The way to the Electron-Ion Collider in the U.S.

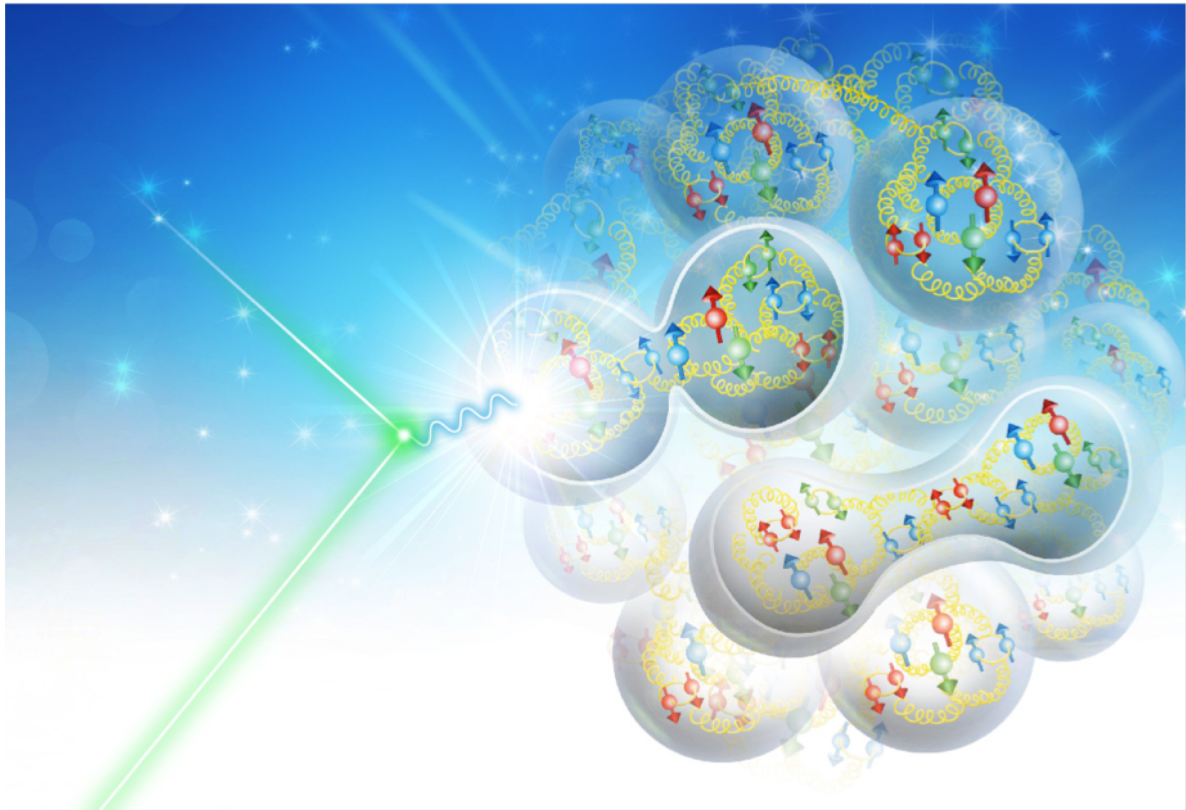
Nuclear Physics and its frontiers

Why an Electron-Ion Collider?

Accelerator design

Machine-Detector-Computing interface

Status of the Electron-Ion Collider project



Markus Diefenthaler (EIC^2, Jefferson Lab)

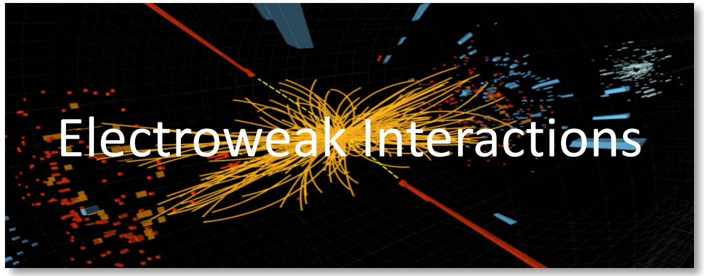
EIC^2
EIC Center at Jefferson Lab

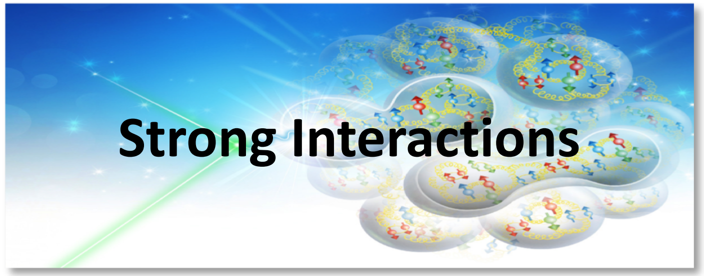
Jefferson Lab
Exploring the Nature of Matter

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

The Standard Model of Physics





Further exploration of the Standard Model

Dark matter searches

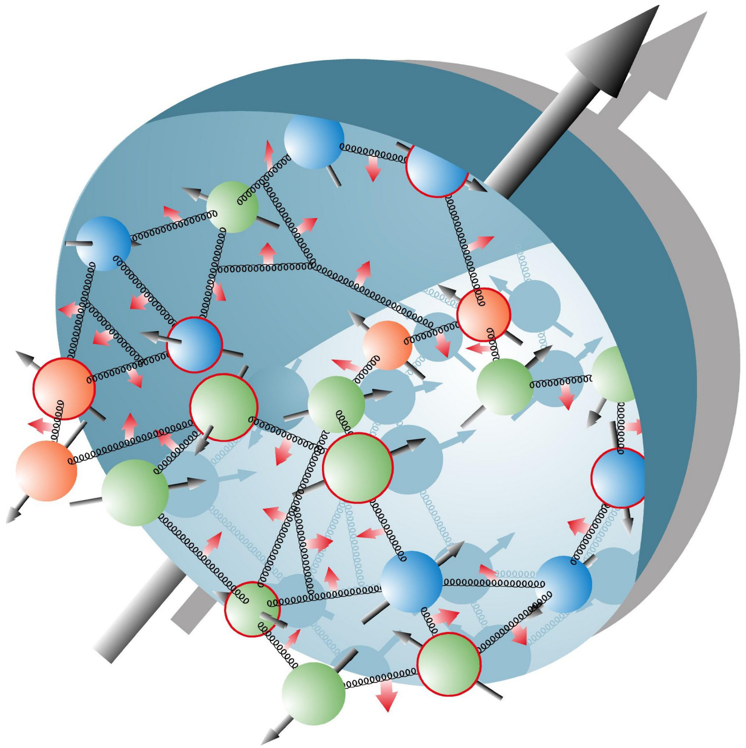
Electroweak symmetry breaking

Deeper understanding of QCD:

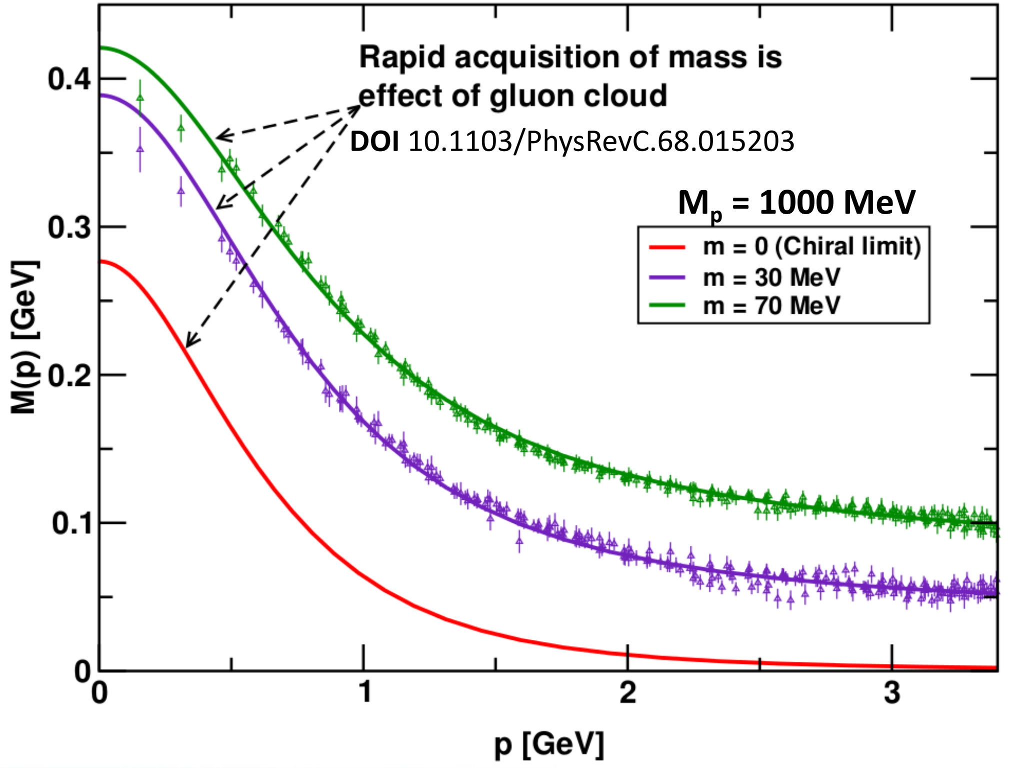
"Jefferson Lab's unique and exciting mission is to expand humankind's knowledge of the universe by **studying the fundamental building blocks of matter** within the nucleus: subatomic particles known as **quarks and gluons**."

The dynamical nature of nuclear matter

Nuclear Matter Interactions and structures are inextricably mixed up



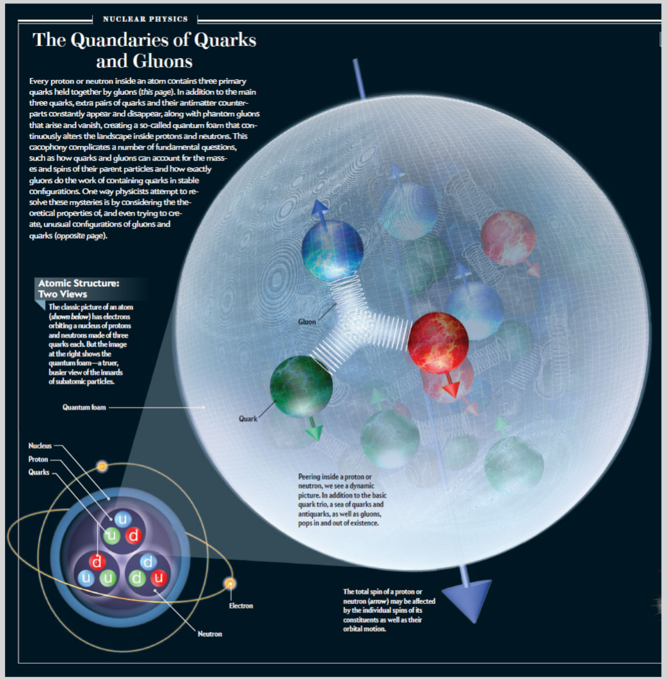
Observed properties such as mass and spin emerge out of the complex system



Ultimate goal Understand how matter at its most fundamental level is made

To reach goal precisely image quarks and gluons and their interactions

The glue that binds us all



- QCD is the fundamental theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei.

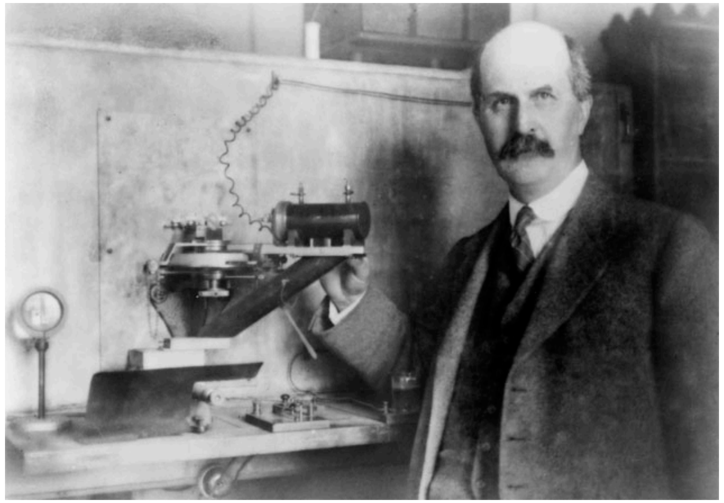
Facts

- The essential features of QCD (e.g. asymptotic freedom, chiral symmetry breaking, and color confinement) are driven by gluons:
  - asymptotic freedom
  - chiral symmetry breaking
  - color confinement
- Unique aspect of QCD is the self interaction of the gluons.
- Half of the nucleon momentum is carried by gluons.
- Most of mass of the visible universe emerges from gluons.

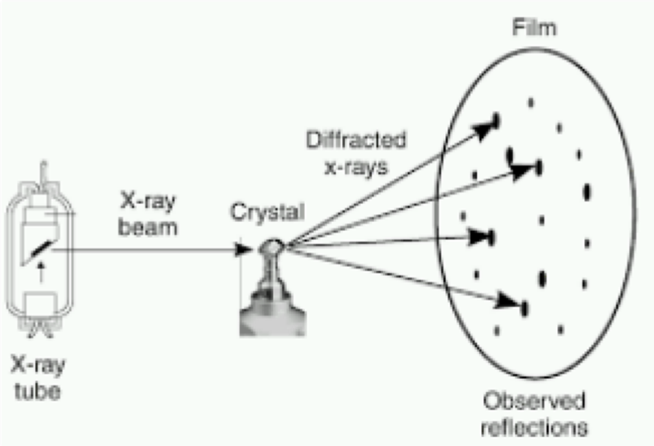
Introduction

A new frontier in Nuclear Physics

But 100 years ago…



William Henry Bragg (ca. 1915)

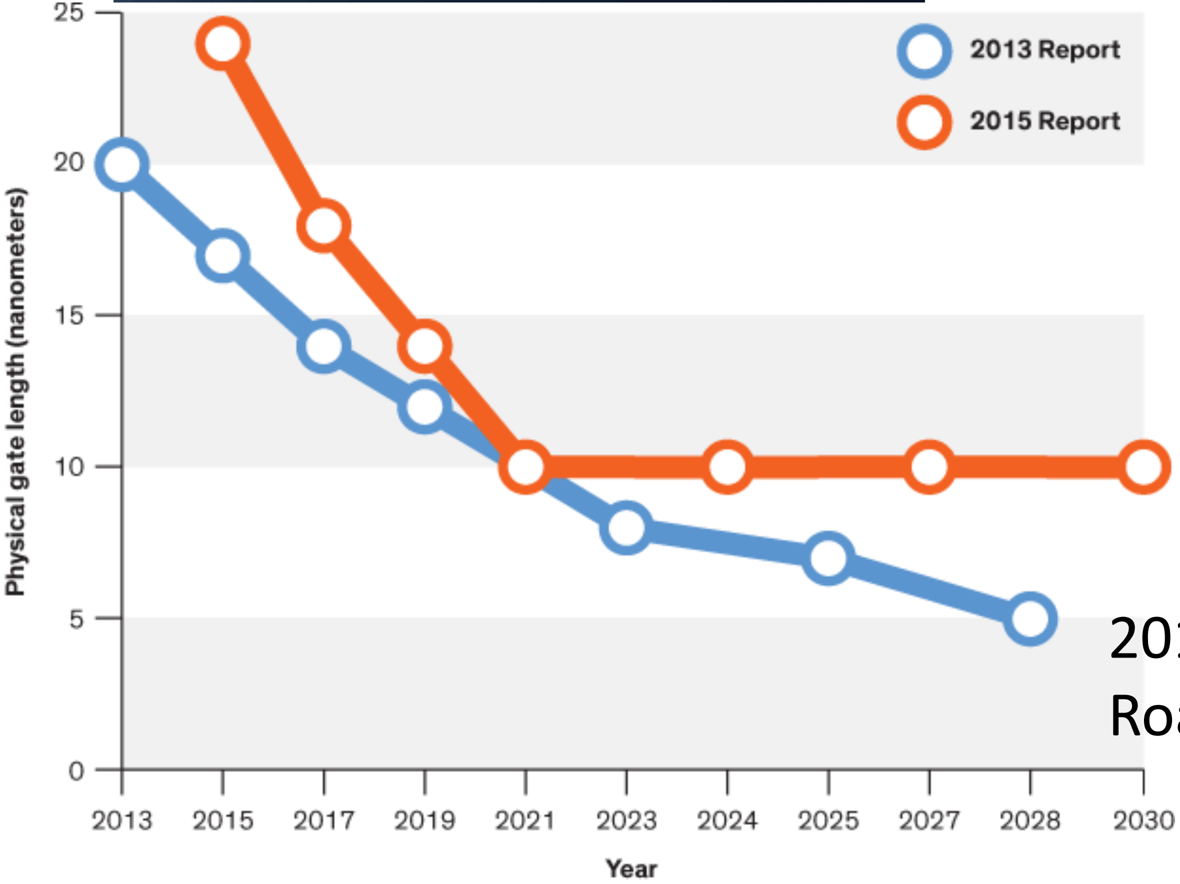


We learned to map atoms inside matter using x-ray crystallography.
This is where it all begins.

The deep knowledge of atomic structures and electromagnetism is the basis of today's technology: Atomic- or nanotechnology

Limits of nanotechnology: Atoms

Microelectronics improve with reduction of the "feature size"



We are now down to 10 nanometers. (about 100 atoms wide).
Progress becomes more and more difficult.

2015 International Technology Roadmap for Semiconductors

Can we go smaller?

Quarks (and gluons)

Nobel Prize in Physics 1990

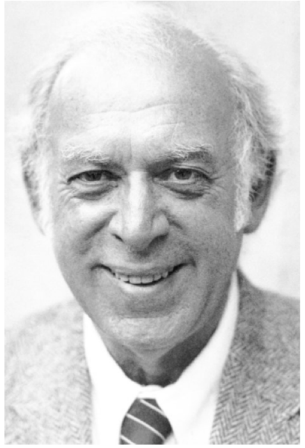


Photo from the Nobel Foundation archive.

Jerome I. Friedman

Prize share: 1/3

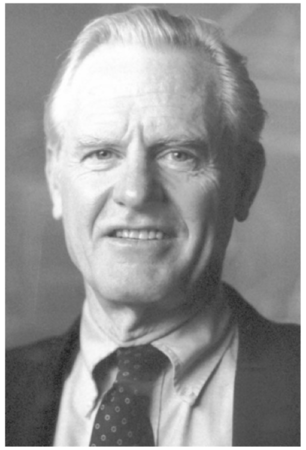


Photo from the Nobel Foundation archive.

Henry W. Kendall

Prize share: 1/3

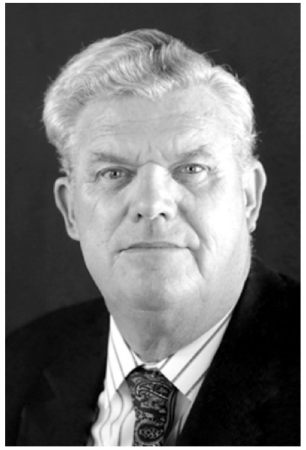


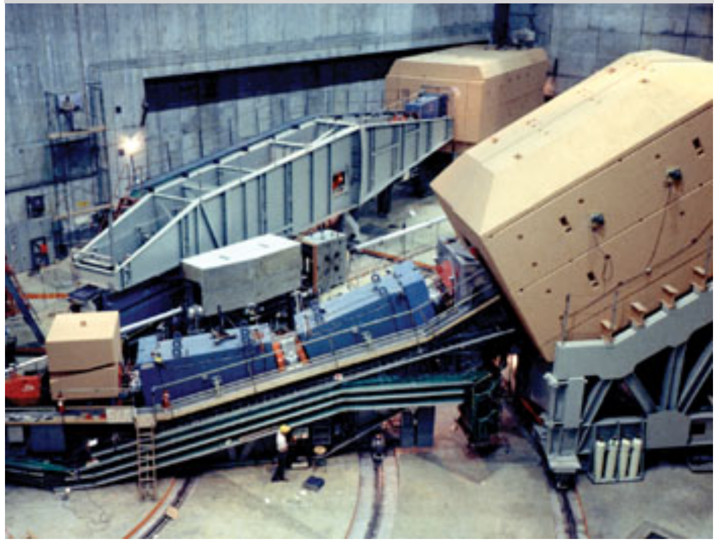
Photo: T. Nakashima

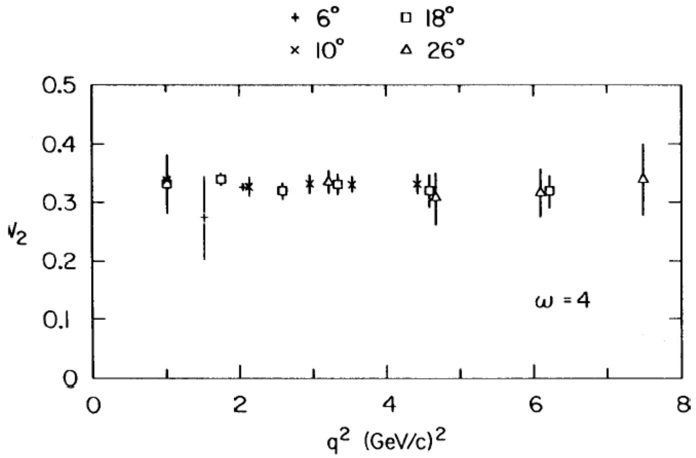
Richard E. Taylor

Prize share: 1/3

Discovery of quarks The Nobel Prize in Physics 1990 was awarded "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the **development of the quark model in particle physics**."

SLAC-MIT Experiment 1969

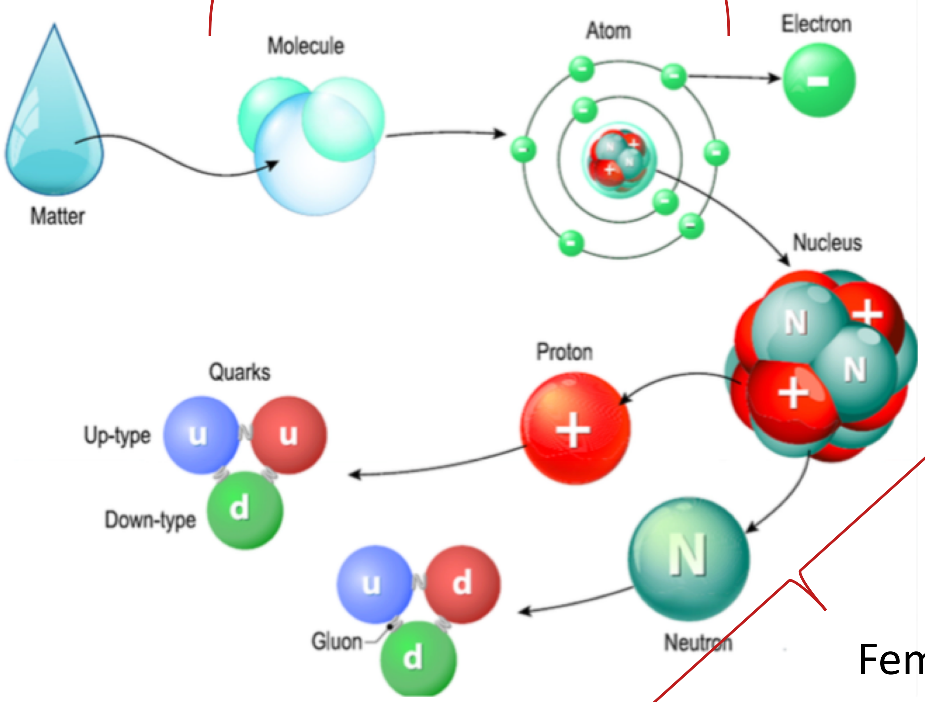




Structure of matter

Nanoworld (scale ~10^{-9} meters)

A million times smaller



Femtoworld (scale ~10^{-15} meters)

Can we manipulate quarks and gluons?

We have known for half a century that quarks (and gluons) and their interactions make up 99% of mass in the visible universe.. however.. no way to map quarks and gluons in the nucleus.. till now!

Advances in Nuclear Physics

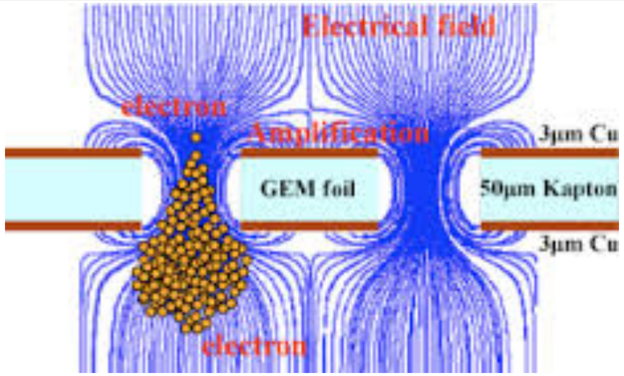
Theory of the strong interaction

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\,\mathrm{d}y\,\mathrm{d}q_\mathrm{T}^2} = {} & \frac{4\pi^2\alpha^2}{9Q^2 s} \sum_{j,j_A,j_B} e_j^2 \int \frac{\mathrm{d}^2\boldsymbol{b}_\mathrm{T}}{(2\pi)^2} e^{i\boldsymbol{q}_\mathrm{T}\cdot\boldsymbol{b}_\mathrm{T}} \\
& \times \int_{x_A}^{1} \frac{\mathrm{d}\xi_A}{\xi_A} f_{j_A/A}(\xi_A;\mu_{b_*})\, \tilde{C}^{\mathrm{CSS1,\ DY}}_{j/j_A}\left(\frac{x_A}{\xi_A}, b_*; \mu_{b_*}^2, \mu_{b_*}, C_2, a_s(\mu_{b_*})\right) \\
& \times \int_{x_B}^{1} \frac{\mathrm{d}\xi_B}{\xi_B} f_{j_B/B}(\xi_B;\mu_{b_*})\, \tilde{C}^{\mathrm{CSS1,\ DY}}_{\bar{j}/j_B}\left(\frac{x_B}{\xi_B}, b_*; \mu_{b_*}^2, \mu_{b_*}, C_2, a_s(\mu_{b_*})\right) \\
& \times \exp\left\{ -\int_{\mu_{b_*}^2}^{\mu_Q^2} \frac{\mathrm{d}\mu'^2}{\mu'^2} \left[A_{\mathrm{CSS1}}(a_s(\mu');C_1) \ln\left(\frac{\mu_Q^2}{\mu'^2}\right) + B_{\mathrm{CSS1,\ DY}}(a_s(\mu');C_1,C_2) \right] \right\} \\
& \times \exp\left[-g^{\mathrm{CSS1}}_{j/A}(x_A, b_\mathrm{T}; b_\mathrm{max}) - g^{\mathrm{CSS1}}_{\bar{j}/B}(x_B, b_\mathrm{T}; b_\mathrm{max}) - g^{\mathrm{CSS1}}_{K}(b_\mathrm{T}; b_\mathrm{max}) \ln(Q^2/Q_0^2) \right] \\
& + \text{suppressed corrections.}
\end{aligned}
$$

Quantumchromo-dynamics (QCD)

Accelerator technologies

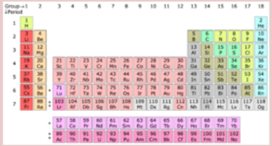
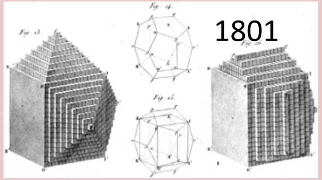
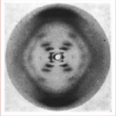
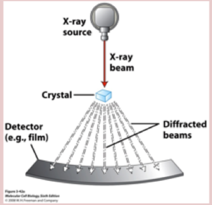
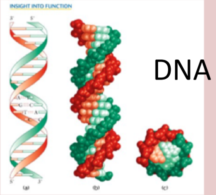
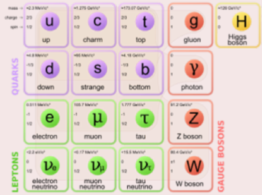
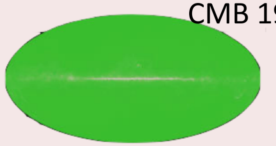
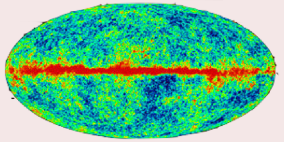
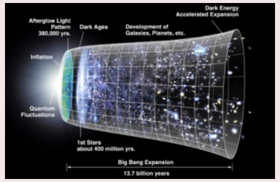
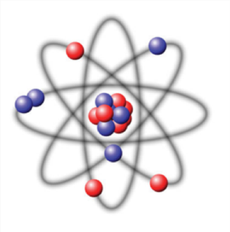
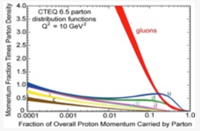
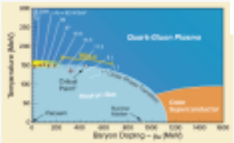
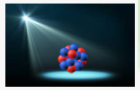
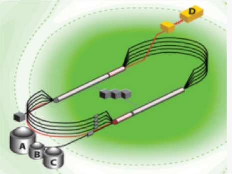
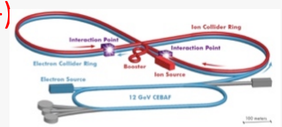
Detector technologies



Computer technologies

Steady advances in all of these areas mean that →

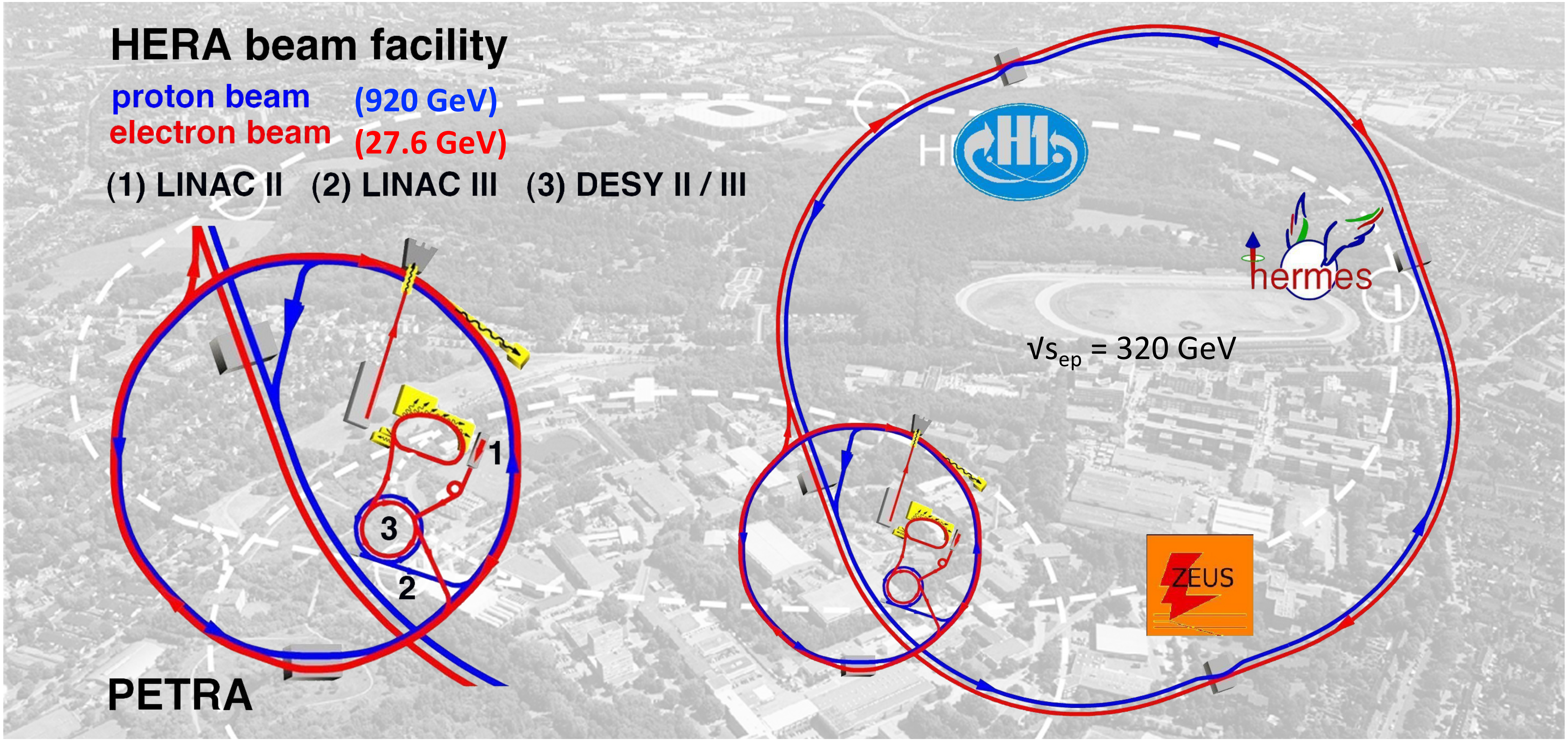
EIC: A new frontier in science

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes (Date)	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure 1801 	X-ray Diffraction (~1920)  	Solid state physics Molecular biology DNA 
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure CMB 1965 	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$	Non-perturbative QCD Structure 2017   	CEBAF12 (2018)   Electron-Ion Collider (2025+) 	Structure & Dynamics in QCD 

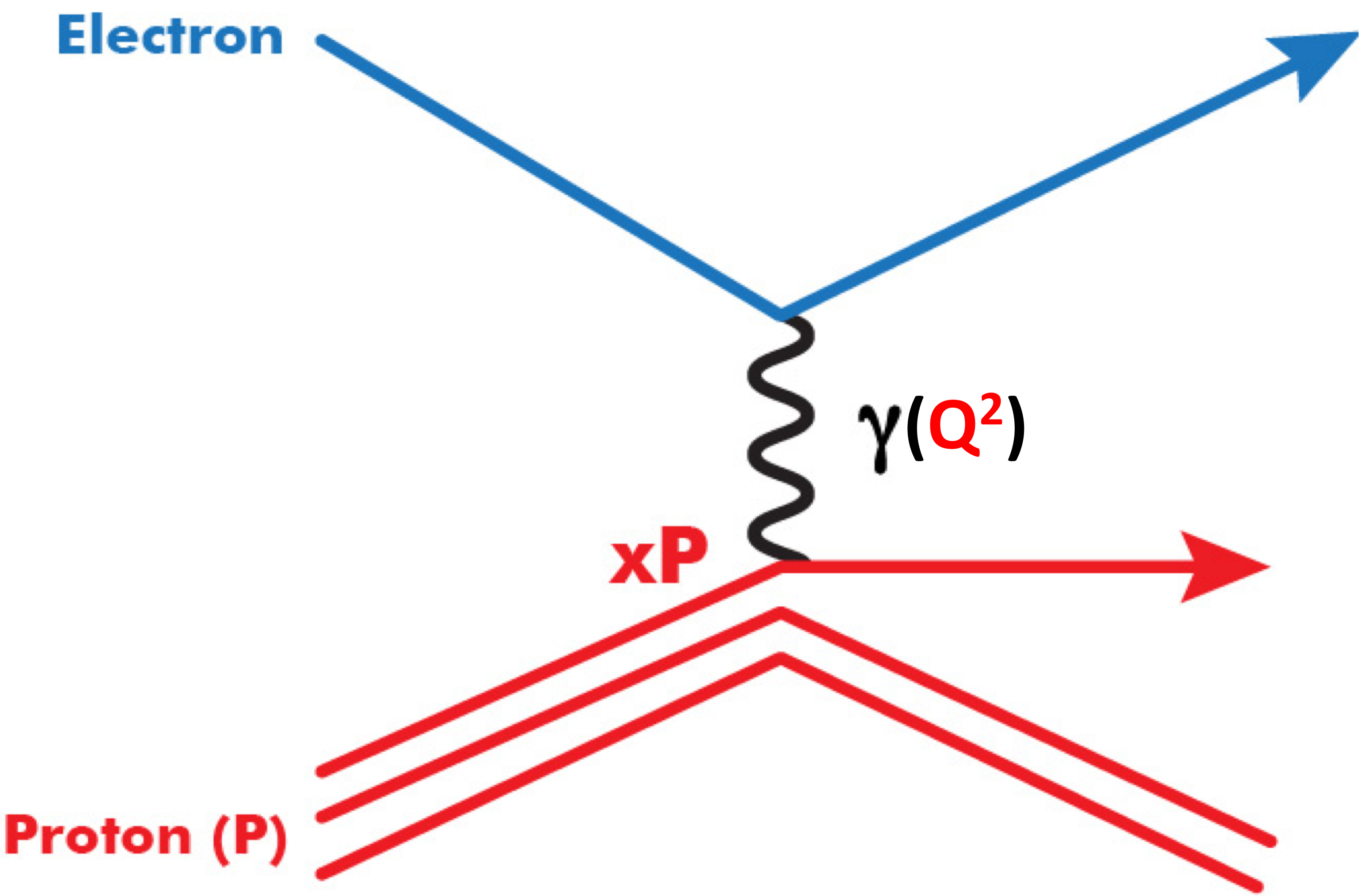
Prologue

The first Electron-Ion Collider

HERA: The first Electron-Ion Collider



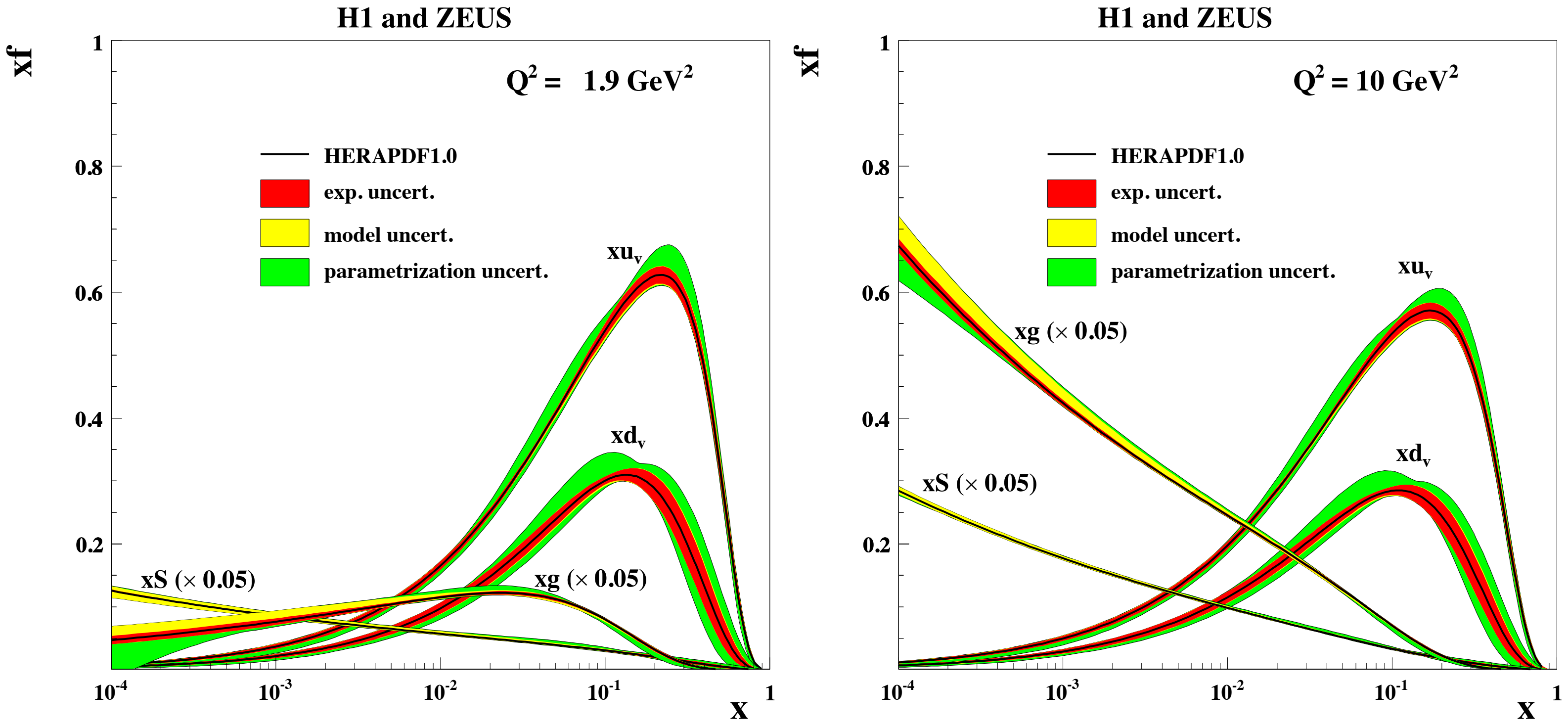
Deep-inelastic scattering (DIS) of electrons off protons



Parton distribution functions (PDF)

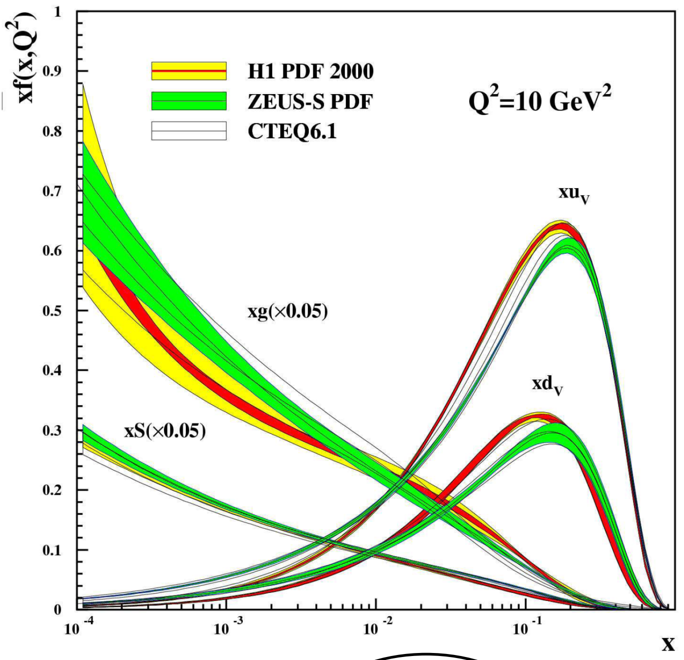
Observable cross section → structure functions → **QCD analysis** PDFs

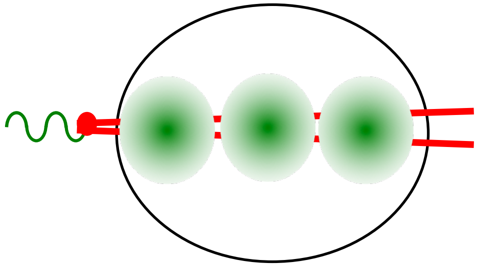
process-dependent | **universal**



QCD at extremes: Parton saturation

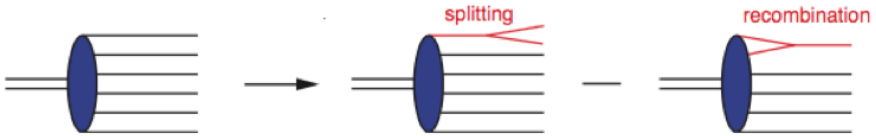
Dramatic rise of gluon PDF



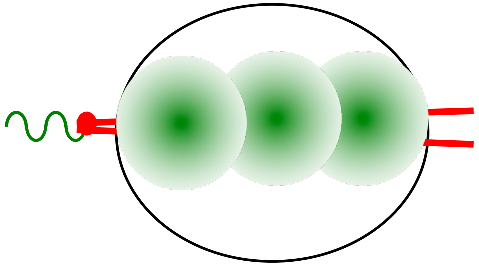


In nuclei, the interaction probability enhanced by A⅓

Parton splitting and recombination



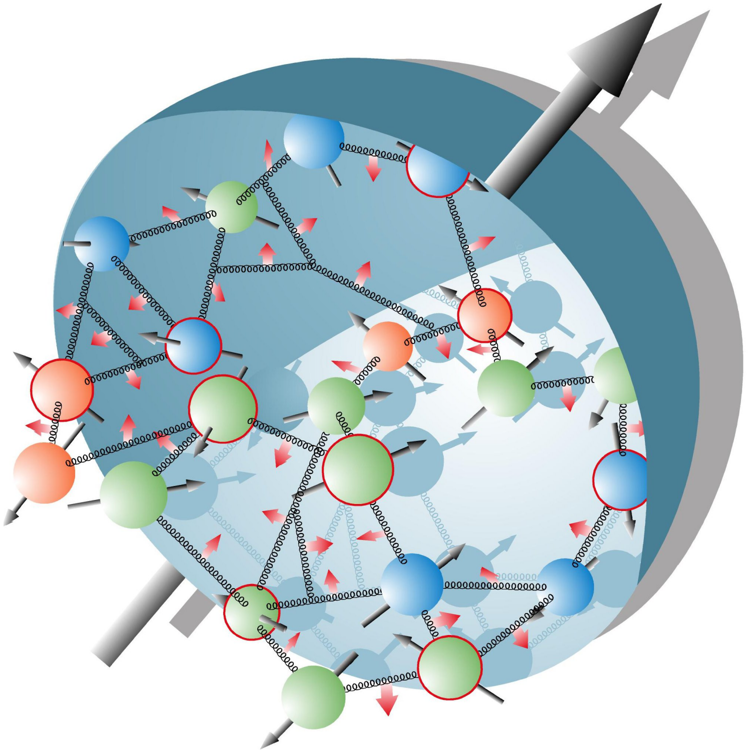
- rise of gluon PDF cannot go on forever as x becomes smaller and smaller
- **parton saturation**: parton recombination must balance parton splitting
- unobserved at HERA for a proton and expected at extreme low x



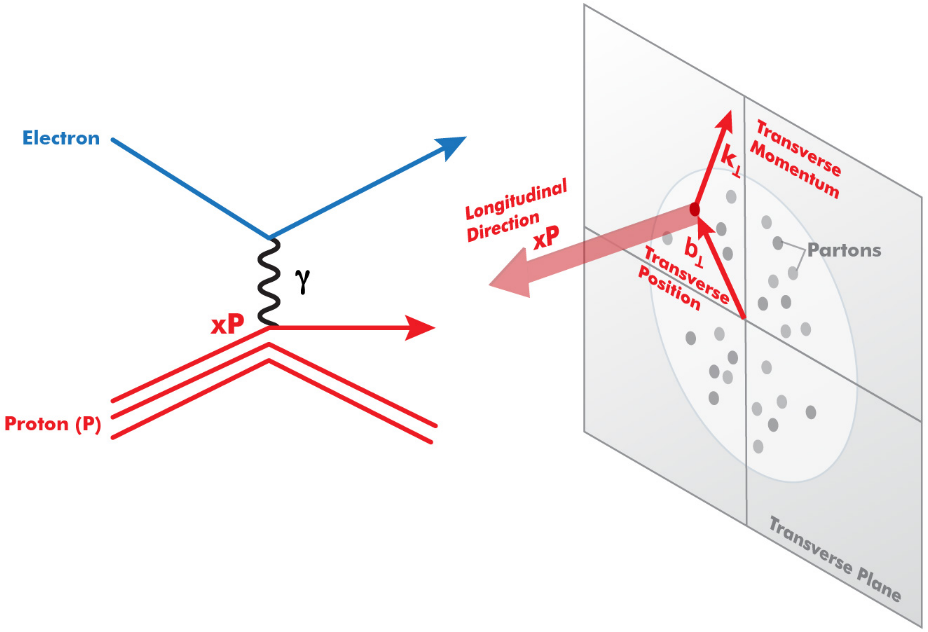
Will nuclei saturate faster as color leaks out of nucleons?

Polarized DIS measurements

Polarization



Novel QCD phenomena



3D imaging in space and momentum

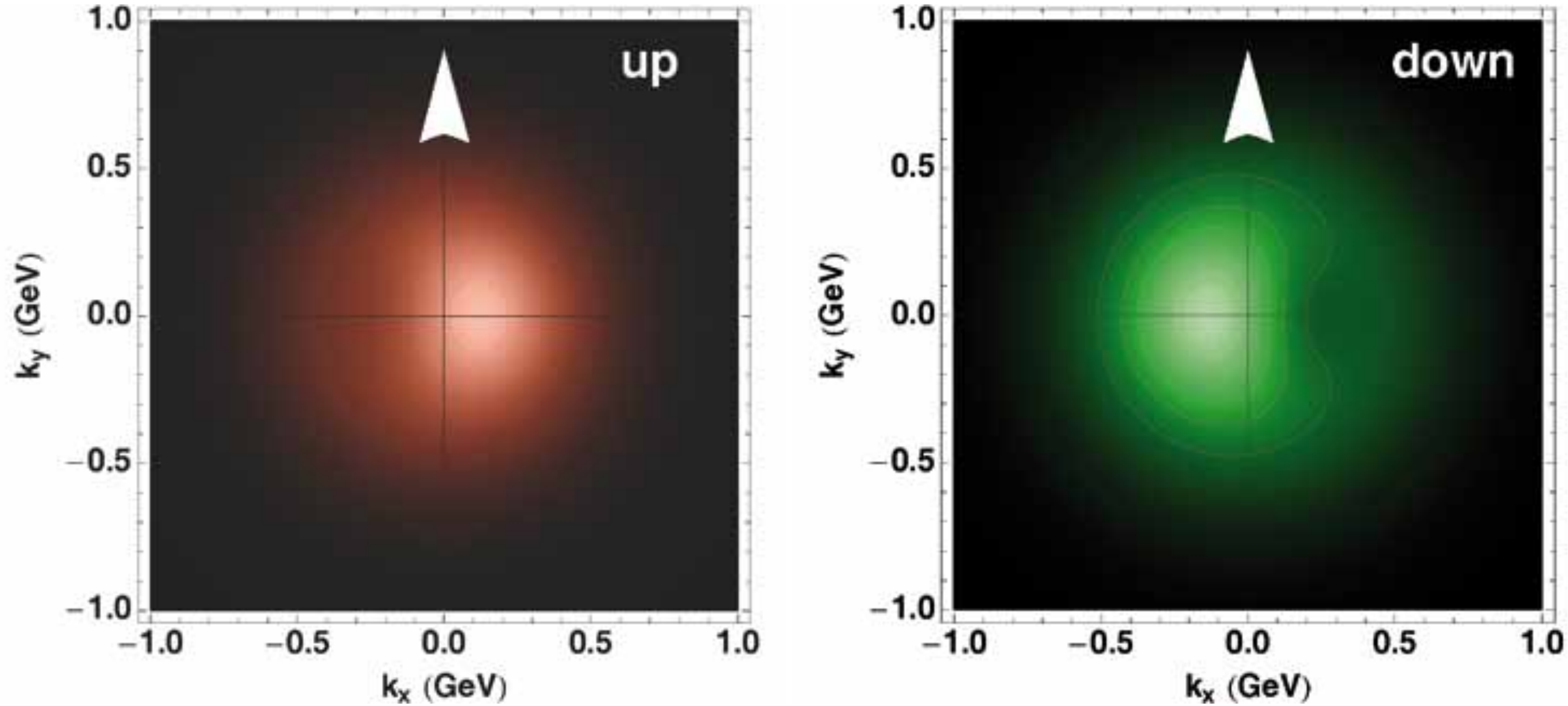
longitudinal structure (PDF)

+ transverse position Information (GPDs)

+ transverse momentum information (TMDs)

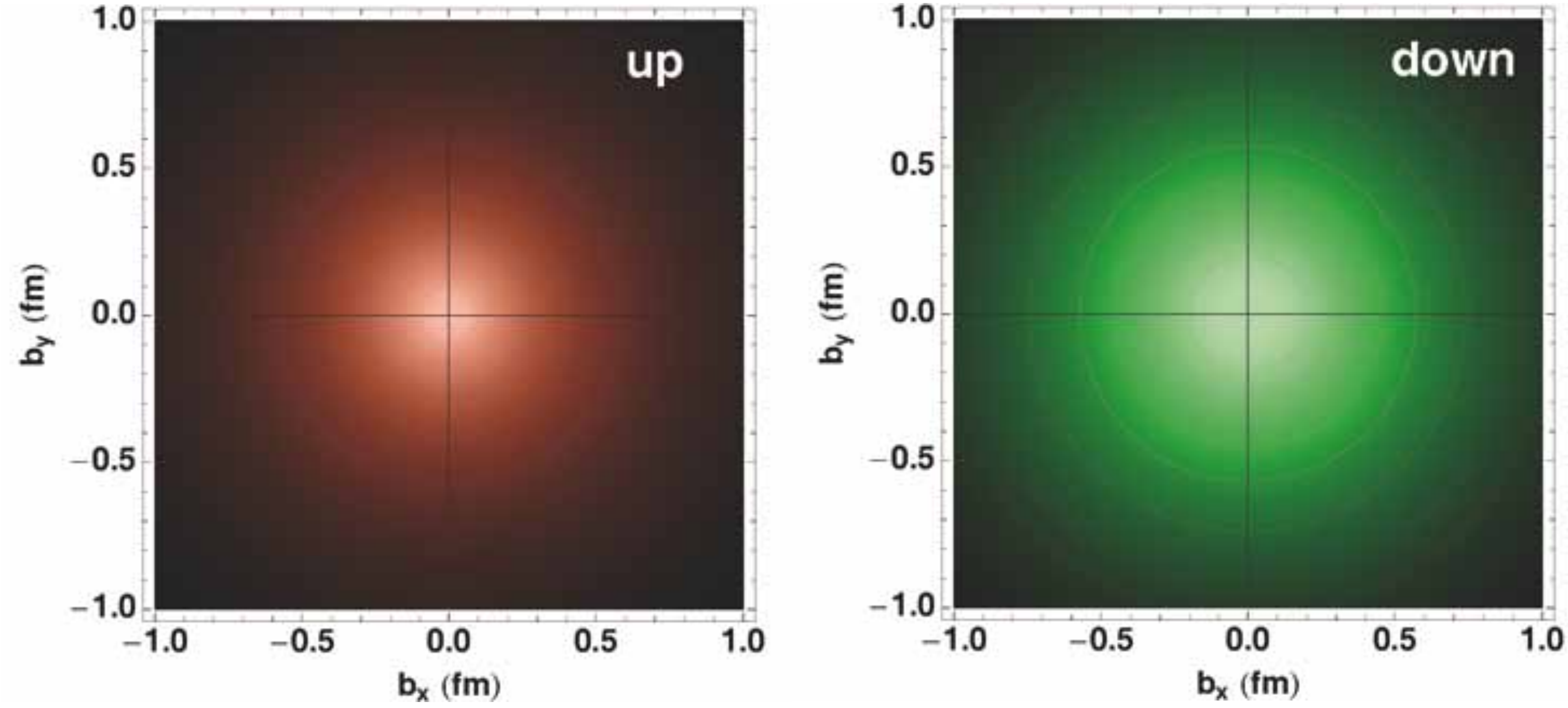
order of a few hundred MeV

Transverse momentum information (TMDs)



distortion of quark distributions for a transversely polarized proton

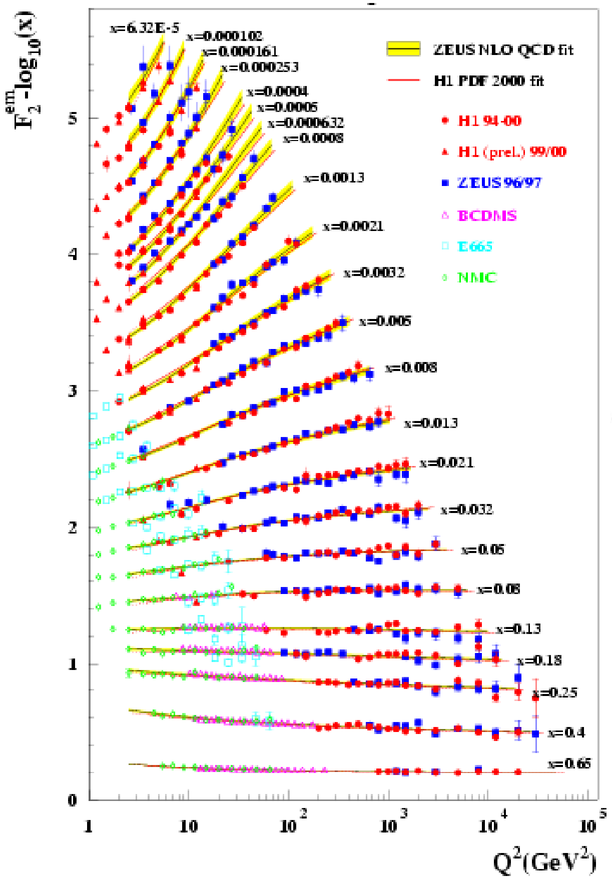
Transverse position information (GPDs)

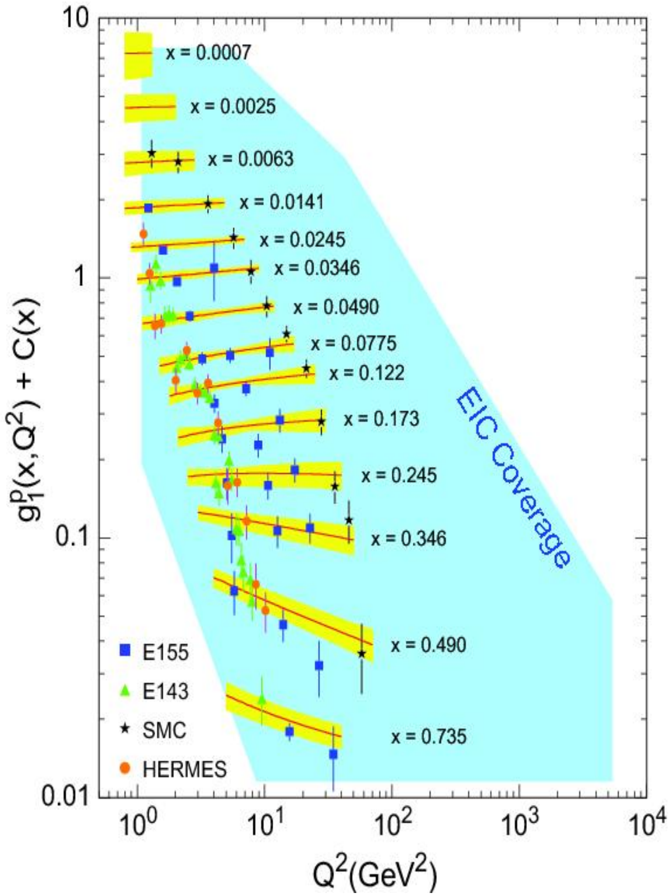


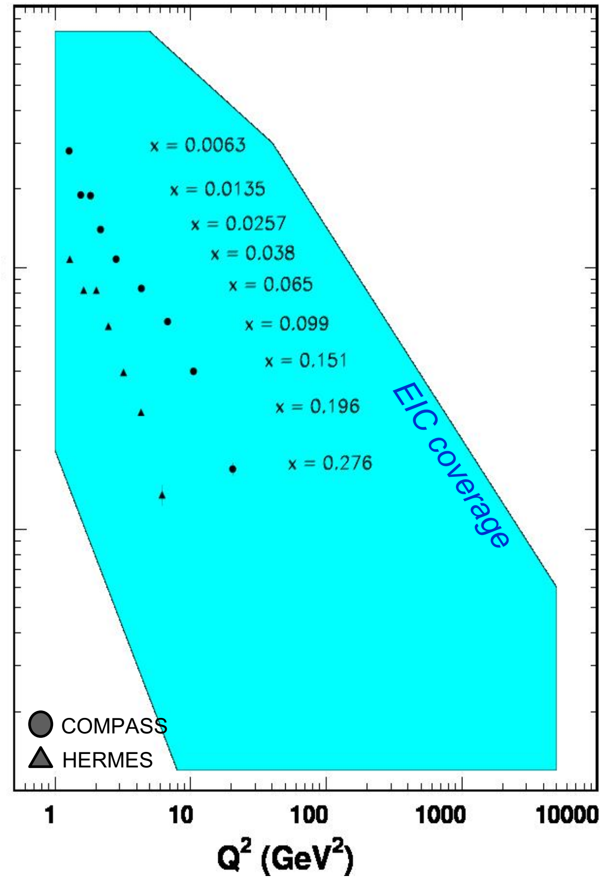
core of positive charge in the center

cloud of negative charge around it

World Data on F_2^p World Data on g_1^p World Data on h_1^p







momentum

spin

transverse spin

Future nuclear physics facility

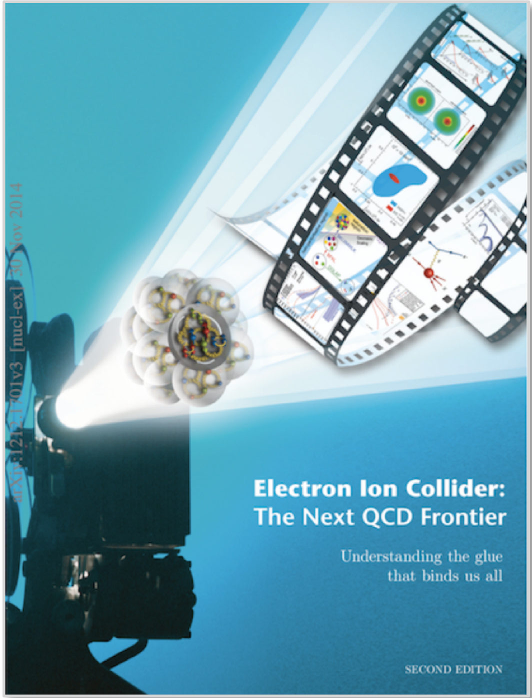
The Electron-Ion Collider Project

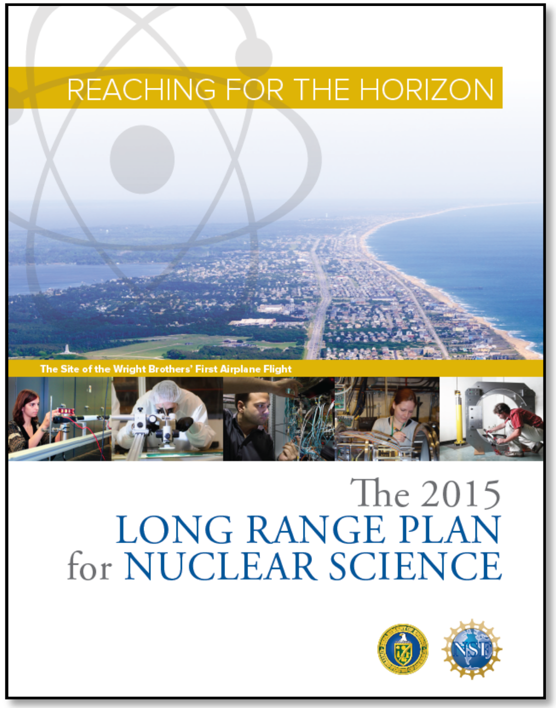
Why an Electron-Ion Collider?

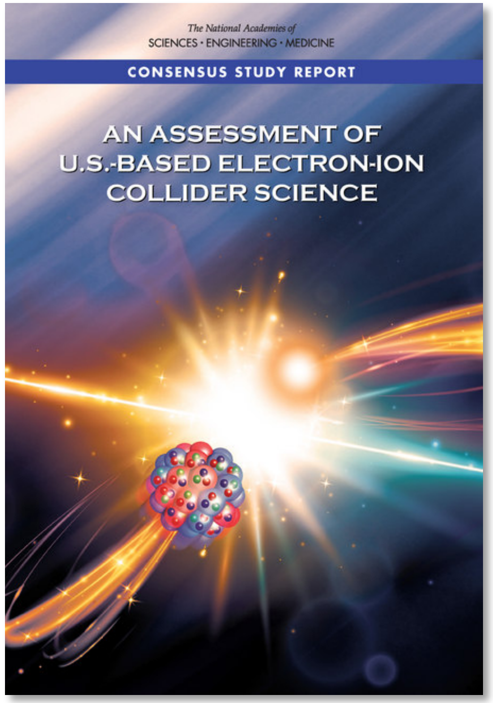
Right tool:

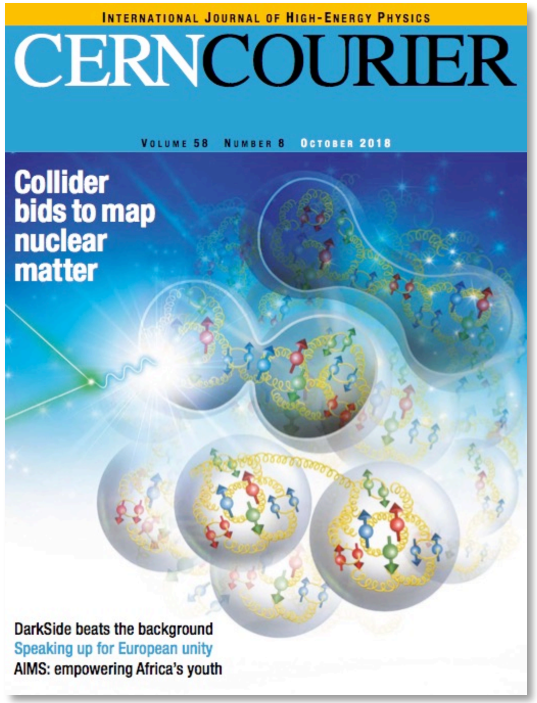
- to precisely **image quarks and gluons** and their interactions
- to explore the new **QCD frontier of strong color fields in nuclei**
- to understand **how matter at its most fundamental level is made**.

Understanding of nuclear matter is **transformational**, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.

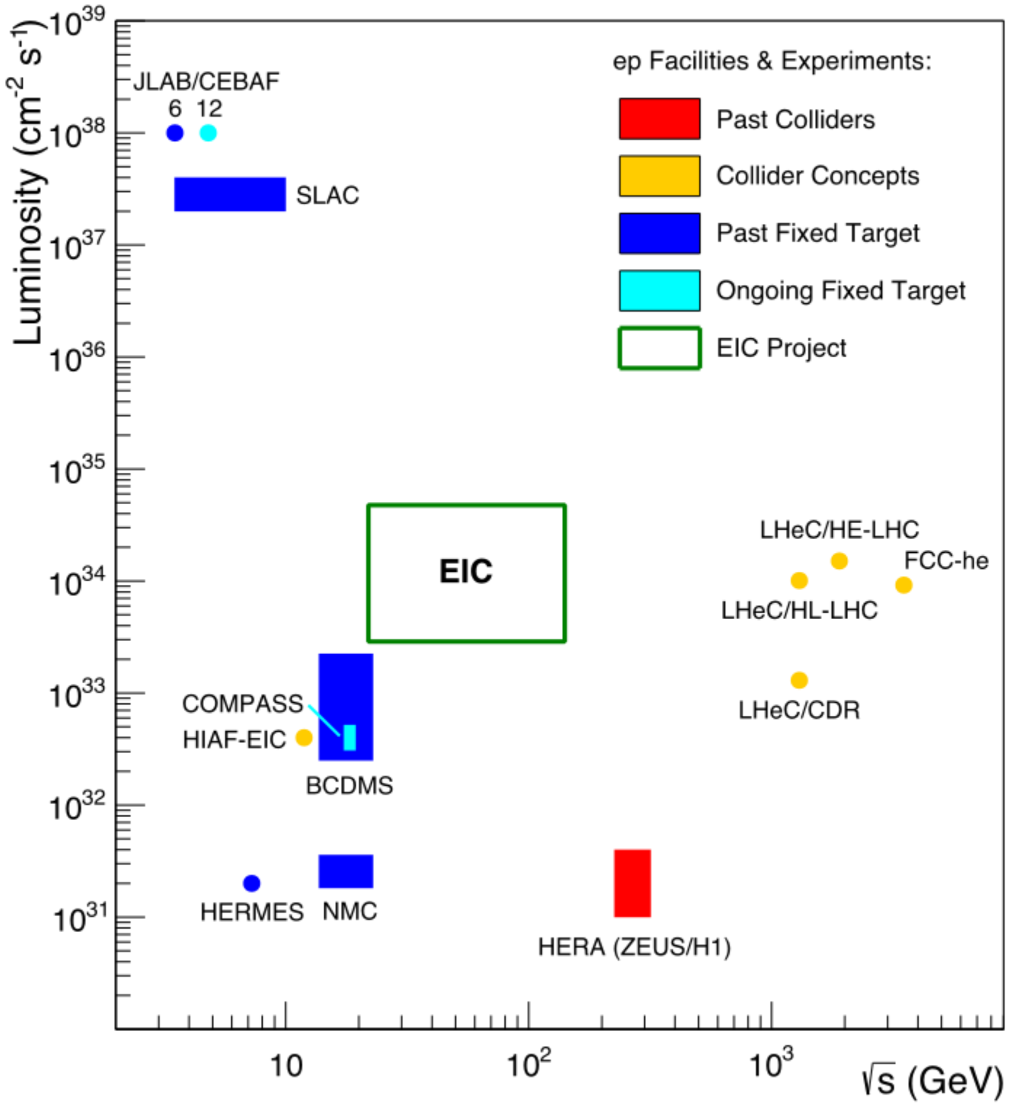








The Electron-Ion Collider (EIC)



Frontier accelerator facility in the U.S.

World's first collider of

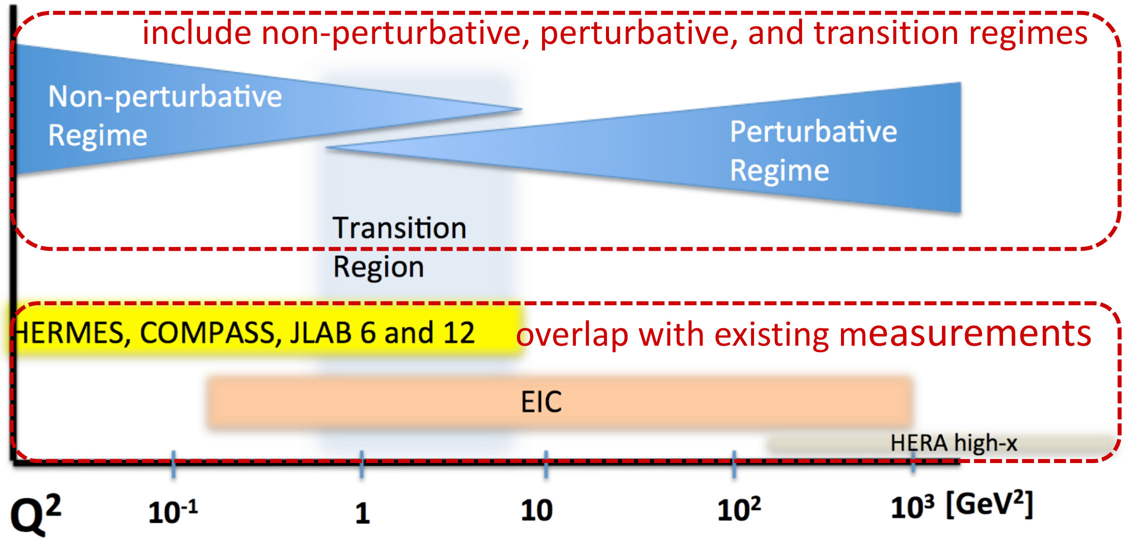
- polarized electrons and polarized protons/light ions (d, ^{3}He)
- electrons and nuclei

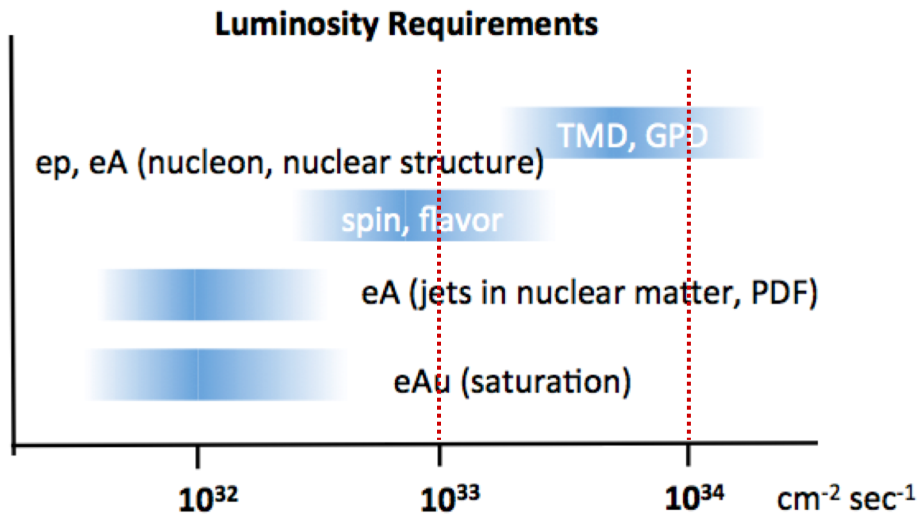
Versatile range of

- beam energies
- beam polarizations
- beam species (p → U)

High luminosity

EIC: Ideal facility for studying QCD





Various beam energy

broad Q^2 range for

- studying evolution to Q^2 of ~1000 GeV^2
- disentangling non-perturbative and perturbative regimes
- overlap with existing experiments

High luminosity

high precision

- for various measurements
- in various configurations

EIC: ideal facility for studying QCD

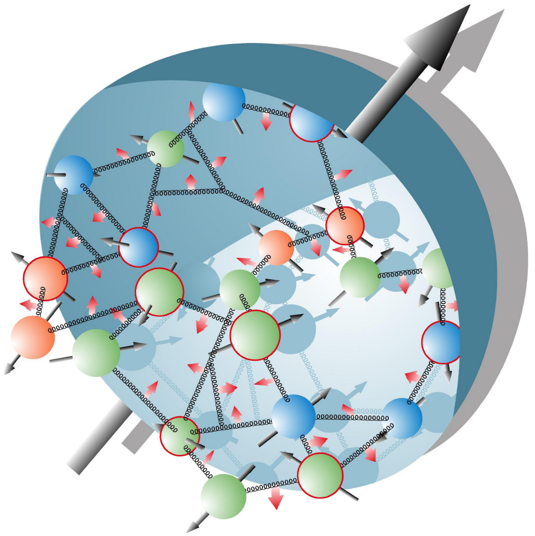
Polarization

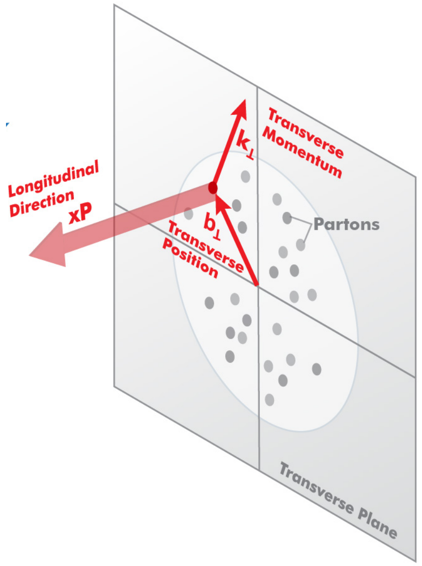
Understanding hadron structure cannot be done without understanding spin:

- polarized **electrons** and
- polarized **protons/light ions**

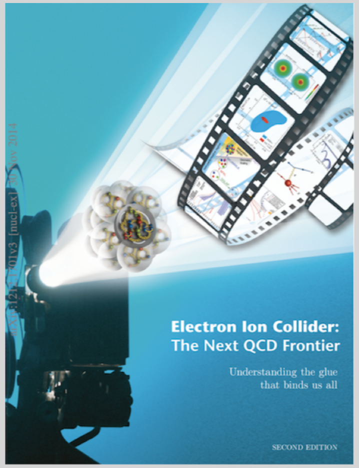
Transverse and longitudinal polarization of light ions (p, d, ^{3}He)

- 3D imaging in space and momentum
- spin-orbit correlations

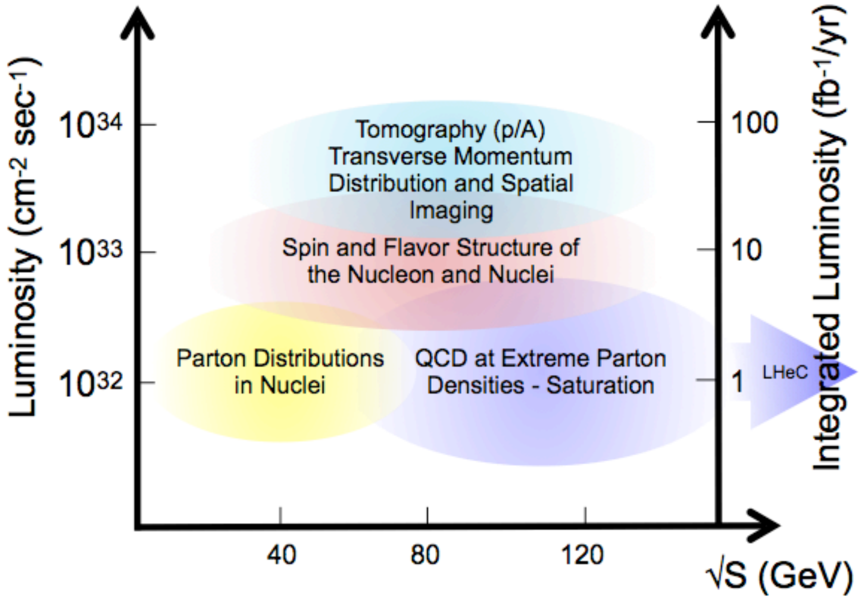


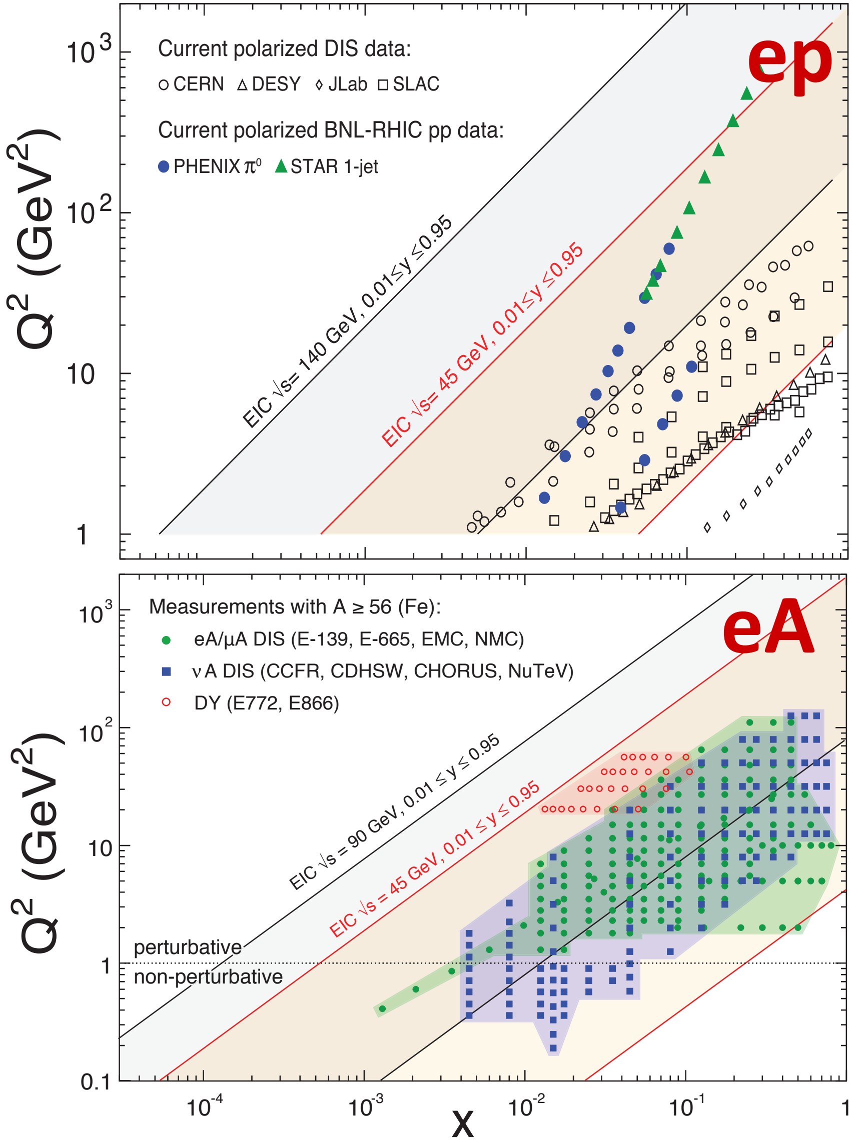


EIC science program



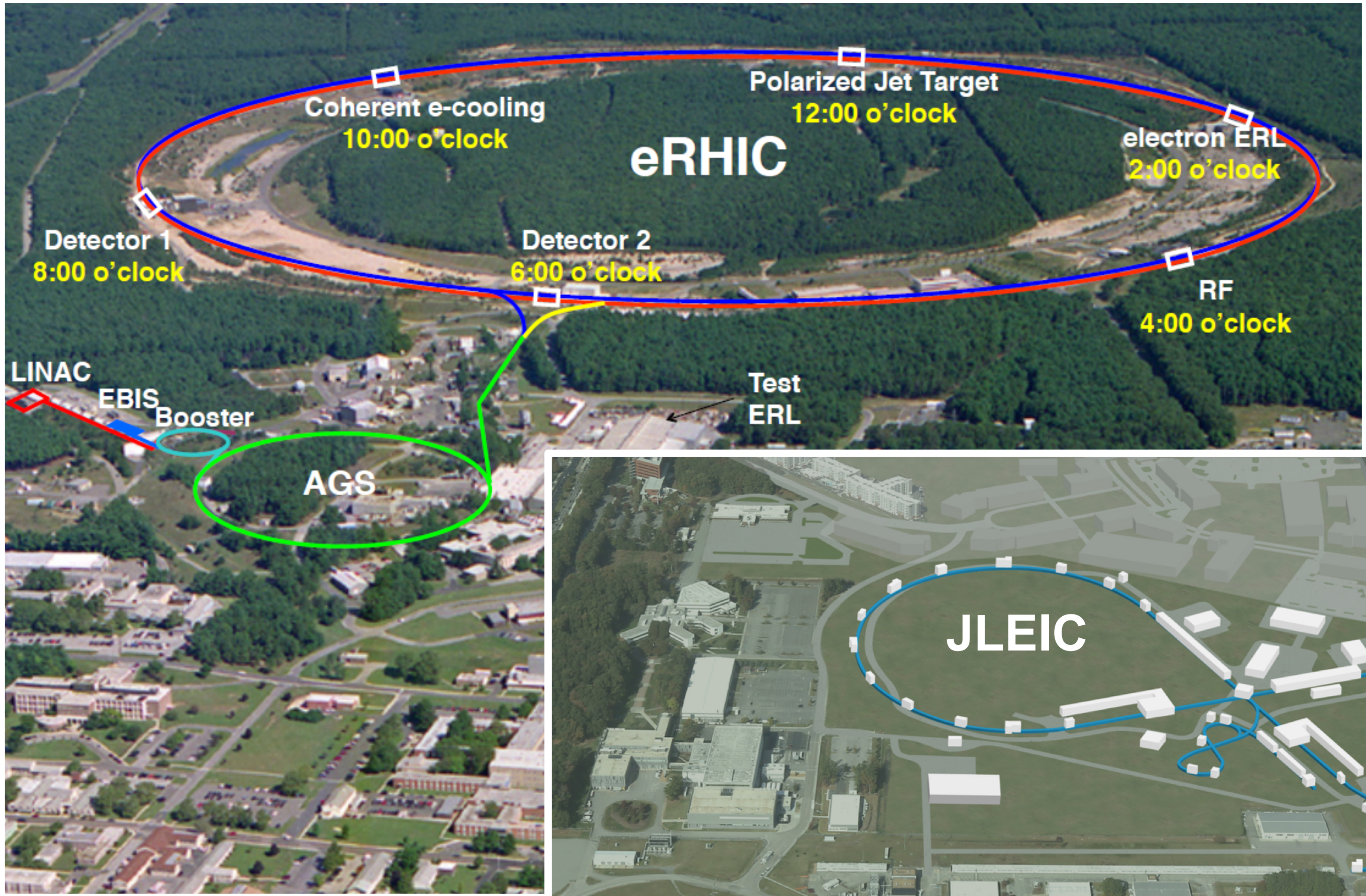
Study **structure** and **dynamics** of **nuclear matter** in **ep** and **eA collisions** with high luminosity and versatile range of beam energies, beam polarizations, and beam species.



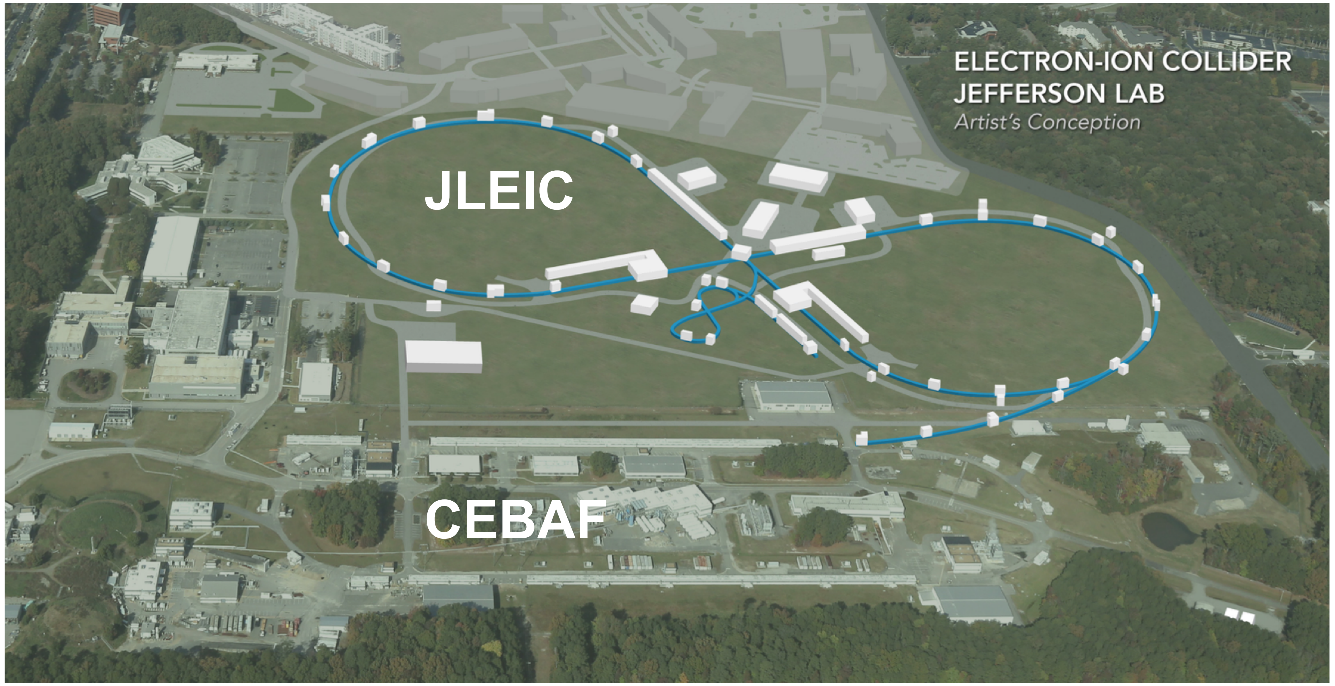


Jefferson Lab

Realization of the science case



Brookhaven Lab
Long Island, NY

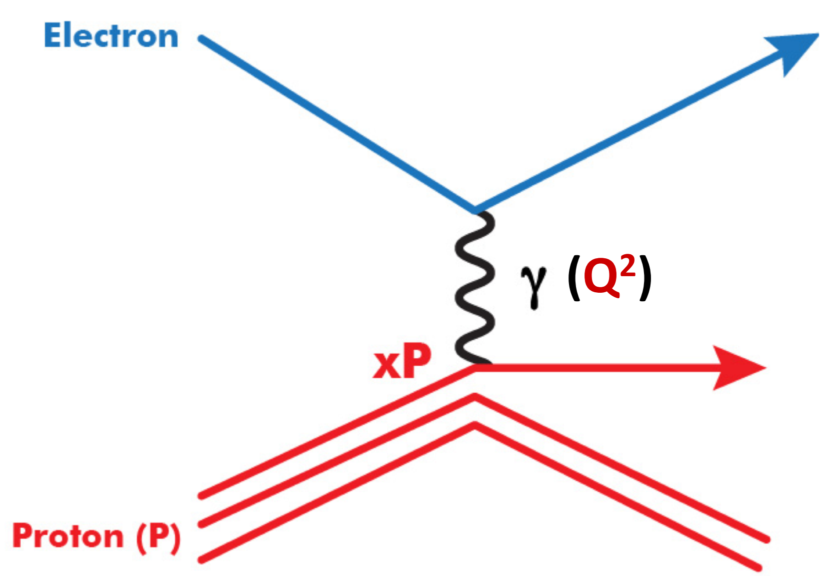


Jefferson Lab
Newport News, VA

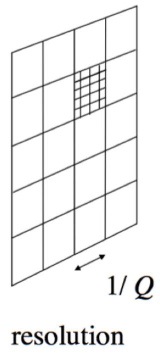
Accelerator design

Designing the right probe

Electron-Proton Scattering

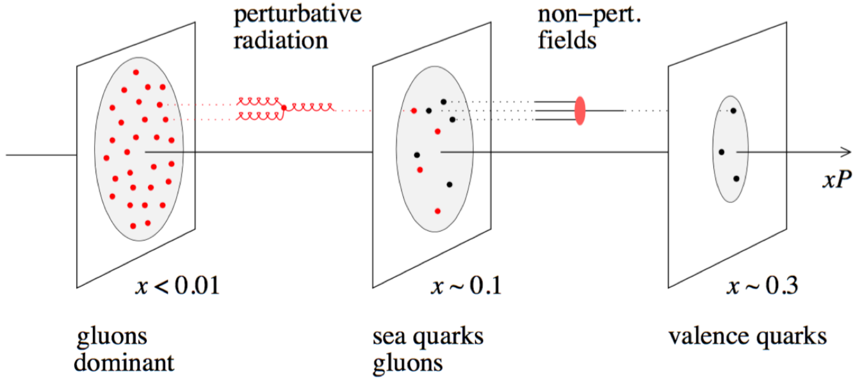


Ability to change Q^2 changes the resolution scale



$Q^2 = 400\ \text{GeV}^2$
$\Rightarrow 1/Q = 0.01$ fm

Ability to change **x** projects out different con-figurations where different dynamics dominate

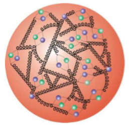


Jefferson Lab

Where EIC Needs to be in x (nucleon)

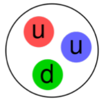
Saturation Regime: Needs to be Accessed via Ions

Collective Regime



Many-body Regime

Few-body Regime



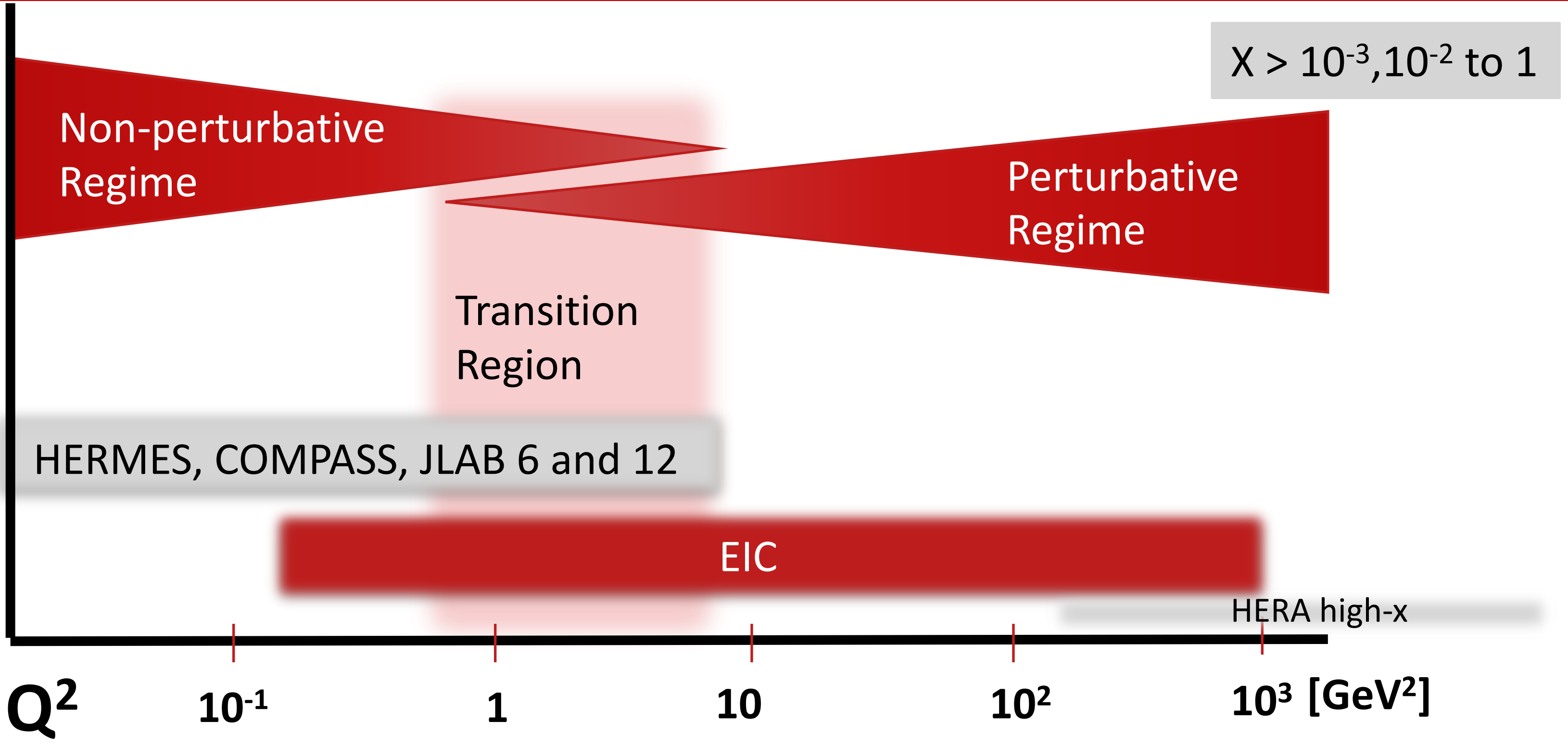
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 X (for proton)

QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Main interest for EIC Nucleon/Nuclear Program

Where EIC needs to be in Q^2



- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

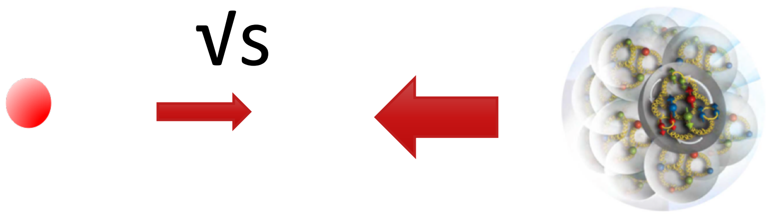
Disentangle Pert./Non-pert., Leading Twist/Higher Twist

Designing The Right Probe: √s

What are the right parameters for the collider for the EIC science program?

We know the x range: down to ~ $10^{-3\text{-}4}$
We know the Q^2 range: up to ~1000 GeV^2

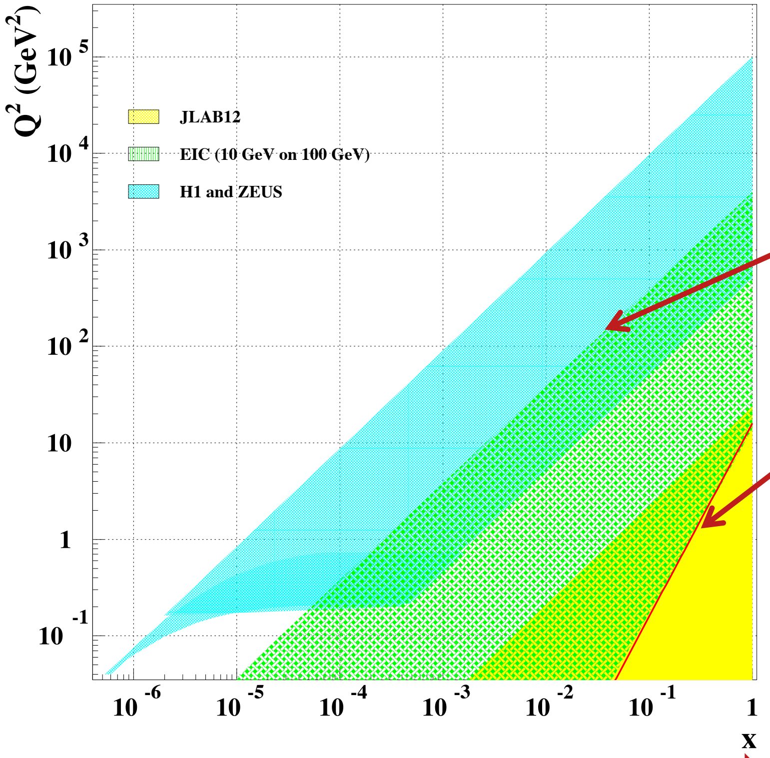
$Q^2 = sxy$, $s = 4E_e E_{hadron}$
→ energies we need.



order 10 GeV electron

order 100 GeV/u ion

JLEIC parameters (nucleon)



Cross section decreases rapidly with higher X

This edge determined by √s:
√s = 65 GeV

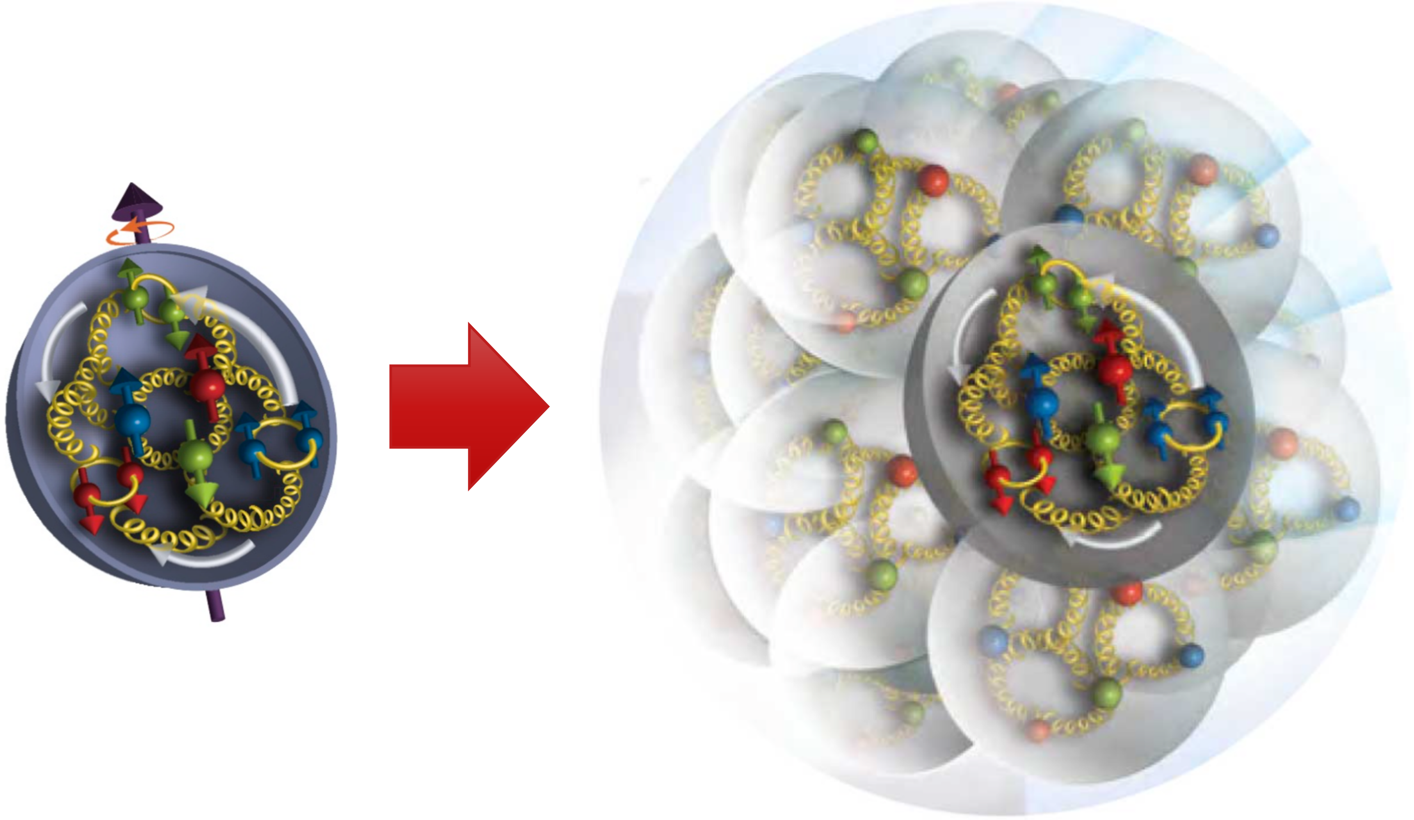
This edge determined by proton beam energy:
E_{proton} < 100 GeV -> $E_{electron}$ = 10 GeV^2

Measure at x of 10^{-3} to 1, exclusive processes
Luminosity: x 10 to 100 that of HERA

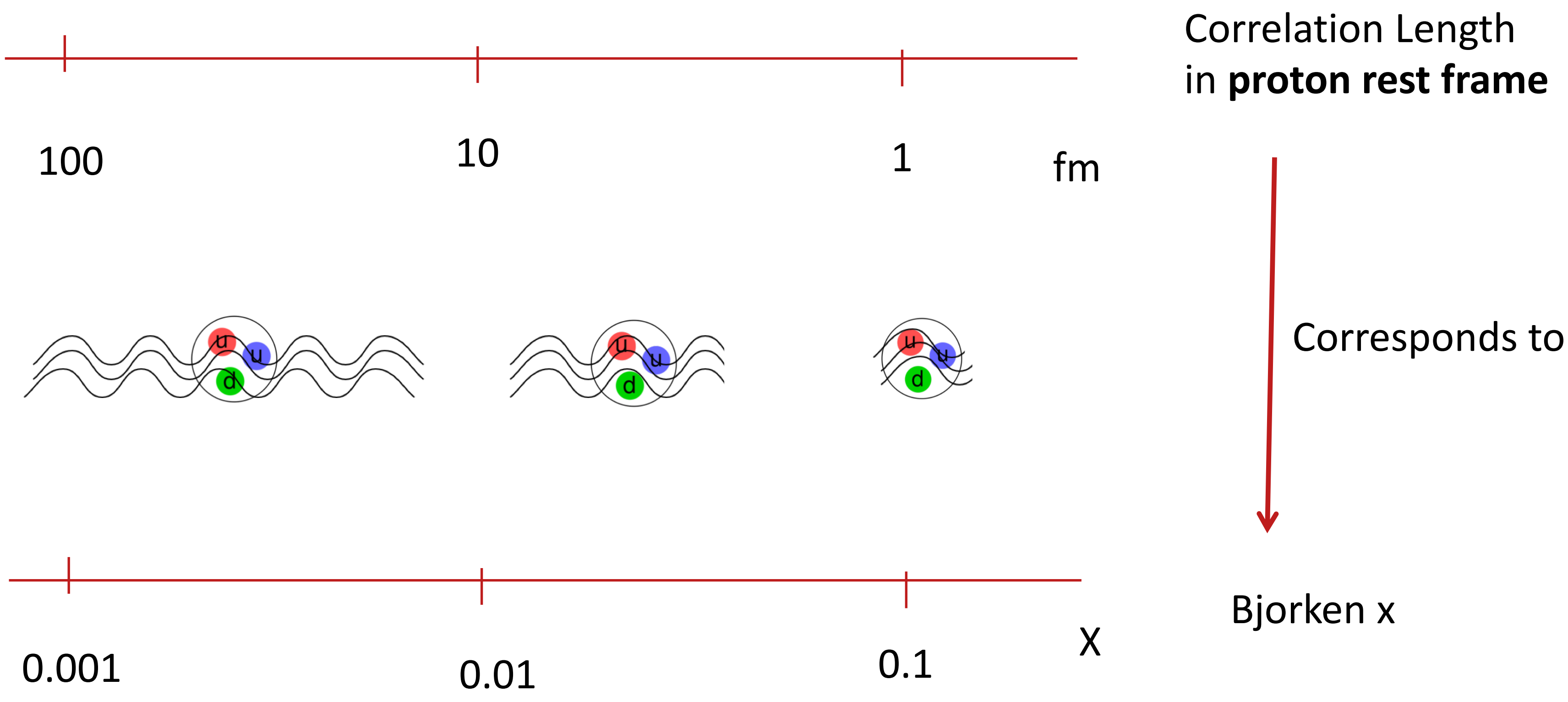
Sets some of the basic parameters of the JLEIC design

Higher beam energies required for eA measurements, e.g., nuclear PDFs

Understanding the nuclei at the next level

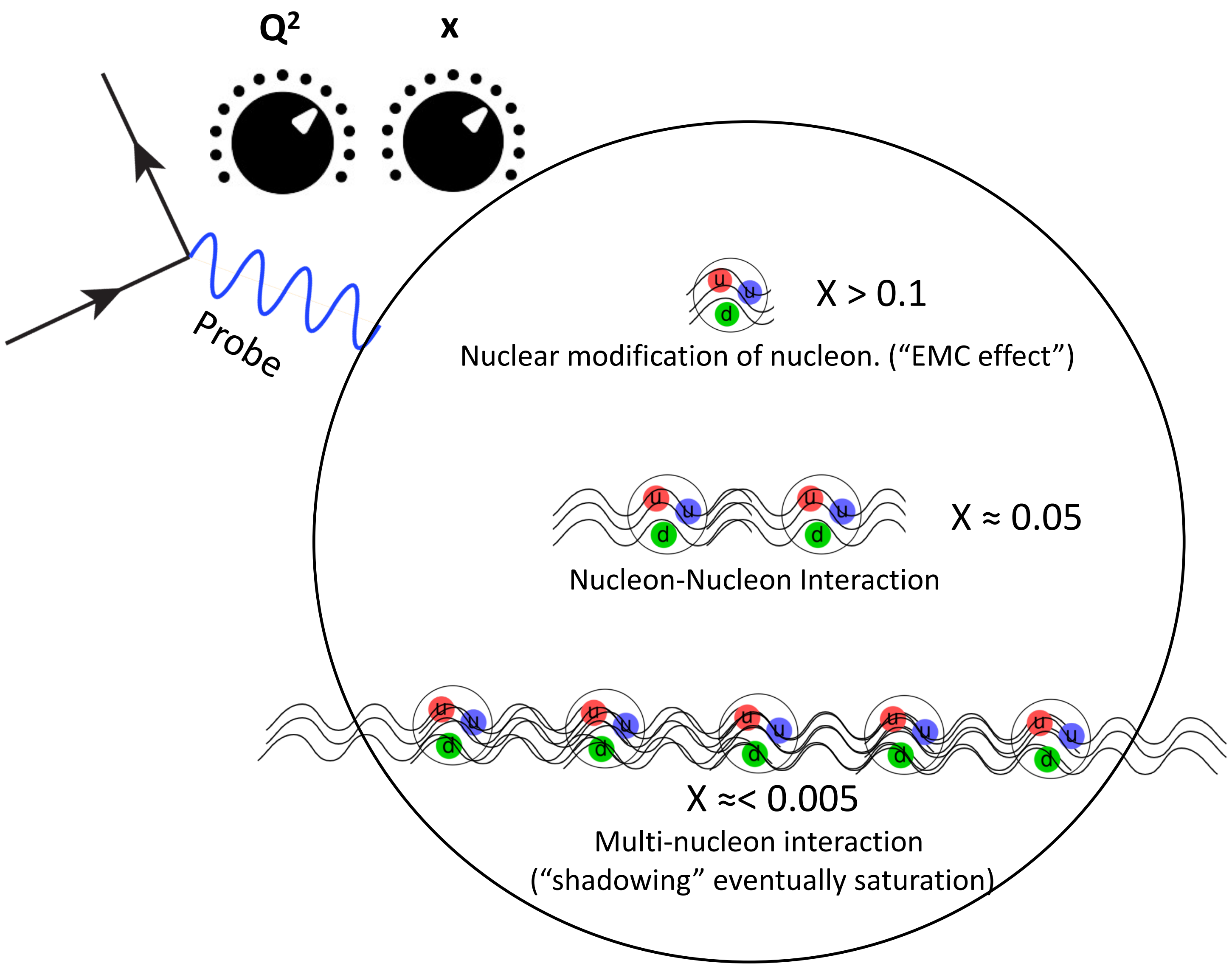


Bjorken x and length scale



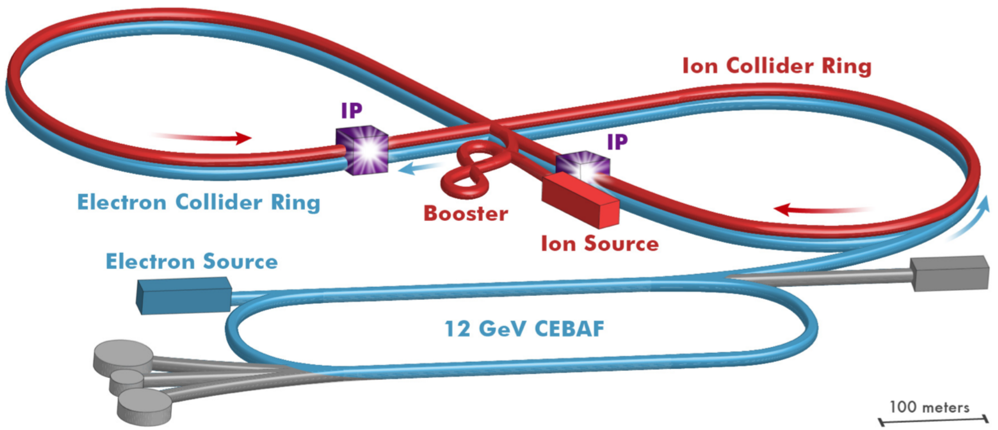
In the proton rest frame, QCD field (x < 0.1) extends far beyond the proton charge radius

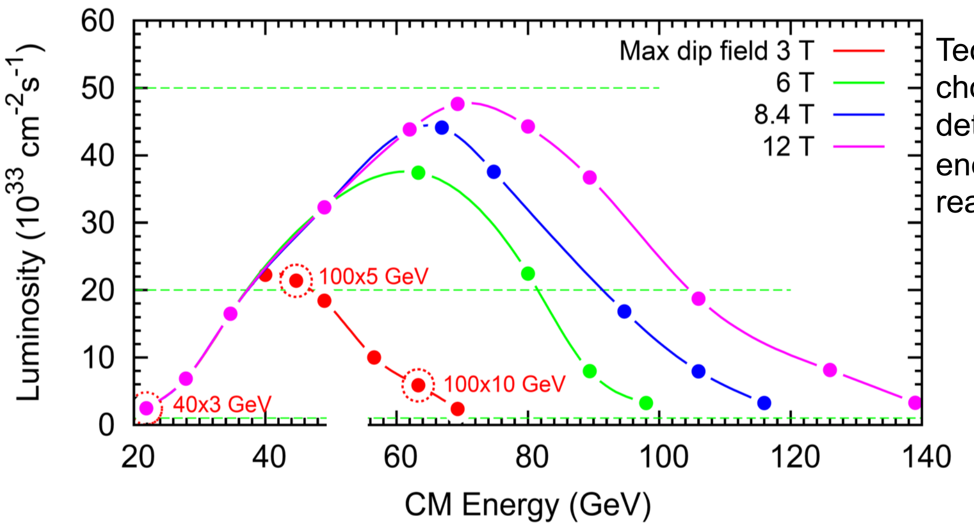
Probing the nucleon interaction in the nuclei



JLEIC design strategy: High luminosity and polarization

>80% polarization for both **electrons** and **light ions**





Technology choice determines energy reach.

Figure-8 shaped ring-ring collider

- zero **spin tune** (net spin precession)
- energy-independent **spin tune**
- **polarization** easily preserved and manipulated:
  - by small solenoids
  - by other compact spin rotators

High luminosity

- high-rate collision of short bunches
  - with small emittance
  - with low charge
- **ion beam:** high-energy electron cooling (R&D)
- **electron beam:** synchrotron radiation damping

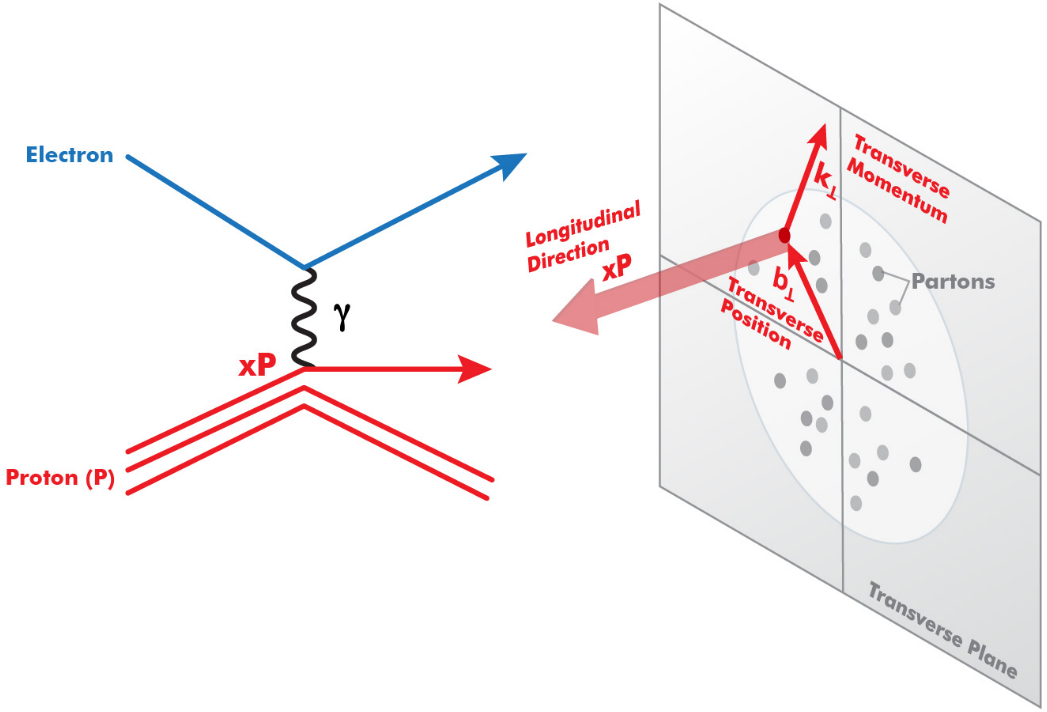
JLEIC energy reach √s =**20 –100 GeV**, upgradable to **140 GeV** using 12 T magnets (HE-LHC, FCC)

Detector design

General design considerations

Mapping position and motion of quarks and gluons

Study nuclear matter **beyond longitudinal description** makes the **requirements for IR and detector design different** from all previous colliders including HERA.



3D imaging in space and momentum

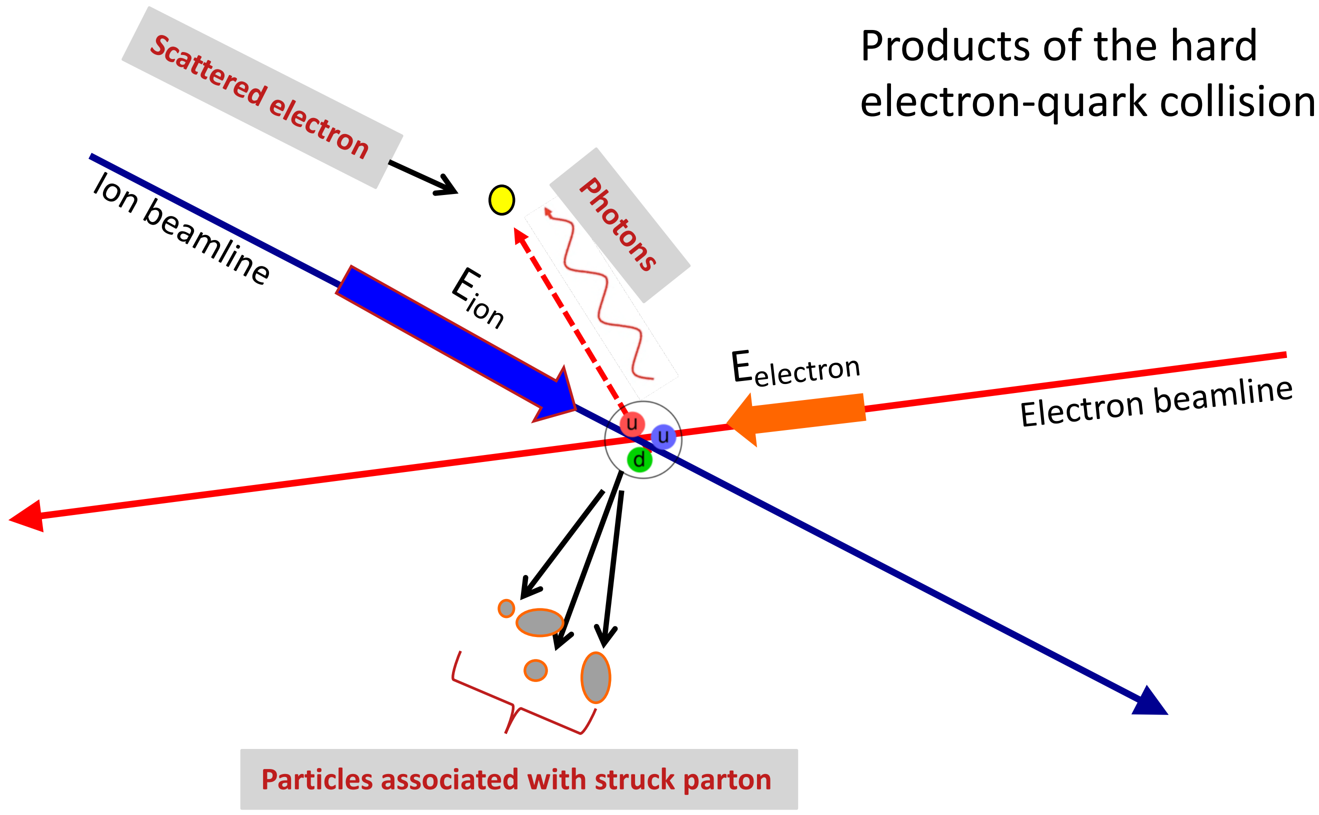
longitudinal structure (PDF)

+ transverse position Information (GPDs)

+ transverse momentum information (TMDs)

order of a few hundred MeV **measurement**

Particle Identification

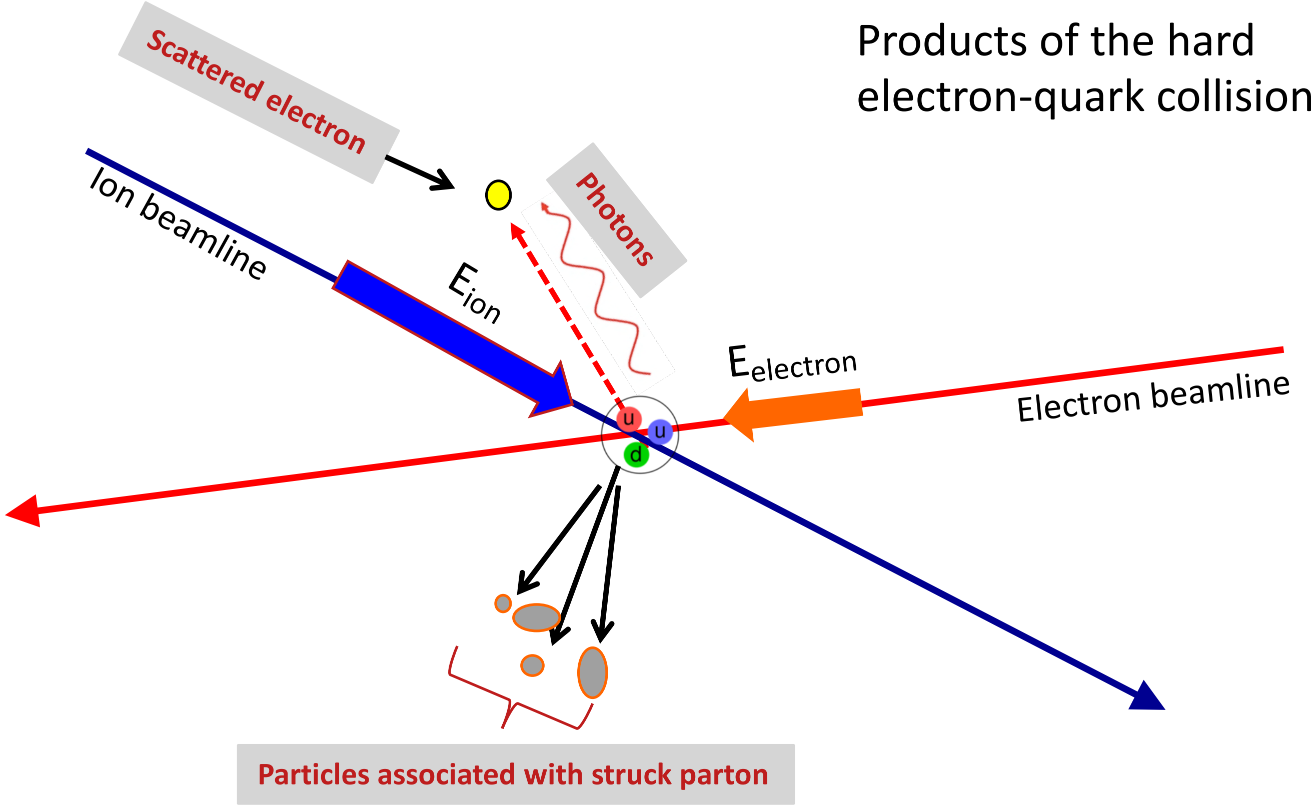


Products of the hard electron-quark collision

Transverse and flavor structure measurement of the nucleon and nuclei: The particles associated with struck parton must have its species identified and measured. **Particle ID much more important than at HERA** colliders.

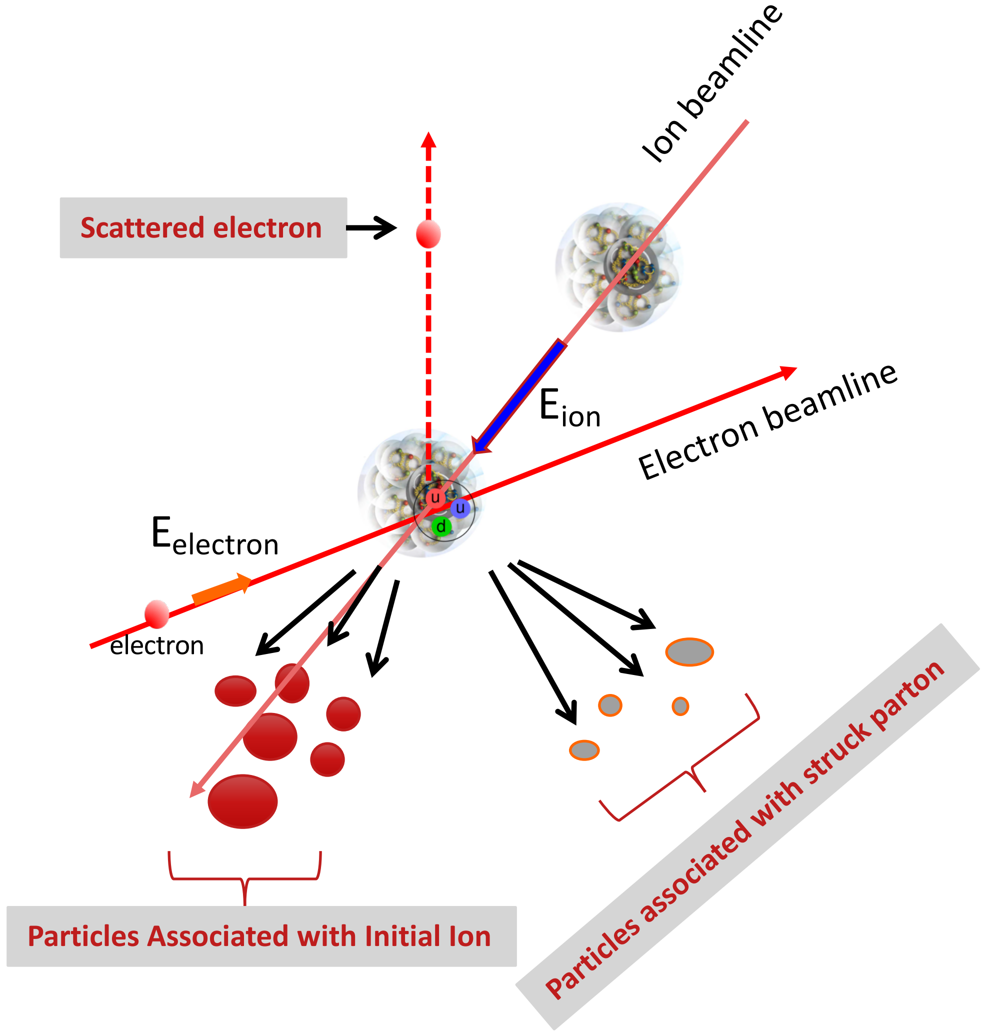
Final-state particles in the central rapidity

Products of the hard electron-quark collision

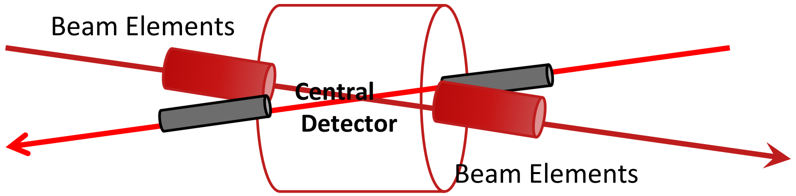


Asymmetric collision energies will boost the final state particles in the ion beam direction: **Detector requirements change as a function of rapidity.**

Final-state particles



The aim is to get **~100% acceptance** for all final state particles, and measure them with good resolution.



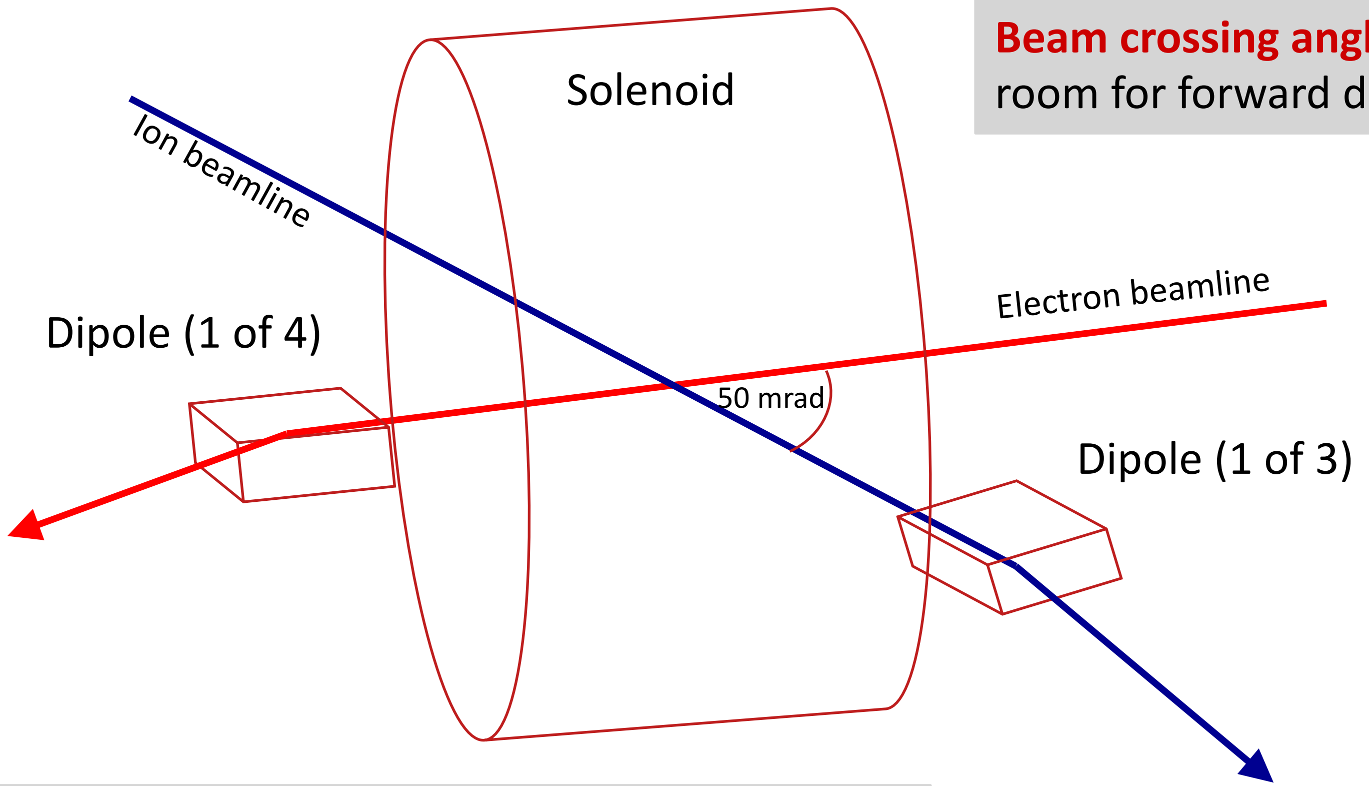
Experimental challenges:

- beam elements limit forward acceptance
- central Solenoid not effective for forward

Interaction region concept

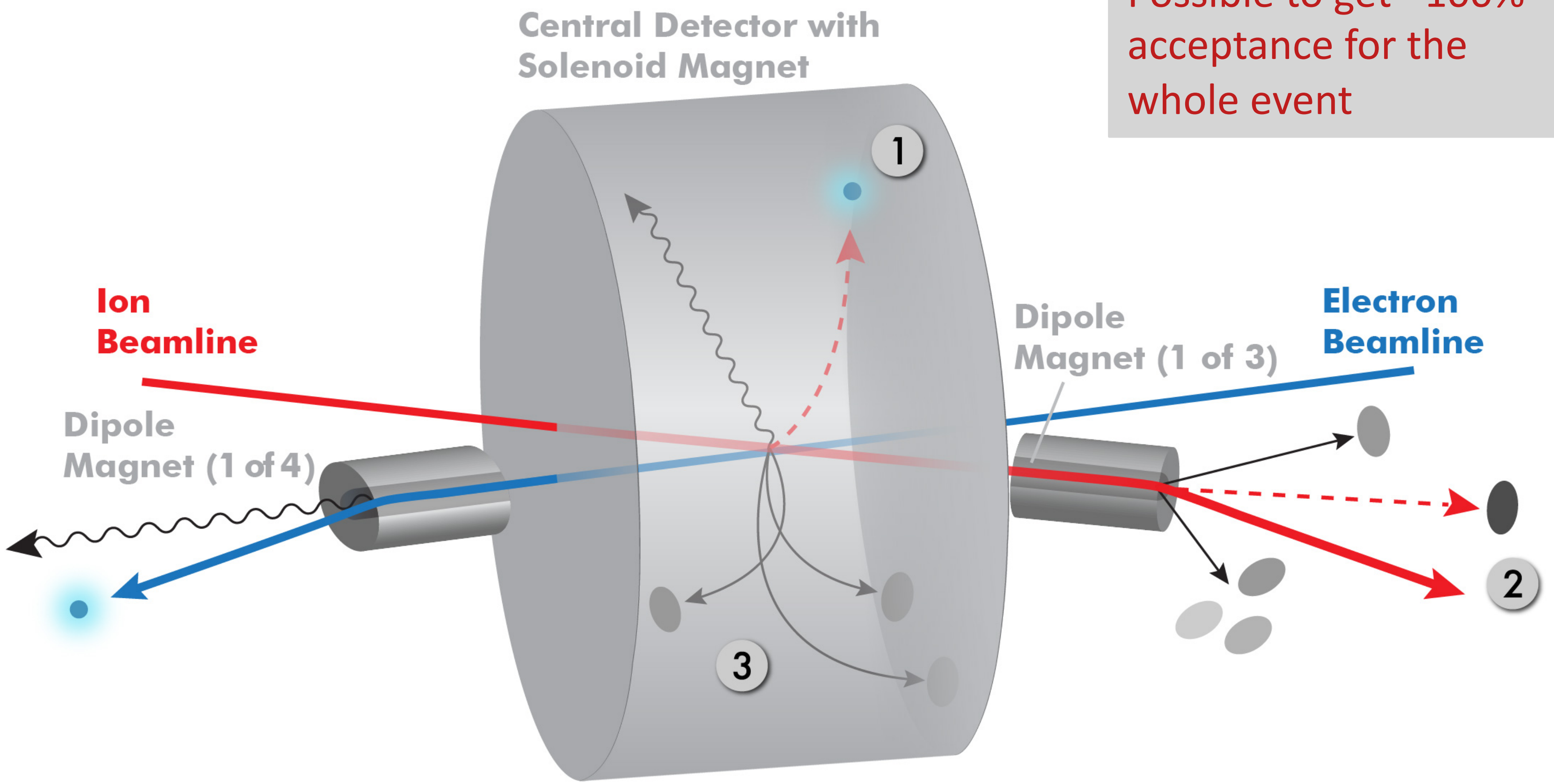
NOT TO SCALE!

Beam crossing angle creates room for forward dipoles



Dipoles analyze the forward particles
and create space for detectors in the forward direction

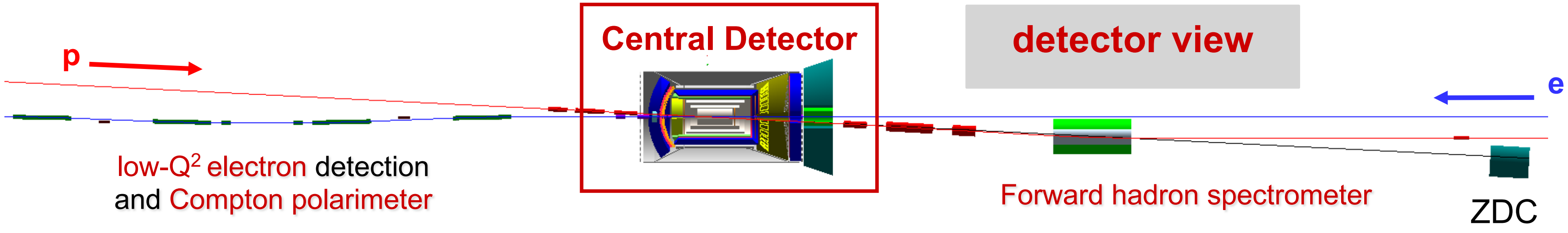
Interaction region concept



Possible to get ~100% acceptance for the whole event

Total acceptance detector (and IR)

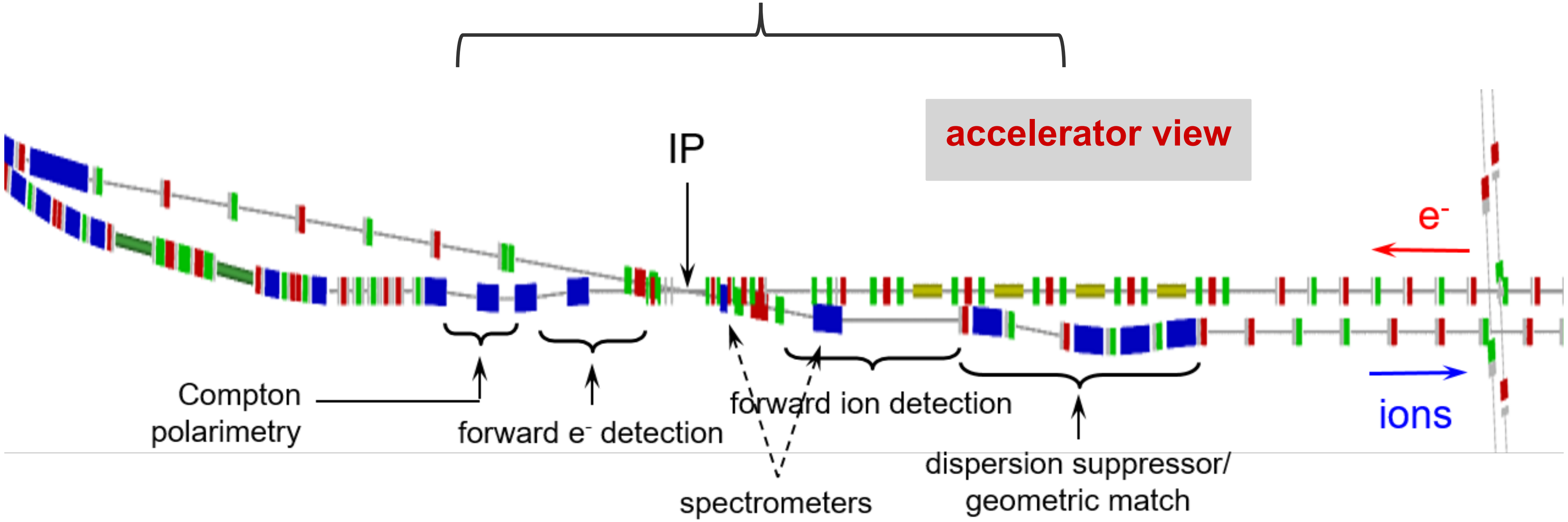
Detector and interaction region



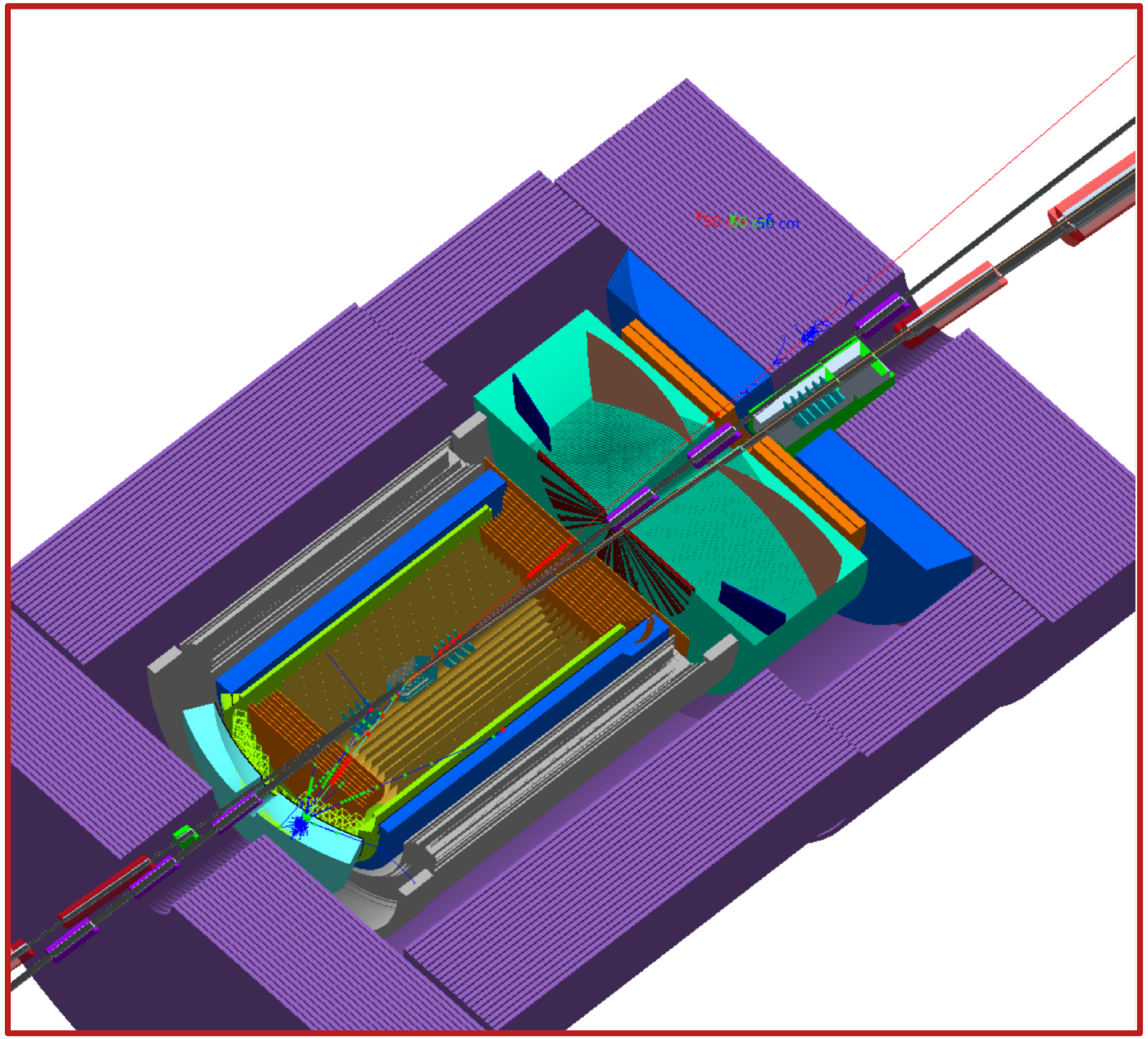
Extended detector: 80m

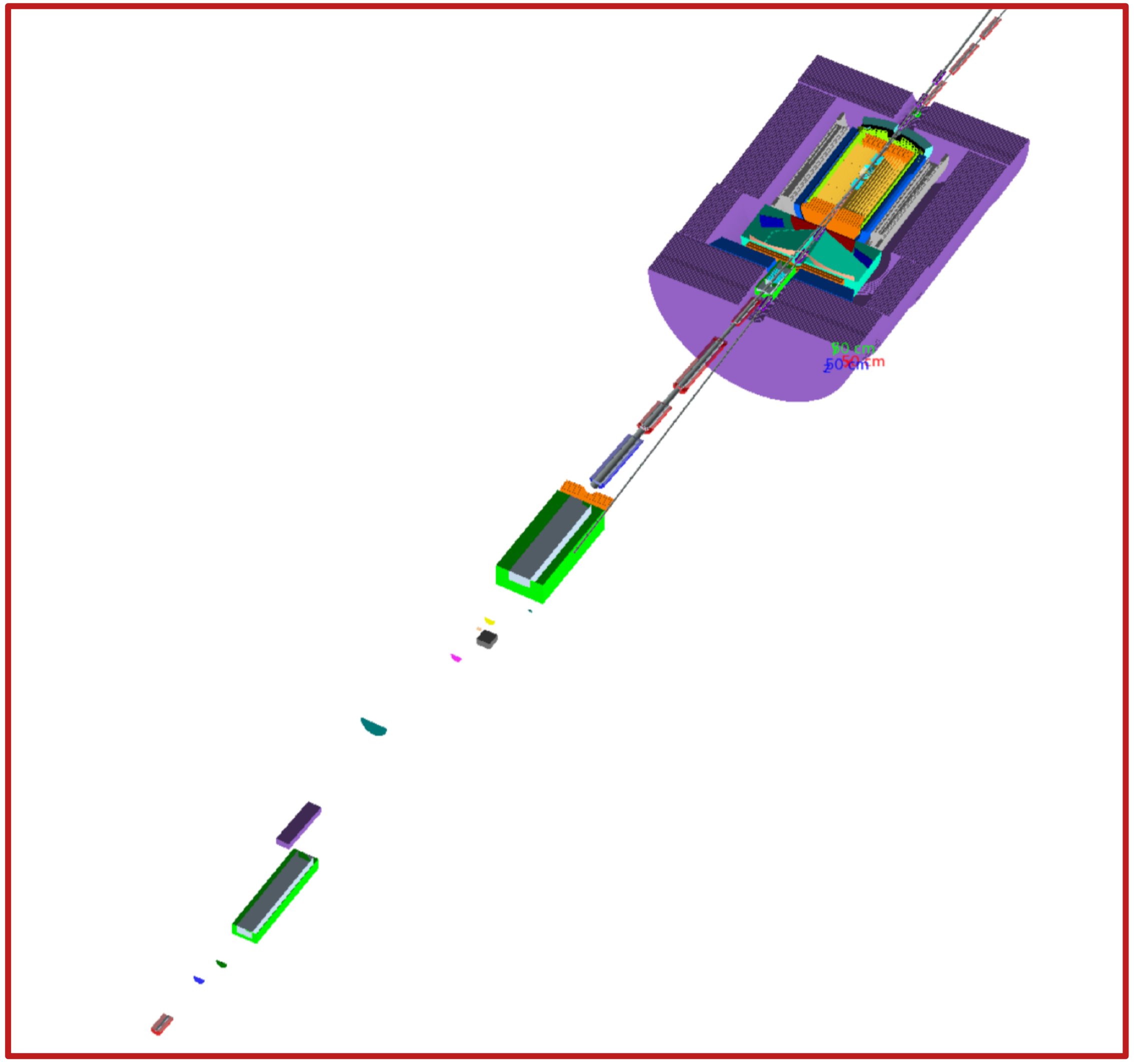
30m for multi-purpose chicane, 10m for central detector, 40m for the forward hadron spectrometer

fully integrated with accelerator lattice

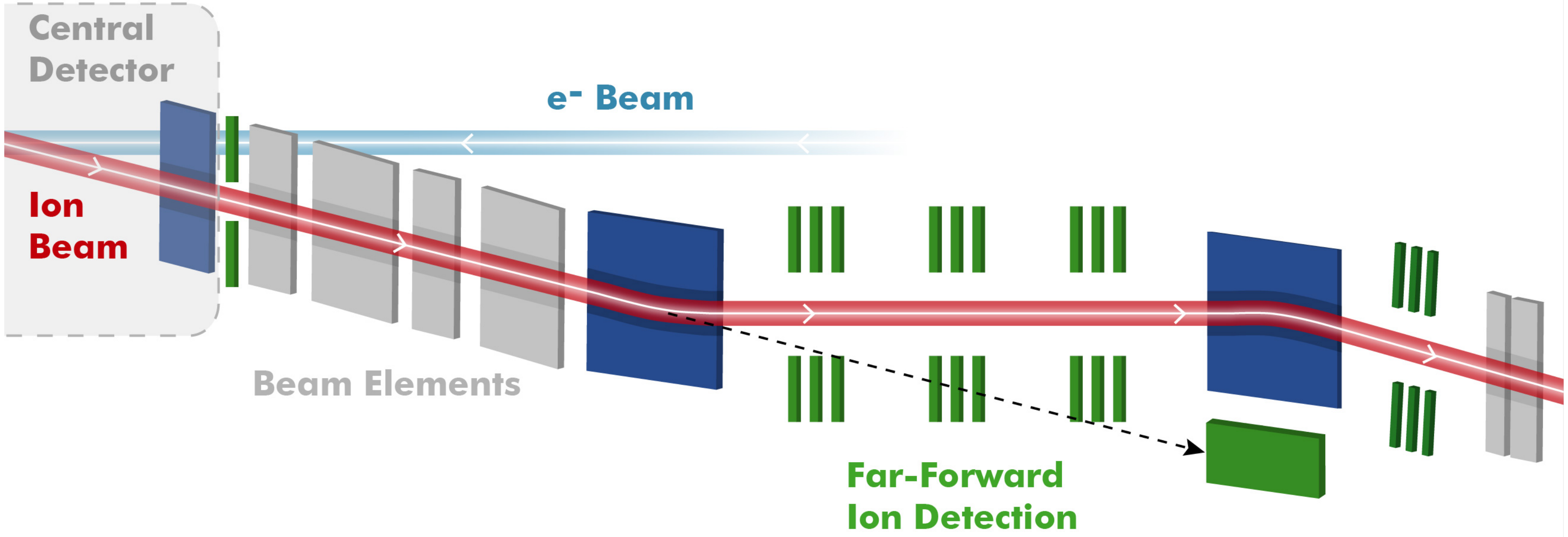


Simulation of the JLEIC Detector





Far-forward ion detection

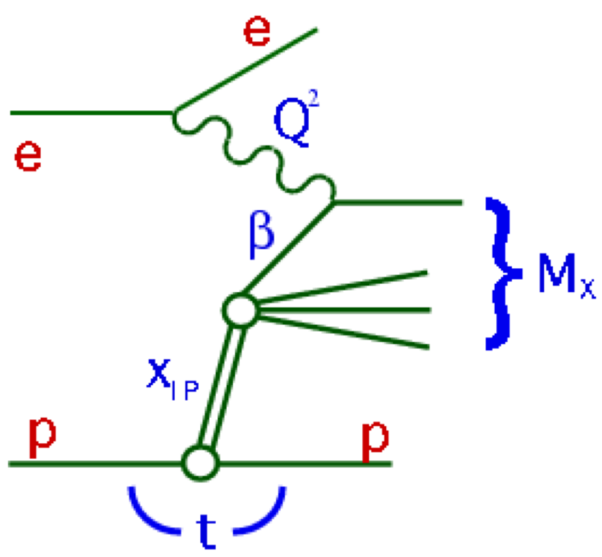


Forward detection requirements
- good acceptance for recoils nucleons (rigidity close to beam)
- good acceptance for fragments (rigidity different than beam)

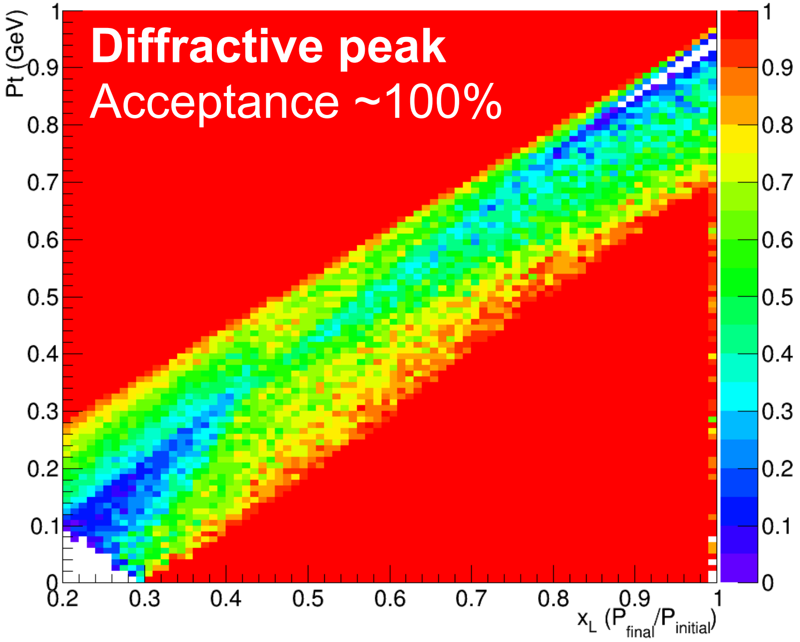
Example for far-forward detection: Diffractive DIS

Diffractive DIS

Signature for saturation

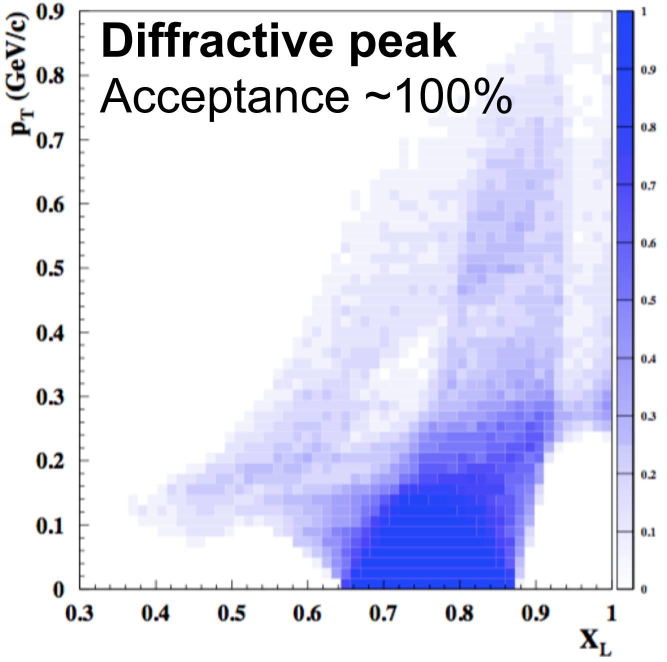


JLEIC



ZEUS

Leading Proton Spectrometer



Identify the scattered proton p'

- distinguish from proton dissociation
- measure $X_L = E_p'/E_p$, and P_t (or t)

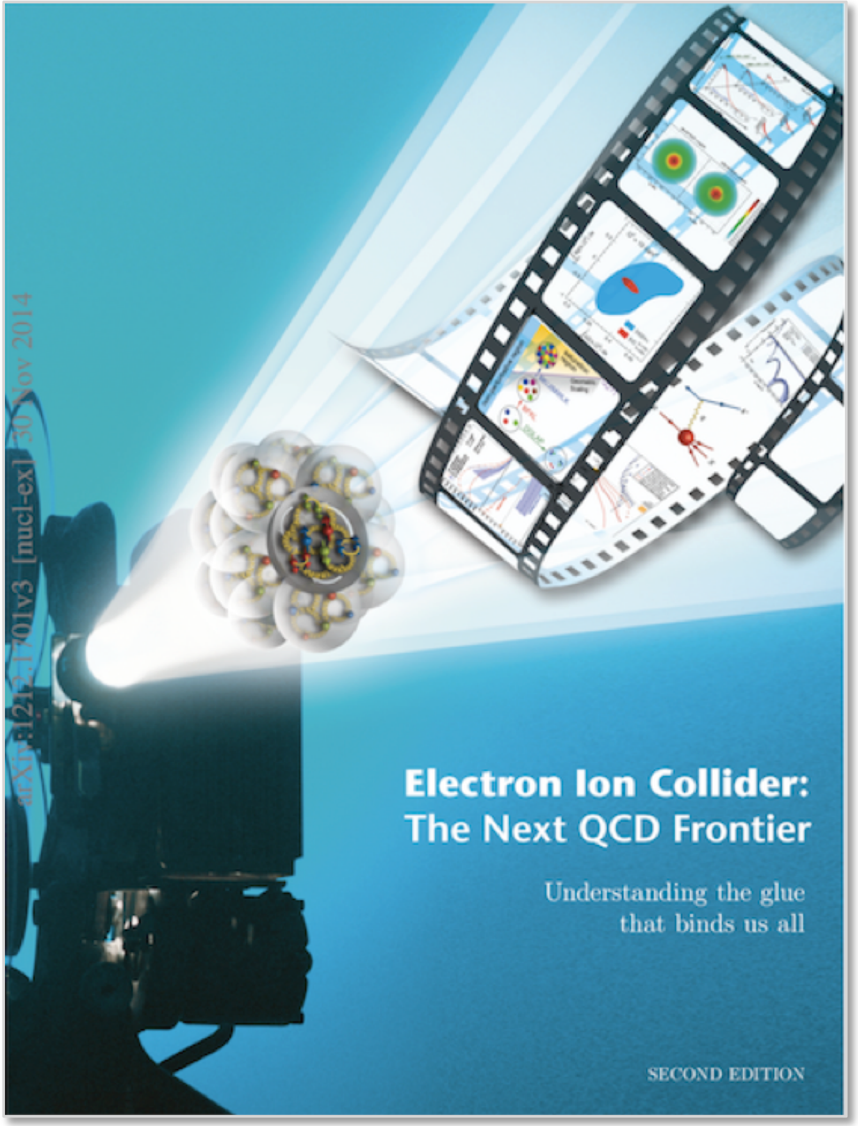
Measurement for p' in DDIS

diffractive peak X_L>~.98

EIC Community

Status of the EIC project

EIC White Paper



A **white paper** is an authoritative report or guide that informs readers concisely about a complex issue and presents the issuing body's philosophy on the matter.

Spin and Three-Dimensional Structure of the Nucleon

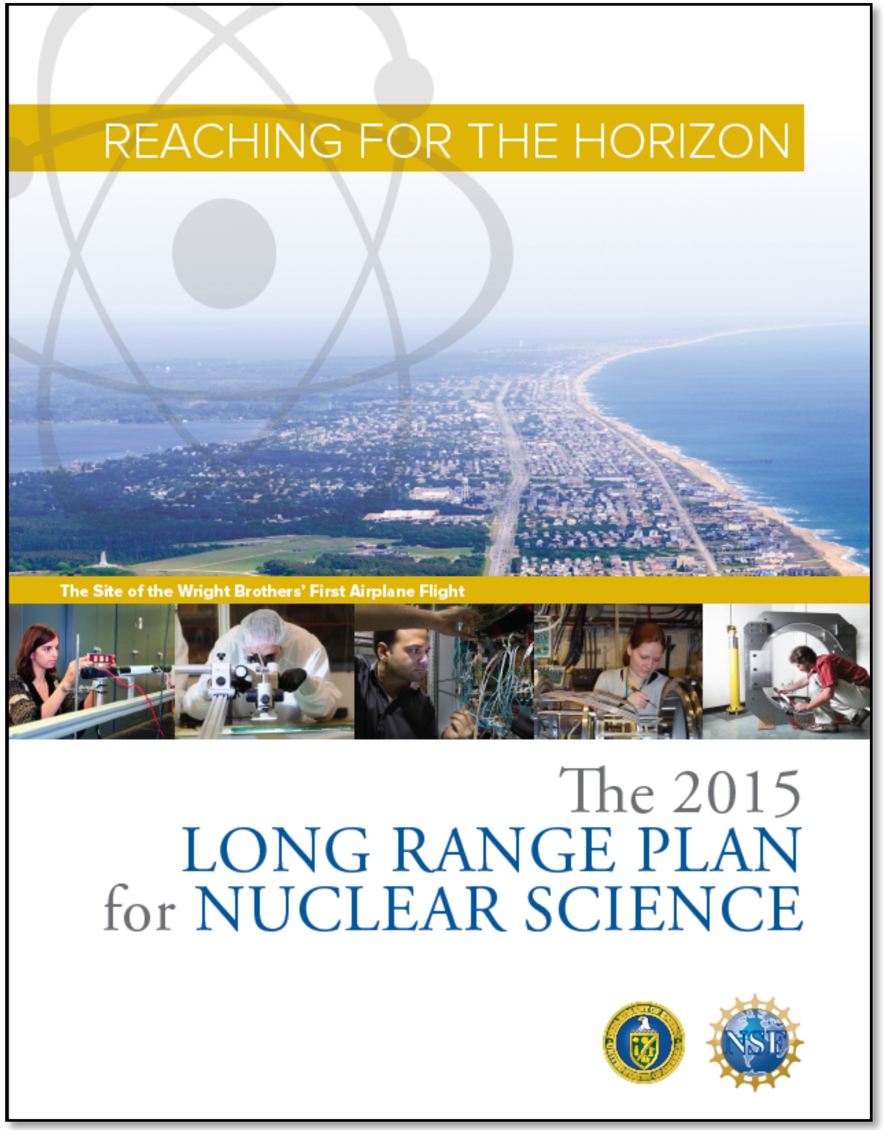
The Longitudinal Spin of the Nucleon
Confined Motion of Partons in Nucleons: TMDs
Spatial Imaging of Quarks and Gluons: GPDs

The Nucleus: A Laboratory for QCD

Physics of High Gluon Densities in Nuclei
Quarks and Gluons in the Nucleus
Connections to pA, AA and Cosmic Ray Physics

Possibilities at the Luminosity Frontier: Physics Beyond the Standard Model

2015 Nuclear Science Long-Range Plan



1. **The highest priority in this 2015 Plan is to capitalize on the investments made.**
   - **12 GeV** – unfold quark & gluon structure of hadrons and nuclei
   - **FRIB** – understanding of nuclei and their role in the cosmos
   - **Fundamental Symmetries Initiative** – physics beyond the SM
   - **RHIC** – properties and phases of quark and gluon matter
2. We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.
3. **We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.**
4. We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

NAS: EIC Science Assessment

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
next formal step on EIC science case (before CD0)

NAS committee

Ani Aprahamian, Co-Chair (University of Notre Dame)
Gordon Baym, Co-Chair (U. Illinois at Urbana-Champaign)
Christine Aidala (University of Michigan)
Richard Milner (MIT)
Ernst Sichtermann (LBNL)
Zein-Eddine Meziani (Temple University)
Thomas Schaefer (NC State University)
Michael Turner (University of Chicago)
Wick Haxton (University of California-Berkeley)
Kawtar Hafidi (Argonne)
Peter Braun-Munzinger (GSI)
Larry McLerran (University of Washington)
Haiyan Gao (Duke)
John Jowett (CERN)

Meetings in Feb., Apr., Sept. 2017
Report released in July 2018

NAS charge

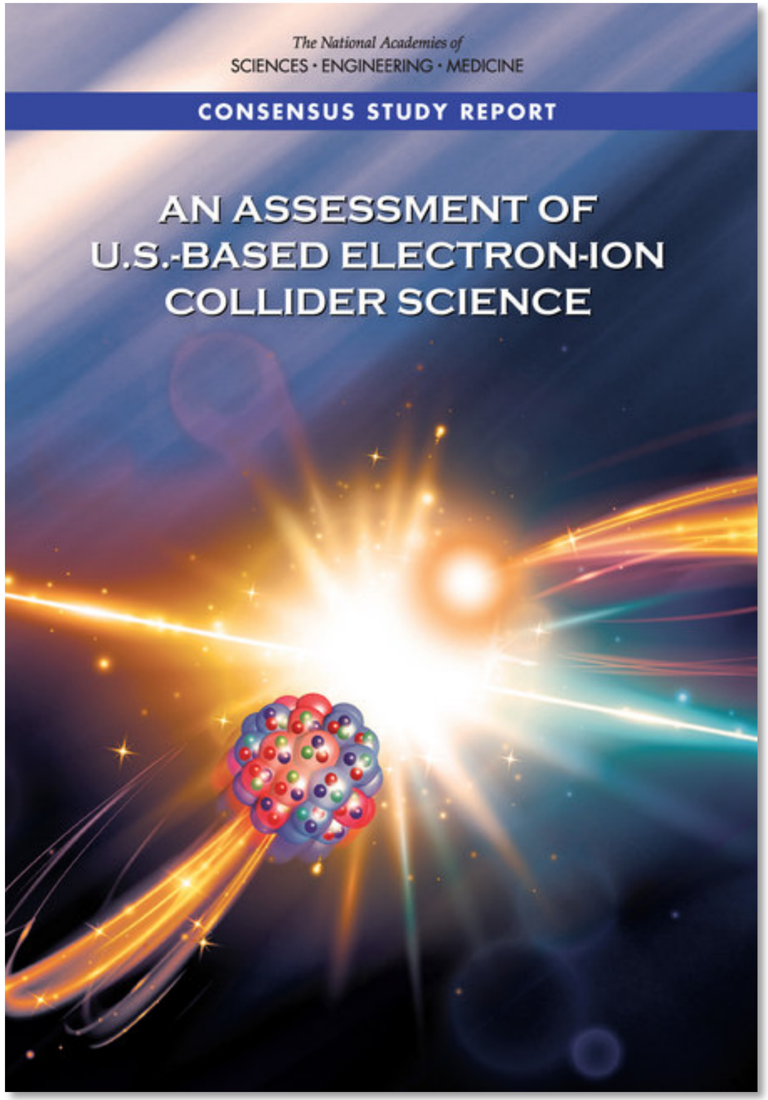
1 What is the **merit and significance of the science** that could be addressed by an EIC facility and what is its **importance in the overall context of research in nuclear physics** and the physical sciences in general?

2 What are the **capabilities of other facilities, existing and planned, domestic and abroad**, to address the science opportunities afforded by an EIC? What **unique scientific role** could be played by a domestic EIC that is complementary to existing and planned facilities at home and abroad?

3 What are the **benefits of US leadership** in nuclear physics if a domestic EIC were constructed?

4 What are the **benefits to other fields of science and to society** of establishing such a facility in the US?

NAS report



"In summary, the committee finds a compelling scientific case for such a facility. 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. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator based science and society, from medicine through materials science to elementary particle physics."

Status of the EIC project

President's Budget FY 2020 Budget Justification

See Volume 4 – Science, pages 269-326 for Nuclear Physics

Page 270

"The 2015 NSAC LRP for Nuclear Science recommended a high-energy, high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction following the completion of FRIB. Consistent with that vision, in 2016 NP commissioned a National Academy of Sciences (NAS) study by an independent panel of external experts to assess the uniqueness and scientific merit of such a facility. The report, released in July 2018, **strongly supports the scientific case for building a U.S.-based EIC, documenting that an EIC will advance the understanding of the origins of nucleon mass, the origin of the spin properties of nucleons, and the behavior of gluons**."

Page 272

"The Request for Construction and Major Items of Equipment (MIEs) includes:"

(…)

Other Project Costs (OPC) funding to support high priority, critically needed accelerator R&D to retire high risk technical challenges for the proposed U.S.-based EIC. Subsequent to the FY 2018 National Academy of Science Report confirming the importance of a domestic EIC to sustain U.S. world leadership in nuclear science and accelerator R&D core competencies. **Critical Decision-0, Approve Mission Need, is planned for FY 2019**."

EIC realization imagined

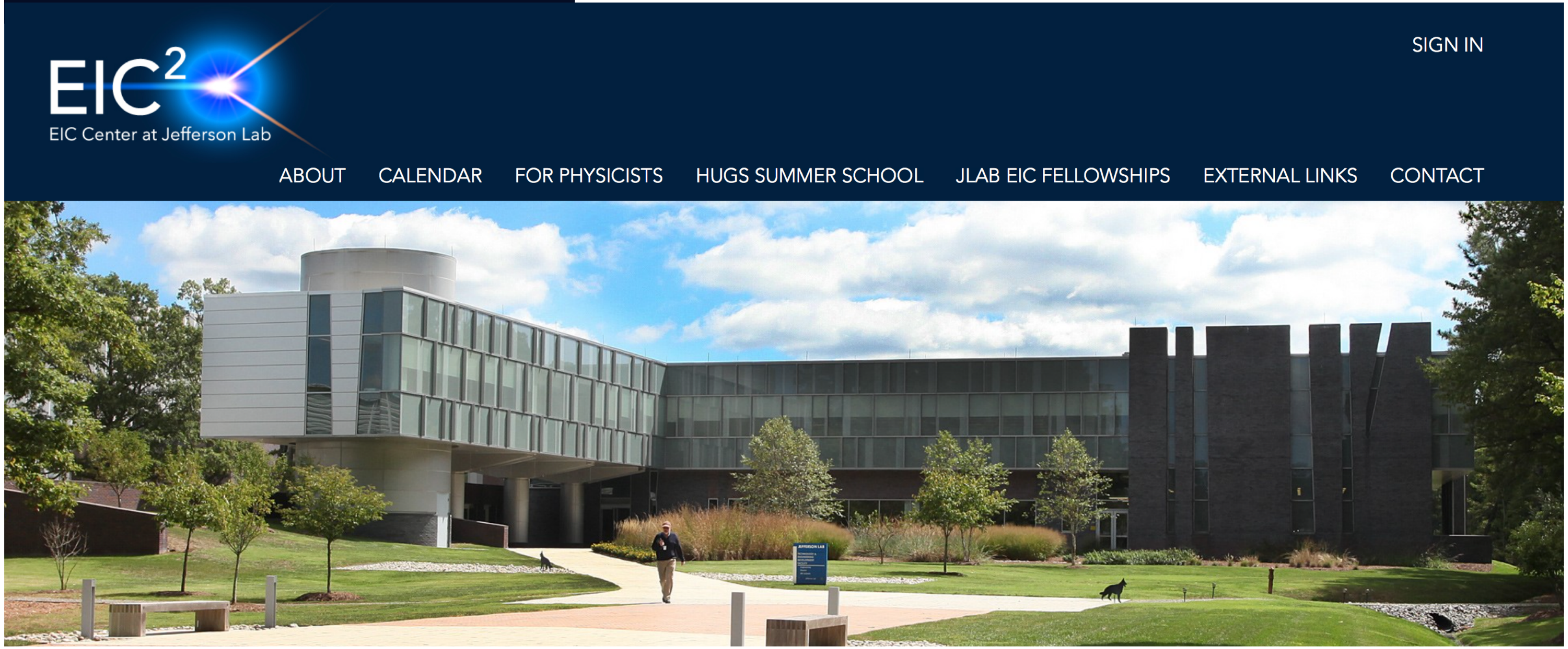
- **July 2018** NAS report on EIC science case
- **FY19** CD-0 (US Mission Need statement)
- **FY19 – FY20** critical EIC accelerator R&D questions could be answered
- **FY20 – FY21** site selection
- **FY21** EIC construction has to start **after FRIB completion**
- **FY22** construction starts
- **FY30** Start of EIC science program

EIC^2@JLab

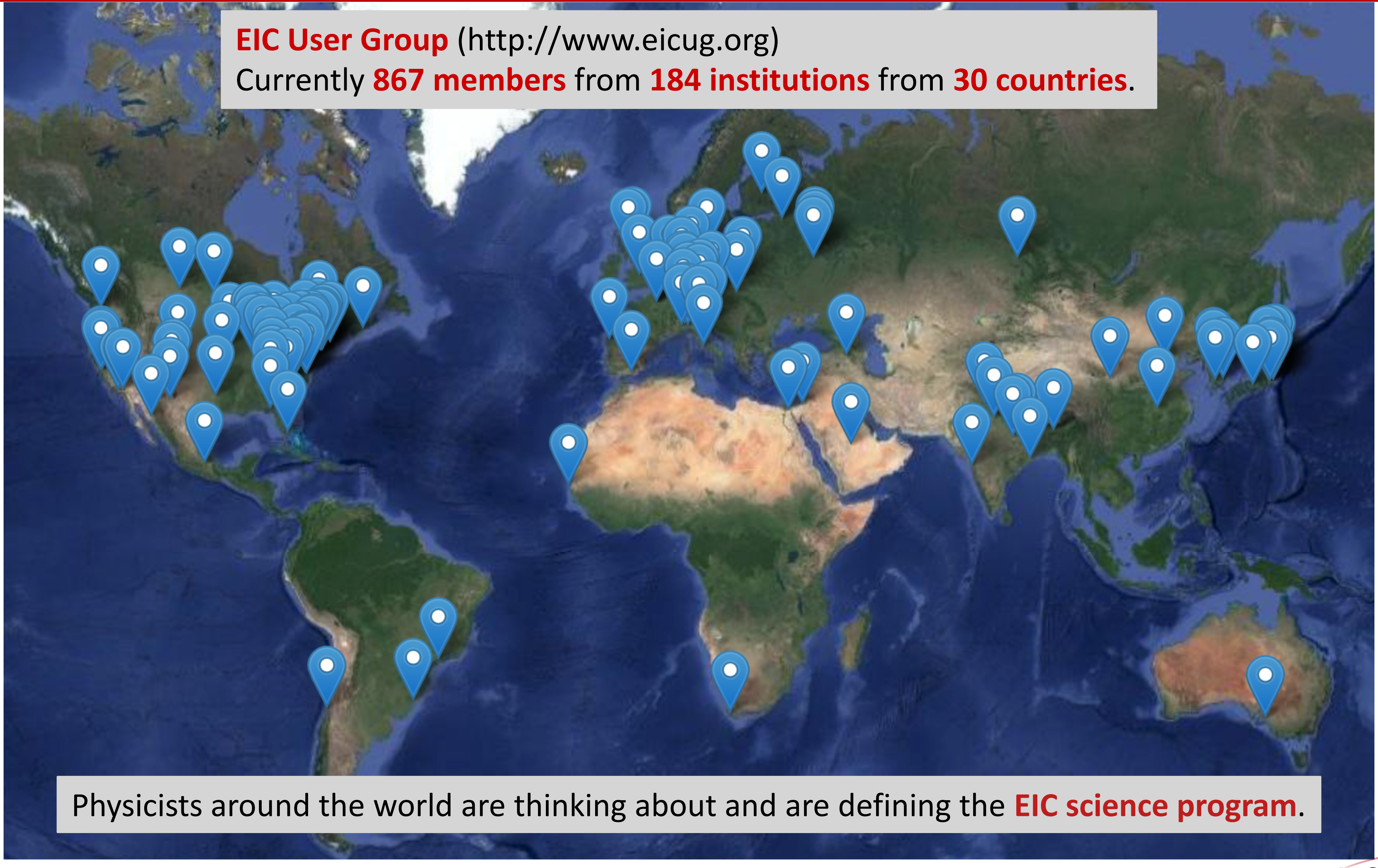
EIC^2

EIC Center at Jefferson Lab

- advance and promote the science program at a future electron-ion collider facility: fellowships, seminars, summer school, workshops
- emphasis is on the close connection of EIC science to the current JLab 12 GeV science program



EIC User Group



Jefferson Lab

Markus Diefenthaler

mdiefent@jlab.org

Summary

- Outstanding questions raised both by the science at HERMES/COMPASS/JLAB and RHIC/LHC, have naturally led to the science and design parameters of the EIC.
- EIC will enable us to embark on a **precision study of the nucleon and the nucleus at the scale of sea quarks and gluons**, over all of the kinematic range that are relevant.
- What we learn at JLAB 12 and later EIC, together with advances enabled by FRIB and LQCD studies, will open the door to **a transformation of Nuclear Physics**.