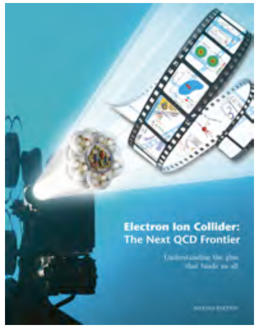
Center for Frontiers in Nuclear Science



The US Electron Ion Collider

Physics Overview and Realization Plans

Understanding the Glue That Binds Us All

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Stony Brook University

BROOKHAVEN NATIONAL LABORATORY

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:

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

(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 has Fundamental Consequences

Emergence of spin, mass & confinement, gluon fields

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

- 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)

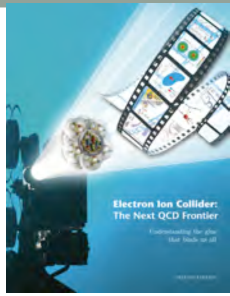
- Ultra-dense color (gluon) fields:
  - Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?

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

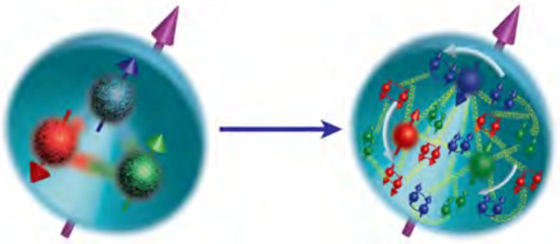
Experimental insight and guidance crucial for complete understanding of *how* hadrons & nuclei emerge from quarks and gluons

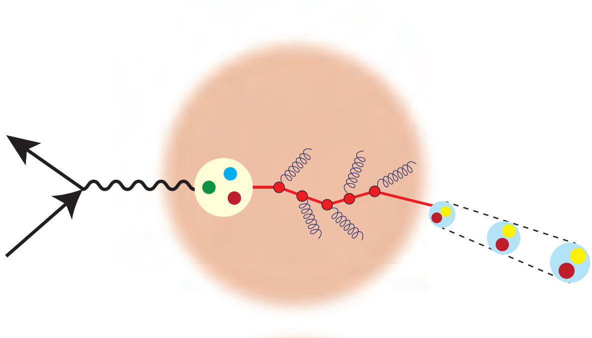


A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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?

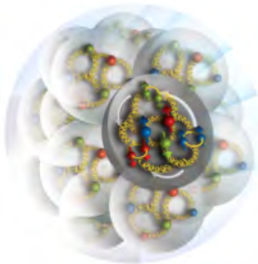




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

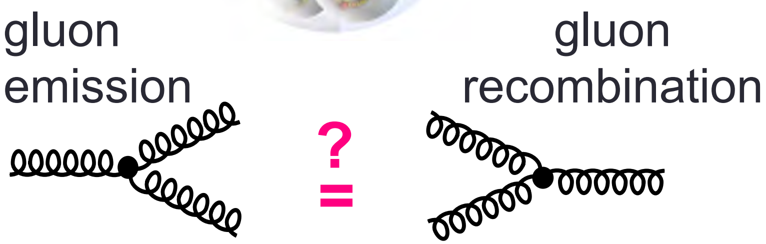
How do the confined hadronic states emerge from these quarks and gluons?

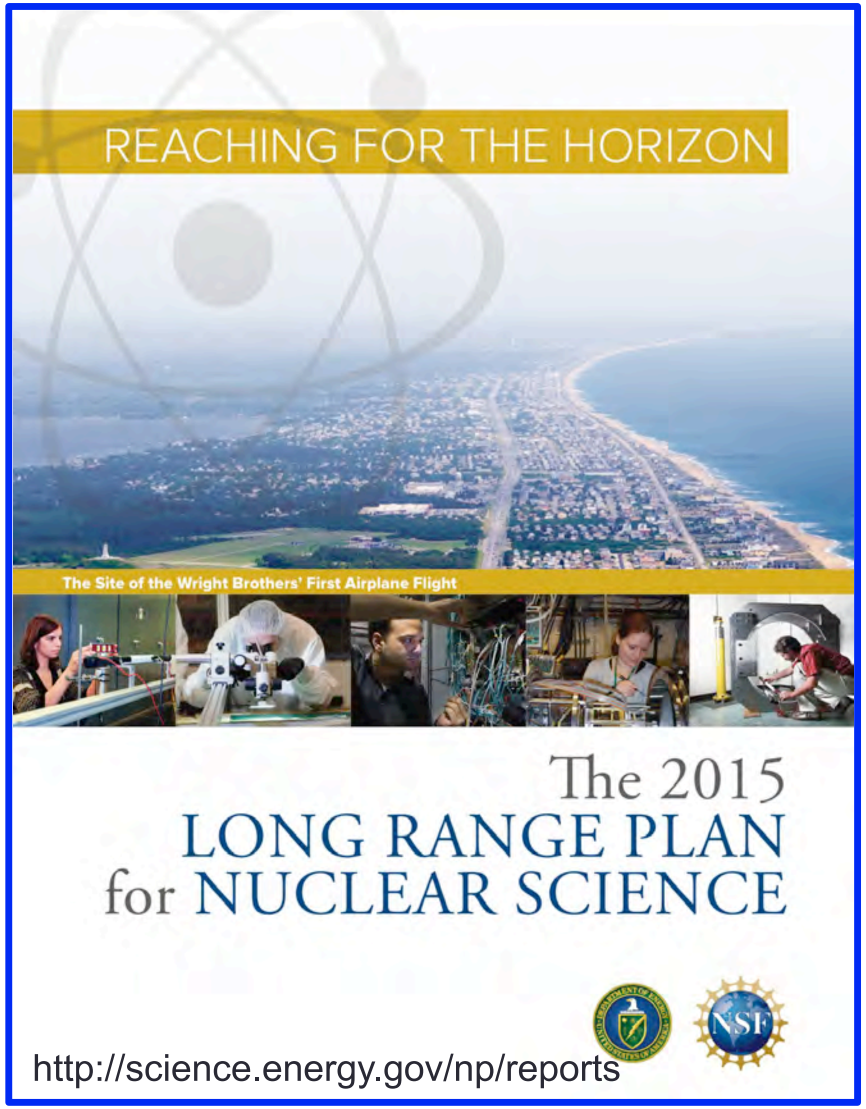
How do the quark-gluon interactions create nuclear binding?



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?





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

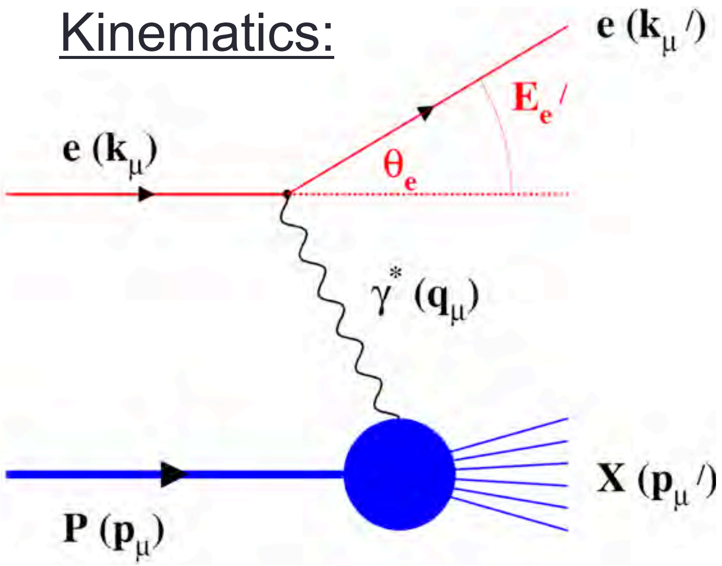
Increase anticipated soon after project officially begins

Since FY 2017

EIC Accelerator R&D already assigned $7M/yr

Deep Inelastic Scattering: Precision and control

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$s = 4\,E_t\,E_e \qquad x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu};\ p_t \text{ with respect to } \gamma$$

Inclusive events:

e+p/A → e'+X

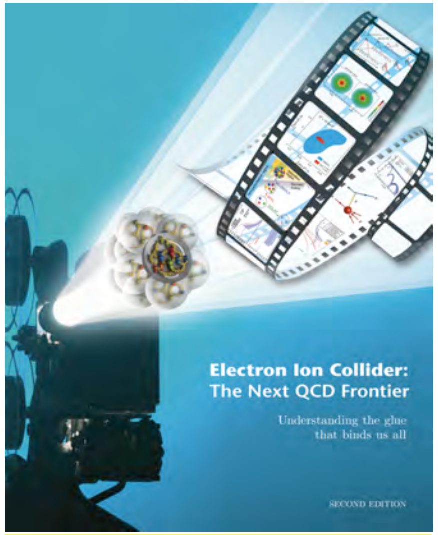
detect only the scattered lepton in the detector

Semi-inclusive events:

e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with identified hadrons/jets in the detector

The Electron Ion Collider



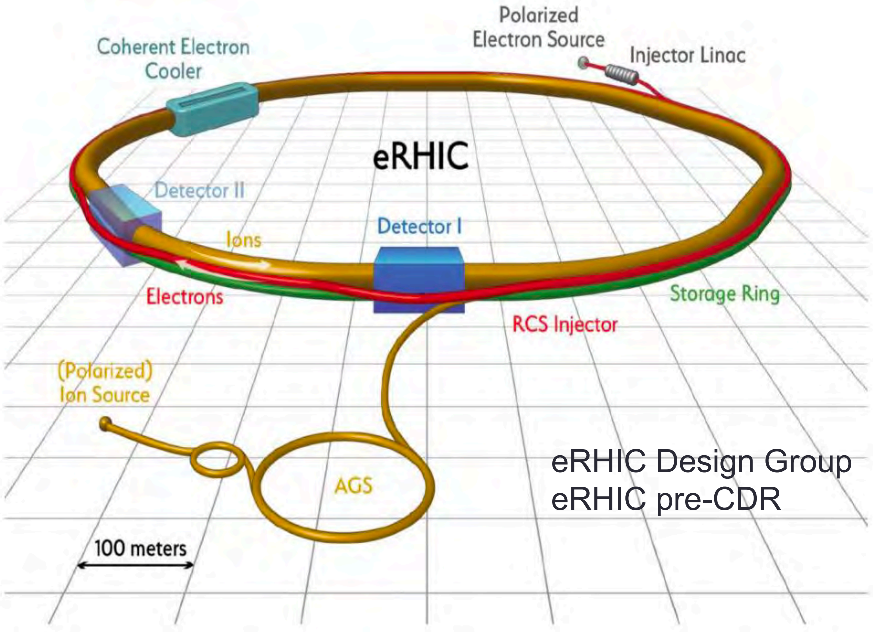
1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

For e-N collisions at the EIC:
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} 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

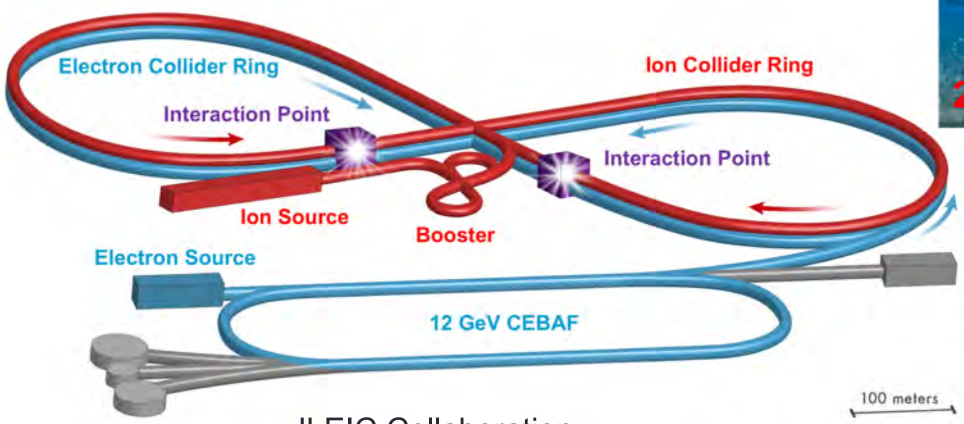
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure



eRHIC Design Group
eRHIC pre-CDR

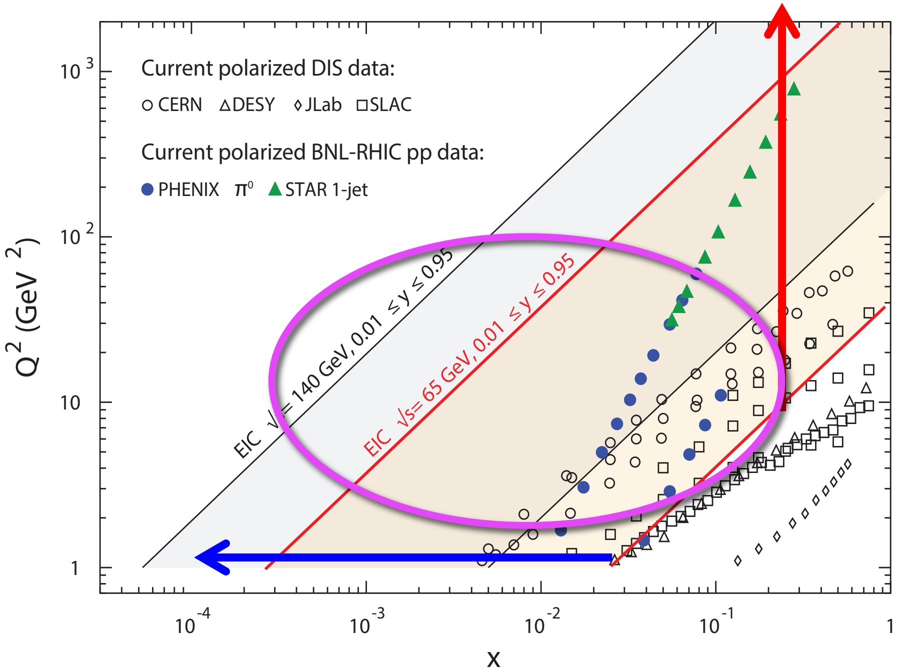
2018



JLEIC Collaboration
JLEIC Pre-CDR

The Science Of EIC

EIC: Kinematic reach & properties

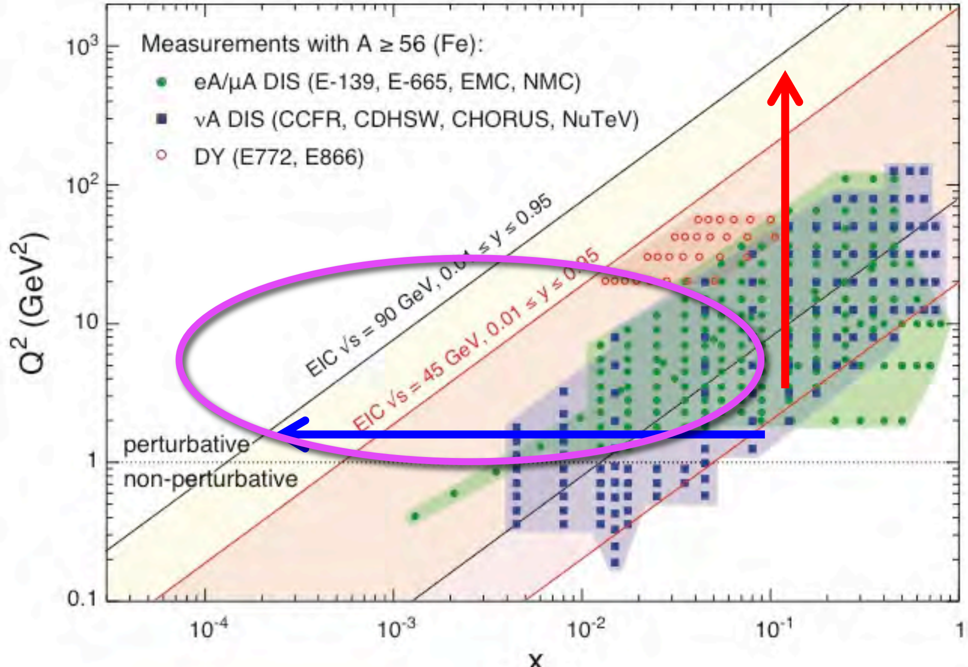


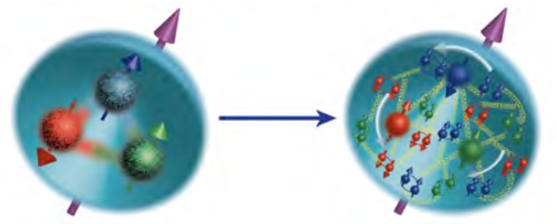
For e-N collisions at the EIC:

- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



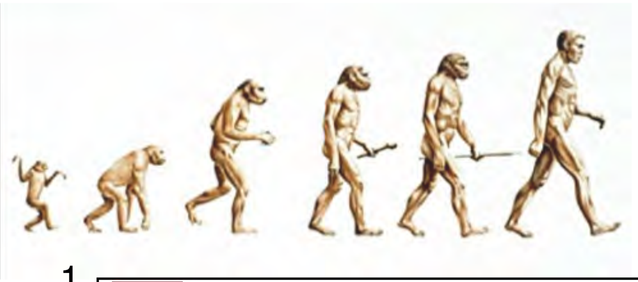


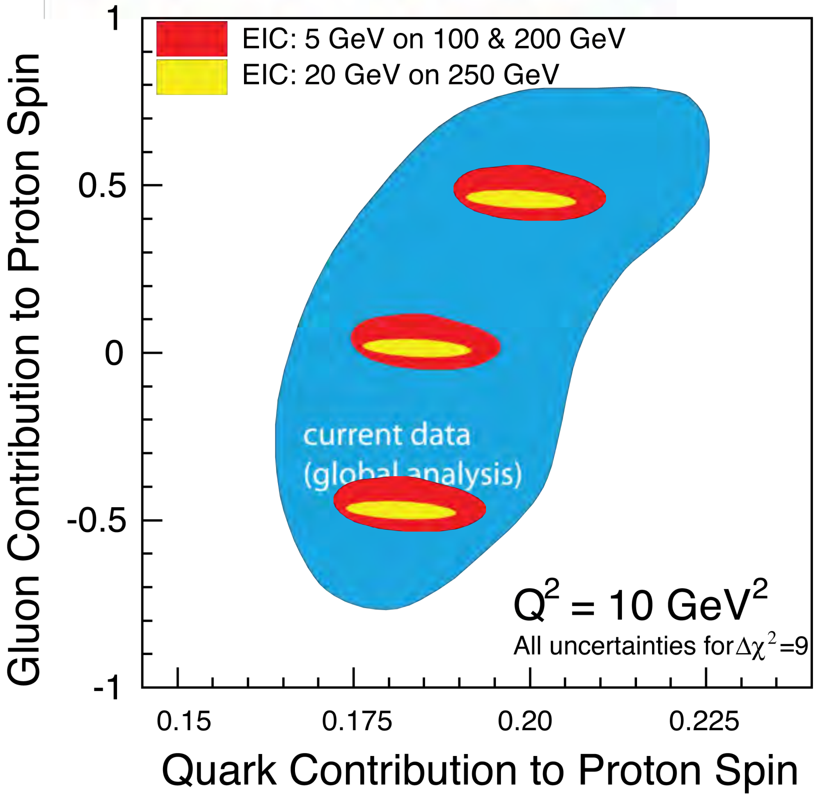
Understanding of Nucleon Spin

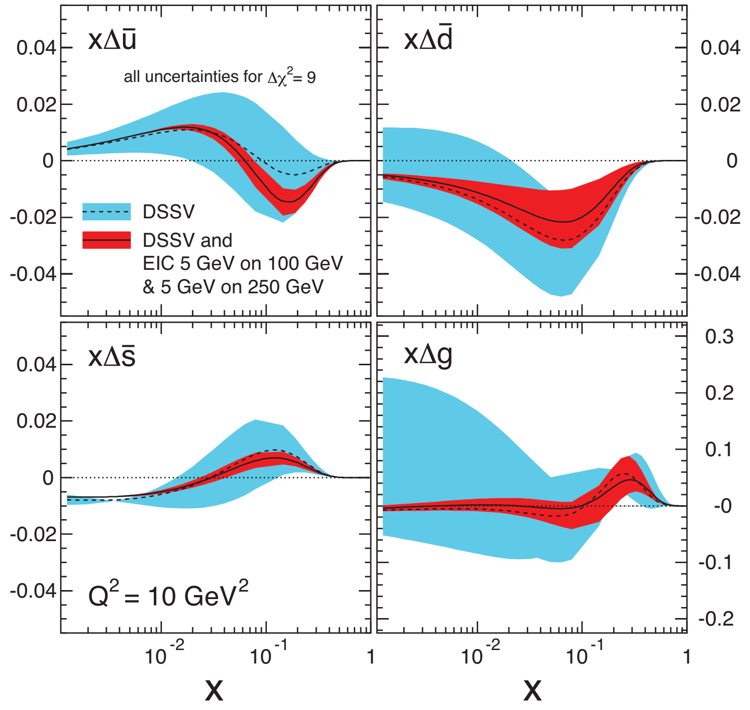
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

Precision in $\Delta\Sigma$ and Δg ➔ A clear idea Of the magnitude of L_Q+L_G







3-Dimensional Imaging Quarks and Gluons

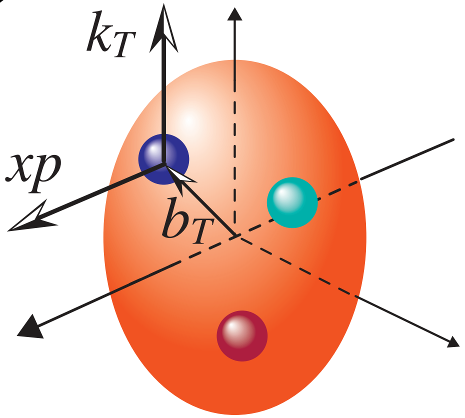
Wigner functions $W(x,b_T,k_T)$

offer unprecedented insight into confinement and chiral symmetry breaking.

$W(x,b_T,k_T)$

Momentum space $\int d^2b_T$ → $f(x,k_T)$

$\int d^2k_T$ ***Coordinate space*** → $f(x,b_T)$



Spin-dependent 3D momentum space images from semi-inclusive scattering
→ **TMDs**

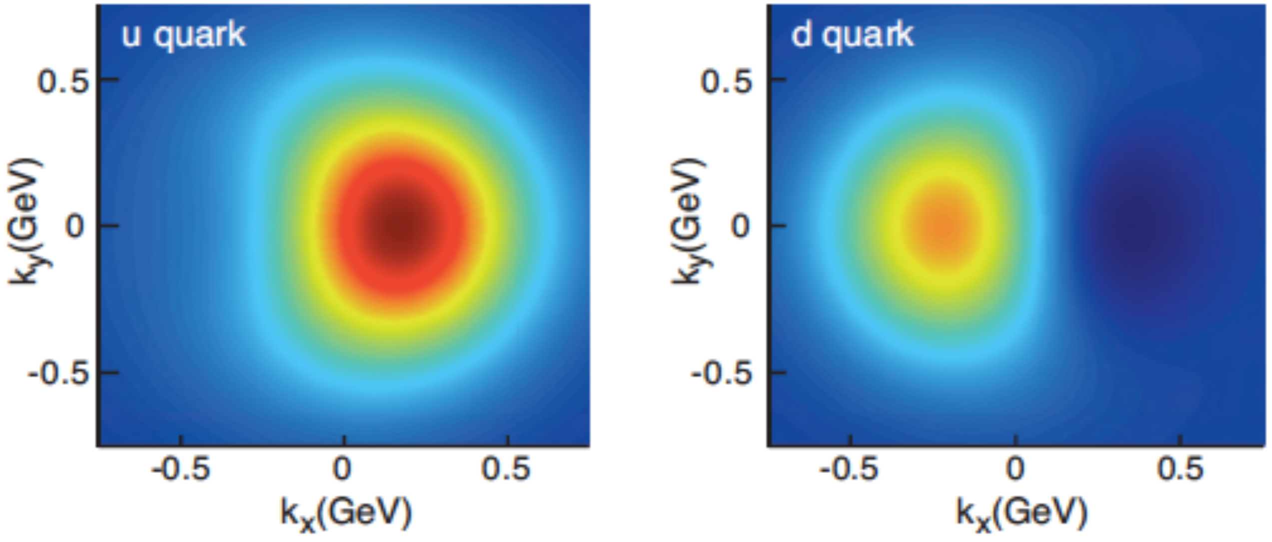
Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply Virtual Compton Scattering and Deeply Virtual Vector Meson production)
→ **GPDs**

Position and momentum → Orbital motion of quarks and gluons

2+1 D partonic image of the proton with the EIC

Spin-dependent 3D momentum space images from semi-inclusive scattering

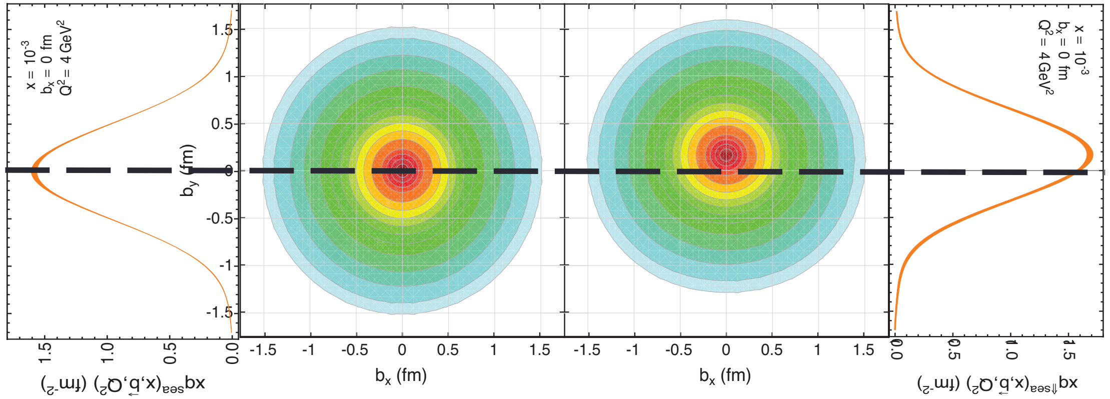
Transverse Momentum Distributions



Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

sea-quarks
unpolarized polarized

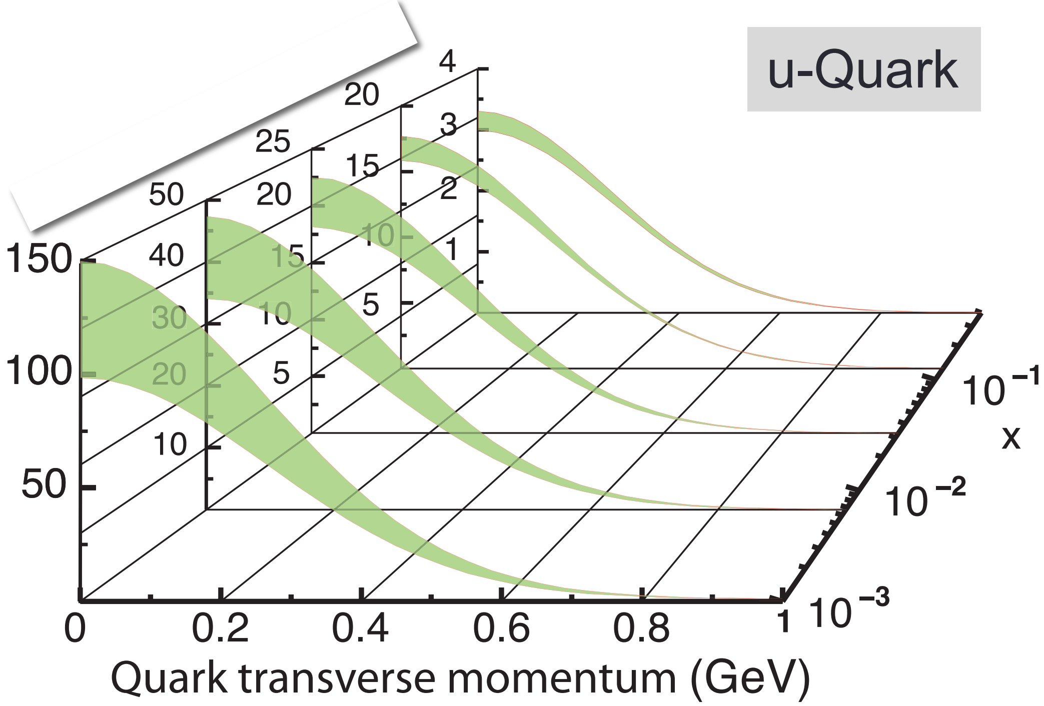


2+1 D partonic image of the proton with the EIC

Spin-dependent 3D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions

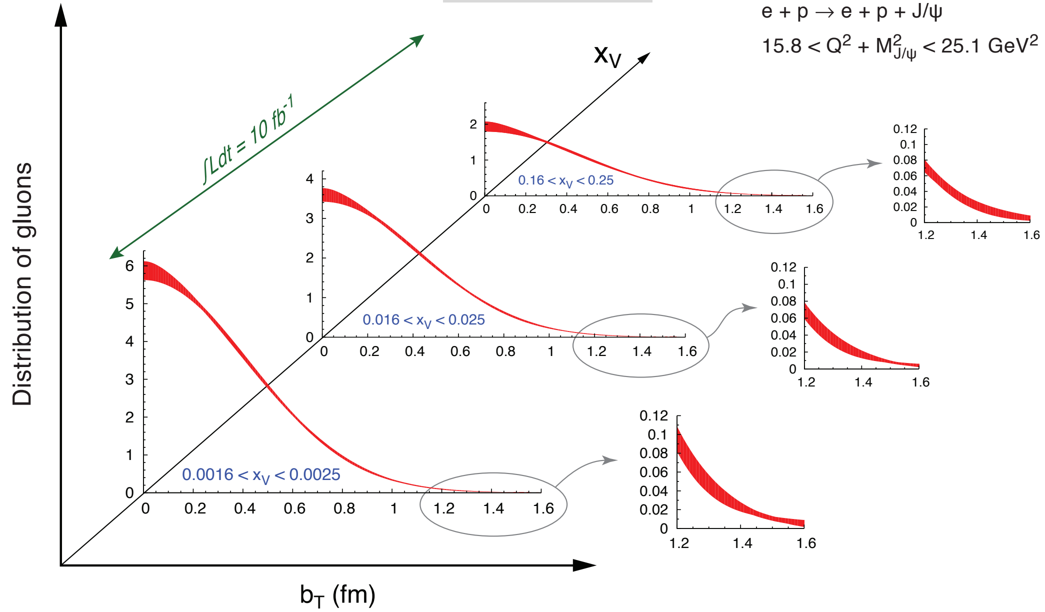
u-Quark



Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

Gluons

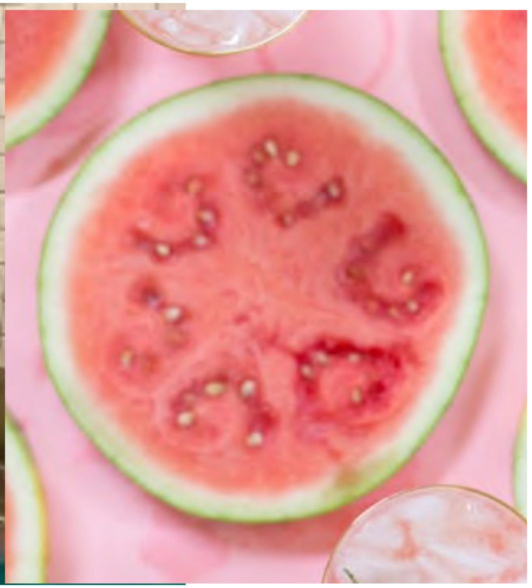


Study the evolution of momentum and position distributions over wide range in x

Study of internal structure of a watermelon:

A-A (RHIC)

1) Violent collision of melons



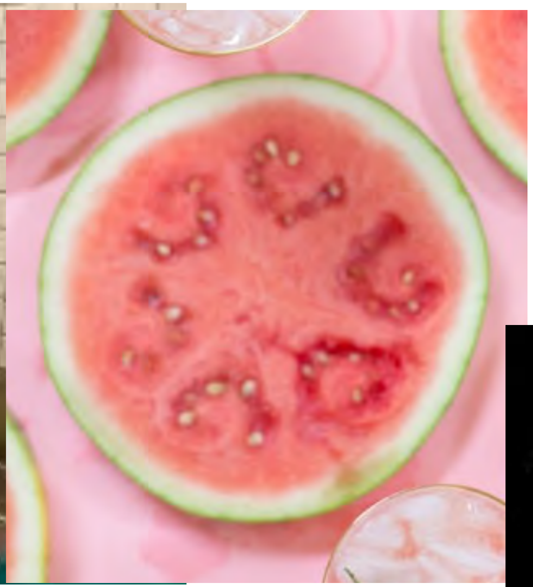
2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

Study of internal structure of a watermelon:

A-A (RHIC)

1) Violent collision of melons



2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

3) MRI of a watermelon

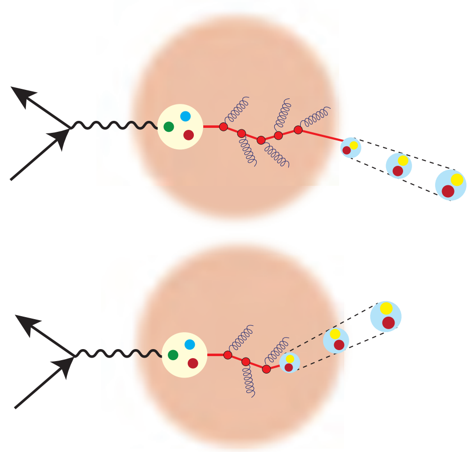
Non-Violent e-A (EIC)

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

Unprecedented ν, the virtual photon energy range @ EIC : *precision & control*

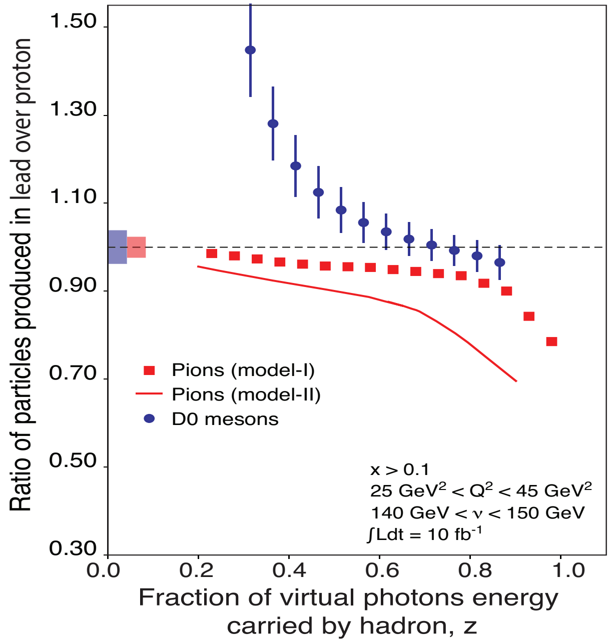
$$\nu = \frac{Q^2}{2mx}$$



Control of ν by selecting kinematics;
Also under control the nuclear size.

(colored) Quark passing through cold QCD matter emerges as color-neutral hadron ➔ Clues to color-confinement?

Energy loss by light vs. heavy quarks:



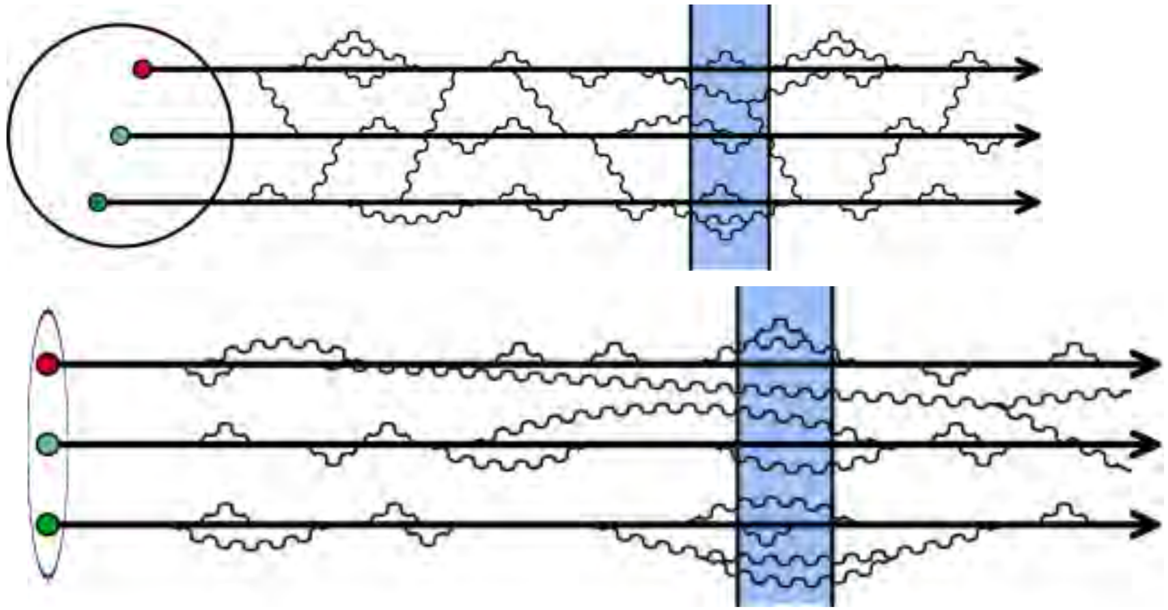
Identify π vs. D^0 (charm) mesons in e-A collisions:
Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

Need the collider energy of EIC and its control on parton kinematics

How does a Proton look at low and very high energy?

Low energy: High x
Regime of fixed target exp.

High energy: Low- x
Regime of a Collider

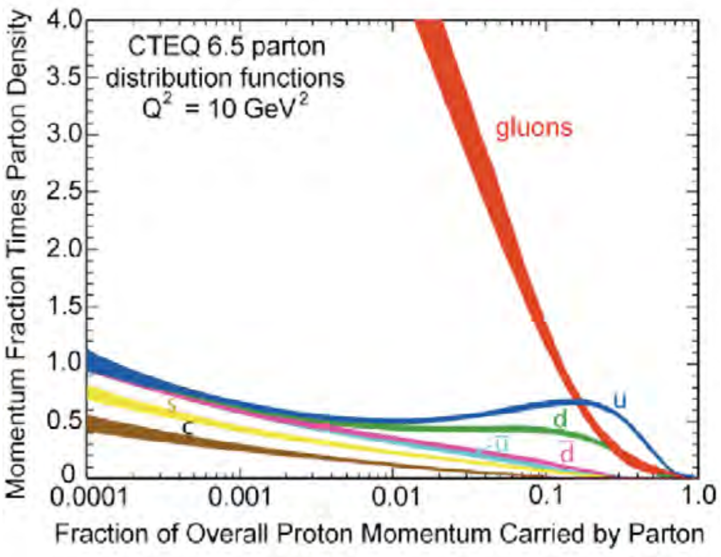


Cartoon of boosted proton

At high energy:

- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate further smaller x gluons ➔ which intern radiate more……. Leading to a **runaway growth?**

What do we learn from low-x studies?

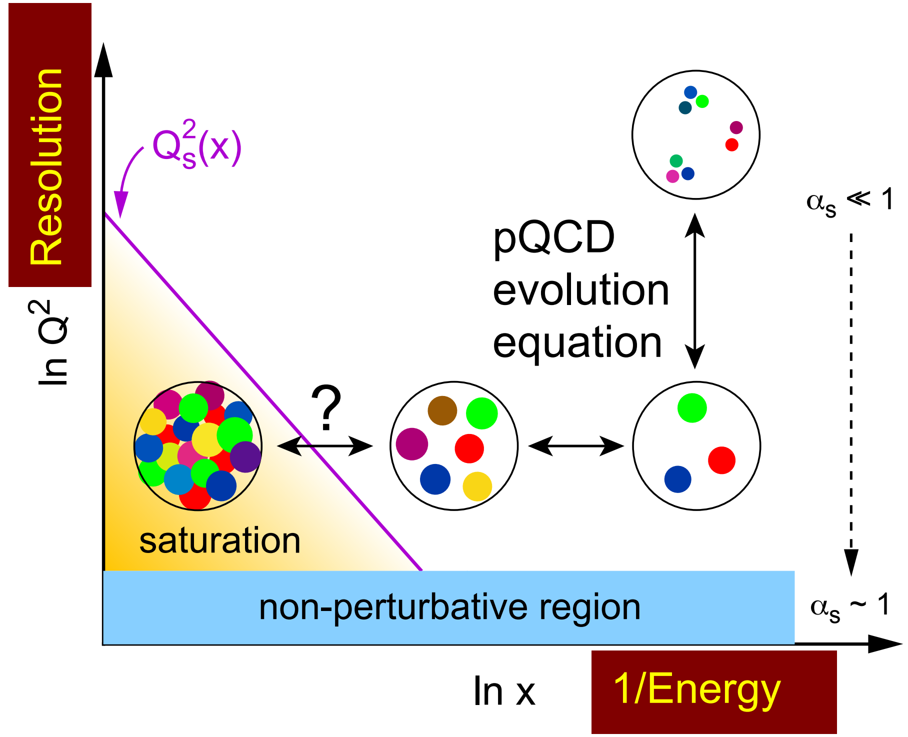


What tames the low-x rise?

- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable

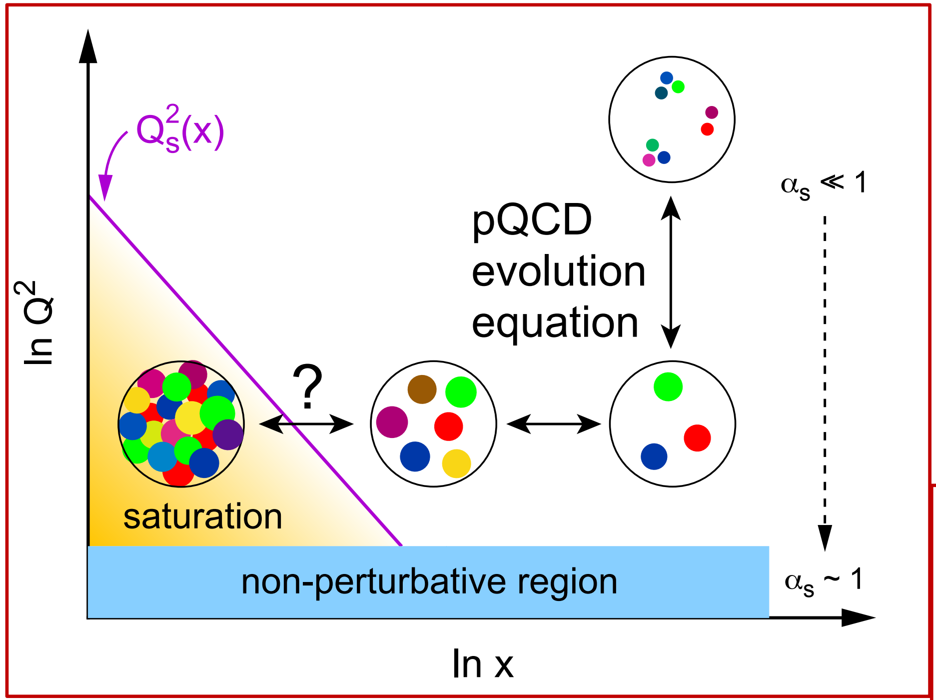
gluon emission = gluon recombination

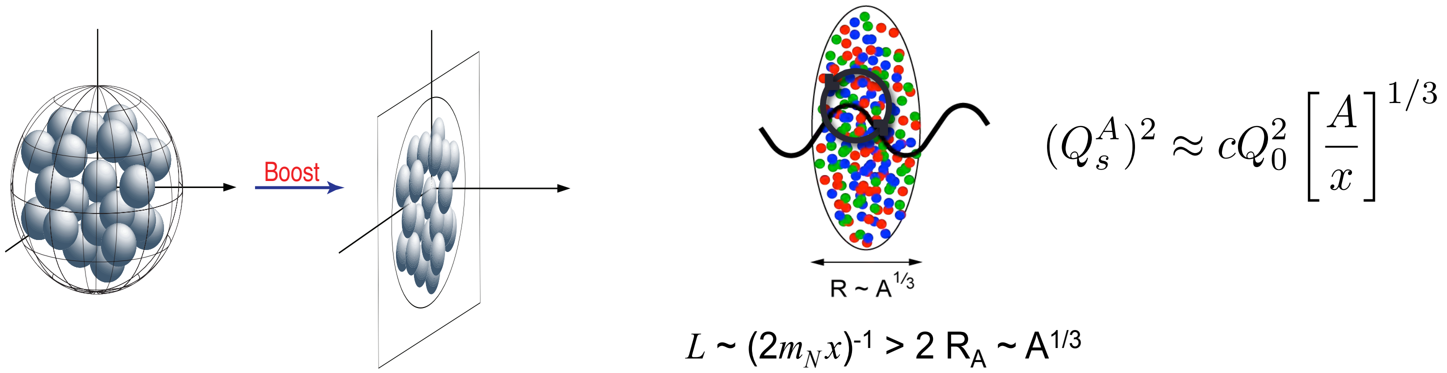
At Q_S

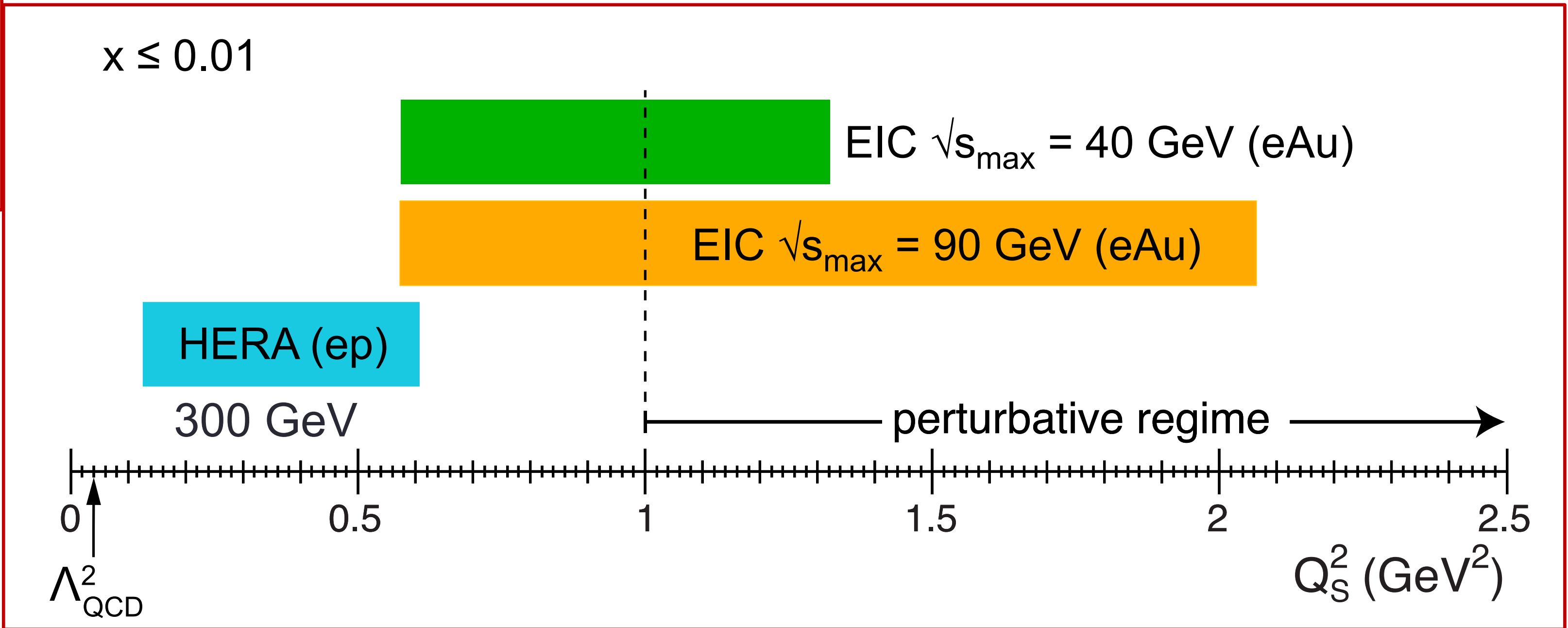


First observation of gluon recombination effects in nuclei:
➔leading to a *collective* gluonic system!
First observation of g-g recombination in *different* nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

Advantage of the nucleus over proton

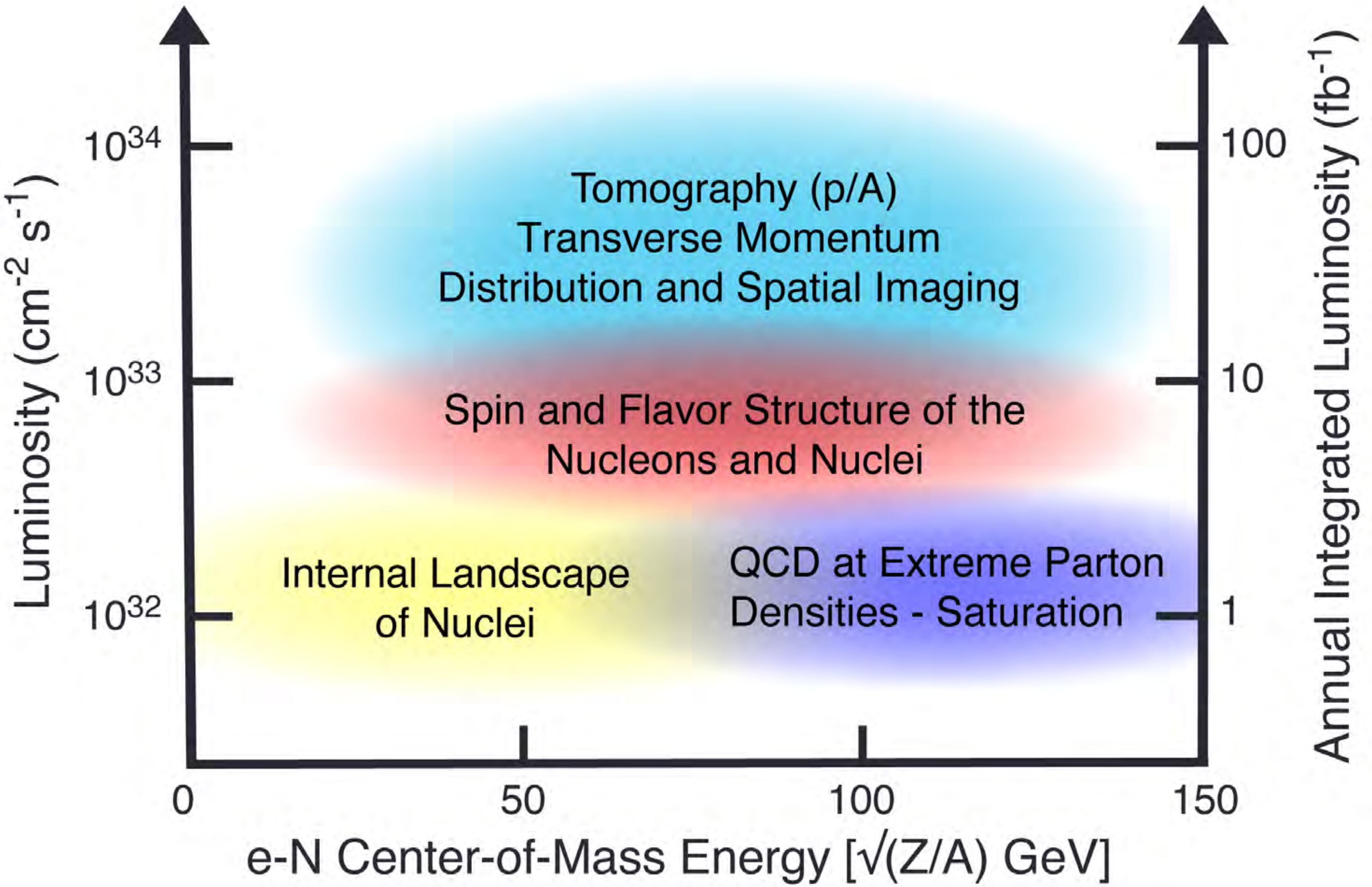


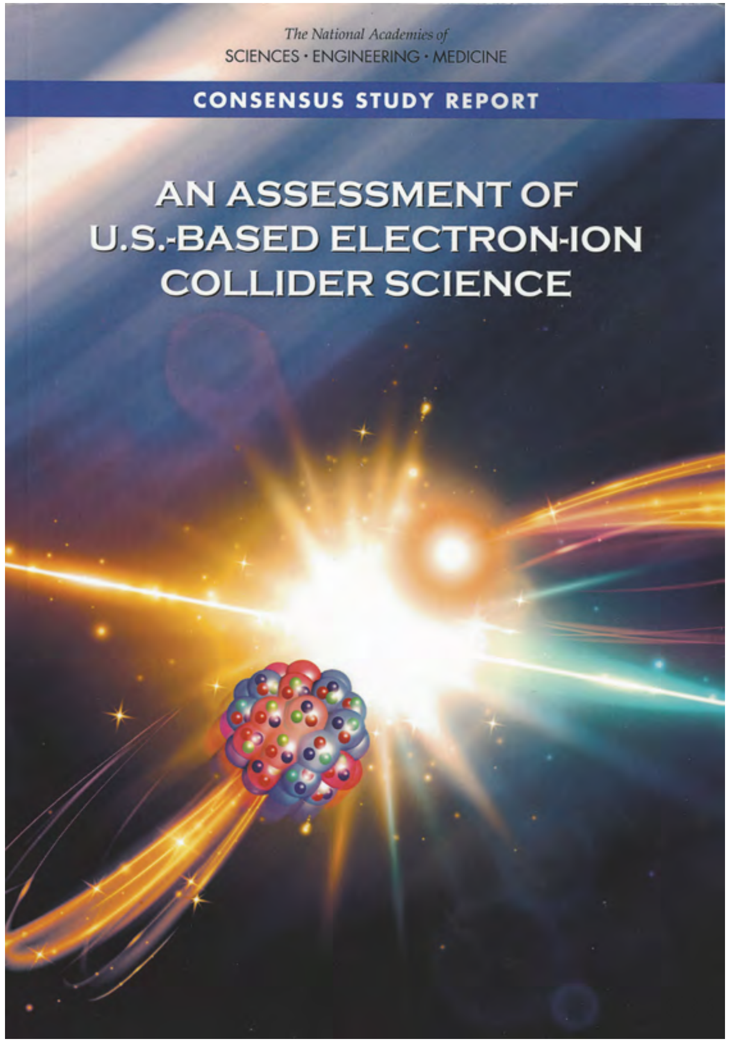




Accessible range of saturation scale $Q_s{}^2$ at the EIC with e+A collisions. arXiv:1708.01527

Summary: EIC Physics: CM vs. Luminosity vs. Integrated luminosity





Consensus Study Report on the US based Electron Ion Collider

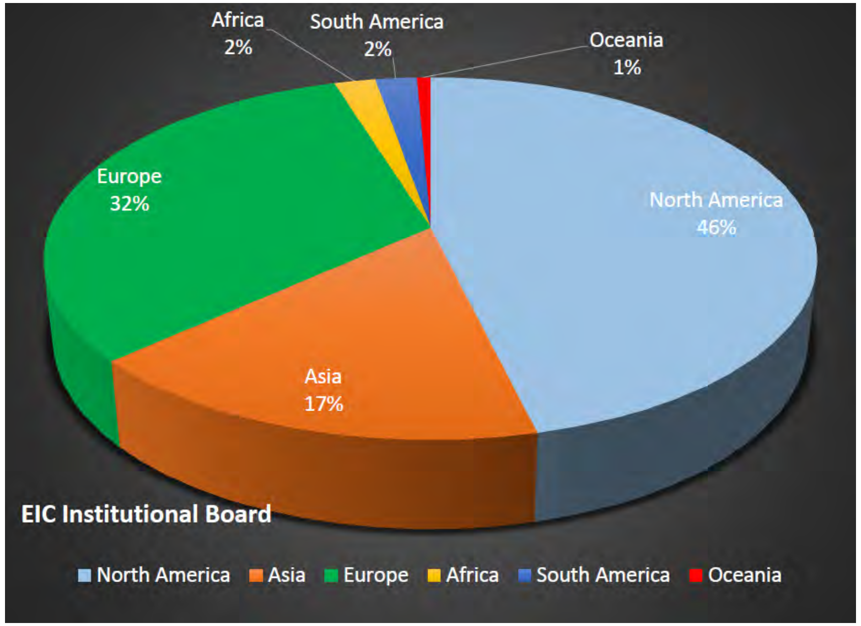
Summary:

The science questions that an EIC will answer *are central* to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would *advance accelerator science and technology* in nuclear science; it would as well *benefit other fields of accelerator based science and society*, from medicine through materials science to elementary particle physics

The EIC Users Group: EICUG.ORG

Formally established in 2016
890+ Ph.D. Members from 30 countries, 189 institutions

New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC² at Jefferson Laboratory



EICUG Structures in place and active.

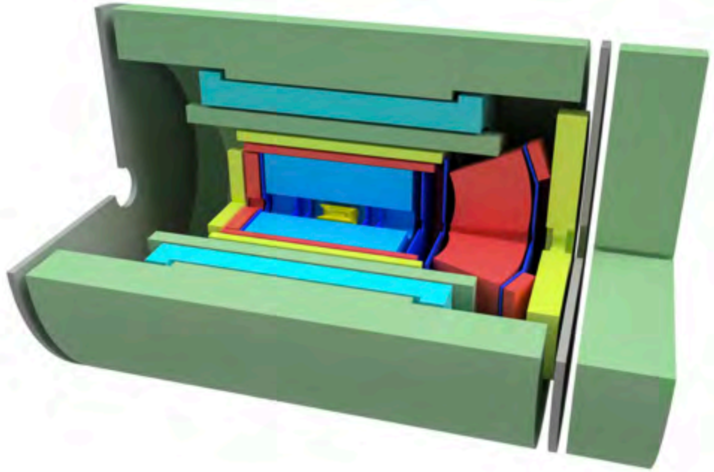
EIC UG Steering Committee
EIC UG Institutional Board
EIC UG Speaker's Committee

Task forces on:
-- Beam polarimetry
-- Luminosity measurement
-- Background studies
-- IR Design

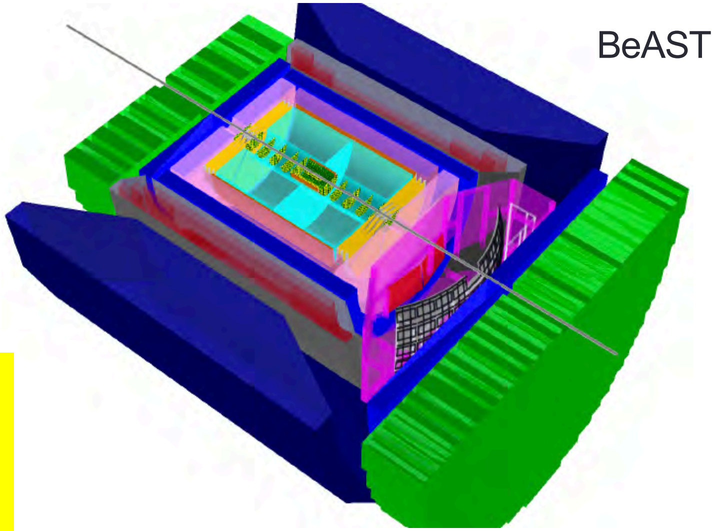
Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**, **FIU (2020)**, **Warsaw (2021)**

EIC Detector Concepts: integration of detectors in to machine lattice

EIC Day 1 detector, with BaBar Solenoid

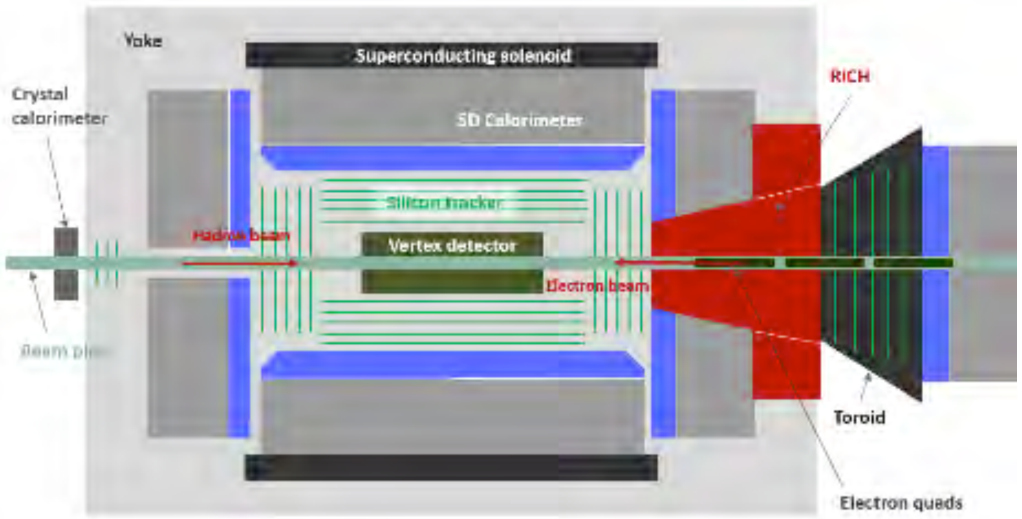


BeAST at BNL

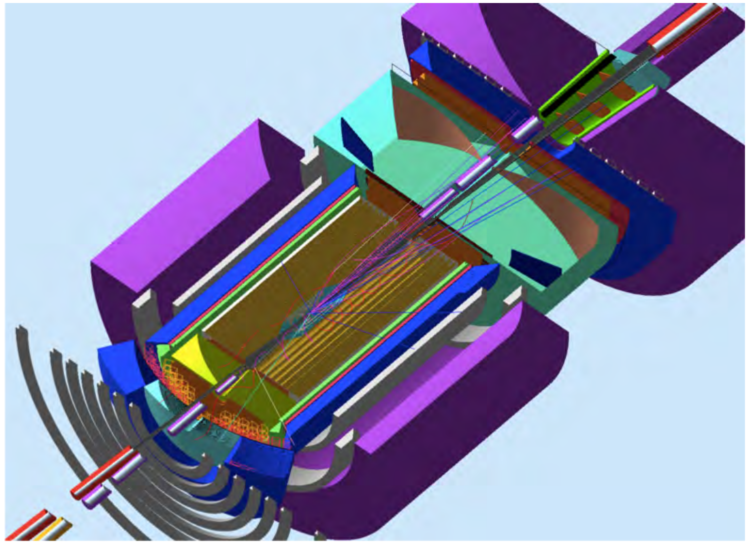


Ample opportunity and need for additional contributors and collaborators

TOPSiDE: Time Optimized PID Silicon Detector for EIC



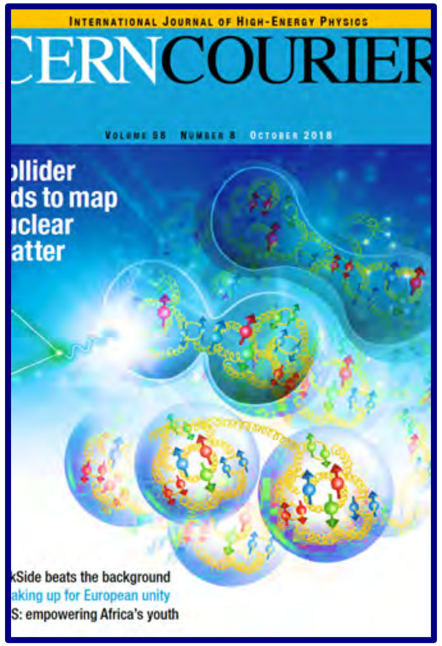
JLEIC Detector Concept, with CLEO Solenoid



Opportunities for YOU: Physics beyond the EIC White Paper:

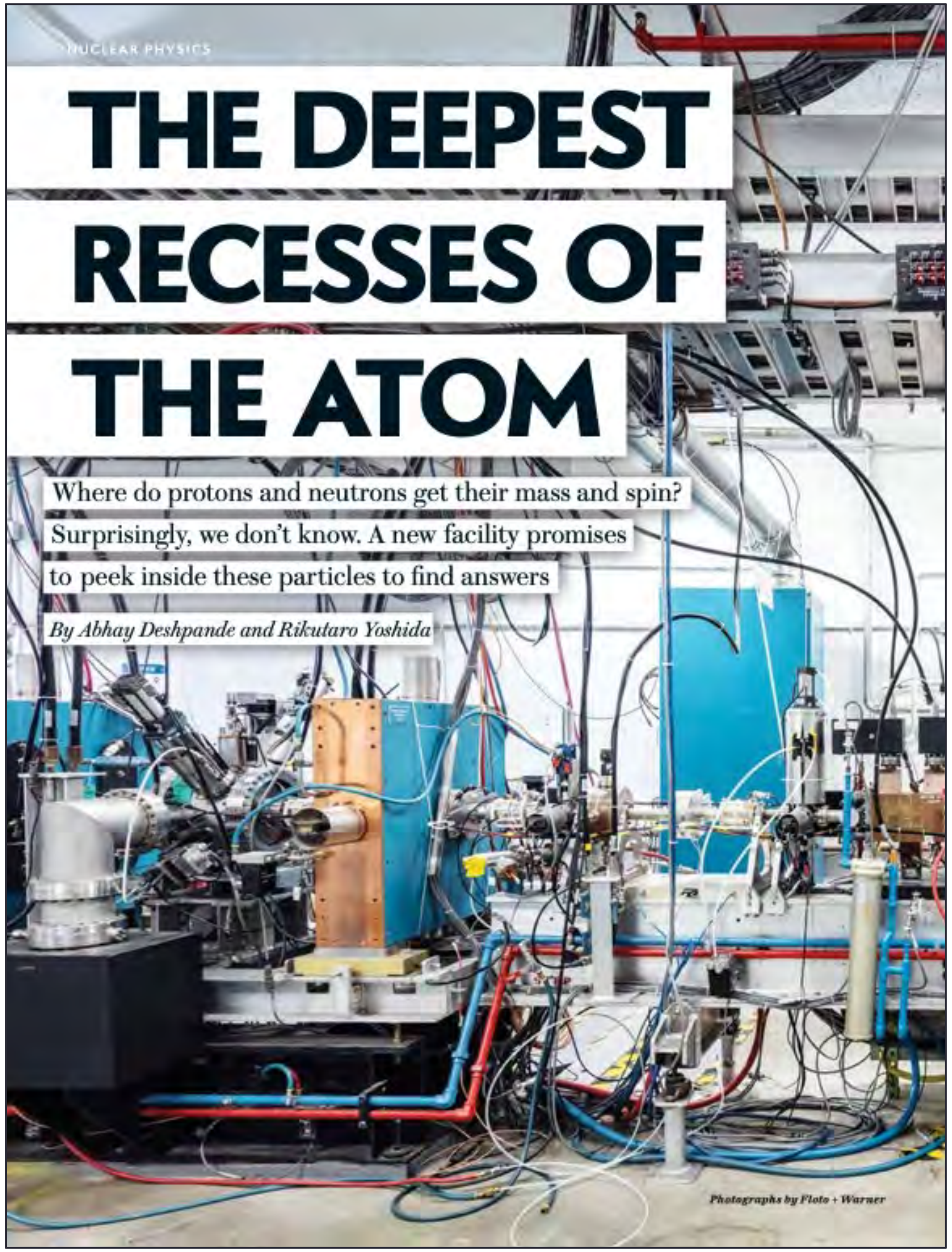
- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??) Does polarization of hadron play any role?
- Quark Exotica: 4,5,6 quark systems…?
- Impact of precision measurements of unpolarized PDFs, especially at high x, for LHC
- What role would TMDs in e-p play in W-Production at LHC?
- Study of jets: Internal structure of jets
- Jet propagation in nuclei… energy loss in cold QCD medium: a topic interest
- Initial state affects QGP formation!….. p-A, d-A, A-A at RHIC and LHC: many puzzles
- Gluon TMDs at low-x!
- Polarized light nuclei in the EIC
- Entanglement entropy in nuclear medium and its connections to fragmentation, hadronization and confinement

R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)



E. Aschenauer
R. Ent
October 2018

A. Deshpande
& R. Yoshida
June 2019



Summary:

- Science of EIC: Gluons that bind us all… understanding their role in QCD
- EIC's precision, control and versatility will revolutionize our understanding QCD
  - 3D nucleon/nuclear structure, cold nuclear matter & physics high gluon density
- The US EIC project has significant momentum on all fronts right now:
  - National Academy's positive evaluation → Science compelling, fundamental and timely
  - Funding agencies taking note of the momentum: not just in the US but also internationally
- The science of EIC, technical designs (eRHIC and JLEIC) moving forward
  - Pre-CDRs prepared by BNL (eRHIC) and JLab: machine & IR designs
  - Independent Cost Review underway ➔ CD0 anticipated soon. Siting decision process also underway.

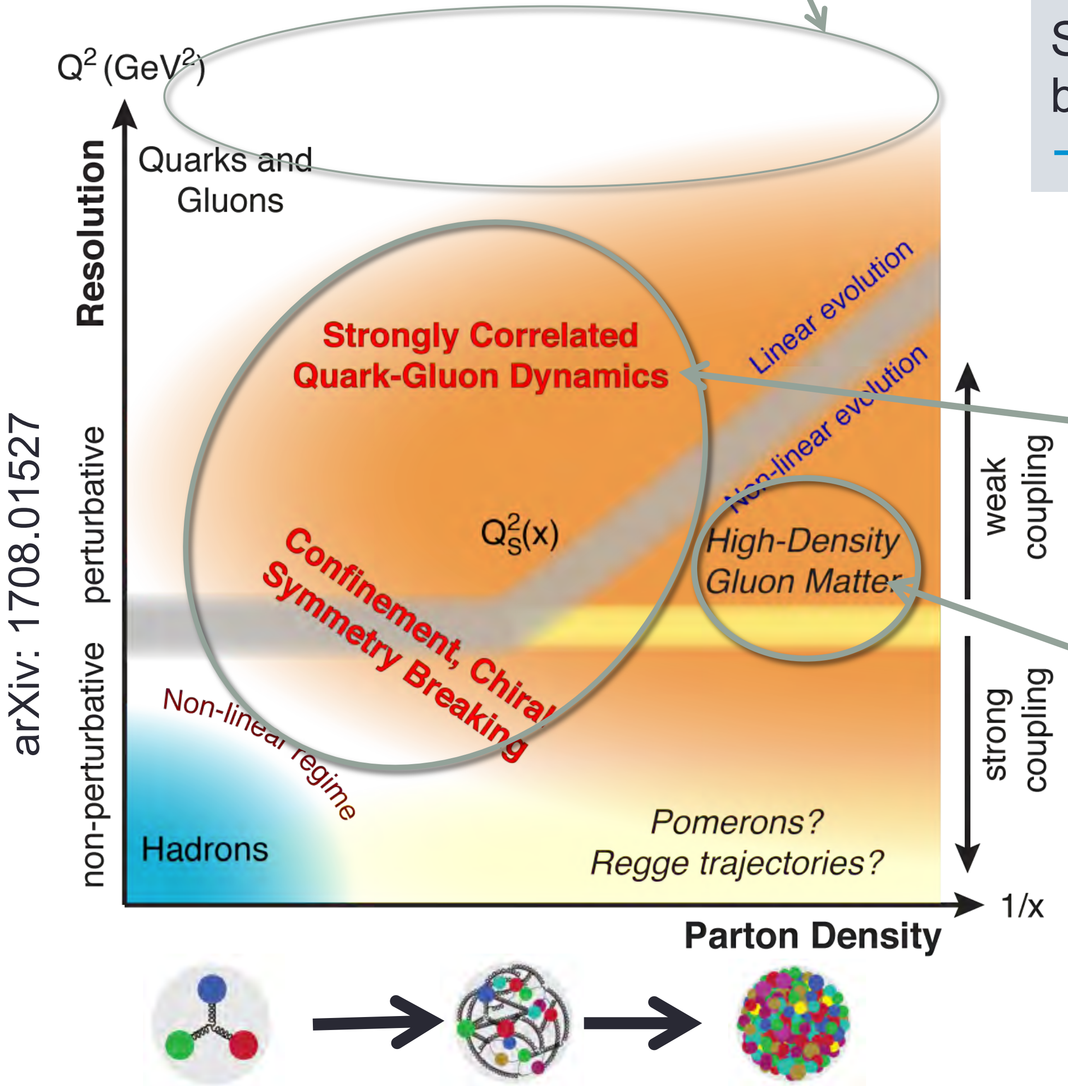
Technically driven schedule: 1^{st} collisions in about 10 years

Thank you.

QCD Landscape to be explored by a future facility

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

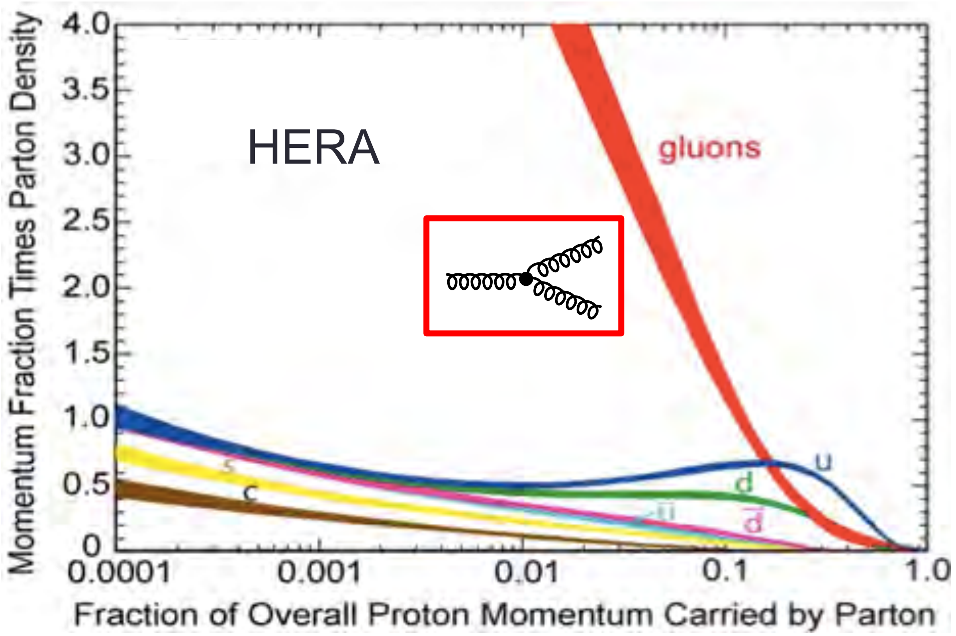


Systematically explore correlations in this region.

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

Gluon and the consequences of its interesting properties:

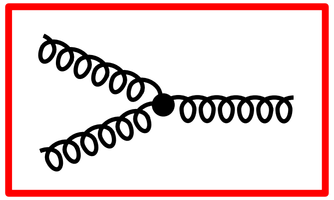
Gluons carry color charge ➔ Can interact with other gluons!



Apparent "indefinite rise" in gluon distribution in proton!

What could **limit this indefinite rise?** → saturation of soft gluon densities via gg→g recombination must be responsible.

recombination

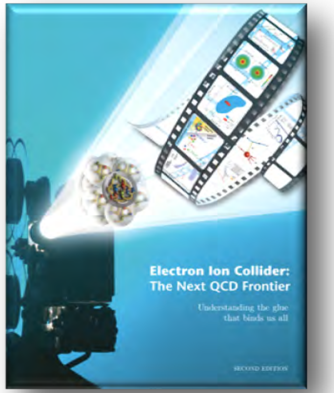


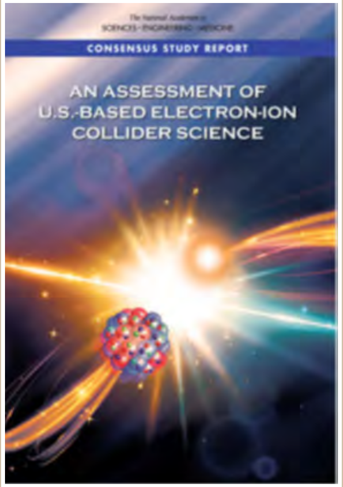
Where? No one has unambiguously seen this before!

If true, effective theory of this →"Color Glass Condensate"

In order to definitively answer the compelling scientific questions elaborated in Chapter 2, including the origin of the mass and spin of the nucleon and probing the role of gluons in nuclei, a new accelerator facility is required, an electron-ion collider (EIC) with unprecedented capabilities beyond previous electron scattering programs. An EIC must enable the following:

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

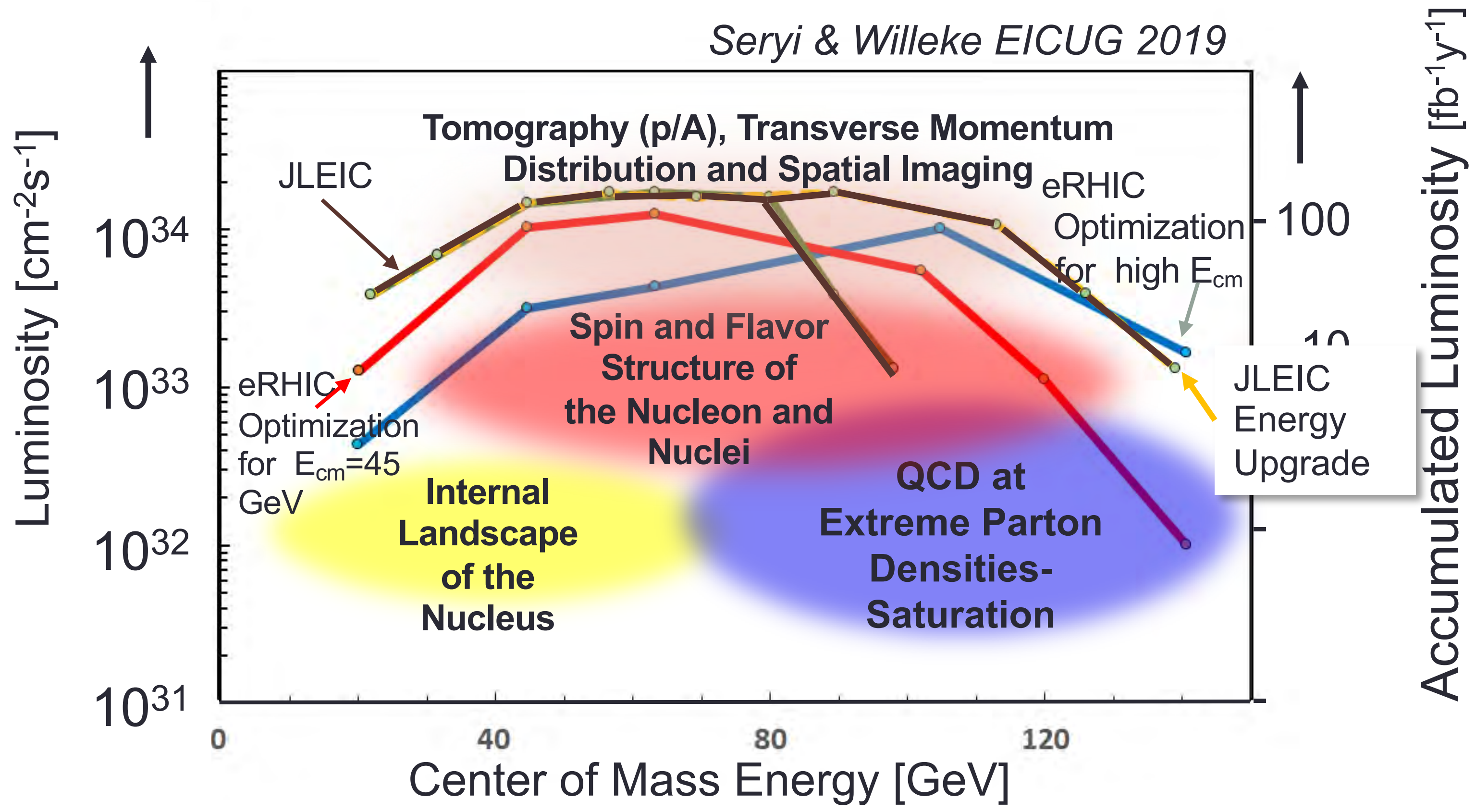




NAS Study endorses machine parameters suggested by the 2012 White Paper and 2015 NSAC Long Range Plan

Luminosity calculations for the EIC at BNL & JLab

IR Designs can be adjusted to obtain peak luminosity at different center of mass energies. The curves below show luminosity vs E_{cm} with IRs optimized for high or low center of mass energy. *With two IRs, in principle both optimization can coexist in the same machine*



For e-A collisions, the E_{cm} scale needs to be reduced by a factor $(Z/A)^{1/2}$

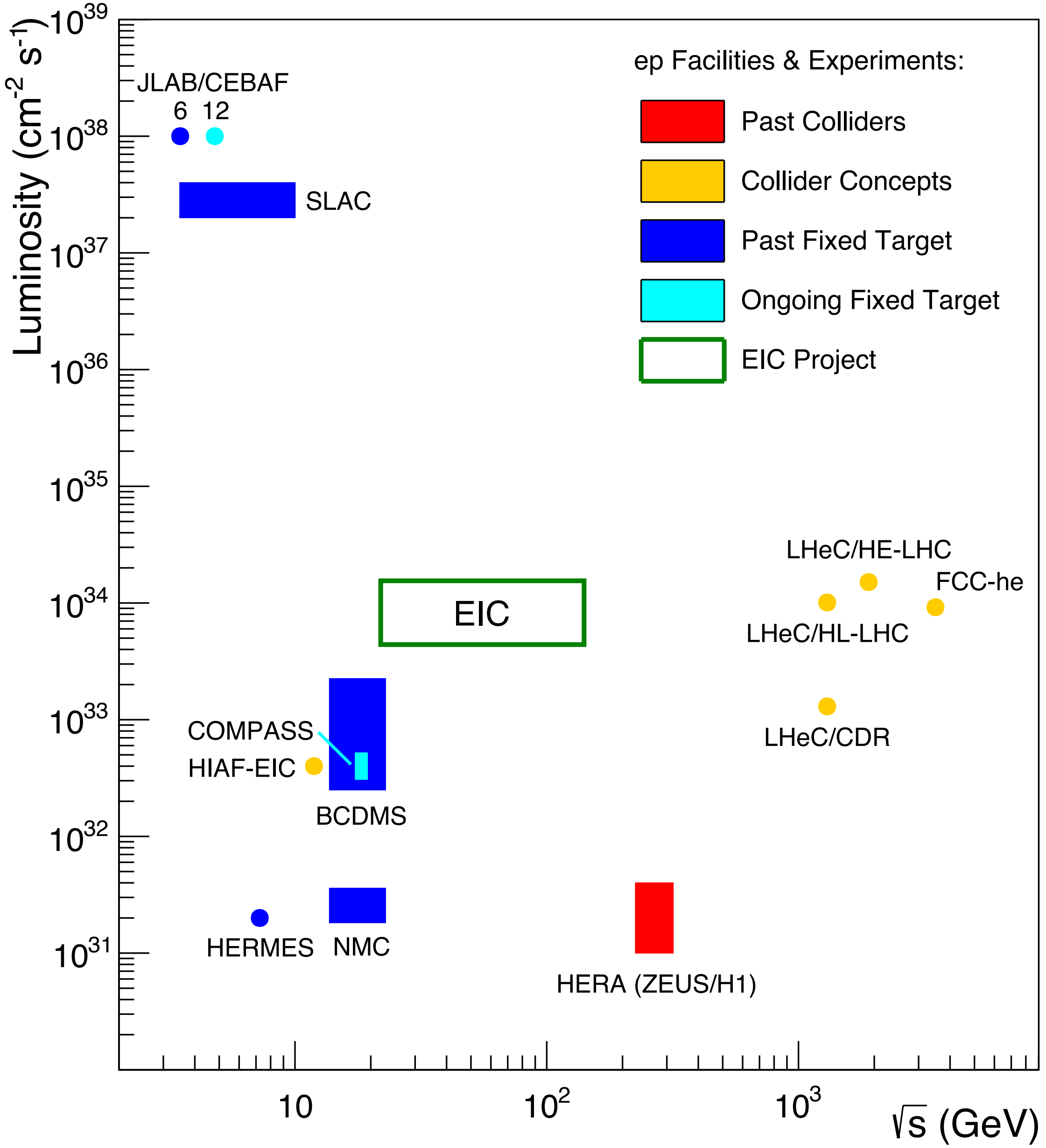
EIC @ JLab & Energy Upgrade

EIC @ BNL High energy optimization

EIC @ BNL Low energy optimization
(Motivated by interest of EICUG intermediate to high-x)

- Increased crossing angle to 50mrad
- Electron quads brought in closer: small β^*
- Increase number bunches

Uniqueness of the US EIC among all DIS Facilities



All DIS facilities in the world.

However, if we ask for:

- high luminosity & **wide reach in √s**

No other facility has or plans for
- **polarized lepton & hadron beams**
- **nuclear beams**

EIC stands out as a truly unique facility …