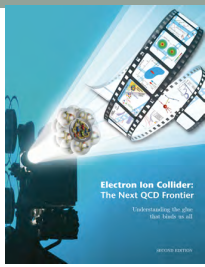
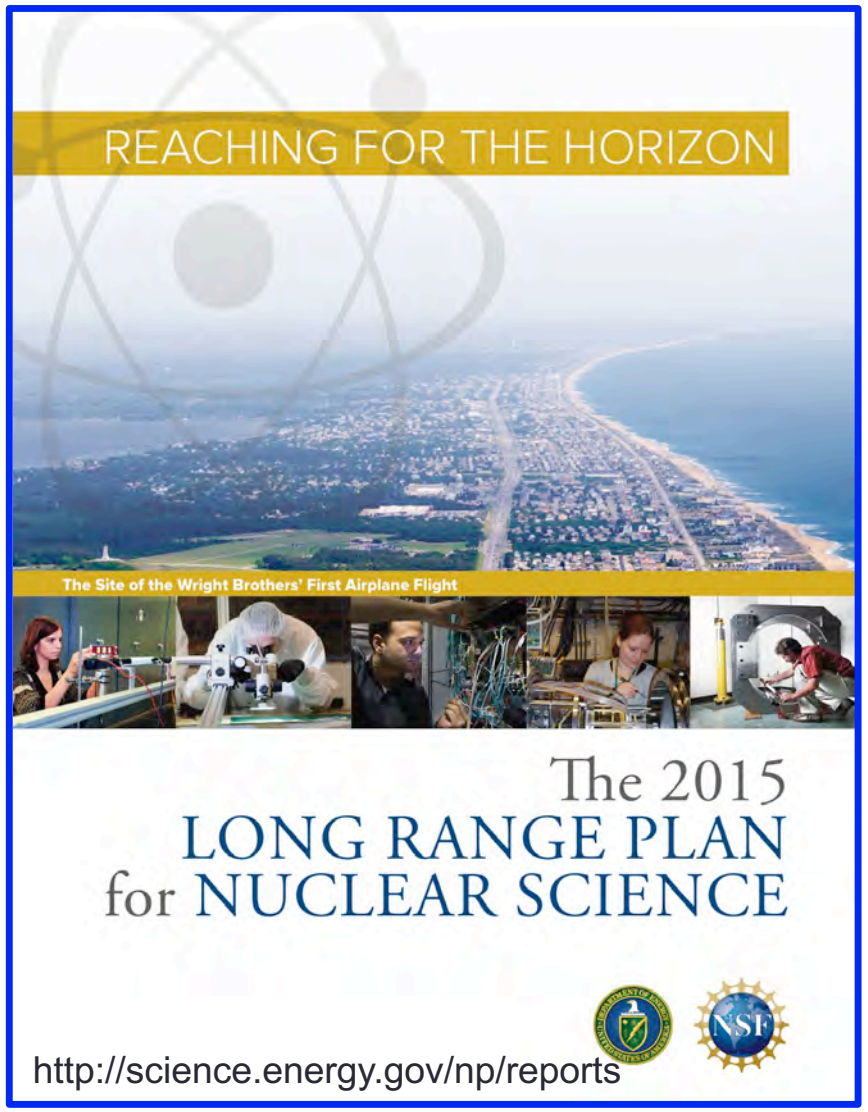
Center for Frontiers in Nuclear Science



Electron Ion Collider: The next QCD frontier

"Science: Compelling & fundamental, Realization: Timely"



RECOMMENDATION:

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

Initiatives:

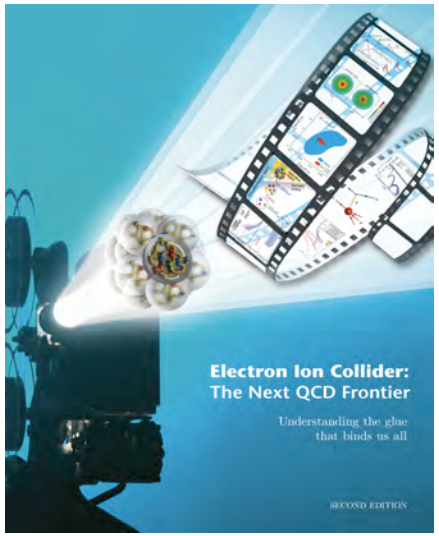
Theory

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

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:

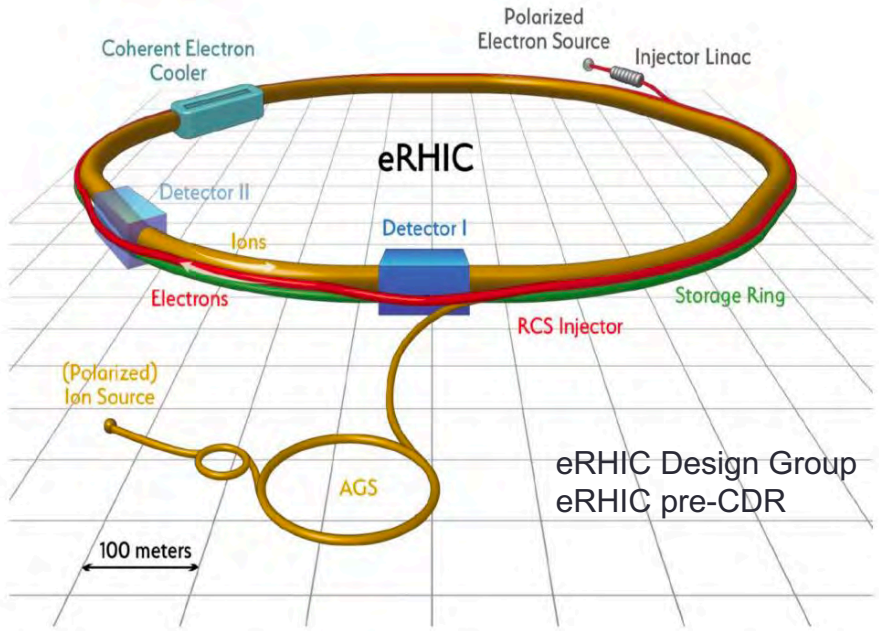
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

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

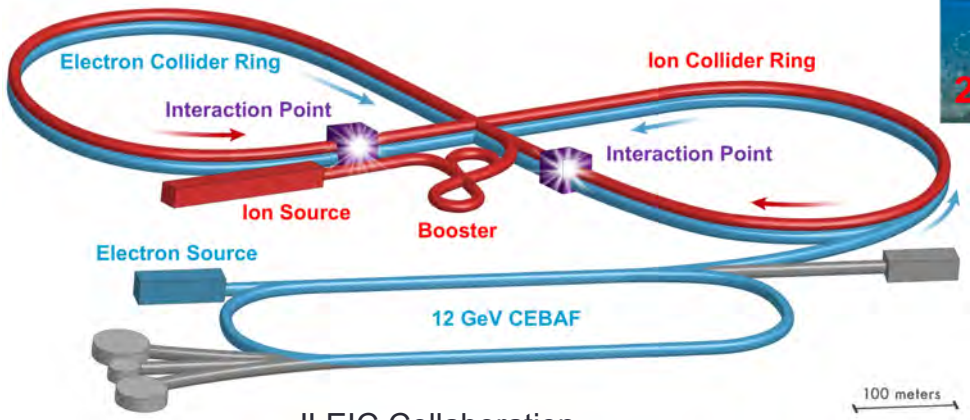
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure



2018

eRHIC Design Group
eRHIC pre-CDR



JLEIC Collaboration
JLEIC Pre-CDR

The National Academy Reviewed the EIC

2017-2018

Statement of Task from the Office of Science (DOE/NSF) to the

National Academy of Science, Engineering & Medicine (NAS)

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.

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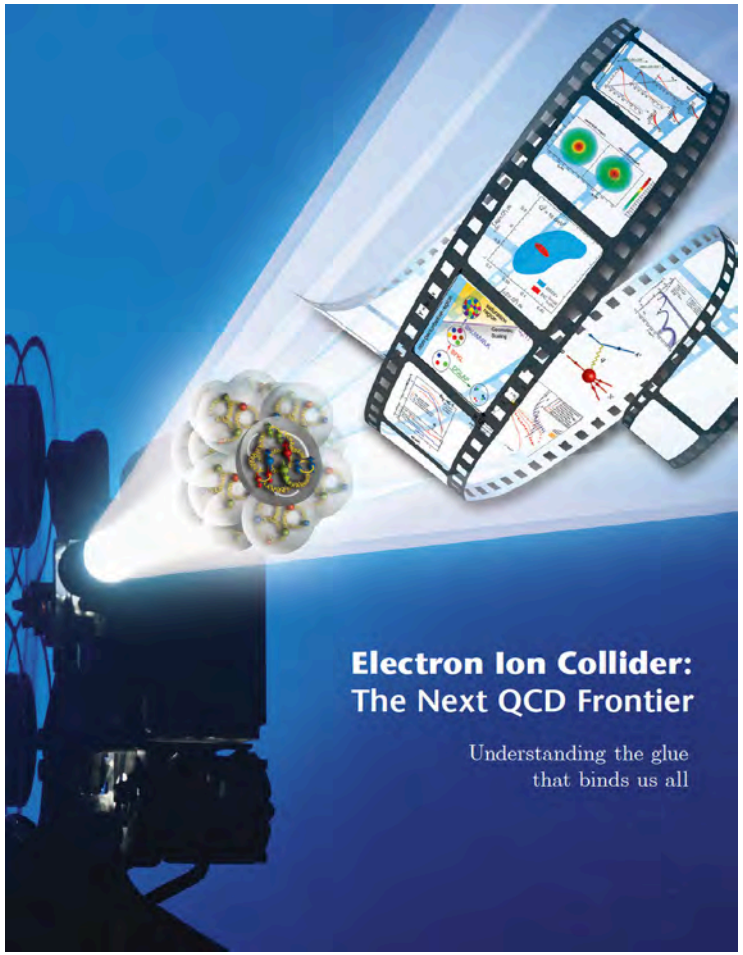
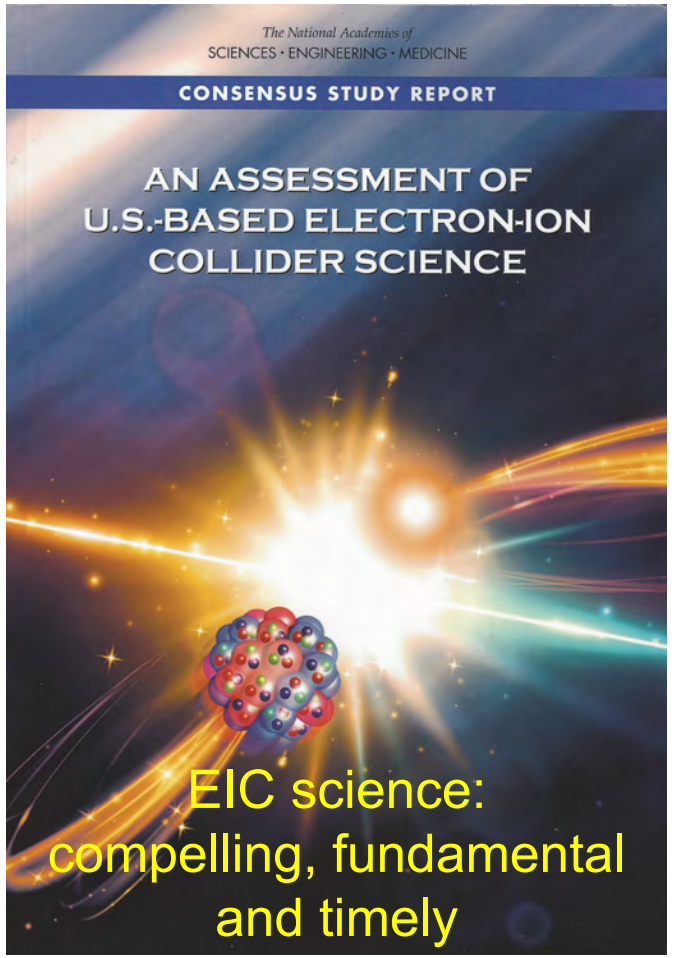
In particular, the committee will address the following questions:

- 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?

EIC Science Endorsed Unanimously by the NAS



Developed by US QCD community over two decades

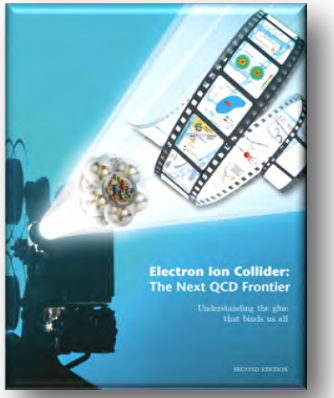


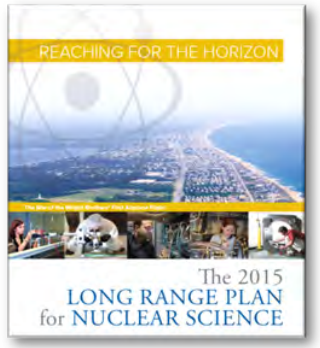
Developed by NAS with broad science perspective

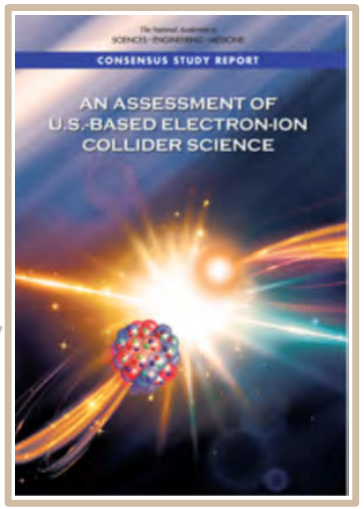
A consensus report
July 26, 2018

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:

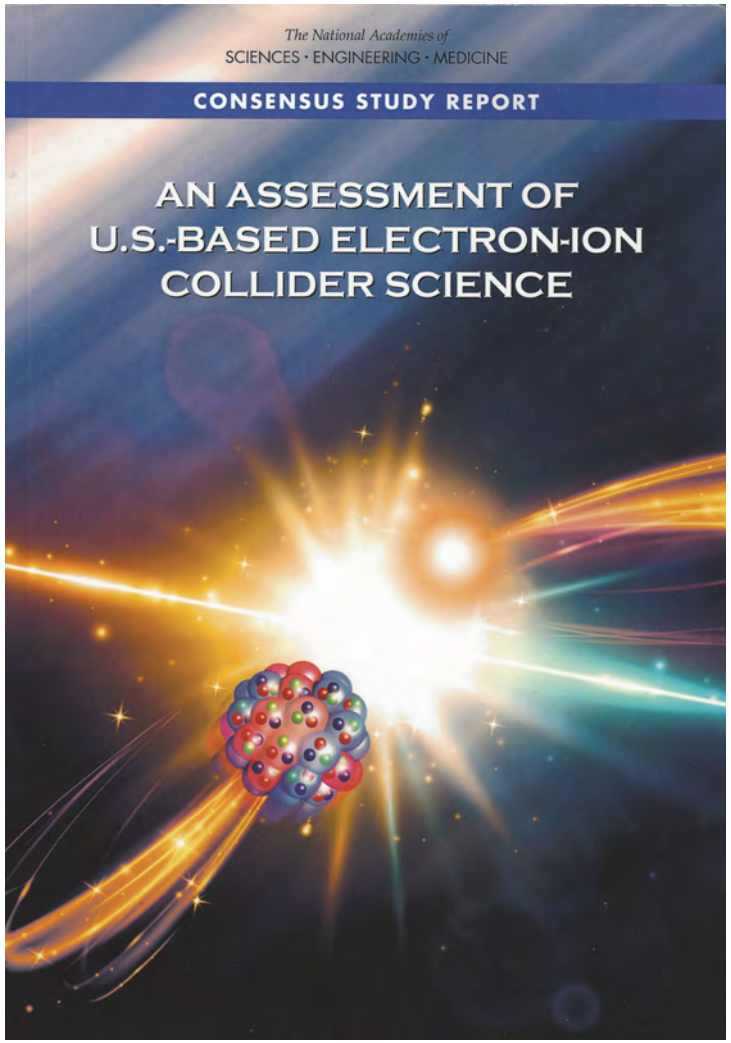
- Extensive center-of-mass energy range, from ~20-~100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times 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



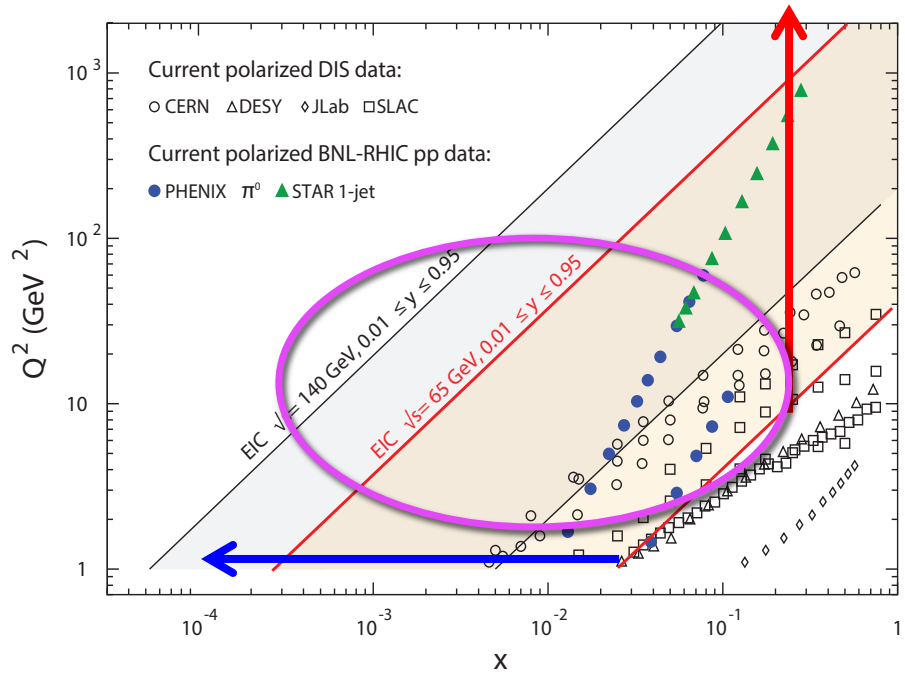
Consensus Study Report on the US based Electron Ion Collider

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 Compelling And Fundamental Science Of EIC

EIC: Kinematic reach & properties

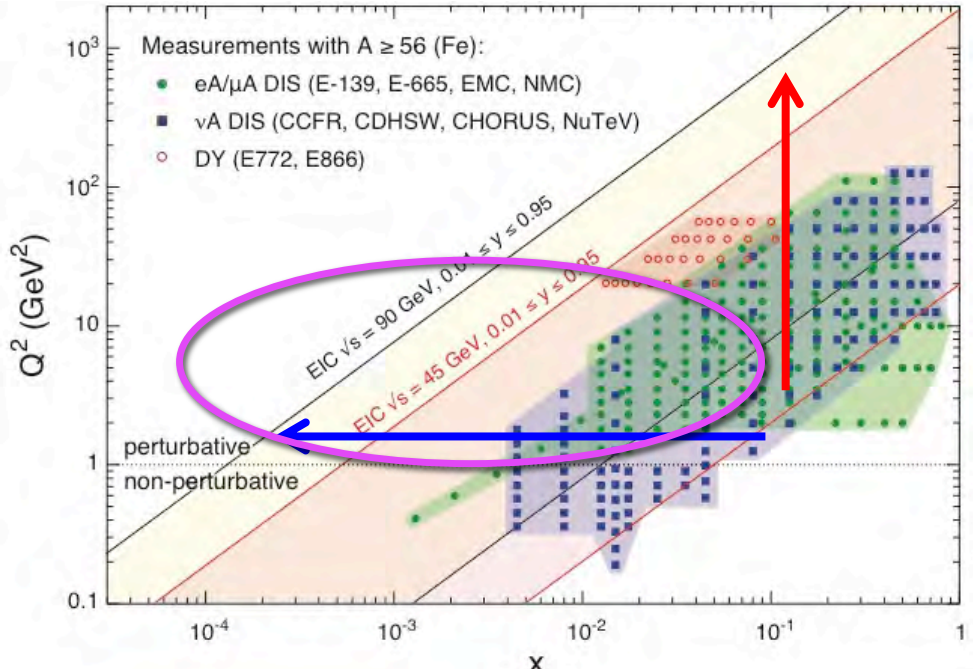


For e-N collisions at the EIC:

- ✓ **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:

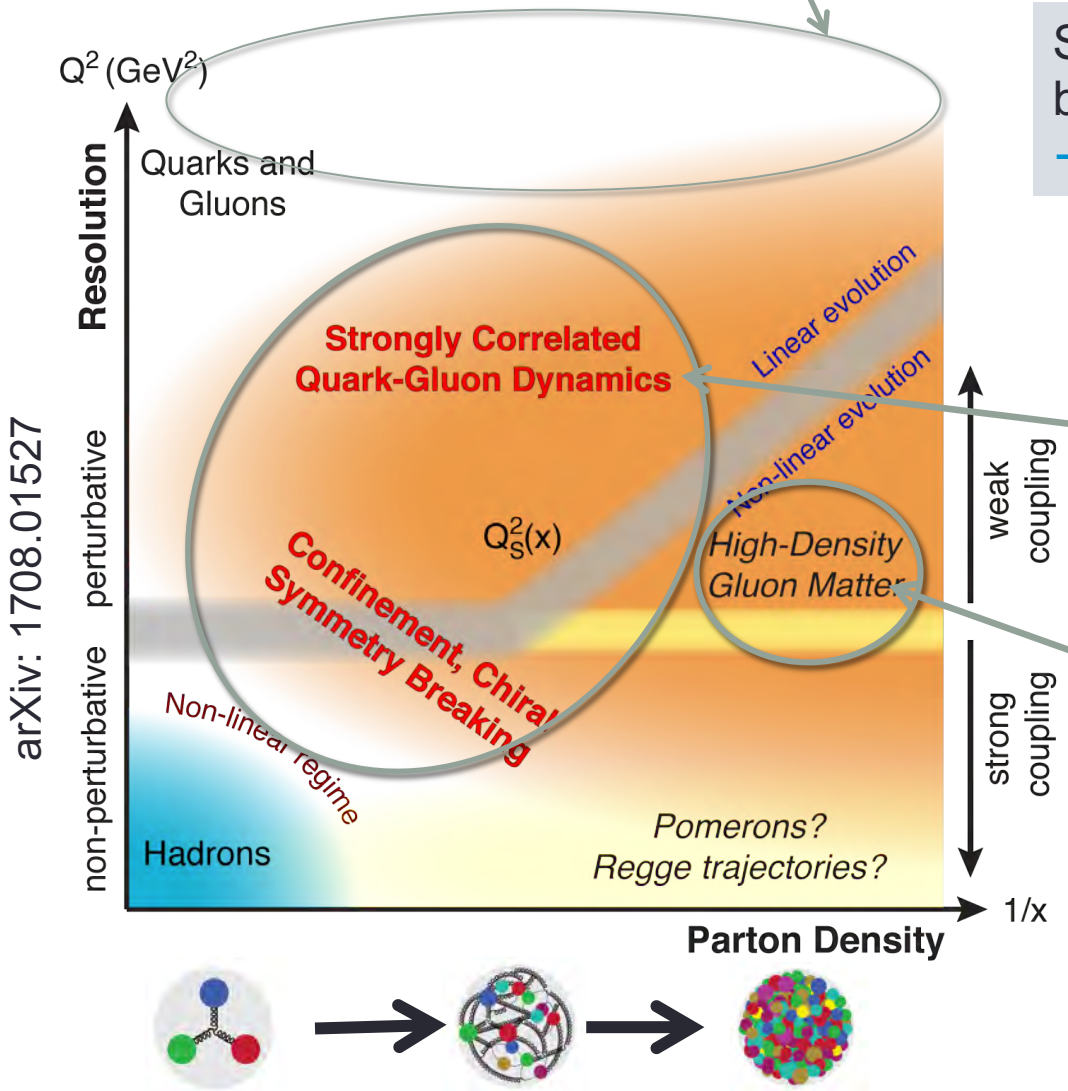
- ✓ **Wide range in nuclei**
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



QCD Landscape to be explored by EIC

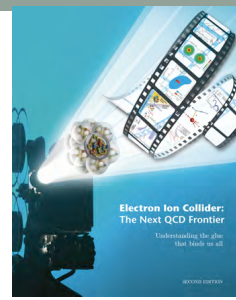
QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described

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



EIC will systematically explore correlations in this region.

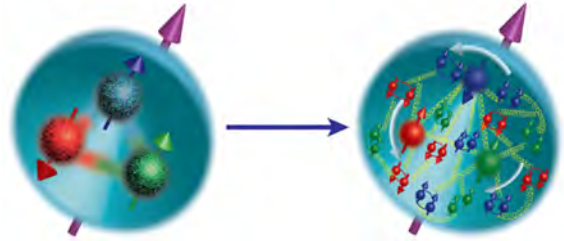
An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter

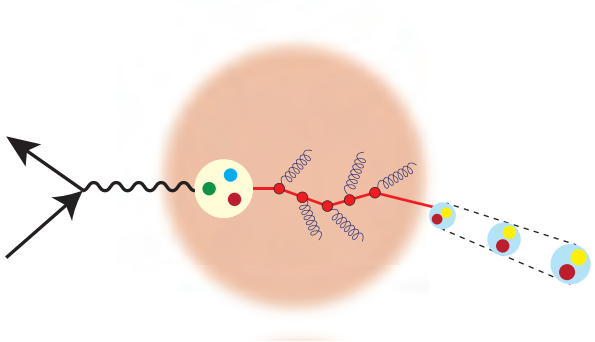


A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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?





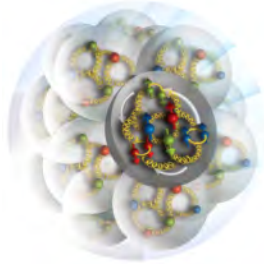
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

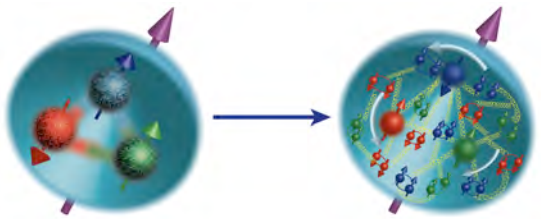
How do the quark-gluon interactions create nuclear binding?

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 ? = gluon recombination

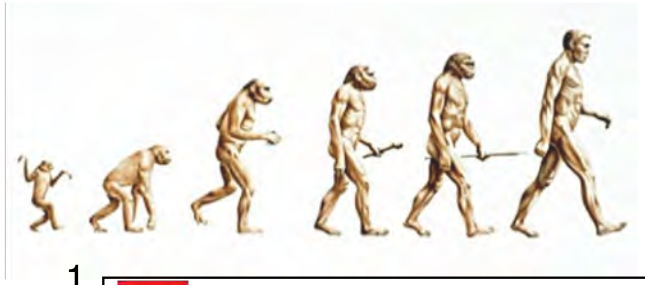


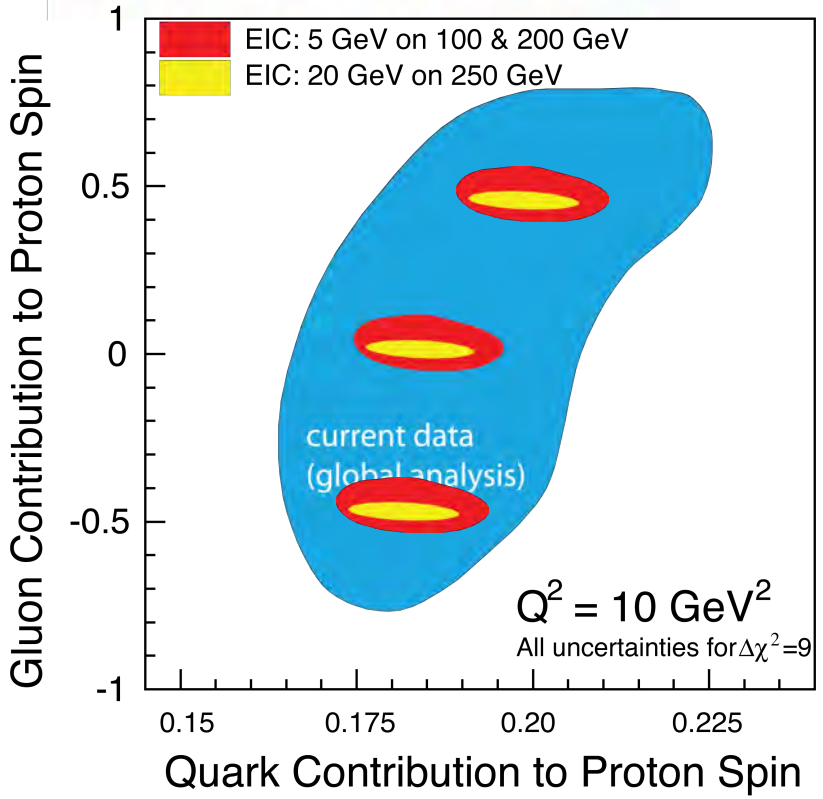
Understanding of Nucleon Spin

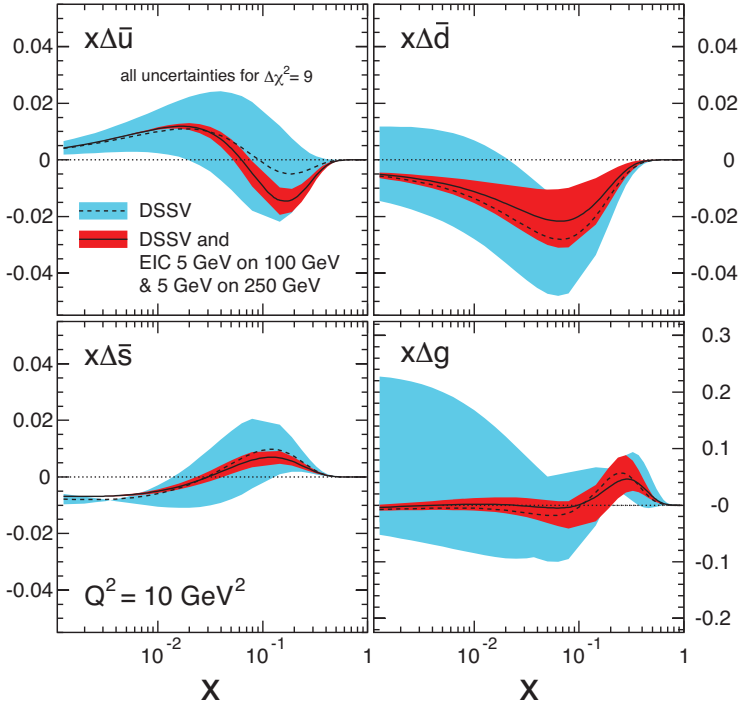
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + \left[\Delta g + L_G\right]$$

$\Delta\Sigma/2$ = 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

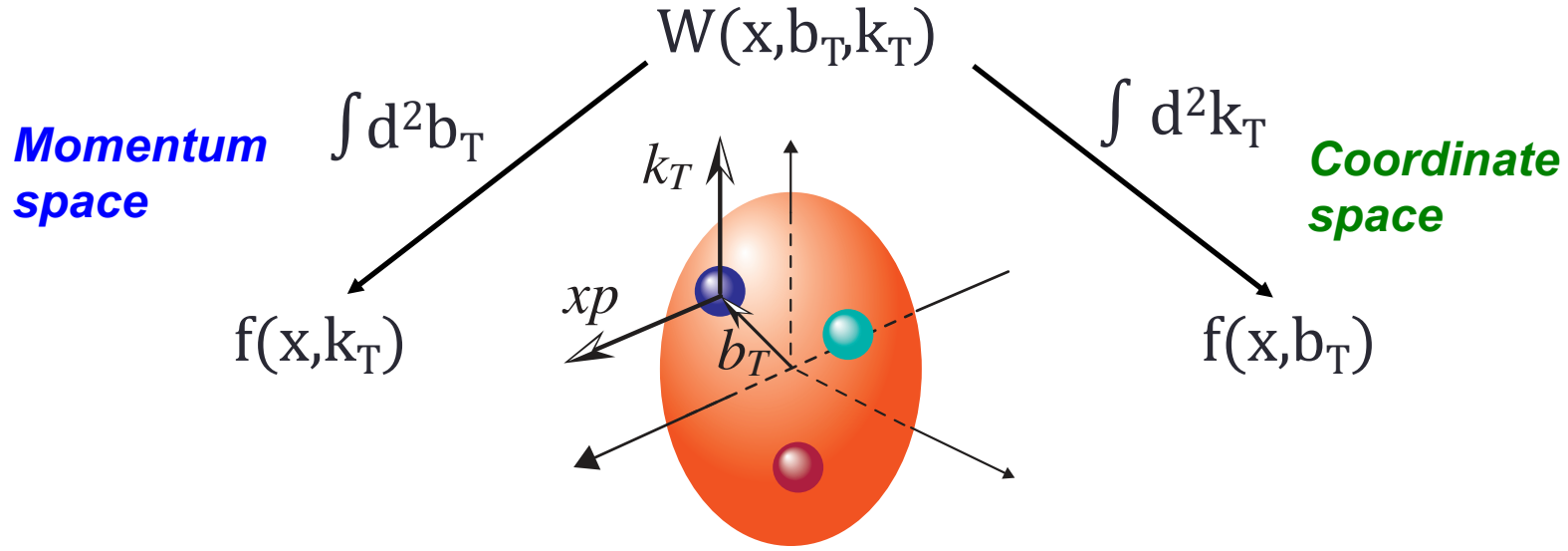






3-Dimensional Imaging Quarks and Gluons

Wigner functions $W(x,b_T,k_T)$
offer unprecedented insight into confinement and chiral symmetry breaking.



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

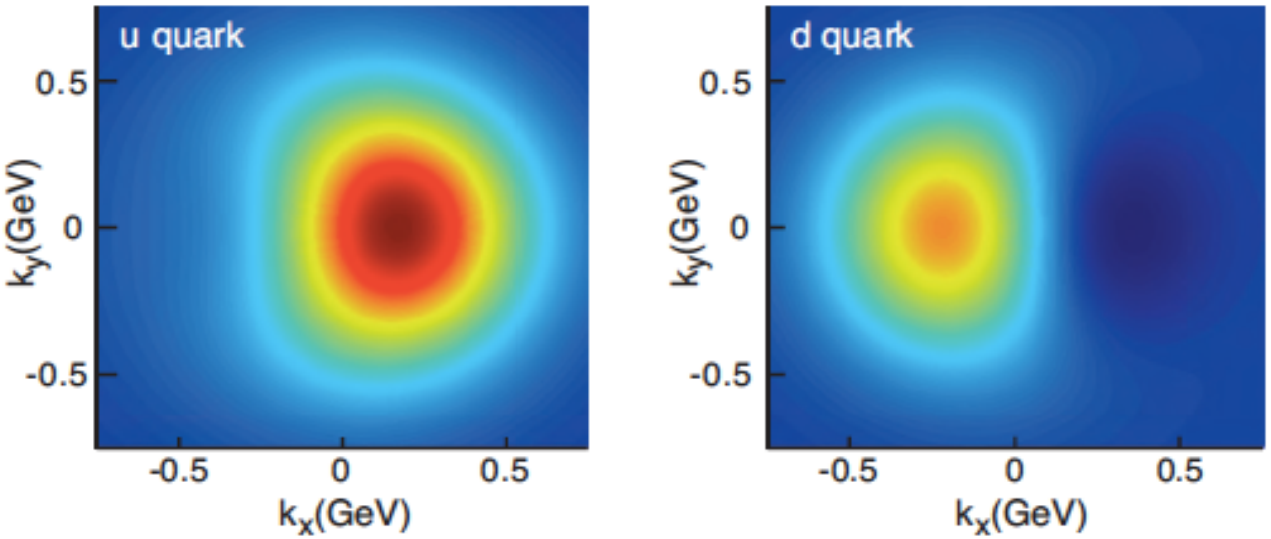
Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply Virtual Compton Scattering and Deeply Virtual Vector Meson production)
→ **GPDs**

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

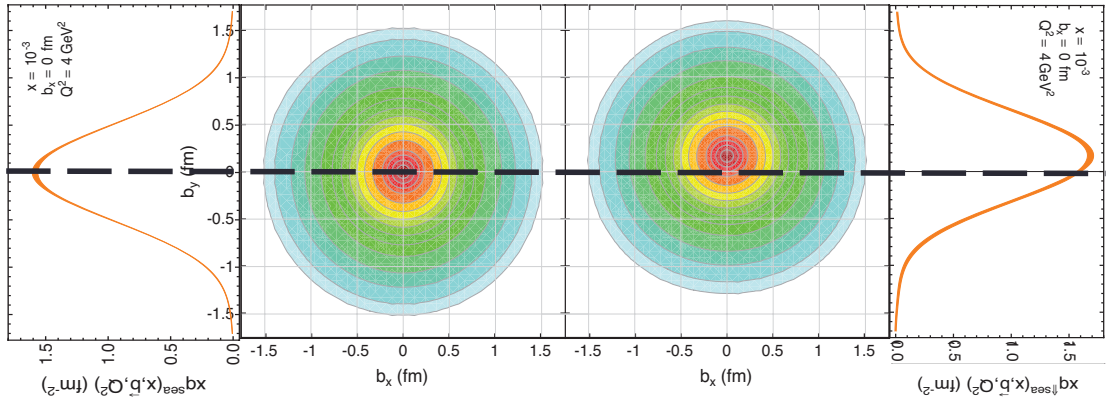


Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

sea-quarks

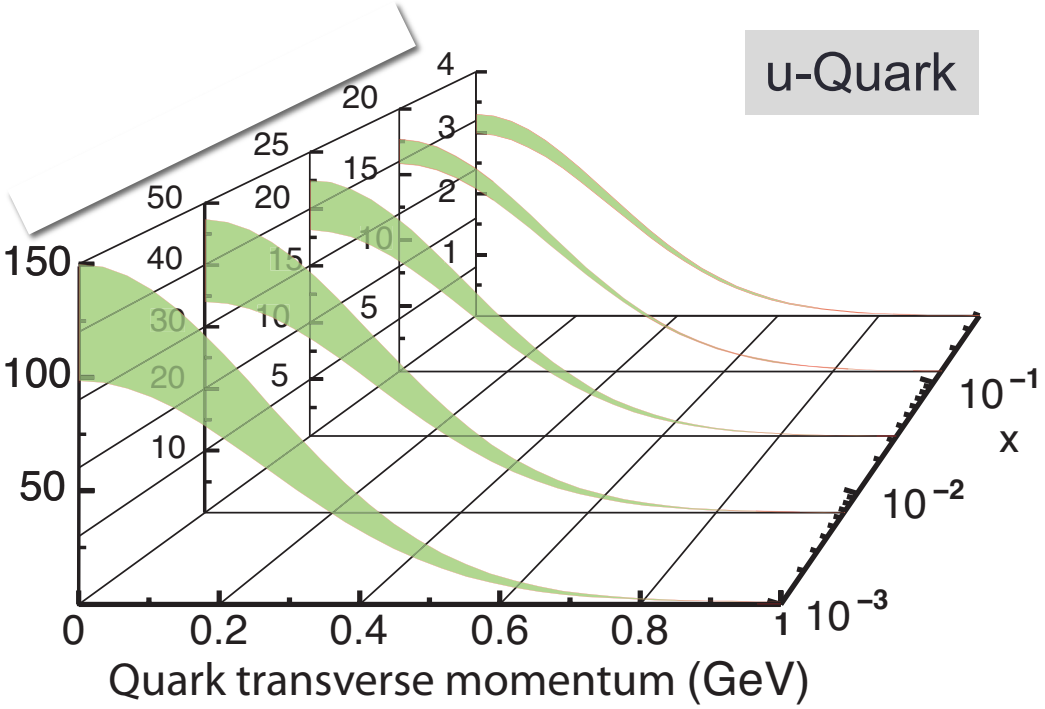
unpolarized polarized



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

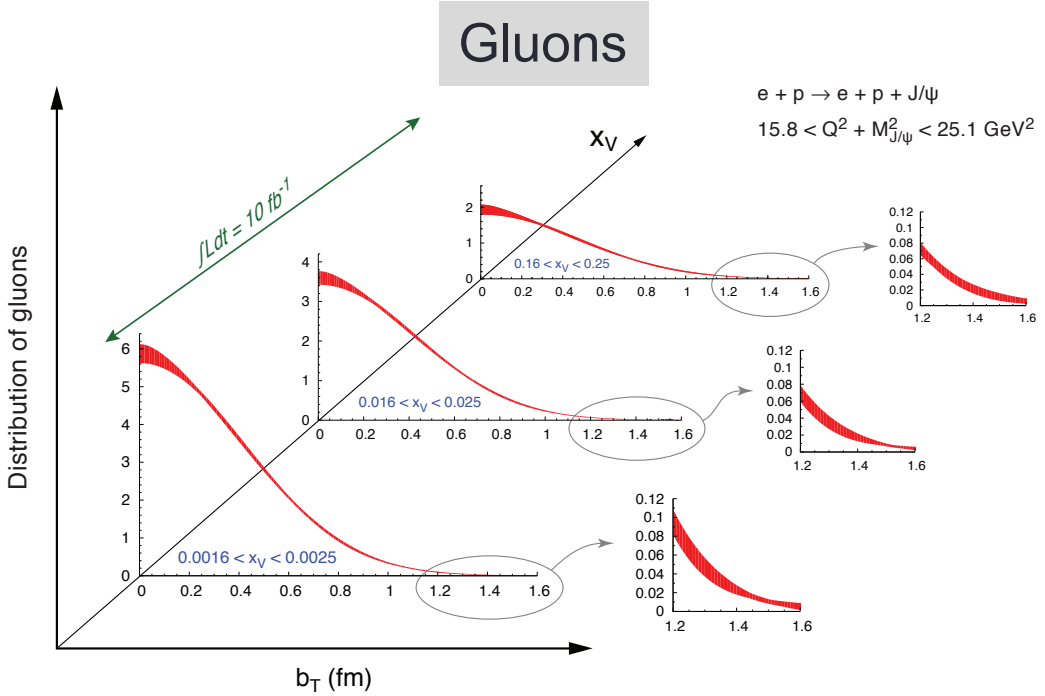
Spin-dependent 3D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions



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

Transverse Position Distributions



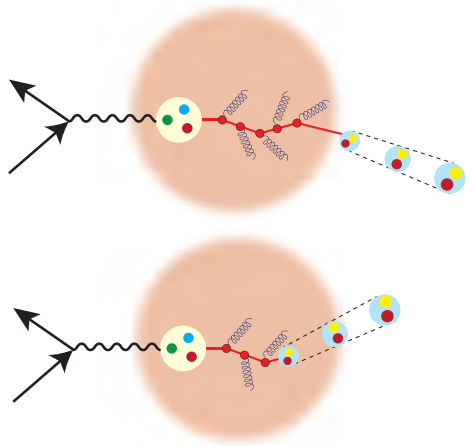
Study the evolution of momentum and position distributions over wide range in x

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

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

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

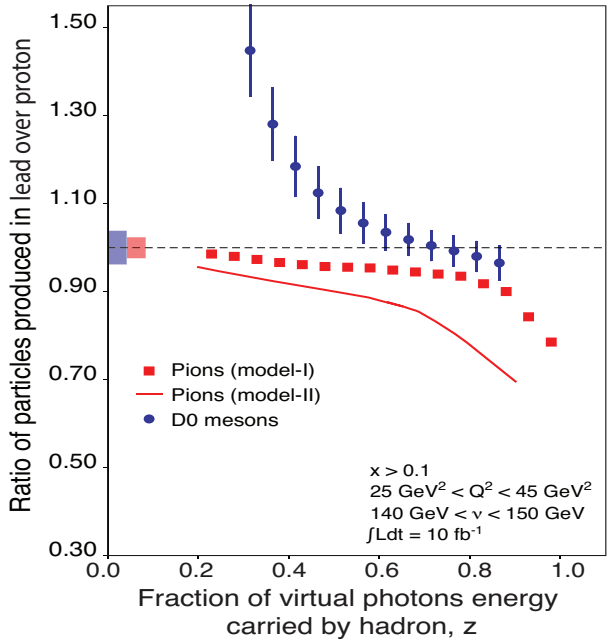


Control of ν by selecting kinematics;

Also under control the nuclear size.

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

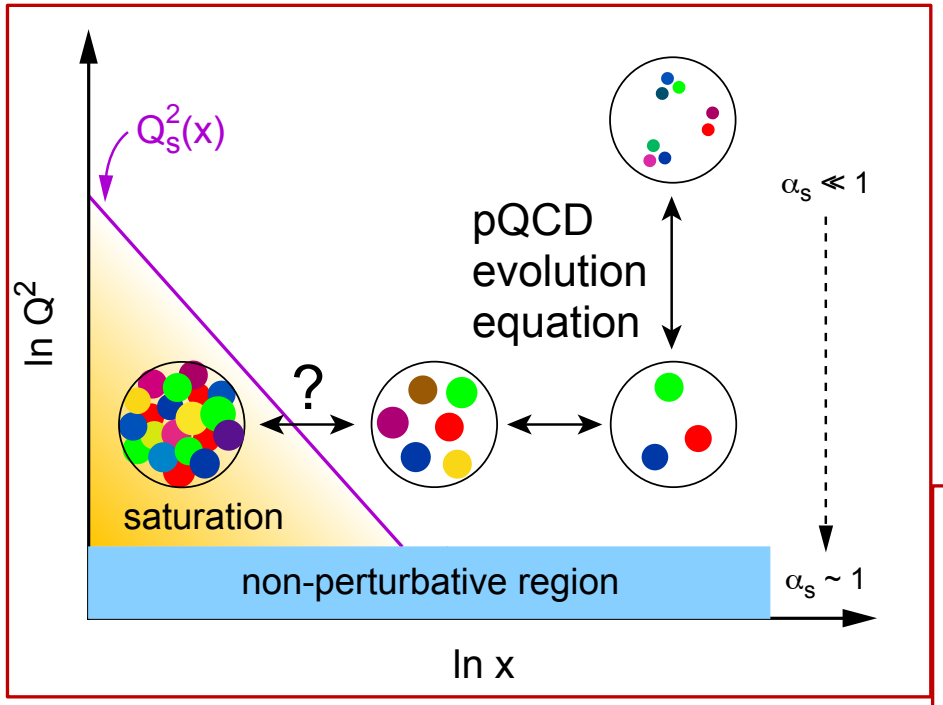
Energy loss by light vs. heavy quarks:

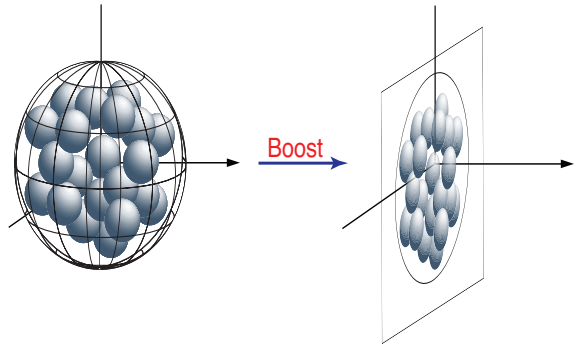


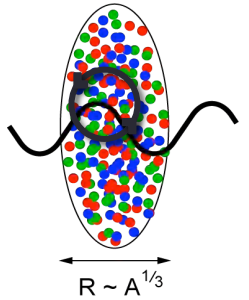
Identify π vs. D^0 **(charm)** mesons in e-A collisions:
Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

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

Advantage of the nucleus over proton

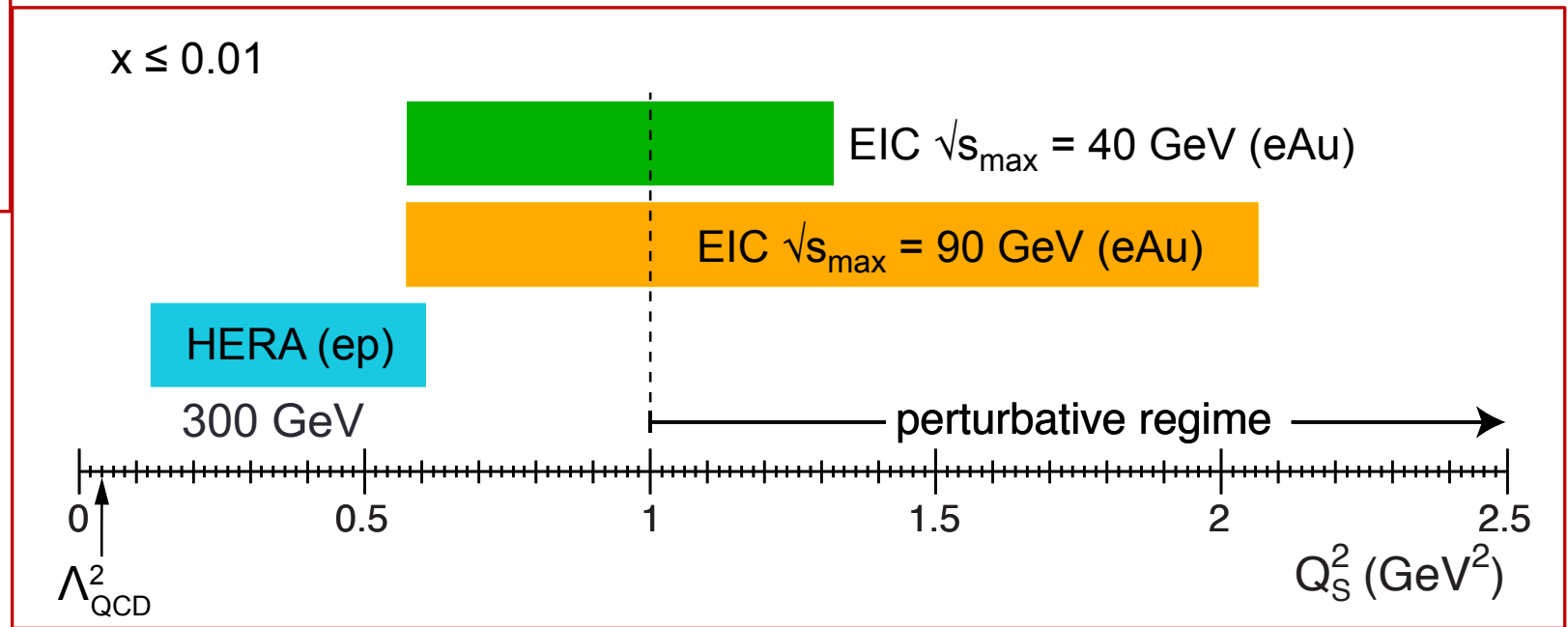






$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

$L \sim (2m_N x)^{-1} > 2\,R_A \sim A^{1/3}$

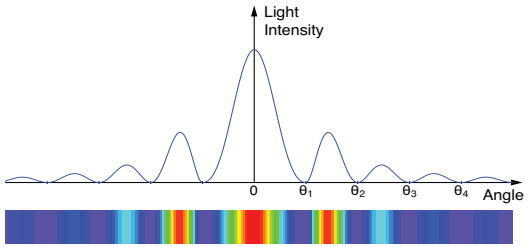


Accessible range of saturation scale Q_s^2 at the EIC with e+A collisions.
arXiv:1708.01527

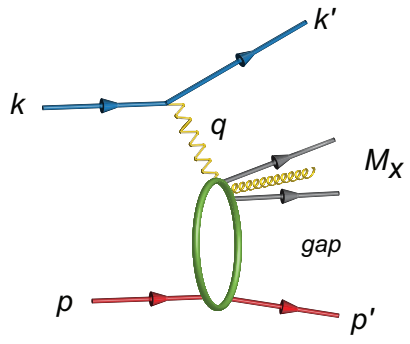
Diffraction : Optics and high energy physics

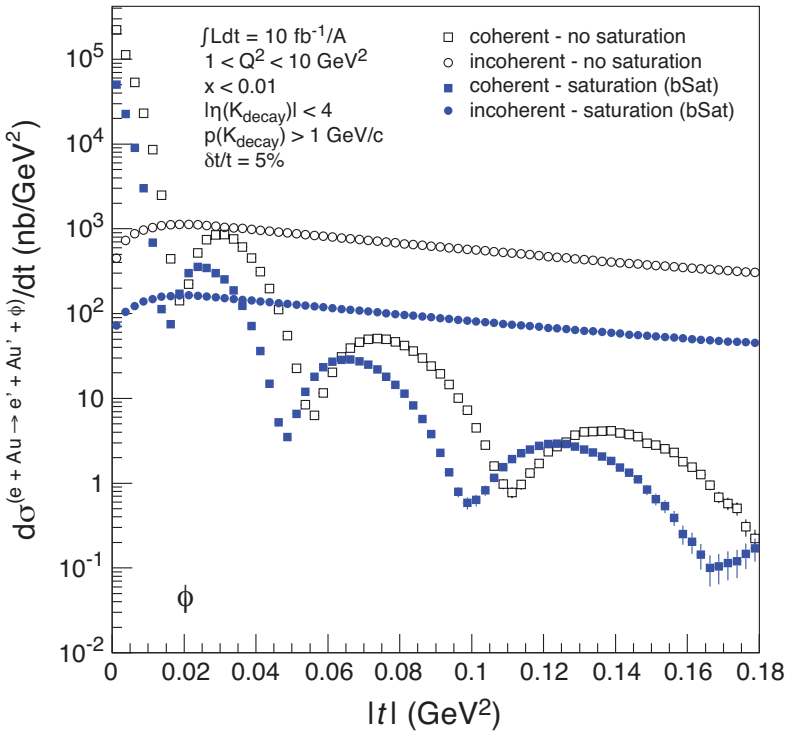
Light with wavelength λ obstructed by an opaque disk of radius R suffers diffraction:
k → wave number

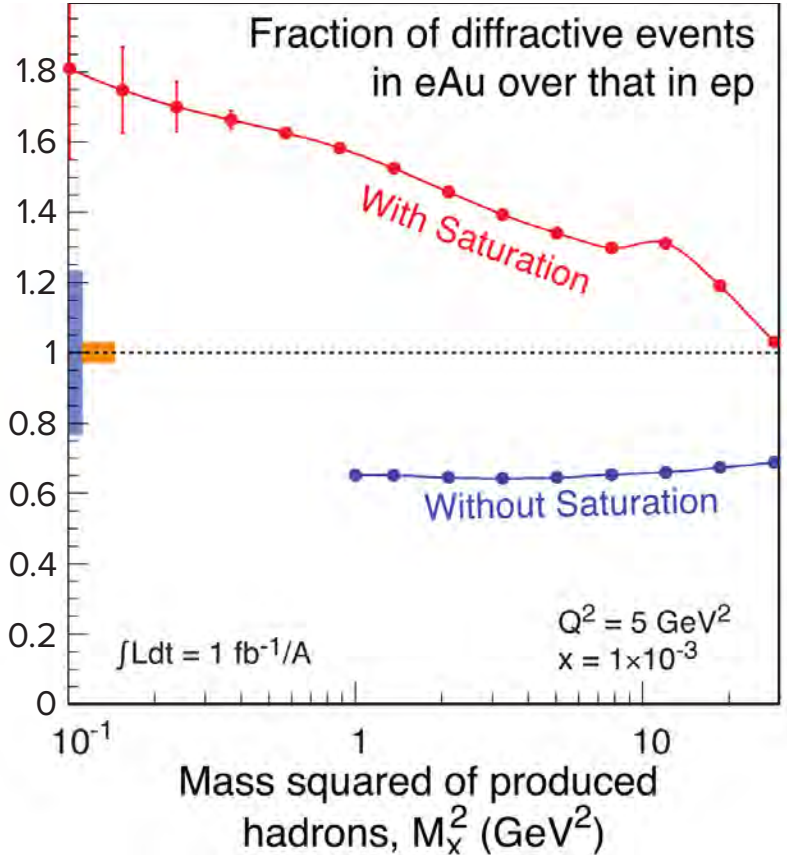
$$|t| \approx k^2\theta^2 \quad \theta_i \sim \frac{1}{(kR)}$$



$$\sigma_{\text{diff}} \propto [g(x, Q^2)]^2$$







At HERA : ep: 10-15% diffractive

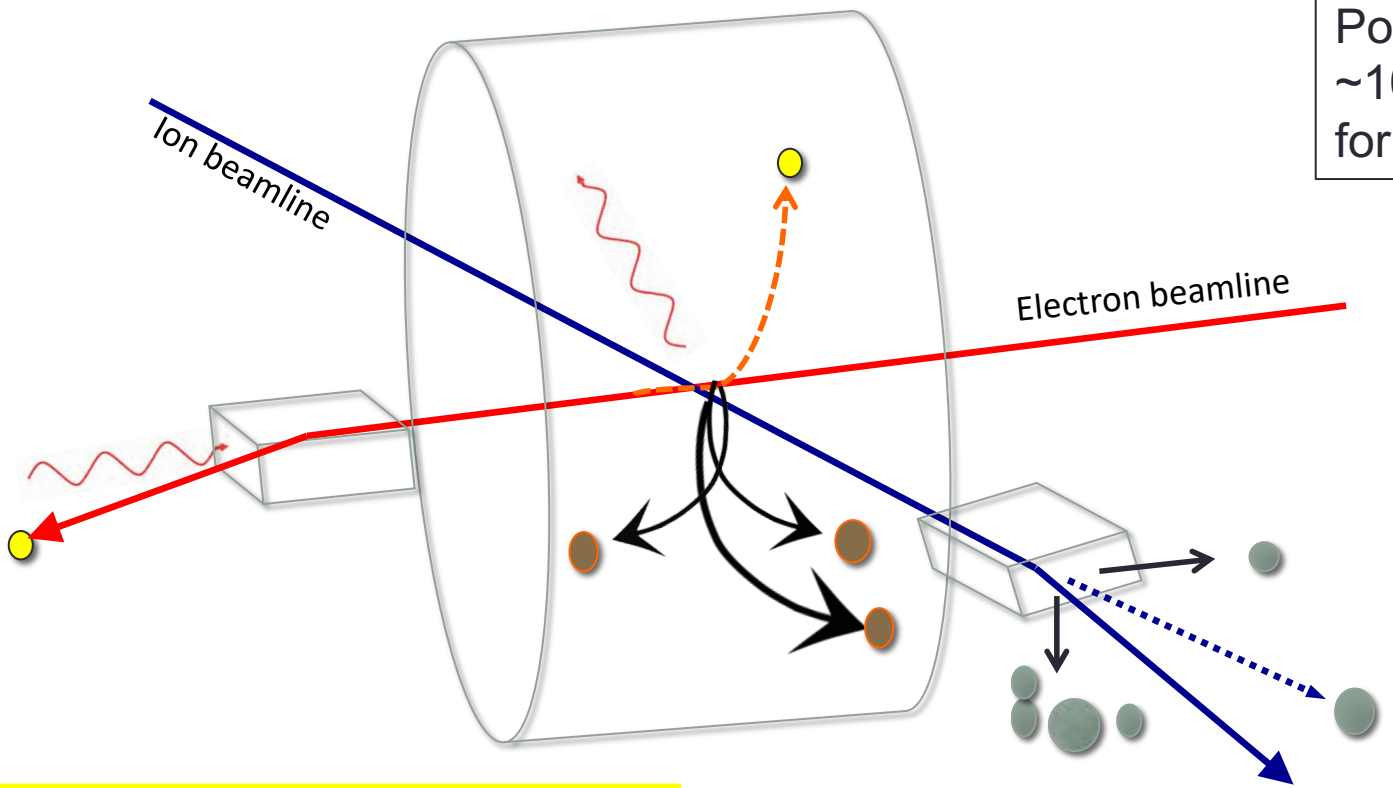
At EIC eA, if Saturation/CGC eA: 25-30% diffractive

EIC realization is timely

Path to realization

Detector integration with the Interaction Region

Lessons learned from HERA



Possible to get ~100% acceptance for the whole event

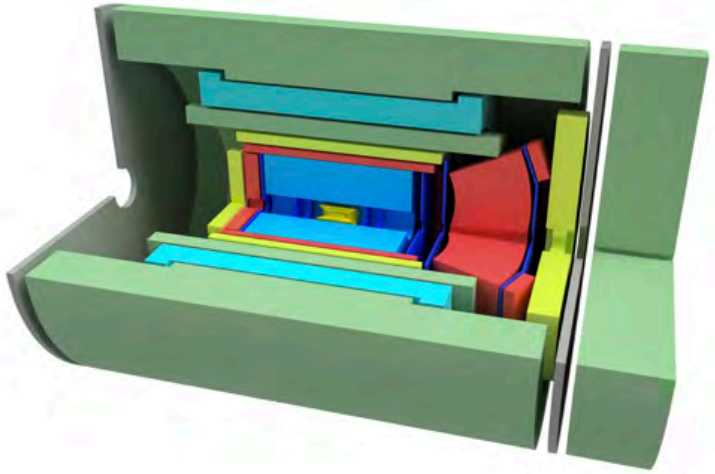
Total acceptance detector (and IR)

Crossing angles:
eRHIC: 25 mrad
JLEIC : 50 mrad

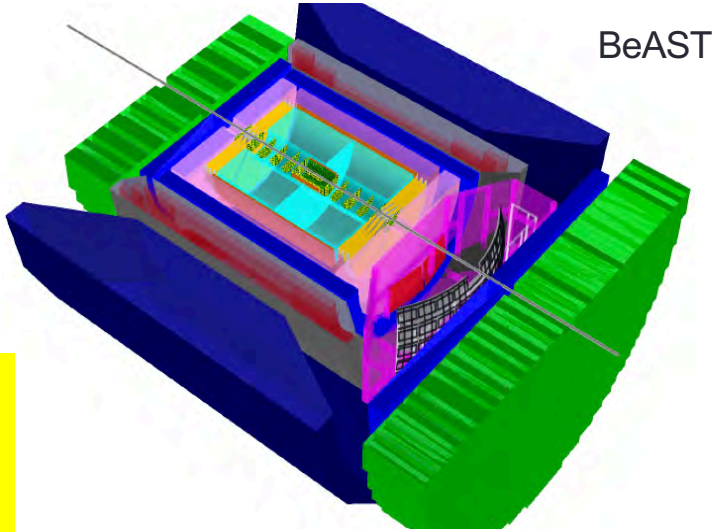
Figure Courtsey: Rik Yoshida

EIC Detector Concepts, others expected to emerge

EIC Day 1 detector, with BaBar Solenoid

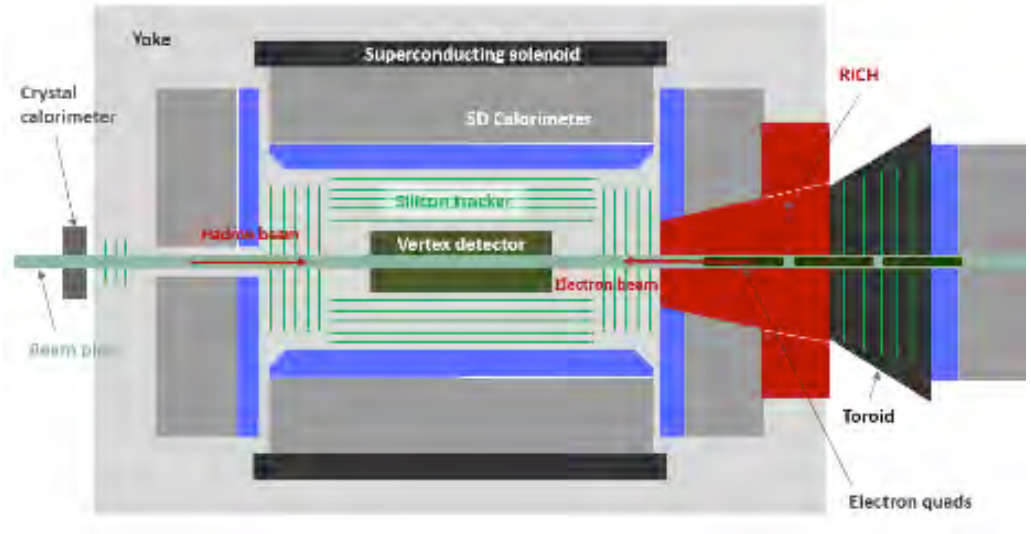


BeAST at BNL

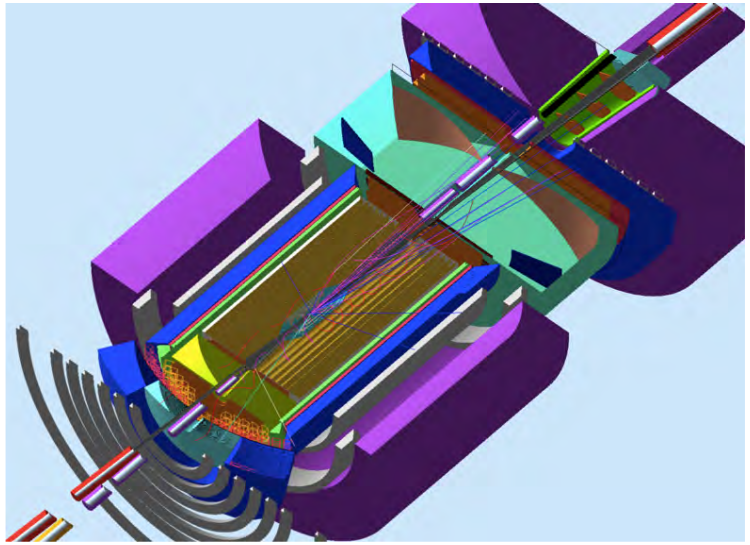


Ample opportunity and need for additional contributors and collaborators

TOPSiDE: Time Optimized PID Silicon Detector for EIC



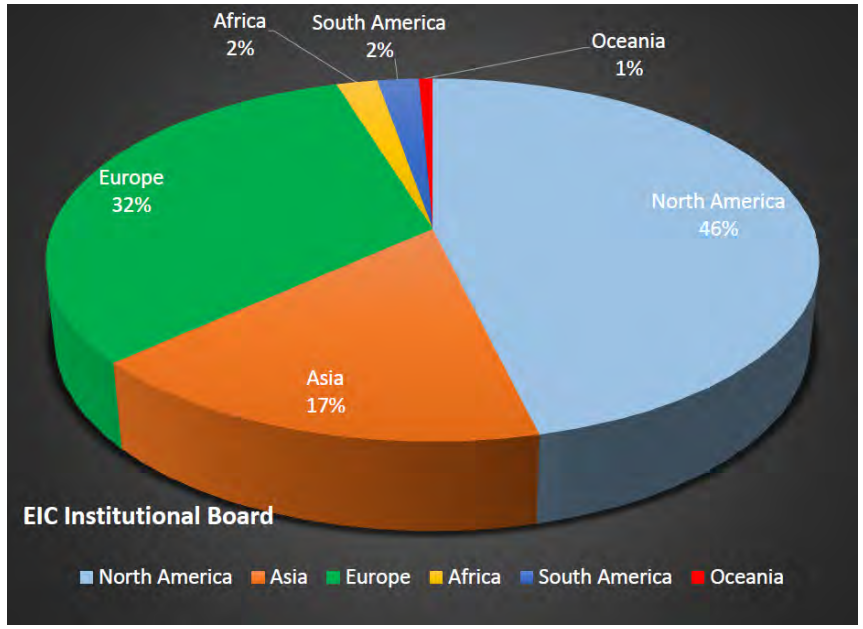
JLEIC Detector Concept, with CLEO Solenoid



The EIC Users Group: EICUG.ORG

Formally established in 2016
864 Ph.D. Members from 30 countries, 184 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 (w/ European Representative)
EIC UG Institutional Board
EIC UG Speaker's Committee (w/European Rep.)

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)**

http://www.stonybrook.edu/cfns

- Established in Fall 2017 with generous support from the Simon's Foundation and NY State. A collaboration between Stony Brook & BNL to create a frontier research center to support the US Electron Ion Collider (EIC) and enhance the US Nuclear Science

- Participation from EIC and QCD enthusiasts from around the world.

Director: Abhay.Deshpande@stonybrooke.edu
Contact: Ciprian.Gal@stonybrook.edu or CFNS_contacts@stonybrook.edu

Vision:

To support and help the US EIC community to realize the US EIC with the best possible physics (including new ideas beyond the EIC White Paper). Invest in and support young researchers in the field.

Activities:

- Workshops & meetings
  - 4 large workshops & 3-4 adhoc meetings per year
- Post doctoral fellow program: CFNS and **joint-University-CFNS** post docs with remote institutions
- Bi-monthly joint seminars (SBU/BNL)
  - 40+ seminars and special talks / year
- Visitors program & exchange visitor program with other research centers being established
- Annual summer school for 30+ students being planned starting in August 2019

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

EIC support, outreach and other news

European Particle Physics Strategic Update (EPPSU):

- CERN management very well informed about the US EIC. Very supportive. Encouraged strong involvement and input on EIC in the European High Energy Strategy Planning activity (currently underway)
- EIC Physics Whitepaper led by the European EICUG collaborators,
- an accelerator design paper led by BNL and JLab together:

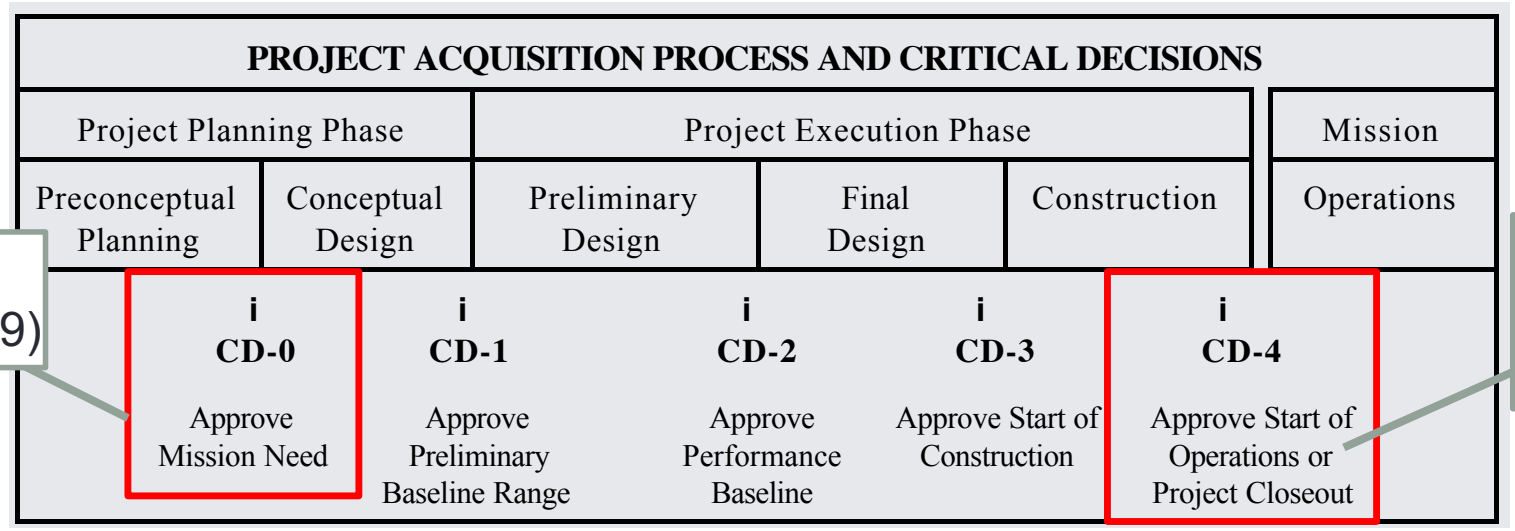
➔ both well received at Grenada, Spain (EPPSU meeting held in May 2019)

Recent success in funding of EIC as part of the Hadron studies (Strong2020) in European Nuclear Physics $Eu 12M (Saclay, INFN and others) over 3 years

Optimism for realization of funding from

- BMBF Germany in near future for dedicated QCD studies aimed at the EIC/QCD
- a Consortium of California Universities and California national labs supported by UC Chancellor's office for the EIC

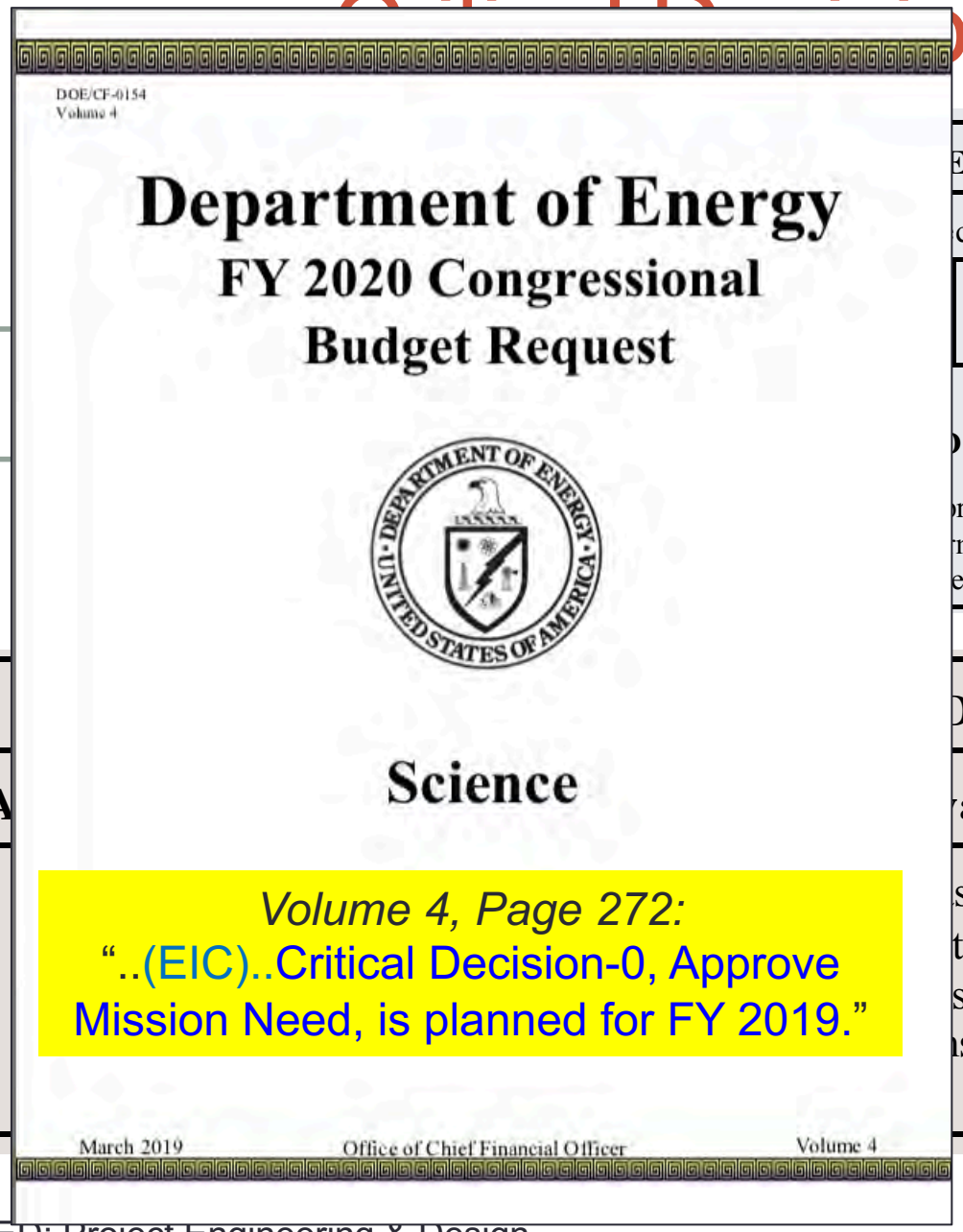
Critical Decision Process DOE



CD-0	CD-1	CD-2	CD-3	CD-4
Actions Authorized by Critical Decision Approval				
• Proceed with conceptual design using program funds • Request PED funding	• Allow expenditure of PED funds for design	• Establish baseline budget for construction • Continue design • Request construction funding	• Approve expenditure of funds for construction	• Allow start of operations or project closeout

PED: Project Engineering & Design

Critical Decision Process DOE


DOE/CF-0154
Volume 4

Department of Energy
FY 2020 Congressional
Budget Request

Science

Volume 4, Page 272:
"..(EIC)..Critical Decision-0, Approve Mission Need, is planned for FY 2019."

March 2019 Office of Chief Financial Officer Volume 4

ESS AND CRITICAL DECISIONS

ct Execution Phase		Mission
Final Design	Construction	Operations

-2	i CD-3	i CD-4
rove rmance eline	Approve Start of Construction	Approve Start of Operations or Project Closeout

Technical feasibility (~2030)

	D-2	CD-3	CD-4
A		val	
•	seline budget tion sign nstruction	• Approve expenditure of funds for construction	• Allow start of operations or project closeout
•			

PED: Project Engineering & Design

Summary:

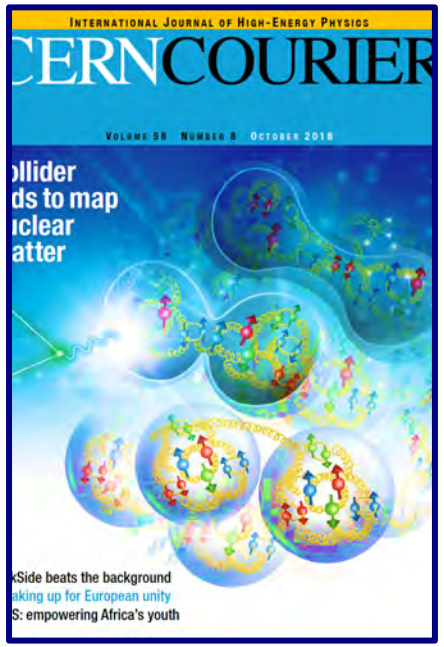
- Science of EIC: Gluons that bind us all… understanding their role in QCD
- EIC's precision, control and versatility will revolutionize our understanding QCD

- The US EIC project has significant momentum on all fronts right now:
  - National Academy's positive evaluation → Science compelling, fundamental and timely
  - EIC Users Group is energized, active and enthusiast: organized
    - EICUG led working groups on polarimetry, luminosity measurement, IR design evolving
  - 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
  - CFNS, EIC^2 Centers established in the US to help EIC Users

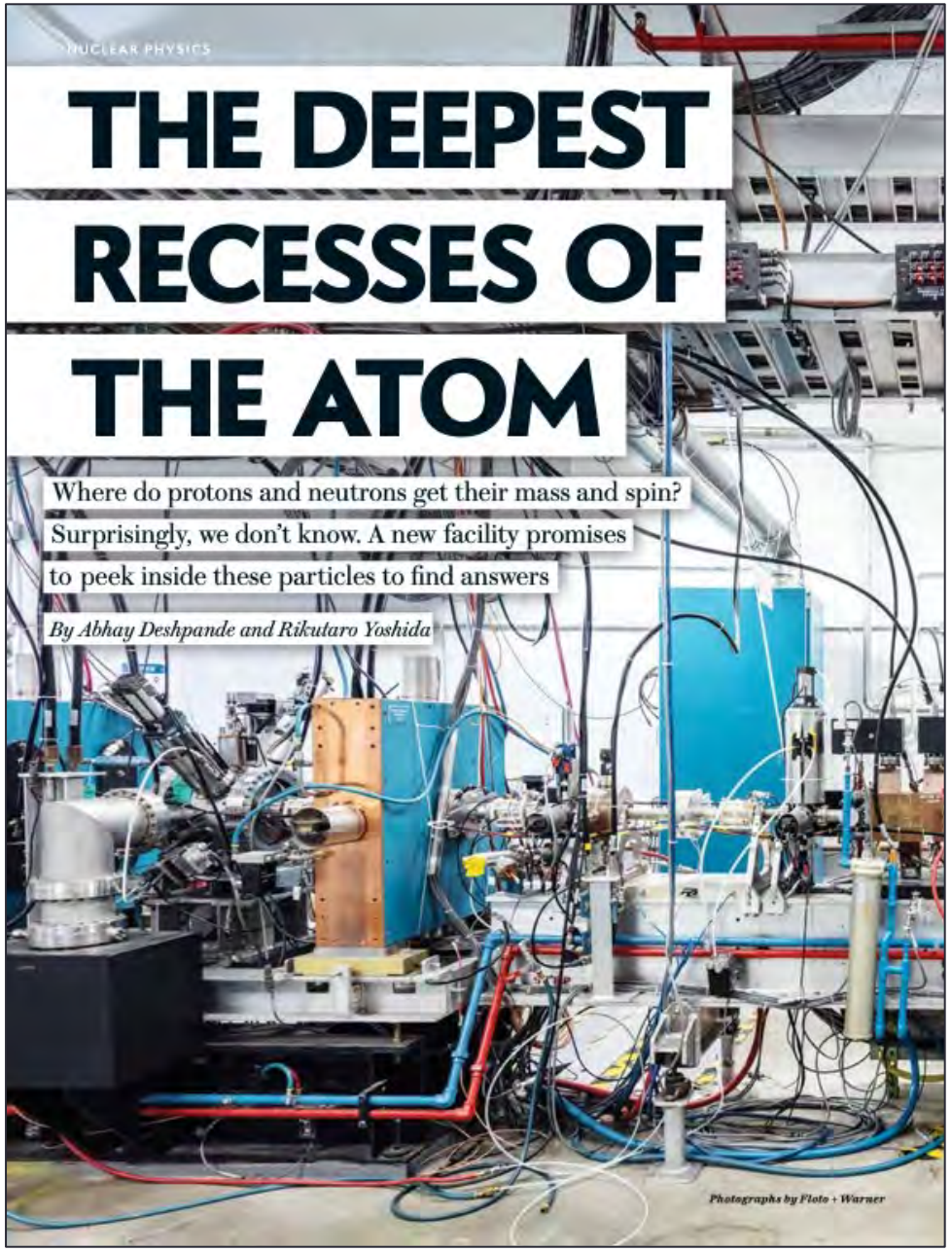
- **Independent Cost Review underway → CD0 anticipated soon. Exciting times ahead….**

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



E. Aschenauer
R. Ent
October 2018

A. Deshpande
& R. Yoshida
June 2019



Thank you.

NAS Consensus: EIC science compelling, fundamental, and timely

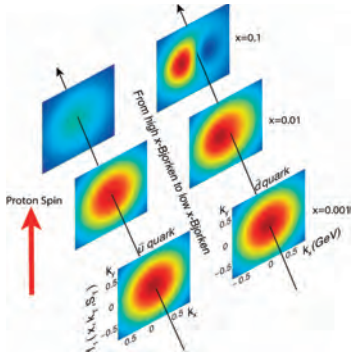
July 26, 2018

- **Finding 1**: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems of gluons?
- **Finding 2:** These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.
- **Finding 3**: An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics.
- **Finding 4:** An EIC would maintain U.S. leadership in the accelerator science and technology of colliders and help to maintain scientific leadership more broadly.
- **Finding 5:** Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

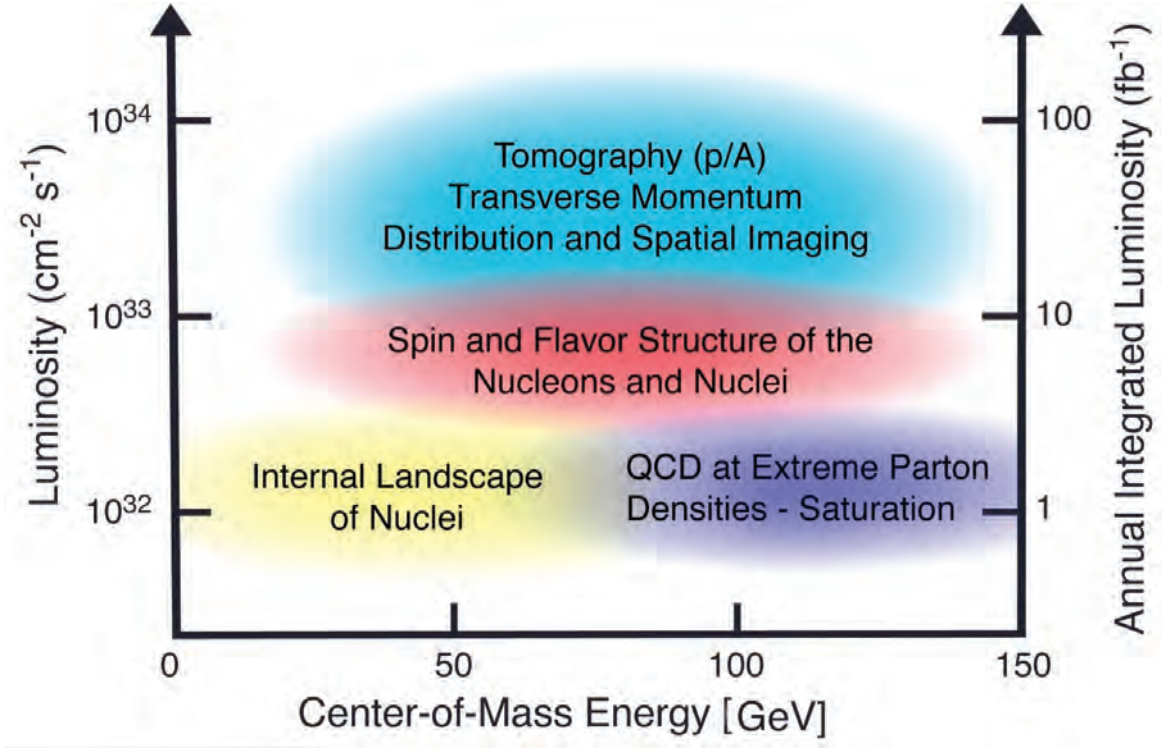
National Academy's Findings

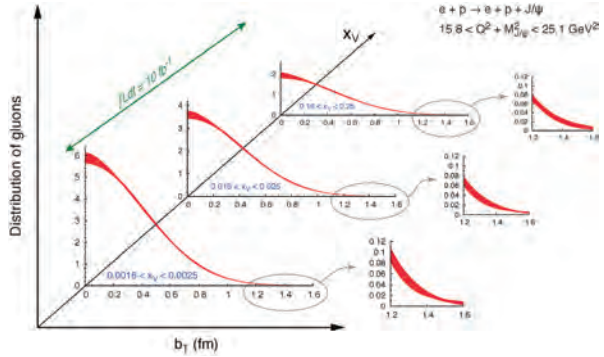
- **Finding 6:** The current accelerator R&D program supported by DOE is crucial to addressing outstanding design challenges.
- **Finding 7**: To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD, and furthermore, to glean the fundamental insights into QCD that an EIC can reveal.
- **Finding 8**: The U.S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high-luminosity polarized EIC as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.
- **Finding 9:** The broader impacts of building an EIC in the United States are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.

EIC science and required luminosity

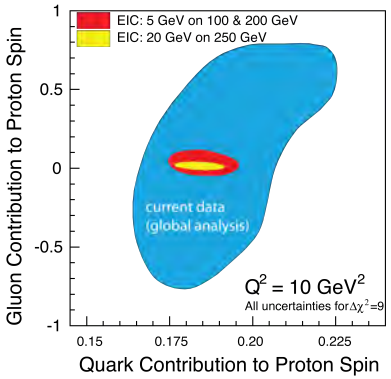


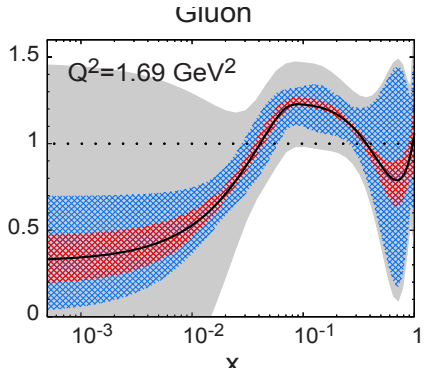
2+1D imaging of quarks and gluons, dynamics, and emergence of spin & mass

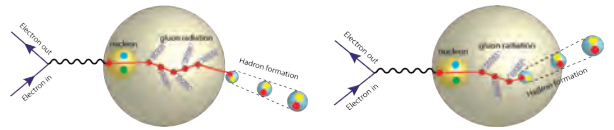




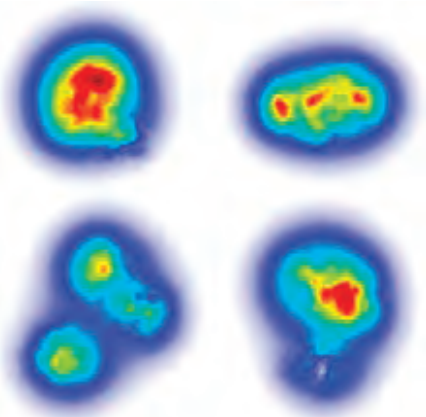
Gluon imaging in nucleons



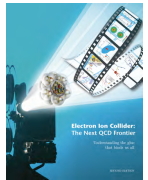




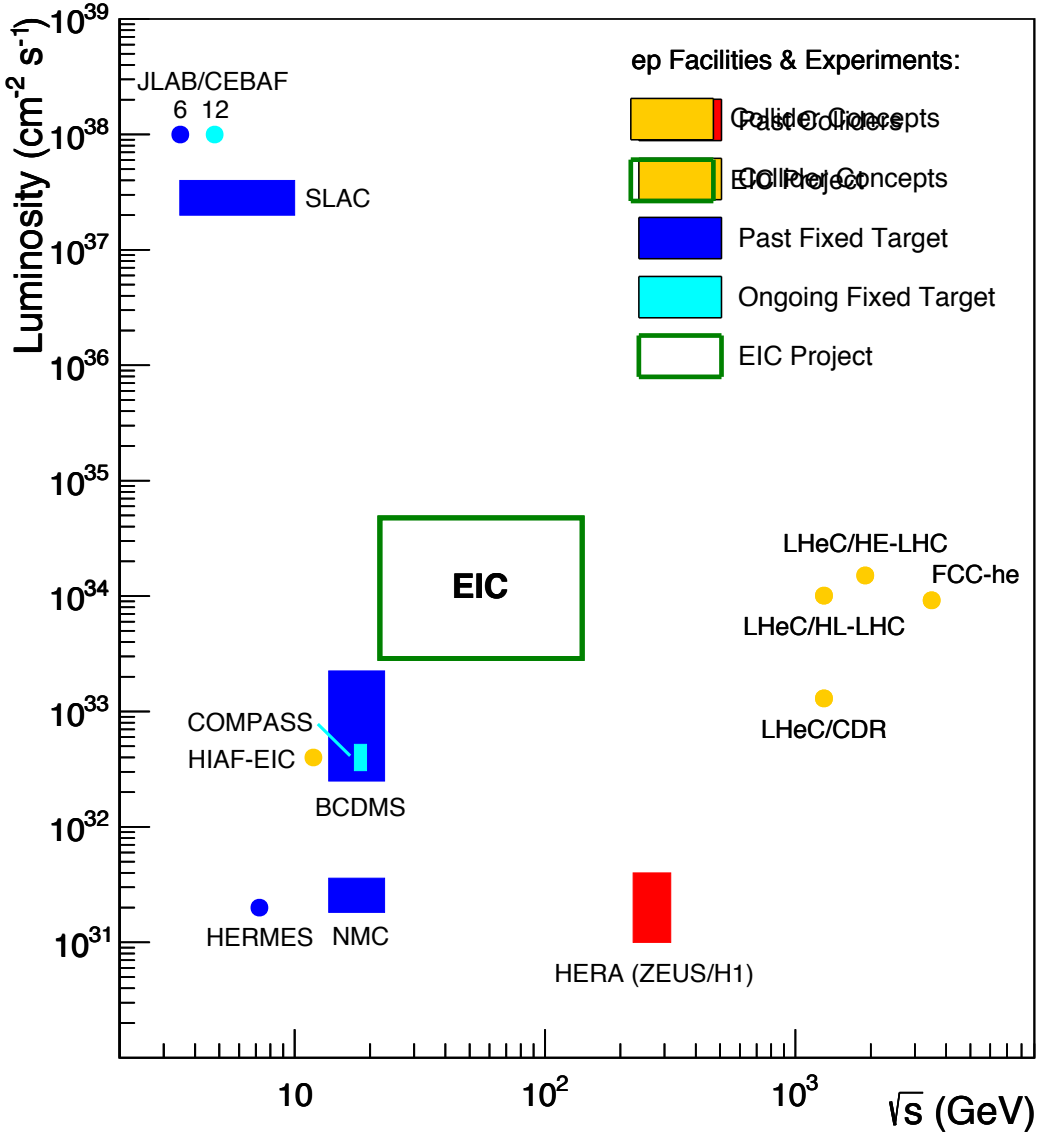
Color propagation, neutralization in nuclei & hadronization



Gluons at high energy in nuclei:
(Gluon imaging in nuclei)



Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

However, if we ask for:

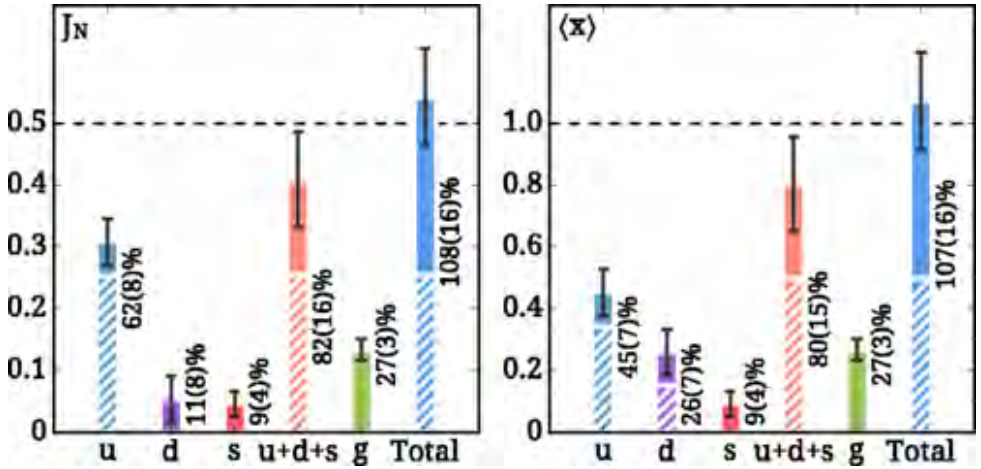
- high luminosity & wide reach in √s
- polarized lepton & hadron beams
- nuclear beams

EIC stands out as unique facility …

Recent progress in Lattice QCD

- For the first time PDFs are attempted to being calculated on the lattice! While the current uncertainty estimates are hotly debated amongst experts, *eventual* precision lattice calculations will need precision experimental measurements….
  - Accessing Gluon Distribution in Large Momentum Effective Theory, Jian-Hui Zhang et al., PRL 122, 142001, April 2019
  - First Direct lattice-QCD calculation of the x-dependence of the pion PDF, J-W.Chen et al, arXiv 1804.01483
  - Parton Distribution functions and one loop matching, https://doi.org/10.1142/S2010194516600533 , X. Ji et al.

C. Alexandrou et al. PRL 119, 142002 (2017)



Nucleon spin and momentum distribution

- **Gluon's spin contribution on Lattice: $S_G = 0.5(0.1)$:** Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- **J_q calculated on Lattice QCD:** χQCD Collaboration, PRD91, 014505, 2015