# Electron–Ion Collider
## A major new scientific facility to probe the heart of nuclear matter

Garth Huber

University of Regina

Prairie Universities Physics Seminars
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CRSNG

SAPIN-2021-00026
SAPPJ-2023-00041


- Founded 1974
- Only Comprehensive University in the Prairies
  - 16,860 students, incl. 2,191 Grad Students (Fall 2023)
  - Physics Dept. offers B.Sc., M.Sc. and Ph.D.
- World University Ranking (2023): 601-800

  (same group as Carleton, Concordia, Memorial, UNB, Windsor)

# Outline

- Brief introduction to quarks and gluons
- The science problem in brief
- Major scientific motivations for the Electron–Ion Collider (EIC)
- Where will it be built?
- EIC Canada and URegina involvement

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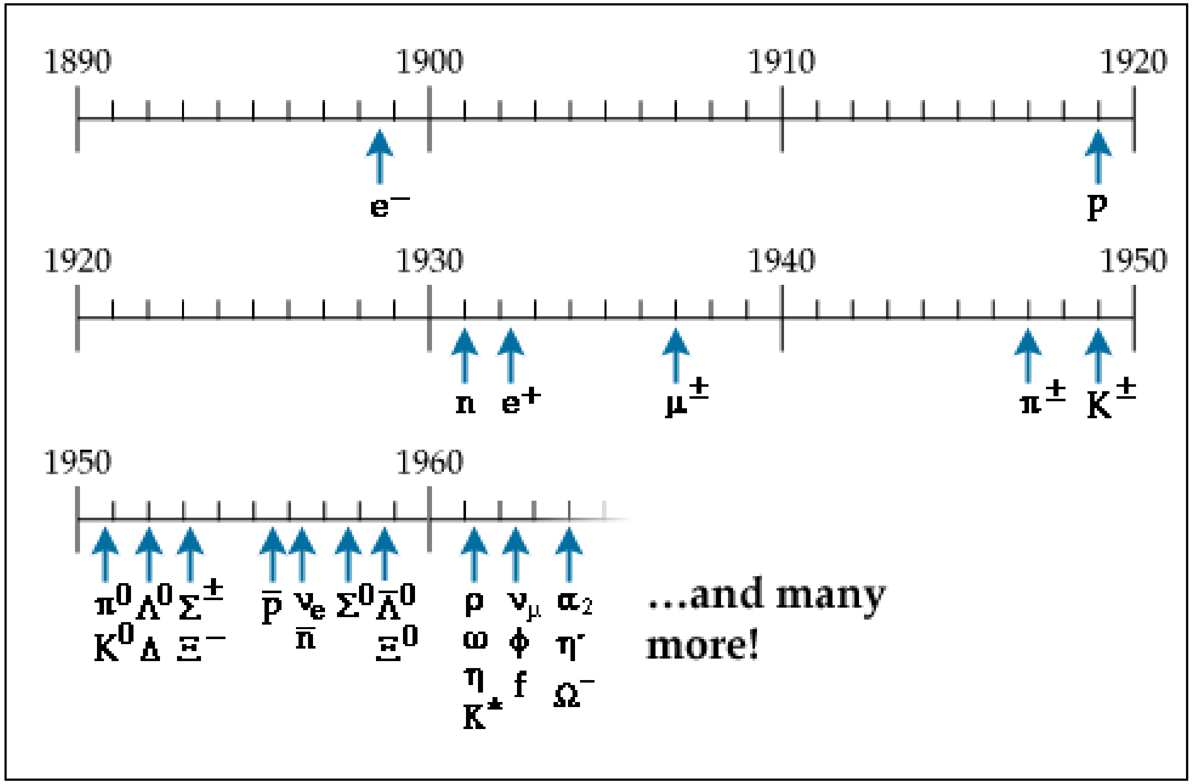
# The Particle Zoo

- Circa 1950, the first particle accelerators began to uncover many new particles.
- Most of these particles are unstable and decay very quickly, and hence had not been seen in cosmic ray experiments.
- Could all these particles be fundamental?

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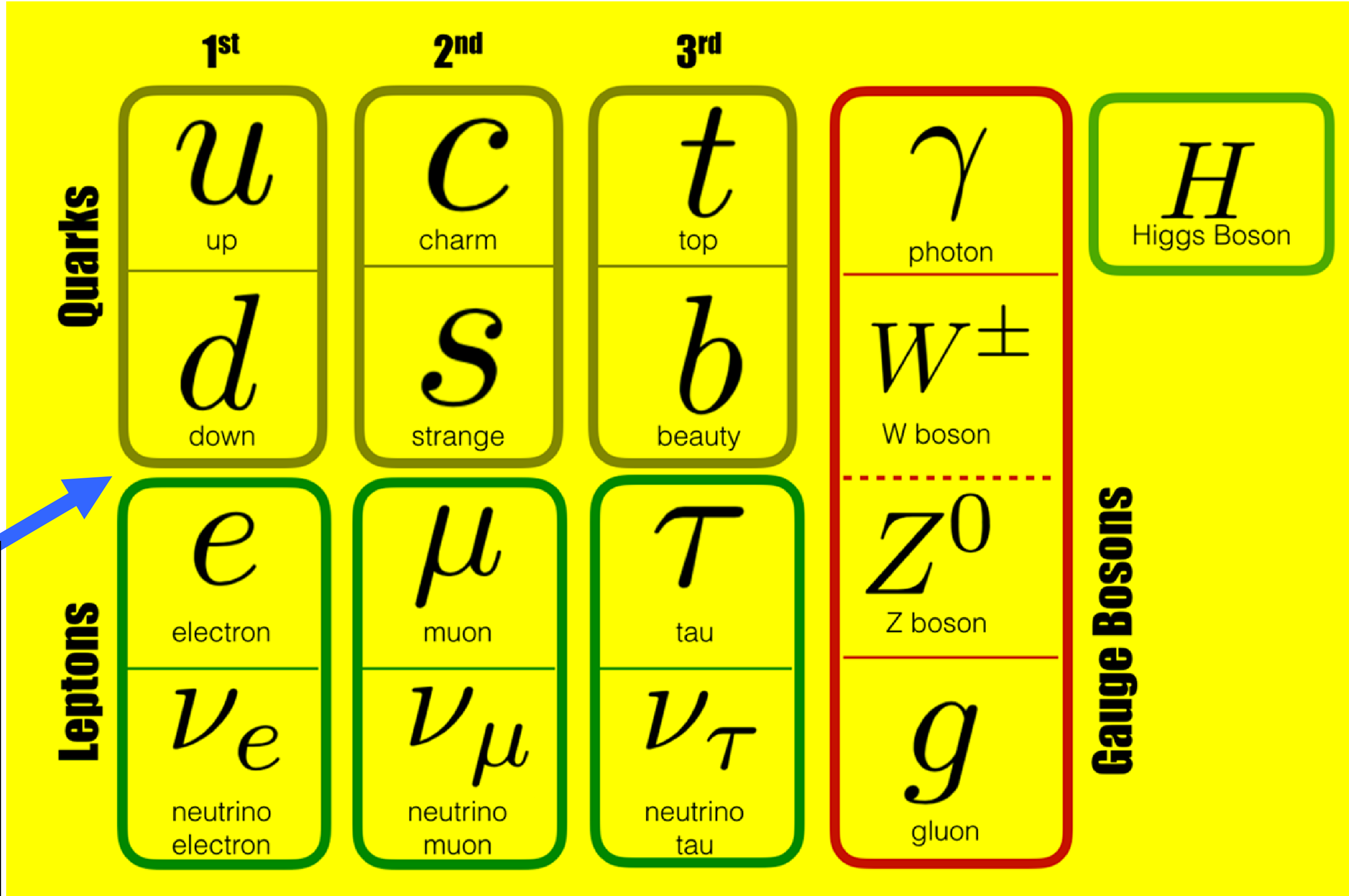
# Quarks, Leptons and their Fundamental Interactions




The ground state of matter

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# Quantum Electrodynamics
# Quantum Chromodynamics

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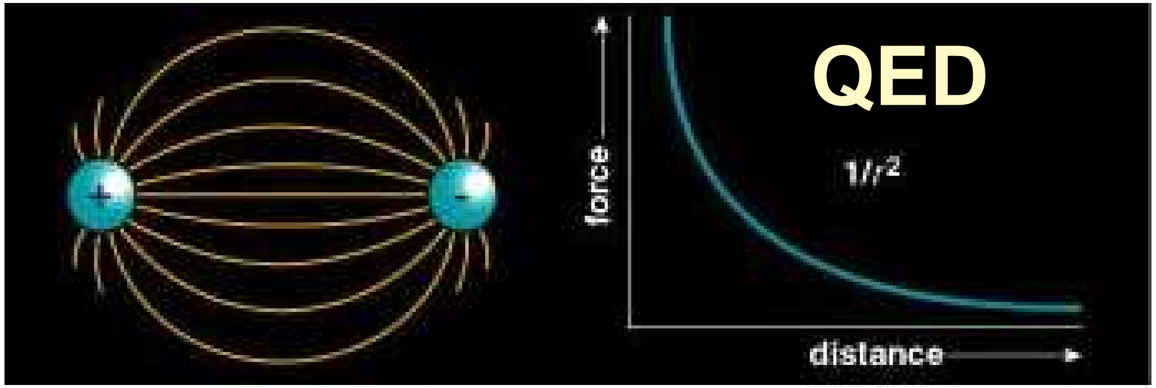
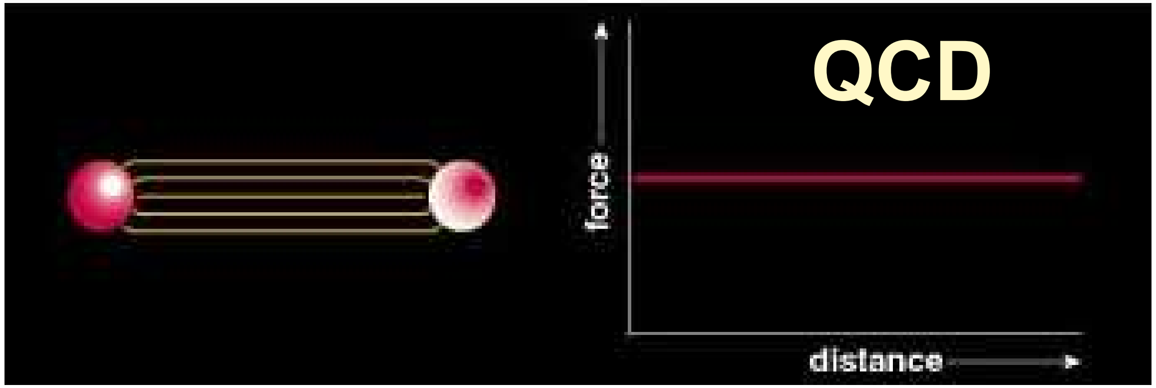
The gluons of QCD carry color charge and interact strongly (in contrast to the photons of QED)




**Quarks (and their color charge) are confined inside strongly–interacting particles called hadrons**

# Quark & Gluon Momenta within Proton

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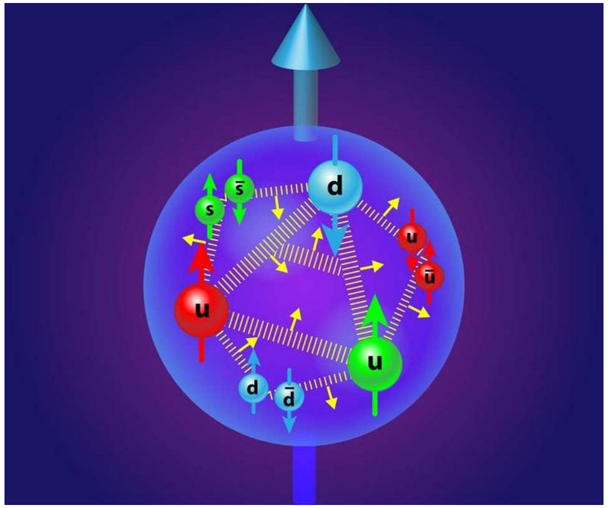
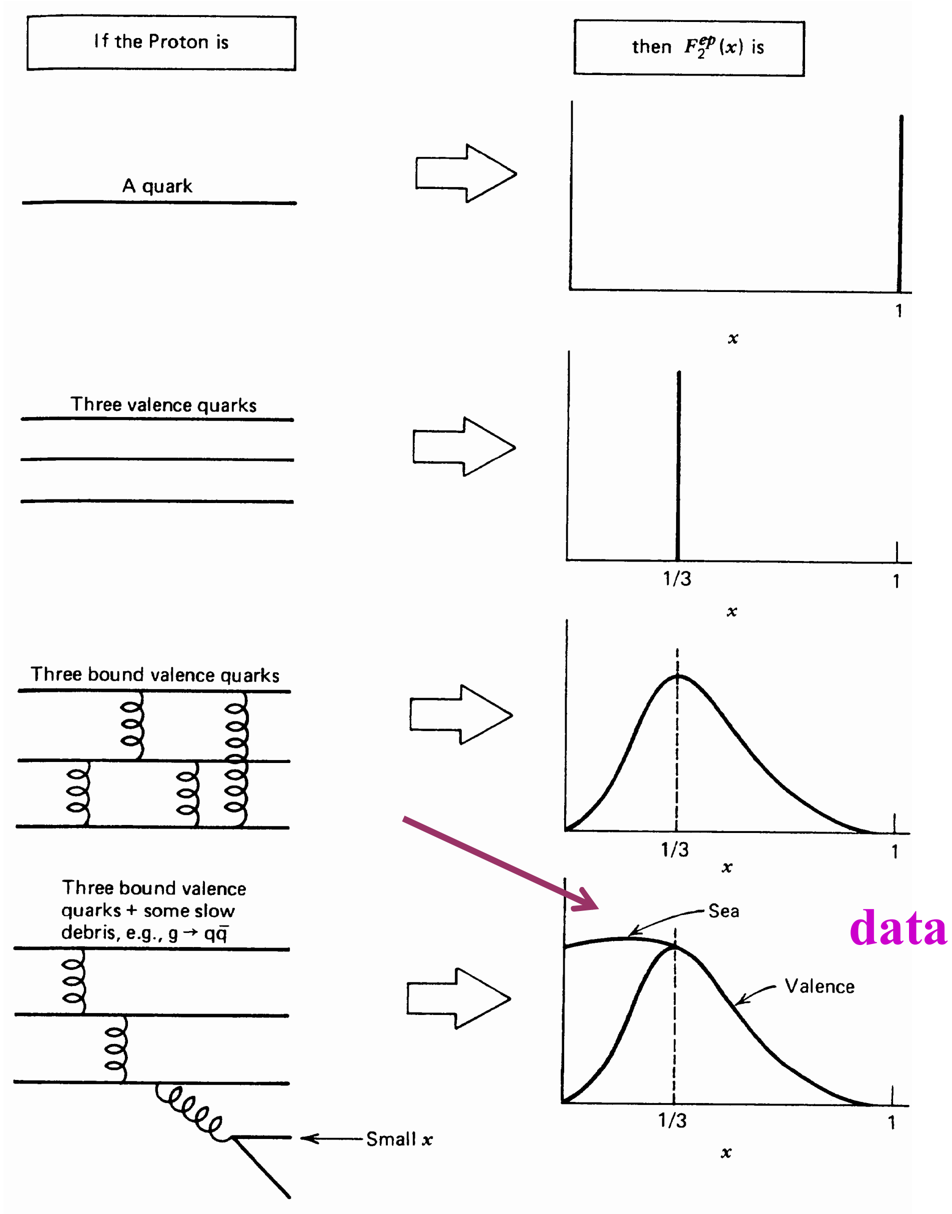
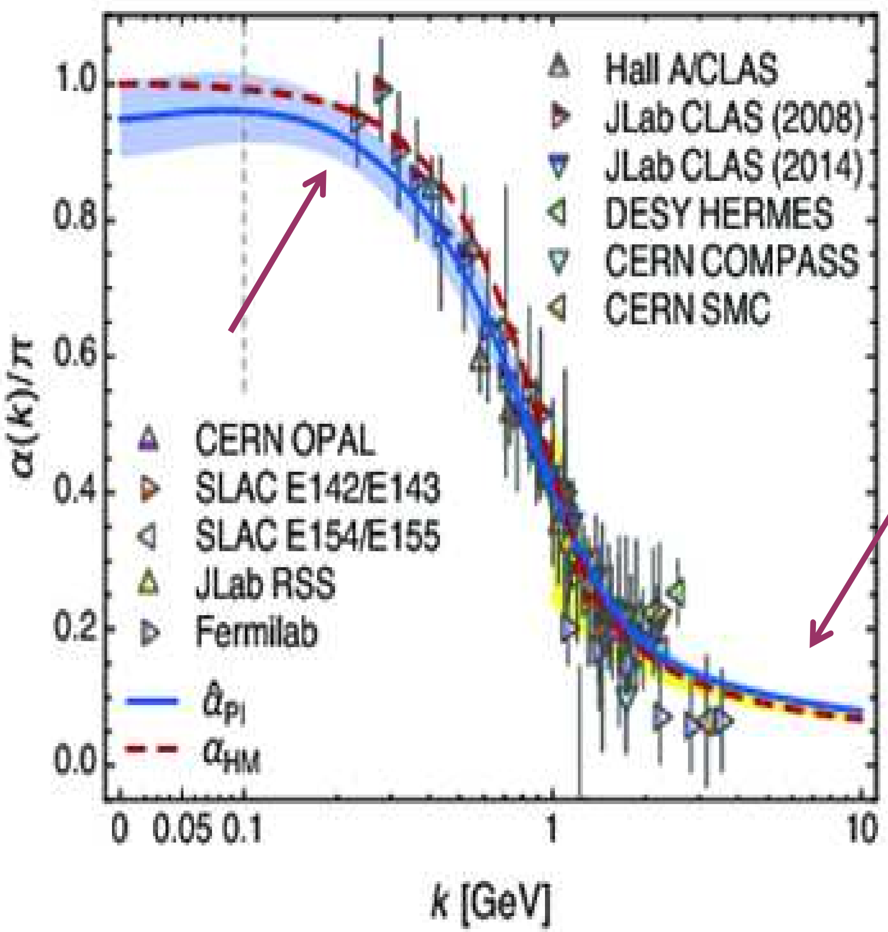
VALENCE QUARKS: $qqq$
required for correct proton quantum numbers.
SEA QUARKS: virtual $q\bar{q}$ pairs allowed by uncertainty principle.



- $x$ represents fraction of proton momentum carried by struck parton (quark or gluon).
- Quarks inside proton have probability ($P$) distribution ($f(x)=dP/dx$) to have momentum fraction $x$.



# QCD's Dual Nature




Binosi, Mezrag, Papavassiliou, C.D. Roberts, Rodriguez-Quintero,
PRD **96** (2017) 054026. arXiv:1612.04835

## Short Distance Interaction:

- Short distance quark-quark interaction is feeble.
  - Quarks inside protons behave as if they are nearly unbound, pQCD.
  - Asymptotic Freedom.
  - Nobel prize: Friedman, Kendall and Taylor, 1990.

## Long Distance Interaction:

- Quarks strongly bound within hadrons.
  - Color confinement (strong QCD).
  - Quantitative QCD description of nucleon's properties (i.e. understanding of the confinement regime) remains a puzzle!

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# Food for thought

Recall: Mass of Proton **~ 938 [MeV/$c^2$]**

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→ **~99% of our mass comes from quark–gluon interactions in the nucleon, which are very complex!**

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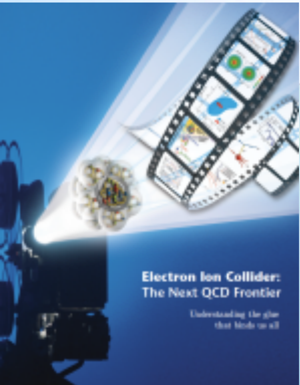
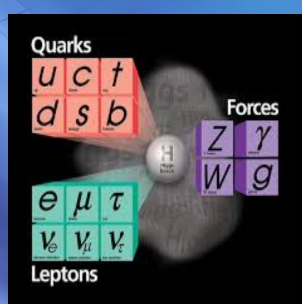


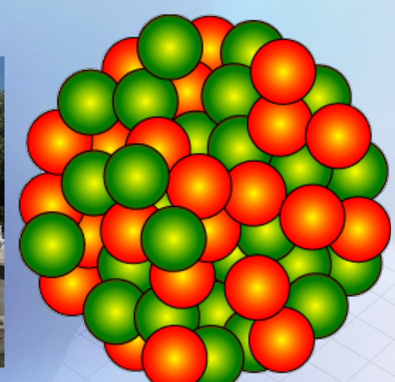

arXiv 1212.1701.v3
Eur. Phy. J. A52, 9 (2016)

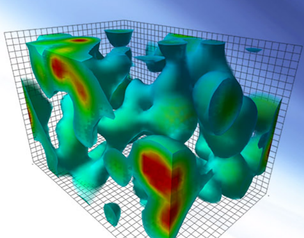
# Electron Ion Collider: The next QCD frontier

*Understanding the **Glue** that Binds Us All*

This talk is based on the work of a large number of scientists, excited about the EIC science and involved in the EIC project, now organized as the EIC Users Group





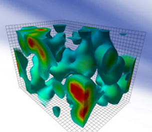
Abhay Deshpande

# Why an Electron Ion Collider

- **Interactions and structure are mixed up in nuclear matter:** Nuclear matter is made of quarks that are bound by gluons that also bind themselves. Unlike with the more familiar atomic and molecular matter, the interactions and structures are inextricably mixed up, and the **observed properties** of nucleons and nuclei, such as mass & spin, **emerge** out of this complex system.

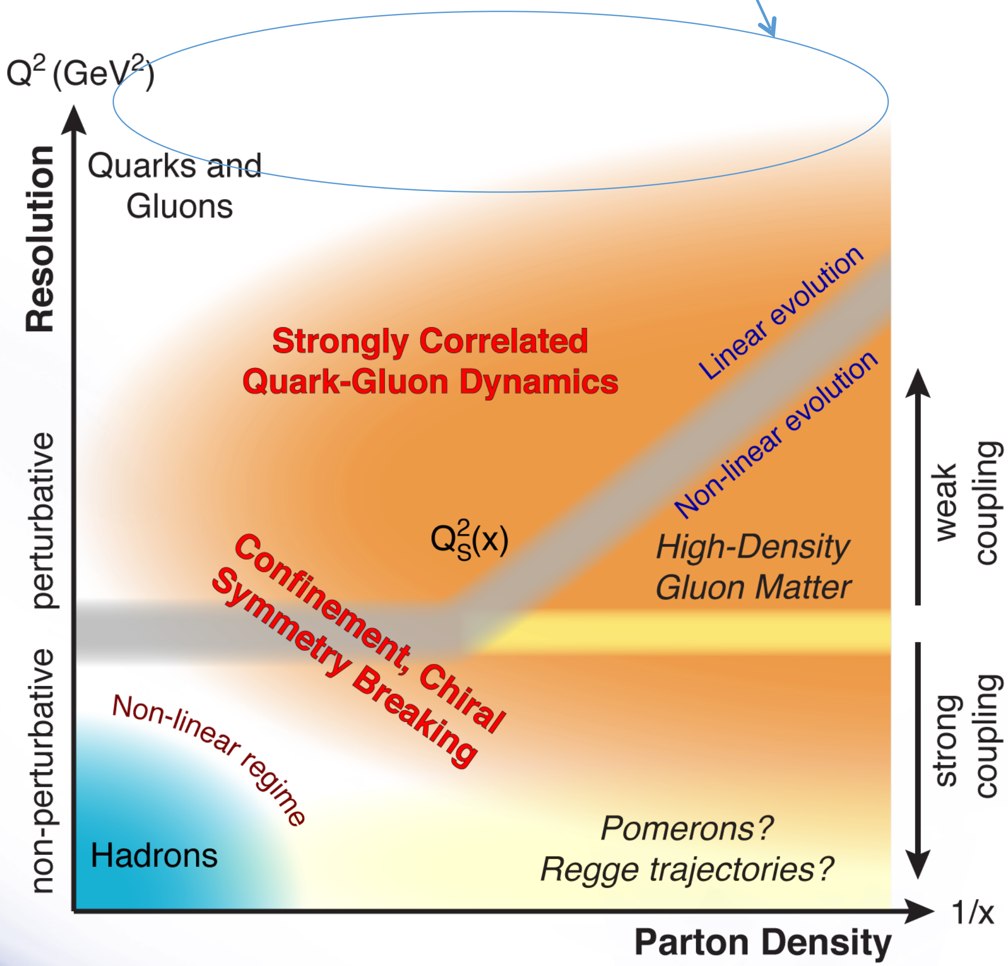
- **Gaining understanding of this dynamic matter → transformational:** Gaining detailed knowledge of this astonishing dynamical system at the heart of our world **could be transformational**, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.

- **The Electron Ion Collider is the right tool:** A new US-based facility, high-energy, high-luminosity Electron Ion collider (EIC), capable of a versatile range of beam energies, polarizations, and species, is required to precisely **image** the quarks and gluons and their interactions, to explore the new QCD frontier of **strong color fields** in nuclei – to *understand* how matter at its most fundamental level is made.



# QCD Landscape explored by EIC

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



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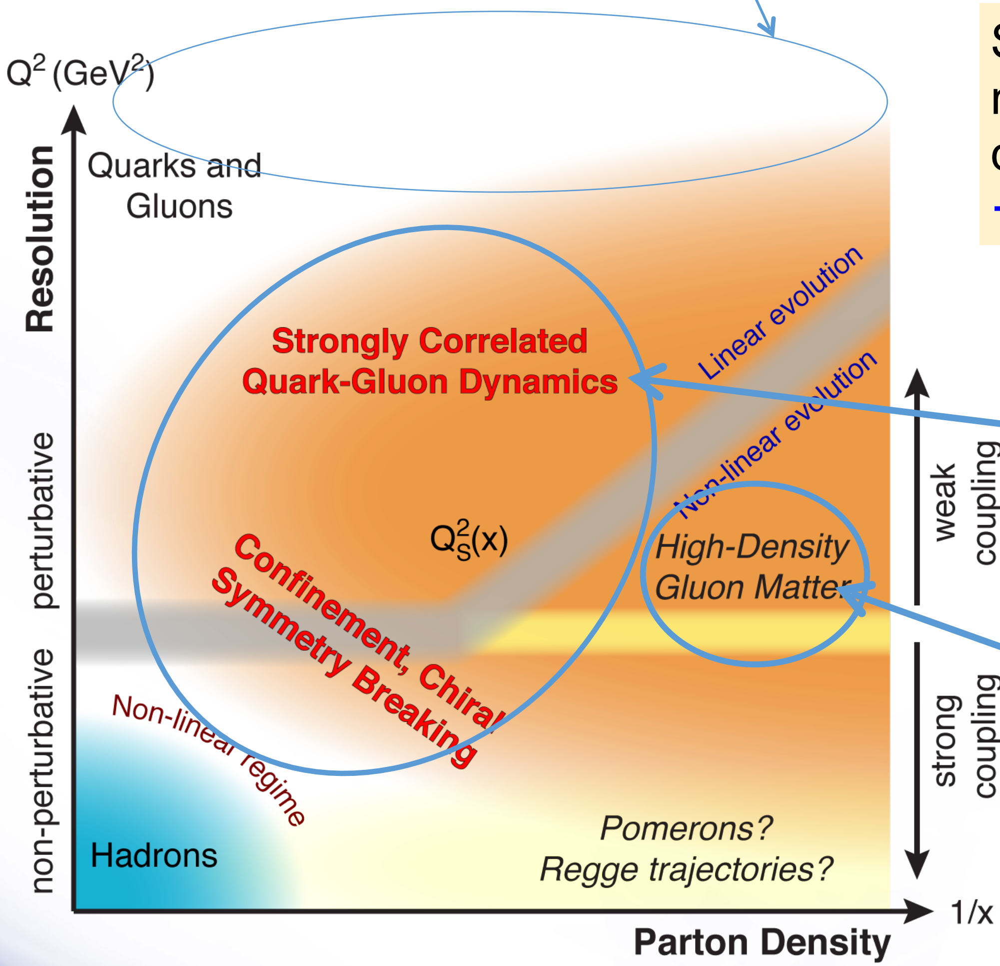



Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

EIC systematically explores correlations in this region.

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

# Non-linear Structure of QCD: Fundamental Consequences

- Quark (Color) confinement:
  - Consequence of nonlinear gluon self-interactions
  - Unique property of the strong interaction
- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions – Generalized Parton Distributions (GPDs)
- Ultra-dense color (gluon) fields:
  - Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?

# Emergent Dynamics in QCD

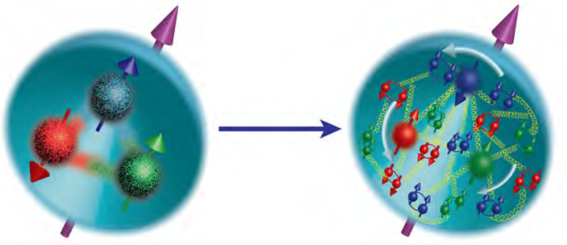
***Without gluons,* there would be no nucleons,**

***no atomic nuclei… no visible world!***

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

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

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



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How do the nucleon properties emerge from them and their interactions?

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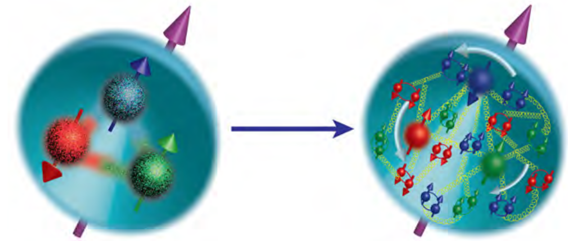

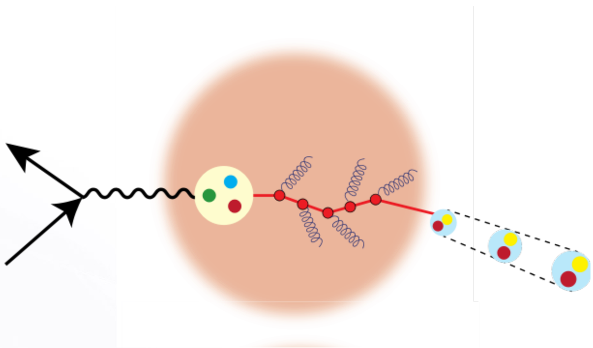

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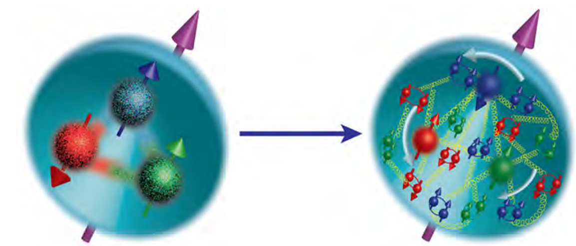

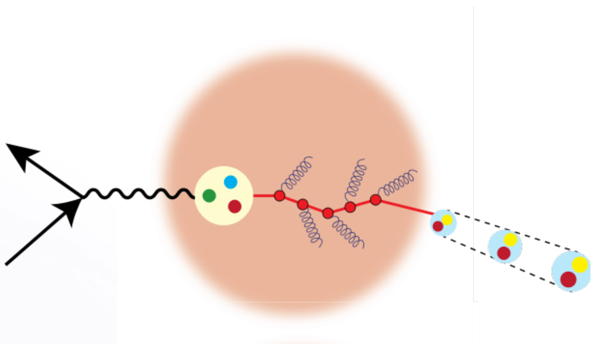

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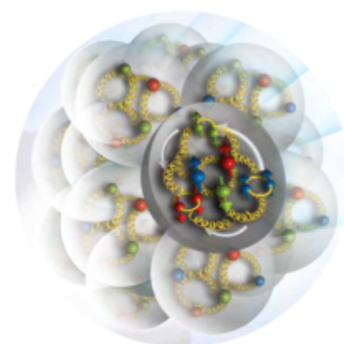
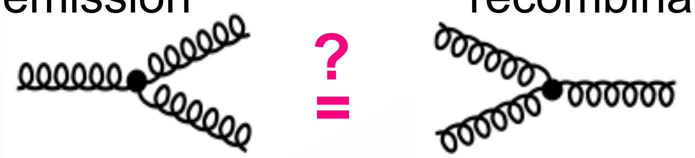


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

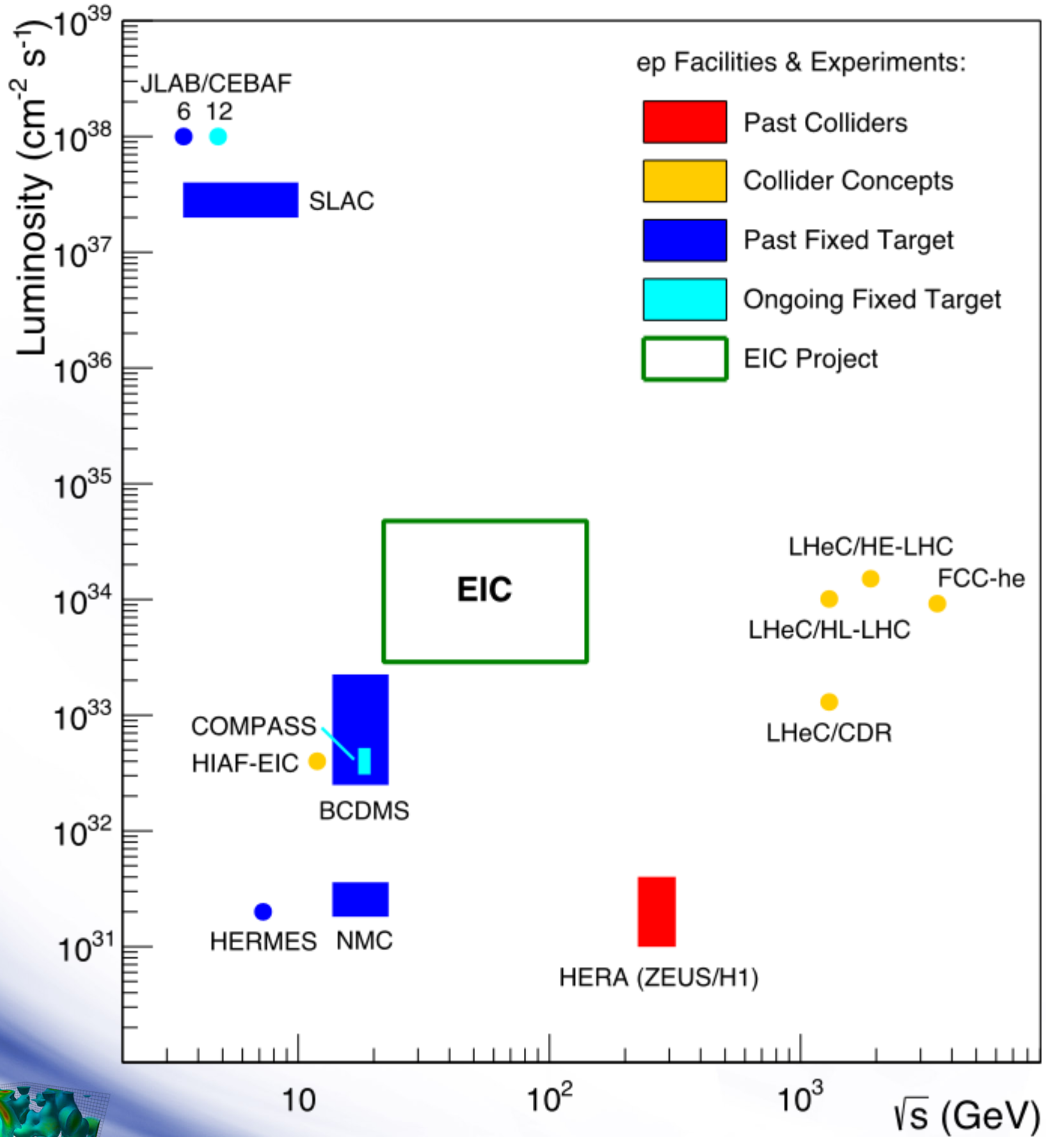
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission

gluon recombination



# Uniqueness of EIC among all DIS Facilities




All DIS facilities in the world.

However,
if we ask for:

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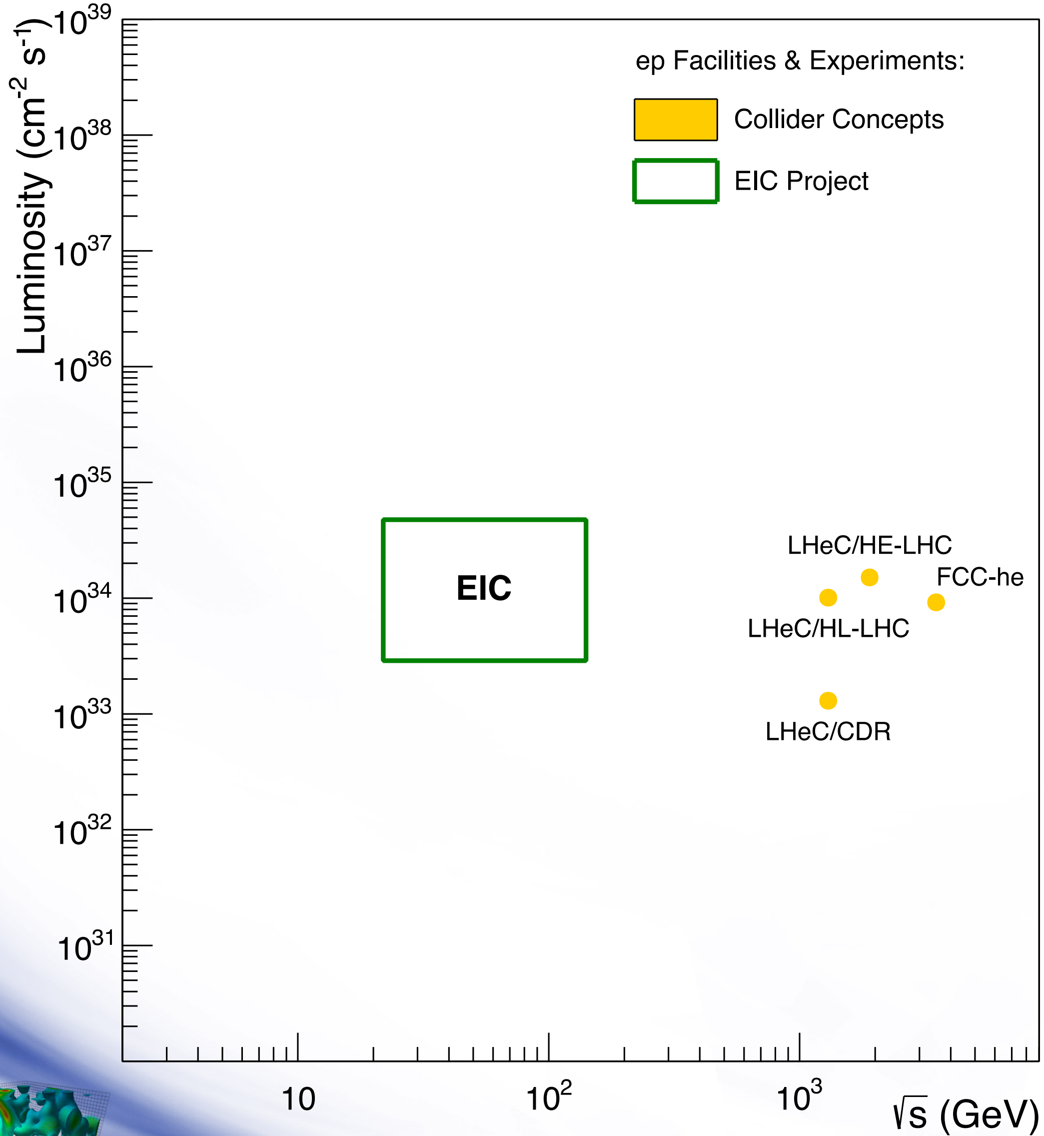


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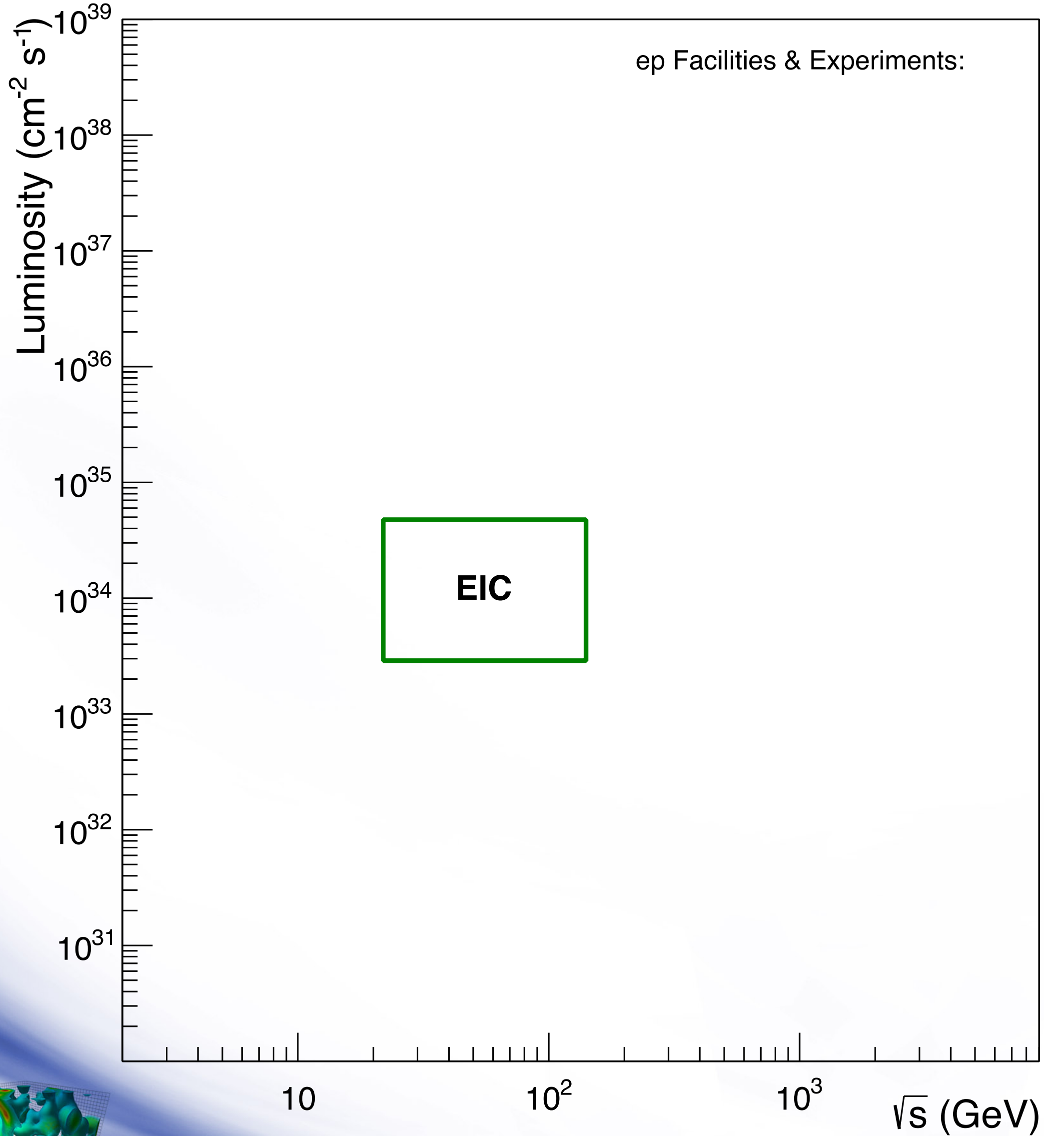


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However,
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- high luminosity & wide reach in √s
- polarized lepton & hadron beams
- nuclear beams

**EIC stands out as unique facility …**

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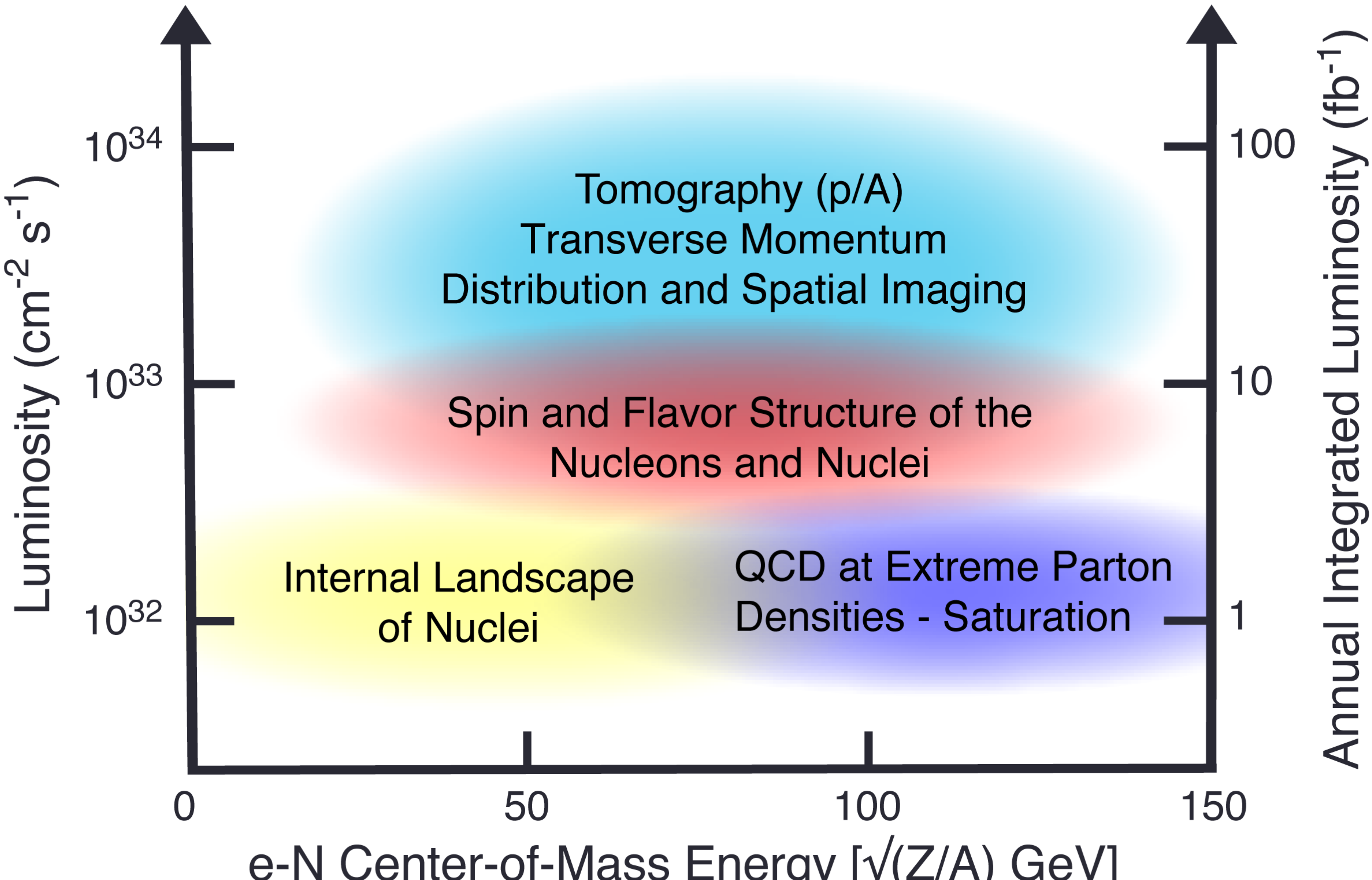
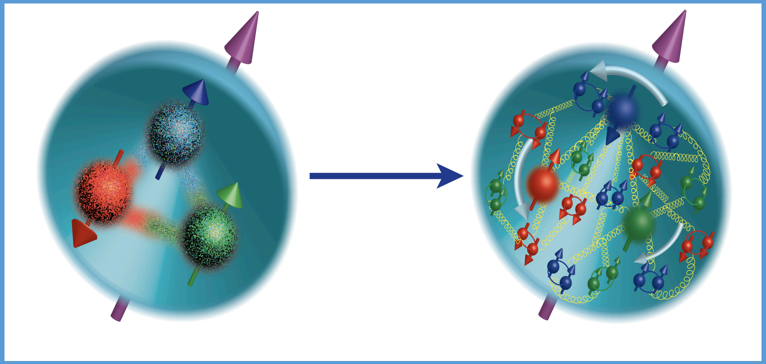


# The world's first polarized electron-proton collider

## Polarized proton as a laboratory for QCD



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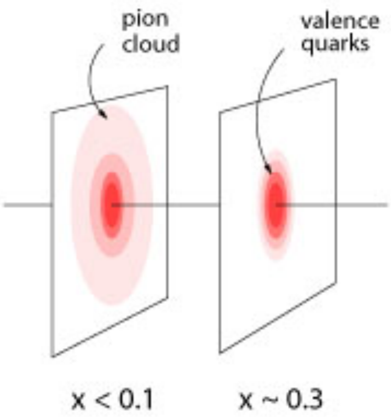
# What does a proton look like with increasing energy?




**One** of several possible scenarios: a pion cloud model

A parton core in the proton gets increasingly surrounded by a meson cloud with decreasing x
→ large impact on gluon and sea-quark observables

**What do we expect to see:**

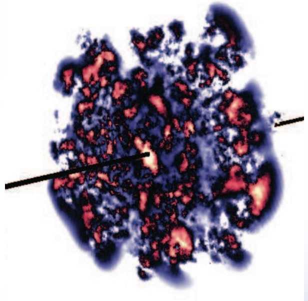
- $q\bar{q}$ pairs (sea quarks) generated at small(ish)-x are predicted to be unpolarized
- gluons generated from sea quarks are unpolarized

→ needed:

- high precision measurement of flavor separated polarized quark and gluon distributions as functions of x
- high precision spatial imaging: Gluon radius ~ sea-quark radius ?

**What happens in the gluon dominated small-x regime?**

- possible scenario: lumpy glue



**EIC will explore the dynamical spatial structure of hadrons**

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

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

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

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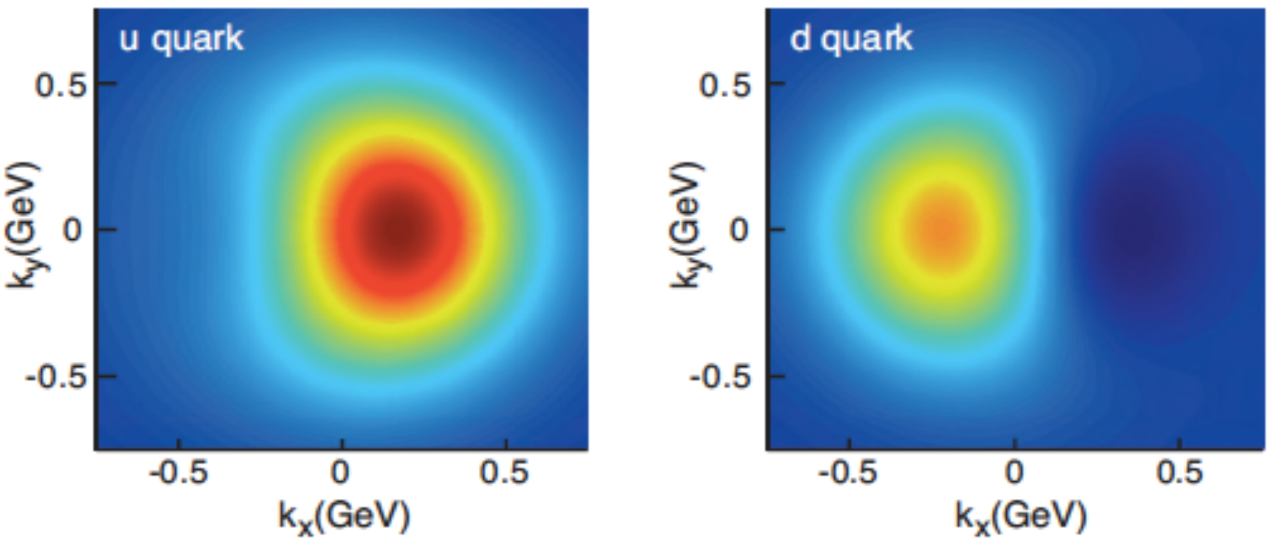

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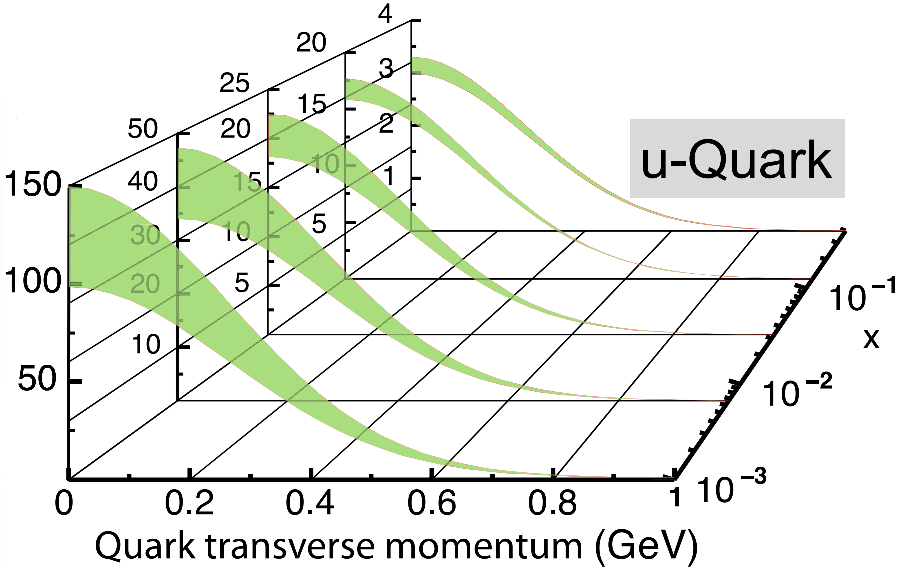

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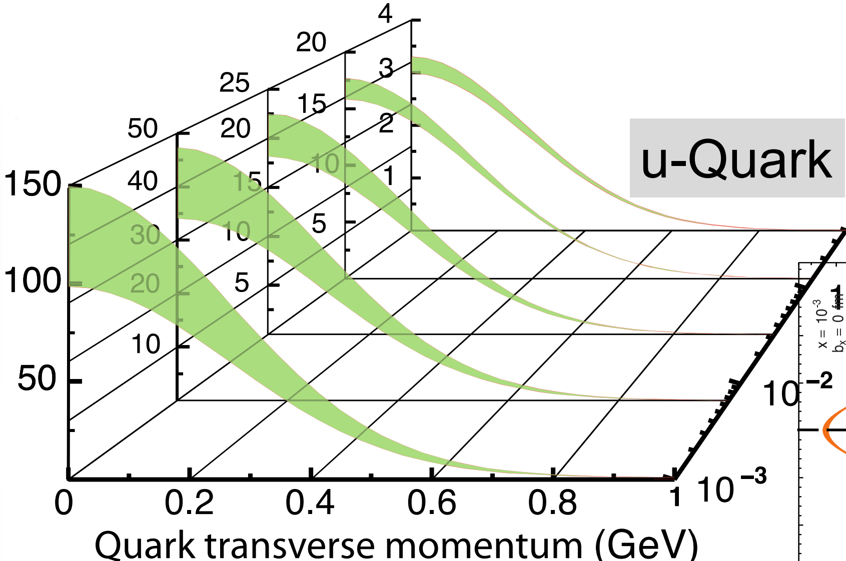
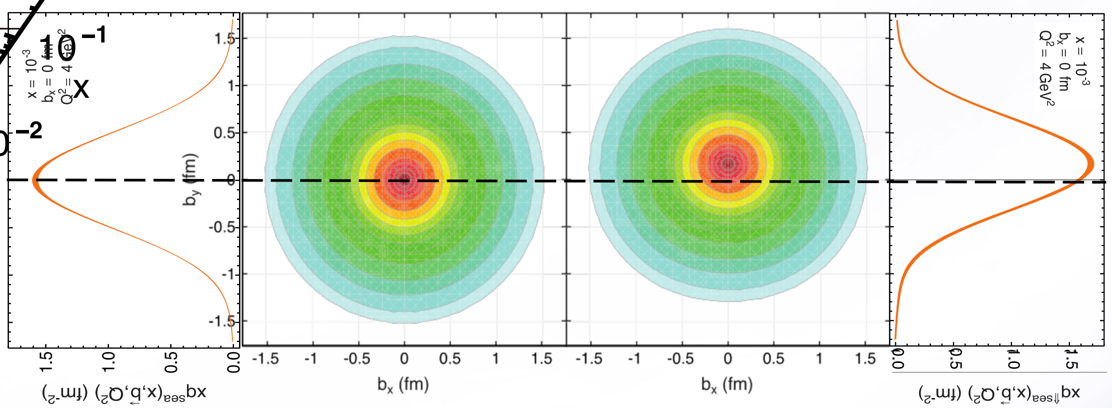



**Transverse Position Distributions**

sea-quarks
unpolarized polarized



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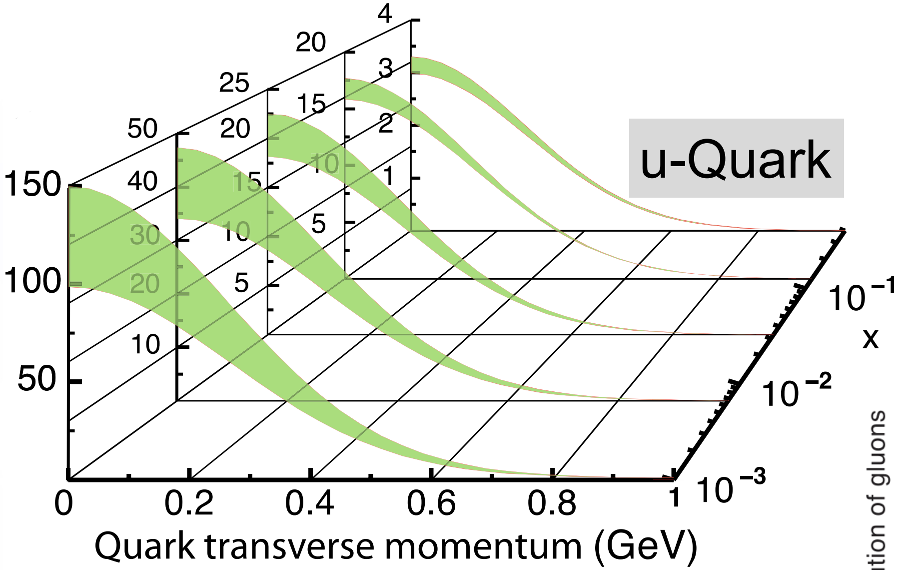


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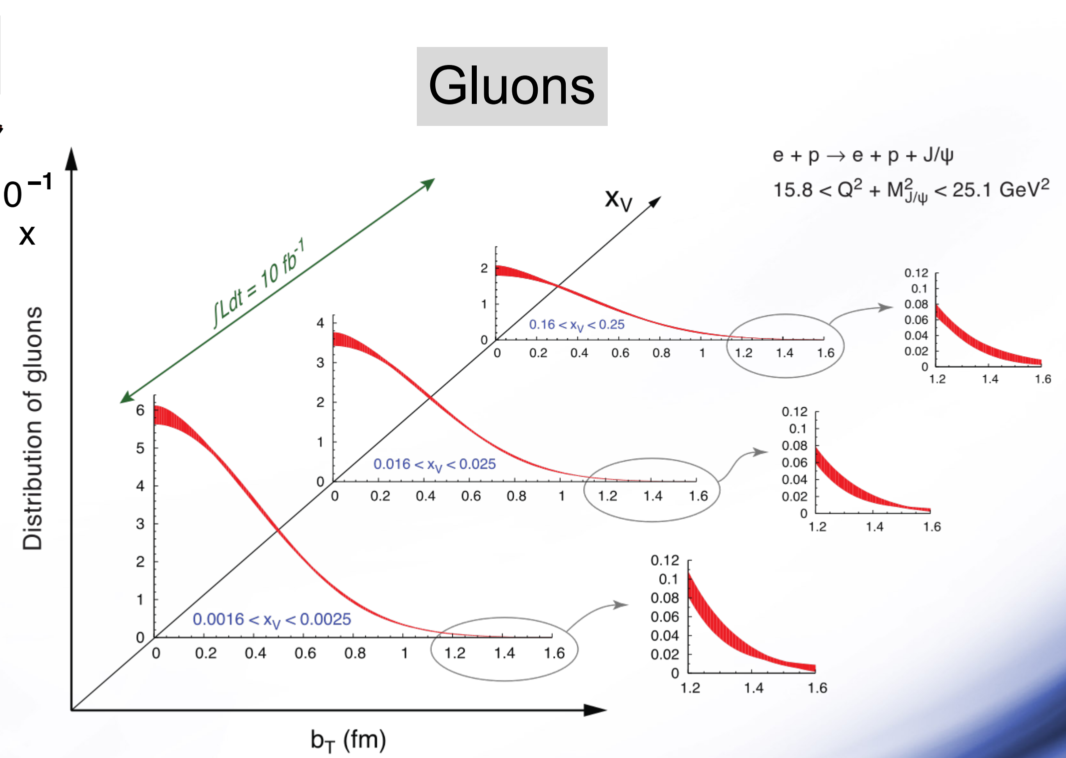
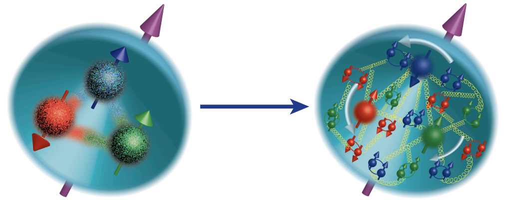


# Understanding Nucleon Spin

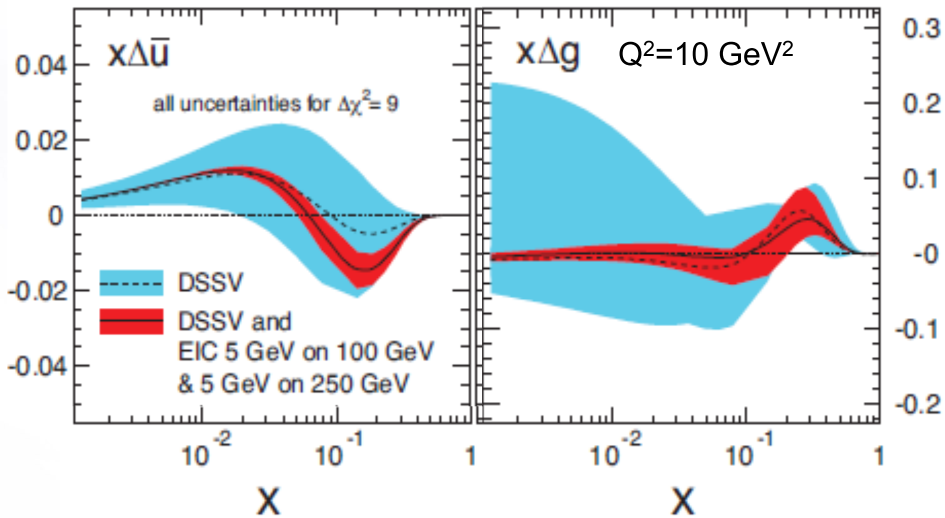


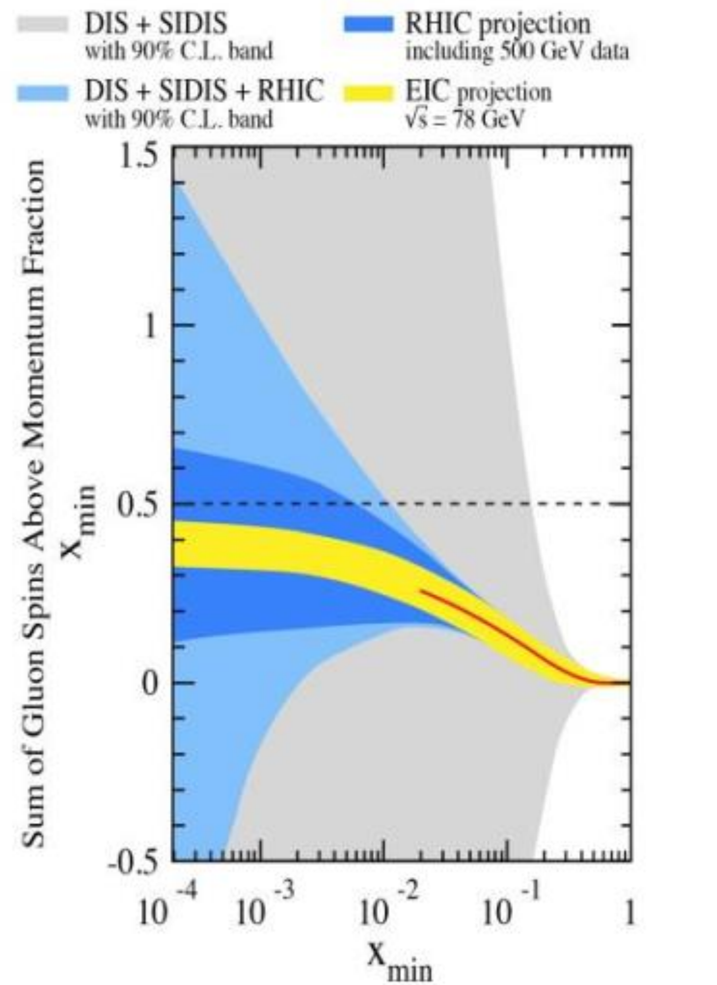
"Helicity sum rule"

$$\frac{1}{2}\hbar = \frac{1}{2}\Delta\Sigma + \Delta G + \sum_q L_q^z + L_g^z$$

quark contribution — gluon contribution — orbital angular momentum

EIC projected measurements:
precise determination of polarized PDFs of quark sea and gluons ➔ precision $\Delta G$ and $\Delta\Sigma$
→ A clear idea of the magnitude of $\sum L_q + L_g$



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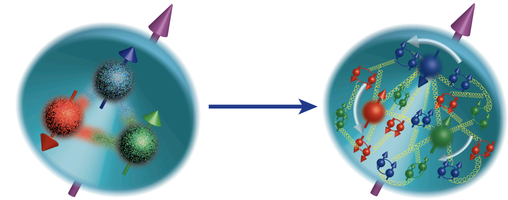

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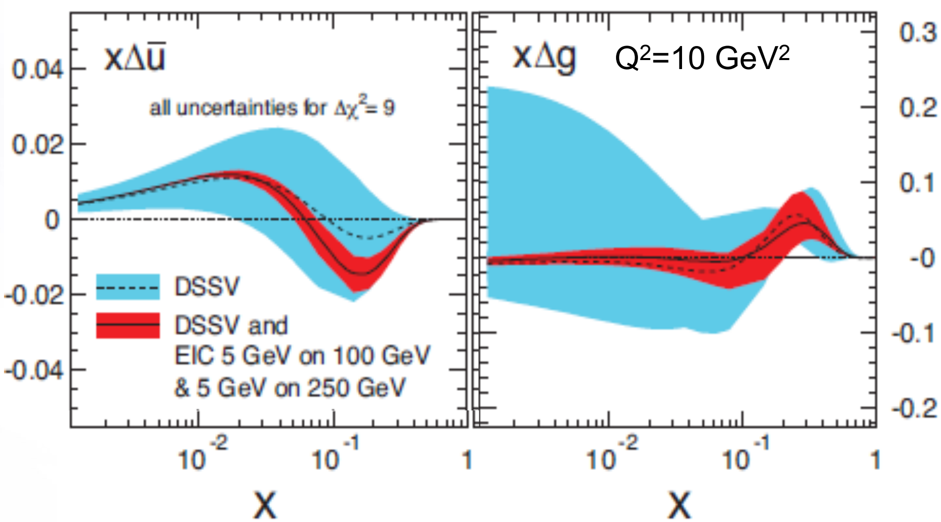
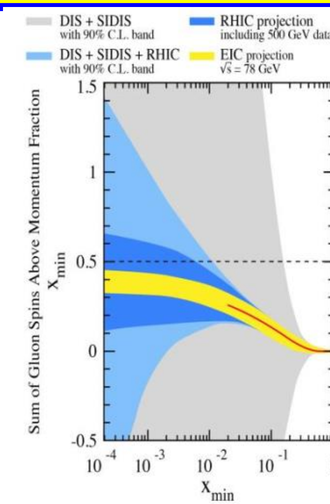
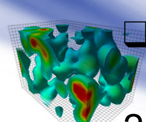
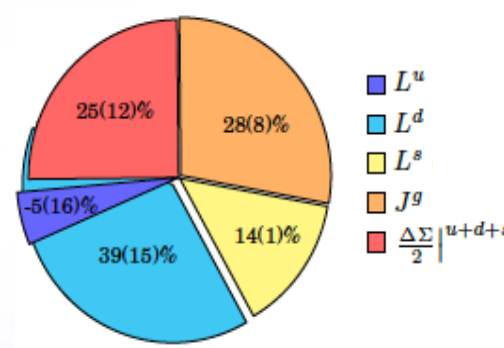


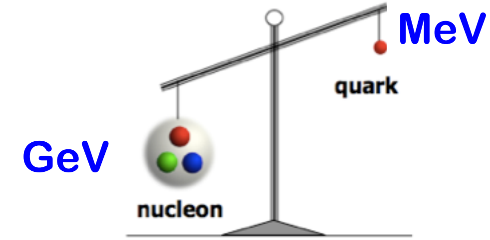

## Spin and Lattice: Recent Activities

- ❑ **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:**
  ◻◻QCD Collaboration, PRD91, 014505, 2015





# Understanding Nucleon Mass




Relativistic motion — χ Symmetry Breaking — Quantum fluctuation

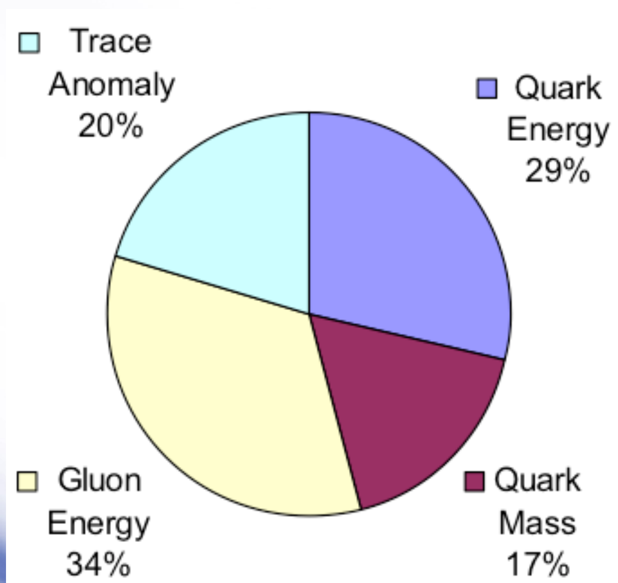
$$M = \overbrace{E_q + E_g} + \chi_{m_q} + T_g$$

Quark Energy — Gluon Energy — Quark Mass — Trace Anomaly

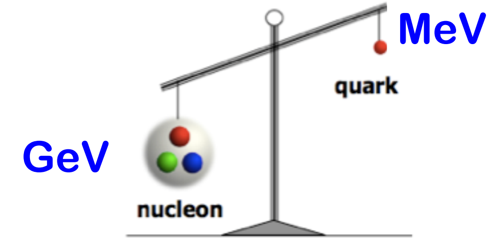
"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

*The 2015 Long Range Plan for Nuclear Science*

- **Preliminary Lattice QCD results:**



# Understanding Nucleon Mass

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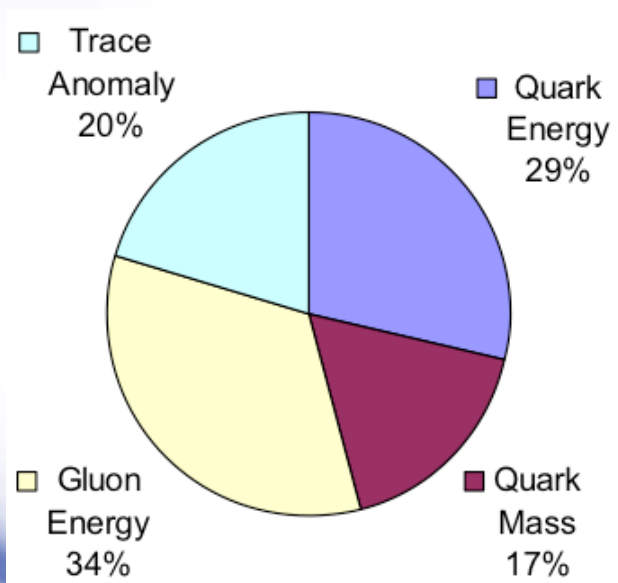
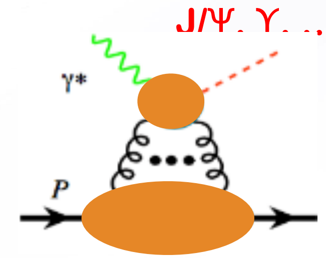
## ❑ Preliminary Lattice QCD results:




## ❑ EIC's expected contribution in:

◇ Trace anomaly:

*Upsilon production near the threshold*

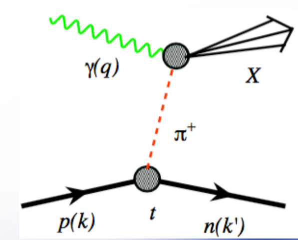


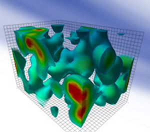

◇ Quark-gluon energy:

∝ *quark-gluon momentum fractions*

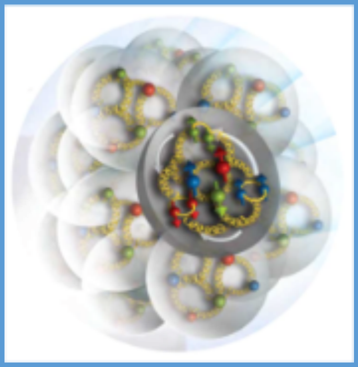
*In nucleon with DIS and SIDIS*

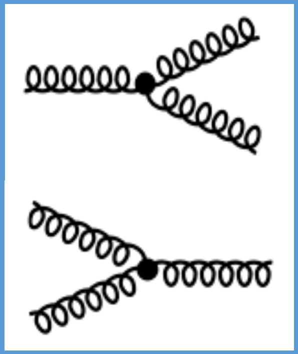
*In pions and kaons with Sullivan process*



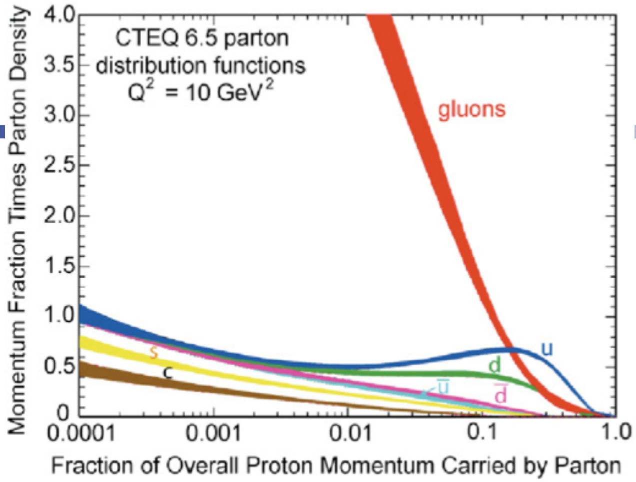
# The Nucleus as a laboratory for QCD

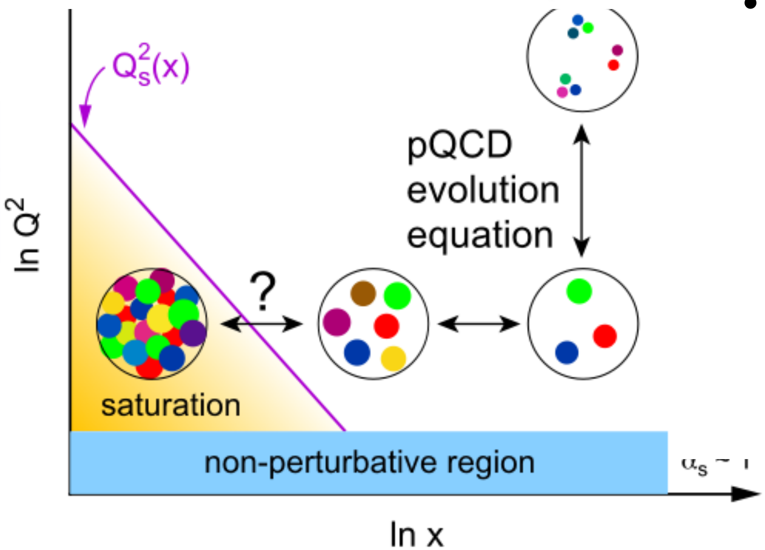




- How does a *dense nuclear environment* affect the quarks and gluons, their correlations, and their interactions?
- What happens to the *gluon density in nuclei*? Does it *saturate at high energy*, giving rise to a gluonic matter with *universal properties* in all nuclei, even the proton?

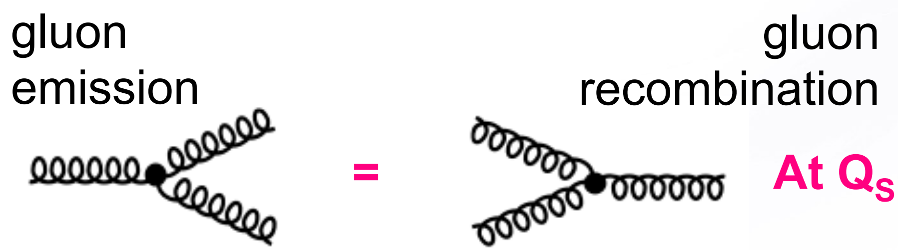
# Gluon saturation at low-x



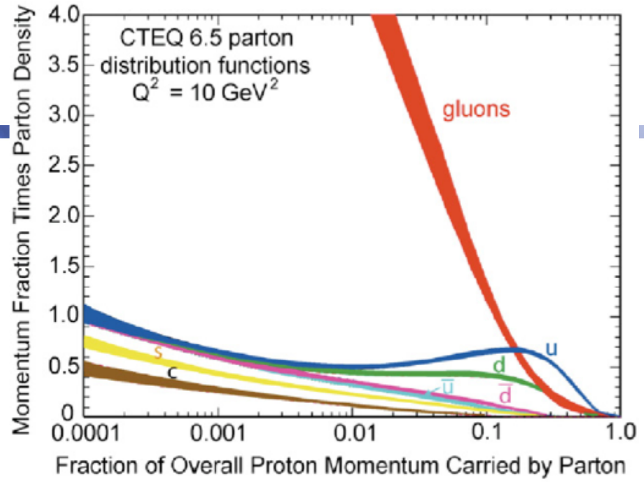



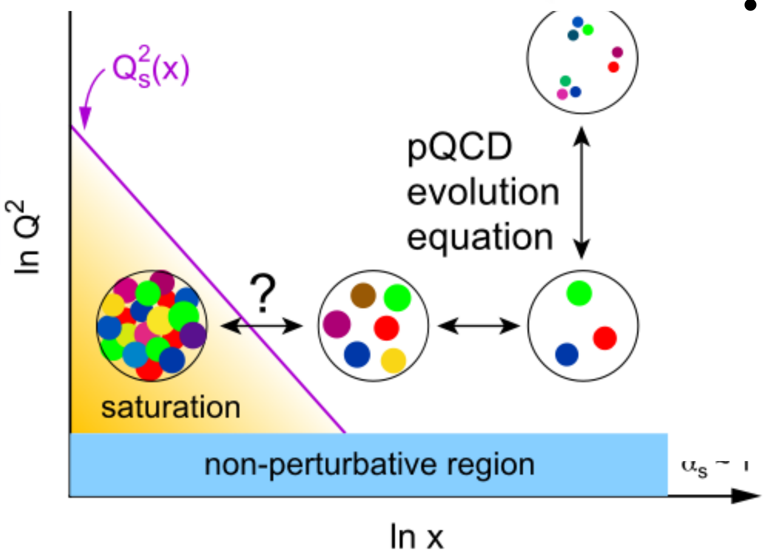

## What tames the low-x rise?

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



# Gluon saturation at low-x

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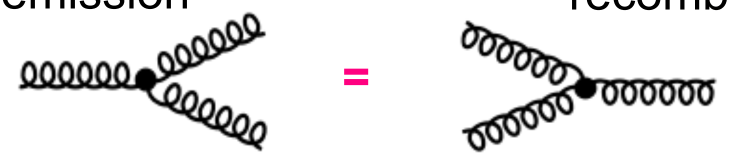
gluon emission = gluon recombination



At $Q_S$

**First observation of gluon recombination effects in nuclei:**

**➔ leading to a collective gluonic system**

**First observation of gluon recombination in different nuclei**

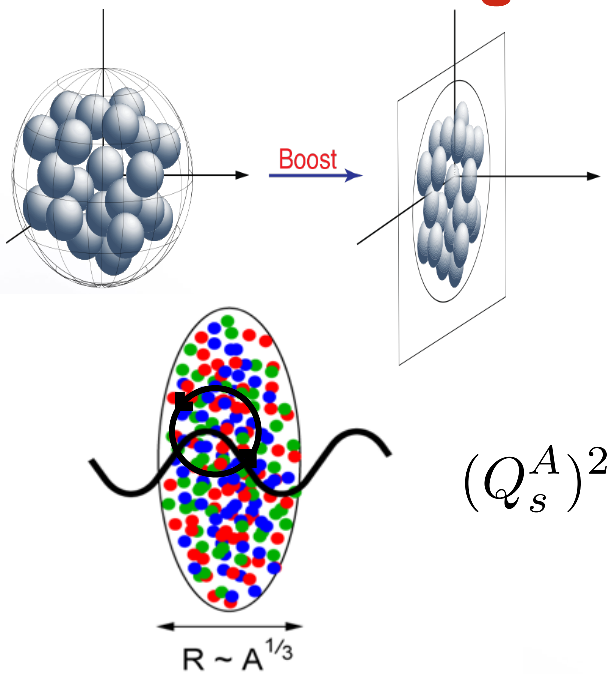
**→ Is this a universal property?**

**What is the new effective theory in this regime?**

# How to explore/study this new phase of matter?

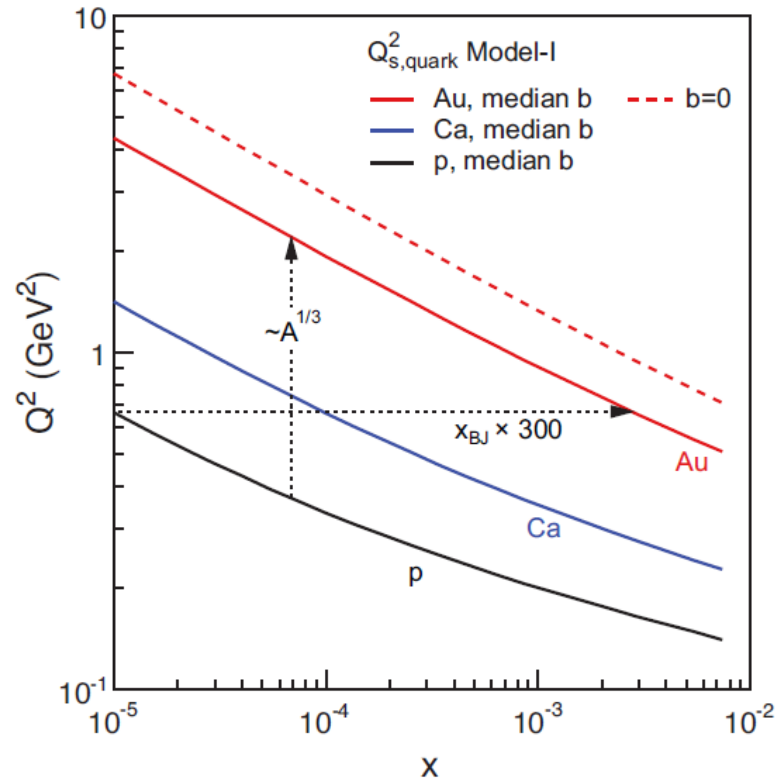
(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

## Advantage of nucleus →




$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

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



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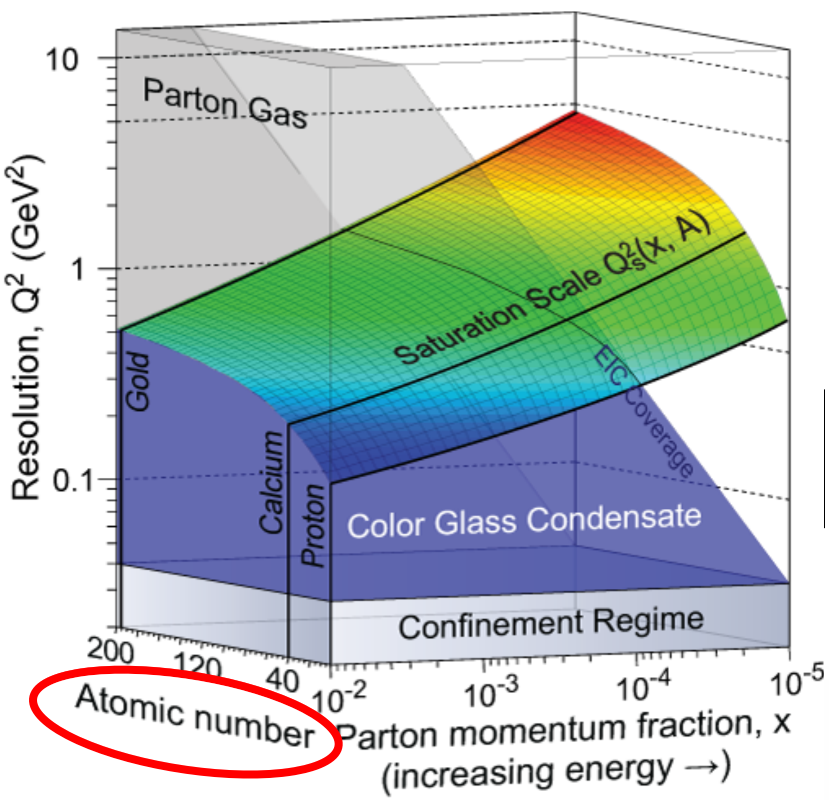
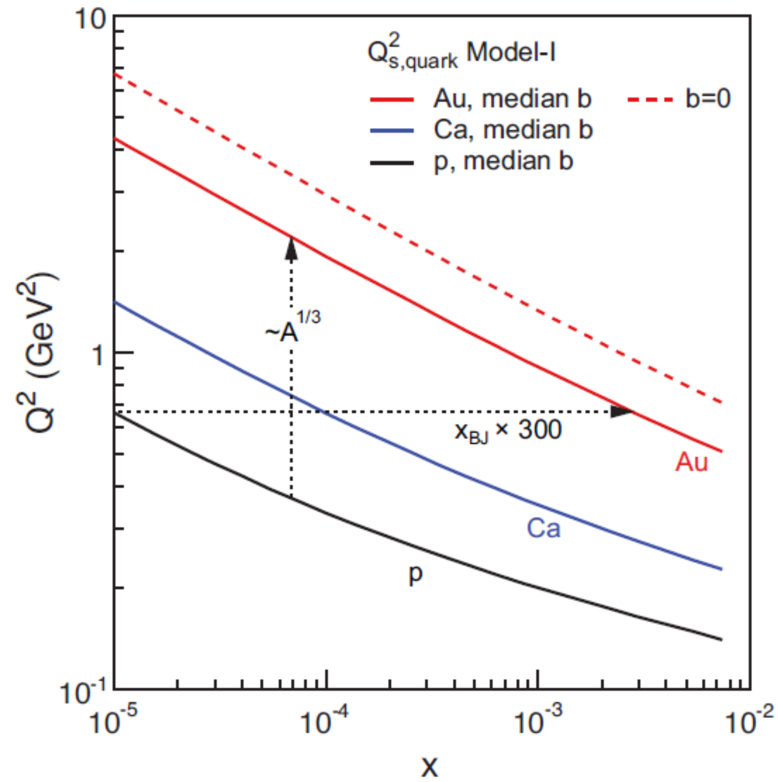



$L \sim$

$1/3$



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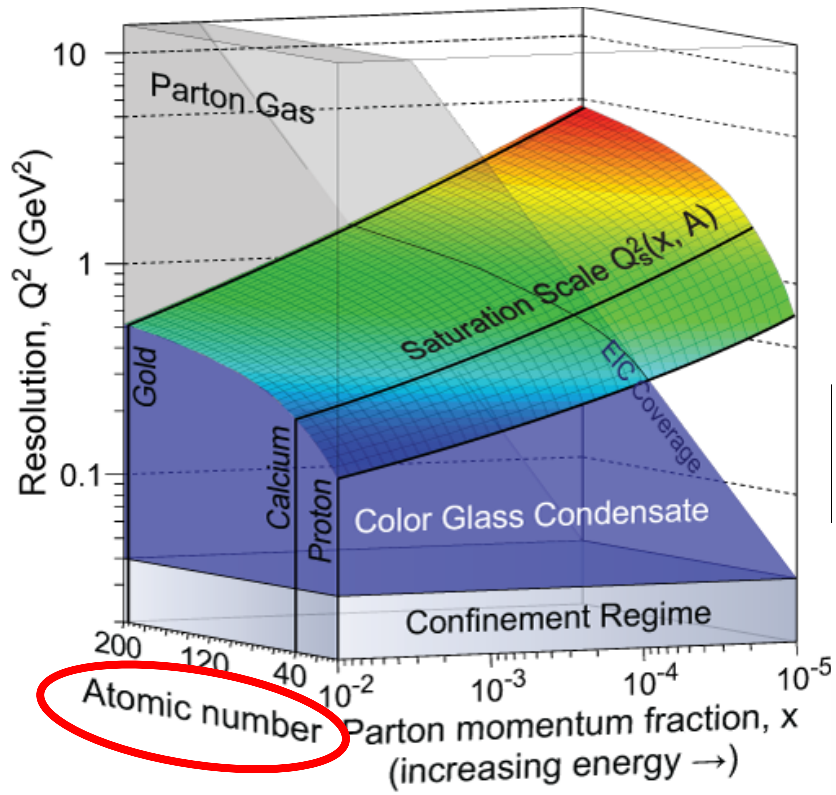
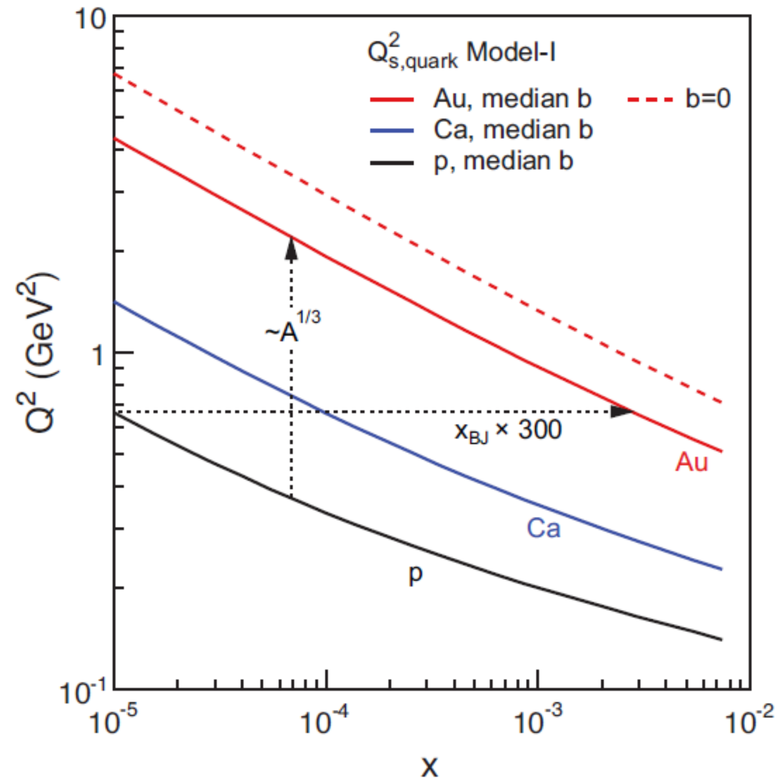



$L \sim$ $1/3$




Enhancement of $Q_S$ with A:

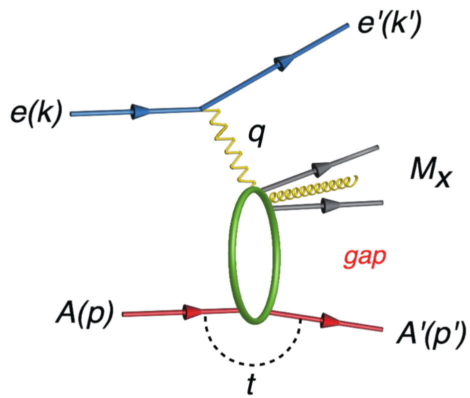
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

# Diffraction for the 21$^{st}$ Century

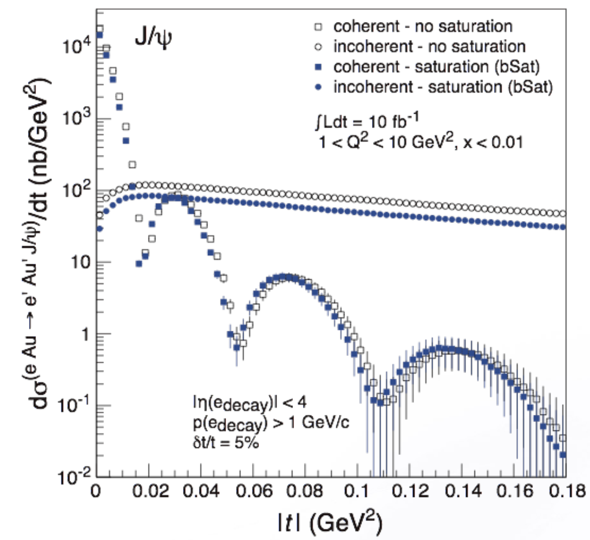
Diffraction cross-sections have strong discovery potential:

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

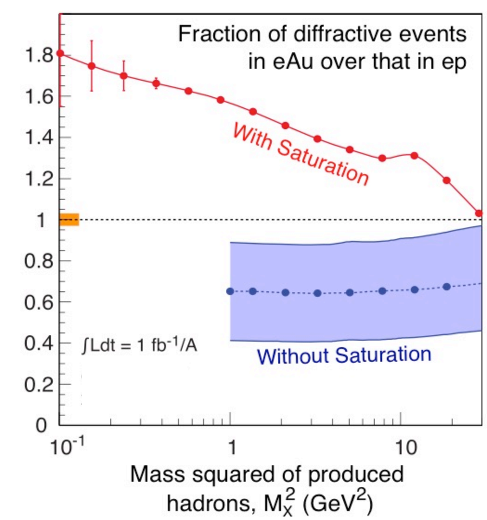
Dramatic changes in cross-sections with onset of non-linear strong color fields



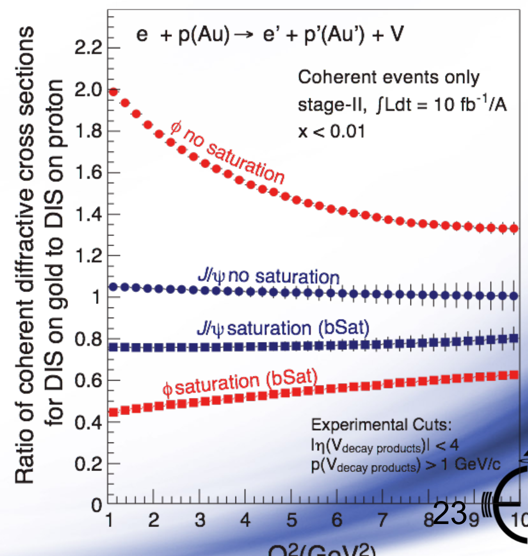

Extracting the gluon distribution $\rho(b_T)$ of nuclei via Fourier transformation of $d\sigma/dt$ in diffractive J/ψ production




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

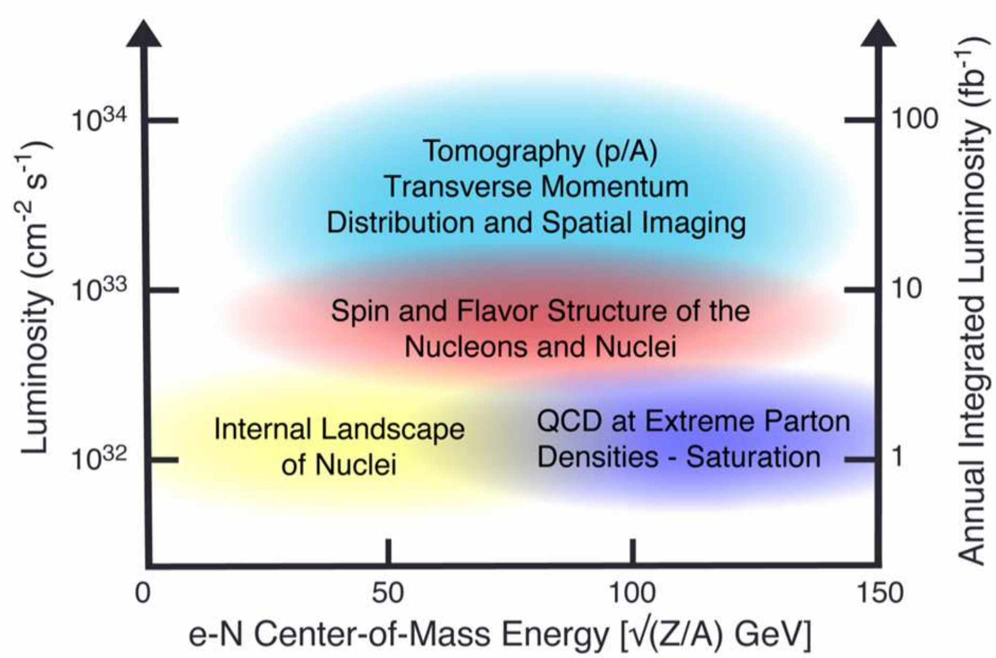



Probing $Q^2$ dependence of gluon saturation in diffractive vector meson production



# Collider Requirements

- **Polarized electron and light ion beams (*p*,*d*,$^3$He)**
  - Double polarization absolutely required for nucleon tomography and spin structure studies
- **Wide variety of unpolarized nuclear beams (*A*)**
  - Needed for gluon saturation and other studies
- **High luminosity & energy**
- **Variable CM energy**
- **EIC demands frontier ideas and technologies in accelerator physics**

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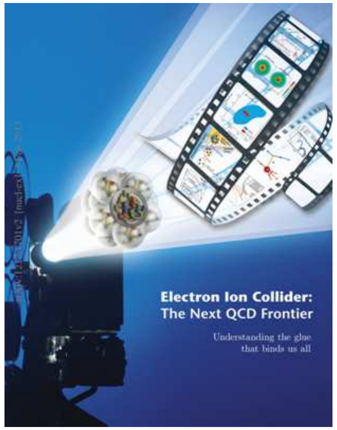
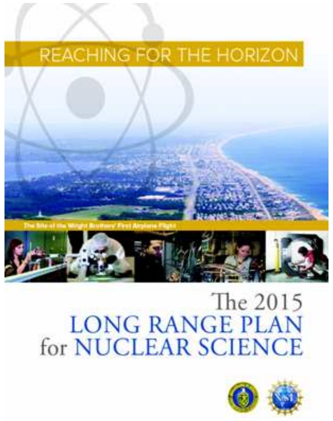
# A long journey to get here…




## EIC White Papers (2012,14,16)

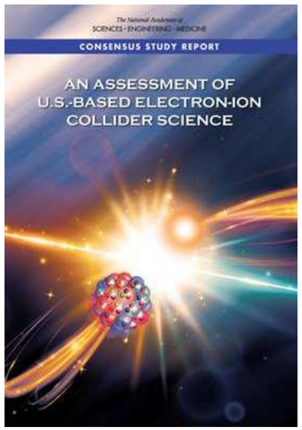
Development of EIC science case*: "The next QCD frontier: Understanding the glue that binds us all".* arXiv: 1212.1701

As science case matures and expands, white paper updated in 2014, 2016: Eur.Phys.J.A **52** (2016) 268




## Nuclear Science Advisory Committee (2015)

*"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction"*




## National Academy of Science Review (2018)

Asked by DOE to review EIC science case in light of the NSAC recommendation.

Very strong endorsement: *"questions to be addressed are profound… science case is compelling"*

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# US Department of Energy: 2020 – 2022

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Department of Energy

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

JANUARY 9, 2020

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

**WASHINGTON, D.C.** – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at cost between $1.6 and $2.6 billion, will smash electrons into protons and heavi an effort to penetrate the mysteries of the "strong force" that binds the atomic

"The EIC promises to keep America in the forefront of nuclear physics research accelerator technology, critical components of overall U.S. leadership in science **Secretary of Energy Dan Brouillette.** "This facility will deepen our understandin expected to be the source of insights ultimately leading to new technology and

- Projected cost: US$1.7-2.8 billion
- USDOE engaged with international partners: Resource Review Board (RRB) with NSERC, CFI representation
- 2031-2: First beam/operations

**Lots of momentum in Washington:**

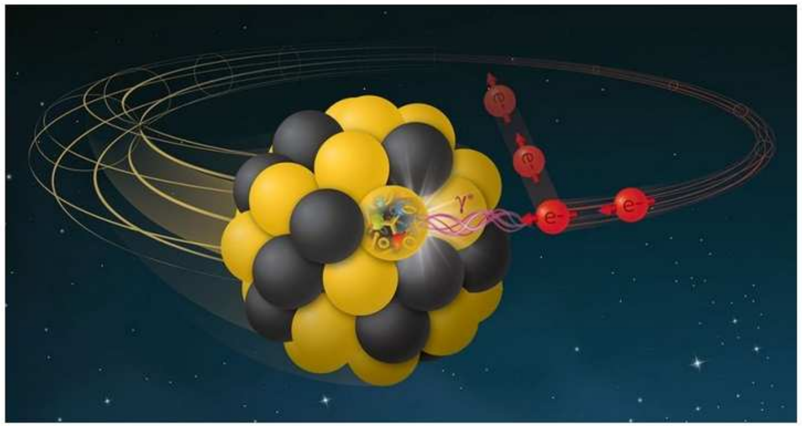
- 2022 Inflation Reduction Act (IRA) allocated US$138.24M to EIC
- All funds through long lead procurement (CD-3A) approved by Congress
- Shift from progress constrained by funding to progress determined by ability to advance the design through hiring, partnering and collaboration

Office of Science

## Electron-Ion Collider Achieves Critical Decision 1 Approval

JULY 6, 2021

Office of Science » Electron-Ion Collider Achieves Critical Decision 1 Approval

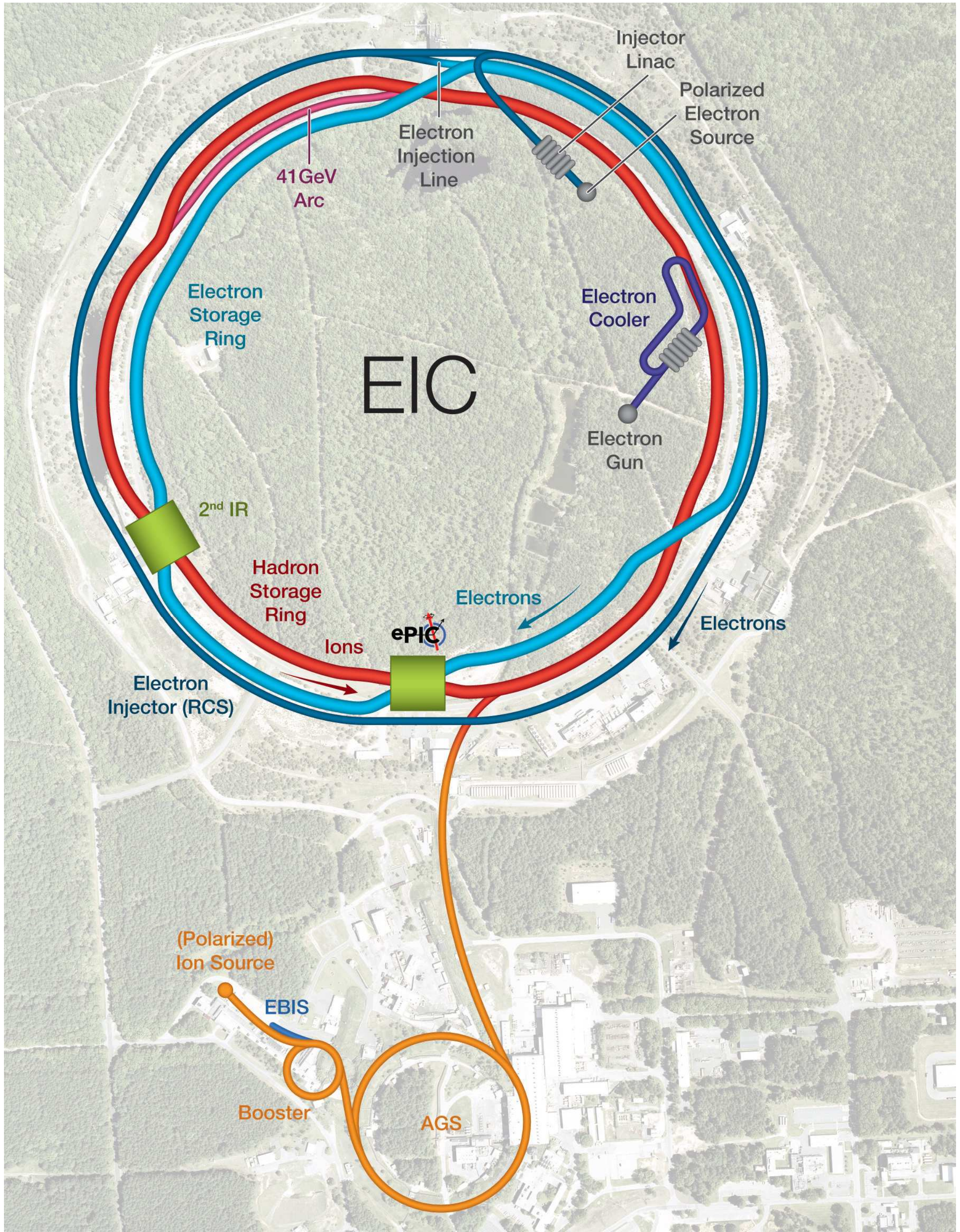


UPTON, NY and NEWPORT NEWS, VA – The U.S. Department of Energy (DOE) has granted Critical Decision 1 (CD-1) for the Electron-Ion Collider (EIC), a one-of-a-kind nuclear physics research facility to be built at DOE's Brookhaven National Laboratory on Long Island. Following DOE's

# eRHIC Realization @ BNL

Use existing Relativistic Heavy Ion Collider (RHIC)

- Up to 275 GeV protons (polarized).
- Existing: tunnel, detector halls, hadron injector complex (AGS).
- Build new 18 GeV electron linac and add high intensity electron storage ring in same tunnel.
- Achieve high luminosity, high energy *e–p*/A collisions with full acceptance detectors.
- High luminosity achieved by extensions of state–of–the–art beam cooling techniques.

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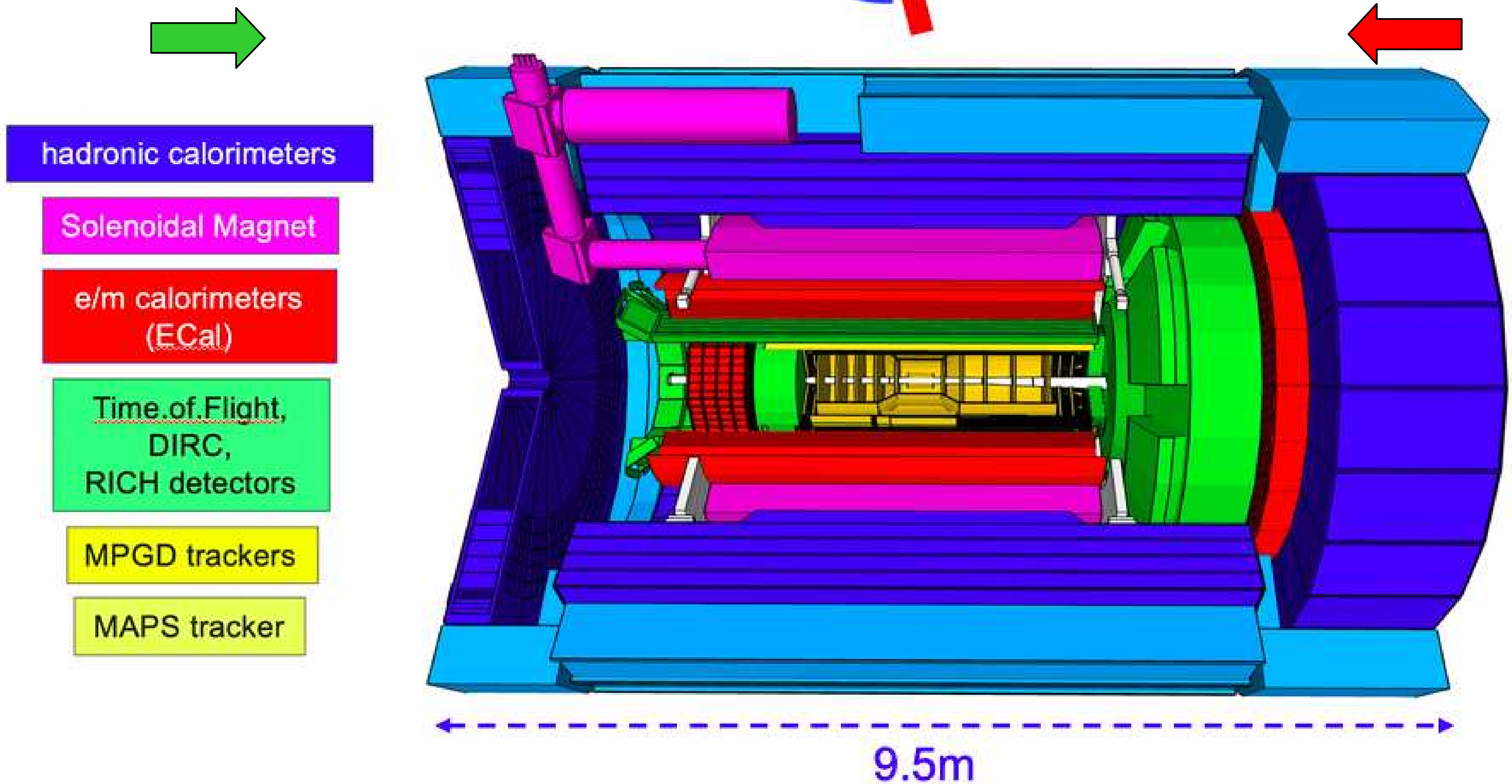
# electron-Proton/Ion Collider (Detector #1)

ePIC

**48 – 275 GeV**
**proton or ion beam**

**5 – 18 GeV**
**electron beam**

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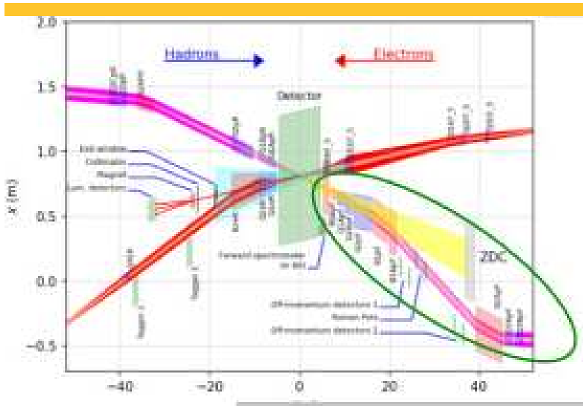
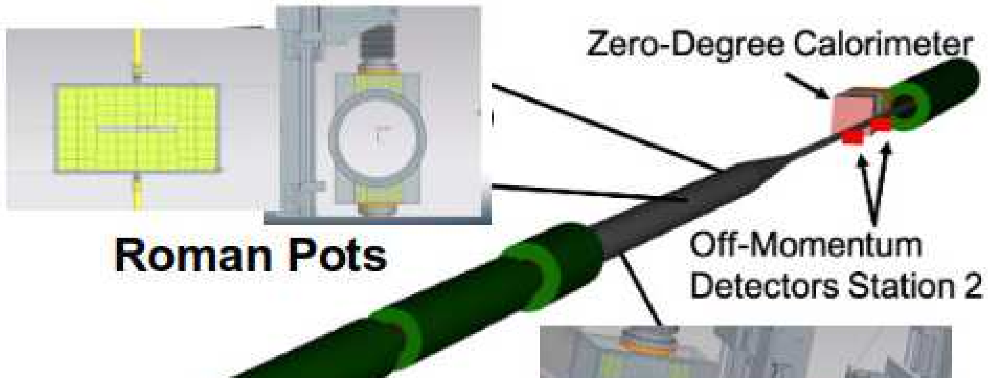
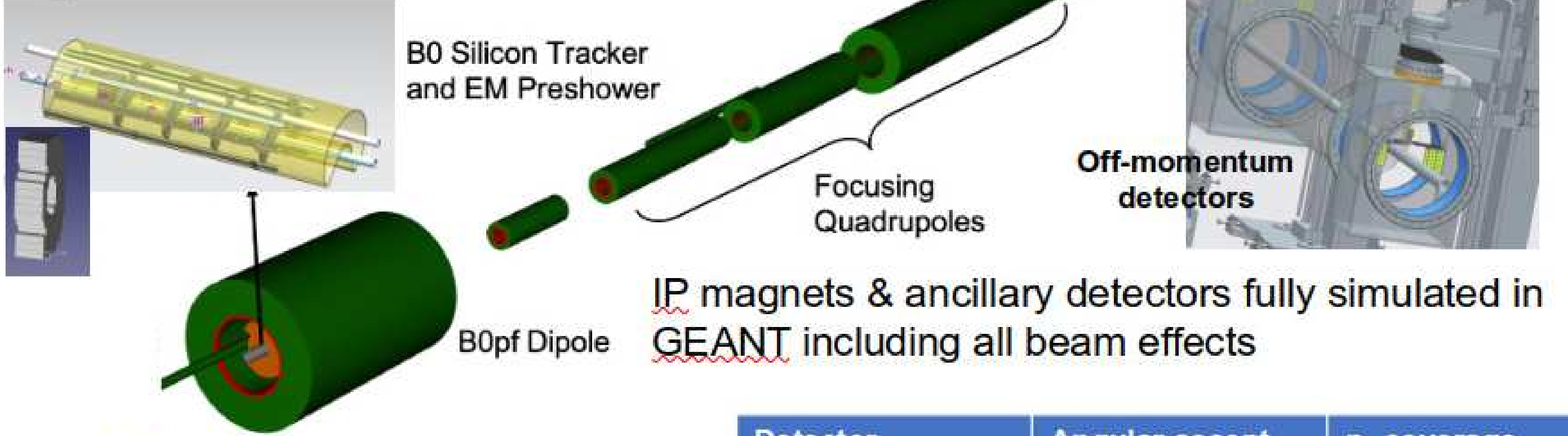
# ePIC Far Forward Detector Integration



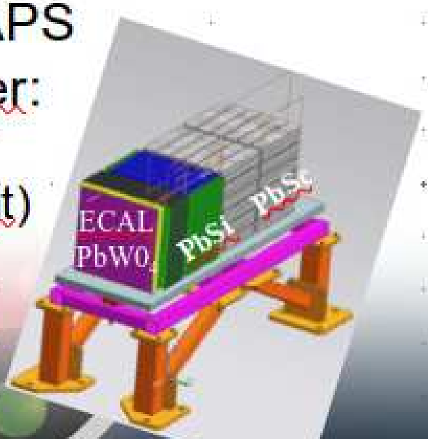






IP magnets & ancillary detectors fully simulated in GEANT including all beam effects

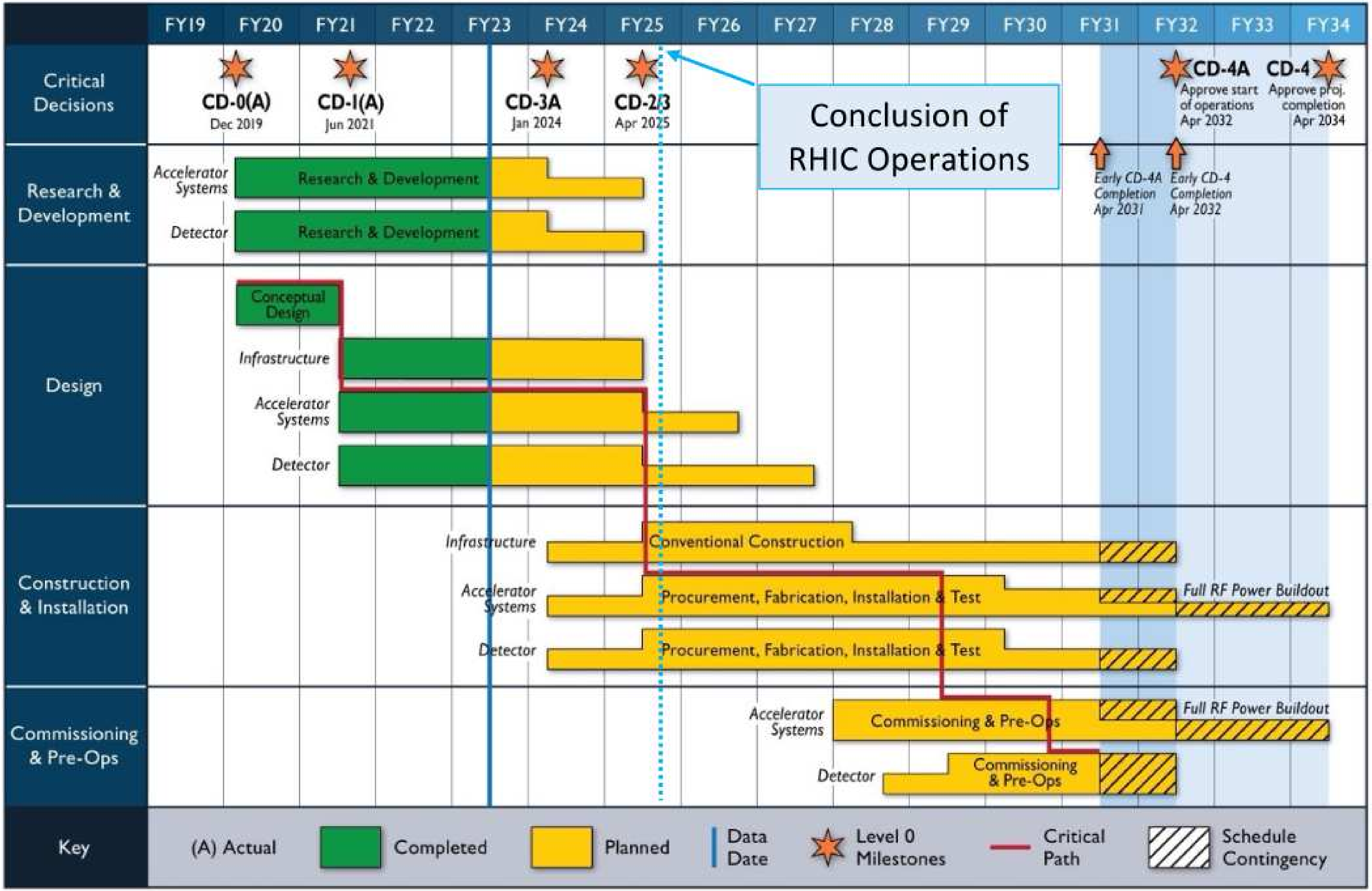
## Technologies defined

- Silicon: AC-LGAD & MAPS
- Zero Degree Calorimeter:
  - ECAL (PbWO4)
  - HCAL (PbSi + PbScint)




| Detector | Angular accept. [mrad] | $p_T$ coverage |
|---|---|---|
| ZDC @ ~30m | <5.5 ( | $p_T$<1.3 GeV |
| Roman Pots | 0*<<5.0 ( | *Low $p_T$(t) cutoff (beam optics) |
| Off-Momentum Detectors | 0.< <5.0 ( | Low-rigidity particles from nuclear breakups |
| B0 forward spectrometer | (4.6< | High $p_T$(t) |

# EIC Schedule

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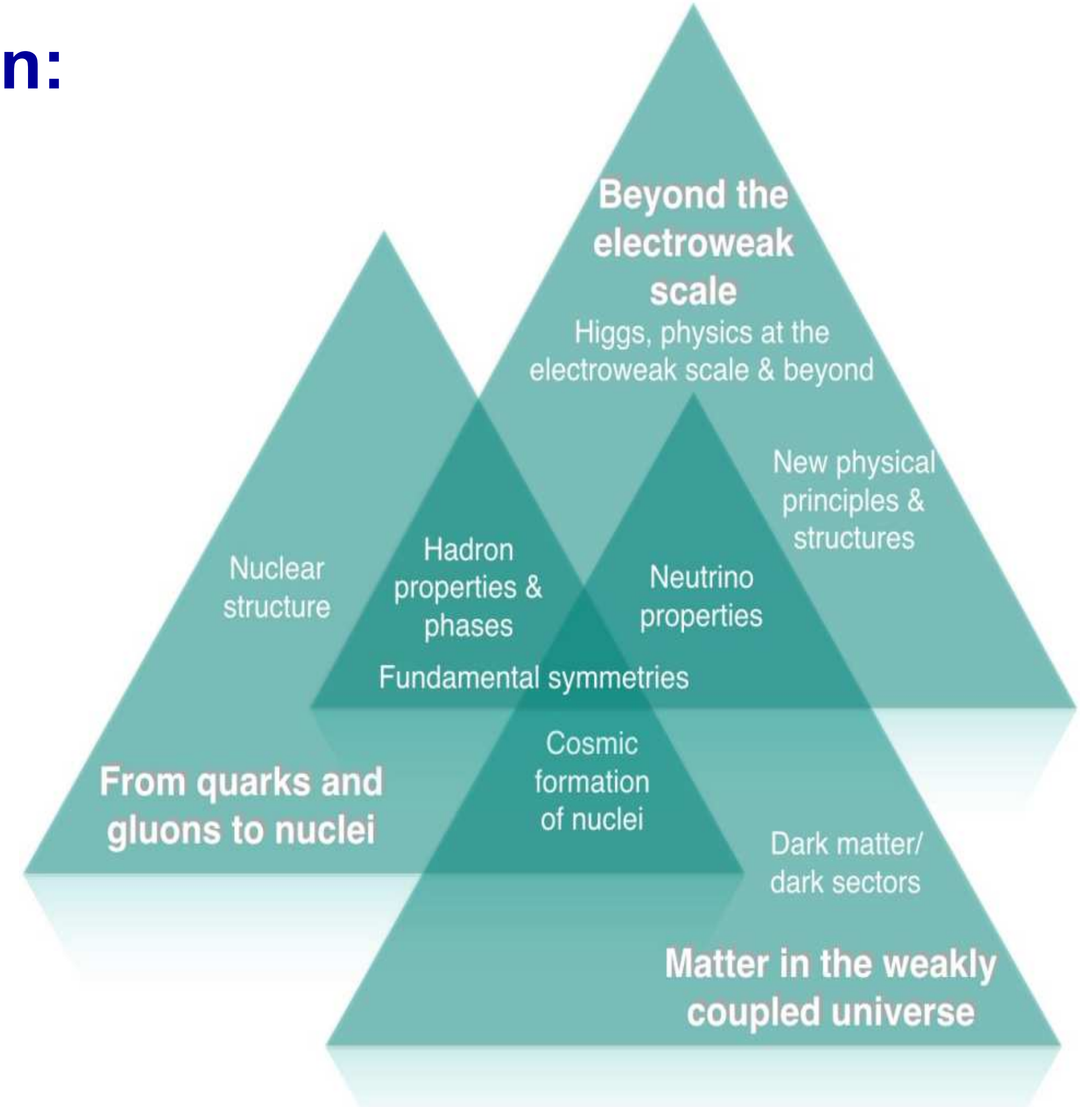
## Excerpt from 2022-2036 Plan:

- **Hadron Properties and Phases**
  - How do quarks and gluons give rise to the properties of nucleons and other hadrons, and to the hadronic phases of matter in extreme conditions?
- **Nuclear Structure**
  - How does nuclear structure emerge from nuclear forces and ultimately from quarks and gluons?
- **Cosmic Formation of Nuclei**
  - How do the properties of nuclei explain the formation of the elements in the universe?




SubatomicPhysics.ca

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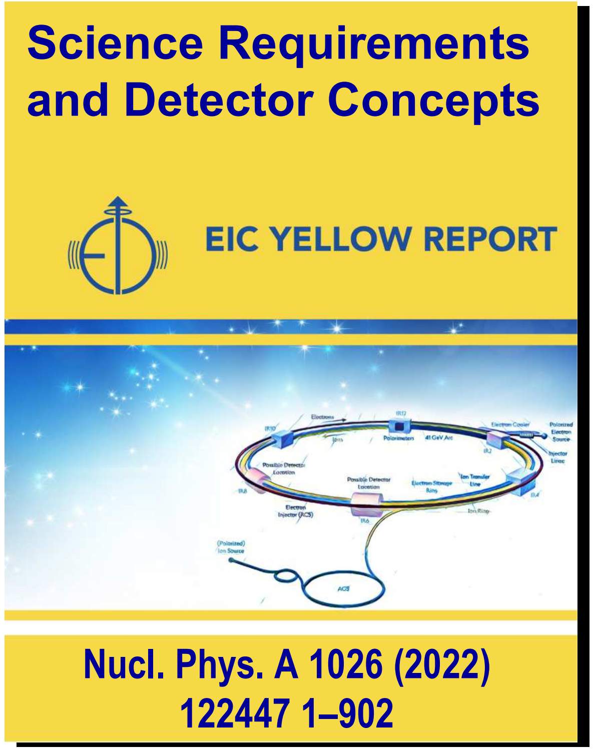
**EIC is listed as a flagship project for Canadian science!**

# Canadian Involvement in EIC




**2021:** From Yellow Report…

… **to two large detector proposals**

with Canadian involvement

**2022:** Proposal Selection

… **to one large EIC Project detector Collaboration (EPIC)**

- Joint WG's formed and consolidation process undertaken
- Coordination with EIC project on development of technical design

## EIC Canada focus areas

***Hardware:***

- **Calo:** Si–pixel imaging + SciFi hybrid barrel
- **Barrel ECAL Technical Coordinator**: Z. Papndreou
- Building towards significant CFI–IF proposal for Calorimetry in 2025 competition

***Simulations:***

- **ePIC Software WG co–convenor**: W. Deconinck
- **Software framework:** community–oriented (dd4hep, edm4hep, ACTS)
- **Novel AI work:** inner tracker design optimization, calo design using hierarchical density-based clustering
- **Event generators:** far forward region studies (ZDC, B0)
- **Physics:** Meson Form Factors at high $Q^2$
  XYZ Spectroscopy
  Charged lepton universality ($e \rightarrow \tau$)

## New Collaborators Welcome!

University of Manitoba — Mount Allison University — University of Regina

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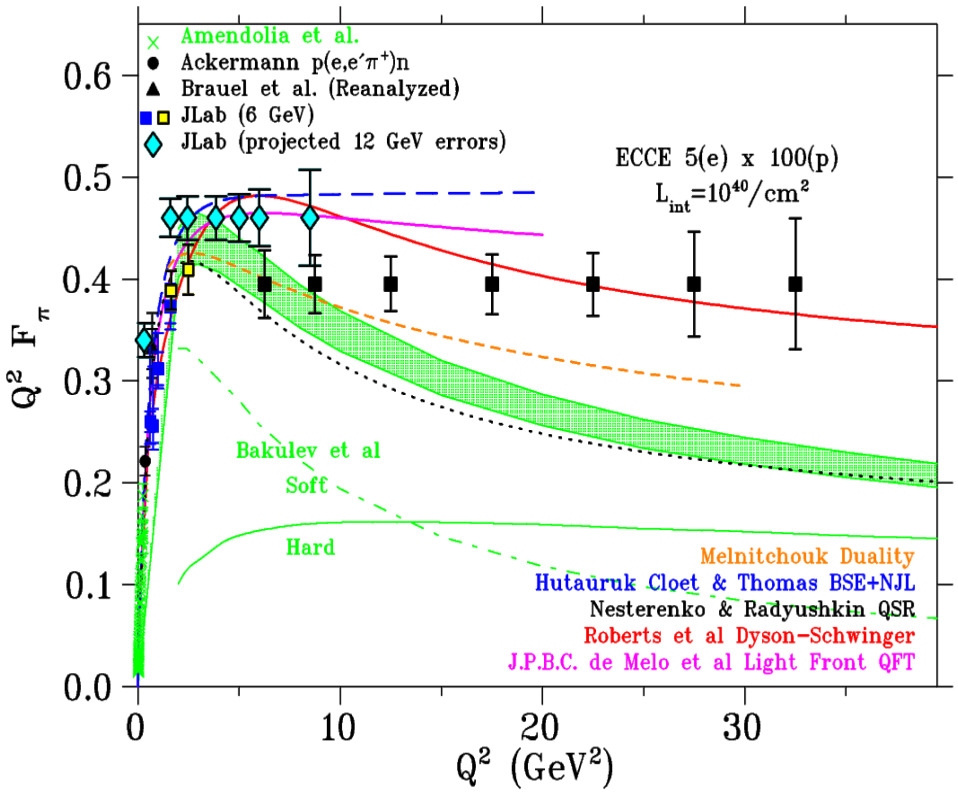
# Pion form factor as probe of emergent mass generation in hadrons

- Electromagnetic form factors of charged pion ($F_\pi$) and kaon ($F_K$) are rich source of insights into the roles played by confinement and Dynamical Chiral Symmetry Breaking in fixing the hadron's size, mass, defining the transition from strong- to perturbative-QCD domains
- Regina group pion form factor feasibility simulations were instrumental in establishing importance of EPIC ZDC performance for *t* reconstruction resolution
- Extension to feasibility studies of kaon form factor utilizing far forward detectors is underway at URegina




Projections published in Eur.Phys.J. A **55** (2019) 190 and J.Phys.G **48** (2021) 075106.

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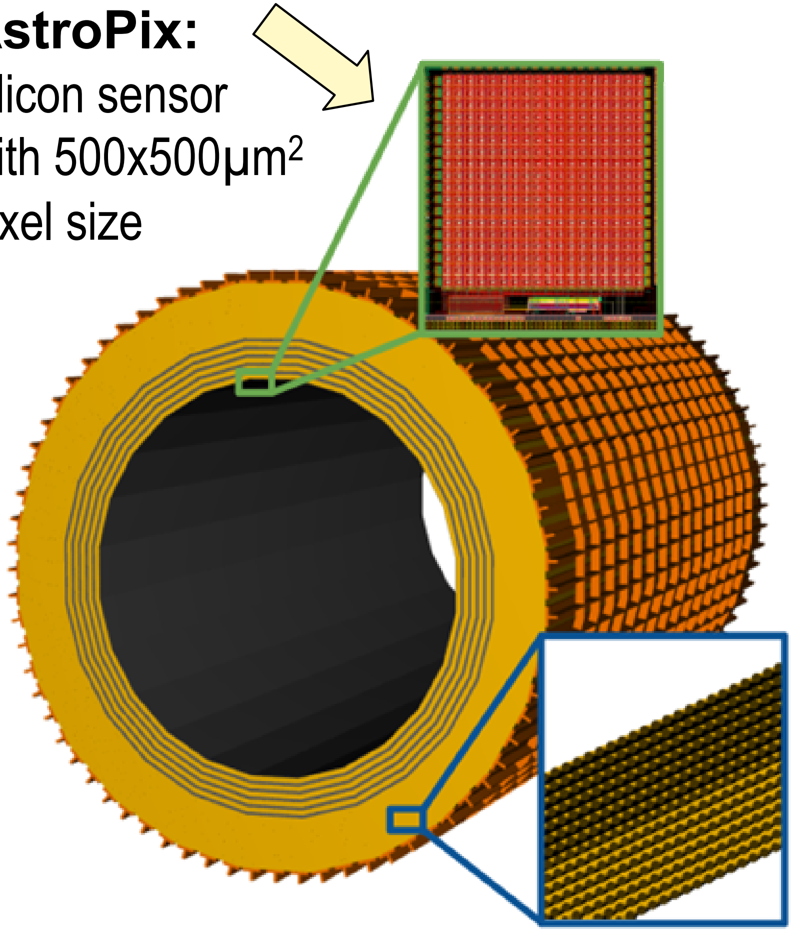
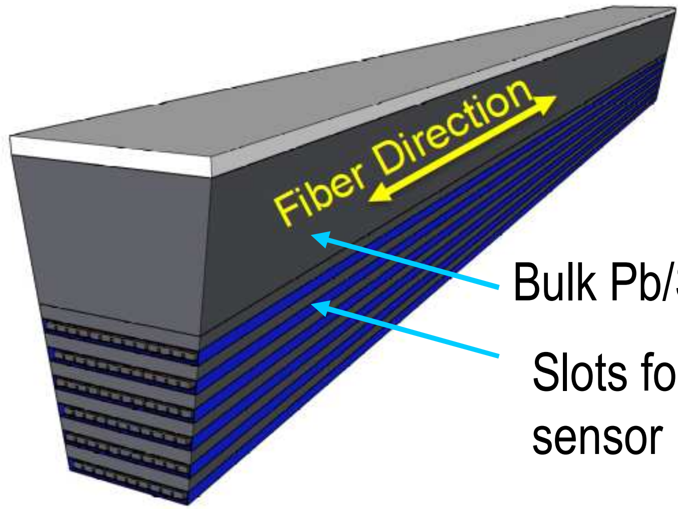
# Barrel Electron Calorimeter (bECAL)

Energy resolution – Primarily from Pb/SciFi layers (+ Imaging pixels energy information)
Position resolution – Primarily from Imaging Layers (+ 2-side Pb/SciFi readout)

**AstroPix:**
silicon sensor
with 500x500μm$^2$
pixel size






Bulk Pb/SciFi section

Slots for AstroPix
sensor layers

**Inner:** interleaved layers of imaging Si sensors with PbSciFi (SFIL – SciFi imaging layers)

**Outer:** bulk Pb/SciFi section

**SciFi Layers**
with two sided
SiPM readout

48 sectors:
- Bulk at Argonne Nat. Lab.
- SFIL at UManitoba

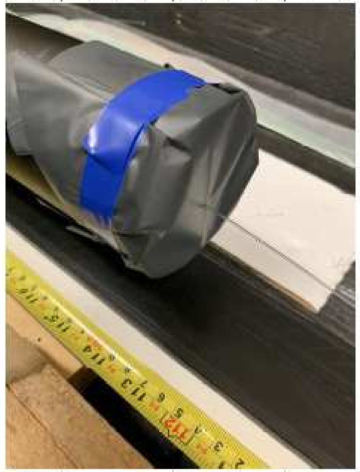
Slide by:
Z. Papandreou
(URegina)

Garth Huber huberg@uregina.ca

# bECAL Fiber Measurements

## Photodiode Station


## Npe Station (soon)



90Sr source
SiPM-PMT coinc

URegina students (K. Suresh, S. Oresic) at Jefferson Lab optical fiber beam tests

Slide by: Z. Papandreou (URegina)

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# Development of ePIC Computing Model

Streaming Readout

## The ePIC Streaming Computing Model

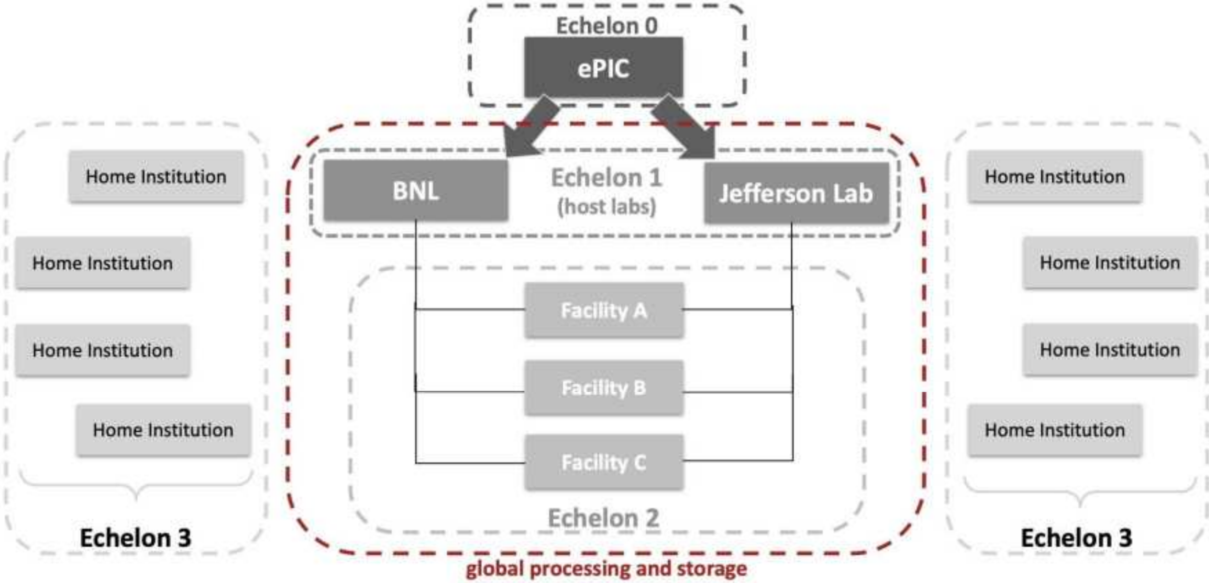
**Four Tiers:**

**Echelon 0**: ePIC Experiment

**Echelon 1**: Host Labs

**Echelon 2**: Global processing and data facilities, includes HPC and HTC resources.

**Echelon 3**: Home institute computing




EIC Canada has held active allocation for 4 years

- ~50-100 core-years/year, 100 TB during proposal and initial ePIC development phase
- Supported majority of EIC simulations until shift to Open Science Grid (where 5k-10k core-years)
- Primary use for EIC Canada researchers and for **international contribution proof of concepts**
  - E.g. Digital Research Alliance of Canada as a first Echelon 2 facility

Digital Research Alliance of Canada | Alliance de recherche numérique du Canada



Slide by: W.Deconinck (UManitoba)

# Potential EIC Accelerator Contributions

- **TRIUMF has discussed in-kind accelerator contributions with EIC Project Office**
  - EIC Accelerator Partnership Workshop organized by TRIUMF in October 2021
- **EIC Partner Workshop identified some areas of TRIUMF interest**
  - Superconducting RF (SRF), e.g. crab cavities for HL-LHC
    - Would enable reaching the highest luminosity with the EIC
    - Starting design of 394 MHz crab cavities and cryomodules (these are not the "big" crab cavities)
  - Spin/beam dynamics calculations
    - To enable highest polarization even at high luminosity
  - Magnet technologies
    - Kicker systems in ring
  - Pulsed Power Systems
    - Collaborating with ANL on Fast Pulsed HV Systems
  - Project preparation document (PPD)
- **New Collaborators Welcome!**

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# Summary

- **The best summary is provided by the main findings of the National Academy of Sciences 2018 study:**
- 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?
- The committee concludes that an EIC is timely and has the support of the nuclear science community. The science that it will achieve is unique and world leading.
- **The EIC is an exciting opportunity for the next generation of physicists** (expected program: 2030-2060)

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