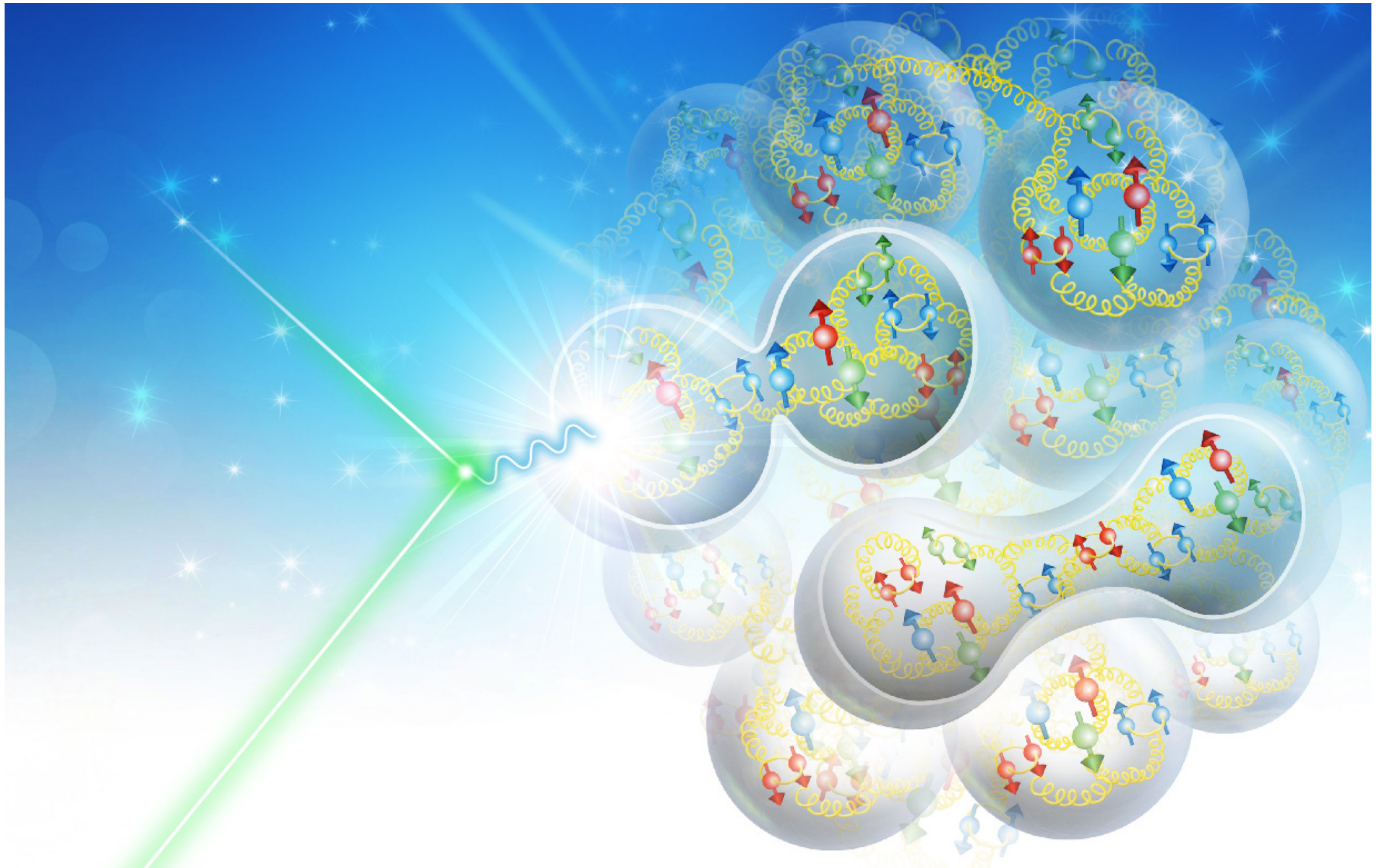
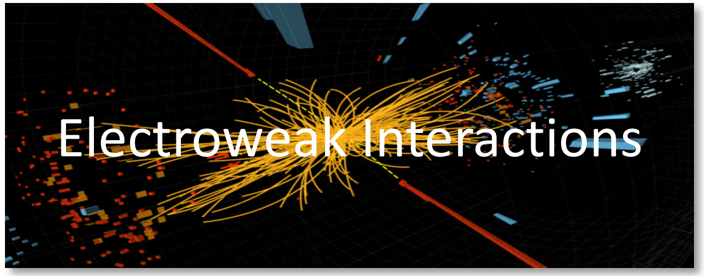
Overview about EIC Science Program

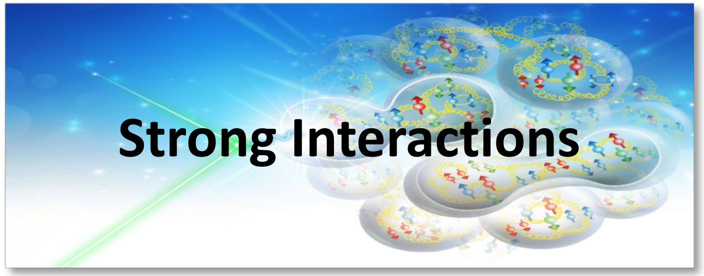
Towards a New Frontier in Nuclear Physics



Markus Diefenthaler
Staff Scientist II
Experimental Nuclear Physics

The Standard Model of Physics





Further exploration of the Standard Model

Dark matter searches

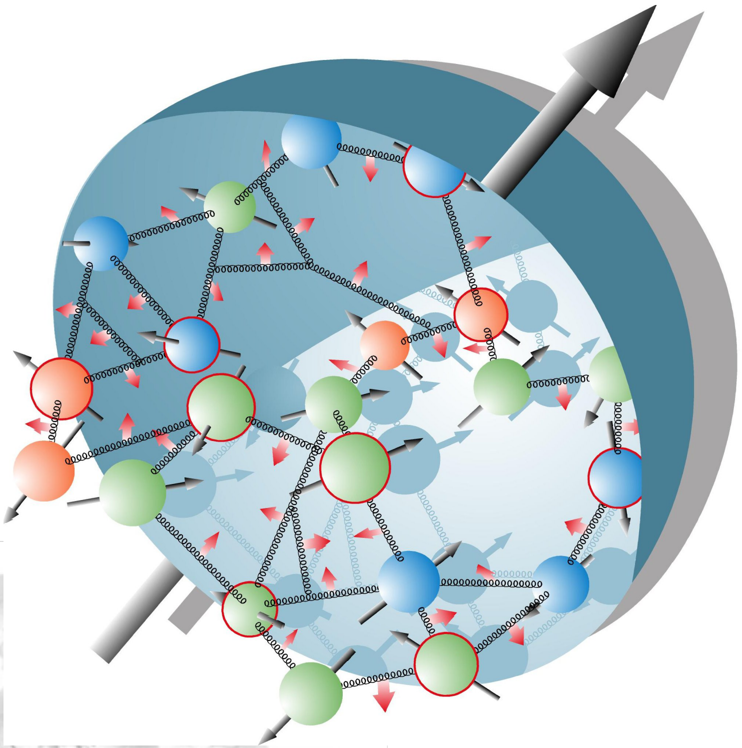
Electroweak symmetry breaking

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**."

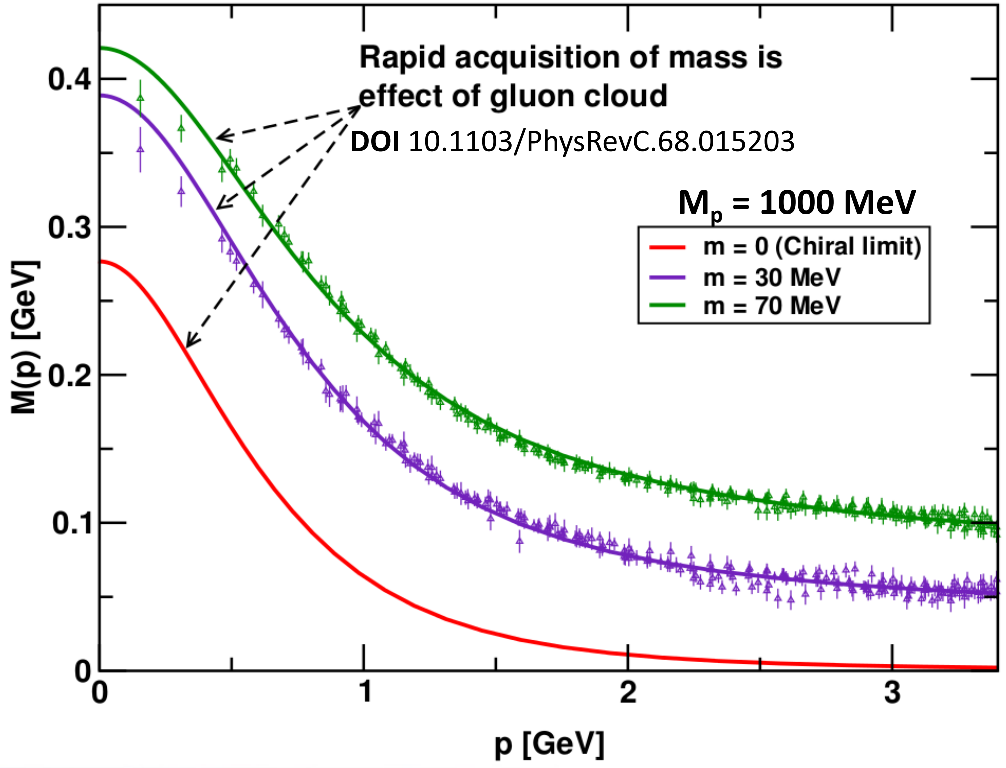
The dynamical nature of nuclear matter

Nuclear Matter Interactions and structures are inextricably mixed up



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

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

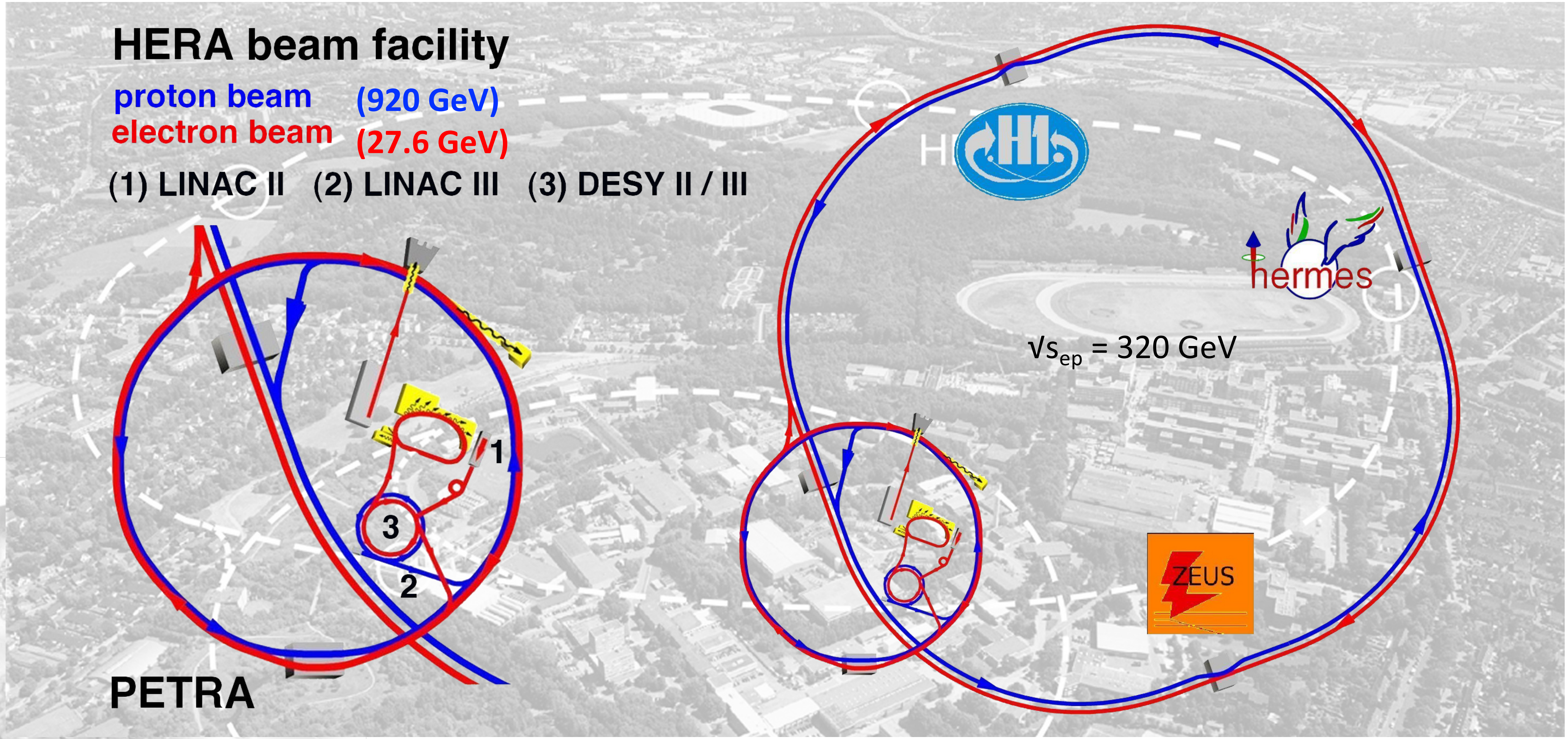


To reach goal precisely image quarks and gluons and their interactions

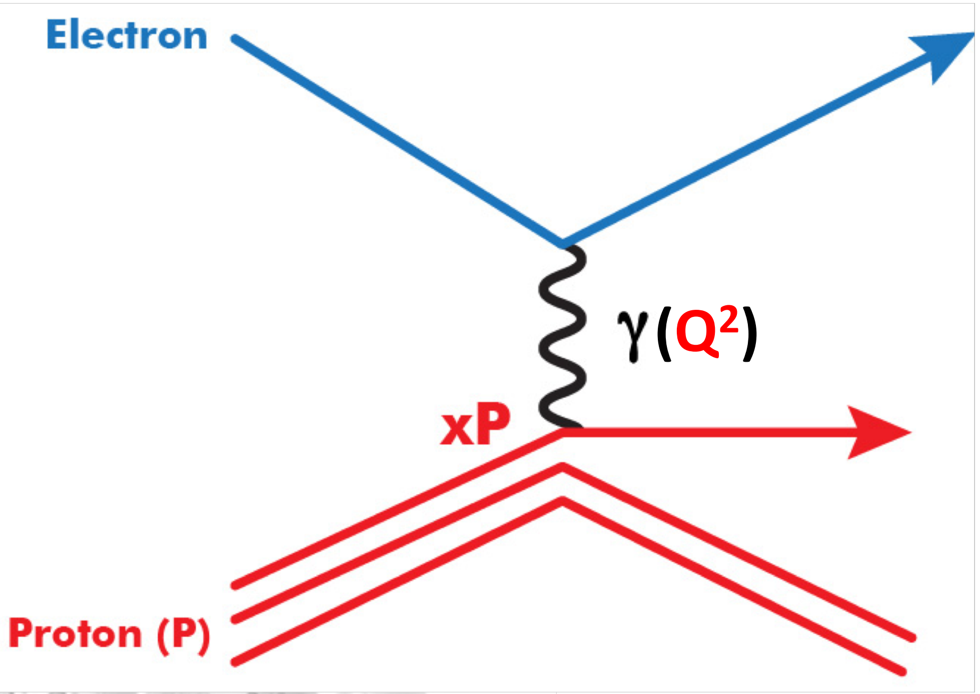
Pioneering measurements

The first Electron-Ion Collider

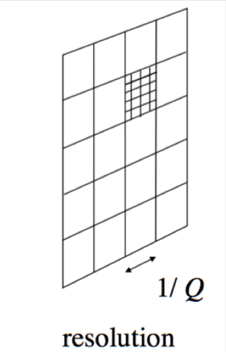
HERA: The first Electron-Ion Collider



Deep-inelastic scattering (DIS) of electrons off protons

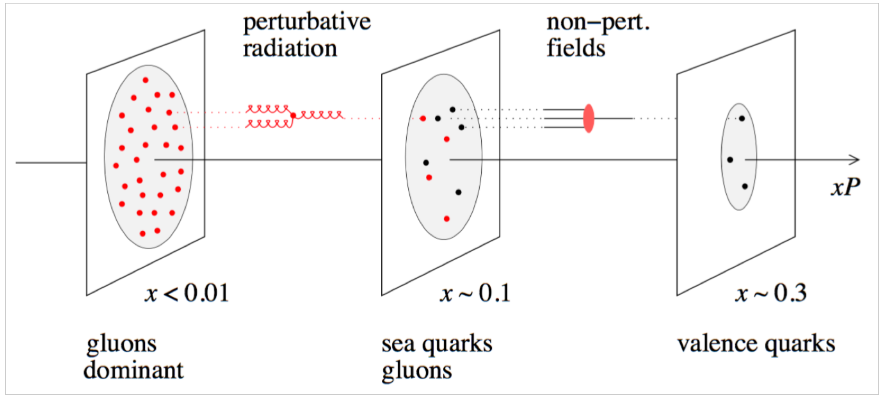


Ability to change Q^2 changes the resolution scale



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

Ability to change x projects out different configurations where different dynamics dominate



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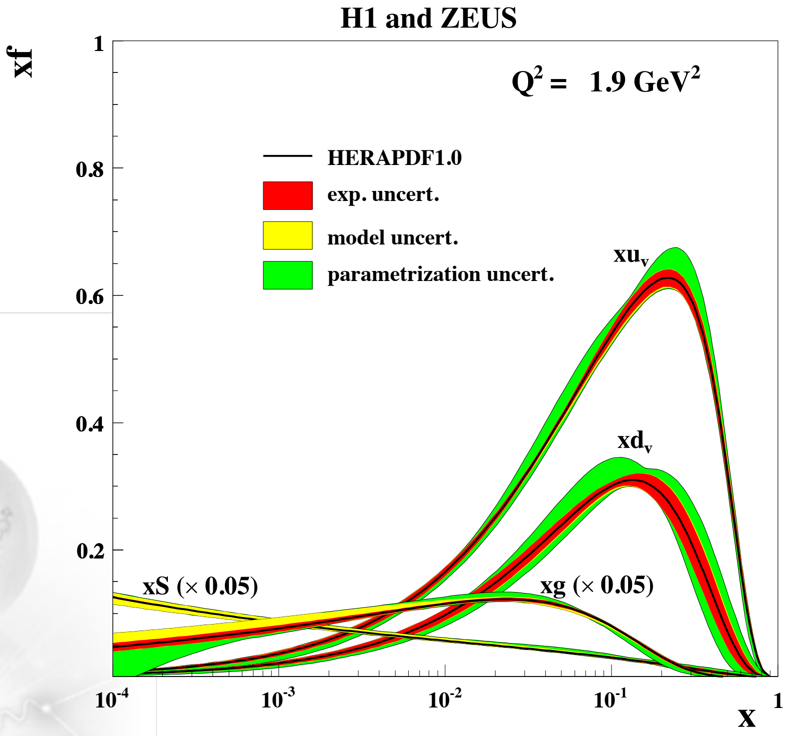
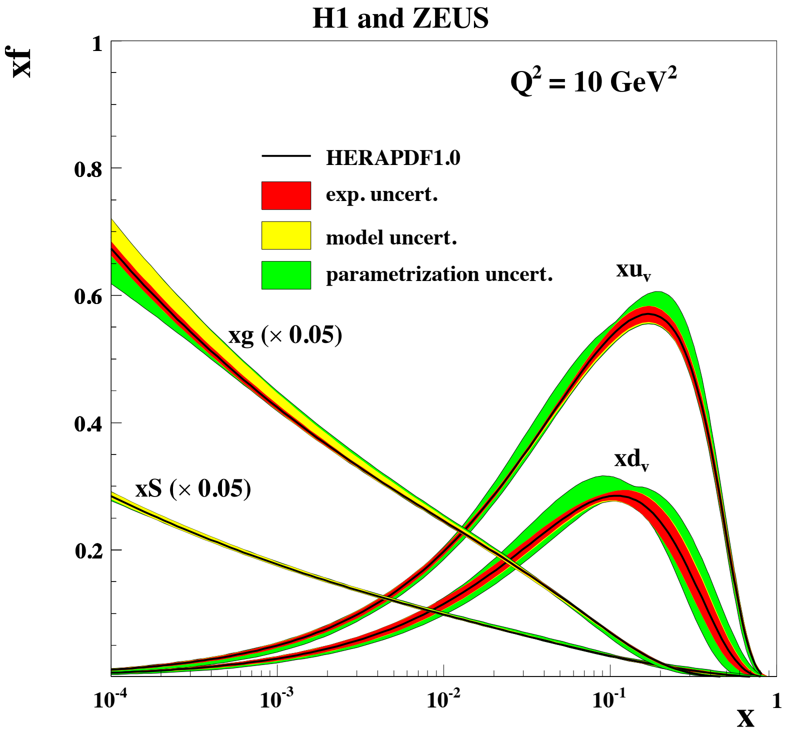
Parton distribution functions (PDF)

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

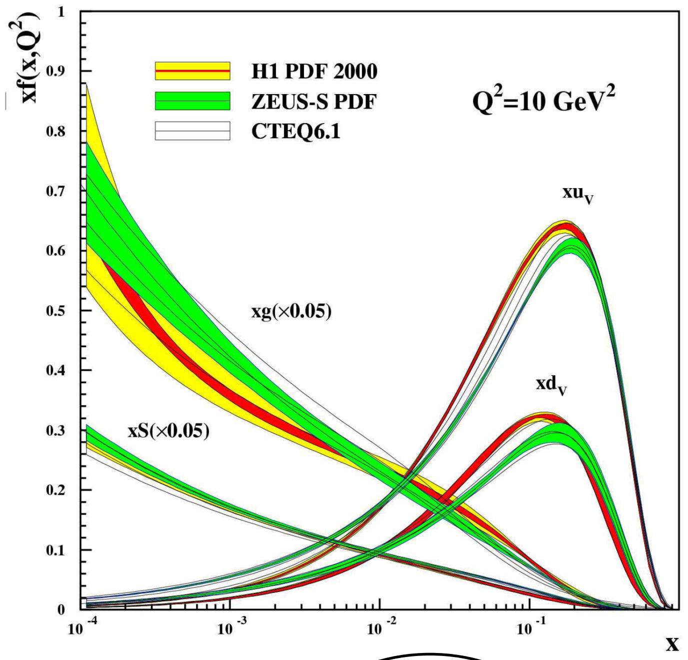
process-dependent → **universal**



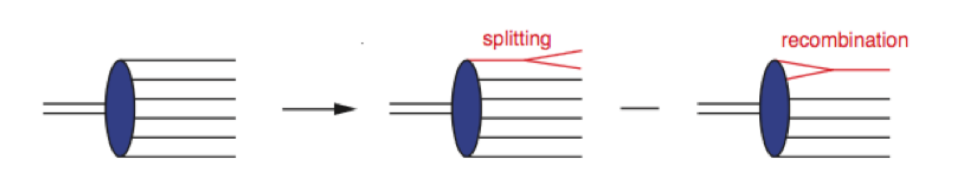


QCD at extremes: Parton saturation

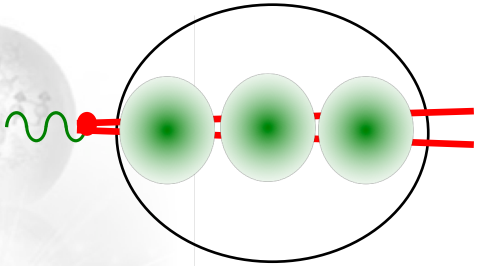
Dramatic rise of gluon PDF



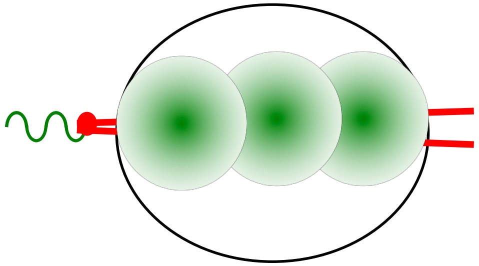
Parton splitting and recombination



- 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*



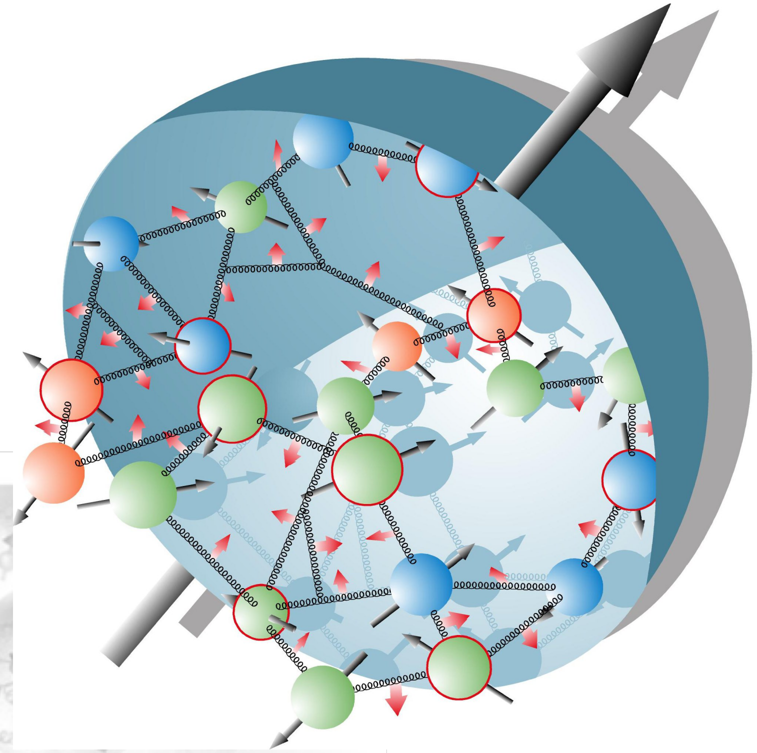
In nuclei, the interaction probability enhanced by $A^{1/3}$



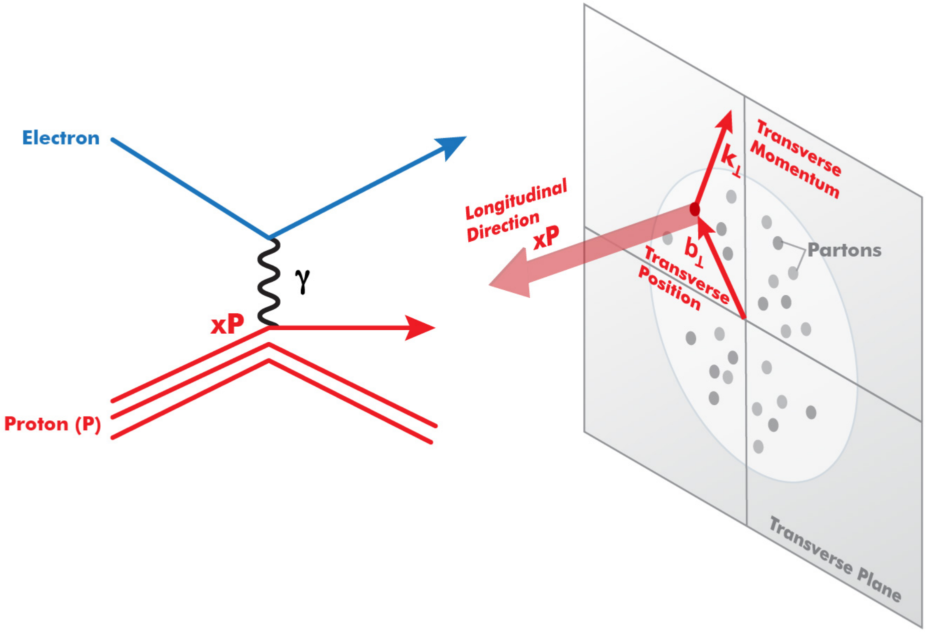
Will nuclei saturate faster as color leaks out of nucleons?

Polarized DIS measurements

Polarization



Novel QCD phenomena



3D imaging in space and momentum

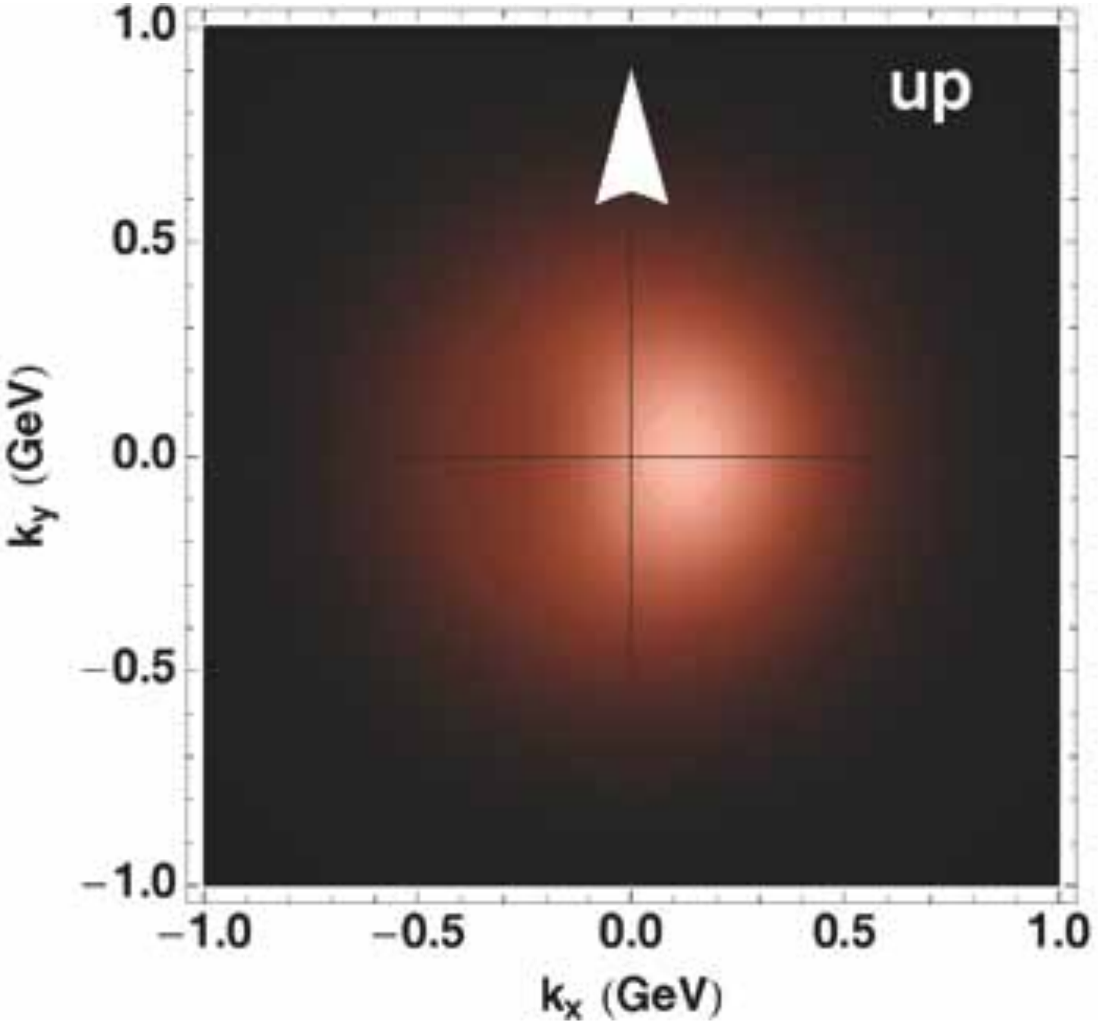
longitudinal structure (PDF)

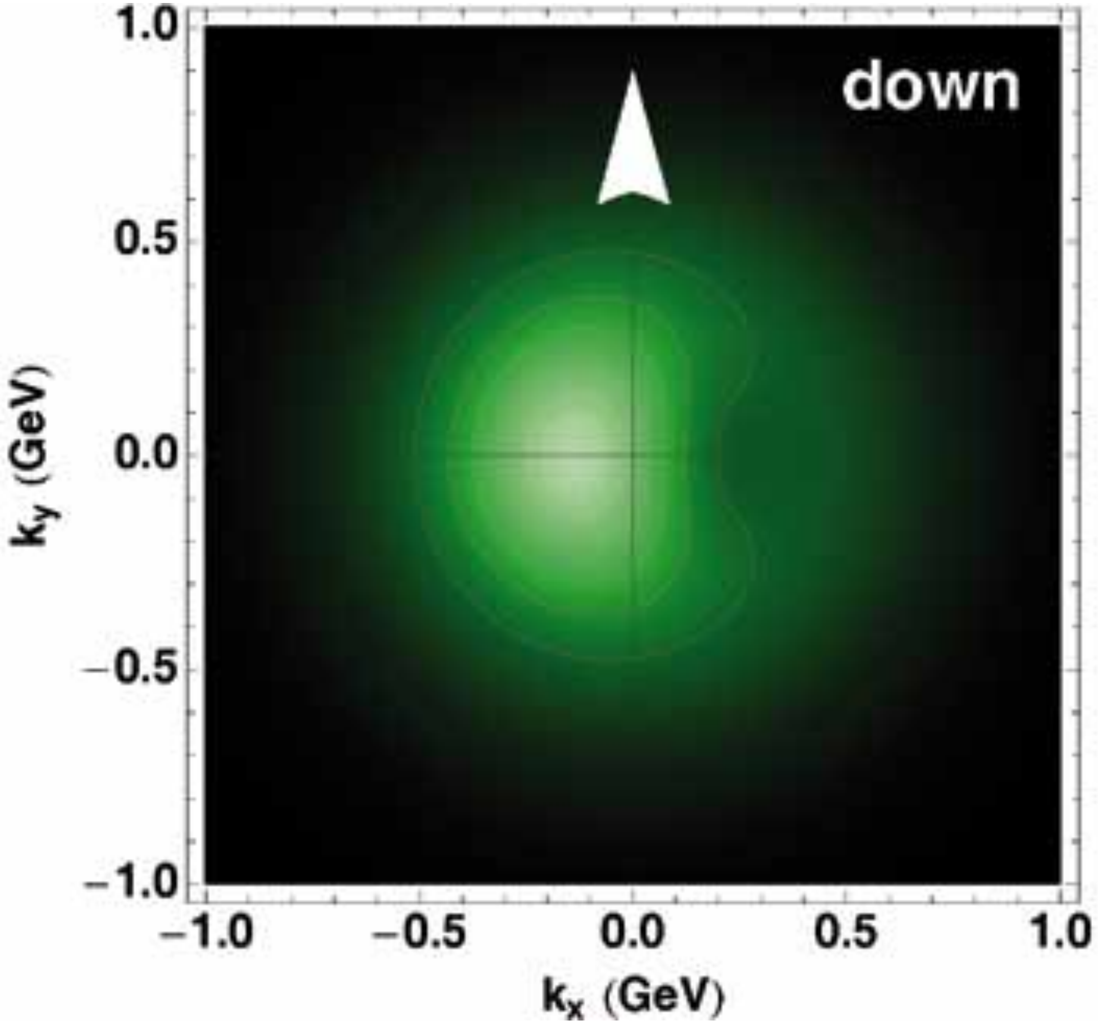
+ transverse position Information (GPDs)

+ transverse momentum information (TMDs)

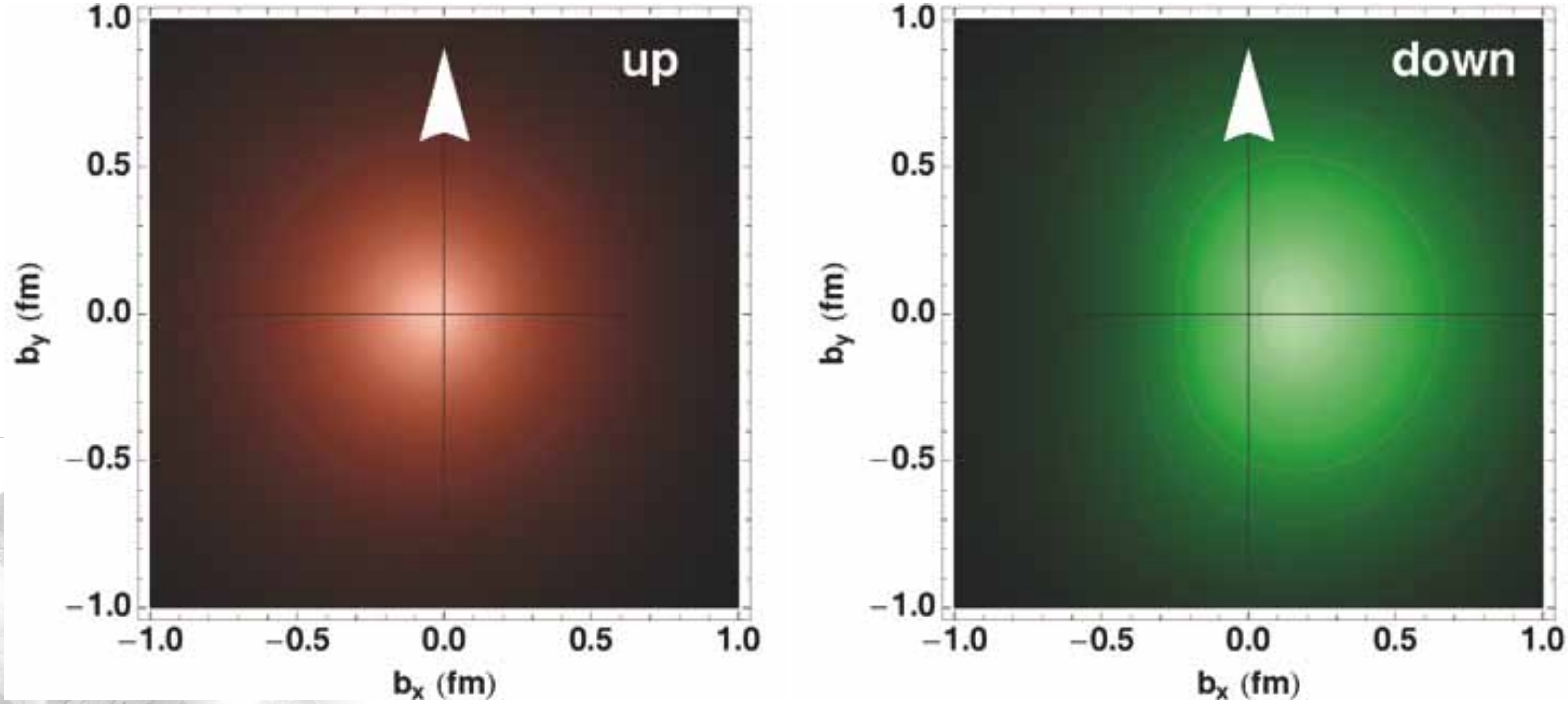
order of a few hundred MeV

Transverse momentum information (TMDs)





Transverse position information (GPDs)



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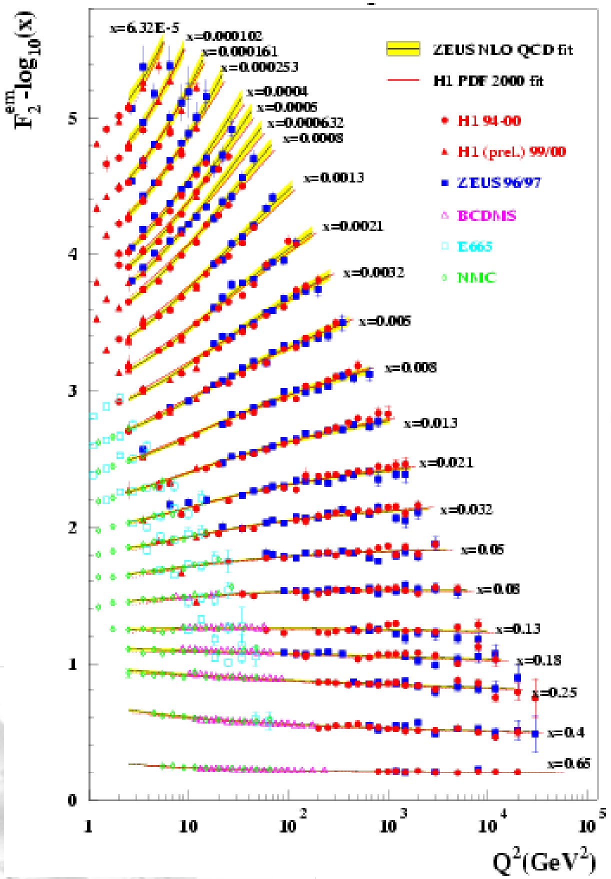
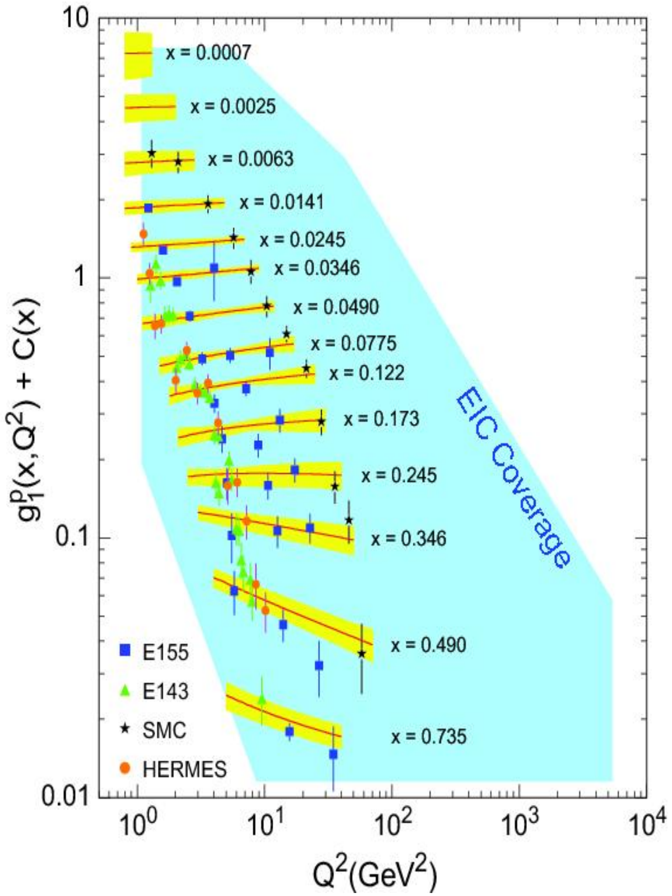
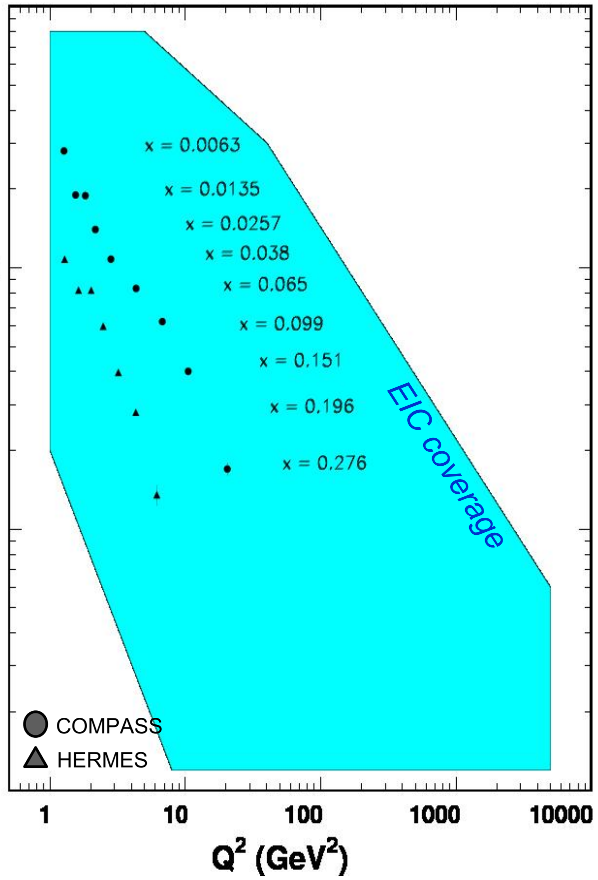
World Data on F_2^p World Data on g_1^p World Data on h_1^p



momentum



longitudinal spin



transverse spin

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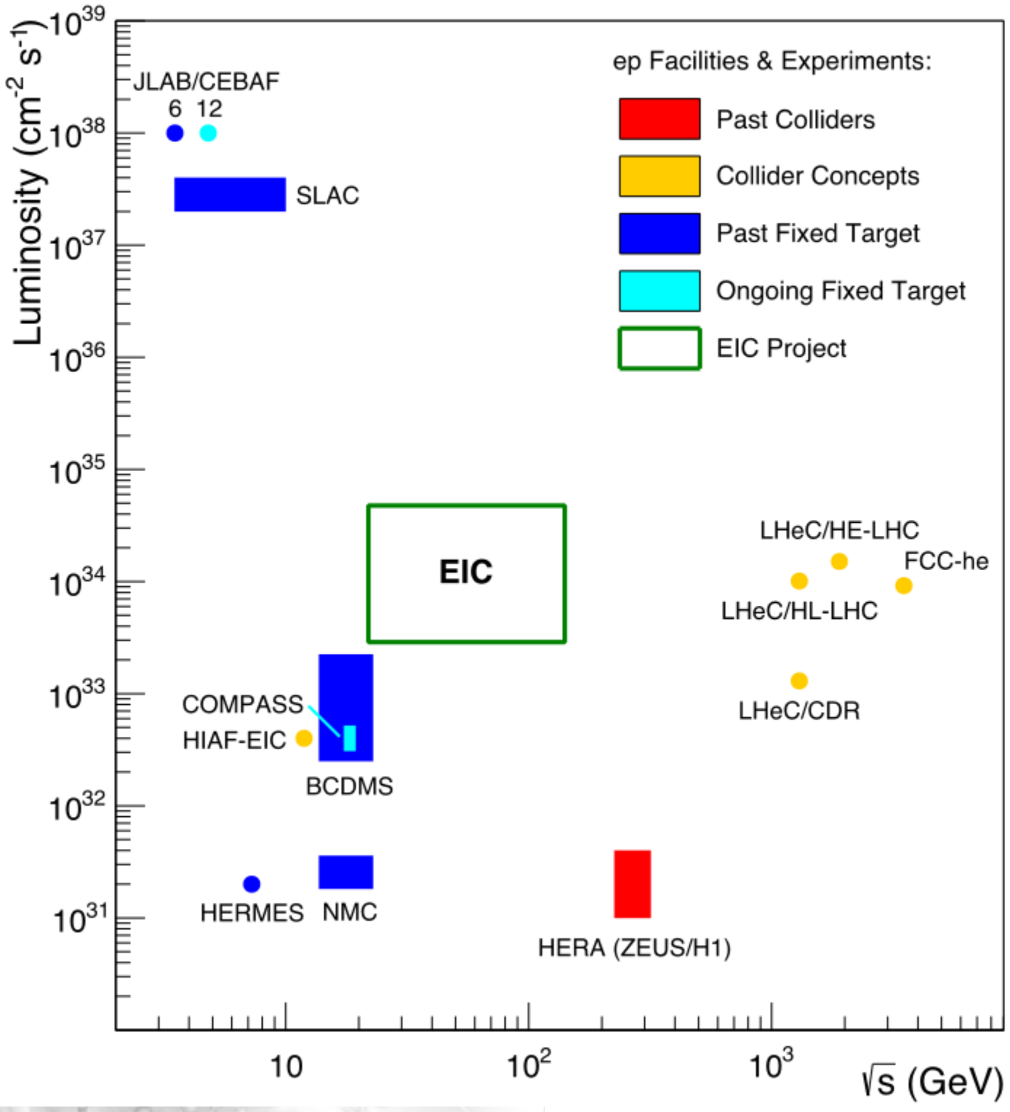
A new frontier in Nuclear Physics

The Electron-Ion Collider Project

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

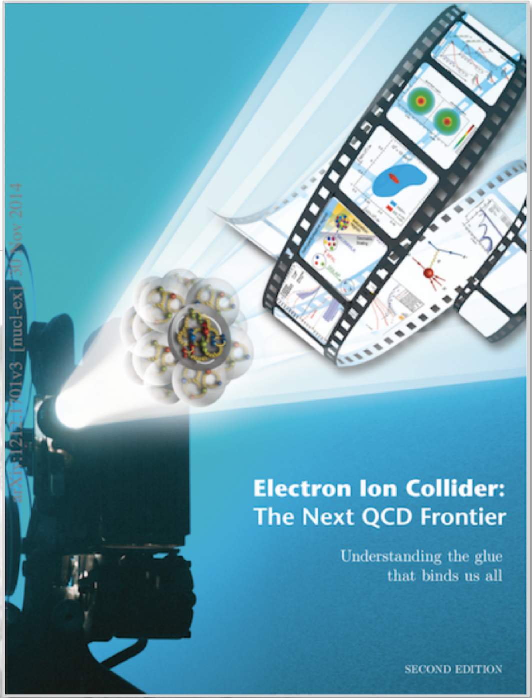
- beam energies
- beam polarizations (longitudinal, transverse, tensor)
- beam species (p → U)

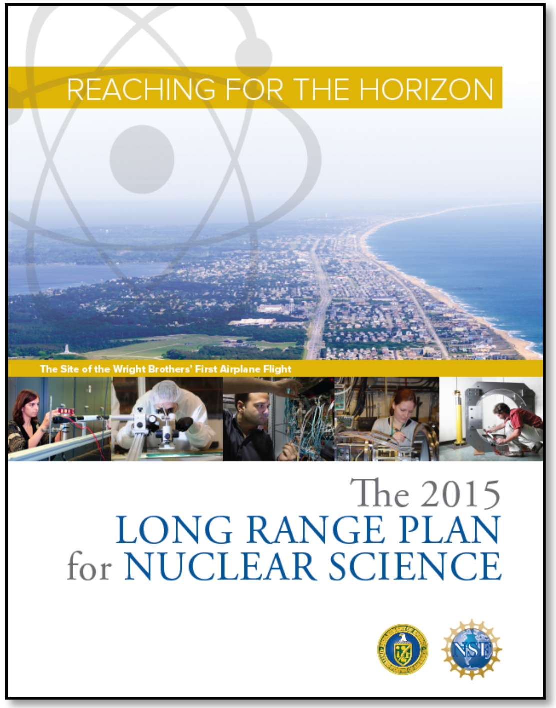
High luminosity

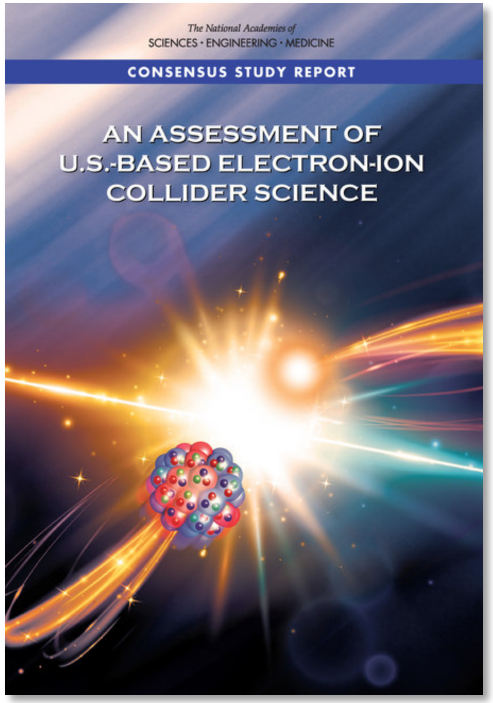
Why an Electron-Ion Collider?

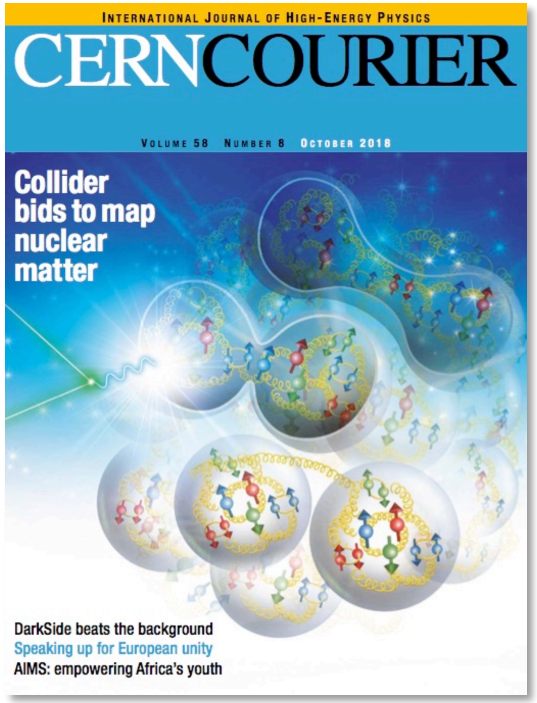
Right tool:
- to precisely **image quarks and gluons** and their interactions
- to explore the new **QCD frontier of strong color fields in nuclei**
- to understand **how matter at its most fundamental level is made**.

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.

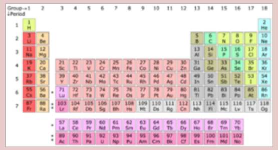
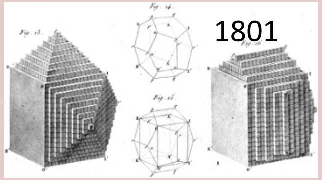
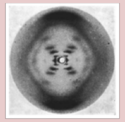
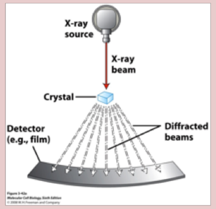
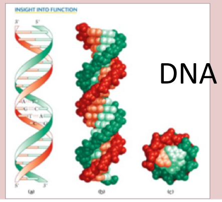
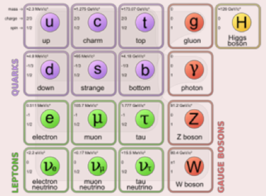
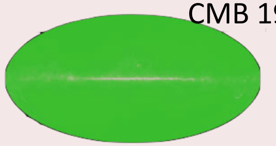
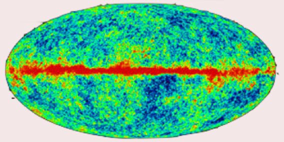
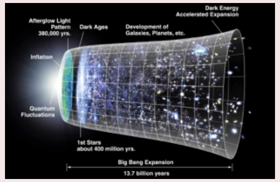
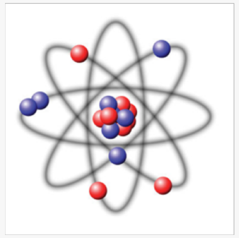
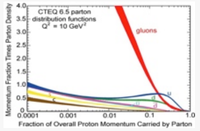
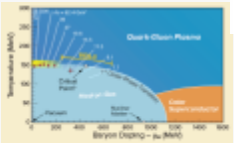
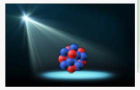
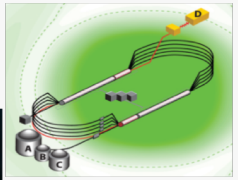
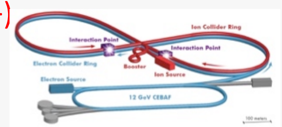




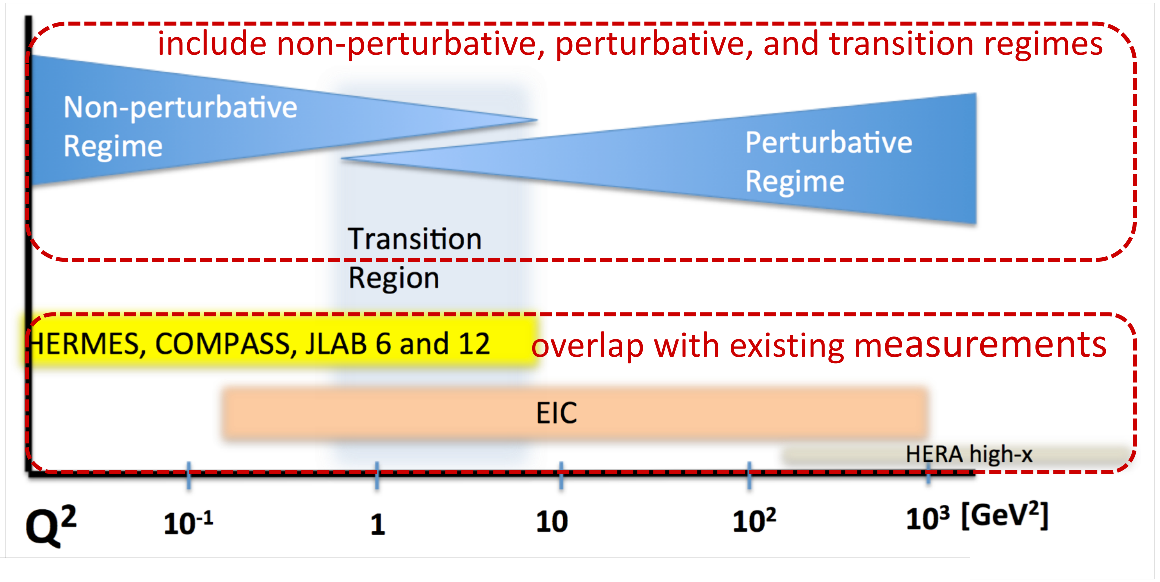


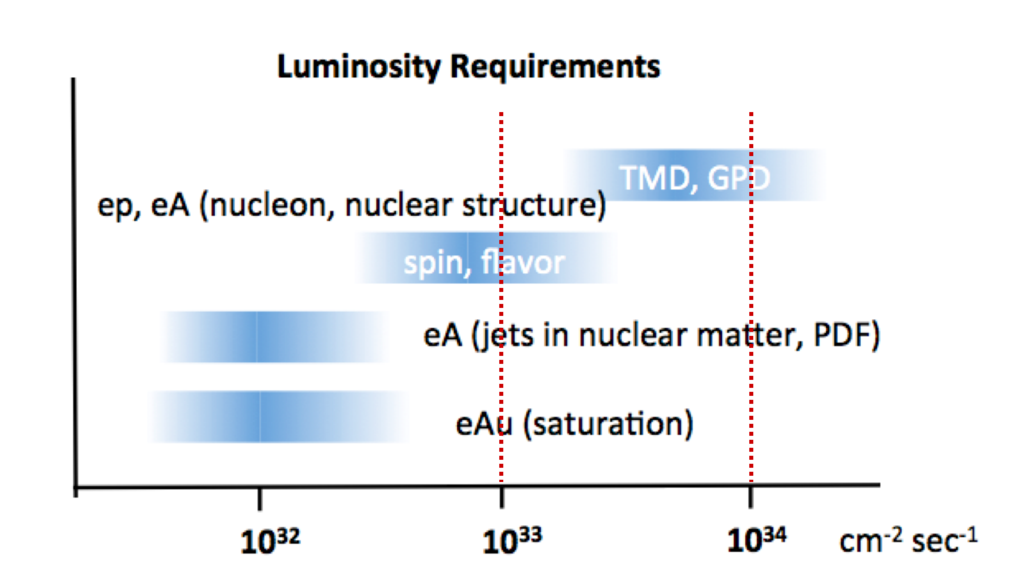


EIC: A new frontier in science

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 

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

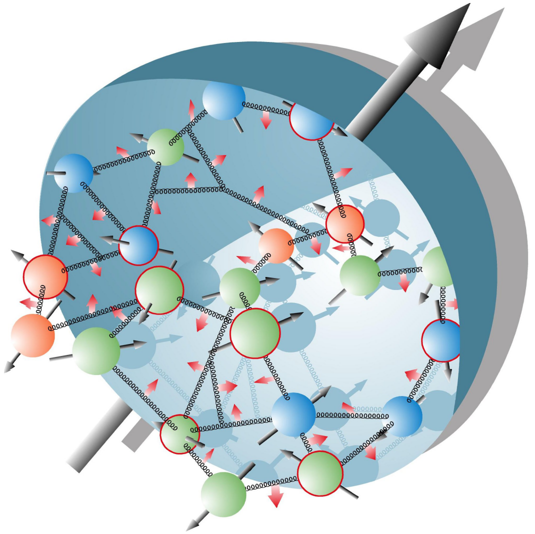
- for various measurements
- in various configurations

EIC: ideal facility for studying QCD

Polarization

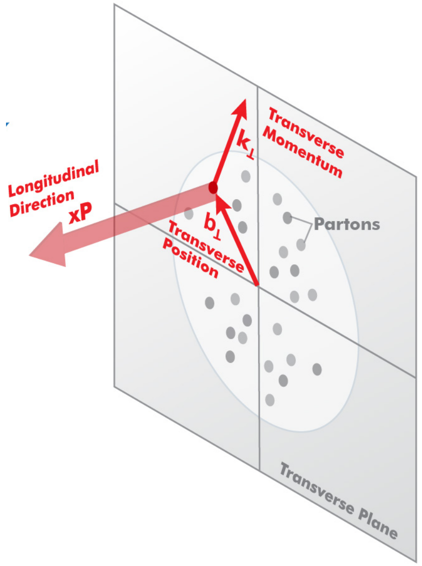
Understanding hadron structure cannot be done without understanding spin:

- polarized **electrons** and
- polarized **protons/light ions (d, ^{3}He)** including tensor polarization for d

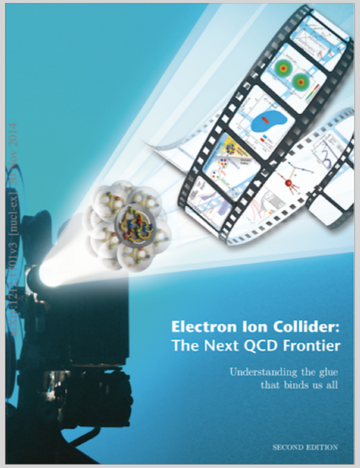


Longitudinal and transverse and polarization of light ions (d, ^{3}He)

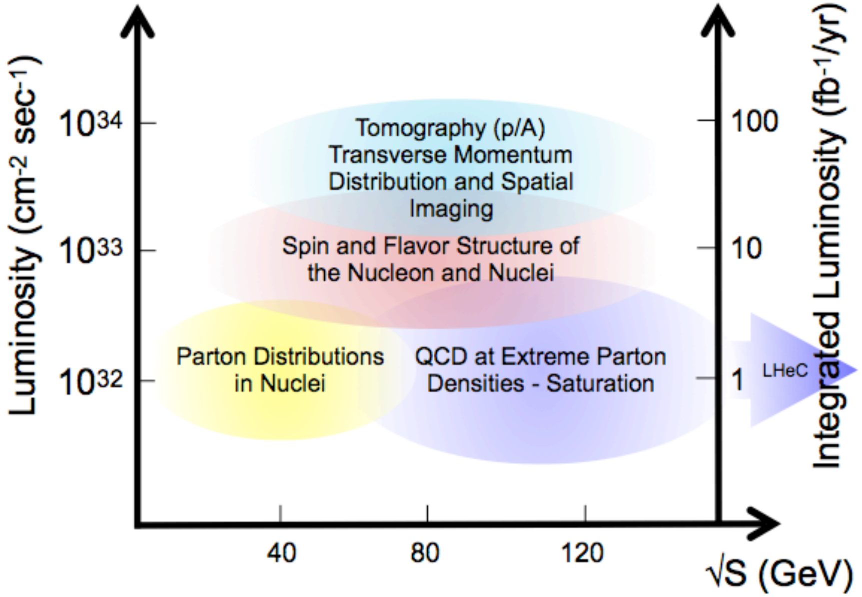
- 3D imaging in space and momentum
- spin-orbit correlations

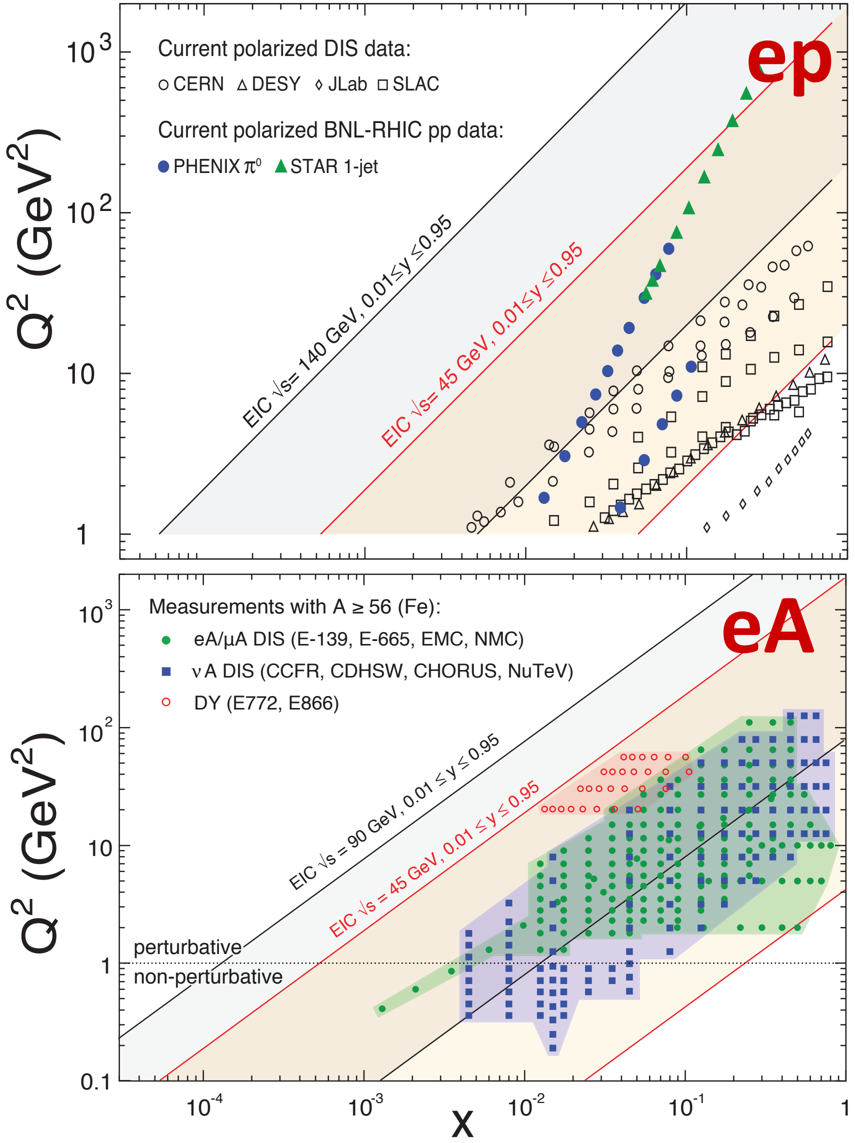


EIC science program

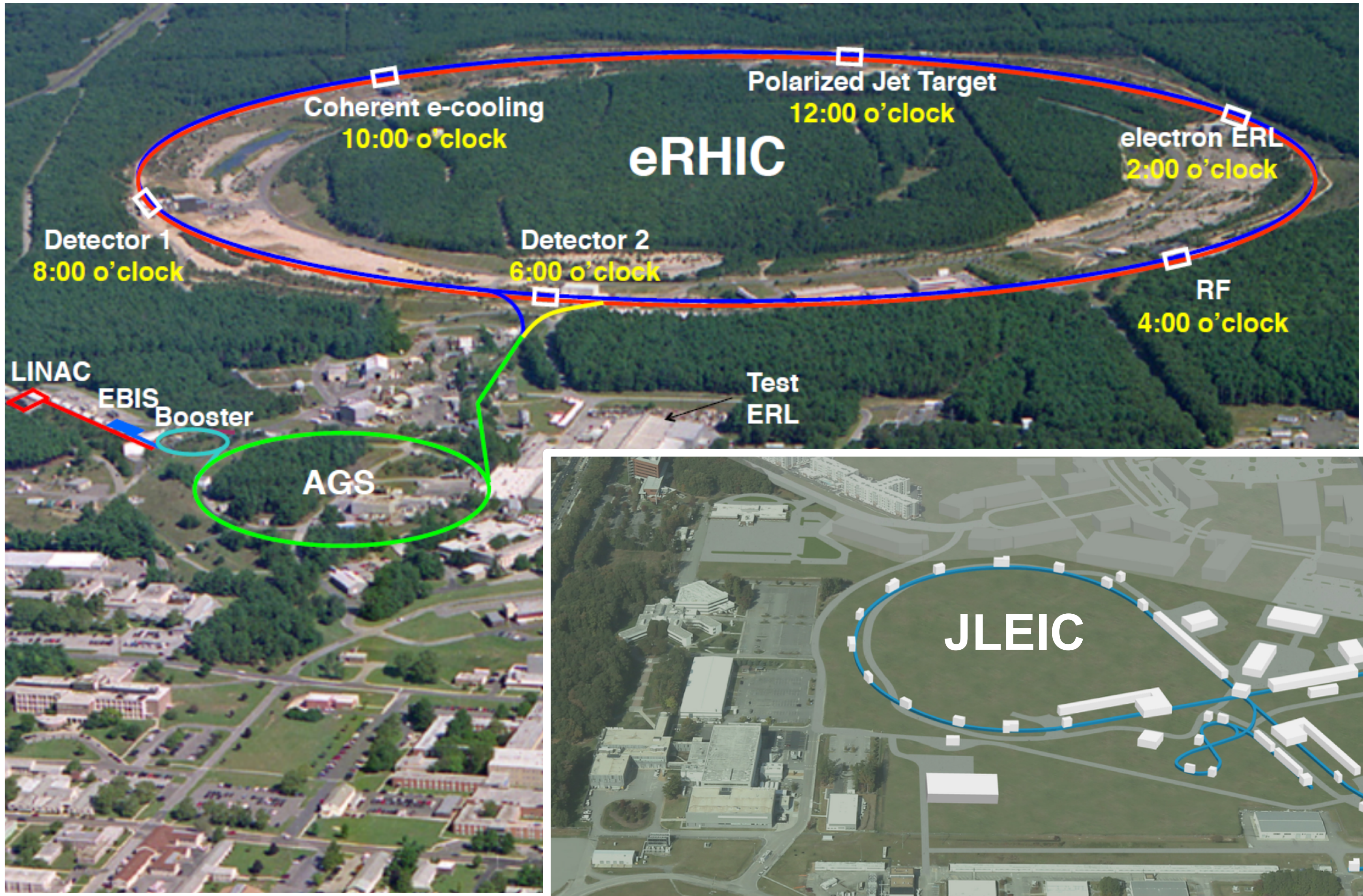


Study **structure** and **dynamics** of **nuclear matter** in **ep** and **eA collisions** with high luminosity and versatile range of beam energies, beam polarizations, and beam species.

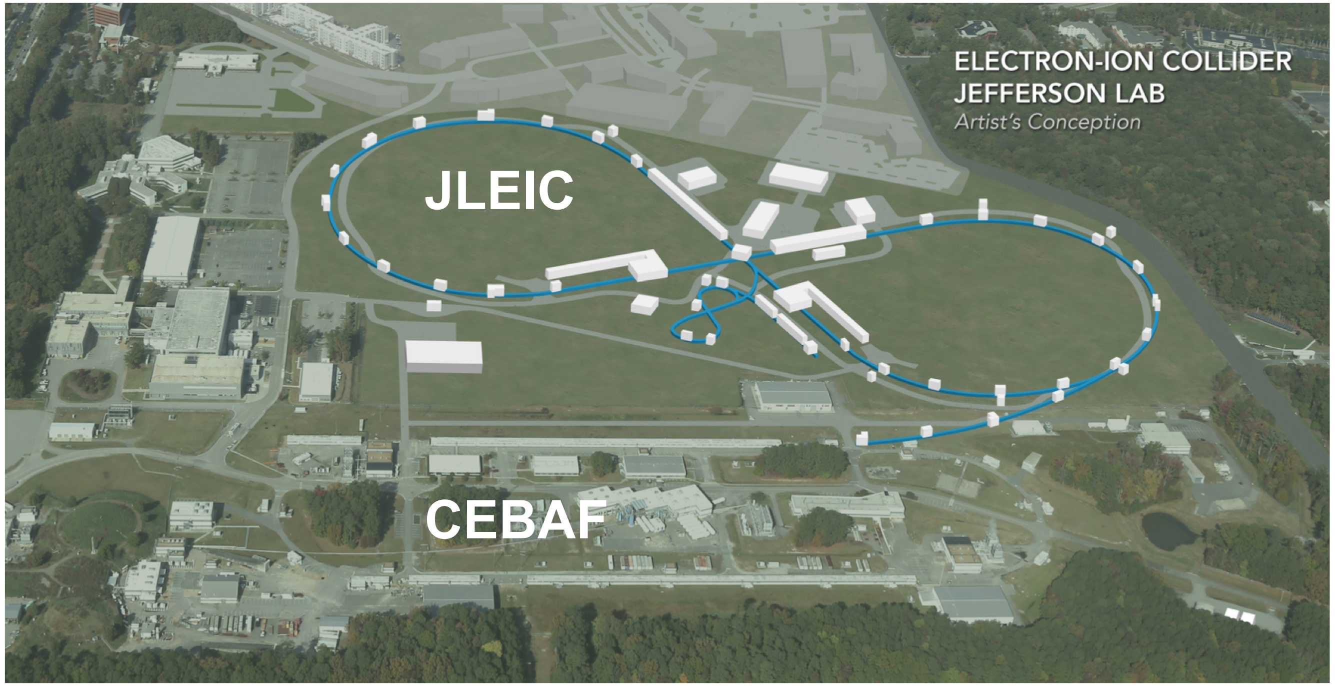




Realization of the science case



Brookhaven Lab
Long Island, NY

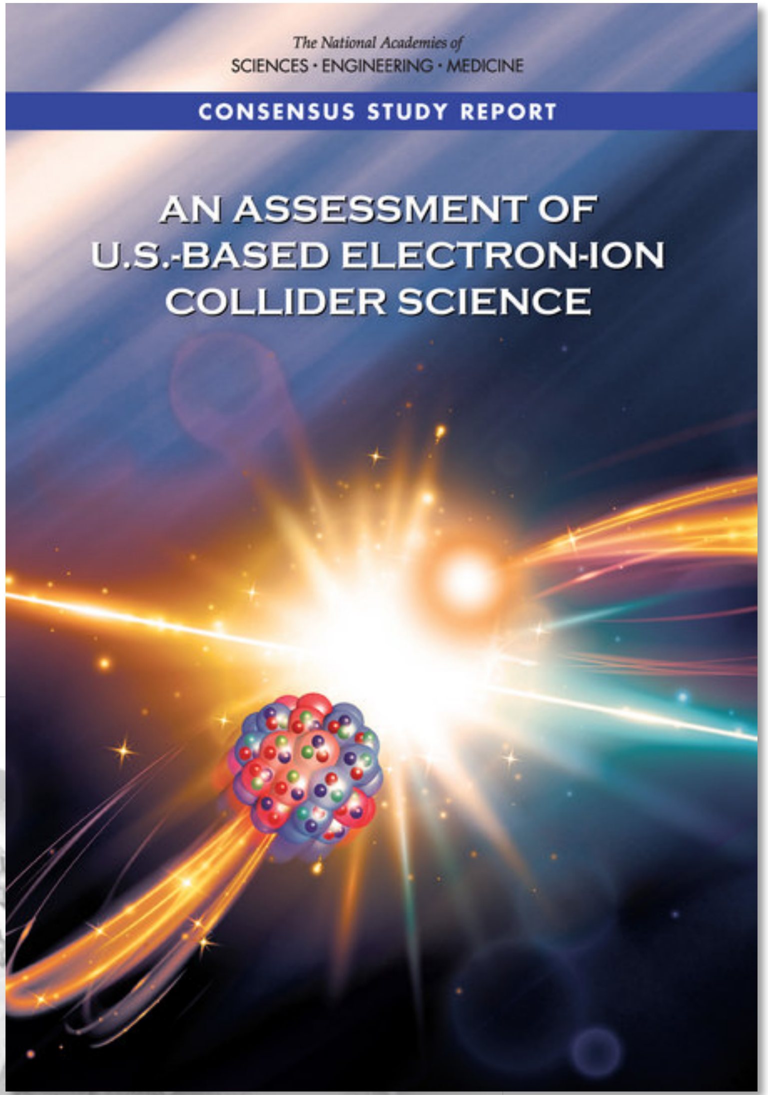


Jefferson Lab
Newport News, VA

Frontier accelerator facility in the U.S.

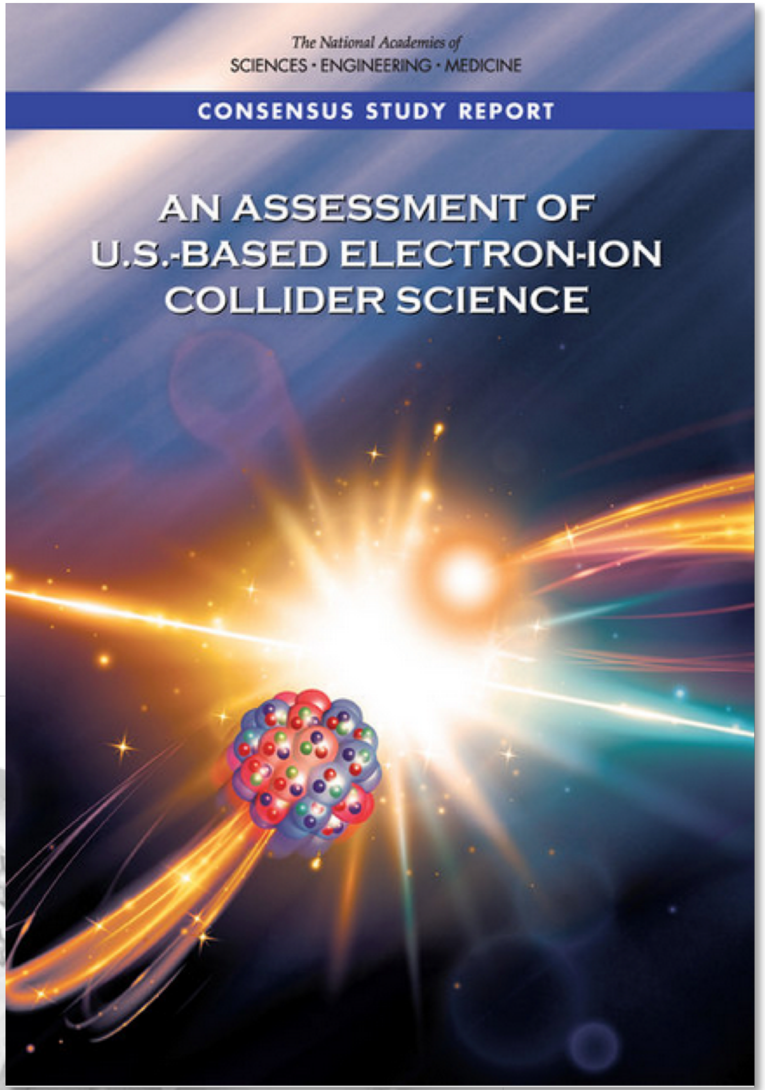
Performance requirements for the EIC

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."

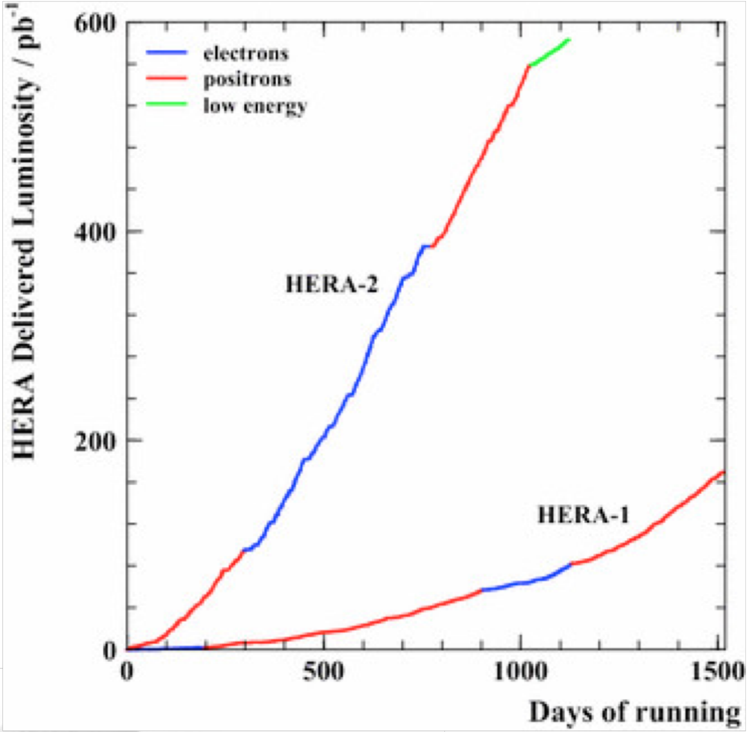
NAS report: Performance requirements



- Extensive center-of-mass energy range, from ~20-100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times higher than the earlier electron-proton collider Hadron-Electron Ring Accelerator (HERA) at Deutsches Elektronen-Synchrotron (DESY), to allow unprecedented three-dimensional (3D) imaging of the gluon and sea quark distributions in nucleons and nuclei.
- Spin-polarized (~70 percent at a minimum) electron and proton/light-ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin. Polarized colliding beams have been achieved before only at HERA (with electrons and positrons only) and Relativistic Heavy Ion Collider (RHIC; with protons only).
- One or more interaction regions, which integrate the detectors into the collider and preserve the extensive kinematic coverage for measurements.

- $\sqrt{s_{ep}}$ range ~20 to ~100 GeV upgradable to ~140 GeV
- Ion beams from D to heaviest stable nuclei
- 100 to 1000 times HERA luminosity
- At least ~70% polarization for electrons, protons and light ions
- One or more IR with integrated detector with high acceptance

Luminosity requirements for the EIC



In HERA-2, ~600 pb^{-1} of integrated luminosity was delivered (to ZEUS) over ~1000 days of running.

The means that HERA-2 delivered ~0.6 pb^{-1}/day or ~4 pb^{-1}/week of integrated luminosity during "running". There were two collider experiments, so inflate this a little to **6 pb^{-1}/week** .

HERA average luminosity (while running)

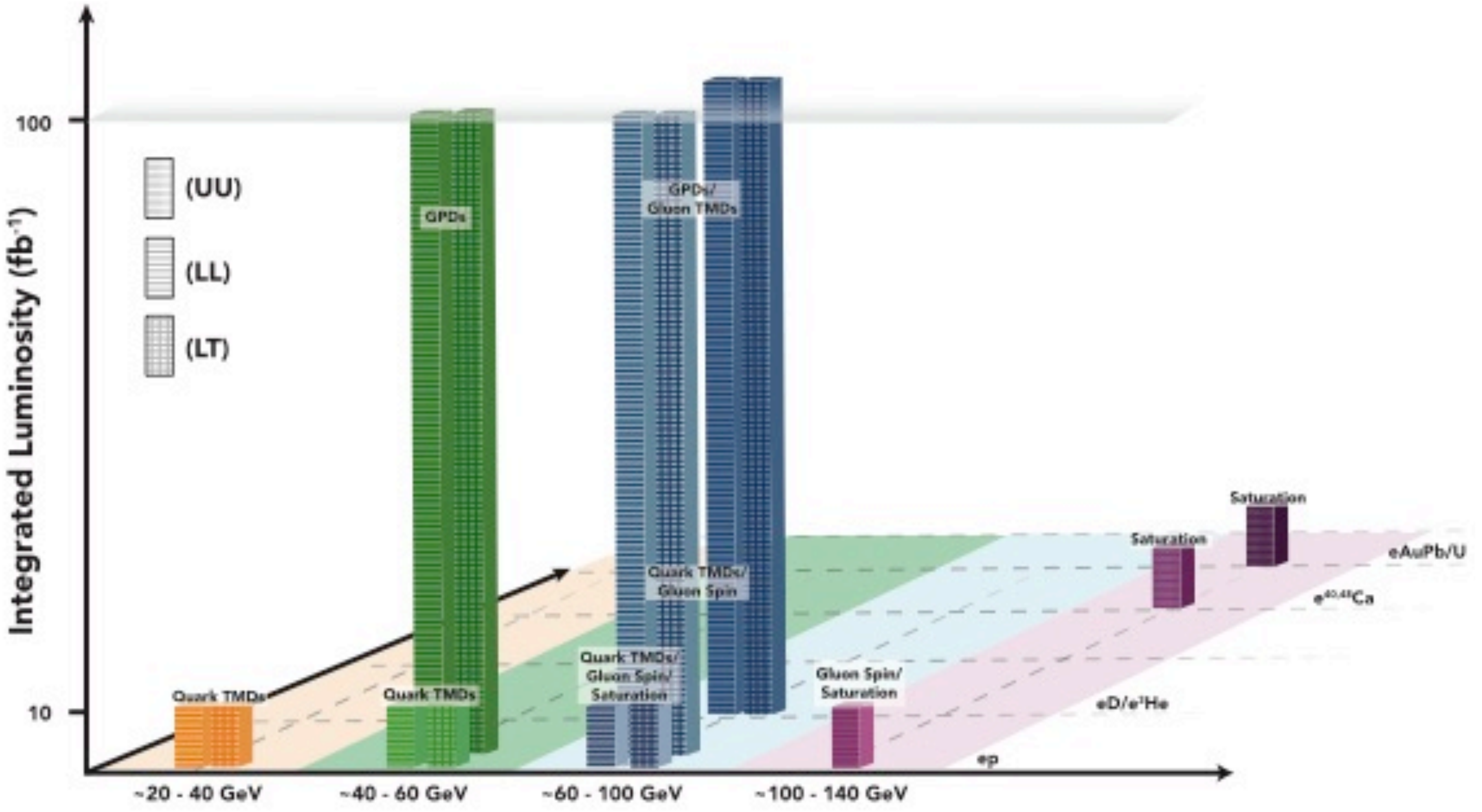
- 6 pb^{-1}/(one week in seconds) = 10^{31} $cm^{-2}s^{-1}$

EIC luminosity 100 – 1000 times HERA luminosity:

- **0.6 fb^{-1} to 6 fb^{-1}/week** of running or
- **average luminosity** (while running) of **10^{33} to 10^{34} cm^{-2} s^{-1}**

6 fb^{-1}/week ➔ 100 fb^{-1}/year assuming 10^7 s in year (running ~1/3 of the year or a *snowmass* year)

Projected luminosity needs (EIC Whitepaper)



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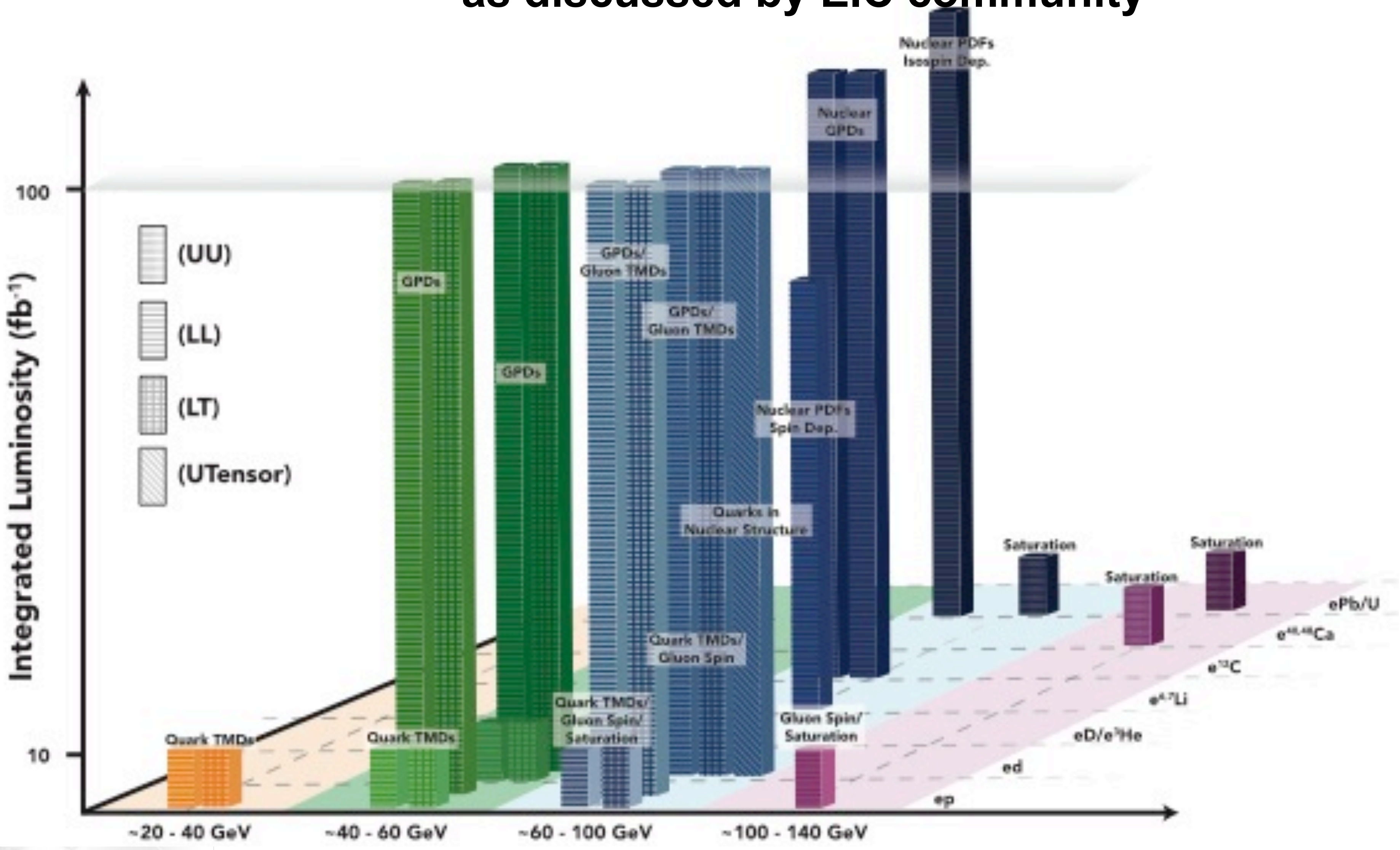
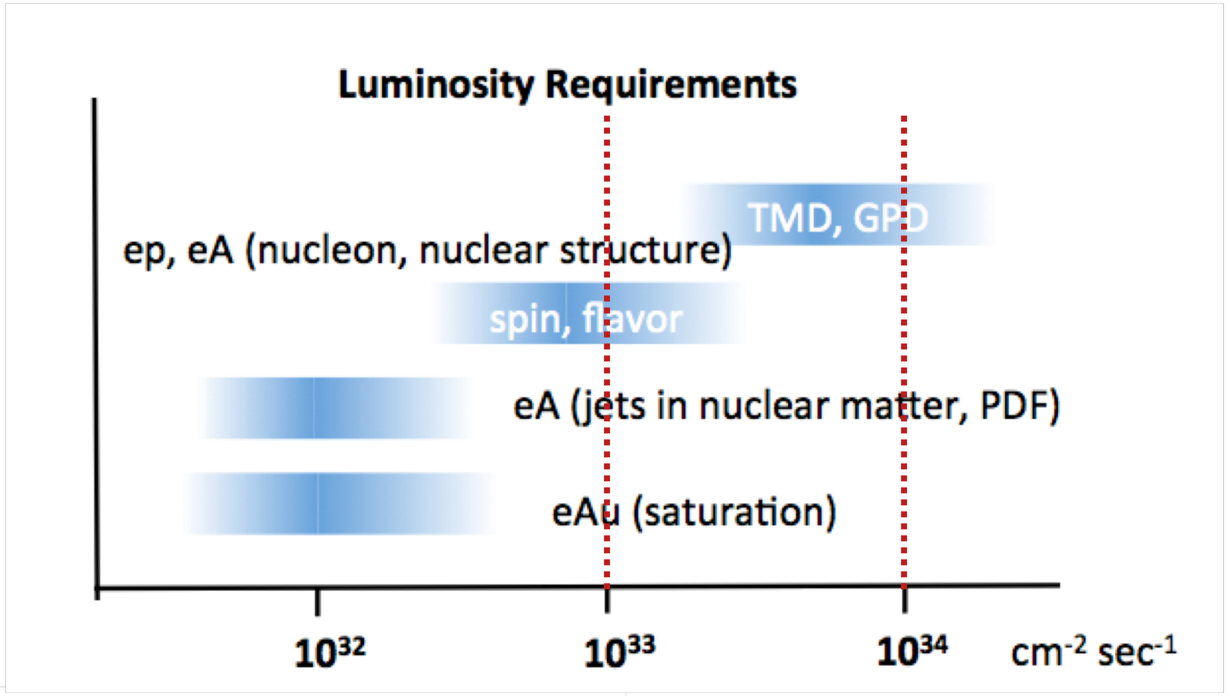
Projected luminosity needs (beyond EIC Whitepaper)

as discussed by EIC community



Luminosity requirements



Central mission of EIC (nuclear and nucleon structure) requires **high luminosity** (10^{34}).

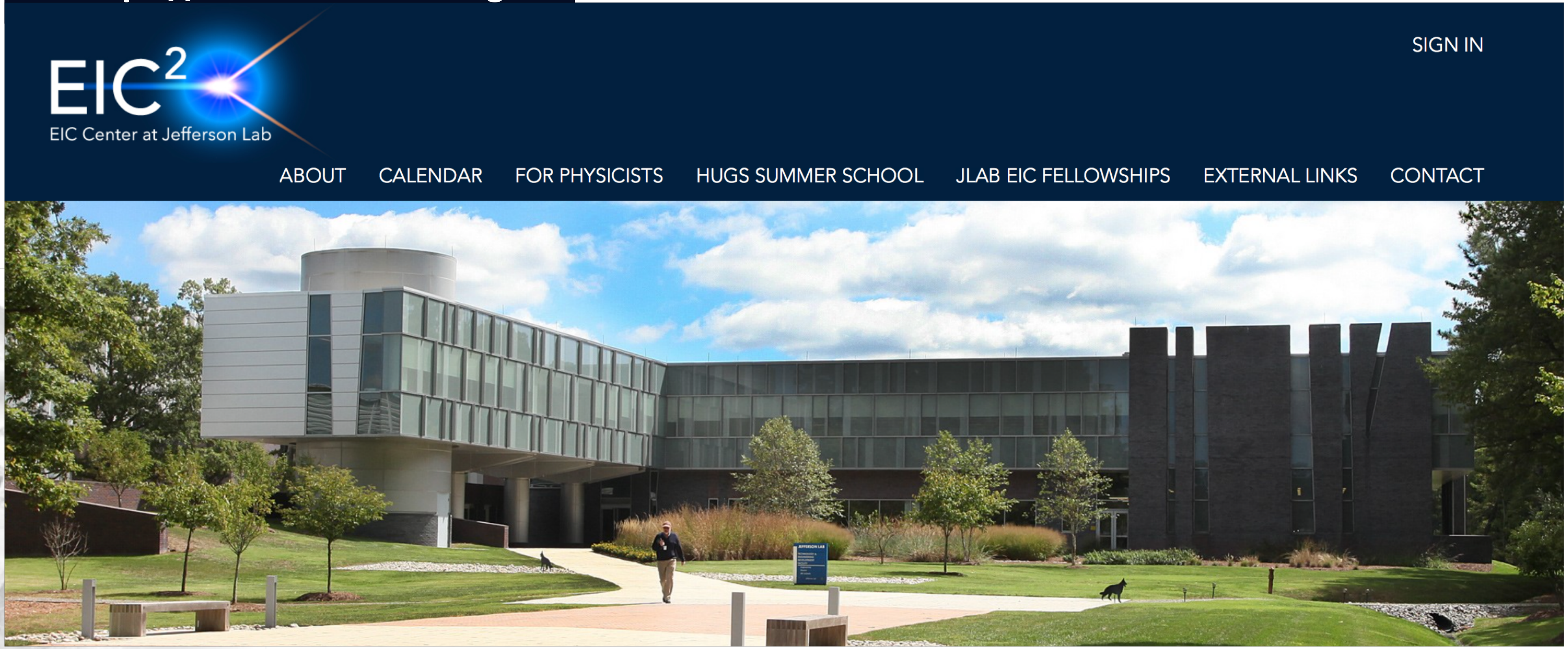
We cannot start the nucleon structure program without high luminosity
We need high-luminosity at the start of physics running at the EIC.

EIC^2@JLab

EIC^2
EIC Center at Jefferson Lab

https://www.eiccenter.org

- 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



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Summary

- 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.
- This requires a **high luminosity**, **highly versatile EIC**.
- 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**.