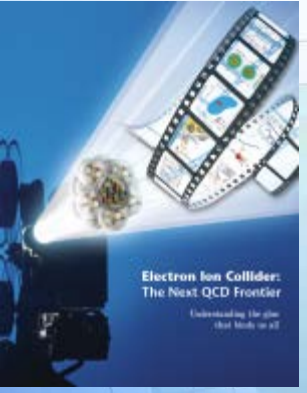
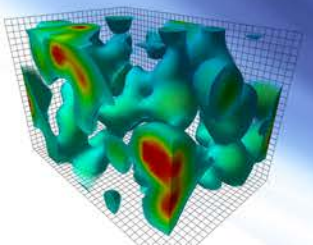


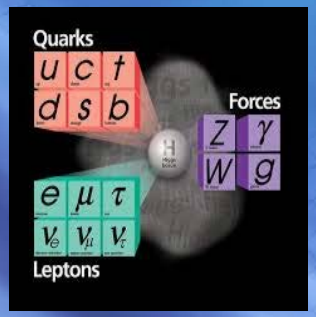
arXiv 1212.1701.v3
Eur. Phy. J. A52, 9 (2016)

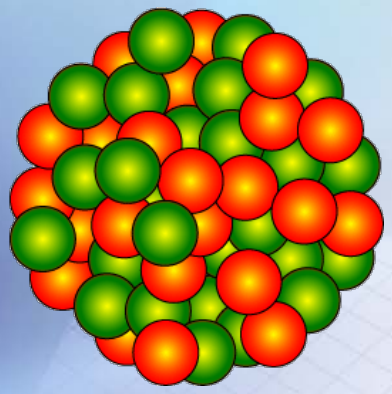
Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

EIC Project Overview and The Path Forward







Abhay Deshpande

Stony Brook University

QCD: The Holy Grail of Quantum Field Theories

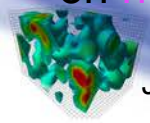
- QCD : “nearly perfect” theory that explains nature’s strong interactions, is a fundamental quantum theory of quarks and gluon fields
- QCD is rich with symmetries

$$SU(3)_C \times \boxed{SU(3)_L \times SU(3)_R} \times \boxed{U(1)_A \times U(1)_B}$$

(1) (2) (3)

(1) Gauge “color” symmetry : unbroken but confined
(2) Global “chiral” flavor symmetry: exact for massless quarks
(3) Baryon number and axial charge (massless quarks) conservation
(4) Scale invariance for massless quarks and gluon fields
(5) Discrete C, P & T symmetries

- Chiral, Axial, Scale & P&T symmetries broken by quantum effects: Most of the visible matter in the Universe emerges as a result
- Inherent in QCD are the deepest aspects of relativistic quantum field theories: (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry) ➔ all depend on non-linear dynamics in QCD

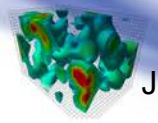


Non-linear Structure of QCD: Fundamental Consequences

- Quark (Color) confinement:
  - Consequence of nonlinear gluon self-interactions
  - Unique property of the strong interaction

- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions – Generalized Parton Distributions (GPDs)

- Ultra-dense color (gluon) fields:
  - Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?



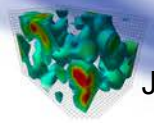
Emergent Dynamics in QCD

***Without gluons,* there would be no nucleons,**

no atomic nuclei… *no visible world!*

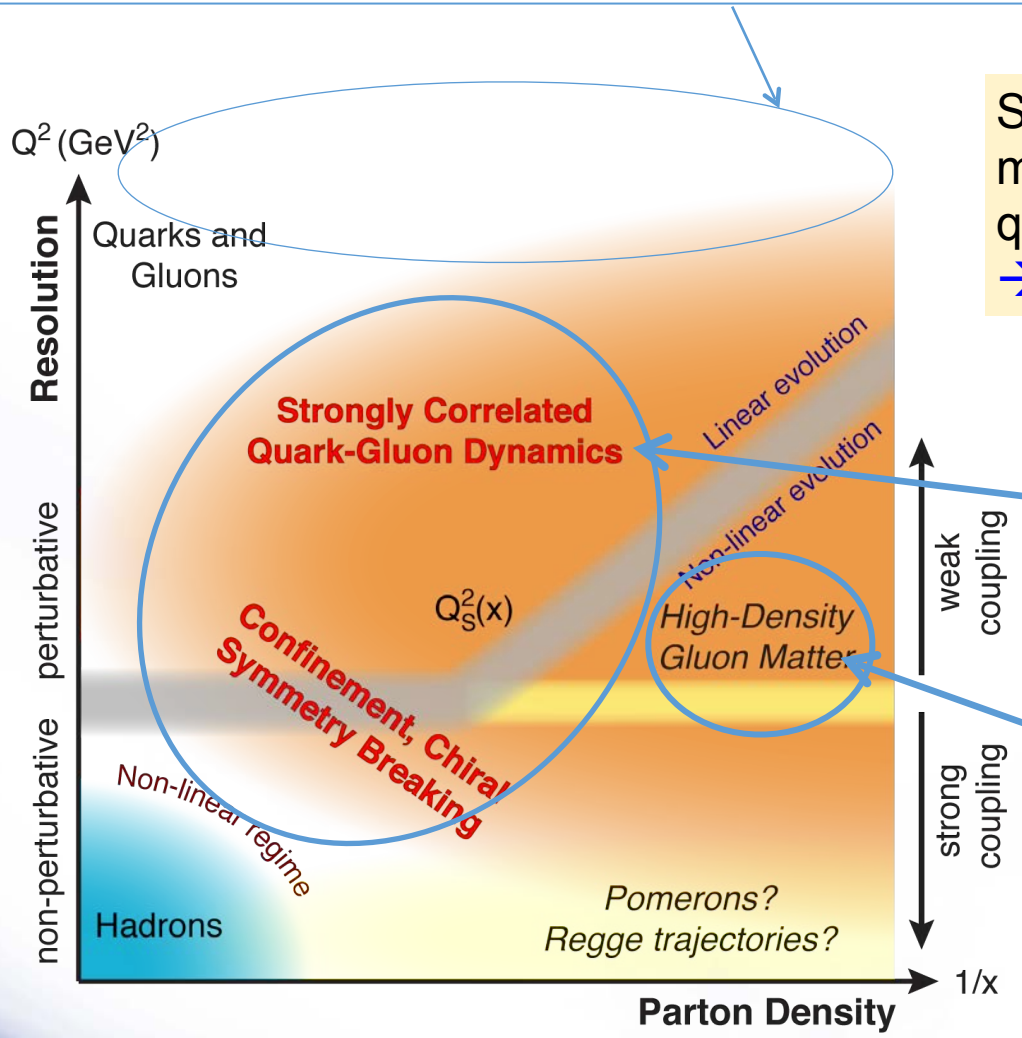
- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% of the proton's momentum, a significant fraction of the nucleon's spin, and are essential for the dynamics of confined partons
- Properties of hadrons are emergent phenomena resulting not only from the equation of motion but are also inextricably tied to the properties of the QCD vacuum. Striking examples besides confinement are spontaneous symmetry breaking and anomalies
- The nucleon-nucleon forces emerge from quark-gluon interactions: how this happens remains a mystery

Experimental insight and guidance crucial for complete understanding of *how* hadrons & nuclei emerge from quarks and gluons



QCD Landscape explored by EIC

QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described

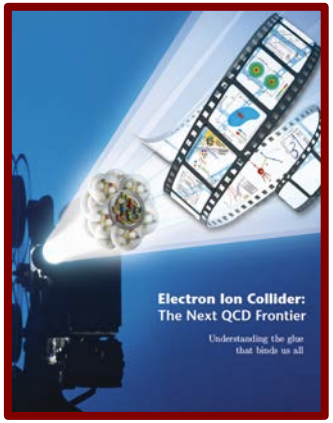


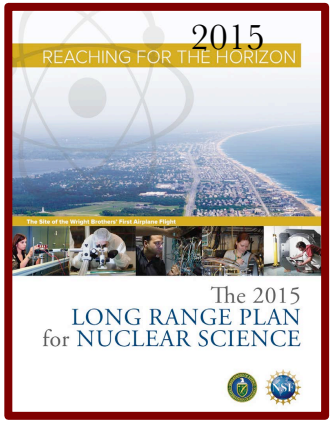
Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

EIC systematically explores correlations in this region.

An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter

Science Case for the EIC

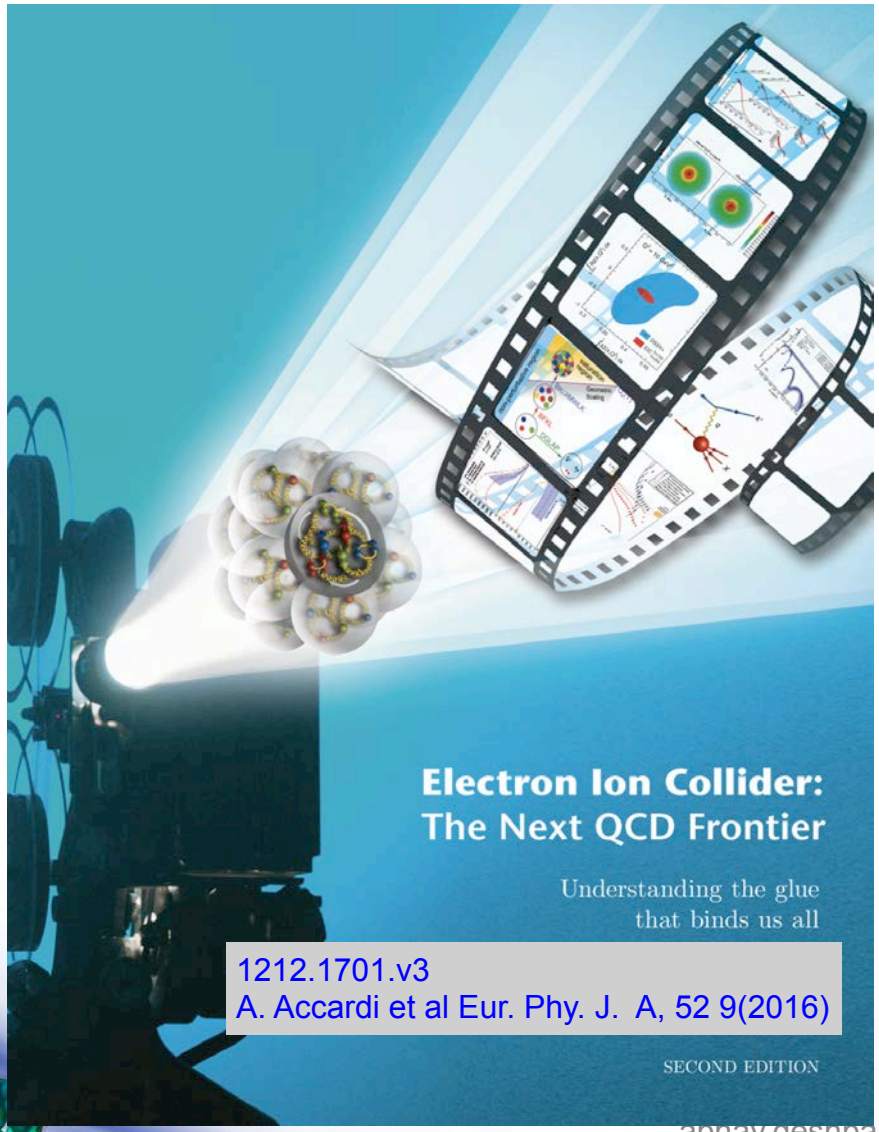




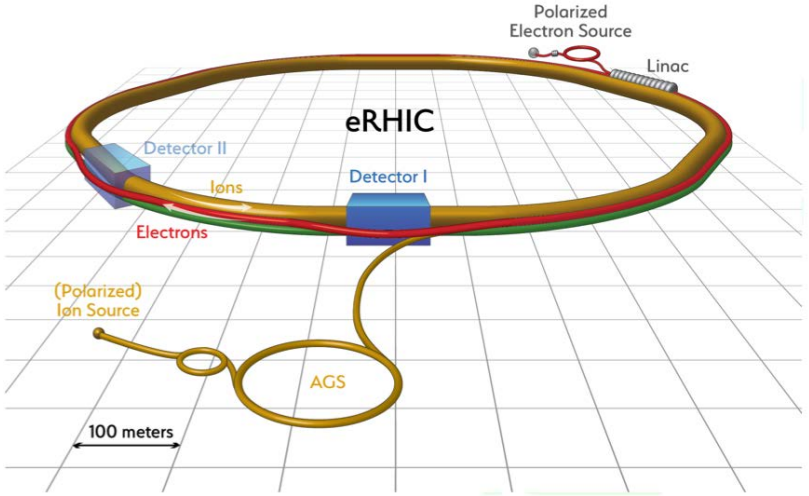
- 2010/2011 Workshop on EIC Science at the INT. 150+ Participants, wrote a comprehensive Summary: arXiv:1108.1713, (500+ Pages). Ed.. D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang
  - Had Golden, Silver and Bronze physics measurements.
  - Categorized not just by the importance and interest, but uniqueness that was associated with EIC 's capabilities in realizing them.
- Golden measurements mentioned there were then refined and collected in to an EIC White Paper 2012-2014, Ed. A. Deshpande, Z.-E. Meziani, J.-W. Qiu
- Case for the EIC recommendation in the NSAC Long Range Plan 2015: …*A high luminosity, high energy polarized electron ion collider… highest priority for US nuclear science*

The Electron Ion Collider

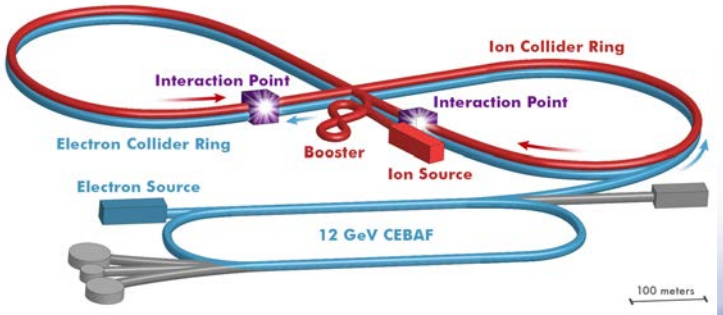
Two options of realization!



1212.1701.v3
A. Accardi et al Eur. Phy. J. A, 52 9(2016)



Not to scale



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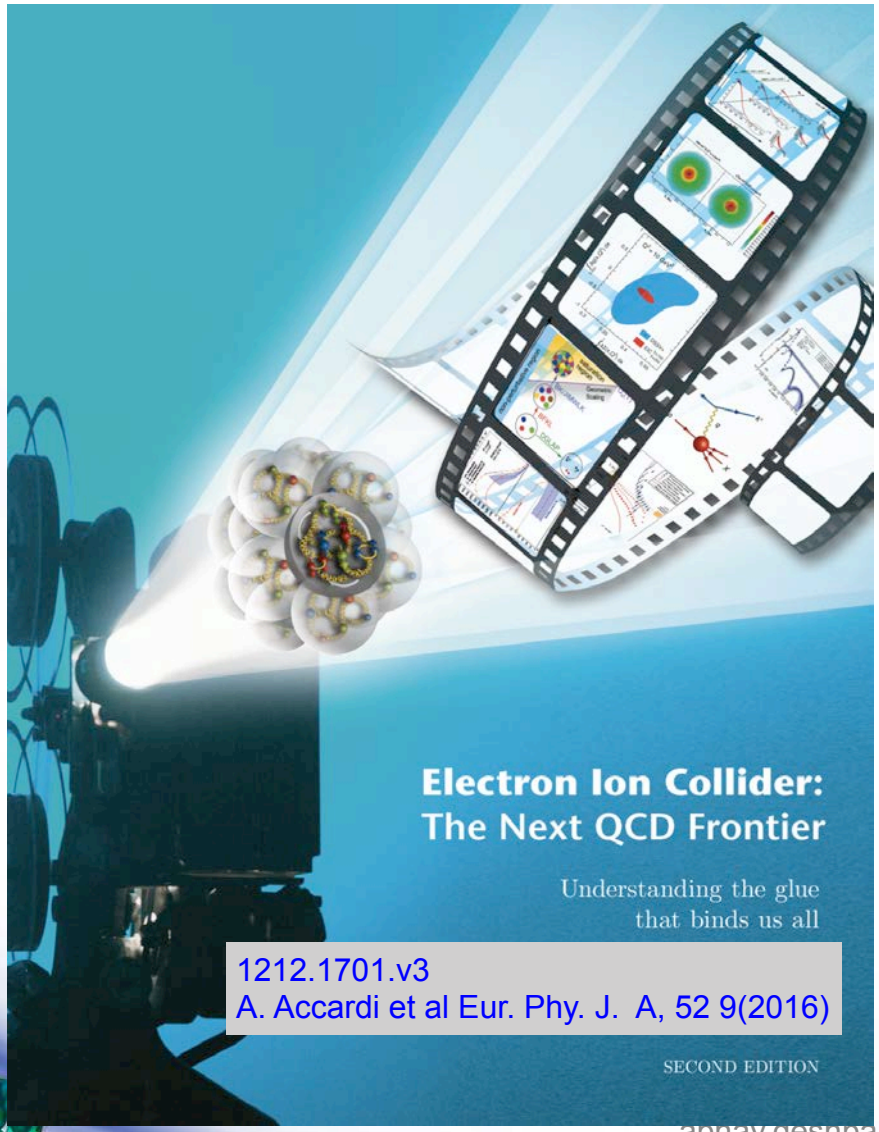

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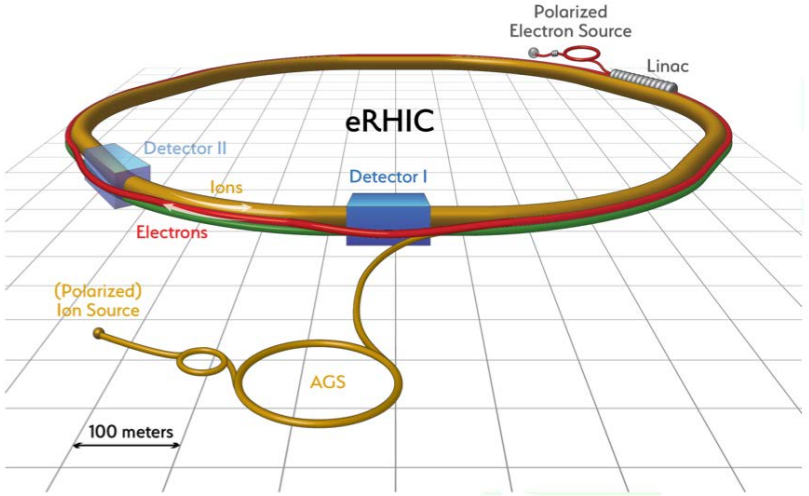

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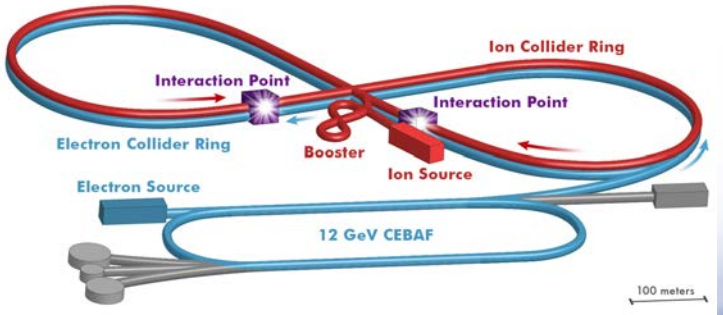


The Electron Ion Collider

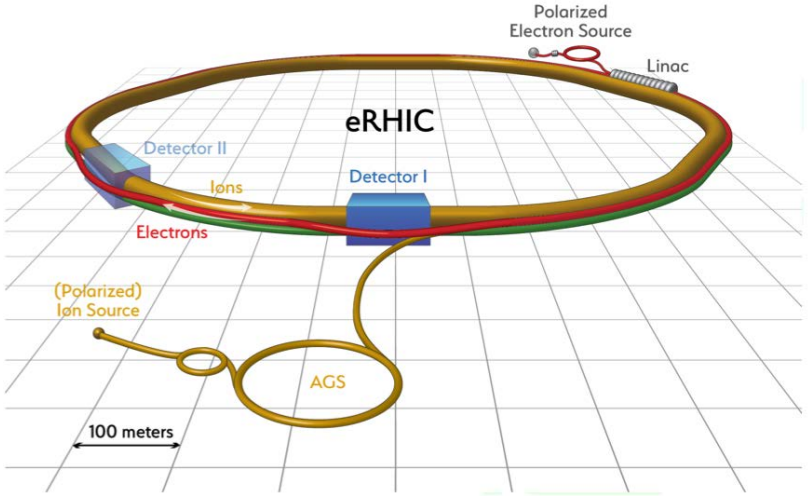
Two options of realization!

For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

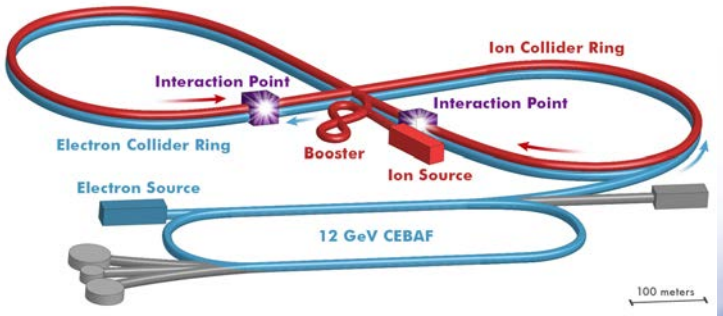
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy



Not to scale

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure



The Electron Ion Collider

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World's first
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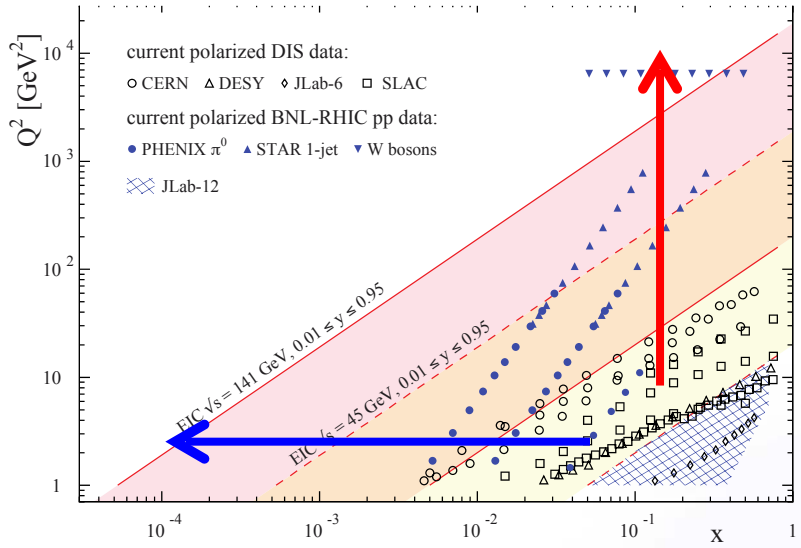
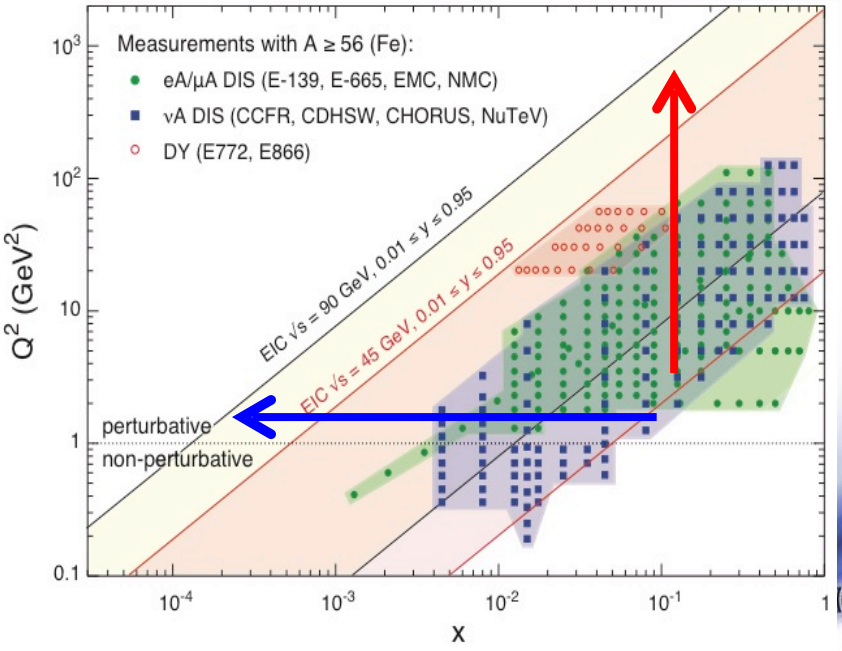
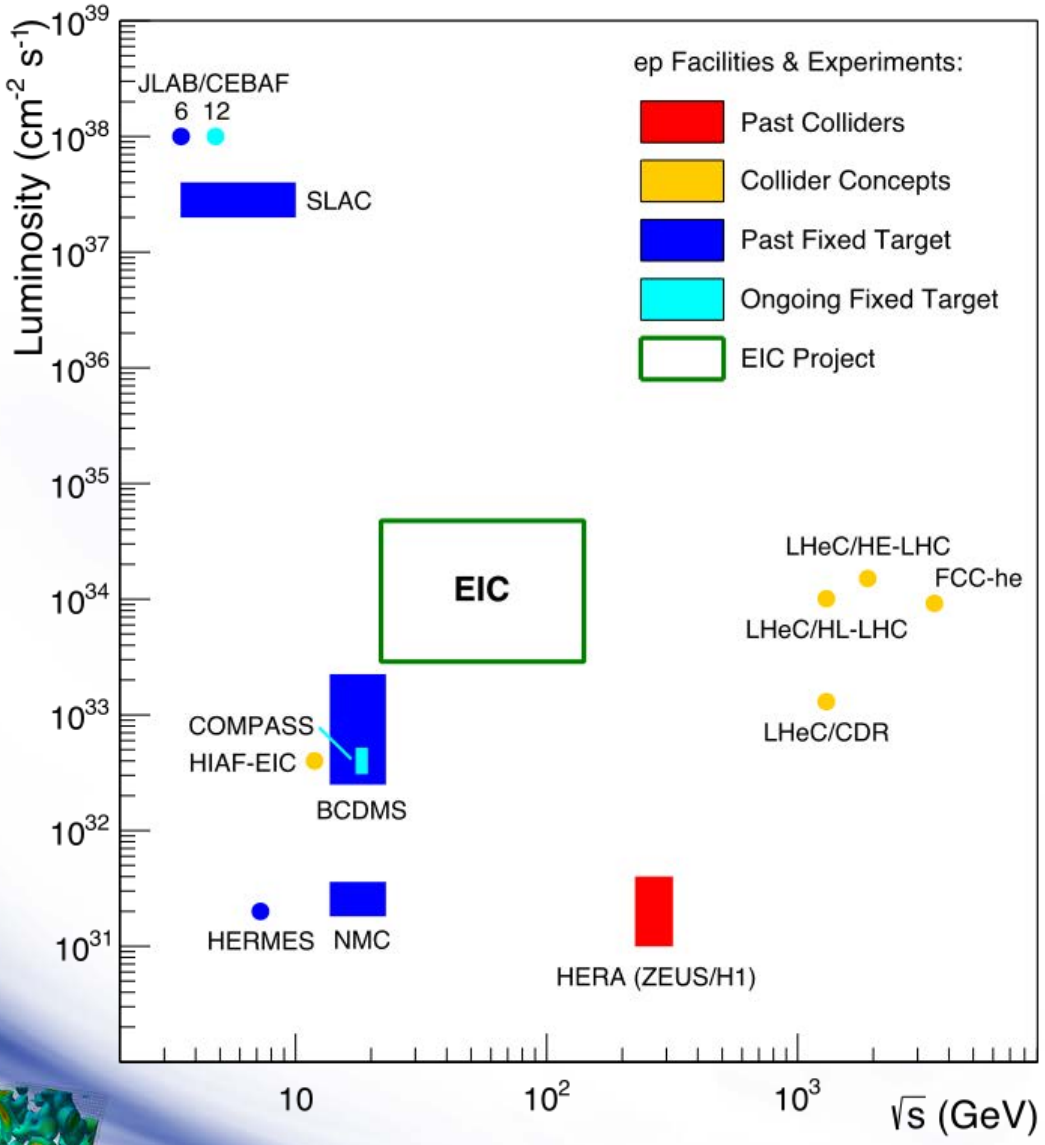
EIC White Paper: 1212.1701.v3
A. Accardi et al Eur. Phy. J. A, 52 9(2016)





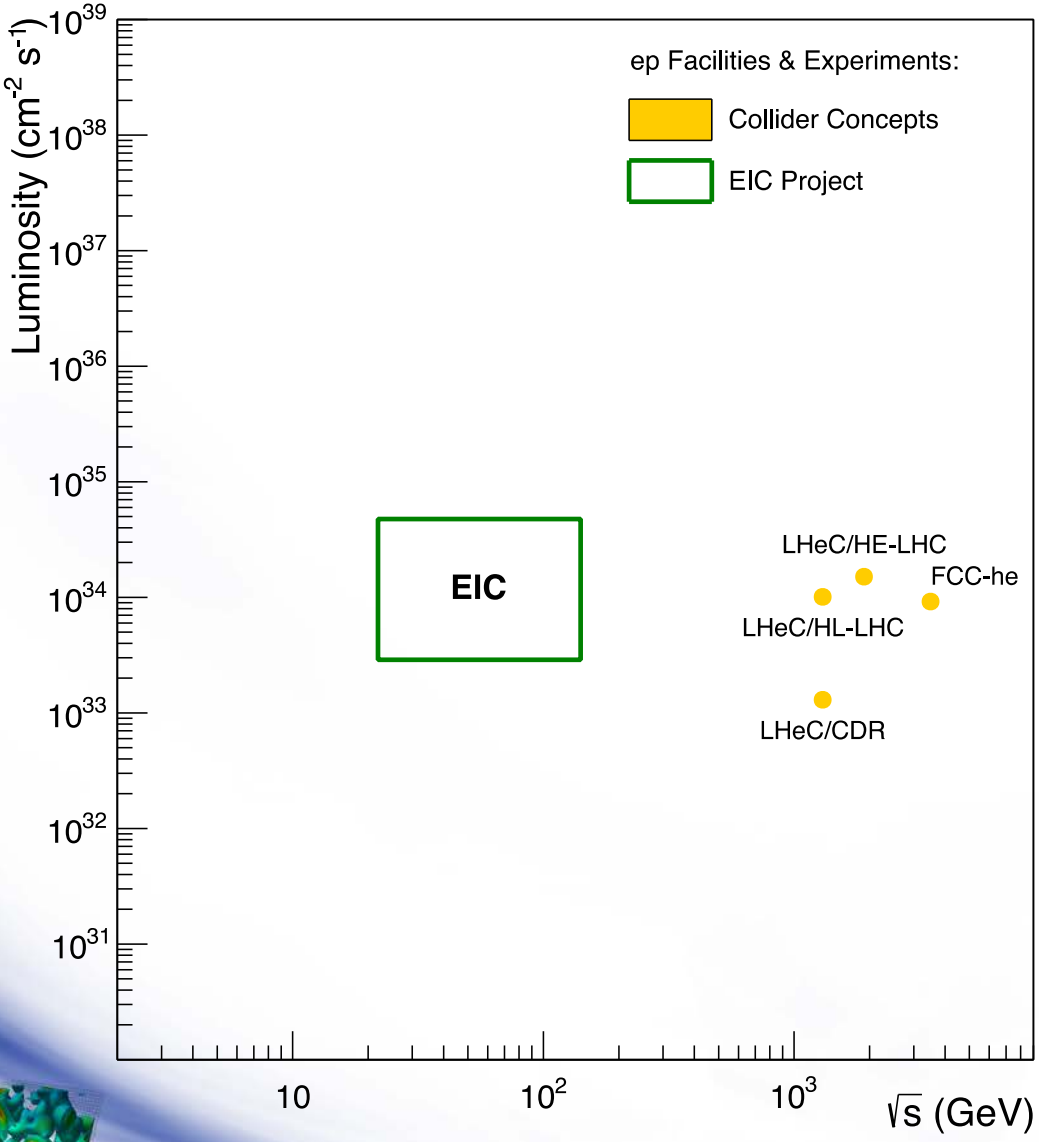
Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

However,
if we ask for:

Uniqueness of EIC among all DIS Facilities

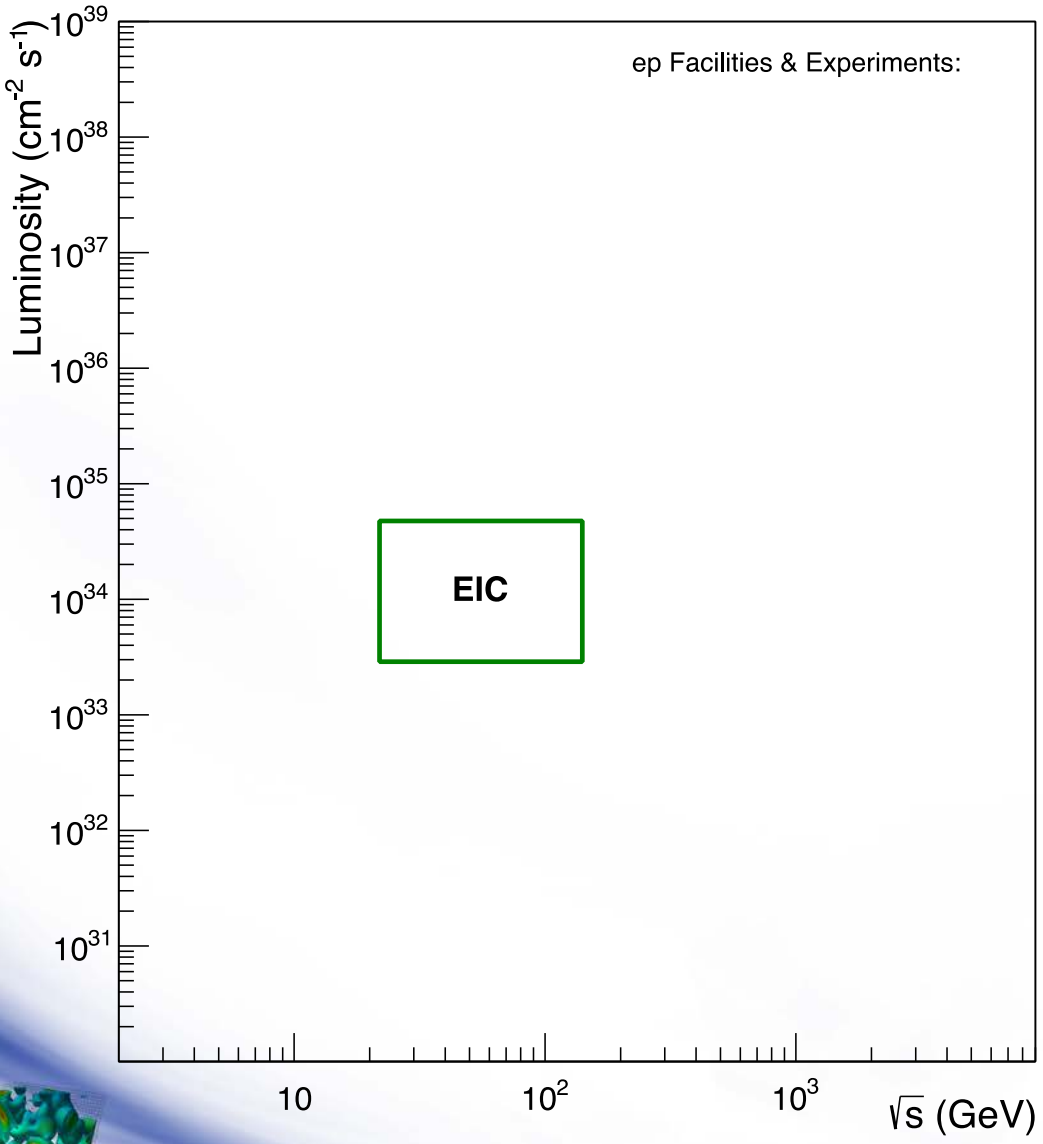


All DIS facilities in the world.

However,
if we ask for:

- high luminosity &
  wide reach in √s

Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

However,
if we ask for:

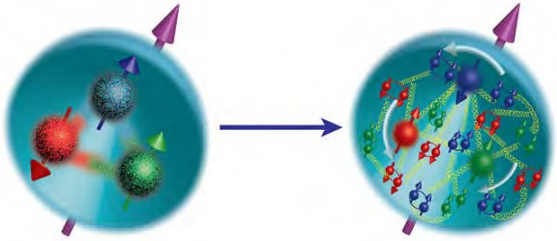
- high luminosity & wide reach in √s
- polarized lepton & hadron beams
- nuclear beams

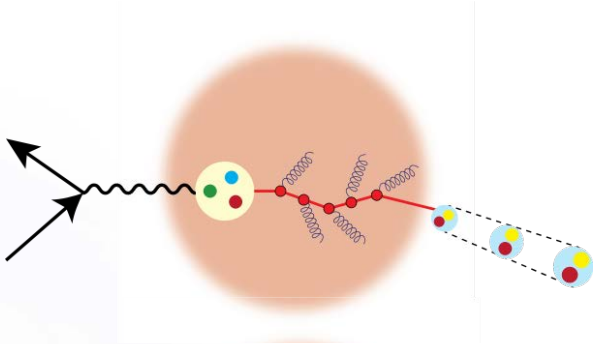
EIC stands out as unique facility …

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?

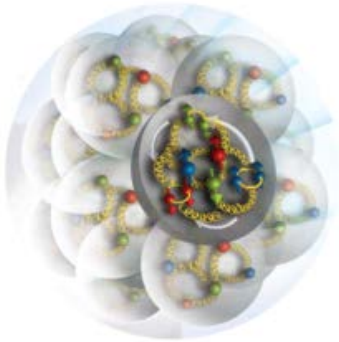




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

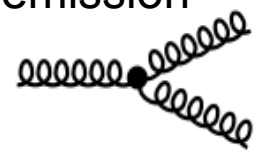
How do the quark-gluon interactions create nuclear binding?



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?

gluon emission



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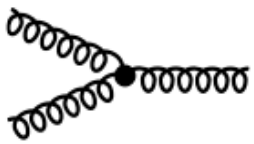
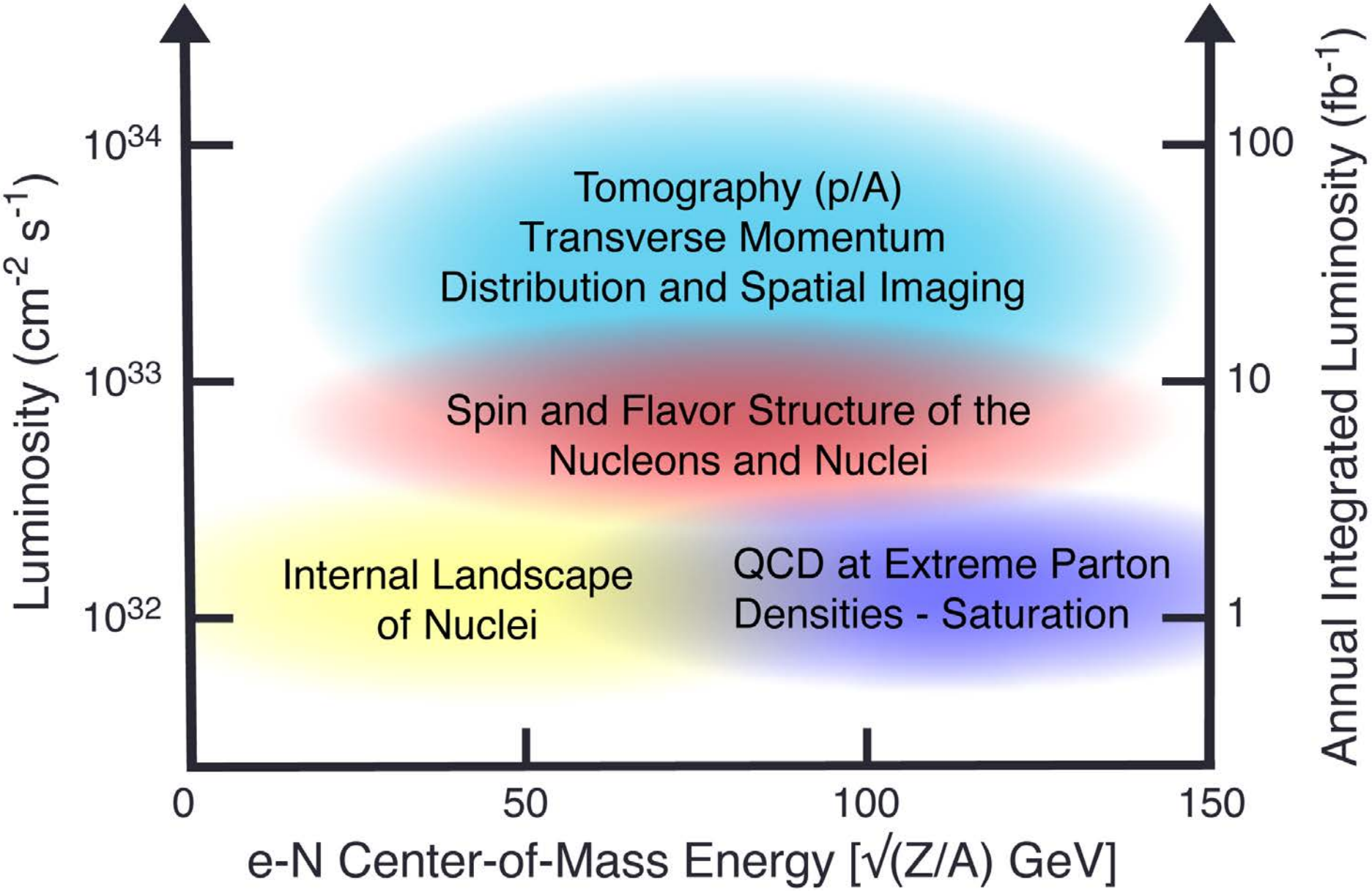
gluon recombination



EIC Physics: CM & Luminosity



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

RECOMMENDATION:

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

Initiatives:

Theory
Detector & Accelerator R&D

Detector R&D money ~1.3M/yr since 2011; significant increase anticipated soon.

Anticipated Now:
NEW Money for EIC Accelerator R&D already assigned $7m/yr

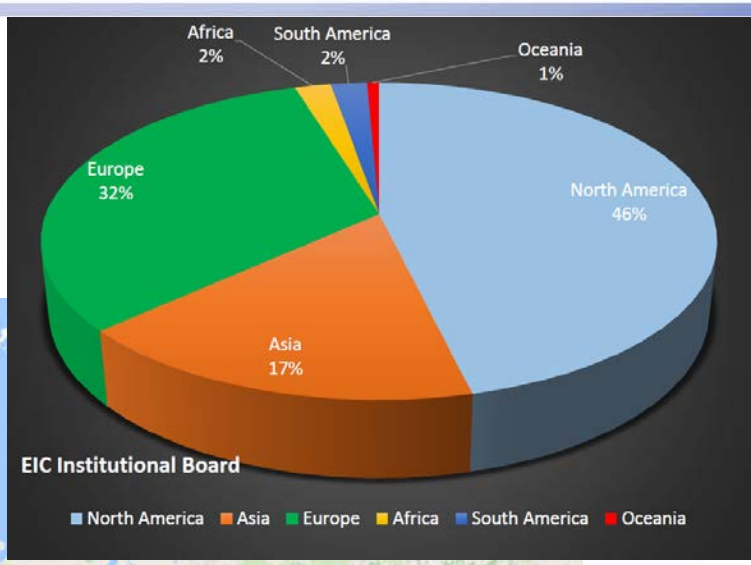
http://science.energy.gov/np/reports

The EIC Users Group: EICUG.ORG

(no students included as of yet)

788 collaborators, 29 countries, 169 institutions... (June, 2018)

Map of institution's locations



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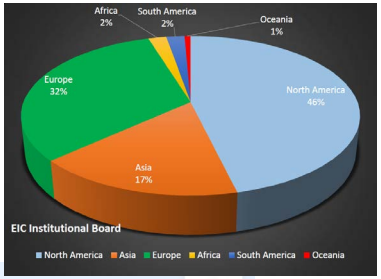


- Established, enthusiastic and active
- Setting up working groups for polarimetry, luminosity measurements, interaction region design, software use
- New physics ideas initiated with new influx of people….

Next meeting:

Catholic American University, Washington DC, July 29-Aug 2

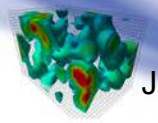
https://www.jlab.org/conferences/eicugm18/

Detector design and other experimental issues

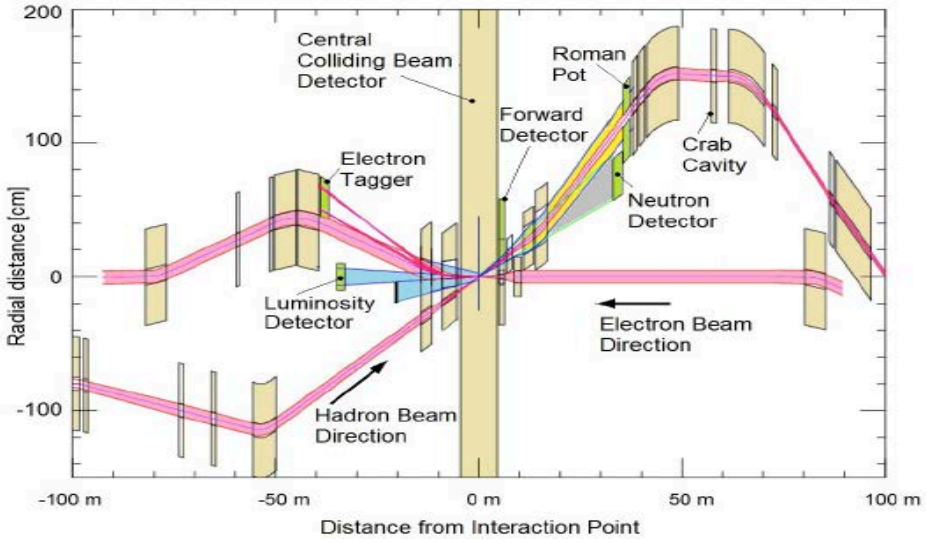
- Detector R&D program since 2011 at ~1.3M/yr has created many technical solutions for generic EIC detector detector. It is expected that these will become more specific over the next years to finalize detector designs.
  - https://wiki.bnl.gov/conferences/index.php/EIC_R%25D

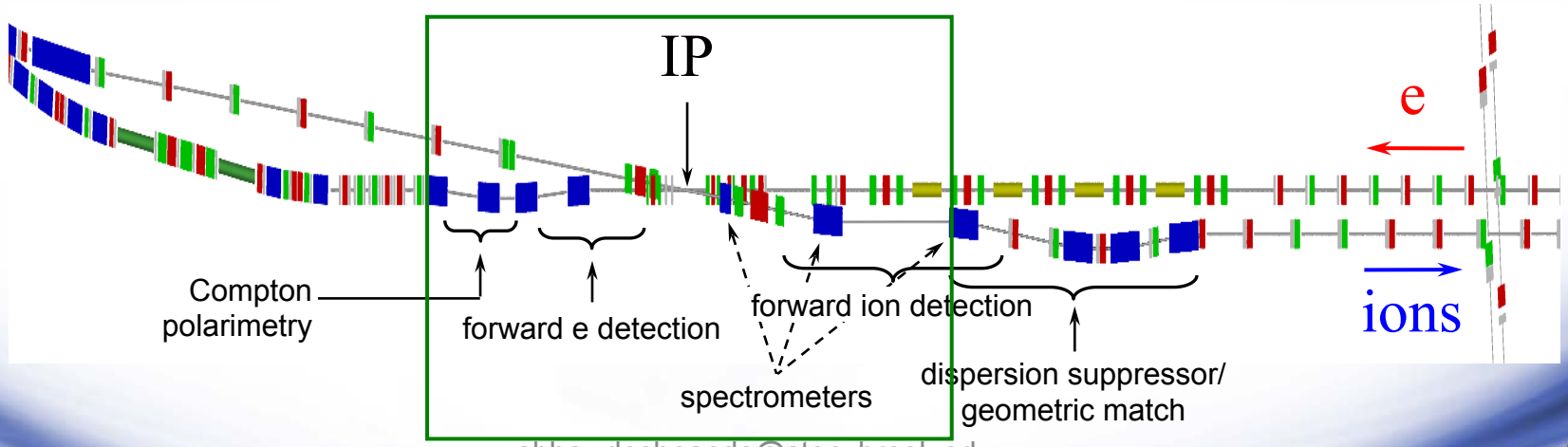
- Other systematic uncertainties that need solution and careful consideration:
  - Hadron beam polarimetry 2-3% or
    - deuteron, ^{3}He, and other heavier beams
  - Polarization of electrons over a wide range of energies better than 2% in real machine/detector setup
  - Luminosity measurement of better than1-2%

- EIC Users Group has formed task forces on each of these for both generic and specific solutions of each design of the EIC and IR design.



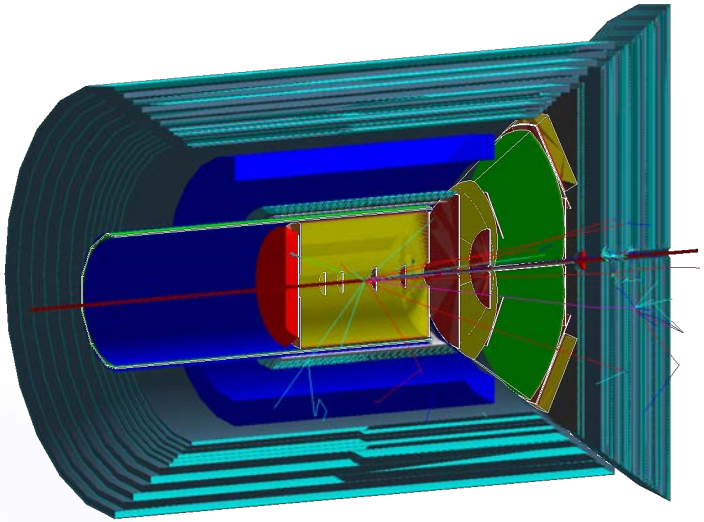
EIC "IR + Detector" Concepts



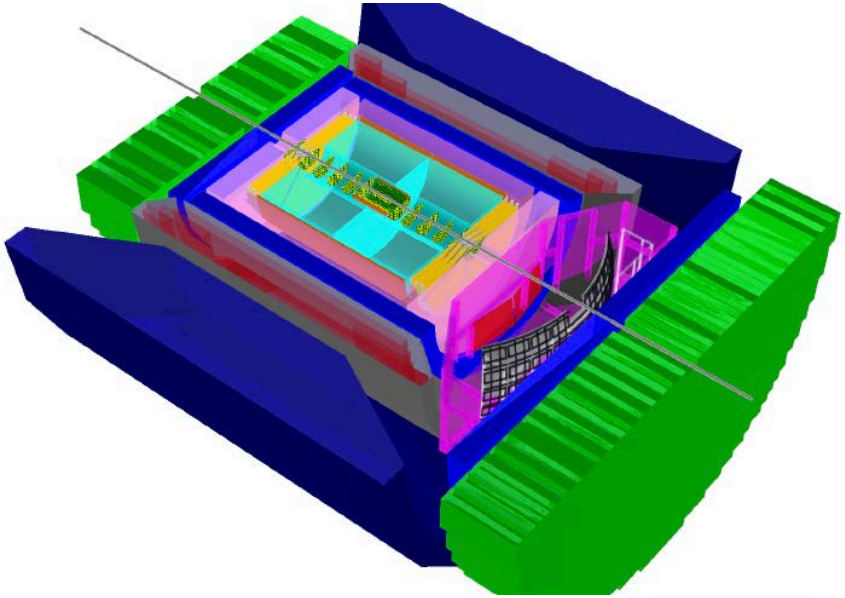


EIC "IR + Detector" Concepts

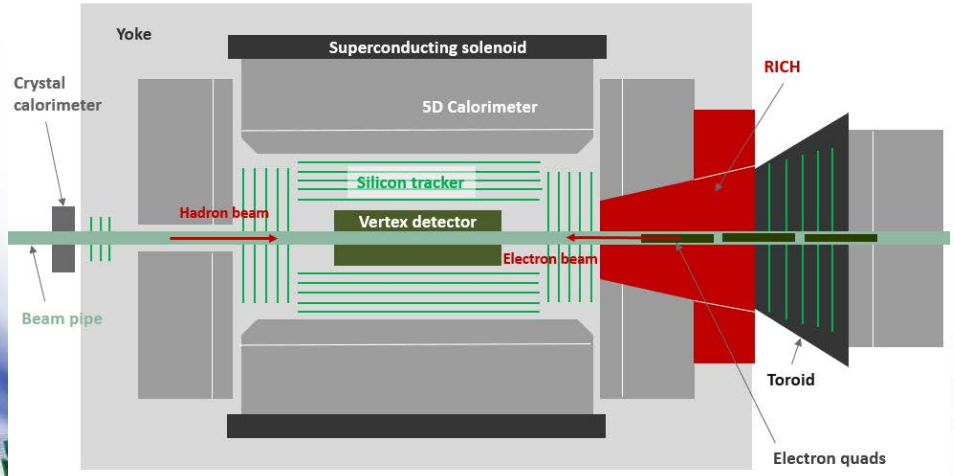
"EIC Day 1 Detector "



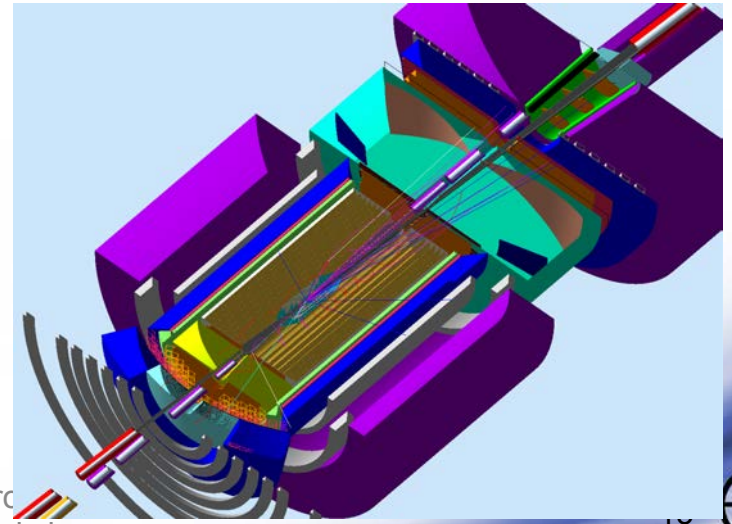
eRHIC Detector



TOPSiDE by ANL

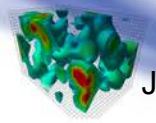


JLEIC Detector



New Users → New Physics → Lots of activities

- Jet studies at the EIC:
  - Systematic investigations of general issues in jet-finding at an EIC
  - Understanding of "micro-jets" – jets with only few hadrons
  - Understanding the jet structure modifications in nuclei vs. protons
  - Energy loss in cold QCD matter (Nuclei) vs. hot QCD matter at RHIC and LHC
- Precision measurements of the "initial state" for collisions leading to the QGP being studied at RHIC and LHC
- Precision PDF measurements in proton, neutron & photons at the EIC:
  - Study the free neutron PDFs through tagging and on-shell extrapolation
  - Study the gluon PDFs at large Bjorken x through evolution and open-charm production
  - Study of gluons TMDs
  - Study the potential impact on Higgs studies in the High-Luminosity LHC era
  - Study the impact of TMDs @ EIC on W-production at the LHC
  - Polarized and unpolarized photon PDFs
- Measurements of PDFs in pions and kaons through the Sullivan process
  - Theoretical studies of the equivalence of near-off-shell and on-shell pions and kaons
  - Study the extraction of, and expected differences of, quark and gluon PDFs in pions, kaons and nucleons, and the relation to their physical masses
- Nucleon structure with electroweak probes, and precision BSM physics (i.e. $Sin^2\Theta_W$)
- Heavy quark & quarkonia production with 100-1000 times HERA luminosity
- In view of new discoveries of multi-quark XYZ states: what could EIC contribute?



New Users → New Physics → Lots of activities

- M
- In view of new discoveries of multi-quark

Highly Active EIC Community has evolved

T. Hallman, Office of NP at the NSAC meeting March 23, 2016

Next Formal Step on the EIC Science Case

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
Division on Engineering and Physical Science
Board on Physics and Astronomy
U.S.-Based Electron Ion Collider Science Assessment

Summary

The National Academies of Sciences, Engineering, and Medicine ("National Academies") will form a committee to carry out a thorough, independent assessment of the scientific justification for a U.S. domestic electron ion collider facility. In preparing its report, the committee will address the role that such a facility would play in the future of nuclear science, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics. The need for such an accelerator will be addressed in the context of international efforts in this area. Support for the 18-month project in the amount of $540,000 is requested from the Department of Energy.

Mail reviews received; proposal approved for funding in PAMS; PR package in PAMS being processed.

Progress is also being made on a second Joint NAS study on Space Radiation Effects Testing

National Academy of Sciences Review

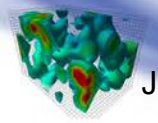
Duration: 18 months (starting approximately February 2017)

Committee: A. Aprahamian & **Gordon Baym** (Co-Chairs), C. Aidala, P. Bruan-Munzinger, H. Gao, K. Hafidi, **W. Haxton**, J. Jowett, L. McLerran, Z.-E. Meziani, R. Milner, T. Schaefer, E. Sichtermann, **M. Turner**, L. Merminga

Meetings: 02/01/2017, 04/19/2017, 06/09/2017, 07/14/2017, 09/11/2017, 11/27/2017

Report: To be released any time in the next month (~July 2018).

URL: https://www8.nationalacademies.org/cp/projectview.aspx?key=49811



Charge to the National Academy

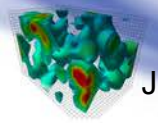
The committee will assess the scientific justification for the US domestic electron ion collider facility. In particular the committee will address the following questions:

Presented to the NAS committee on April 2017 by AD on behalf of the EICUG

- ◇ What is the merit and significance of the science? What is its importance in the overall context of research in nuclear physics and physical sciences in general?
- ◇ Capabilities of other facilities, existing and planned, domestic and international? What would be the unique scientific role of the US EIC complementary to existing and planned facilities?

EICUG Provided input on this later in review process

- ◇ What are the benefits of the US leadership in nuclear physics?
- ◇ What are the benefits to other fields of science and to society?



Center for Frontiers in Nuclear Science

http://www.stonybrook.edu/cfns/

- **Funded by Simon's Foundation & NY State** & supported by Stony Brook University and BNL
  - International Advisory Committee Chaired by R. Milner (MIT)
  - Program advisory committee Chaired by A. Deshpande (Director of the Center)
- World-wide members of EIC Users Group are welcome to participate & lead its activities, visit us, initiate new programs teach for EIC…in summer schools…
- **Expanding the EIC science through new ideas: Workshops, Visitors, Discussions**
  - Bi-Monthly Seminars on Blue Jeans (see web pages)
  - Grad student and Post doctoral fellow program launched (Joint Post doctoral fellows 5, and Center fellows 4, about to be advsertized)
  - National and international visitor program to start in Summer 2018
  - A EIC QCD summer school planned starting in 2019

  2018 Workshops
  - Light ion beams at the EIC, Ghent Belgium, (February 2018)
  - Pre-DIS workshop on EIC and its connections to other areas, Kobe, (April 2018)
  - GPD measurements at the EIC (June, 2018 @ Stony Brook)
  - Short Range Nuclear correlations EIC at FRIB (September 2018 @ BNL)
  - Entropy Entanglement and connections to Confinement (September 2018 @ Stony Brook)
  - Ultrahigh energy gamma rays and very forward physics @ the EIC (October 2018 @ Stony Brook)
  - Inaugural meeting of the Center (November 2018)
- **Summer Schools in QCD and EIC science :**
  - US National Nuclear Physics Summer School 2018 at Yale University
  - Gordon Research Center Meeting 2018
  - EINN 2018 in Paphos Greece
- Please contact me (Abhay Deshpande)

Center for EIC at Jefferson Lab

https://www.eiccenter.org/eic-center-jefferson-lab

EIC Center at Jefferson Lab (EIC²@Jlab) is organized to advance and promote the science program at a future EIC facility. Particular emphasis is on the close connection of EIC science to the current 12 GeV CEBAF program.

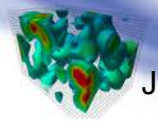
Consolidates and connects the existing EIC Physics and detector development activities at Jlab12 including:

- Weekly meetings, hosting and organizing adhoc meetings, keeping documentation on EIC and JLEIC
- LDRD projects, EIC Detector R&D funded activities, HUGS Summer School, local hosting of visitors and planning of EICUG activities
- Graduate student and post doctoral fellow program
- Participation & activities coordinated by Rik Yoshida

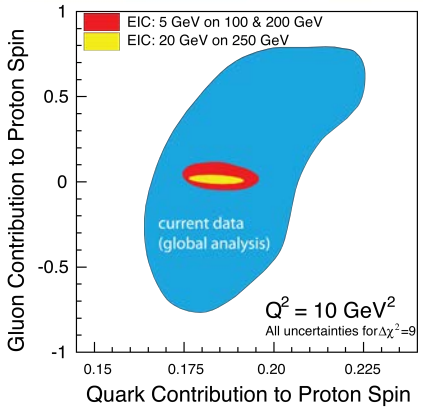
Path forward for the EIC:

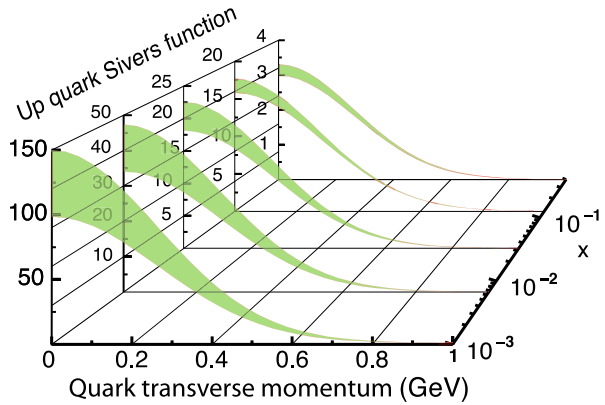
- DOE requested a science review conducted by a panel appointed by the National Academy of Science (NAS)
  - Expect report by ~July 2018 (?)

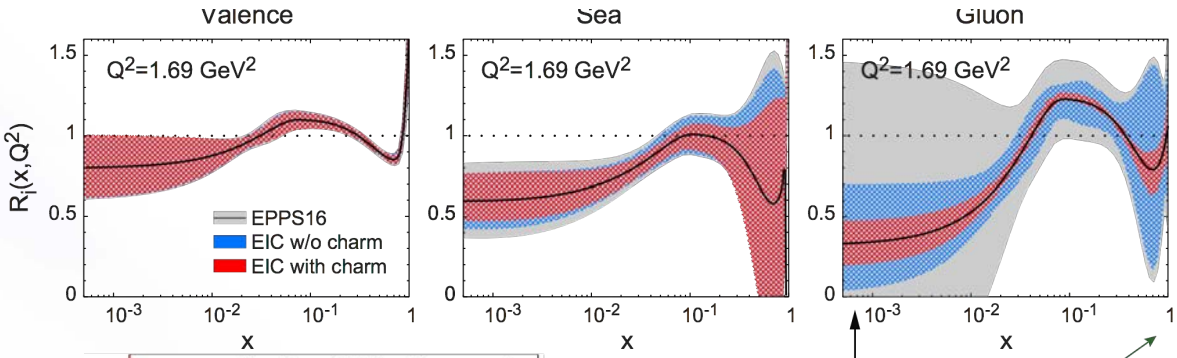
- Positive NAS review will trigger the DOE's CD process
  - CD0 ("critical need for science") FY19 after NAS report
  - CD1 after EIC design technical/cost review & site selection (FY20-FY21)
  - Major Construction funds ("CD3") earliest by FY23"
    - Assuming 1.6% sustained increase over inflation of the next several years (Long Range Plan) as discussed in the US LRP

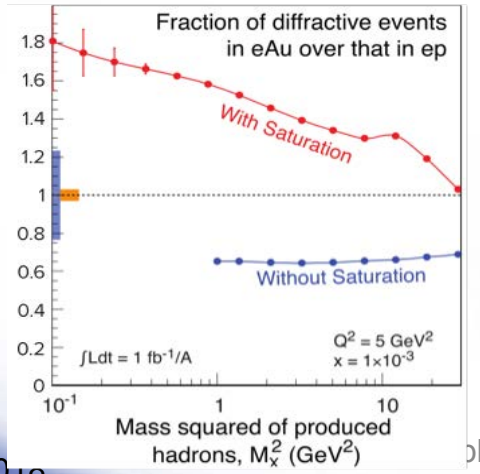


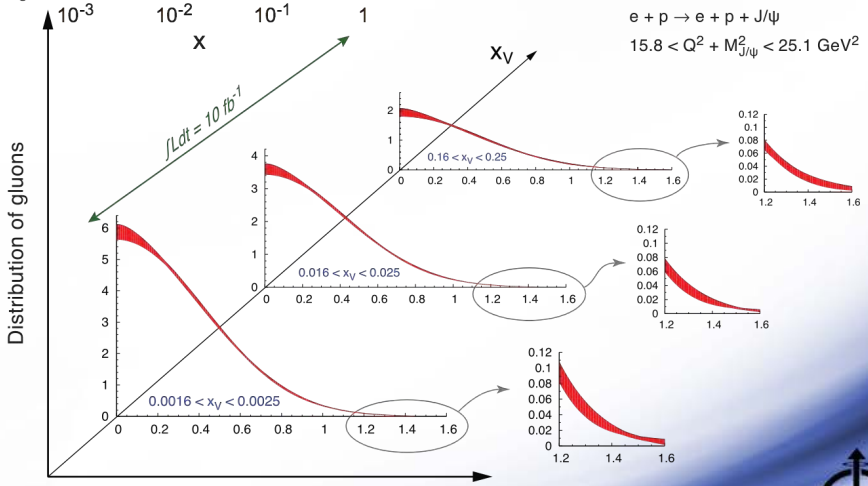
Summary of EIC Results 2028-2032: @ DIS2032











Summary

- The EIC will profoundly impact our understanding of QCD and its dynamics ➔ the **structure of nucleons and nuclei in terms of sea quarks & gluons**
- The EIC will enable **imaging** and provide **unprecedented kinematic reach** into **yet unexplored regions of phase spaces in QCD** with its high luminosity/energy, nuclei & beam polarization

⇒***High potential for discovery within QCD with broad impact beyond***

- **O**utstanding questions raised by the science at BNL, CEBAF and CERN, and other hadron physics facilities around the world have **naturally led to the EIC Science & design parameters**
  - ❖**World wide interest** in collaborating on the EIC
- Accelerator scientists at BNL and JLab together with international accelerator scientists are providing the intellectual and technical leadership to realize this frontier accelerator facility.

Exciting times for Nuclear Science: 12 GeV → EIC

If you are not already part of it, now is a good time to join us!