The Electron-Ion Collider (EIC)

North America's Next
Large Particle Collider

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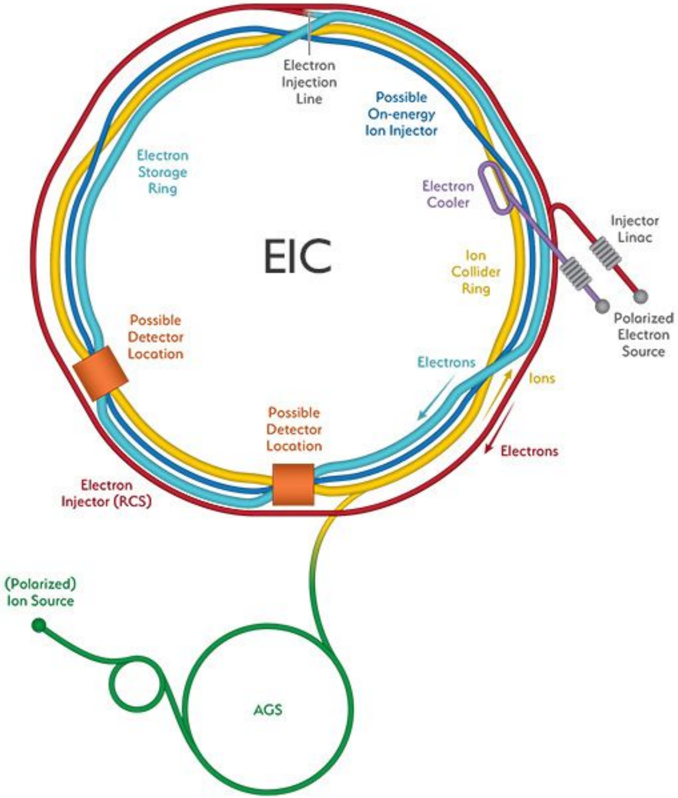
EIC Canada Collaboration (eic-canada.org)

With material by Michael Gericke, Dave Hornidge, Garth Huber, Juliette Mammei, Zisis Papandreou. Supported in part by NSERC SAPIN-2020-00049, SAPPJ-2021-00026.

What is the Electron-Ion Collider?

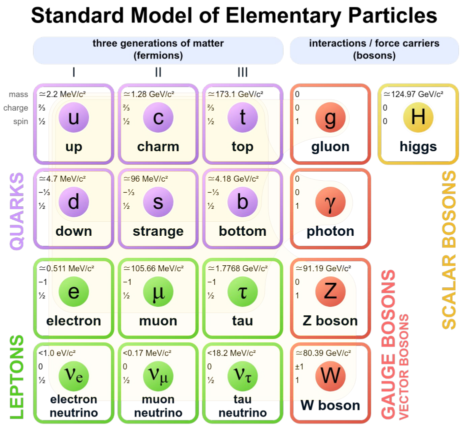
- **First major collider** to be built in North America in the 21st century
  - **Polarized electrons**, 10-20 GeV
  - **Polarized light ions** (p, d, ^{3}He) and unpolarized nuclei → U, 50-250 GeV
  - Center-of-mass energy of 28-140 GeV
  - **High luminosity** $\mathcal{L}$ of 10^{33}–10^{34} cm^{-2} s^{-1}
  - Second interaction region possible
- International facility with estimated cost of about US$2.5B
- Large community of 1000+ users at 220+ institutions in 30+ countries
- Site: Brookhaven National Lab, NY

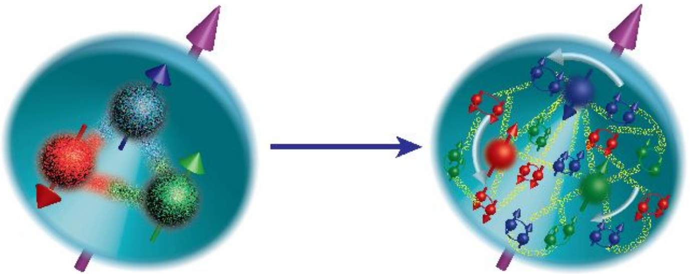


Electron-Ion Collider: Bridge From Quarks to Nuclei

- While we understand the fundamental building blocks and their interaction, **observable properties of nuclear matter emerge out of a complex system** of **strongly interacting quarks and gluons that is not as well understood.**

Mission of EIC: How do up and down quarks, sea quarks, and gluons create the building blocks of the nuclei of atoms, neutrons, and protons?





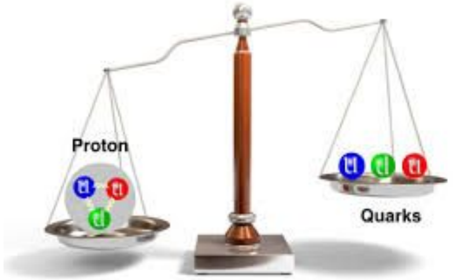
Electron-Ion Collider: Bridge From Quarks to Nuclei

Mission of EIC: How do up and down quarks, sea quarks, and gluons create the building blocks of the nuclei of atoms, neutrons, and protons?

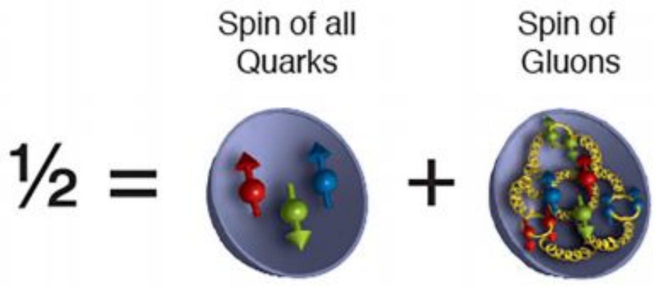
- The strong force, **Quantum Chromodynamics (QCD)**, is arguably the least understood of the fundamental forces in nature.
- Gaining a detailed understanding of the **dynamical system** at the heart of our world's matter could be transformational.
- Imaging the quarks and gluons, and their interactions in nucleons and nuclei, requires **versatility in center of mass energy**, polarization of hadronic species, at a **high luminosity** to enable precision

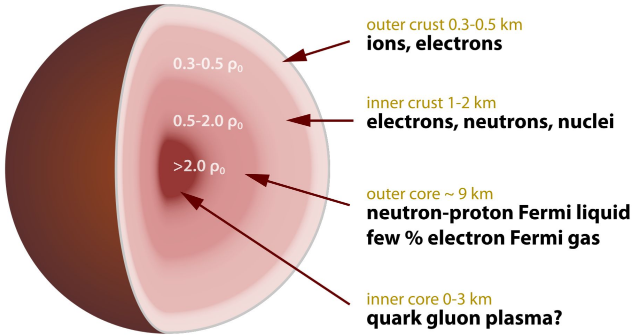
The Electron-Ion Collider is the right tool for this program.

The EIC Will Answer Three Big Questions



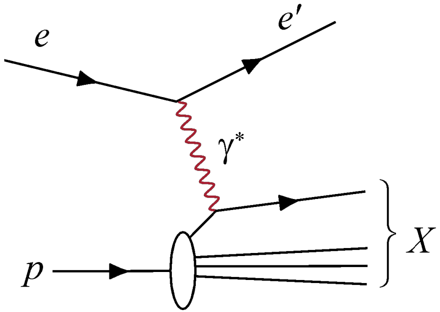
- How does the **mass of the nucleon** arise?
  - While the Higgs mechanism can explain all of the mass of the electron, it accounts for only a small part of the mass of the proton and neutron
- How does the **spin of the nucleon** arise?
  - Three spin ½ quarks, bound by gluons, each with angular momentum, form a spin ½ proton.
- What are the **emergent properties** of dense systems of gluons?
  - How does nuclear matter behave at extremely high densities found in astrophysical systems?





Accessing Quarks in Electron-Ion Collisions

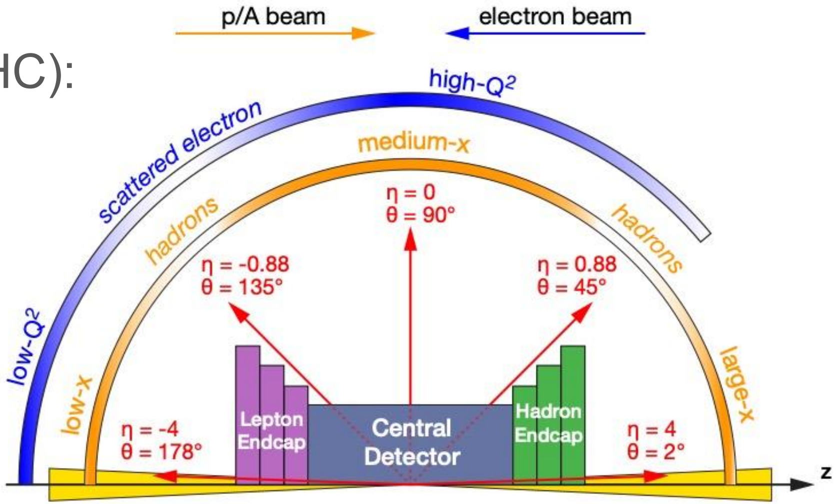
Key variables **x and Q^2** in **deep-inelastic scattering (DIS)**



- Four-momentum transfer of virtual photon
  $\mathbf{Q^2} = -q^2 = -(k - k')^2$ (resolution of our probe)
- Fraction of momentum of struck quark **x**

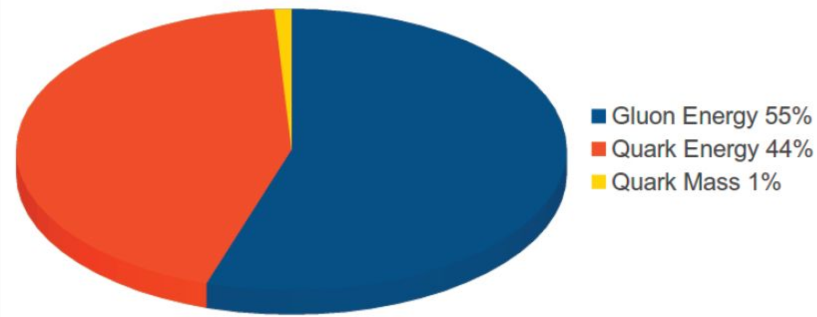
Asymmetric reaction (unlike e.g. pp at LHC):

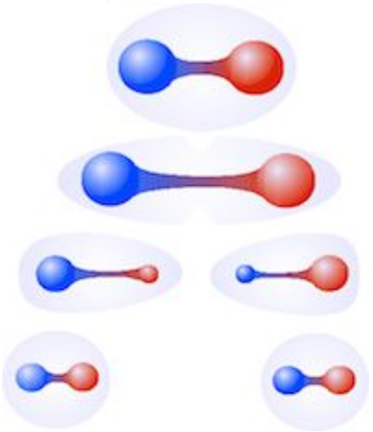
- Electrons in "backward" direction
- Hadrons go in every direction
- Need excellent e^-/π^- separation



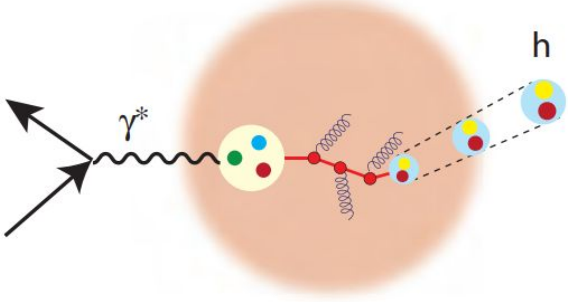
How does the mass of the nucleon arise?

- Vast majority of the nucleon's mass is due to quark-antiquark pairs, the gluons, and the energy of quarks moving at the speed of light.
- Confinement allows only colorless combinations of quarks. Struck quarks "hadronize" into these colorless states. The details of hadronization (including screening and nuclear medium effects) tell us about the components of mass.





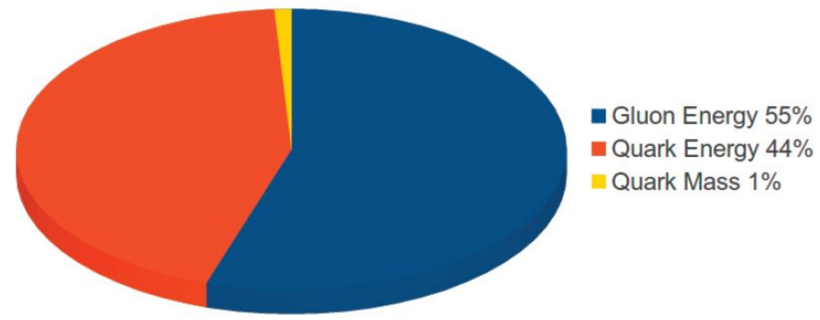
Confinement

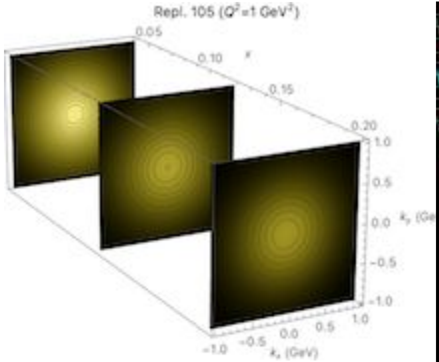


Hadronization

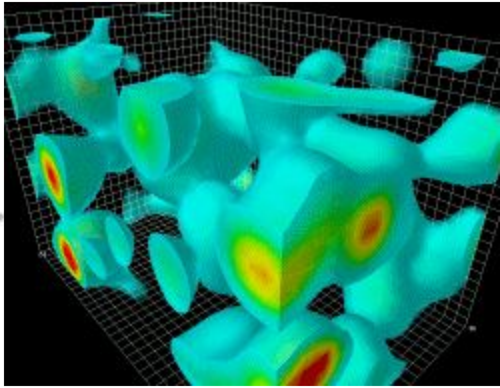
How does the mass of the nucleon arise?

- EIC will allow "proton tomography" in the multiple dimensions of x, Q^2, and impact parameter, allowing for spatial and momentum 3D maps (*i.e.* TMDs, GPDs, Wigner fcns).
- This will allow us to pinpoint the different contributions coming from quarks, gluons, and quark-antiquark pairs.





Proton Tomography

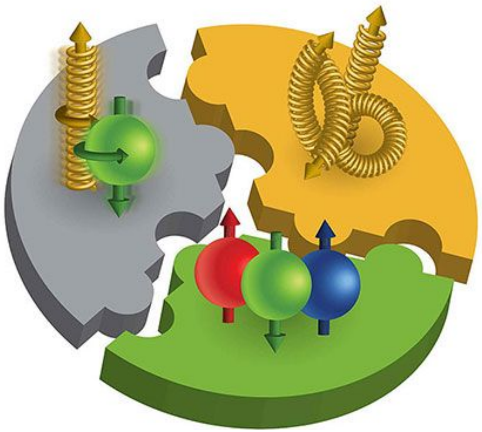


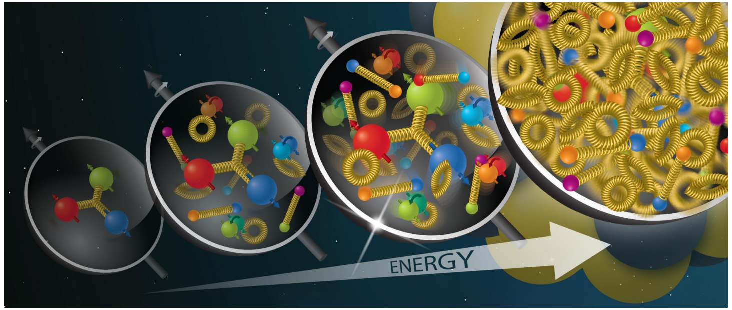
Vacuum gluon fluctuations

How does the spin of the nucleon arise?

- **Polarized electrons** colliding with **polarized hadrons**: a world's first!
- The EIC will be able to separate the spin contribution from quark spin, gluon spin, and from quark and gluon angular momentum.

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \boldsymbol{\Delta G(\mu)} + L_{Q+G}(\mu)$$





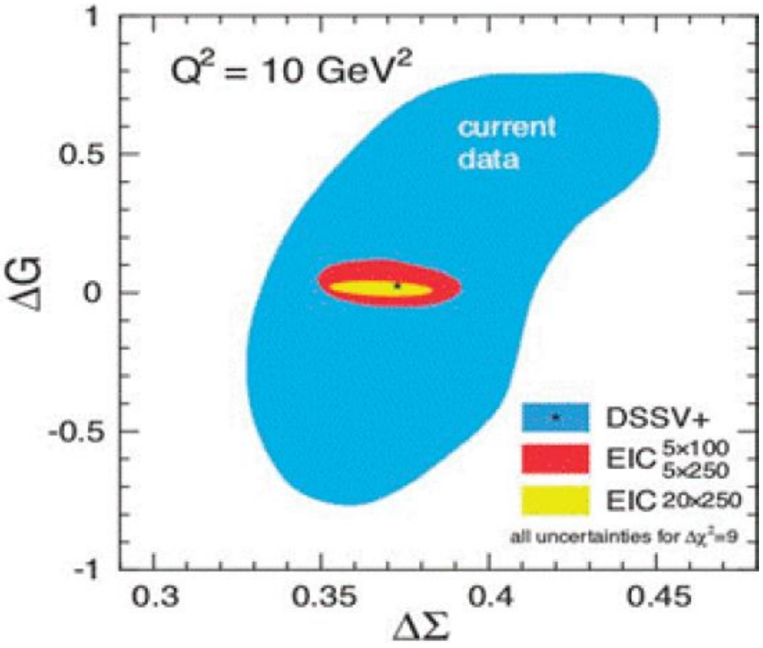
How does the spin of the nucleon arise?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \boldsymbol{\Delta G(\mu)} + L_{Q+G}(\mu)$$

$$\Delta\Sigma(\mu) = \sum_f \int_0^1 \Delta q(x,\mu)dx$$

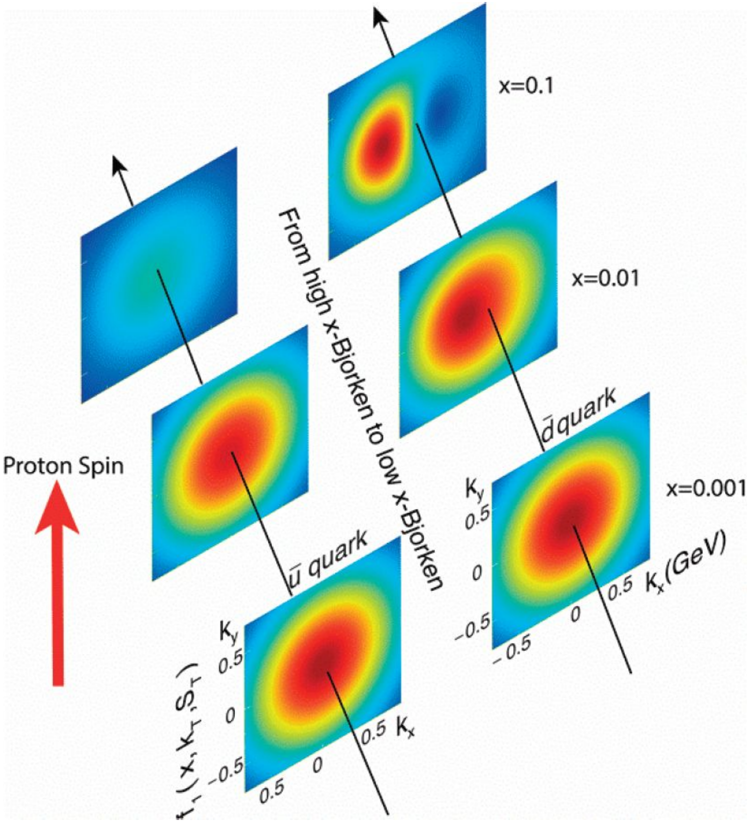
$$\Delta G(\mu) = \int_0^1 \Delta g(x,\mu)dx$$

$$L_{Q+G}(\mu) = \int_0^1 [l_q(x,\mu) + l_g(x,\mu)]dx$$



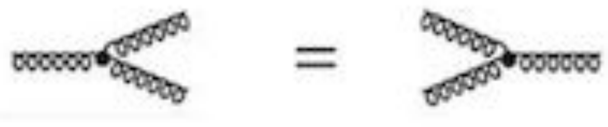
How does the spin of the nucleon arise?

- Adds unique spin degrees of freedom to “proton tomography”
- Example: the asymmetry in the d-bar transverse momentum profile for various x and Q^2 for transversely polarized protons allows us to extract how much of the proton’s spin is carried by the quark angular momentum.

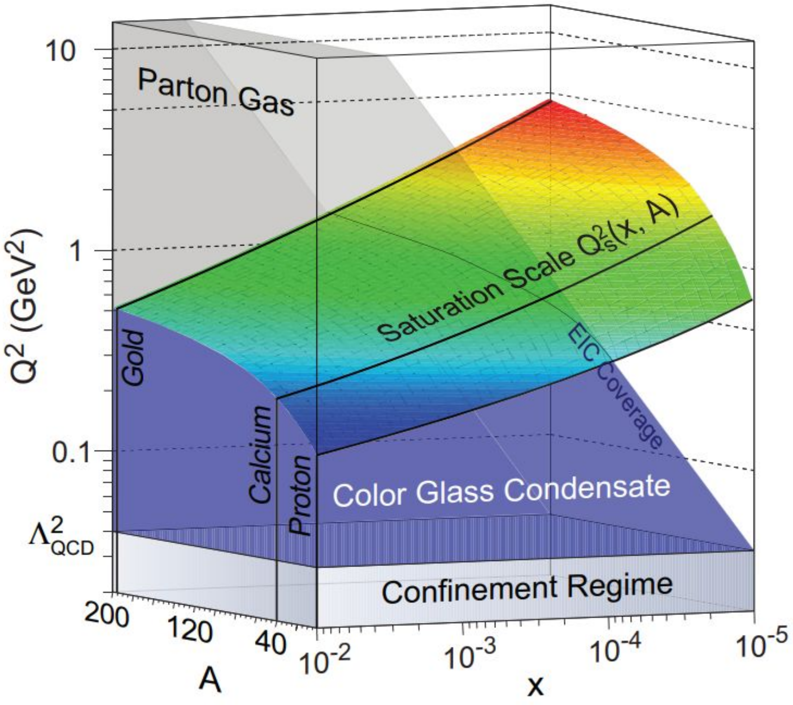


What emerges from dense gluon systems?

- Gluons in QCD are the only gauge bosons with a self-coupling: they can split and recombine.



- At the saturation densities, splitting and recombination are in balance.
- But even at lower densities of the proton, there are quark/gluon correlations.

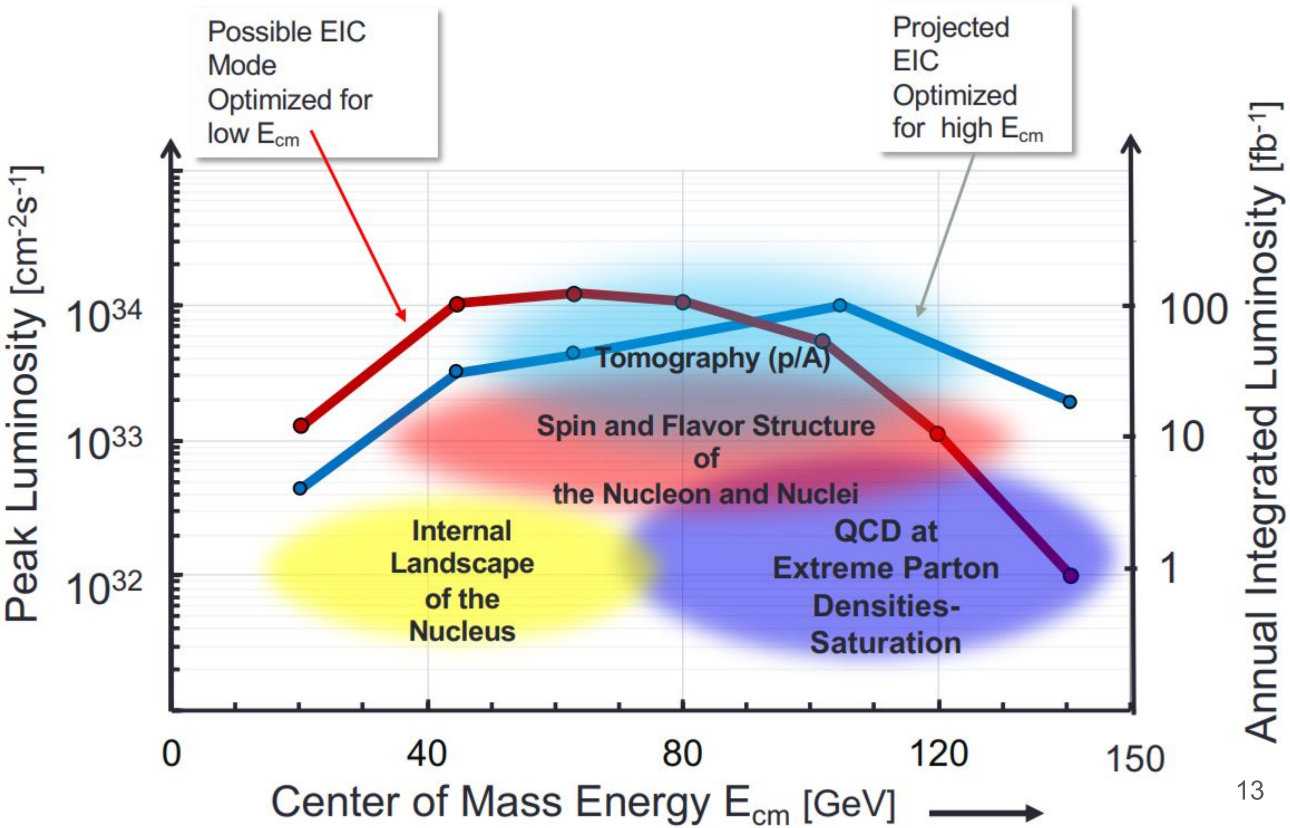


The EIC Luminosity Landscape

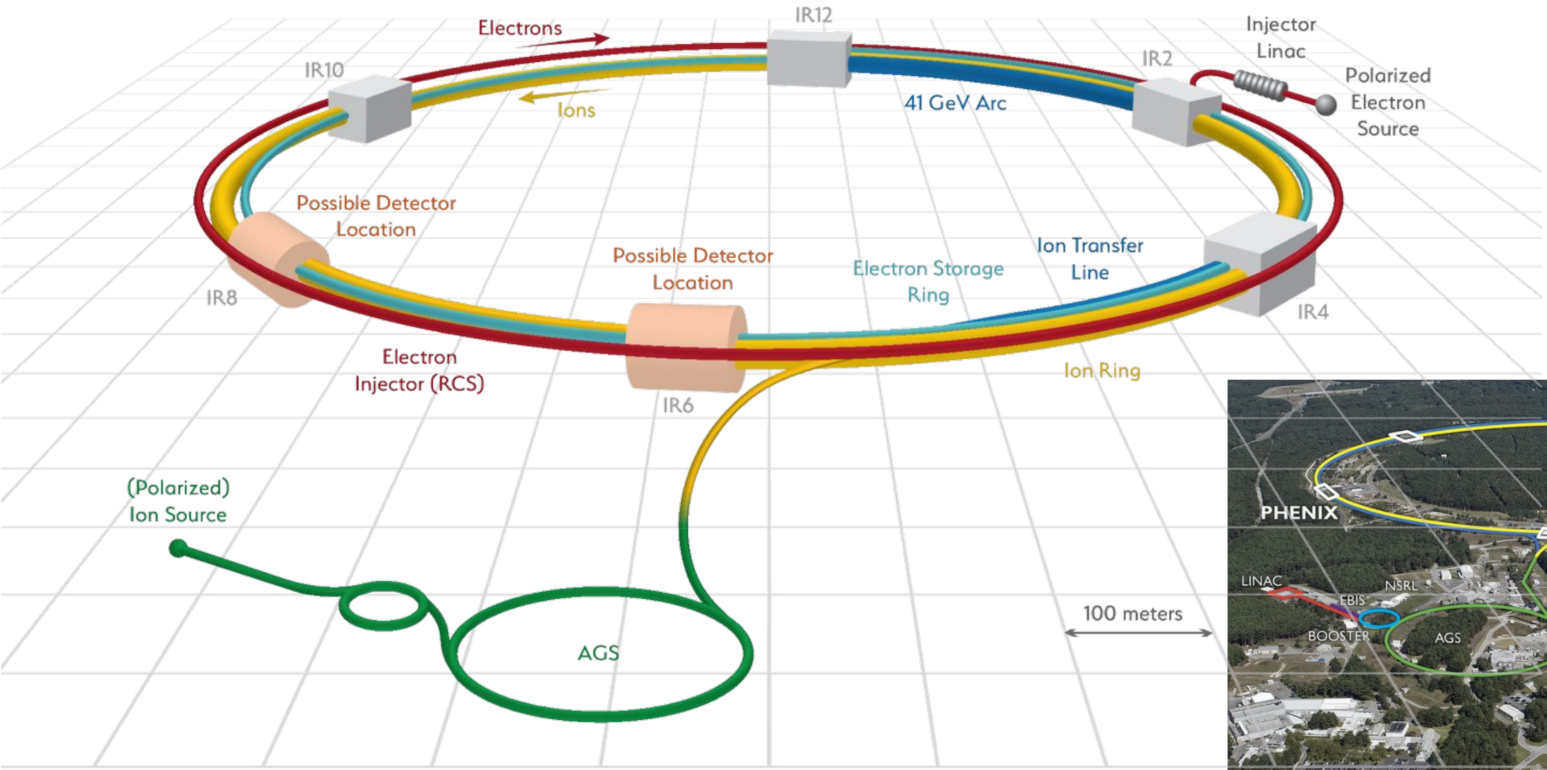
Low and high energy collisions probe different physics.

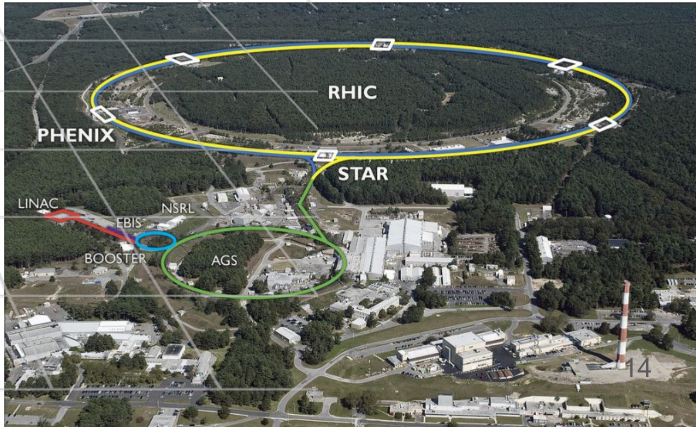
Proton tomography observables in multiple kinematic and spin dimensions require high luminosity.

Yellow Report process for considered decision on mutual optimization.



EIC Design Leverages Existing RHIC Facility





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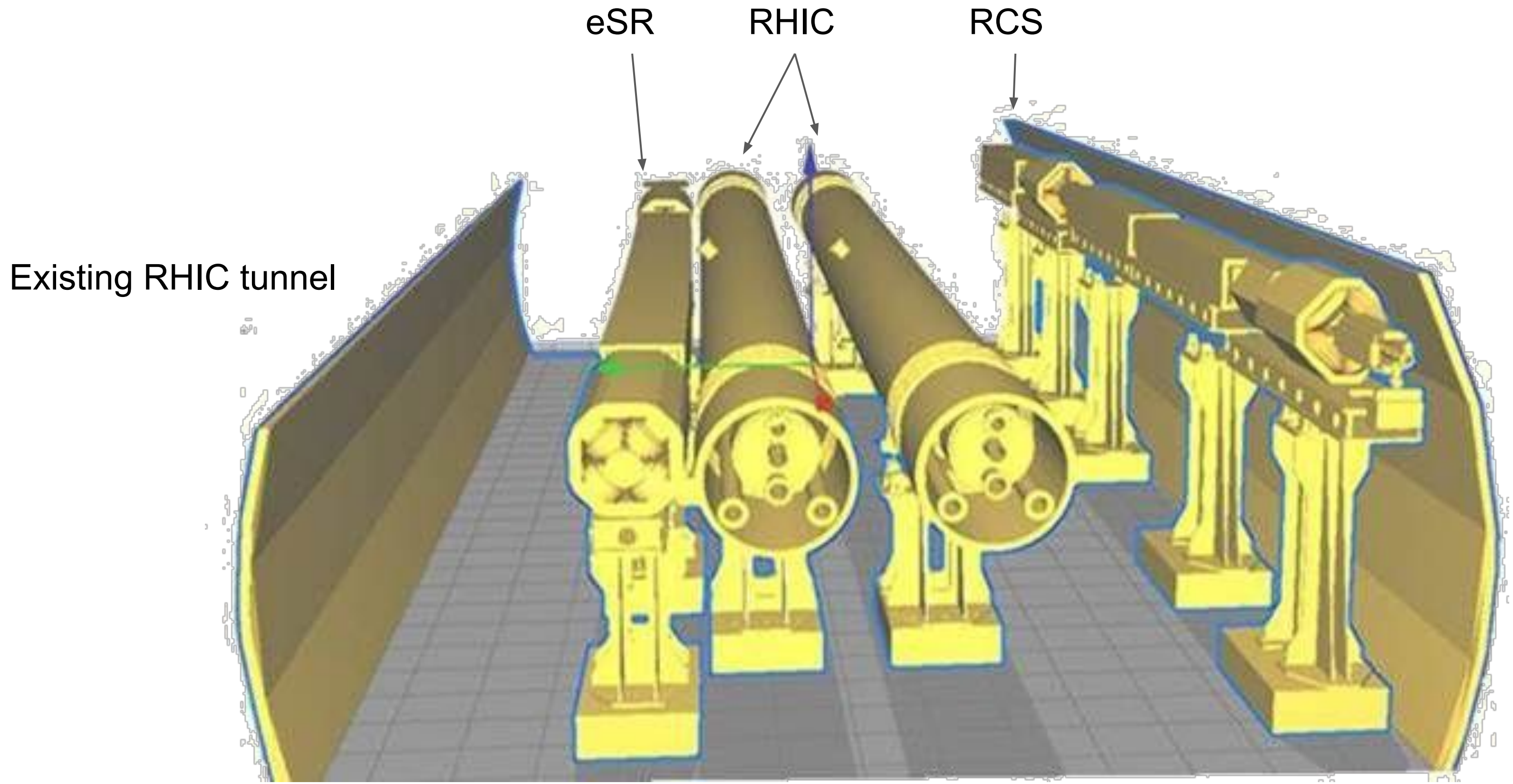
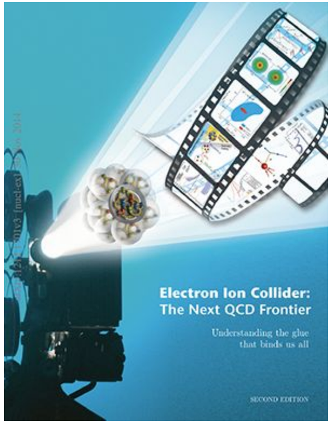
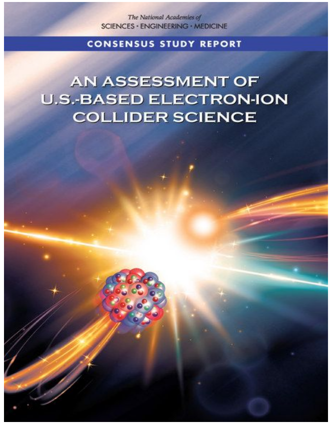
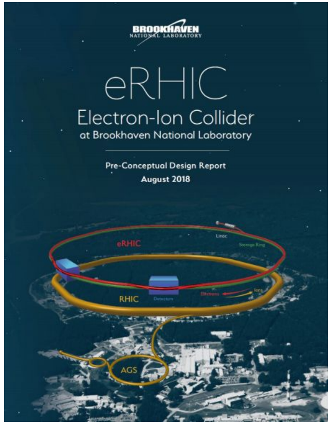


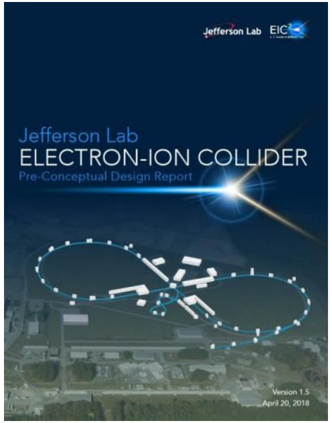
Milestones in the Electron-Ion Collider Development

- **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
  - eRHIC at Brookhaven National Lab
  - JLEIC at Jefferson Lab
- **2019**: U.S. Dept. of Energy 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**

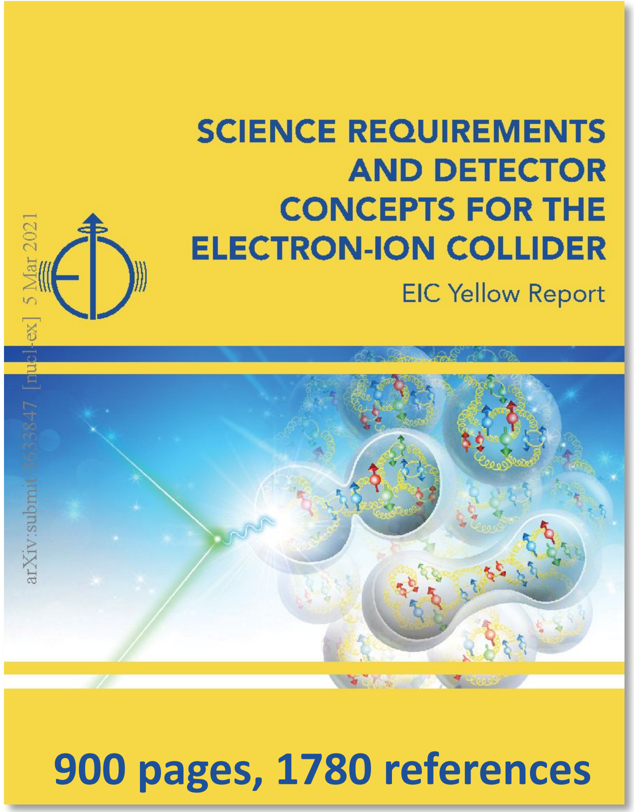








Milestones in the Electron-Ion Collider Development



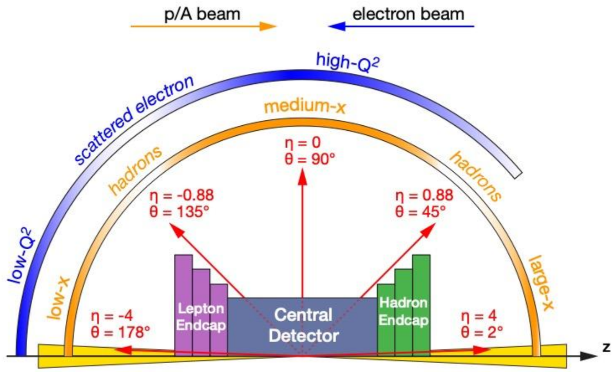
The **2021 EIC Yellow Report** describes the physics case, the resulting detector requirements, and the evolving detector concepts for the experimental program at the EIC.

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).

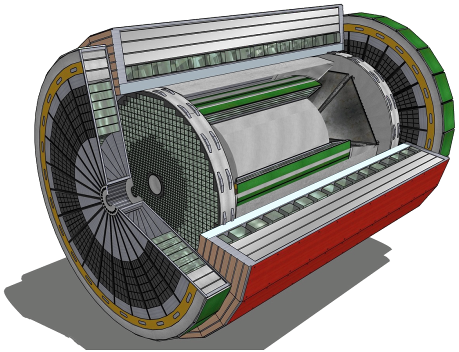
The EIC Yellow Report is aligned with the current project plans and was an important input to the DOE CD-1 decision.

Reference: arXiv:2103.05419

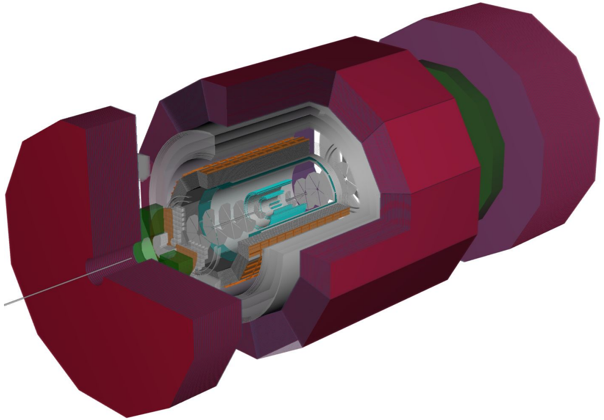
EIC IRs Design and Detector Development



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

Milestones in the Electron-Ion Collider Development

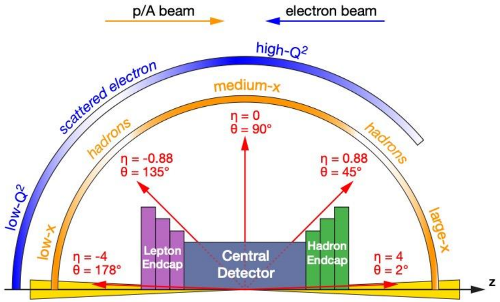
- **2021:** Large detector proposal development:
  - **ATHENA**: 3T solenoid, Si+MM+GEM tracker, imaging barrel EM cal, proximity-focused RICH
  - **ECCE**: 1.5T BaBar solenoid, Si+muRWell trackers, projective SciGlass EM cal, modular RICH

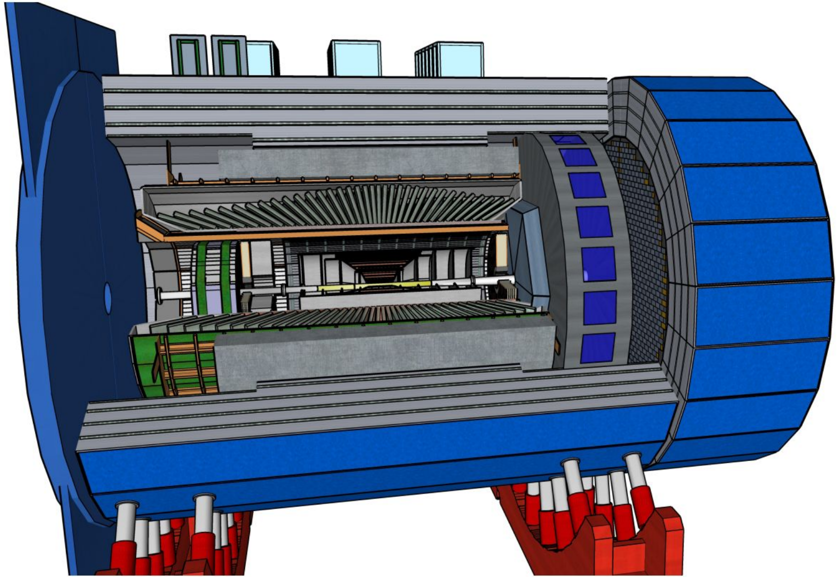
ATHENA: A Totally Hermetic Electron-Nucleus Apparatus

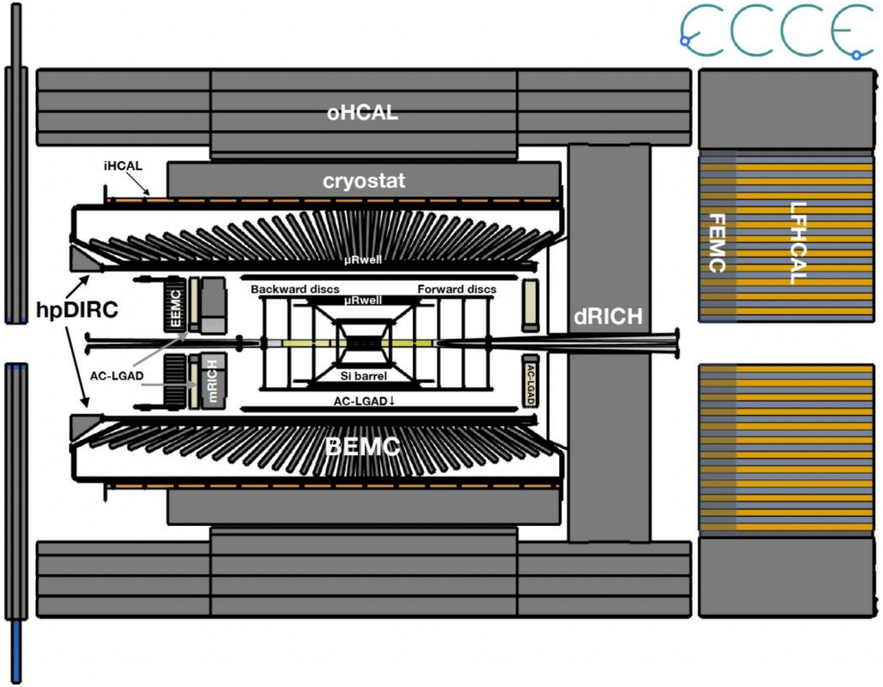
EIC Comprehensive Chromodynamics Experiment

  - CORE: smaller effort focused on specific exclusive reaction channels at 2nd IR
- **2022:** Selection of ECCE proposal as reference for EIC project detector
  - 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

EIC Project “Detector-1”







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 recently published 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 **EIC "Detector-1" 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

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

Key Characteristics:

- New 3T magnet
- Tracking: Si MAPS vertex, MicroMegas barrel, GEMs + μRWELL endcaps
- PID: hpDIRC, AC-LGAD ToF, dual radiator RICH, proximity-focused RICH
- Calo: Si-pixel imaging + SciFi hybrid barrel, PbWO + SciGlass hybrid endcaps
- Software: CERN-oriented (dd4hep, gaudi, ACTS)

EIC Canada involvement:

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

Canadian resources:

- ComputeCanada full sims

ECCE — *EIC Comprehensive Chromodynamics Experiment*

Key Characteristics:

- BaBar 1.5T magnet
- μRWell & Si tracker
- PID DIRC/mRICH/dRiCH
- Calo: Barrel, e-/Hadron endcap, Roman pots, ZDC, B0

EIC Canada involvement:

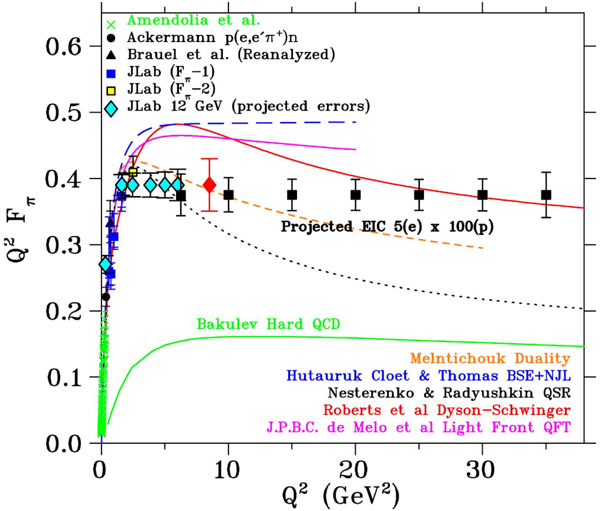
- U Regina: G. Huber (meson form factors at high Q^2); Z. Papandreou (spectroscopy of XYZ states)
- Event generators, Far forward detector studies
- Novel AI Work: Inner tracker design optimization; calo design using hierarchical density-based clustering

Canadian resources:

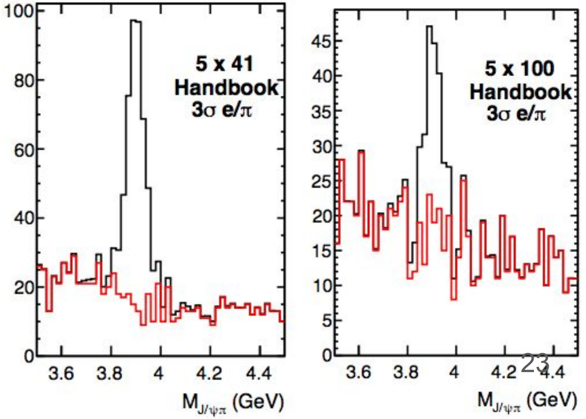
- JLab ifarm, Regina resources

Canadian Contributions: U. Regina

- 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 Flavor 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

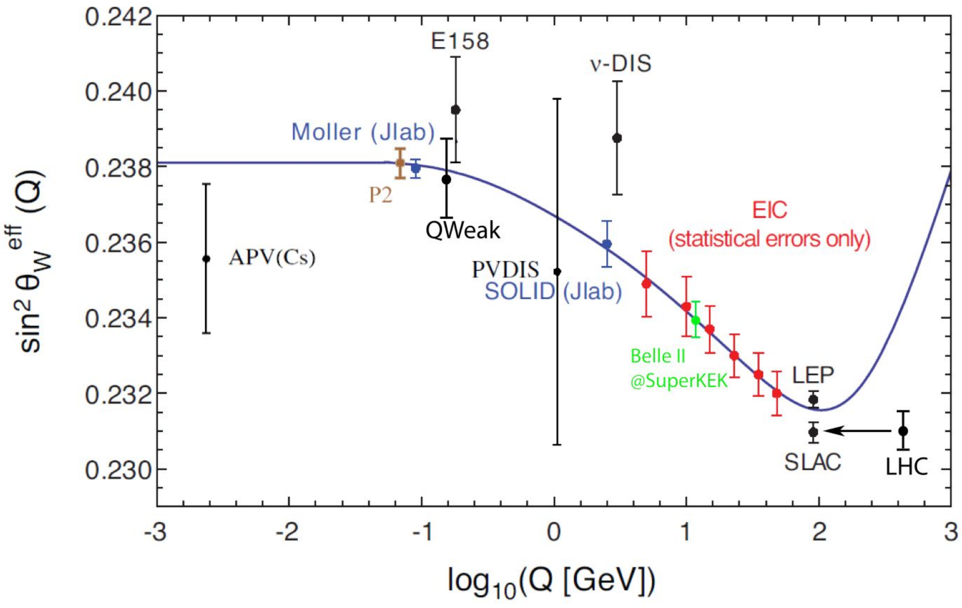


M(Z → J/ψ π)



Canadian 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

Connections Between EIC and TRIUMF Programs

- Key **accelerator expertise** at TRIUMF that enable the EIC physics program
  - SRF, e.g. **crab cavities** for HL-LHC: enable reaching the **highest luminosity** with the EIC
  - **Spin/beam dynamics** calculations: enable **highest polarization** even at high luminosity
  - Magnet technologies
  - TRIUMF hosted **EIC Accelerator Partnership Workshop** in 2021
- Key **detector technology expertise** at TRIUMF of relevance to EIC
  - **Large TPC detectors**: building on RHIC STAR detector, synergy with ISAC detectors
  - **Ultra-thin silicon tracking detectors**: TIGRESS-Silicon Tracker ARray (TI-STAR), EIC MAPS detectors
  - **Photon-based detectors**: EIC particle ID with Cerenkov or TOF, could use LaBr4 as ISAC
  - **Hybrid silicon detector technology**: low gain avalanche diode on CMOS electronics for radiation hard tracking, high gain avalanche diode for UV photon detection
- Significant opportunity to align TRIUMF efforts with EIC physics program

Thanks to Oliver Kester, Bob Laxdal, Fabrice Retière for discussions and insights.

EIC in the Vision for Canadian Subatomic Physics

- The Electron-Ion Collider will **uniquely address three profound questions** about nucleons and how they are assembled to form the nuclei of atom
  - **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 Electron-Ion Collider will enable **groundbreaking discoveries** across a multidisciplinary subatomic physics research portfolio.
  - Canadian involvement will **enhance the global recognition** of Canada's contributions to discovery research.
- The Electron-Ion Collider will lead to **major international collaboration** in research, technology, and innovation
  - Canadian subatomic physics community is uniquely positioned to contribute to a more **competitive Canada in discovery and innovation**.

Thank you

We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC). This research was enabled in part by support provided by Calcul Québec and Compute Canada.

New investigators are very much welcome, with full and associate member options available.

Aspiring graduate students can express interest at eic-canada.org

In the current phase we provide research opportunities in design and development of detectors.

EIC Canada – Projected Involvement

Connections Between EIC and TRIUMF Programs

- Strong engagement from Oliver Kester and Jens Dilling at TRIUMF, on both the accelerator science and the physics program
- TRIUMF participation in EIC Accelerator Workshop (UK/virtual, October 2020)
  - E.g. Bob Laxdal: “TRIUMF and the EIC”
- Direction connections between TRIUMF and the EIC accelerator design team

Erich Vogt’s “HERA Model” at the HERA electron-proton collider:

- Canadian contributions to both accelerator and detectors/data analysis
- IPP projects ZEUS and HERMES with significant Canadian involvement
- TRIUMF contributed to accelerator and the physics program of HERMES

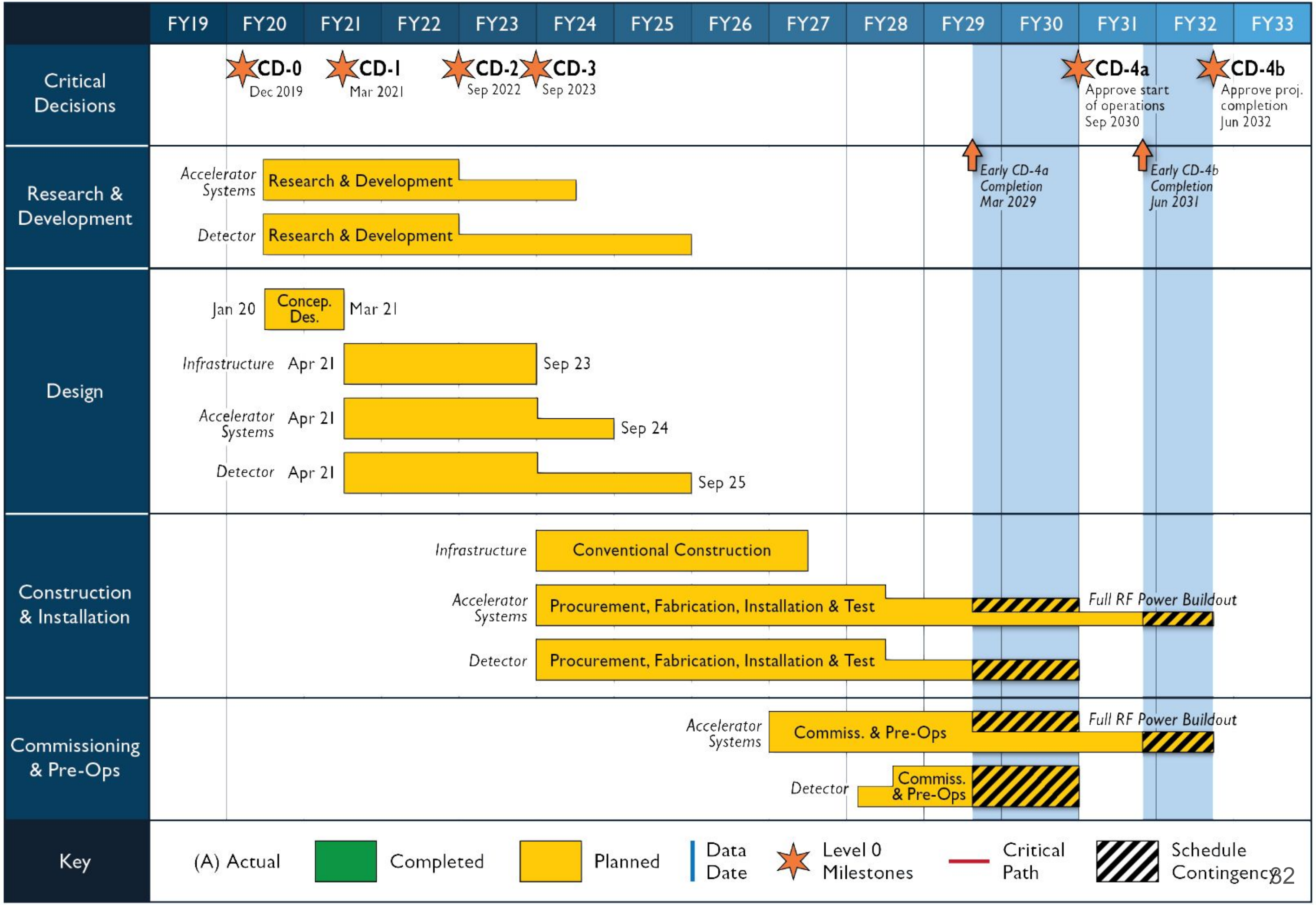
From HERA to EIC: EIC Canada would want to include TRIUMF’s scientific expertise in addition to its technical expertise.

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 Belle II collaboration is feasible
  - PI FTEs: growth to **~10 PIs** by start of operations in 2029
  - HQP: growth to **~20 HQP** by start of operations 2029
  - More detailed projections in EIC SAP LRP brief (at eic-canada.org)
- Funding resources:
  - **CFI: $1.5M to $6M** infrastructure on 2025-2028 timescale
  - **NSERC: Grow to $550k/year** by start of operations 2029

EIC Project Organization

Schedule

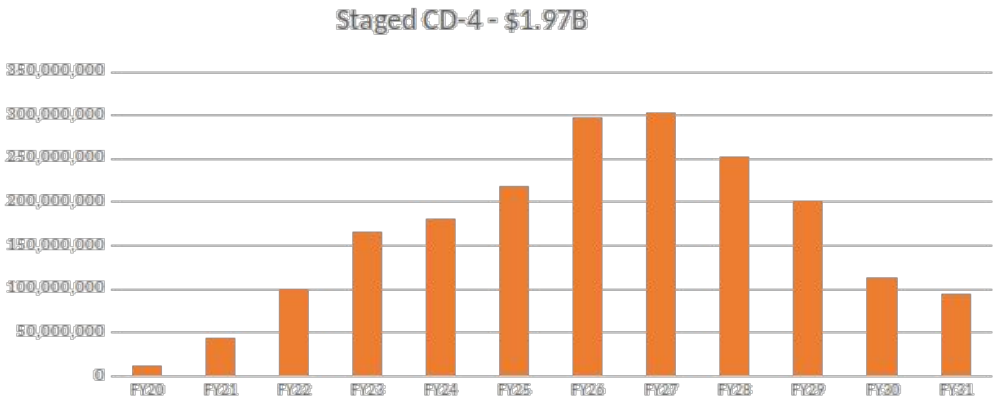


Ref: EIC UG, July 15, 2020

Reference Schedule and Funding Profile

Critical Decisions:

- CD-1: March 2021
- CD-2: September 2022
- CD-3: September 2023
- CD-4a: September 2030
- CD-4b: June 2032

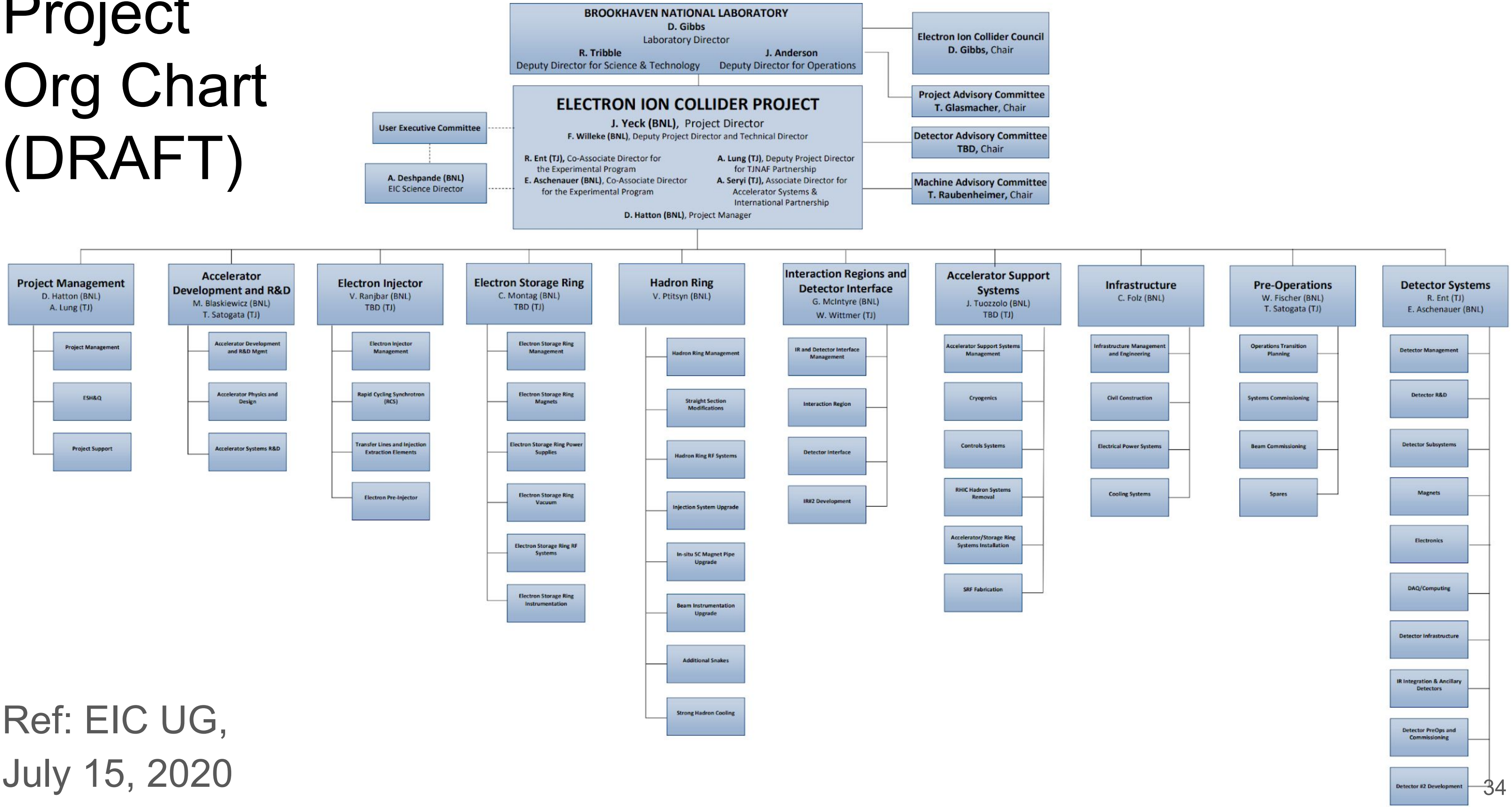


Staged Luminosity:

- Operations Start CD-4a
- Full RF Power Installed by CD-4b

Ref: EIC UG, July 15, 2020

Project Org Chart (DRAFT)



Ref: EIC UG, July 15, 2020