

THE US-BASED ELECTRON- ION COLLIDER AND PROSPECTS FOR NUCLEON IMAGING STUDIES

Rolf Ent
Jefferson Lab

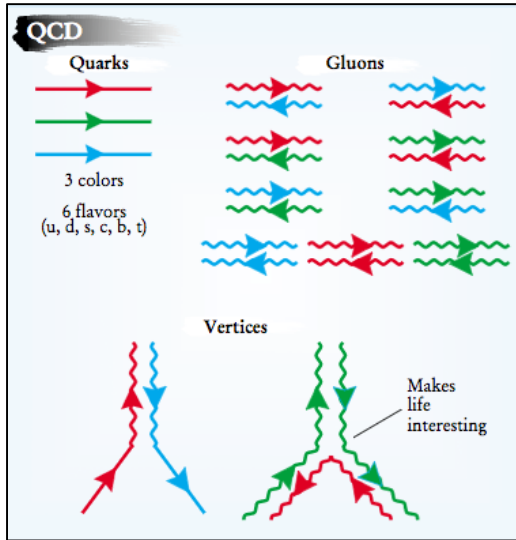
Outline

- Why an Electron-Ion Collider?
- Status of the US-Based Electron-Ion Collider
- Prospects of the EIC for 1D and 3D Imaging Science
- Polarized Deuteron and Polarized ^3He Beams
- EIC Science with Unpolarized & Polarized Deuteron Beams
- Summary & Possible EIC Realization

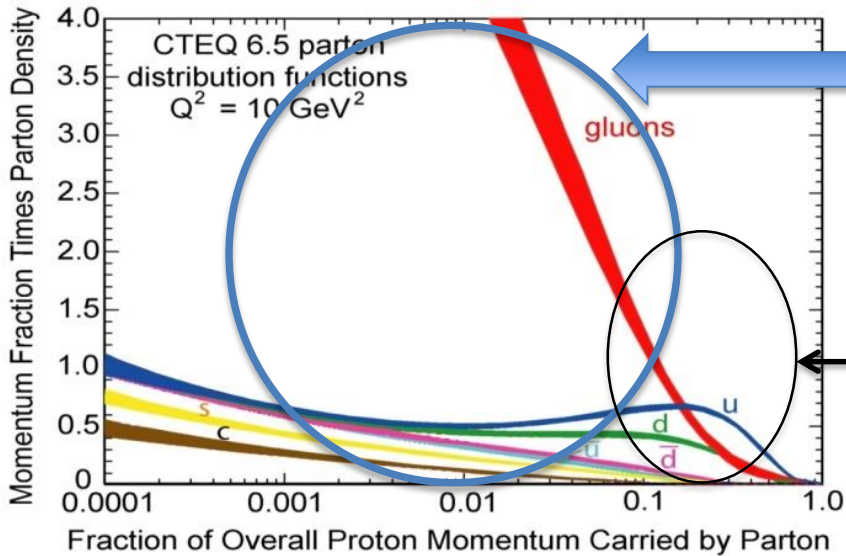
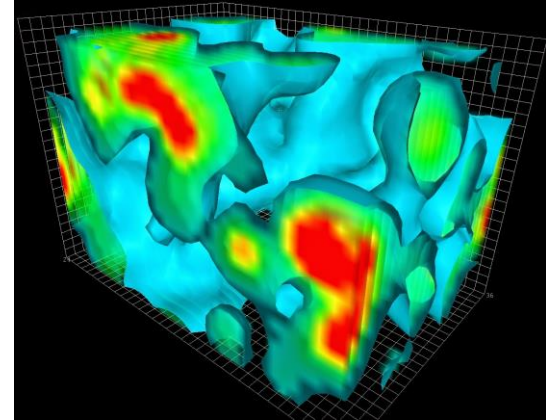
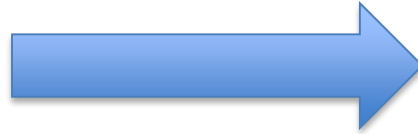
Why an Electron-Ion Collider

- **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.

Cold Matter is Unique



Structure and Interaction are entangled because of gluon self-interaction.



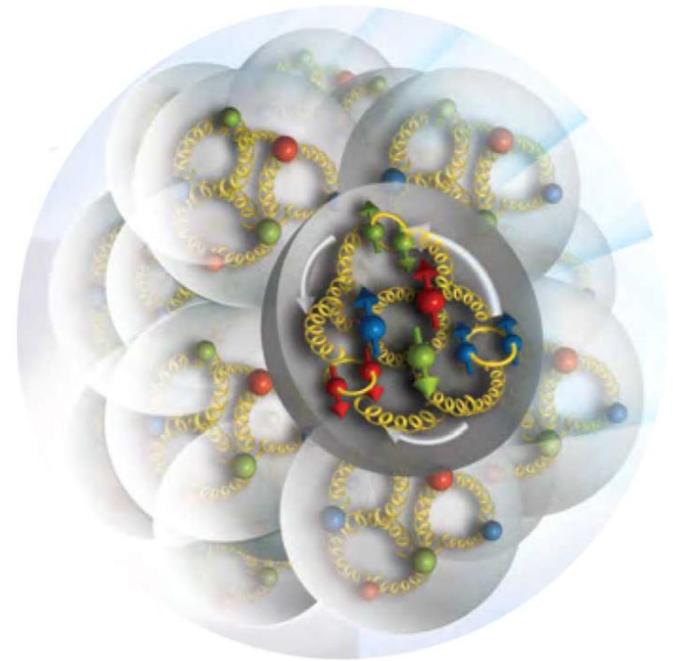
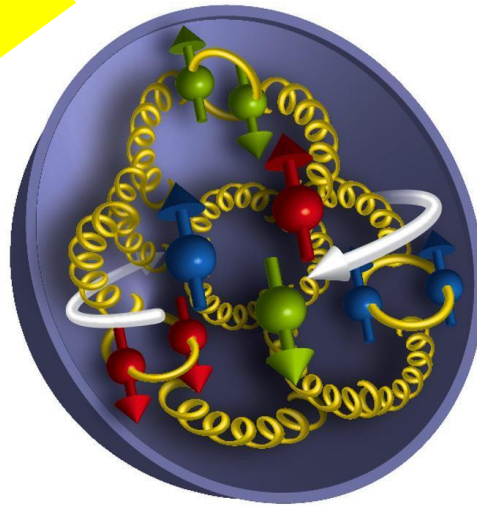
EIC needed to explore the gluon dominated region

JLAB 12 to explore the valence quark region

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



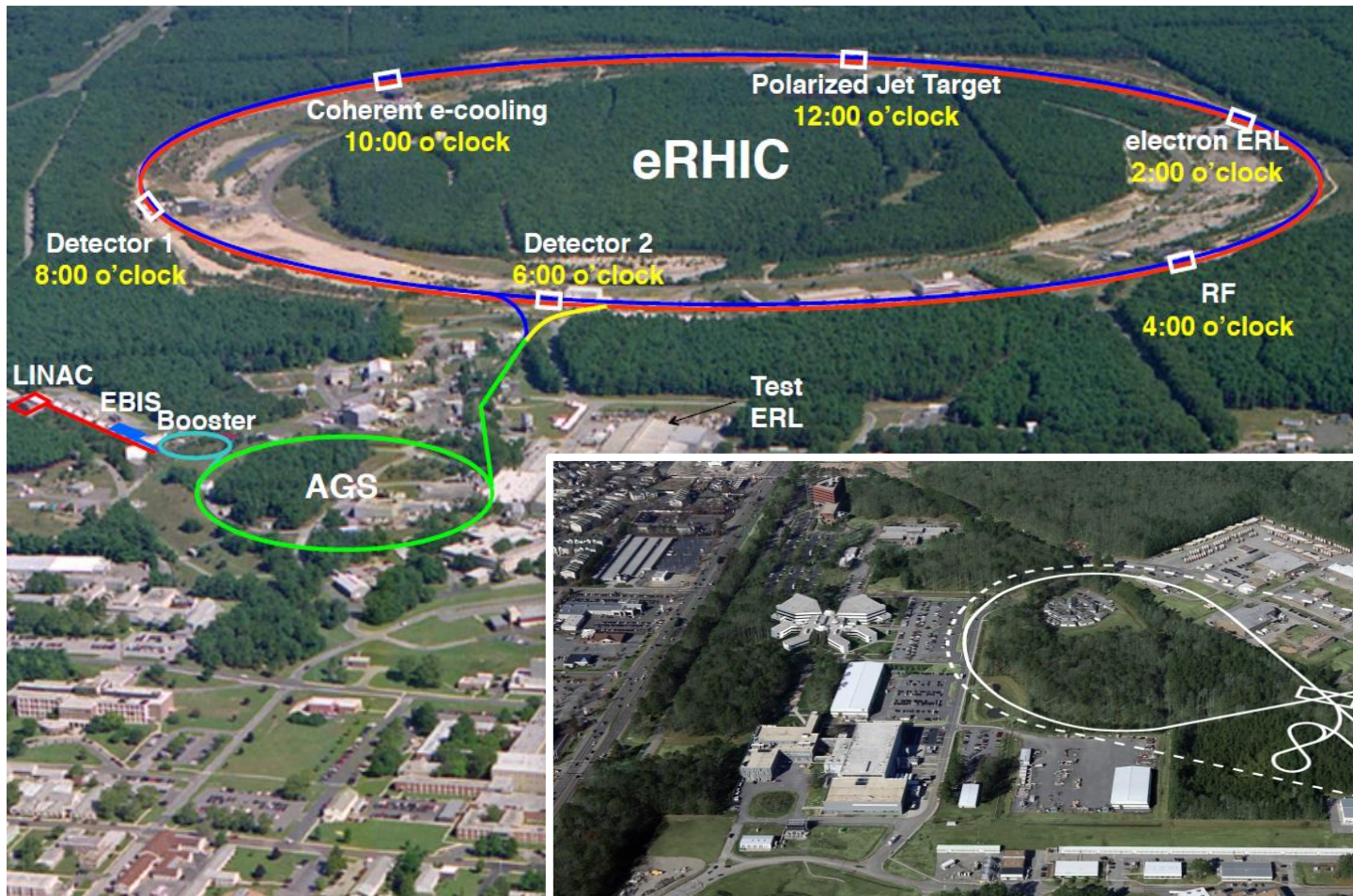
.. is just beginning

Outline

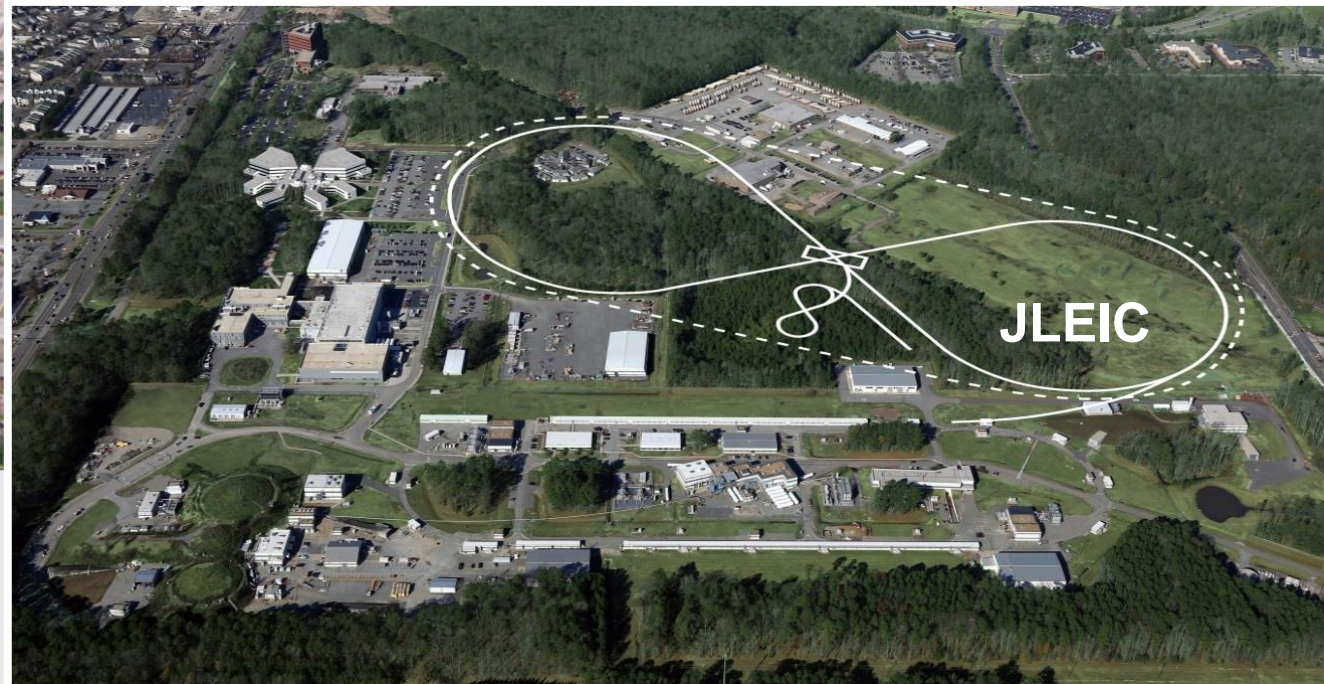
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US-Based EICs

Brookhaven Lab
Long Island, NY

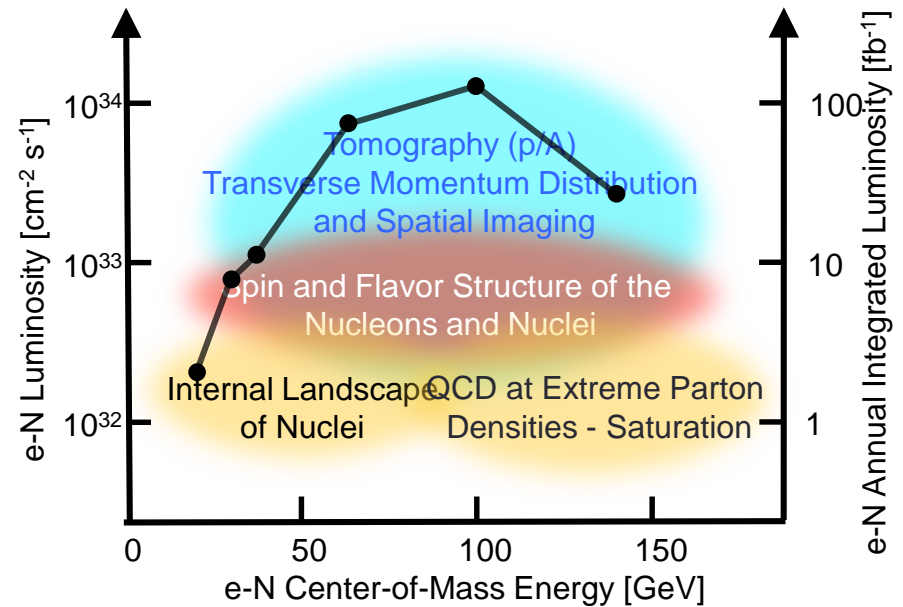
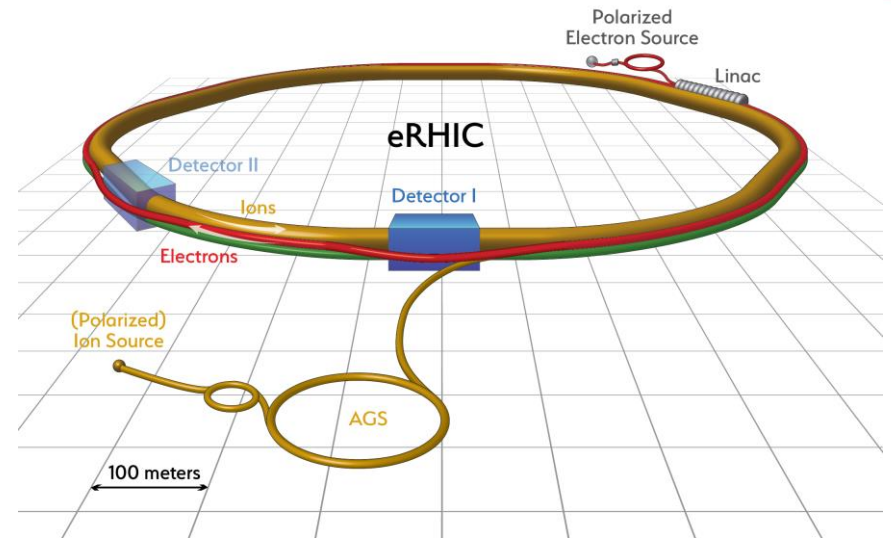


Jefferson Lab
Newport News, VA



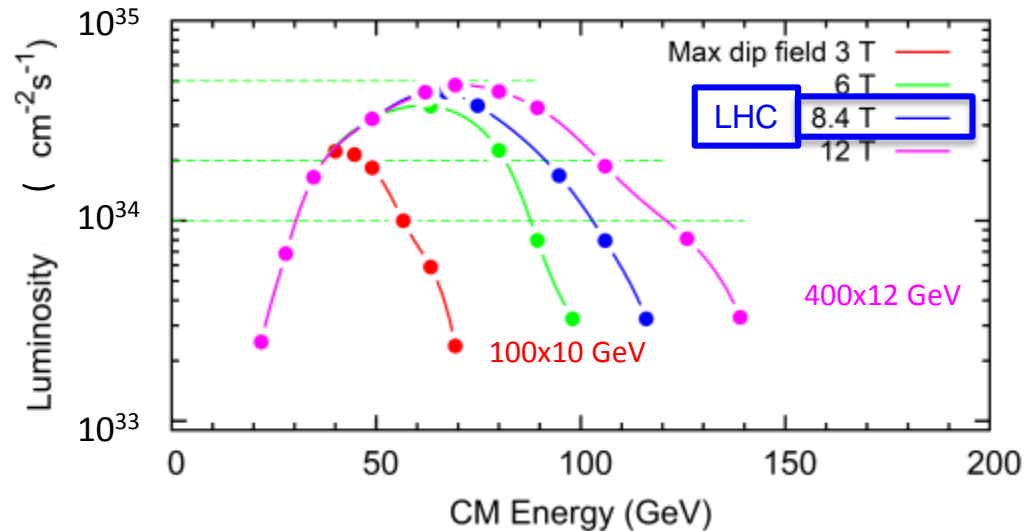
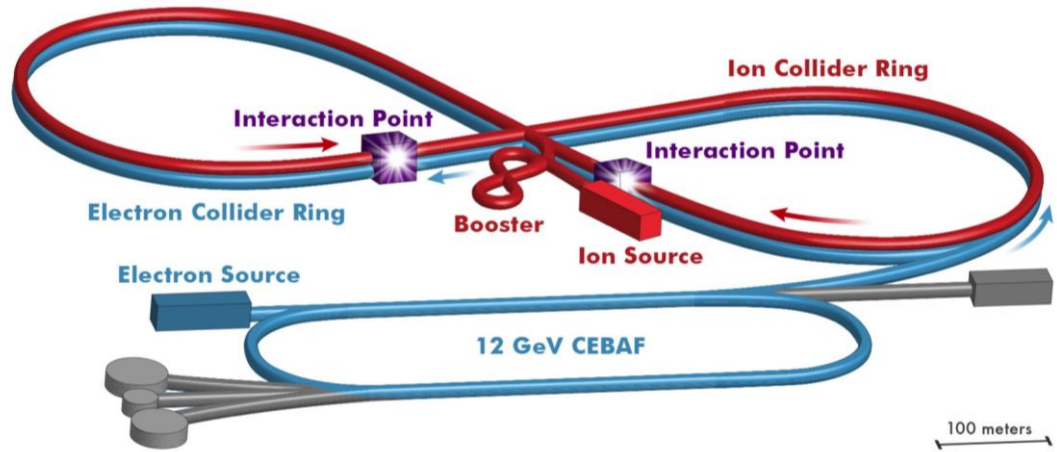
eRHIC Realization

- 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



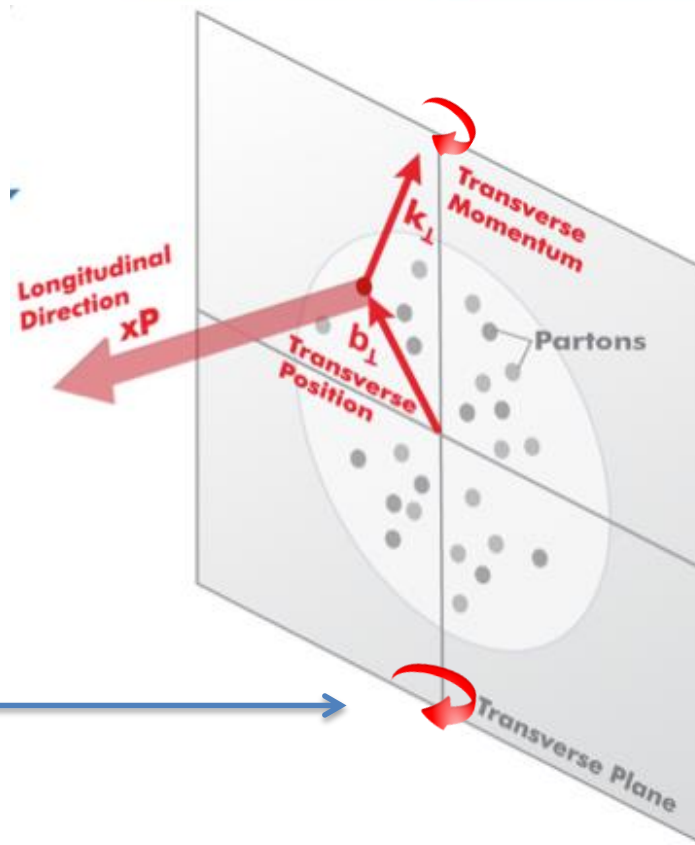
JLEIC Realization


- Use existing CEBAF for polarized electron injector
- **Figure 8** Layout: Optimized for high ion beam polarization
 ➔ polarized deuterons
- Energy Range:
 \sqrt{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

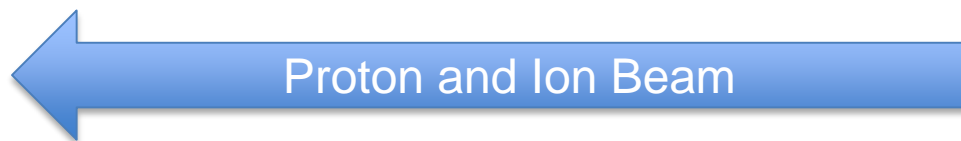


3D Structure of Nucleons and Nuclei

- 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) 

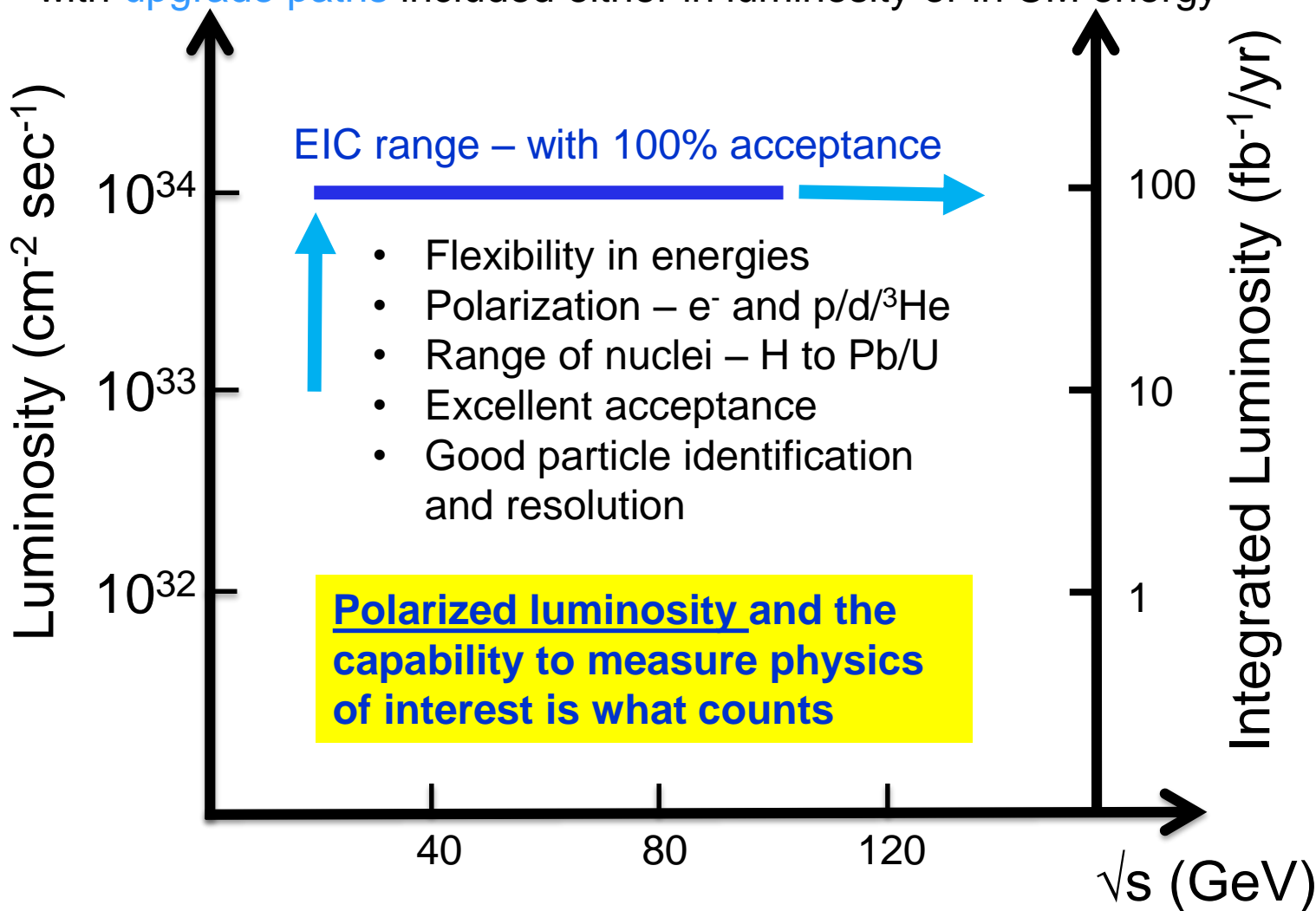


Need to keep $[100 \text{ MeV}]_T/E_{\text{proton, ion}}$ manageable ($\sim >10^{-3}$) $\rightarrow E_{\text{proton}} \sim < 100 \text{ GeV}$

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

Physics vs. EIC Design Requirements

What the nuclear physicists dream off and drives the EIC designs, with **upgrade paths** included either in luminosity or in CM energy

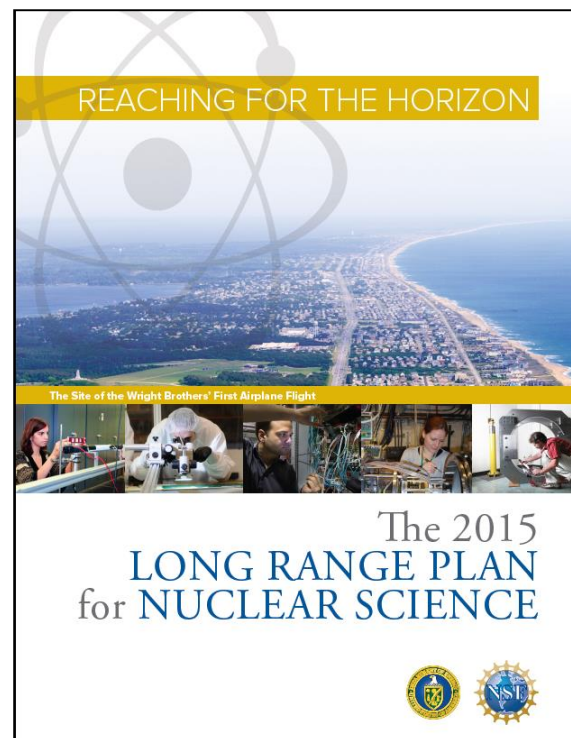


Nuclear Science Long-Range Planning



Every 5-7 years the US Nuclear Science community produces a Long-Range Planning (LRP) Document

2015



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

National Academy of Sciences

Project Information

| | |
|----------------------------|---|
| Project Title: | U.S.-Based Electron Ion Collider Science Assessment |
| PIN: | DEPS-BPA-15-01 |
| Major Unit: | Division on Engineering and Physical Sciences |
| Sub Unit: | Board on Physics & Astronomy DEPS |
| RSO: | Lancaster, James |
| Subject/Focus Area: | Math, Chemistry and Physics |

NAS is currently assessing

- Science case for EIC
- Benefit to US

Meetings in Feb., Apr., Sep.
Report expected early 2018

Project Scope

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

In particular, the committee will address the following questions:

- What is the merit and significance of the science that could be addressed by an electron ion collider facility and what is its importance in the overall context of research in nuclear physics and the physical sciences in general?
- What are the capabilities of other facilities, existing and planned, domestic and abroad, to address the science opportunities afforded by an electron-ion collider? What unique scientific role could be played by a domestic electron ion collider facility that is complementary to existing and planned facilities at home and elsewhere?
- What are the benefits to U.S. leadership in nuclear physics if a domestic electron ion collider were constructed?
- What are the benefits to other fields of science and to society of establishing such a facility in the United States?

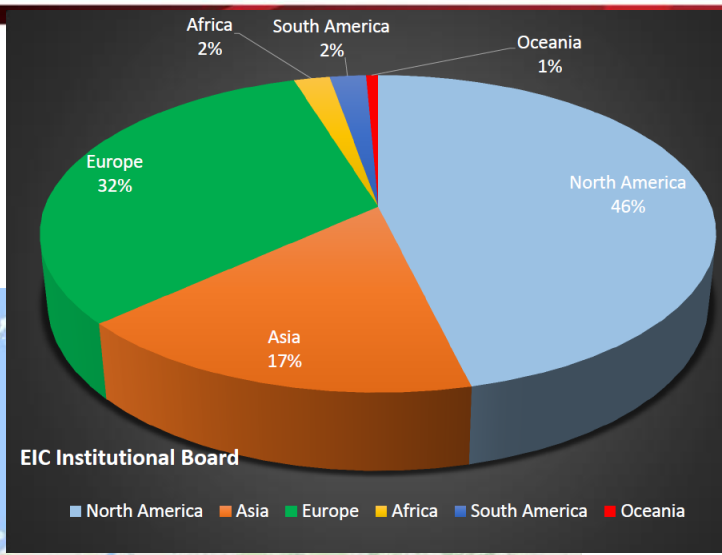
Project Duration: 18 months

Worldwide Interest in EIC Physics

The EIC Users Group: EICUG.ORG

(no students included as of yet)

708 collaborators, 29 countries, 162 institutions... (September, 2017)



Outline

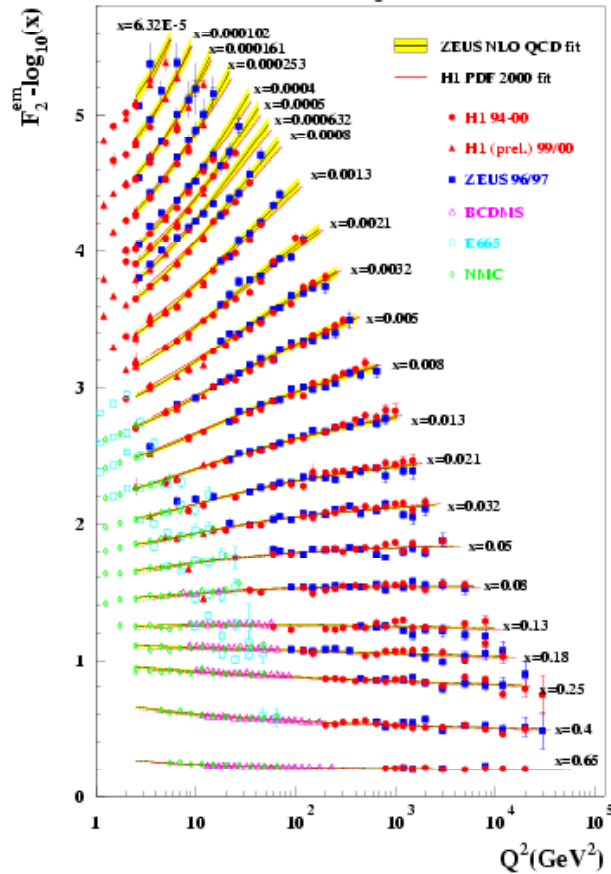
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World Data on F_2^p

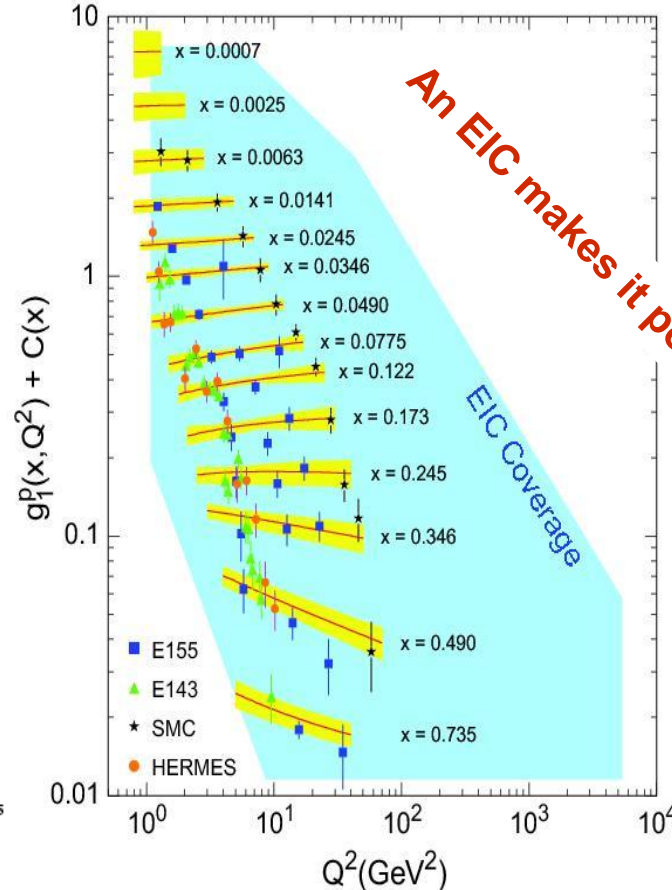
World Data on g_1^p

World Data on h_1^p

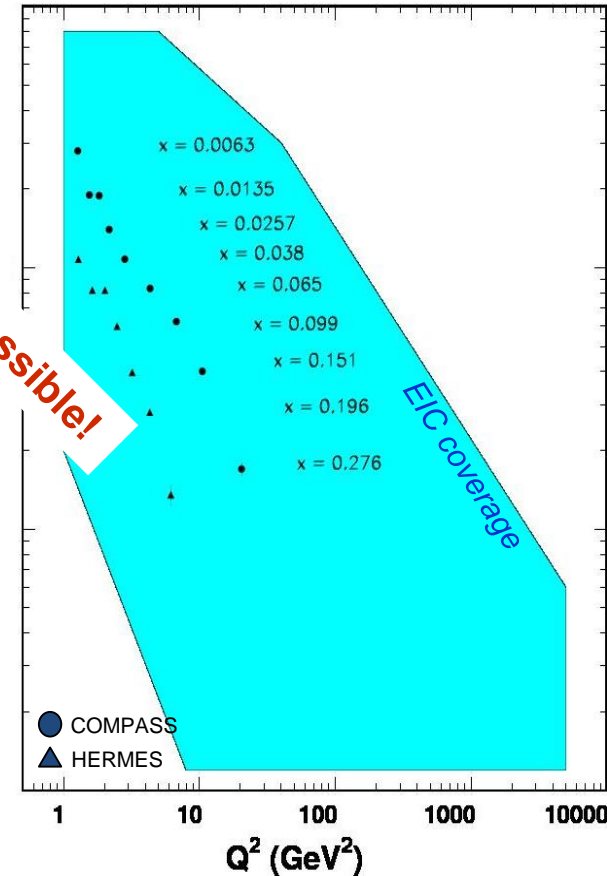
$$F_{UT}^{\sin(\phi_h+\phi_s)}(x, Q^2) + C(x) \propto h_1$$



momentum



spin



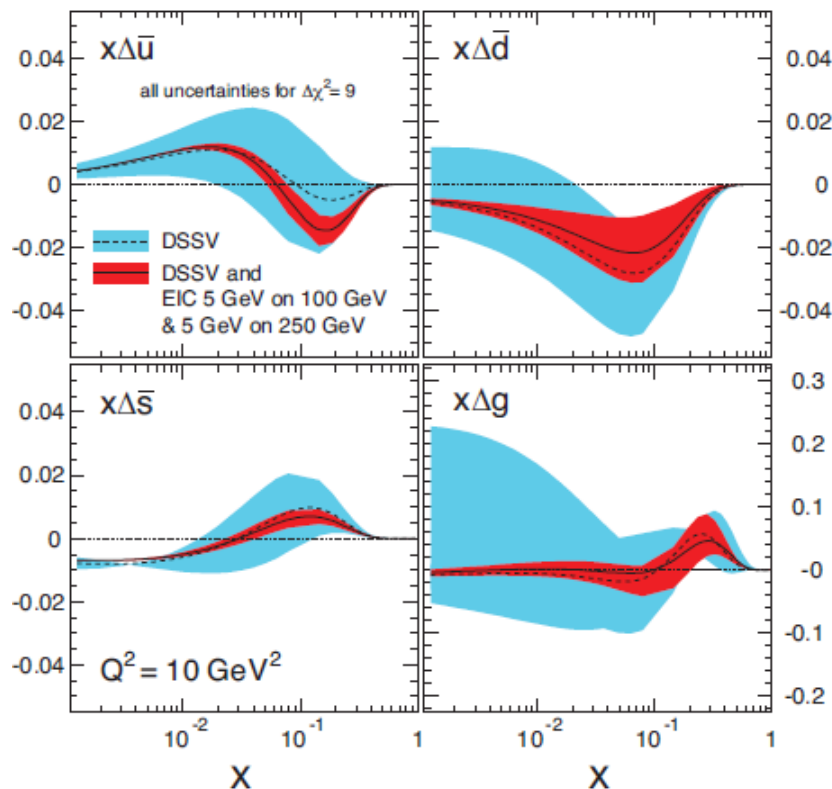
transverse spin ~
angular momentum

Helicity PDFs at an EIC

A Polarized EIC:

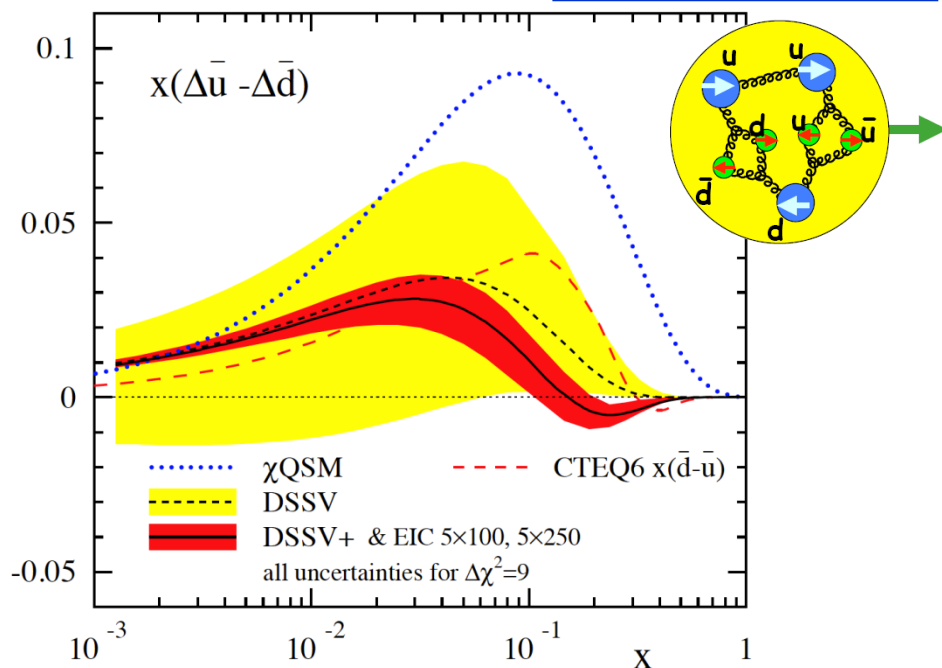
- Tremendous improvement on $x\Delta g(x)$
- Good improvement in $\Delta\Sigma$
- Spin Flavor decomposition of the Light Quark Sea

Needs range of \sqrt{s} , here from ~ 45 to ~ 70



Needs range of $\sqrt{s} \sim 30-70$
(and good luminosity)

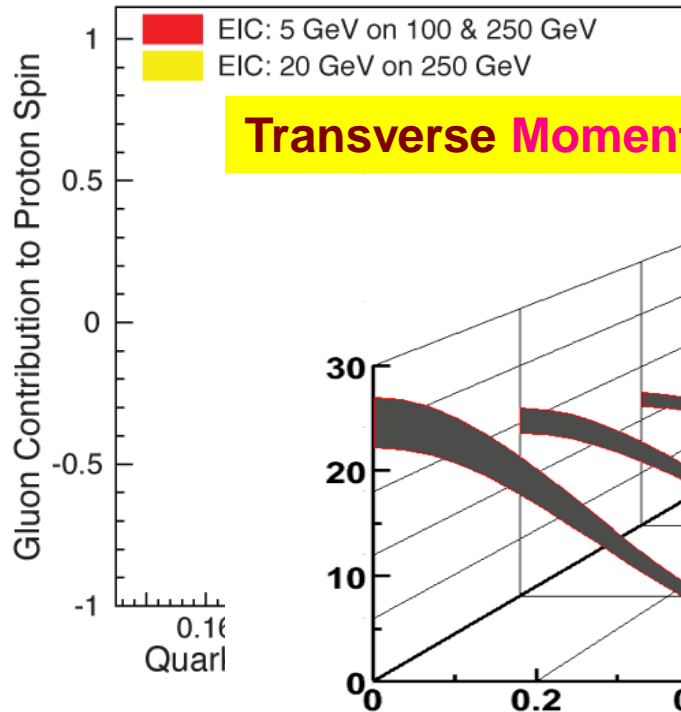
Many models predict
 $\Delta\bar{u} > 0, \Delta\bar{d} < 0$



2+1 D partonic image of the proton

Spatial distance from origin \times Transverse Momentum
 \rightarrow Orbital Angular Momentum

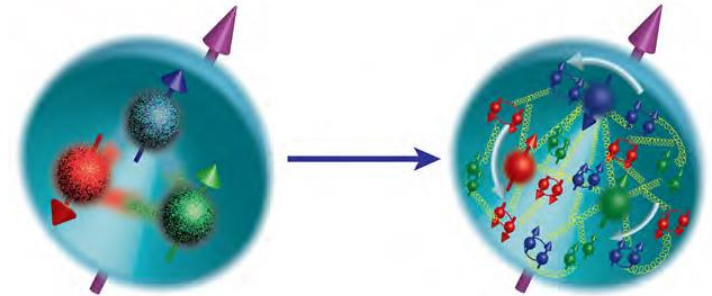
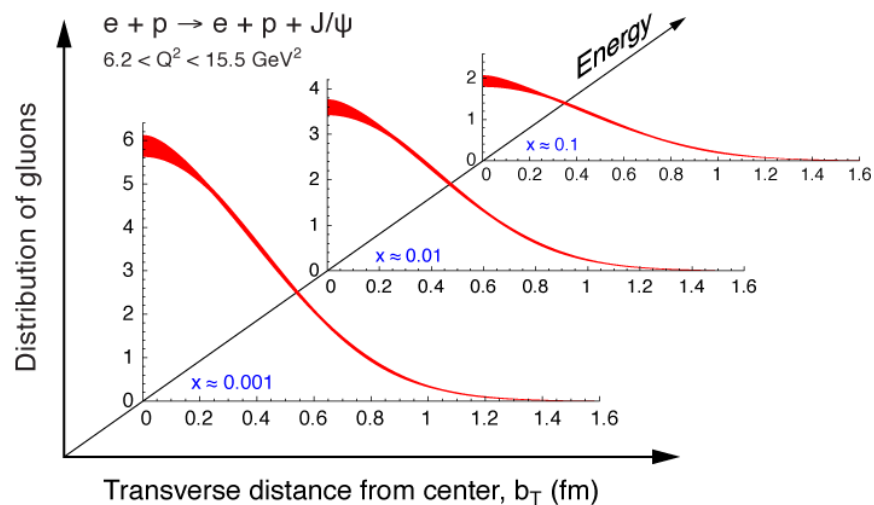
Helicity Distributions: ΔG and $\Delta \Sigma$



Transverse Momentum Distributions

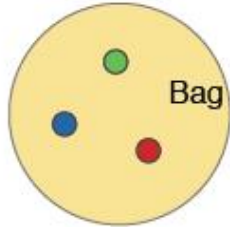
$$Q^2 = 2.4 \text{ GeV}^2$$

Transverse Position Distributions

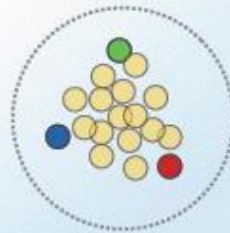
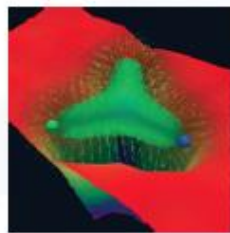
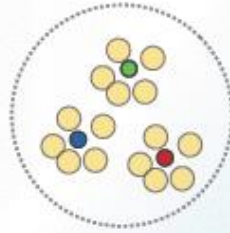
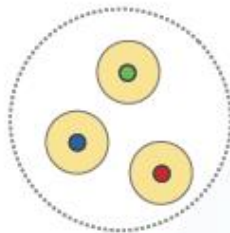


What does a proton or (nucleus) look like?

Static



Boosted



Bag Model: Gluon field distribution is wider than the fast moving quarks.

Gluon radius > Charge Radius

Constituent Quark Model: Gluons and sea quarks hide inside massive quarks.

Gluon radius ~ Charge Radius

Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks:

Gluon radius < Charge Radius

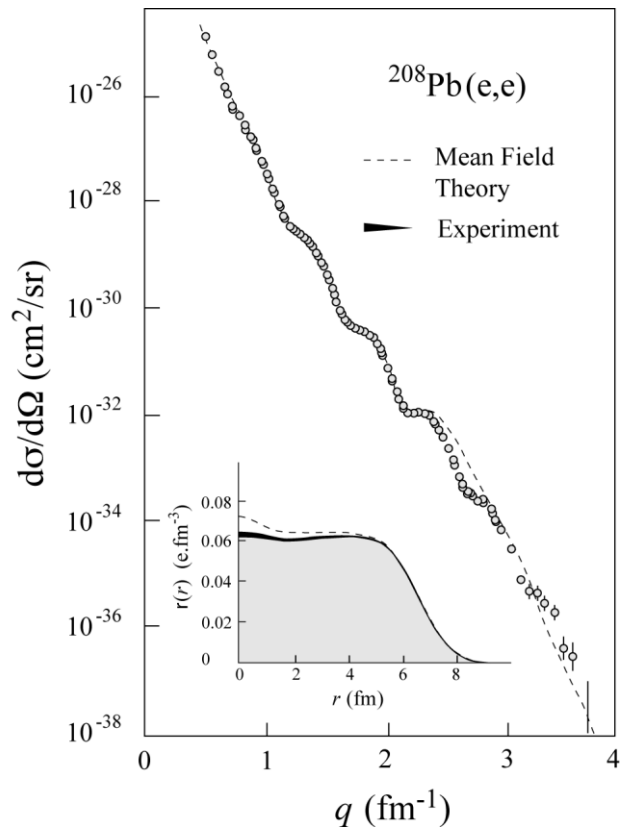
**Need transverse images of the quarks
and gluons in protons and nuclei**

Exposing different layers of the nuclear landscape with electron scattering

History:

Electromagnetic

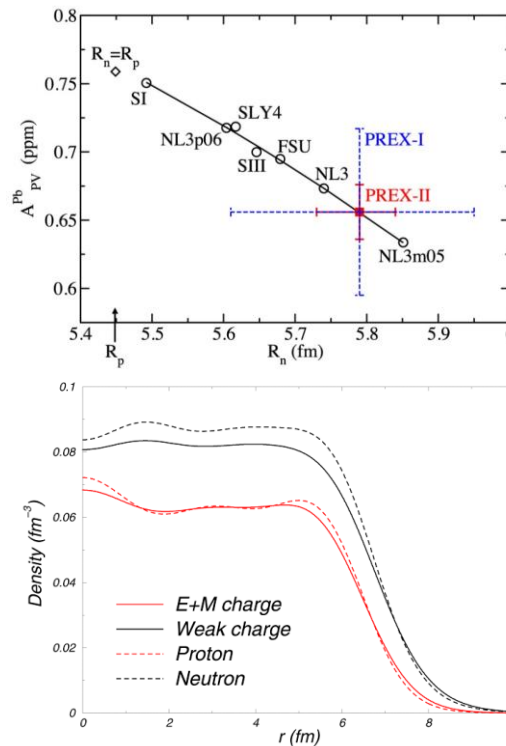
Elastic electron-nucleus scattering \rightarrow charge distribution of nuclei



Present/Near-future:

Electroweak

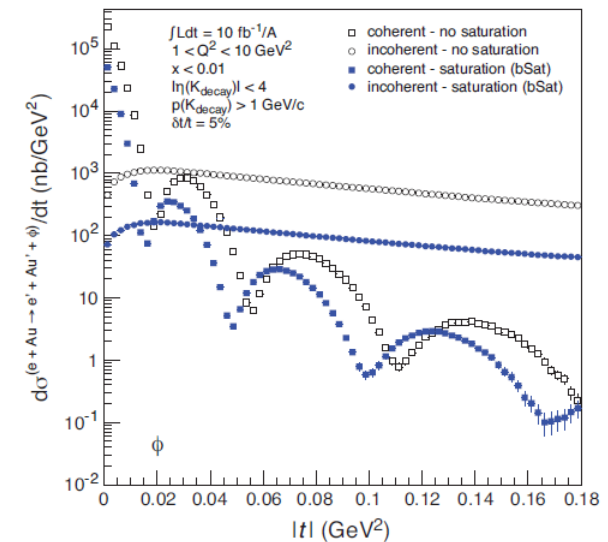
Parity-violating elastic electron-nucleus scattering (or hadronic reactions e.g. at FRIB) \rightarrow neutron skin



Future:

Color dipole

ϕ Production in coherent electron-nucleus scattering \rightarrow gluon spatial distribution of nuclei



Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

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Polarized ^3He Beams

Polarized ^3He beams have been done before...

... even with high polarization (up to 95% with Stern-Gerlach!)

But, beam currents were limited.

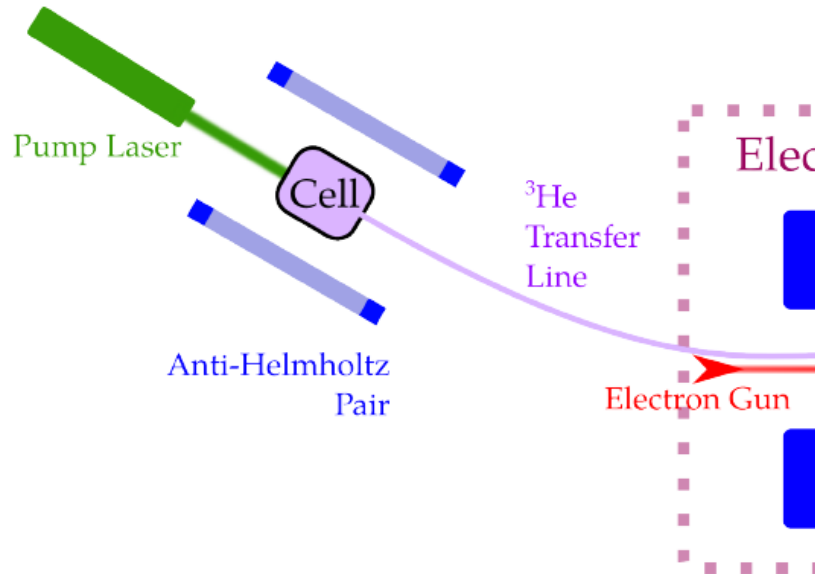
What seems the obvious solution: use EBIS

(Electron Beam Ion Source injector)

Polarized ^3He Beams

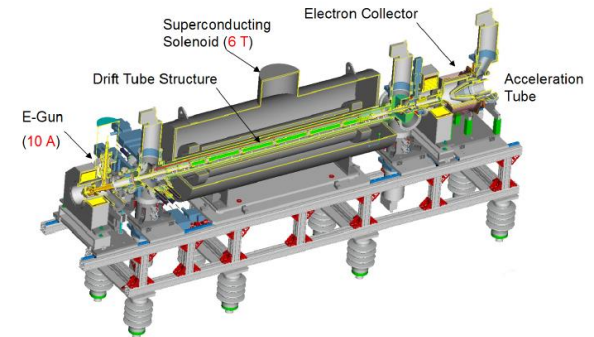
Source Design Goals

- Polarize to $\sim 70\%$ at 1 torr with 10 W laser
- Transfer $\sim 10^{14}$ $^3\text{He}/\text{s}$ to EBIS at 5 T & 10^{-7} torr
- Deliver 1.5×10^{11} $^3\text{He}^{++}$ ions per 20 μsec pulse



RHIC's Electron Beam Ion Source

- 5 T Solenoid B Field; 1.5 m Ion Trap
- 20 keV electrons up to 10 A, 575 A/cm² Current Density
- **Any** species, switch between species in 1 sec



Polarized 2H Beams

Polarized 2H beams have been done before at IUCF and COSY*...

... even with high polarization and with good (RF) spin-flip efficiency (~98%)

But, one needs to overcome depolarizing spin resonances above ~10 GeV beam energies, as the deuteron is so sensitive to them due to its small (g-2) value. It is the higher-order resonances that ruin polarization and polarization lifetime in a racetrack.

What seems the obvious solution: use a figure-8 ring

* SPIN@COSY: Spin-manipulating polarized deuterons and protons

M.A. Leonova, A.W. Chao, A.D. Krisch, V.S. Morozov, R.S. Raymond, D.W. Sivers, V.K. Wong (Michigan U.) , A. Garishvili, R. Gebel, A. Lehrach (Julich, Forschungszentrum) et al.

AIP Conf.Proc. 1149 (2009) 168-173

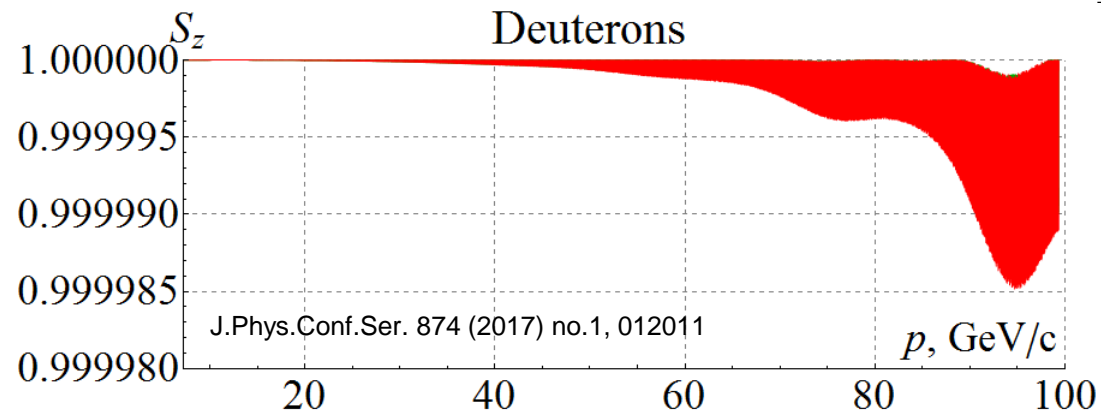
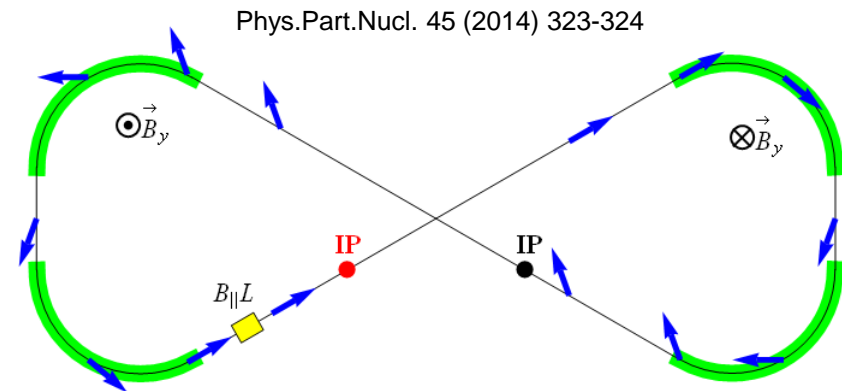
* Spin-Manipulating Polarized Deuterons

E.J. Stephenson (Indiana U., IUCF) , A. Chao (SLAC & Michigan U.) , A.M. Kondratenko (Novosibirsk, GOO Zaryad) , V.S. Morozov (Jefferson Lab) , F. Hinterberger (Bonn U., HISKP) , A.D. Krisch, M.A. Leonova, R.S. Raymond, D.W. Sivers, V.K. Wong (Michigan U.)

Conf.Proc. C110328 (2011) 747-751

Polarized 2H Beams

- Properties of a figure-8 structure
 - Spin precessions in the two arcs are exactly cancelled
 - In an ideal structure (without perturbations) all solutions are periodic
 - The spin tune is zero independent of energy
- A figure-8 ring provides unique capabilities for polarization control
 - Local spin rotator determines spin tune and local spin direction
 - $B_{\parallel}L$ of only 3 Tm provides deuteron polarization stability up to 100 GeV
 - A conventional ring at 100 GeV would require $B_{\parallel}L$ of 1200 Tm or $B_{\perp}L$ of 400 Tm
- Recent progress:
 - Start-to-end deuteron acceleration (folding in analytic-calculated spin tune requirement and orbit excursion due to magnet misalignments)
 - Deuteron spin is highly stable in figure-8 rings



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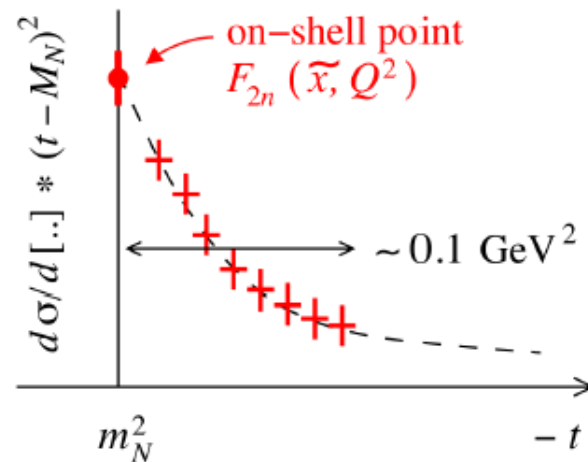
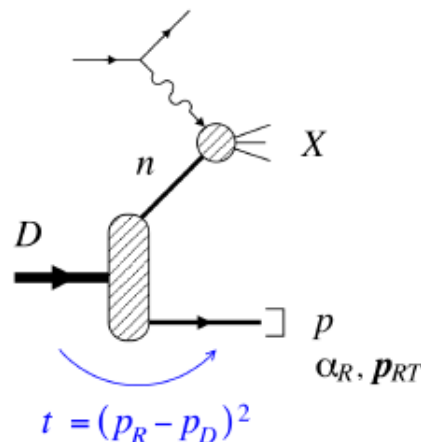
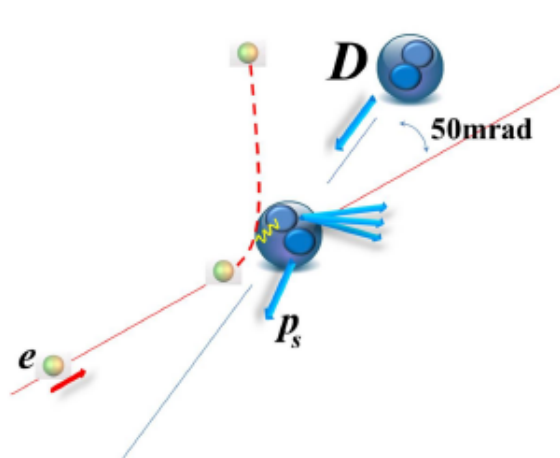
EIC Science with Unpolarized & Polarized Deuteron Beams

Need to obtain a consistent high-precision data set, allowing for multi-dimensional mapping, of BOTH proton and neutron.

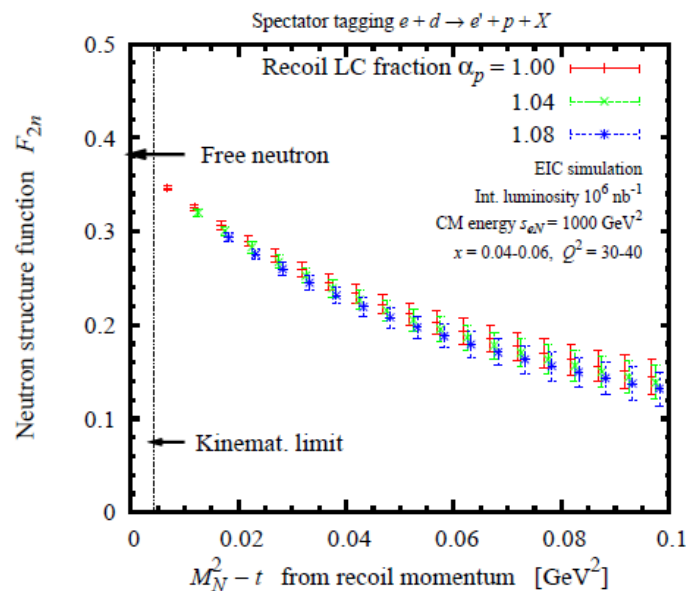
Consistent = similar bins
similar systematics

Given that one gets the “cleanest” neutron structure information from tagging with spectator protons, this may very well imply longer run times for e-d than for e-p...

(Tagged) Neutron Structure Extrapolation in t

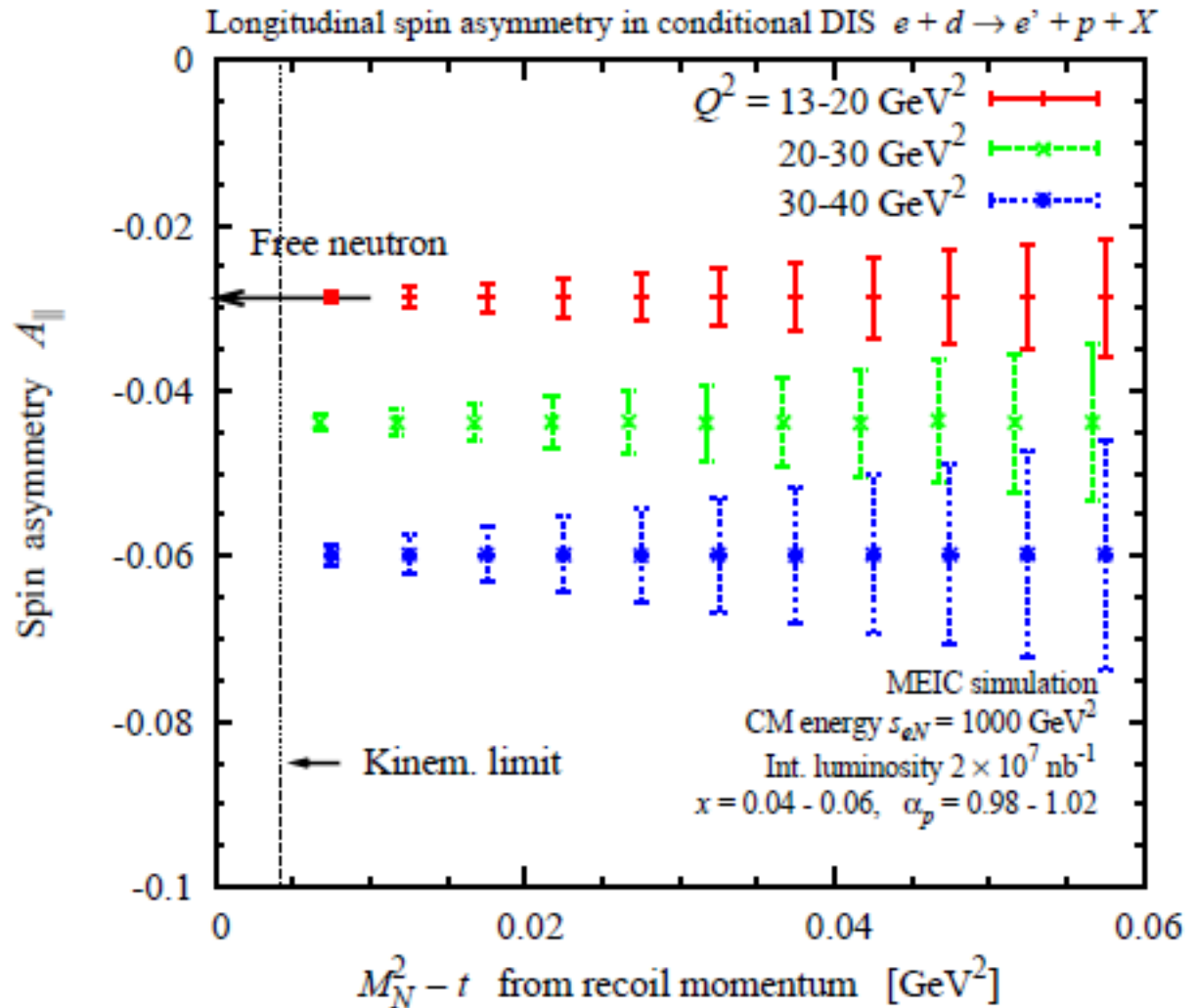
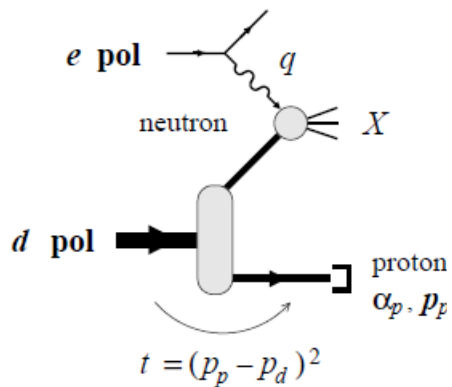


- t resolution better than 20 MeV, $<$ fermi momentum
- Resolution limited/given by ion momentum spread
- Allow precision extraction of F_{2n}^n neutron structure function



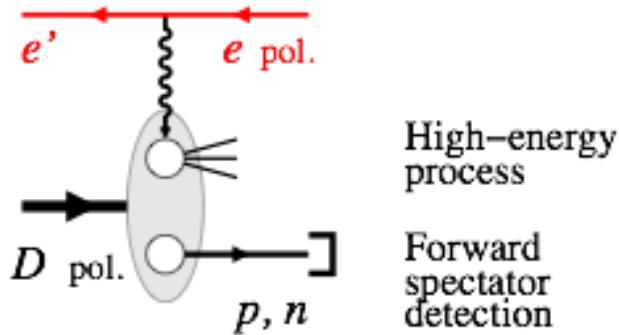
C. Weiss et al, see <https://www.jlab.org/theory/tag/>

(Tagged) Polarized Neutron Structure



C. Weiss et al, see <https://www.jlab.org/theory/tag/>

Tagging → Neutron spin structure



$$A_{\parallel n} = \frac{\sigma(+ -) - \sigma(+ +)}{\sigma(+ -) + \sigma(+ +)}$$

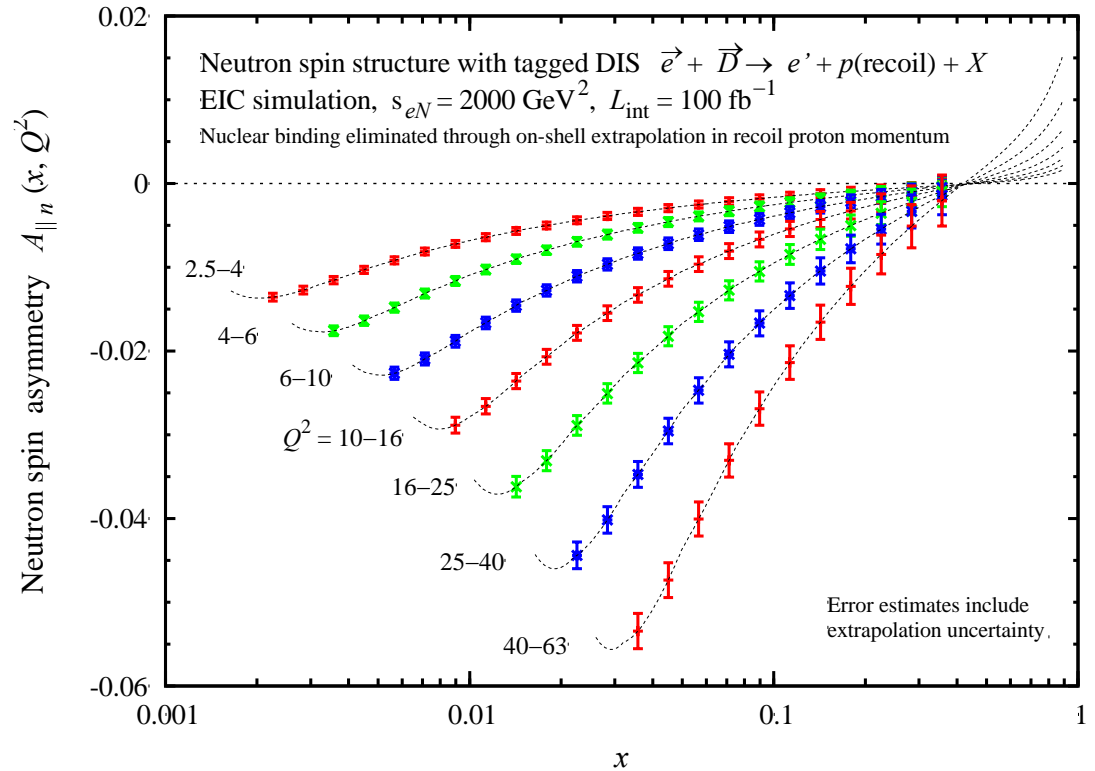
$$= D \frac{g_1}{F_1} + \dots$$

$$D = \frac{y(2 - y)}{2 - 2y + y^2}$$

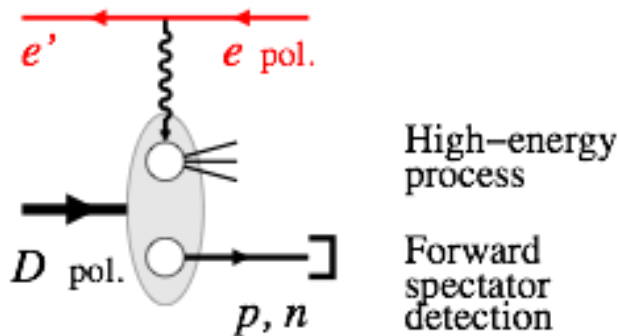
depolarization factor

$$y = \frac{Q^2}{xs_{eN}}$$

Tag the recoil proton:
Study the neutron's q-g spin structure function.
Also for other few body nuclei



Tagging → study of nuclear binding



- Another area of interest: Measurement of the kinematics of the spectator nucleon indicator of the strength and (hence) the nature of its *binding* with the in-play nucleon(s):

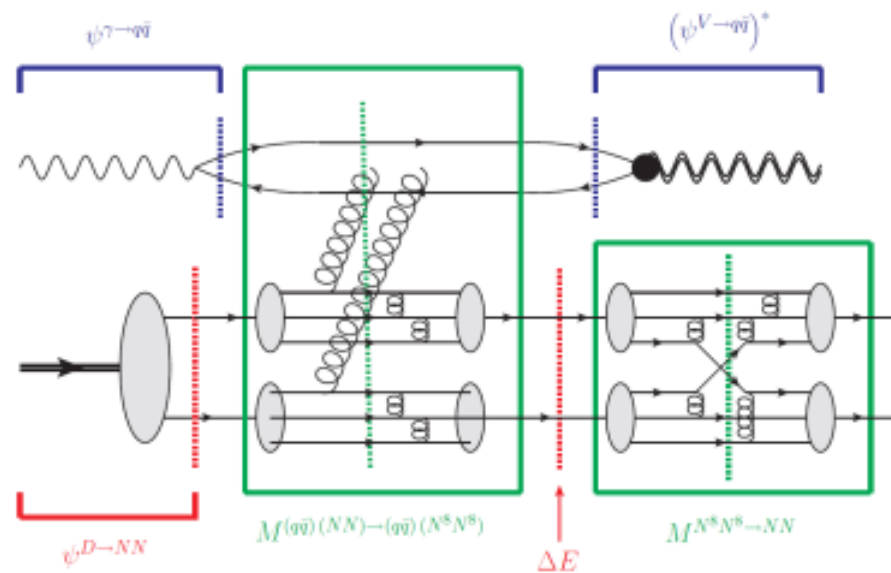
→ quark-gluon origin of the nuclear binding

(also for other light nuclei: $^3,4\text{He}$, $^6,7\text{Li}$, ^9Be , $^{10,11}\text{B}$, ^{12}C)

Alternatively, also with e-d:



Exclusive measurements of tagged (polarized) protons and neutrons in coincidence with vector mesons probe the short-range quark-gluon nature of nuclear forces



Miller, Sievert and Venugopalan,
Phys. Rev. C 93 (2016) 045202

Determining large-x Parton Distributions with EIC

Procedure: use projected EIC data in CTEQ-Jefferson Lab “CJ” PDF Fits

So far, have used JLEIC 10x100 GeV² projections in bins $0.1 < x < 0.9$ for:

- ✓ F_2^p
- ✓ F_2^n from deuterium with tagged proton spectator
- F_2^d

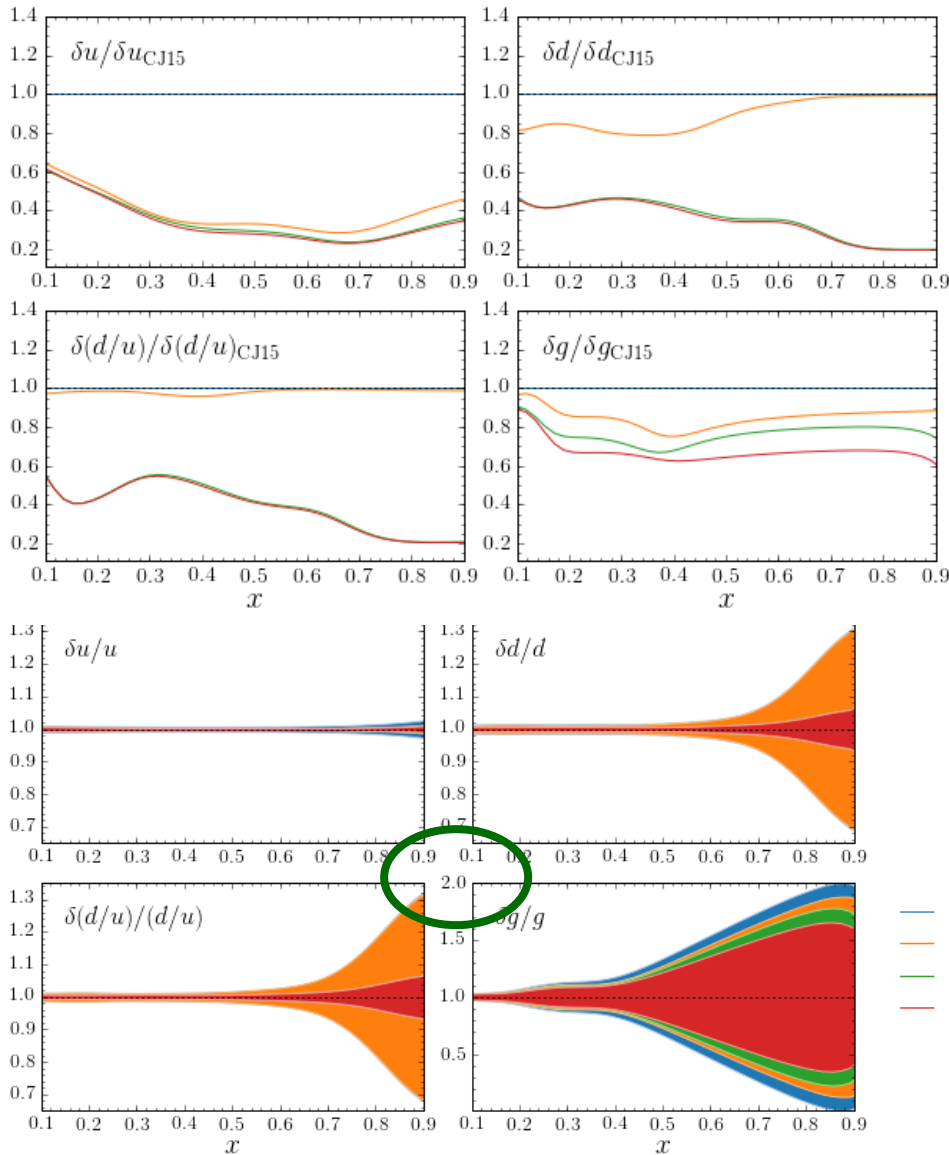
Measurements ranging to high (up to a few 1000 GeV²) will enable studies of target mass, higher twist, pert/nonpert. studies)

Can check on-shell extrapolation by measuring F_2^p from deuterium with tagged neutron spectator, comparing to proton target data

Can check nuclear corrections to F_2^d against F_2^n (tagged)

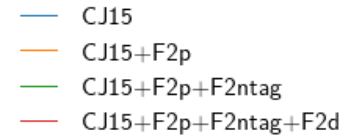
A. Accardi (Hampton),
R. Ent, J. Furlotova,
C. Keppel, K. Park,
R. Yoshida (JLab),
M. Wing (UC London)

EIC e-d (with n_{tag}) projection with 100/fb luminosity



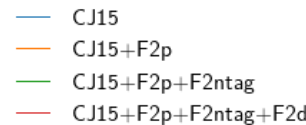
- d quark precision will become comparable to current u!! (becomes ~5% at $x = 0.9$)*

- similar improvement in $g(x)$

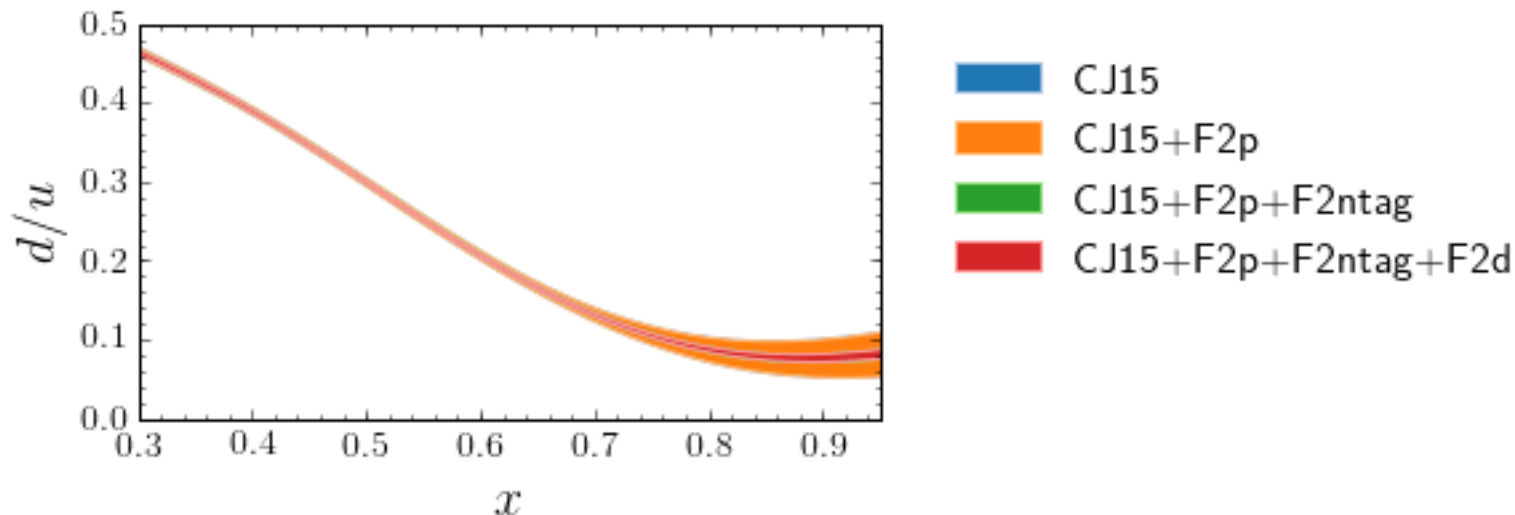


- The u quark uncertainty becomes less than ~1%; may be important for large mass BSM new particles.

- With d quark nailed by F_2^n , fitting F_2^d data will explore details of nuclear effects



Improved $d(x)$ precision is good news



- The d-quark goes from a few 10% to ~few% percent level
- Resolve long-standing mystery of d/u at large x , bell-weather for fundamental models of nucleon structure
- $D/(p+n)$ in one experiment for the first time – unprecedented handle on nuclear medium modifications
- Facilitate accurate neutron excess/isoscalar corrections
 - Important also for neutrino physics and nuclear PDFs

Outline

- Why an Electron-Ion Collider?
- Status of the US-Based Electron-Ion Collider
- Prospects of the EIC for 1D and 3D Imaging Science
- Polarized Deuteron and Polarized ^3He Beams
- EIC Science with Unpolarized & Polarized Deuteron Beams
- Summary & Possible EIC Realization

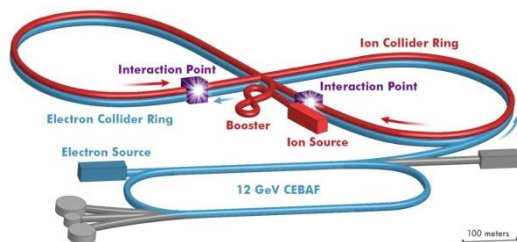
Many EIC Related Meetings

- The Flavor Structure of the Nucleon Sea (INT-17-68W), October 2-13, 2017. Organizers C. Aidala, W. Detmold, J. Qiu, W. Vogelsang
- Physics Opportunities at an ElecTron Ion Collider (POETIC 2018), Regensburg, Germany, March 19-22, 2018. Organizer A. Schaefer
- 26th International Conference on Deep-Inelastic Scattering and Related Matters (DIS 2018), Kobe, Japan, April 16-20, 2018. Organizer Y. Yamazaki
- EIC Users Group Meeting 2018, Catholic University of America, Washington, D.C., July 30 – August 3, 2018. Organizer T. Horn
- Probing Nucleons and Nuclei in High-Energy Collisions (INT-18-3), October 1 – November 18, 2018. Organizers: Y. Hatta, Y. Kovchegov, C. Marquet, A. Prokudin

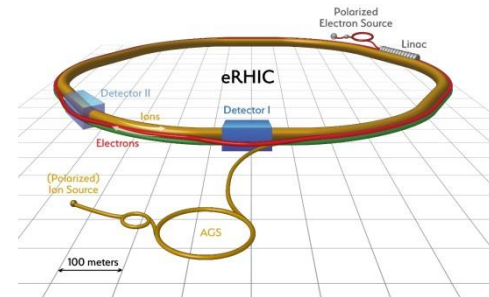
(not complete, also topical workshops and ECT meetings related to EIC science)*

In fact, essentially all conferences & workshops related to hadron physics have an EIC slot

BNL and JLAB working together



Adapted from
F. Willeke (BNL)



Complementary expertise

JLab expertise:

- Polarized electron sources
- Superconducting RF development
- Superconducting RF production and industrialization
- Superconducting LINAC technology
- [Energy-recovery LINACs](#)
- Superconducting LINAC beam physics
- Acceleration and transport of polarized electron beams

BNL expertise:

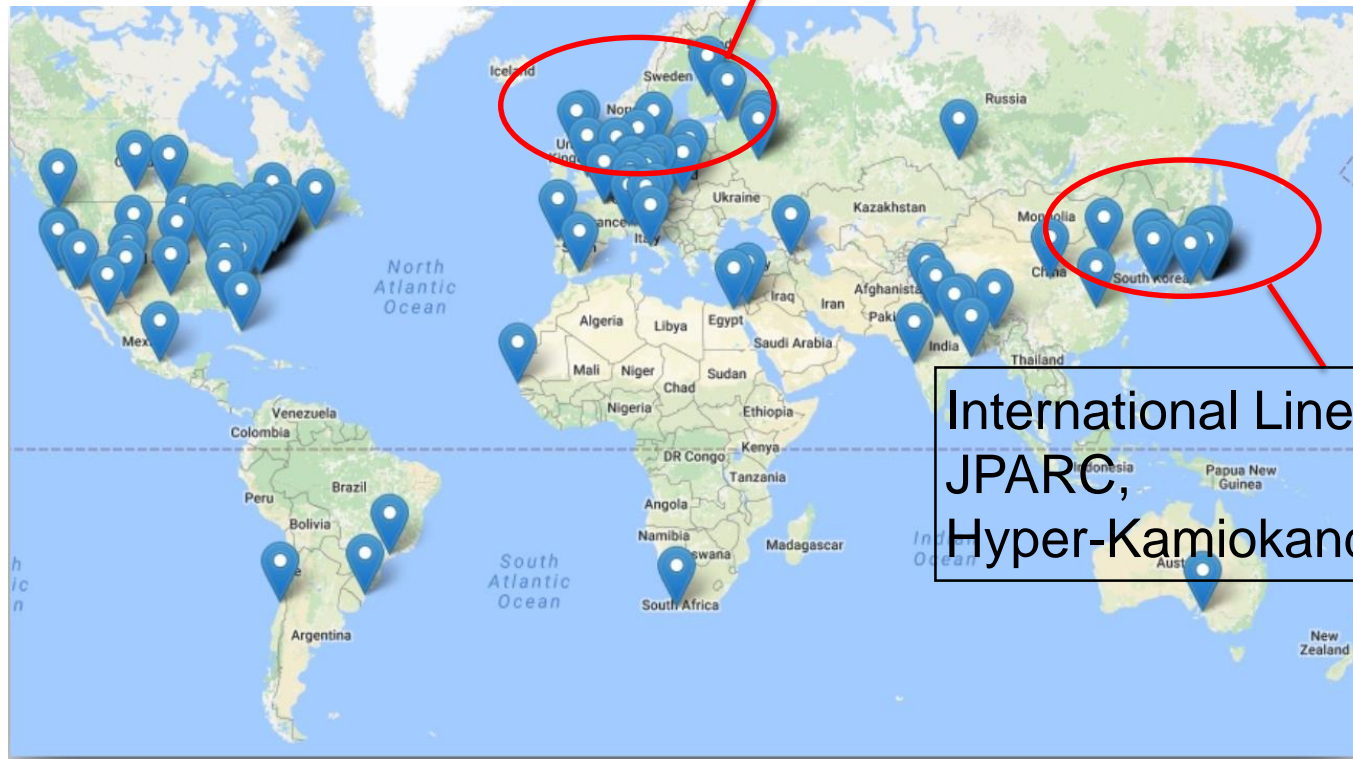
- Ion/proton beam sources
- Ion acceleration
- Ion spin preservation
- Hadron beam dynamics
- RF for hadron beams
- Hadron beam instrumentation
- Superconducting magnets
- Storage beam ring physics
- Electron cooling

Accelerator R&D going on with strong cooperation between BNL and JLAB under DOE NP guidance

Opportunity for the US to Lead!

US has a unique opening

Large Hadron Collider,
Facility for Antiproton and Ion Research



International Linear Collider,
JPARC,
Hyper-Kamiokande

US, just finishing Facility for Rare Isotope Beams is in an ideal position to take the initiative

EIC Realization Imagined

With a formal NSAC/LRP recommendation, what can we (or I) speculate about any EIC timeline?

- It seemed unlikely that a CD-0 (US Mission Need statement) would be awarded before completion of a National Academy of Sciences study
 - Indeed, a study was initiated and is ongoing
 - 1st meeting February 1-2, 2nd meeting April 19-20, 3rd meeting September 11-12
 - Report anticipated early 2018 ... assuming positive ...
 - This would/could imply CD-0 Late 2018
- (critical) EIC accelerator R&D questions will not be answered until ~2019?
- Site selection may occur perhaps around 2019/2020?
- EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20
- Most optimistic scenario would have EIC funds start in FY20, perhaps more realistic (yet optimistic) construction starts in FY22-23 timeframe
- Best guess for EIC completion assuming NAS blessing would be 2025-2030 timeframe

Summary

- EIC Program aim: Revolutionize the QCD understanding of nucleon and nuclear structure and associated dynamics. Explore new states of QCD.
- 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. JLab12 will have set the foundation at the scale of valence quarks!
- What we learn at JLab12 and later EIC, together with advances enabled by FRIB and LQCD studies, will open the door to a transformation of Nuclear Science.
- Outstanding questions raised both by the science at RHIC/LHC and at HERMES/COMPASS/Jefferson Lab, have naturally led to the science and design parameters of the EIC
- There exists world wide interest in collaborating on the EIC
- Accelerator scientists at RHIC and JLab, in collaboration with many outside interested accelerator groups, can provide the intellectual and technical leadership to realize the EIC, a frontier accelerator facility.

The future of QCD-based nuclear science demands an
Electron Ion Collider

The Electron Ion Collider

For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/³He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33-34} \text{ cm}^{-2}\text{sec}^{-1}$
100-1000 times HERA
- ✓ 20--100 (140) GeV Variable CoM

For e-A collisions at the EIC:

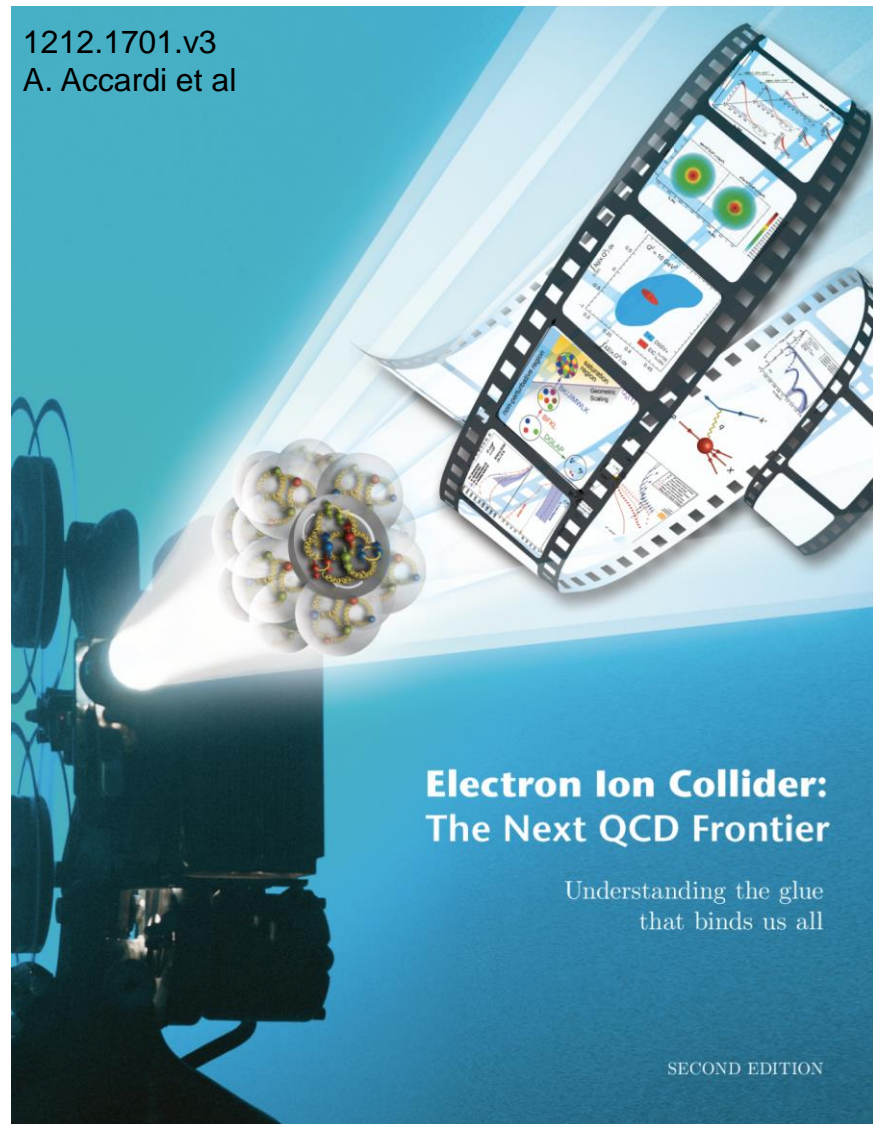
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first

Polarized electron-proton/light ion
and **electron-Nucleus collider**

Two proposals for realization of the
science case -
both designs use DOE's significant
investments in infrastructure

1212.1701.v3
A. Accardi et al



Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

SECOND EDITION

EIC Requirements

Requirements from Physics:

- ❑ High Luminosity: $10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$ and higher → nucleon/nuclei imaging
- ❑ Flexible center of mass energy → wide kinematic reach
- ❑ Electrons (0.8) and protons/light nuclei (0.7) highly polarized → study of spin structure
- ❑ Wide range of nuclear beams (D to Pb/U) → high gluon densities
- ❑ Room for a wide acceptance detector with good PID (e/h & π , K, p) → flavor dependence
- ❑ Full (or large) acceptance for tagging, exclusivity, protons from elastic reactions, neutrons from nuclear breakup → target/nuclear fragments

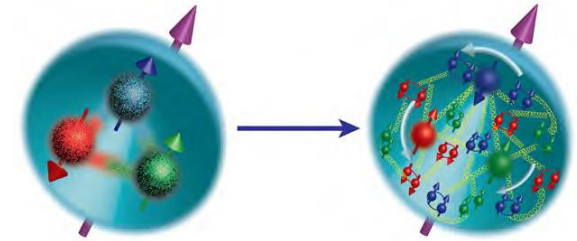
The “sweet spot” for the EIC parameters is a balance of

- High enough energies to reach high Q^2 (up to $\sim 1000 \text{ GeV}^2$)
- Low enough proton energy to measure transverse scale of $\sim 100 \text{ MeV}$ well.
- High enough energy to explore collective effects towards saturation.
- High enough luminosity for the nucleon/nuclei imaging.
- IR and Detector with acceptance and performance to fully measure the relevance processes

A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter:

How are the sea quarks and gluons, and their spins, **distributed in space and momentum** inside the nucleon?

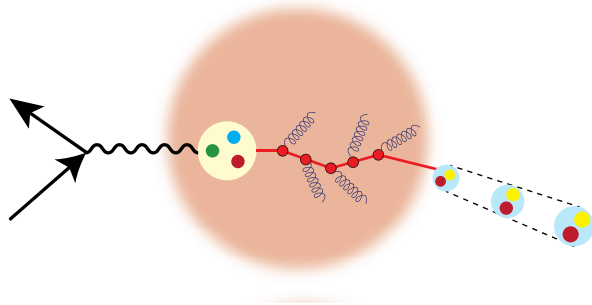
How do the **nucleon properties emerge** from them and their interactions?



How do color-charged quarks and gluons, and colorless jets, **interact with a nuclear medium**?

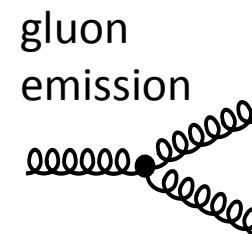
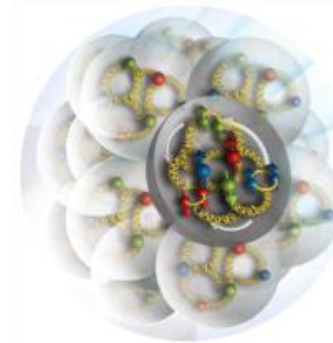
How do the **confined hadronic states emerge** from these quarks and gluons?

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



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

What happens to the **gluon density in nuclei**? Does it **saturate at high energy**, giving rise to a **gluonic matter with universal properties** in all nuclei, even the proton?



?=?

