Lattice QCD: Helping set the stage for the future Electron-Ion Collider

Christine A. Aidala
University of Michigan

Lattice 2026
University of Maryland
July 31, 2026

QCD: How far have we come?

- The challenge of confinement: d.o.f. of our QFT not the d.o.f. we work with in experiment

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  - 2004 Nobel Prize, end of HERA running 2007, early discoveries first few years after Relativistic Heavy Ion Collider turned on in 2001, …
  - Within the framework of perturbative QCD, various developments and ideas through the 1990s and early 2000s, e.g. resummation techniques, nonlinear evolution at small *x*, transverse-momentum-dependent PDFs, GPDs to encode spatial distributions of partons in the nucleon, …

Closing the "discovery and development" phase for lattice QCD in the early 2000s…

VOLUME 92, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 16 JANUARY 2004

High-Precision Lattice QCD Confronts Experiment

C. T. H. Davies,[1] E. Follana,[1] A. Gray,[1] G. P. Lepage,[2] Q. Mason,[2] M. Nobes,[3] J. Shigemitsu,[4] H. D. Trottier,[3] and M. Wingate[4]

(HPQCD and UKQCD Collaborations)

[1]*Department of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[2]*Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, New York 14853, USA*
[3]*Physics Department, Simon Fraser University, Vancouver, British Columbia, Canada*
[4]*Physics Department, The Ohio State University, Columbus, Ohio 43210, USA*

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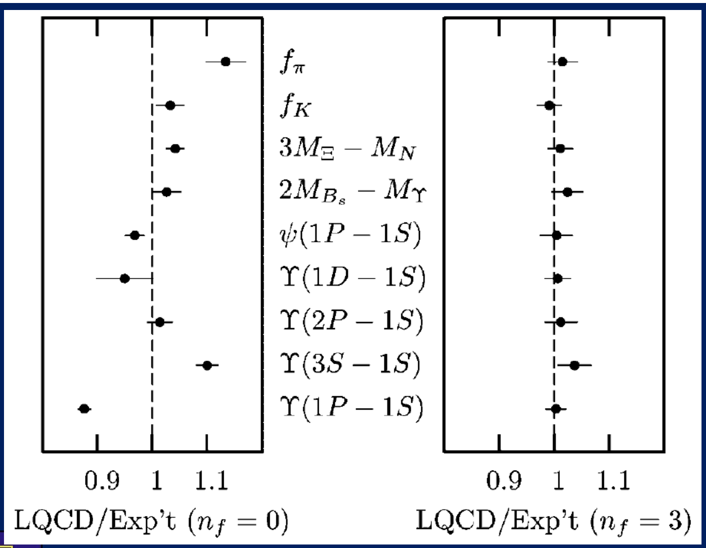
(MILC Collaboration)



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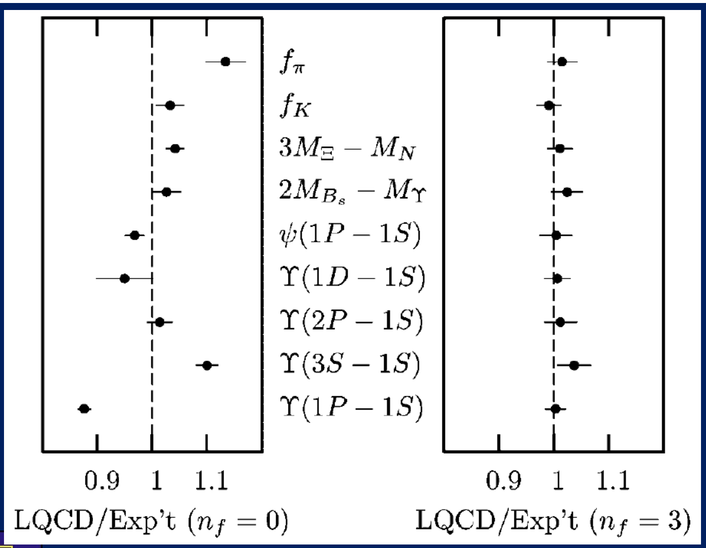
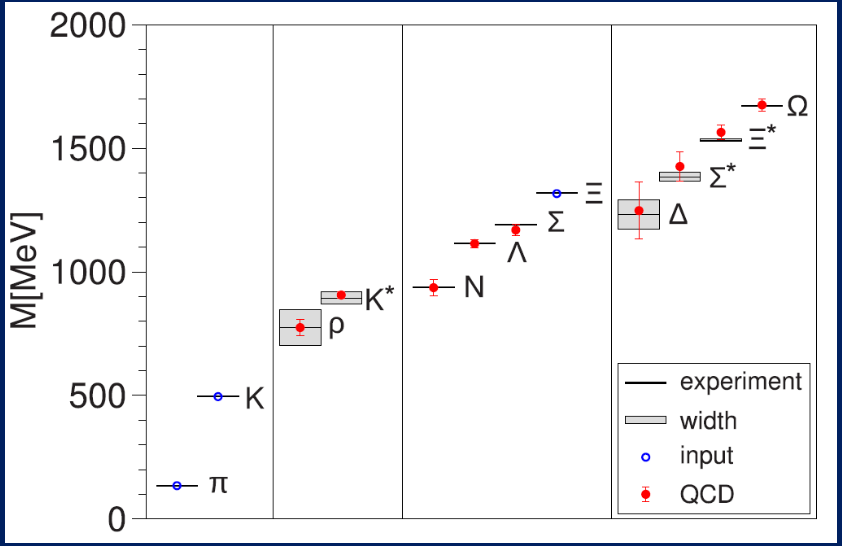


21 NOVEMBER 2008 VOL 322 SCIENCE

Ab Initio Determination of Light Hadron Masses

S. Dürr,[1] Z. Fodor,[1,2,3] J. Frison,[4] C. Hoelbling,[2,3,4] R. Hoffmann,[2] S. D. Katz,[2,3] S. Krieg,[2] T. Kurth,[2] L. Lellouch,[4] T. Lippert,[2,5] K. K. Szabo,[2] G. Vulvert[4]



Closing the "discovery and development" phase for lattice QCD in the early 2000s…

PHYSICAL REVIEW D **81,** 074503 (2010)

Physical point simulation in 2 + 1 flavor lattice QCD

S. Aoki,[1,2] K.-I. Ishikawa,[4] N. Ishizuka,[1,3] T. Izubuchi,[2,5] D. Kadoh,[3,*] K. Kanaya,[1] Y. Kuramashi,[1,3] Y. Namekawa,[3] M. Okawa,[4] Y. Taniguchi,[1,3] A. Ukawa,[1,3] N. Ukita,[3] T. Yamazaki,[3] and T. Yoshié[1,3]

(PACS-CS Collaboration)

Physics Letters B 701 (2011) 265–268

Contents lists available at ScienceDirect

Physics Letters B

ELSEVIER

www.elsevier.com/locate/physletb

Lattice QCD at the physical point: Light quark masses

Budapest–Marseille–Wuppertal Collaboration

S. Durr[a,c], Z. Fodor[a,c,d,*], C. Hoelbling[a,b], S.D. Katz[d,a], S. Krieg[a,c], T. Kurth[a], L. Lellouch[b], T. Lippert[c,a], K.K. Szabo[a], G. Vulvert[b]

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PHYSICS LETTERS B

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S. Du

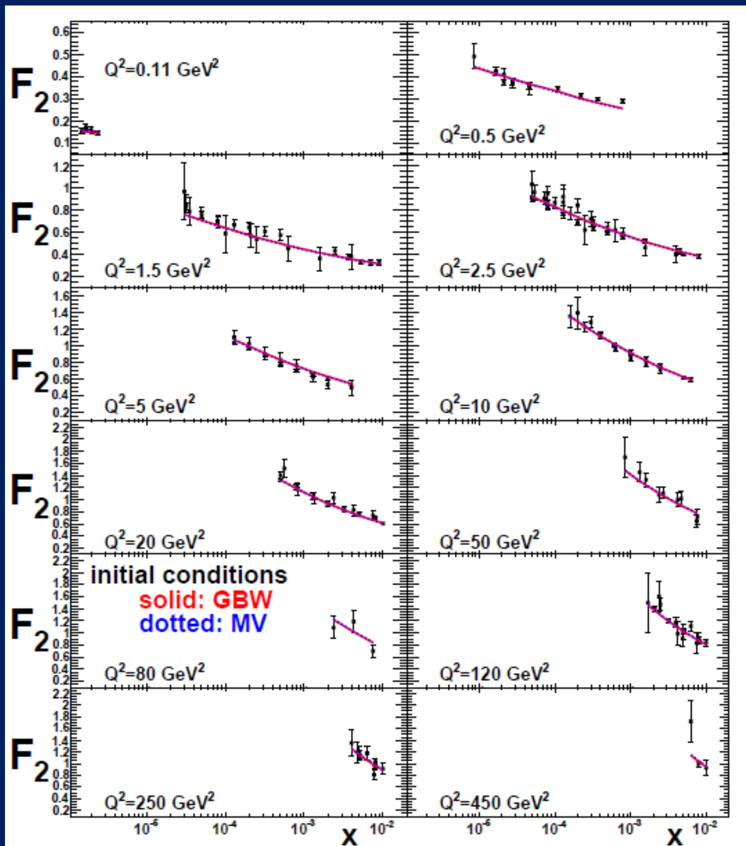
K.K. Szabo[a], G. Vulvert[b]

We're now marching our way deeper into the second phase: ***quantitative QCD***

The era of quantitative QCD

New ideas and techniques are necessary but not always sufficient—need *practical implementations* to be able to perform *quantitative* calculations!

Example: Phenomenological applications of a non-linear gluon saturation regime



Fits to proton structure function data at low parton momentum fraction *x*.

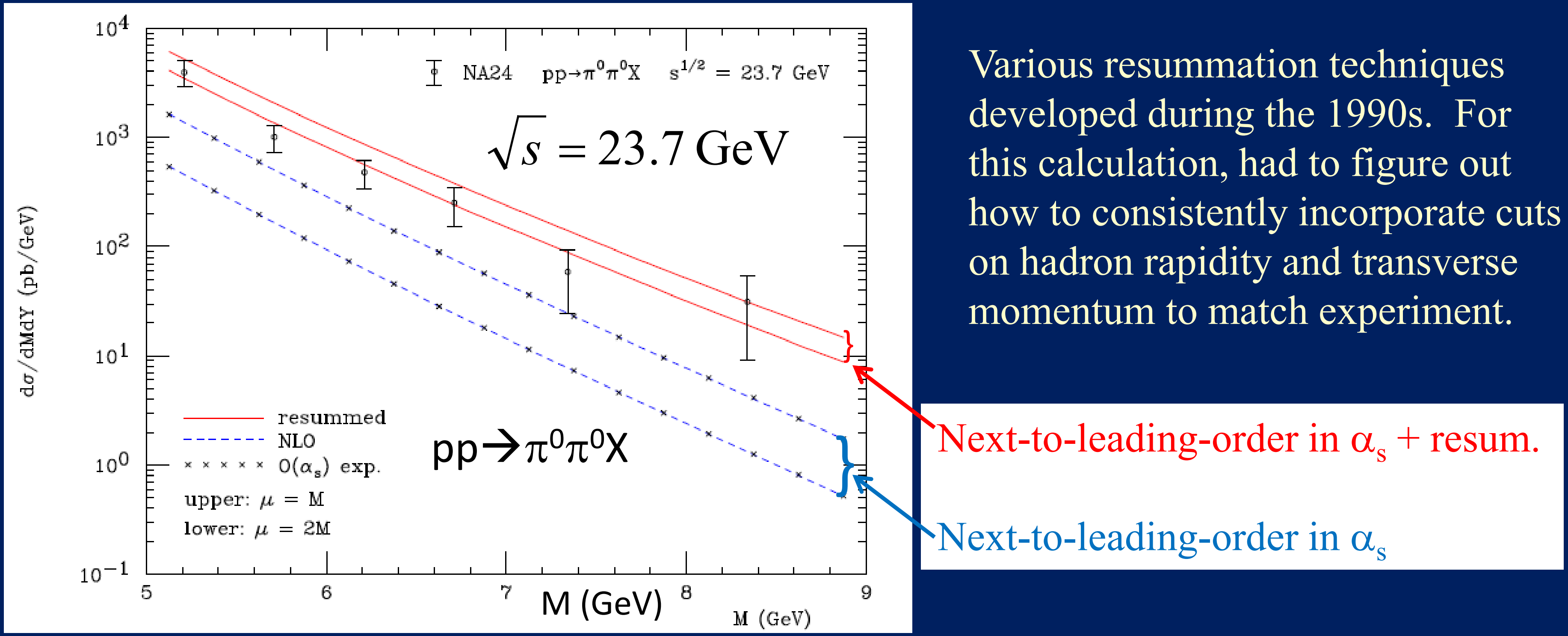
Non-linear QCD meets data: A global analysis of lepton-proton scattering with running coupling BK evolution

Phys. Rev. D80, 034031 (2009)

Javier L. Albacete[1], Néstor Armesto[2], José Guilherme Milhano[3] and Carlos A. Salgado[2]

Basic framework for non-linear QCD developed ~1997-2001. But had to wait for running coupling BK evolution in 2007 to compare directly to data

Example: Threshold resummation Extending perturbative calculations to lower energies



Various resummation techniques developed during the 1990s. For this calculation, had to figure out how to consistently incorporate cuts on hadron rapidity and transverse momentum to match experiment.

Almeida, Sterman, Vogelsang PRD80, 074016 (2009)

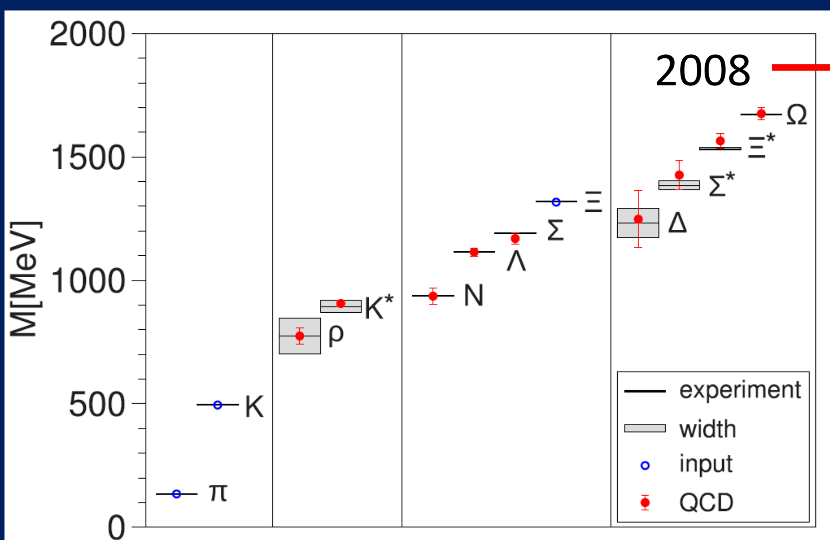
Example: Lattice calculations of light baryon masses with isospin splitting

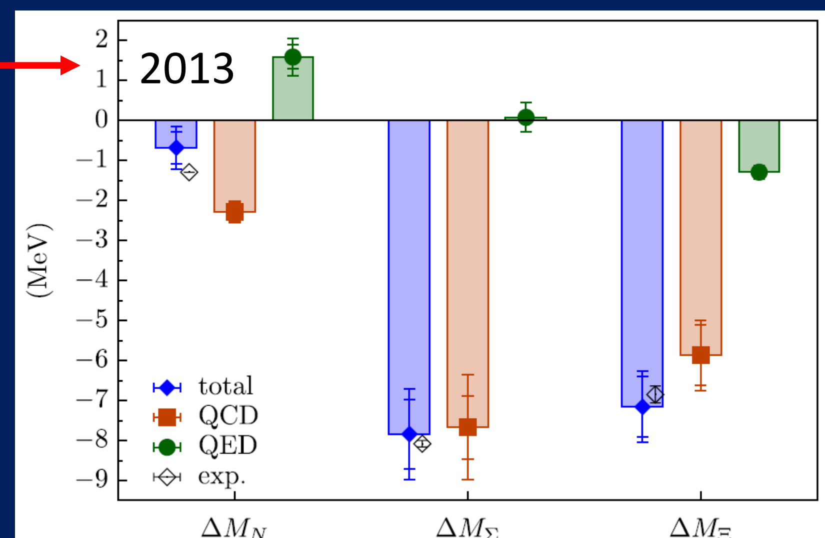
PRL **111,** 252001 (2013) PHYSICAL REVIEW LETTERS week ending 20 DECEMBER 2013

Isospin Splittings in the Light-Baryon Octet from Lattice QCD and QED

Sz. Borsanyi,[1] S. Dürr,[1,2] Z. Fodor,[1,2,3] J. Frison,[4,5,†] C. Hoelbling,[1] S. D. Katz,[3,6] S. Krieg,[1,2] Th. Kurth,[1] L. Lellouch,[4,5] Th. Lippert,[2] A. Portelli,[4,5,7,*] A. Ramos,[4,5,‡] A. Sastre,[4,5] and K. Szabo[1]

(Budapest-Marseille-Wuppertal Collaboration)





2000 MeV vertical axis scale → 11 MeV vertical axis scale

Example: Lattice calculations of the Collins-Soper kernel

- At the Transversity 2014 workshop in Cagliari, I asked about calculating this on the lattice and was told it would be impossible…

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- LaMET had already been introduced (Ji, PRL 2013)…
- But needed to wait until 2019 (Ebert, Stewart, Zhao, PRD + JHEP) to figure out the Wilson line geometry on the lattice

Collins-Soper kernel for TMD evolution from lattice QCD

Phiala Shanahan,[1,*] Michael Wagman,[1,2,†] and Yong Zhao[1,3,‡]
[1]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA 02139*
[2]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[3]*Physics Department, Brookhaven National Laboratory, Building 510A, Upton, New York*

(Received 4 April 2020; accepted 8 July 2020; published 22 July 2020)

at large hadron momentum [30–37]. In particular, it was recently shown in Refs. [32,33] how this approach may be used to extract the Collins-Soper kernel nonperturbatively from computations of matrix elements of nonlocal quark bilinear operators with staple-shaped Wilson lines. Here, this approach is implemented numerically for the first time, in a proof-of-principle calculation in quenched QCD. The

The Electron-Ion Collider

- A facility to bring the era of quantitative QCD to maturity!

The Electron-Ion Collider

- A facility to bring the era of quantitative QCD to maturity!

- The first *QCD-motivated* facility *designed in the era of quantitative QCD*

A QCD-motivated facility: Control

The more aspects of the collisions we can control/manipulate, the more powerful our tools

- Collision species → state of matter to be studied, geometry, path length, quark flavor/isospin, electroweak vs. strong interactions
- Energy → distance/time scales, probes accessible, states of matter
- Polarization → spin-spin and spin-momentum correlations in QCD systems or in hadronization, sensitivity to system properties

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Some aspects we *select* rather than control

- Overlap of colliding nuclei, final-state produced particles and their kinematics, …

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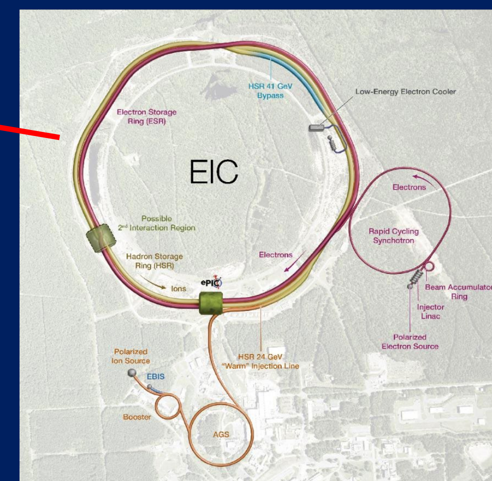
The future Electron-Ion Collider, as a QCD-focused facility, will operate with exquisite control over the colliding systems. A "tabletop experiment for giants"!

The Electron-Ion Collider

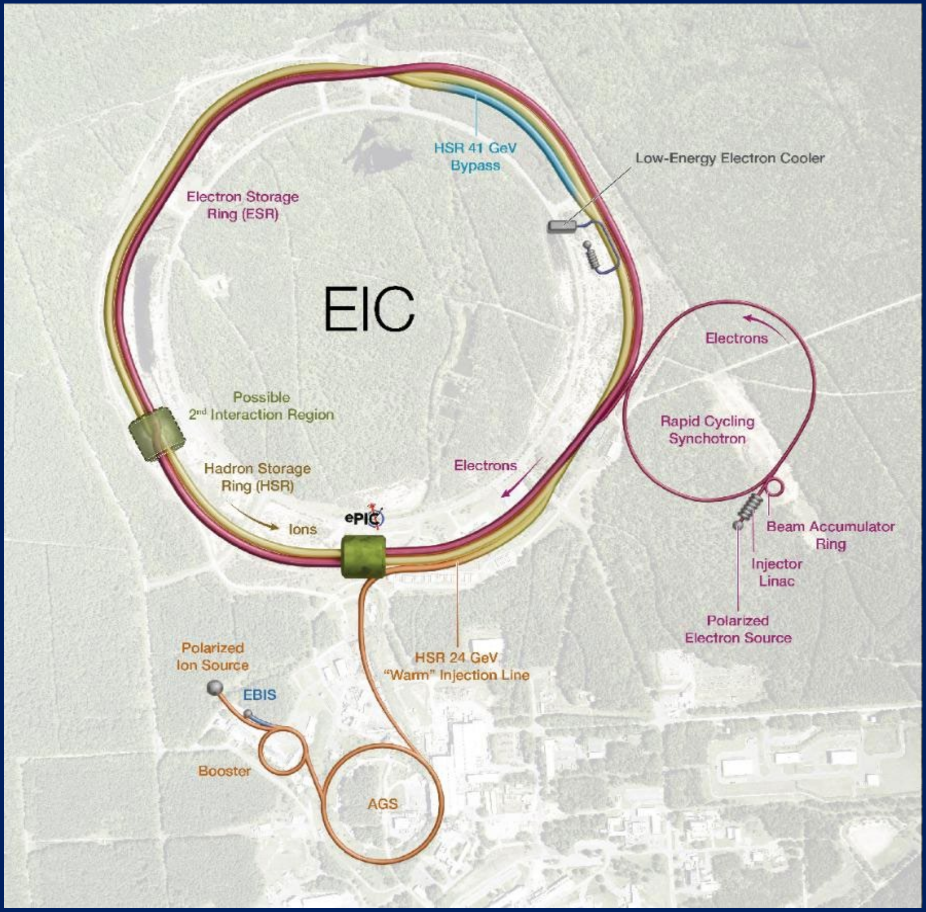
A joint endeavor by Thomas Jefferson National Accelerator Facility and Brookhaven National Lab, to be sited at BNL



Builds upon Dept. of Energy's ~$2B+ investment in the Relativistic Heavy Ion Collider complex

The Electron-Ion Collider

- Highly polarized electron (~70%) and proton (~70%) beams
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium
- Variable $e + p$ center-of-mass energies from ~20-100 GeV
  - Upgradable to ~140 GeV
- $e + p$ luminosity $10^{33} - 10^{34}$ cm^{-2} s^{-1}
  → 10-100 fb^{-1}/yr
- Accommodate a future 2nd interaction region



Protons: 41, 100 – 275 GeV
Electrons: 5 – 10 GeV (upgradable to 18 GeV)

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  - Including polarized ^{3}He and possibilities for polarized deuterons!
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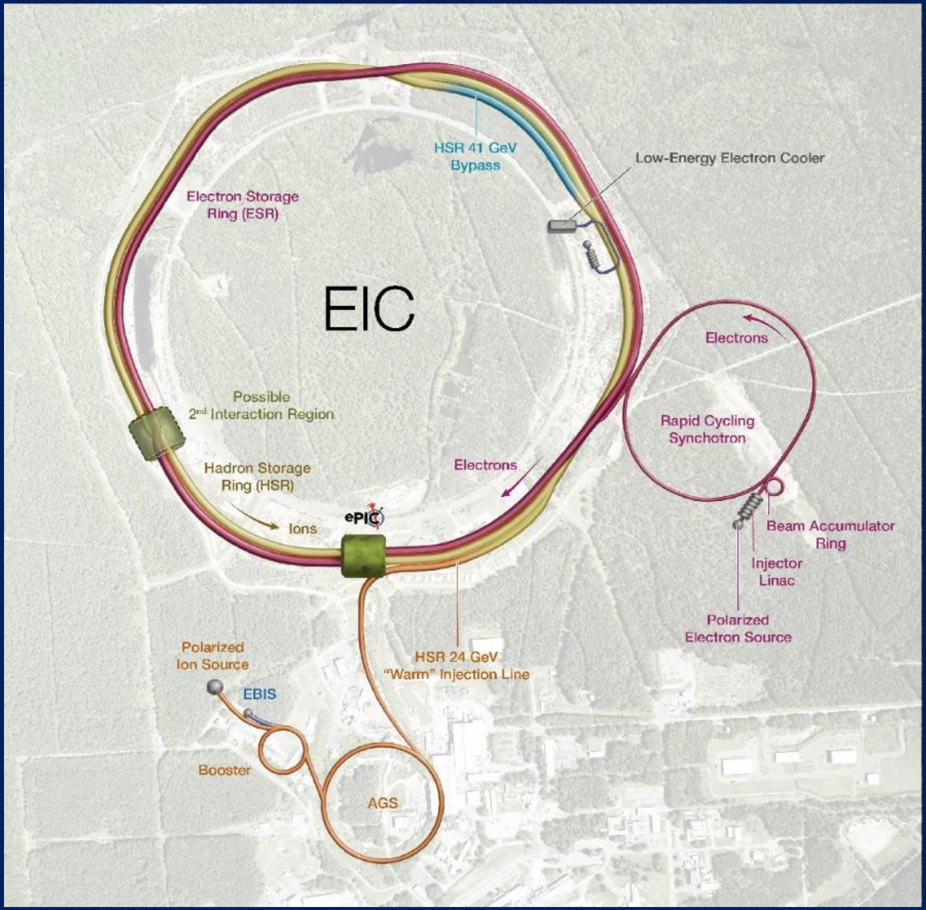

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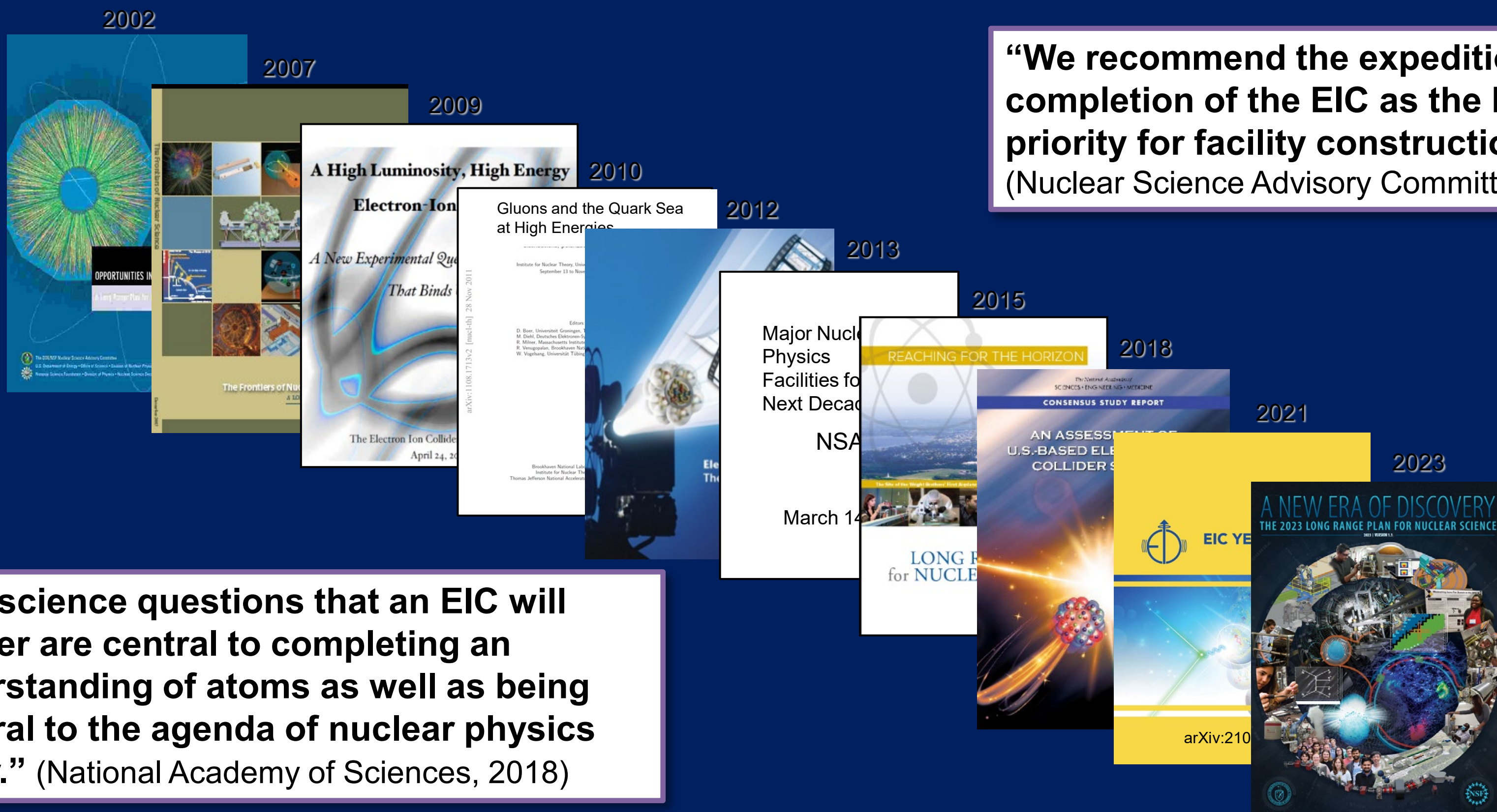
EIC science case built over decades



“We recommend the expeditious completion of the EIC as the highest priority for facility construction.” (Nuclear Science Advisory Committee, 2023)

“The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today.” (National Academy of Sciences, 2018)

27

EIC science pillars

How do quarks, gluons, and orbital angular momentum contribute to proton spin?

Spin is a fundamental quantum property of matter.

SPIN

(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

EIC science pillars

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How does the mass of visible matter emerge from quark-gluon interactions?

Atom:
Binding/Mass = 0.00000001
Nucleus:
Binding/Mass = 0.01
Proton:
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MASS

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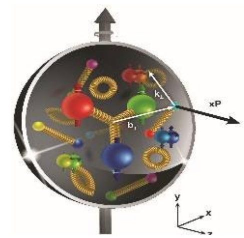

How are quarks and gluons distributed in space and momentum inside the nucleon and nuclei?

Detailed **3D imaging** of nucleons and nuclei.

3D-Imaging

(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

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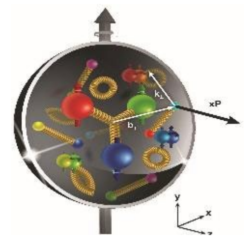

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How do the quark-gluon interactions **create nuclear binding**?

QCD in Nuclei

(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

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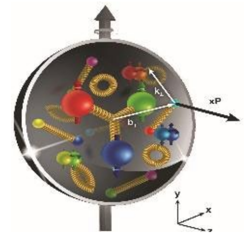

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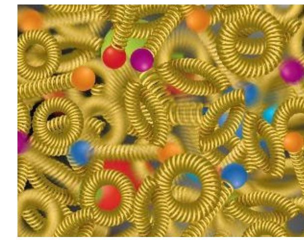
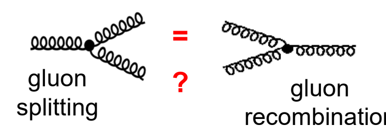


Does gluon density in nuclei saturate at high energy?

How does **a dense nuclear environment affect** the quarks and gluons, their correlations and interactions?



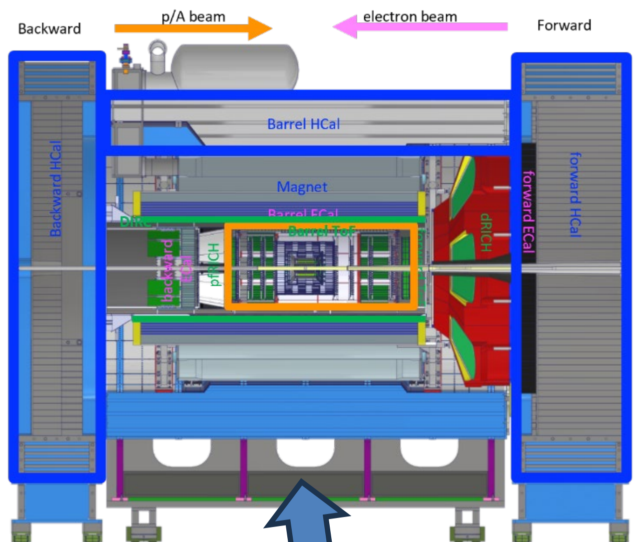
Dense Gluon Systems

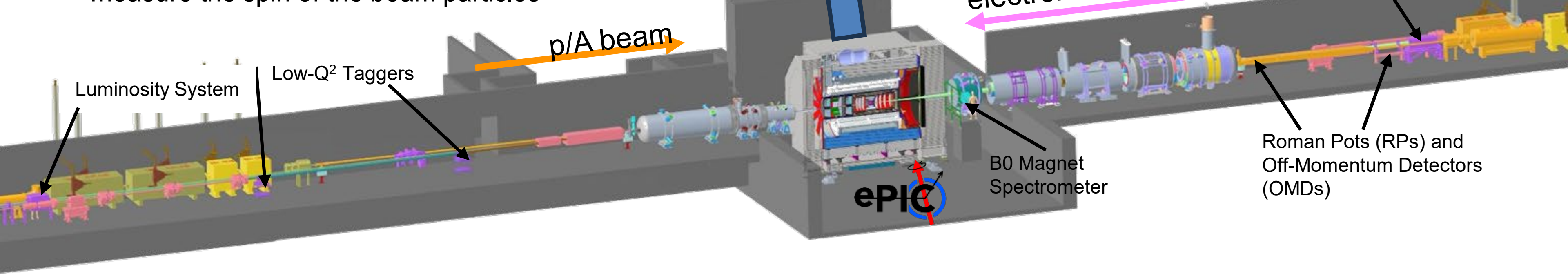
(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

ePIC: A state-of-the-art general purpose detector ***for QCD***

26 subsystems over ± 40 m to measure particle momenta, energy and type

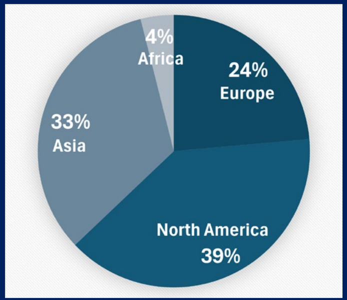
- 2T Solenoid (⌀ 2.84 m)
- 3 hadronic calorimeters
- 3 electromagnetic calorimeters
- 4 particle identification detectors
- Various silicon and micro-pattern gas tracking detectors
- 7 detectors integrated into the accelerator lattice
- Fully streaming readout electronics and DAQ → integrating AI/ML capabilities
- Electron and hadron polarimetry to measure the spin of the beam particles



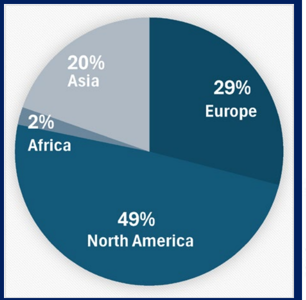


The ePIC Collaboration

Institutions:



Collaborators:



>1100 collaborators
183 institutions
26 countries

ePIC Collaboration – January 2025

EIC User Group

www.eicug.org

Broader than the ePIC Collaboration.

Theorists play an important role, and more are welcome!

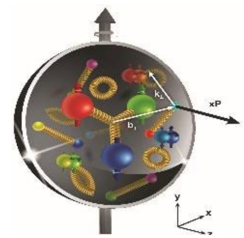
Theoretical advancements offer new tools and new insights, with the power to shift—drastically or subtly—the way we think about the physics we study.

Electron-Ion Collider User Group:
Currently >1500 members from 313 institutions in 43 countries.
(~25% theorists, ~10% accelerator physicists, ~65% experimentalists)

EIC science pillars

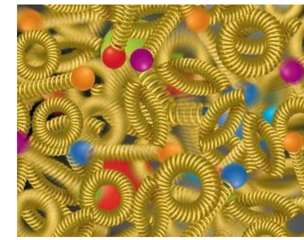
SPIN

MASS



3D-Imaging

QCD in Nuclei



Dense Gluon Systems

(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

EIC science pillars

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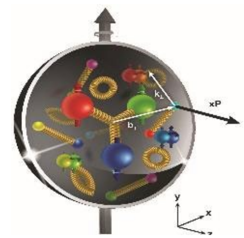

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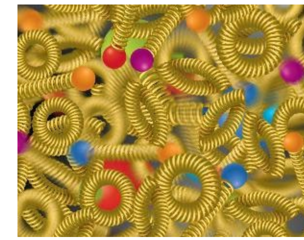

Dense Gluon Systems

(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

- Gluon trace anomaly contribution to nucleon mass
  - More than a decade for lattice calculations to advance before these measurements are performed at the EIC

EIC science pillars

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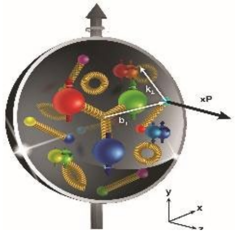

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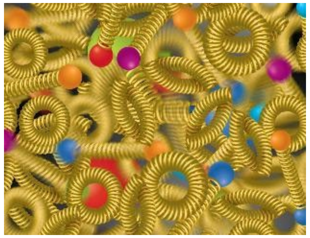

Dense Gluon Systems

(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

- Gluon generalized parton distributions (GPDs) in the proton – will require high luminosity and therefore come later at the EIC
  - Also more than a decade for lattice calculations to advance

EIC science pillars

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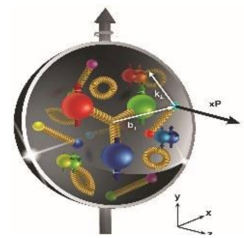
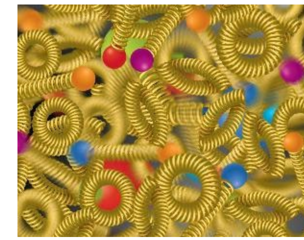


3D-Imaging

QCD in Nuclei



Dense Gluon Systems

(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

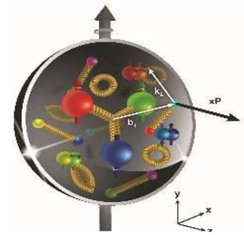
- Meson structure (1D) via the "Sullivan process" – beam proton fluctuates to e.g. $n\pi^+$ or $\Lambda^0 K^+$, so effectively do $e^- + \pi^+$ or $e^- + K^+$ scattering
  - Also more than a decade for lattice calculations to advance

Eur.Phys.J.A 55, 190 (2019)

EIC science program - 2026

SPIN

MASS



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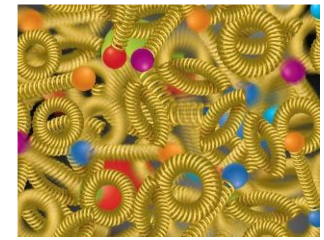


Dense Gluon Systems

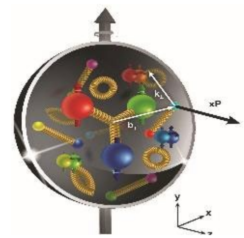
(National Academies of Sciences, Medicine, and Engineering 2018 Consensus Study Report)

- *Hadronization* – Hadron structure and formation are flip sides of the “confinement coin,” but hadronization is **much** less studied. What are the various ways that colored objects become well-defined colorless bound states?
  - Can quantum computing or other potential approaches to calculating real-time dynamics provide insight into hadronization??

EIC science program - 2026

SPIN

MASS



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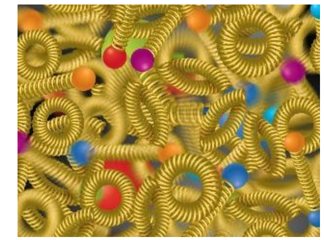

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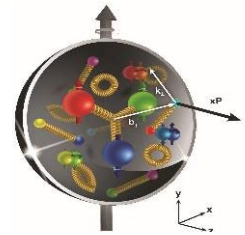
  - Can quantum computing or other potential approaches to calculating real-time dynamics provide insight into hadronization??
    - Timeline – EIC first data 2035 at earliest. Operate for ~15 years until ~2050. Actively analyze data for another ~10 until ~2060…

EIC science program - 2026

SPIN

MASS



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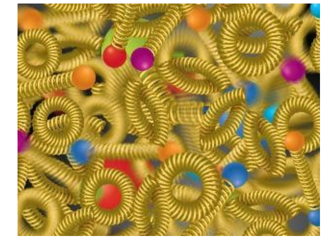


Dense Gluon Systems

(National Academies of Sciences, Medicine, and Engineering 2018 Consensus Study Report)

- *Longer-range correlations when a proton breaks up: fracture functions* – (Trentadue + Veneziano, PLB 323, 201 (1994)) – hybrids between structure and fragmentation functions, simultaneously describing fragmentation of a hard-scattered parton and what happens to the proton remnant
  - Possible connections to ideas about entanglement entropy, recently calculated on lattice? (Amorosso, Syritsyn, Venugopalan 2024 - 2026)

Some other thoughts

- QCD+QED and isospin splitting for *transverse-momentum-dependent* PDFs??
  - Very naïve valence quark picture of orbiting *electrical* charges in a proton vs. neutron—would expect QED effects to be (a lot?) larger than for collinear nucleon structure

Some other thoughts

- Can lattice say anything on energy density fluctuations in a proton??
  - Since 2010, an increasing number of signatures traditionally associated with quark-gluon plasma production have been observed in proton-proton collisions in which an unusually large number of hadrons are produced
  - Has led to phenomenological studies related to energy density fluctuations in the proton

Mäntysaari, Schenke, Shen, Tribedy
https://arxiv.org/abs/1706.05937

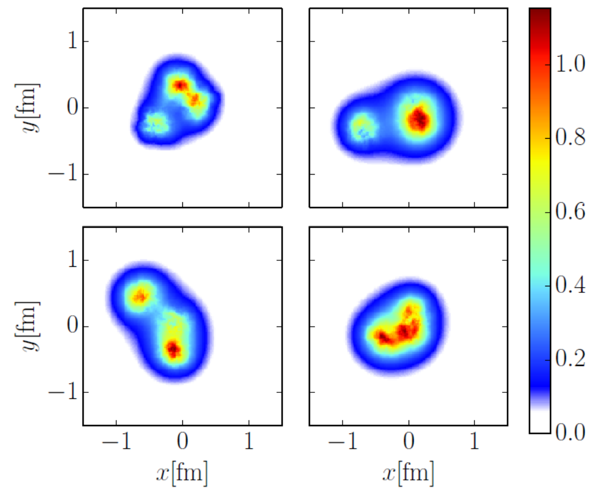
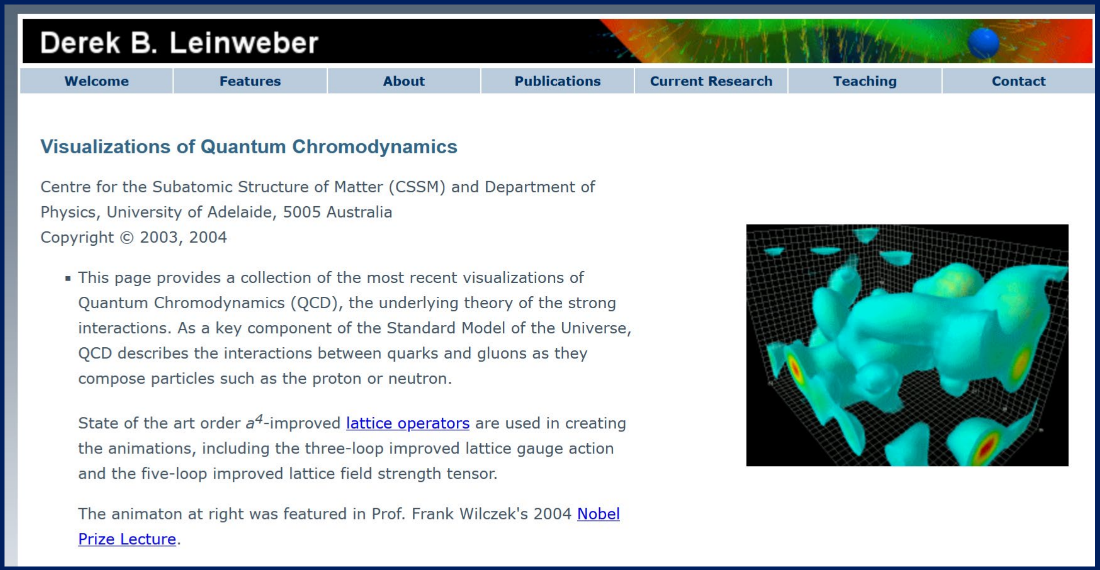


Figure 1: Illustration of the event-by-event fluctuations of the proton density profile.

Some other thoughts

http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/


Derek B. Leinweber

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Visualizations of Quantum Chromodynamics

Centre for the Subatomic Structure of Matter (CSSM) and Department of Physics, University of Adelaide, 5005 Australia
Copyright © 2003, 2004

- This page provides a collection of the most recent visualizations of Quantum Chromodynamics (QCD), the underlying theory of the strong interactions. As a key component of the Standard Model of the Universe, QCD describes the interactions between quarks and gluons as they compose particles such as the proton or neutron.

  State of the art order a^4-improved lattice operators are used in creating the animations, including the three-loop improved lattice gauge action and the five-loop improved lattice field strength tensor.

  The animaton at right was featured in Prof. Frank Wilczek's 2004 Nobel Prize Lecture.

Mäntysaari, Schenke, Shen, Tribedy
https://arxiv.org/abs/1706.05937

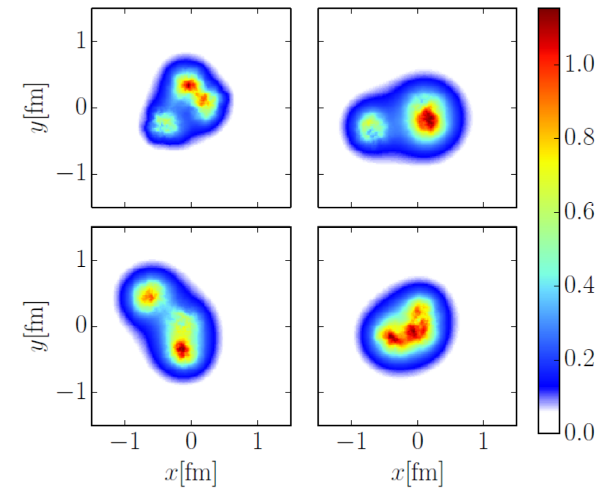

Figure 1: Illustration of the event-by-event fluctuations of the proton density profile.

Could lattice do something similar to this in a proton rather than for the vacuum??
Would be interested in the relative intensity and spatial scales of the fluctuations.

The era of quantitative QCD: Broadening the "light cone"

- What physics opportunities are we overlooking because of the EIC community's historical focus on perturbative frameworks??
- Is the lattice community missing physics opportunities because of its own historical focus areas??

https://sketchplanations.com/looking-under-the-lamppost

The era of quantitative QCD: Broadening the "light cone"

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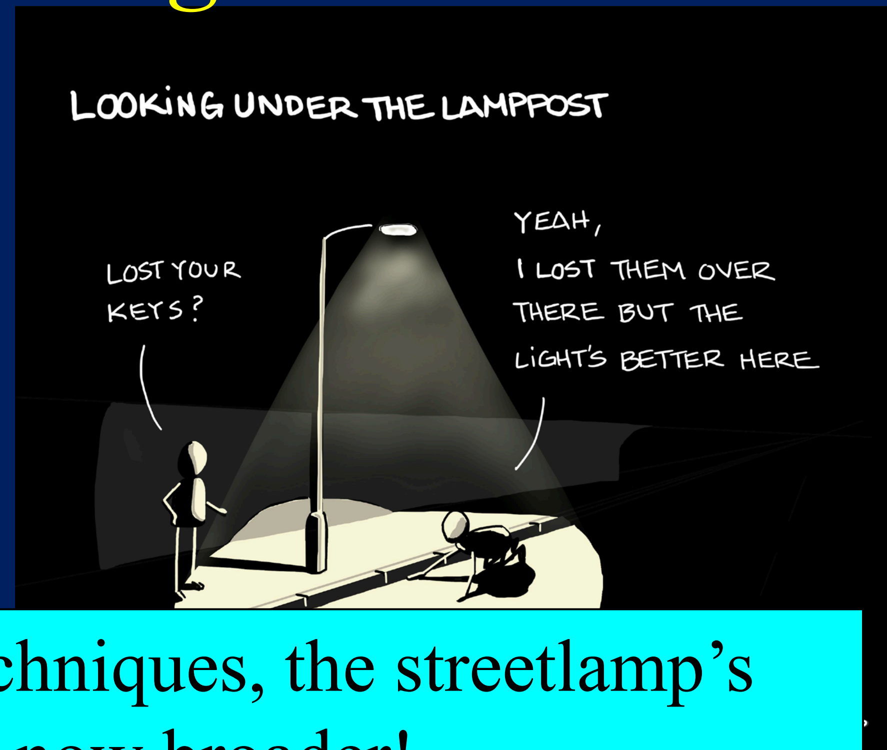
- Is the lattice community missing physics opportunities



With modern tools and techniques, the streetlamp's "light cone" is now broader!

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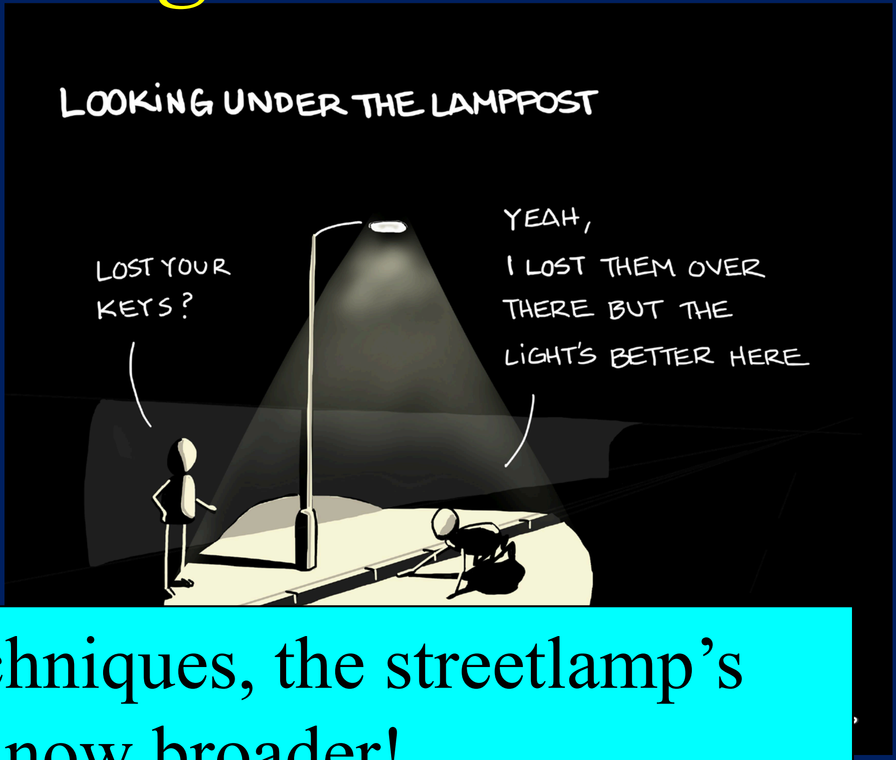

With modern tools and techniques, the streetlamp's "light cone" is now broader!

…Not to mention that now we all have individual smart phones with flashlights…

Theory and experiment: Roles depend on goals!

- If goal is e.g. to constrain a quantity as best as possible as input for something else
  → combine info from theory and experiment (while making sure you're doing so in a self-consistent way, …)

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- Helpful to be very explicit about goals of any given study and how our handling of various data/information fits those goals

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In the age of big data, how can we continuously keep the most important/relevant pieces of information readily in mind and help others in the community to do so?

Conclusions

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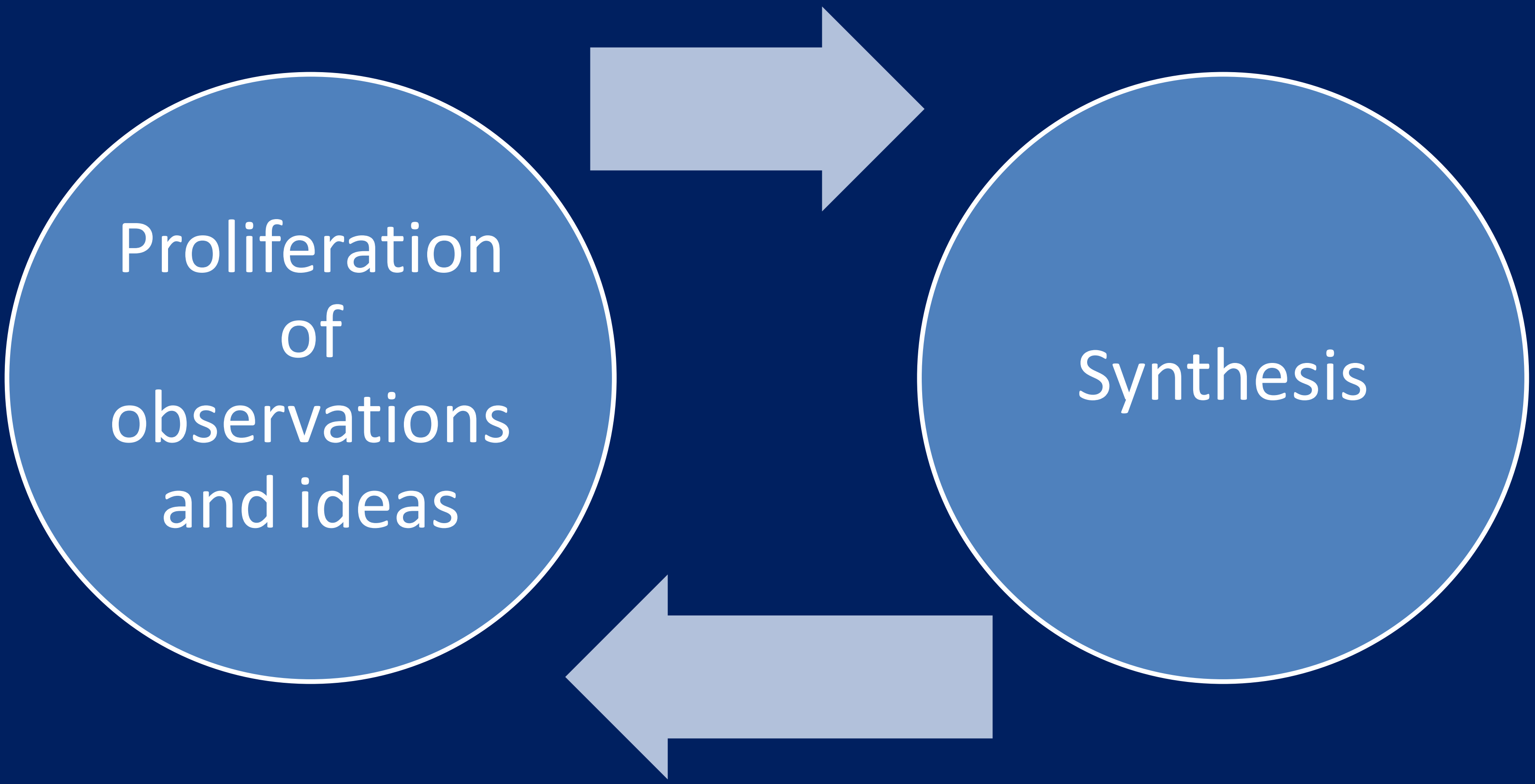
Computational first-principles QCD and the EIC: Bringing the age of quantitative QCD to maturity

Extra

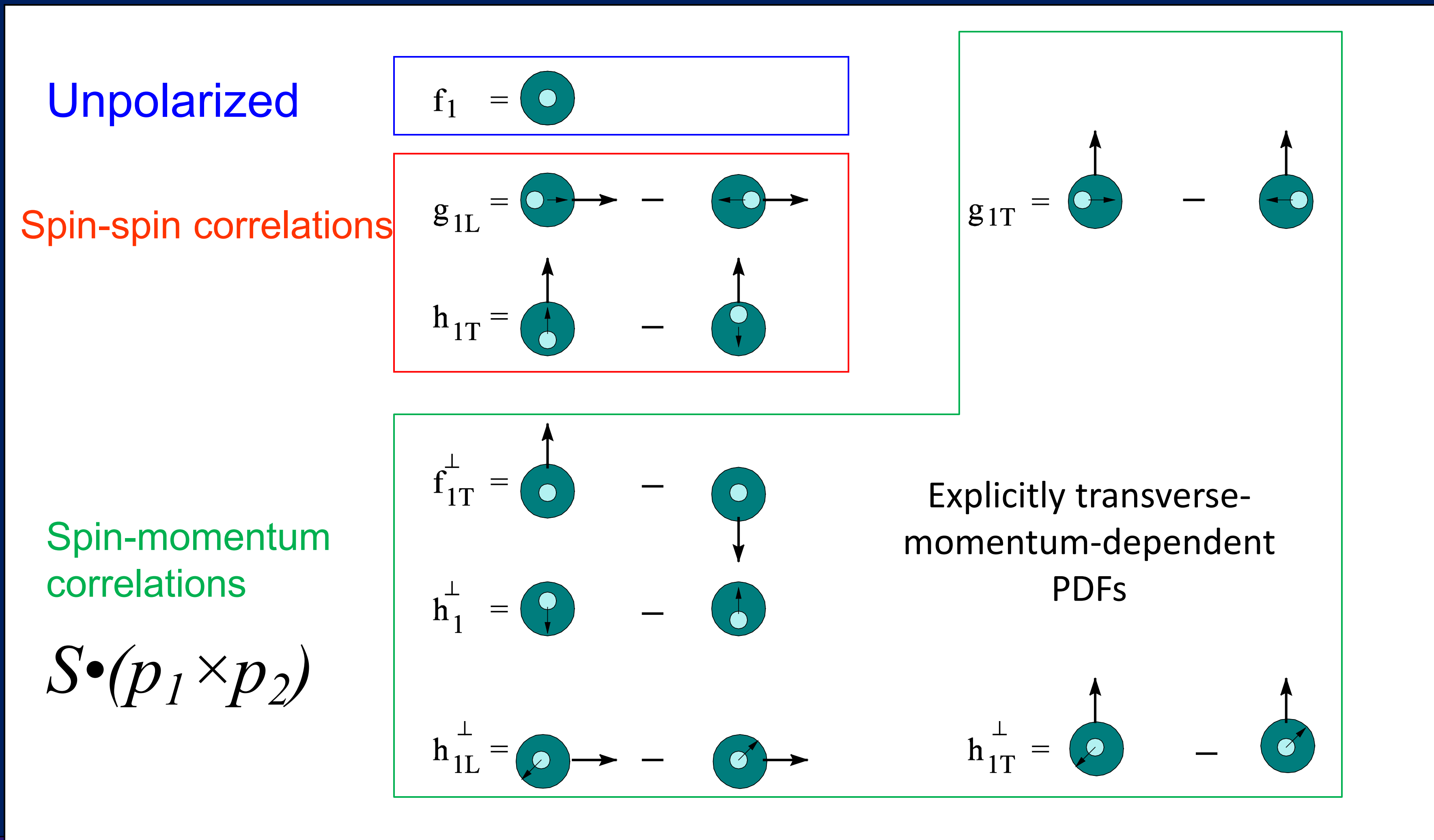
How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?

A cyclical process



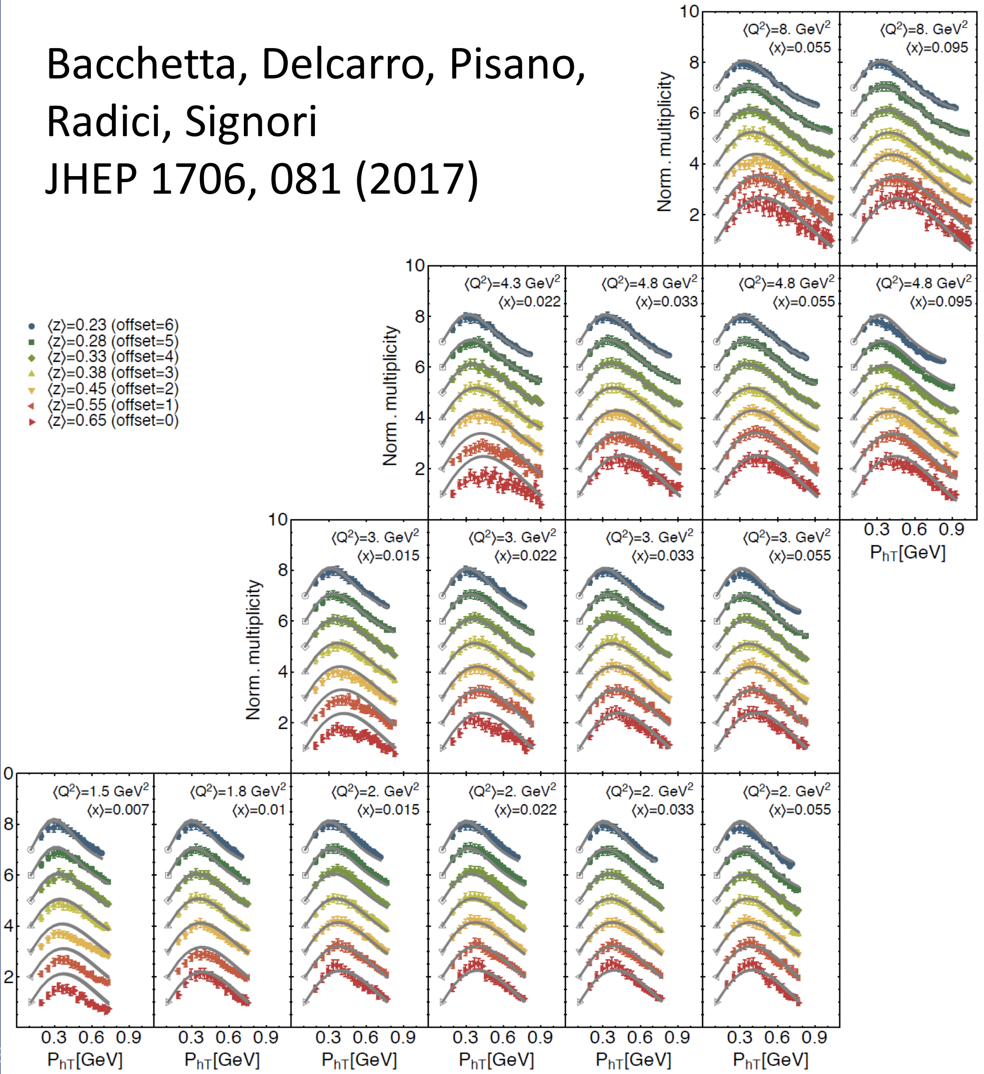
Example: Spin-spin and spin-momentum correlations in QCD bound states



Example: Fits of transverse-momentum-dependent PDFs

- First global fit of unpolarized TMD PDFs, including semi-inclusive DIS, Drell-Yan, and Z boson data

Bacchetta, Delcarro, Pisano, Radici, Signori
JHEP 1706, 081 (2017)



Model EIC early science program

Year - 1

Run:
10 GeV electrons on 115 GeV/u heavy ion beams (Ru or Cu)

Commission:
electron polarization (in parallel)

Year - 2

Run:
10 GeV long. polarized electrons on 130 GeV/u Deuterium

Last weeks 10 GeV long. polarized electrons and 130 GeV polarized protons

Commission:
proton polarization (in parallel)

Year - 3

Run:
10 GeV long. polarized electrons on 130 GeV transverse polarized protons

Commission:
Commission running with hadron spin rotators.

(Last weeks switch to longitudinal proton polarization?)

Year - 4

Run:
10 GeV long. polarized electrons on 100 GeV Au

10 GeV long. polarized electrons on 250 GeV transverse and longitudinal polarized protons

Commission:
Commission hadron accelerator to operate with not centered orbits

Year - 5

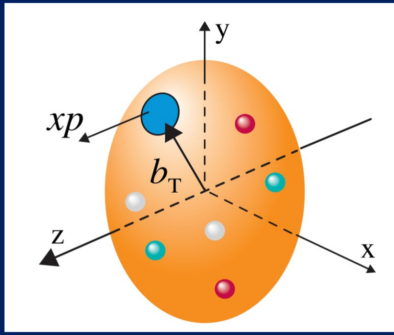
Run:
10 GeV long. polarized electrons on 100 GeV Au

10 GeV long. polarized electrons on 166 GeV transverse and longitudinal polarized He^3

Run plans notional but based on commissioning of the EIC collider capabilities

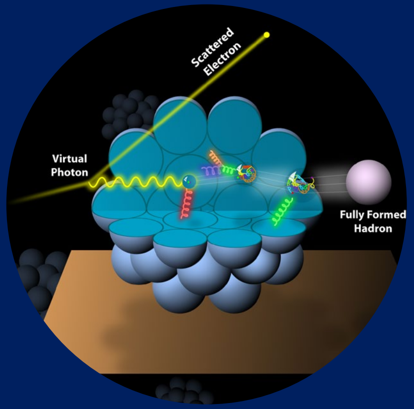
Time to install additional equipment to reach design current, luminosity and maximum energies

The EIC science program



- How do the nucleon properties like mass and spin emerge from quarks and their interactions?

- How are the sea quarks and gluons distributed in space and momentum inside the nucleon? How is spin dynamically generated?



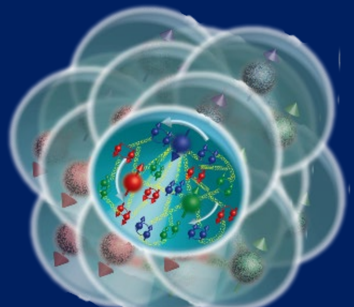
- How do new confined hadronic states emerge after the breakup of a nucleon?

- In what manner do color-charged quarks and gluons, along with colorless jets, interact with the nuclear medium?

- What impact does a high-density nuclear environment have on the interactions, correlations, and behaviors of quarks and gluons?

- What is the mechanism through which quark-gluon interactions give rise to nuclear binding?

- Is there a saturation point for the density of gluons in nuclei at high energies, and does this lead to the formation of gluonic matter with universal properties across all nuclei, including the proton?



EIC science program - 2026

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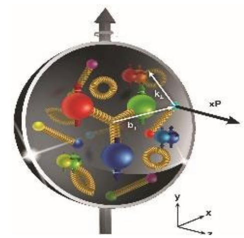

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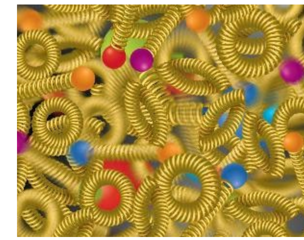
QCD in Nuclei



Dense Gluon Systems

(National Academies of Sciences, Medicine, and Engineering 2018 Consensus Study Report)

- *Color flow and interactions* – we know that ultimately factorization is an approximation. If use an electron to knock a quark out of a proton, there must be color exchange/soft gluon radiation between the scattered quark and the proton beam remnant. Observable as soft pion production in particular angular region?
  - For decay of an electroweak state to hadrons, must instead have color exchange between the decay q and $\bar{q}$ rather than either of them and the proton beam remnant

Factorization

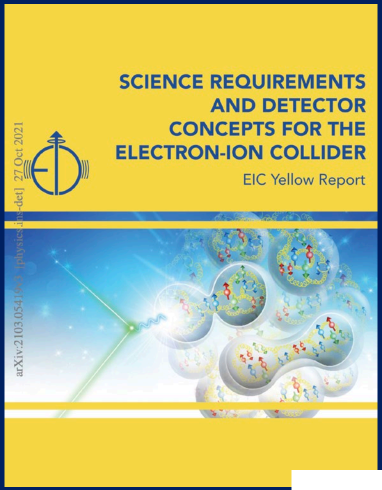
- Factorization of scattering processes involving hadrons is the exception, not the norm!
- What's interesting is breaking factorization in ways that teach us something
  - Explore unique properties of QCD as only Standard Model non-Abelian gauge theory that admits bound states
- Ideas for EIC most welcome
  - Correlated hadronization across the current and target fragmentation regions??
  - ??

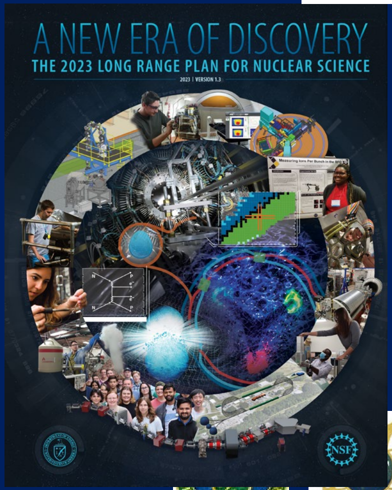
Building the experimental program

- Development of EIC Yellow Report 2020
  - Detector and machine design parameters driven by physics objectives

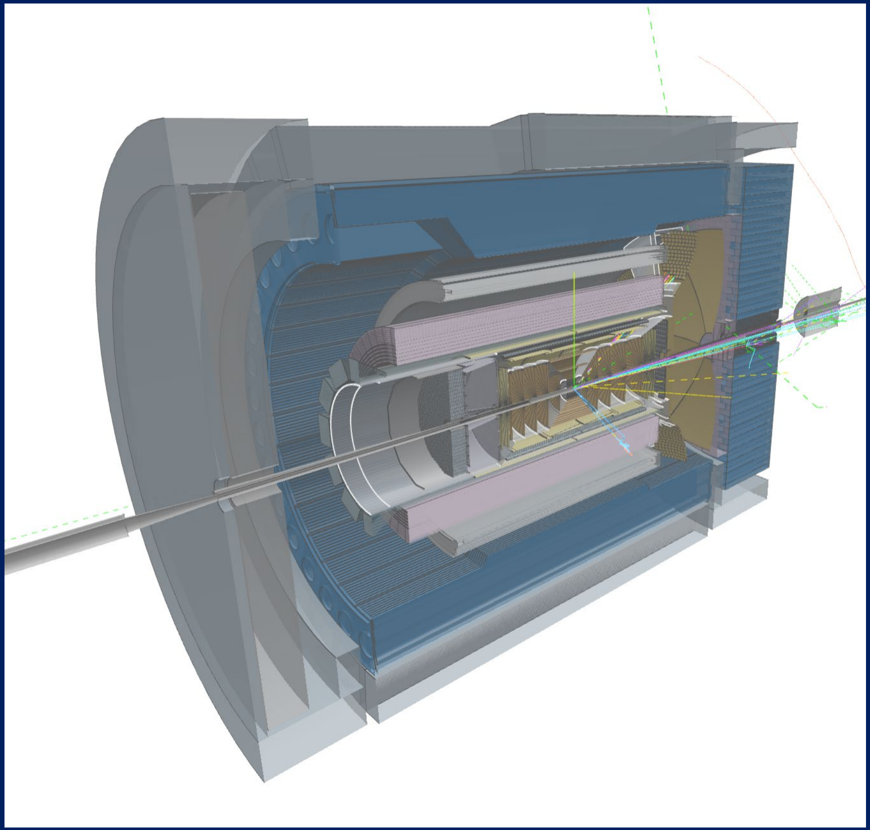
- Subsequent call for proposals and review process 2021-22 led to establishment of ePIC Collaboration, with charter ratified in Feb 2023

- Oct 2023: EIC/ePIC endorsed as highest priority for new facility construction in the U.S. Long Range Plan for Nuclear Science





Computing-detector integration



ePIC event display by Dmitry Romanov

Streaming readout and DAQ:

- **High-speed data flow:** The front-end electronics are designed to support a total bandwidth of up to 50 Tbps, with over 3,000 fiber streams feeding data from the detector to the computing system.
- **Zero dead time:** By avoiding a traditional hardware trigger, the system eliminates dead time and allows for unbiased data collection.

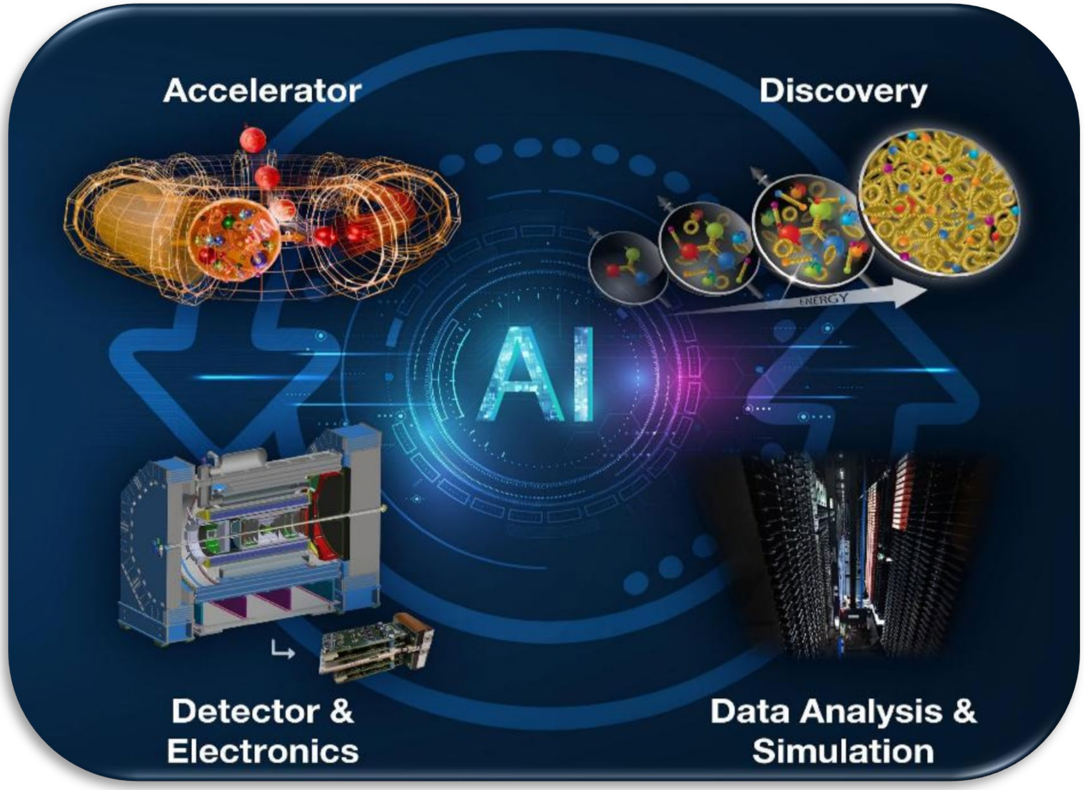
AI and ML in the data pipeline:

- **Intelligent data filtering:** AI/ML algorithms can select the most relevant collision events to study.
- **Real-time feedback:** AI can enable rapid detector diagnostics and optimization, with systems capable of automatically calibrating detectors and validating data.

Streaming computing model:

- **Continuous calibration and alignment:** Enables rapid delivery of scientific results.
- **Echelon model:** Organizes resources across the computing hierarchy and enables international contributions.

An AI-native collider



- First large-scale facility to leverage AI from the R&D and design phases to discovery.
- Accelerator, detector, and data analysis will all use — and push the evolution of — advanced AI techniques with potential impacts for other fields and facilities.
- BNL-led foundation model for particle/nuclear physics detectors ("FM4NPP") is already running on RHIC data and is being adapted for ePIC and future colliders.

https://arxiv.org/abs/2508.14087

EIC Project Status (as of May 2026)

- The EIC project is already underway, with an estimated total cost of about **$3.1 billion**, **CD-3B, Long-Lead Procurements, approved Jan 2026**, and roughly **$402 million spent so far**.
- Key activities planned for FY26–FY27 include:
  - Remove and repurpose RHIC equipment for EIC
  - New York State financed EIC buildings and infrastructure
  - DOE start EIC construction

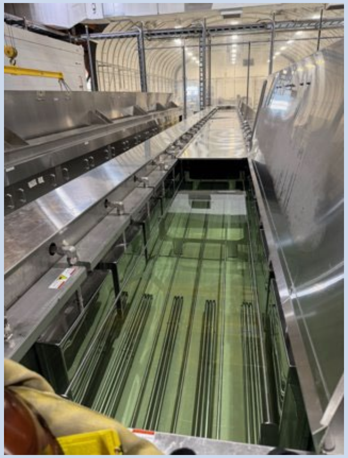
In-kind contributions by international partners (accelerator $50M and detector $90M)

Existing collider workforce and expertise are engaged in EIC construction

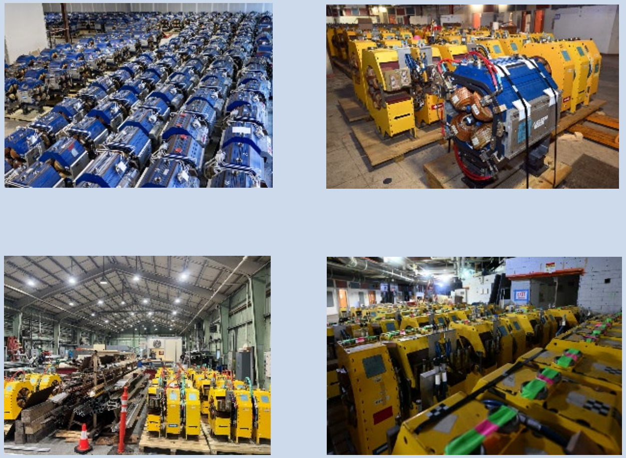
DOE Under Secretary D. Gil –
End of RHIC and Start of EIC

Blue Ring Removal –
April 2026

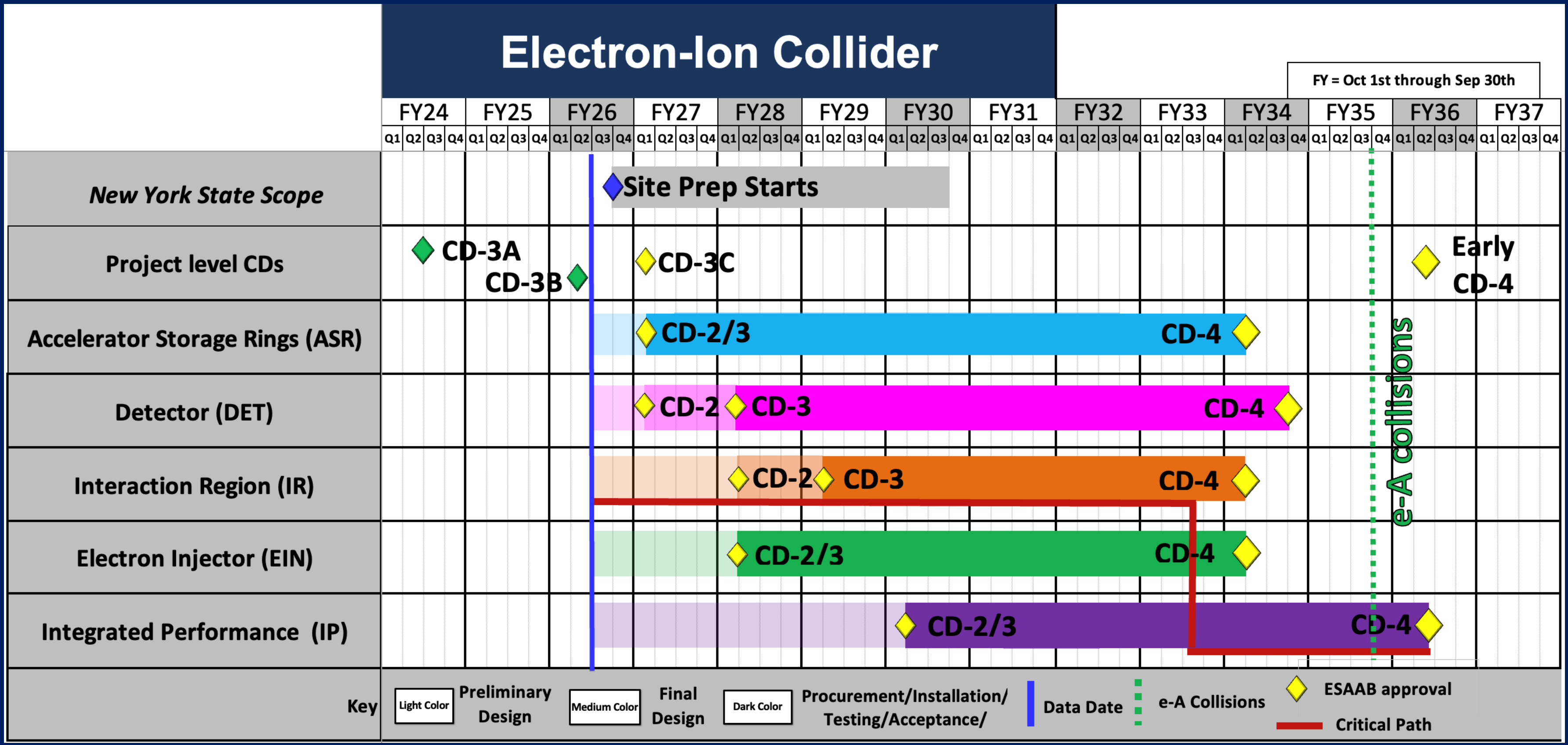
Ultrasonic Tank –
Clean Room Assembly



Arrival of ANL APS &
MIT Bates Magnets



Preliminary project schedule (as of May 2026)



This is a high-level technically driven schedule – needs to be adjusted when funding profile is known