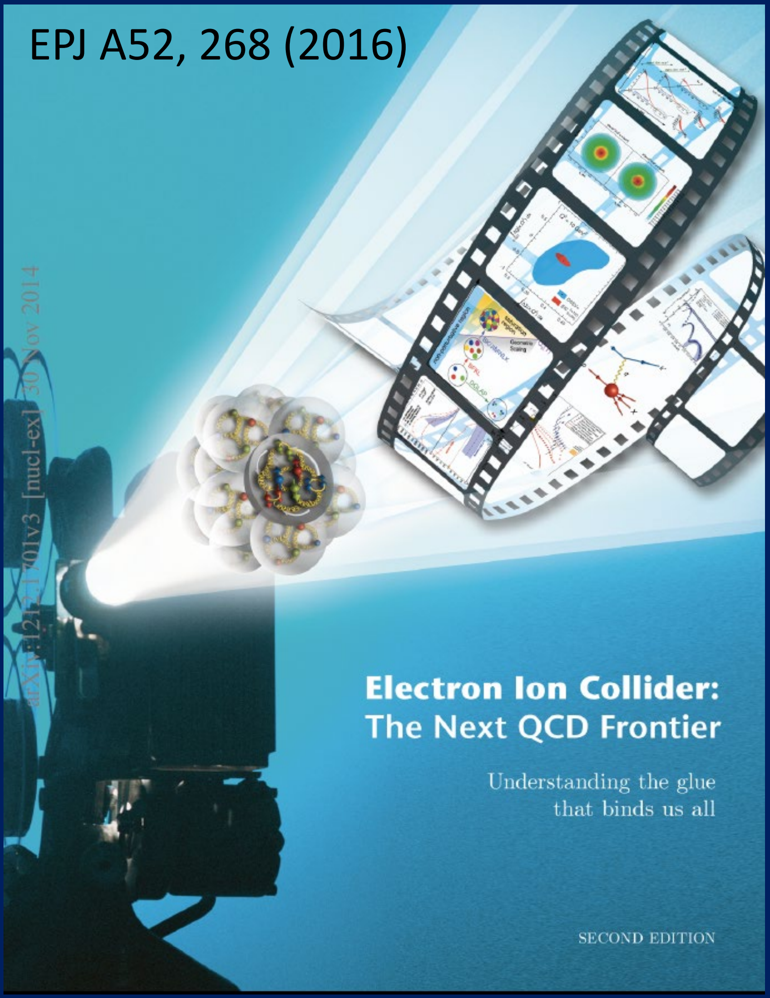
The Electron-Ion Collider: A Facility to Bring the Era of Quantitative QCD to Maturity

Christine A. Aidala
University of Michigan
Fulbright Scholar, University of Pavia

REF 2019
Pavia, Italy
November 25, 2019



QCD: How far have we come?

- The challenge of confinement: dof of our QFT not the dof we work with in experiment
- Three-decade period after initial birth of QCD dedicated to “discovery and development”

→ Symbolic closure: Nobel prize 2004 - Gross, Politzer, Wilczek for asymptotic freedom

QCD: How far have we come?

- The challenge of confinement: dof of our QFT not the dof we work with in experiment
- Three-decade period after initial birth of QCD dedicated to “discovery and development”

→ Symbolic closure: Nobel prize 2004 - Gross, Politzer, Wilczek for asymptotic freedom

Now in early years of second phase: ***quantitative QCD***

The era of quantitative QCD: Perturbative techniques/ideas

- In perturbative QCD, since 1990s starting to consider detailed internal *dynamics* that parts with traditional parton model ways of looking at hadrons—and perform <u>phenomenological calculations</u> using these new ideas/tools

  E.g.:
  - Various *resummation* techniques
  - *Non-linear evolution* at small momentum fractions
  - *Spin-spin* and *spin-momentum* correlations in QCD bound states
  - Techniques to handle *target-mass and higher-twist corrections*
  - *Spatial* distributions of partons in QCD bound states
  - Role of *color flow* in hadronic scattering, and concrete approaches to consider classes of *factorization-breaking* processes

Effective field theories

– Color Glass Condensate
– Soft-Collinear Effective Theory
– Heavy Quark Effective Theory
– Large Momentum Effective Theory
– . . .

Nonperturbative methods

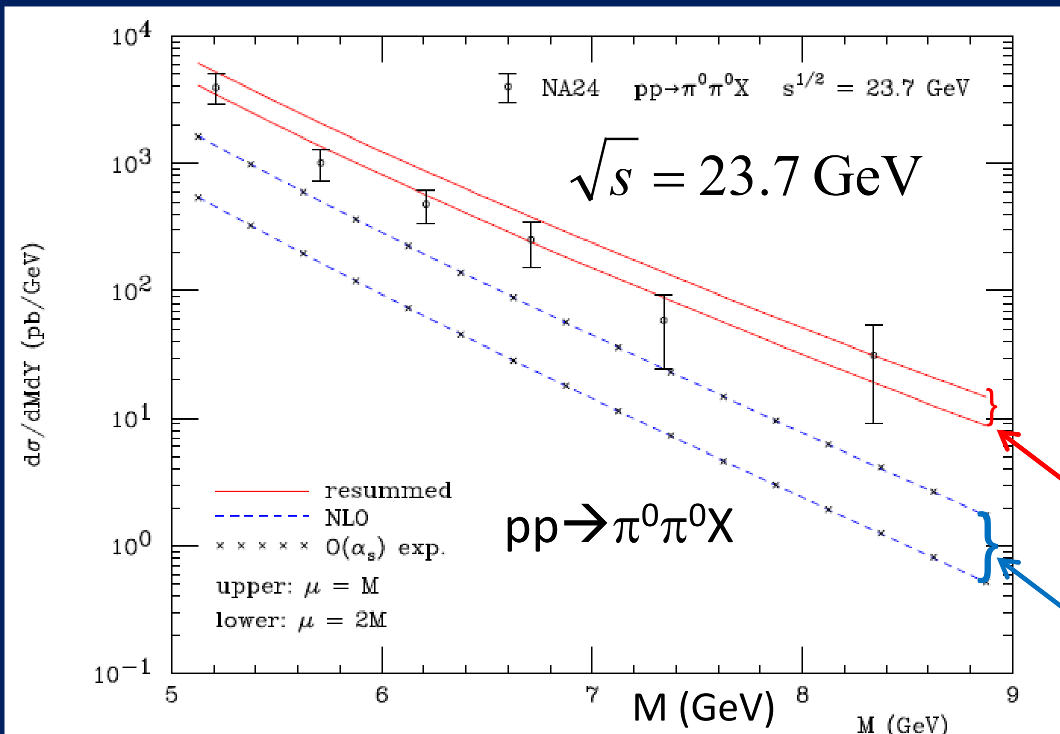
- Lattice QCD less and less limited by computing resources—first calculations at the physical pion mass in 2010 (after 36 years!)
  - Plus recent new ideas on how to calculate previously intractable quantities (quasi-PDFs, …)
- AdS/CFT "gauge-string duality"—first fundamentally new handle to try to tackle (~)QCD in decades

Nonperturbative methods

- Lattice QCD less and less limited by computing resources—first calculations at the physical pion mass in 2010 (after 36 years!)
  - Plus recent new ideas on how to calculate previously intractable quantities (quasi-PDFs, …)
- AdS/CFT "gauge-string duality"—first fundamentally new handle to try to tackle (~)QCD in decades

Quantitative *basic research in QCD (usually) implies* ***phenomenological calculations****…*

Example: Threshold resummation Extending perturbative calculations to lower energies

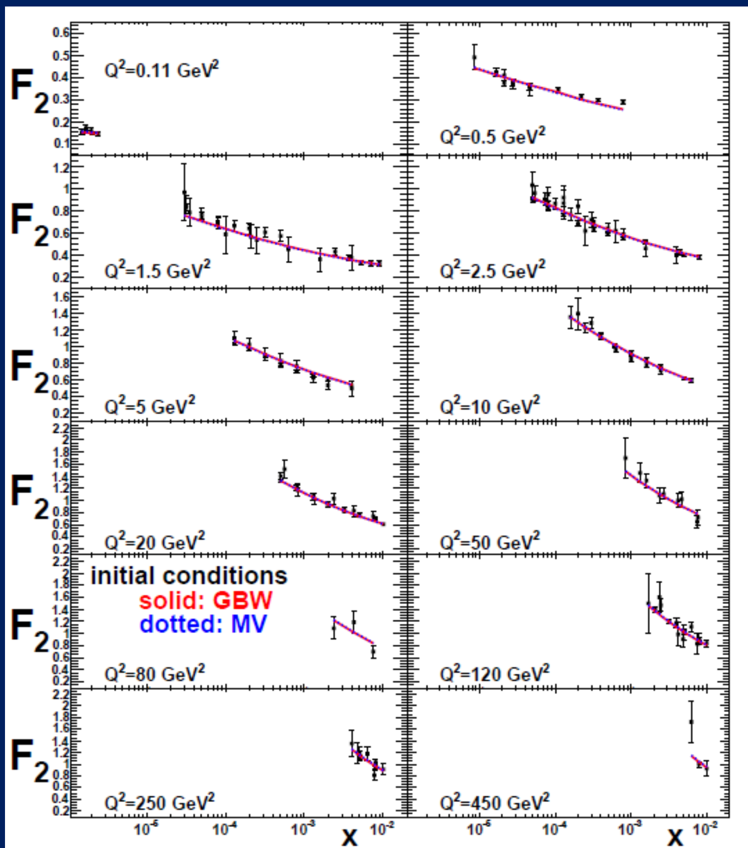


Next-to-leading-order in α_s + resum.

Next-to-leading-order in α_s

Almeida, Sterman, Vogelsang PRD80, 074016 (2009)

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

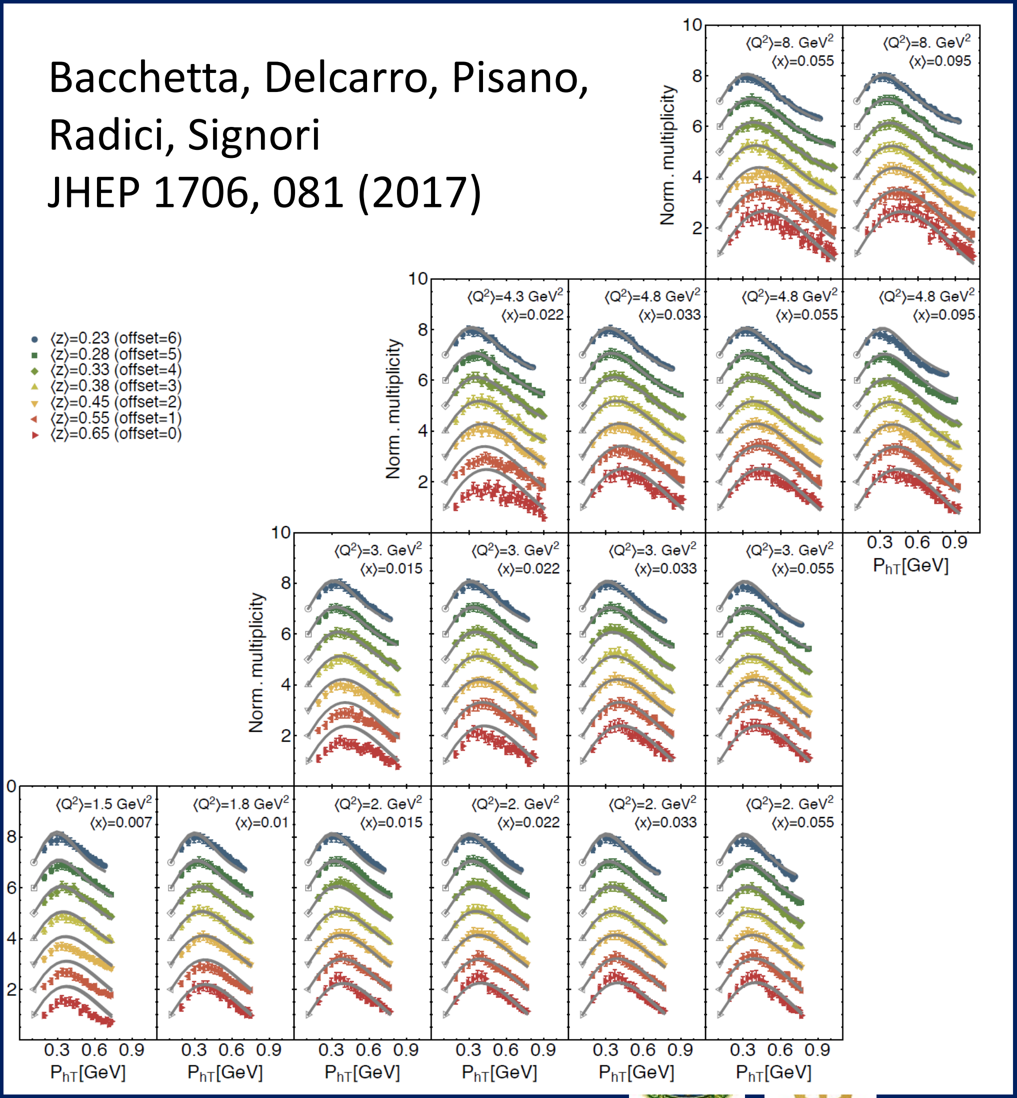
Phys. Rev. D80, 034031 (2009)

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: Fits of transverse-momentum-dependent PDFs

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

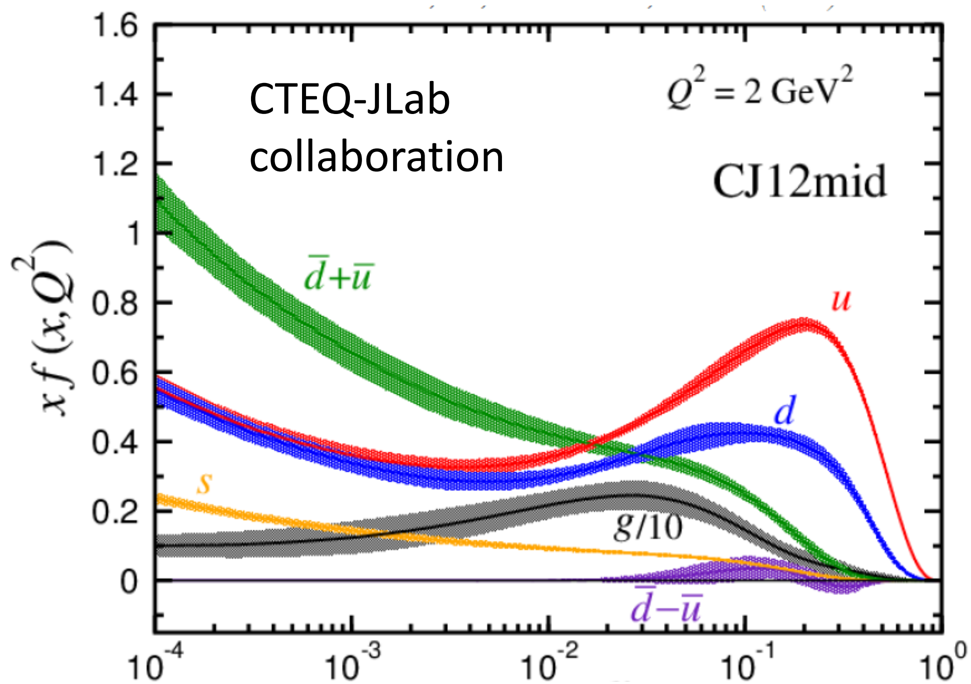


Example: Fits to collinear quark and gluon distributions including much wider range of data

- Incorporate corrections for target mass, higher-twist, and nuclear effects

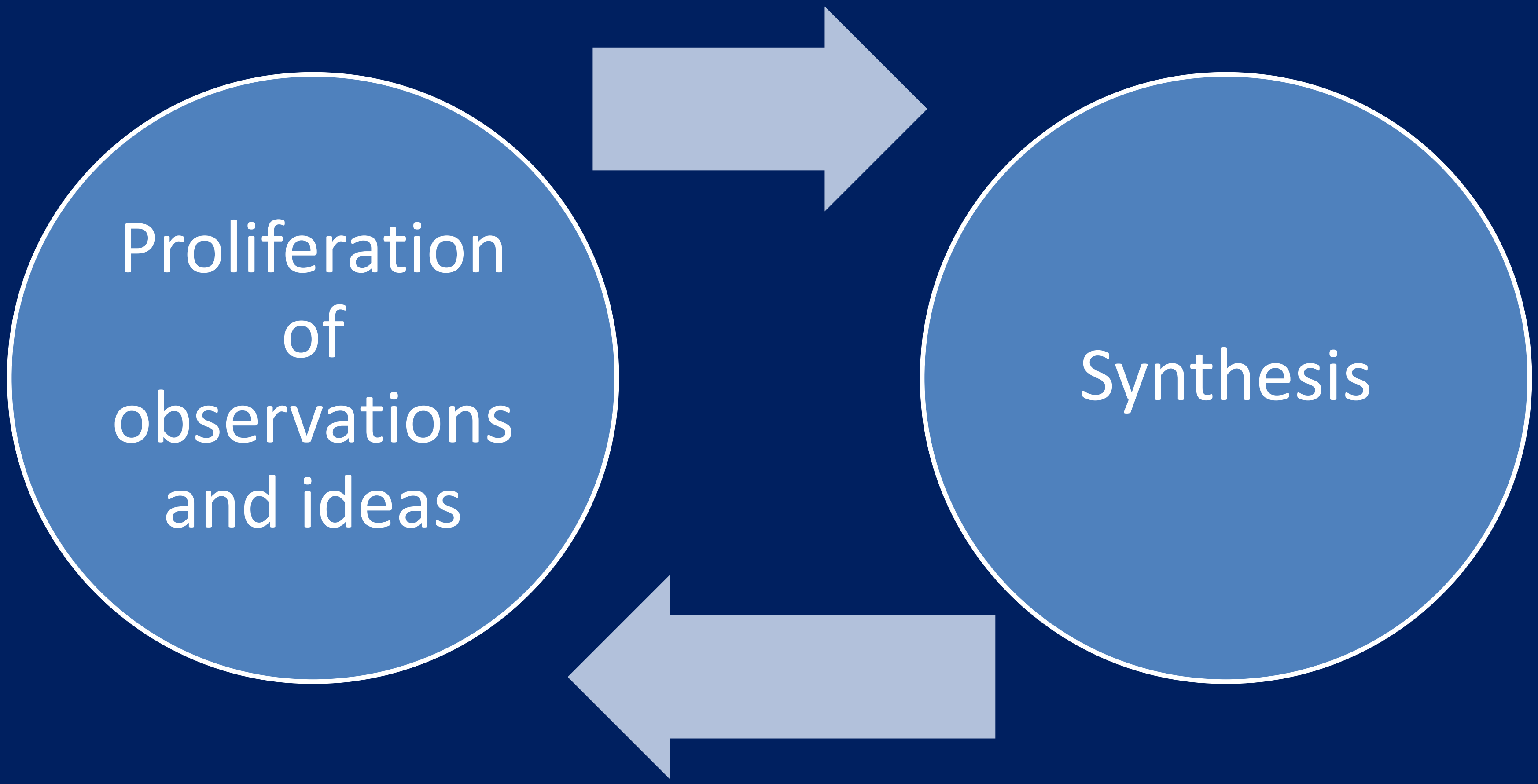
- Can in turn make predictions for future measurements in extended kinematic regions

Owens, Accardi, Melnitchouk, PRD87, 094012 (2013)



Collinear momentum fraction *x*

A cyclical process

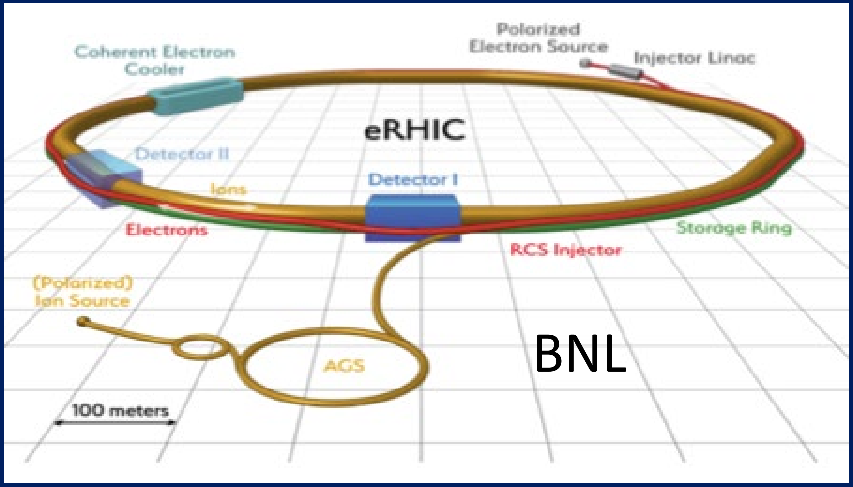


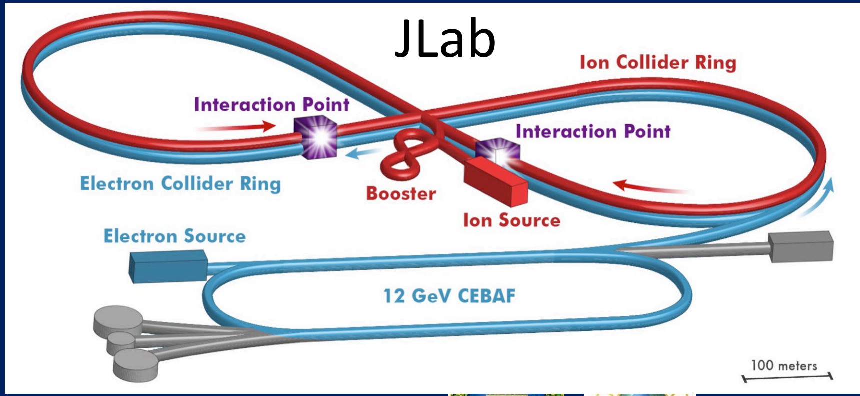
Next-generation QCD facility: The Electron-Ion Collider

Key science questions:

- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents?*
- *What are the emergent properties of dense systems of gluons?*

Two candidate sites: Brookhaven National Lab and Jefferson Lab

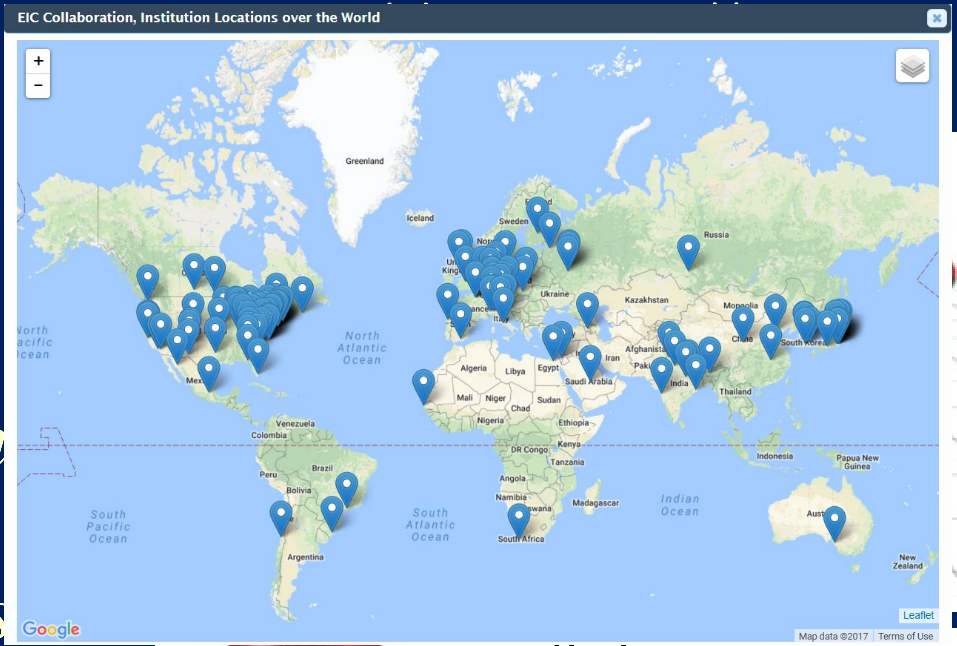


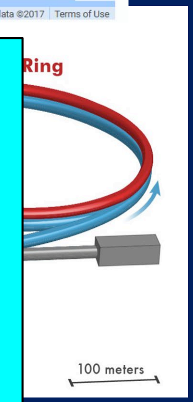


Next-generation QCD facility: The Electron-Ion Collider

Key science questions:

- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents*
- *W… p… s…*





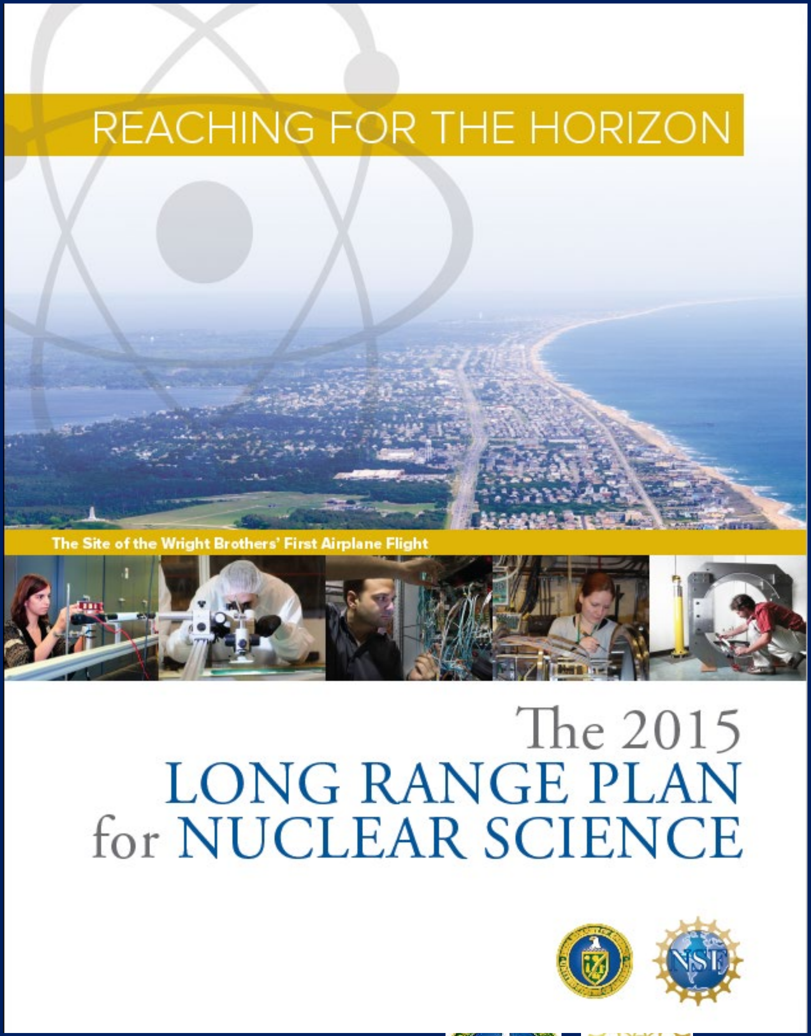
Electron-Ion Collider User Group: Currently 971 members from 194 institutions in 30 countries (25% theorists)

www.eicug.org

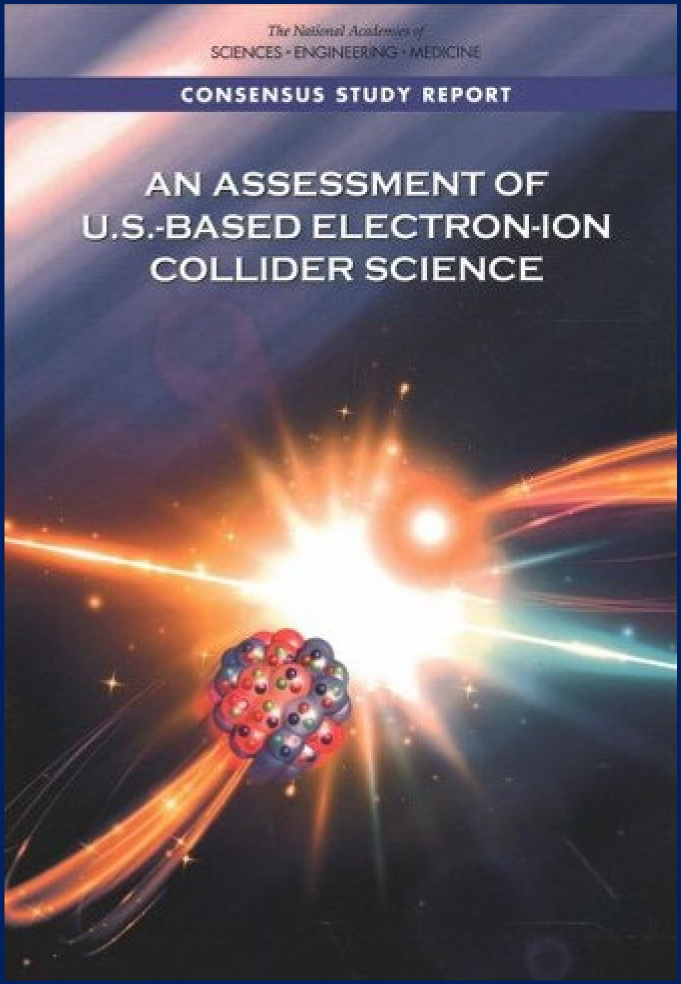
UNIVERSITÀ DI PAVIA

2015 U.S. Nuclear Physics Long-Range Plan

- EIC endorsed by U.S. nuclear community as highest priority facility for new construction after completion of Facility for Rare Isotope Beams (FRIB)



2018 U.S. National Academy of Sciences report

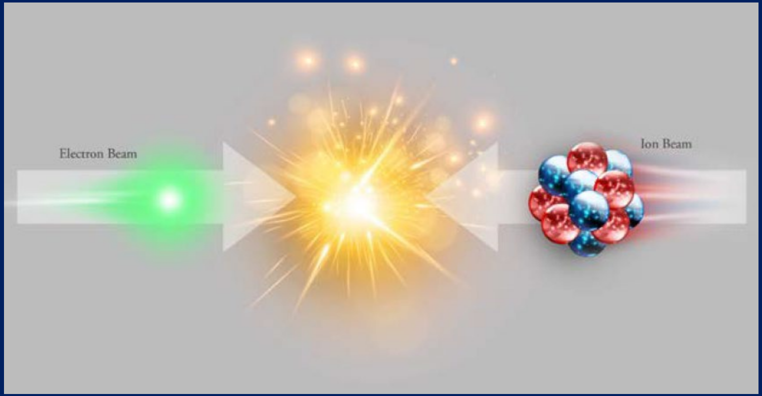


2016 – U.S. Dept. of Energy charged National Academy of Sciences with assessing the science case of a U.S.-based Electron-Ion Collider

July 2018 National Academy Consensus Report found that the science that can be addressed by an EIC is "compelling, fundamental, and timely"

An EIC as envisioned in the NAS report

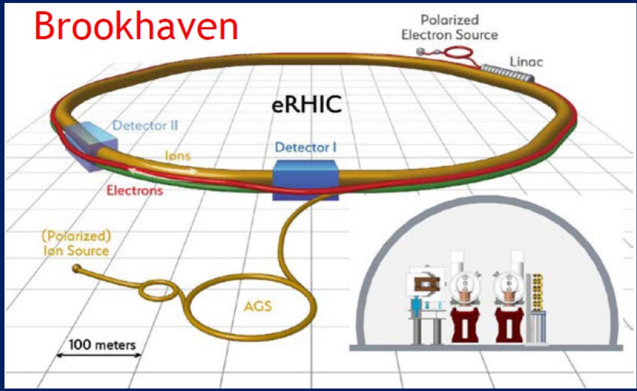
An advanced accelerator that collides beams of electrons with beams of protons or heavier ions (atomic nuclei).

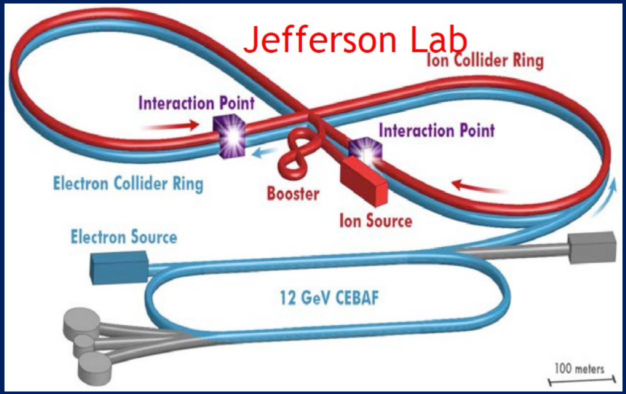


Electron-ion center of mass energy ~20-100 GeV, upgradable to ~140 GeV.

High luminosity and polarization

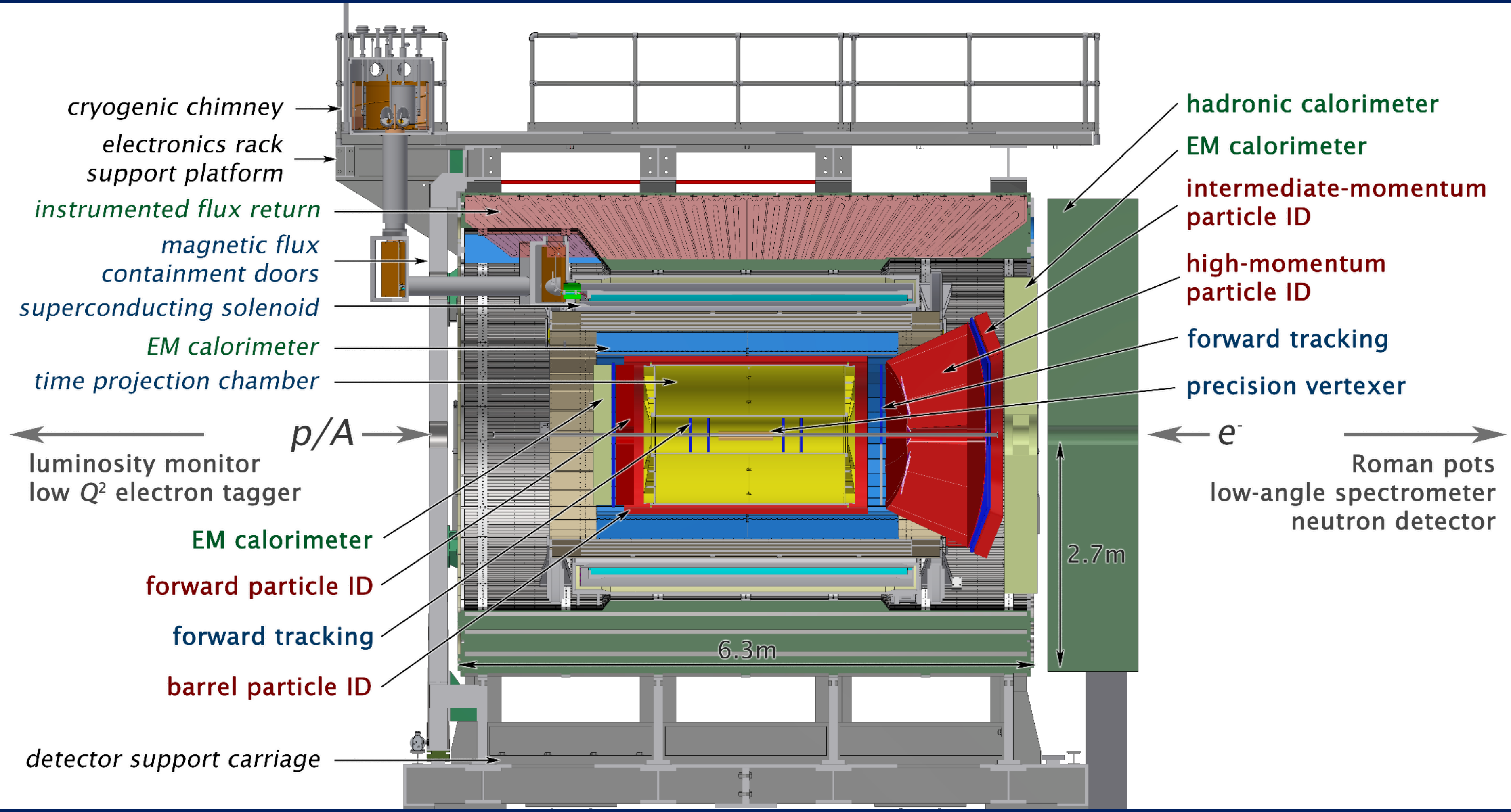
1) Highly polarized electrons, E ~ 4 GeV to possibly 20 GeV
2) Highly polarized protons, E ~ 30 GeV to some 300 GeV, and heavier ions





Two possible configurations: Brookhaven National Lab and Jefferson Lab

An EIC detector concept



EIC: Status and recent developments

Site selection process underway

- Independent Cost Review to establish cost range
  - Documentation submitted to DOE May 1, 2019, reviewed May-June
  - Final report submitted August 2, 2019
- Site Assessment Panel
  - Convened by DOE Office of Science (chaired by James Siegrist, DOE/HEP)
  - Responses to 6 criteria submitted August 2, 2019
  - Lab presentations, Q&A sessions on October 8, 2019
- Further decision process internal to DOE

EIC: Status and recent developments

- EIC discussed with funding agencies from various countries at IUPAP Working Group 9 (Nuclear Physics) Meeting, August 2-3, 2019
- Latest annual EIC Users Meeting held in Paris, July 22-26, 2019
- EIC Physics and Detector Conceptual Development
  - 12-18 months study getting started now
  - Two working groups: Physics, Detector concepts
  - 2-day organizational meeting to be held at MIT December 12-13, 2019
  - Summaries to be published as "Yellow Reports" in spring 2021

EIC: Status and recent developments

- EIC discussed with funding agencies from various countries at IUPAP Working Group 9 (Nuclear Physics) Meeting, August 2-3, 2019
- Latest annual EIC Users Meeting held in Paris, July 22-26, 2019
- EIC Physics and Detector Conceptual Development
  - 12-18 months study getting started now
  - Two working groups: Physics, Detector concepts
  - 2-day organizational meeting to be held at MIT December 12-13, 2019
  - Summaries to be published as “Yellow Reports” in spring 2021

Community hoping for first data ~2030

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?

(One way of dividing up)
Areas of study in QCD

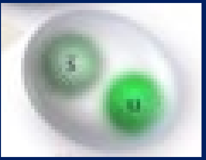
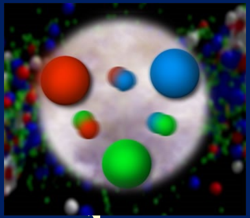
- *Structure/properties* of QCD matter

- *Formation* of states of QCD matter

- *Interactions* within QCD

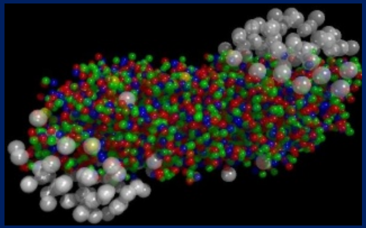
Structure/Properties of QCD matter

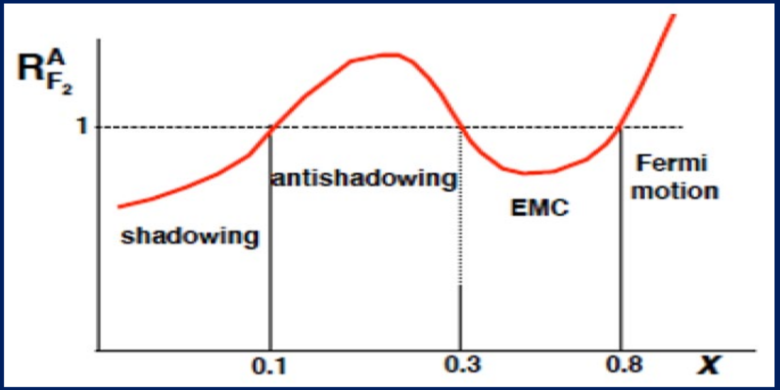
- Bound states: Mesons and baryons

- Bound states of bound states: Nuclei, neutron stars


- Deconfined states: Quark-gluon plasma

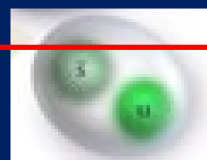


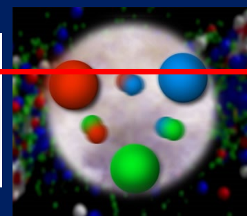


Nuclei aren't just superpositions of free nucleons

Structure/Properties of QCD matter

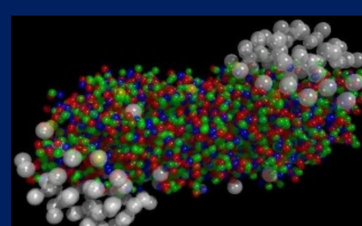
- Bound states: Mesons and baryons



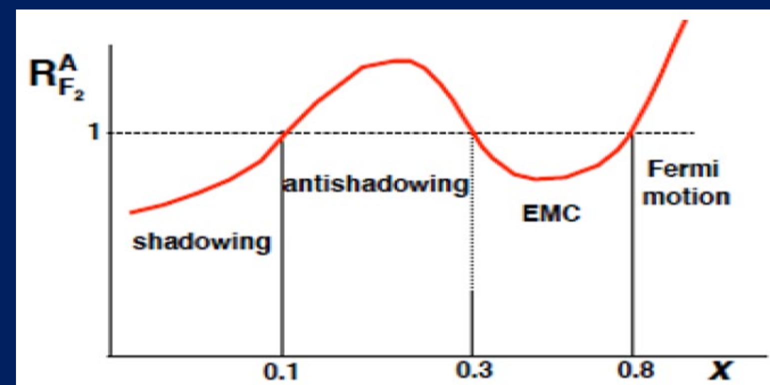


- Bound states of bound states: Nuclei, neutron stars

- Deconfined states: Quark-gluon plasma

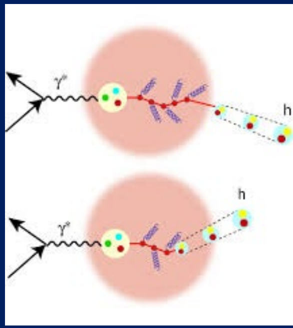


EIC will address

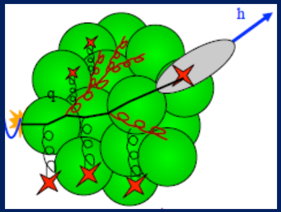


Nuclei aren't just superpositions of free nucleons

Formation of states of QCD matter

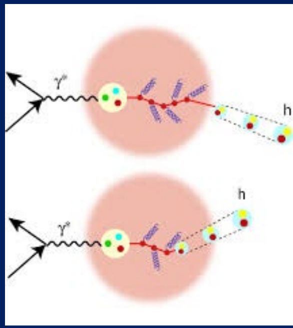


- Hadronization mechanisms
- Formation of bound states of bound states
- Jet structure
- Equilibration of QGP
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments

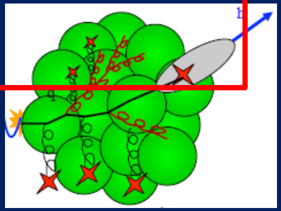


MICHIGAN
UNIVERSITÀ DI PAVIA

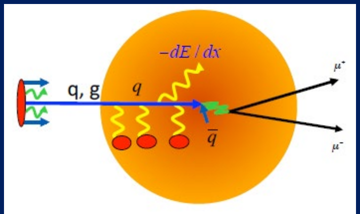
Formation of states of QCD matter

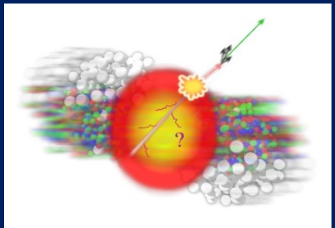


- Hadronization mechanisms
- Formation of bound states of bound states
- Jet structure
- Equilibration of QGP
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments

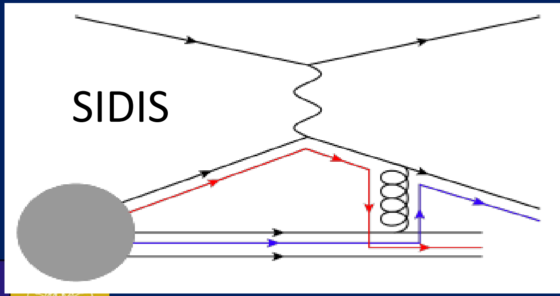


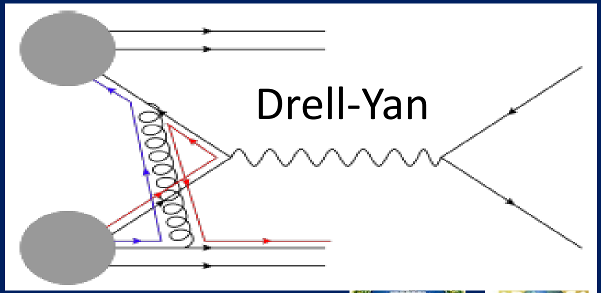
Interactions within QCD





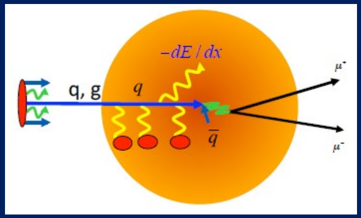
- Parton energy loss in cold and hot QCD matter
- Flow of partons within quark-gluon plasma
- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One parton → multiple hadrons
    - Multiple partons → one hadron
- Color flow effects
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of partons across colliding hadrons

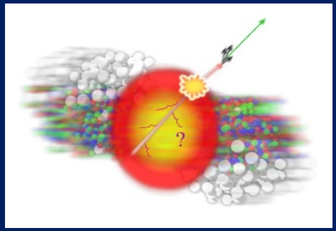




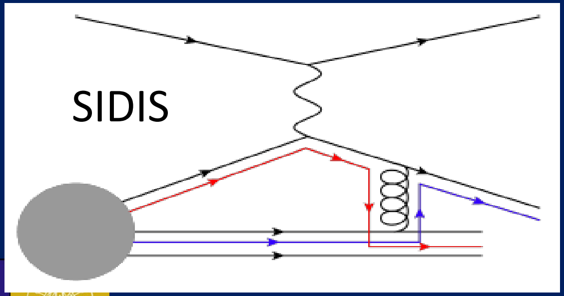
Interactions within QCD

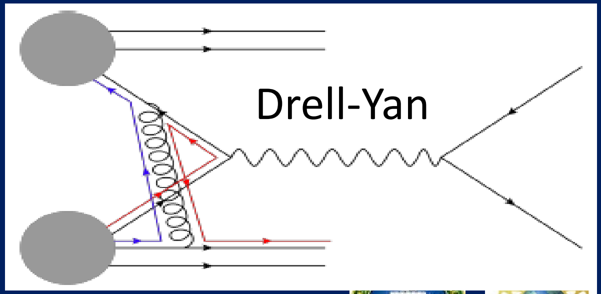
- Parton energy loss in cold and hot QCD matter
- Flow of partons within quark-gluon plasma





- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One parton → multiple hadrons
    - Multiple partons → one hadron
- Color flow effects
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of partons across colliding hadrons





Resummation

- Working with multiscale problems in QCD
- EIC accelerator and detectors being designed with QCD in mind, in an era in which the community has already gone beyond thinking primarily in terms of inclusive observables
- Detectors will be ~hermetic
- In principle can measure observables with many scales—what classes of multiscale observables will be most useful for pushing us to develop our ideas, calculational tools, and understanding?

Evolution

- EIC being designed to run over a wide range of center-of-mass energies (~20-140 GeV)
  - Data at different c.m. energies explicitly required e.g. to constrain longitudinal structure function F_L
- Also explicit plans to measure collinear as well as transverse-momentum-dependent observables, linear and nonlinear regimes
- Plenty of opportunities to "exercise" different types of evolution machinery for phenomenology
- Can something new be learned about evolution?

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??
  - ??

What can we learn from QED, EW analogs?

- Are we taking full advantage of what can be learned from analog calculations and measurements in the QED and EW sectors?
- Effects may be orders of magnitude smaller than in QCD, but QED calculations and measurements are often orders of magnitude more precise than in QCD
  - Greater dialog with e.g. AMO community could be valuable
- EIC will be able to probe nucleons and nuclei with high-virtuality photons, ~real photons, and color dipoles
  - How best to exploit these complementary probes?

Role of open data?

- In the longer-term future, will be interested in/able to describe increasingly complex, less inclusive observables
- Would be interested in input from the theory community on the value and importance of creating open data sets from the EIC
  - Requires resources—the more general-purpose the open data set is, the more resources required to make it usable in practice. Priorities?

Summary

An Electron-Ion Collider as a versatile QCD facility with

- polarized electrons
- a range of unpolarized nuclear species
- polarized protons and polarized light nuclei
- center-of-mass energies from ~20 to ~140 GeV
- luminosities $10^{33\text{-}34}$ cm^{-2} s^{-1}

and corresponding detectors designed for a comprehensive QCD program will bring our current era of quantitative basic research in QCD to maturity

Summary

An Electron-Ion Collider as a versatile QCD facility with

- polarized electrons
- a range of unpolarized nuclear species
- polarized protons and polarized light nuclei
- center-of-mass energies from ~20 to ~140 GeV
- luminosities $10^{33\text{-}34}$ cm^{-2} s^{-1}

and corresponding detectors designed for a comprehensive QCD program will bring our current era of quantitative basic research in QCD to maturity

New ideas on how to fully exploit the facility for maximum physics impact always welcome

Extra

Mapping out the partonic structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

Theoretical and experimental concepts to describe and access position only born in mid-1990s. Pioneering measurements over past decade.

Polarized protons first studied in 1980s. How angular momentum of quarks and gluons add up still not well

Measurements of flavor distributions in valence region. Flavor structure at lower momentum fractions

Accounted for theoretically from beginning of QCD, but more detailed, potentially observable effects of color have come to forefront in last few years . . .

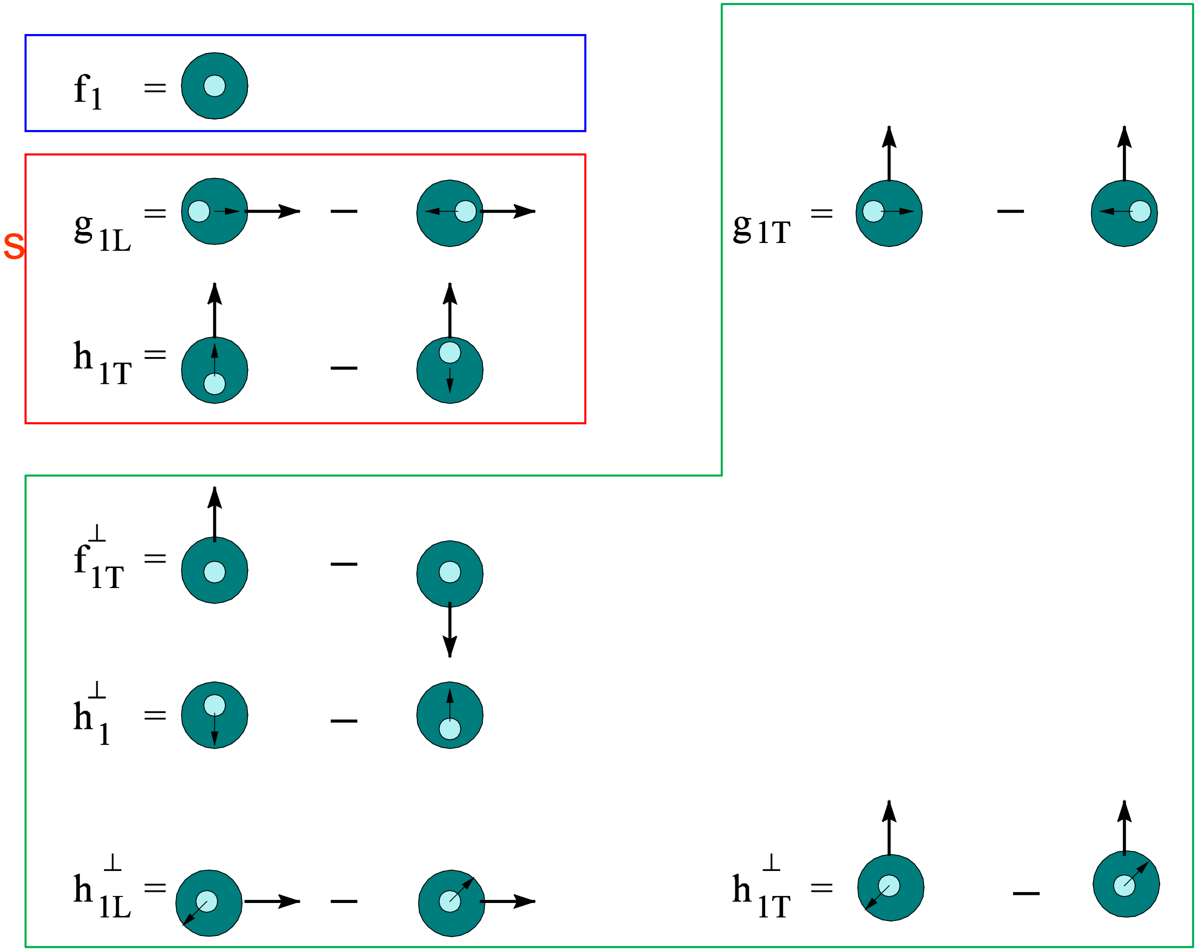
Example: Spin-spin and spin-momentum correlations in QCD bound states

Unpolarized

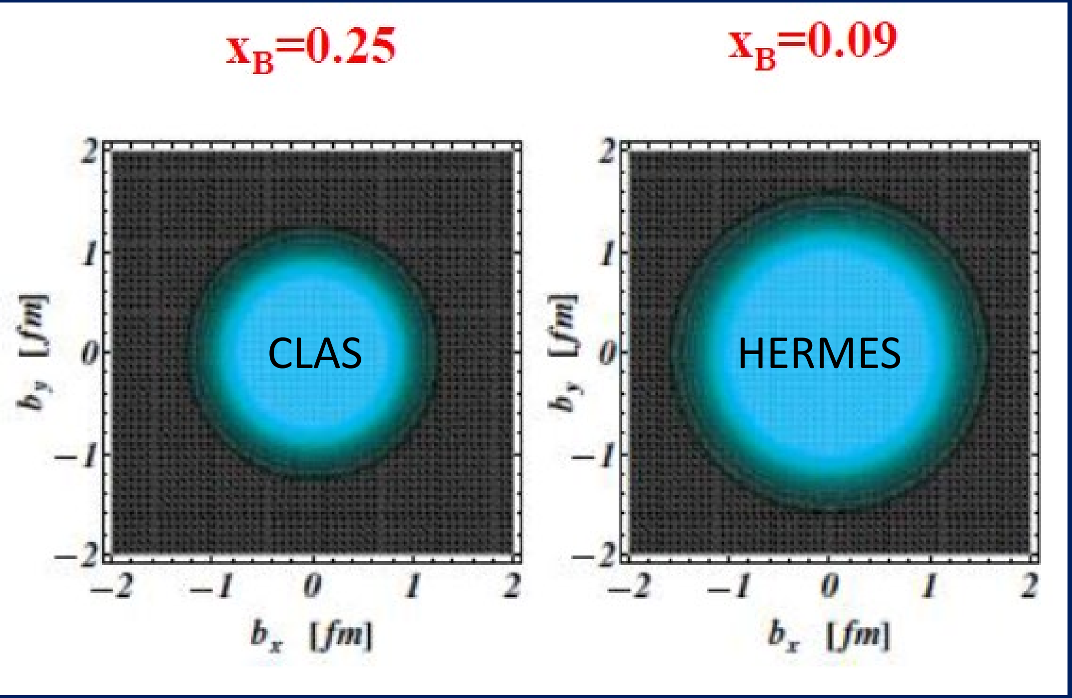
Spin-spin correlations

Spin-momentum correlations

$S \bullet (p_1 \times p_2)$



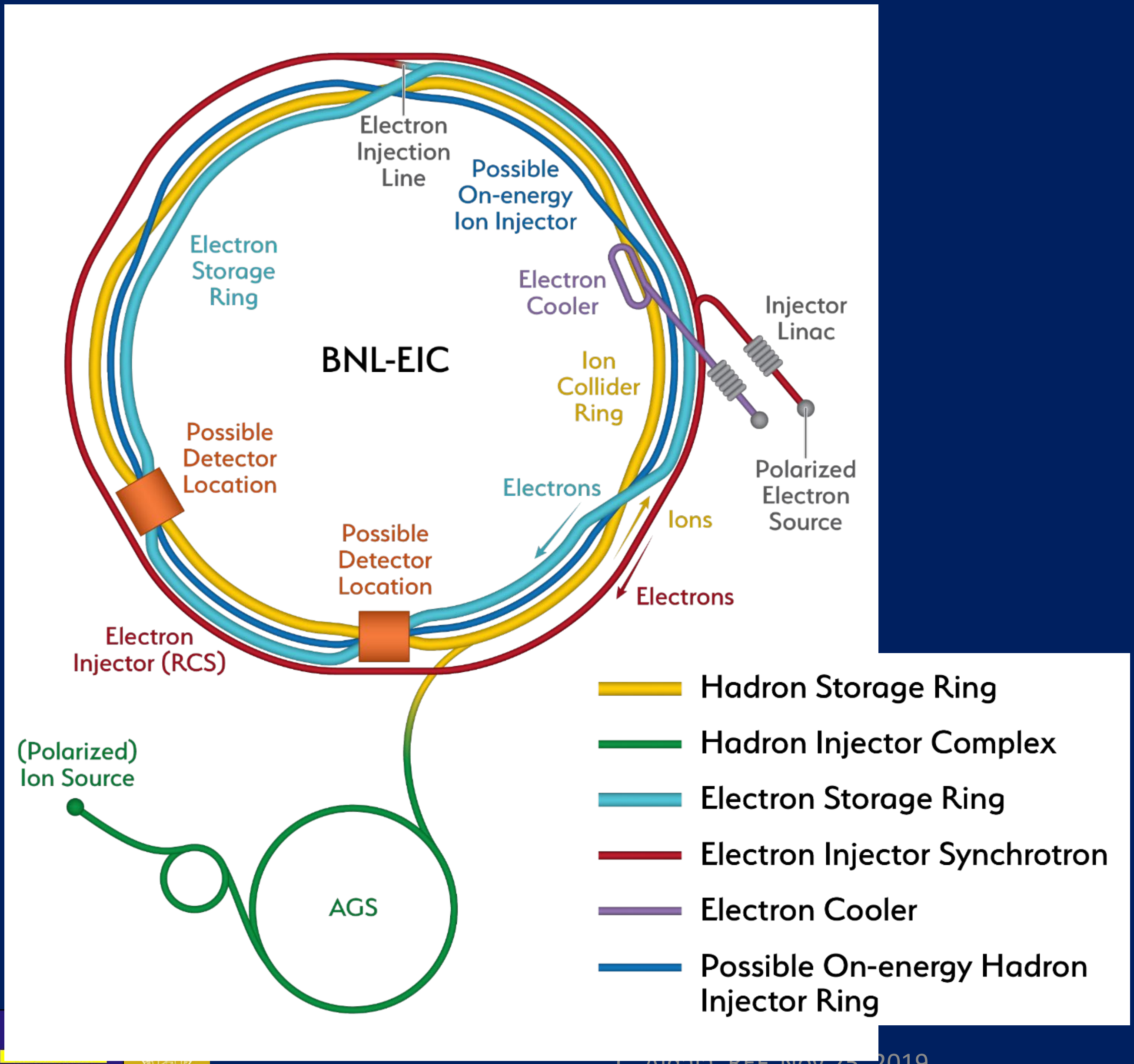
Example: Exploring spatial distributions



Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013) 066202

Spatial charge densities measured via deeply virtual Compton scattering

Initial evidence that quarks carrying larger momentum fractions (25% vs. 9%) in the nucleon are distributed over a smaller volume in space



Electron Injection Line
Possible On-energy Ion Injector
Electron Storage Ring
Electron Cooler
Injector Linac
BNL-EIC
Ion Collider Ring
Polarized Electron Source
Possible Detector Location
Electrons
Ions
Possible Detector Location
Electrons
Electron Injector (RCS)
(Polarized) Ion Source
AGS
Hadron Storage Ring
Hadron Injector Complex
Electron Storage Ring
Electron Injector Synchrotron
Electron Cooler
Possible On-energy Hadron Injector Ring

Site Assessment Criteria

1. Scientific Merit of the Proposal
2. Technical Maturity
3. Schedule for Achieving the Full Range of the NSAC Machine Parameters
4. Proposal Costs Including Consideration of All Major Risks
5. Assurance of Successful Project Delivery
6. Value Added for each Site