The Future of Deep Inelastic Scattering

Exploring Structure and Dynamics

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And

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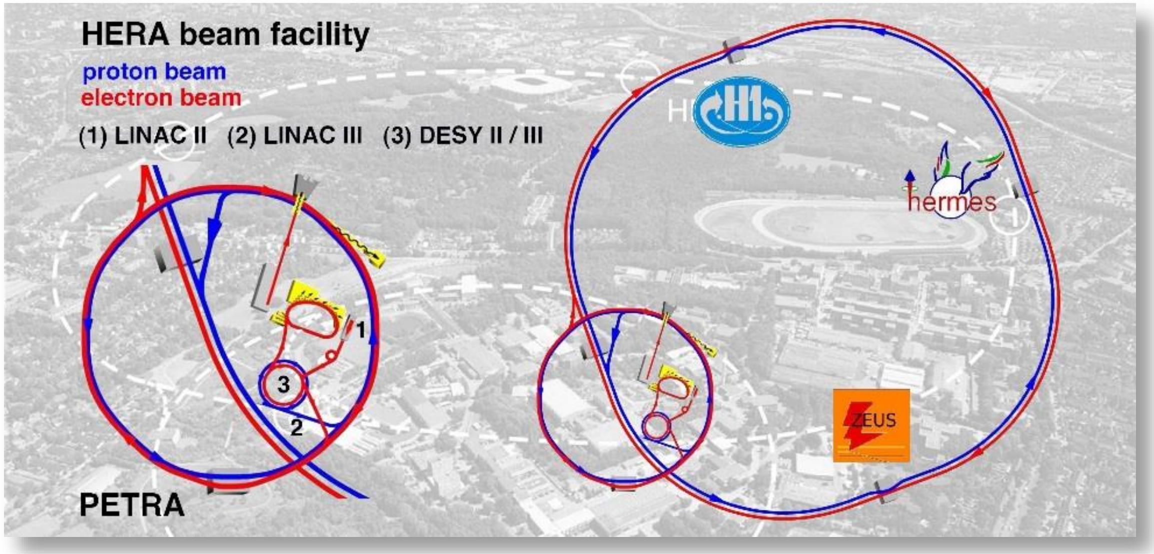
THE CATHOLIC UNIVERSITY of AMERICA

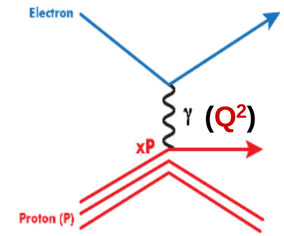
Jefferson Lab
Thomas Jefferson National Accelerator Facility

2017 ICFA Seminar

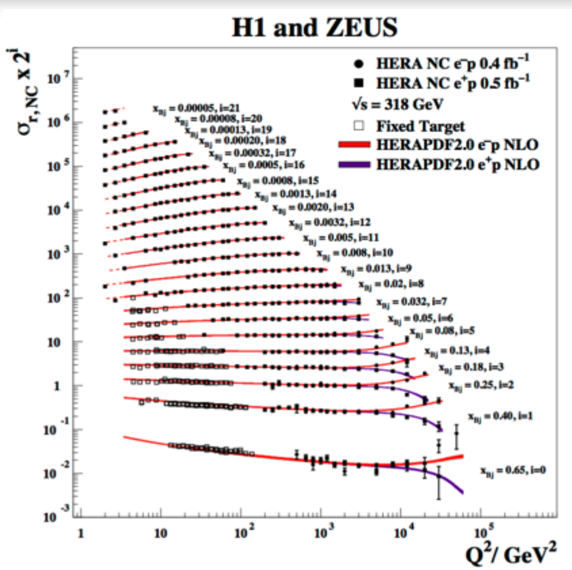
6-9 November 2017
Shaw Center, Ottawa, Ontario, Canada

HERA – The first Electron-Proton Collider



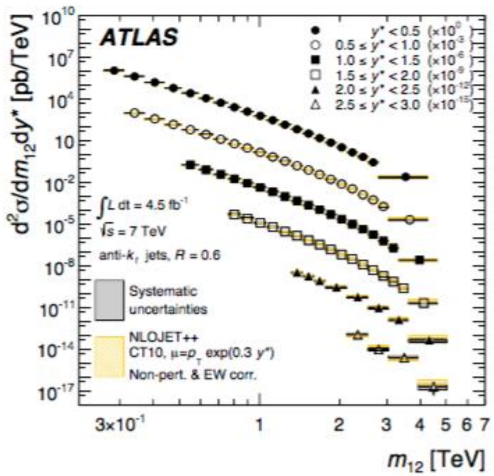


- Changing **Q^2** changes the resolution scale
- Changing **x** projects out configurations where different dynamics dominate



[From Eur. Phys. J. C75(2015)12,580]

PDF & pQCD

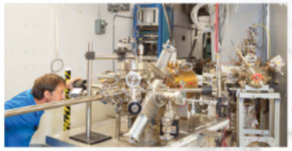


Proton ≈ beam of partons: Allows us to use proton beams in HEP experiments and achieve precision.

CEBAF AT JEFFERSON LAB

12 GeV

Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) enables world-class fundamental research of the atom's nucleus. Like a giant microscope, it allows scientists to "see" things a million times smaller than an atom.



1 INJECTOR

The injector produces electron beams for experiments.

2 LINEAR ACCELERATOR

The straight portions of CEBAF, the linacs, each have 25 sections of accelerator called cryomodules. Electrons travel up to 5.5 passes through the the linacs to reach 12 GeV.

Project Completion Approved September 27, 2017

8 EXPERIMENTAL HALL D

Hall D is configured with a superconducting solenoid magnet and associated detector systems that are used to study the strong force that binds quarks together.

3 CENTRAL HELIUM LIQUEFIER

The Central Helium Liquefier keeps the accelerator cavities at -456 degrees Fahrenheit.

4 RECIRCULATION MAGNETS

Quadrupole and dipole magnets in the tunnel focus and steer the beam as it passes through each arc.

5 EXPERIMENTAL HALL A

Hall A is configured with two High Resolution Spectrometers for precise measurements of the inner structure of nuclei. The hall is also used for one-of-a-kind, large-installation experiments.

6 EXPERIMENTAL HALL B

The CEBAF Large Acceptance Spectrometer surrounds the target, permitting researchers to measure simultaneously many different reactions over a broad range of angles.

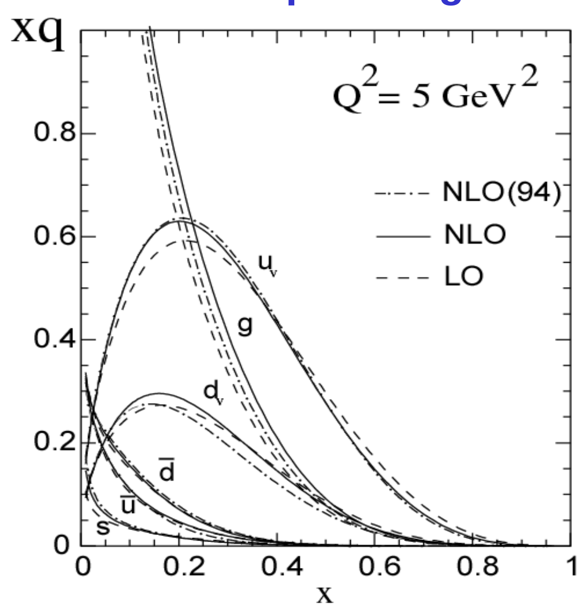
7 EXPERIMENTAL HALL C

The Super High Momentum Spectrometer and the High Momentum Spectrometer make precise measurements of the inner structure of protons and nuclei at high beam energy and current.

Jefferson Lab at 12 GeV: Science Questions

- ❑ What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- ❑ Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- ❑ Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- ❑ What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?
- ❑ Can we discover evidence for physics beyond the standard model of particle physics?

Valence quark region

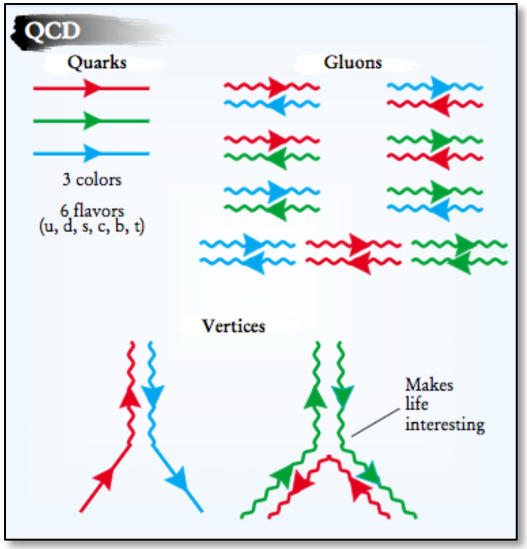


12 GeV

REQUIRES:

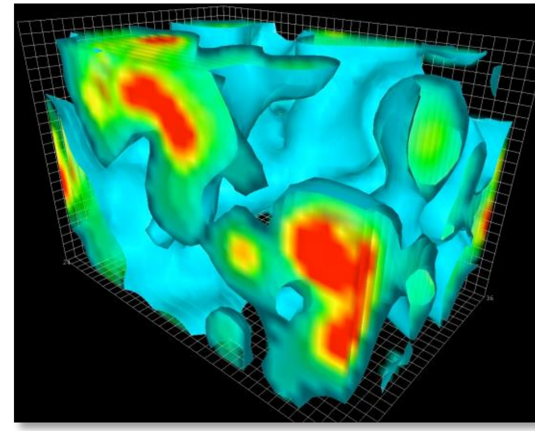
- *High beam polarization*
- *High electron current*
- *High target polarization*
- *Large solid angle spectrometers*

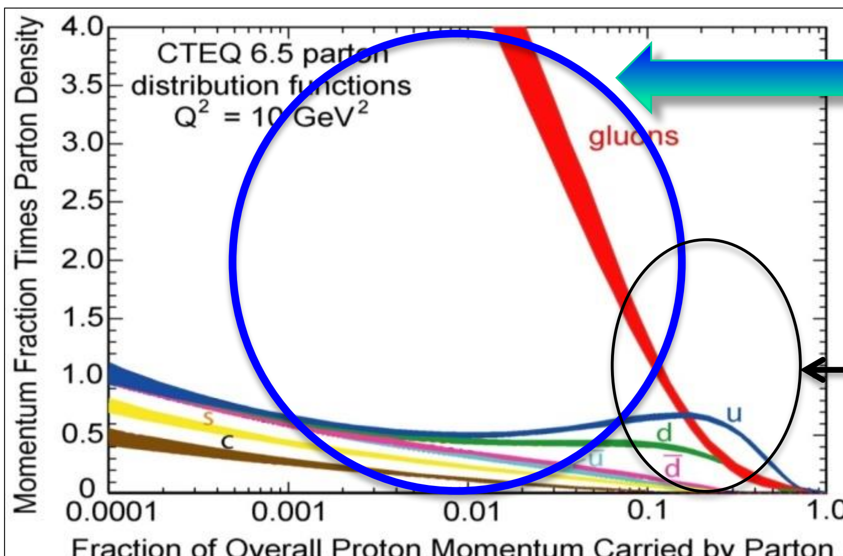
Cold Matter is Unique



Structure and Interaction are entangled because of gluon self-interaction

Observed properties such as mass and spin emerge from this complex system.





EIC needed to explore the gluon dominated region

JLAB 12 to explore the valence quark region

Physics Goals of new DIS Colliders

- (3D) Nucleon substructure
- Development of QCD
- Structure of the photon, pomeron, pion, kaon, D, A…
- Precision EW measurements

Electron-Ion Collider (EIC)

- Spin – 3D nucleon imaging
- Origin of hadron mass and spin
- Nuclear/medium effects
- Role of gluons in nuclear structure to onset of saturation

LHeC-FCCep

- Unfolding all partons (NC+CC)
- New physics (Higgs, DM, RPV SUSY, LQs)
- EW below and beyond Z, Top physics
- Gluon saturation

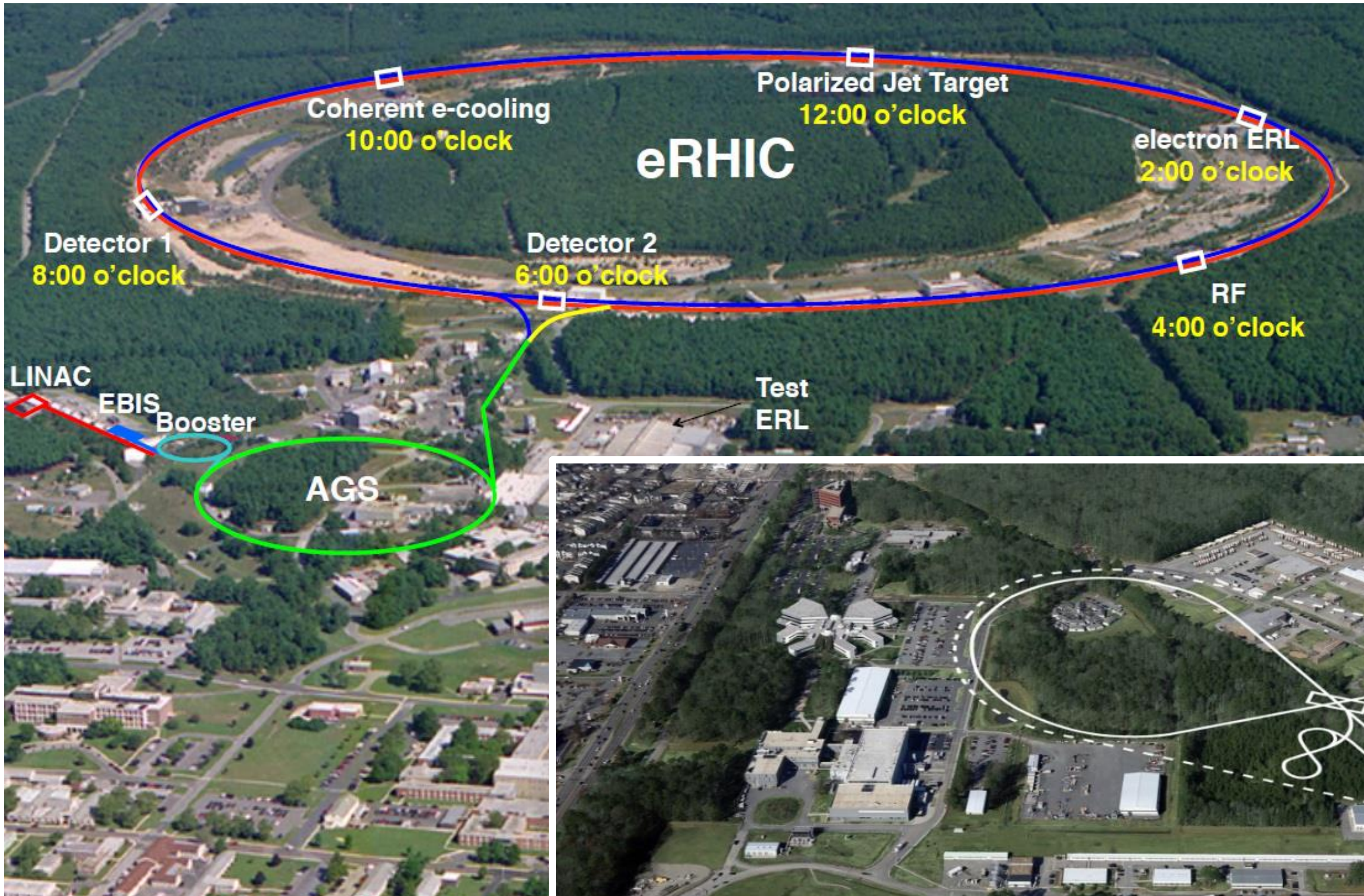
EIC: The World's First Polarized Electron-Ion Collider

- **Interactions and structure are mixed up in nuclear matter:** Nuclear matter is made of quarks that are bound by gluons that also bind themselves. Unlike with the more familiar atomic and molecular matter, the interactions and structures are inextricably mixed up, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

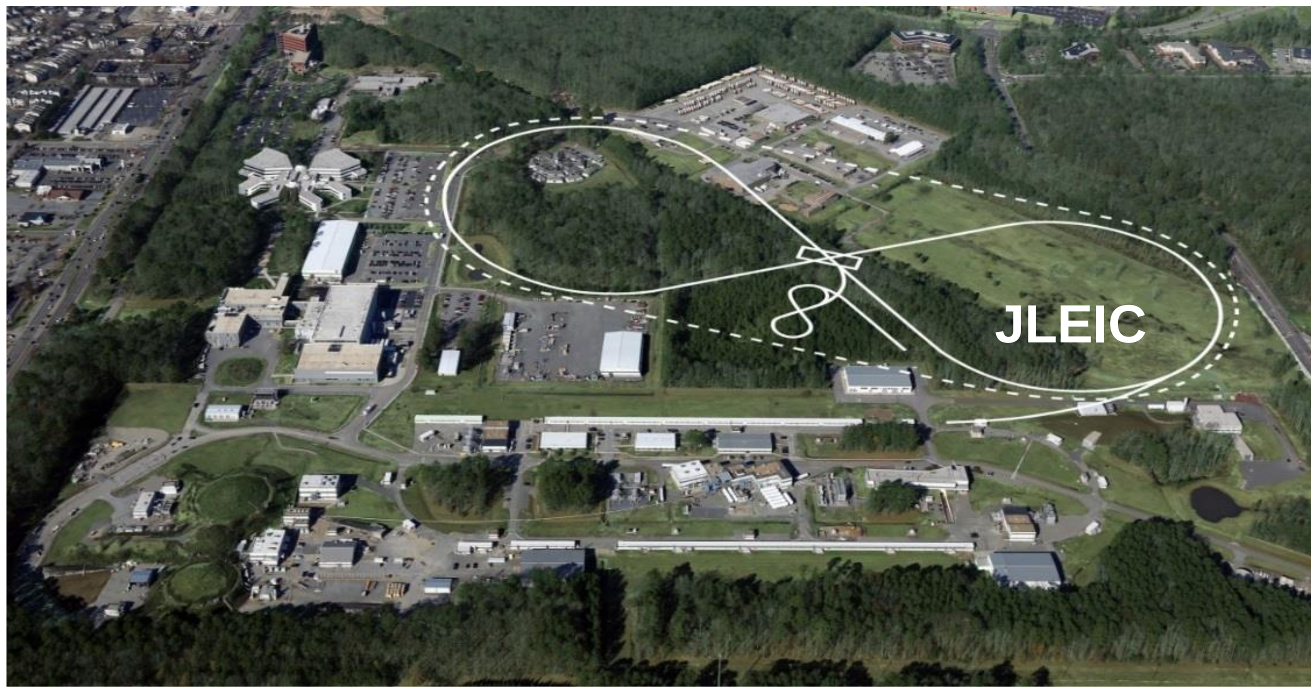
- **Gaining understanding of this dynamic matter is transformational** Gaining detailed knowledge of this astonishing dynamical system at the heart of our world will be transformational, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.

- **The Electron Ion Collider is the right tool:** A new US-based facility, EIC, with a versatile range of beam energies, polarizations, and species, as well as high luminosity, is required to precisely image the 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.

US-Based EICs

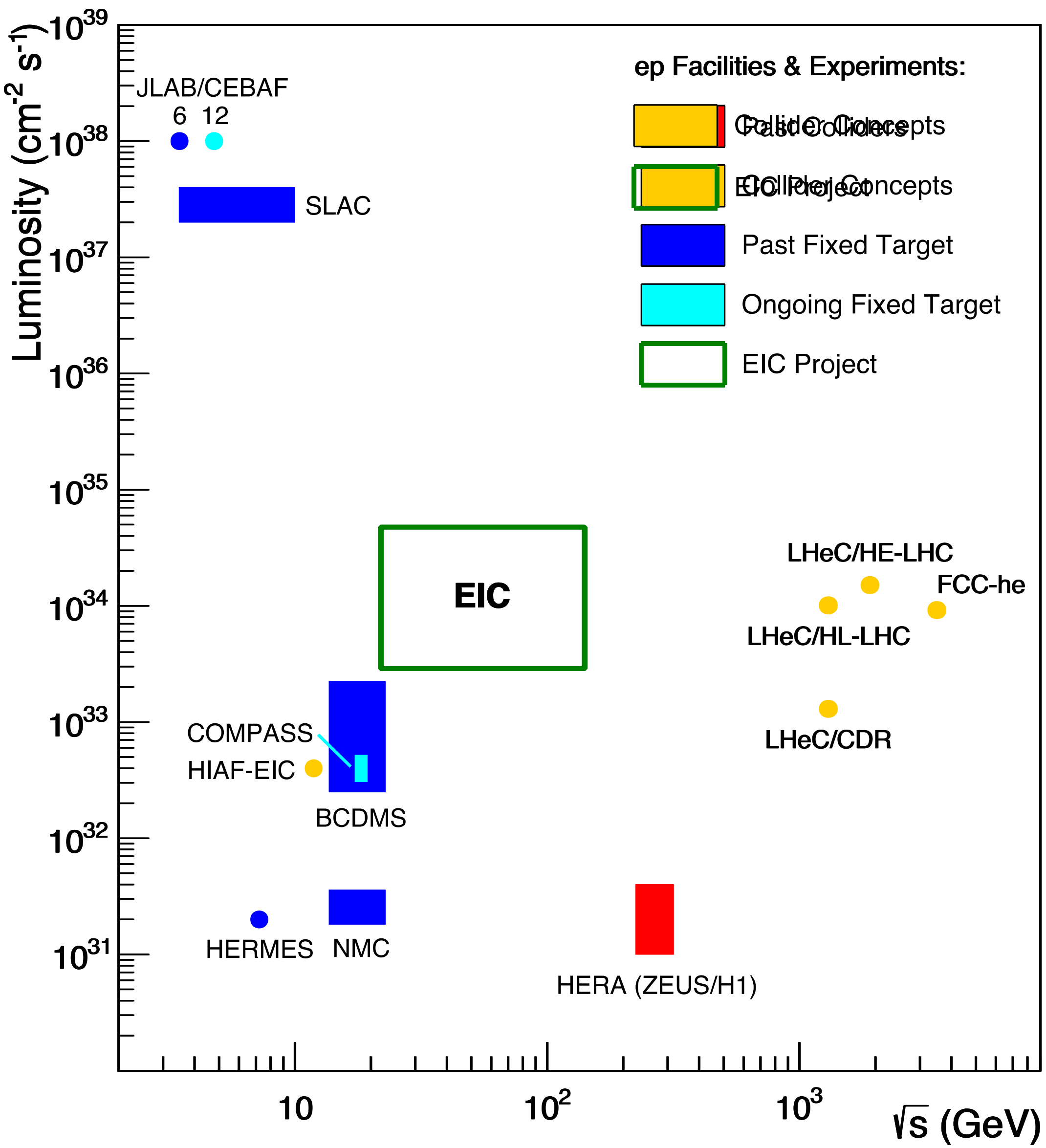


Brookhaven Lab
Long Island, NY



Jefferson Lab
Newport News, VA

Lepton-Proton Scattering Facilities



All DIS facilities in the world.

However,
if we ask for:

- ➢ high luminosity & wide reach in √s
- ➢ nuclear beams

EIC and LHeC stand out as unique facilities …

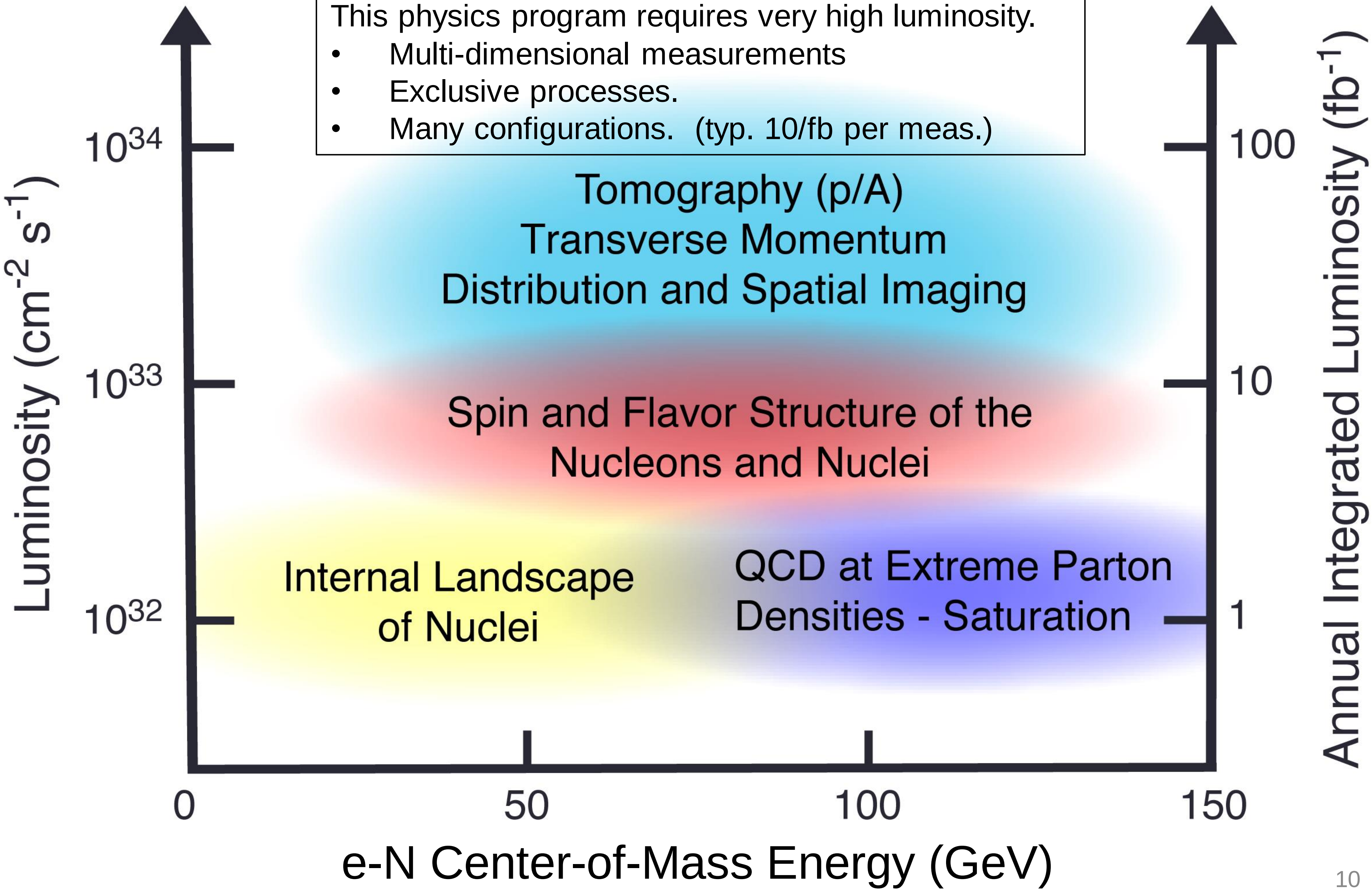
- ➢ In addition: polarized lepton & hadron beams

EIC stands out as unique facility …

EIC Science Program

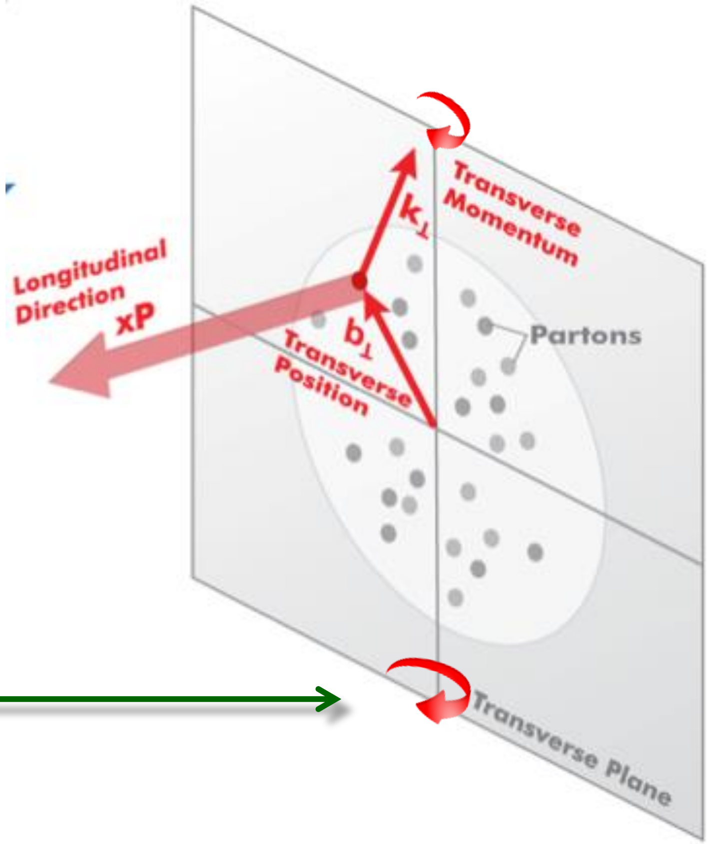
This physics program requires very high luminosity.

- Multi-dimensional measurements
- Exclusive processes.
- Many configurations. (typ. 10/fb per meas.)



3D Structure of Nucleons and Nuclei

- EIC is a machine to completely map the 3D structure of the nucleons and nuclei
- We need to measure positions and momenta of the partons transverse to its direction of motion.
- These quantities (k_T, b_T) are of the order of a few hundred MeV.
- Also their polarization!



k_T, b_T (~100 MeV)

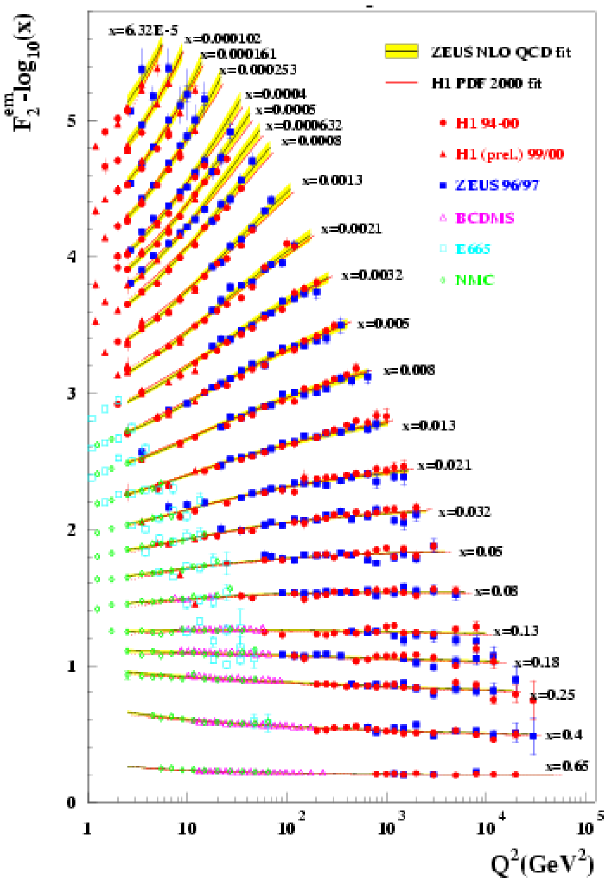
Proton and Ion Beam

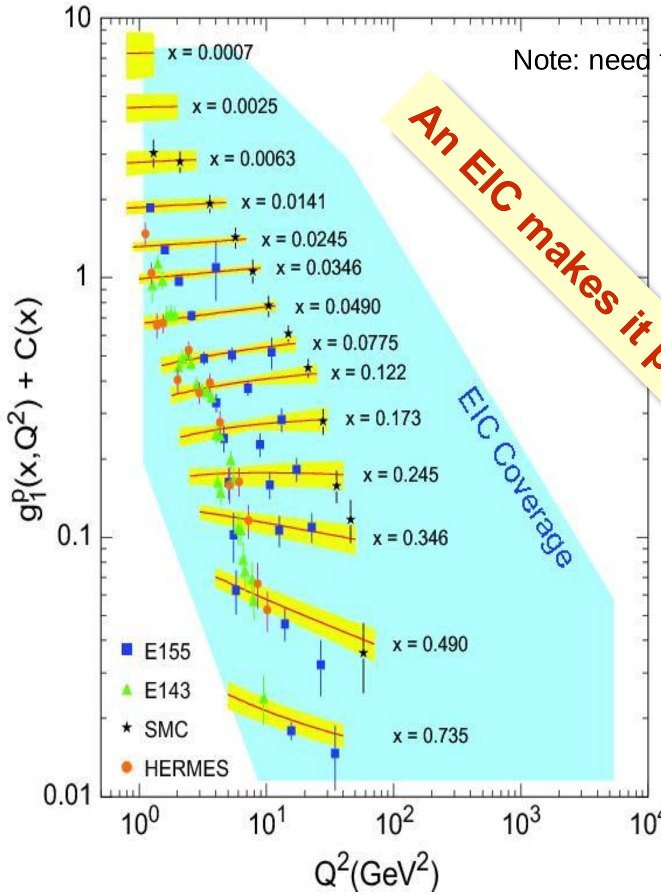
Need to keep $[100\ \mathrm{MeV}]_T/E_{proton,Ion}$ manageable (~ >10^{-3}) ➔ E_{proton} ~< 100 GeV

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high

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

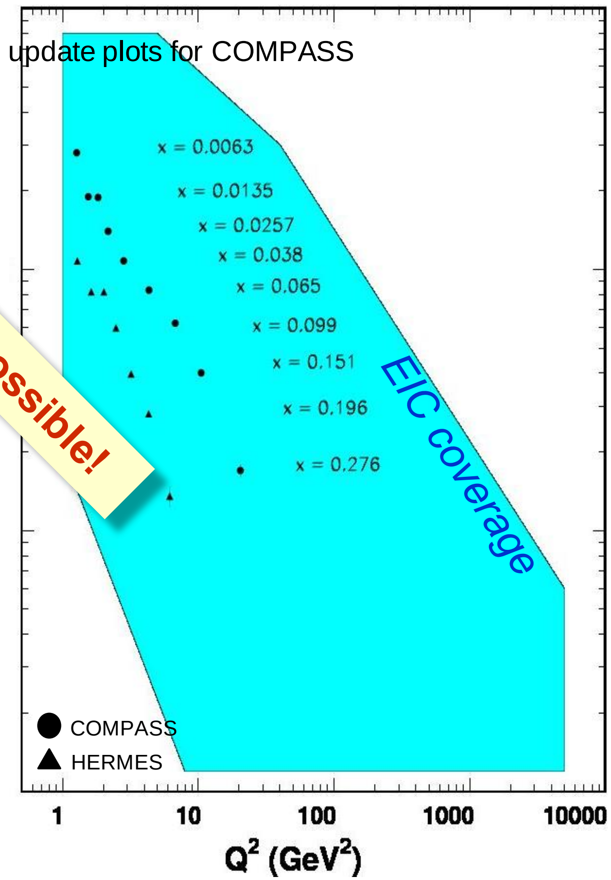
$F_{UT}^{\sin(\phi_h+\phi_s)}(x,Q^2) + C(x) \propto h_1$





Note: need to update plots for COMPASS

An EIC makes it possible!



Momentum

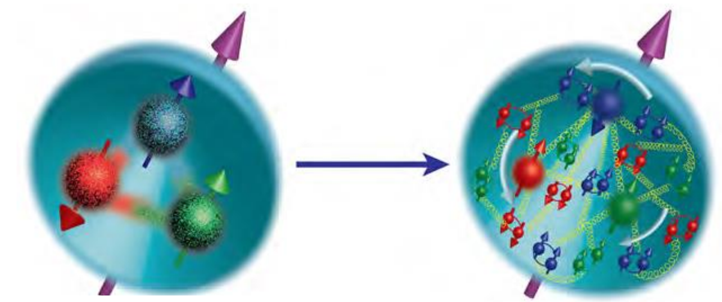
Spin

Transverse spin ~ Angular momentum

2+1 D partonic image of the proton

(Spatial distance from origin) X *(Transverse Momentum)*

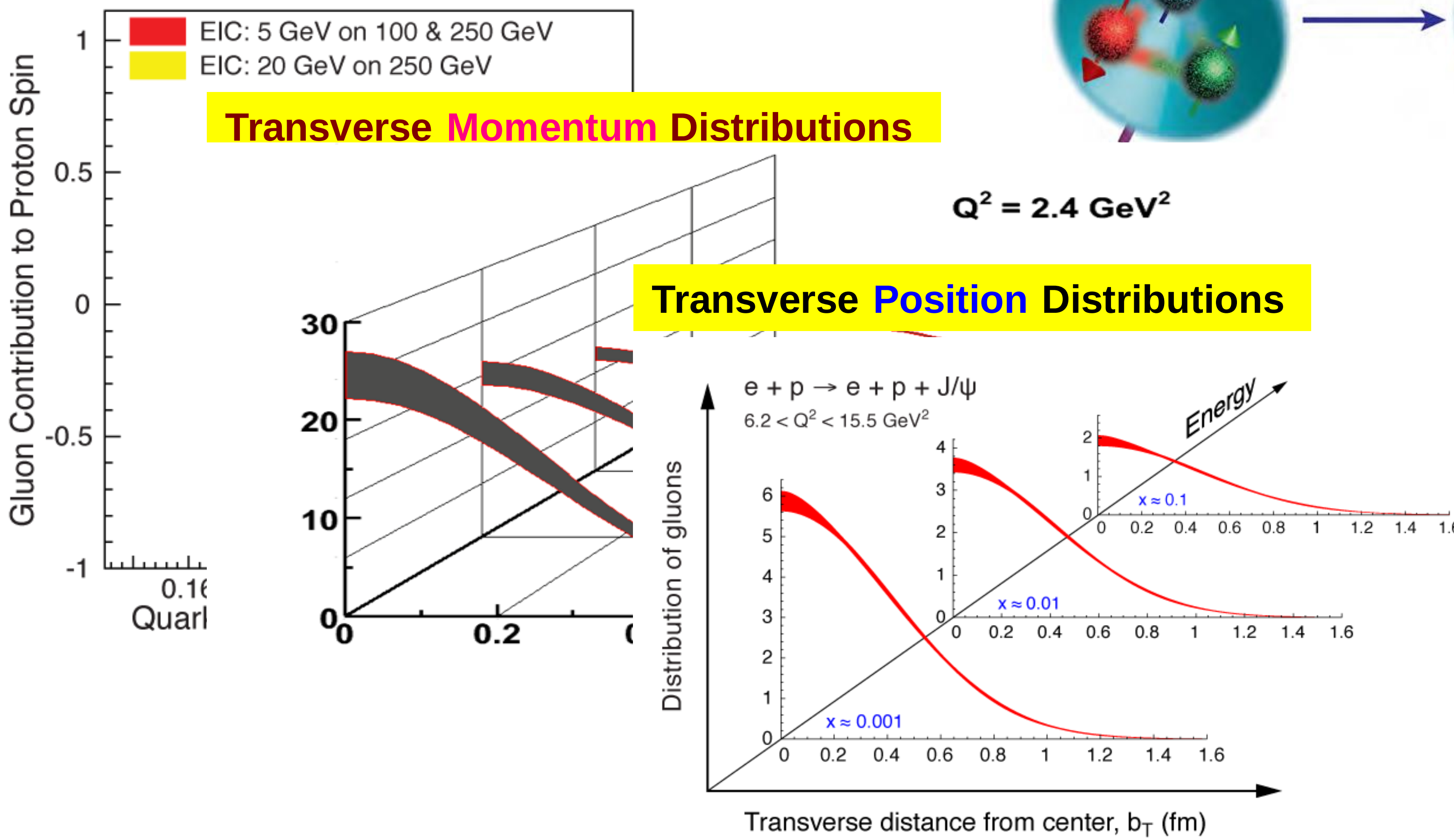
→ **Orbital Angular Momentum**

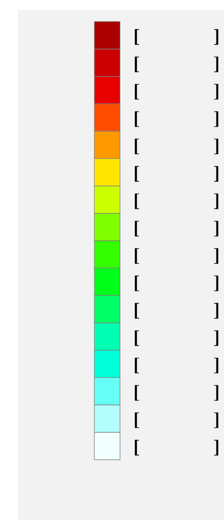


Helicity Distributions: ΔG and ΔΣ

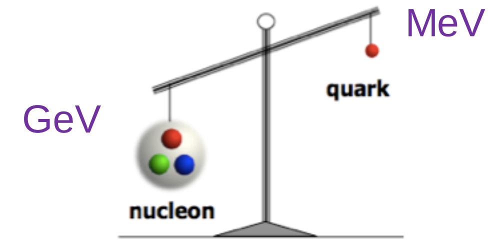
Transverse Momentum Distributions

Transverse Position Distributions





Understanding Nucleon Mass



Relativistic motion → $E_q + E_g$

χ **Symmetry Breaking** → χm_q

Quantum fluctuation → T_g

$$M = E_q + E_g + \chi m_q + T_g$$

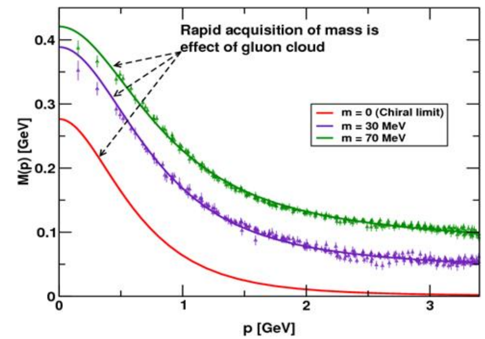
Quark Energy → E_q

Gluon Energy → E_g

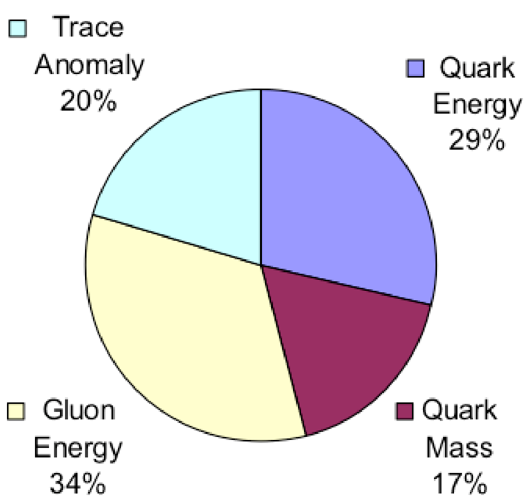
Quark Mass → m_q

Trace Anomaly → T_g

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" *The 2015 Long Range Plan for Nuclear Science*



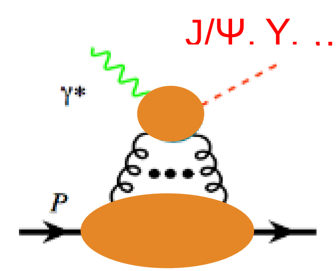
Preliminary Lattice QCD results:



EIC's expected contribution in:

- Trace Anomaly:

  Upsilon production near the threshold

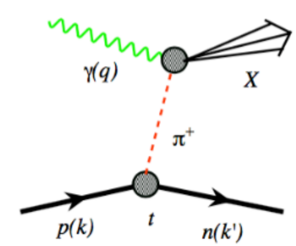


- Quark-gluon Energy:

  $\propto$ *quark-gluon momentum fractions*

  In nucleon with DIS and SIDIS

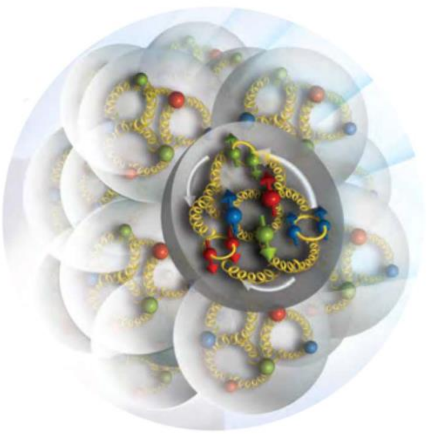
  In pions and kaons with Sullivan process



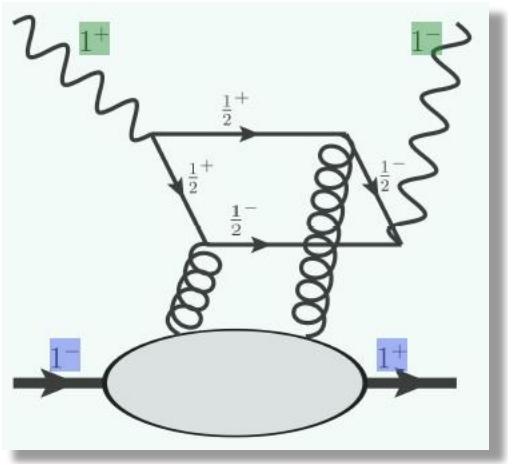
Exotic Glue in Nuclei

Exotic Glue in Nuclei =

- gluons **not** associated with individual nucleons in nucleus
- operator in nucleon = 0 & operator in nuclei ≠ 0



Targets with J ≥ 1 have leading twist gluon contribution
$\Delta(x,Q^2)$: double helicity flip (Jaffe and Manohar, 1989)
Changes both photon and target helicity by two units…



$$\Delta(x, Q^2) = A_{+-,-+}$$

Measurable in unpolarized Deep Inelastic Scattering with a **transversely polarized J ≥ 1 target like the deuteron** as azimuthal variation.

Parton model interpretation:
$\Delta(x,Q^2)$ informs how much more momentum of a transversely polarized particle is carried by a gluon with spin aligned rather than perpendicular to it in the transverse plane.

[Shanahan, Detmold, et al.]

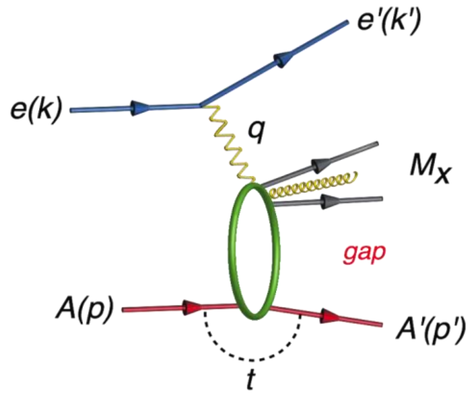
LQCD calculation: gluon transversity distribution in the deuteron, m_π = 800 MeV
→ **First evidence for non-nucleonic gluon contributions to nuclear structure**

Diffraction for the 21st Century

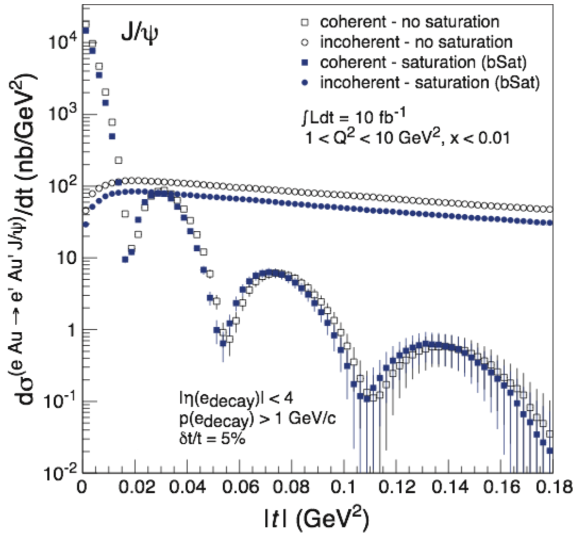
Diffraction cross-sections have strong discovery potential:

High sensitivity to gluon density in linear regime: $\sigma \sim [g(x,Q^2)]^2$

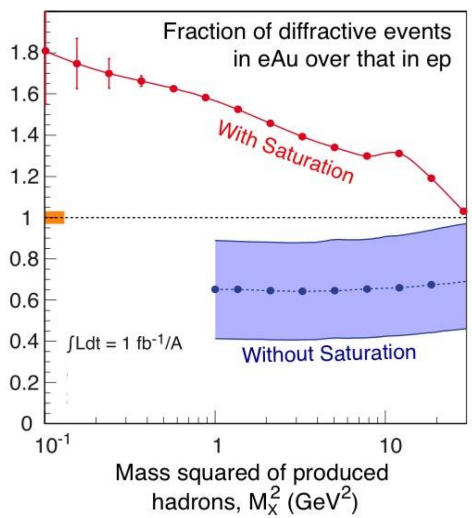
Dramatic changes in cross-sections with onset of non-linear strong color fields



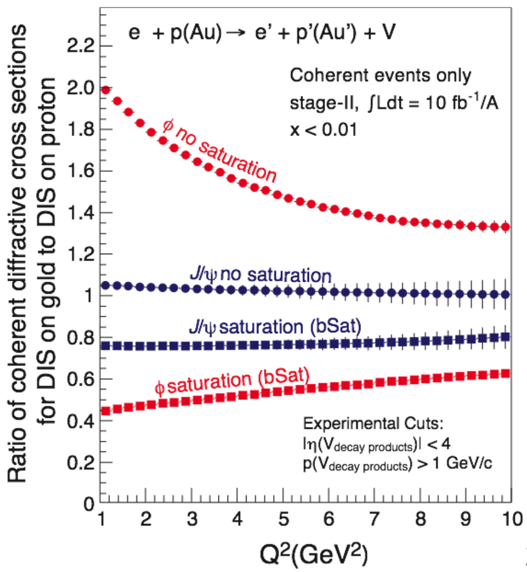
Extracting the gluon distribution $\rho(b_T)$ of nuclei via Fourier transformation of $d\sigma/dt$ in diffractive J/ψ production



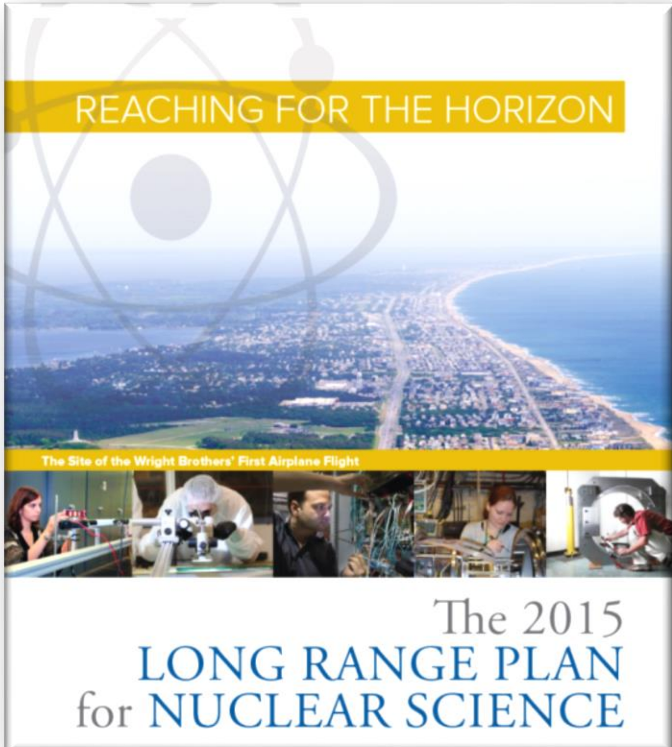
Probing gluon saturation through measuring $\sigma_{diff}/\sigma_{tot}$



Probing Q^2 dependence of gluon saturation in diffractive vector meson production



2015 NSAC Long Range Plan



RECOMMENDATION III

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

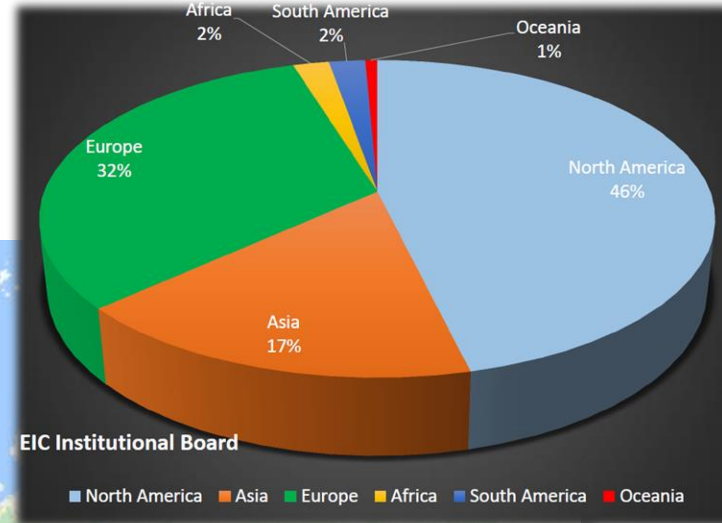
National Academies of Science Study underway

- First meeting February 1-2, 2017
- Second meeting April 19-20, 2017
- Third meeting September 11-12, 2017
- **Expect report in spring 2018**

Worldwide Interest in EIC Physics

The EIC Users Group: EICUG.ORG

719 collaborators, 29 countries, 165 institutions... (November, 2017)



Recent and Upcoming EIC Events

- **INT Workshop series:**
  - Spatial and Momentum Tomography of Hadrons and Nuclei (INT-17-3), August 28, 2017 - September 29, 2017 (I. Cloet, K. Hafidi, Z.-E. Meziani, B. Pasquini)
  - The Flavor Structure of Nucleon Sea (INT-17-68W), October 2-13, 2017 (C. Aidala, W. Detmold, J. Qiu, W. Vogelsang)
  - Probing Nucleons and Nuclei in High Energy Collisions (INT-18-3), October 1, 2018 - November 18, 2018 (Y. Hatta, Y. Kovchegov, C. Marquet, A. Prokudin)

- 6th International Workshop on Deep-Inelastic Scattering and Related Topics (DIS 2018), Kobe, Japan, April 16-20, 2018

- Physics Opportunities at an ElecTron-Ion Collider (POETIC 2018) conference, Regensburg, Germany, March 19-22, 2018

- EICUG meeting 2018 - July 30, 2018 - Friday, August 4, 2018 / The Catholic University of America hosted by Professor Tanja Horn - Major focus will be on steps after NAS report leading to anticipated CD0 EIC project award!

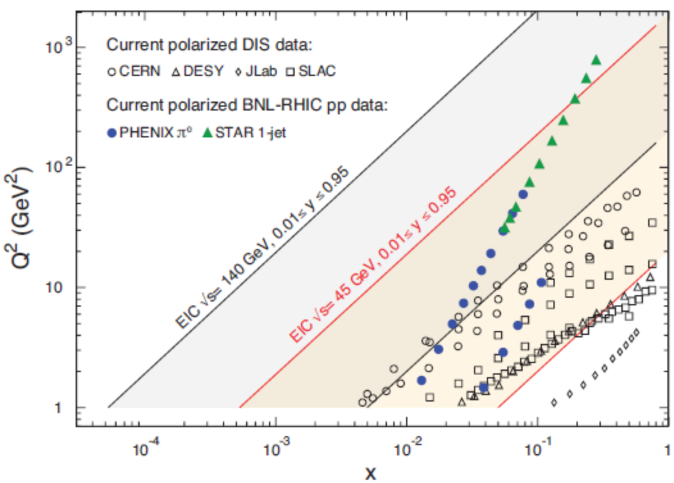
EIC vs LHeC

EIC: L = about 10^{34} $cm^{-2}s^{-1}$
E_{cm} = 20- ~100 GeV

- *Variable energy range*
- ***Polarized** and heavy ion beams*
- *High luminosity in energy region of interest for **nuclear science/QCD***

World's first polarized e-p collider and world's first e-A collider, at medium energy

$x_{min} \sim 1 \times 10^{-4}$

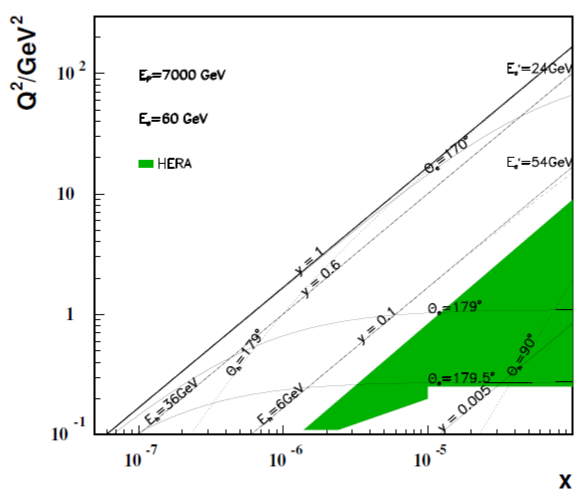


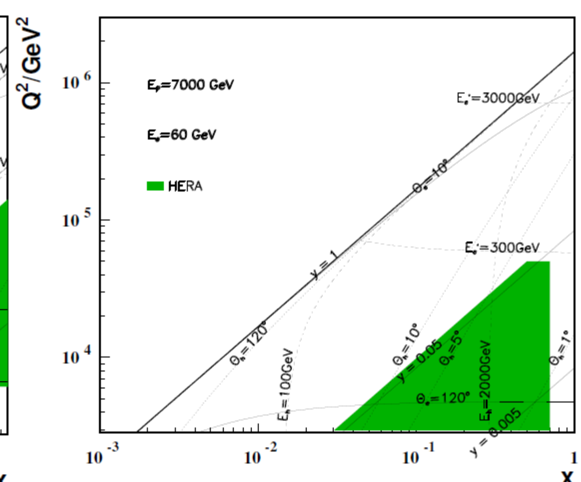
LHeC: L = 10^{34} $cm^{-2}s^{-1}$
E_{cm} ~ 400-1200 (1800) for HL (HE) LHC

- *Add ~60 GeV electrons to **LHC***
- *High luminosity takes benefit of large γ's (= E/m) of beams*

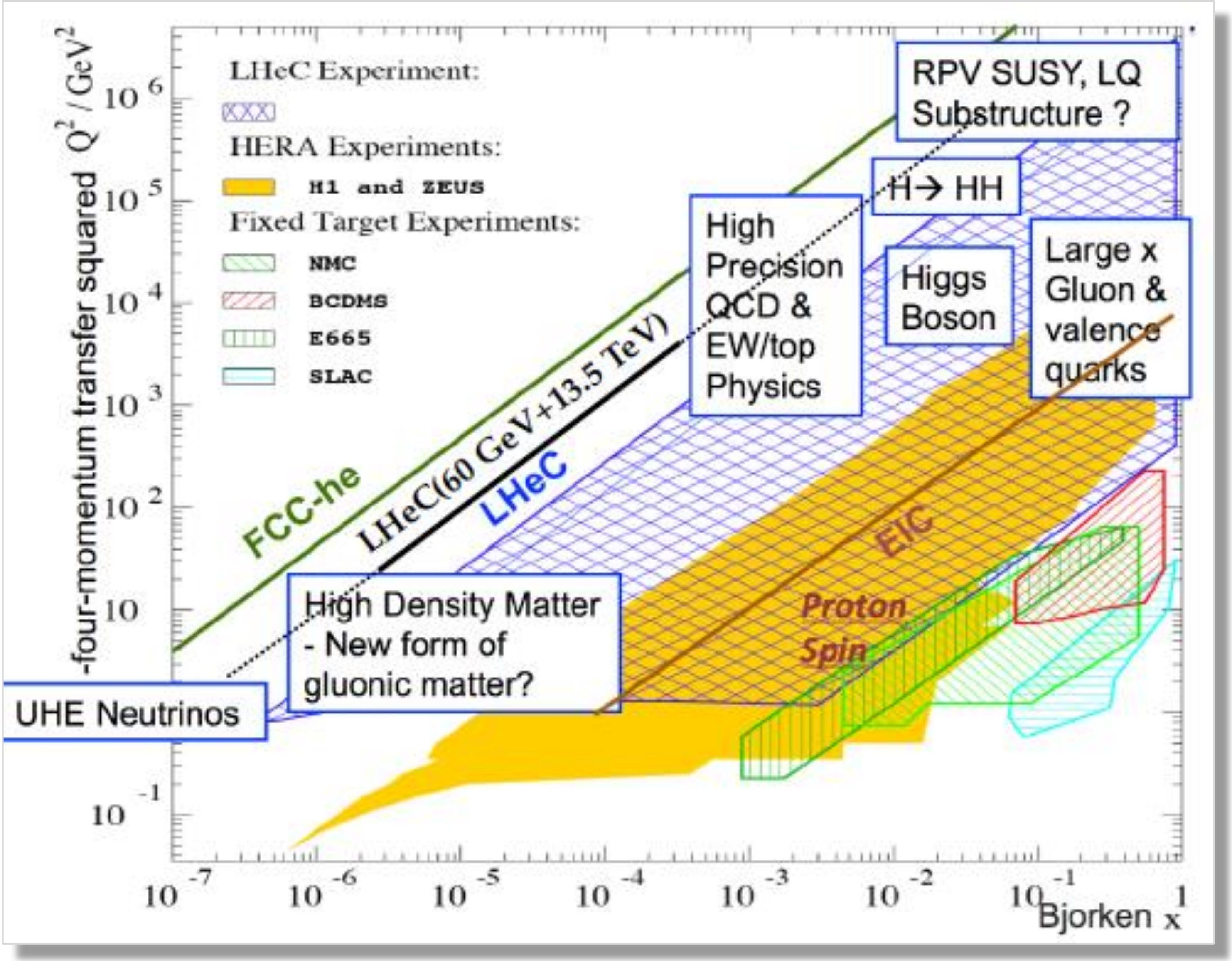
Energy frontier e-p collider and first e-A collider at TeV energy

$x_{min} \sim 5 \times 10^{-7}$





Electron-Proton Scattering (ep → eX)

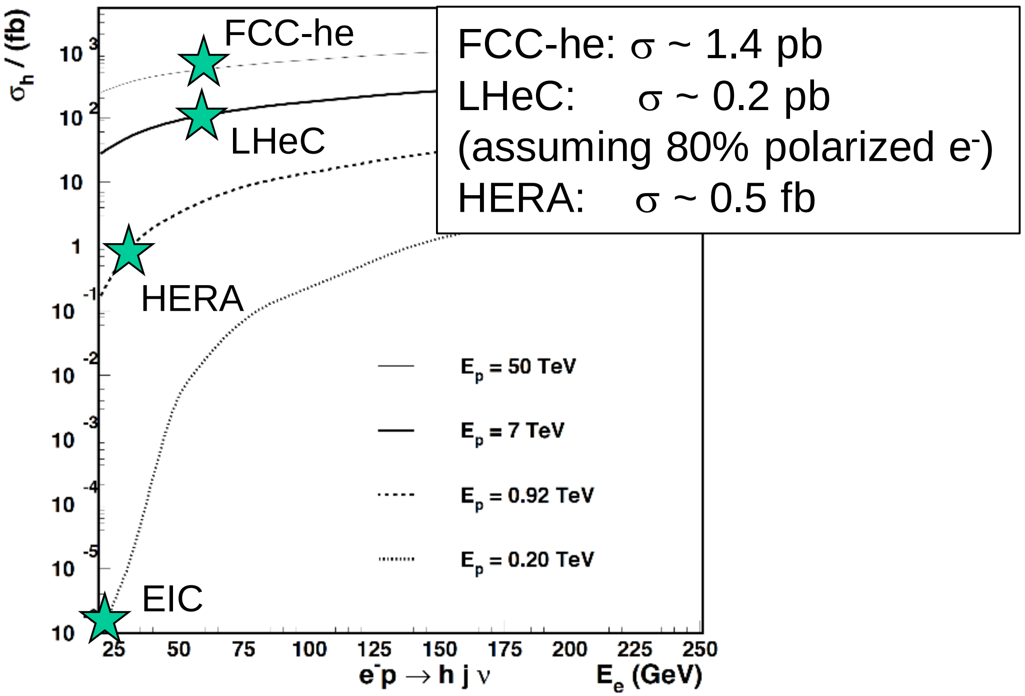


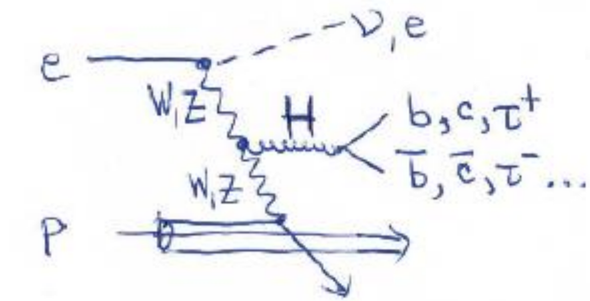
Also **eA → eX**

Gluons in nuclei, into anticipated saturation region

Precision for Higgs at the LHeC

After the Higgs (arXiv:1211.5102):
Sets scale → LHeC luminosity goal = 10^{34}
(2x electron current, 0.5x β^*)





LHeC Higgs		CC (e^-p)
Polarisation		-0.8
Luminosity [ab^{-1}]		1
Cross Section [fb]		196
Decay	BrFraction	N^H_{CC} e^-p
$H \to b\bar{b}$	0.577	113 100
$H \to c\bar{c}$	0.029	5 700
$H \to \tau^+\tau^-$	0.063	12 350
$H \to \mu\mu$	0.00022	50
$H \to 4l$	0.00013	30
$H \to 2l2\nu$	0.0106	2 080
$H \to gg$	0.086	16 850
$H \to WW$	0.215	42 100
$H \to ZZ$	0.0264	5 200
$H \to \gamma\gamma$	0.00228	450
$H \to Z\gamma$	0.00154	300

1 ab^{-1} in 10 years
Hbb coupling (S/N = 1) down to 1%

With its unique Higgs measurements and precision N^{3}LO PDFs and $\delta\alpha_s$ measurements, **an ep upgrade can transform the LHC facility into a precision Higgs factory.**

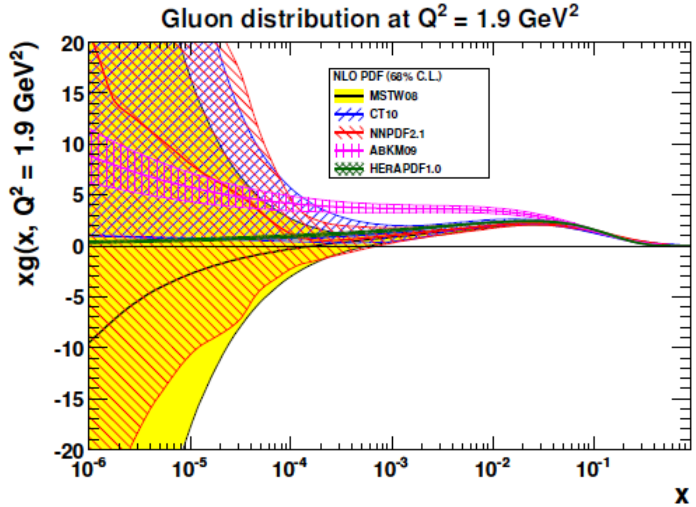
Gluon PDF – much less known than we wish

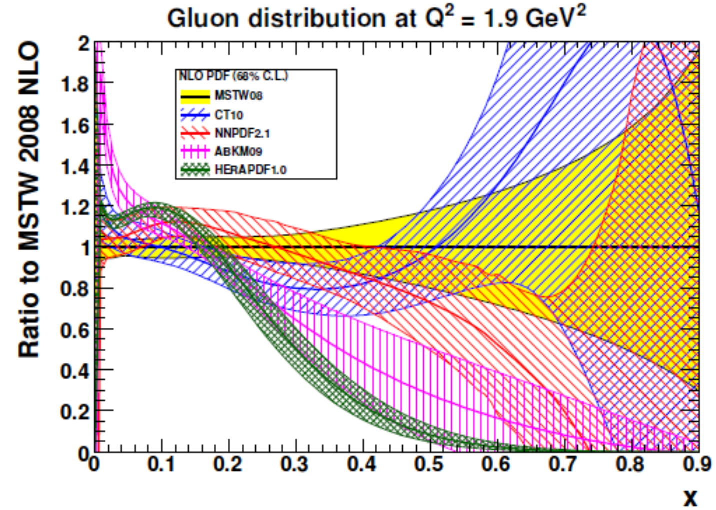
You may not realize that you will need it…

LOGARITHMIC Bjorken x SCALE

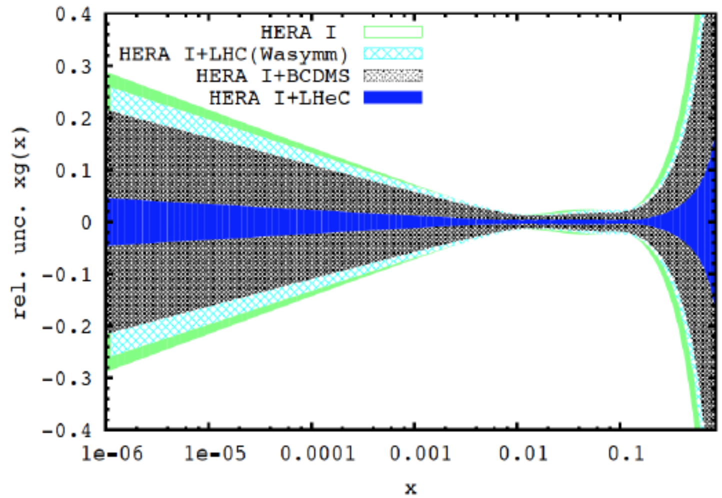
LINEAR Bjorken x SCALE

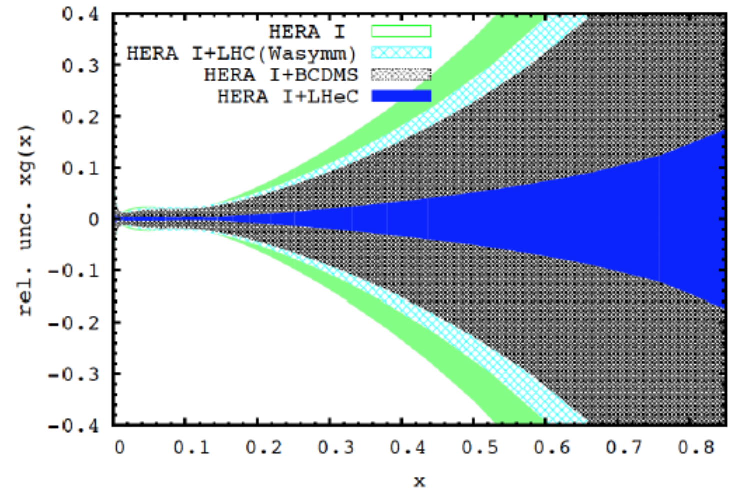
CURRENT





FUTURE



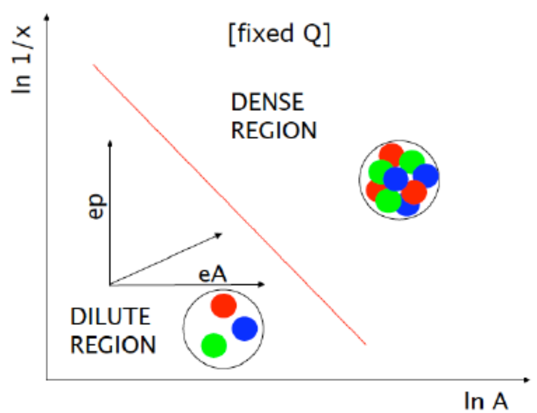


LHeC Study Group

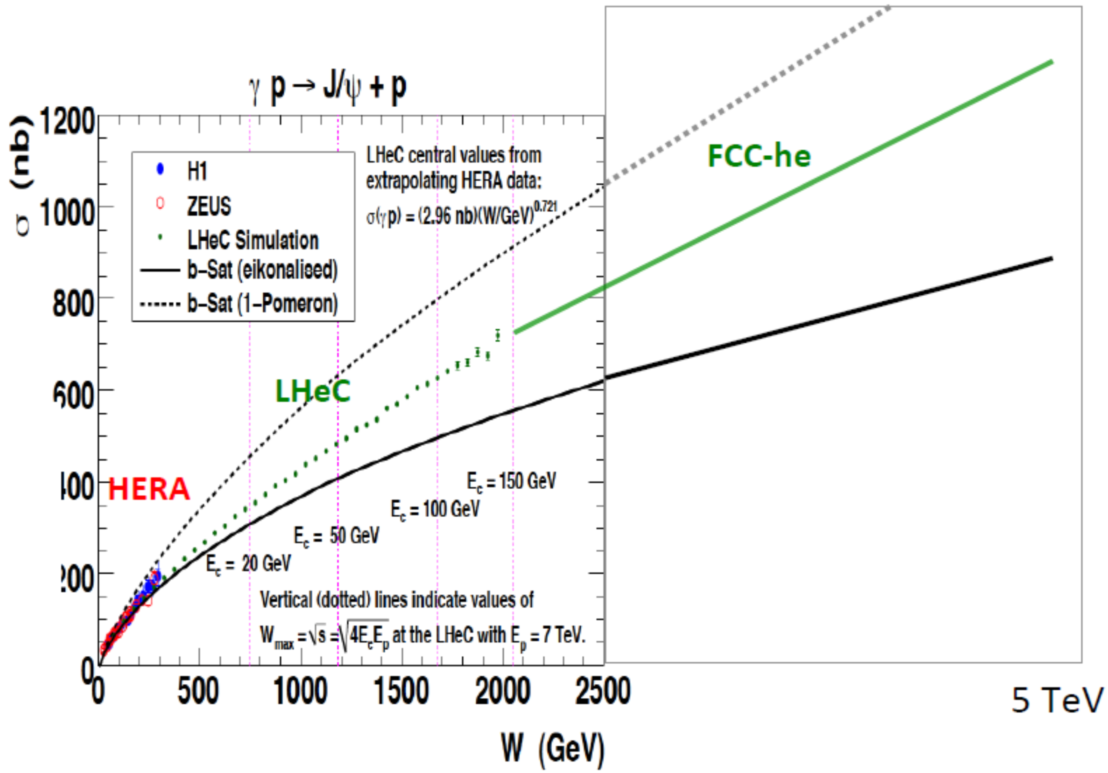
Vector Mesons at the LHeC and the FCC-he

Precision Measurements of Vector Mesons and Diffraction to very high W ~ xg^2

(sensitive to gluon distribution squared!)



Higher energy (1/x), higher A

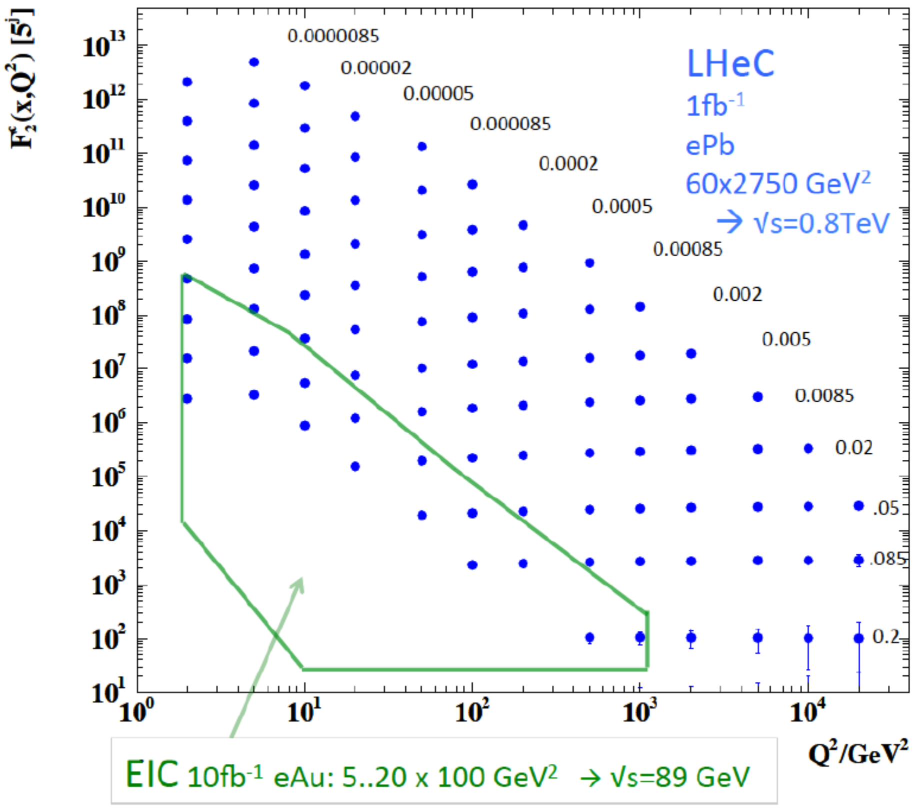


W= √(ys) extends to ~2 TeV at LHeC

W = √(ys) extends to ~5 TeV at FCC-he

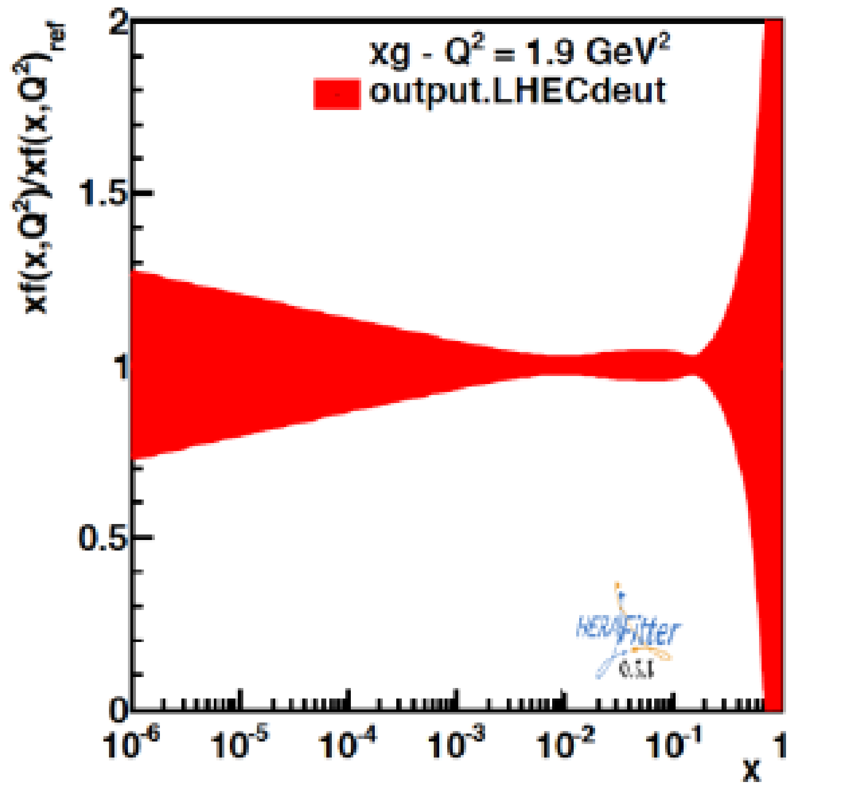
Charm Structure Function in Nuclei

Charm density in nuclei



Impact parameter measurement in eA

Gluon density uncertainty in LHeC/e-A



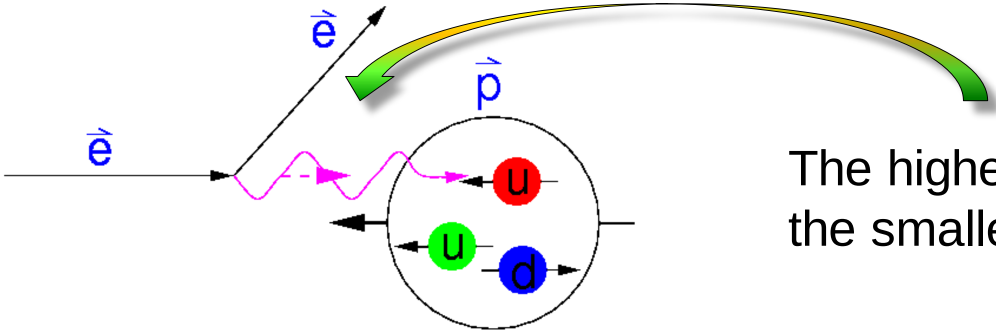
$1fb^{-1}$ of sole eA isoscalar data fitted

Recent and Upcoming LHeC Events

- LHeC CDR: arXiv:1206.2913
- Webpage: lhec.web.cern.ch

- Recent LHeC Workshop at CERN, September 2017. indico 639067
- Next workshop of the PERLE testfacility collaboration: 15/16.1.2017 Daresbury
- Next large LHeC Workshop 2018: 27-29. June 2018 in Paris (Orsay)

Summary

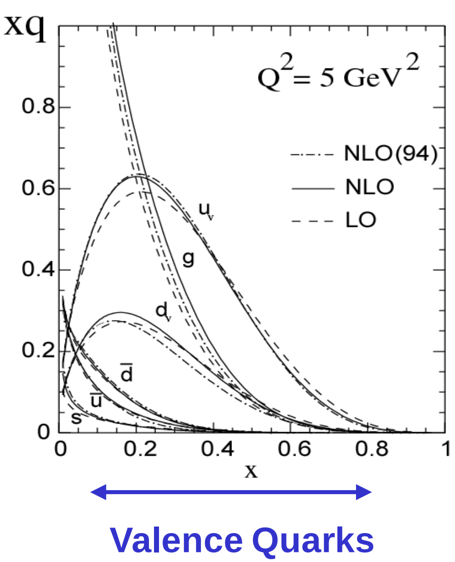


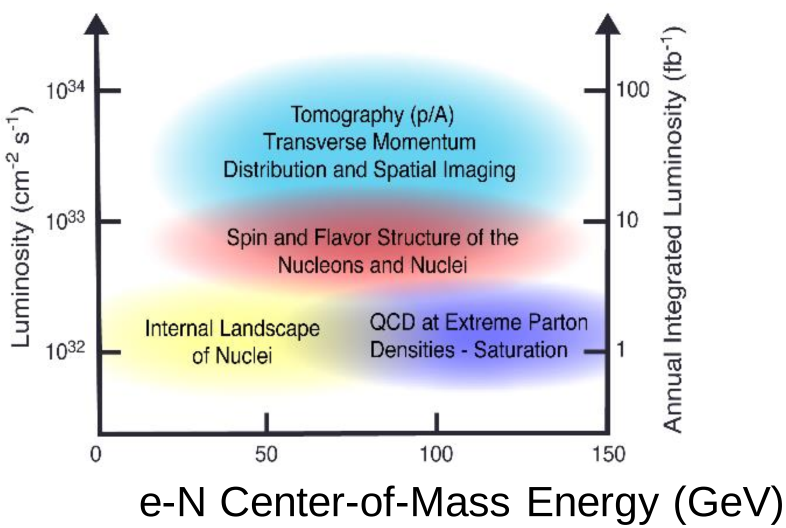
The higher the collision energy, the smaller the probe.

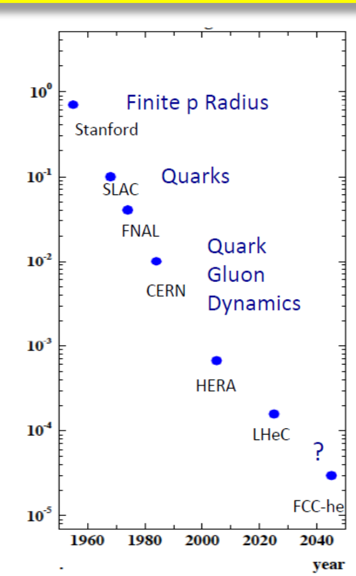
CEBAF 12 GeV
Probe about 40th of the proton diameter

Electron-Ion Collider:
Probe about 500th of the proton diameter

LHeC/FCC-he:
Resolving proton/quark substructure?



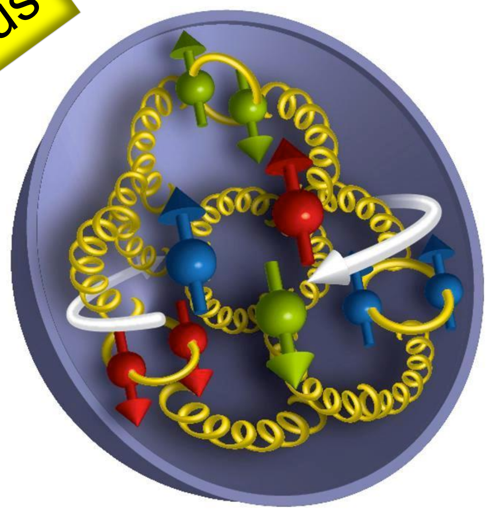


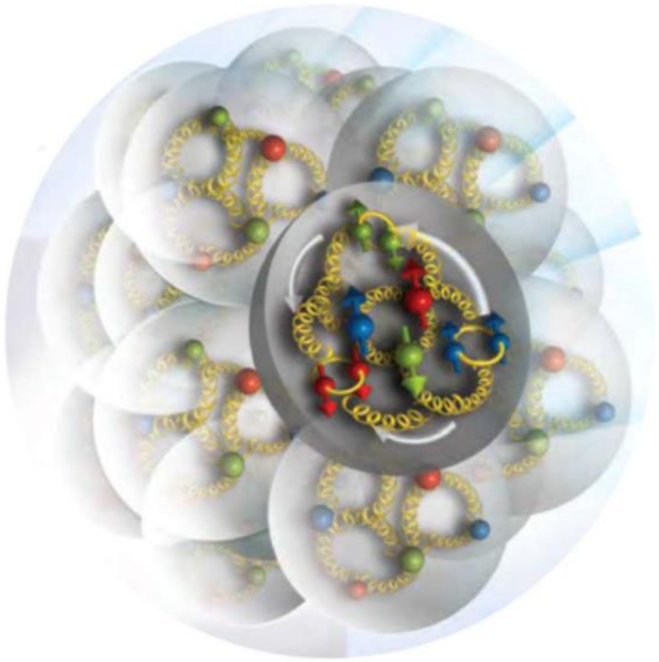


Nuclear Femtography

Science of mapping the position and motion of quarks and gluons in the nucleus.

Artist's Conception of Quark and Gluons in a proton and nucleus

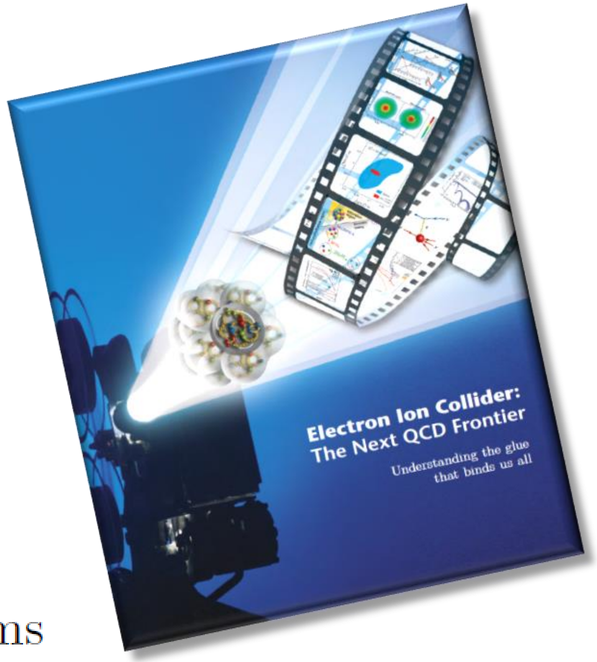




... is just beginning

EIC Requirements

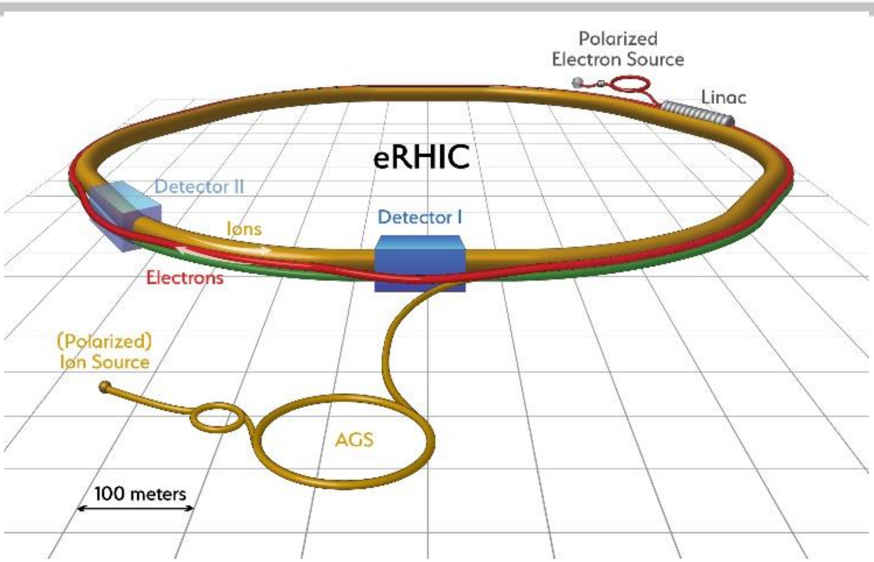
From the 2013 EIC White Paper:

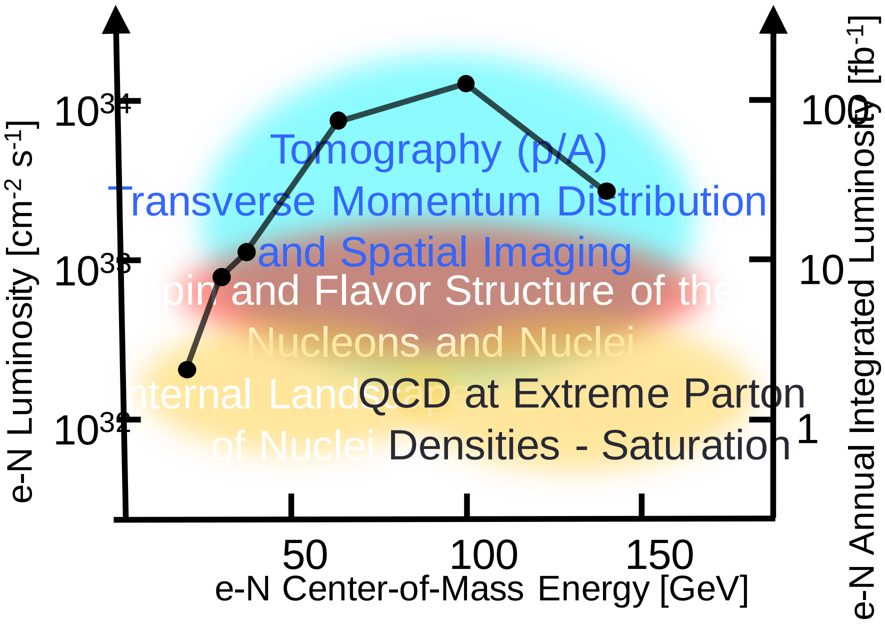


- Highly polarized ($\sim$ 70%) electron and nucleon beams
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from $\sim$ 20 – $\sim$100 GeV, upgradable to $\sim$150 GeV
- High collision luminosity $\sim 10^{33-34}$ cm^{-2}s^{-1}
- Possibilities of having more than one interaction region

eRHIC Realization

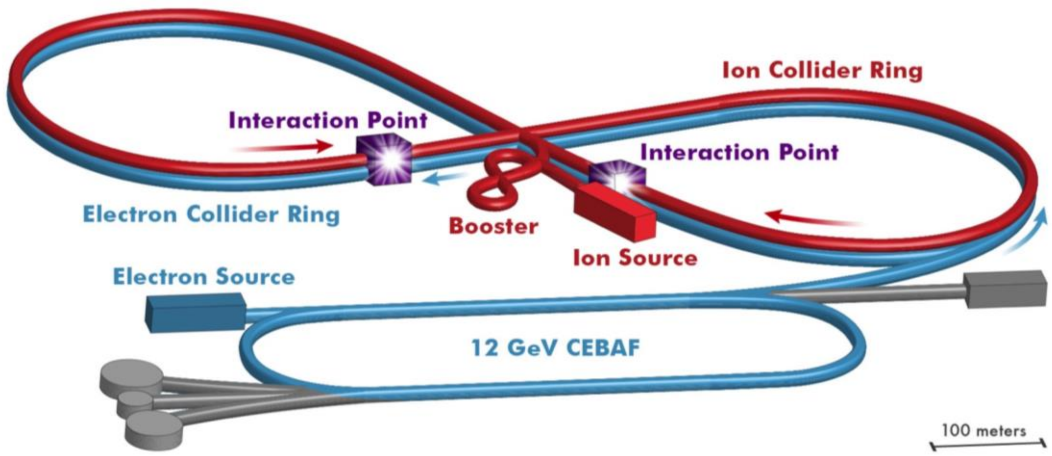
- Use existing RHIC
  - Up to 275 GeV protons
  - Existing: tunnel, detector halls & hadron injector complex
- Add 18 GeV e-accelerator in the same tunnel
  - Use either high intensity Electron Storage Ring or Energy Recovery Linac
- Achieve high luminosity, high energy e-p/A collisions with full acceptance detectors and strong hadron cooling
- Luminosity and/or energy staging are possible



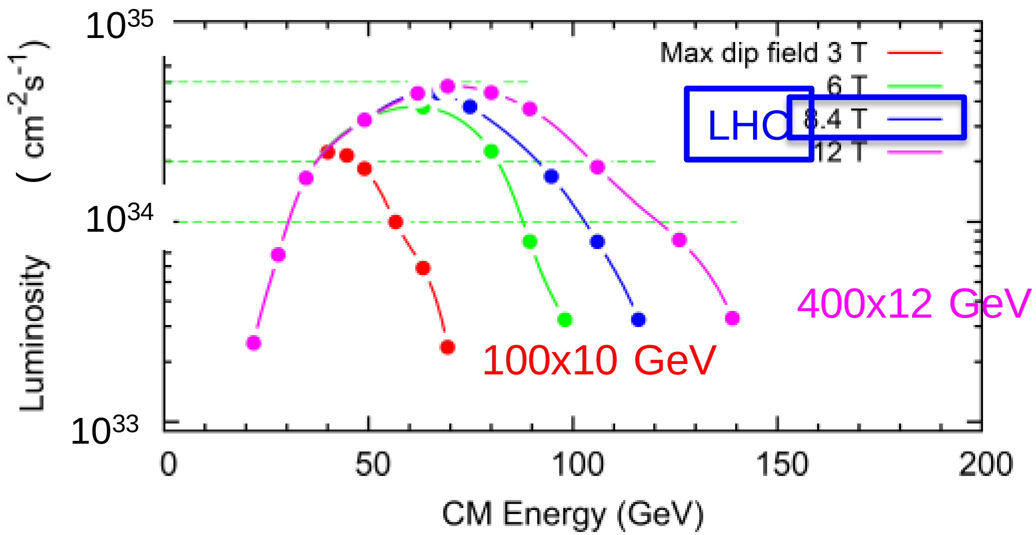


JLEIC Realization

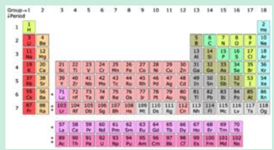
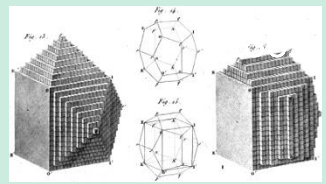
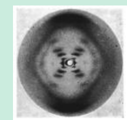
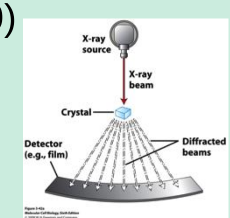
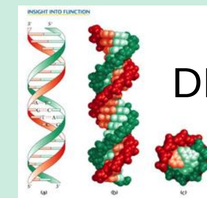
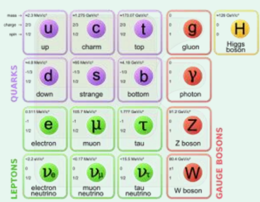
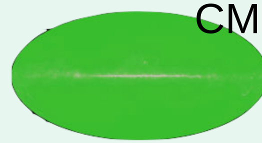
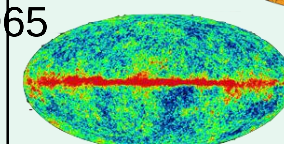
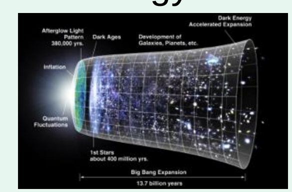
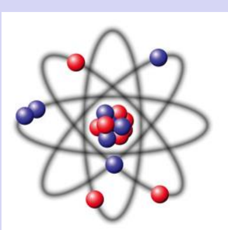
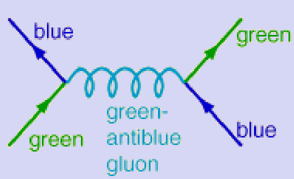
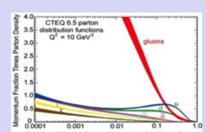
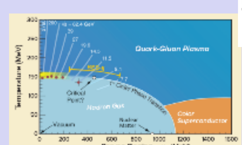
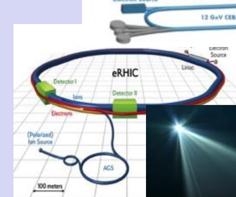
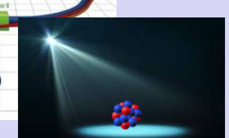
- ❑ Use existing CEBAF for polarized electron injector
- ❑ Figure 8 Layout: Optimized for high ion beam polarization
  ➔ polarized deuterons



- ❑ Energy Range:
  √s : 20 to 65 - 140 GeV
  (magnet technology choice)
- ❑ Fully integrated detector/IR
- ❑ JLEIC achieves initial high luminosity, with technology choice determining initial and upgraded energy reach



EIC: A Portal to a New Frontier

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes (Date)	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure 	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   	Electron-Ion Collider (2025+)   	Structure & Dynamic in QCD 

EIC: a high luminosity machine

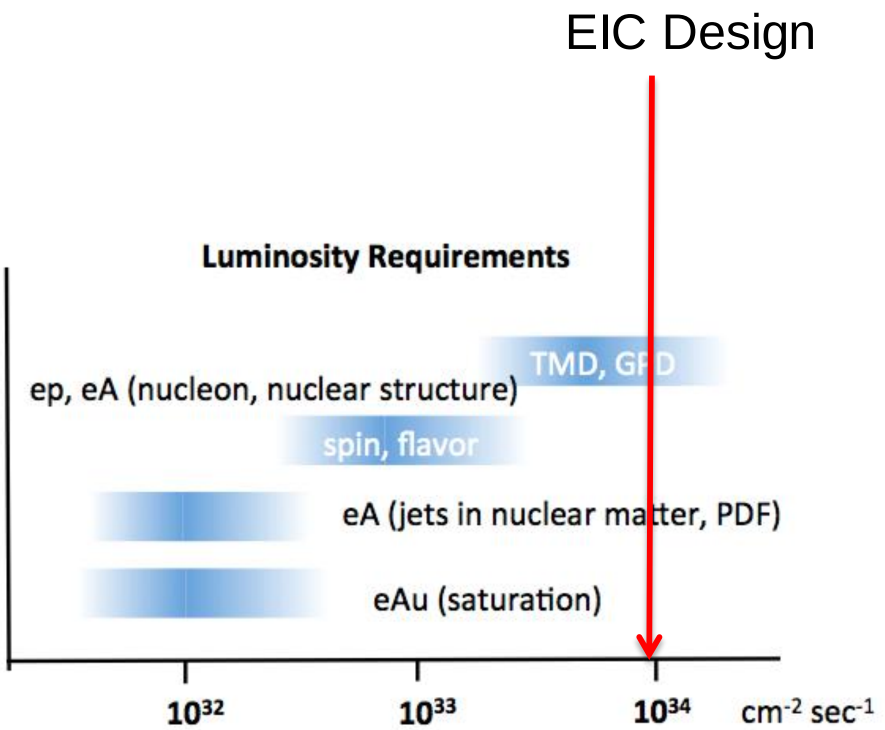
EIC has unprecedented flexibility

- Variable energies of both beams.
- L polarization of electron beams.
- L & T polarization of p/ion beams
- Many different ion species.

Many run configuration for any given topic.

Even a “low luminosity physics topic” will mean e.g. ep, ed, e^3He, e^4He, e^9Be, $e^{12}C$, $e^{40}Ca$, $e^{48}Ca$…etc. + polarization s
they are high luminosity in practice.

Need to have high luminosity (10^{34}) from Day 1. The project will not work if 80% of the physics objectives are unreachable until an upgrade much later



Need also good (100%) acceptance *<u>Polarized luminosity</u> and the capability to measure physics of interest is what counts*