Future Electron-Ion Collider at BNL: The Quest to Understand the Fundamental Structure of Nuclear Matter

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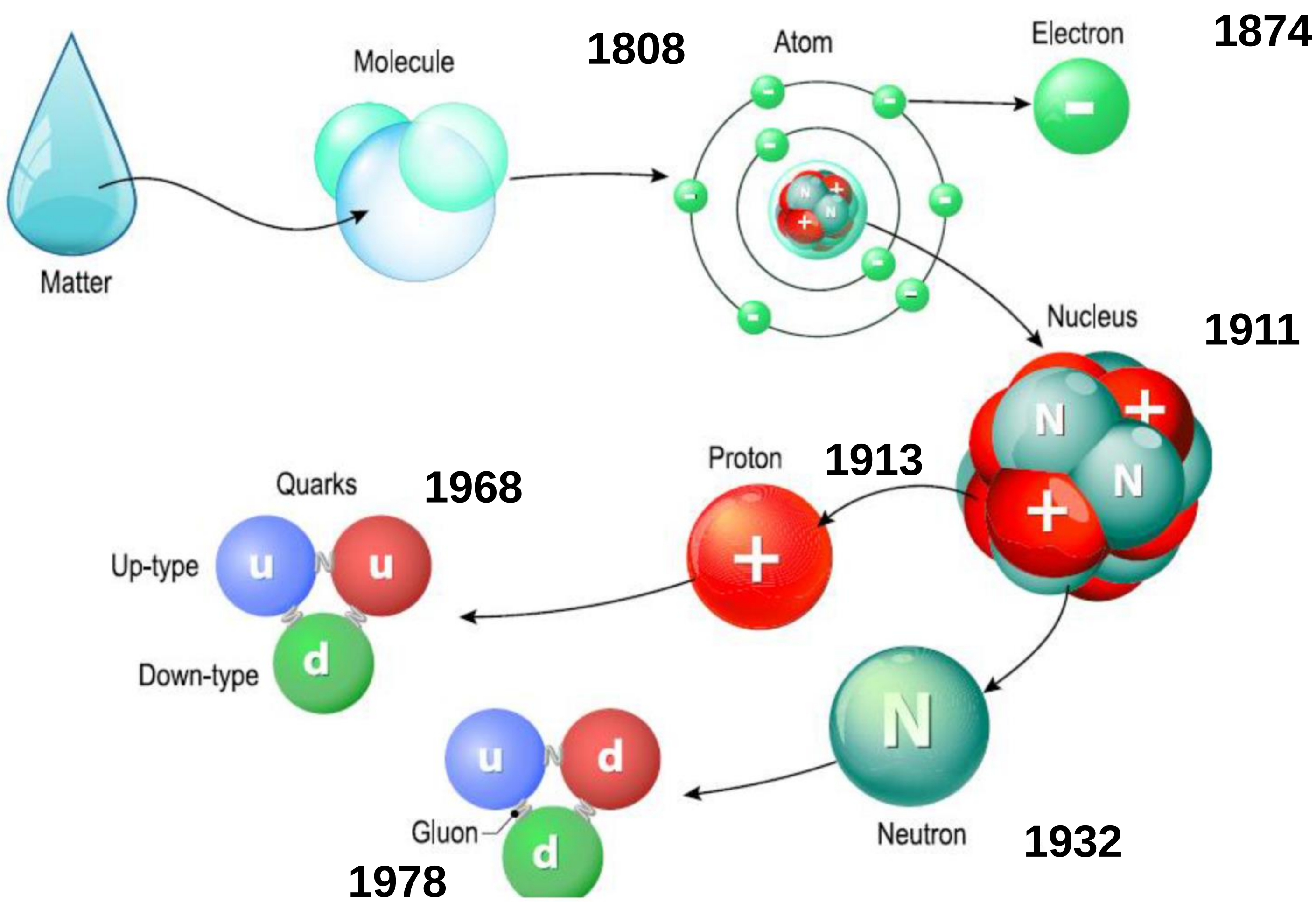
Electron Ion Collider

BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- The Quest to Understand the Fundamental Structure of Matter
- 3D Sub-Atomic Structure: Nuclear Femtography
- High Energy Electron Scattering – 1 Longitudinal Dimension
    - Path Towards 3D Sub-Atomic Structure
- EIC Planning and Science
- The US-Based Electron-Ion Collider (EIC) and Status
- EIC Summary – A Portal to a New Frontier

The Quest to Understand the Fundamental Structure of Matter



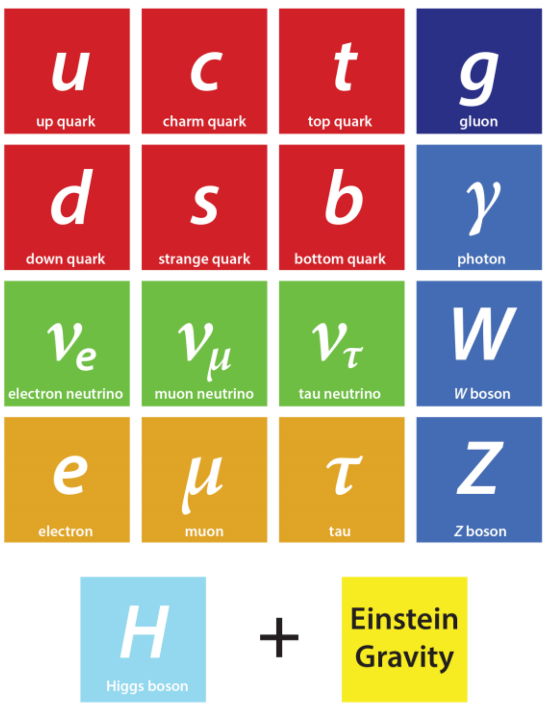
*EIC: Understanding the Glue that Binds Us All - **Without gluons, there would be no nucleons, no atomic nuclei… no visible world!***

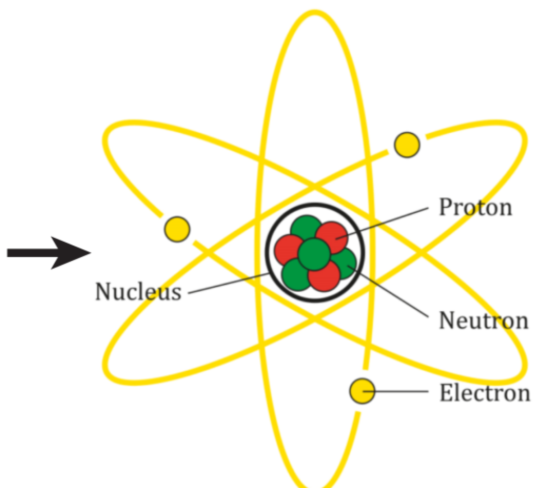
What is the World Made of?

Standing on the bathroom scales tells us our weight, i.e. quantifies our mass.

All the matter in the visible universe is understood in terms of subatomic particles and their constituents and interactions.

The Standard Model of Physics explains the fundamental structure of the visible matter in terms of quarks, gluons and their interactions.



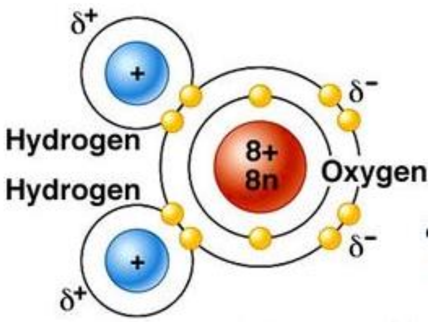


However, the mass of the quarks is much less than the mass of the proton.
The gluons are massless.
How can this make sense?

Nuclear Femtography – Subatomic Matter is Unique

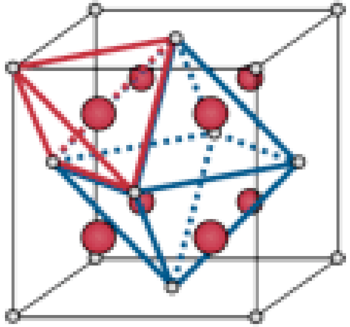
Most known matter has localized mass and charge centers – vast "open" space

Molecule:



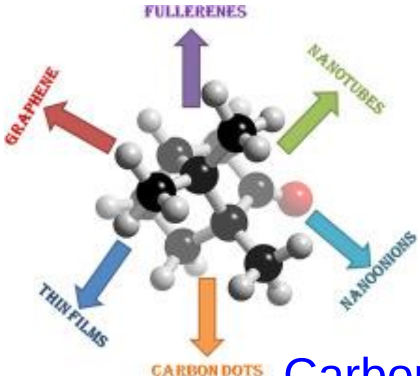
"Water"

Crystal:



Rare-Earth metal

Nanomaterial:

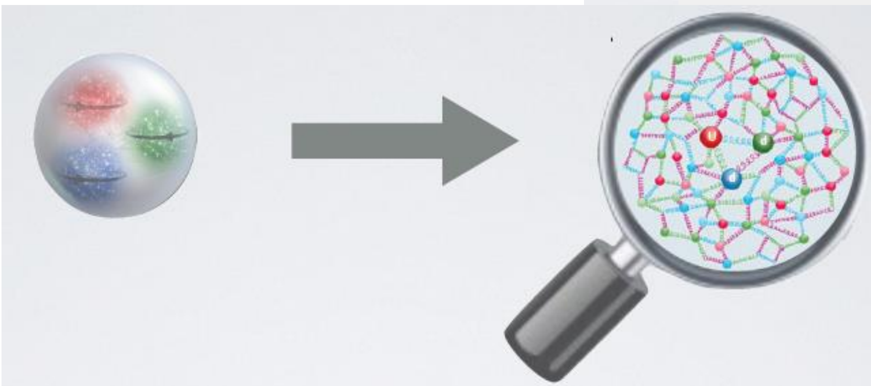


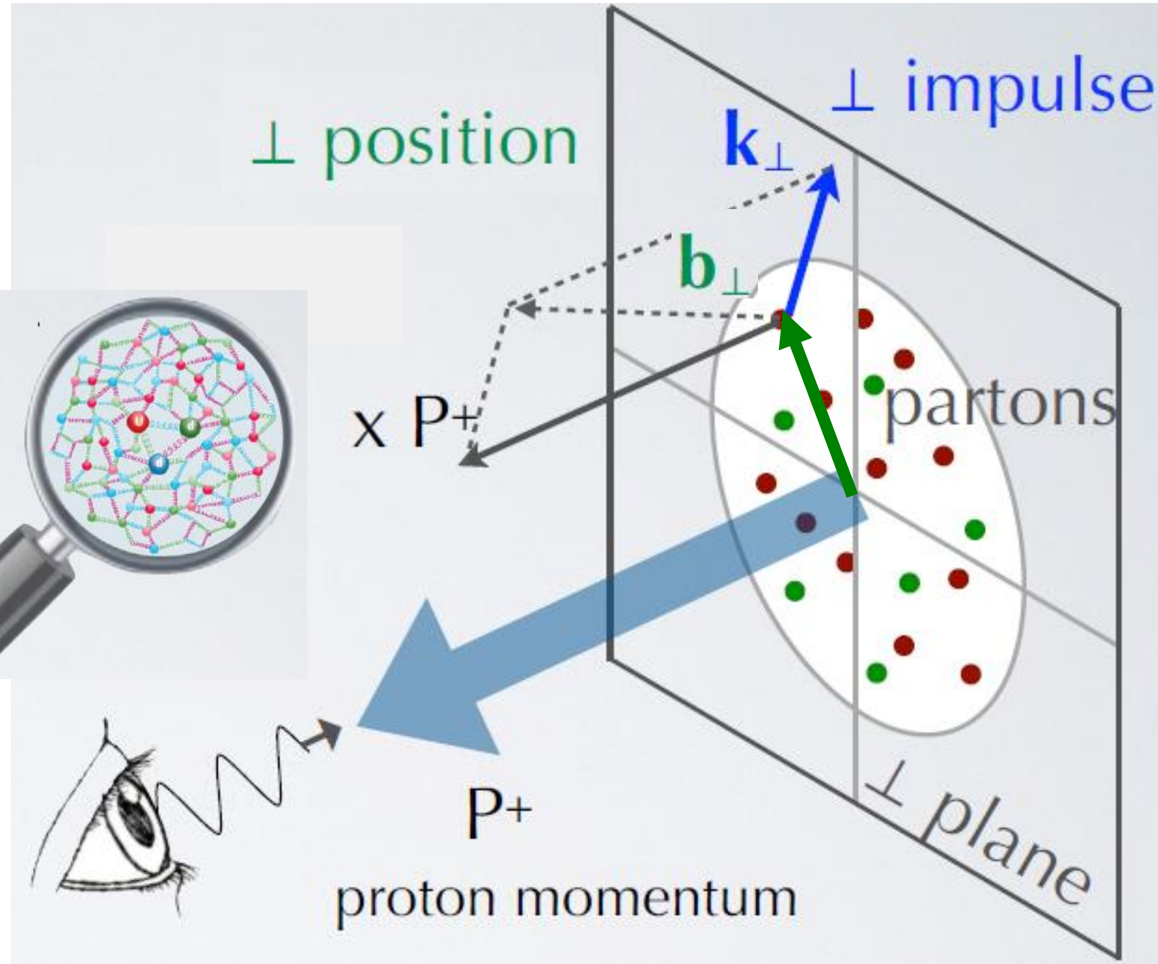
Carbon-based

Not so in nuclear matter! – unlike the more familiar molecular and atomic matter, the interactions and structures are inextricably mixed up in protons and other forms of nuclear matter, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

Imaging Physical Systems is Key to New Understanding

In other sciences, imaging the physical systems under study has been key to gaining new understanding.





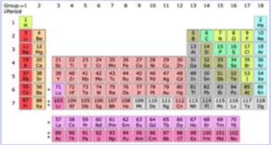
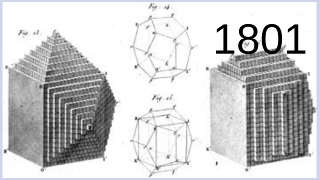
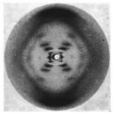
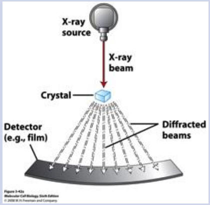
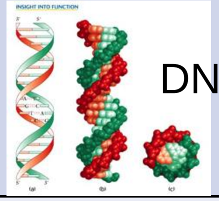
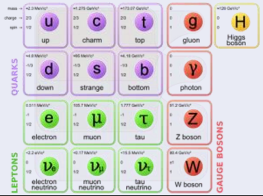
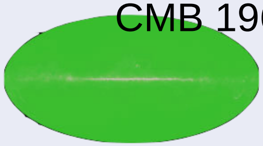
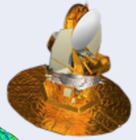
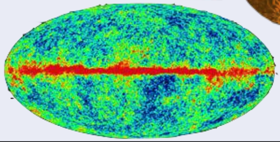
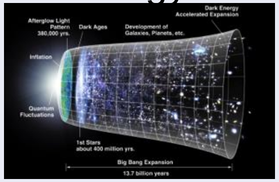
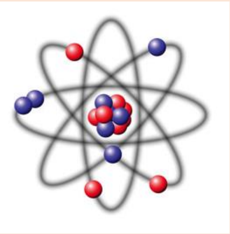
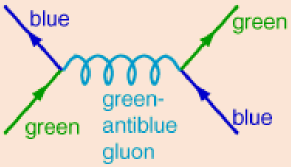
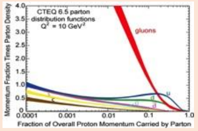
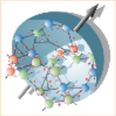
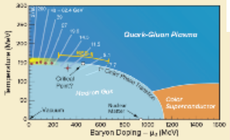
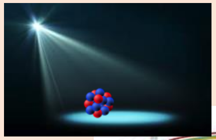
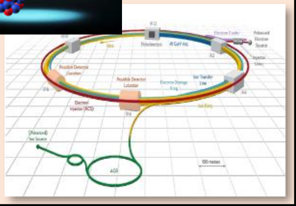
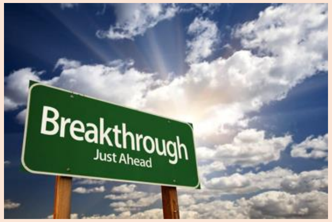
Structure mapped in terms of

b_T = transverse position

k_T = transverse momentum

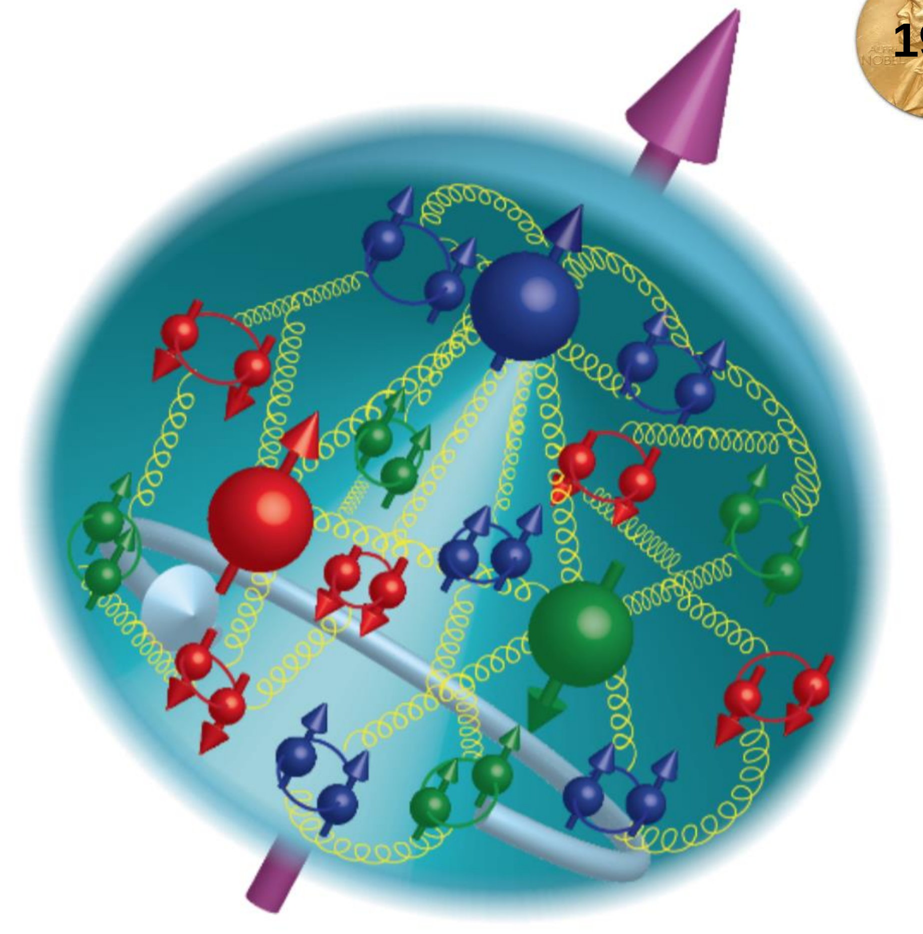
Also information on orbital angular momentum: **r** x **p**

Imaging Physical Systems is Key to New Understanding

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920)  	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure  CMB 1965	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \bar{\psi}(i\not{\partial} - g\not{A})\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$ 	Non-perturbative QCD. Structure 2017   	Electron-Ion Collider (~2030)  	Structure & Dynamics in QCD 

21st Century View of the Fundamental Structure of the Proton

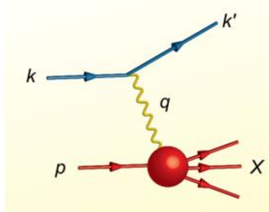
- Elastic electron scattering determines charge and magnetism of nucleon
- Approx. sphere with <r> ≈ 0.85 Fermi
- The proton contains quarks, as well as dynamically generated quark-antiquark pairs and gluons.
- Quark and gluon momentum fractions (in specific Infinite Momentum Frame) are well mapped out.
- The proton spin and mass have large contributions from the quark-gluon dynamics.



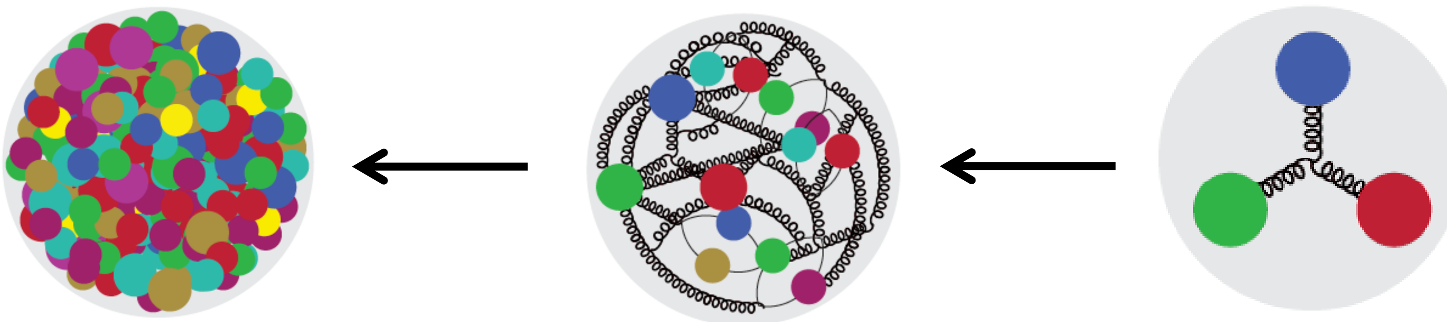
High Energy Electron Scattering

Lorentz Invariants

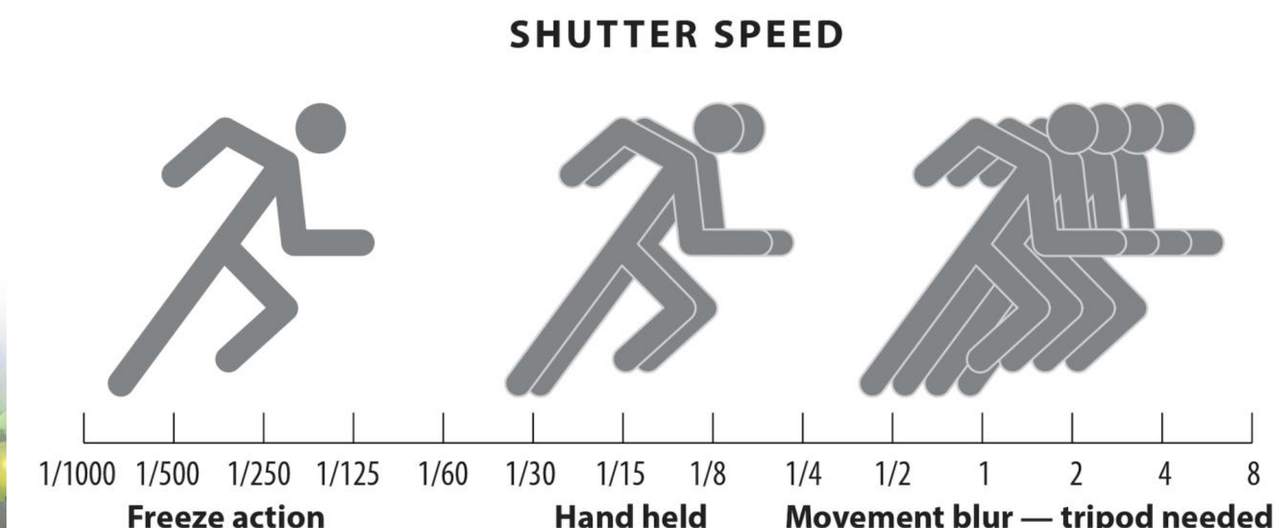
- $E^2_{CM} = (p+k)^2$
- $Q^2 = -(k-k')^2$
- $x = Q^2/(2p\bullet q)$



Snapshots where 0 < x < 1 is the shutter exposure time

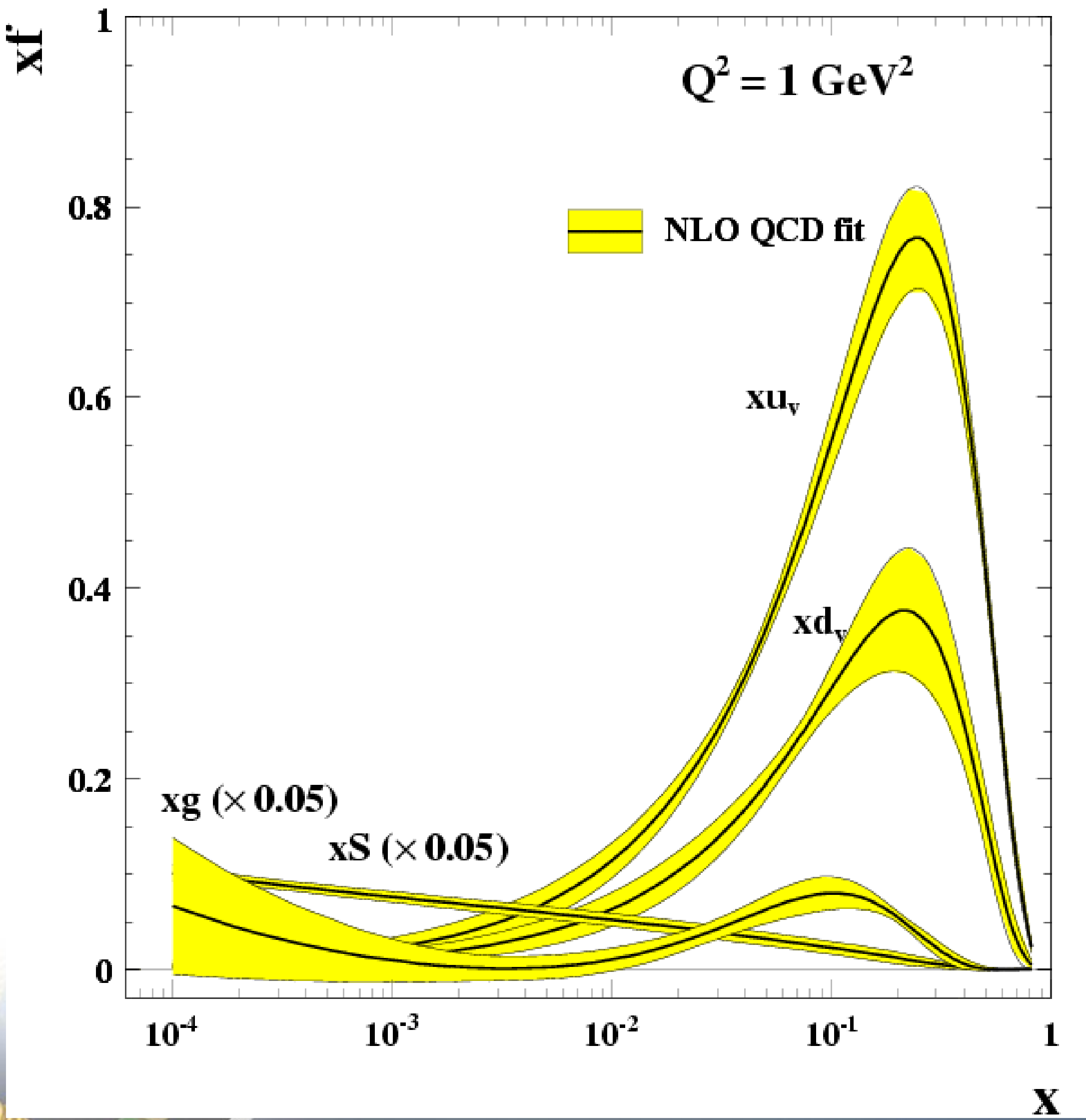


$x \approx 10^{-4}$	$x \approx 10^{-2}$	$x \approx 0.3$
Probe non-linear dynamics short exposure time	**Probe rad. dominated medium exposure time**	**Probe valence quarks long exposure time**



R. Milner

1 Longitudinal Momentum Distributions



1/Q ~ spatial resolution

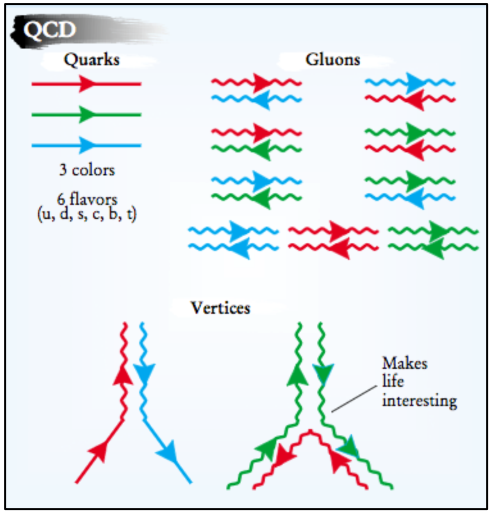
Note the scale factor of × **0.05** for g, S

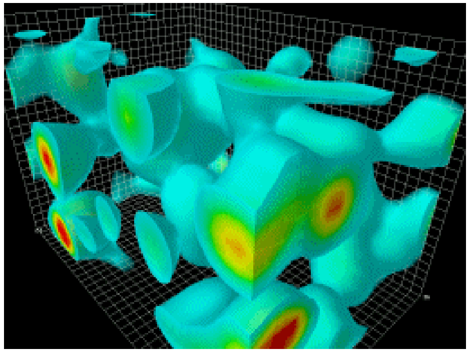
g – gluons
S – quark sea
u, d – up, down valence quarks

R. Yoshida
C. Gwenlan

EIC: 21st Century Laboratory of Emergent Dynamics in QCD

- 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 confinement
- Properties of hadrons – composite systems of quarks and gluons – are emergent phenomena and 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



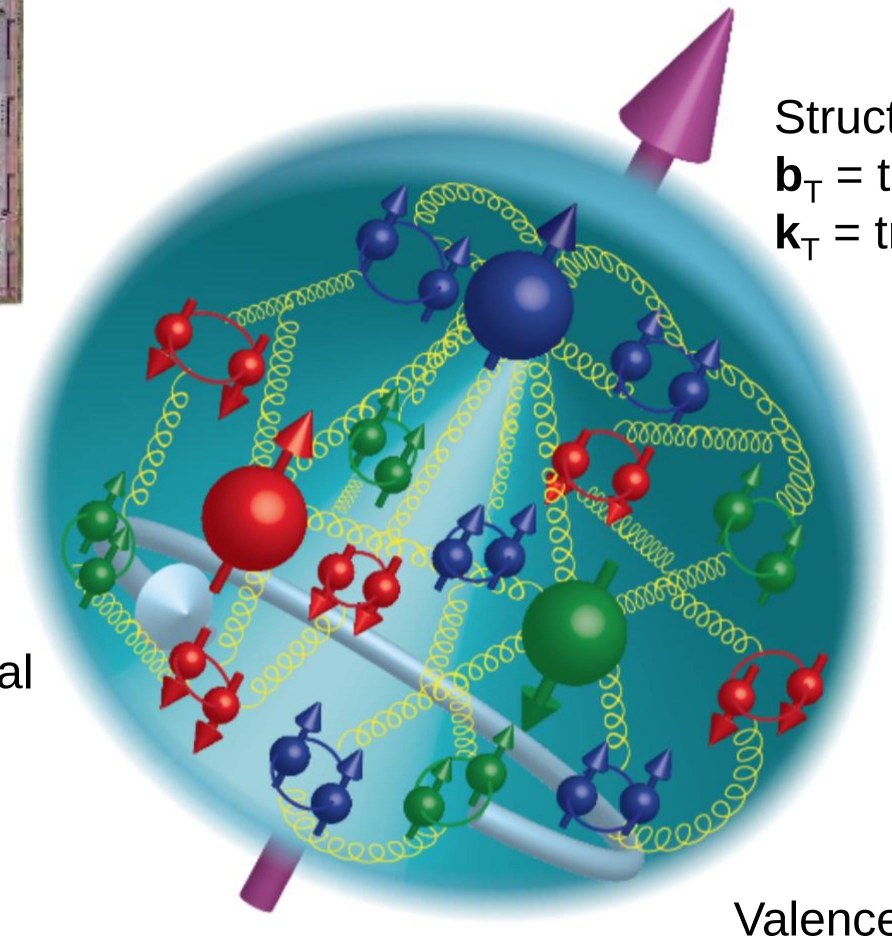


- The goal of the EIC is to provide us with an understanding of the internal structure of the proton and more complex atomic nuclei that is comparable to our knowledge of the electronic structure of atoms, which lies at the heart of modern technologies

Nuclear Femtography: 2 New Dimensions Transverse to Longitudinal Momentum

Recall orbital angular momentum: **r** x **p**

Structure mapped in terms of
b$_T$ = transverse position
k$_T$ = transverse momentum



Spin!
Nuclei!

Goal:
Unprecedented
21st Century Imaging
of Hadronic Matter

Direction of longitudinal momentum normal to plane of slide

Valence Quarks: JLab 12 GeV
Sea Quarks and Gluons: EIC

Exploring the 3D Nucleon Structure

- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
  - High luminosity, large acceptance experiments with polarized beams and targets.
  - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- **Deep Exclusive Scattering (DES)** cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location $\mathbf{b_T}$.

- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum ($\mathbf{k_T}$) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

Nuclear Femtography

What is Needed Experimentally?

experimental measurements categories to address EIC physics:

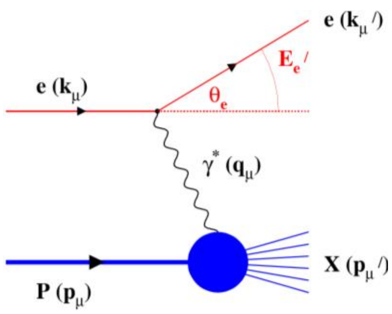
Parton Distributions in nucleons and nuclei

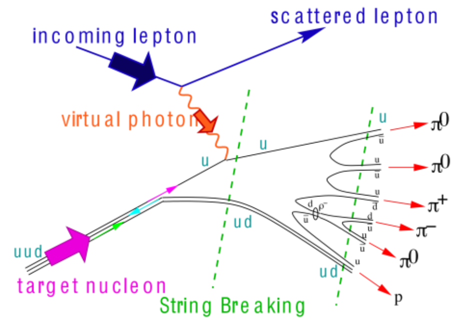
Spin and Flavor structure of nucleons and nuclei

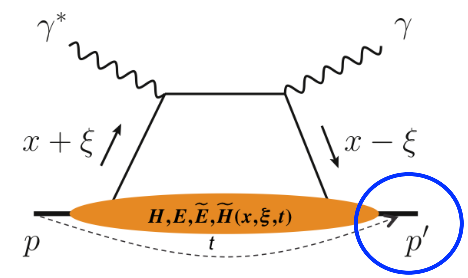
Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging







inclusive DIS

- measure scattered electron
- multi-dimensional binning: x, Q^2
  → reach to lowest x, Q^2 impacts Interaction Region design

semi-inclusive DIS

- measure scattered electron and hadrons in coincidence
- multi-dimensional binning: x, Q^2, z, p_T, Θ
  → particle identification over entire region is critical

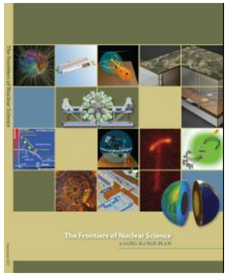
exclusive processes

- measure all particles in event
- multi-dimensional binning: x, Q^2, t, Θ
- proton p_t: 0.2 - 1.3 GeV
  → cannot be detected in main detector
  → strong impact on Interaction Region design

$\int Ldt$: 1 fb^{-1} | 10 fb^{-1} | 10 - 100 fb^{-1}

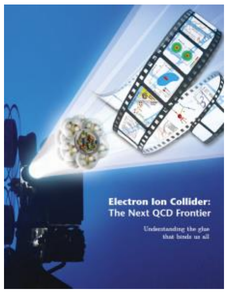
machine & detector requirements

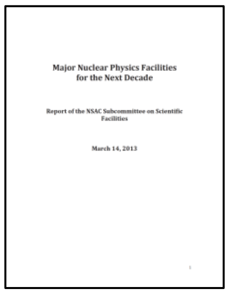
U.S. Electron-Ion Collider Planning 2007-18



2007 Nuclear Science Advisory Committee (NSAC) Long-Range Plan

"An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier"




Major Nuclear Physics Facilities for the Next Decade

Report of the NSAC Subcommittee on Scientific Facilities

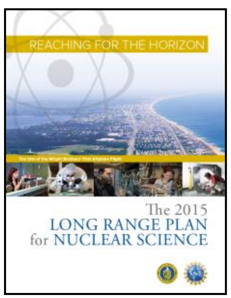
March 14, 2013

2013 Electron Ion Collider White Paper

(Writing committee convened by Jefferson Lab and BNL)

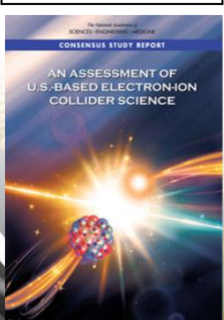
2013 NSAC Subcommittee on Future Facilities

Identified EIC as **absolutely central** to the nuclear science program of the next decade



2015 NSAC Long-Range Plan

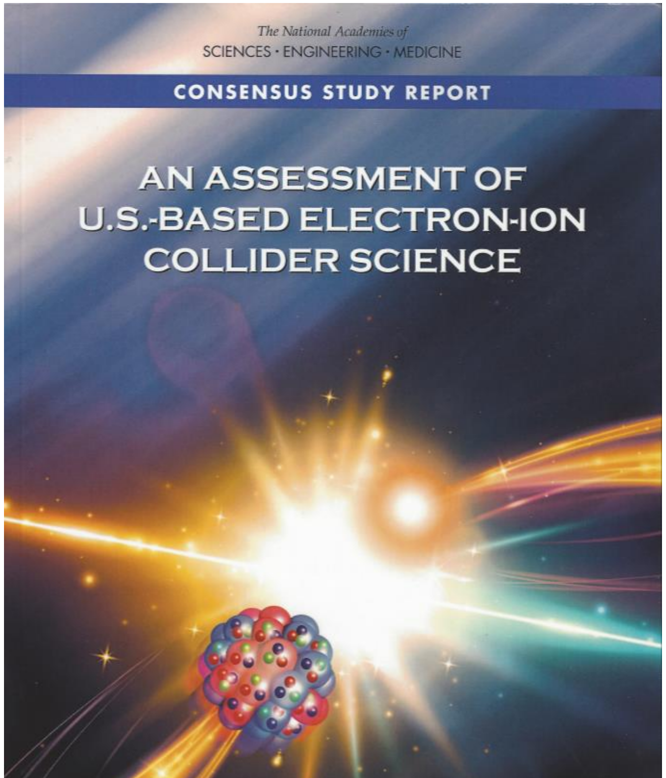
"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."



2018 National Academy of Sciences (NAS) – Assessment of U.S. Based Electron-Ion Collider Science

"…the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

EIC Science – Findings of the NAS Committee



EIC science is compelling, timely and fundamental

Developed by NAS committee with broad science perspective

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

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

- **Finding 2:** These three high-priority science questions can be answered by an EIC with **highly polarized beams** of electrons and ions, with sufficiently **high luminosity** and sufficient, and **variable**, center-of-mass **energy**.

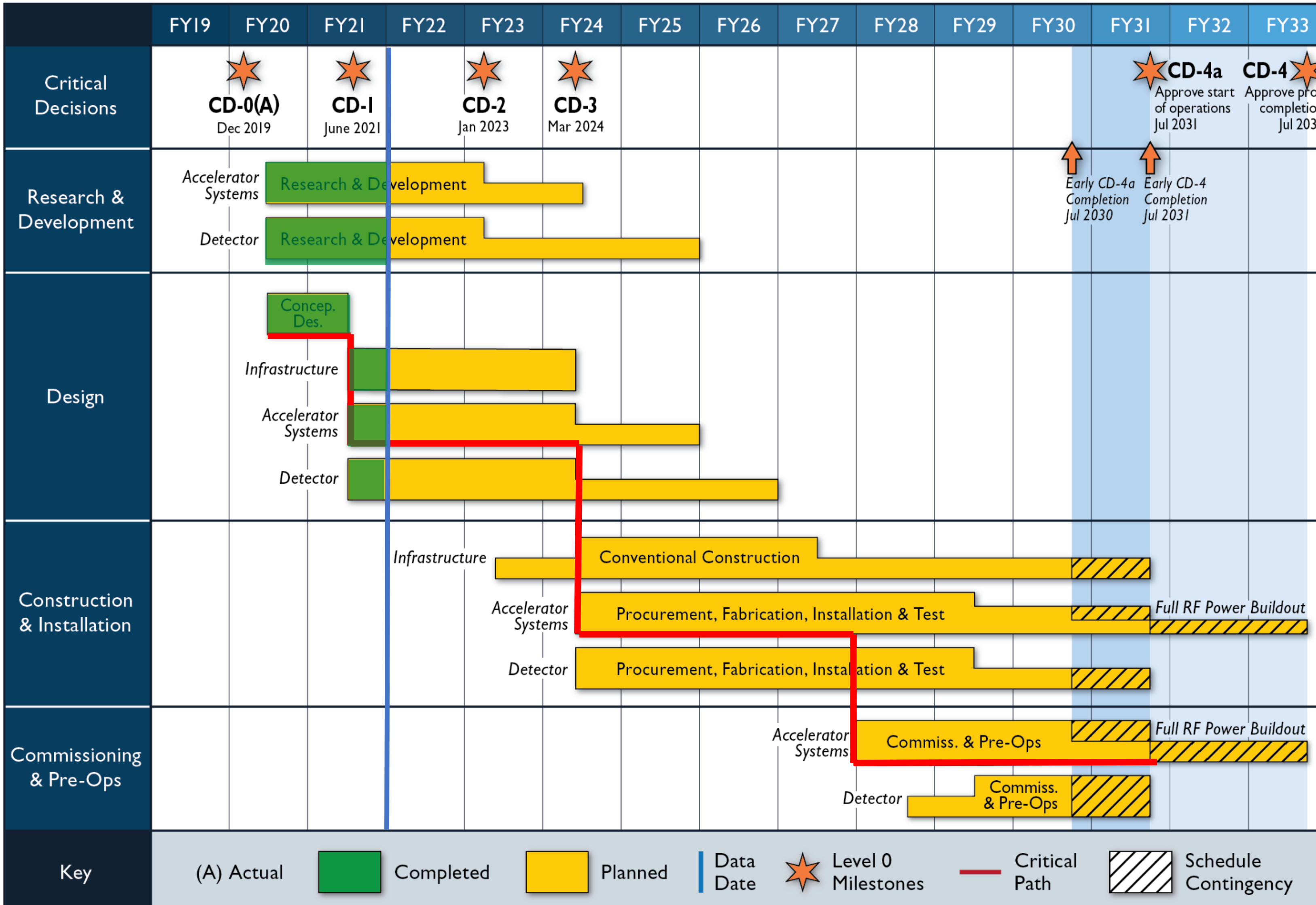
EIC Recent History

Event	Date
DOE Mission Need Statement Approved	January 22, 2019
DOE Independent Cost Review	July 2019
DOE Electron Ion Collider Site Assessment	October 2019
Critical Decision – 0 (CD-0) Approved	December 19, 2019
DOE Site Selection Announced	**January 9, 2020**
BNL TJNAF Partnership Agreement	May 7, 2020
DOE Office of Science Status Review	September 9-11, 2020
Independent EIC Conceptual Design Review	November 16-18, 2020
DOE Office of Science CD-1 Review	January 26-29, 2021
DOE Independent Cost Review	January - February 2021
CD-1 Approval	**June 29, 2021**

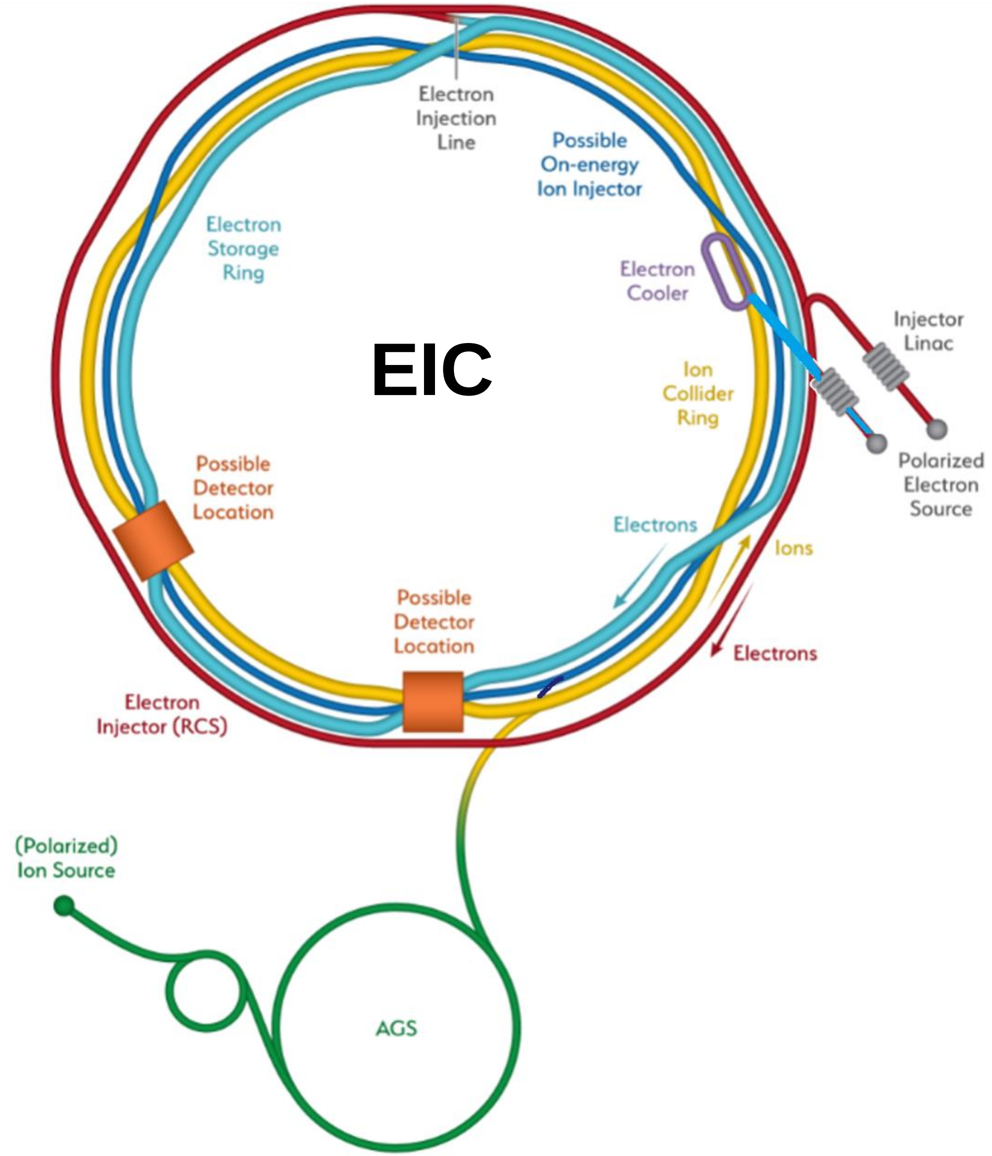
Schedule

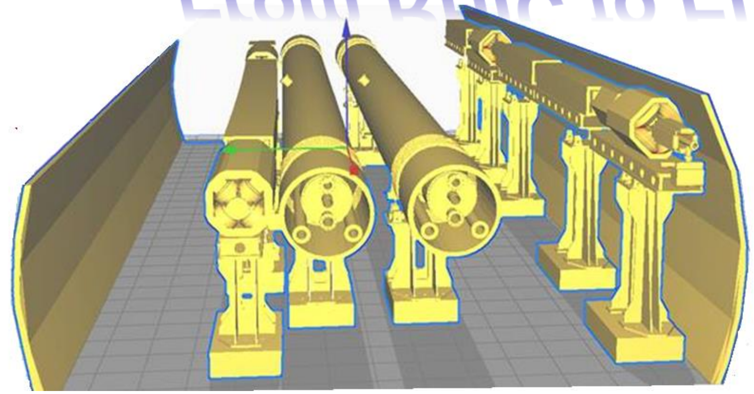
Goal for CD-2/3A: early 2023

EIC operations are a decade away



From RHIC to EIC





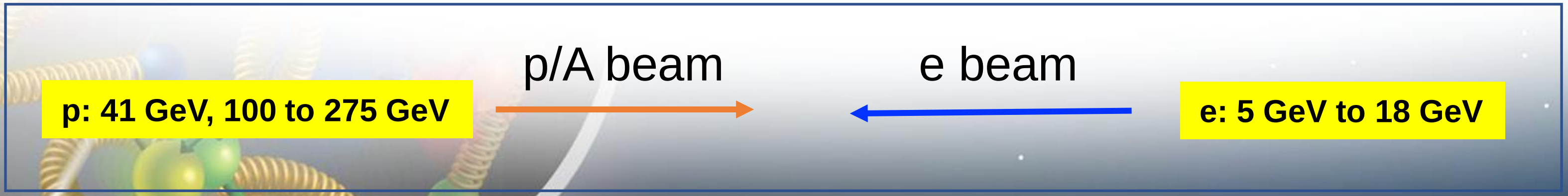
The strong hadron cooling facility completes the facility

- Hadron Storage Ring
- Electron Storage Ring
- Electron Injector Synchrotron
- Possible on-energy Hadron injector ring
- Hadron injector complex

EIC Design per NSAC and NAS Requirements

Note: this is per definition, as these were the parameters given to the labs for the independent cost review and independent EIC site assessment.

• Center of Mass Energies	20 GeV – 140 GeV
• Maximum Luminosity	10^{34} cm^{-2}s^{-1}
• Hadron Beam Polarization	80%
• Electron Beam Polarization	80%
• Ion Species Range	p to Uranium
• Number of interaction regions	up to two

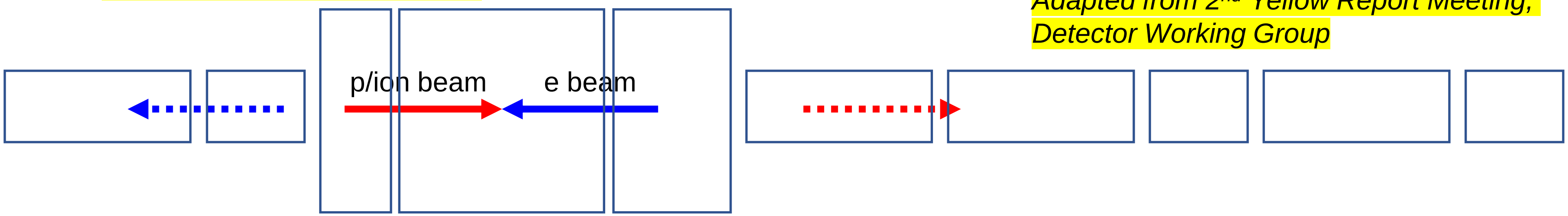


Cartoon/Model of the Extended Detector and IR

- ❑ EIC physics covers the entire region (backward, barrel/central, forward)
- ❑ The detector requirements differ in these regions due to the EIC asymmetry
- ❑ Many EIC science processes rely on excellent scattered electron detection and excellent and fully integrated forward detection scheme

p: 41 GeV, 100 to 275 GeV **e: 5 GeV to 18 GeV**

Adapted from 2nd Yellow Report Meeting, Detector Working Group



far-backward e-detection	e final-focus quads	"Central detector", includes e-endcap, barrel, and p/ion endcap detectors	forward dipole incl. h detection	Ion final-focus quads	forward dipole	far-forward h-detection	far-forward h-detection
Low-Q^2 spectroscopy		Inclusive Structure Functions, TMDs, heavy flavors and jets, electrons for GPDs	GPDs/DVCS, tagging, diffraction, high-medium t			Baryon decay π/K structure evaporated n	GPDs, tagging, diffraction, lowest-t
GEMs Diamond detectors?		Vertex and Tracking detectors, particle identification detectors, calorimetry detectors, muon detectors, etc.	Si/GEMs Roman pots, e/γ calorim.			GEMs Roman pots e/γ calorim.	Roman pots ZDCs

physics examples

detector examples

Highly integrated detector system

Highly Integrated detector system: ~75m
1. Central detector: ~10m
2. Backward electron detection: ~35m
3. Forward hadron spectrometer: ~40m

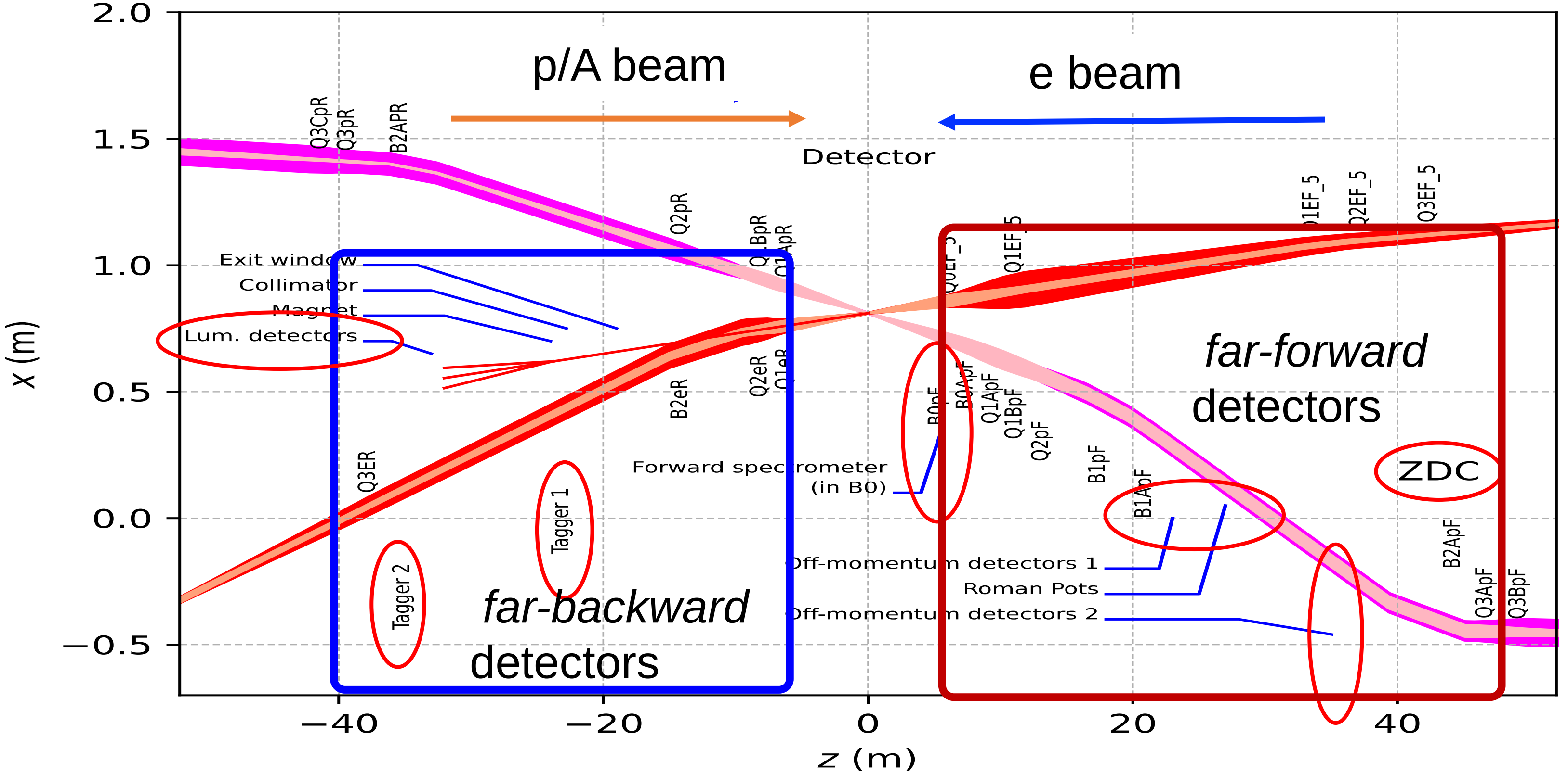
Lesson learned from HERA – ensure low-Q^2 coverage

Various stage detector to capture forward-going protons and neutrons, and also decay products (Δ, Λ).

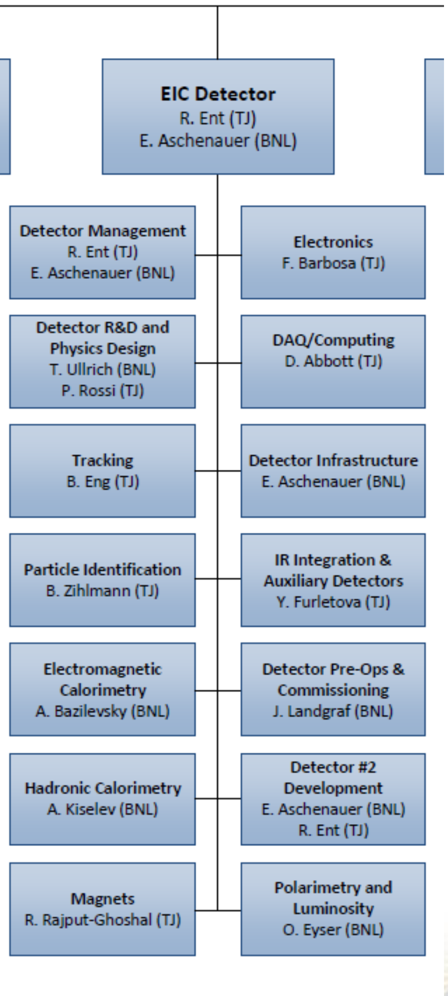
Polarimetry not shown here

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV



Joint responsibility



- Co-associate directors for Experimental Program:
  Rolf Ent (JLab) and Elke Aschenauer (BNL)
  - 6.10 Detectors
  - 6.10.01 Detector Management
  - 6.10.13 Detector #2 Development
- We also heavily utilize Walt Akers (Jlab) who is a Systems Engineer
- R&D scope has both a BNL and JLab person
  - 6.10.02 Detector R&D — Thomas Ullrich (BNL), Patrizia Rossi (JLab)
- Some scope has a BNL person
  - 6.10.05 EM Calorimetry — Alexander Bazilevsky (BNL)
  - 6.10.06 Hadronic Calorimetry — Alexander Kiselev (BNL)
  - 6.10.10 Detector Infrastructure — Elke Aschenauer (BNL) - acting
  - 6.10.12 Detector Pre-Ops — Jeff Landgraf (BNL)
  - 6.10.14 Polarimetry & Luminosity — Oleg Eyser (BNL)
    (but L4 electron polarimetry has David Gaskell (JLab))
- Some scope has a JLab person
  - 6.10.03 Tracking — Brian Eng (JLab)
  - 6.10.04 Particle Identification — Beni Zihlmann (JLab)
  - 6.10.07 Magnets — Renuka Rajput-Ghoshal (JLab)
  - 6.10.08 Electronics — Fernando Barbosa (JLab)
  - 6.10.09 DAQ/Computing — David Abbott (JLab)
  - 6.10.11 IR Integration, Aux. Detectors — Yulia Furletova (JLab)

Much Progress in E&D – with some help of our friends…

Electron Endcap EMCal
- Initial concept (CUA)
- Frame, cooling system (IJCLab-Orsay)

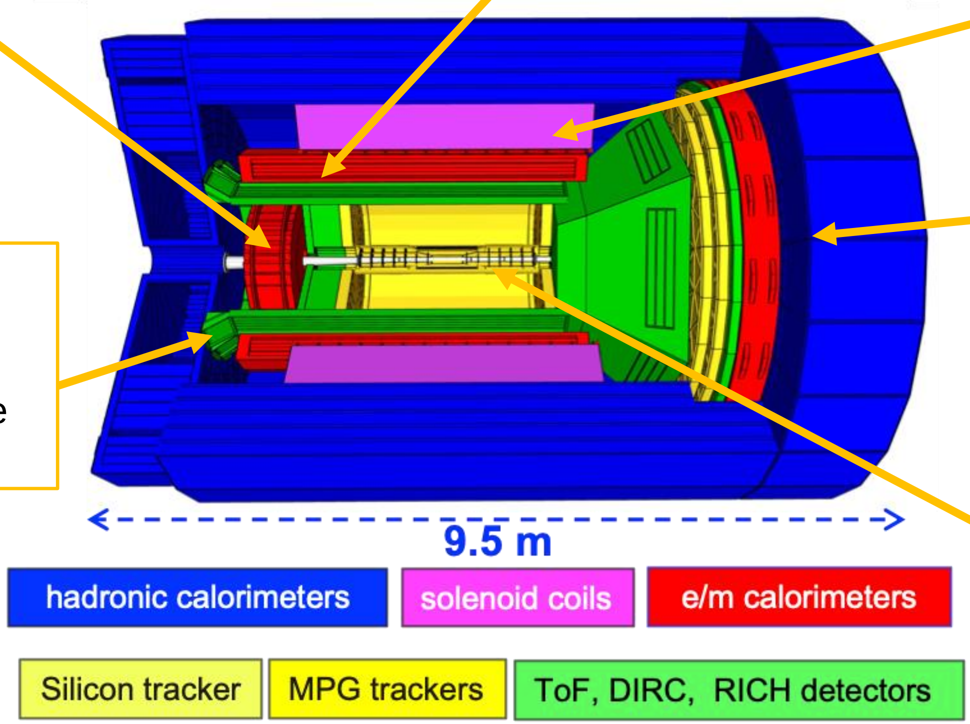
Barrel EMCal Support
- EMCal options (ANL, UCLA, CUA)
- Impact on support structure and frame (MIT, Israel)

Solenoid Preliminary Design
- In-kind contribution from CEA-Saclay, **working with JLab Magnet Group**

Forward EMCal, HCal support + motion
- ORNL
- Similar motion as backward HCal

DIRC
- Re-use concept (CUA, GSI)
- Support structure (GSI)

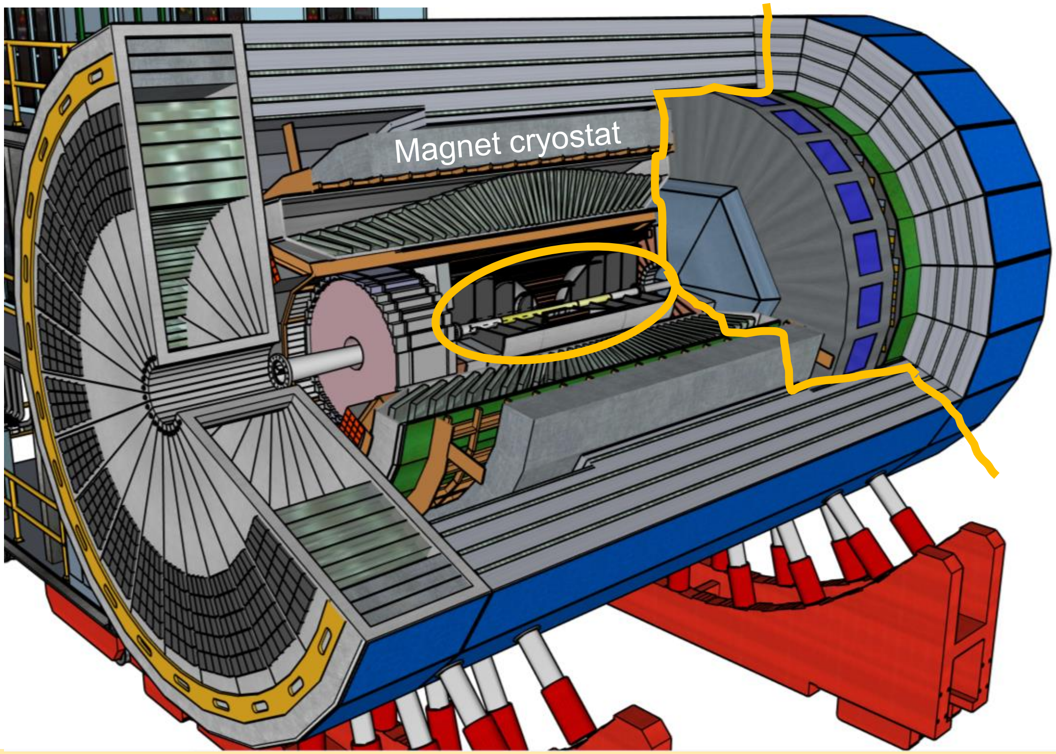
Si Barrel and disks mechanical
- LANL and LBNL **in collaboration with JLab**

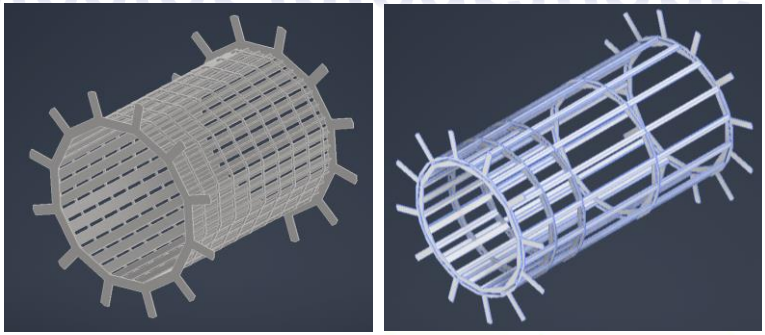


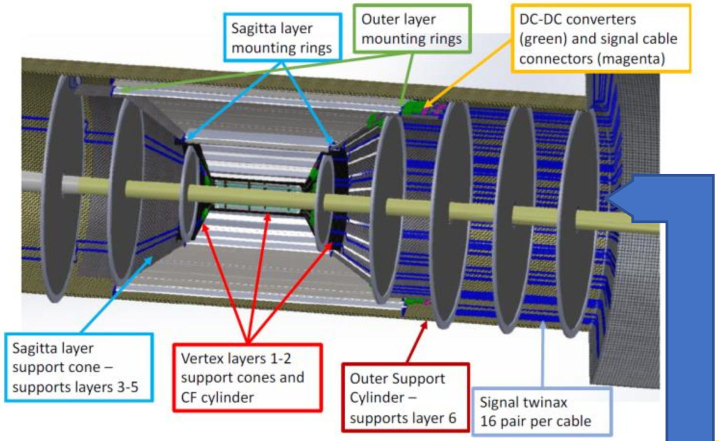
BNL:
- Support for barrel EMCal and a universal frame that holds the DIRC and detectors "within" (backward EMCAl, mRICH, etc.)
- Support of backward Hadron Calorimeter (Hcal), and how to split it for maintenance mode.
- Variations of Barrel Hadron Calorimeter and stacking/assembly modes.
- IR integration.

Progress – Detector Integrations

Example with SketchUp







- Already good engineering concepts for everything left of orange line:
  - Frames to hold different barrel EM calorimeters
  - Universal frame to hold DIRC and detectors inside, including backward EM calorimeter
  - Frame and cooling for backward EM calorimeter
  - Backward hadronic calorimeter and way to split for maintenance → now transferred to hECaL & hHCal
  - Reuse of STAR cradle, may need sleeve or jackets to adjust for EIC detector diameter
- Advanced conceptual as of yet for everything right of orange line
  - Tracking, forward RICH, forward EM calorimeter and hadron calorimeter → recent progress in tracking

Experimental Program Preparation

- Year-long EIC User Group driven EIC Yellow Report activity
  - Science Requirements and Detector Concepts for the EIC
  - arXiv:2103.05419 – 141 citations (10/17/21)
  - To appear in Nuclear Physics A as one volume
- Drives the requirements of EIC detectors
- Call for Collaboration Proposals for Detectors launched

BNL and TJNAF Jointly Leading Process to Select Project Detector		
2020	Call for Expressions of Interest (EOI) https://www.bnl.gov/eic/EOI.php	May 2020
	EOI Responses Submitted	November 2020
	Assessment of EOI Responses	Finalized
2021	Call for Collaboration Proposals for Detectors https://www.bnl.gov/eic/CFC.php	March 2021
	BNL/TJNAF Proposal Evaluation Committee	Spring 2021
	Collaboration Proposals for Detectors Submitted	December 2021
✔	Decision on Project Detector	March 2022

EIC Proto-Collaborations at a Snapshot

- ECCE (https://www.ecce-eic.org)
  - A detector based on an existing 1.5T solenoid in either EIC interaction region
  - Contacts: Or Hen (MIT), Tanja Horn (CUA), John Lajoie (Iowa State)
  - ~80 collaborating institutions
  - Includes institutions from Armenia, Canada, Chile, China, Croatia, Czech, France, Germany, Israel, Japan, Korea, Russia, Senegal, Slovenia, Taiwan, UK

- ATHENA (https://sites.temple.edu/eicatip6/)
  - An EIC experiment at IP6 based on a new 3 T magnet and the YR Reference Detector
  - Spokesperson Silvia Dalla Torre (INFN Trieste), deputy Bernd Surrow (Temple)
  - ~100 collaborating institutions
  - Includes institutions from Armenia, Canada, China, Czech, France, Italy, India, Poland, Romania, UK

- CORE (https://eic.jlab.org/core/)
  - An EIC Detector proposal based on a new 2-2.5 T compact magnet at IP8
  - Contacts: Charles Hyde (ODU) and Pawel Nadel-Turonski (SBU)
  - Smaller-scale effort, ~20 institutions
  - Mainly US-based

International Engagement

- Large international component of EIC User Group.
  - Several representing functions: vice-chair of EICUG, vice-chair of IB, three further international members of Steering Committee.
- Large international component of Yellow Report (417 authors of which 175 (42%) are non-US).
- International interest and in-kind contributions to Detector R&D.
- Strong component of ongoing detector proposal process
  - At highest level, contact person roles of proto-collaboration
  - Various WG lead roles (Canada, France, Italy, Israel, Japan, Korea, UK)
- Interest in EIC scope indicated through earlier Expressions of Interest call
  - To be further solidified during detector proposal process
  - Some signs of encouragement, for example:
    - ✓ EIC featured in Canadian Long-Range Planning exercise
    - ✓ French in-kind support for E&D to 3T Magnet, backward EM calorimeter
    - ✓ Recent UK/STFC support for UK detector R&D to lead role (3M£)
    - ✓ Discussions among Japan and Korea on joint efforts
    - ✓ Large India contribution to scientific efforts (software, validation)

Uniqueness of EIC

- **EIC will be unique facility worldwide**: there is no equivalent of the EIC science capabilities *due to its versatility in energies, polarization, and ion species*.
- Global competition can exist in subsets of the EIC science, e.g.:
  - Ideas for an Electron-Ion Collider in China (EicC) which would operate at center-of-mass energies similar as COMPASS@CERN.
  - Annual ongoing workshops related to adding a high-energy electron beam to interact with LHC beams at CERN (LHeC).
- In addition, several programs have natural complementarity:
  - Consideration to add a fixed-target spin program at the LHC – LHCspin (@LHCb).
  - The AMBER experiment at CERN mainly emphasizing the valence and sea quark regions with pion and kaon beams.
  - Ultraperipheral and heavy-ion reactions at CERN/LHC to constrain low-x behavior.
  - (within the US) The polarized RHIC pp and pA program, addressing universality questions in QCD.
  - (within the US) The Jefferson Lab fixed-target program, mainly emphasizing the valence quark region.

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Summary

- EIC Program aim: Revolutionize the QCD understanding of nucleon and nuclear structure and associated dynamics. Explore new states of QCD.
  - 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?
- An EIC Detector is unique in its integration in the Interaction Region and extends over 75 meters to achieve acceptance for scattered electrons, particles associated with struck quark (or associated gluon), and all particles with initial proton/ion.
- The EIC Detector Technology is well under control. This benefits from a long Generic EIC-related Detector R&D Program hosted by BNL.
- There is large and growing domestic and international interest in the EIC, with the EICUG at ~1300 members now: http://www.eicug.org/pnb/client/
- The Yellow Report (https://arxiv.org/abs/2103.05419, >140 citations already) drives the science requirements and detector concepts of the EIC.
- A Call for Collaboration Proposals for Detectors at the EIC was released in March (https://www.bnl.gov/eic/CFC.php), with deadline of submission December 1, 2021.