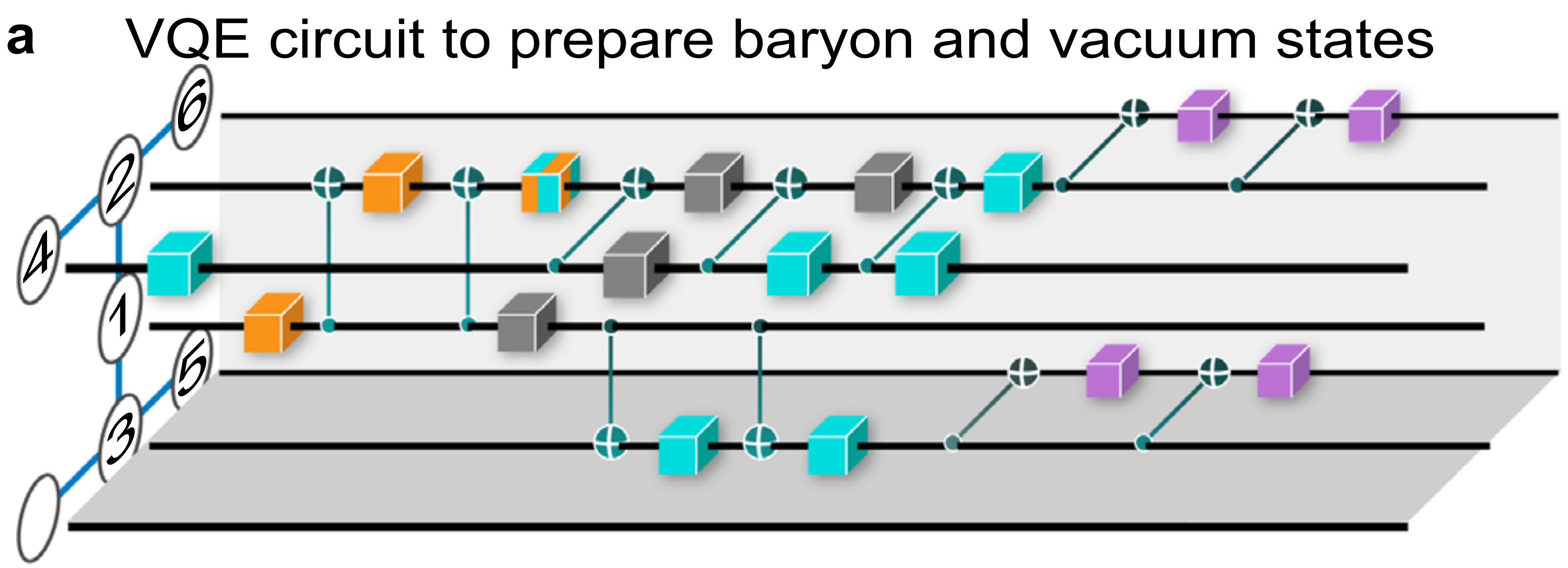
Simulate SU(2) hadron on quantum computer

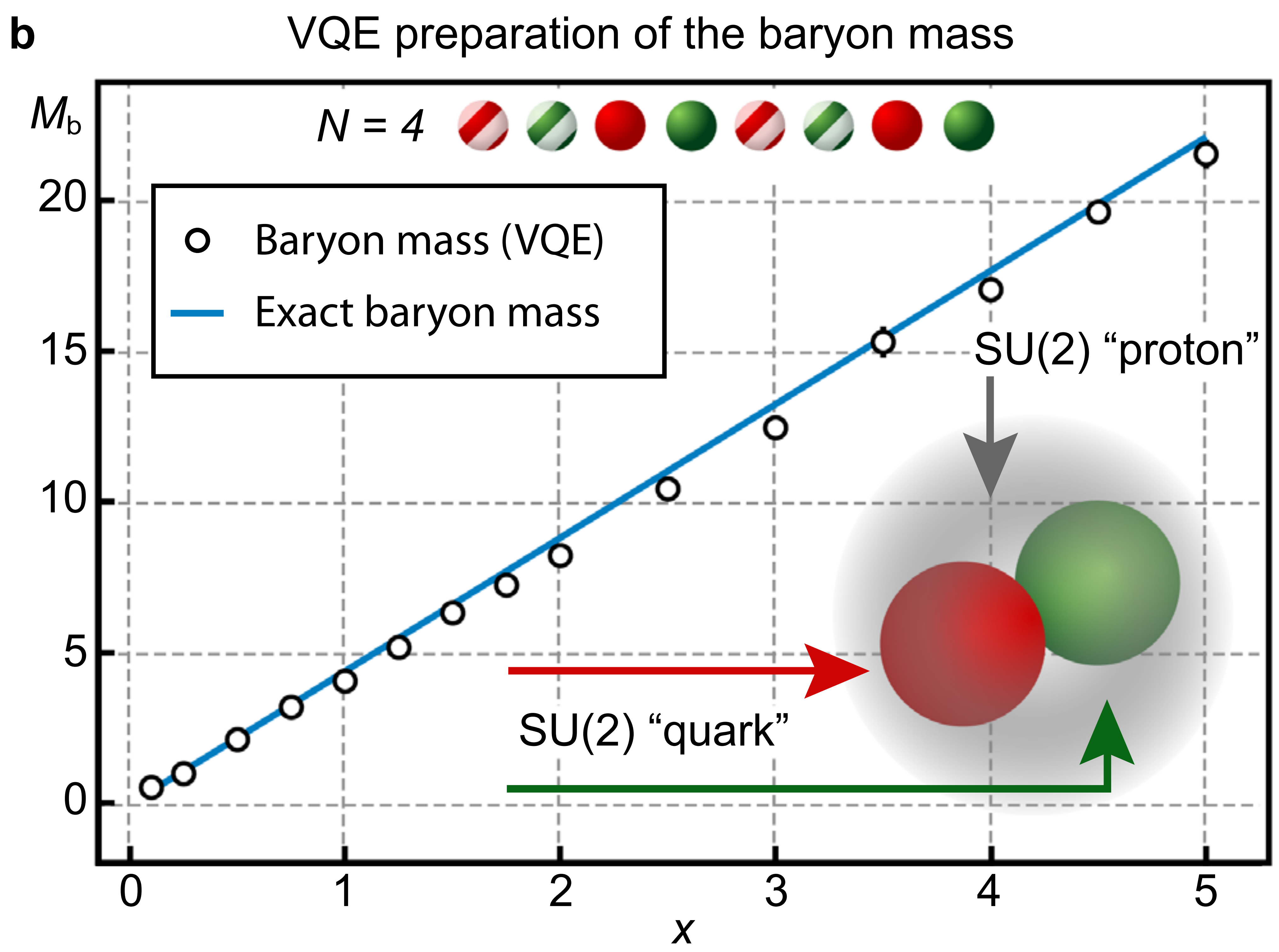
- SU(2) Hamiltonian

Atas et al, Nature Commun. 2021

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







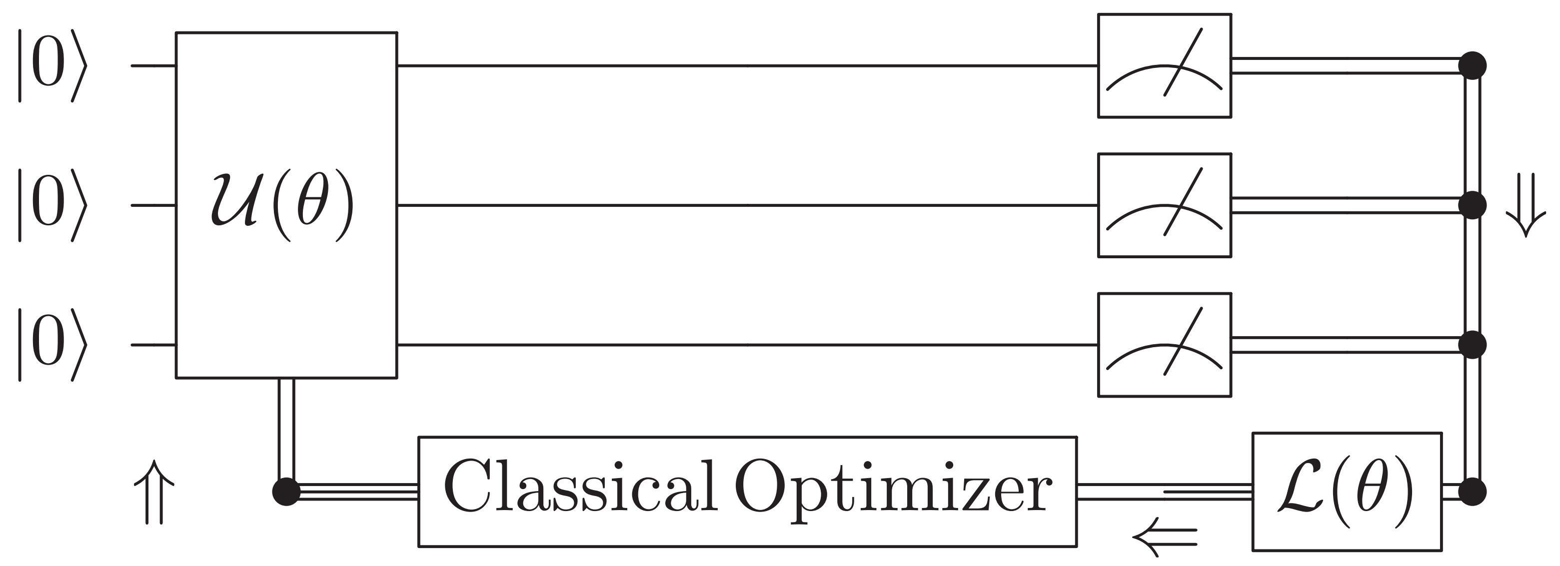
Alternative approaches

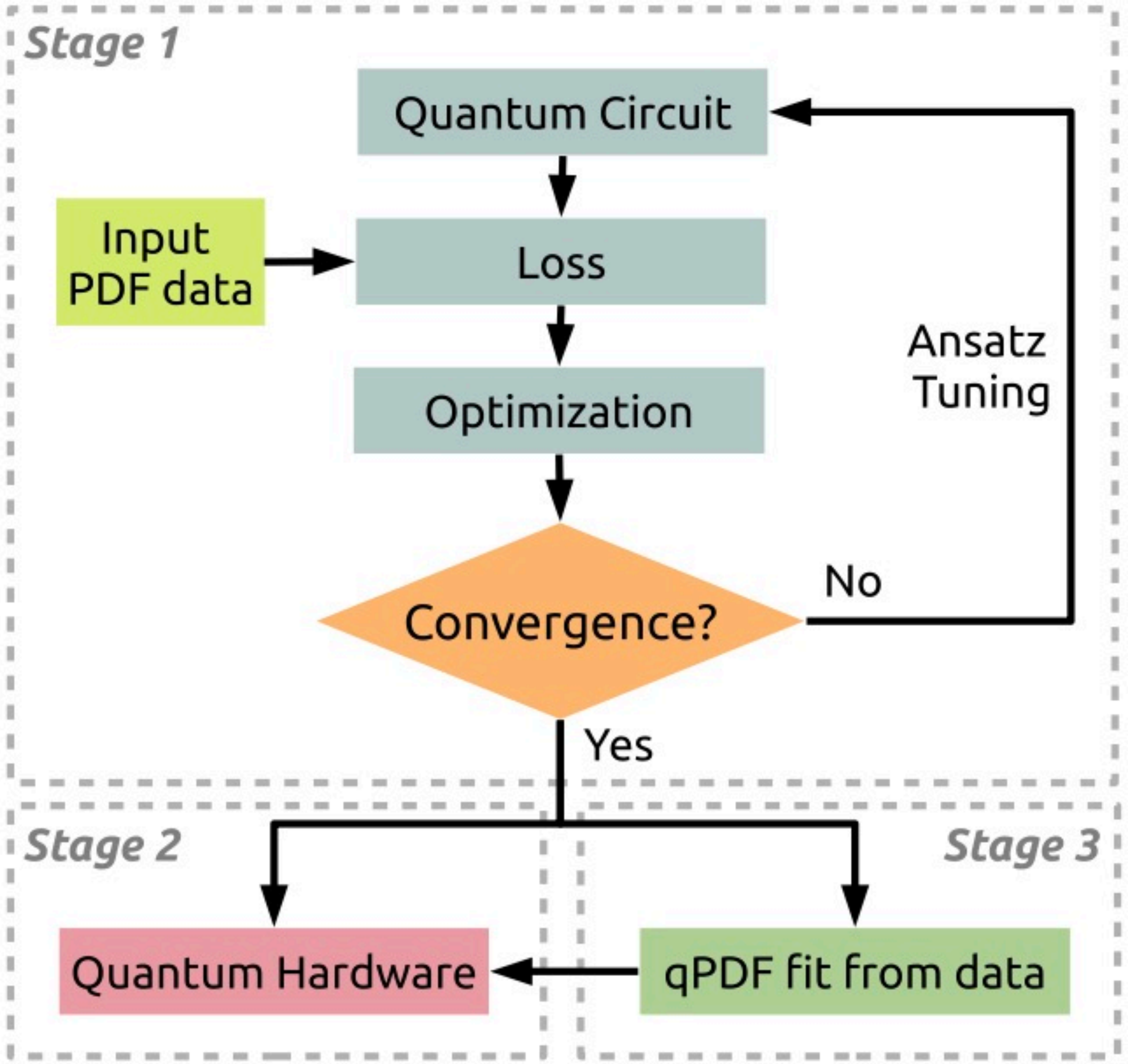
- Global fitting with quantum circuit at initial scale

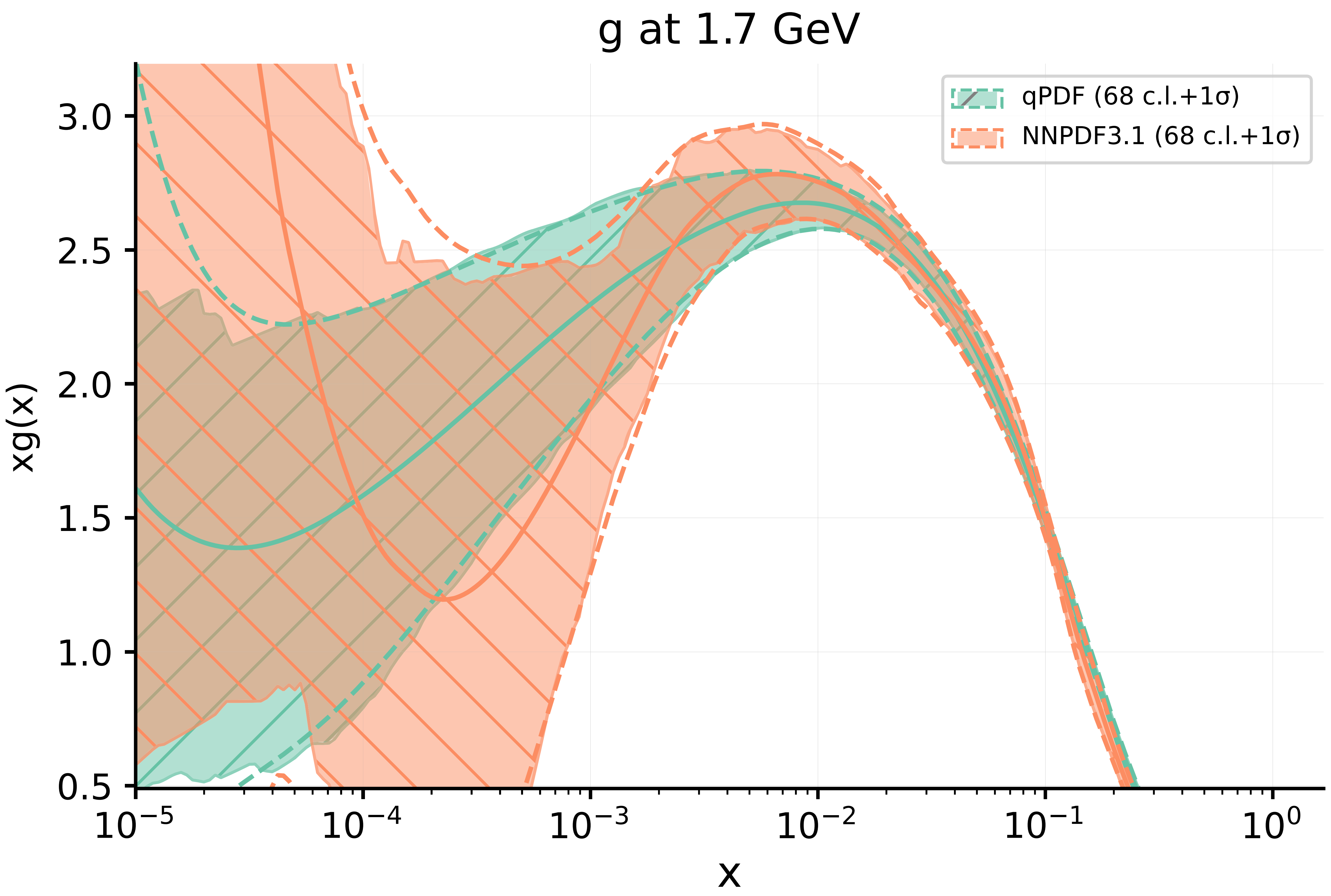
quantum parametrization: $\mathrm{qPDF}_i(x, Q_0, \theta) = \frac{1 - z_i(\theta, x)}{1 + z_i(\theta, x)}$

variational quantum circuit: $z_i(\theta, x) = \langle \psi(\theta, x) | Z_i | \psi(\theta, x) \rangle$

$\mathcal{U}(\theta, x)|0\rangle^{\otimes n} = |\psi(\theta, x)\rangle$







Salinas et al, PRD 2021

Alternative approaches

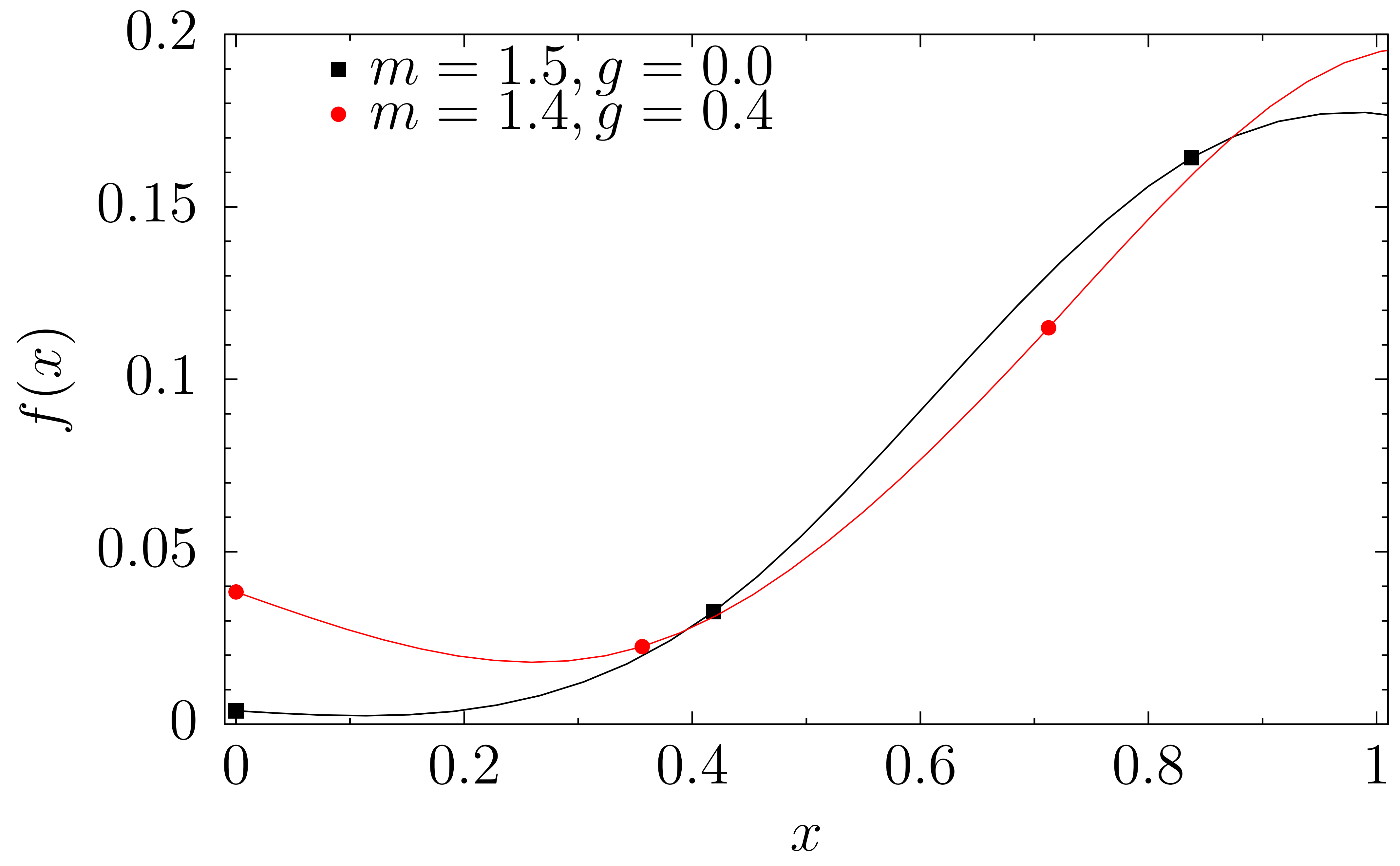
- Global fitting based hadronic tensor

NuQS, PRR 2020

Hadronic tensor: $$W^{\mu\nu}(q) = \mathrm{Re}\int d^dx\, e^{iqx}\langle P|T\{J^\mu(x)J^\nu(0)\}|P\rangle$$

Collinear factorization: $$W^{\mu\nu} = \sum_{i,j} f_i \otimes P_{i\to j} \otimes \hat{W}^{\mu\nu}$$

- A test from exact diagonalization of Hamiltonian in Thirring model



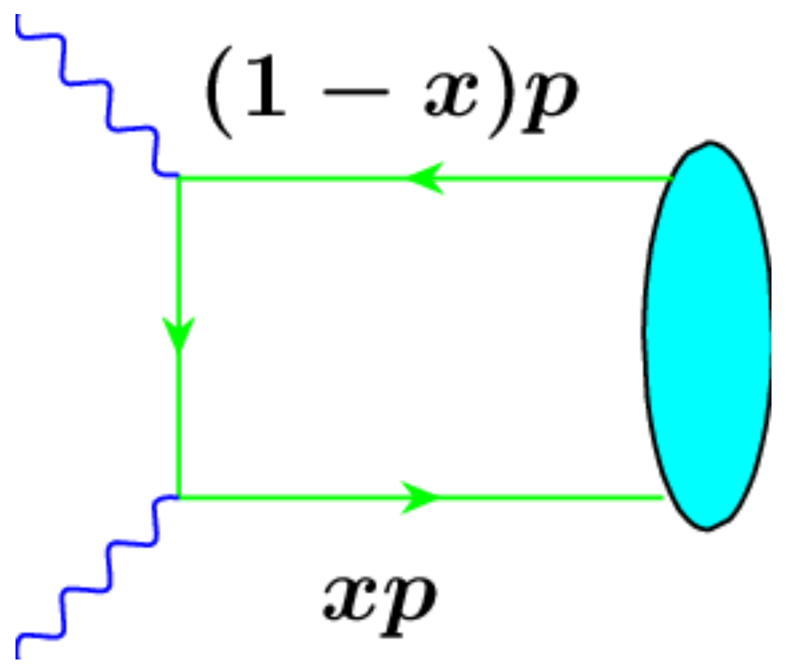
Quantum computing for exclusive hadronization

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

- ✦ LCDA is an essential ingredient in exclusive high-energy QCD processes, e.g. form factor in the process $\gamma^*\gamma \to \pi^0$

$$F(Q^2) = f_\pi \int_0^1 dx\, T_H(x, Q^2; \mu)\phi_\pi(x; \mu) + \mathcal{O}(\Lambda^2_{\mathrm{QCD}}/Q^2)$$

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



- ✦ The current knowledge on LCDA is limited, mainly on models and lattice calculations

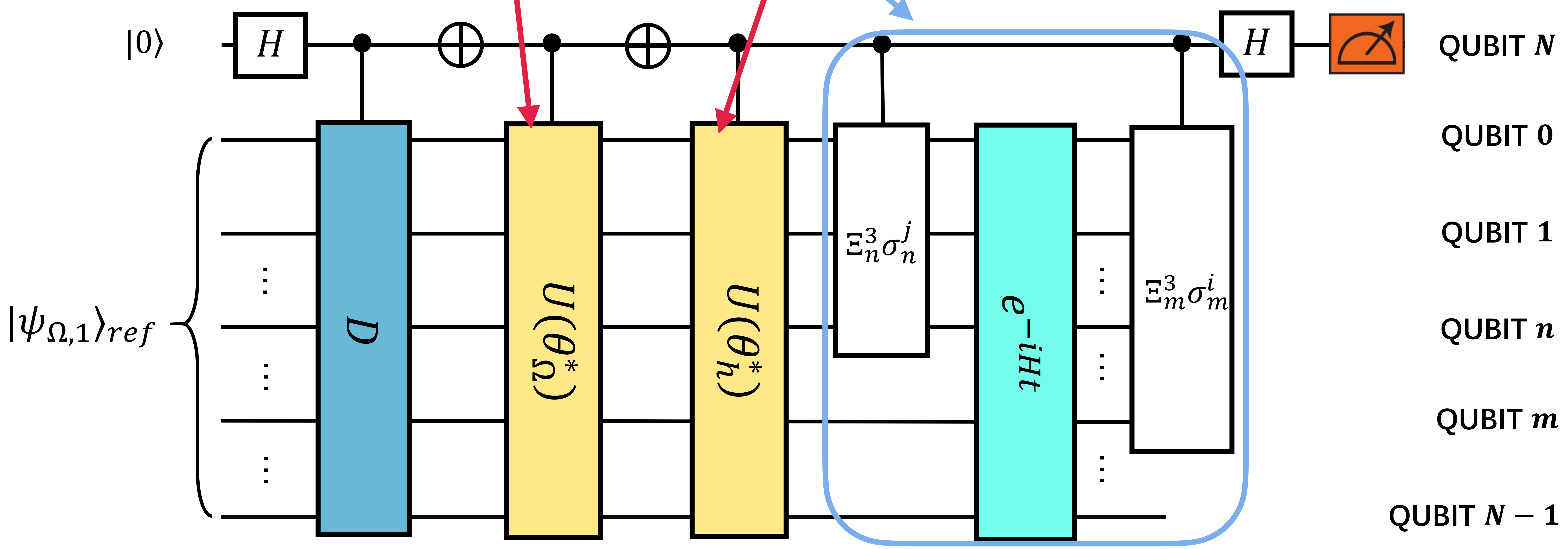
- ✦ First try using quantum computing

LCDA on quantum computer

✦ Quantum circuit

Li et al (QuNu), SCPMA (2023)

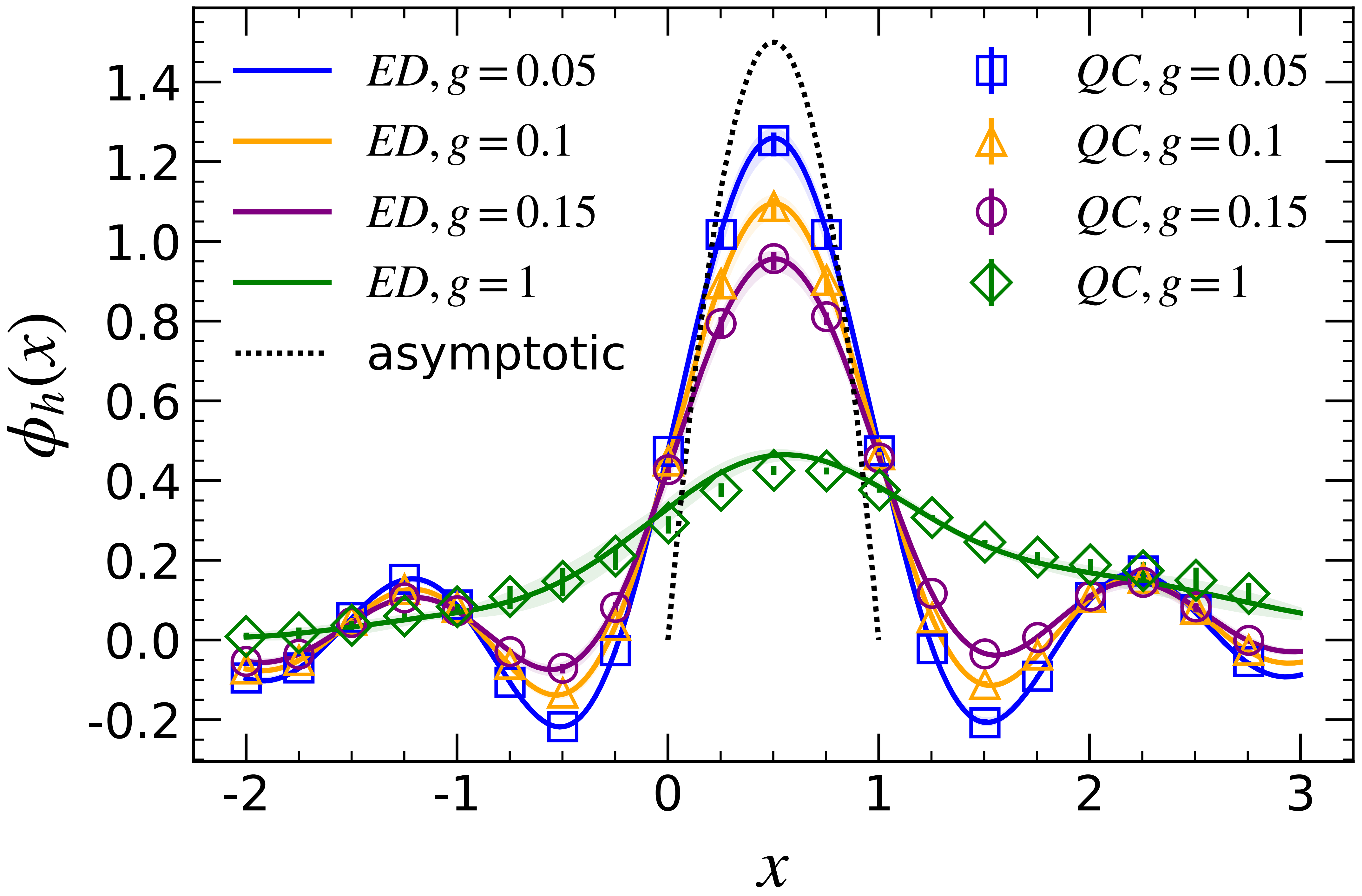
$$|\phi'\rangle = \frac{1}{\sqrt{2}}(|\Omega\rangle|0\rangle + \hat{O}|h\rangle|1\rangle)$$

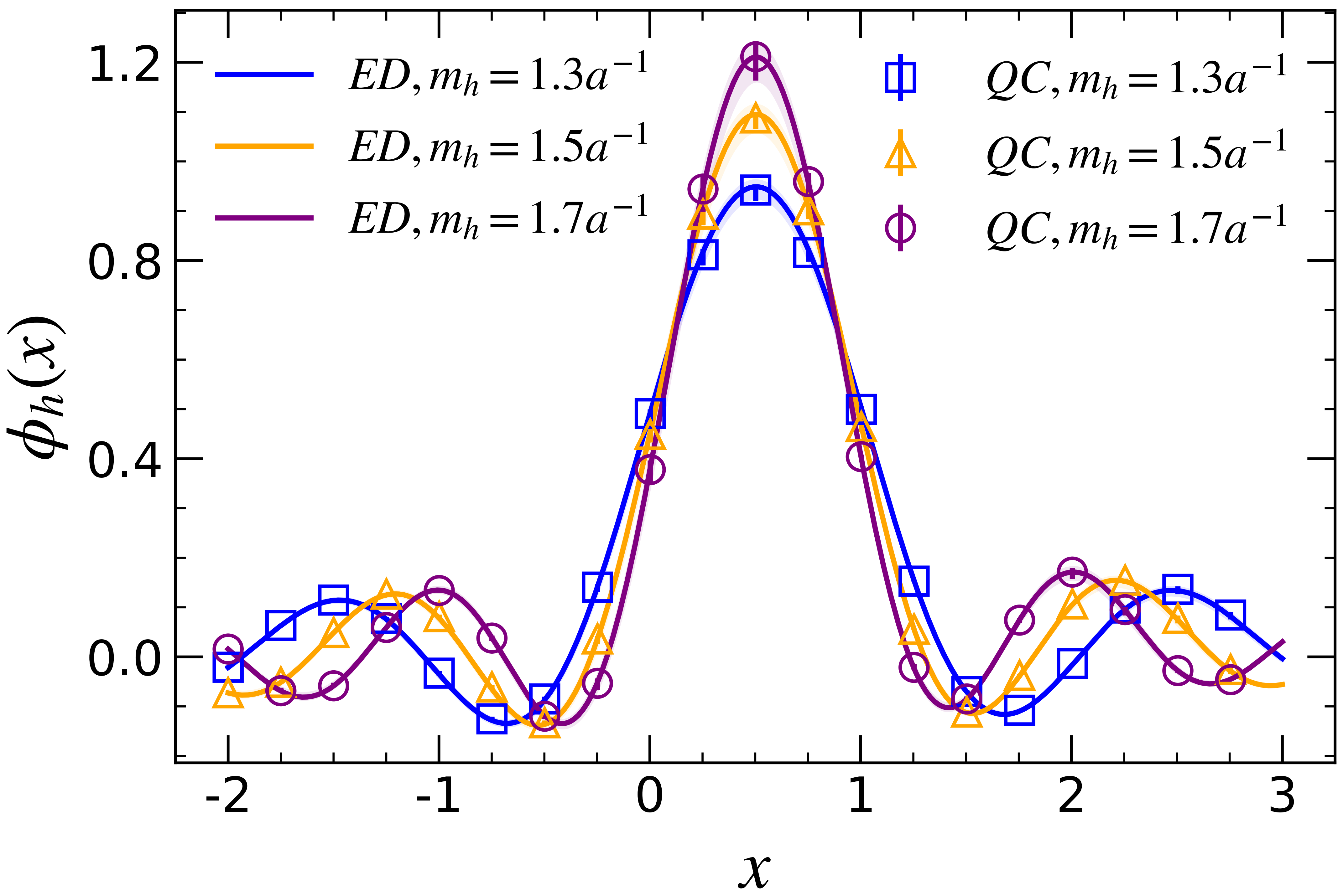


$$D|\psi_{\Omega,1}\rangle_{ref} = |\psi_{\Omega,2}\rangle_{ref}$$

LCDA on quantum computer

✦ Numerical results





- peak gets narrower with decreasing coupling constant or increasing hadron mass
- Converges to asymptotic result in weak coupling limit

Quantum computing for nuclear physics (QuNu)

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Thanks for your attention!