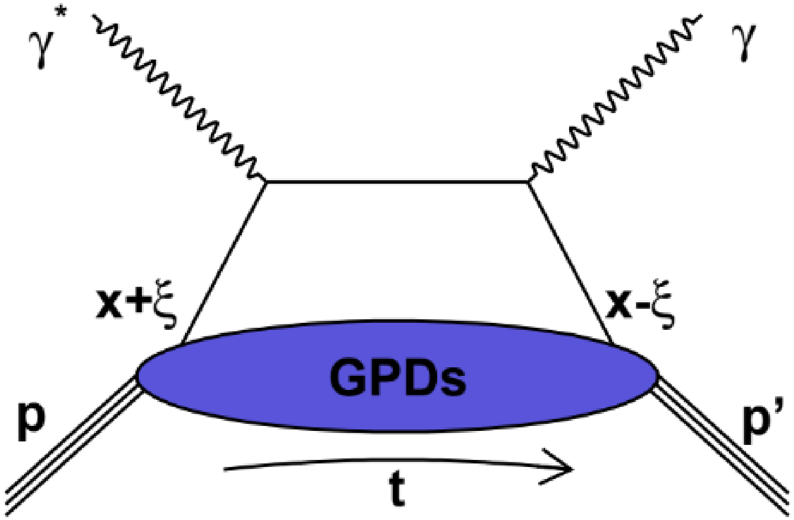
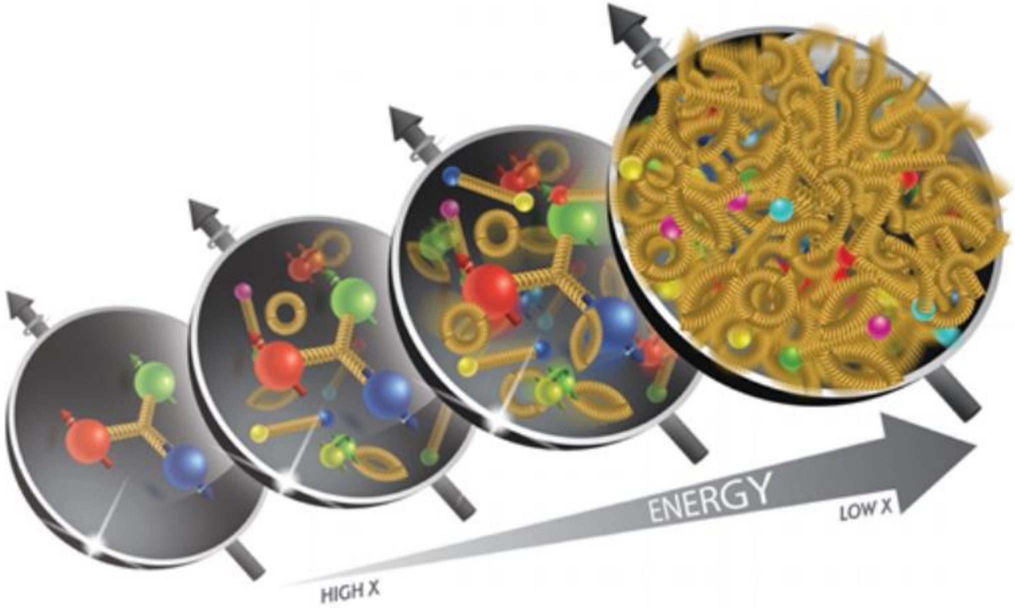
Deeply Virtual Compton Scattering and Spatial Imaging





Lecture 5

Carlos Muñoz Camacho
IJCLab-Orsay (CNRS/IN2P3, France)

Outline

- Lecture 1: Introduction
  - Elastic scattering, form factors (FFs)
  - Deep Inelastic scattering, parton distribution functions (PDFs)
  - Exclusive reactions, Generalized Parton Distributions (GPDs)
- Lecture 2: Deeply Virtual Compton Scattering
  - Experimental results on proton targets
  - Flavor separation using quasi-free neutrons
- Lecture 3: Deeply Virtual Meson Production & GPD models
  - Rosenbluth separation
  - Access to transversity GPDs
  - GPD models and parametrizations
- Lecture 4: GPDs at JLab12 and beyond
  - Review of GPD programs in other facilities worldwide
  - Future experiments at JLab at 12 GeV
- Lecture 5: Electron-Ion Collider
  - Imaging gluons inside the nucleon
  - The EIC project

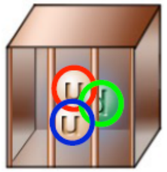
Outline lecture 5

- Introduction
- Physics motivations
- Machine and detector requirements
- Recent (international) developments
- Summary

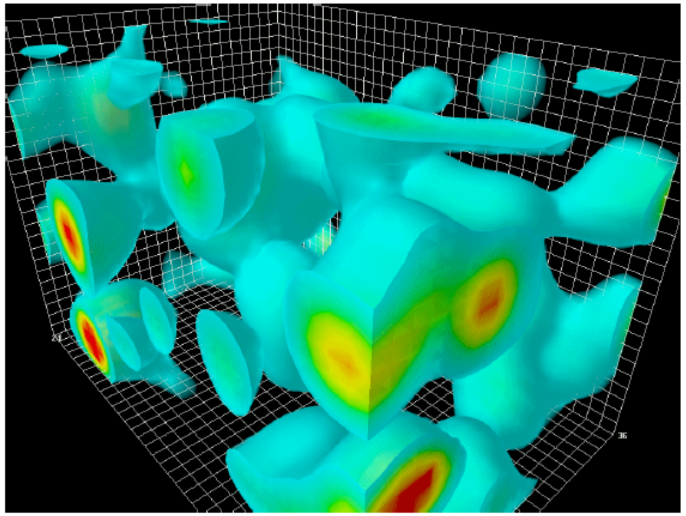
Theoretical foundation

- EIC - A QCD lab to explore the structure and dynamics of the visible world

$$\mathcal{L}_{QCD} = \sum_{j=1}^{n_f} \bar{\psi}_j \left(i D_\mu \gamma^\mu - m_j \right) \psi_j - \frac{1}{4} \mathrm{Tr}\, G^{\mu\nu} G_{\mu\nu}$$



- Interactions arise from fundamental symmetry principles: $SU(3)_c$
- Properties of visible universe such as mass and spin (e.g. proton): Emergent through complex structure of the QCD vacuum



D. Leinweber: Quantum fluctuations in gluon fields

Major goal:

Understanding QCD interactions and emergence of hadronic and nuclear matter in terms of quarks and gluons

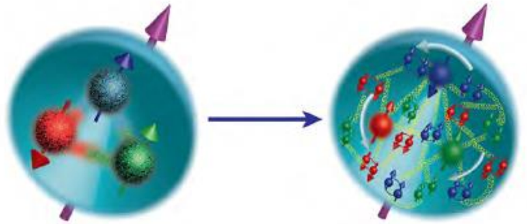
Essential elements looking forward:

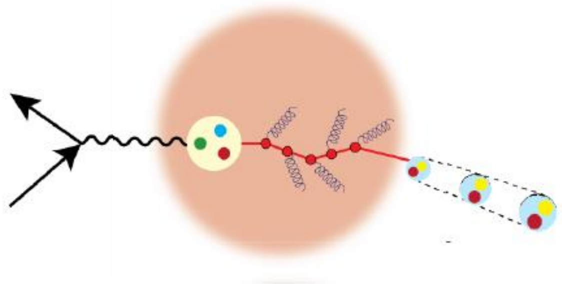
1) Tomography of hadrons and nuclear matter in terms of quarks and gluons
2) Synergy of experimental progress and theory

Motivation – the EIC science program

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?





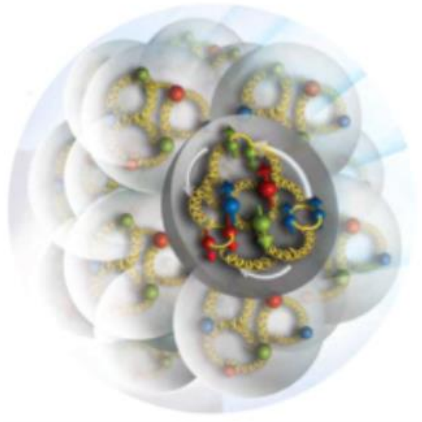
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

How do the quark-gluon interactions create nuclear binding?

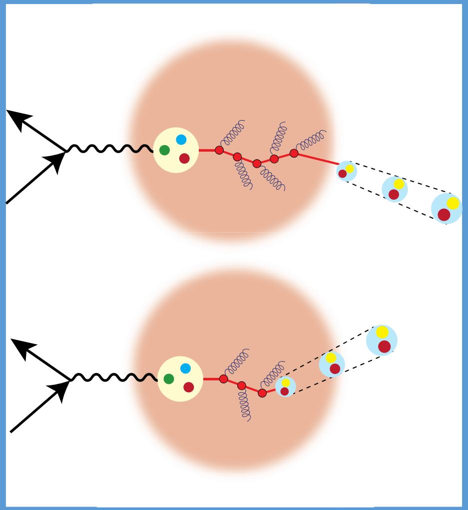
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

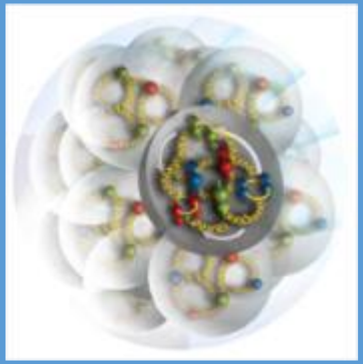
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

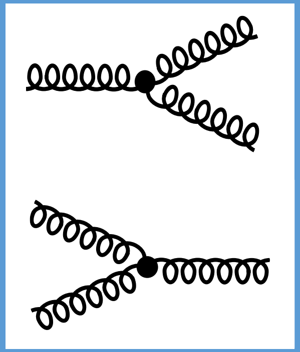


The word's first electron-nucleus collider

The Nucleus as a laboratory for QCD







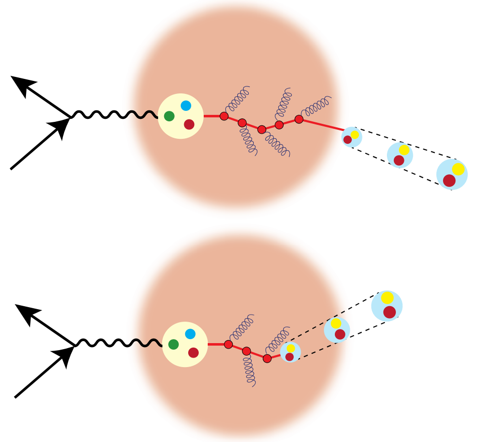
- How do color-charged quarks and gluons, and colorless jets, *interact with a nuclear medium*?
- How do *the confined hadronic states emerge* from these quarks and gluons?
- How does the quark-gluon interaction *create nuclear binding*?

Emergence of hadrons from partons

Nucleus as a Femtometer sized analyzer

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

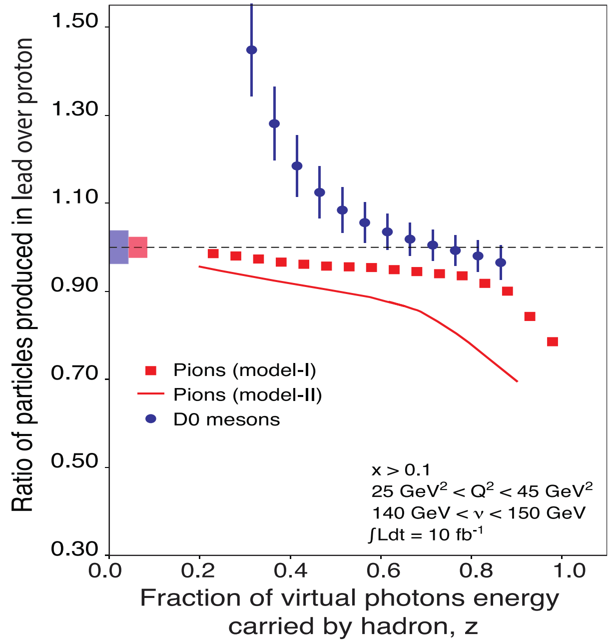
$$\nu = \frac{Q^2}{2mx}$$



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

Colored quark emerges as color neutral hadron ➔ What is the impact of colored media on confinement?

Energy loss by light vs. heavy quarks:



Identify light vs. charm hadrons in e-A:
Understand energy loss of light vs. heavy quarks in cold nuclear matter.
Provides insight into energy loss in the Quark-Gluon Plasma

DIS at collider energies enables control of parton/event kinematics

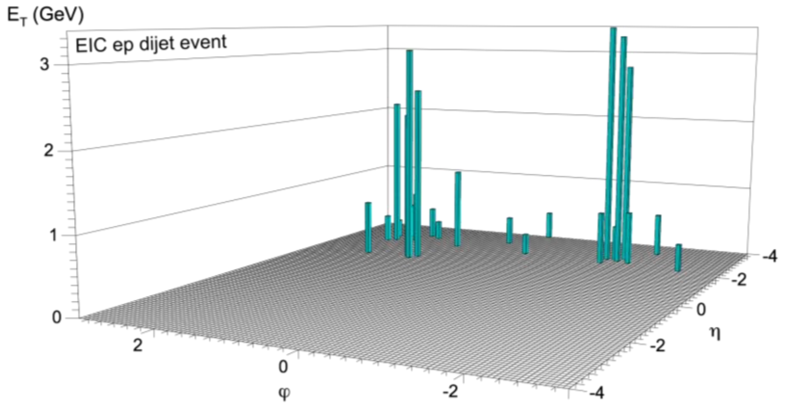
Jets: a window to partons

- Jet: transition process from a parton to hadrons and as such fundamentally encodes hadronization and dynamic confinement.
- Jets are golden tools to study quarks and gluons at RHIC and LHC
- Jets probe the interaction with the medium using the well understood jet shower evolution to extract the space-time dynamics of hadronization.

Jets in eA Collisions

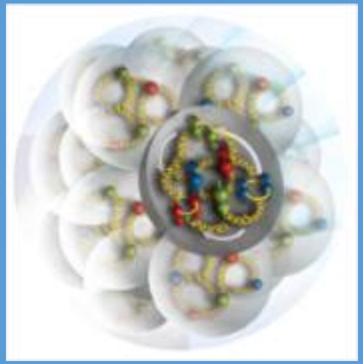
- Jet showers, their correlations and attenuation shed light on hadronization and dynamical nature of confinement in extended colored media
- Determine the transport properties in cold QCD medium
- Gluon distribution from dijets

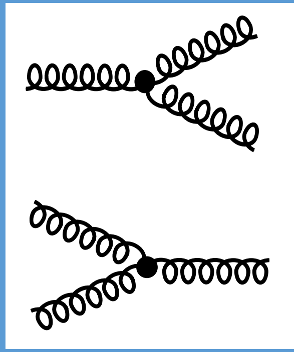
Many opportunities for jet physics in polarized ep



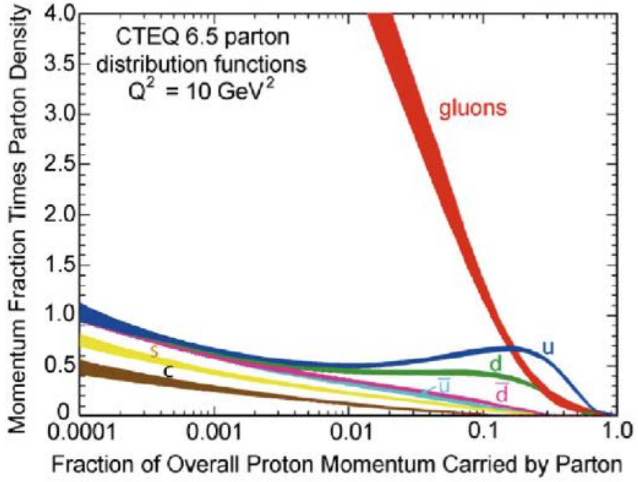
The word's first electron-nucleus collider

The Nucleus as a laboratory for QCD





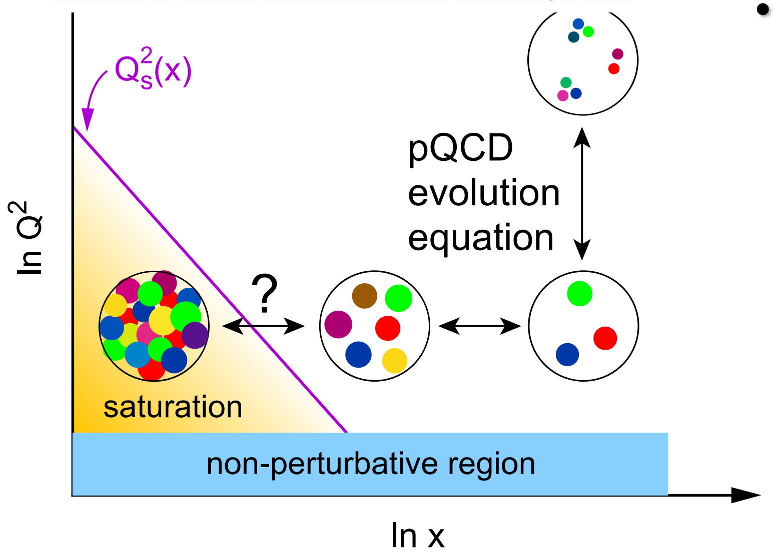
- How does a *dense nuclear environment* affect the quarks and gluons, their correlations, and their interactions?
- What happens to the *gluon density in nuclei*? Does it *saturate at high energy*, giving rise to a gluonic matter with *universal properties* in all nuclei, even the proton?

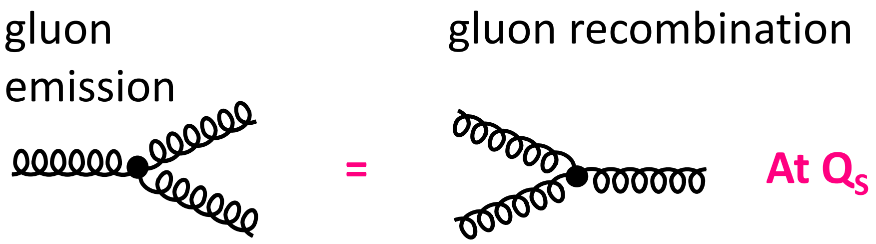


Gluon saturation at low-x

What tames the low-x rise?

- New evolution equations at low x & moderate Q^2
- **Saturation Scale $Q_S(x)$** where gluon emission and recombination become comparable





First observation of gluon recombination effects in nuclei:

➔ leading to a collective gluonic system

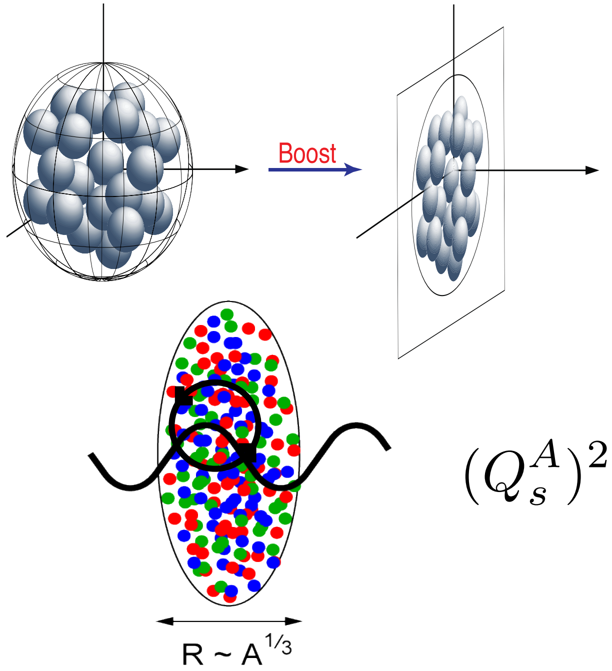
First observation of gluon recombination in different nuclei

→ Is this a universal property?

What is the new effective theory in this regime?

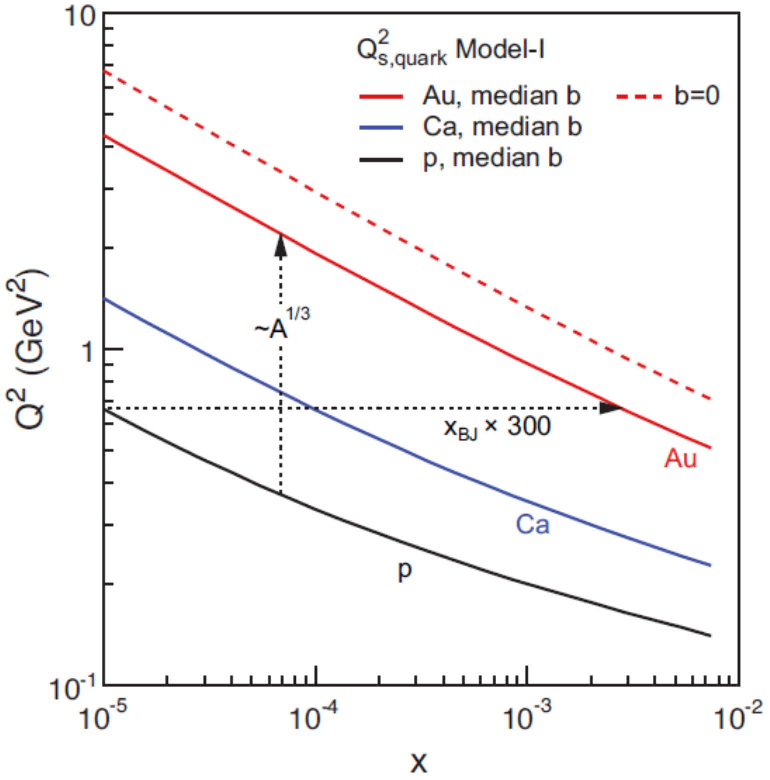
How to explore/study this new phase of matter?

Advantage of nucleus →



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

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



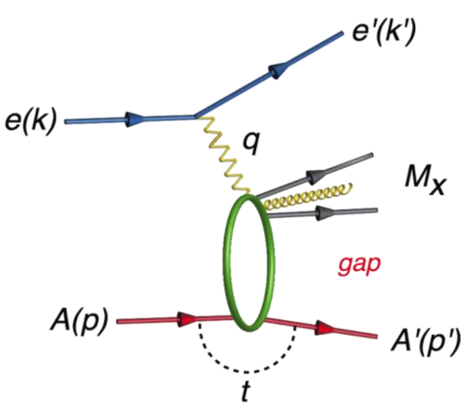
Enhancement of Q_S with A:
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

Diffraction events & gluon densities

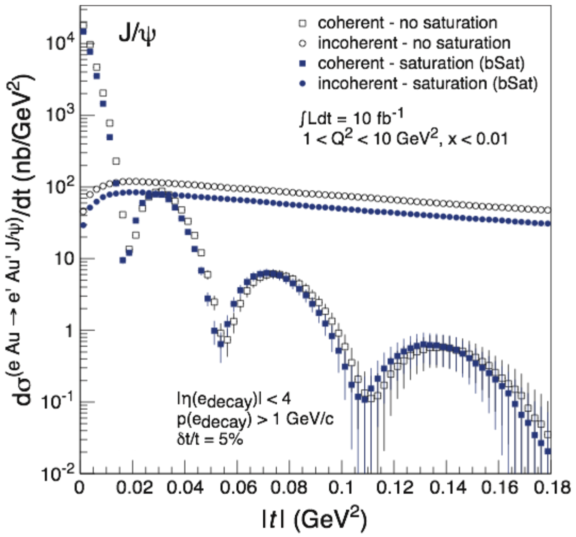
Diffraction cross-sections have strong discovery potential:

High sensitivity to gluon density in linear regime: $\sigma \sim [g(x,Q^2)]^2$

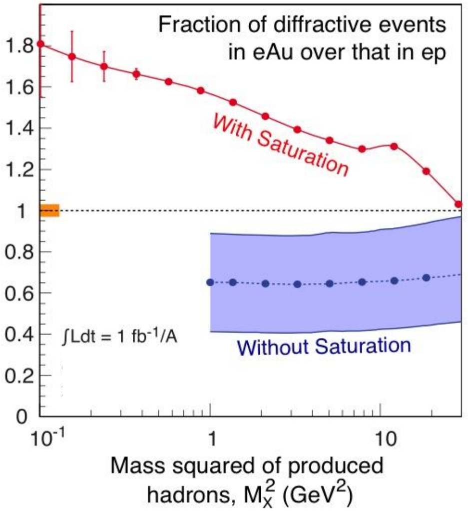
Dramatic changes in cross-sections with onset of non-linear strong color fields



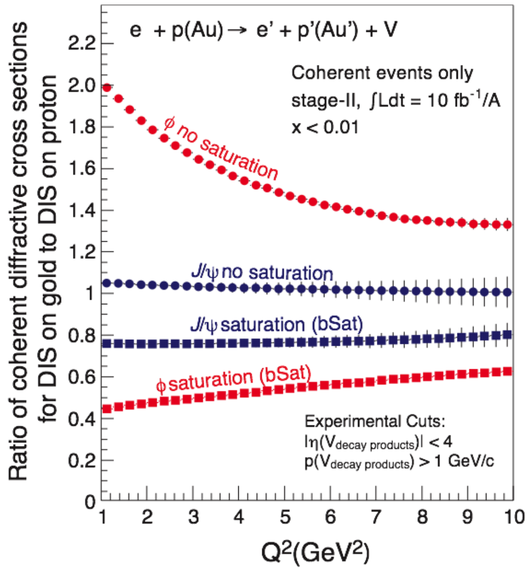
Extracting the gluon distribution $\rho(b_T)$ of nuclei via Fourier transformation of $d\sigma/dt$ in diffractive J/ψ production



Probing gluon saturation through measuring $\sigma_{diff}/\sigma_{tot}$

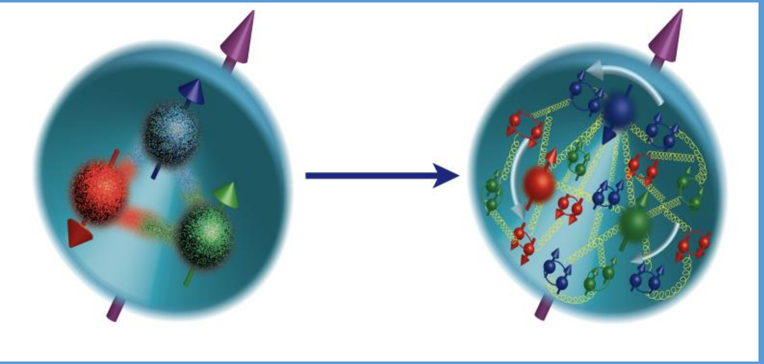


Probing Q^2 dependence of gluon saturation in diffractive vector meson production



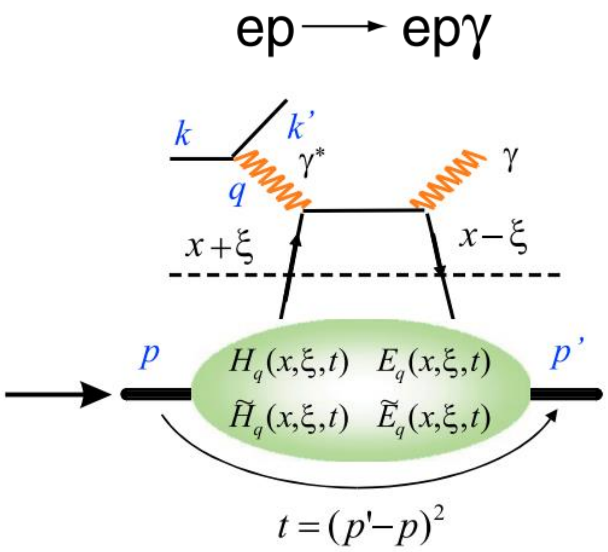
The word's first electron-nucleus collider

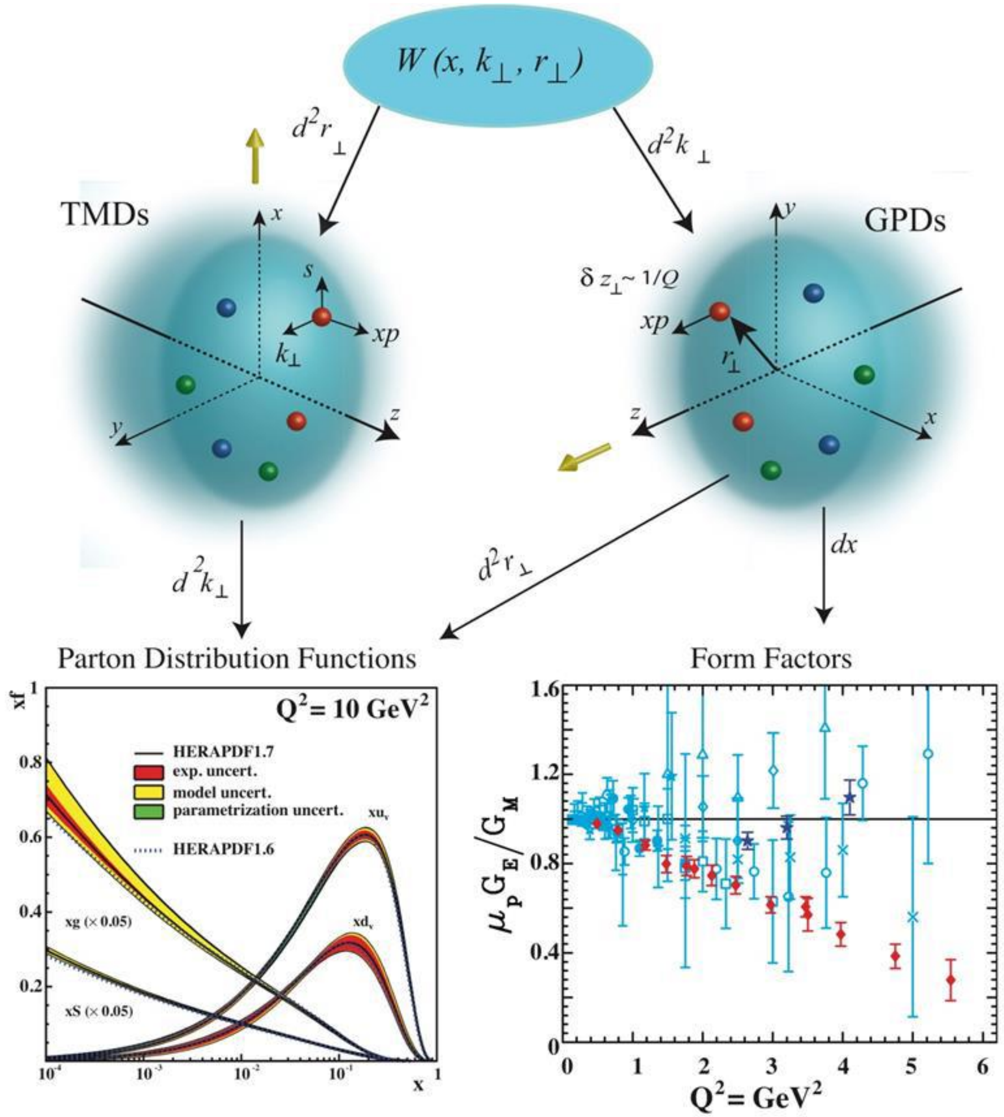
Polarized proton as a laboratory for QCD



- How are the sea quarks and gluons, and their spins, *distributed in space and momentum* inside the nucleon?
- How do the *nucleon properties such as **spin and mass emerge*** from them and their interactions?

3-Dimensional Imaging Quarks and Gluons





- Deeply Virtual Compton Scattering
- Deeply Virtual Meson Production
- Semi-inclusive pions, kaons… production

Three-dimensional imaging of the nucleon

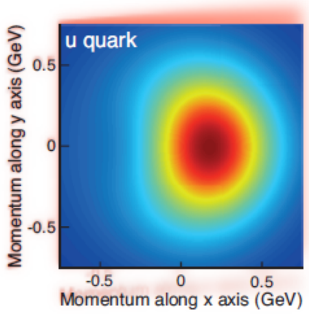
- Transverse Momentum Distribution and Spatial Imaging

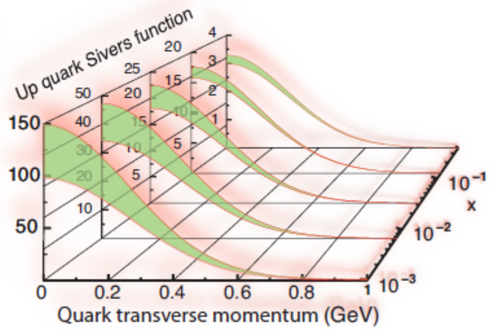
arXiv:1212.1701

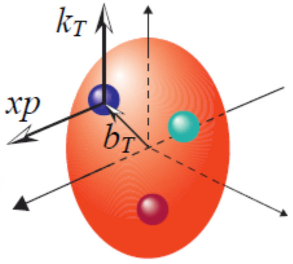
$f(x, k_T)$ 1+2D $\quad \int d^2 b_T \quad W(x, b_T, k_T) \quad \int d^2 k_T \quad$ $f(x, b_T)$ 1+2D

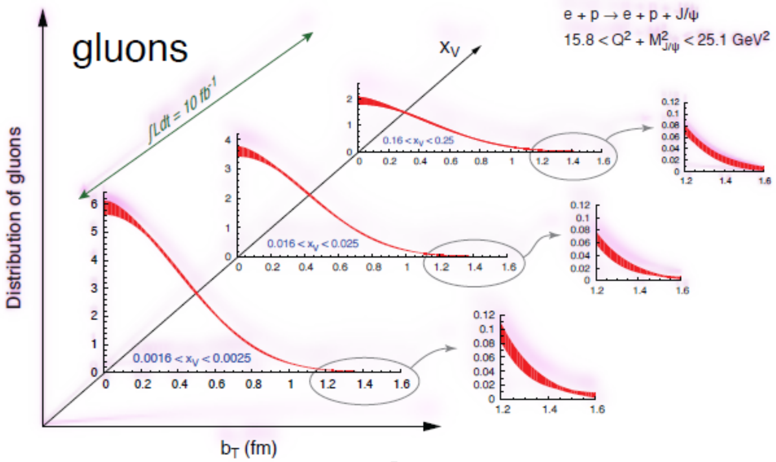
Transverse Momentum Distribution (TMD) ← Wigner Distribution → Impact Parameter Distribution

quarks









Fourier transf.

$b_T \longleftrightarrow \Delta$: $t = -\Delta^2$

$H(x, 0, t)$

$\xi = 0$

$H(x, \xi, t)$

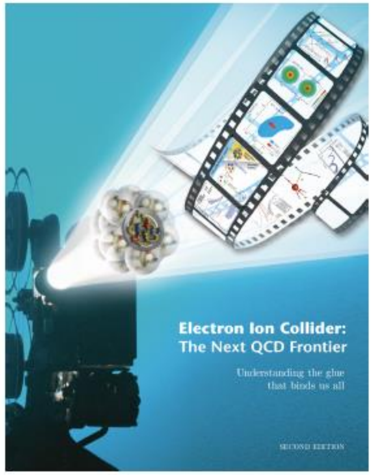
Generalized Parton Distribution (GPD)

- Spin-dependent 1+2D momentum space (transverse) images from semi-inclusive scattering
- Spin-dependent 1+2D impact parameter (transverse) images from exclusive scattering

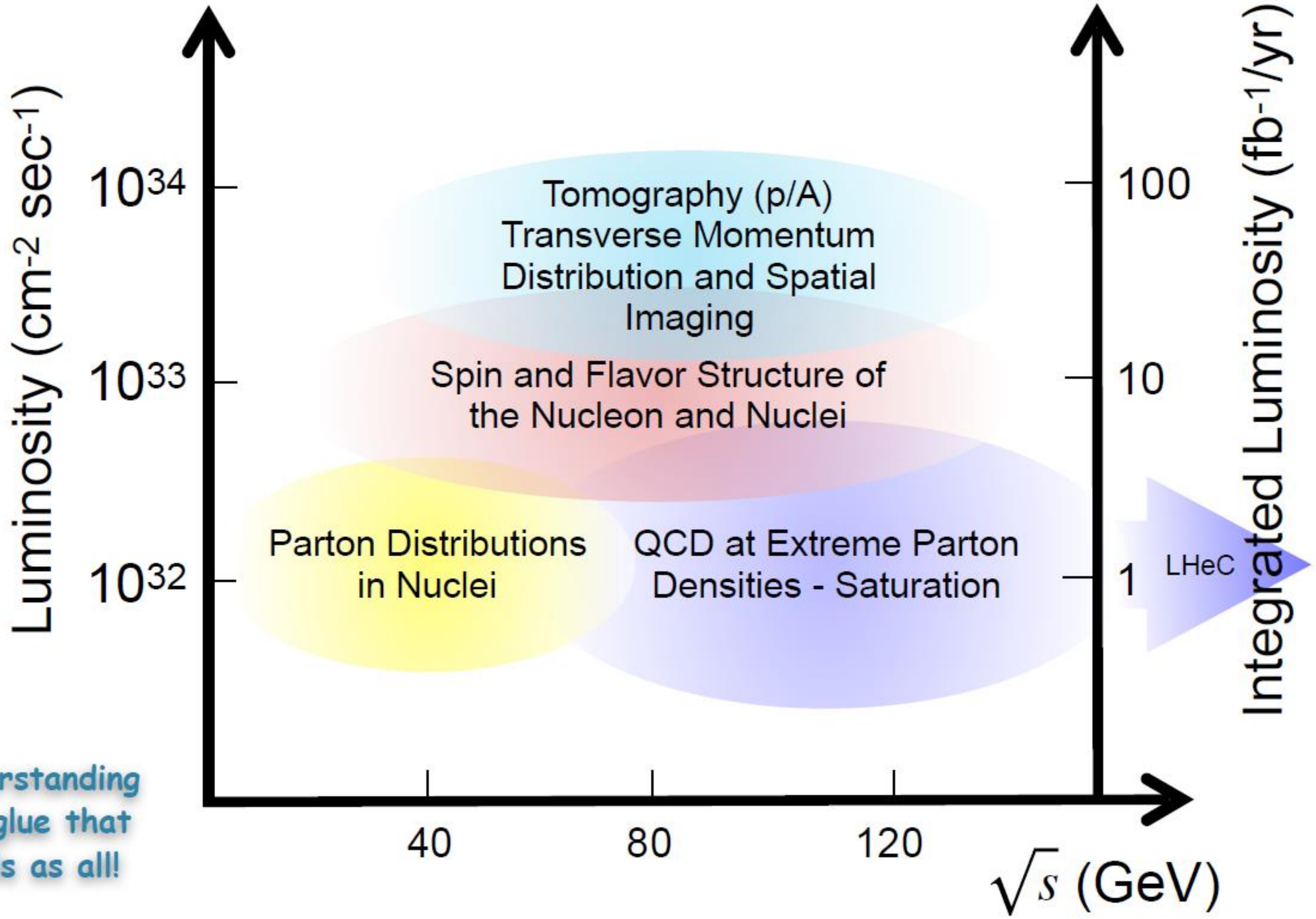
EIC Pillars

- EIC: Study structure and dynamics of matter at high luminosity, high energy with polarized beams and wide range of nuclei
- Whitepaper:

arXiv:1212.1701

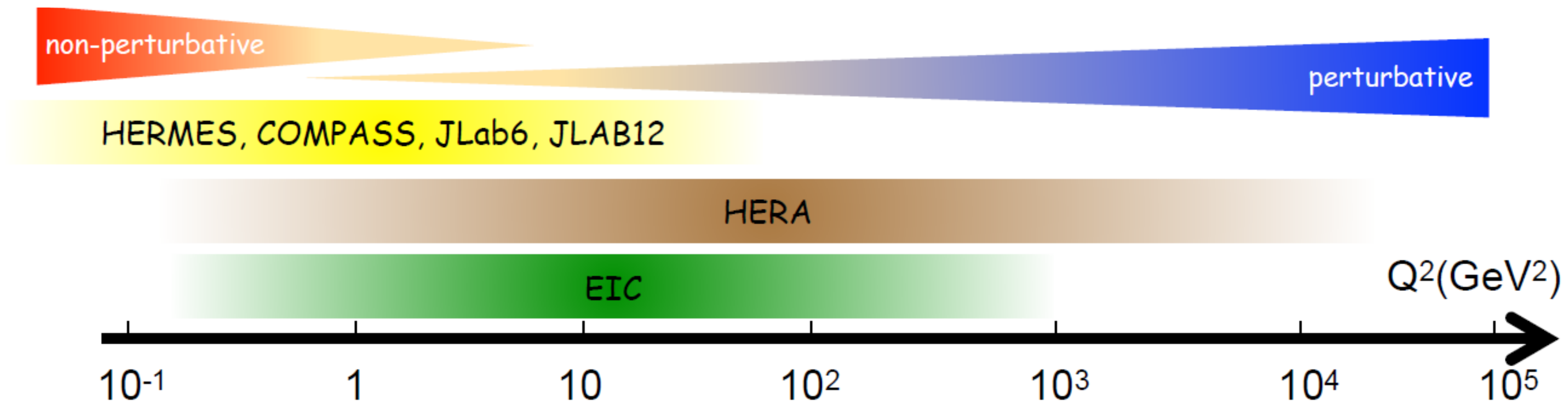


Understanding the glue that binds as all!

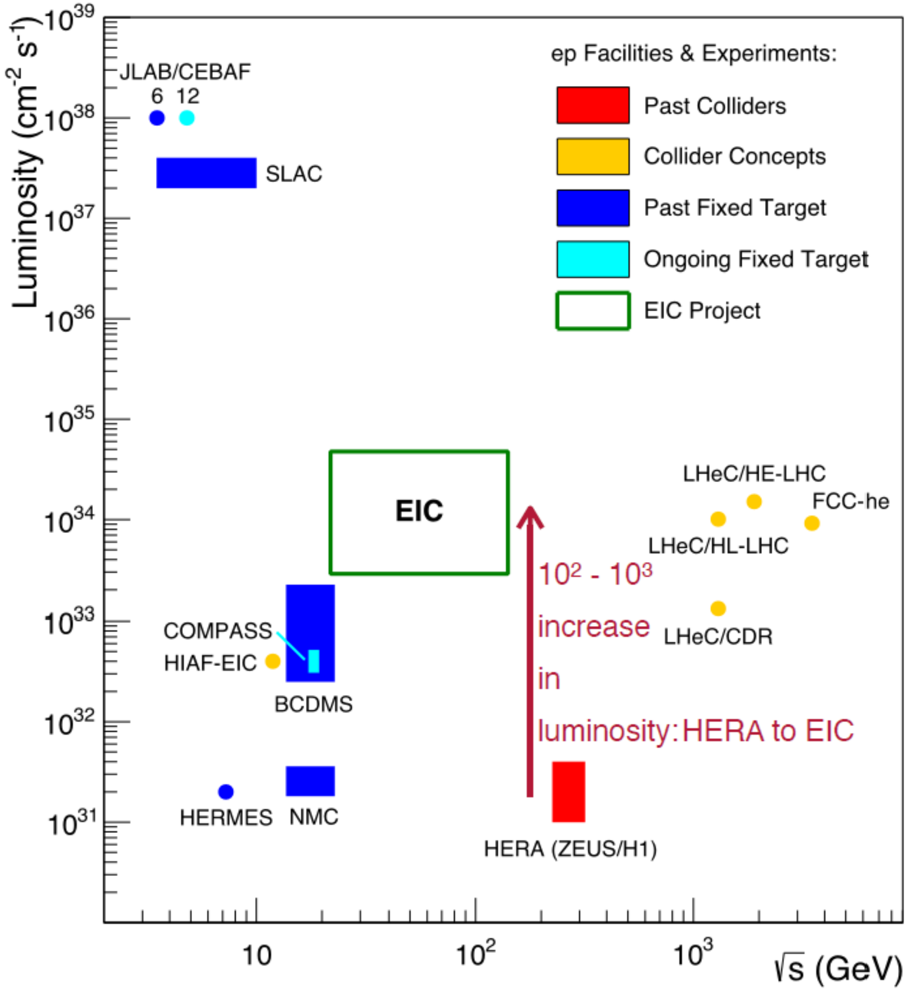


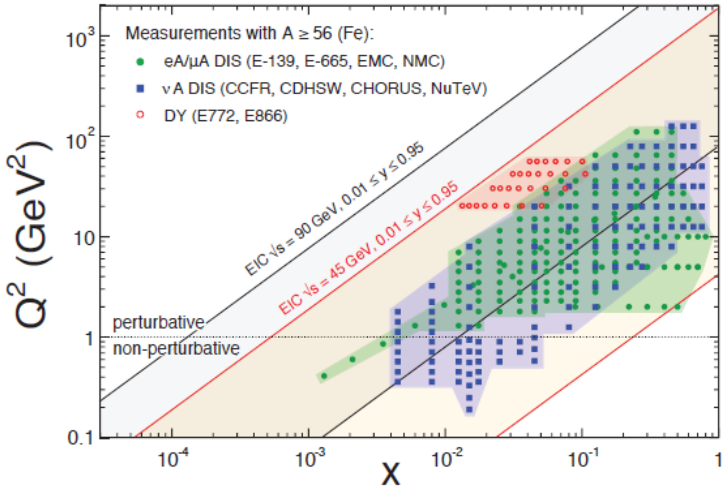
EIC machine requirements

- High luminosity: $10^{33}cm^{-2}s^{-1}$ - $10^{34}cm^{-2}s^{-1}$
- Flexible center-of-mass energy $\sqrt{s} = \sqrt{4\,E_e\,E_p}$: Wide kinematic range $Q^2 = s\,x\,y$
- Highly polarized electron (0.8) and proton / light ion (0.7) beams: Spin structure studies
- Wide range of nuclear beams (d to Pb/U): High gluon density

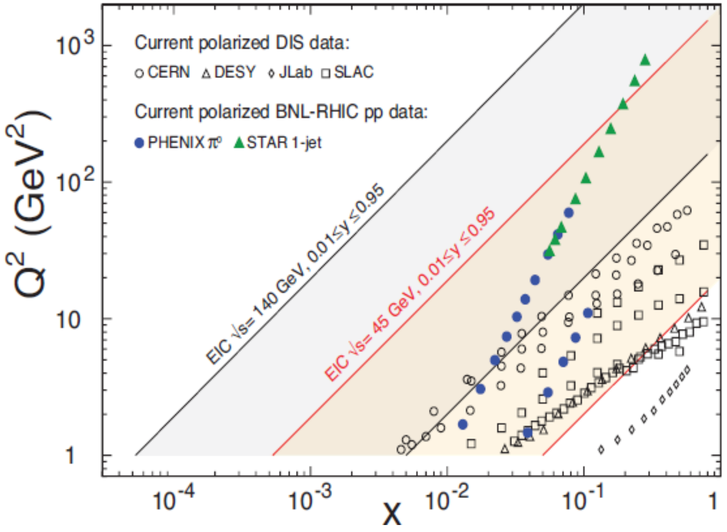


Luminosity and kinematic coverage





eA



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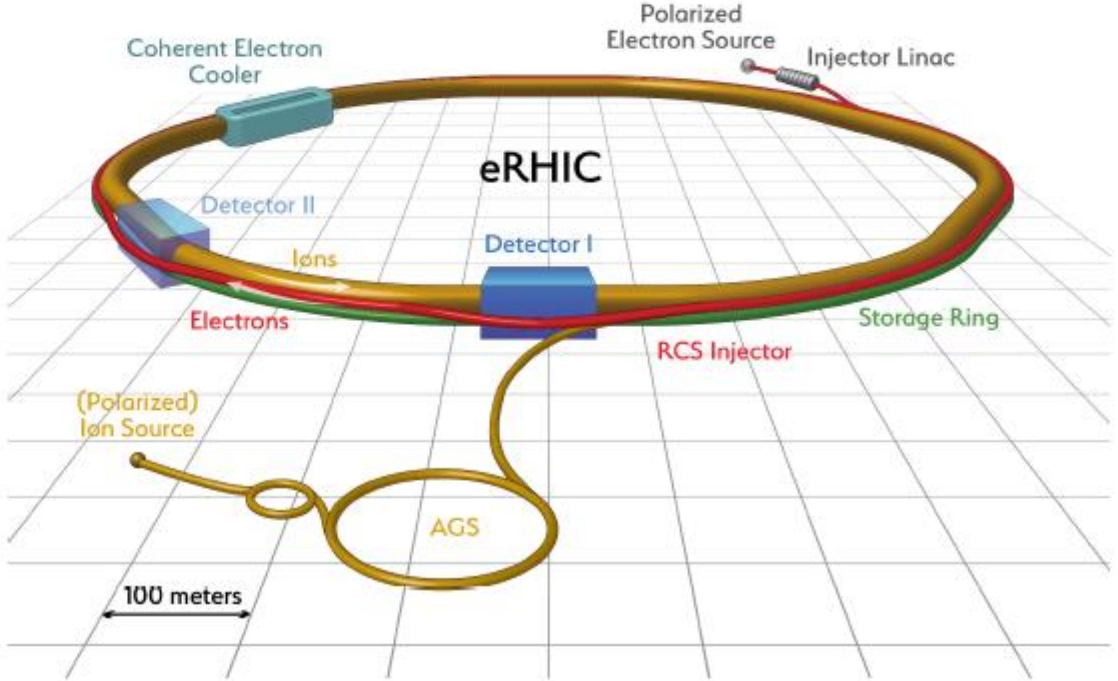
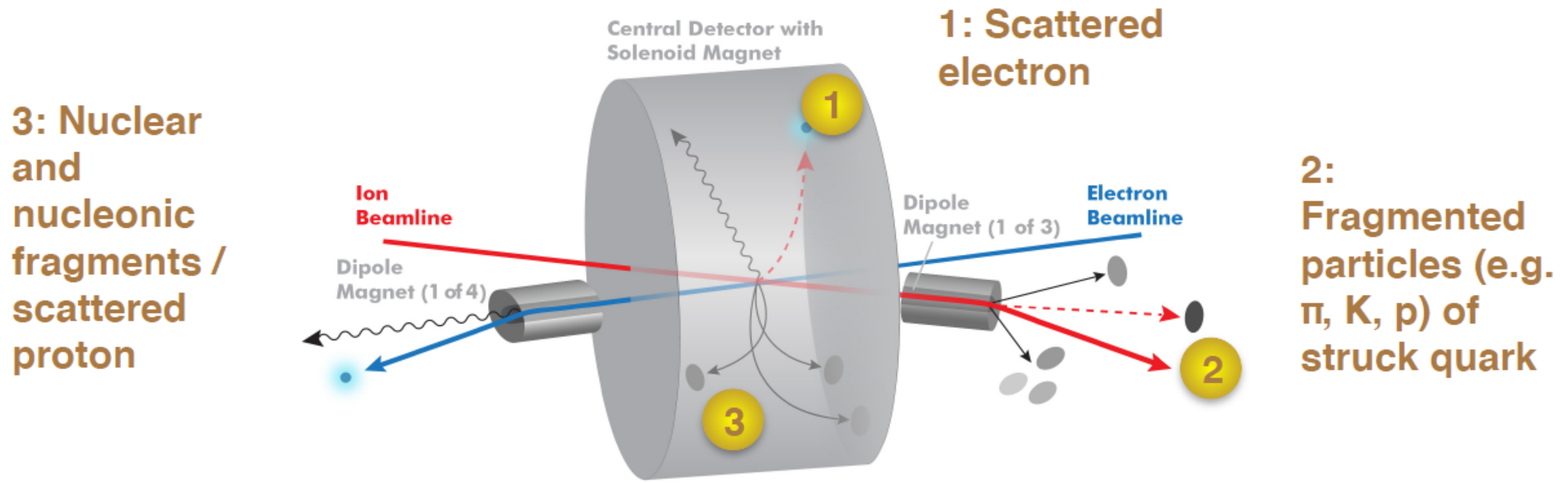
EIC Facility

- Highly polarized electron / Highly polarized proton and lights ions /Unpolarized heavy ions
- CME: ~ 20-100GeV
- Luminosity: ~ $10^{33\text{-}34} cm^{-2}s^{-1}$



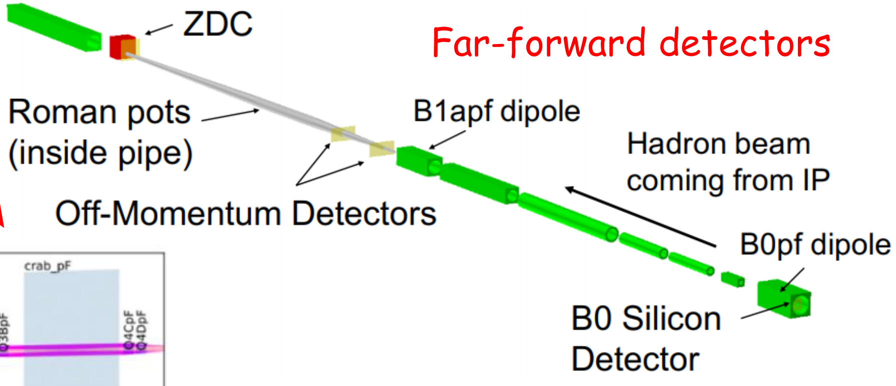
- Polarized electron source and 400 MeV injector linac
- Polarized proton beams and ion beams based on existing RHIC facility
- 2 detector interaction points capability in the design

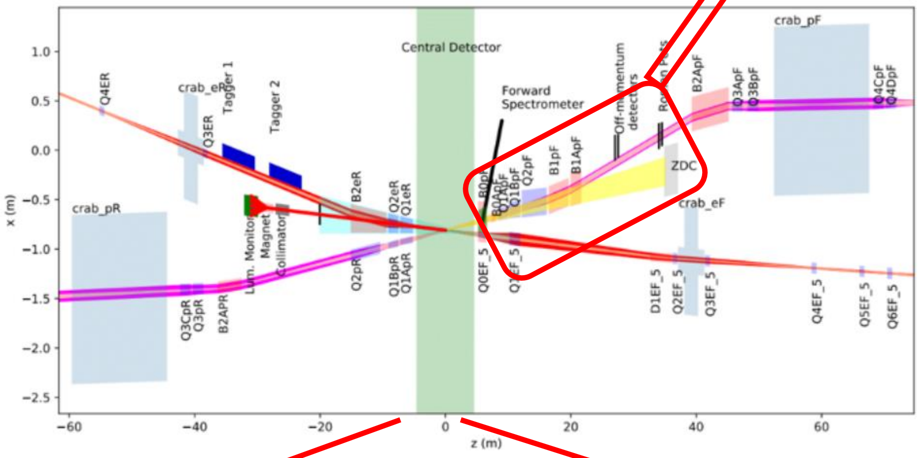
EIC Detector requirements

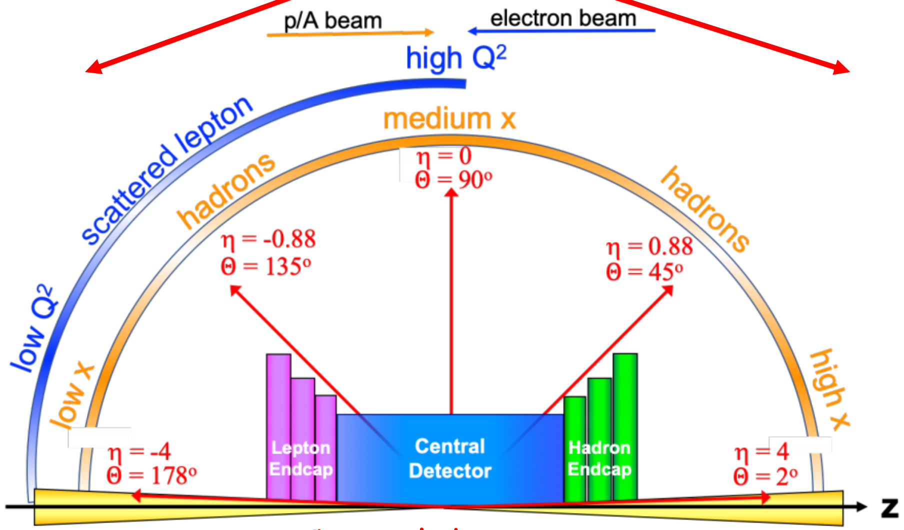


- Acceptance: Close to 4π coverage with a η-coverage (η = -ln(tan(θ/2)) of approximately η < |3.5| combined calorimetry (EM CAL and hadron CAL at least in forward direction) and tracking coverage
- Low dead material budget in particular in rear direction (~5% X/X_0)
- Good momentum resolution Δp/p ~ few %
- Electron ID for e/h separation varies with θ / η at the level of 1:10^4 / ~2-3%/√E for η<-2 and ~7%/√E for -2<η<1
- Particle ID for π/K/p separation over wide momentum range (Forward η up to ~50GeV/c / Barrel η up to ~4GeV/c / Rear η up to ~6 GeV/c)
- High spatial vertex resolution ~ 10-20μm for vertex reconstruction
- Low-angel taggers:
  - Recoil proton
  - Low Q^2 electron
  - Neutrons on hadron direction
- Luminosity (Absolute and relative) and local polarization direction measurement

EIC Detector layout







Central detector

- Asymmetric detector configuration
- Far-forward region critical to many key processes

Generic Detector R&D for EIC

In January 2011 BNL, in association with JLab and the DOE Office of NP, announced a generic detector R&D program to address the scientific requirements for measurements at a future EIC

Goals of Effort

- Enable successful design and timely implementation of an EIC experimental program
  - Quantify the key physics measurements that drive instrumentation requirements
  - Develop instrumentation solutions that meet realistic cost expectations
- Stimulate the formation of user collaborations to design and build experiments

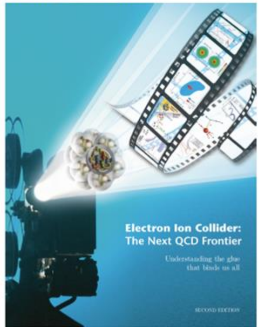
- Peer-reviewed program funded by DOE and managed by BNL with $1M/year to $1.5M/year
- Wide range of R&D programs: Calorimetry / Tracking (GEM, MicroMegas, TPC) incl. silicon / Particle ID (TRD, Dual-RICH, Aerogel RICH, DIRC, TOF) / Polarimetry / Background / Simulation Tools /

EIC Development

- 2012: White paper, updated in 2014
- 2015: Long-range plan:

"Construct a high-energy high-luminosity polarized electron-ion collider as the highest priority for new construction"

arXiv:1212.1701



Understanding the glue that binds as all!

- 2017: Review of the EIC Science Case by the US National Academy of Sciences (NAS)
- 2018: Report by the NAS
- 2019: CD-0 (mission need) from the US Department of Energy
- 2020: Site selection (Brookhaven National Laboratory)

Department of Energy

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

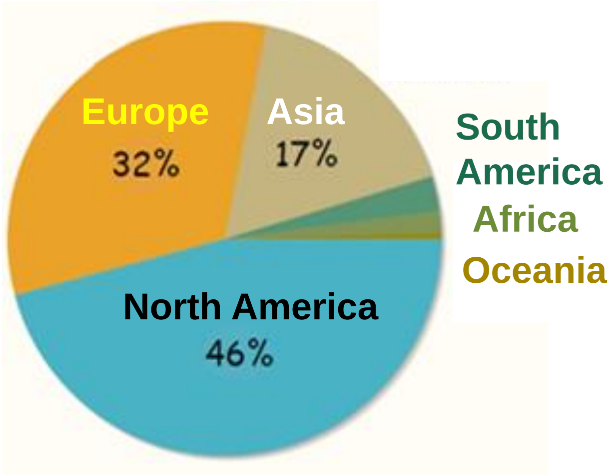
Current project goal: Start of operations in 2032

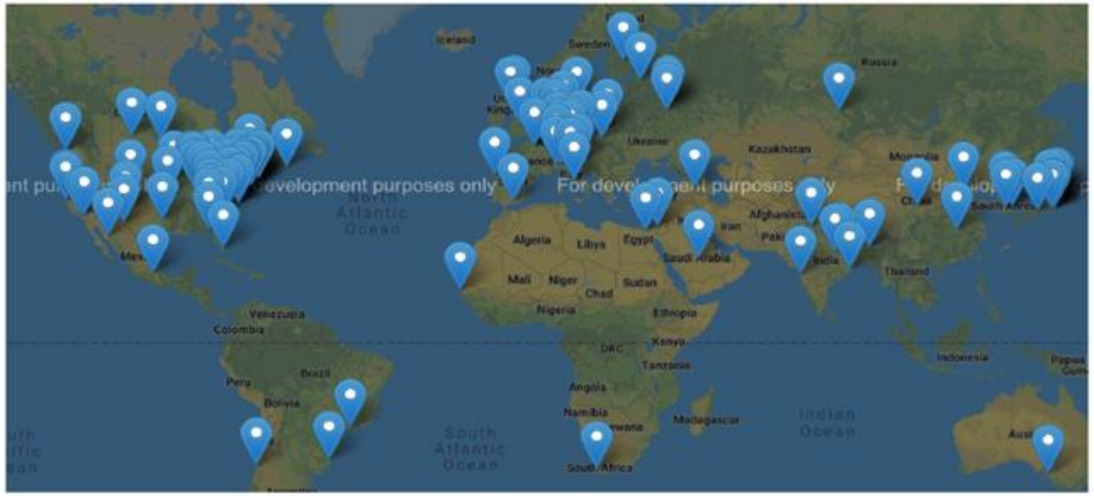
BROOKHAVEN NATIONAL LABORATORY

The EIC Users Group

EICUG organization established in summer 2016, *http://www.eicug.org*

~ 1200 members (+ students and engineers), 240 institutions, 33 countries

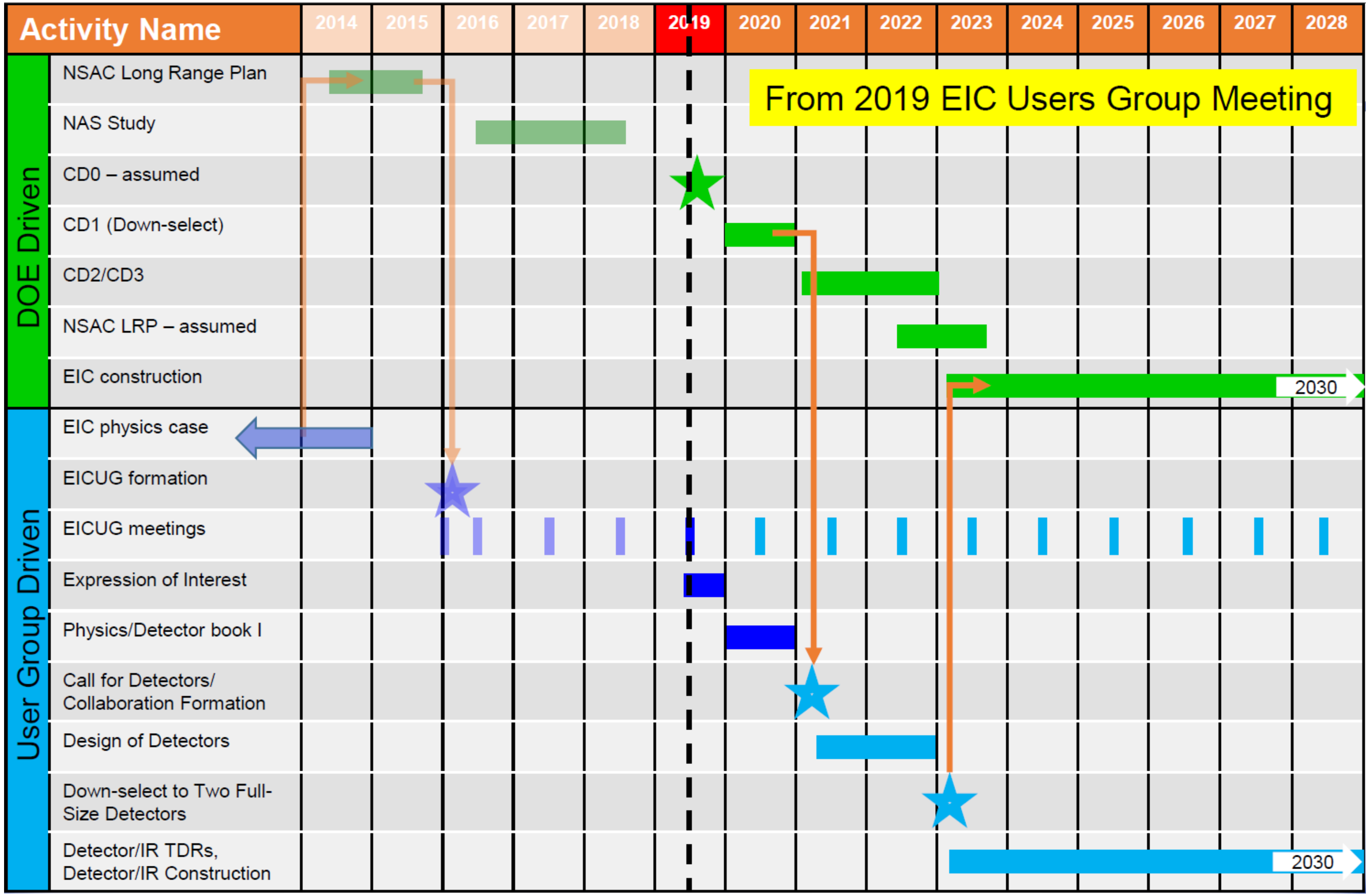




R&D activities:

- EIC Detector R&D program operated by BNL with ~$1M / year
- EIC Accelerator R&D with ~$7M / year

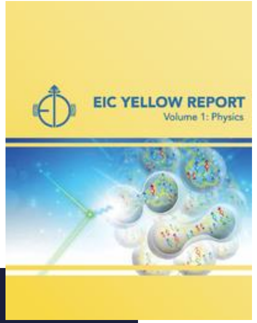
EIC timeline



CD0 = DOE "Mission Need" statement; **CD1** = design choice and site selection
CD2/CD3 = establish project baseline cost and schedule

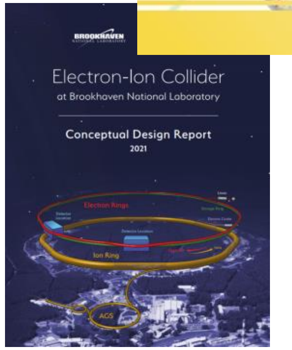
EIC ongoing and future developments

The Yellow Report Initiative



The purpose of the Yellow Report Initiative is to advance the state and detail of the documented physics studies (White Paper, INT program proceedings) and detector concepts in preparation for the realization of the EIC.

- Work started in January 2020
- Report finalized March 8th, 2021, arXiv:2103.05419 [physics.inst-det]



Call for Expression of Interest (EoI), **Nov. 2020**

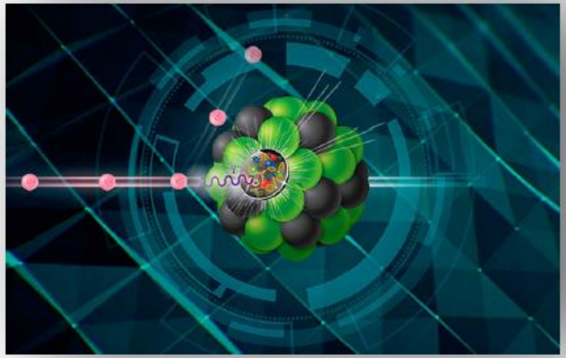
- BNL, in association with JLab, has made a call for a non-binding Expression of Interest (EOI) for potential cooperation on the experimental equipment for EIC

Call for Detector Proposals

- Call issued on March 2021, with a deadline of **December 1st 2021**
- Selection of detectors (by a Detector Advisory Committee) by **~March 2022**

Summary

- **EIC Physics Pillars**: EIC facility will address fundamental questions on the structure and dynamics of nucleons and nuclei in terms of quarks and gluons using precision measurements including:
  - Parton Distributions in Nuclei / QCD at Extreme Parton Densities - Saturation
  - Spin and Flavor Structure of the Nucleon and Nuclei
  - Tomography (p/A) Transverse Momentum Distribution and Spatial Imaging



- **EIC Facility at BNL under BNL/JLab leadership: Added electron storage ring to existing RHIC facility**
  - Luminosity: $\sim 10^{33\text{-}34} cm^{-2} s^{-1}$
  - Polarized e/p and unpolarized heavy ion beams / CME ~20-100GeV
- **EIC Status and Plans:**
  - Awarded CD0 mission statement / Site selection
  - EIC facility construction after FRIB completion realistically in FY22/FY23 timeframe
  - EIC facility completion in roughly a decade from now!

An exciting time is ahead of us to realize a future EIC facility!