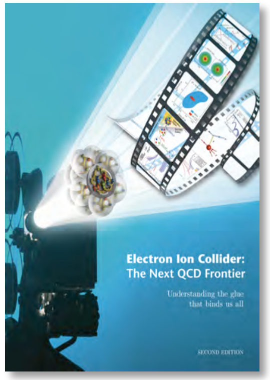
Center for Frontiers in Nuclear Science

See also Ernst Sichtermann, on LD2

The US Electron Ion Collider

Science, Status and Realization Plans

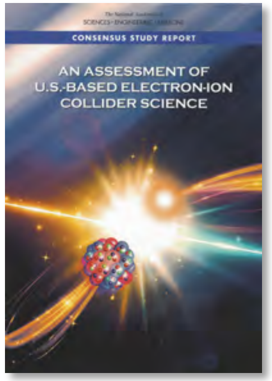
2015



2016

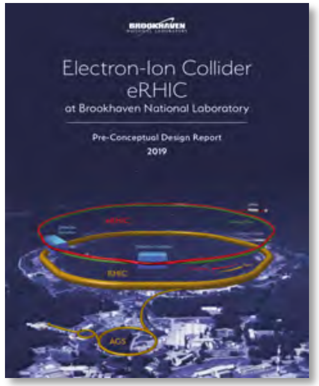
Physics of EIC

2018

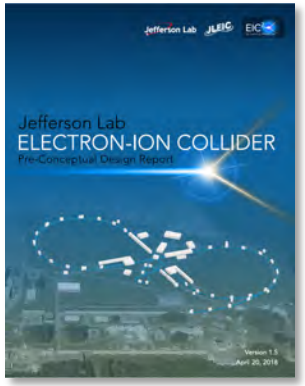


Evaluation

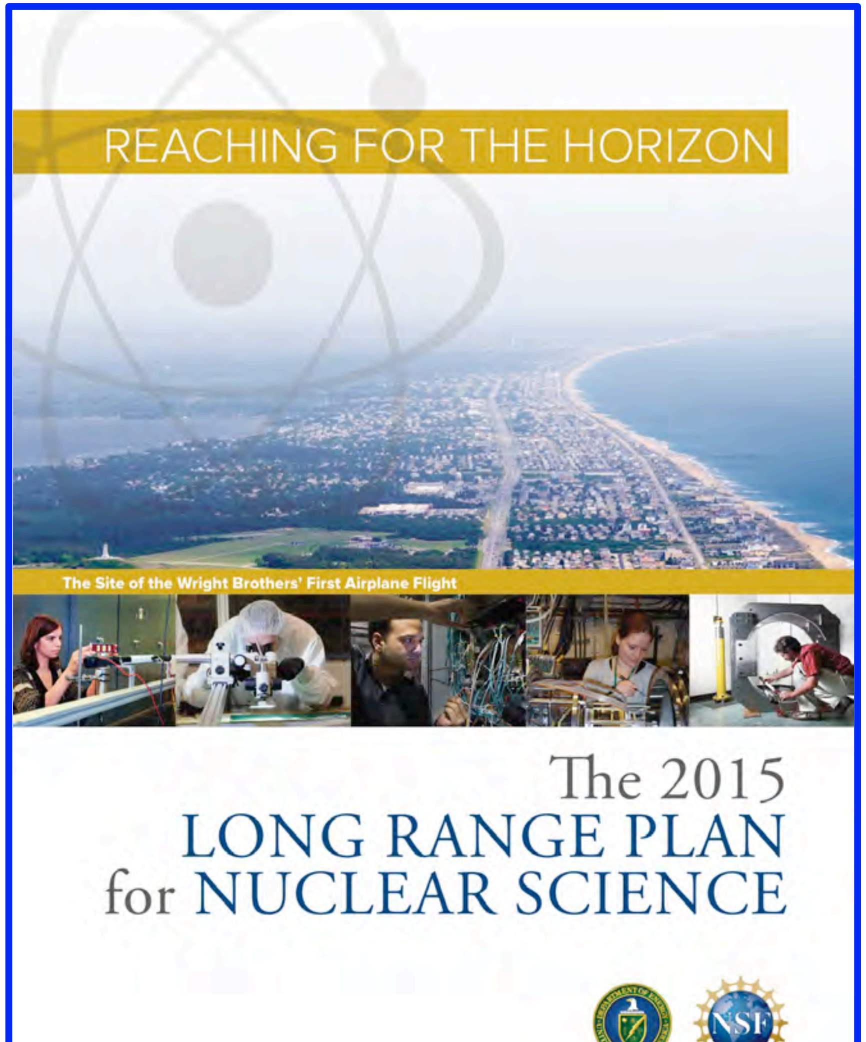
2019



2019



Realization



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

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

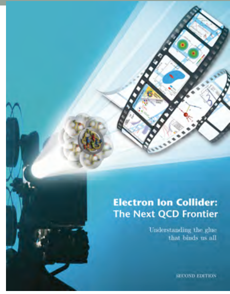
RECOMMENDATION:

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

Initiatives:

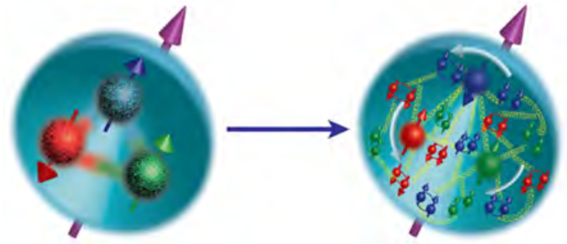
Theory

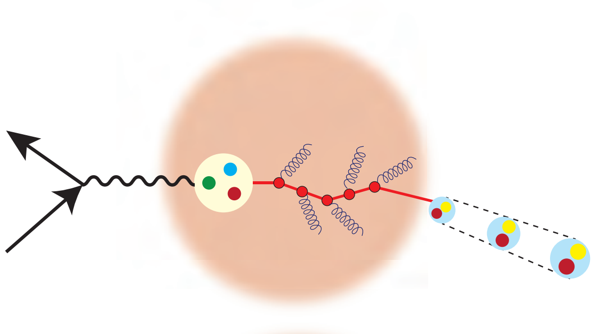
Detector & Accelerator R&D



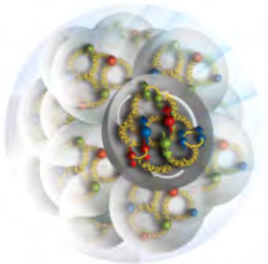
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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?



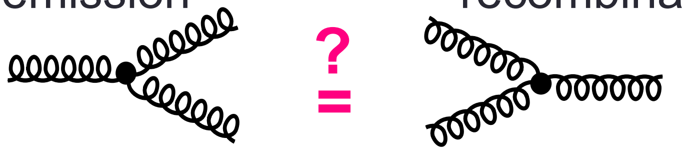


How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?



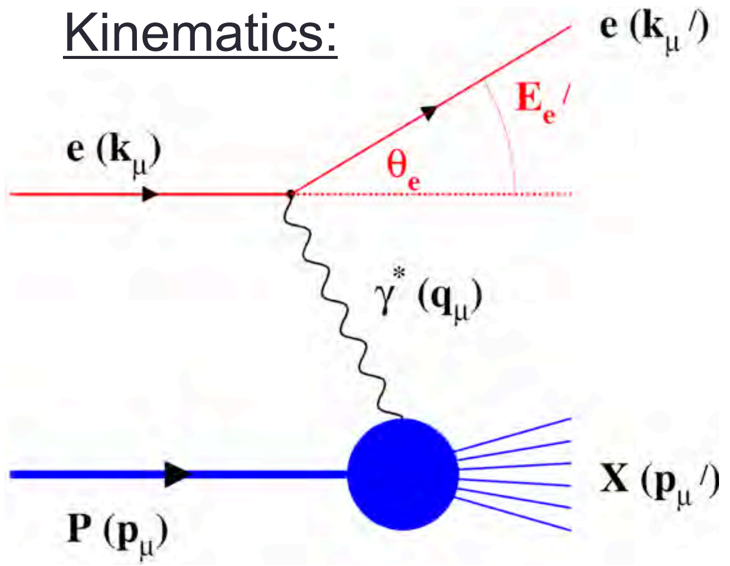
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission ?= gluon recombination



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

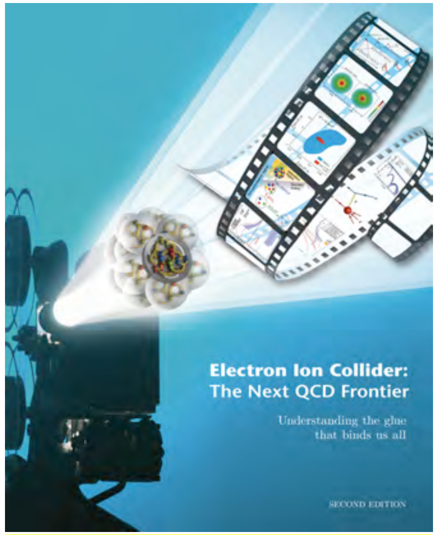
Hadron :

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

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:

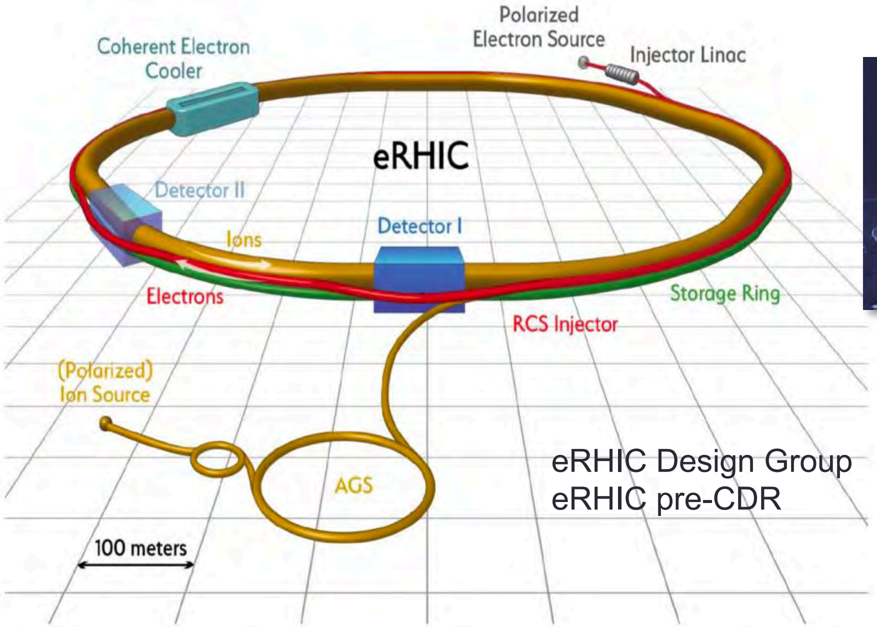
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

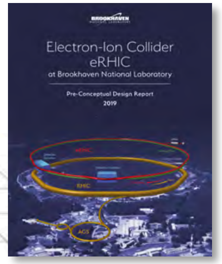
For e-A collisions at the EIC:

- ✓ 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

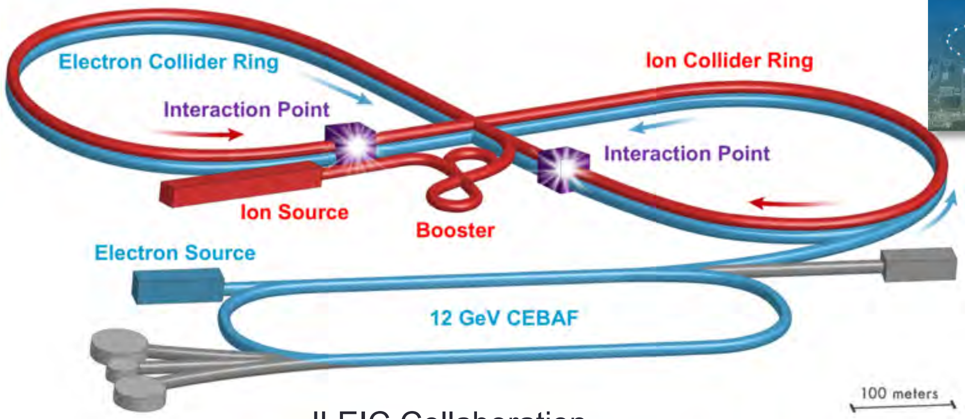
Both designs use DOE's significant investments in infrastructure





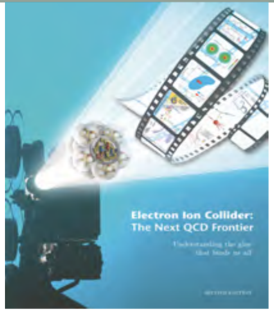
eRHIC Design Group
eRHIC pre-CDR

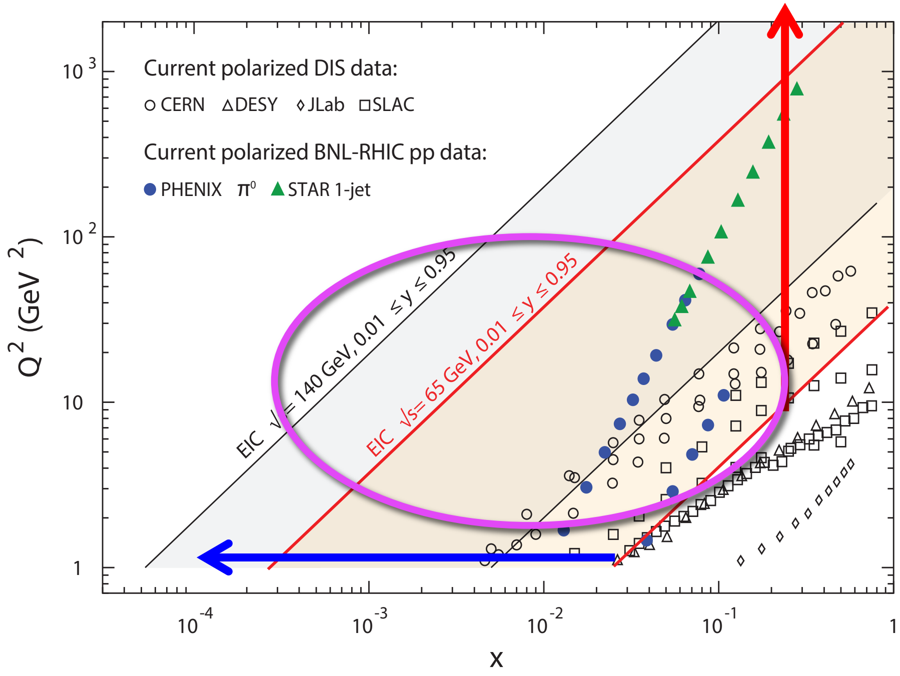
Details in Morozov's talk



JLEIC Collaboration
JLEIC Pre-CDR

EIC: Kinematic reach & properties



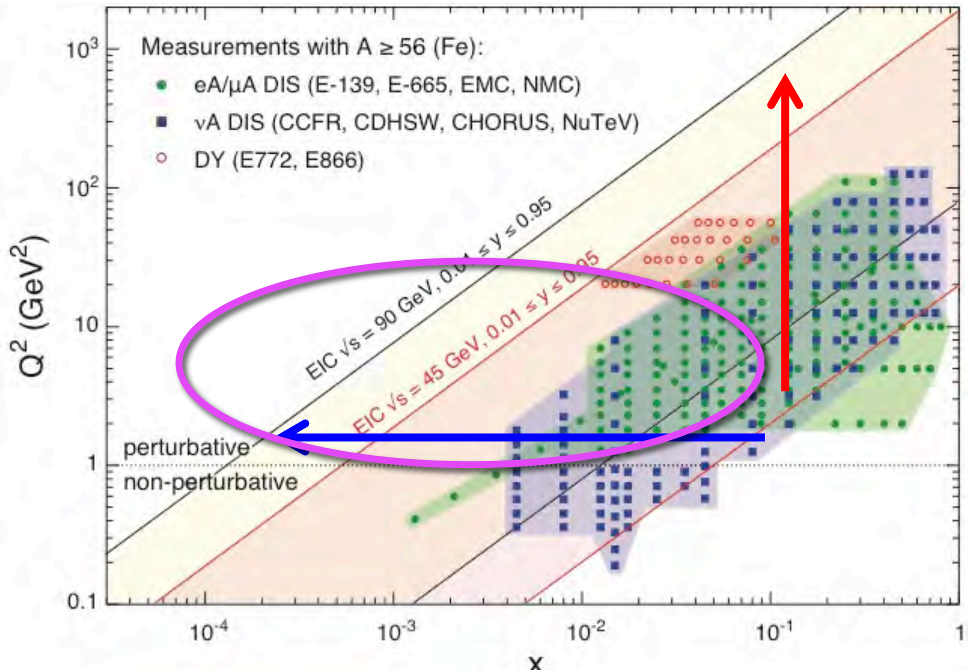


For e-N collisions at the EIC:

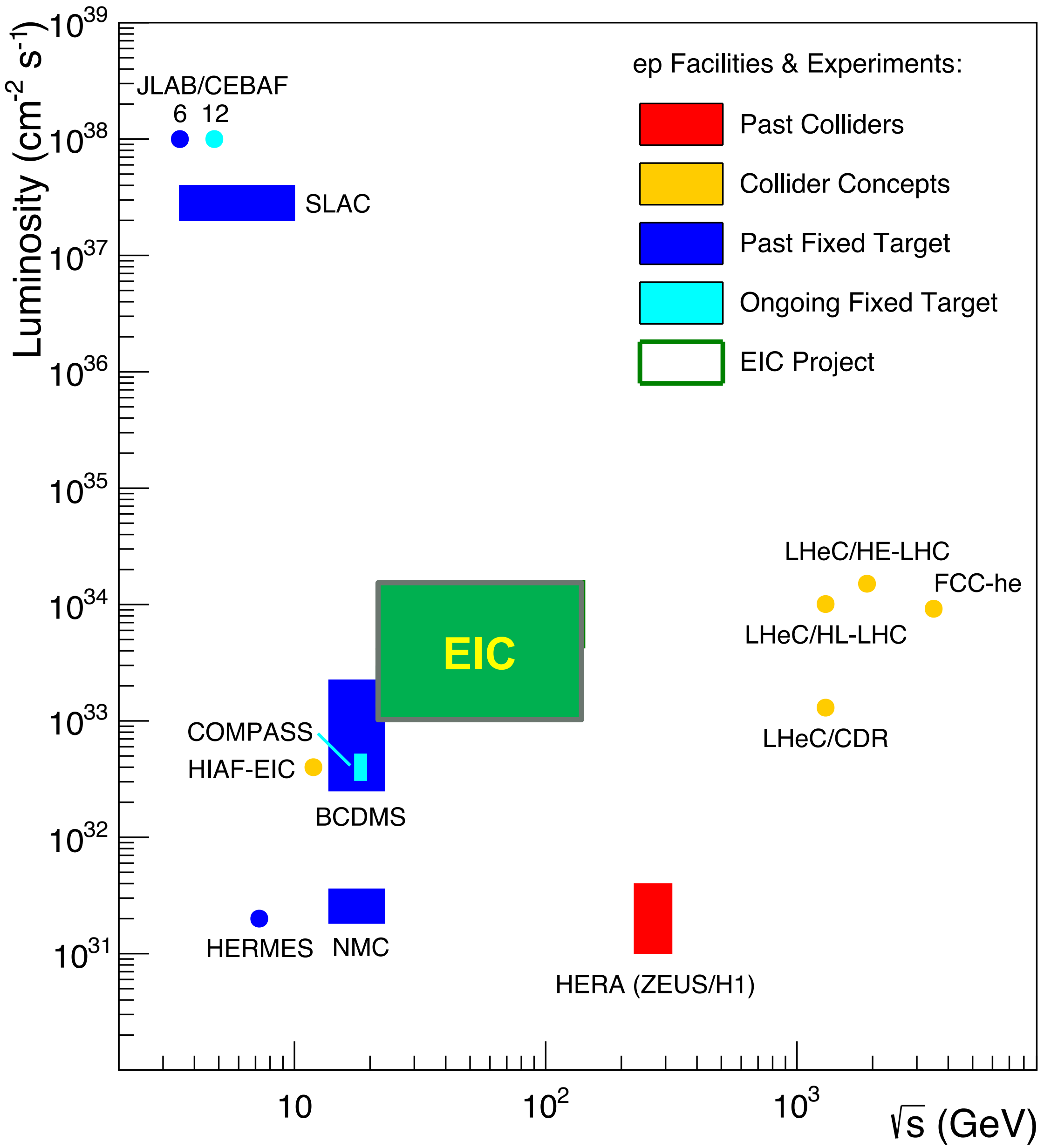
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

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)



Uniqueness of the US EIC among all DIS Facilities



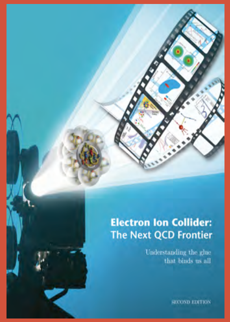
All DIS facilities in the world.

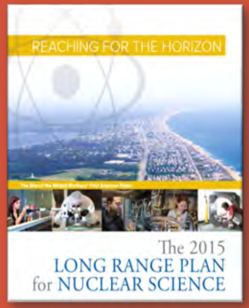
However, if we ask for:

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

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

EIC a truly unique facility



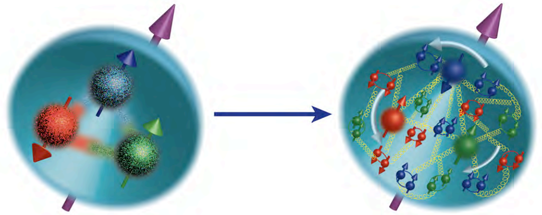


The Science Of EIC

See also:

Yoshitaka Hatta, Alexei Prokudin, Daria Sokhan, Toumas Lappi

Barbara Badelek, Ernst Sichtermann

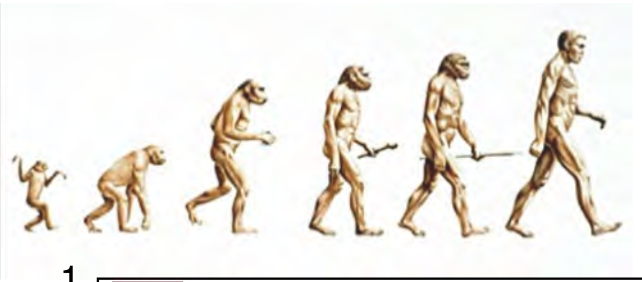


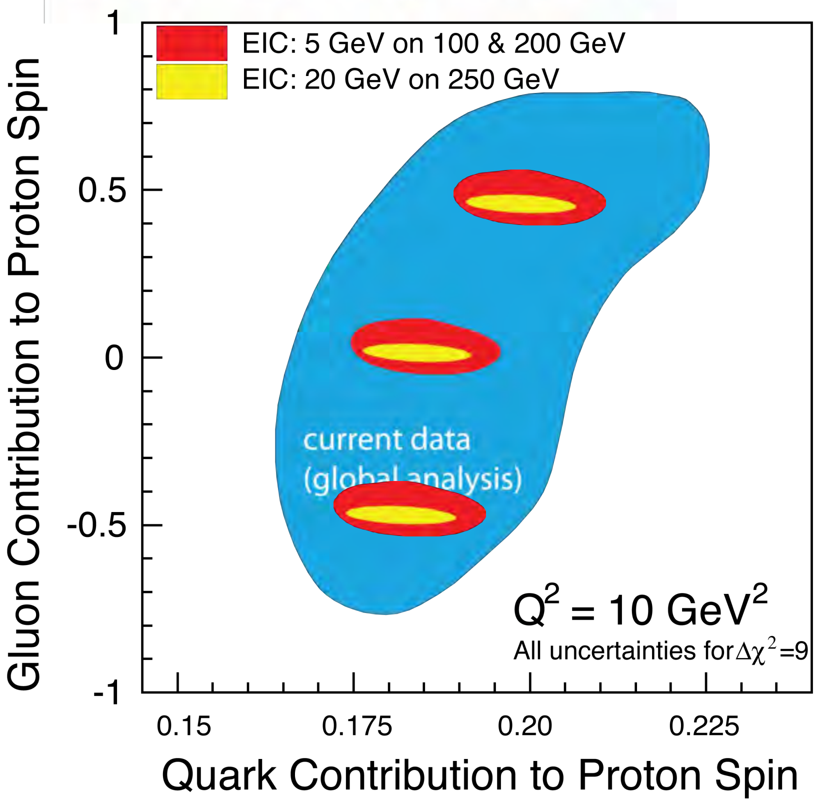
Understanding of Nucleon Spin

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

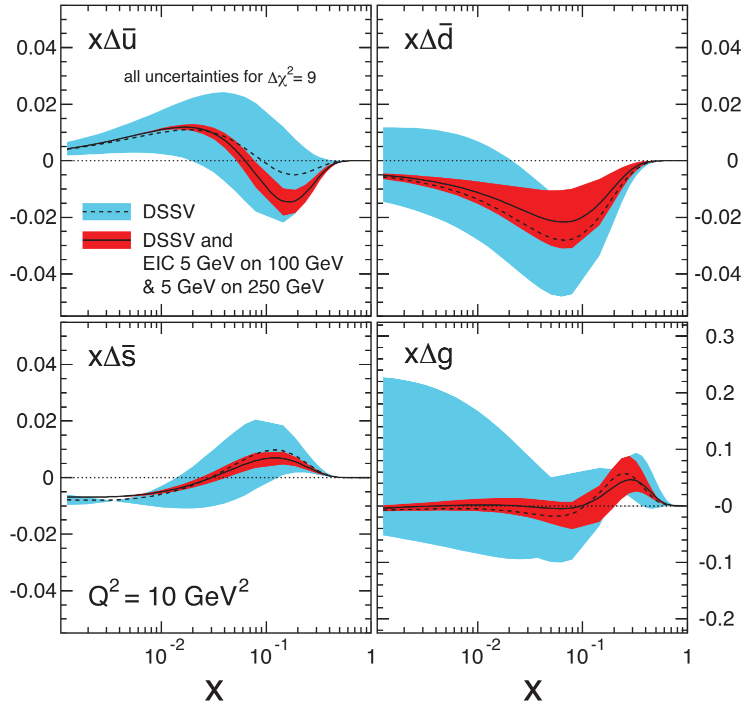
$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

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

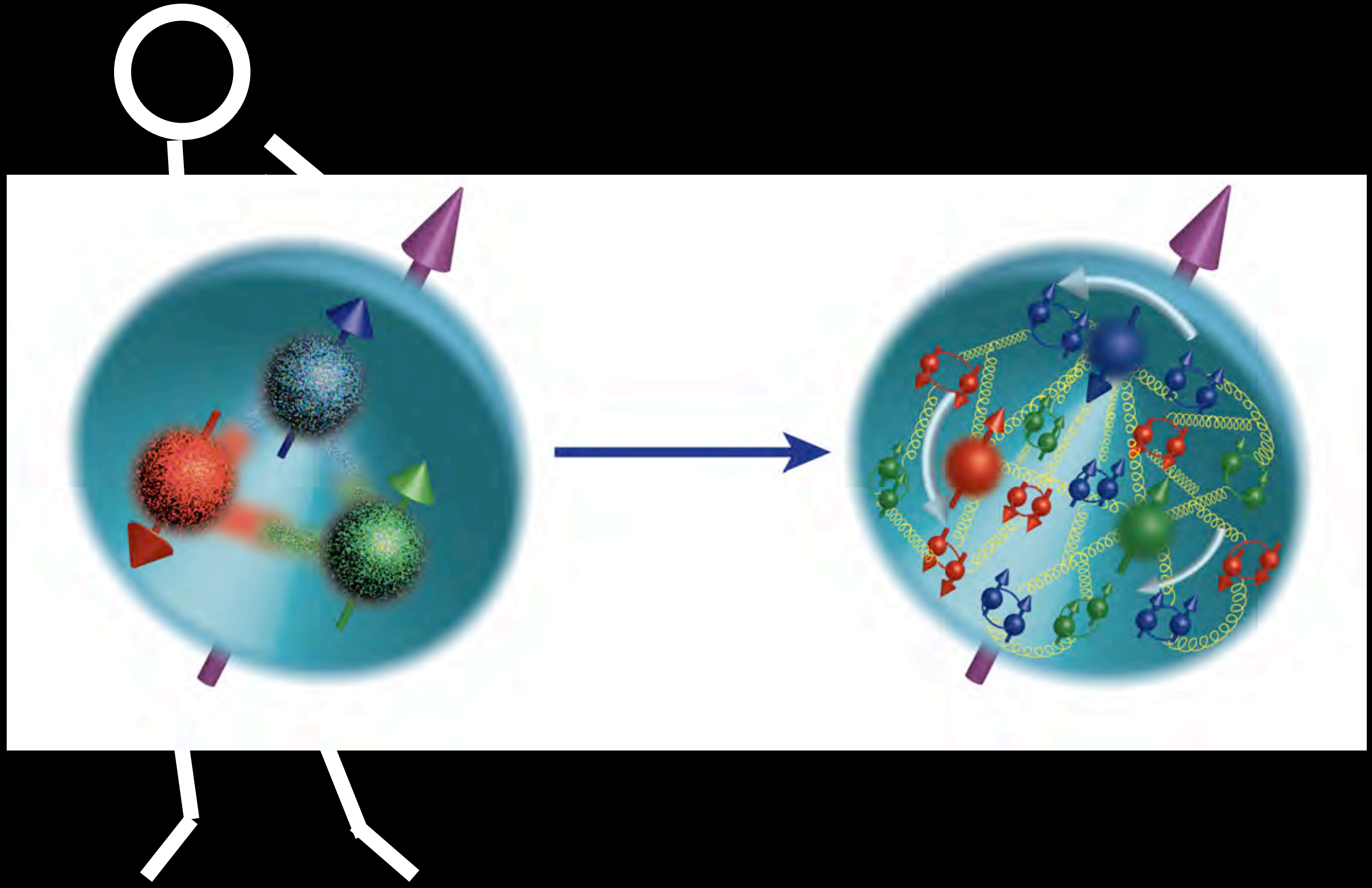




E. Sichtermann
B. Badelek
R. Fatemi



1D 3D

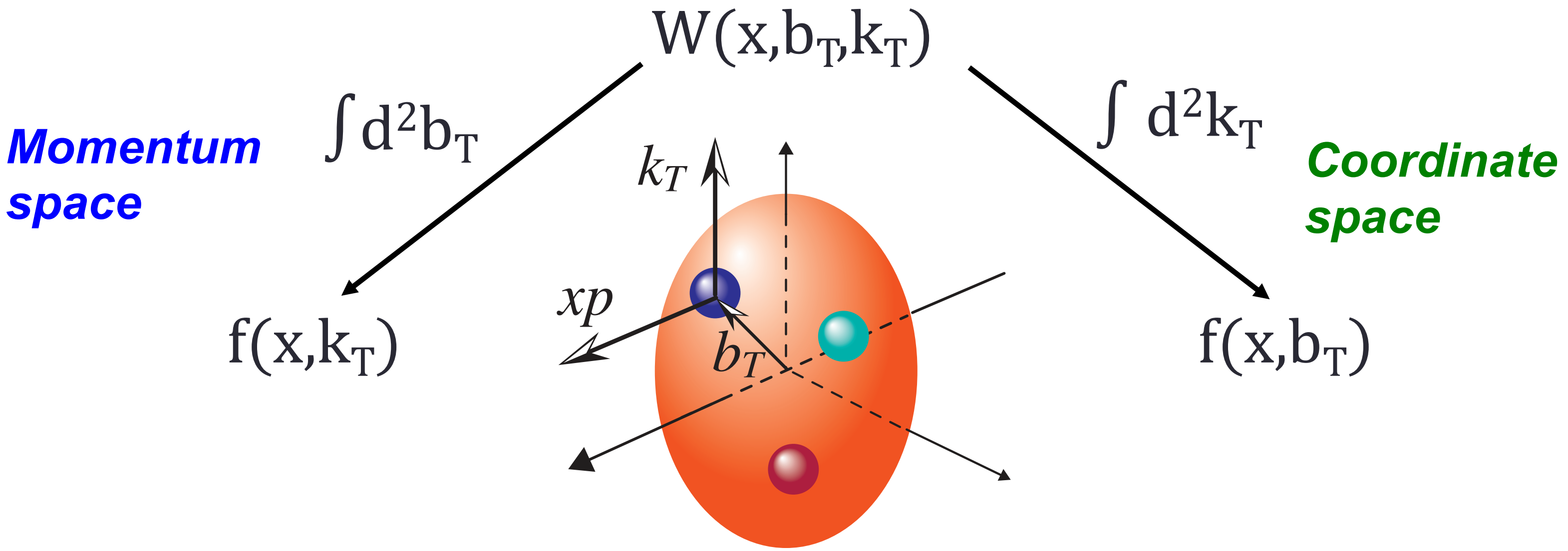


Courtesy: Alssandro Bacchetta

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**

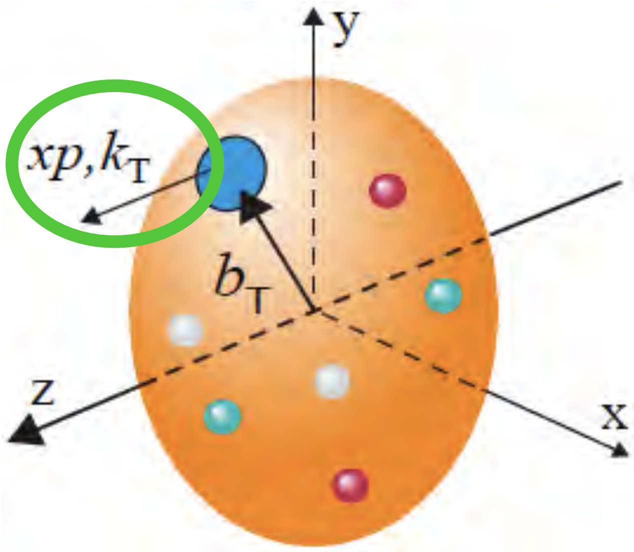
Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply Virtual Compton Scattering and Deeply Virtual Vector Meson production) → **GPDs**

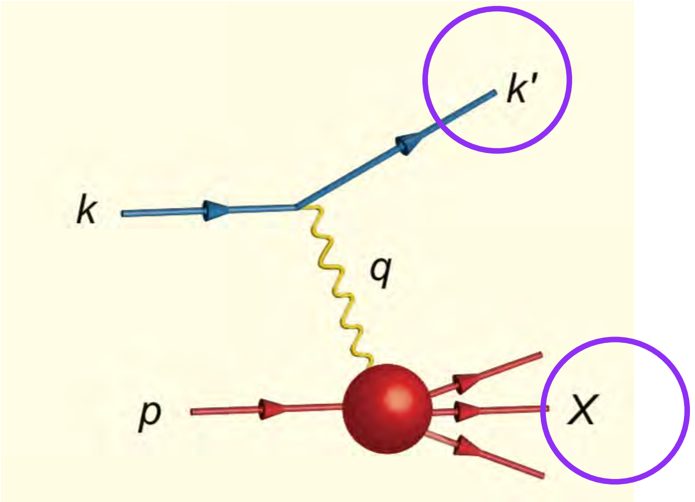
Position and momentum → Orbital motion of quarks and gluons

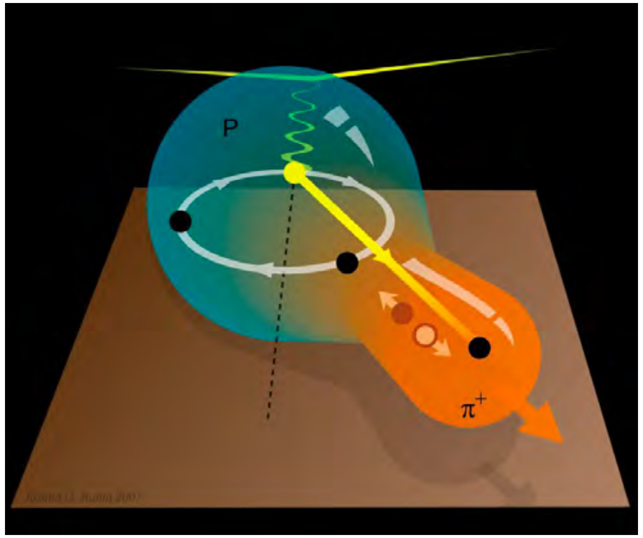
See:
Alexi Prokudin
Daria Sokhan

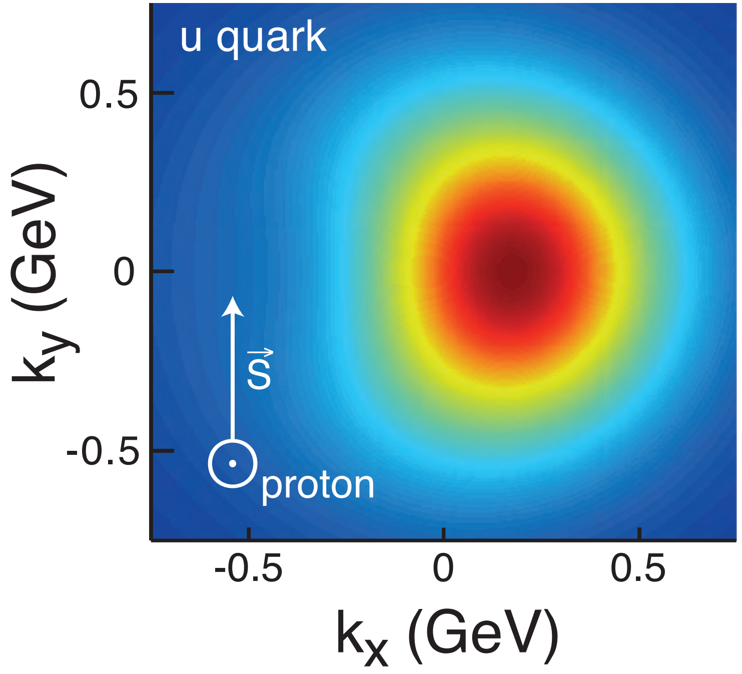
Measurement of Transverse Momentum Distribution

Semi-Inclusive Deep Inelastic Scattering







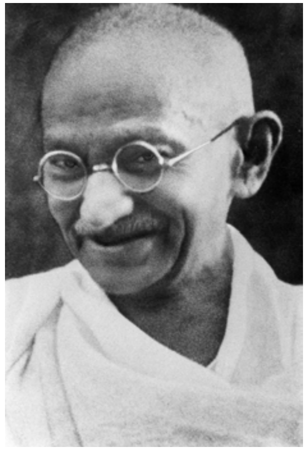


Spatial Imaging of quarks & gluons

Generalized Parton Distributions

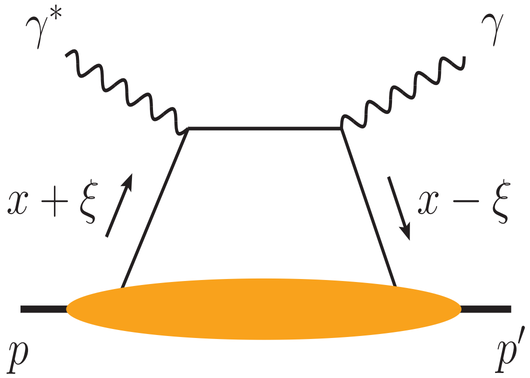
Historically, investigations of nucleon structure and dynamics involved breaking the nucleon…. (exploration of internal structure!)

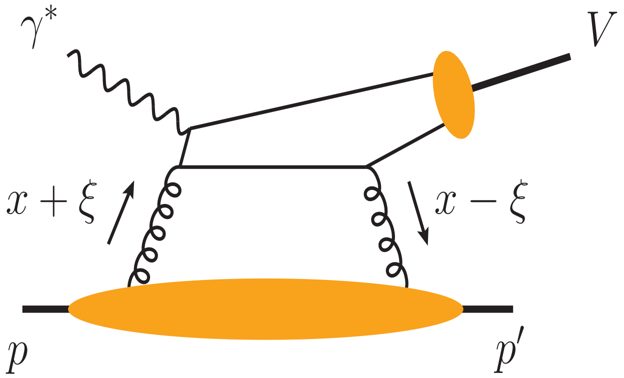
To get to the **orbital motion** of quarks and gluons we need **non-violent collisions**



Exclusive measurements → measure "everything"

Quarks Motion





Gluons: Only @ Collider

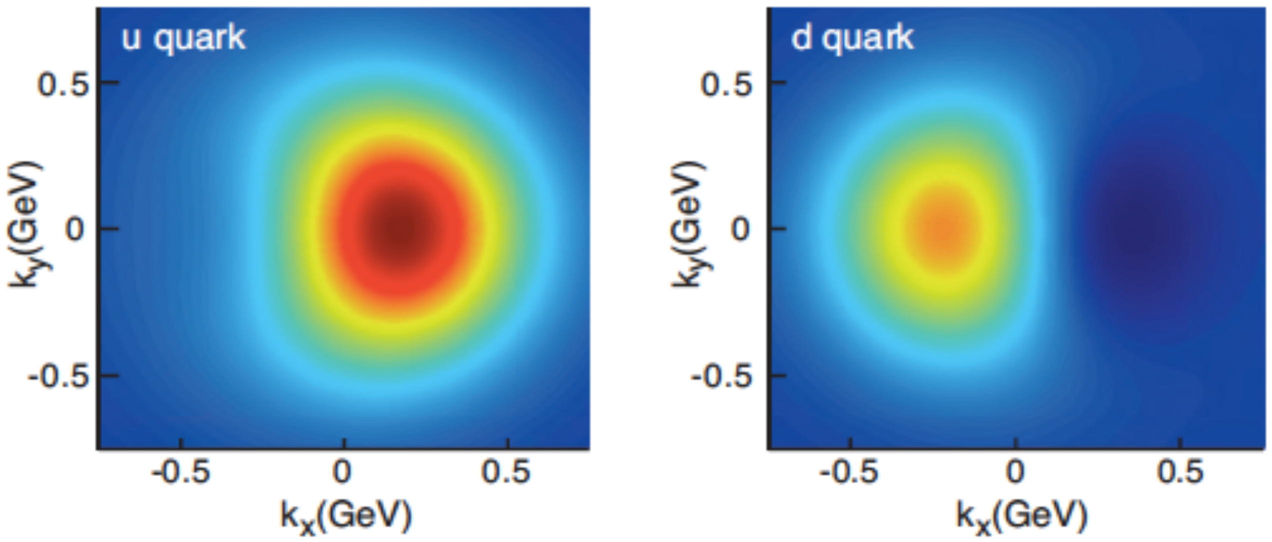
Deeply Virtual Compton Scattering
Measure all three final states
e + **p** → e'+ **p'**+ γ

Fourier transform of momentum transferred=(p-p') → Spatial distribution

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

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

Transverse Momentum Distributions

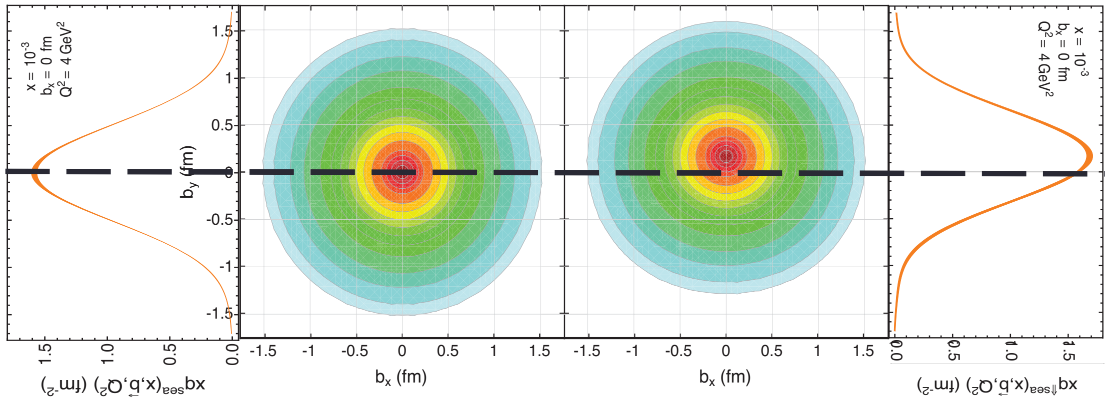


Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

sea-quarks

unpolarized polarized

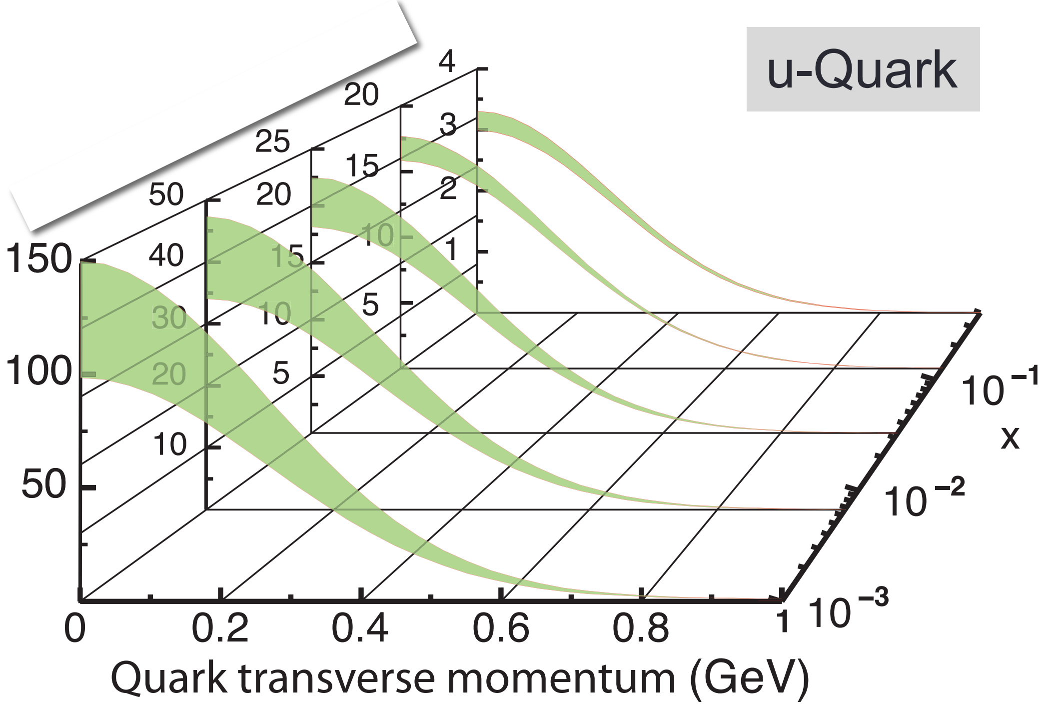


2+1 D partonic image of the proton with the EIC

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

Transverse Momentum Distributions

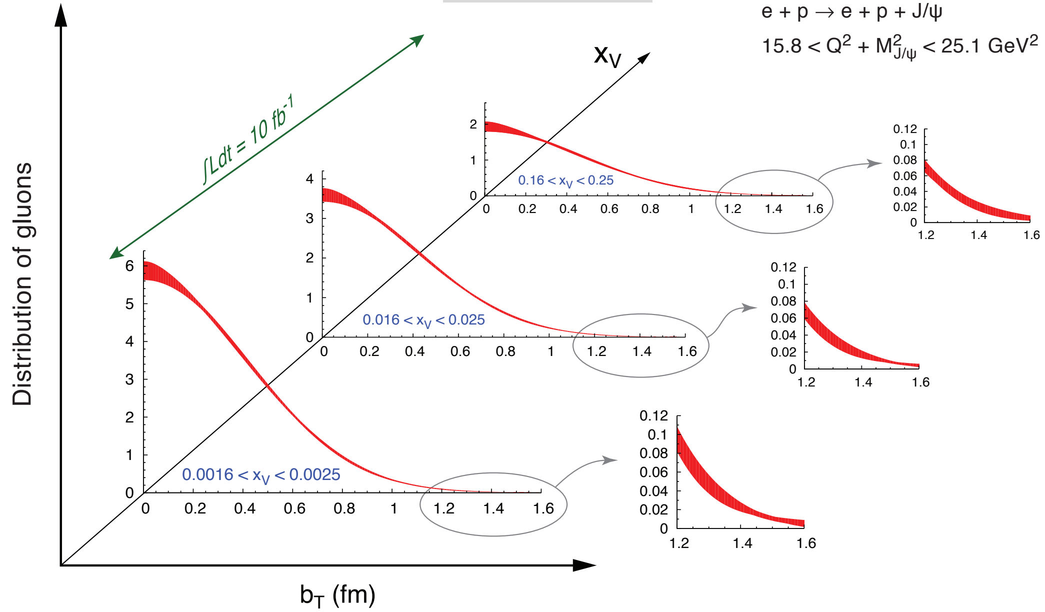
u-Quark



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

Transverse Position Distributions

Gluons

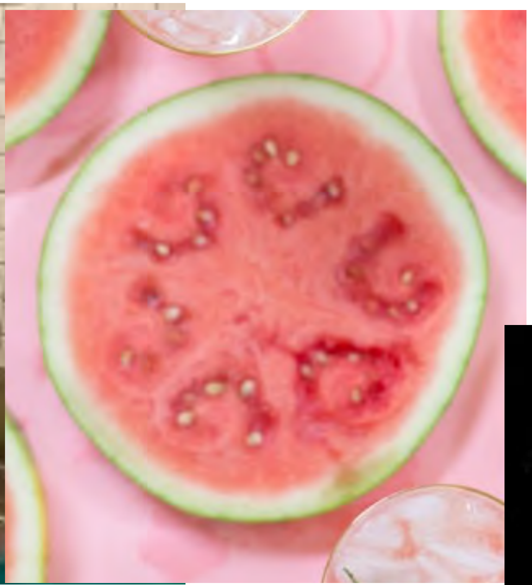


Study the evolution of momentum and position distributions over wide range in x

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)

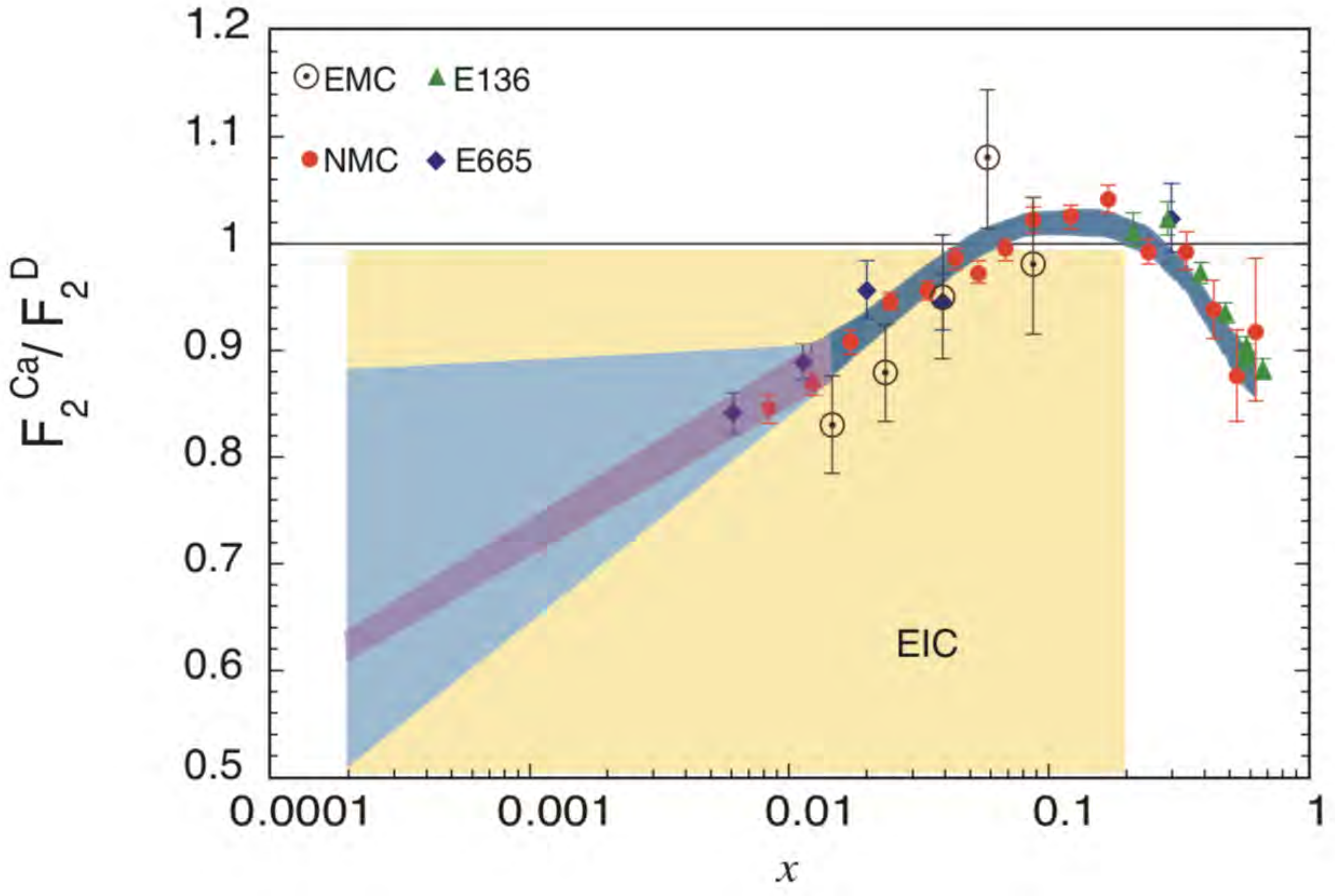
3) MRI of a watermelon

Non-Violent e-A (EIC)

Nuclear PDFs (ratios)

Ratio of F_2 Structure functions of heavy vs. light nuclei
-- See Axel Schmidt's talk Lectures Day 1

No low-x date available. Those that exist are at very low-Q^2, where pQCD methods may not be reliable

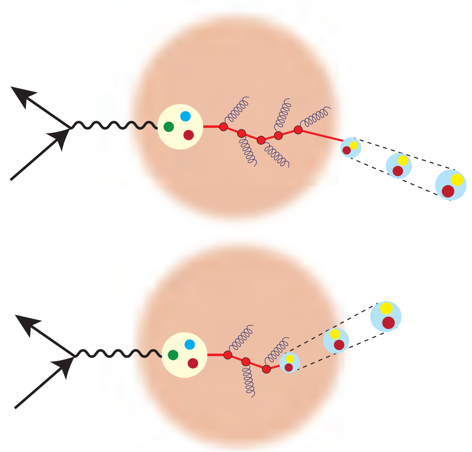


Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

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

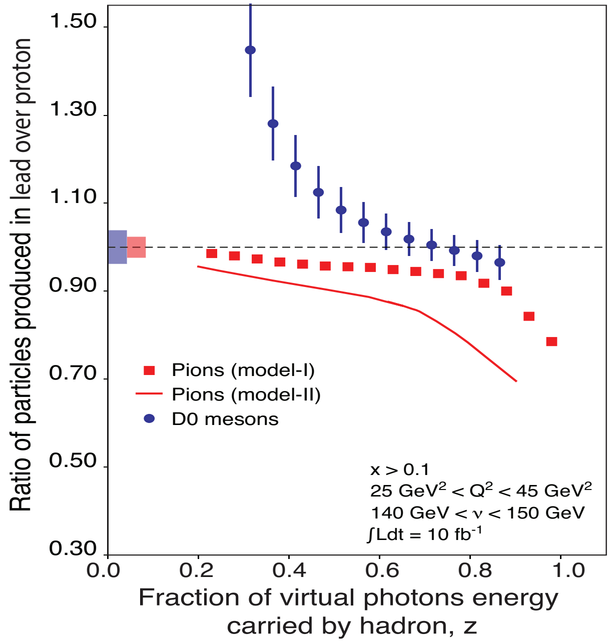
$$\nu = \frac{Q^2}{2mx}$$



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:



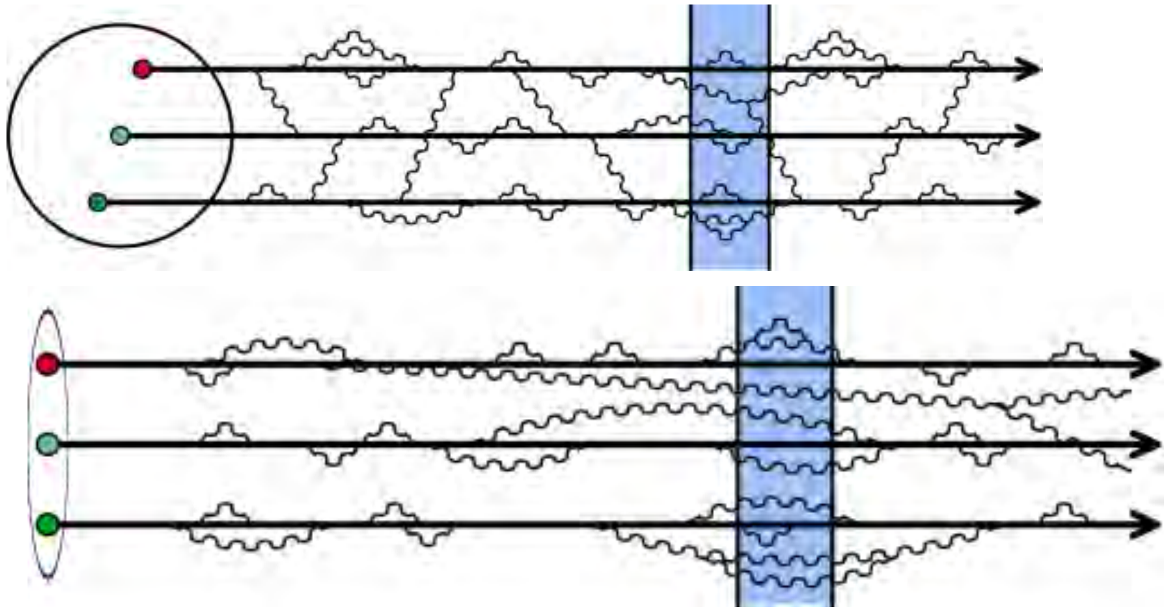
Identify π vs. D^0 (charm) mesons in e-A collisions:
Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

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.

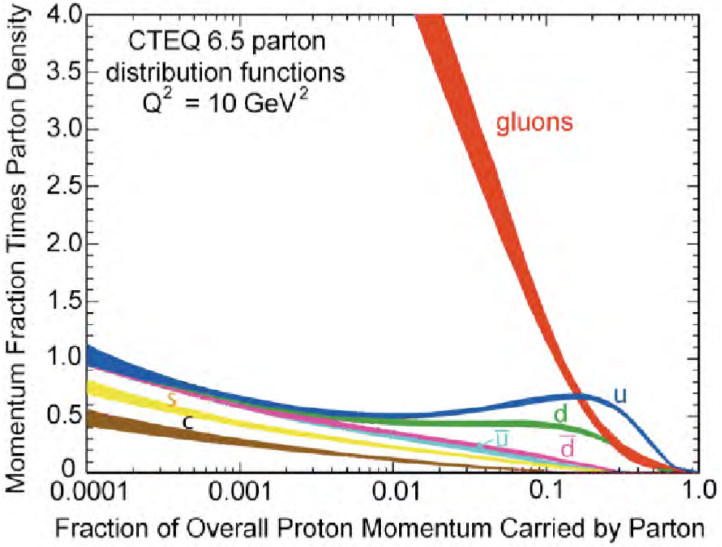
High energy: Low- x
Regime of a Collider



Cartoon of boosted proton

At high energy:

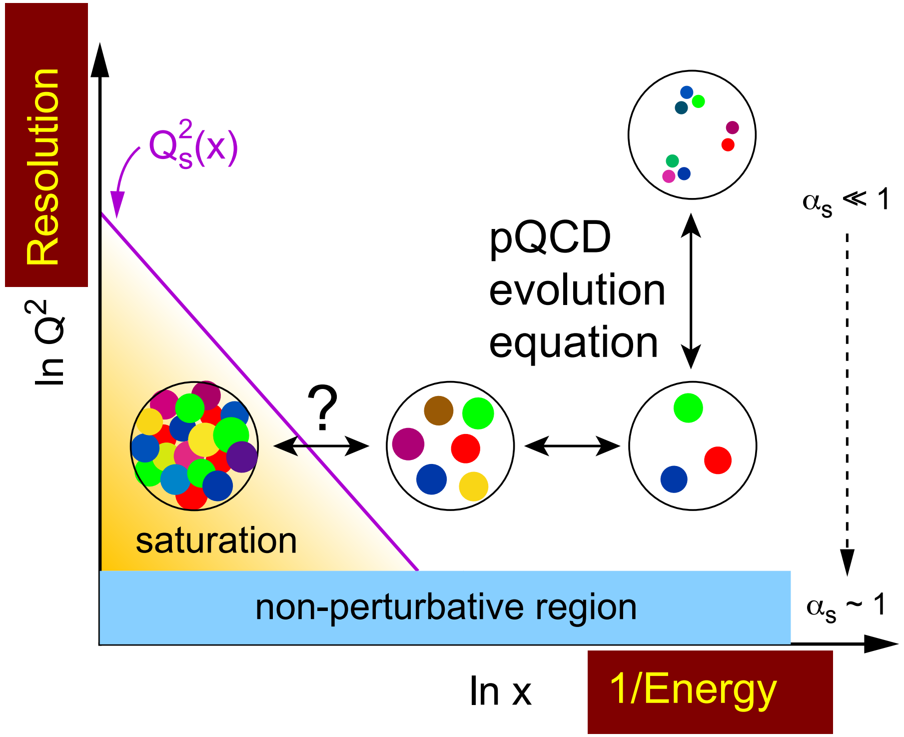
- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate further smaller x gluons ➔ which intern radiate more……. Leading to a **runaway growth?**



What do we learn from low-x studies?

What tames the low-x rise?

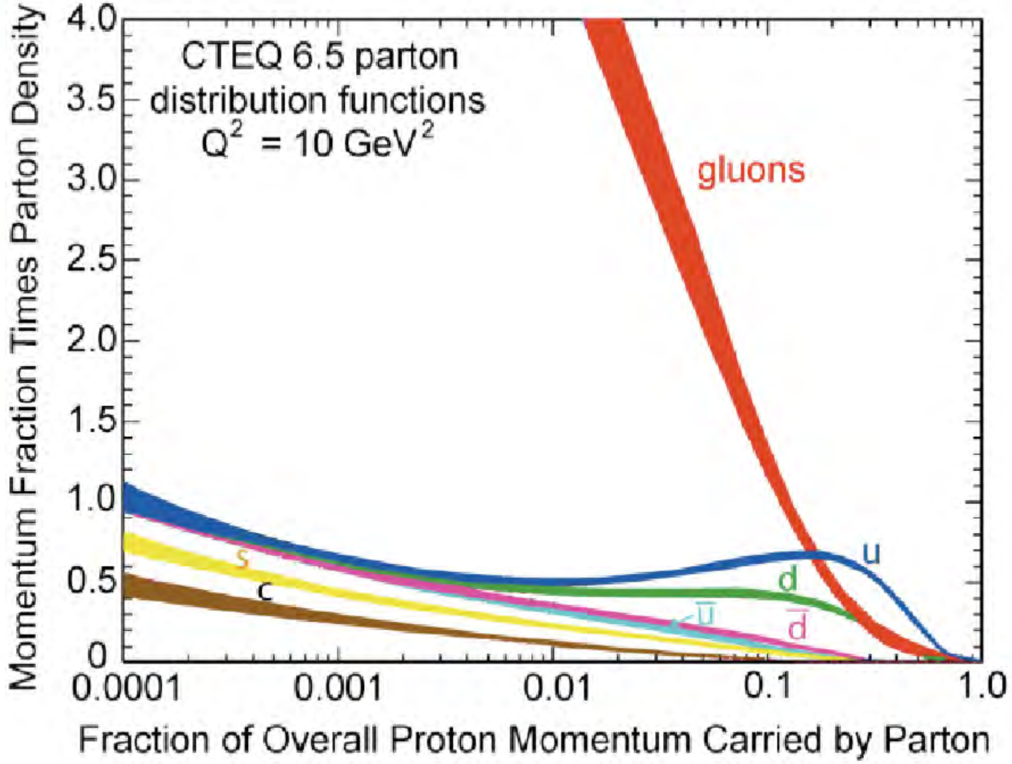
- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable



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?

See talk by T. Lappi

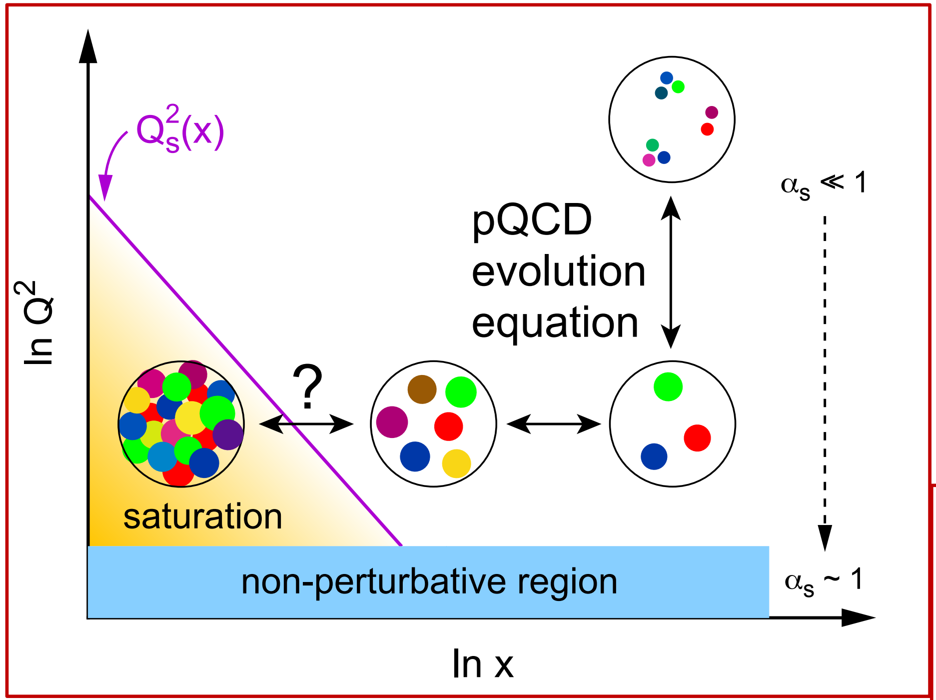
HERA collider at DESY

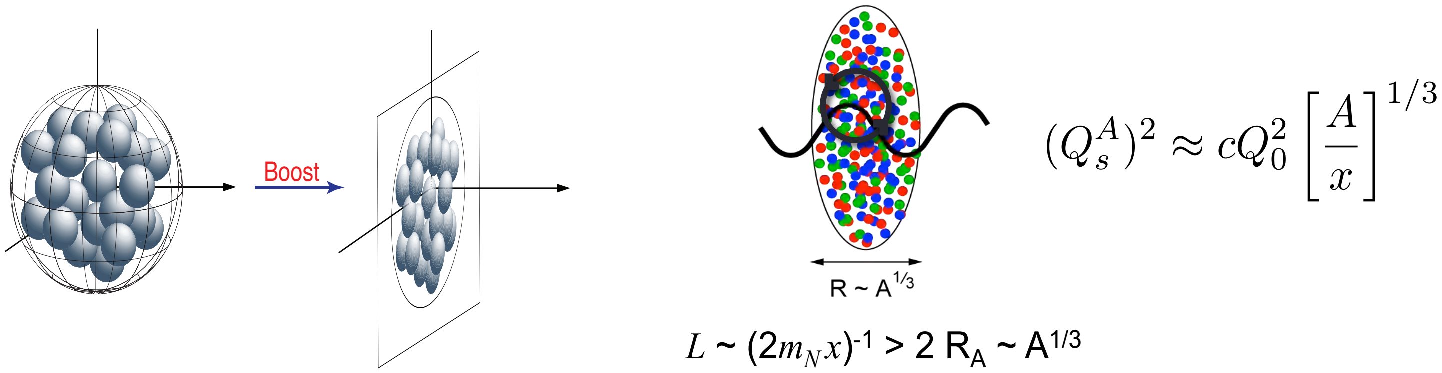


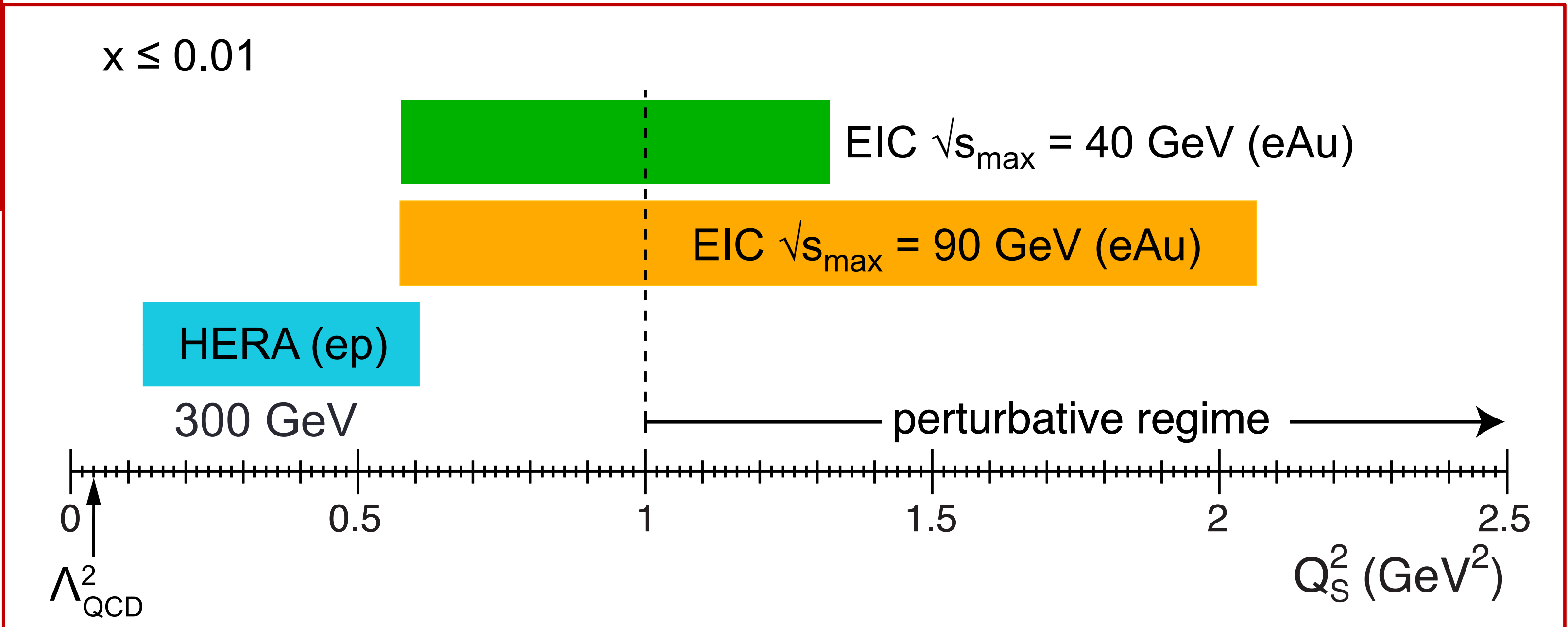
30 GeV electrons x 900 GeV protons ➔ 300 GeV in CoM

EIC ➔
18 GeV electrons x 250 GeV protons ➔ 140 CoM
How would we reach the saturation region?

Advantage of the nucleus over proton







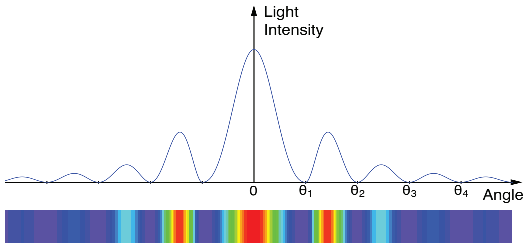
Accessible range of saturation scale $Q_s^{\,2}$ at the EIC with e+A collisions. arXiv:1708.01527

Diffraction : Optics and high energy physics

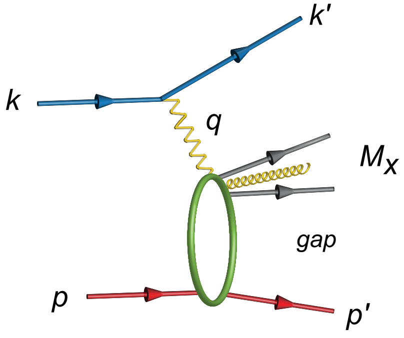
Light with wavelength λ obstructed by an opaque disk of radius R suffers diffraction:

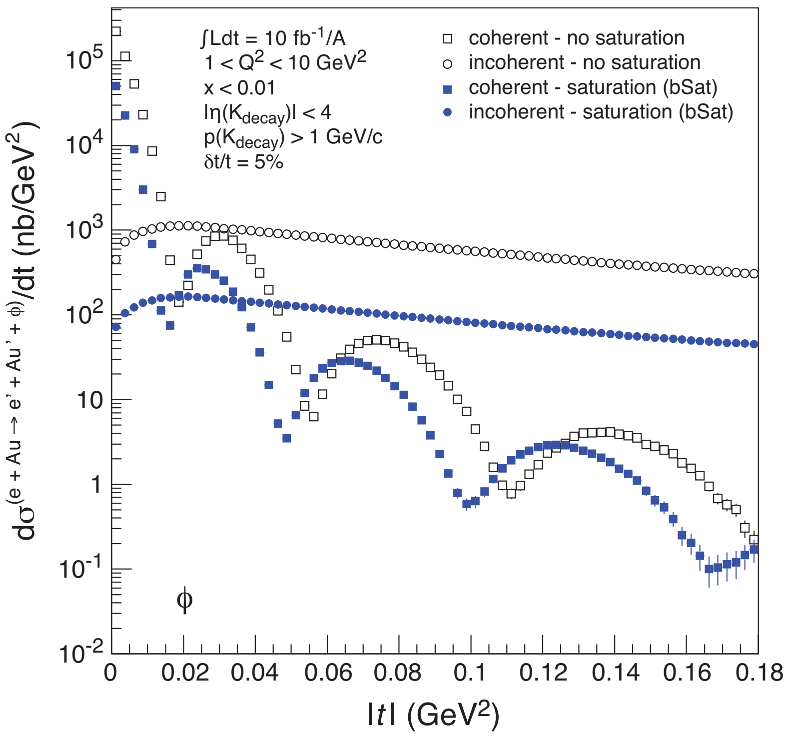
k → wave number

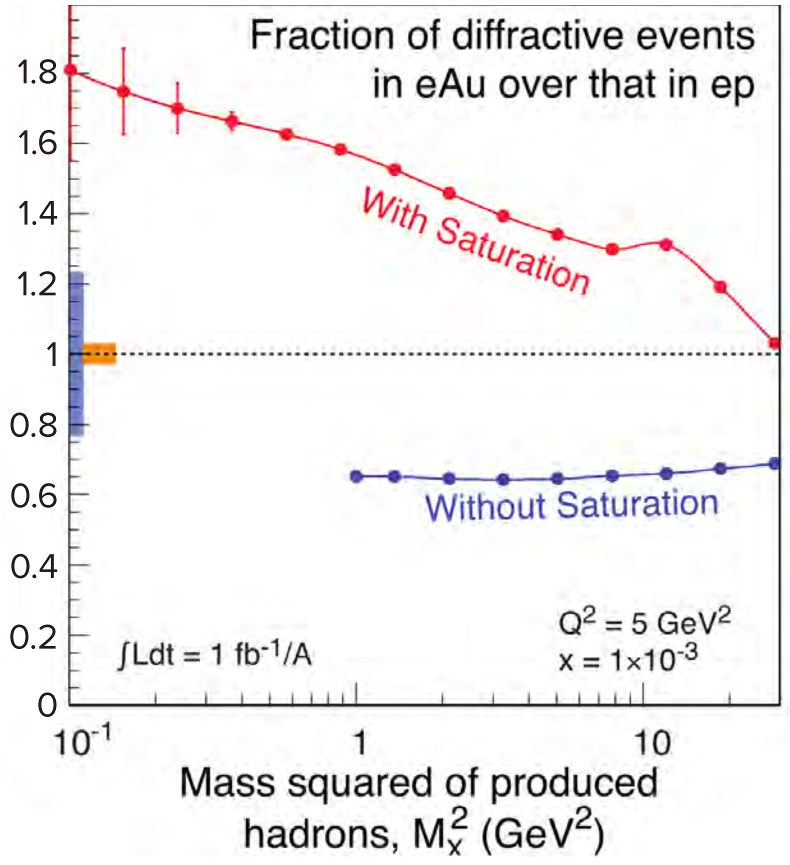
$$|t| \approx k^2\theta^2 \quad \theta_i \sim \frac{1}{(kR)}$$



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



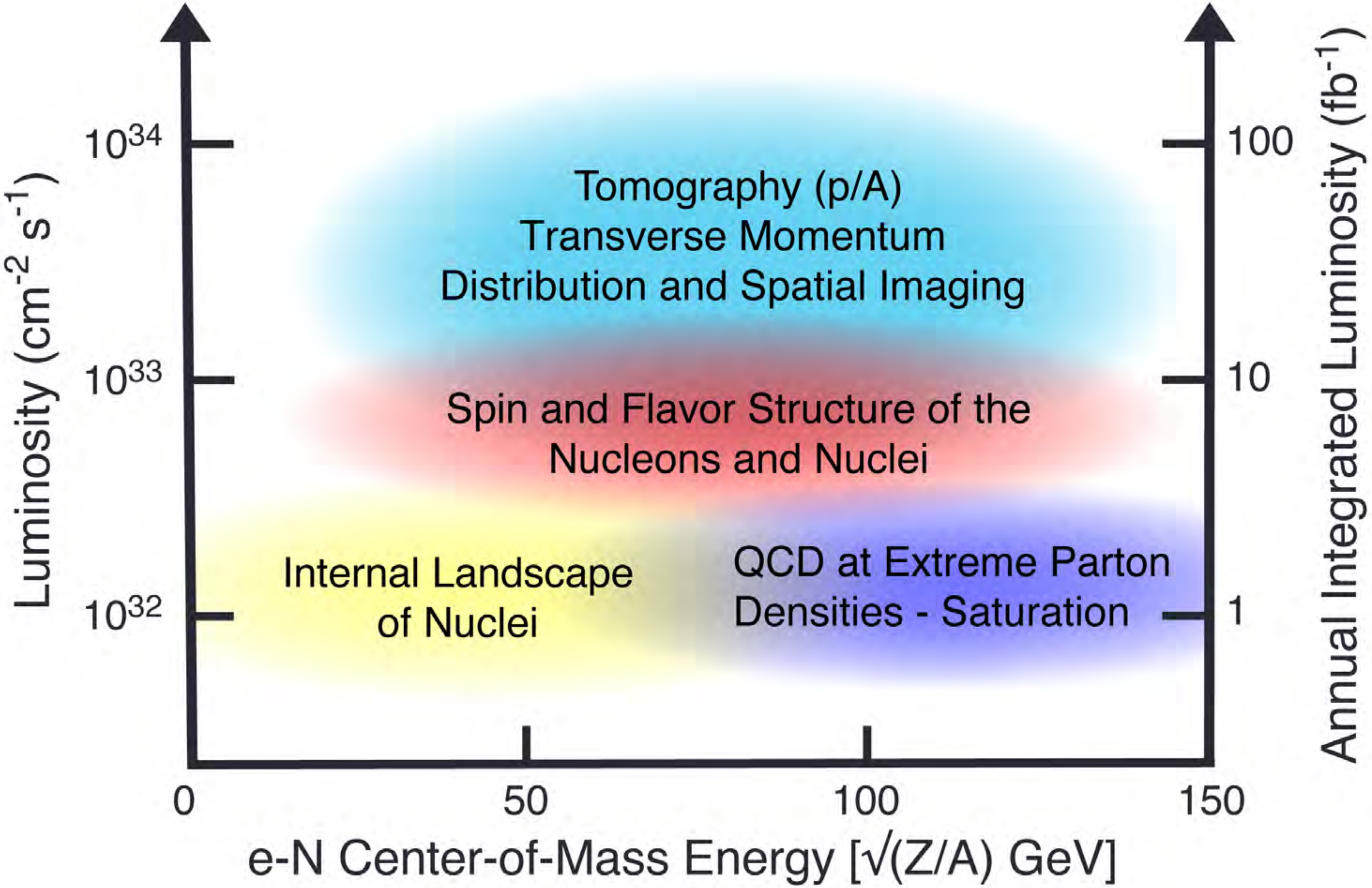




At HERA : ep: 10-15% diffractive

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

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



The National Academy Review of the EIC Science

2017-2018

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

National Academy of Science, Engineering & Medicine (NAS)

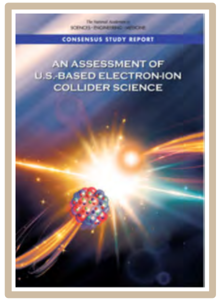
The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the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

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?

NAS Consensus: EIC science compelling, fundamental, and timely

July 26, 2018



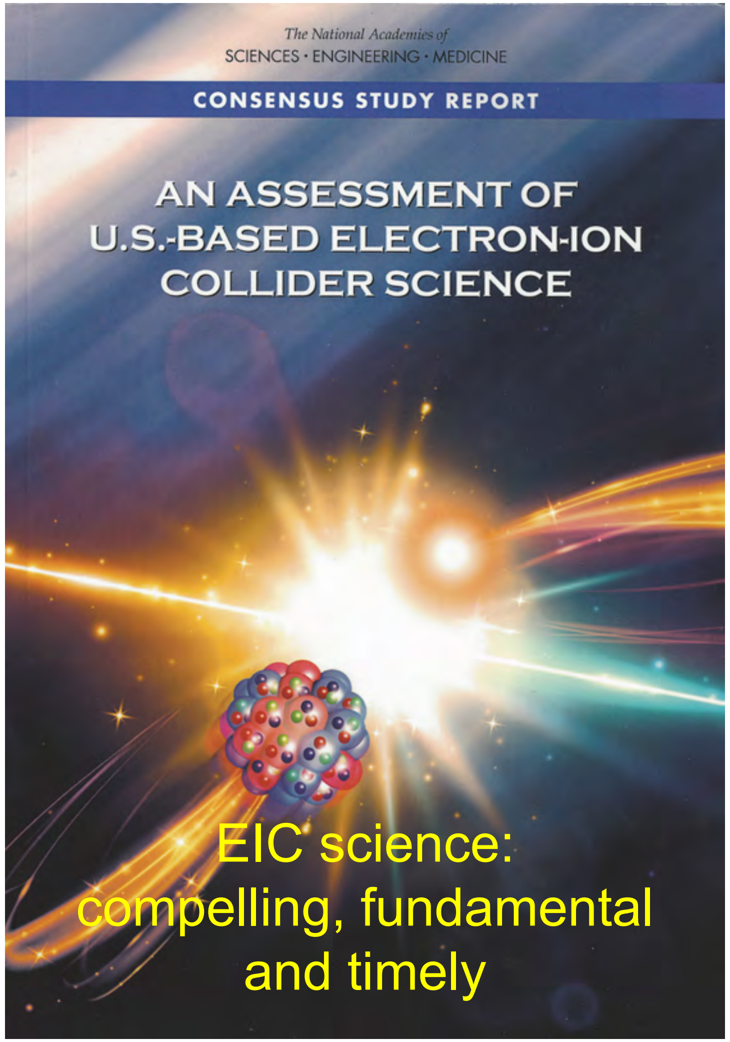
- **Finding 1**: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems 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.

Other findings:

An EIC would be a unique facility in the world

Leadership in the accelerator science and technology of colliders

US EIC Cost effective: takes advantage of existing accelerator infrastructure and expertise ➔ reduced risk



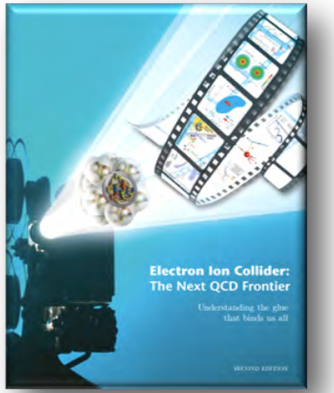
Consensus Study Report on the US based Electron Ion Collider

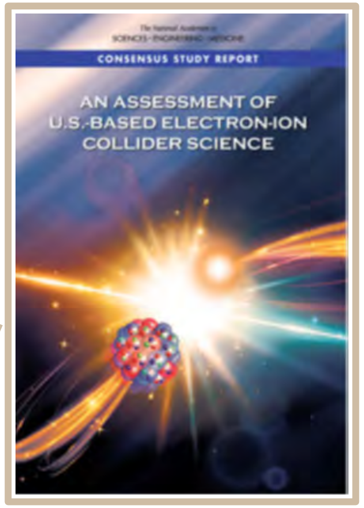
Summary:

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

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:

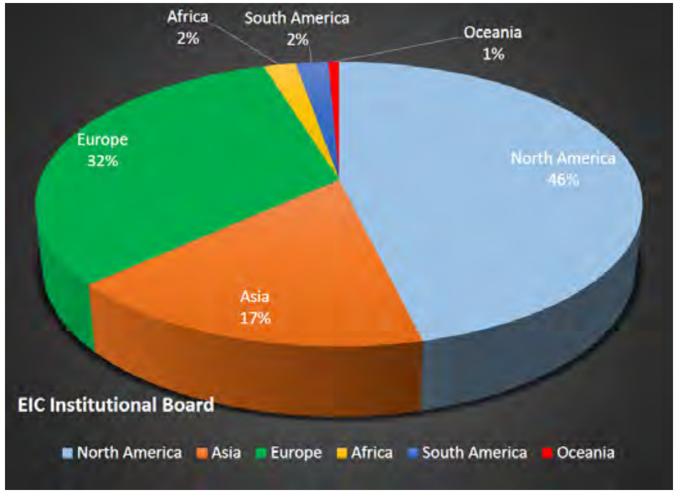
- Extensive center-of-mass energy range, from ~20-~100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times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

The EIC Users Group: EICUG.ORG



Formally established in 2016
~950 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, Institutional Board, Speaker's Committee

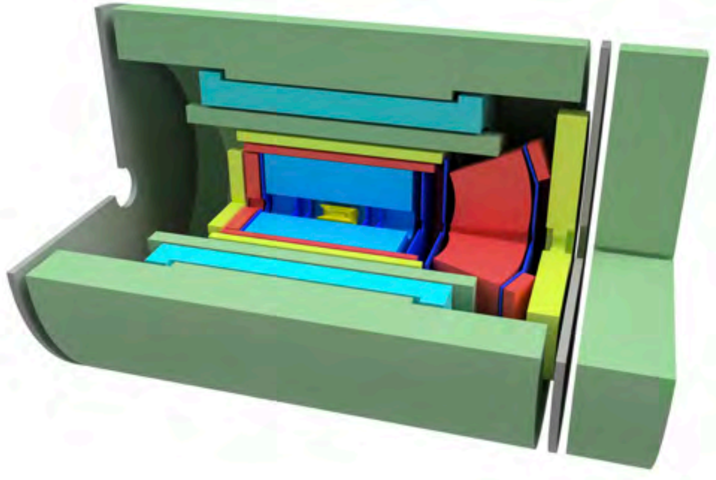
Task forces on:
-- Beam polarimetry, Luminosity measurement
-- Background studies, IR Design

Year long workshops: Yellow Reports for detector design

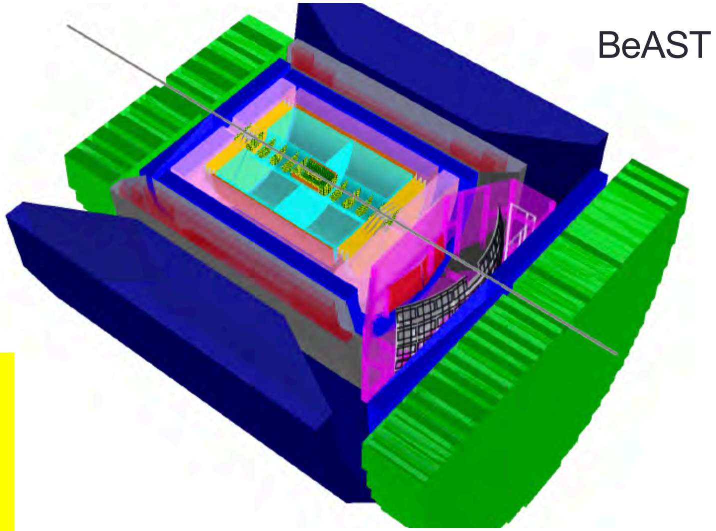
Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**, **FIU (2020)**, **Warsaw (2021)**

EIC Detector Concepts: integration of detectors in to machine lattice

EIC Day 1 detector, with BaBar Solenoid



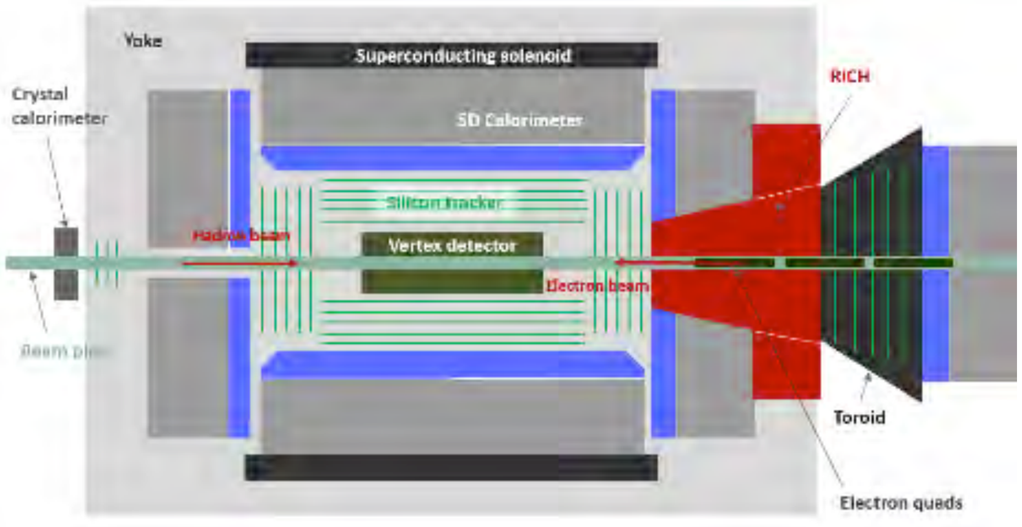
BeAST at BNL



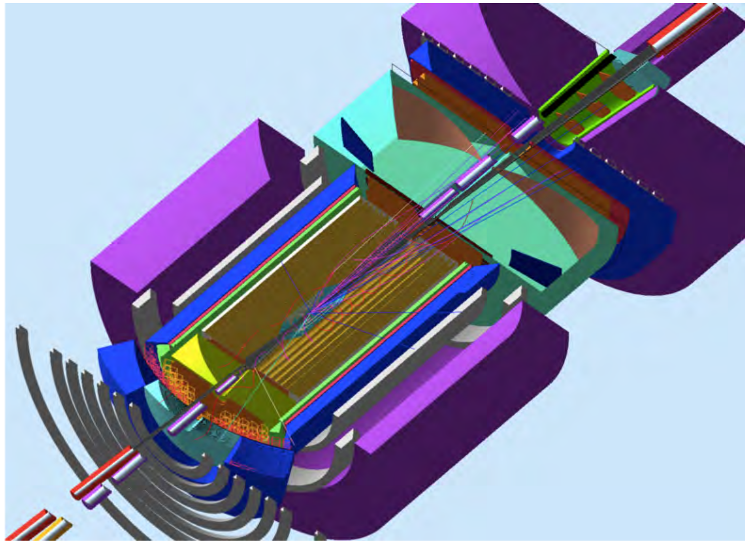
See Alexander Kiselev's talk

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 @ the US EIC beyond the EIC White Paper:

New Studies with proton or neutron target:

- 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?*
- *Gluon TMDs at low-x!*
- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??) Does polarization of hadron play any role?

Physics with nucleons and nuclear targets:

- *Quark Exotica: 4,5,6 quark systems…?*
- Study of jets: Internal structure of jets
- *Studies with 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
- Polarized light nuclei in the EIC
- *Entanglement entropy in nuclear medium and its connections to fragmentation, hadronization and confinement*

Precision electroweak and BSM physics: (workshop at FNAL, November 13-15, 2019

- Electroweak physics and searches beyond the Standard Model

Dir. Of office of NP
Tim Hallman's presentation

EICUG Paris, July 2019

Current Status and Path forward of EIC

The "wickets" are substantially aligned for a major step forward on the EIC

- A Mission Need Statement for an EIC has been approved by DOE
- An Independent Cost Review (ICR) Exercise mandated by DOE rules for projects of the projected scope of the EIC is very far along
- DOE is moving forward with a request for CD-0 (approve Mission Need)
- DOE has organized a panel to assess options for siting and consideration of "best value" between the two proposed concepts
- The Deputy Secretary is the Acquisition Executive for this level of DOE Investment
- **The FY 2020 President's Request includes $ 1.5 million OPC. The FY 2020 House Mark includes $ 10 million OPC and $ 1 million TEC.**

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.

Both Lab managements are committed to working with the DOE, the EICUG and the international partners to realize the US EIC no matter its site (BNL or JLab)