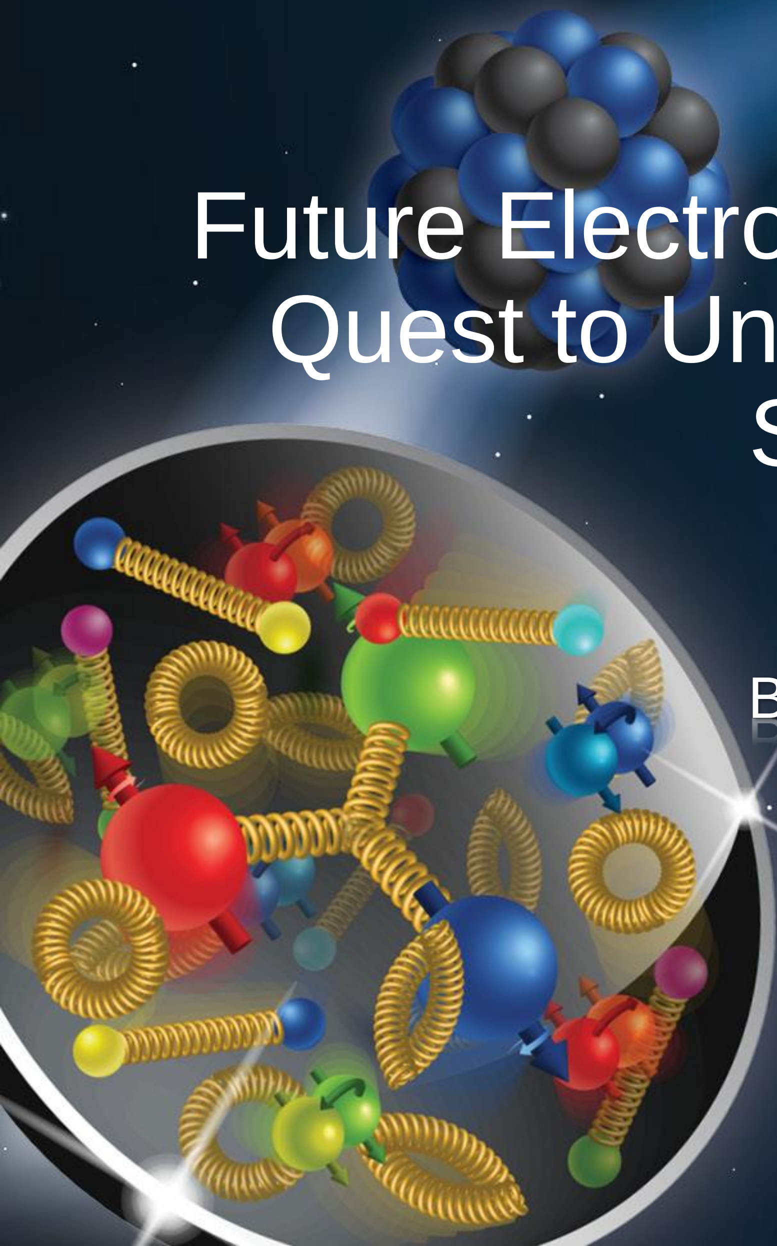
Future Electron-Ion Collider at BNL: The Quest to Understand the Fundamental Structure of Nuclear Matter



Rolf Ent (Jefferson Lab)

Baryons 2022 – International Conference on the Structure of Baryons

7-11 November 2022, Sevilla, Spain

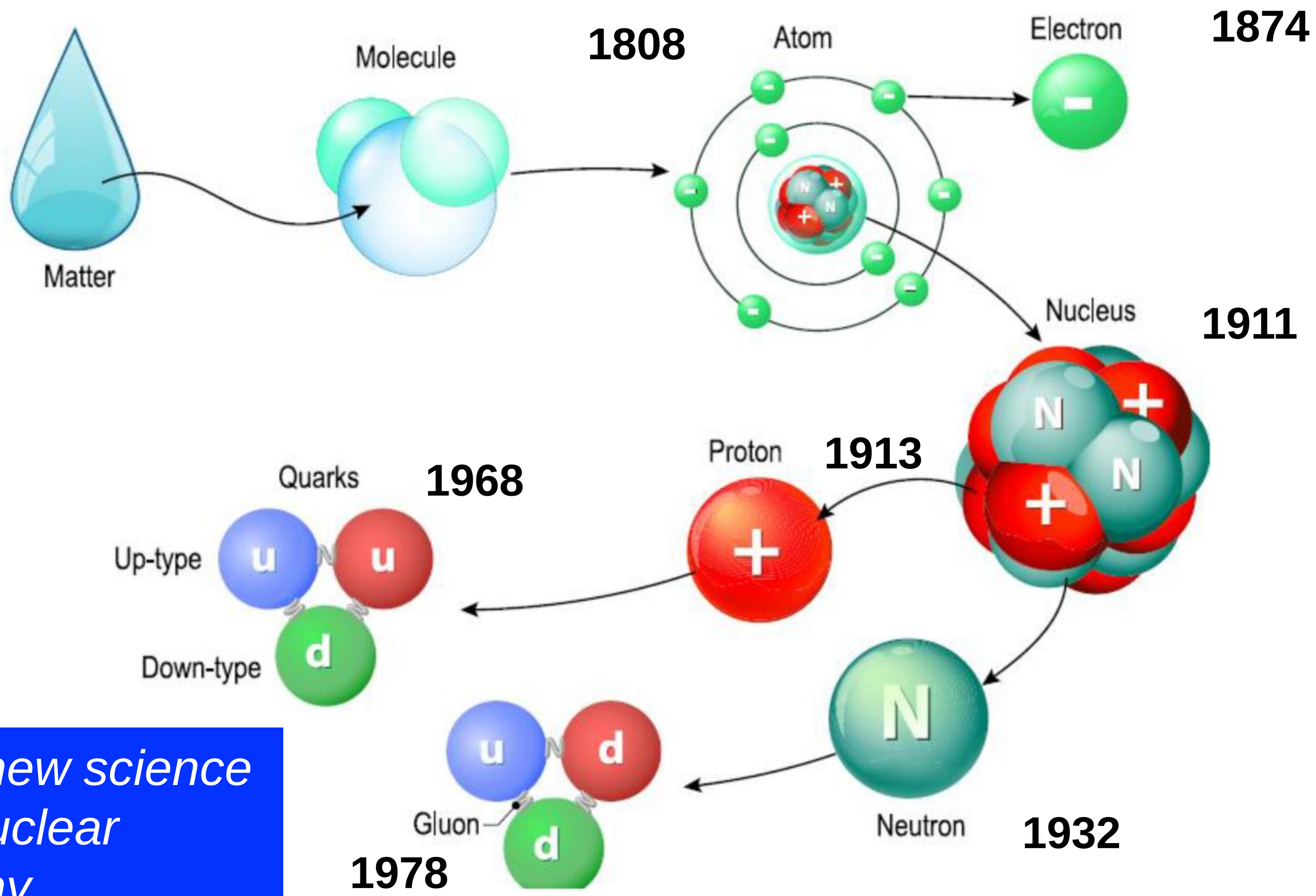
Electron Ion Collider

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
- 21st Century View of the Fundamental Structure of the Proton:
  The Emergence of Mass and Structure
- The US-Based Electron-Ion Collider Scope and Status
- The EIC Detector Concept and Considerations
- EIC and Accelerator Science and Technology
- EIC: 21st Century Laboratory of Emergent Dynamics in QCD

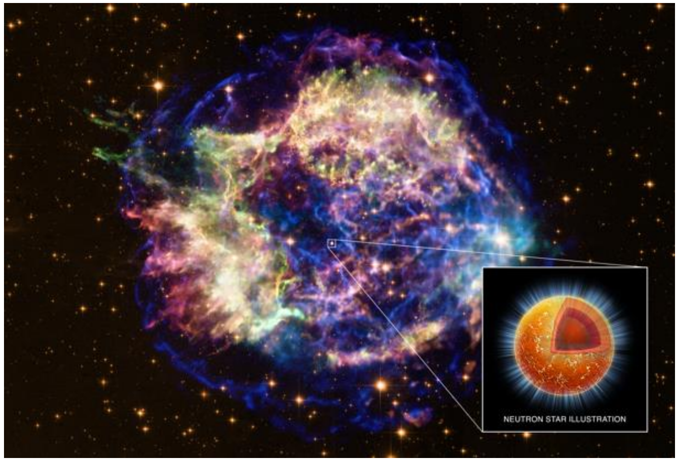
The Quest to Understand the Fundamental Structure of Matter



Towards a new science frontier – Nuclear Femtography

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

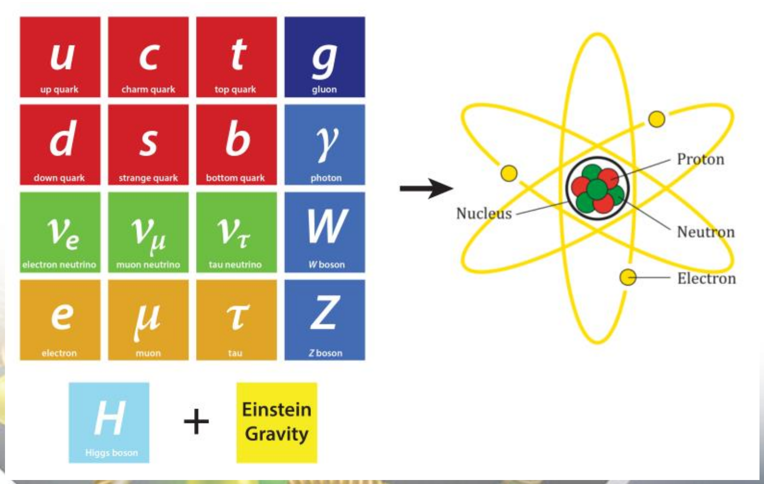
What is the World Made of?



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

During an MRI scan explicit use is made of the spin (or magnetic moment) of a nucleus.

Around us, in the visible world, we see a large variety of structures of nuclear matter.

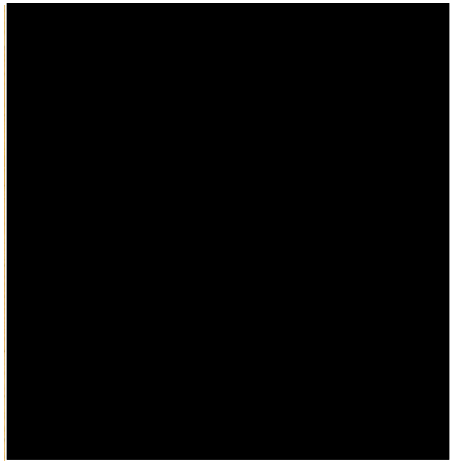


All the matter in the visible universe is understood in terms of subatomic particles and their constituents and interactions.

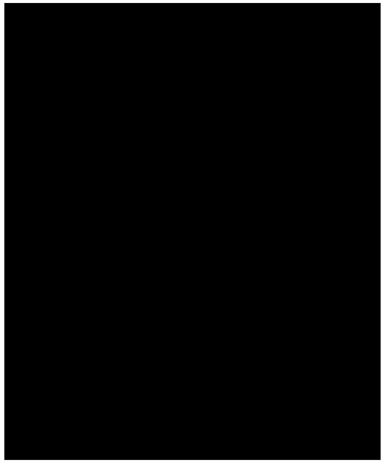
The Standard Model of Physics explains the fundamental structure of the visible matter in terms of quarks, gluons and their interactions.

These particles, interacting together, make up protons and neutrons, which along with electrons, in turn, make up more familiar atoms. This leads to mass, MRI, and visible structure.

What is the World Made of?
What if there were no Gluons and Quark-Gluon Interactions?



Your mass, and the mass of the visible world, would drop by over an order of magnitude



The signals from MRI scans would be reduced by a factor of five.

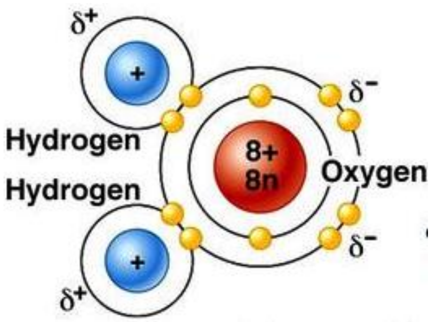
There would be no protons, no neutrons, no atomic nuclei … no visible world!

How is this possible?

Nuclear Femtography – Subatomic Matter is Unique

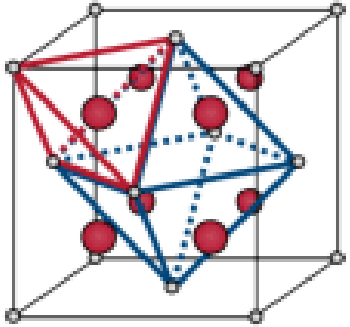
Most known matter has localized mass and charge centers – vast “open” space

Molecule:



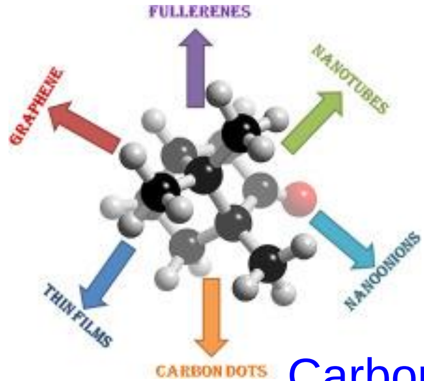
“Water”

Crystal:



Rare-Earth metal

Nanomaterial:

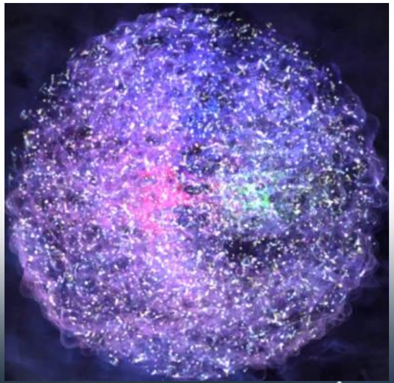


Carbon-based

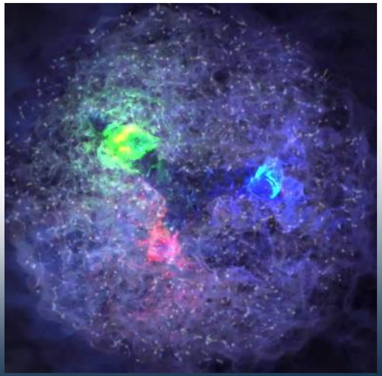
Not so in nuclear matter! – unlike the more familiar molecular and atomic matter, the interactions and structures are inextricably mixed up in protons and other forms of nuclear matter, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

Proton:

Proton:



Proton:



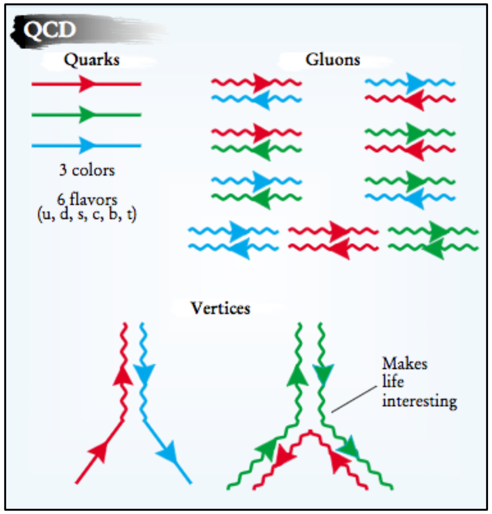
https://www.youtube.com/watch?v=G-9I0buDi4s

The Miraculous World that is Driven by QCD

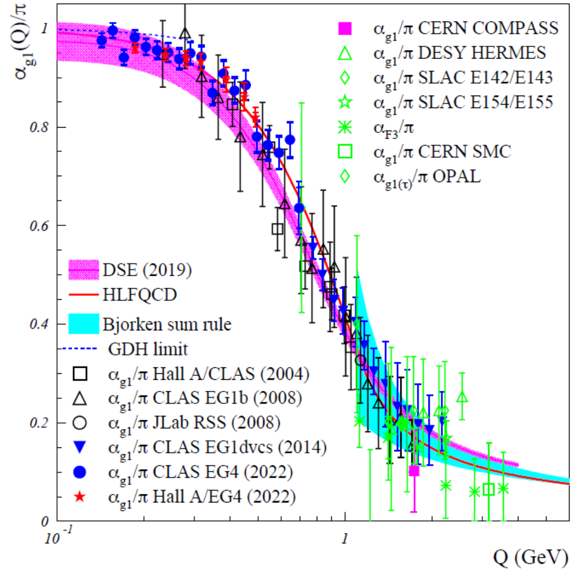
We know the QCD Lagrangian!

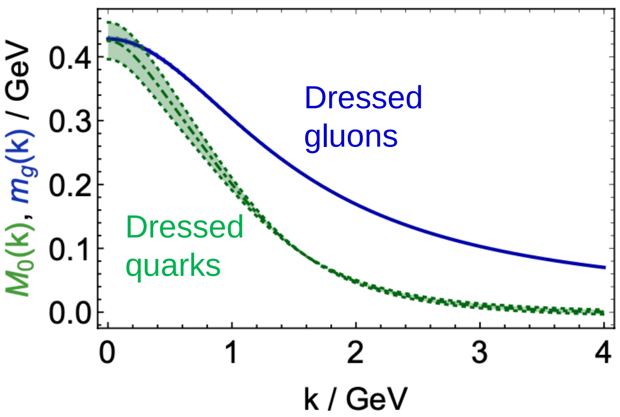
$$L_{QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j \left[i\gamma^{\mu} D_{\mu} - m_j \right] q_j - \frac{1}{4} G^{a}_{\mu\nu} G^{a\mu\nu}$$

$$D_{\mu} = \partial_{\mu} + ig\tfrac{1}{2}\lambda^{a} A^{a}_{\mu},\ G^{a}_{\mu\nu} = \partial_{\mu} A_{\nu} + \partial_{\nu} A_{\mu} \boxed{+\, \boldsymbol{igf^{abc} A^{b}_{\mu} A^{c}_{\nu}}}$$



We know the consequences (in ANY quark-gluon system)!

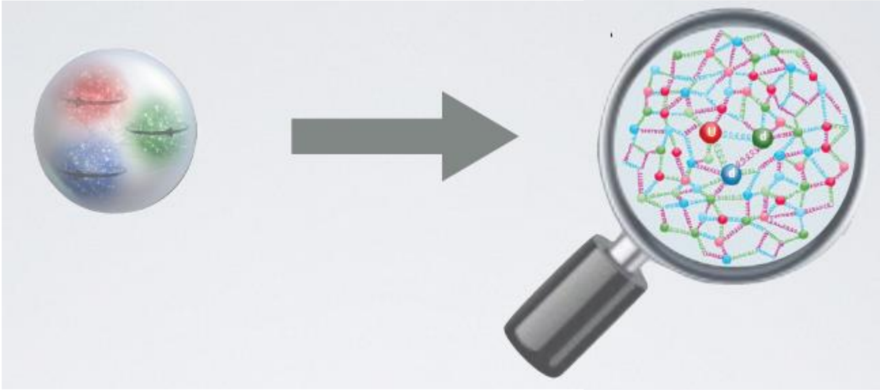


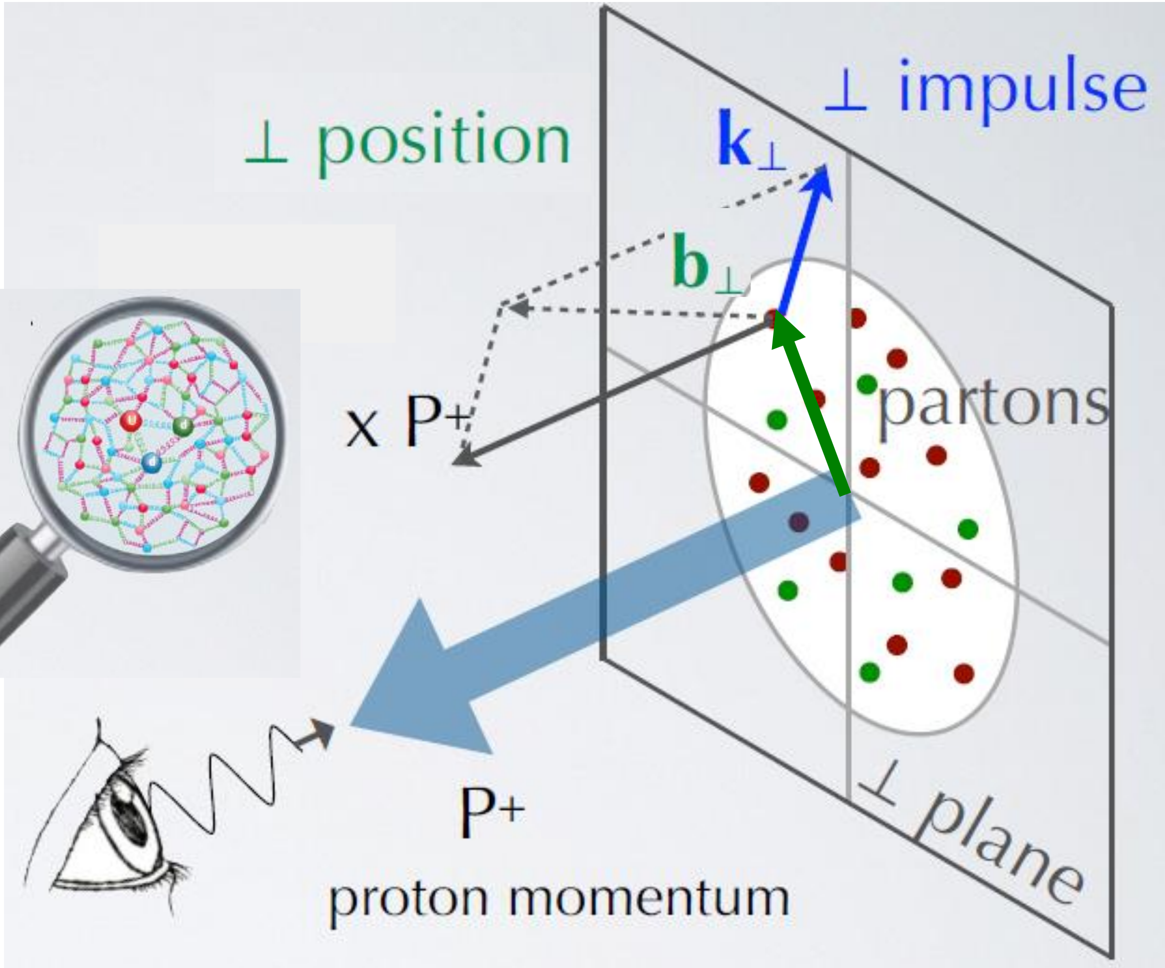


Now we need to understand how this leads to the emergence of the rich variety of structure in "simple" mesons and baryons that Nature has given us (and why this is)!

Nuclear Femtography - Imaging

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**

3D Structure of Nucleons and Nuclei

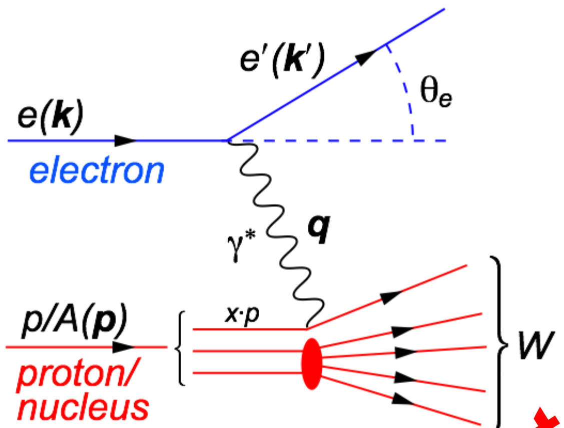
$s = xyQ^2$,
$s = 4E_eE_p$

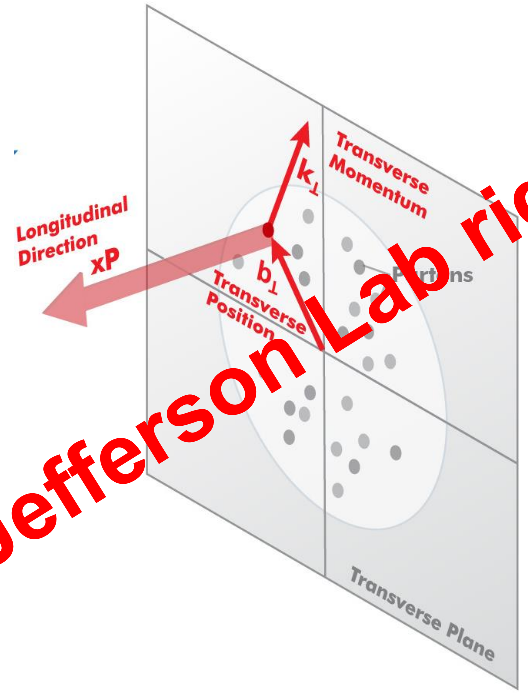
s: center-of-mass energy squared

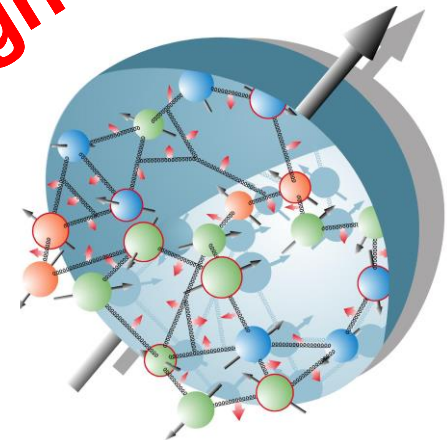
***x*:** the fraction of the nucleon's momentum carried by the struck quark ($0 < x < 1$)

***Q^2*:** resolution power

y: inelasticity







Underway at Jefferson Lab right now!

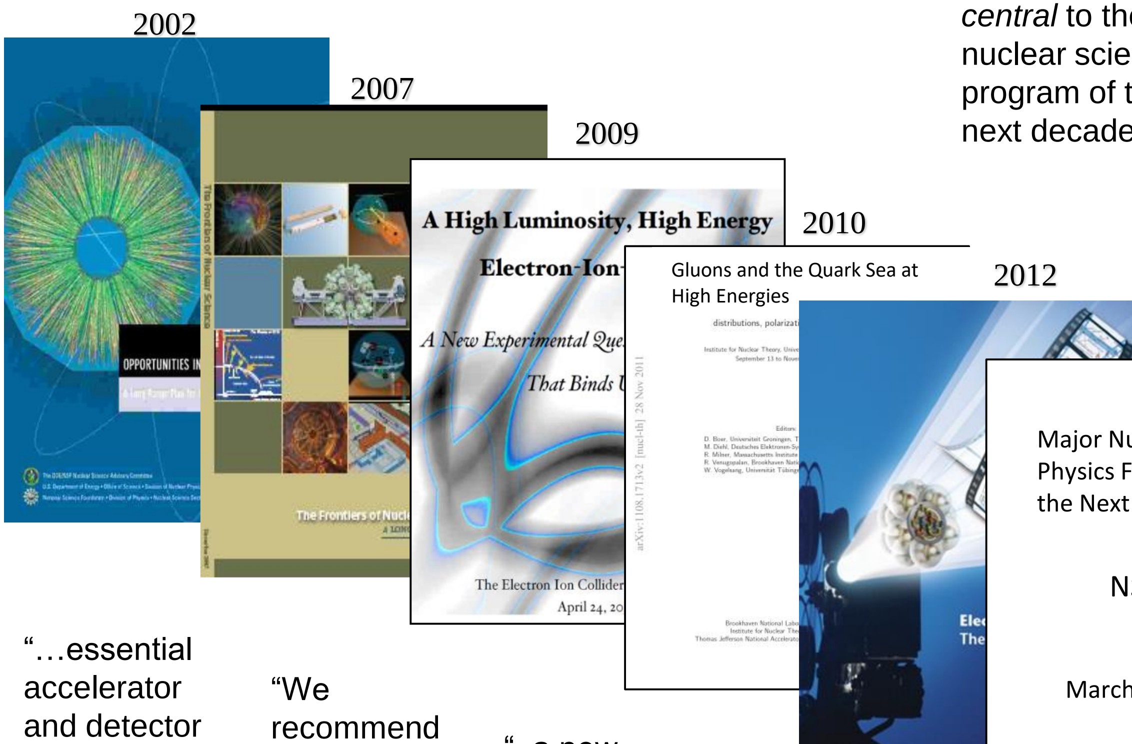
need energy range to unambiguously resolve partons over wide range in x and Q^2 → versatile center-of-mass energy energy $\sqrt{s}$: 20 – 140 GeV

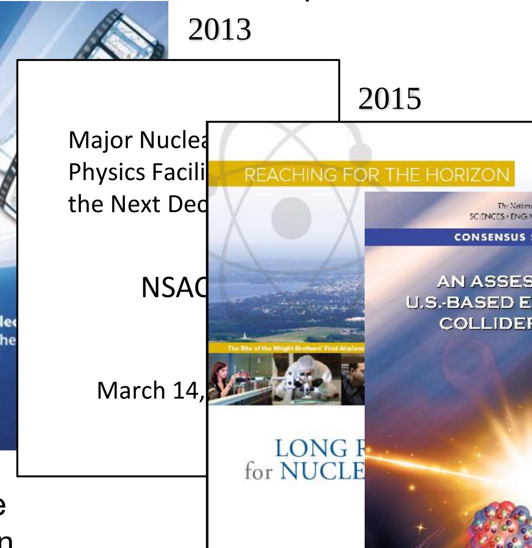
need to resolve parton quantities (k_t, b_t) of order a few hundred MeV in the proton → high luminosity needed: 10^{33}-10^{34} (and high polarization needed)

k_T, b_T (~100 MeV)

Proton and Ion Beam ~100 GeV

The Scientific Foundation for an EIC was Built Over Two Decades





"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

"..a new dedicated facility will be essential for answering some of the most central questions."

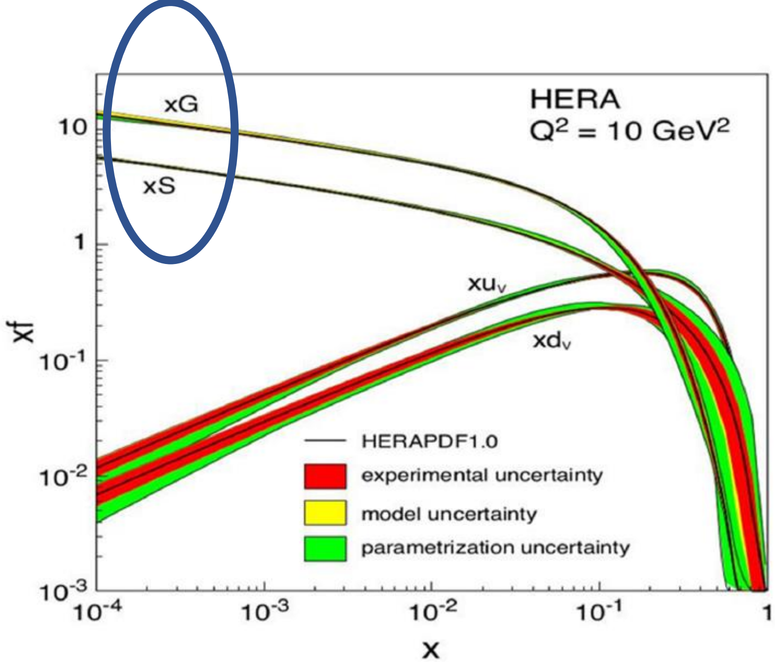
"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

Electron-Ion Collider..*absolutely central* to the nuclear science program of the next decade.

"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

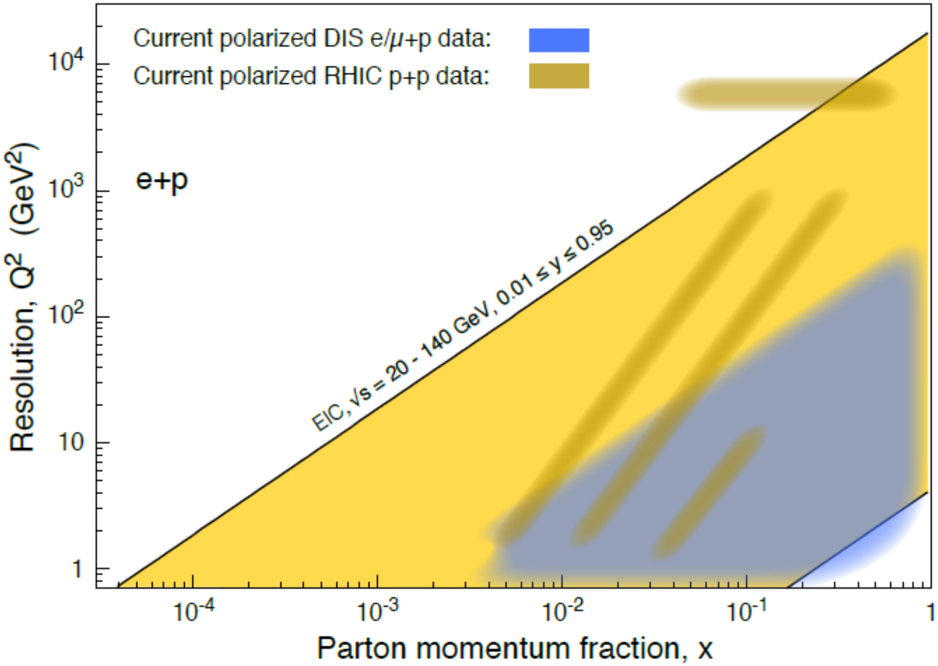
The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

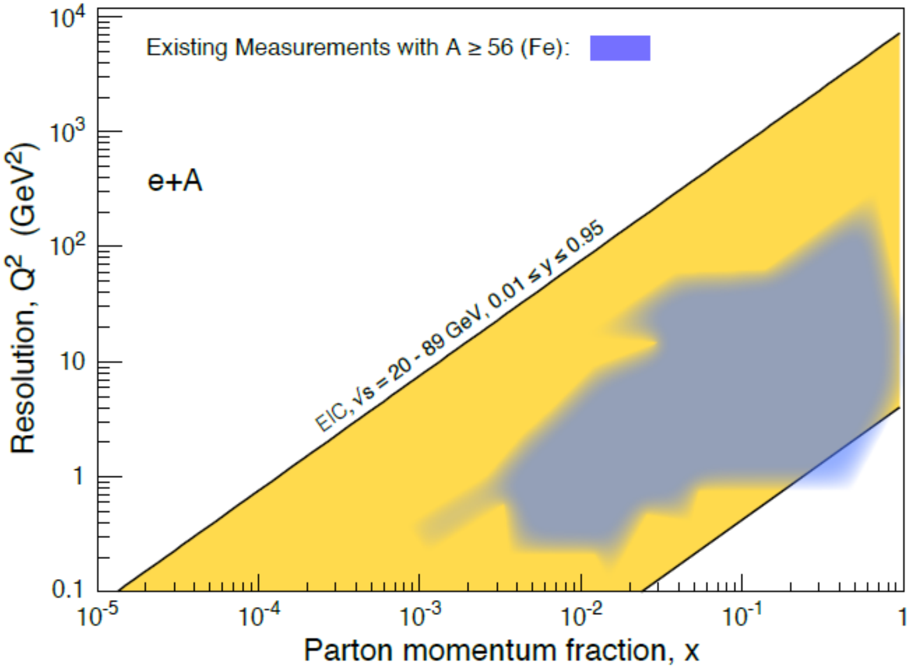
EIC Science Landscape



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

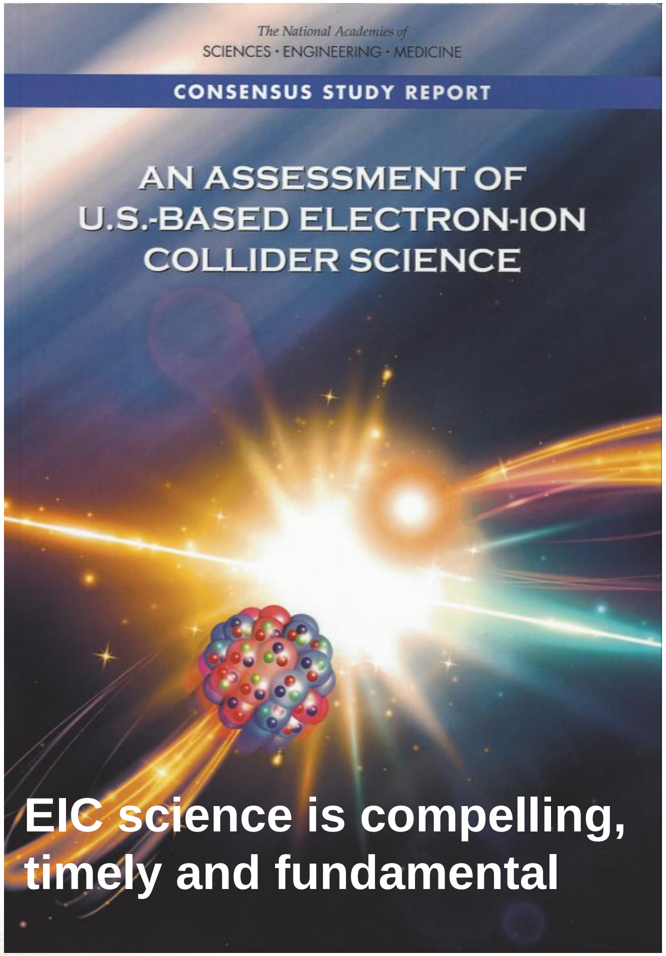
A huge leap in accessible kinematics landscape (into the land of gluons and the quark sea) for polarized e-N and unpolarized e-A reactions!





EIC Science – Findings of the NAS Committee

2018 The National Academies of SCIENCES · ENGINEERING · MEDICINE



EIC science is compelling, timely and fundamental

Developed by NAS committee with broad science perspective

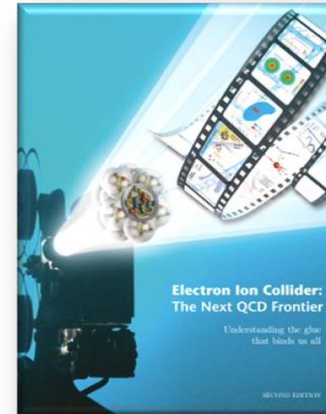
- **Finding 1:** An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:
  - How does the **mass** of the nucleon arise?
  - How does the **spin** of the nucleon arise?
  - What are the **emergent properties**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

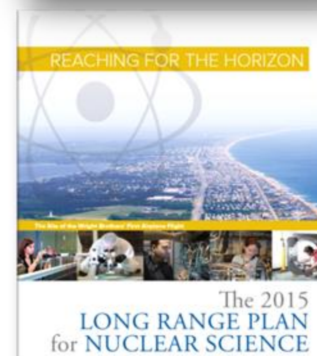
- **Finding 2:** These three high-priority science questions can be answered by an EIC with **highly polarized beams** of electrons and ions, with sufficiently **high luminosity** and sufficient, and **variable**, center-of-mass **energy**.

NAS Report on EIC Requirements

In order to definitively answer the compelling scientific questions elaborated in Chapter 2, including the origin of the mass and spin of the nucleon and probing the role of gluons in nuclei, a new accelerator facility is required, an electron-ion collider (EIC) with unprecedented capabilities beyond previous electron scattering programs. An EIC must enable the following:

- Extensive center-of-mass energy range, from ~20-~100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times higher than the earlier electron-proton collider Hadron-Electron Ring Accelerator (HERA) at Deutsches Elektronen-Synchrotron (DESY), to allow unprecedented three-dimensional (3D) imaging of the gluon and sea quark distributions in nucleons and nuclei.
- Spin-polarized (~70 percent at a minimum) electron and proton/light-ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin. Polarized colliding beams have been achieved before only at HERA (with electrons and positrons only) and Relativistic Heavy Ion Collider (RHIC; with protons only).



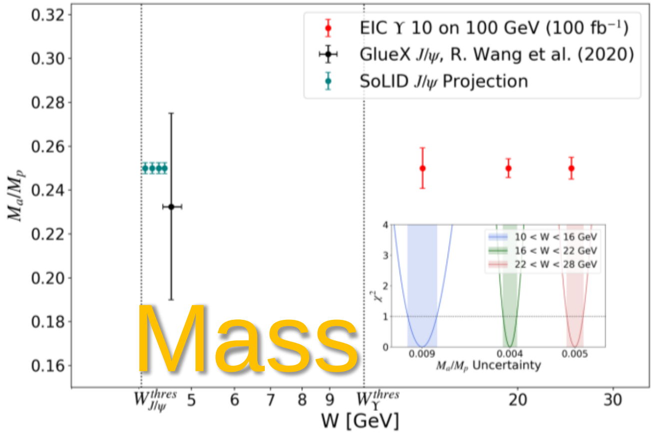


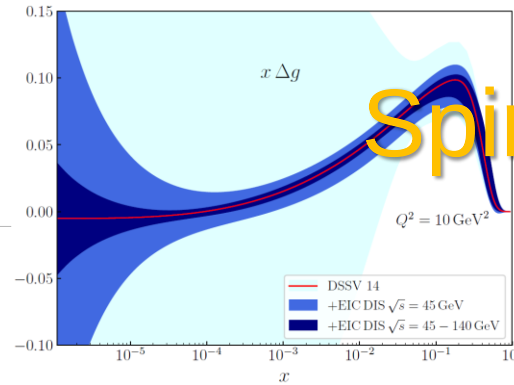
The EIC requirements have remained consistent, see e.g., the 2012 white paper and 2015 NSAC Long Range Plan

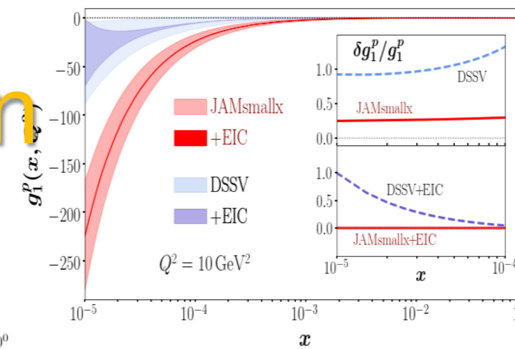
The EIC Will Deliver

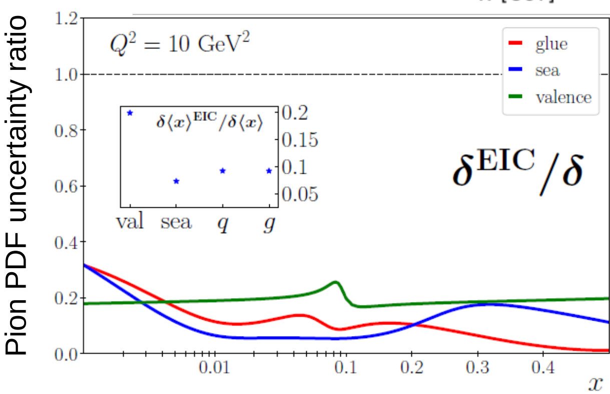
Some highlight plots from new EIC White Paper

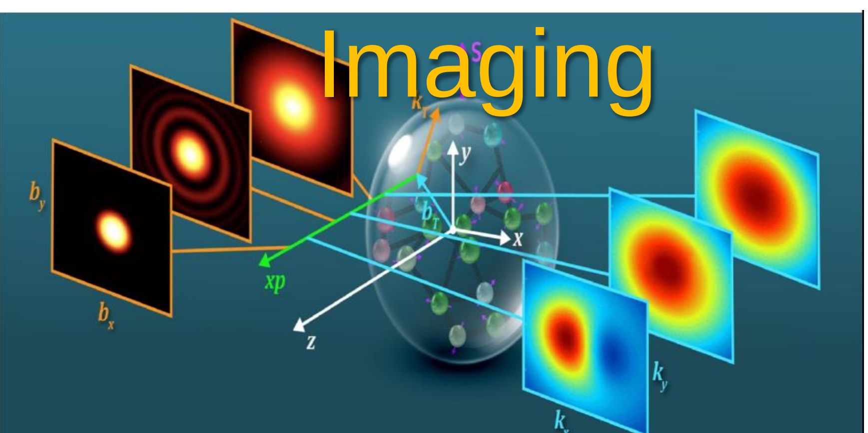
(full draft will be released for EICUG feedback in November)

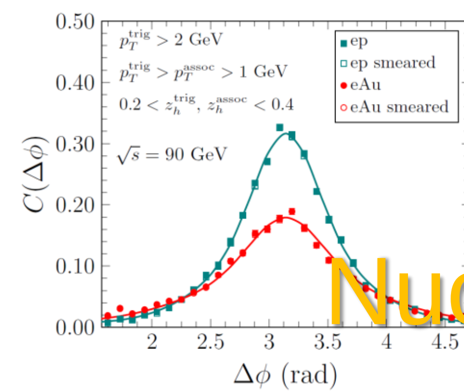


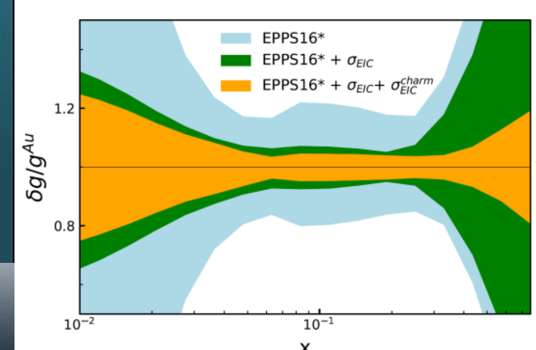


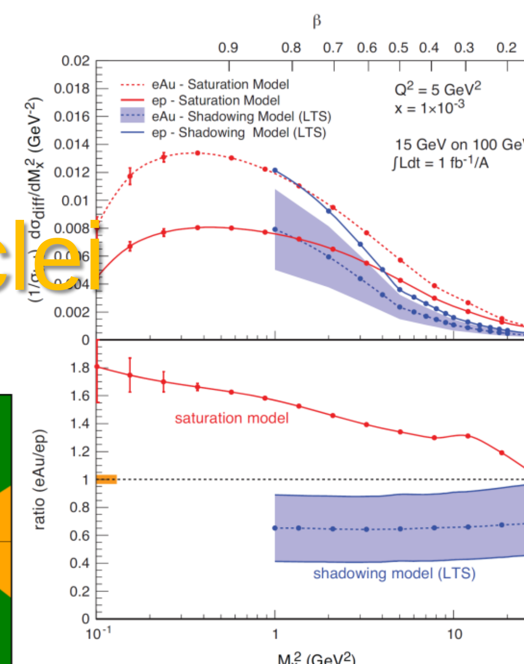






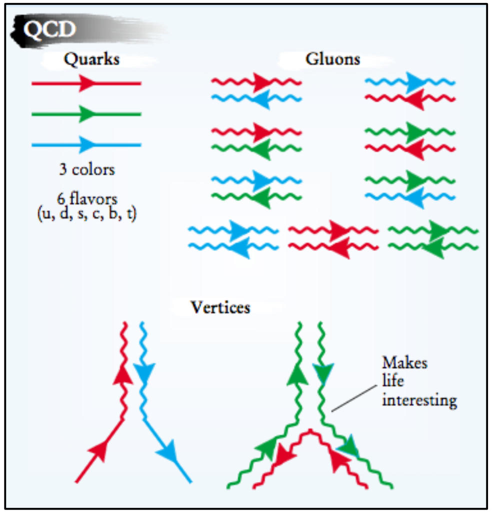


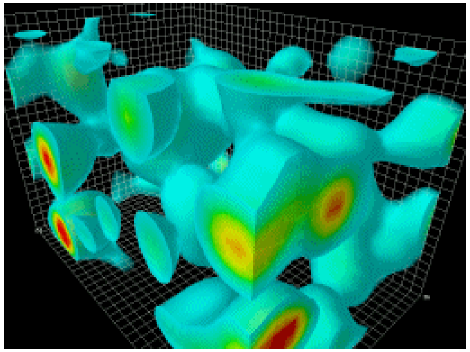




EIC: 21st Century Laboratory of Emergent Dynamics in QCD

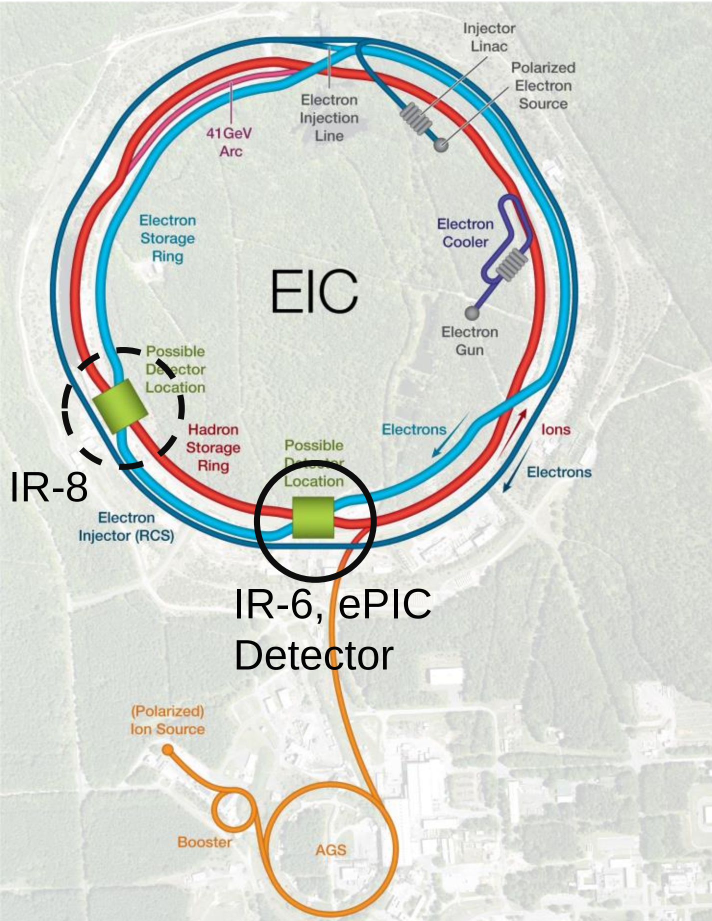
- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% of the proton's momentum, a significant fraction of the nucleon's spin, and are essential for the dynamics of confinement
- Properties of hadrons – composite systems 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

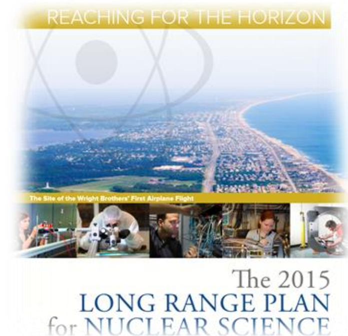


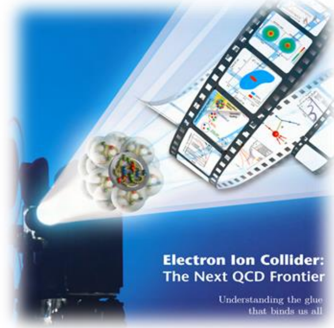


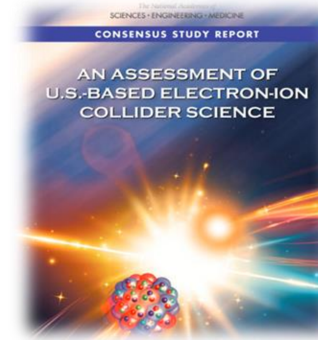
- The goal is to provide us with an understanding of the internal structure of the proton and more complex atomic nuclei that is comparable to our knowledge of the electronic structure of atoms, which lies at the heart of modern technologies

EIC Scope









Project Design Goals

- High Luminosity: L= 10^{33} – 10^{34}cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

IR-8

p/A beam

e beam

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV

EIC Project Recent History

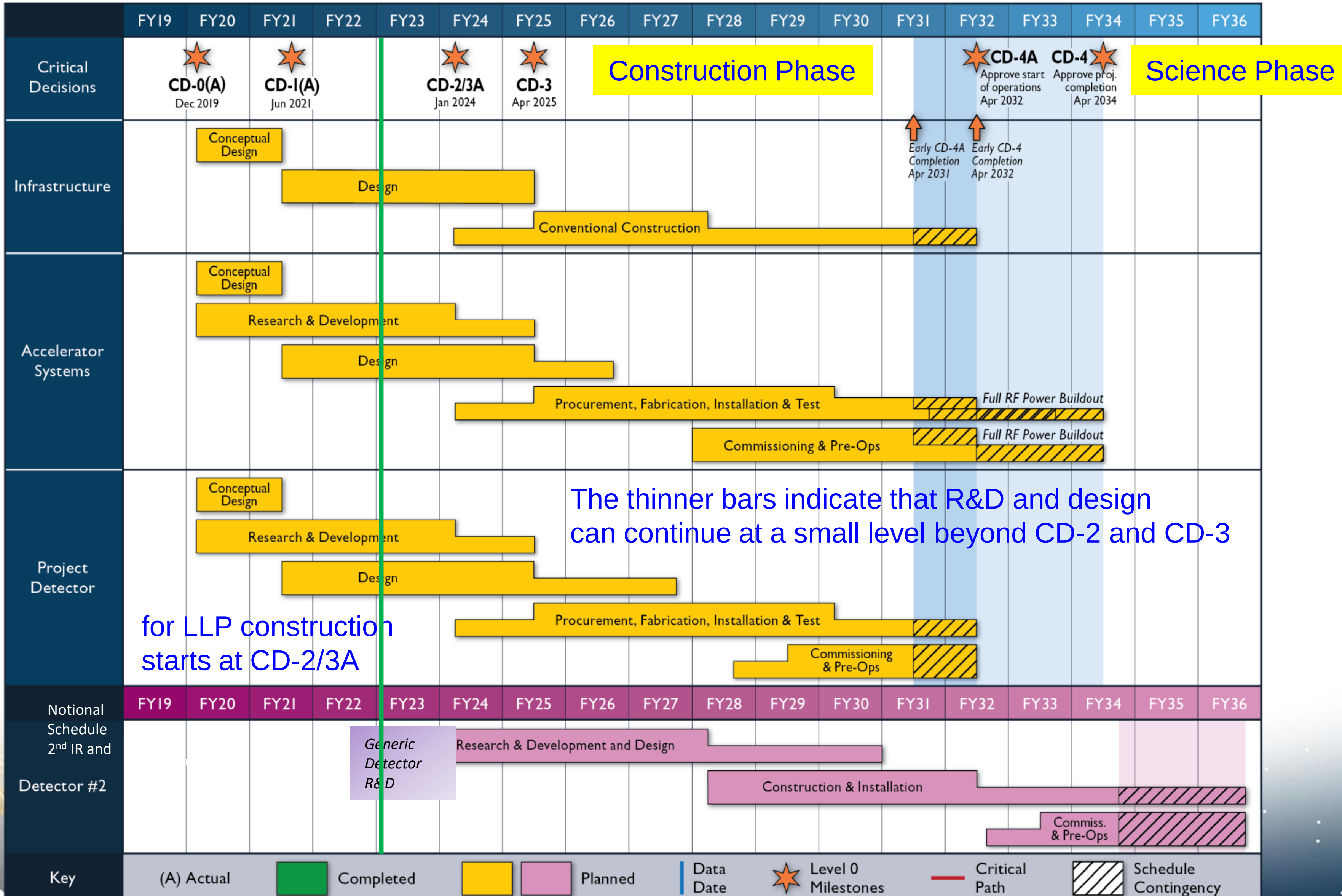
Event	Date
DOE Mission Need Statement Approved	January 22, 2019
Critical Decision – 0 (CD-0) Approved	**December 19, 2019**
DOE Site Selection Announced	January 9, 2020

Feb 28, 2020 @ JLab

Integrated partnership in all Project phases, including co-hosting the EIC experimental program.

BNL - TJNAF Partnership Agreement	May 7, 2020
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, Alternative Selection and Cost Range, Approved	**June 29, 2021**
CD-2/3A, Baseline/Long Lead Procurement	***January 2024***

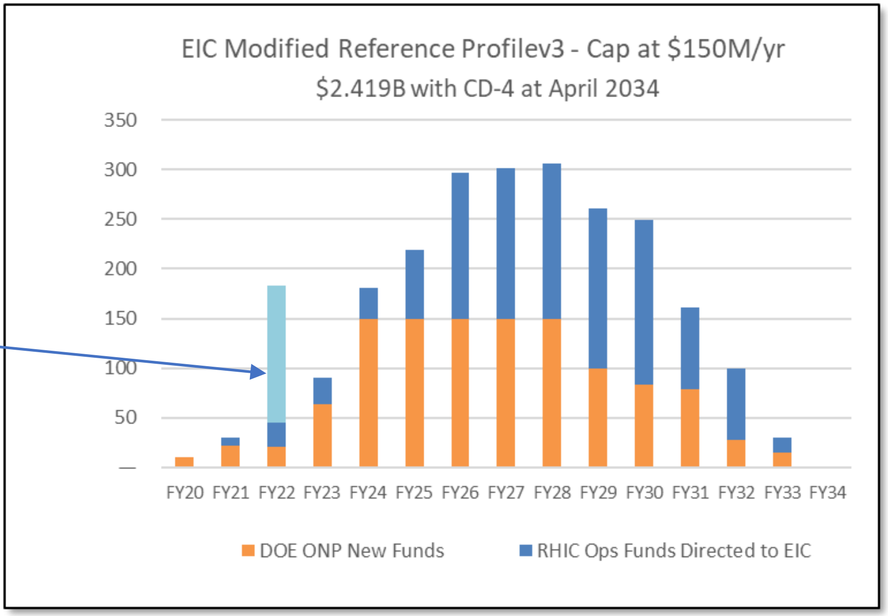
High-Level EIC Reference Schedule



Latest News on the Funding and Schedule

Inflation Reduction Act:
- $217M to Nuclear Physics in FY22 to be spent by FY27.
- Includes EIC (to get to CD-2)
  – $138.24M.

(IRA funds can ONLY be used for project scope, but NOT to add scope)



Schedule: CD-2/3A = January 2024; CD-3 = April 2025; CD-4 Project Completion = 2034
RHIC operations conclude and EIC tunnel work starts in June 2025

Cost: CD-1 cost range of $1.7B-$2.8B

→ The DOE funding to ensure CD-2/3A timeline (baselining, start of long-lead procurement items) and CD-3 (start of construction) seems secured.

→ A Game Changer!

EIC Experimental program preparation

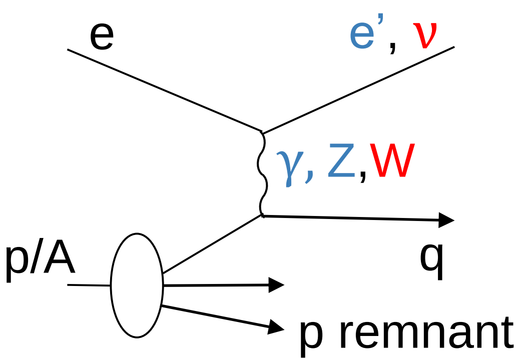
- Year-long EIC User Group driven EIC Yellow Report activity
  - Science Requirements and Detector Concepts for the EIC – Drives the requirements of EIC detectors
  - arXiv:2103.05419 & Nucl. Phys. A 1026 (2022) 122447 – 388 citations (11/06/22)

BNL and TJNAF Jointly Leading Efforts Towards Experimental Program		
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	On-going[&]
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
2022	Decision on Project Detector – “ECCE”	March 2022
	Guide process to joint “Detector-1” Collaboration	Spring 2022
	EPIC Collaboration* Formed – 160 institutions	July 2022
	EIC Software Infrastructure Review	August 2022
	Pre-Resources Review Board Meeting	October 2022

[&]Remains ongoing until formal agreements are in place – it originally led to confirmation that in-kind level assumed for the EIC detector was in range.

*Merger of two large ATHENA and ECCE proposals

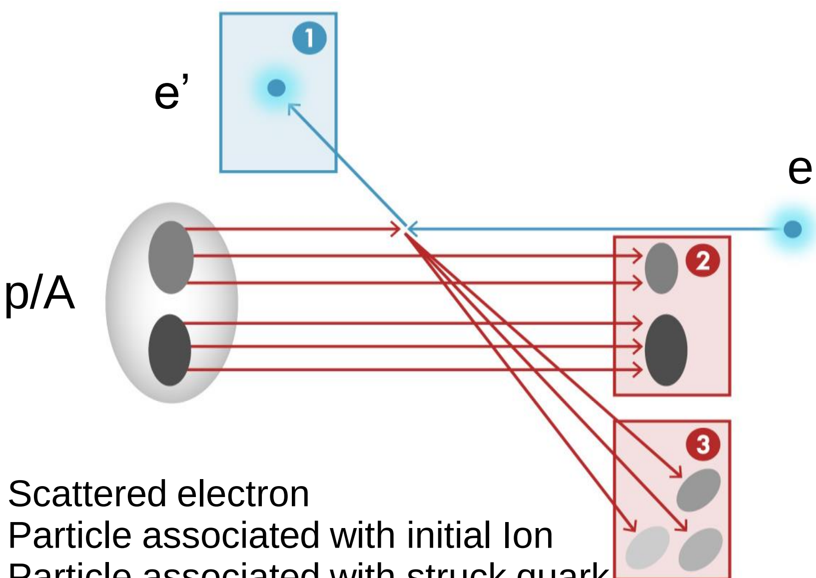
Detector Integration Challenge of the EIC



Aim of EIC is 3D nucleon and nuclear structure beyond the longitudinal description.

This makes the requirements for the machine and detector different from all previous colliders.

"Statistics"=Luminosity × Acceptance



1. Scattered electron
2. Particle associated with initial Ion
3. Particle associated with struck quark (or associated gluon)

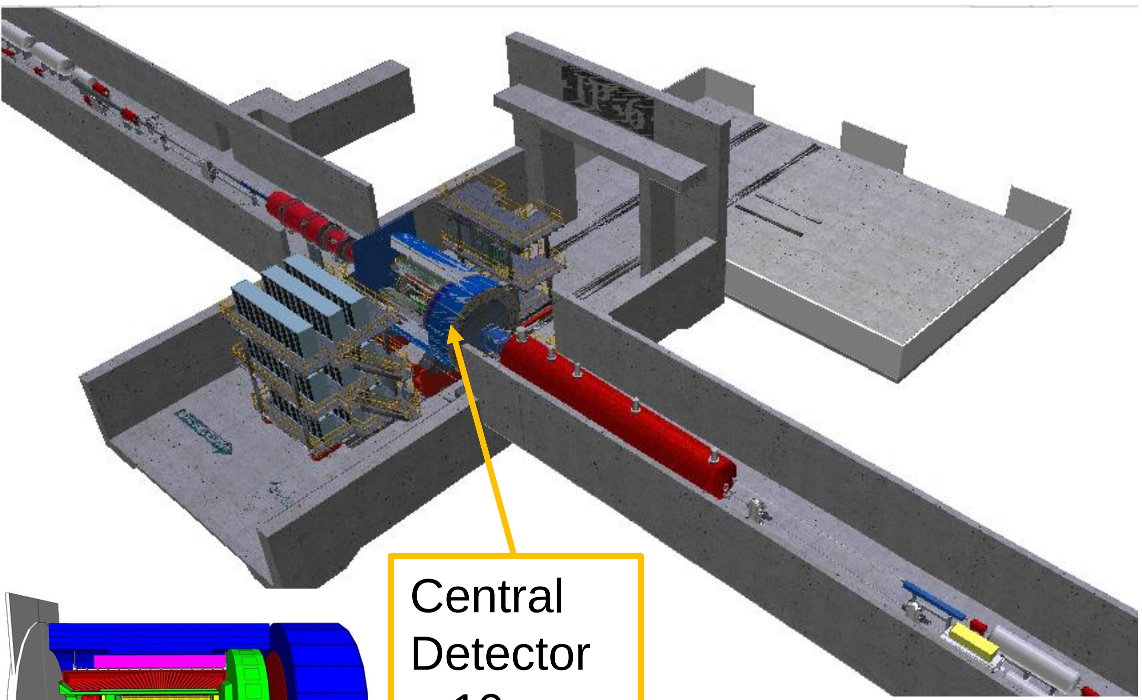
EIC Physics demands ~100% acceptance for all final state particles (including particles associated with initial ion)

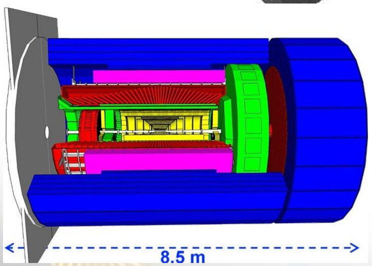
Ion remnant is particularly challenging

- not a usual concern at colliders
- at EIC integrated from the start with a highly integrated (and complex) detector and interaction region scheme.

EIC: Fully Integrated Detector/Interaction Region++

Far-Backward Region ~ 40 m





Central Detector ~ 10 m

Far-Forward Region ~ 40 m

EIC science: ALL particles count!

Many particles with $\beta = 1$, but in the far-forward region @ 30 m distance also many particles with $\beta = 0.5$ or so

→ $\Delta t = 200$ ns

Ultimate EIC Streaming Model: integrate machine, detector, electronics, data acquisition, software and physics analysis.

Multiple prospects for AI at the EIC!

What is Needed Experimentally?

experimental measurements categories to address EIC physics:

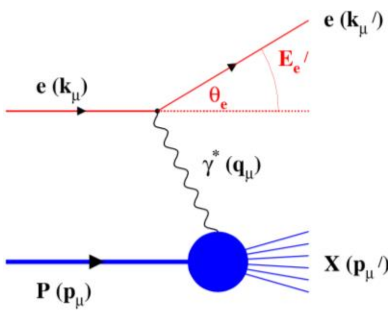
Parton Distributions in nucleons and nuclei

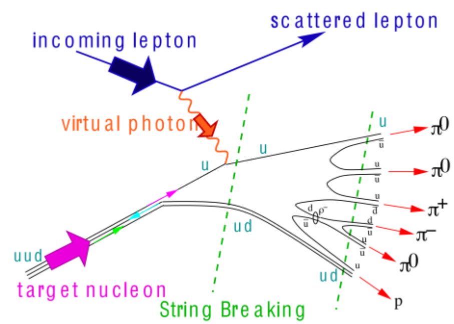
Spin and Flavor structure of nucleons and nuclei

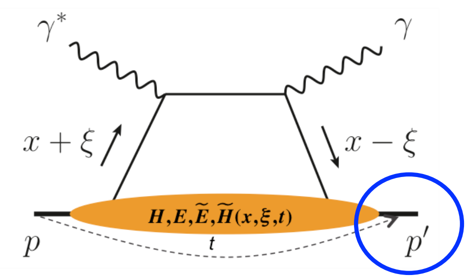
Tomography Transverse Momentum Dist.

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

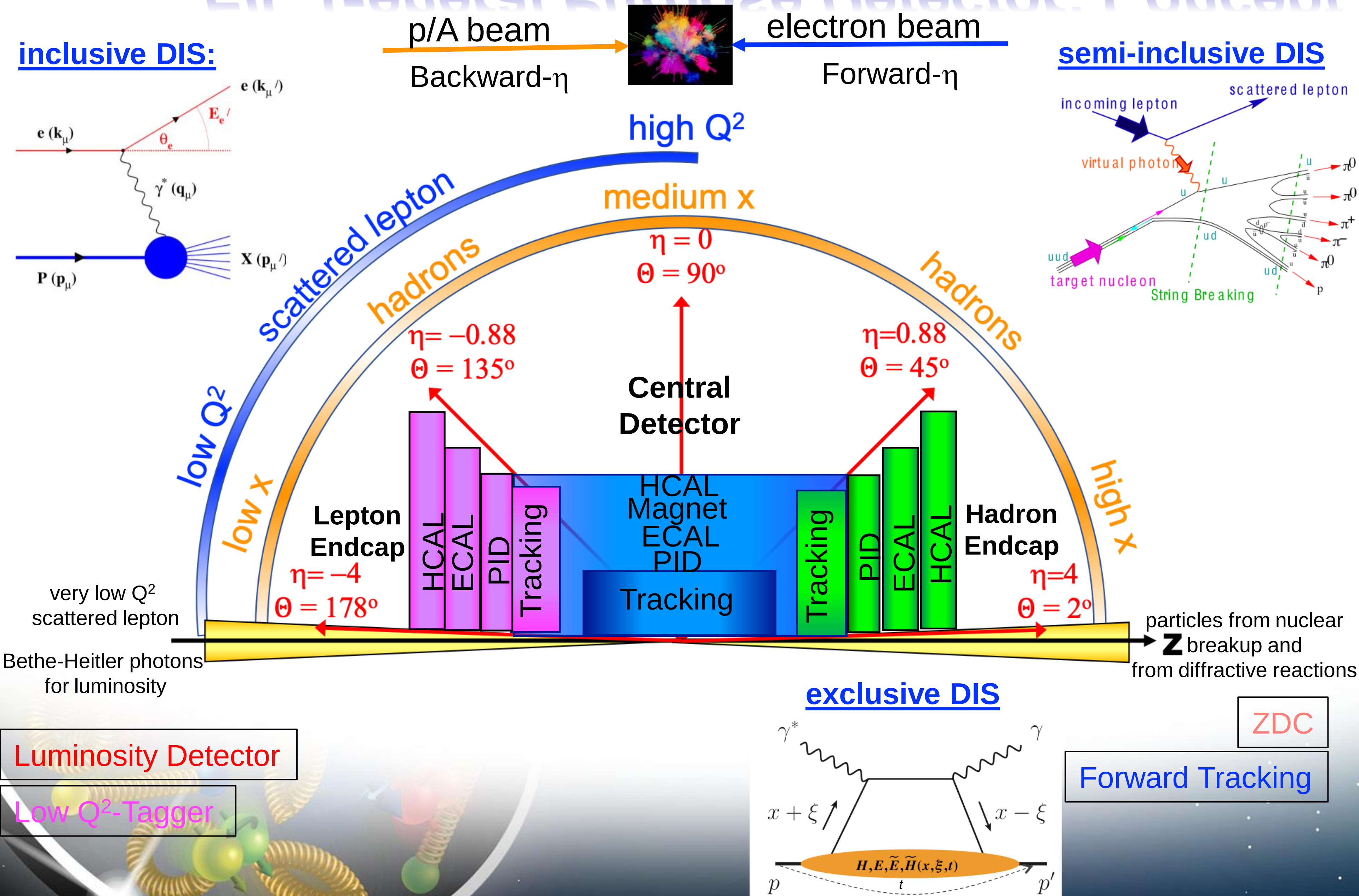
  → cannot be detected in main detector

  → strong impact on Interaction Region design

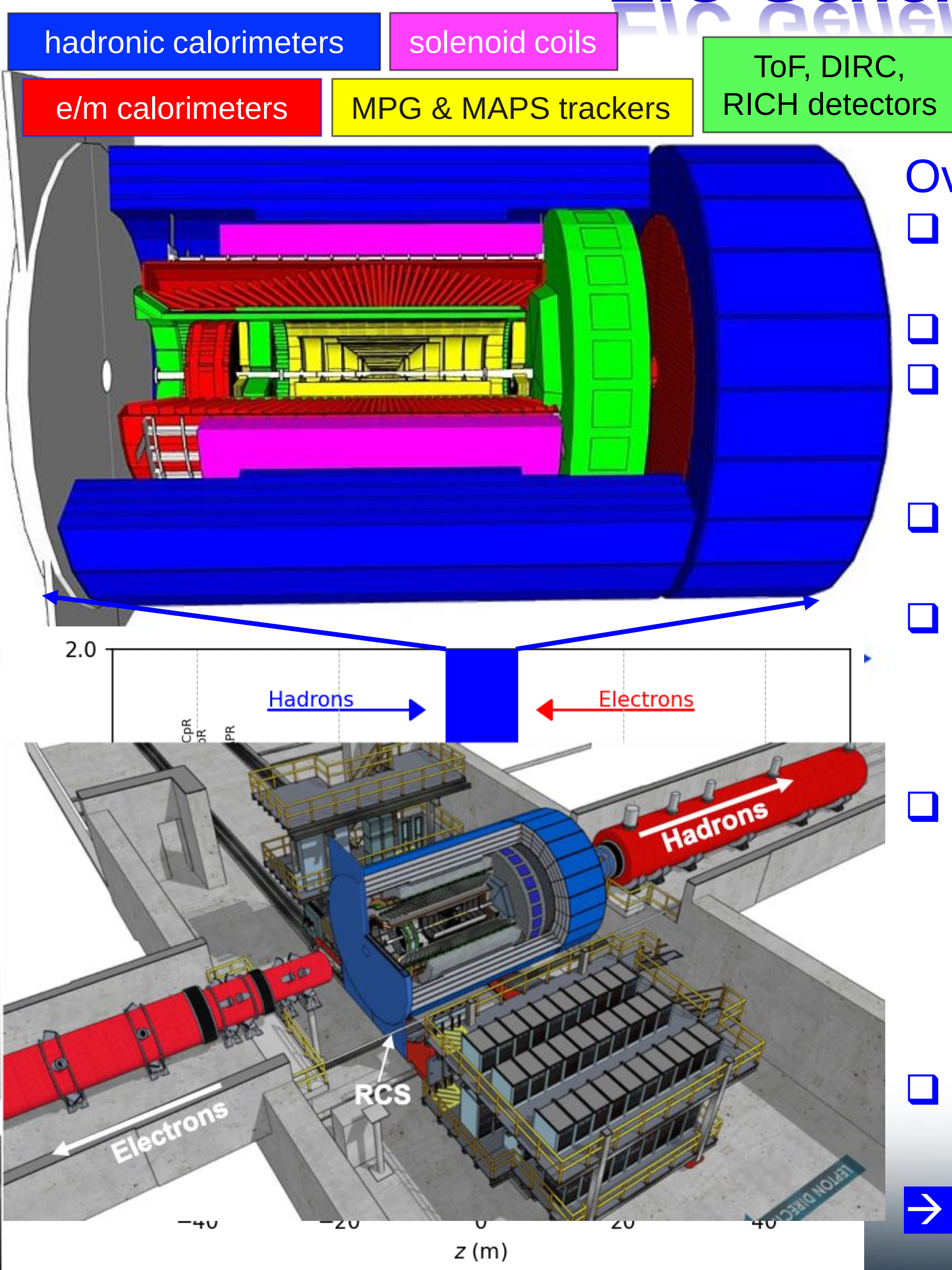
$\int Ldt$: 1 fb^{-1} | 10 fb^{-1} | 10 - 100 fb^{-1}

machine & detector requirements

EIC General Purpose Detector: Concept



EIC General Purpose Detector: ePIC



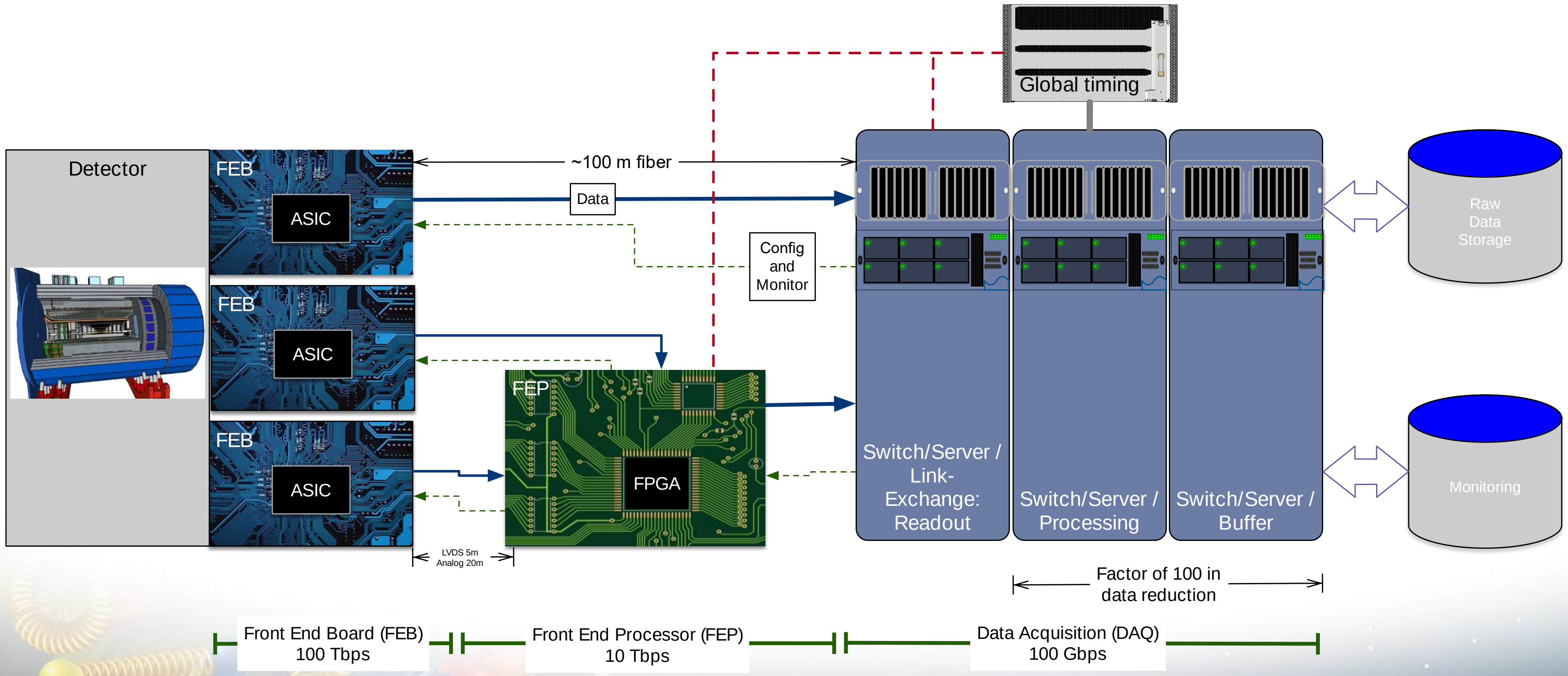
Overall detector requirements:

- Large rapidity ($-4 < \eta < 4$) coverage; and far beyond in especially far-forward detector regions
- large acceptance 1.7 T(up-to 2 T) Solenoid
- High precision low mass tracking
  - small (μ-vertex) and large radius (gaseous-based) tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate π, K, p on track level
  - also need good e/h separation for scattered electron
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - Many ancillary detector integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

→ Integration into wider IR (+/- 40 m) critical

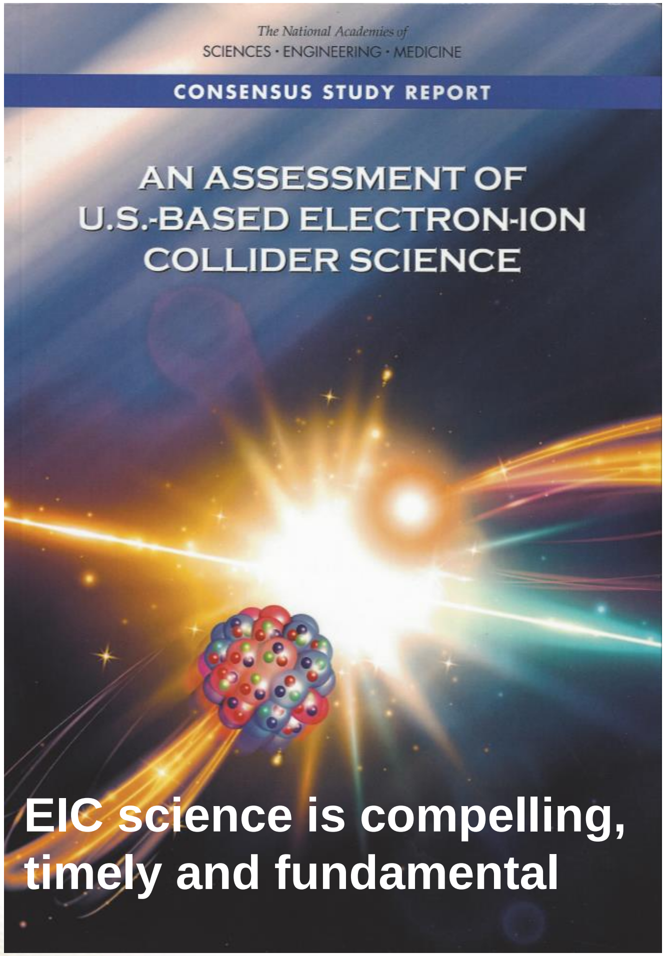
Streaming Readout Architecture

- Triggerless streaming architecture gives much more flexibility to do physics
- Rates quoted are at output of each stage
- Integrate AI/ML as close as possible to subdetectors → cognizant Detector



EIC Science – Findings of the NAS Committee

The National Academies of
SCIENCES · ENGINEERING · MEDICINE



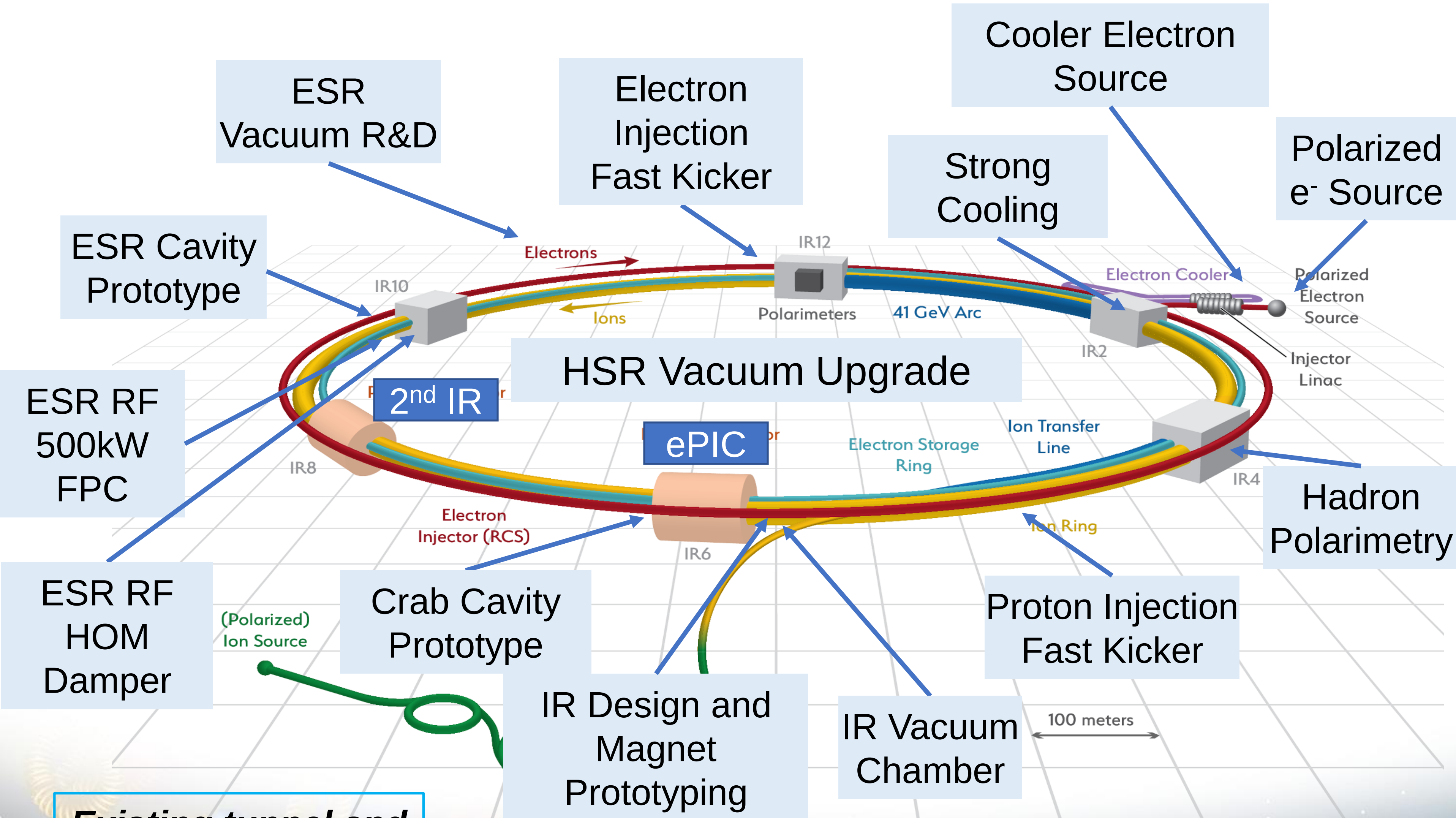
EIC science is compelling, timely and fundamental

Developed by NAS committee with broad science perspective

- **Finding 3:** An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics.

- **Finding 4:** **An EIC would maintain U.S. leadership in the accelerator science and technology of colliders and help to maintain scientific leadership more broadly.**

Accelerator Science and Technology – Ongoing EIC R&D



Existing tunnel and experiment halls

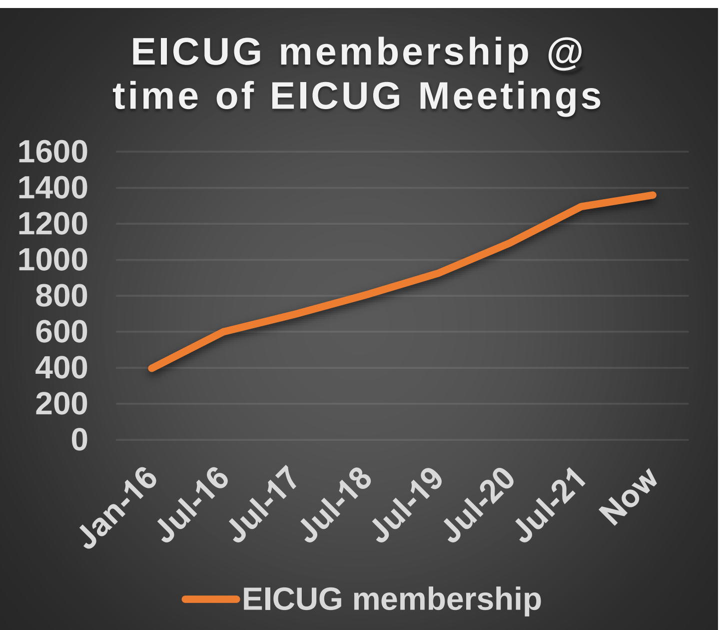
EIC is the ONLY new collider in foreseeable future.
Allows to remain at frontier of Accelerator S&T.
… and enable applications (isotopes, space radiation, water treatment, etc.)

Worldwide Interest in EIC

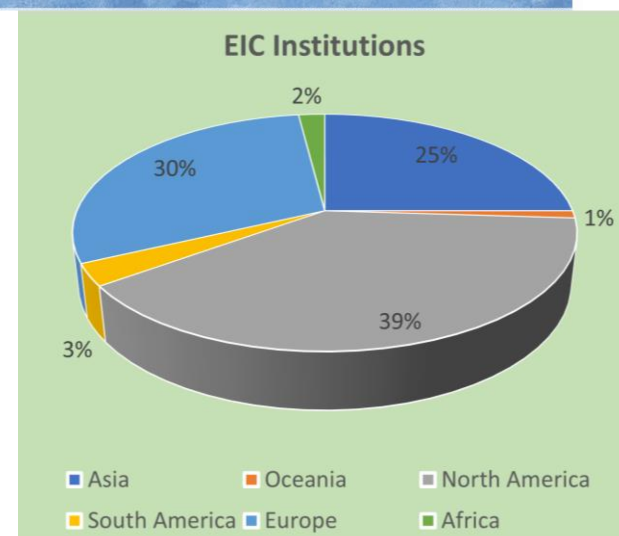
The EIC User Group:
https://eicug.github.io/

Formed 2016 –
- **1370 collaborators,**
- **36 countries,**
- **267 institutions as of November 06, 2022.**

Strong and Growing International Participation.



Annual EICUG meeting
2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 CUA, Washington, DC
2019 Paris, France
2020 Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland



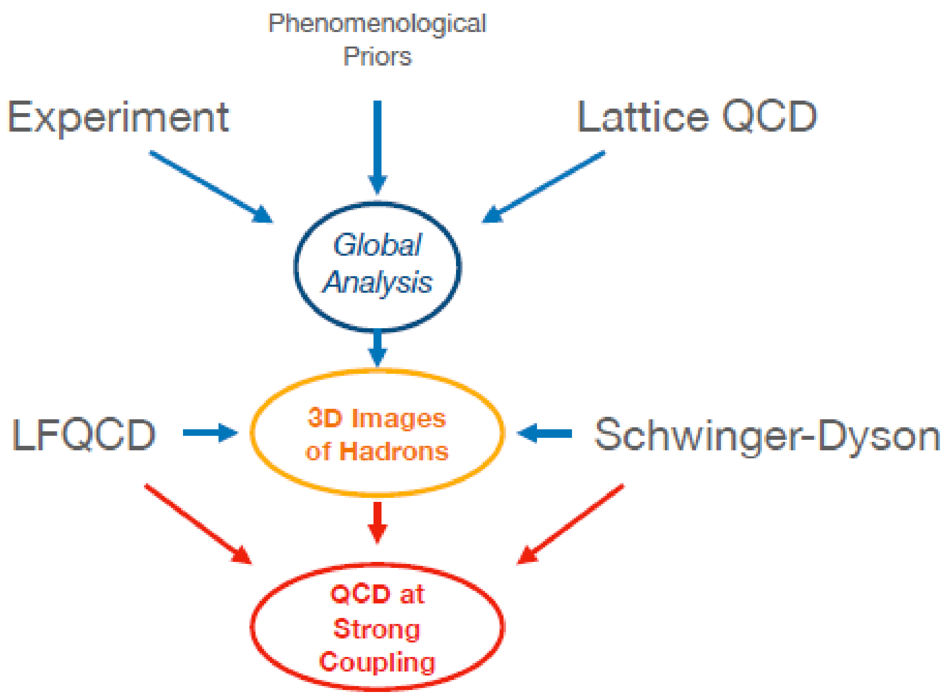
Uniqueness of EIC

- **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 up to 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 at high luminosity (12 GeV and energy extension), adding crucial data in the strongly-interacting valence quark region.

EIC Status: Take-Away Messages

- "***Now is the time to realize the EIC in the U.S.***" (LRP 2015).
- The NAS Report concluded: "***EIC science is compelling, timely and fundamental.***"
- The EIC Science Case is as strong as, if not stronger than, before.
- The EIC is executed as a **partnership of BNL and JLab**, in strong collaboration with the large EIC user community.
- The EIC User Group continues growing, and currently stands at **1370 members in 36 countries.**
  - This is a strong community that has delivered on the EIC Science White Paper, the Yellow Report, and three detector proposals.
  - Efforts towards the ePIC detector and a path to a 2nd detector are ongoing.
- **Recent IRA funding results in a phase change** – the schedule for EIC to CD-3 (~2025) is likely to be technically driven.
  - This underscores DOE/SC is committed to EIC as a top priority
  - The focus of the EIC Project will be schedule, schedule, schedule
- **There will be one EIC with this high level of performance in the world.**
  - This will keep the U.S. on the frontiers of nuclear science, accelerator, and detector technologies.
  - AI & advanced computing is folded in at every stage of EIC, from design to data taking to ultimate science.

Emergent Mass and Structure – a Beautiful Synergy of Experiment, QCD Phenomenology and Lattice QCD

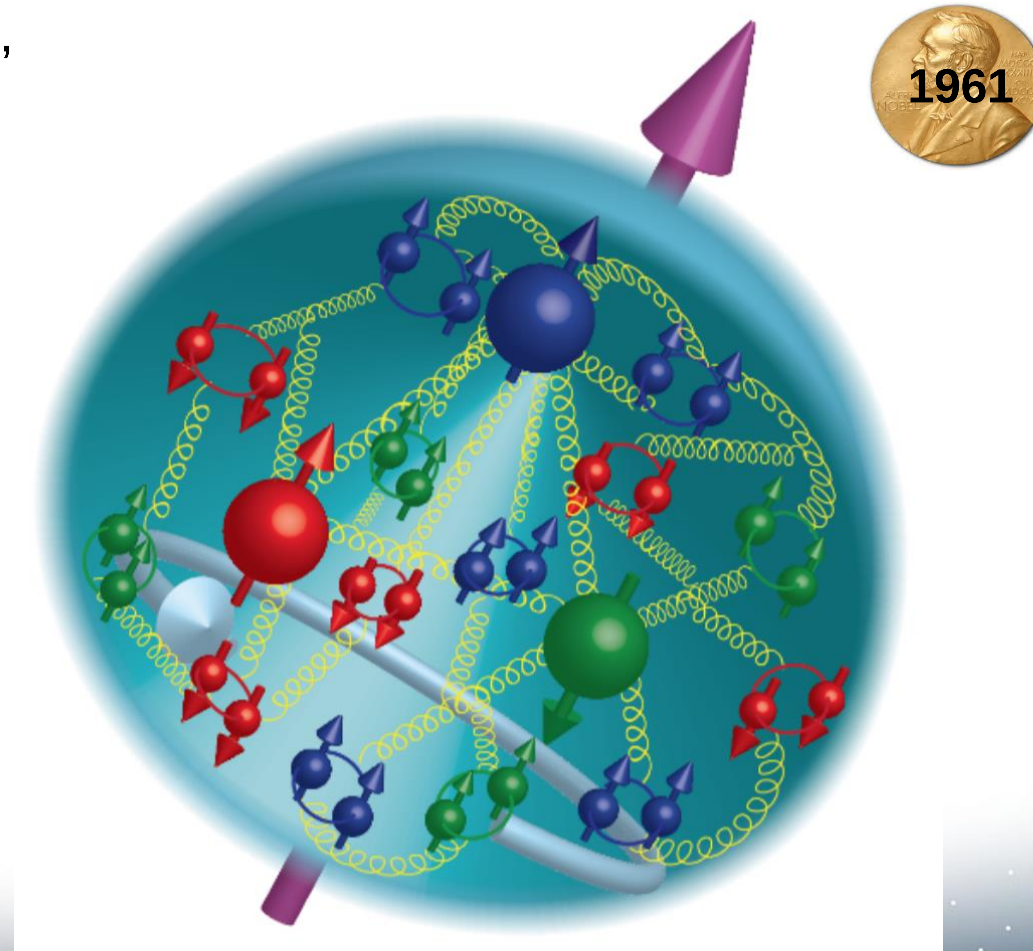


This plot is general and very much applicable to the topic of this conference. It was made in the context of a large group of theorists and experimentalists working together on pion and kaon structure (see talk by Tanja Horn later) in a series of EIC-related workshops ("Pion and Kaon Structure at the EIC"), for an EIC white paper, and a sub-group on meson structure as part of the EICUG Yellow Report initiative. See also the talk by Tanja Horn later. This group continues to meet, with emphasis on the synergy.

Backup

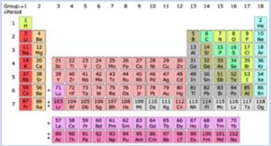
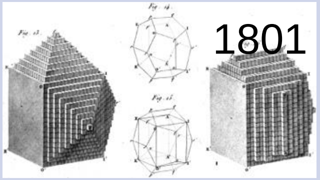
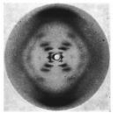
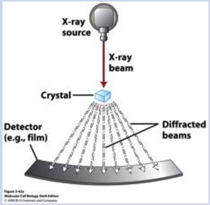
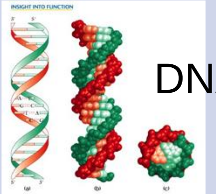
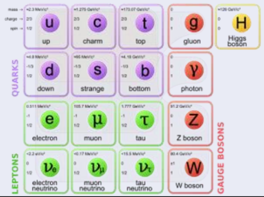
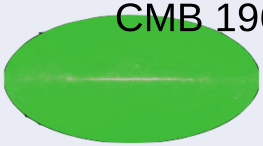
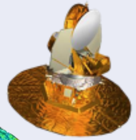
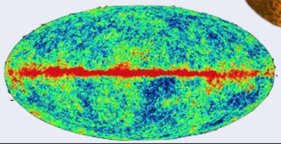
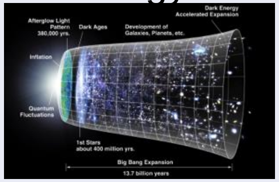
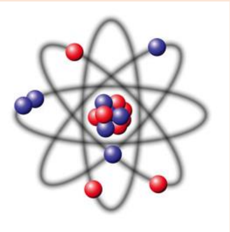
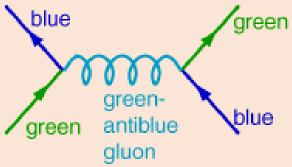
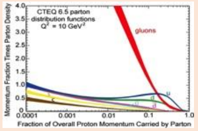
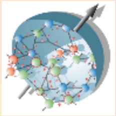
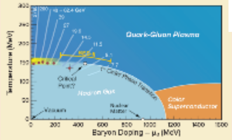
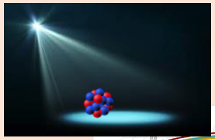
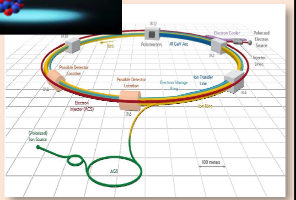
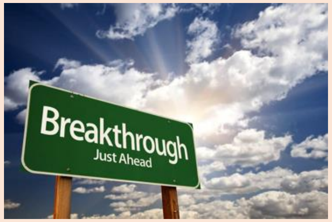
21st Century View of the Fundamental Structure of the Proton

- 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.



In fact, the proton mass and structure emerge from the quark-gluon dynamics

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 $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$ 	Non-perturbative QCD. Structure 2017   	Electron-Ion Collider (~2030)  	Structure & Dynamics in QCD 

EIC Project – Path to CD-2/3A and CD-3

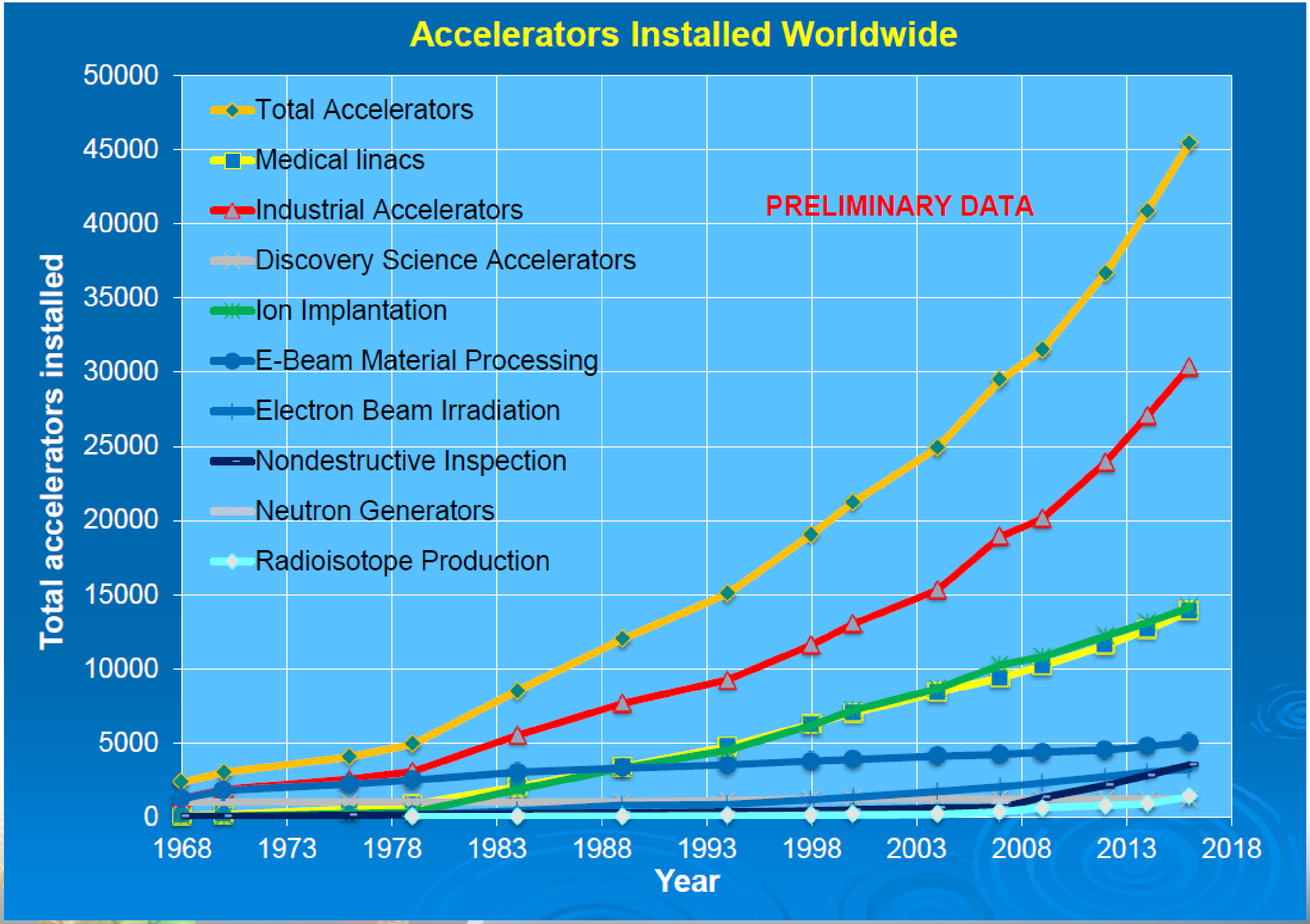
✓ DOE OPA Status Review (Remote)	October 19-21, 2021(A)
✓ Funding Discussion at DOE ONP (In-Person)	April 26, 2022 (A)
✓ FPD Status Update at BNL (Hybrid)	June 28-30, 2022 (A)
• Cost and Schedule Scrutiny Meetings	July - September 2022
• Project Detector Meetings	2022
○ *Technical Subsystem Reviews*	*Feb. – Dec. 2022*
○ *Pre-Resource Review Board Kickoff Meeting*	*October 2022*
• DOE OPA Status Review - Confirm CD-2/3A Plans	Jan. 31 – Feb. 2, 2023
• Preliminary Design and Director's Reviews	June 2023
• DOE CD 2/3A OPA Review and ICR, requires pre-TDR	October 2023
• DOE CD 2/3A ESAAB Approval	January 2024
• DOE CD 3 OPA Review, requires TDR	~January 2025
• DOE CD 3 ESAAB Approval	~April 2025

OPA = Office of Project Assessment
FPD = Federal Project Director
ICR = Independent Cost Review
ESAAB = Energy Systems Acquisition Advisory Board
TDR = Technical Design Report

Schedule – what do the CD milestones mean?

- **CD-0 – Approve mission need**: this documents that a scientific goal or a new capability, requiring material investment exists.
- **CD-1 – Approve Alternative Selection and Cost Range**: serves as a determination that the selected alternative and approach is optimized to meet the mission need defined at CD-0. What is perhaps most relevant is that CD-1 allows for release of Project Engineering and Design (PED) funds, which means the next phases of design of accelerator and detector can begin.
- **CD-2 – Approve Performance Baseline**: CD-2 is an approval of the preliminary design of the project and the baseline scope, cost, and schedule. What is most relevant is that CD-2 means there is now a definitive plan that the project will be measured against in cost, schedule and technical performance.
- **CD-3 – Approve Start of Construction**: CD-3 is an approval of the project's final design and authorizes release of funds for construction. What is most relevant is that projects can now proceed with construction related procurements and activities. CD-3 is sometimes split in CD-3A in a tailored approach to approve start construction for long-lead procurements.
- **CD-4 – Approve Start of Operations or Project Completion**: CD-4 provides recognition that the project's objectives have been met. CD-4 is sometimes split in CD-4A that allows, after agreed-upon criteria for technical success have been met, for transition into operations, and CD-4B that provides the formal closeout of the project.

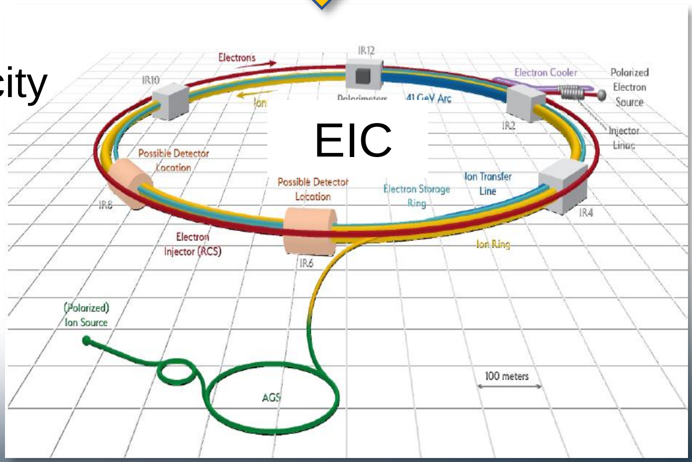
Growing Relevance of Accelerators Worldwide



From: Dr. Robert W. Hamm

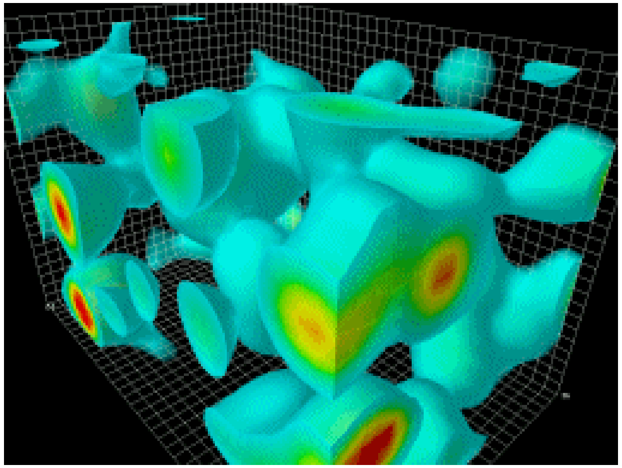
EIC Accelerator Design Overview

- **Hadron storage ring (HSR): 41, 100-275 GeV** (based on RHIC)
  - up to 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance (1.5 nm)
  - strong cooling (coherent electron cooling, ERL)
- **Electron storage ring (ESR): 2.5–18 GeV** (**new**)
  - up to 1160 polarized bunches
    - high polarization by continual reinjection from RCS
  - large beam current (2.5 A) ➔ 9 MW SR power
  - superconducting RF cavities
- **Rapid cycling synchrotron (RCS): 0.4-18 GeV** (**new**)
  - 2 bunches at 1 Hz; spin transparent due to high periodicity
- **High luminosity interaction region(s)** (**new**)
  - $L = 10^{34}\ cm^{-2}s^{-1}$
  - superconducting magnets
  - 25 mrad crossing angle with crab cavities
  - spin rotators (produce longitudinal spin at IP)



In the Subatomic World Everything is Moving!

When we enter the quantum world, particles are confined to small volumes



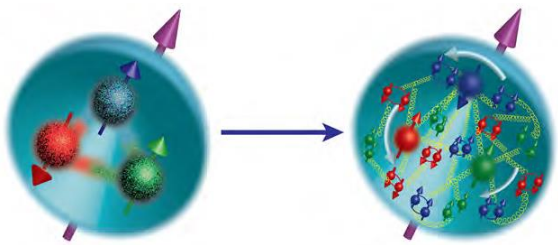
Because of Quantum Mechanics

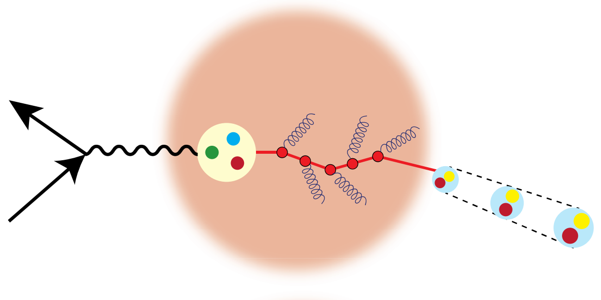
- Particles move at near lightspeed; everything is in continual motion.
- Particles are created and annihilated
- Even the vacuum fluctuates!

EIC Science Questions

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

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

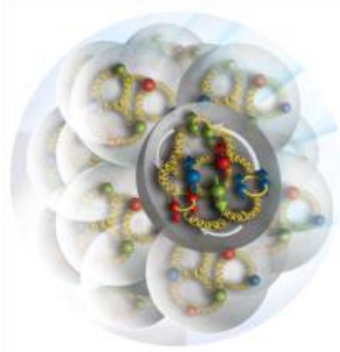




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

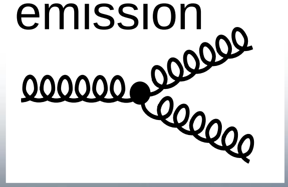
How do the quark-gluon interactions create nuclear binding?



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

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

gluon emission



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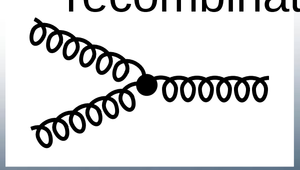
gluon recombination



Exploring the 3D Nucleon Structure

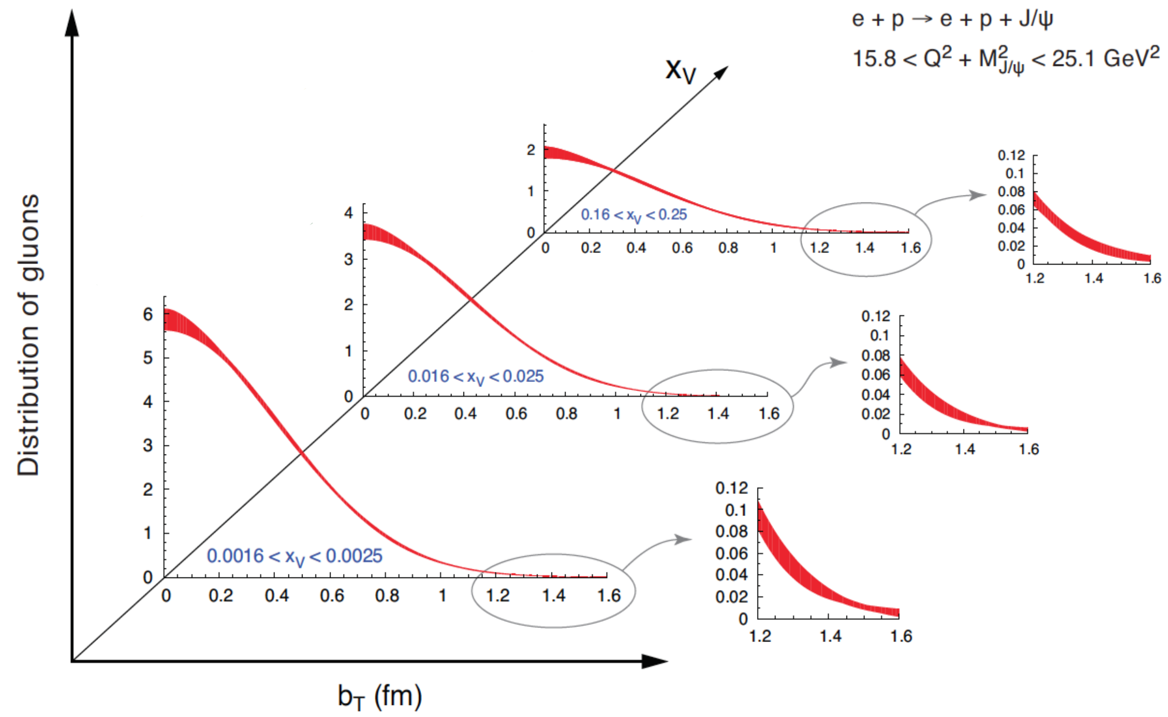
- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
    - High luminosity, large acceptance experiments with polarized beams and targets.
    - Theoretical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

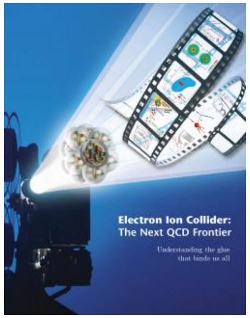
- **Deep Exclusive Scattering (DES)** cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location $\mathbf{b_T}$.

- **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

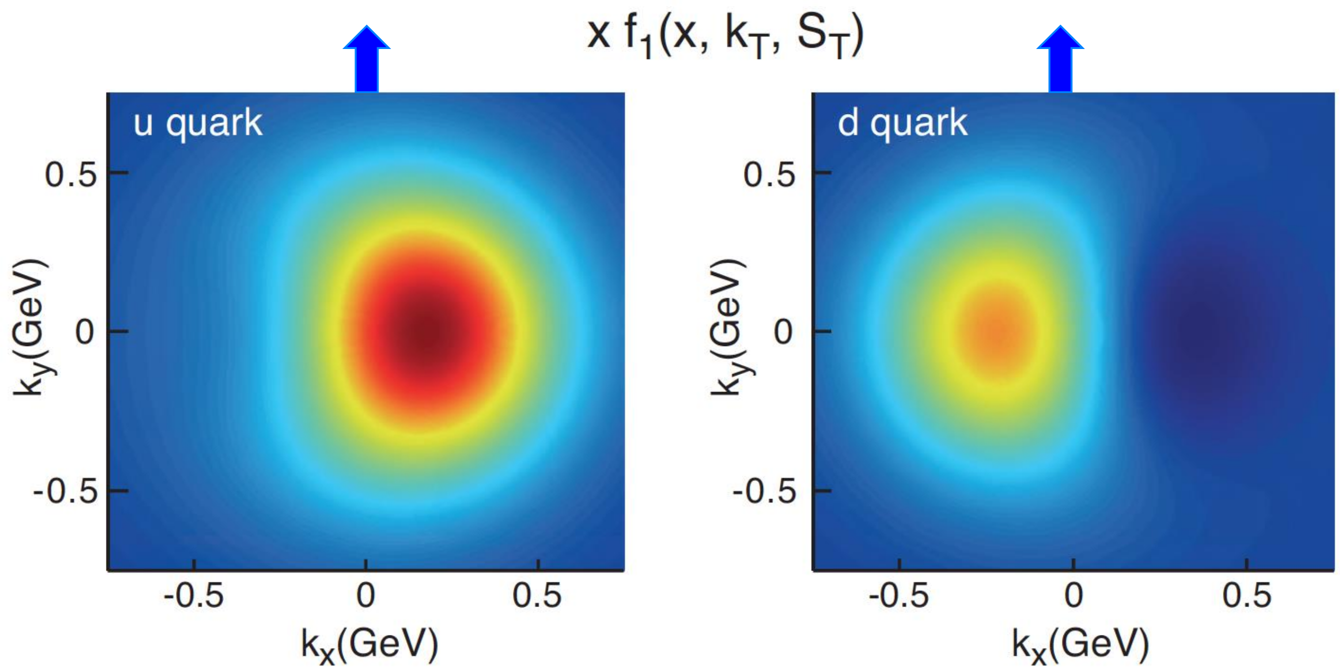
Confined Spatial Correlations: Transverse Spatial Distribution of Gluons

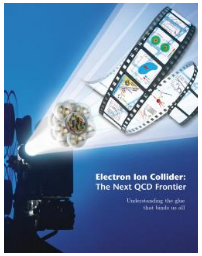




- How are gluons spatially distributed in a proton or a nucleus?
- Is the distribution smooth?
- How does it differ from the charge distribution?
- **First ever tomographic images of ocean of gluons within matter !**

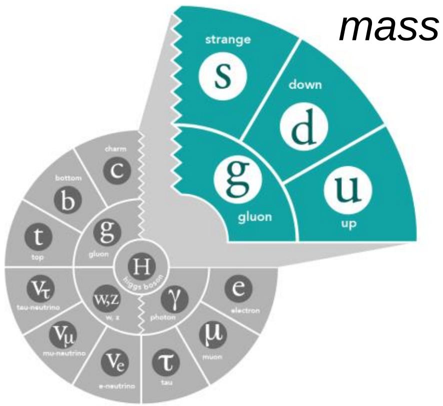
Confined Motion: Transverse Momentum Distributions of Quarks & Gluons





- Spin and the ability to look at transverse momentum together give a powerful new window into QCD
- Transverse Momentum Distributions directly related to orbital motion
- For example, we can explore for the first time **interference in quantum phases due to the color force – impossible with previous purely 1D/longitudinal experiments**

Mass of the Proton, Pion, Kaon



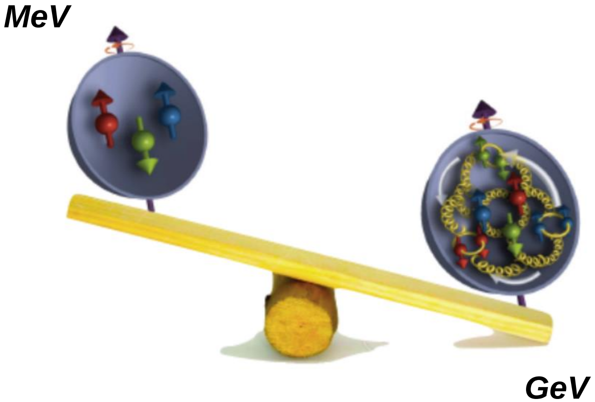
Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.

"Mass without mass!"

Proton

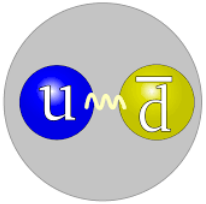
Quark structure: uud
Mass ~ 940 MeV (~1 GeV)
Most of mass generated by dynamics.

Gluon rise discovered by HERA e-p



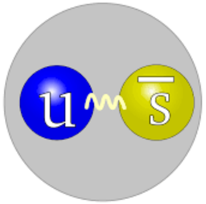
Pion

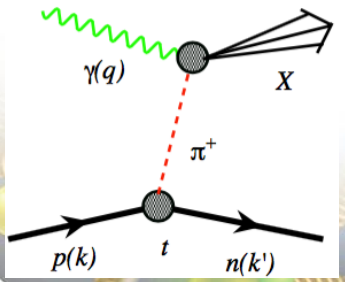
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



Kaon

Quark structure: us
Mass ~ 490 MeV
Boundary between emergent- and Higgs-mass mechanisms.
More or less gluons than in pion?



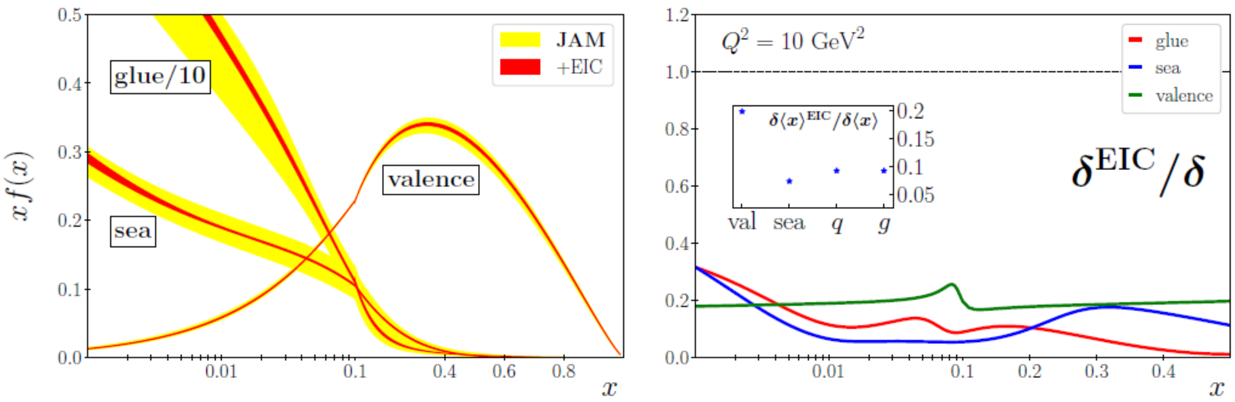


For the proton the EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly"

For the pion and the kaon the EIC will allow determination of the quark and gluon contributions with the Sullivan process.

A.C. Aguilar et al., Pion and Kaon structure at the EIC, arXiv:1907.08218, EPJA 55 (2019) 190.
J. Arrington et al., Revealing the structure of light pseudoscalar mesons at the EIC, arXiv:2102.11788, J. Phys. G 48 (2021) 7, 075106.

Reduction of Pion 1-D Structure Information by EIC



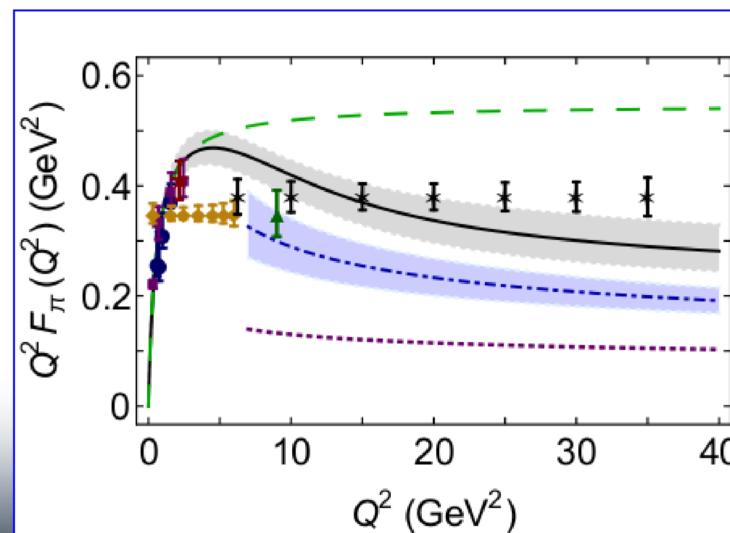
From EIC Yellow Report, P. Barry, W. Melnitchouk, N. Sato et al.

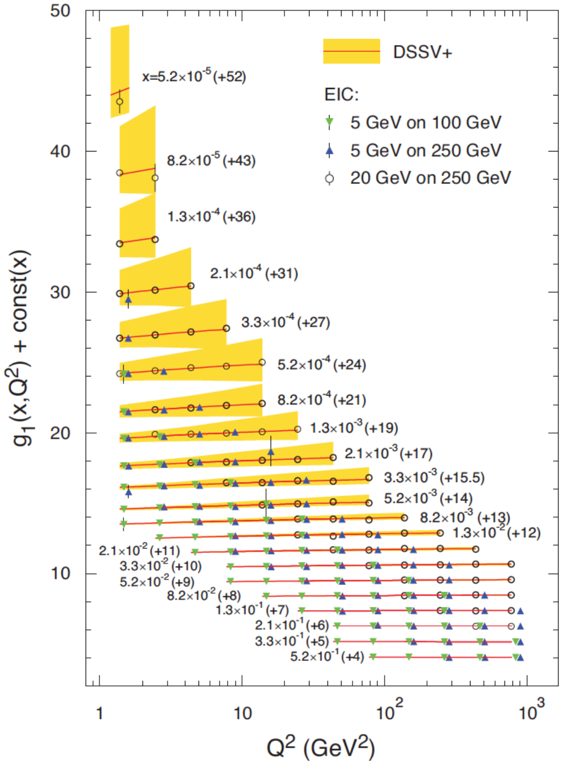
Figure 7.24: Left: Comparison of uncertainties on the pion valence, sea quark and gluon PDFs before (yellow bands) and after (red bands) inclusion of EIC data. Right: Ratio of uncertainties of the PDFs with EIC data to PDFs without EIC data, $\delta^{\rm EIC}/\delta$, for the valence (green line), sea quark (blue) and gluon (red) PDFs, assuming 1.2% systematic uncertainty,

Pion form factor measurement projections at EIC

- Assumed 5 GeV(e^-) x 100 GeV(p) with an integrated luminosity of 20 fb^{-1}/year, and similar luminosities for d beam data

*From A.C. Aguilar et al., EPJ A **55** (**2019**) 10, 190*





The Incomplete Hadron – the Spin Puzzle

"Helicity sum rule"

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

EIC projected measurements:
Precise determination of polarized PDFs of quark sea and gluons ➔ precision ΔG and ΔΣ
➔ Determination of $L_q + L_g$

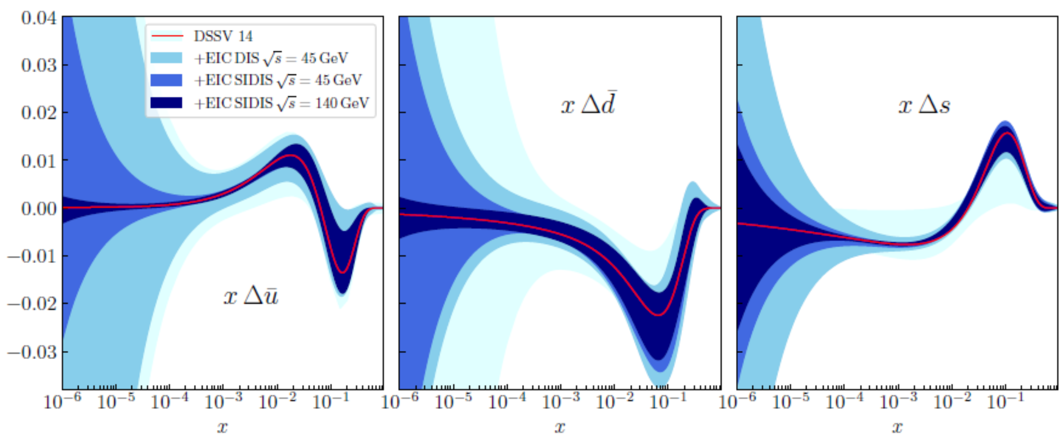


Figure 7.19: Impact of the EIC semi-inclusive measurements on the sea quark helicities $x\Delta\bar{u}(x,Q^2)$, $x\Delta\bar{d}(x,Q^2)$ and $x\Delta s(x,Q^2)$ as a function of x at $Q^2 = 10\,\text{GeV}^2$.

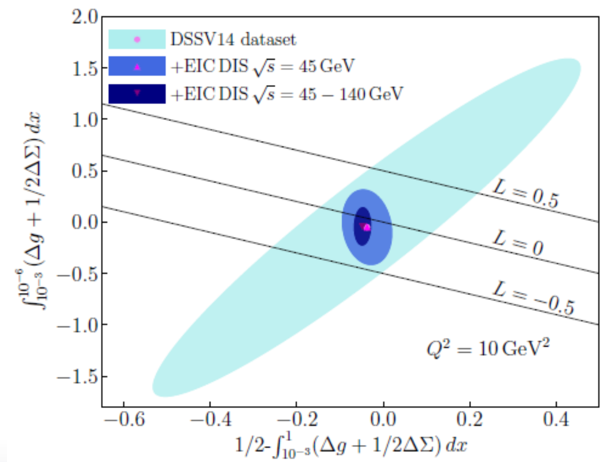


Figure 7.17: Room left for potential orbital angular momentum contributions to the proton spin at $Q^2 = 10\,\text{GeV}^2$, according to present data and future EIC measurements.

What Do We Know of Gluons in Nuclei? Not Much!

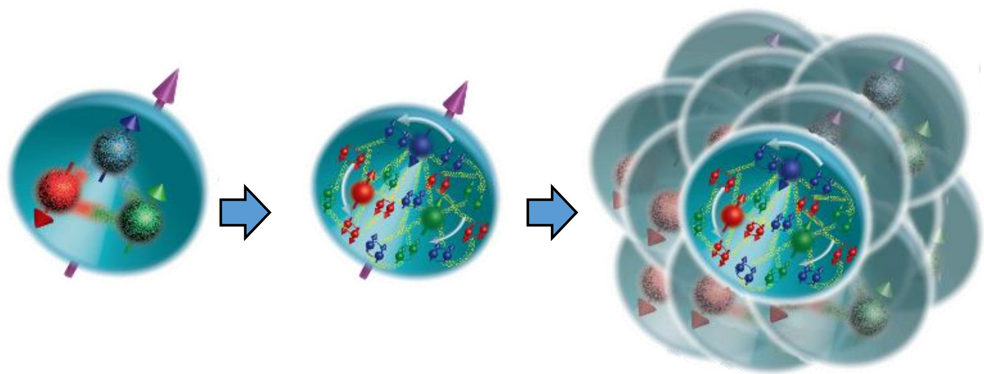
The EIC will, for the first time, provide a complete view of the nucleus:

The Proton (1975)

The Proton (2015)

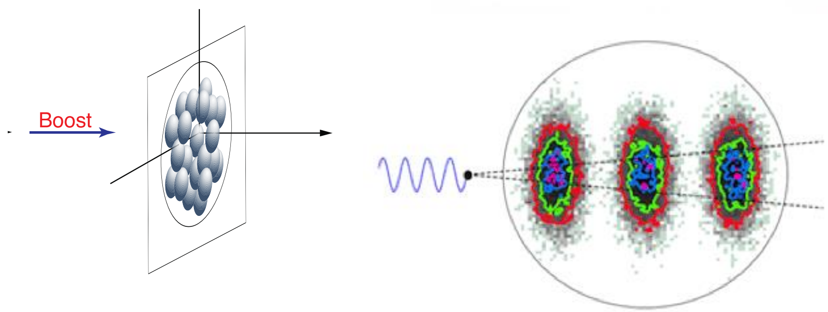
The Proton in a nucleus

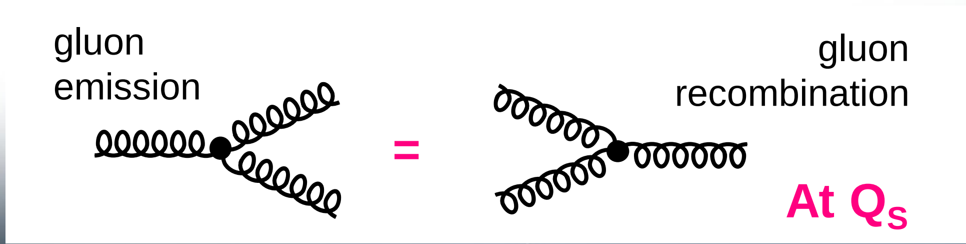
And much more QCD dynamics that can affect the identity of the protons and neutrons

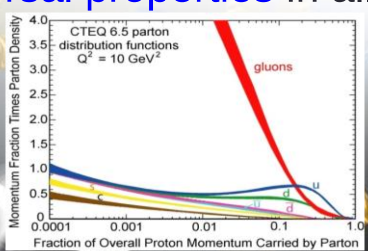


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

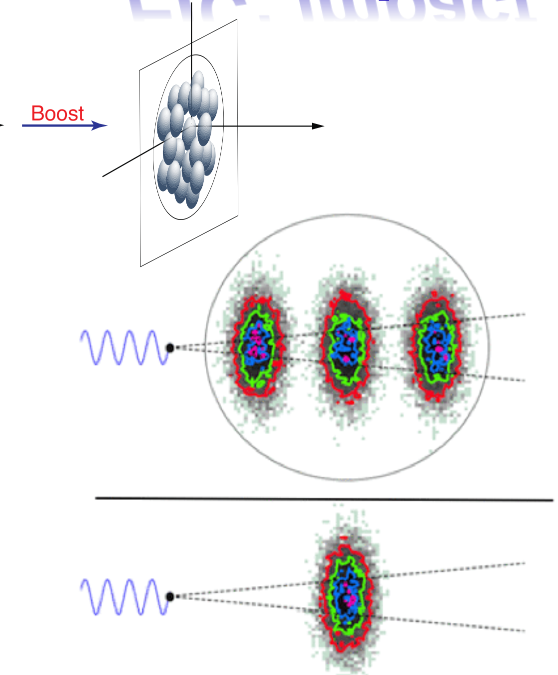
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclear matter?

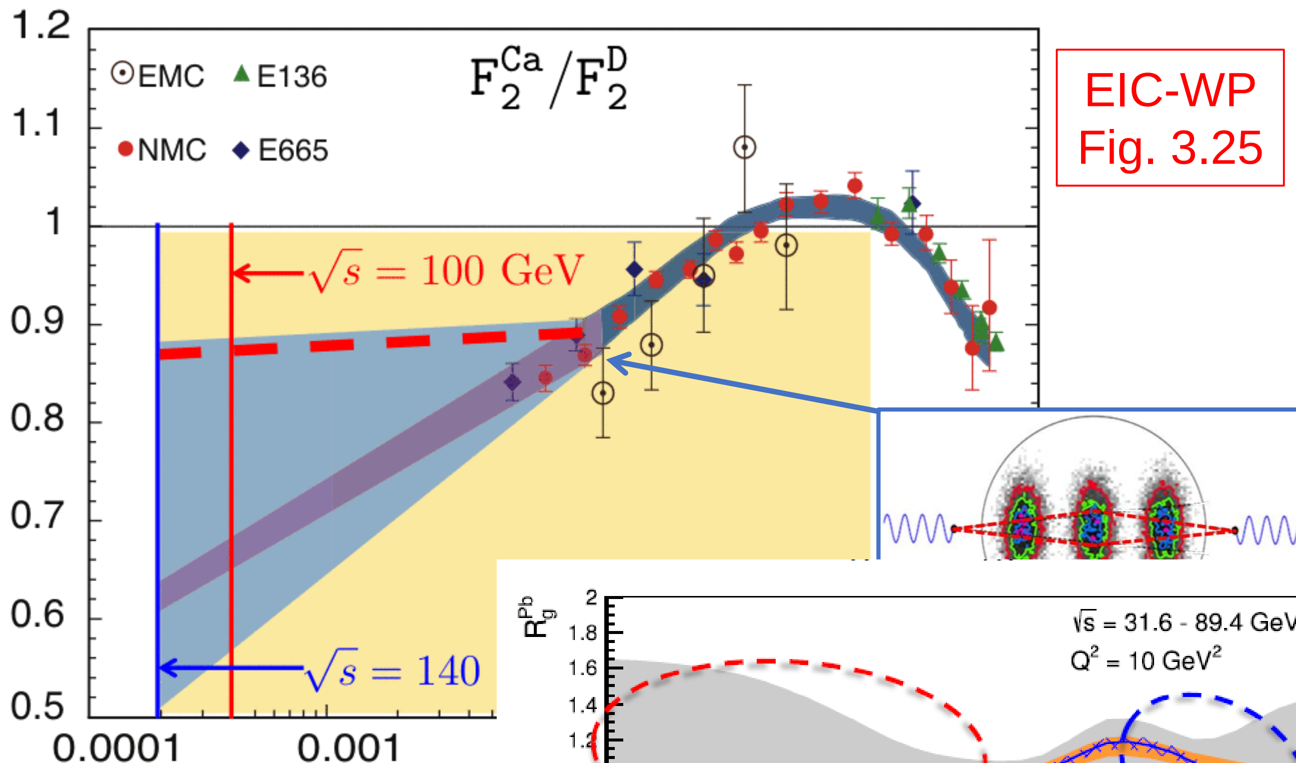




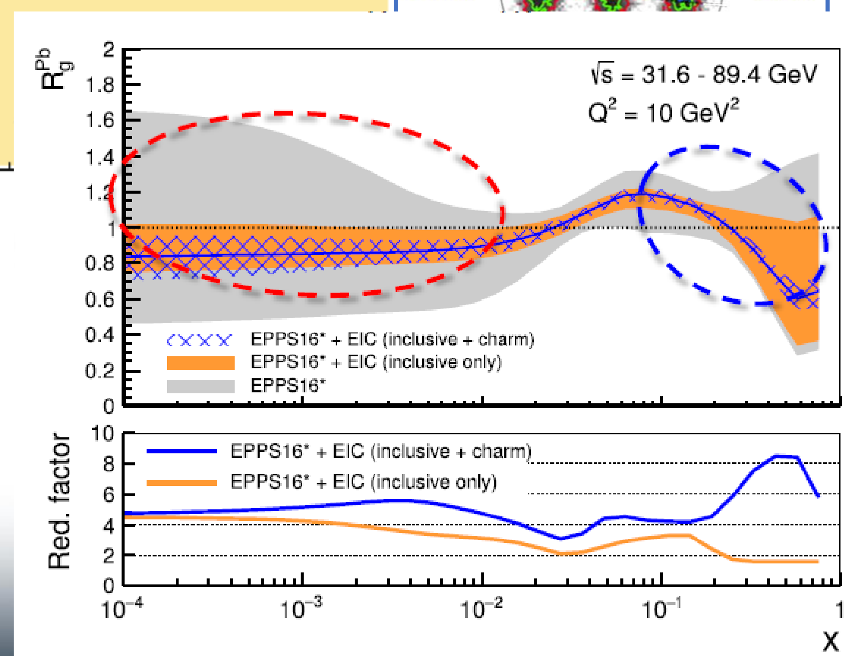


EIC: impact on the knowledge of 1D Nuclear PDFs





EIC-WP
Fig. 3.25



- **Without EIC, large uncertainties in nuclear sea quarks and gluons**
- Complementary to RHIC and LHC pA data.
  ➔ Provides information on initial state for heavy ion collisions
- Does the nucleus behave like a proton at low-x?
  ➔ relevant to the understanding of astronomical objects

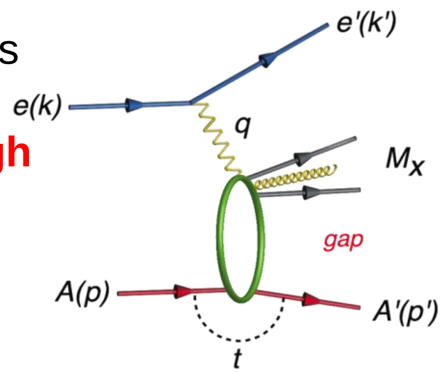
Diffraction for the 21st Century

Many ways to get to gluon distribution in nuclei, but diffraction most sensitive

HERA surprise: A 7 TeV equivalent electron bombarding the proton … but nothing happens to the proton in 10-15% of cases

Diffractive event

Diffraction cross-sections have strong discovery potential due to their **high sensitivity to gluon density**: $\sigma \sim [g(x,Q^2)]^2$

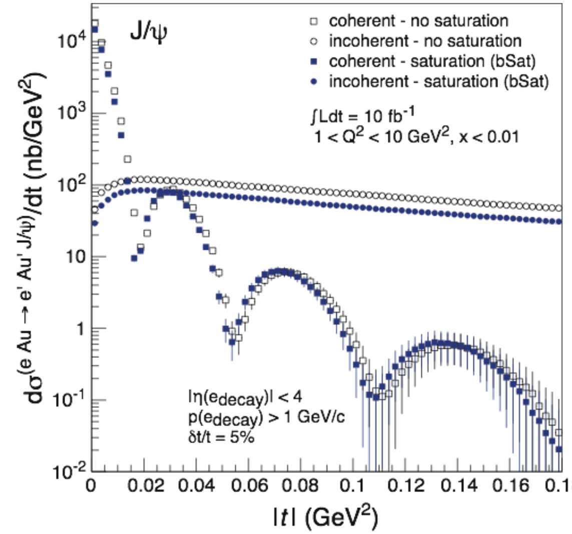


gluon emission

gluon recombination

At Q_S

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



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

Predictions for eA for such hard diffractive events range up to: 25-30%... given saturation models