EIC Canada

Canadian Contributions to a Major New DOE Facility

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Mount Allison University
Sackville, NB
CANADA

59th International Winter Meeting on Nuclear Physics
Bormio, Italy
24 January 2023

Mount Allison
UNIVERSITY

NSERC
CRSNG

New Brunswick, CANADA

Where is New Brunswick?

One of 4 Atlantic Provinces

<u>New Brunswick</u>

Population: 780,000
Area: 72,908 km^2

English and French

Lobster, Lumber, and High Tides

Where is Sackville?

<u>Sackville</u>

Population: 8,500
Latitude: 46° N

Mount Allison University:

- 2,200 students
- Undergrads only

Bay of Fundy

Highest tides in the world — 16 m!

$\tau \approx 12.5 - 12.7$ h
Bay

$N_2 \approx 12.66$ h
Moon

Special thanks to:

Garth Huber (Regina)

Wouter Deconinck (Manitoba)

Abhay Deshpande (Stony Brook)

for providing figures and slides.

Electron-Ion Collider Collaboration Canada

University of Manitoba

- Wouter Deconinck
- Michael Gericke
- Juliette Mammei
- Savino Longo

University of Regina

- Garth Huber
- Zisis Papandreou

Mount Allison University

- DLH

TRIUMF

Also presently 4 PDFs, 14 grad students, and one undergrad.

Collaboration is growing!

EIC User Group

- 31 members from Canada, including theoretical, experimental, and accelerator physicists.
- 7 institutions from Canada.
- 8th largest country by member count
- Deconinck elected as international representative on global Steering Committee (2020–2021).

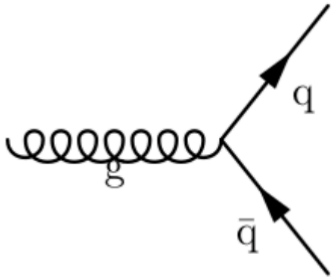
Outline

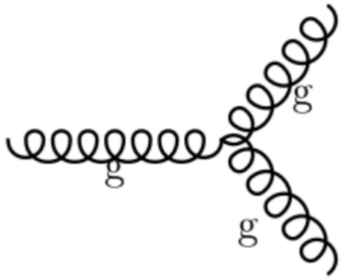
- Scientific Motivation
- Proposed EIC Facility
- Canadian Contributions and Physics Program
- Summary

Non-linear Structure of QCD: Fundamental Consequences

Quark (colour) confinement:

Consequence of non-linear gluon self-interaction
Unique property of the strong interaction.
Makes calculations very challenging.





Strong Quark-Gluon interactions:

Confined motion of the quarks and gluons. Transverse Momentum-Dependent Parton Distributions — TMDs.
Confined spatial correlations of quark and gluon distributions. Generalized Parton Distributions — GPDs.

Ultra-dense colour (gluon) fields.

Is there a universal many-body structure due to ultra-dense colour fields at the core of **all** hadrons and nuclei?

Emergent Dynamics in QCD

Quarks and gluons are kind of a big deal…

Massless gluons, and 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 occurs remains a mystery…*

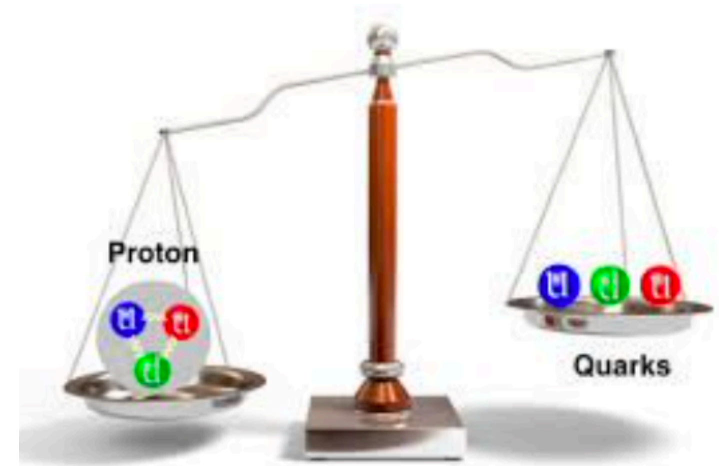
Experimental insight and guidance are crucial for complete understanding of how hadrons and nuclei emerge from quarks and gluons.

Scientific Motivation for the EIC

The EIC hopes to shed some light on **three important questions:**

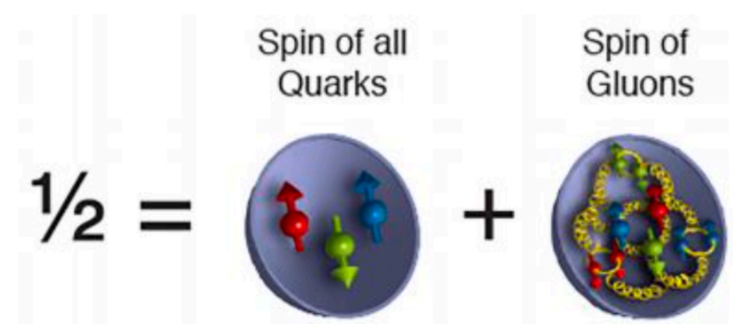
1. How does the **mass of the nucleon** arise?

   While the Higgs mechanism can explain all of the mass of the electron, it accounts for only a small part of the mass of the proton and neutron.



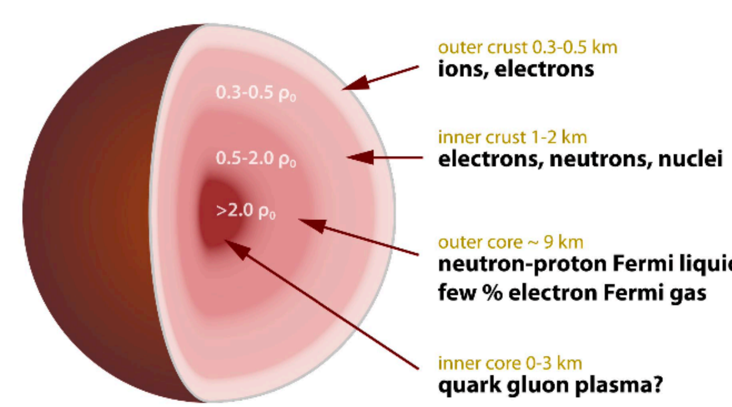
2. How does the **spin of the nucleon** arise?

   Three spin-1/2 quarks, bound by gluons, each with angular momentum, form a spin-1/2 proton.



3. What are the **emergent properties of dense systems of gluons**?

   How does nuclear matter behave at extremely high densities found in astrophysical systems?



Proton Mass $m_p \approx 938$ MeV/c^2

Proton constituents: $2\ u$ quarks $\rightarrow\ 2 \times 3$ MeV/c^2 ≈ 6 MeV/c^2

$1\ d$ quark $\rightarrow\ 1 \times 6$ MeV/c^2 ≈ 6 MeV/c^2

Total quark mass in proton: 12 MeV/c^2 !

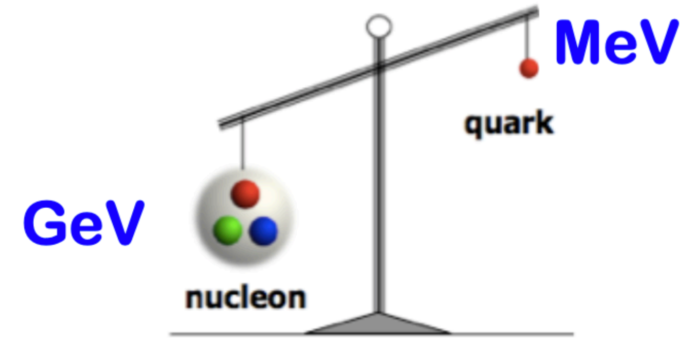
Where does the proton's mass come from?!

It's incorporated in the binding energy associated with the gluons!

99% of our mass comes from the quark-gluon interactions in the nucleon.

VERY COMPLEX SYSTEM!

Understanding Nucleon Mass



Relativistic motion

χ symmetry breaking

Quantum fluctuation

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

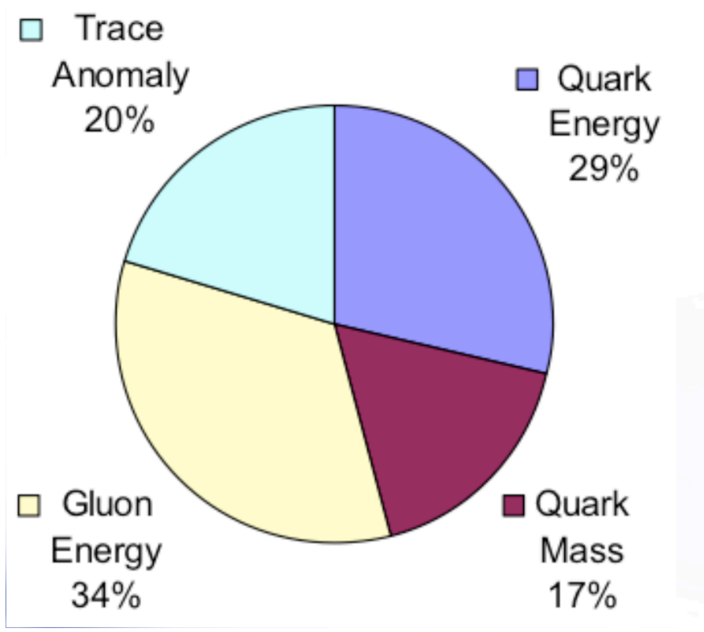
Quark energy

Gluon energy

Quark mass

Trace anomaly

Preliminary Lattice Results



"... 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 DOE 2015 Long Range Plan for Nuclear Science

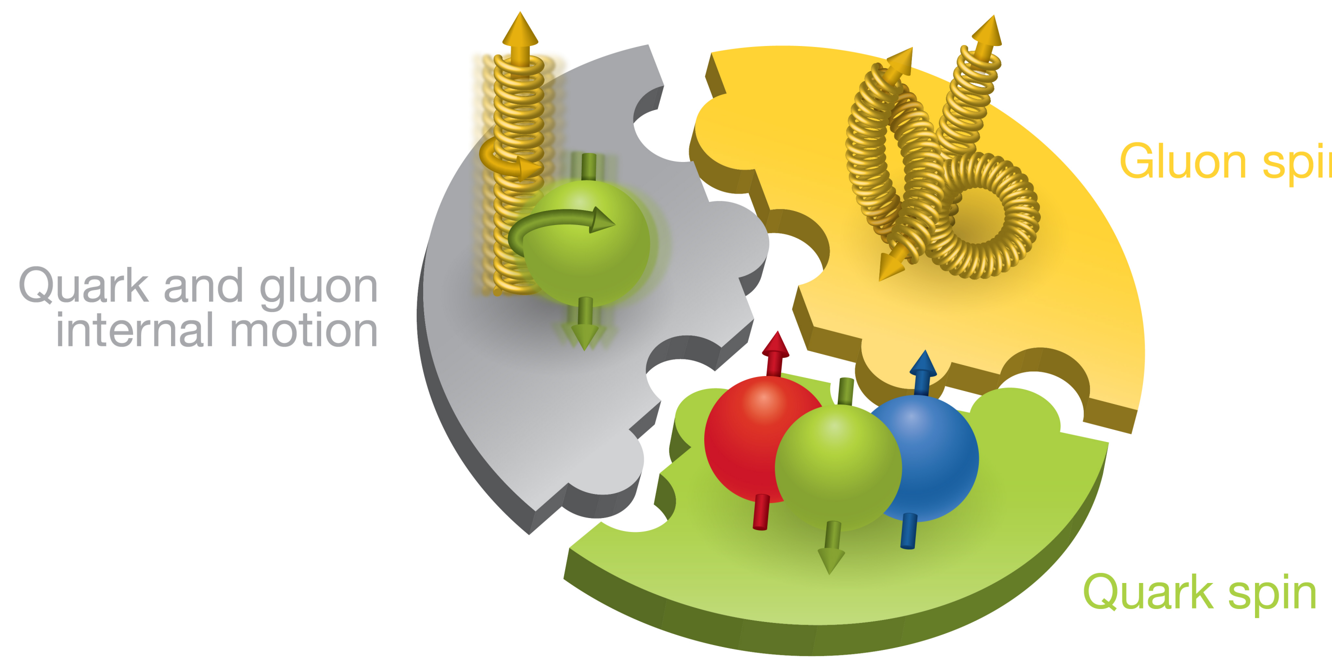
EIC:

- Trace anomaly via Υ production near threshold
- Quark-Gluon energy from q-g momentum fractions

Proton Spin

"Helicity sum rule"

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark spin}} + \underbrace{\Delta G}_{\text{gluon spin}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$



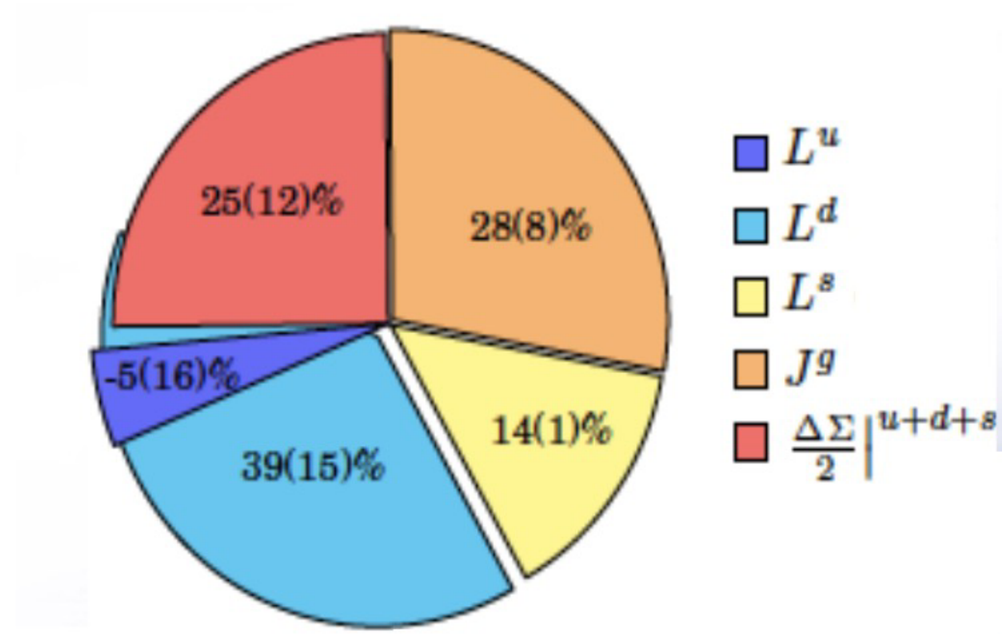
Spin and Lattice: Recent Activities

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, PRD **91**, 014505 (2015).



EIC: Precise determination of polarized PDFs of quark sea and gluons. → Precision $\Delta\Sigma$ and ΔG

Magnitude of $\sum_q L_q^z + L_g^z$

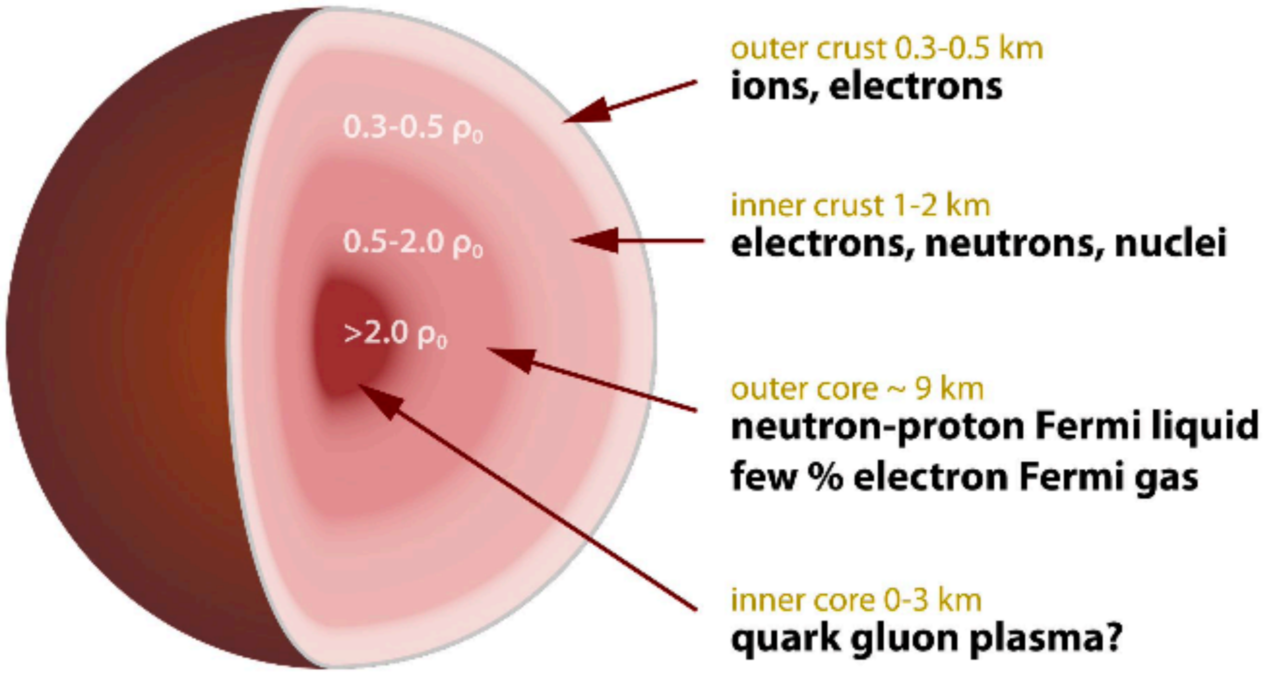
Emergent Properties of Dense Systems of Gluons

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?

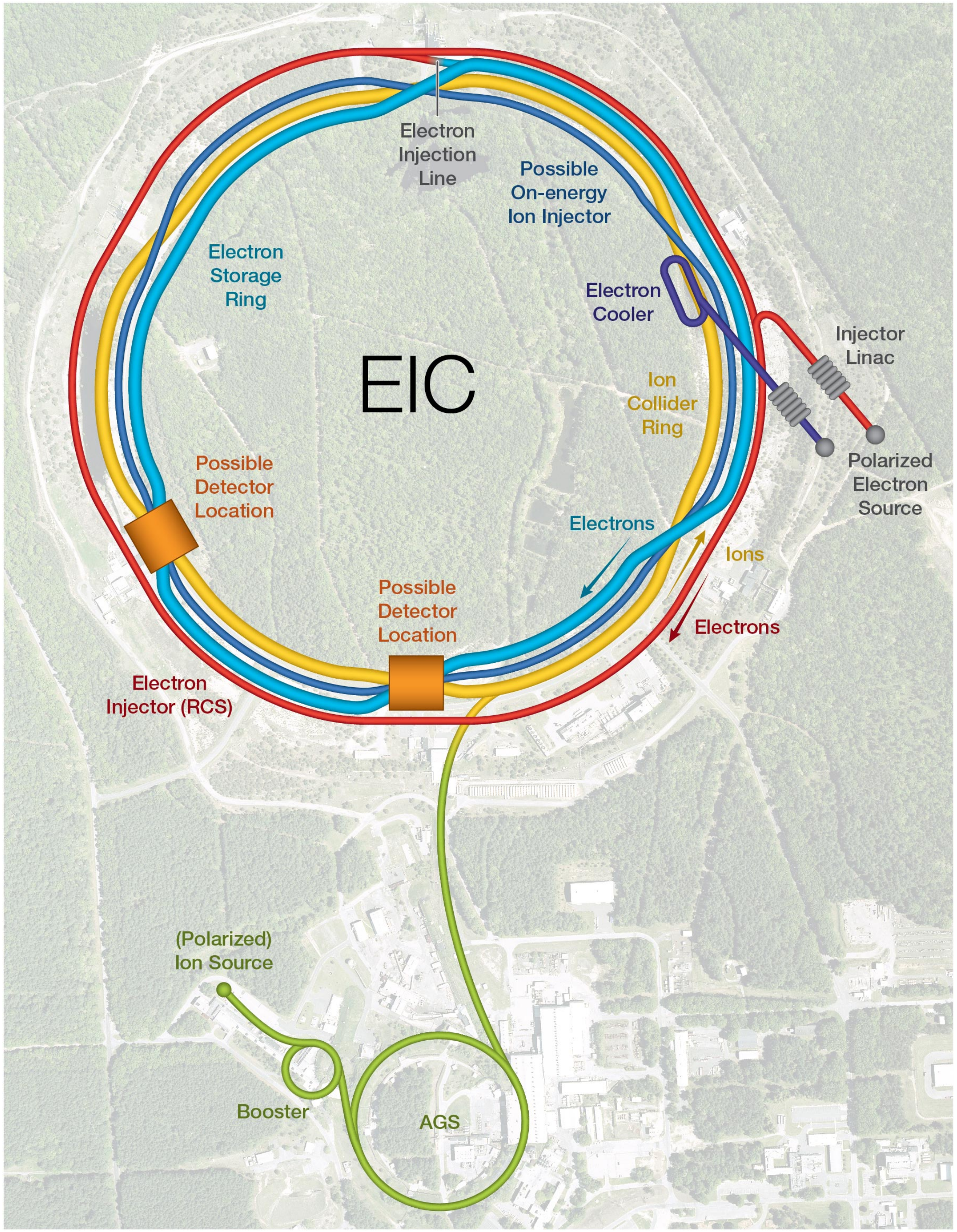
EIC:

C.M. energy
High luminosity



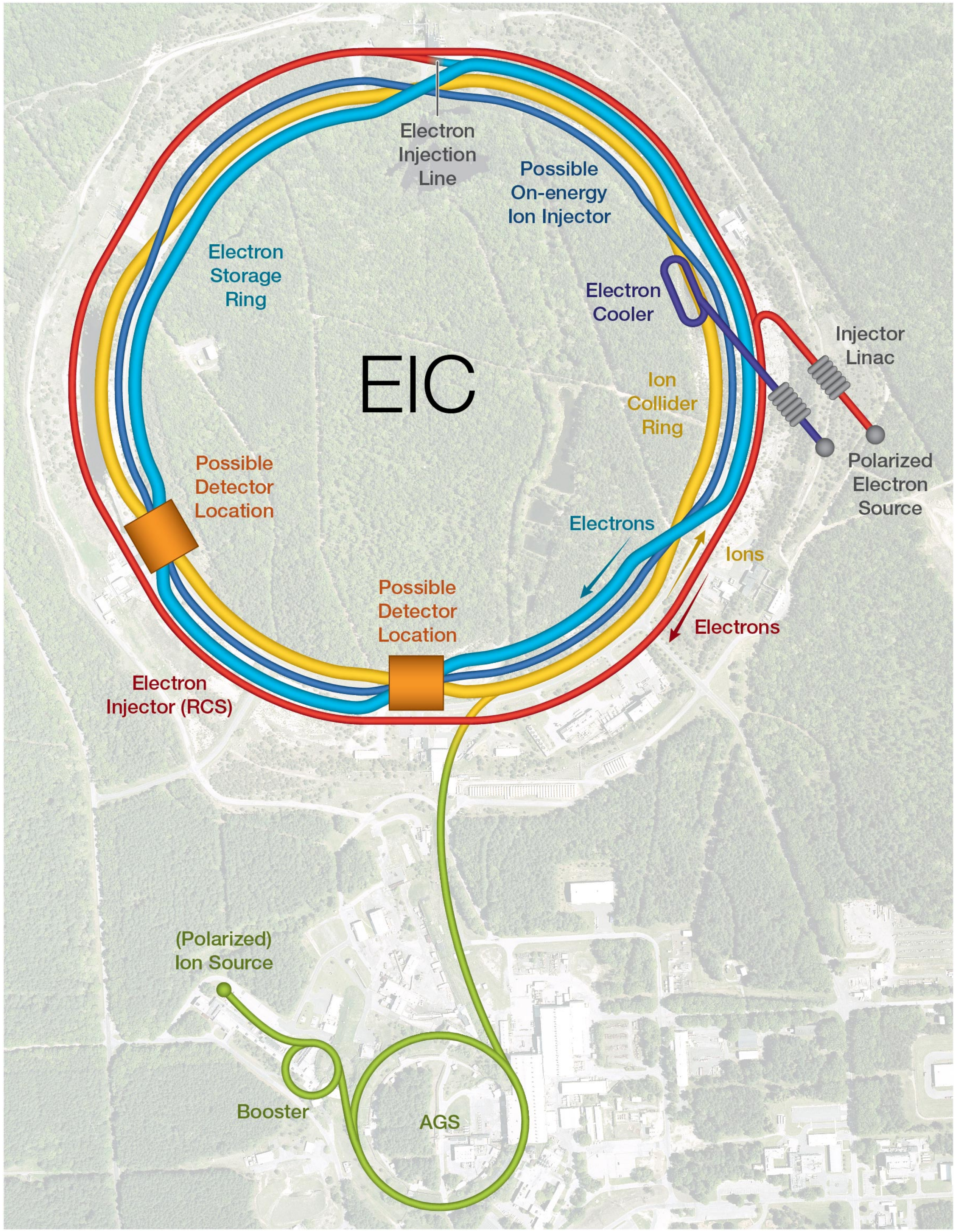
What is the Electron-Ion Collider?

- **First major collider** to be built in North America in the 21st century.
  - **Polarized electrons:** 10–20 GeV
  - **Polarized light ions:** (p, d, ^{3}He) and unpolarized nuclei → U, 50–250 GeV
  - C.M. energy of $\sqrt{s} = 28 - 140$ GeV
  - **High luminosity** $10^{33} - 10^{34}$ cm^{-2}s^{-1}
  - 2nd interaction region possible
- International facility with estimated cost of about US$2B
- Large community of 1000+ users at 220+ institutions in 30+ countries
- Site: BNL on Long Island, NY.

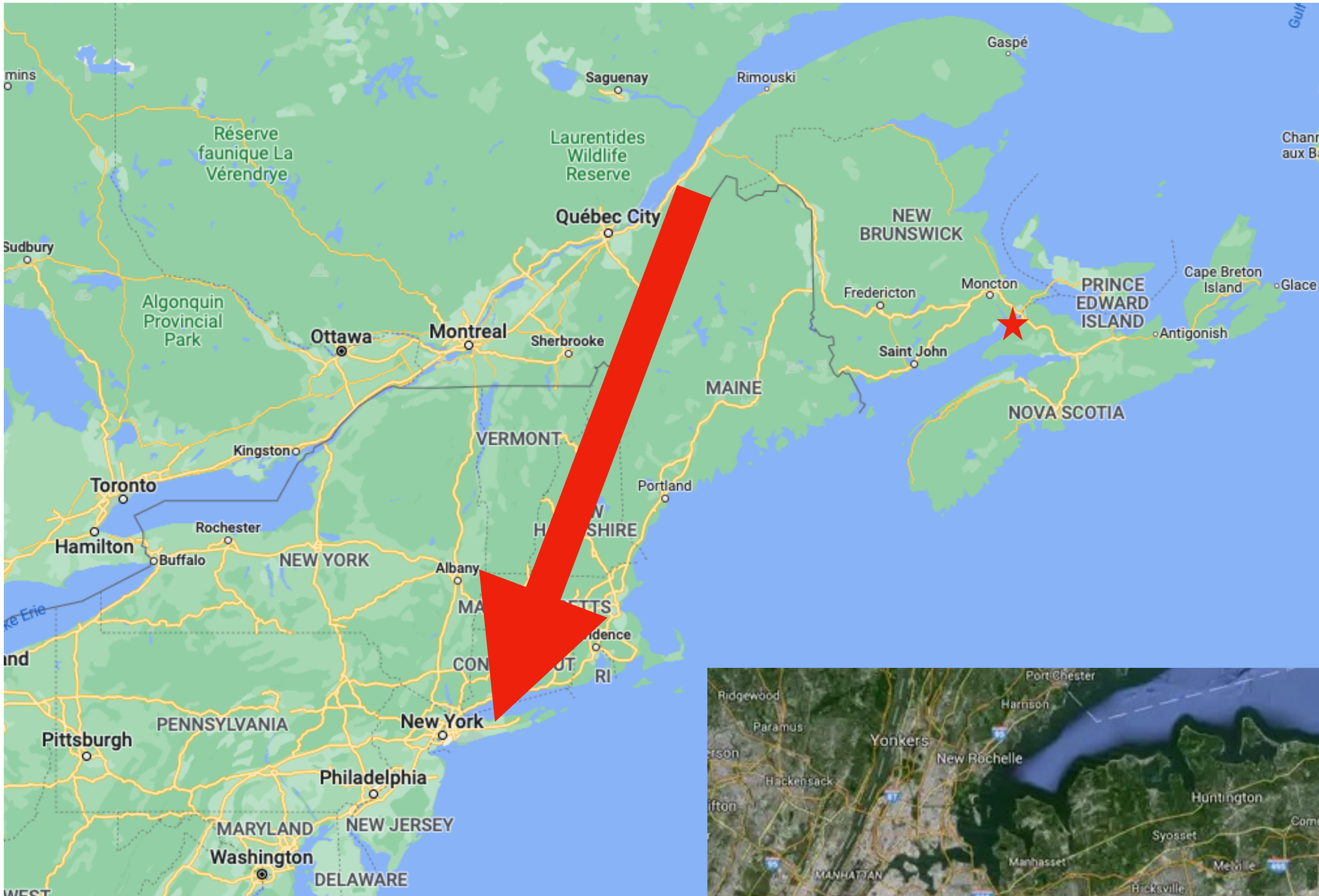


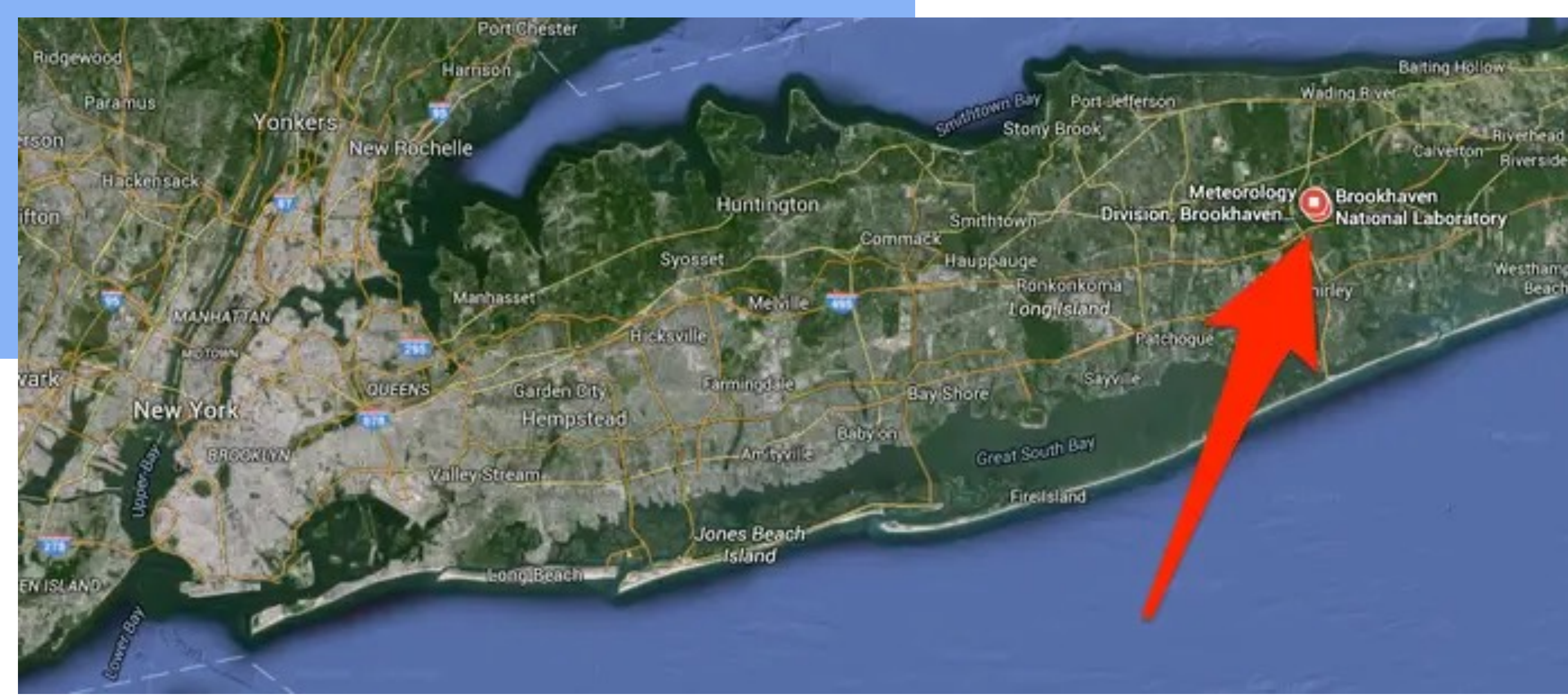
What is the Electron-Ion Collider?

- Make use of existing Relativistic Heavy Ion Collider (RHIC).
- Existing tunnel, detector halls, hadron injector complex (AGS).
- Build new 20-GeV electron linac and add high-intensity 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.



Brookhaven National Laboratory



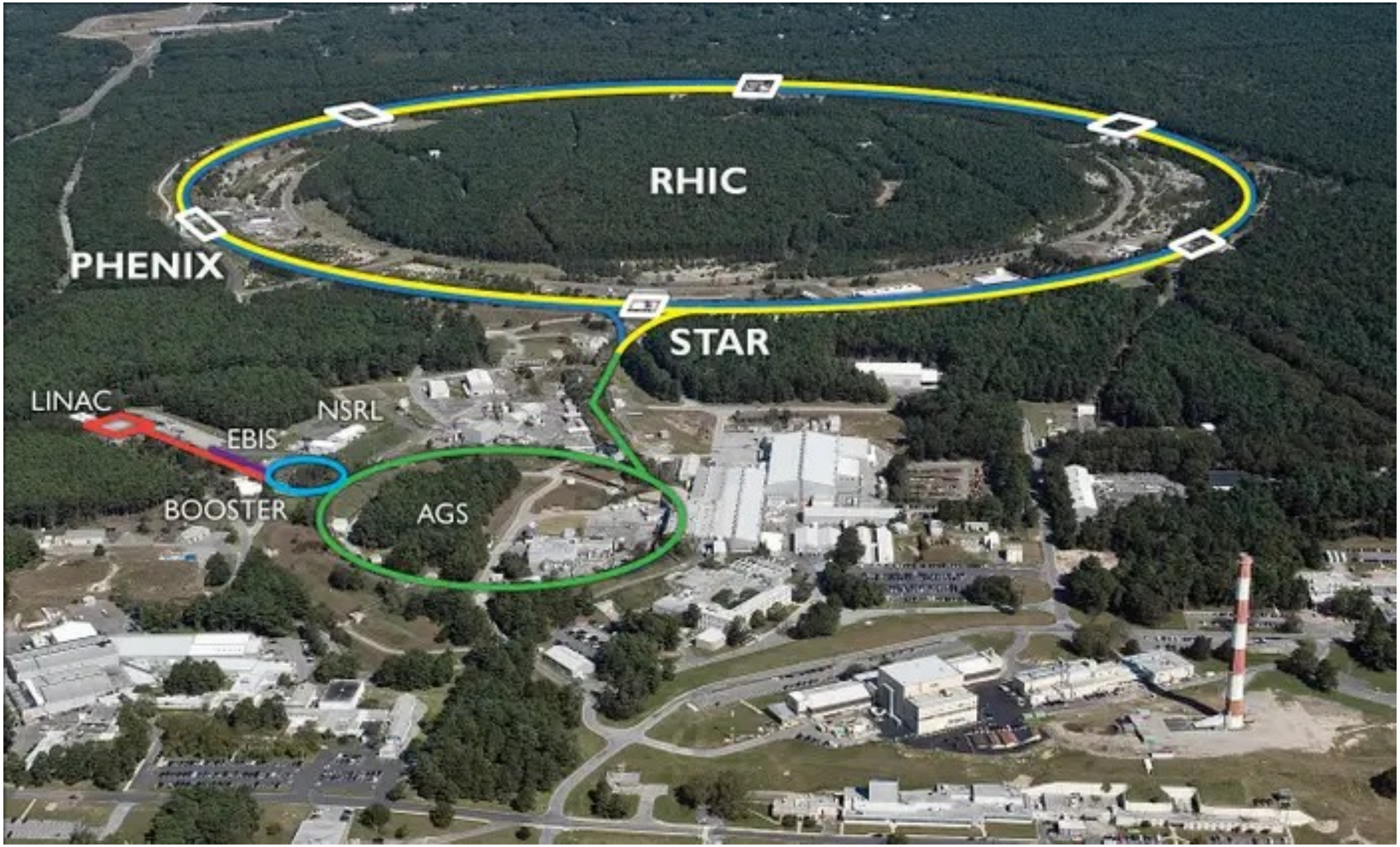


Upton, NY on
Long Island

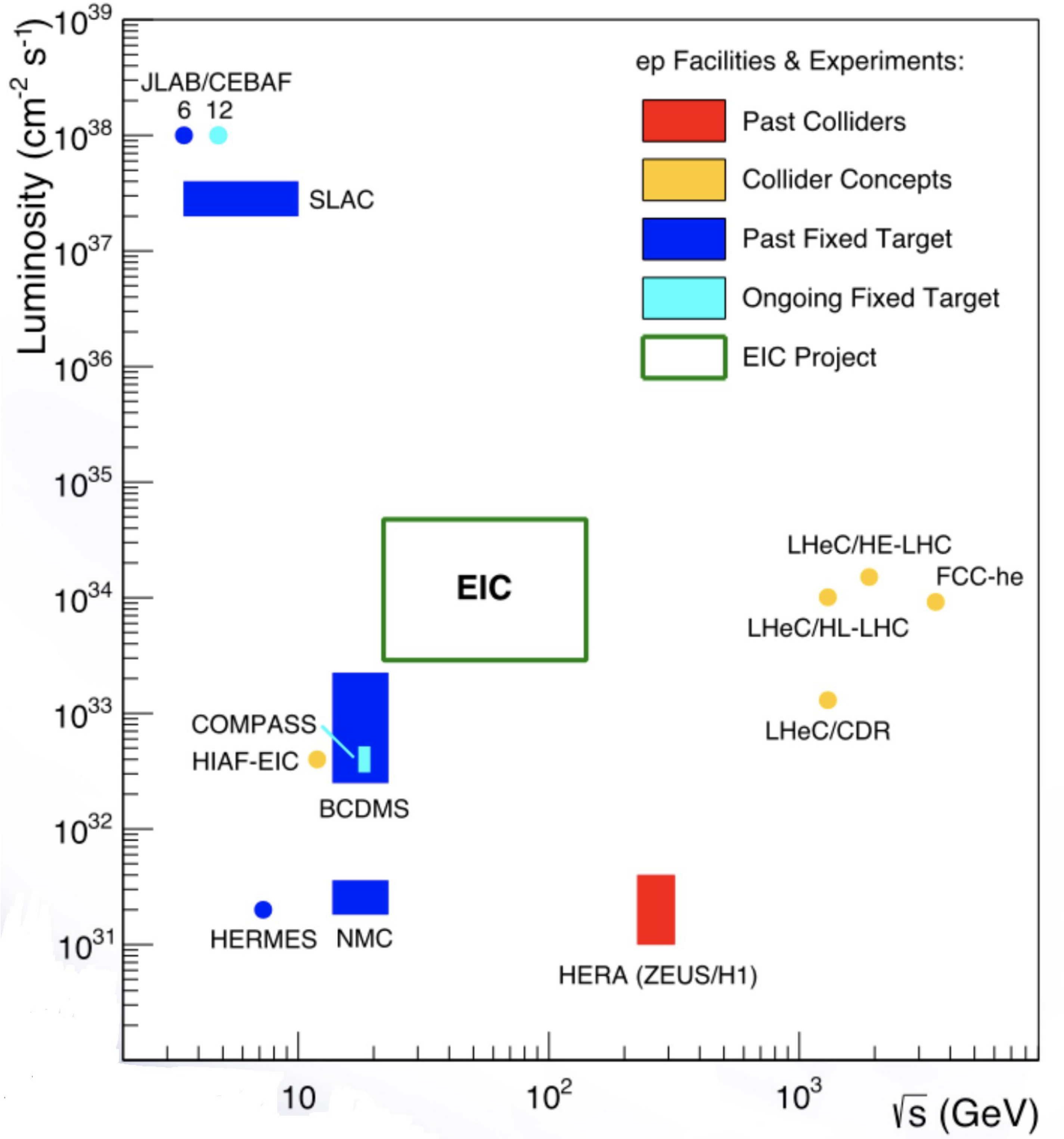
1100 km from Sackville by car…

Brookhaven National Laboratory

Existing Infrastructure



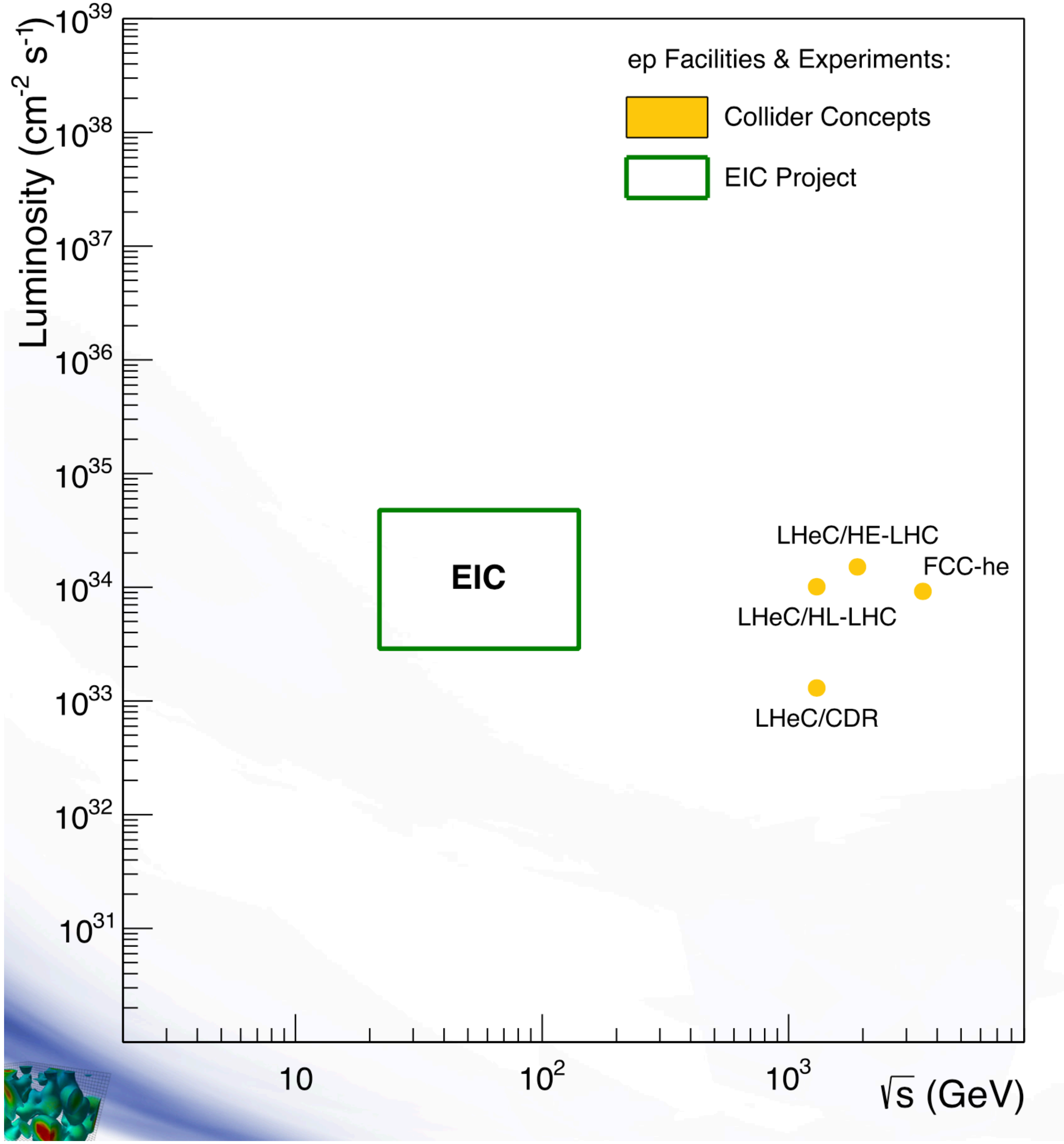
EIC Compared to other DIS Facilities



All DIS Facilities in the world.

DIS — Deep Inelastic Scattering

EIC Compared to other DIS Facilities



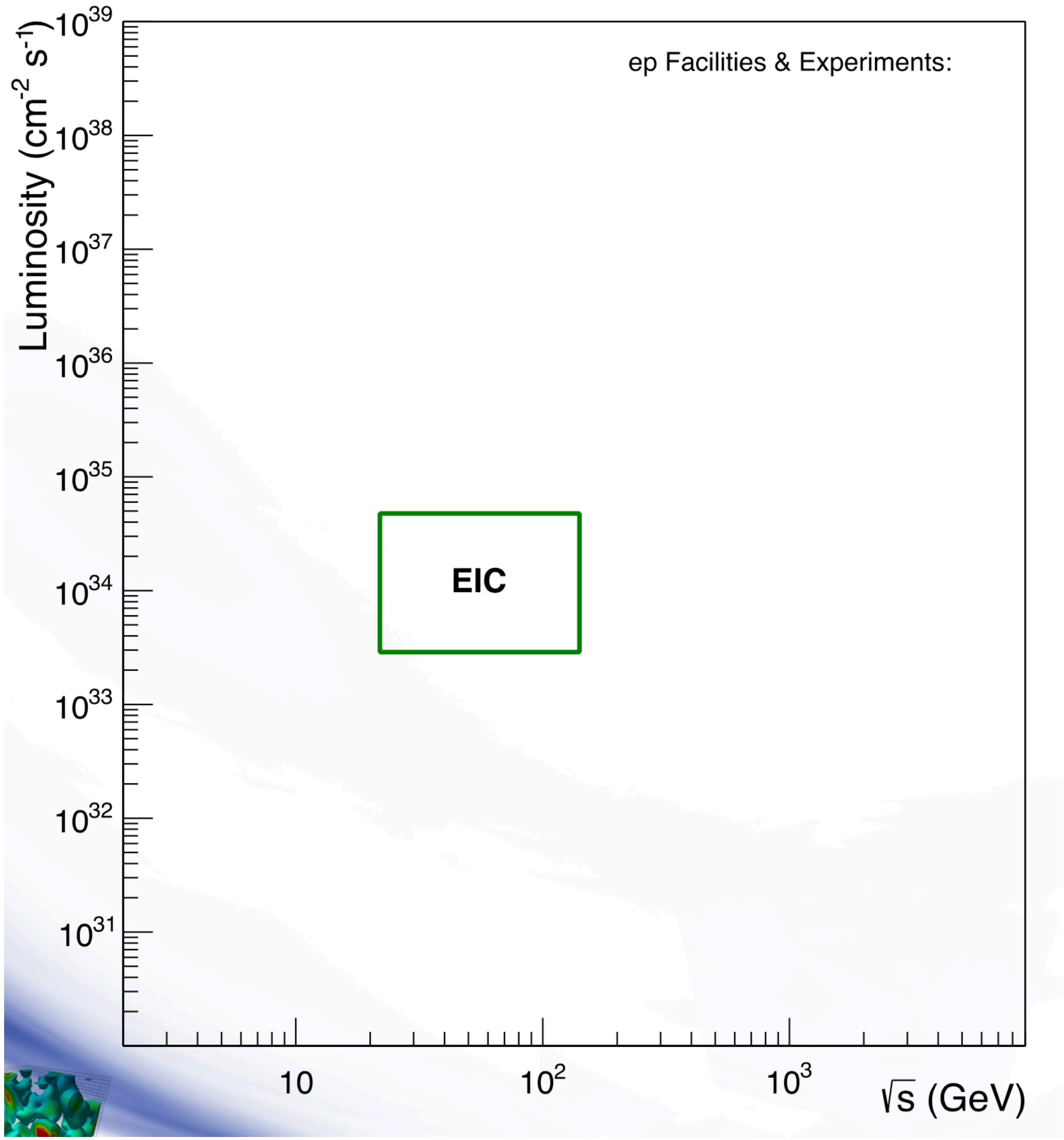
All DIS Facilities in the world.

However, if we ask for:

1. high luminosity and wide range of $\sqrt{s}$

DIS — Deep Inelastic Scattering

EIC Compared to other DIS Facilities



All DIS Facilities in the world.

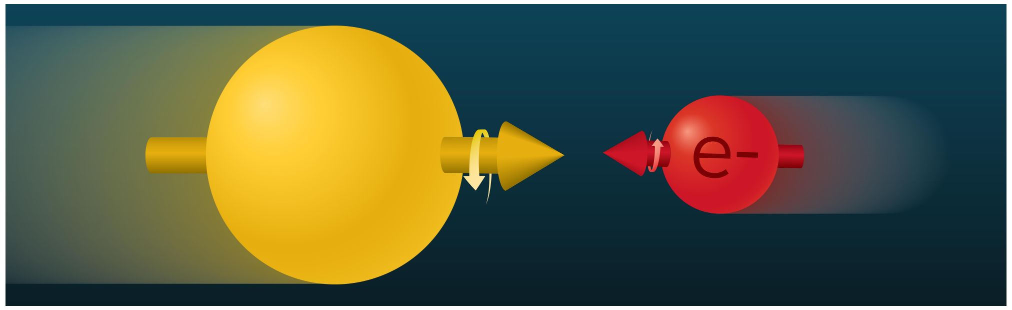
However, if we ask for:

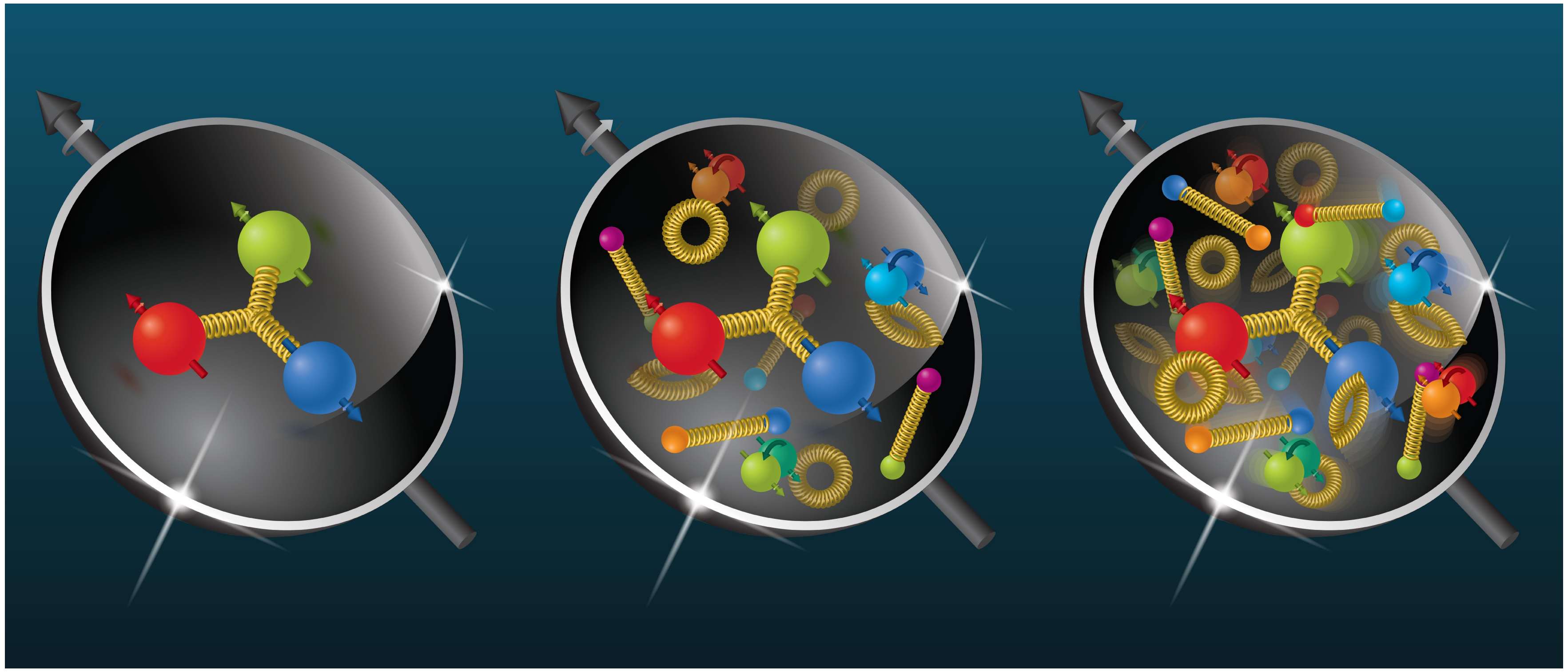
1. high luminosity and wide range of $\sqrt{s}$
2. polarized lepton and hadron beams
3. nuclear beams

EIC is unique!

DIS — Deep Inelastic Scattering

The World's First Polarized Electron-Proton Collider





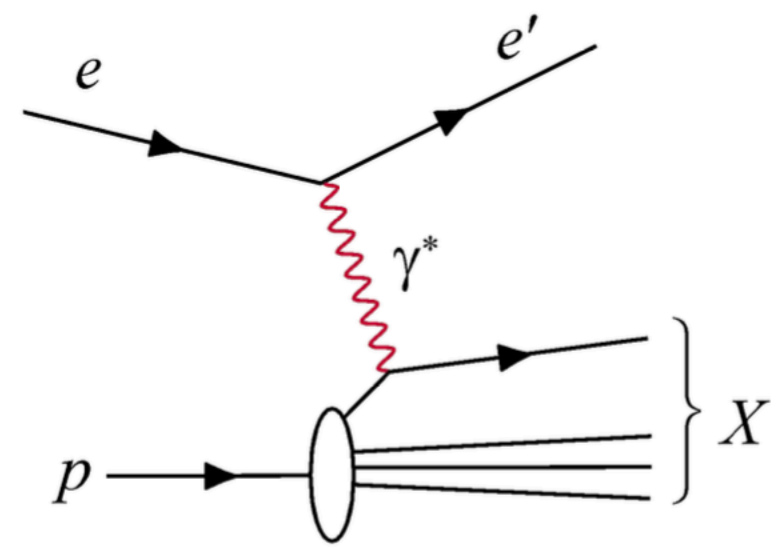
Polarized proton as a laboratory for QCD

How are the sea quarks and gluons — and their spins — ***distributed in space and momentum*** inside the nucleon?

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

Accessing Quarks in Electron-Ion Collisions

Key variables x and Q^2 in DIS



Four-momentum transfer of the virtual photon

$$Q^2 = -q^2 = -(k-k')^2$$ resolution of probe

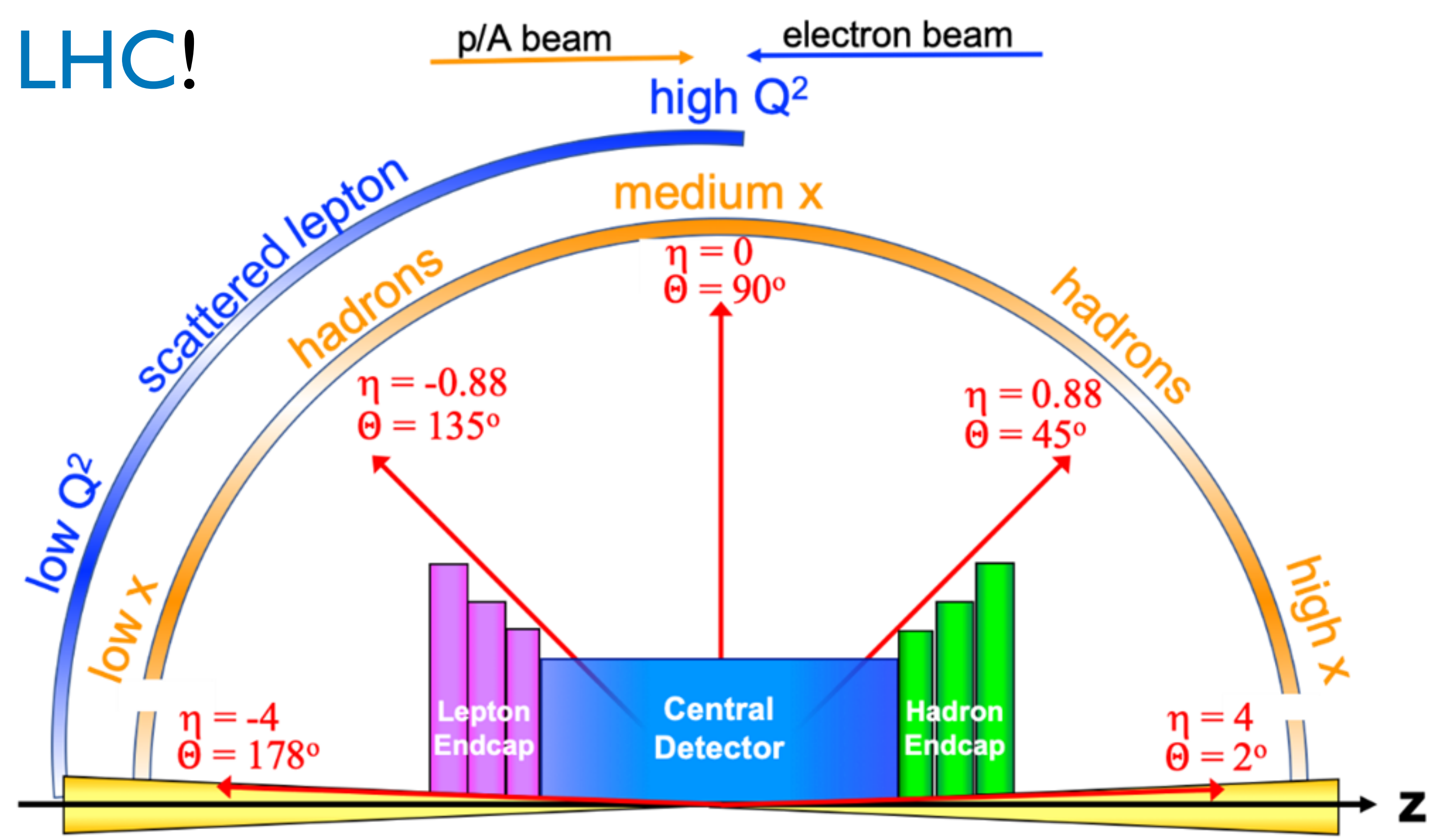
Momentum fraction of struck quark x

Asymmetric reaction unlike pp at LHC!

Electrons in backward direction

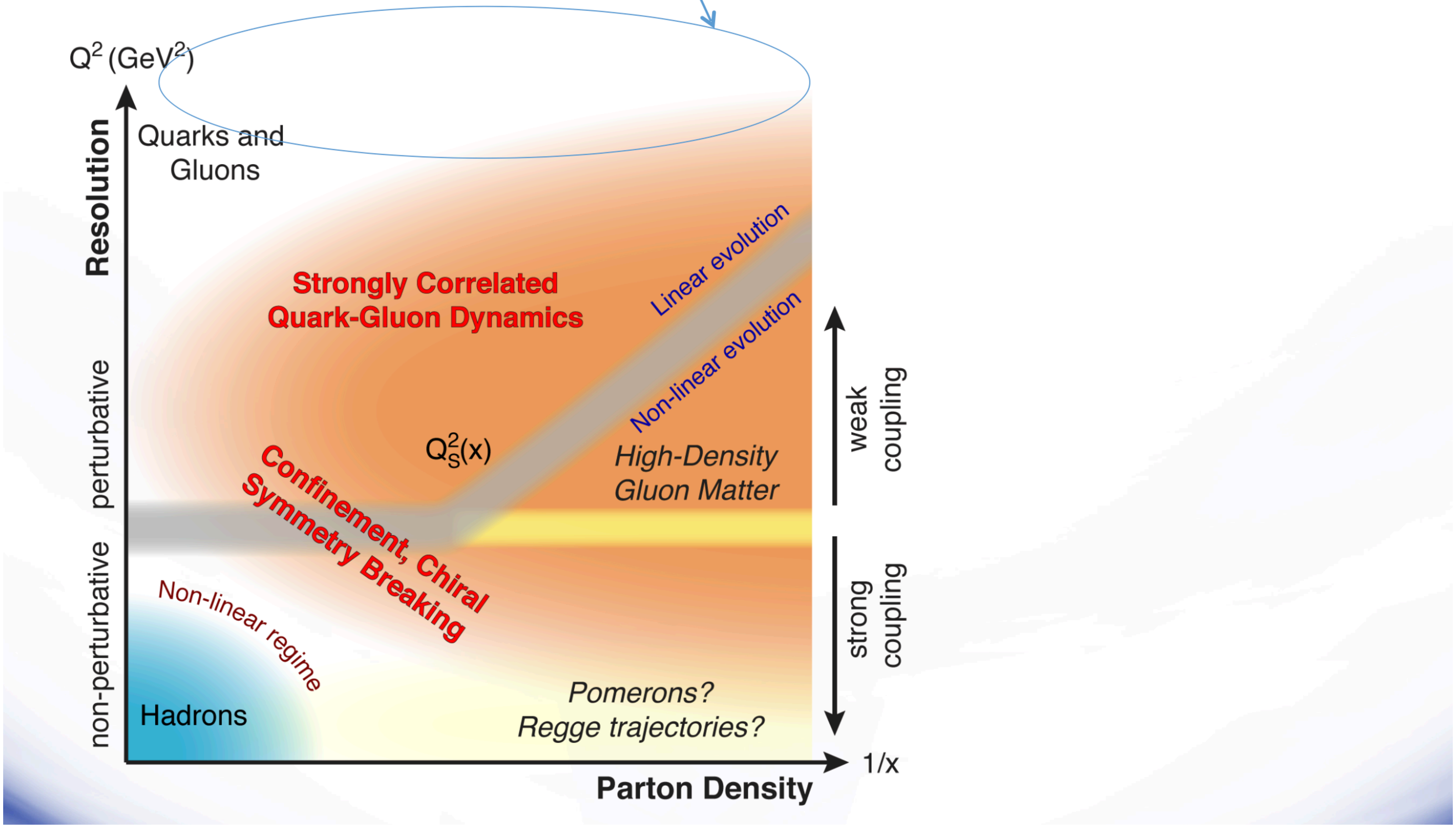
Hadrons go in every direction

Need excellent e^-/π^- separation



QCD Landscape Explored by EIC

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



QCD Landscape Explored by EIC

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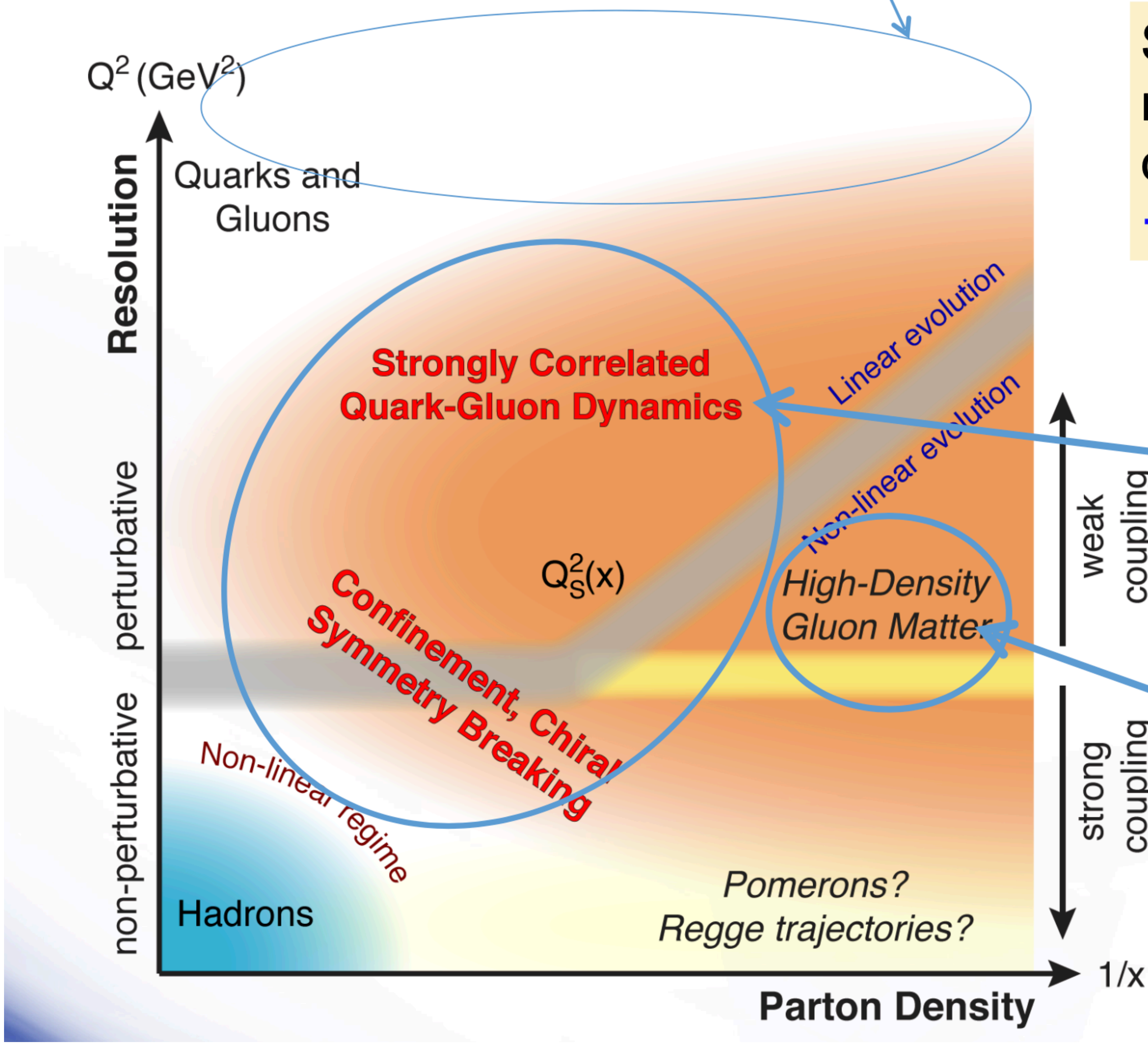
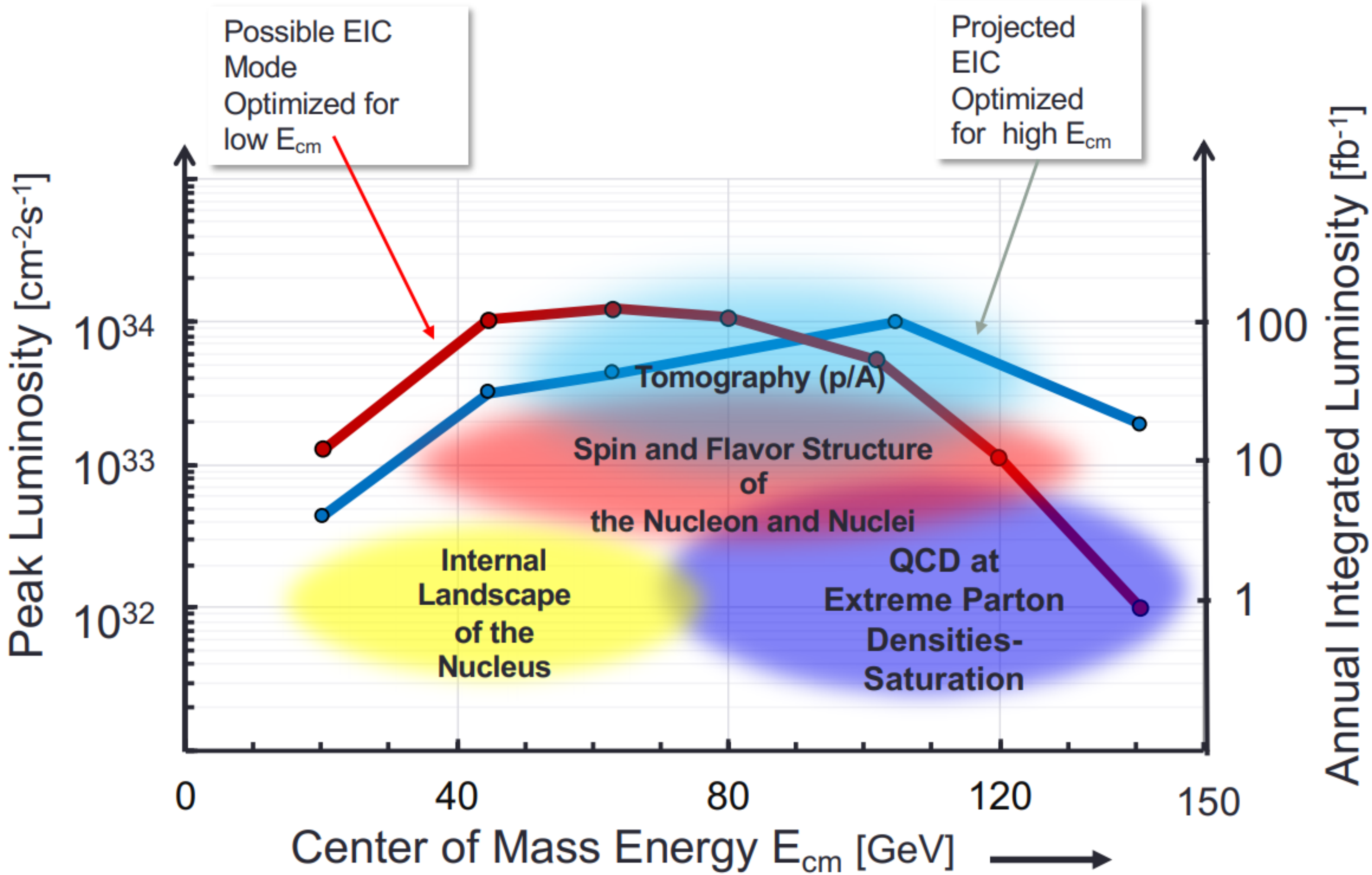


Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

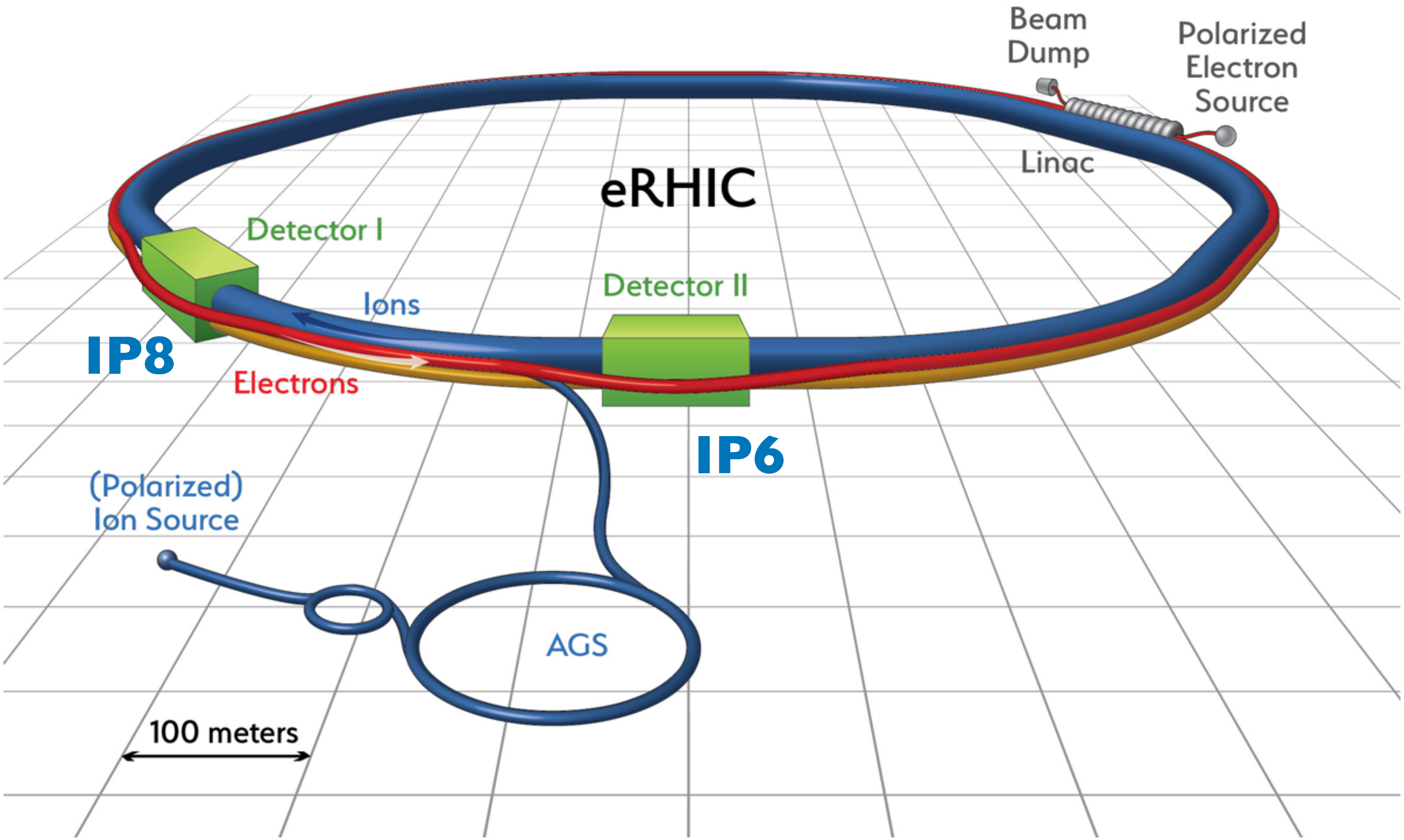
EIC systematically explores correlations in this region.

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

QCD Landscape Explored by EIC



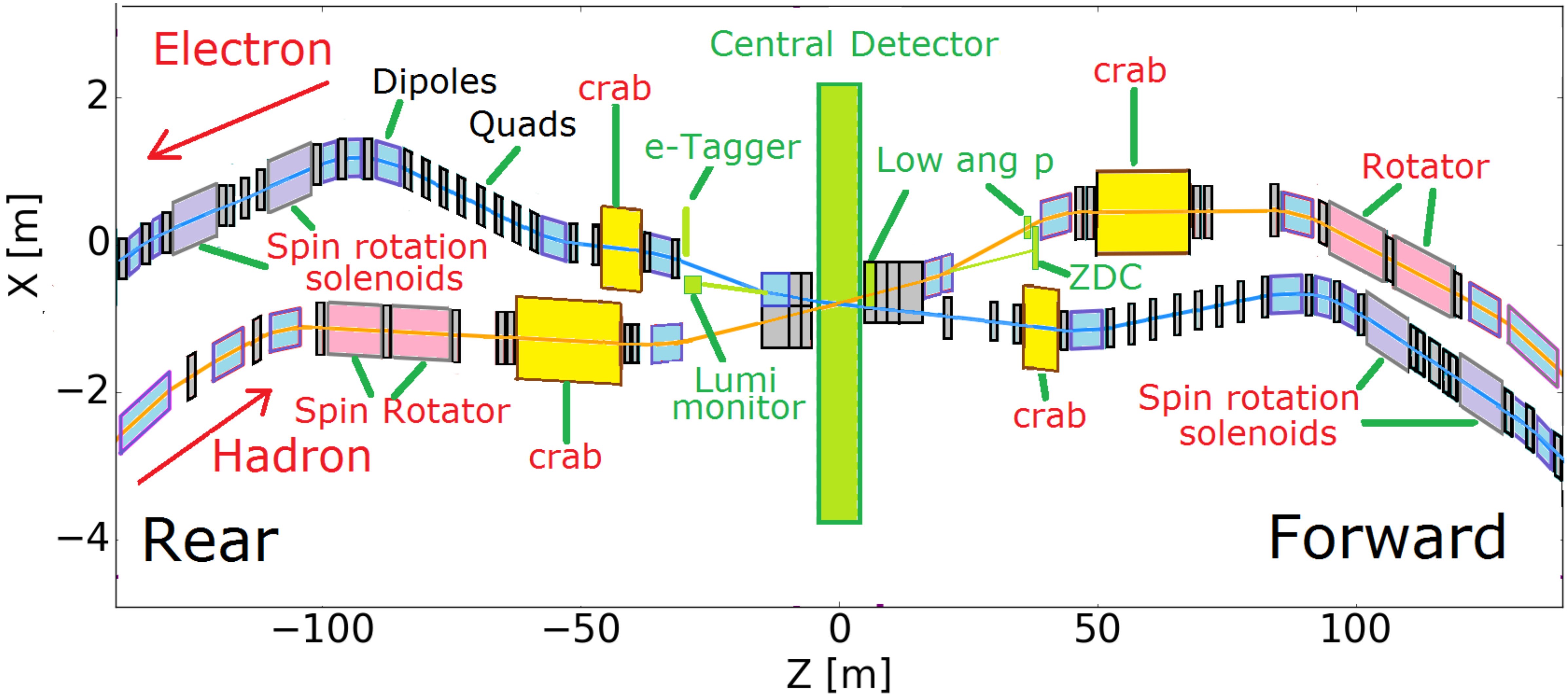
eRHIC Proposal



IP = Interaction Point
6 = 6 o'clock
8 = 8 o'clock

A detector is presently envisioned at only one IP but a second is possible.

Interaction Region

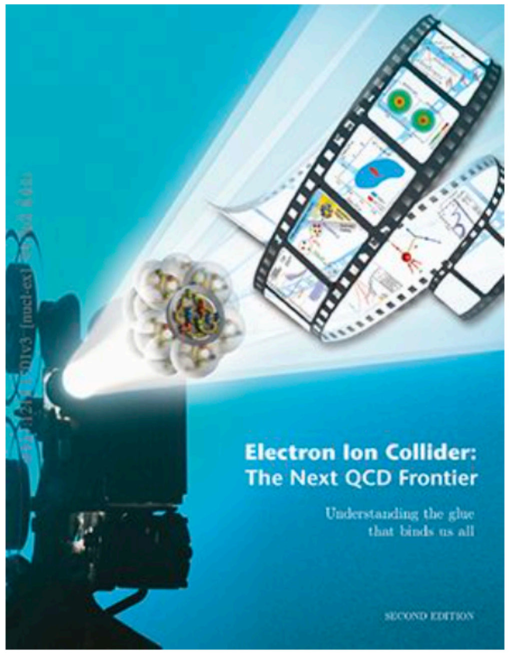


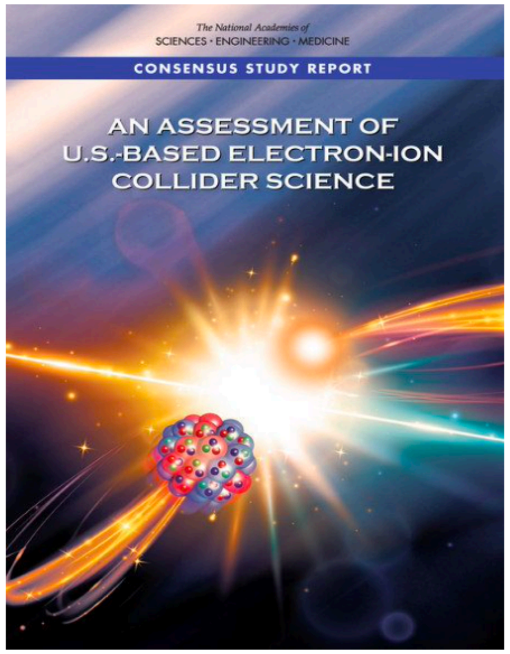
Reactions take place where the ***e*** and ***p/A*** beams cross.

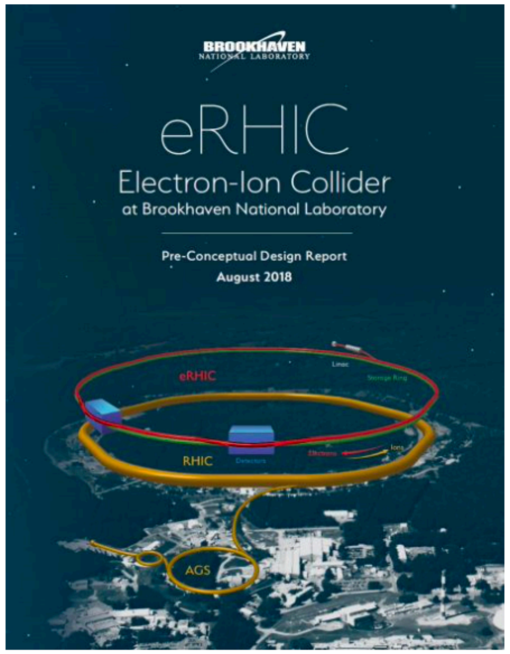
Crossing angle is an important consideration in simulations.

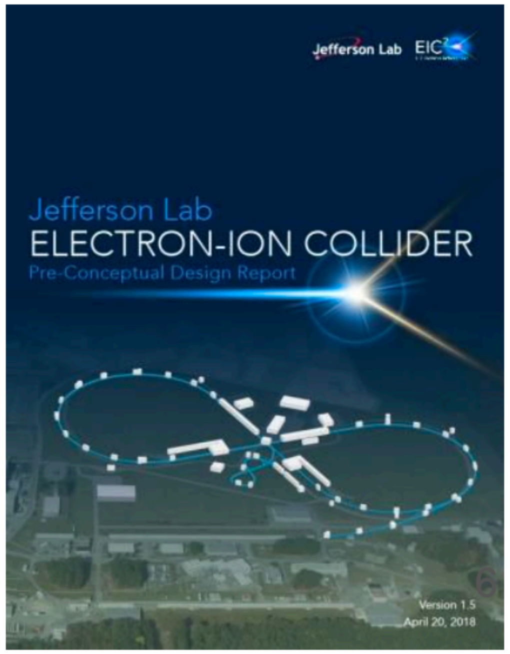
EIC Milestones

- **2012:** Community White Paper.
- **2018:** Nat. Acad. of Sci., Eng., and Med., An Assessment of U.S.-Based Electron-Ion Collider Science.
- **2018:** Two pre-conceptual design reports.
- **2019:** U.S. DOE Critical Decision 0 (CD-0, approval of mission need, project start).
- **2020:** Site selection of Brookhaven National Lab.
- **2020:** Yellow Report to advance the state and detail of physics studies and detector concepts.
- EIC project as partnership between two labs: **Brookhaven National Lab** and **Jefferson Lab.**

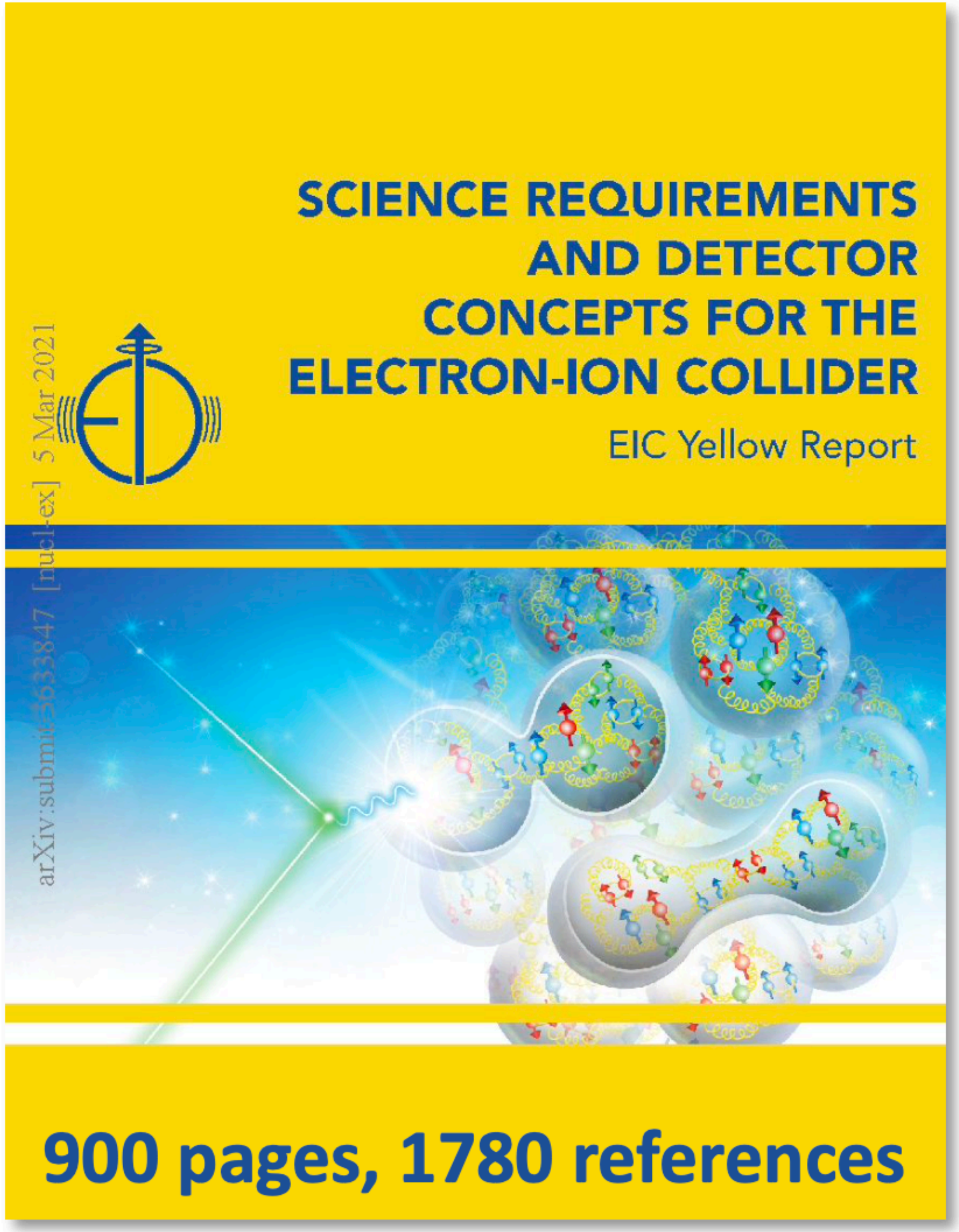








EIC Milestones



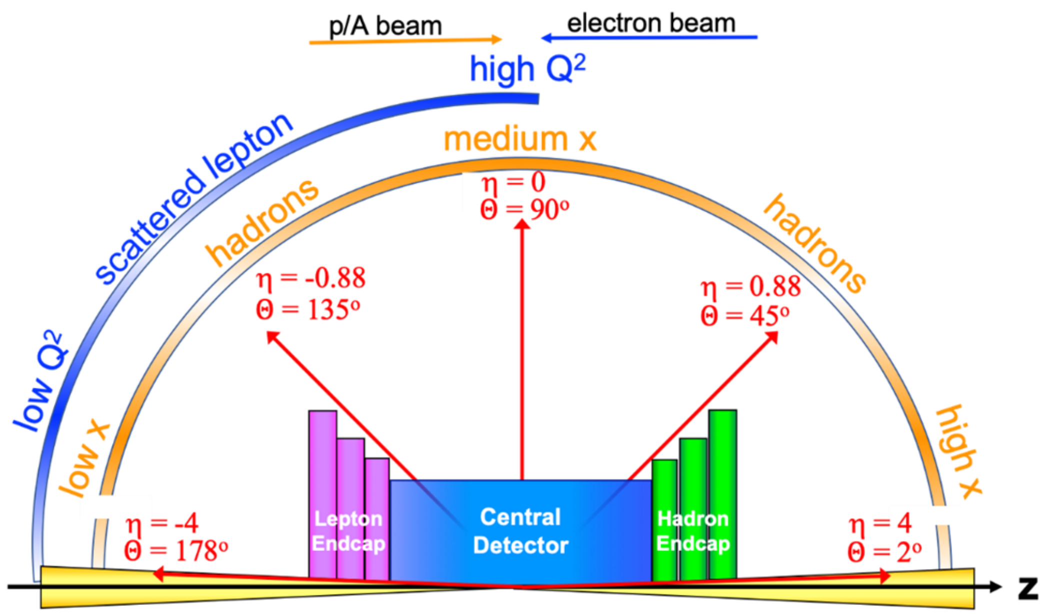
The **2021 EIC Yellow Report** describes the physics case, the resulting detector requirements, and the evolving detector concepts for the experimental program at the EIC.

The studies leading to the EIC Yellow Report were commissioned and organized by the EIC User Group (1257 scientists from 251 institutions in 33 countries).

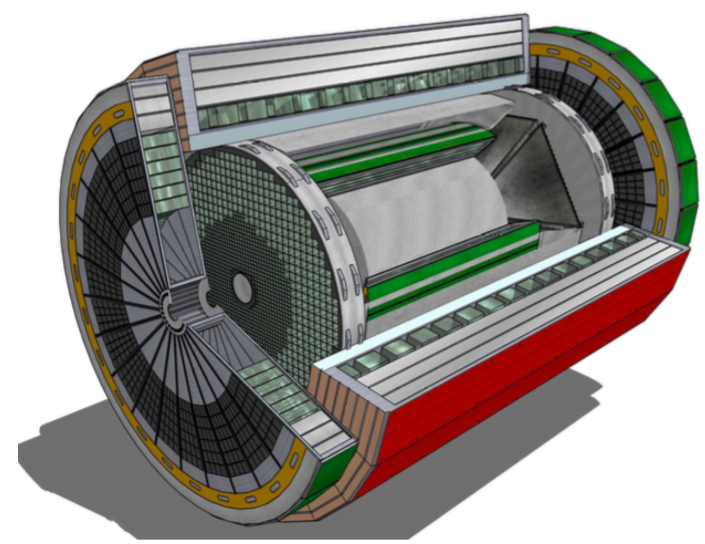
The EIC Yellow Report is aligned with the current project plans and was an important input to the DOE CD-1 decision.

Reference: arXiv:2103.05419

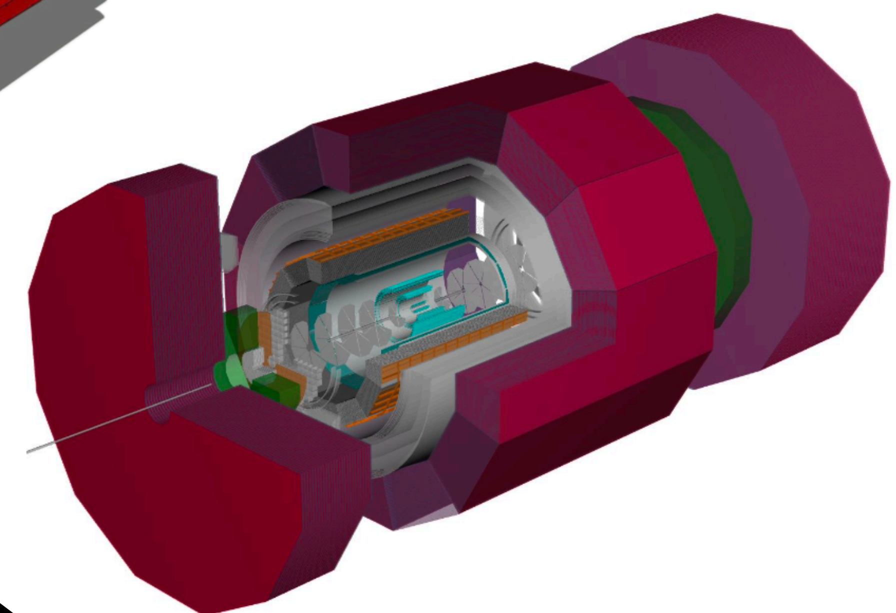
Interaction-Region Design and Detector Development



Asymmetric Kinematics



Detector Concepts



Detailed Simulations

Long list of detector technologies were evaluated in light of performance specifications in the "Detector Requirements/R&D Handbook" and Yellow Report.

EIC Milestones

- **2021:** Large detector proposal development:
  - **ATHENA:** 3T solenoid, Si+MM+GEM tracker, imaging barrel EM cal, proximity-focused RICH.
  - **ECCE:** 1.5T BaBar solenoid, Si+muRWell trackers, projective SciGlass EM cal, modular RICH.

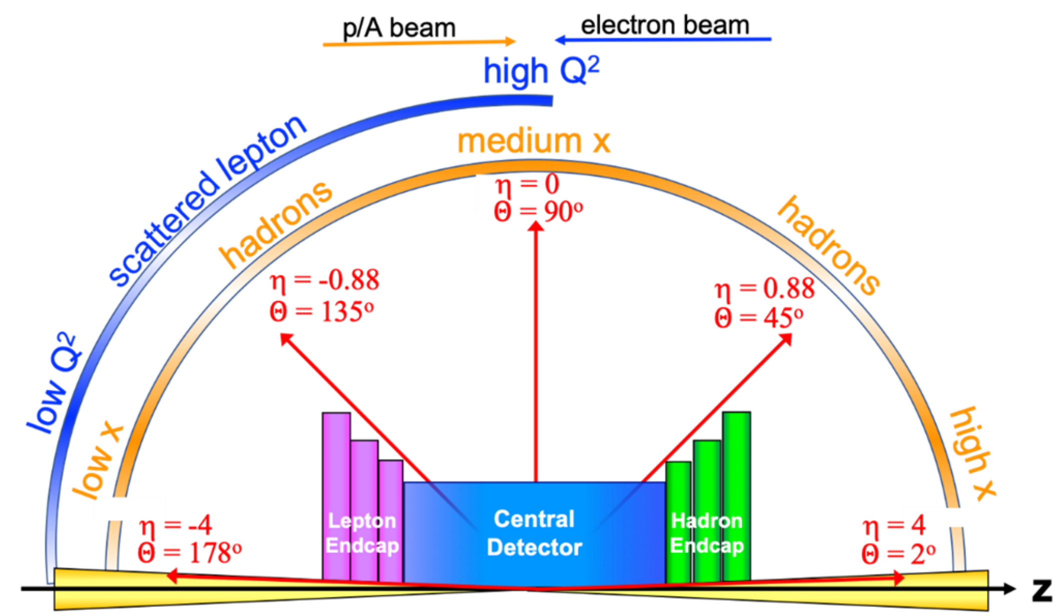
ATHENA: A Totally Hermetic Electron-Nucleus Apparatus

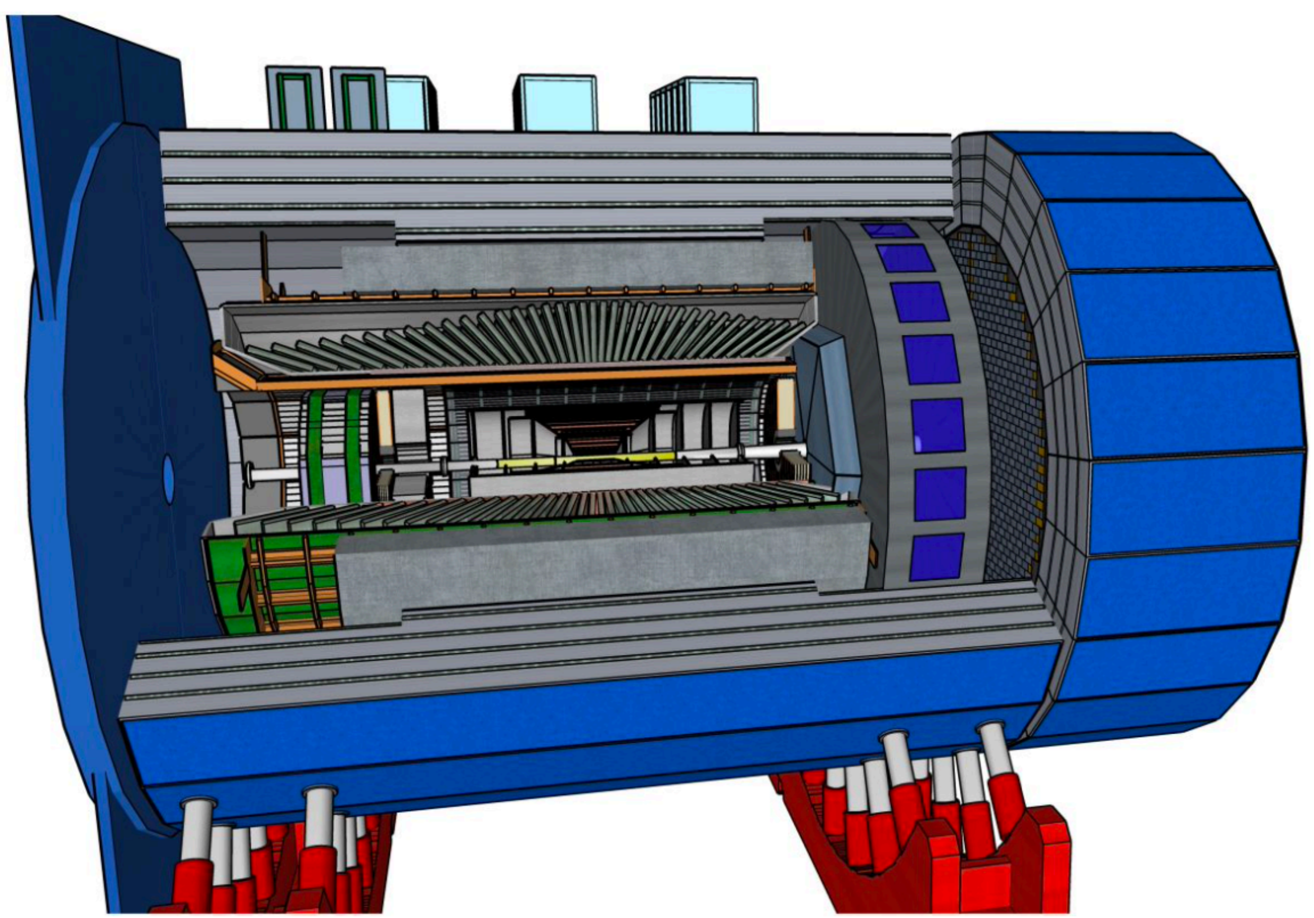
EIC Comprehensive Chromodynamics Experiment

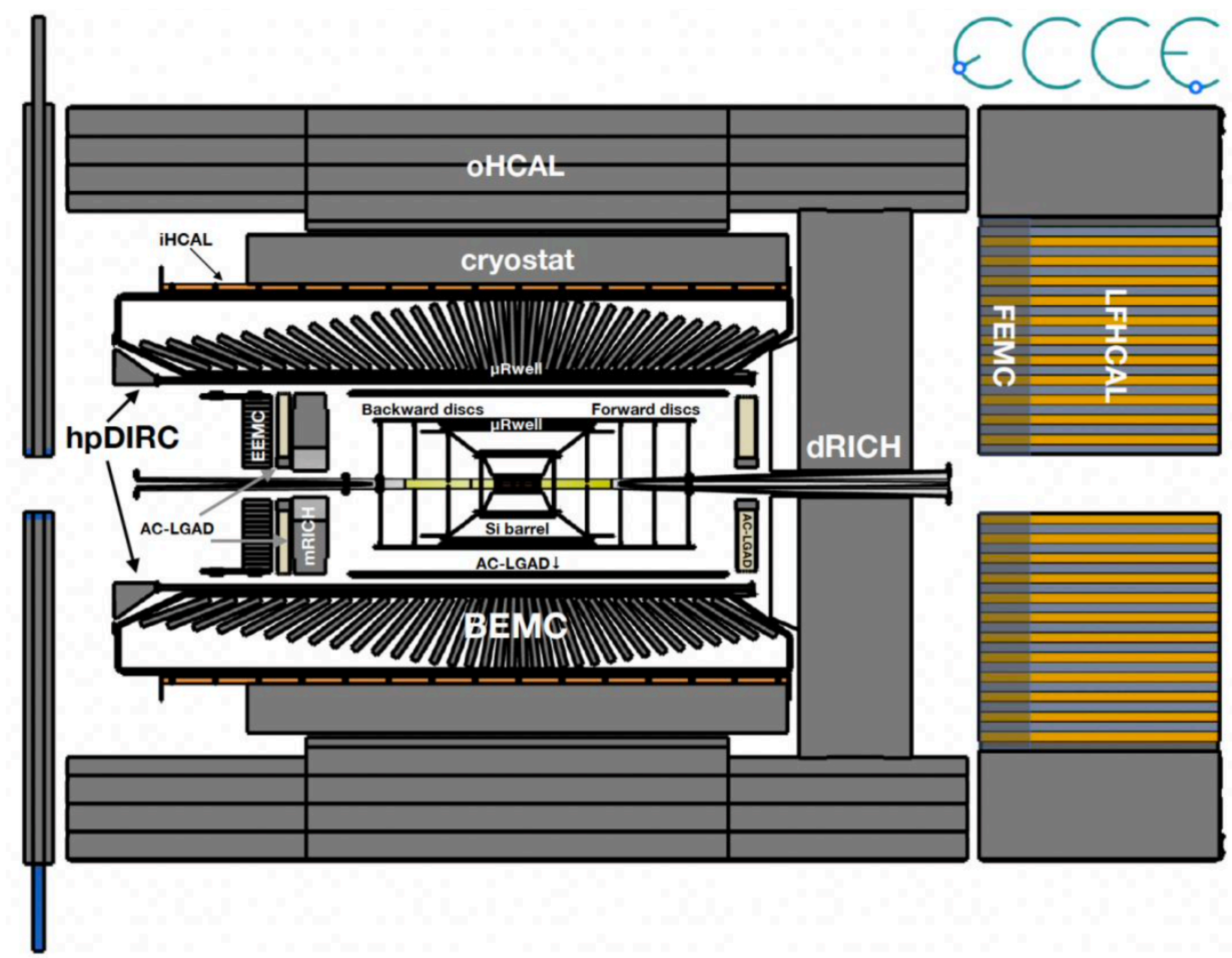
  - **CORE**: smaller effort focused on specific exclusive reaction channels at 2nd IR.
- **2022:** Selection of ECCE proposal as reference for EIC project detector at IP6 (where STAR is).
  - DPAP advisory panel: ECCE design achieves physics goals with lowest risk and cost.
  - Successful integration of ATHENA and ECCE communities within two months!
- **2023:** Detector TDR for EIC Project CD-2/3a review (by January 2024)
  - 2022: technology selection for few areas where multiple options.
  - 2023: finalization of design parametrization.

ePIC

Project Detector







Based predominantly on the ECCE proposal.

EIC Canada Collaboration

- **Coordinating the Canadian participation in the Electron Ion Collider.**
- Chartered in 2020 after EIC Project CD-0 decision and BNL site selection.
- Current initiatives:
  - Input to the 2022-2036 Canadian Subatomic Physics Long Range Plan
  - NSERC Subatomic Physics Project Research Grants (2021-2023: funding of 8 HQP)
  - Interfacing with partner and funding organizations:
    - National funding agencies and research facilities (NSERC, CFI, TRIUMF
    - International partners (EIC User Group, BNL, JLab, working groups and consortia)
  - Participation in both Detector Proposals (ATHENA: Mt. A, U. Manitoba; ECCE: U. Regina)
  - Participation in the EPIC collaboration (working group conveners)
- Current membership:
  - PIs at three institutions U. Regina, U. Manitoba, Mt. Allison U.
  - First step to joining: institutions and PI must join the EIC User Group
- Management plan, members, leadership and further details at eic-canada.org

Canadian Involvement in EIC Yellow Report, Proposals

Science Requirements and Detector Concepts

EIC YELLOW REPORT

Executive summary
arxiv:2103.05419

2021: From Yellow Report…

…to two large collaboration detector proposals with Canadian involvement

2022: proposal selection

…to one large EIC Project detector collaboration

2024: Construction/Installation

2030: First Beam/Operations

ATHENA: A Totally Hermetic Electron-Nucleus Apparatus

EIC Canada focus areas:

- Calo: Si-pixel imaging + SciFi hybrid barrel PbWO + SciGlass hybrid endcaps
- Software: CERN-oriented (dd4hep, gaudi, ACTS)

EIC Canada leadership roles:

- U Manitoba (W. Deconinck: software WG co-convener)
- Mt Allison U (D. Hornidge)

Canadian resources:

- ComputeCanada full simulations

ECCE *EIC Comprehensive Chromodynamics Experiment*

EIC Canada focus areas:

- Calo: Barrel, e-/Hadron endcap, far forward region: roman pots, ZDC, B0

EIC Canada leadership roles:

- U Regina: G. Huber (meson form factors at high Q2); Z. Papandreou (spectroscopy of XYZ states)
- Event generators, far forward studies
- Novel AI Work: Inner tracker design
- optimization; calo design using hierarchical density-based clustering

Canadian resources:

- U. Regina computing resources

University of Manitoba — Mount Allison University — University of Regina

Supported in part by NSERC SAPIN-2020-00049, SAPPJ-2021-00026.

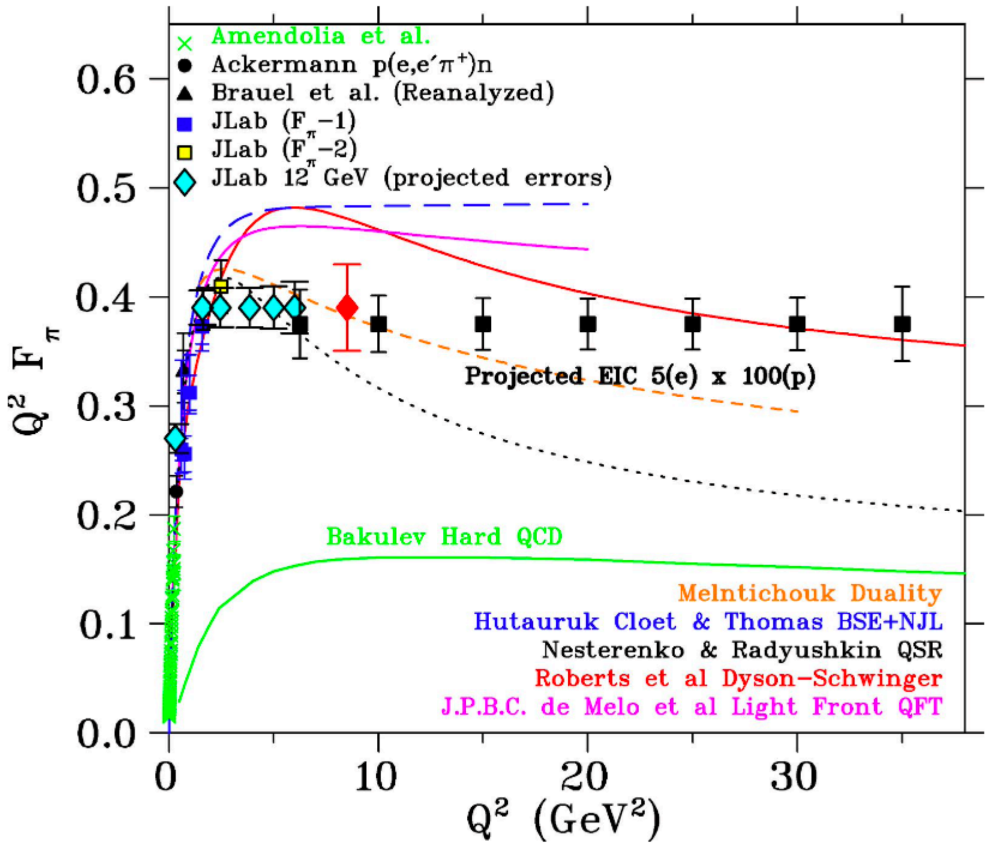
Canadian Interests/Contributions at the EIC
near term

- Extend Pion and Kaon Form-Factor Studies
- *XYZ* Spectroscopy
- Extend Studies of Leptoquark sensitivity
- PVES to determine interference structure functions

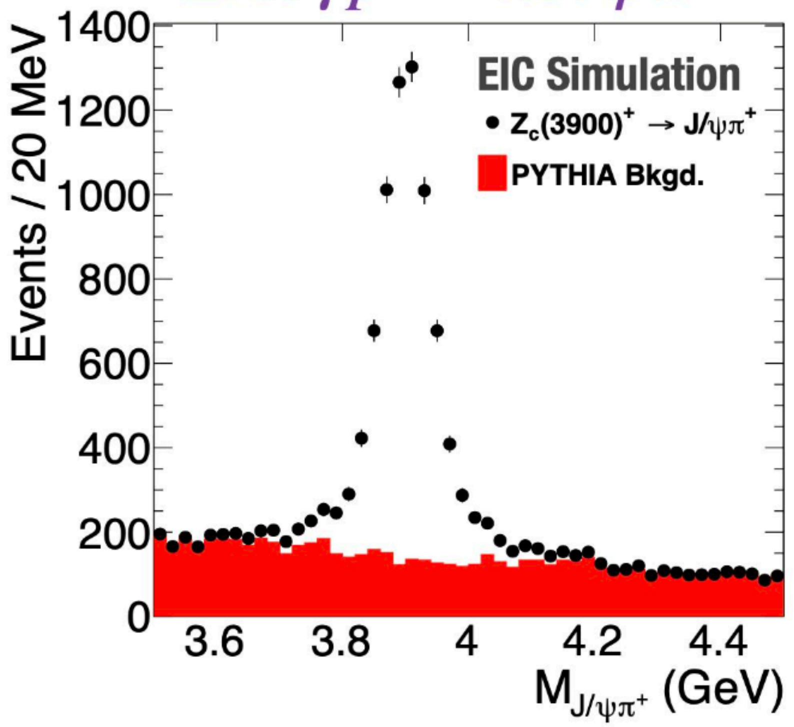
- Machine Learning for calorimeter design optimization
- Compton polarimetry
- HV-MAPS electron detector
- Electron endcap calorimeter prototype

Contributions: U. Regina / Mt. Allison

- Pion form factors as probe of emergent mass generation in hadrons.
  - Precision at high momentum transfers.
- Light and heavy quark spectroscopy.
  - Hadron Spectroscopy has components in: Semi-inclusive, Heavy Flavour and Exclusive.
  - Explore underlying degrees of freedom in Charmonium states.
  - Explore Bottomonium Exotic Sector.
- Artificial intelligence detector co-design.
- Detector development (ongoing with ANL, UM).
  - EM barrel calorimeter based on GlueX Pb SciFi design, with AstroPix (low-power ATLASPix) silicon imaging layers for shower profile measurements.



EIC: $\gamma p \rightarrow nJ/\psi\pi^+$



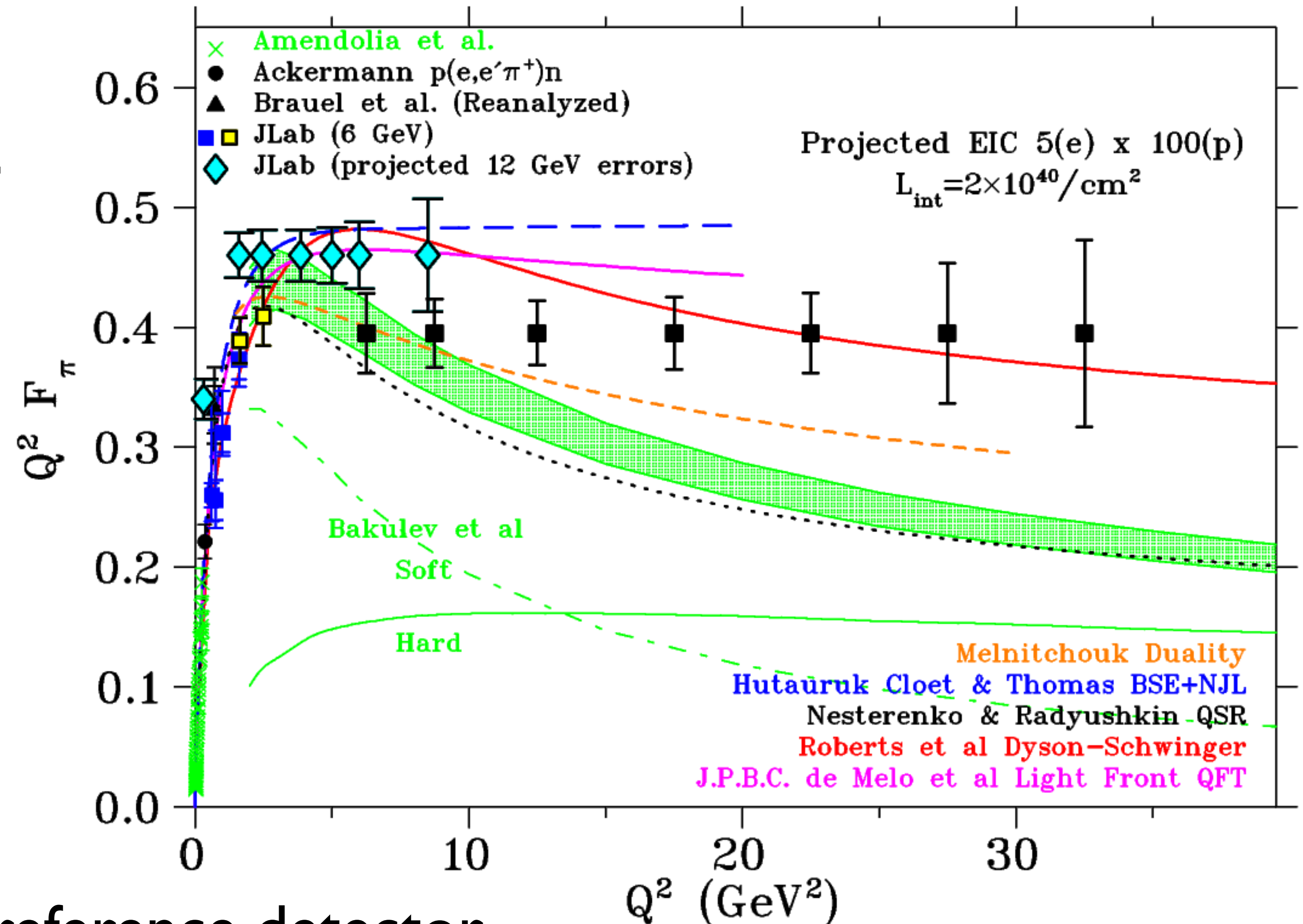
Pion and Kaon FF Measurements

Rich insights into hadron structure → Dynamical Chiral Symmetry Breaking

Exclusive reaction $p(e,e'\pi^+n)$ at EIC can possibly extend Q^2 reach of $F_\pi(Q^2)$

- Triple coincidence.
- Need model help — LT separation not possible.

Kaon is even more challenging.



Projected $F_\pi(Q^2)$ results for ECCE reference detector.

Work continues on $F_K(Q^2)$ simulations.

Extension of JLab 6- and 12-GeV programs.

Heavy and Light Quark Spectroscopy

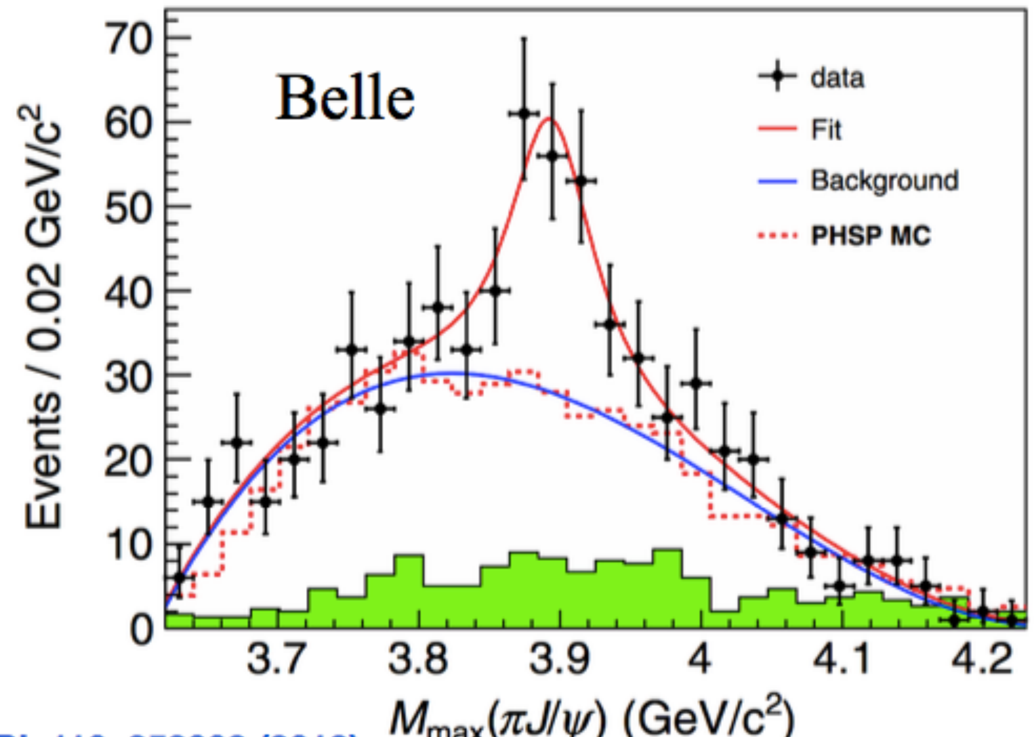
Recent evidence for *non-standard* exotic heavy mesons.

The so called ***XYZ* states**.

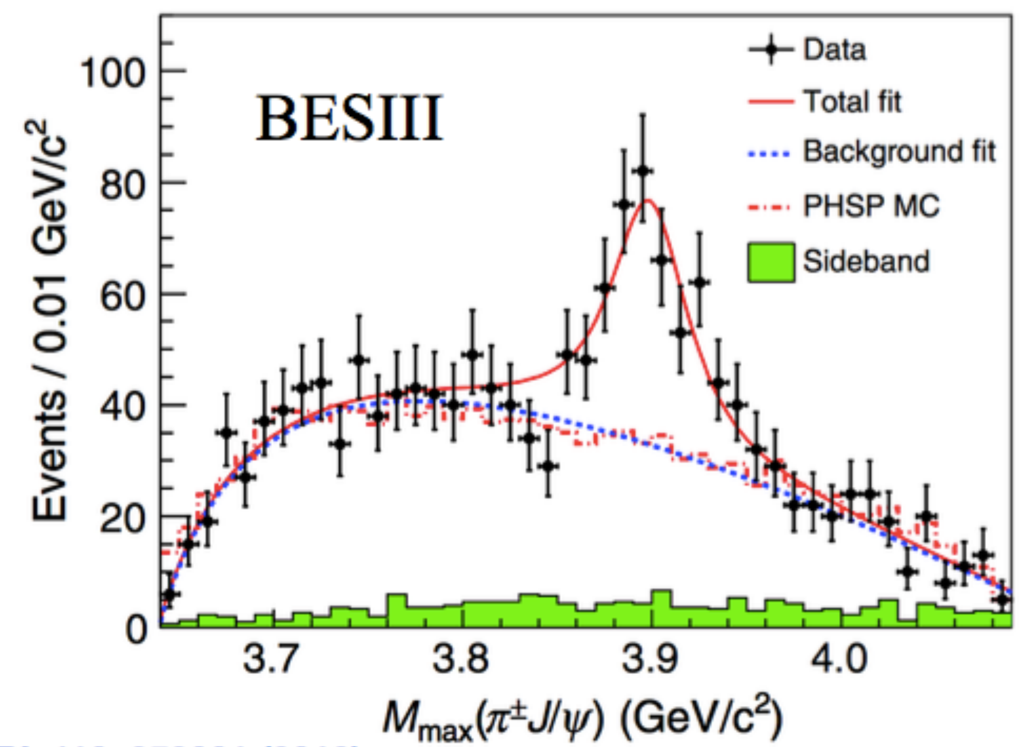
- ***Y* states:** same quantum numbers as the photon. $J_{PC} = 1^{--}$
- ***Z* states:** all exotic charge states. Decay into quarkonium state and a light charged meson.
- ***X* states:** all other neutral states with quantum numbers NOT $J_{PC} = 1^{--}$

Charmonium structure discovered at Belle and observed at both BESIII and LHCb in the decay of the $\Upsilon(4260)$, given the name $X(3872)$.

Superposition of exotic and conventional $c\bar{c}$ states??



PRL 110, 252002 (2013)



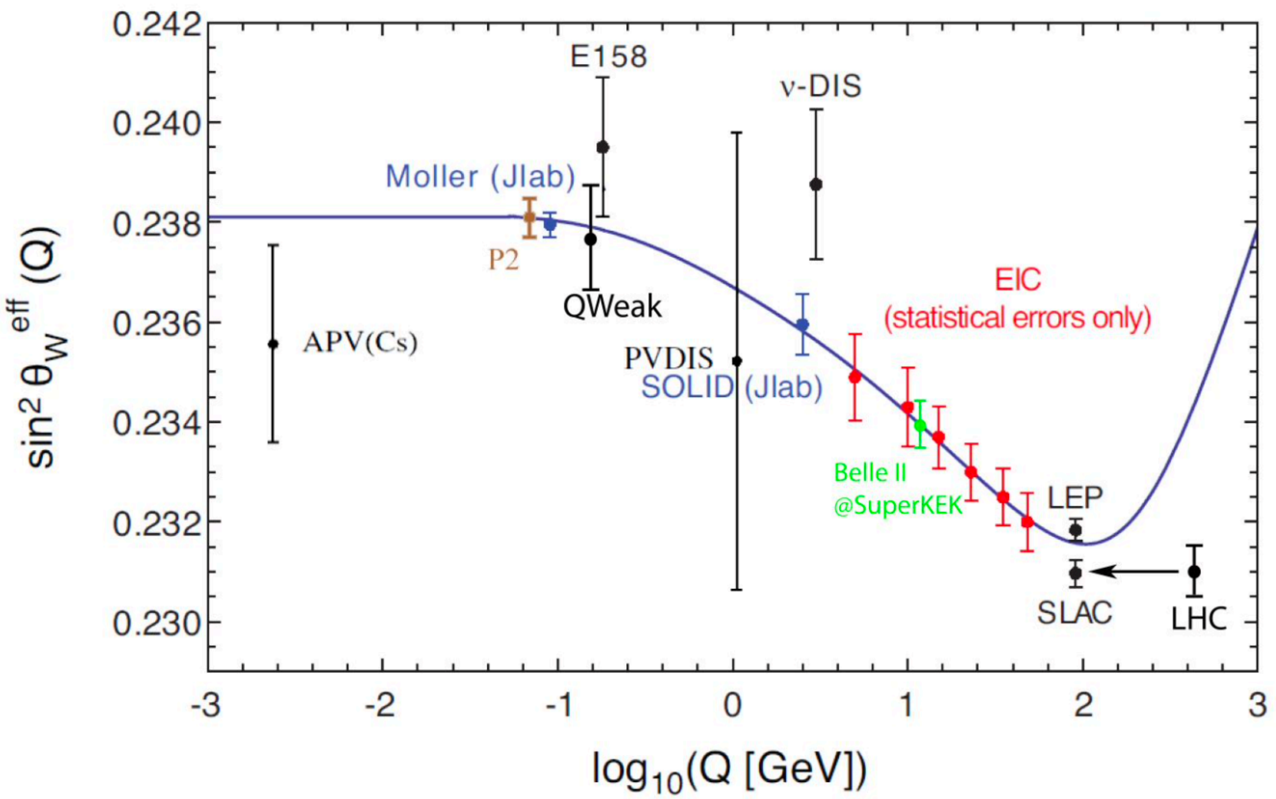
PRL 110, 252001 (2013)

Some EIC advantages:

- Well controlled initial state
- High luminosity
- "Clean" environment
- Flexibility in tuning kinematics

Contributions: U. Manitoba

- Exploiting parity-violation in weak interaction to access observables:
  - Strangeness in nucleon (fixed target).
  - Precision searches for new physics.
- CC and NC program of precision $\sin^2\theta_W$ measurements at the EIC span unexplored region between low energy and Z-pole (LHC).
- BSM: leptoquark, CLFV.
- Polarimetry detector development:
  - Electron spectrometer with HV-MAPS.
- Core software development efforts.

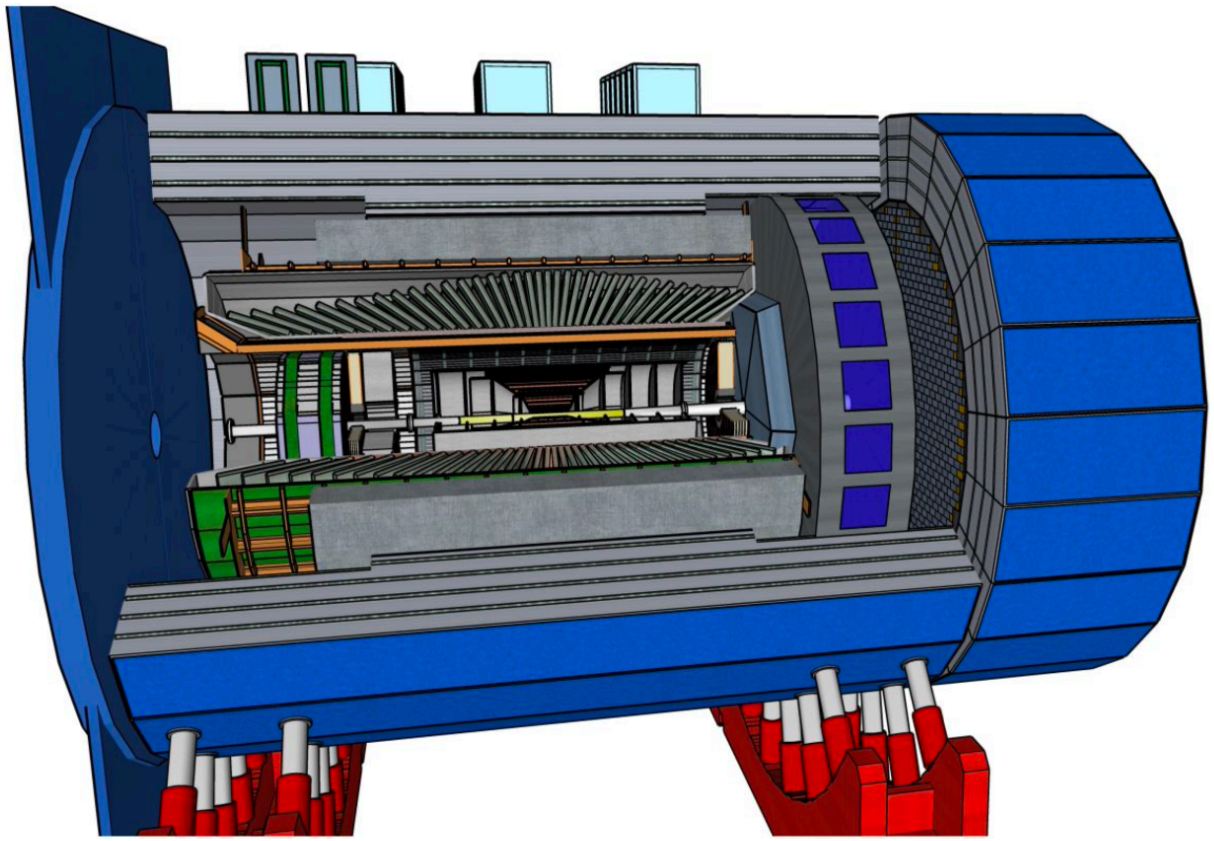


Ref: YX Zhao, Eur.Phys.J.A (2017) 53:55

Projected Involvement by Canadian University PIs

- EIC logically follows extensive physics programs at Jefferson Lab, Brookhaven National Lab, and connects to other existing Canadian programs.
- Anticipate **major detector construction effort** by EIC Canada Collaboration (calorimetry, polarimetry).
- A community similar in size to the Canadian Belle II Collaboration is our goal.
  - PI FTEs: growth to **~10 PIs** by start of operations in 2029.
  - HQP: growth to **~20 HQP** by start of operations 2029.
  - Detailed projections in EIC SAP LRP brief (at eic-canada.org).

Aspirations For Major Detector Construction In Canada



Electromagnetic Calorimetry:

- Consortium of U. Regina, U. Manitoba, ANL, and UC Santa Cruz on imaging calorimetry, using experience of GlueX barrel calorimeter.
- Calorimeter pulse-shape discrimination in the electron endcap (PbWO4 technology).
- Positioning for CFI IF 2025 application for calorimeter construction.

Compton Polarimetry for EIC Electron Beam:

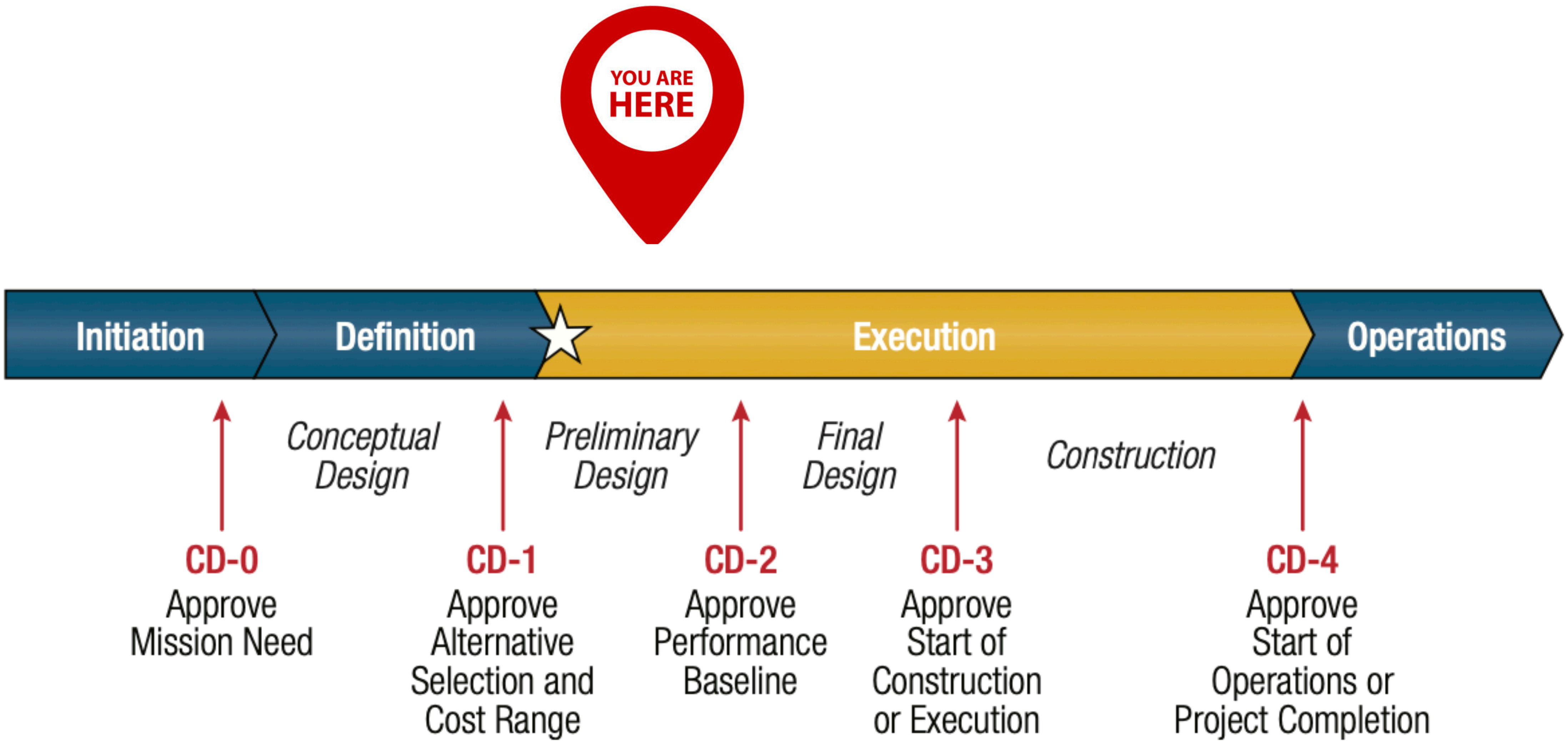
- HV-MAPS technology at U. Manitoba for Compton polarimeters at JLab, KEK.
- Photon polarimetry based on MOLLER and Belle II experience (U. Manitoba).

Online/Offline Production Software:

- Experience throughout JLab and EIC programs, including proposal stages.

Much of this work will be undertaken with help from TRIUMF.

EIC Timeline



2024: Begin construction/installation

2030: First beam and operations

Summary

- **Interactions and structure are entangled in nuclear matter.**

  Quarks are bound by gluons, but gluons also bind themselves.
  Can't separate interactions and structure.
  Observed properties of nucleons and nuclei — such as mass and spin — emerge from this complex system.

- **Solving this puzzle could be transformational.**

  Perhaps even in a more dramatic way than the understanding of the atomic and molecular structure of matter led to the understanding of new frontiers, sciences, and technologies.

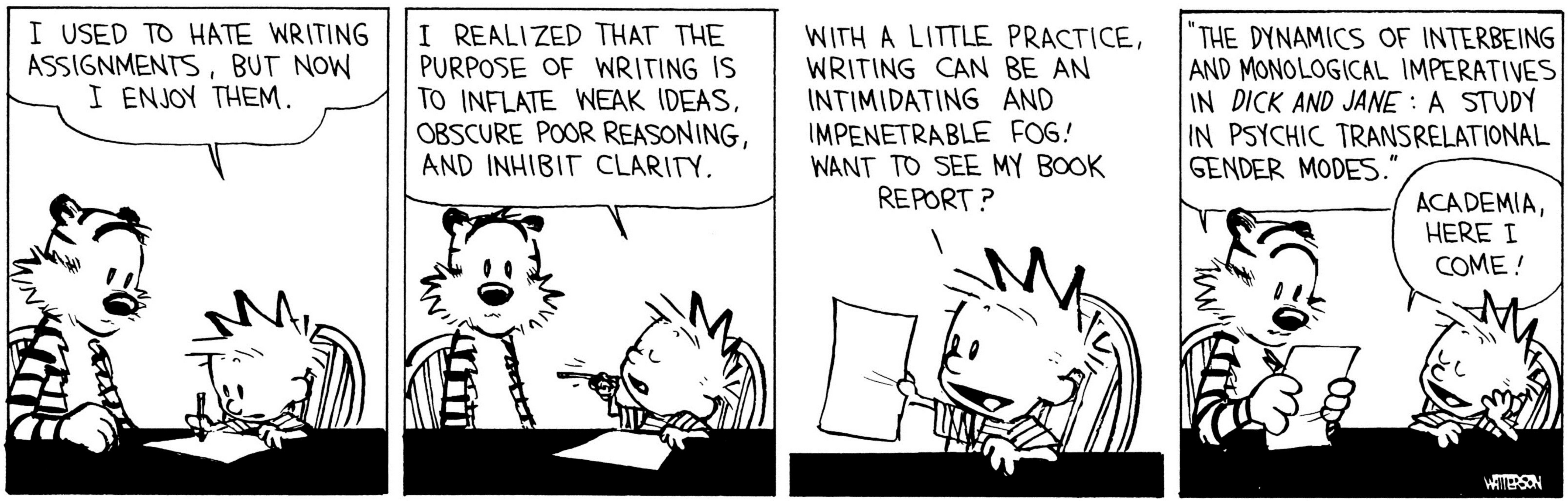
- **The Electron-Ion Collider is the right tool.**

  High-energy, high-luminosity facility and a versatile range of beam energies, polarizations, and species.
  Precisely image the quarks and gluons, and their interactions.
  Explore the new QCD frontier of strong colour fields of nuclei.
  Help us understand how matter at its most fundamental level is made.

- **Ideal for the next generation of scientists.**

  Operations anticipated from 2030–2060.

Thank You!


I USED TO HATE WRITING ASSIGNMENTS, BUT NOW I ENJOY THEM.
I REALIZED THAT THE PURPOSE OF WRITING IS TO INFLATE WEAK IDEAS, OBSCURE POOR REASONING, AND INHIBIT CLARITY.
WITH A LITTLE PRACTICE, WRITING CAN BE AN INTIMIDATING AND IMPENETRABLE FOG! WANT TO SEE MY BOOK REPORT?
"THE DYNAMICS OF INTERBEING AND MONOLOGICAL IMPERATIVES IN *DICK AND JANE*: A STUDY IN PSYCHIC TRANSRELATIONAL GENDER MODES."
ACADEMIA, HERE I COME!
WATTERSON