The Electron-Ion Collider: The Quest to Understand the Fundamental QCD Structure of Matter

Rolf Ent (Jefferson Lab)

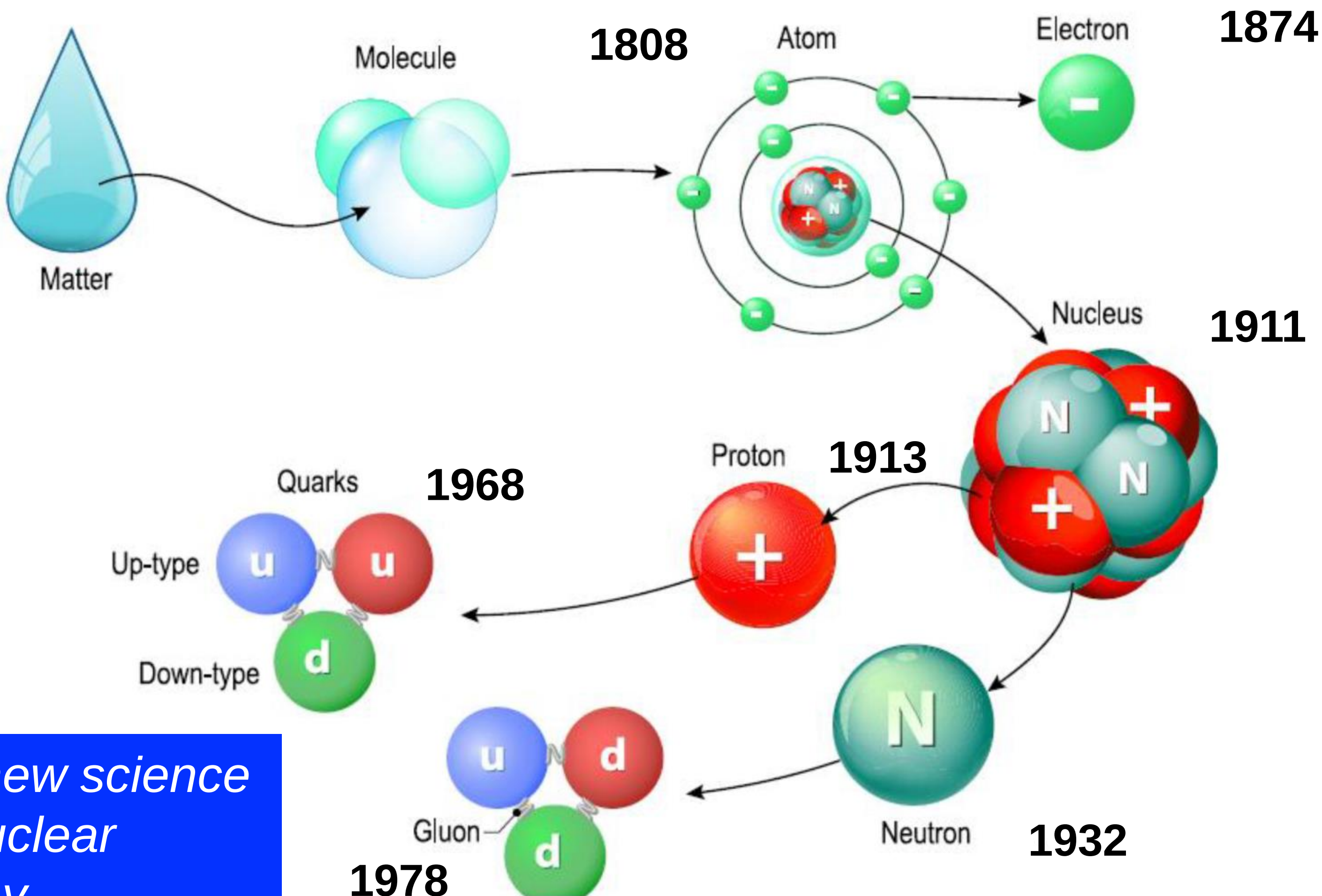
TIDC Autumn School on Electron-Ion Collider

Augyst 28th, 2023

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
- 21st Century Laboratories of Emergent Dynamics in QCD
- The US-Based Electron-Ion Collider (EIC)
- EIC Science Examples
- EIC Scope and Detector Integration for Physics
- EIC Status
- Proton Visualization – Artistic View Based on 1D Data
  → On to QCD Reality in 3D!
- Work towards Visualization of Nucleus
- EIC Summary: A Portal to a New Frontier

The Quest to Understand the Fundamental Structure of Matter



Towards a new science frontier – Nuclear Femtography

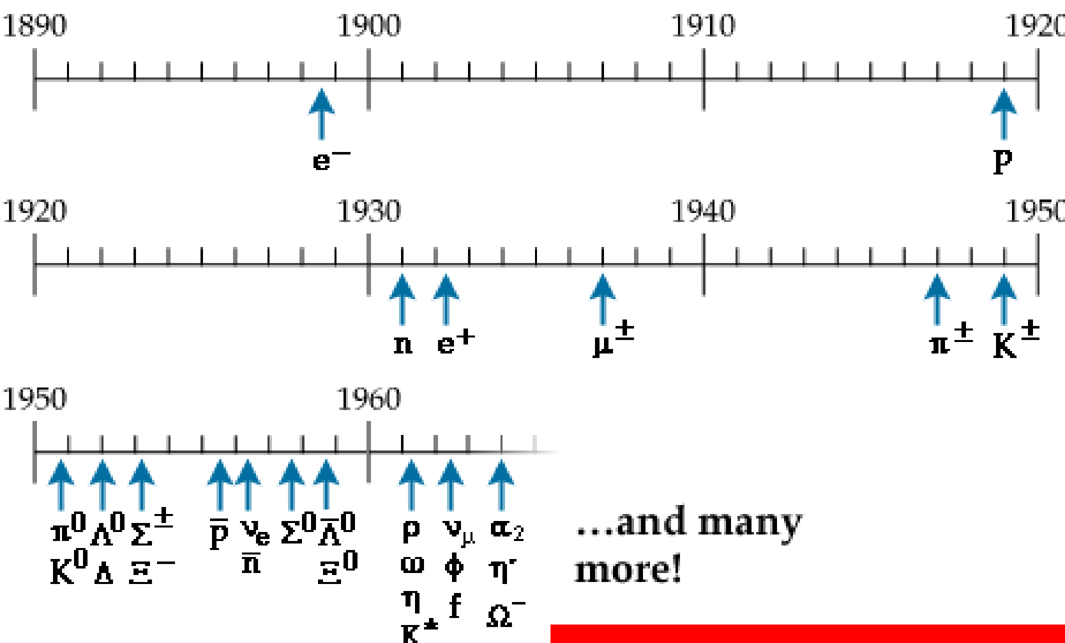
EIC: Understanding the Glue that Binds Us All - ***Without gluons binding the quarks, there would be no nucleons, no atomic nuclei… no visible world!***

Elementary Particles

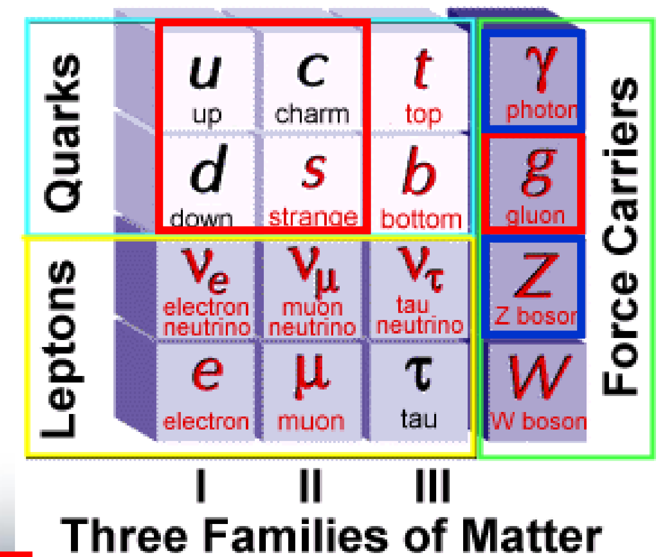
- Protons, neutrons and electrons (**p, n, e**) build all the atoms.
- Proton and neutrons make up 99.9% of the visible mass in the universe.
- Dozens of new particles were discovered in the past century.
- Strong interaction: strength can be 100 times the electromagnetic one

  leptons (e, μ, ν,..): not involved in strong interaction

  hadrons [mesons(π, K,…) and baryons (p, n,…)]: **involved in strong interaction**



Electron Scattering

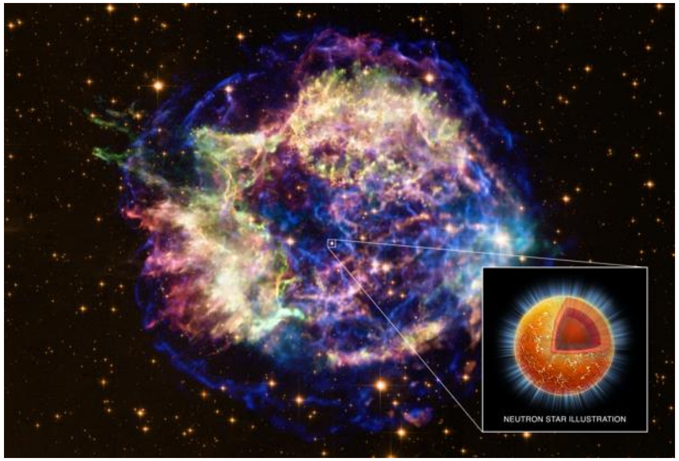


Quarks & Gluons: QCD

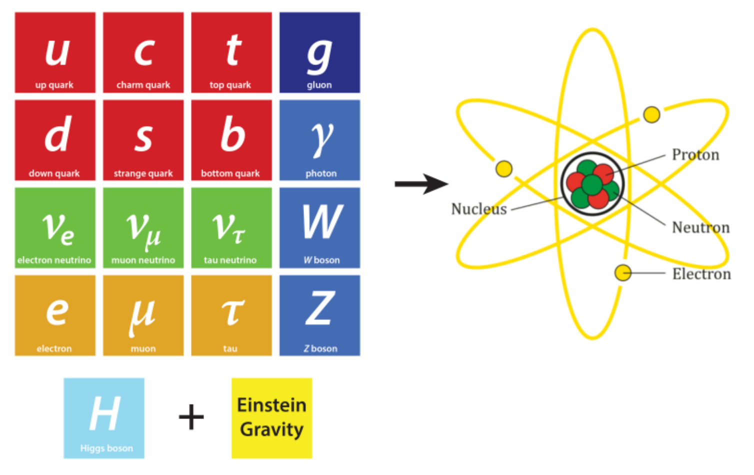
What Is The World Made Of?

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.

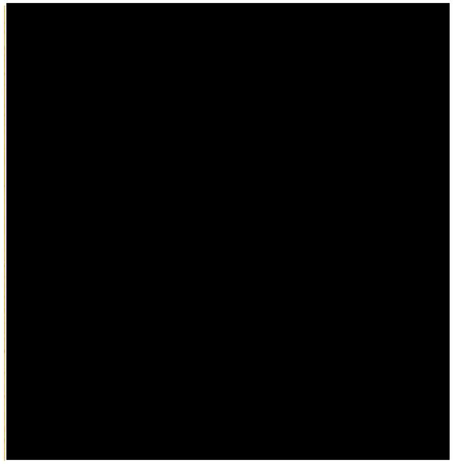


All the matter in the visible universe is understood in terms of subatomic particles and their constituents and interactions.

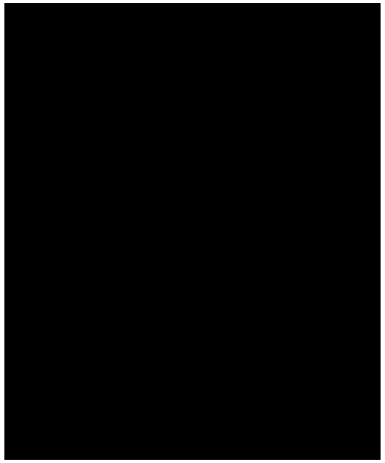
The Standard Model of Physics explains the fundamental structure of the visible matter in terms of quarks, gluons and their interactions.

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?



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

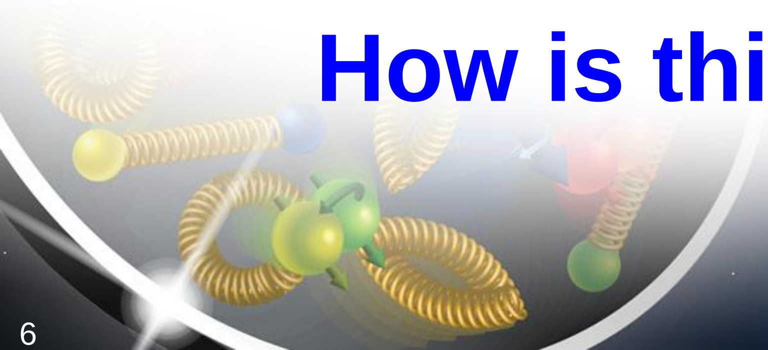


The signals from MRI scans would be reduced by a factor of five.

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

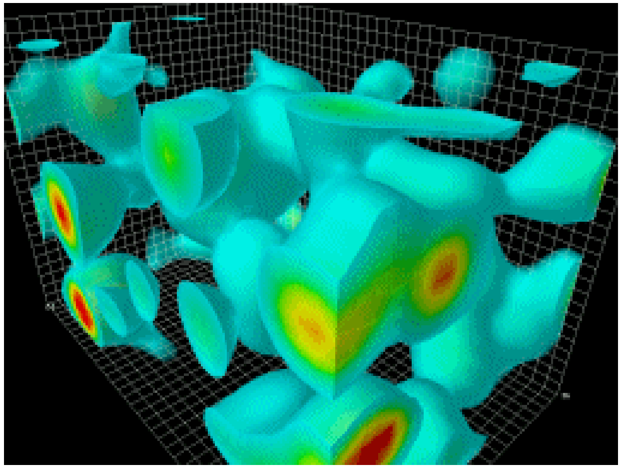
What If There Were No Quark-Gluon Interactions?

How is this possible? → EIC



In the Subatomic World Everything is Moving!

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



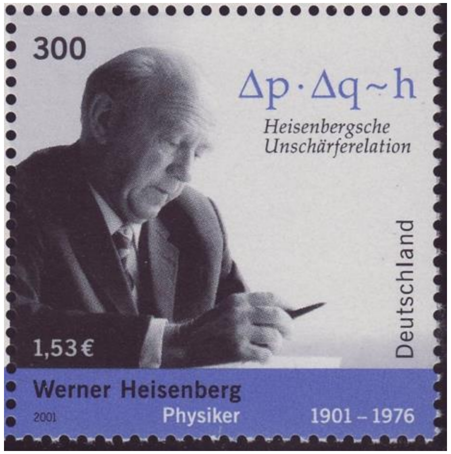
Because of Quantum Mechanics

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

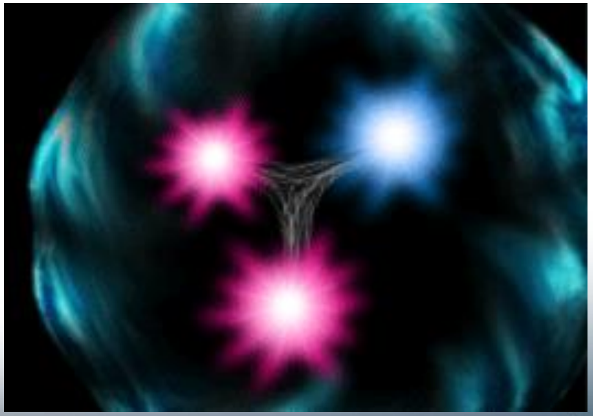
The Strange Quantum World

- Heisenberg's uncertainty principles say we can not measure momentum *p* and position *x* with absolute precision, or energy *E* and time *t*.

1. $\Delta p \, \Delta x \geq \frac{1}{2} \hbar$ 2. $\Delta E \, \Delta t \geq \frac{1}{2} \hbar$



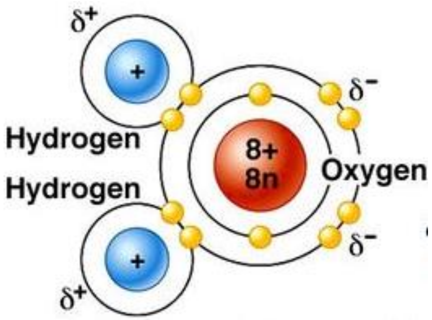
- Consequences:
  1. Particles that are bound or confined to small volumes will reach near-relativistic velocities
     - Protons inside atomic nuclei move with ~1/5 the speed of light, and quarks inside protons move at relativistic speeds.
  2. Pairs of virtual matter and anti-matter are continuously created and destroyed, borrowing their mass/energy by the uncertainty principle
     - They do not exist as observable entities, but their existence is exerted on other particles as subtle pressure, like the Casimir effect in the vacuum.
     - This means that conservation of energy can be temporarily broken, and matter/anti-matter pairs with larger mass than the proton can live short times inside this proton.



Nuclear Femtography – Subatomic Matter is Unique

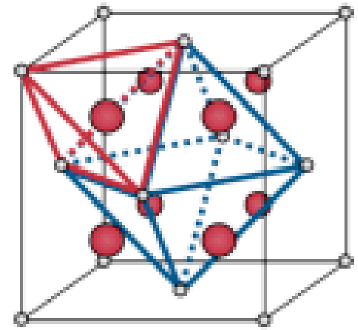
Most known matter has localized mass and charge centers – vast “open” space

Molecule:



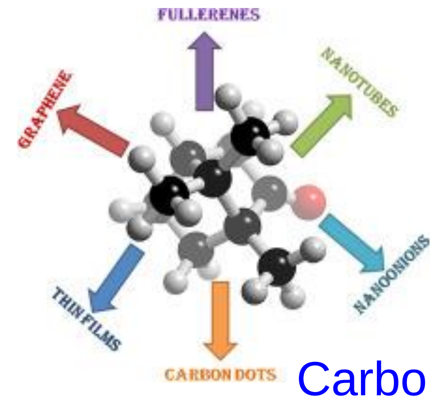
“Water”

Crystal:



Rare-Earth metal

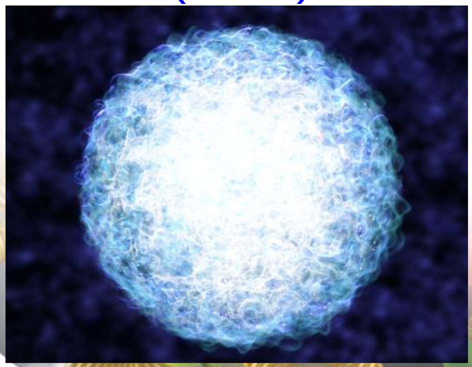
Nanomaterial:



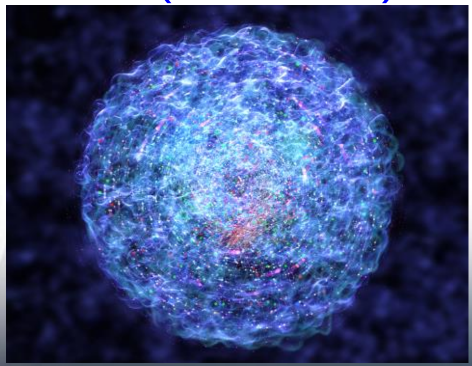
Carbon-based

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.

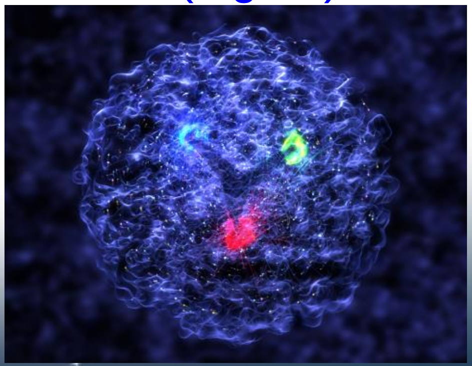
Proton (low-x):



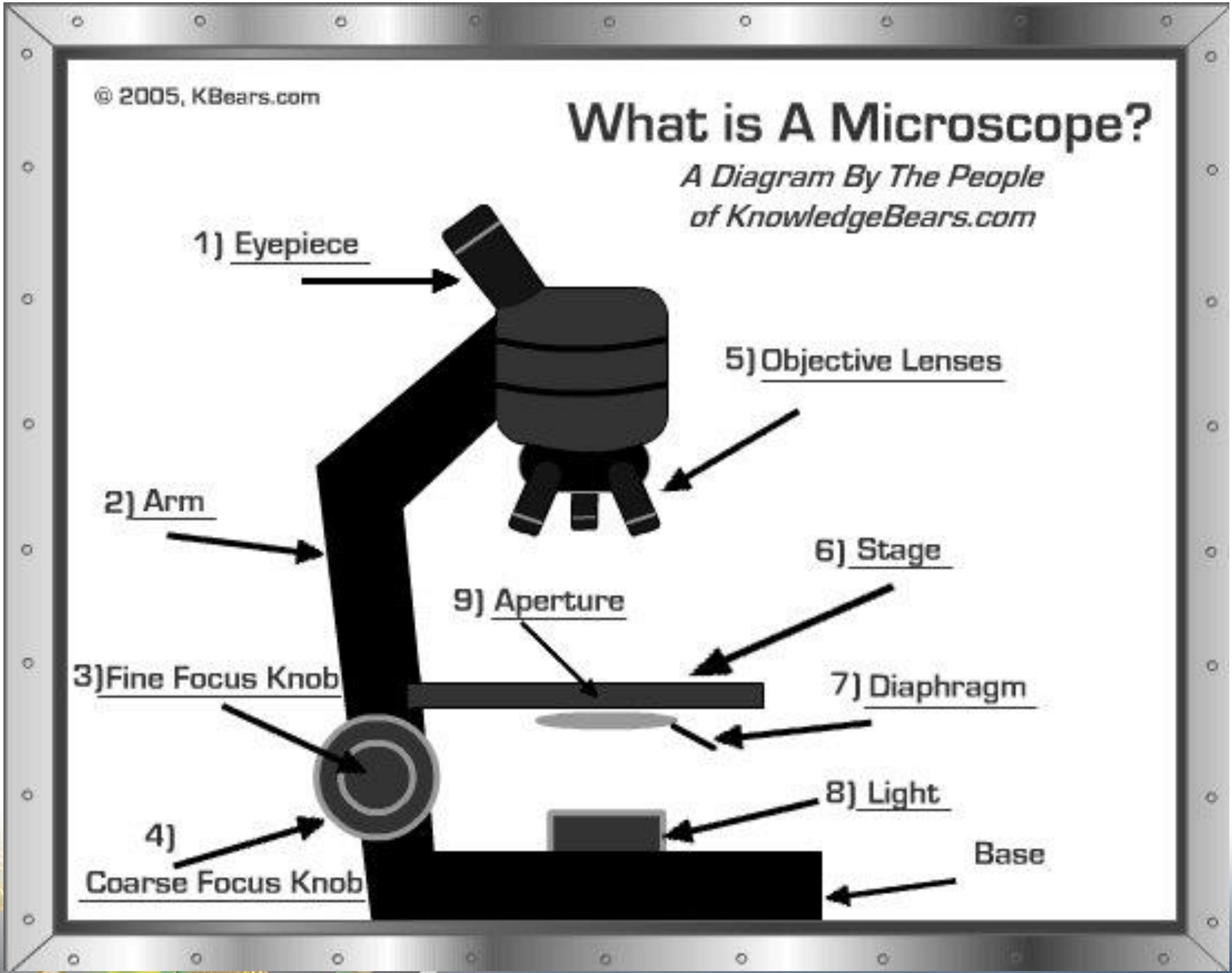
Proton (medium-x):



Proton (high-x):



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



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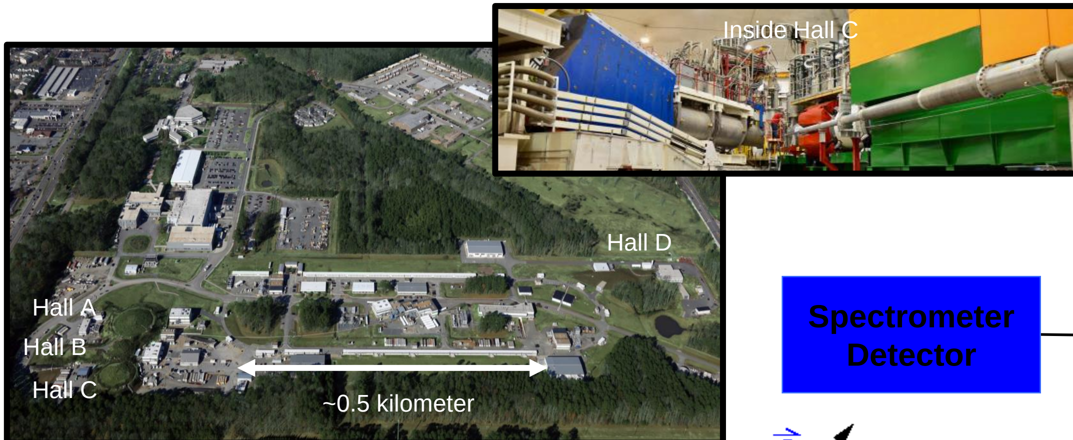
What is A Microscope?
A Diagram By The People
of KnowledgeBears.com
1) Eyepiece
2) Arm
3)Fine Focus Knob
4)
Coarse Focus Knob
5) Objective Lenses
6) Stage
7) Diaphragm
8) Light
9) Aperture
Base

Jefferson Lab as Example – An Electron Microscope to Image Protons and Nuclei

Created to build and operate the Continuous Electron Beam Accelerator Facility (CEBAF), world-unique user facility for Nuclear Physics

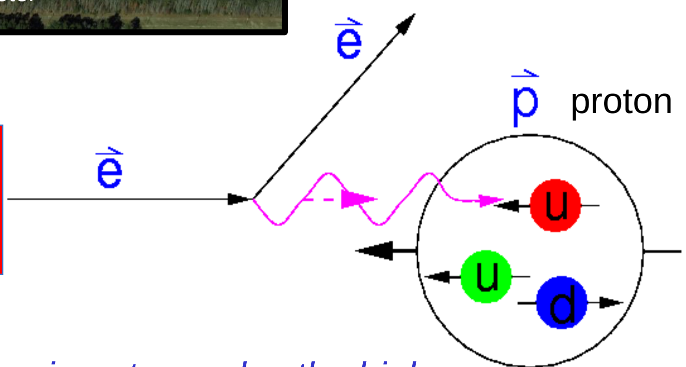


Computer

Spectrometer Detector

Data acquisition

Source of Photons Electron accelerator



$$d_{probed} \propto \lambda = \frac{\hbar}{p}$$

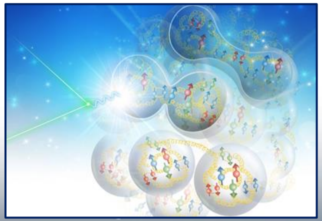
$\approx 2\,x\,10^{-17}$ m

~ 1/50 the size of the proton for p = 10 GeV

Electron scattering experiments employ the high momentum point-like electrons, and electromagnetic interactions, which are well understood, to probe nuclear structure (which isn't).

E_{CM} ~ 3.3 (@6 GeV), 4.5 (@12 GeV)

nucleus



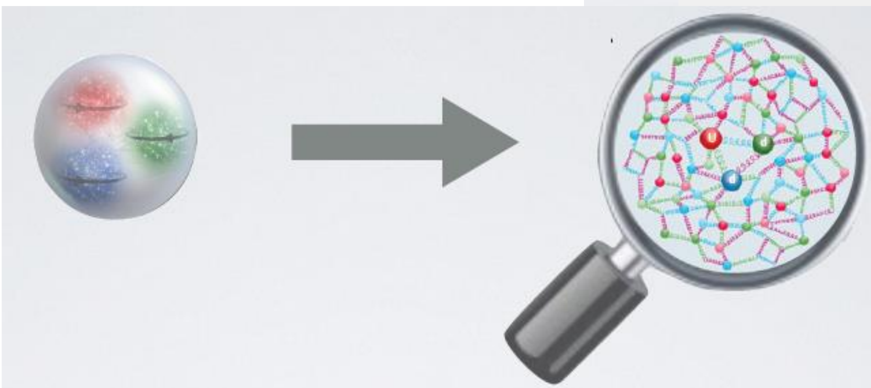
Jefferson Lab Stats:

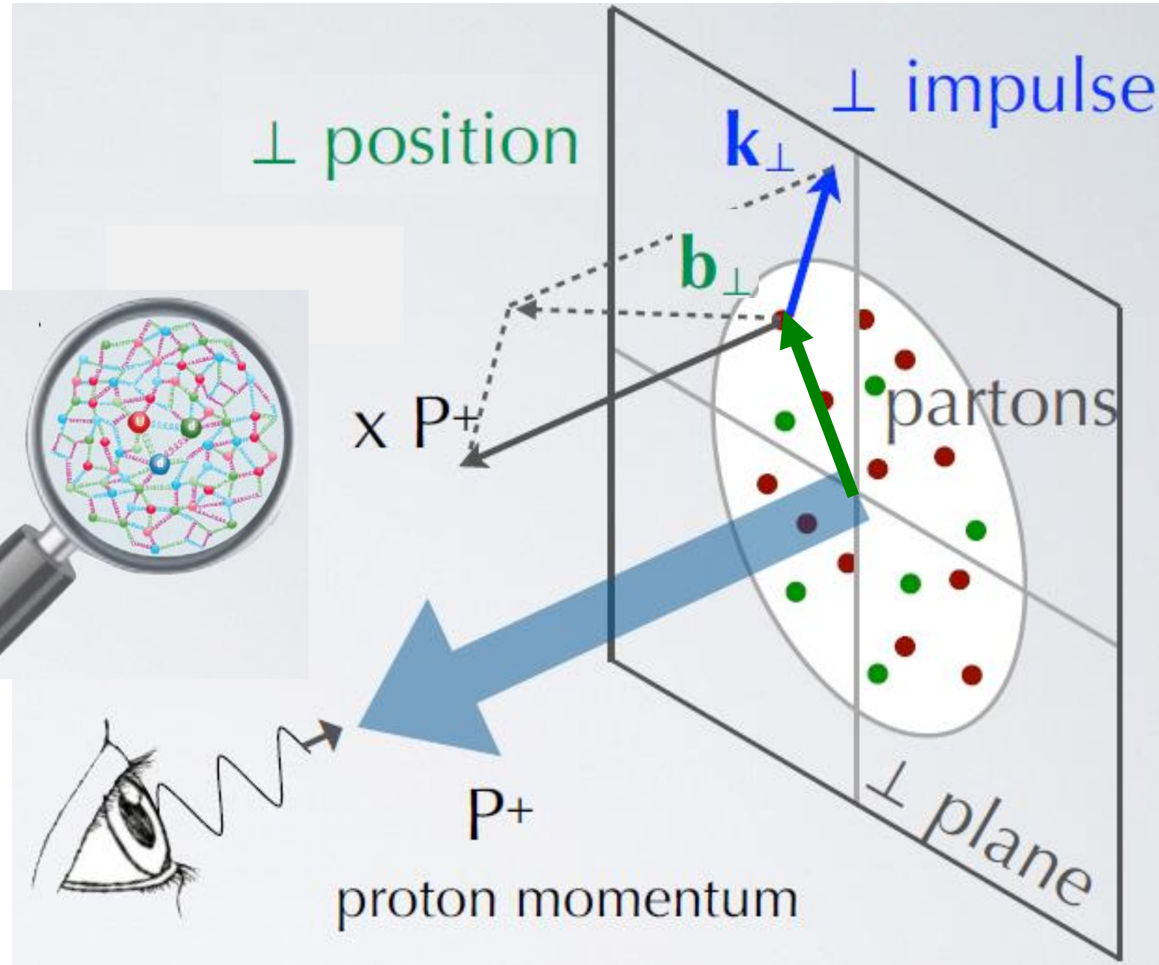
- Located in Newport News, VA
- 169-acre site
- In operation since 1995
- ~800 employees
- 1,889 Active Users (FY22)
- 1/3 of Users are from non-US Institutions, from 37 countries
- >700 PhDs granted to-date
- On average 30% of US PhDs in nuclear physics
- FY2022 Costs: ~$200M (~2/3 operations, ~1/3 new construction)

(EIC has E_{CM} in 29 GeV to 140 GeV range and will be a much larger electron microscope to peer into the realms of gluons and the quark sea).

Nuclear Femtography - Imaging

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

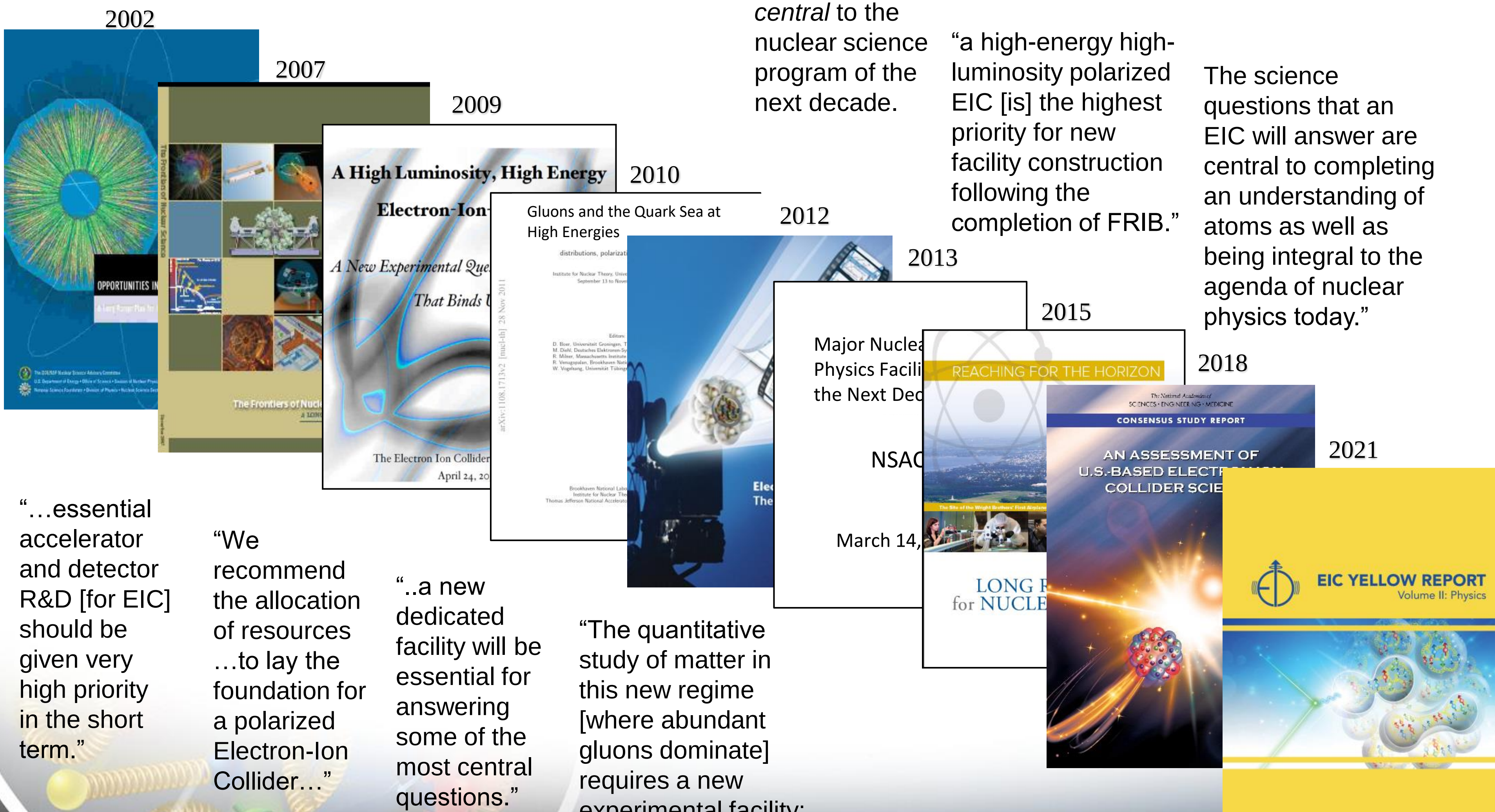




Structure mapped in terms of
$\mathbf{b}_T$ = transverse position
$\mathbf{k}_T$ = transverse momentum

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

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.."

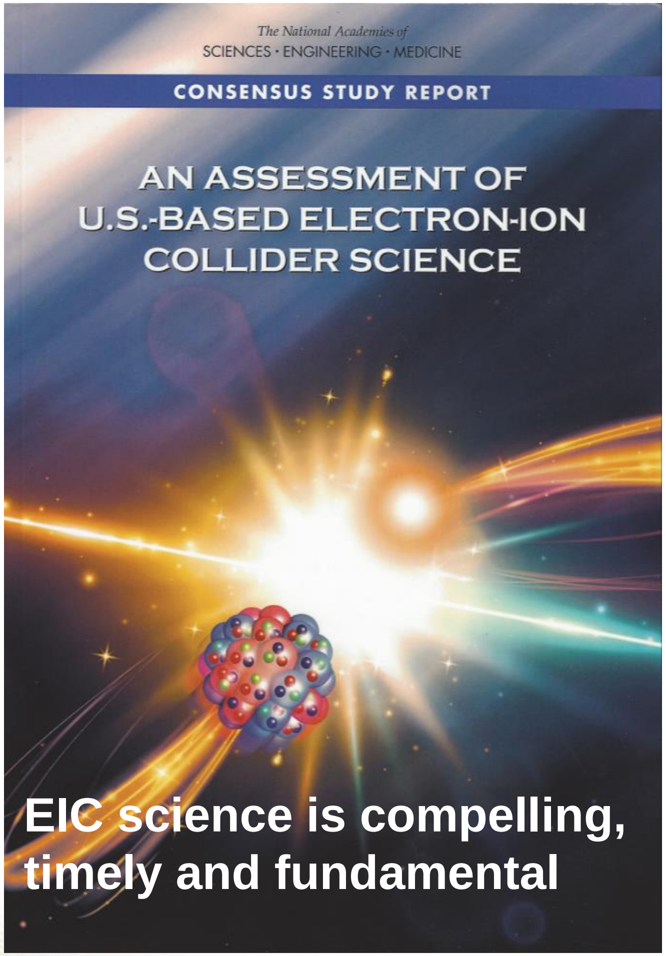
Electron-Ion Collider..*absolutely central* to the nuclear science program of the next decade.

"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 – 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

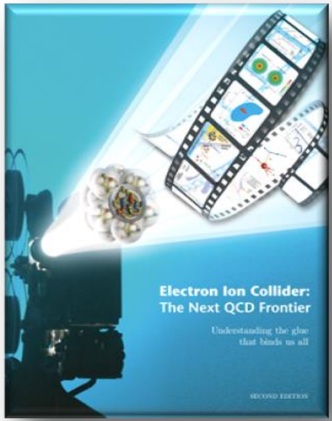
- **Finding 1:** An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:
  - How does the **mass** of the nucleon arise?
  - How does the **spin** of the nucleon arise?
  - What are the **emergent properties**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

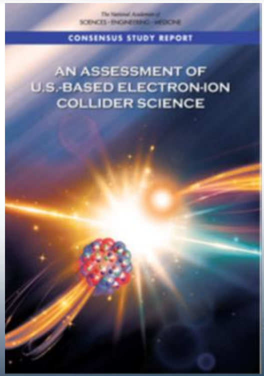
- **Finding 2:** These three high-priority science questions can be answered by an EIC with **highly polarized beams** of electrons and ions, with sufficiently **high luminosity** and sufficient, and **variable**, center-of-mass **energy**.

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:

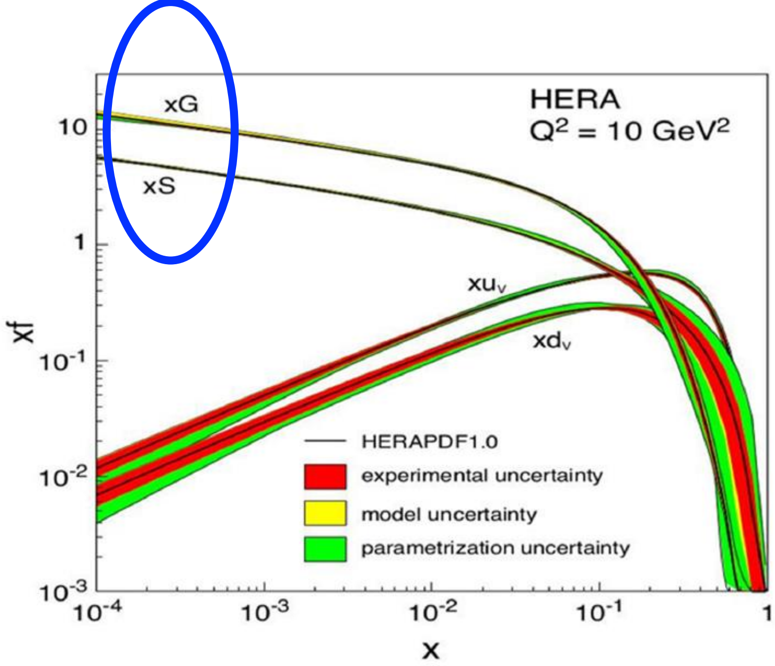
- Extensive center-of-mass energy range, from ~20-~100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times 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).





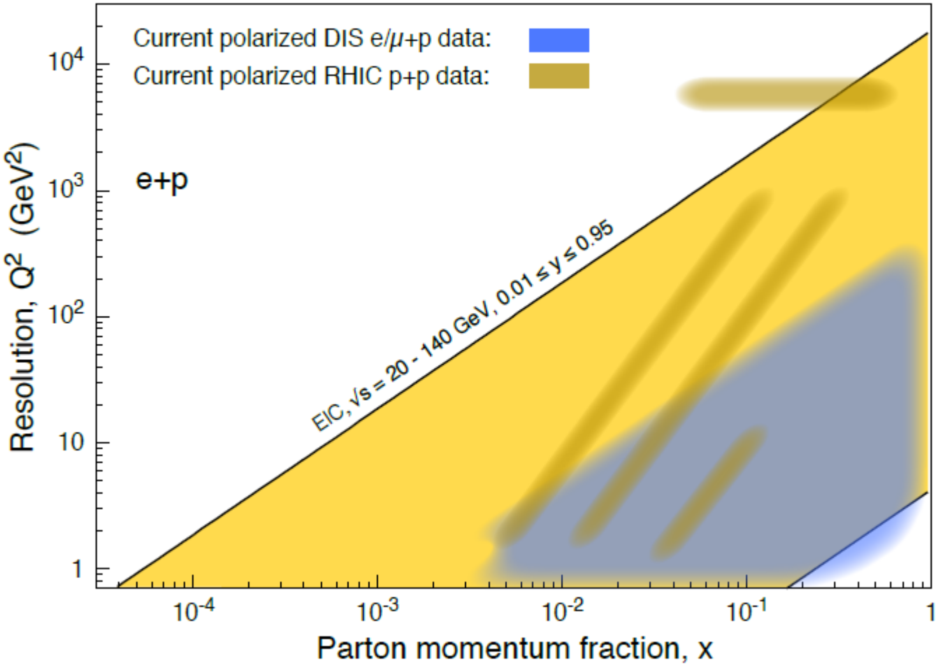
The EIC requirements have remained consistent, see e.g., the 2012 white paper and 2015 NSAC Long Range Plan

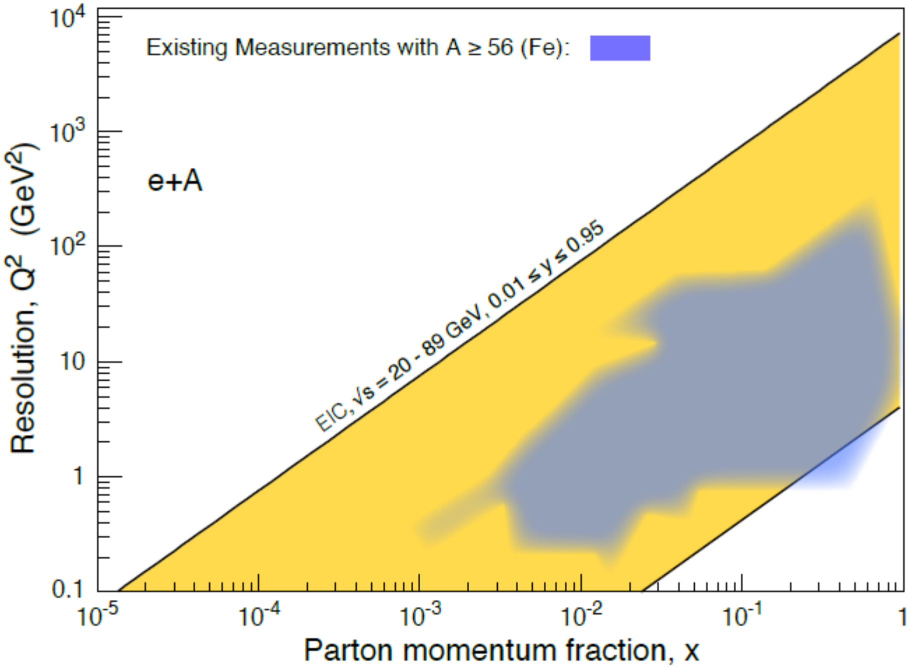
EIC Science Landscape



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

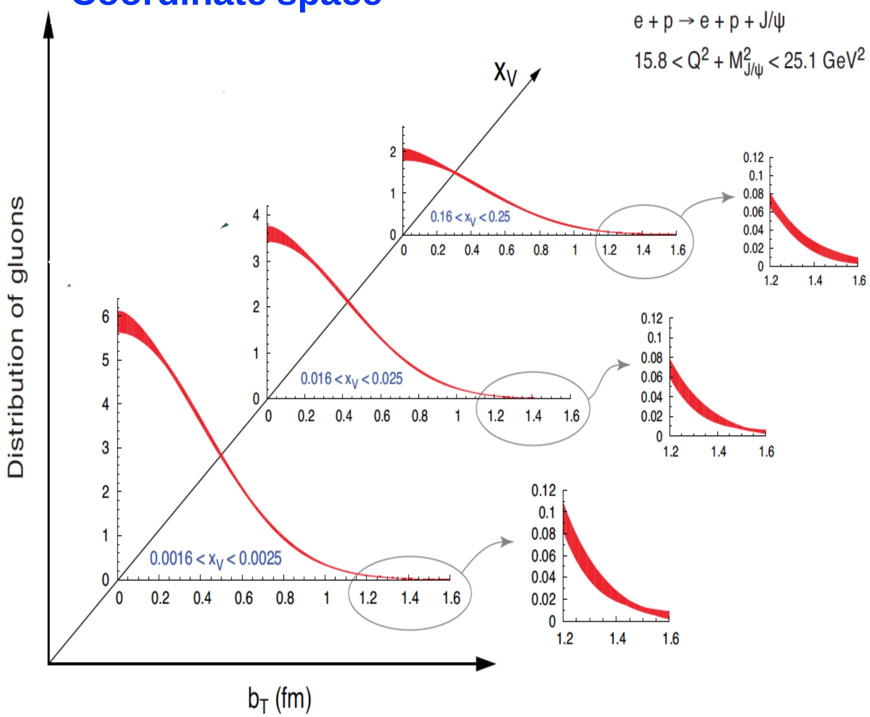
A huge leap in accessible kinematics landscape (into the land of gluons and the quark sea) for polarized e-N and unpolarized e-A reactions!



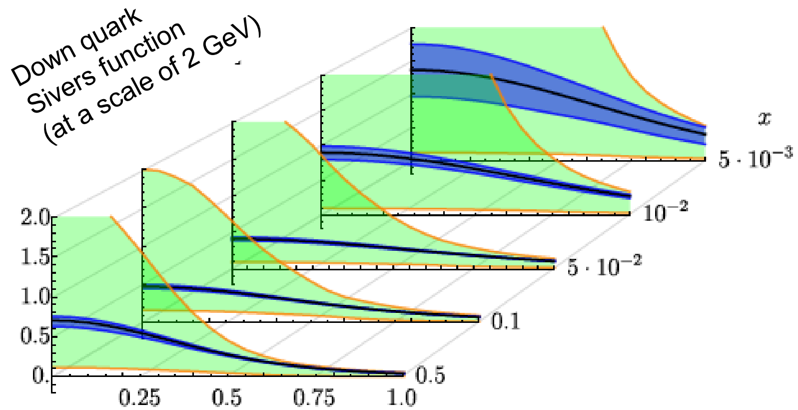


EXAMPLE 1 – 3D Imaging

Coordinate space



Momentum space



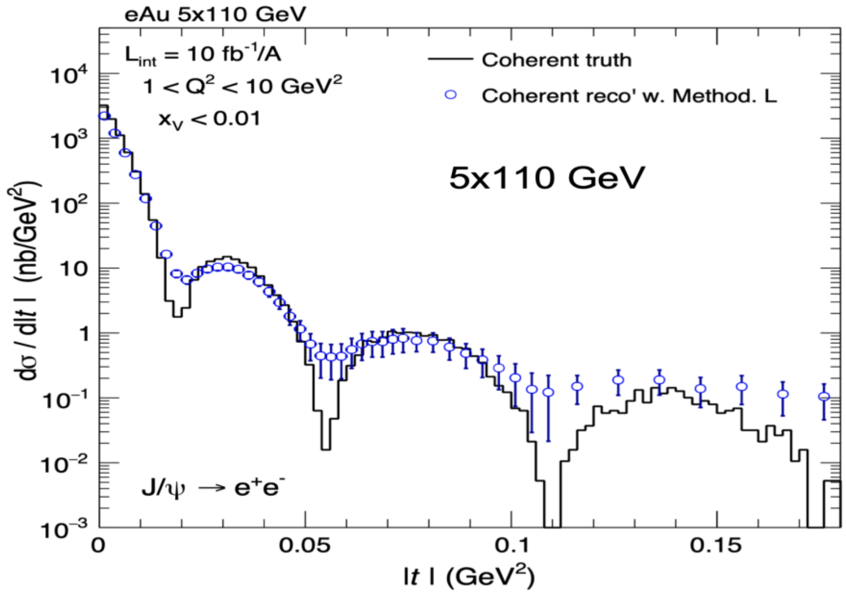
The green-shaded areas represent the current uncertainty, while the blue-shaded areas are the uncertainties when including the EIC pseudodata.

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

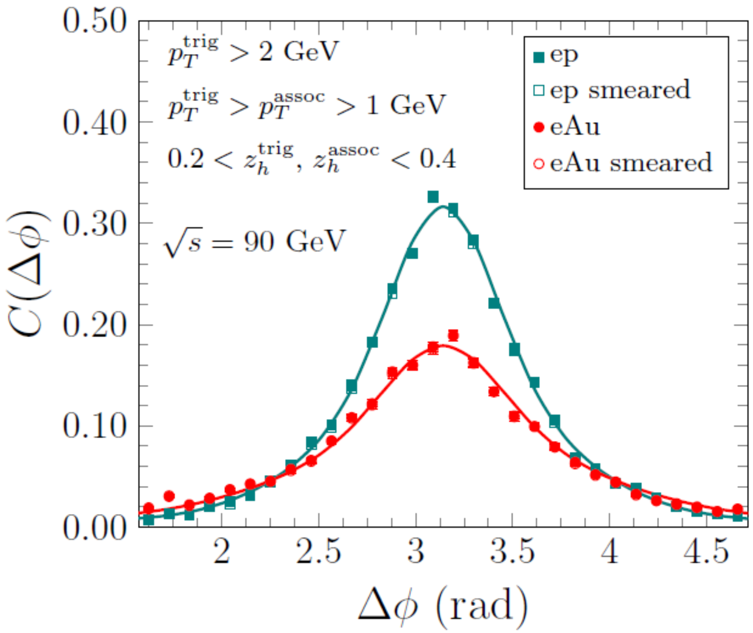
- Spin and the ability to look at transverse momentum together give a powerful new window into QCD
- Distributions directly related to orbital motion
- **We can explore for the first-time interference in quantum phases due to the color force – impossible with 1D/longitudinal experiments !**

EXAMPLE 2 – Dense Gluon Systems

3D imaging of nuclei



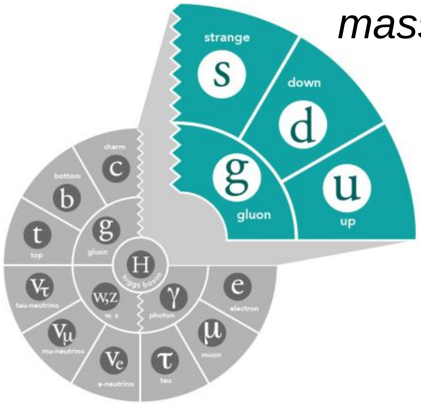
Hadron-Hadron Correlation functions



- How are gluons spatially distributed in a nucleus? Is the distribution smooth?
- How does it differ from the charge distribution?
- **We can explore the onset of gluon saturation in the form factor pattern !**

- The angle between the two hadrons h1 and h2 in the azimuthal plane, Δϕ, is sensitive to the transverse momentum of gluons to and their self-interaction — the mechanism that leads to saturation.
- **We can explore for the first-time in a controlled way the effects of these mechanisms – does the ridge disappear or not in nuclei at small x ?**

Mass of the Proton, Pion, Kaon



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

"Mass without mass!"

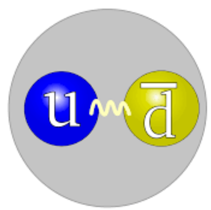
Proton

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

Gluon rise discovered by HERA e-p

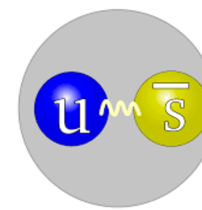
Pion

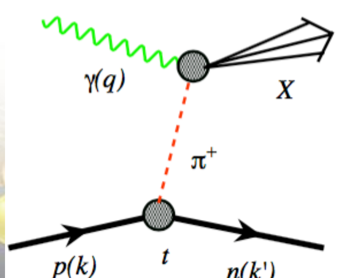
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



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"

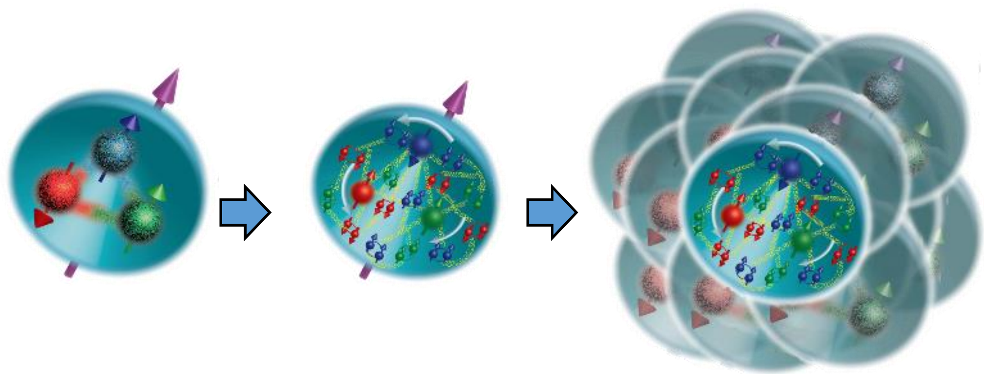
For the pion and the kaon the EIC will allow determination of the quark and gluon contributions with the Sullivan process.

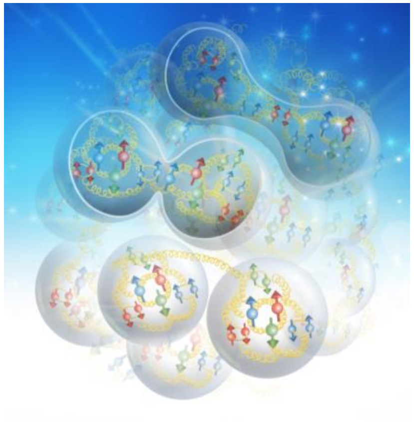
A.C. Aguilar et al., Pion and Kaon structure at the EIC, arXiv:1907.08218, EPJA 55 (2019) 190.
J. Arrington et al., Revealing the structure of light pseudoscalar mesons at the EIC, arXiv:2102.11788.

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

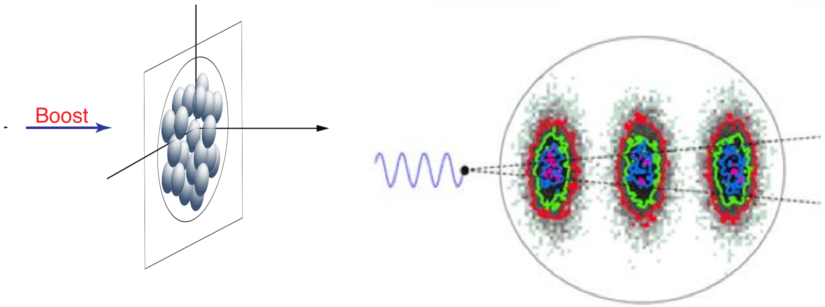
The EIC will, for the first time, provide a complete view of the nucleus:

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

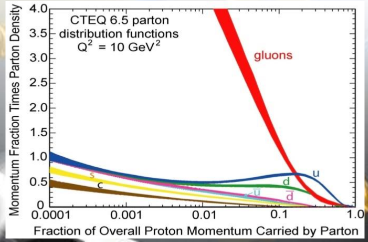


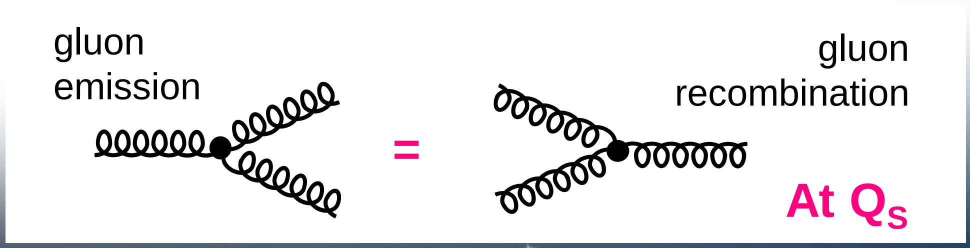


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

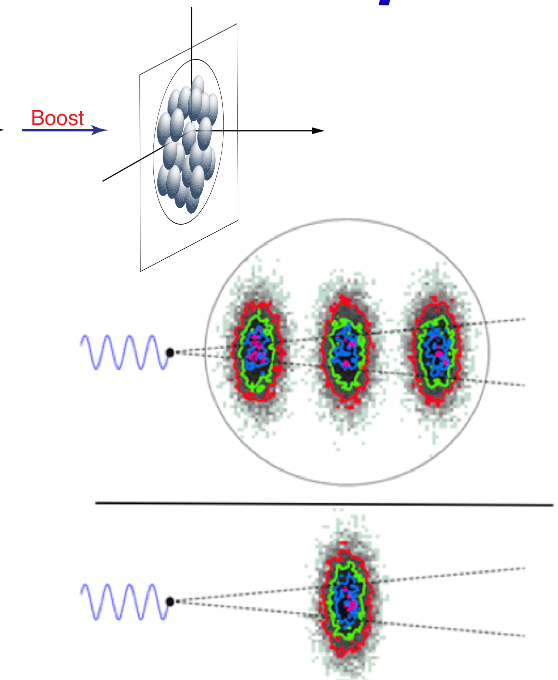


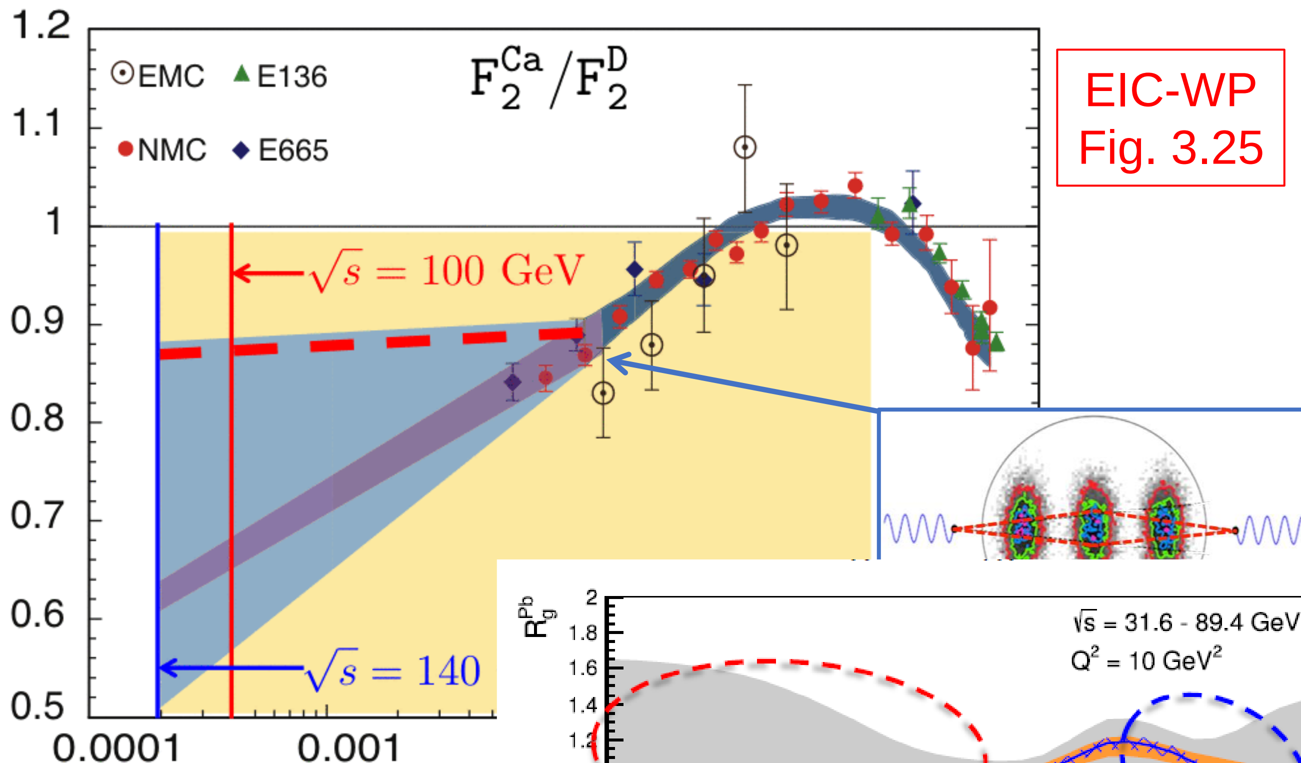
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclear matter?



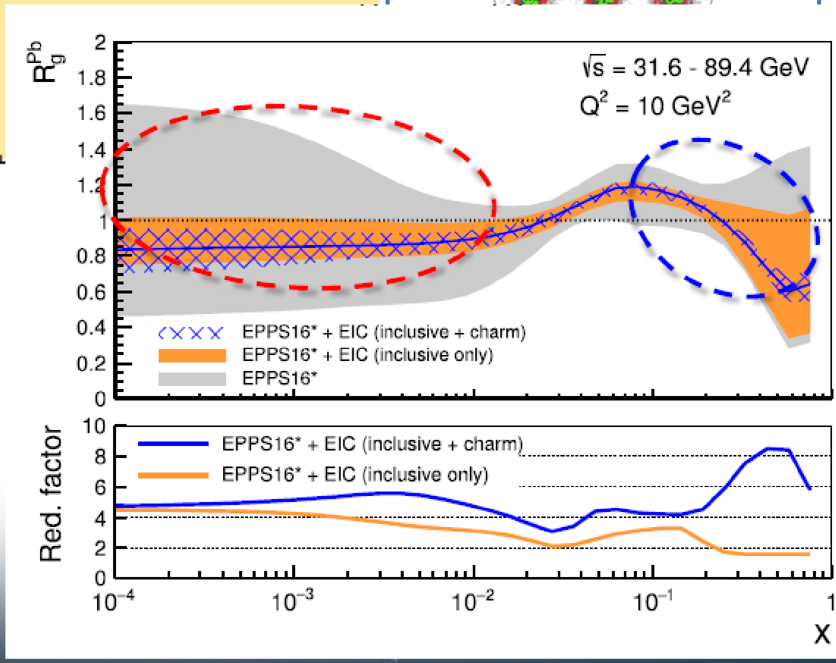


EIC: impact on the knowledge of 1D Nuclear PDFs



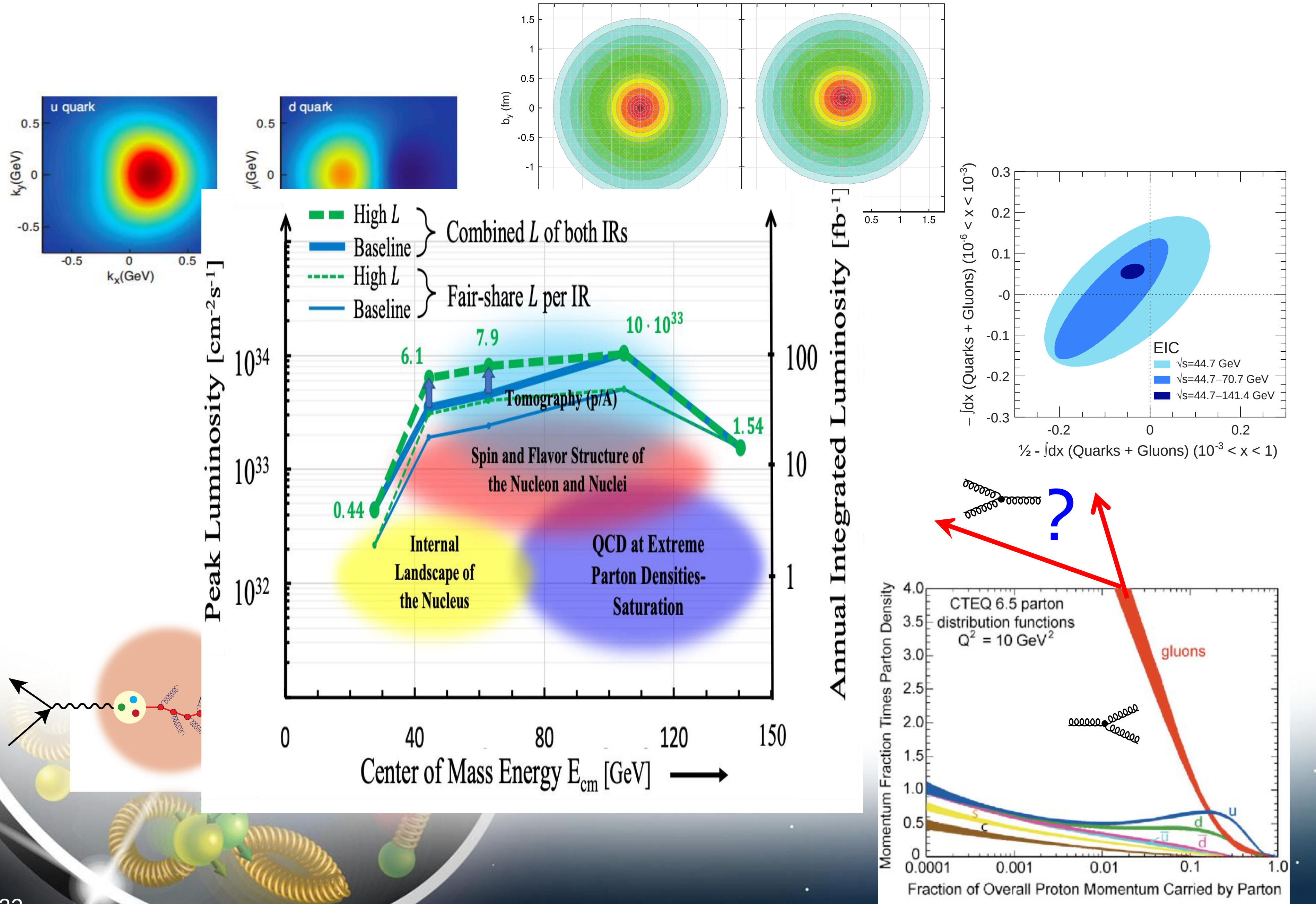


EIC-WP Fig. 3.25



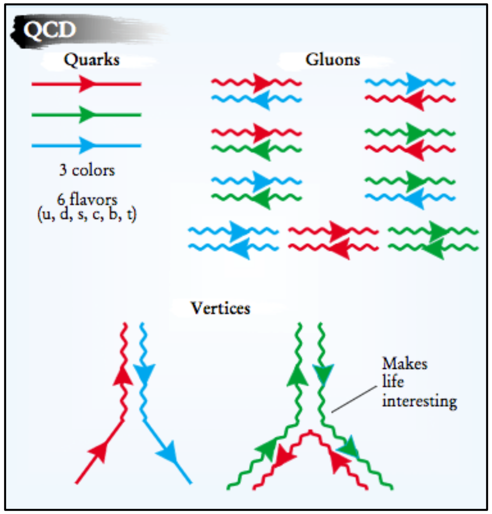
- **Without EIC, large uncertainties in nuclear sea quarks and gluons**
- Complementary to RHIC and LHC pA data.
  ➔ Provides information on initial state for heavy ion collisions
- Does the nucleus behave like a proton at low-x?
  ➔ relevant to the understanding of astronomical objects

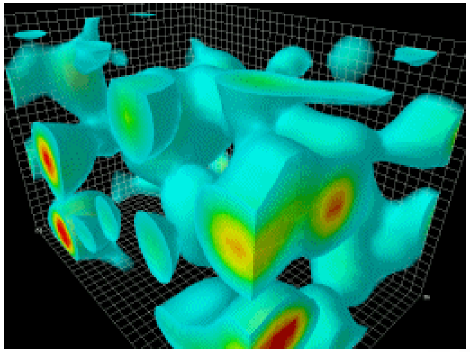
EIC Physics vs. Luminosity & Energy



EIC: 21st Century Laboratory of Emergent Dynamics in QCD

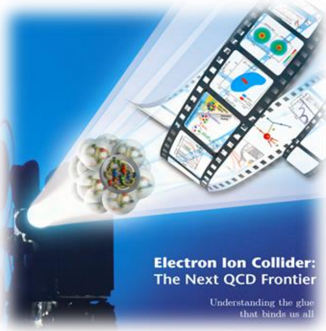
- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% of the proton's momentum, a significant fraction of the nucleon's spin, and are essential for the dynamics of confinement
- Properties of hadrons – composite systems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

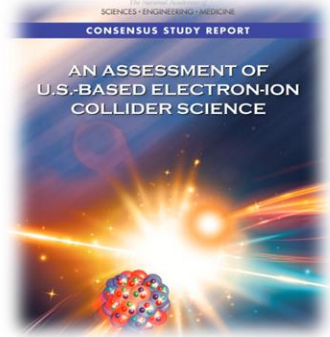


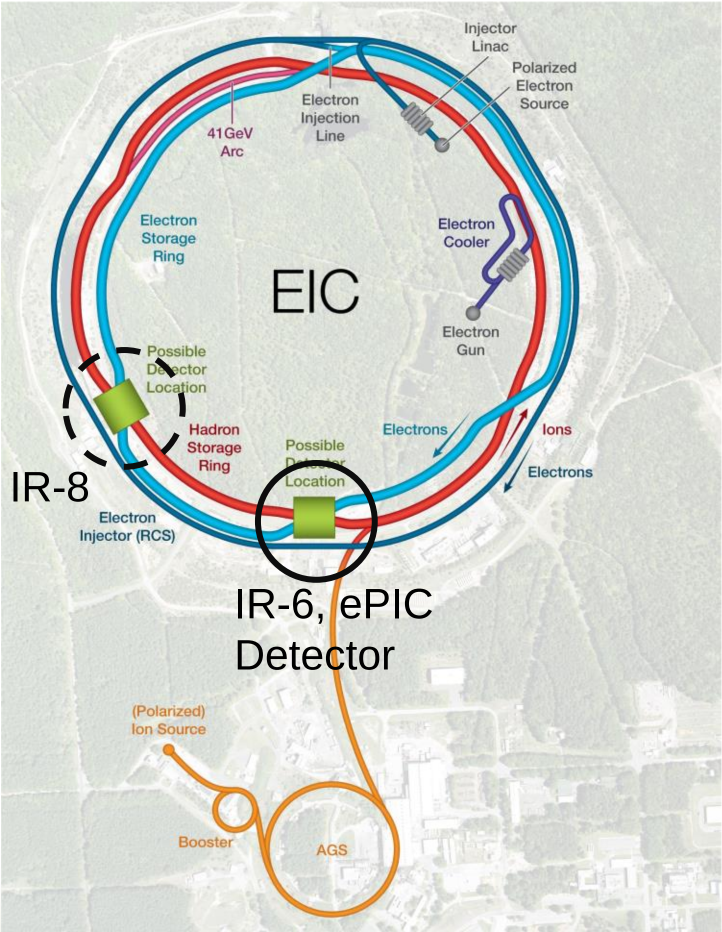


- The goal is to provide us with an understanding of the internal structure of the proton and more complex atomic nuclei that is comparable to our knowledge of the electronic structure of atoms, which lies at the heart of modern technologies

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)

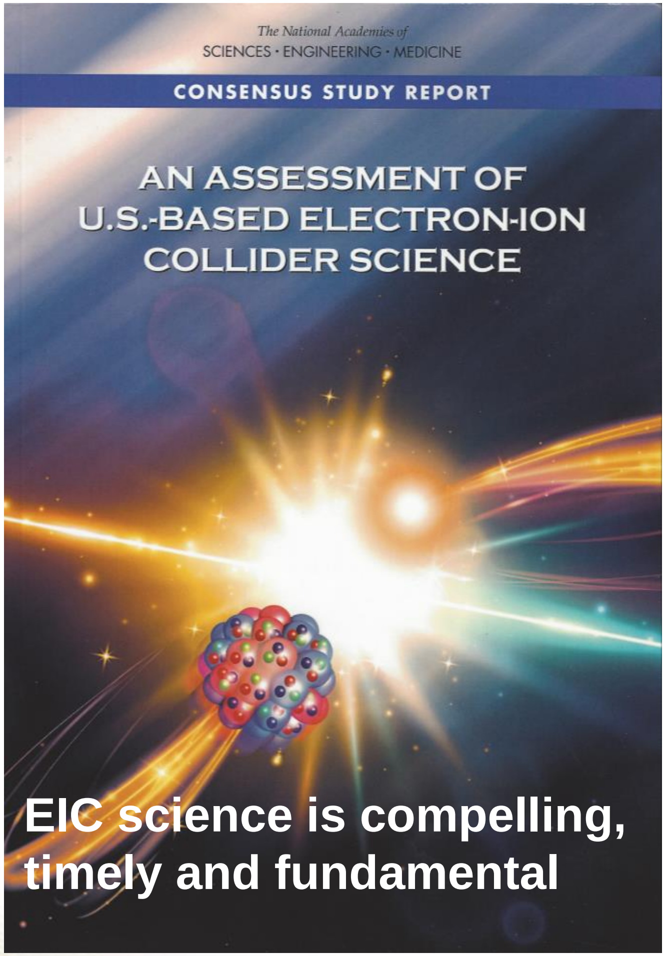
IR-8

p/A beam → ← e beam

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV

EIC 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 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.**

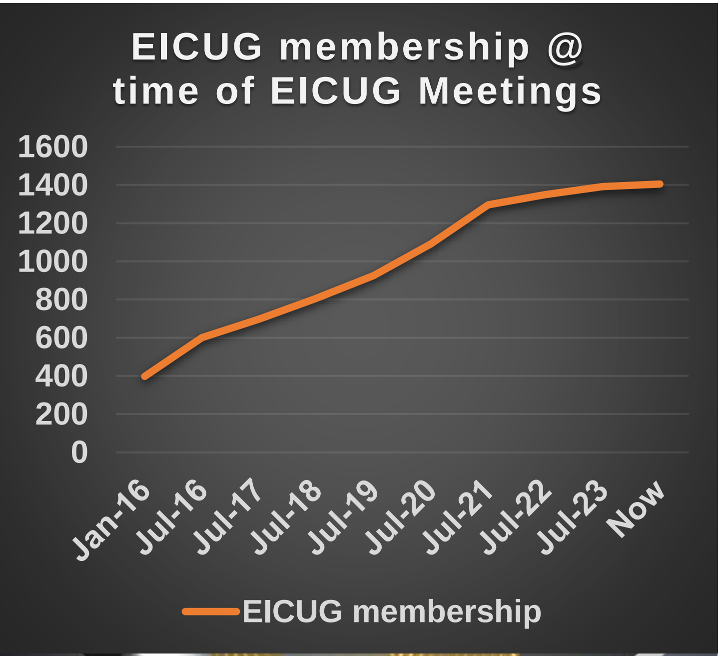
Worldwide Interest in EIC

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

Formed 2016 –

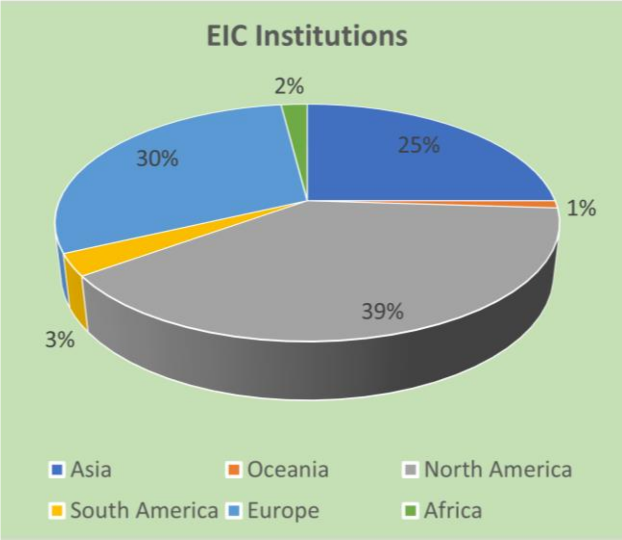
- **1405 collaborators,**
- **37 countries,**
- **279 institutions as of August 20, 2023.**

Strong and Growing International Participation.

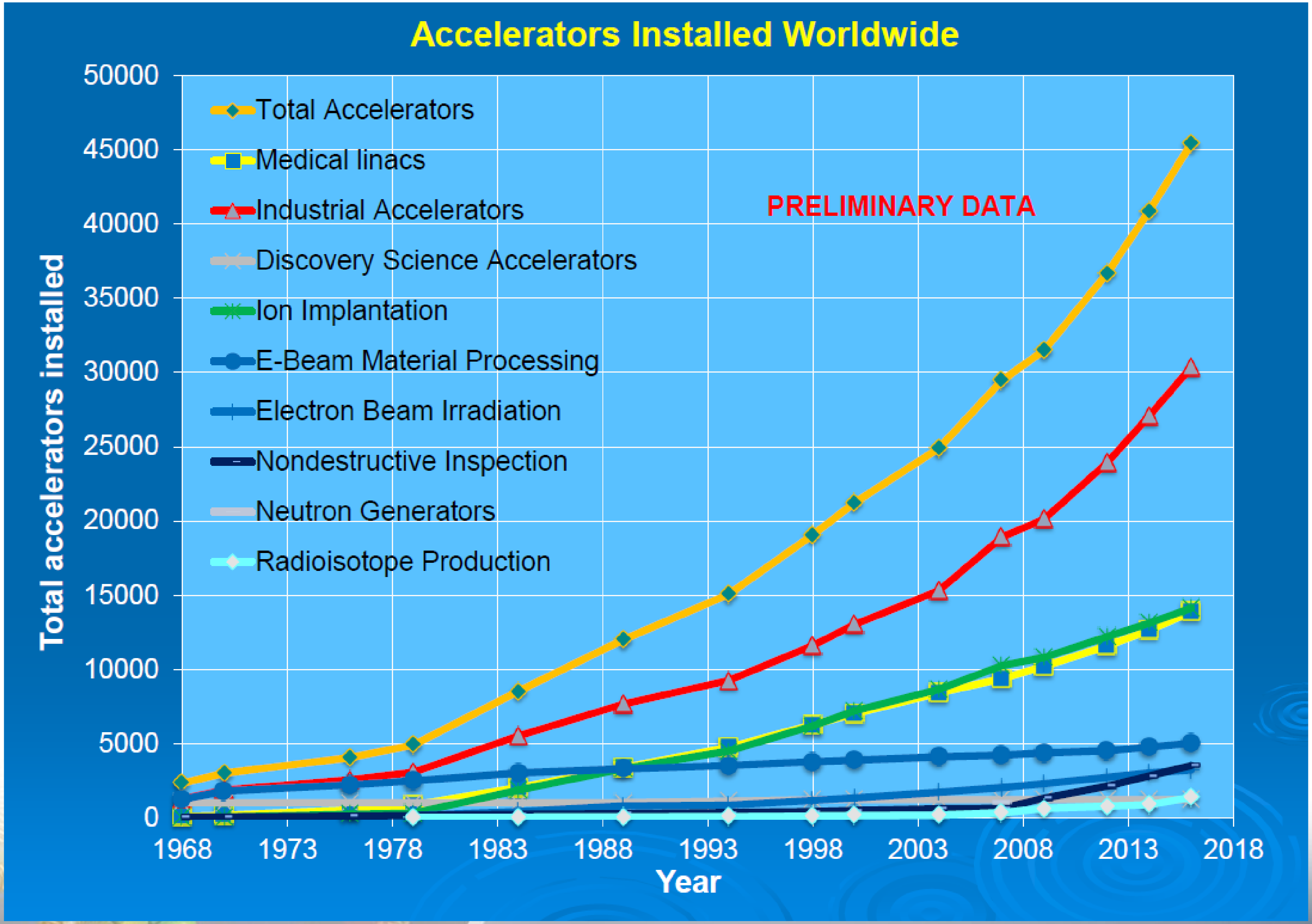


Annual EICUG meeting

2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 CUA, Washington, DC
2019 Paris, France
2020 FIU, Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland
2024 Lehigh U, PA



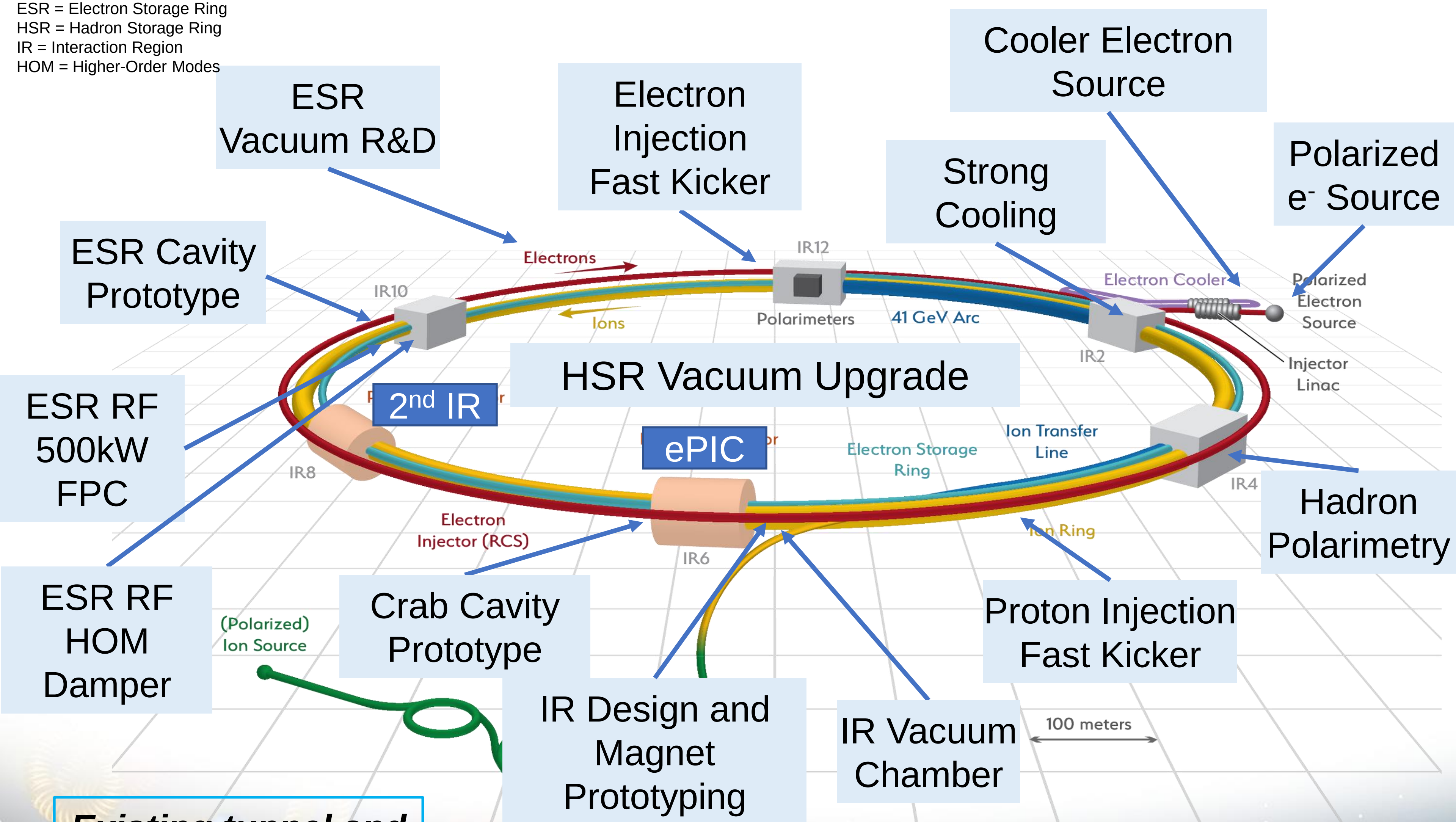
Growing Relevance of Accelerators Worldwide



From: Dr. Robert W. Hamm

Accelerator Science and Technology – Ongoing EIC R&D

ESR = Electron Storage Ring
HSR = Hadron Storage Ring
IR = Interaction Region
HOM = Higher-Order Modes

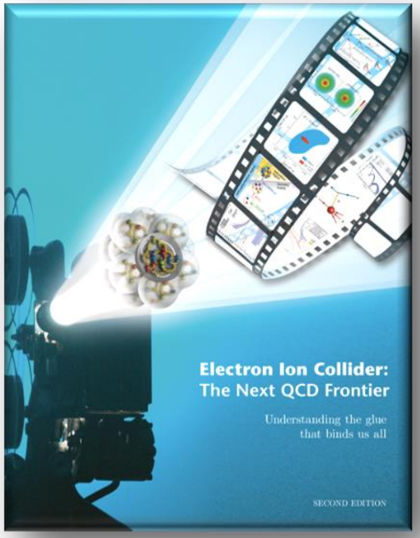


Existing tunnel and experiment halls

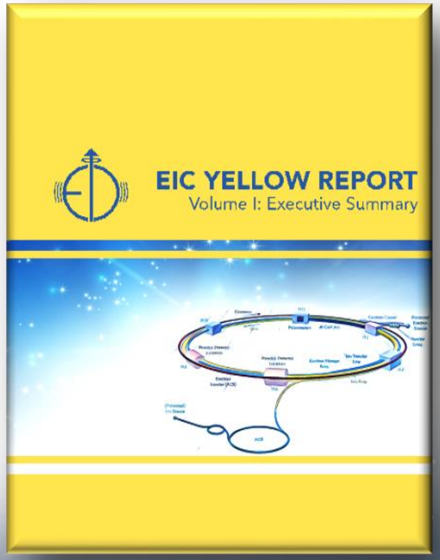
EIC is the ONLY new collider in the next decade!
Allows to remain at frontier of Accelerator S&T

EIC Science is Well Known and Highly Cited

- EIC White Paper that guided the EIC science written following a 10-week program at the Institute for Nuclear Theory
  - Electron-Ion Collider: The Next QCD Frontier: understanding the glue that binds us all
  - arXiV:1212.1701 & Eur. Phys. J. A 52 (2016) 9, 268 – **1459 citations (08/20/2023)**



- Year-long EIC User Group driven EIC Yellow Report activity (December 2019 – February 2021)
  - Science Requirements and Detector Concepts for the EIC
  - arXiv:2103.05419 & Nucl. Phys. A 1026 (2022) 122447 – **595 citations (08/20/2023)**



The EIC is a facility for the world

EIC Project – Some 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
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**

Feb 28, 2020 @ JLab

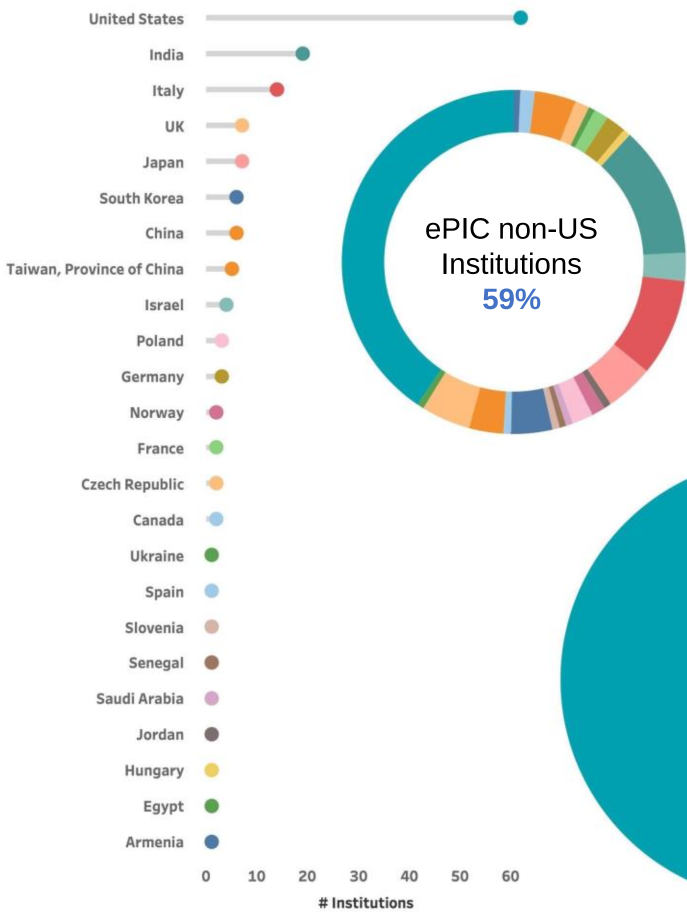
BNL/JLab Integrated partnership in all Project phases, including co-hosting the EIC experimental program.

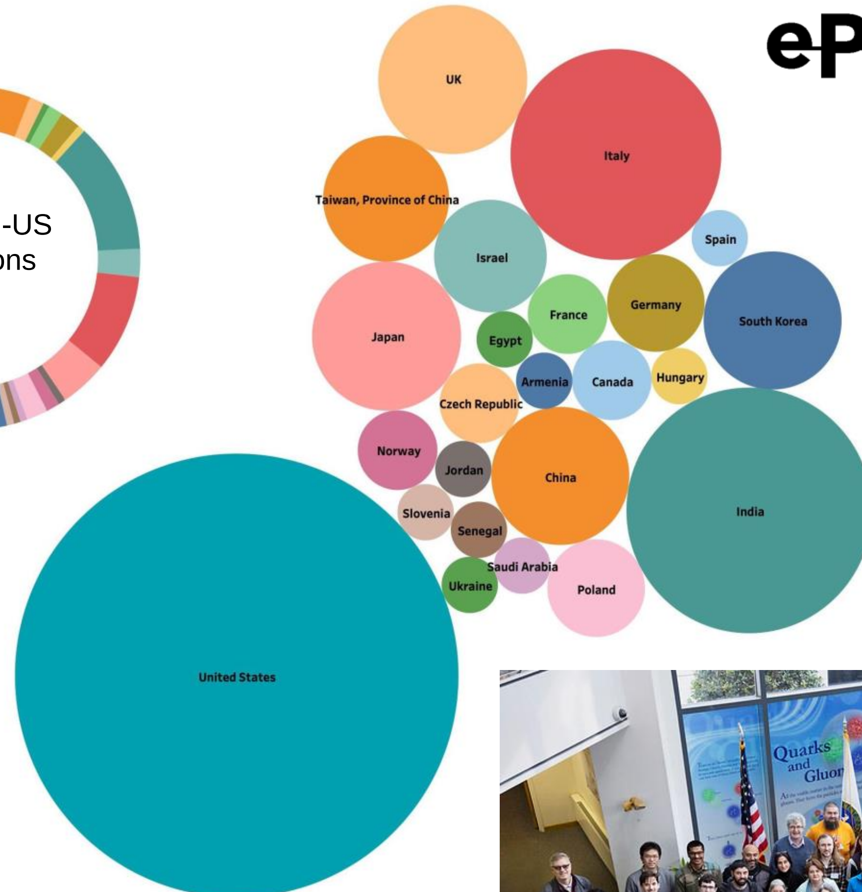
Progress Since CD-1

BNL and TJNAF Jointly Leading Efforts Towards Experimental Program		
2021	EIC Yellow Report (https://arxiv.org/abs/2103.05419)	February 2021
	Call for Collaboration Proposals for Detectors https://www.bnl.gov/eic/CFC.php	March 2021
	Collaboration Proposals for Detectors Submitted	December 2021
2022	Decision on Project Detector – "ECCE"	March 2022
	Process to consolidate ECCE & ATHENA to the EIC Project Detector ePIC	Spring 2022
	EPIC Collaboration* Formed – 160 institutions	July 2022
2023	All subdetector technologies defined	April 2023

EIC Project detector fully defined by 04/2023

The ePIC Collaboration





ePIC formed a year ago.

ePIC is now 171 institutions including 11 new institutions that joined this July 2023.

Representing 24 countries

500+ participants

A truly global pursuit for a new experiment at the EIC!

ePIC Spokesperson:
John Lajoie (Iowa State)

ePIC Deputy Spokesperson:
Silvia Dalla Torre (INFN Trieste)

ePIC Detector

- Asymmetric beam energies
  - → require an asymmetric detector Barrel with electron and hadron endcap → 9.5 m
  - → *Tracking, particle identification, EM calorimetry and hadronic calorimetry functionality in all directions*
  - → very compact Detector **Integration** will be key
- Imaging science program with protons and nuclei
  - → *requires specialized detectors integrated in the Interaction Region over 80 m*
- Science program required momentum resolution
  - → requires a large bore 2T magnet (1.7 T magnet operation point, stretch goal 2T) that has same geometry as the BaBAR magnet.
- Streaming readout electronics model
  - → highest scientific flexibility

hadronic calorimeters (HCAL)

Solenoidal Magnet

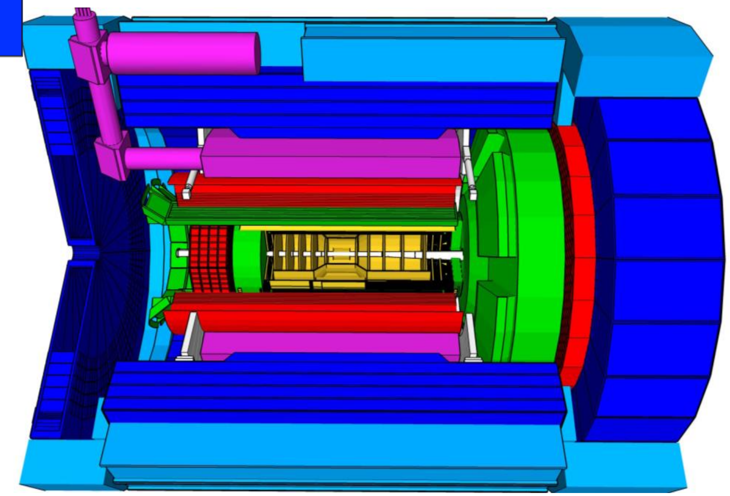
e/m calorimeters (ECal)

Time.of.Flight (ToF), DIRC, RICH detectors

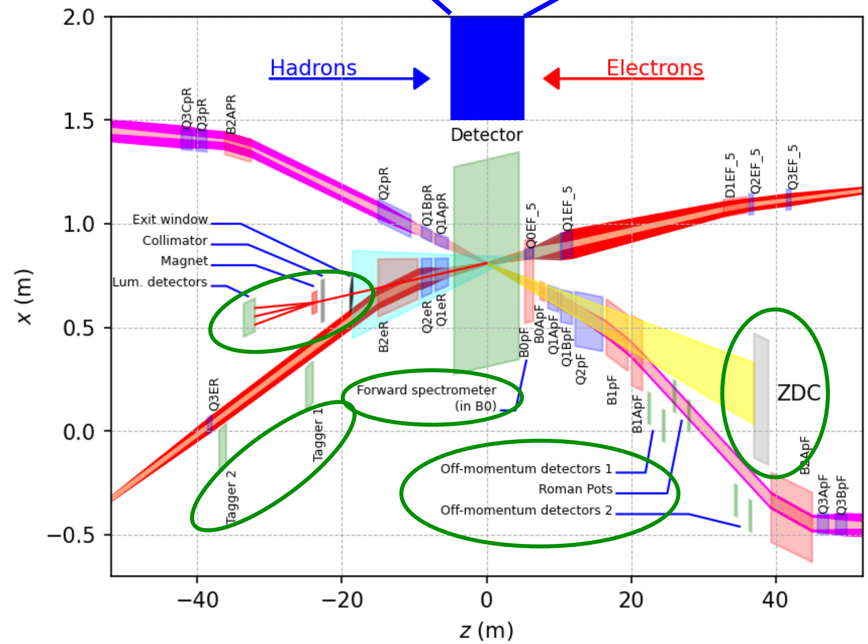
MPGD trackers

MAPS tracker

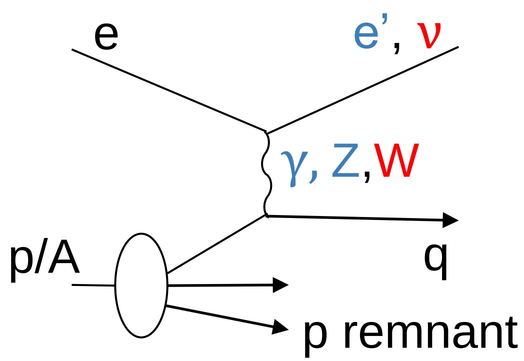
23 Subdetectors incl. Polarimeters + Data Acquisition



9.5 m



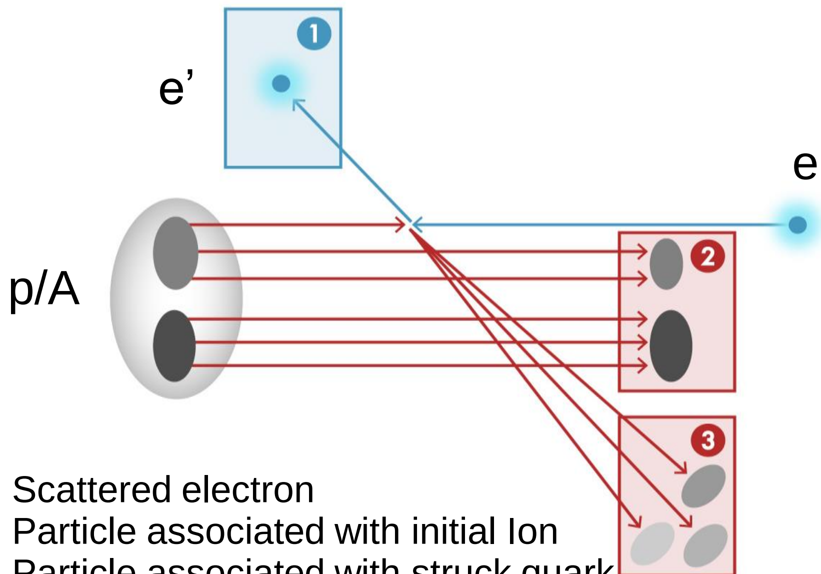
Detector Integration Challenge of the EIC



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.

What is Needed Experimentally?

experimental measurements categories to address EIC physics:

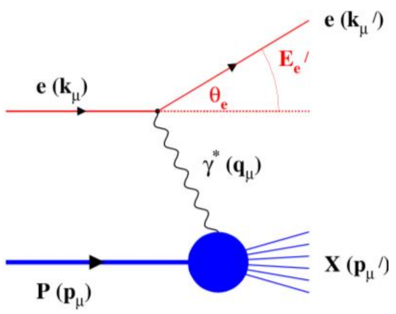
Parton Distributions in nucleons and nuclei

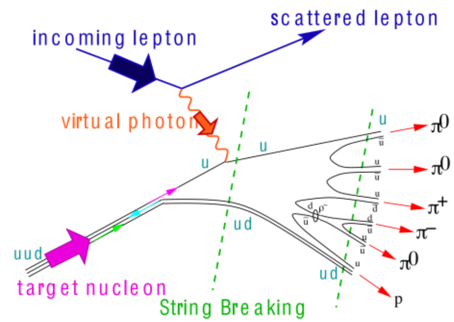
Spin and Flavor structure of nucleons and nuclei

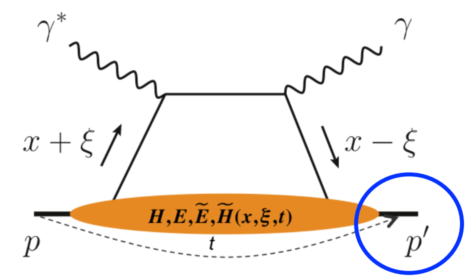
Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging







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

semi-inclusive DIS
- measure scattered lepton 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

Exploring the 3D Nucleon Structure

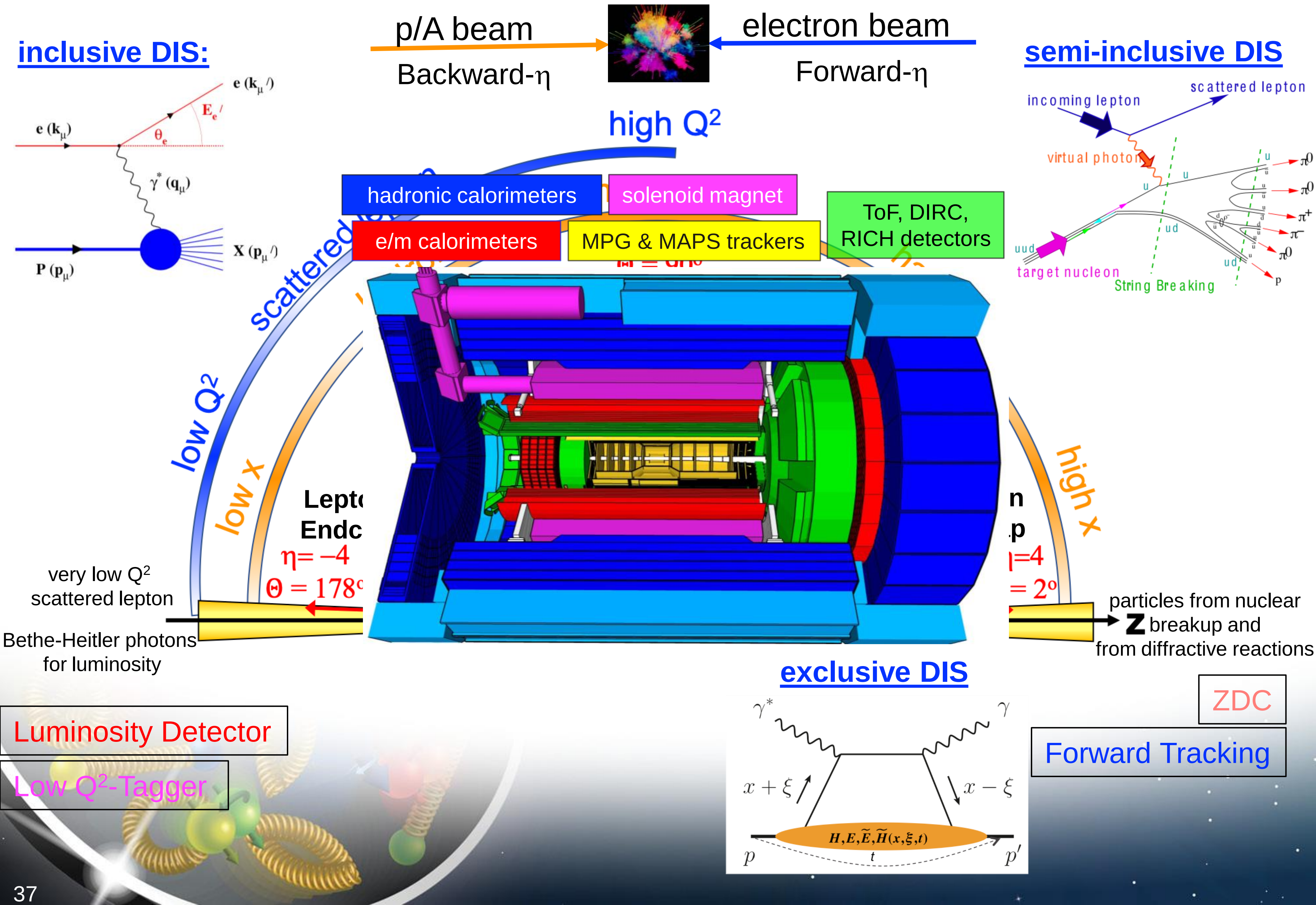
- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
    - High luminosity, large acceptance experiments with polarized beams and targets.
    - Theoretical 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 $\mathbf{b_T}$.

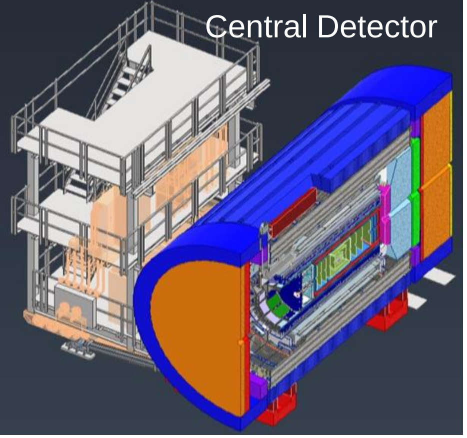
- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum ($\mathbf{k_T}$) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

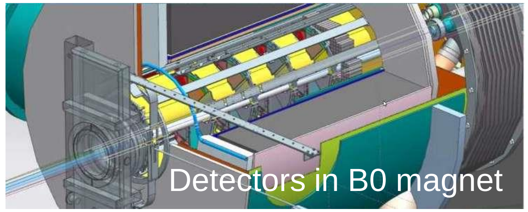
PDFs → Nuclear Femtography

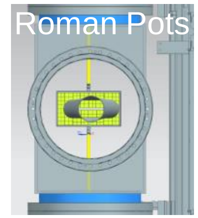
EIC General Purpose Detector: Concept

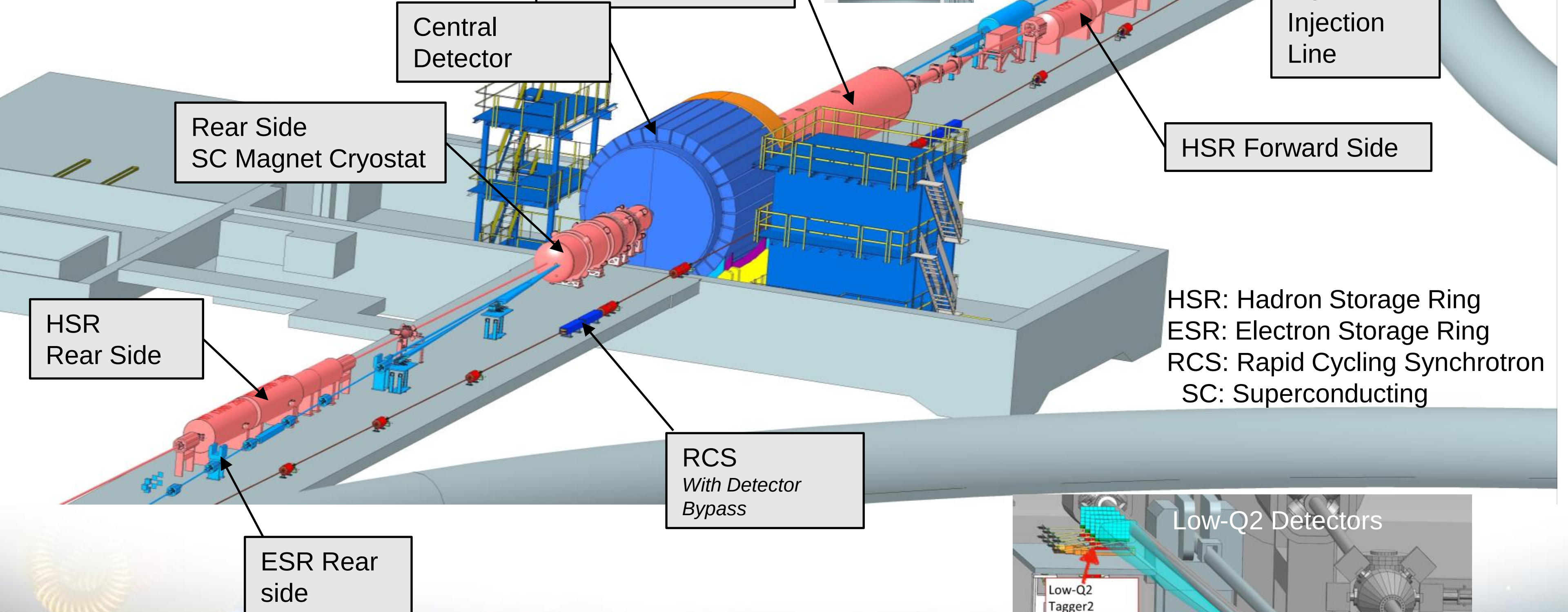


Interaction Region Layout

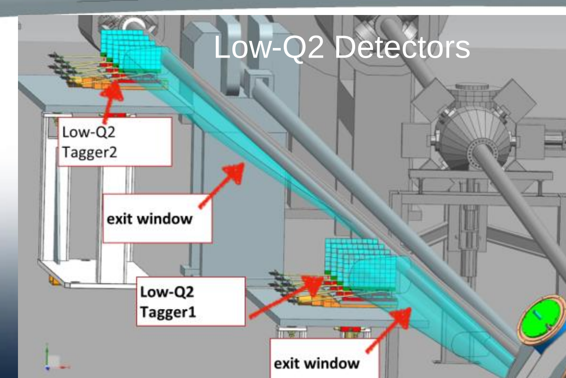






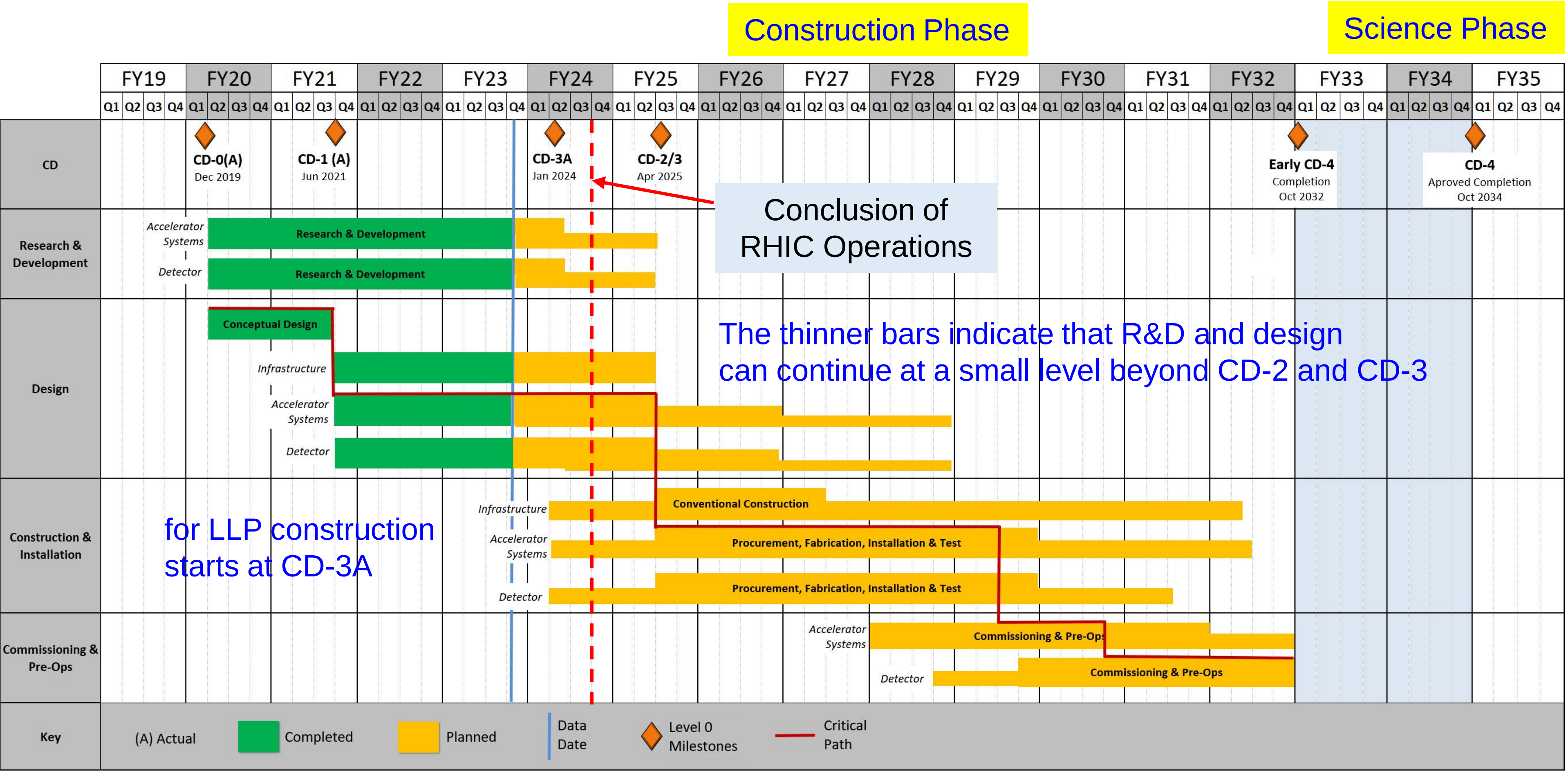


HSR: Hadron Storage Ring
ESR: Electron Storage Ring
RCS: Rapid Cycling Synchrotron
SC: Superconducting



every cm counts… → integration and communication with accelerator team is crucial

EIC High Level Project Schedule



- Recent change replaced CD-4A with project internal milestones
- The logic remains the same though, we start accelerator commissioning with an instrumented beam pipe and the detector in the Assembly Hall. The detector only rolls in later.

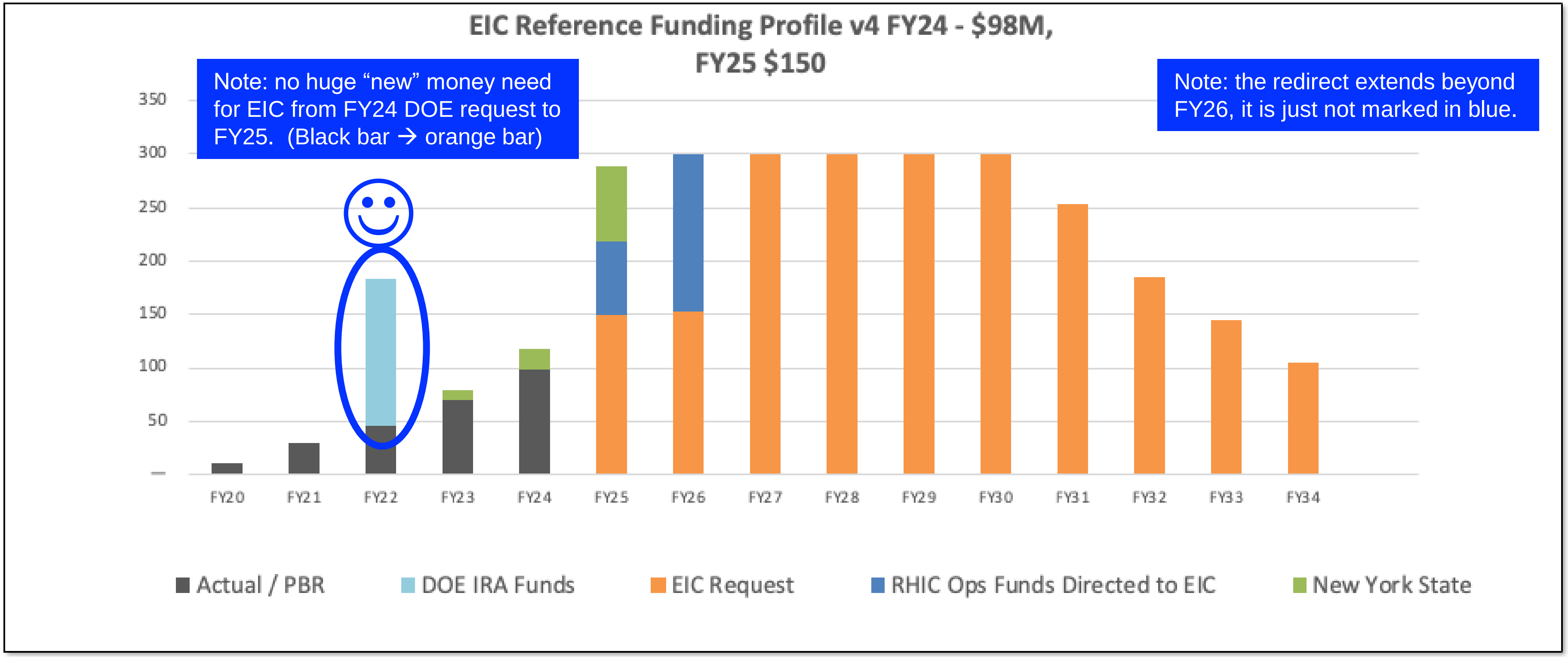
EIC Project – From CD-1 to CD-3A and CD-2/3

- ✓ 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)
- ✓ Project Detector Meetings — 2022/2023
  - *Detector Proposal Advisory Panel closeout* — *March 2022 (A)*
  - *Technical Subsystem Reviews* — *Feb. 2022 – Jul. 2023*
  - *1st Resource Review Board Meeting* — *April 2023 (A)*
  - *2nd Resource Review Board Meeting* — *December 2023*
- ✓ DOE OPA Status Review - Confirm CD-3A Plans — Jan. 31 – Feb. 2, 2023 (A)
- Subsystem Preliminary and Final (LLP) Design Reviews — 2023 (ongoing)
- DOE CD-3A Design Reviews (MAC, DAC) — August 2023
- DOE CD-3A ICR (Independent Costing Review) — October 10-12, 2023
- DOE CD-3A IPR (Independent Project Review) — November 14-16, 2023
- DOE CD-3A ESAAB Approval — ~January 2024

- DOE CD-2/3 OPA Review, requires TDR — ~January 2025
- DOE CD-2/3 ESAAB Approval — ~April 2025

OPA = Office of Project Assessment
FPD = Federal Project Director
LLP = Long-Lead Procurements
MAC, DAC = Machine/Detector Advisory Committee
ESAAB = Energy Systems Acquisition Advisory Board
TDR = Technical Design Report

DOE Reference Funding Plan

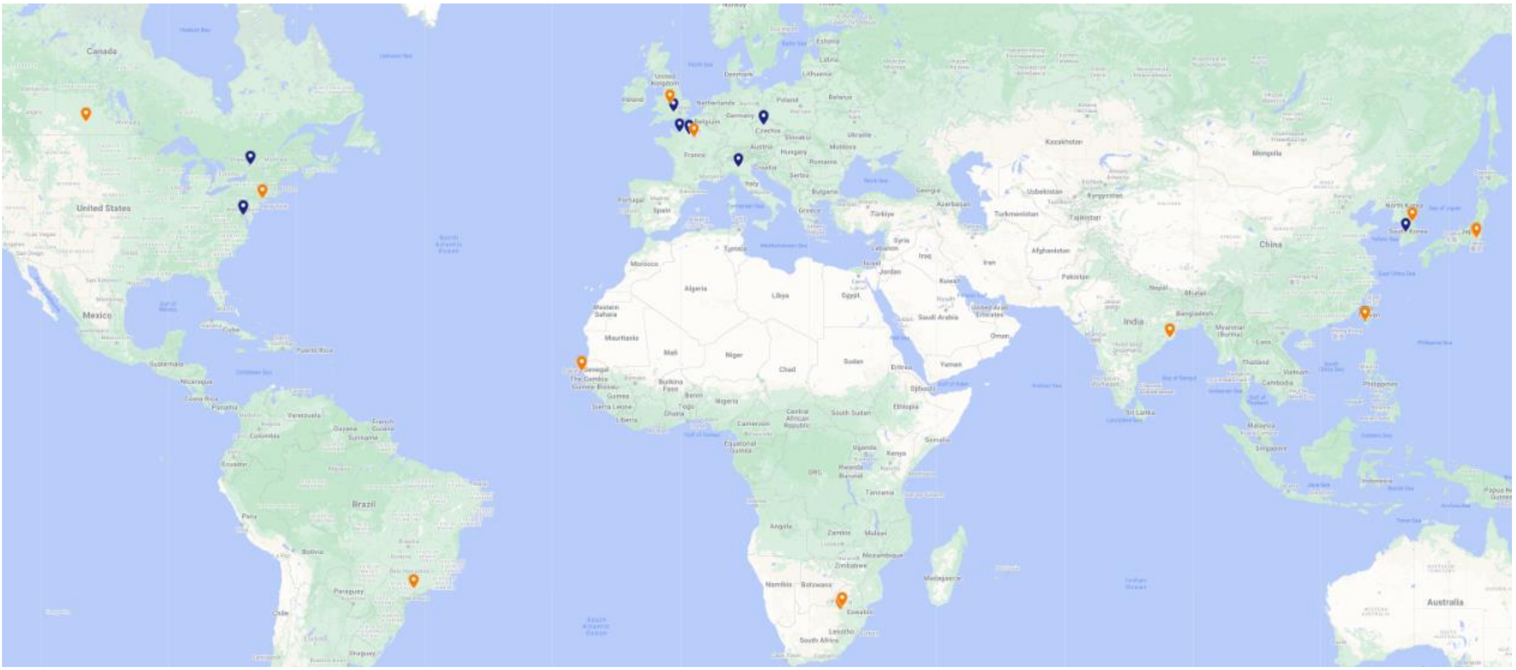


- DOE Inflation Reduction Act funding of $138M allocated in September 2022. Actual FY2023 funding is $70M. DOE request for FY2024 is $98M.
- RHIC shut down planned for June 2025. Significant RHIC Operations funding will be redirected to EIC construction starting in FY2025 and reaching ~$150M/year in FY2026.
- Current funding supports DOE CD-3A, Long Lead Procurement Approval, in January 2024. Long lead procurement mitigate risks: technical, supply chain, inflation, and schedule.
- In-kind contributions anticipated at 5% of accelerator and 30% of the detector, in addition to $100M from NY State to provide new EIC support buildings.

EIC International Engagement

- EIC is a ***unique high-energy, high-luminosity polarized beam collider that will be one of the most challenging and exciting accelerator complexes ever built*.**
- There is large international interest in the EIC, EIC Science and the ePIC detector.
  - Large international component of EIC Yellow Report (417 authors; 175 (42%) are non-US).
  - Large in-kind component of detector R&D (US universities and international).
  - Excellent progress on Engineering and Design (PED) in detector – designs are maturing with help of our many friends. This constitutes a ~$5M in-kind non-DOE PED contribution.
- DOE, BNL, and JLab envision an EIC facility that is "fully international in character."
  - **Governance** is evolving to include international partners.
- International EIC Project Advisory Committee provides advice on the successful delivery of the DOE Project (management, scope, schedule, cost, and performance).
- EIC Advisory Board provides oversight and advice on the construction of the facility, focusing on the accelerator (ANL, BNL, LBNL, TJNAF, TRIUMF, IN2P3, IRFU, STFC, INFN).
- EIC Resource Review Board (RRB) provides oversight of the experiments
  - 1st RRB meeting April 2023 at Long Island, hosted by SBU
    - member countries: **Canada, Czech, France (IN2P3 & IRFU), Italy/INFN, Korea, UK/STFC**, US;
    - observer countries: **Brazil, India, Japan, Taiwan, Senegal, South Africa**;
    - further anticipated at next RRB meeting: **Armenia, Israel, Poland**, hopefully US/NSF.
  - 2nd RRB meeting December 7-8, 2023 in Washington DC, hosted by GWU.

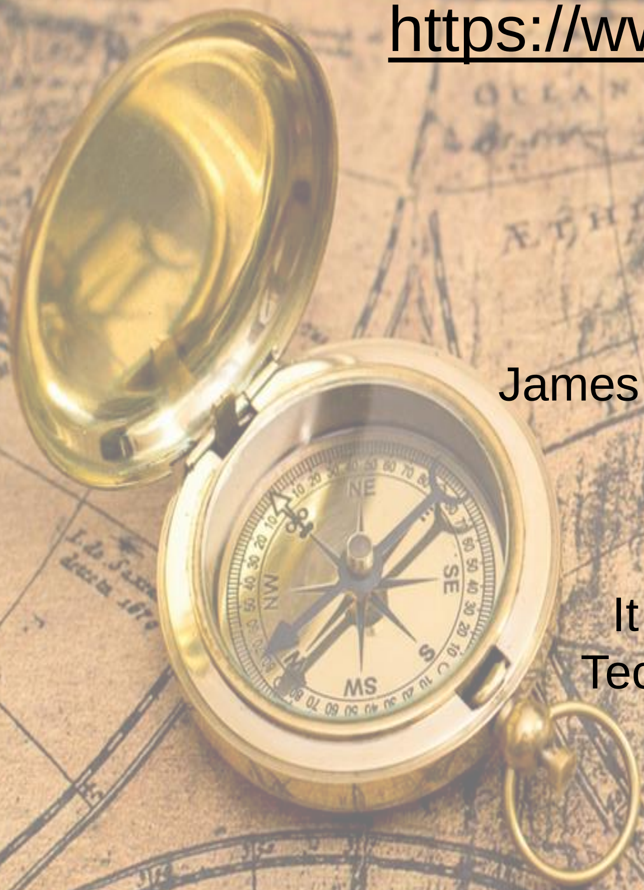
1st Resource Review Board (RRB) Meeting



- First meeting on April 3-4, 2023, at Stony Brook University.
- DOE and the host labs promoting the EIC as a facility “fully international in character.”
- 12 countries participating: Blue markers: RRB members; Orange markers: Observers
- Agenda reflected what we expect to have in future RRB meetings.
- RRB Charter ratified at 1st meeting. Initial Co-Chairs: Haiyan Gao (BNL), Diego Bettoni (INFN).
- 2nd meeting planned for December 7 + 8 in Washington, DC.
  - Topics will include: Common Fund (or not) discussion, Computing (What is expected from partners), Governance (How does change control work for in-kind contributions), Quality Assurance (how does that get folded in reviews and planning documents), International agreements.

Visualization of the Subatomic World

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



This work was a collaborative effort of:
Christopher Boebel (Film Producer, MIT, MA)
Rolf Ent (Physicist, Jefferson Lab, VA)
James LaPlante (Animator, Sputnik Animation, Portland, ME)
Joseph McMaster (Film Producer, MIT, MA)
Richard Milner (Physicist, MIT, MA)

It was funded by the MIT Center for Art, Science & Technology and by Jefferson Lab, Newport News, VA

We gratefully acknowledge the significant role of Rik Yoshida in initiating the project.

ARTS
CENTER FOR ART, SCIENCE & TECHNOLOGY AT MIT

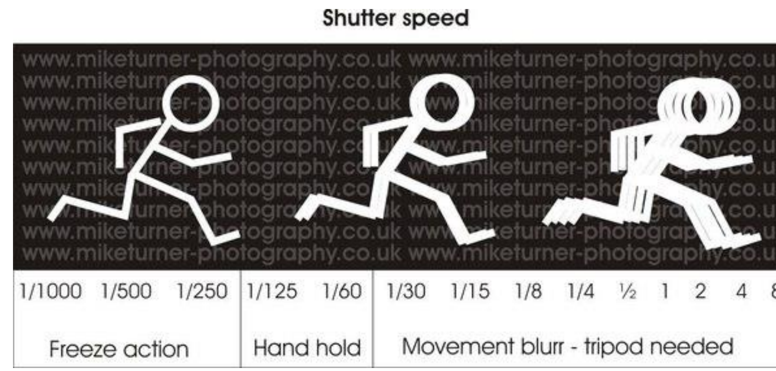
Jefferson Lab
Thomas Jefferson National Accelerator Facility

SPUTNIK ANIMATION

Visualization

- The camera is a device to capture an image on a desired medium, e.g. CCD or film.
- Movie cameras capture a series of individual images in time to give the illusion of having captured motion.
- Essential elements of any camera are
  - the focus which uses a lens to gather light from a selected image

    → pixel size
  - the shutter which is a door that opens for a definite time to allow selected light to reach the medium.
- Use this analogy to visualize the proton structure from available proton structure function data → Snapshots where $0 < x < 1$ is the shutter exposure time and $1/Q$ is the pixel size.



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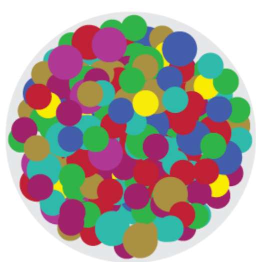
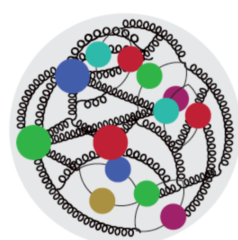
 ←  ← 

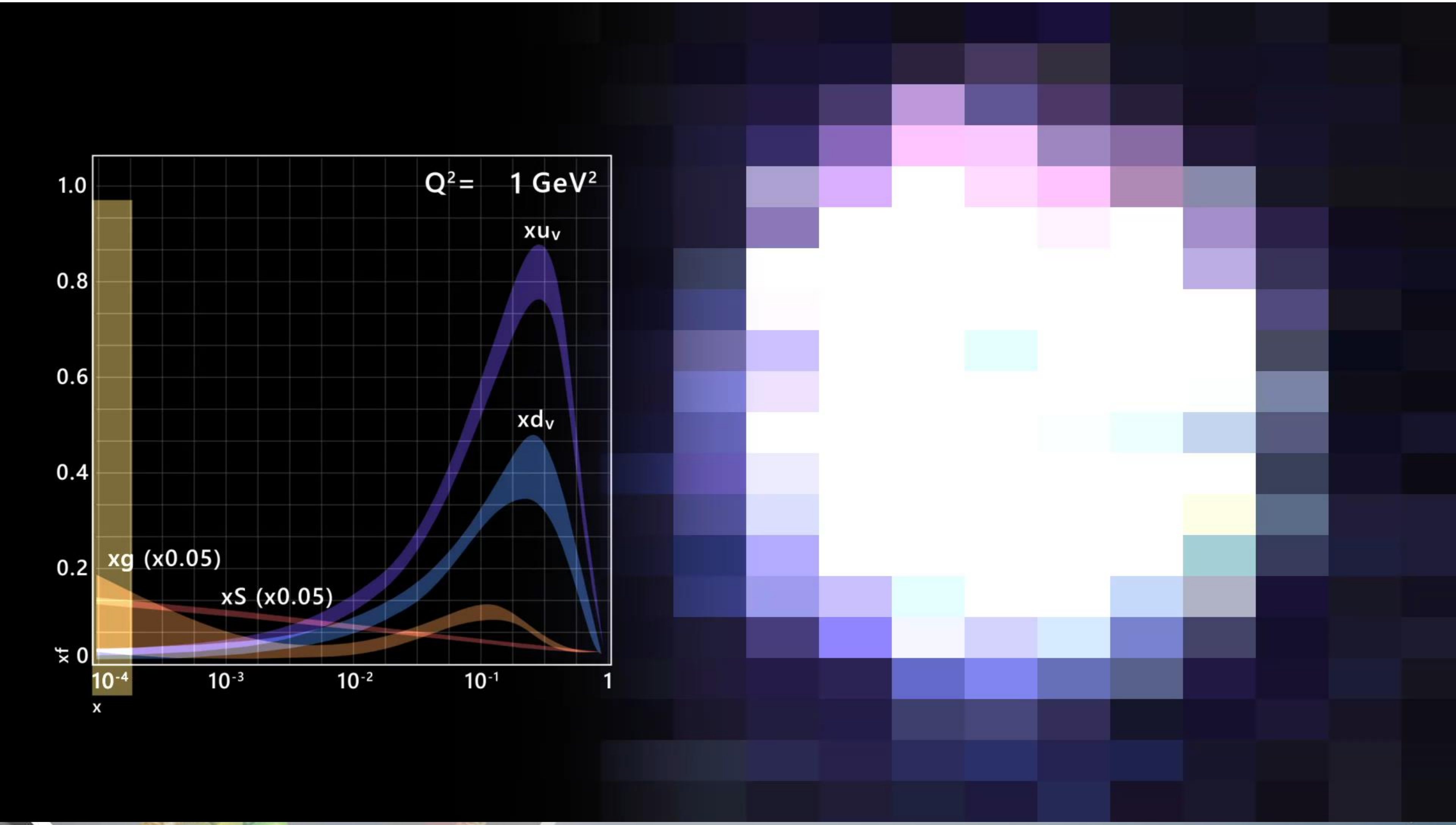
$x \approx 10^{-4}$
Probe gluon dominance short exposure time

$x \approx 10^{-2}$
Probe quark sea and gluons medium exposure time

$x \approx 0.3$
Probe valence quarks long exposure time

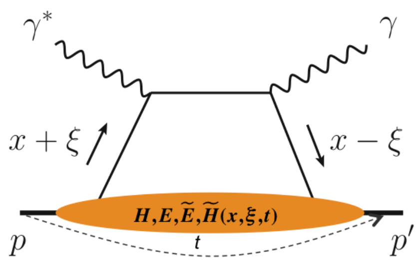
Proton Structure – Artistic Visualization

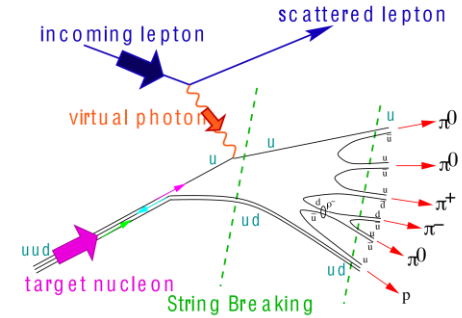
James LaPlante (Sputnik Animation), Richard Milner (MIT), Rolf Ent (JLab)



Note that this strategically stops at x ~ 0.3…

We Need Reality: Proton & Nucleus 3D Distributions





$f(\xi, b_T)$

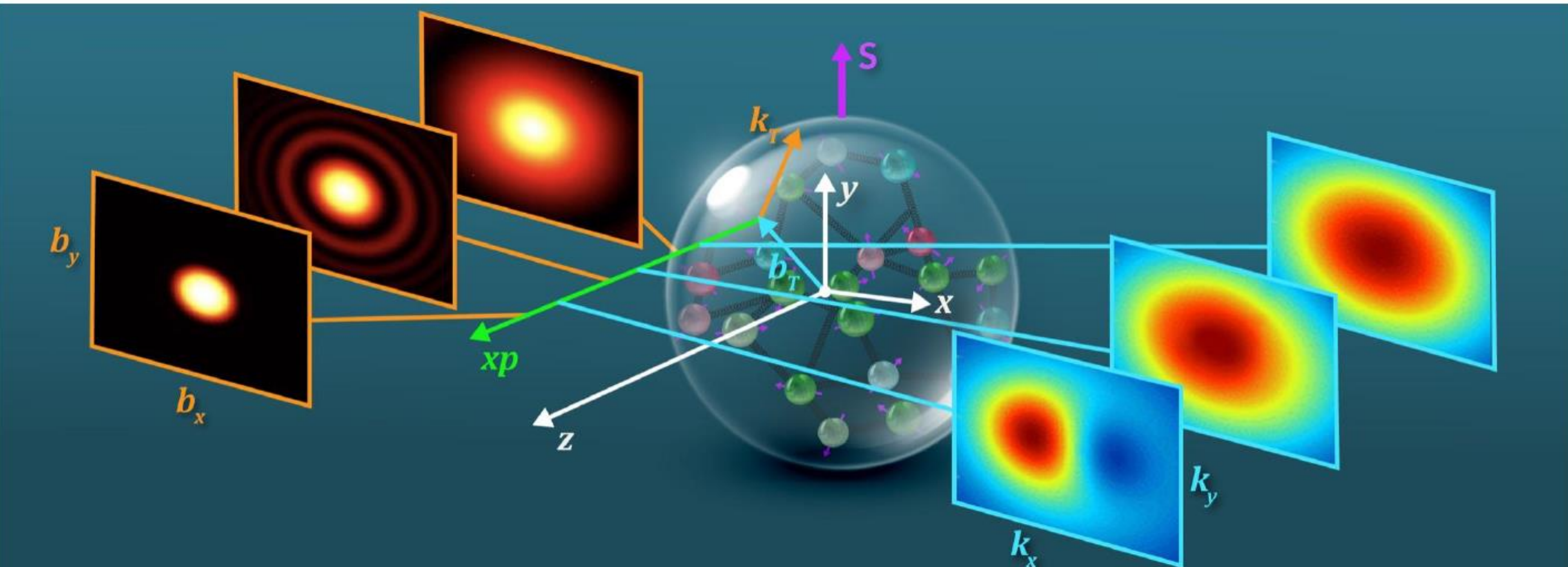
Impact parameter distribution -> **GPDs**

$f(\xi)$

PDFs

$f(\xi, k_T)$

Transverse momentum distribution -> **TMDs**



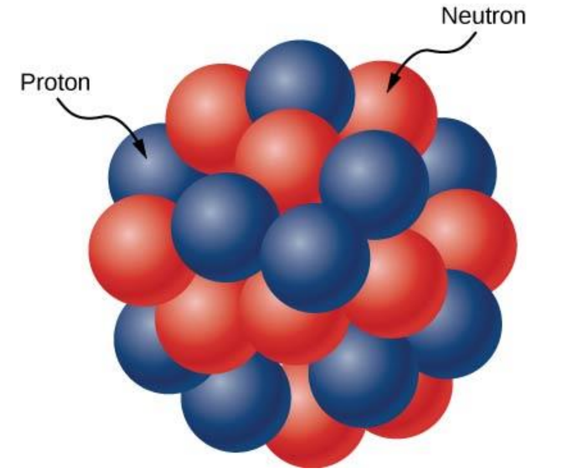
Next: Visualization of Nucleus

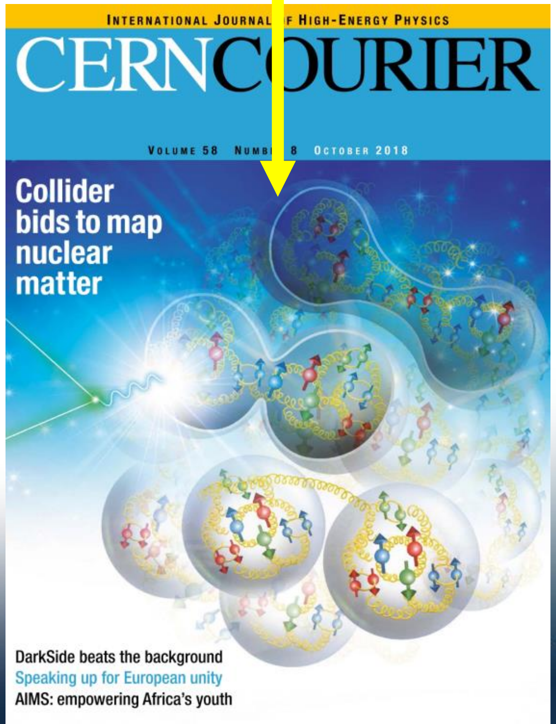
- Animate the atomic nucleus as a densely packed collection of fuzzy, kneadable balls with two identities: protons and neutrons. The animation aims to describe motion and binding, and state-of-the-art nuclear models to be visually communicated.

- Animate the quark and gluon structure of the neutron.

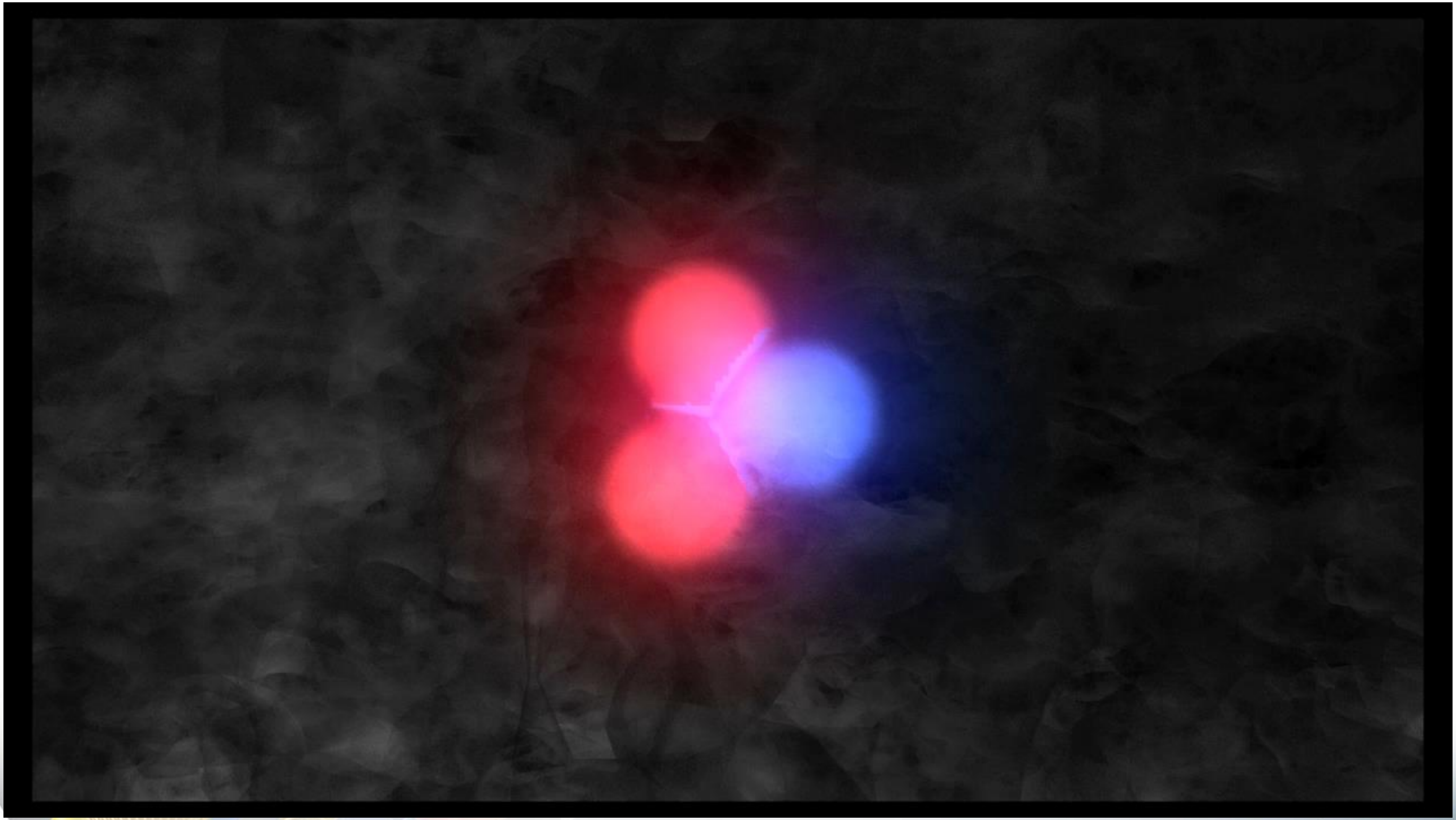
- Animate a series of different nuclei with their various numbers of protons and neutrons (Deuterium: 1 p and 1 n, Helium-4: 2 p and 2 n, Carbon-12: 6 p and 6 n, Calcium-40: 20 p and 20 n, Zircon-90: 40 p and 50 n, Lead-208: 82 p and 126 n).

- Take the animation of the Lead-208 nucleus and now insert our proton and neutron visualizations; show a quark-gluon based animation of nuclear binding, short-range correlations, exotic gluons and saturation.

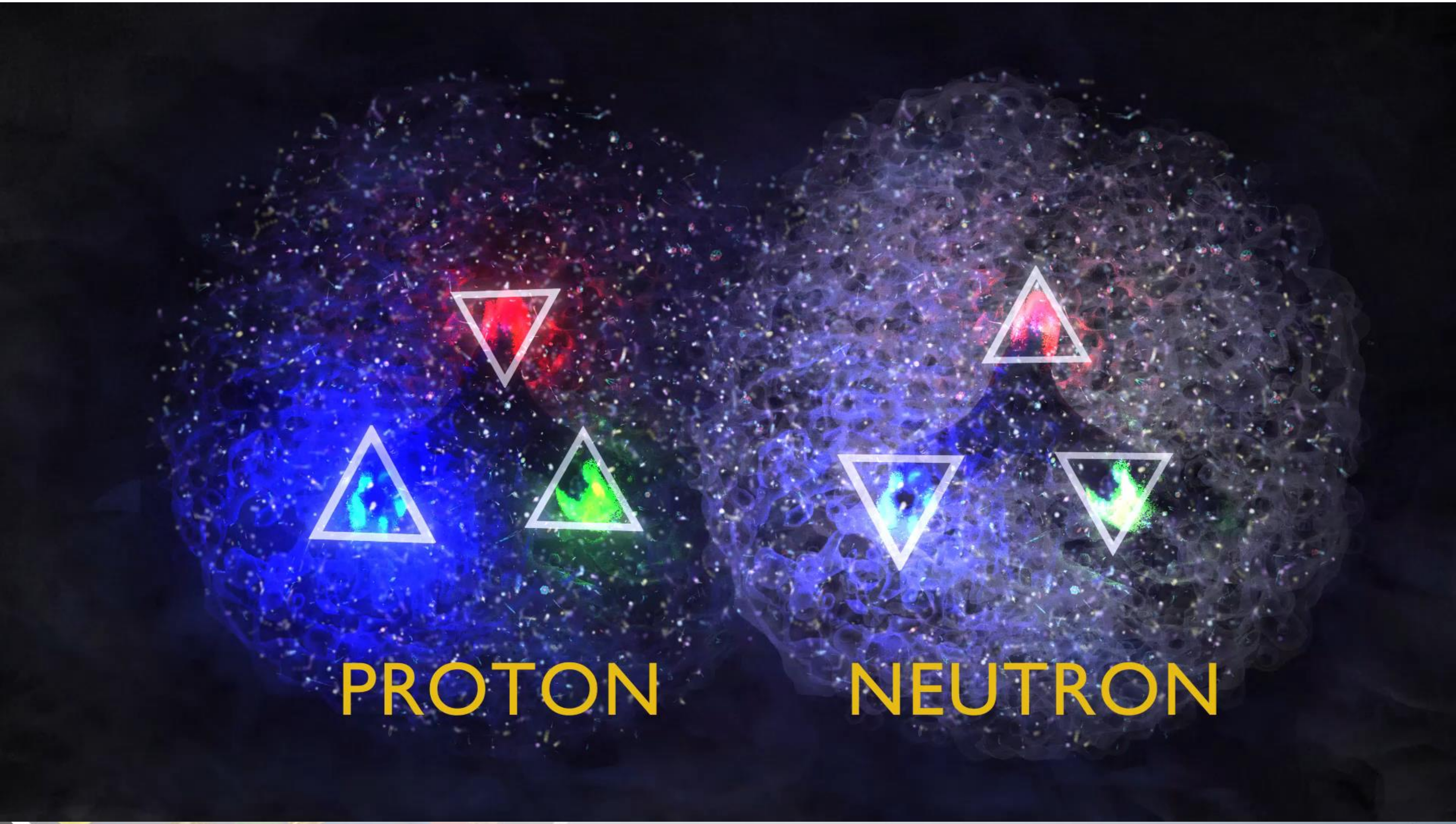




Ongoing: Visualization of Nucleus – Motion and Binding
Helium-4



Ongoing: Visualization of Nucleus – Particles know their quantum numbers, but how de we visualize?

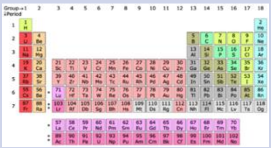
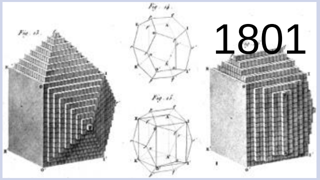
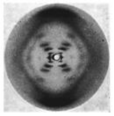
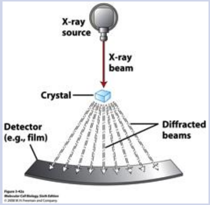
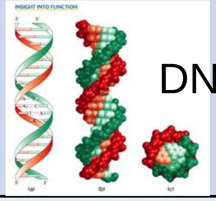
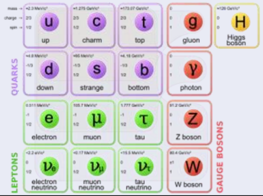
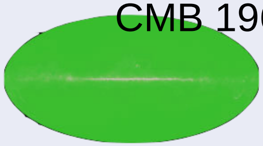
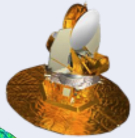
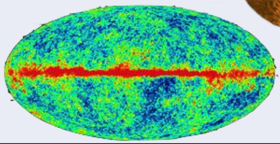
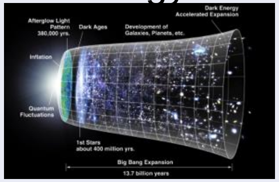
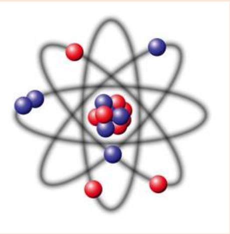
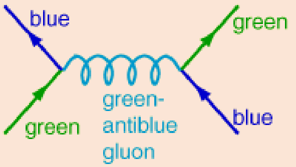
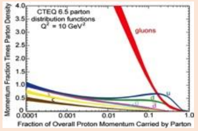
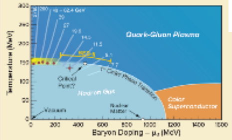
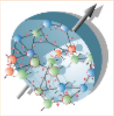
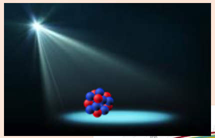
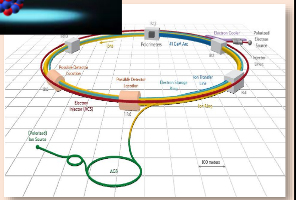
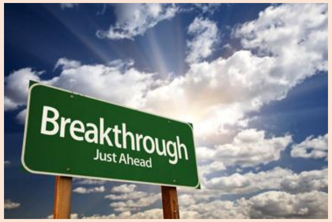


Summary

- EIC Program aim: **Revolutionize the QCD understanding of nucleon and nuclear structure and associated dynamics**. Explore new states of QCD.
- EIC will enable nuclear femtography of the nucleon and the nucleus **at the scale of sea quarks and gluons**, over all of the kinematic range that are relevant. JLab12 will have set the foundation at the scale of valence quarks!
- What we learn at JLab12 and later EIC, together with advances enabled by experiments elsewhere, QCD phenomenology and LQCD studies, may open the door to a transformation of Nuclear Science, and Hadron Structure in particular.
- Outstanding questions raised both by the science at RHIC/LHC and at HERMES/COMPASS/Jefferson Lab, have **naturally led to the science and design parameters of the EIC**
- There exists **worldwide interest** in collaborating on the EIC
- Accelerator scientists at RHIC and JLab, in collaboration with many outside interested accelerator groups, provide the **intellectual and technical leadership to realize the EIC**, a frontier accelerator facility.

The future of QCD-based nuclear science demands an EIC
The construction phase of EIC starts soon, the science phase in a decade
EIC is the ONLY new collider in the next decade!

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

BACK UP

Take-Away Messages

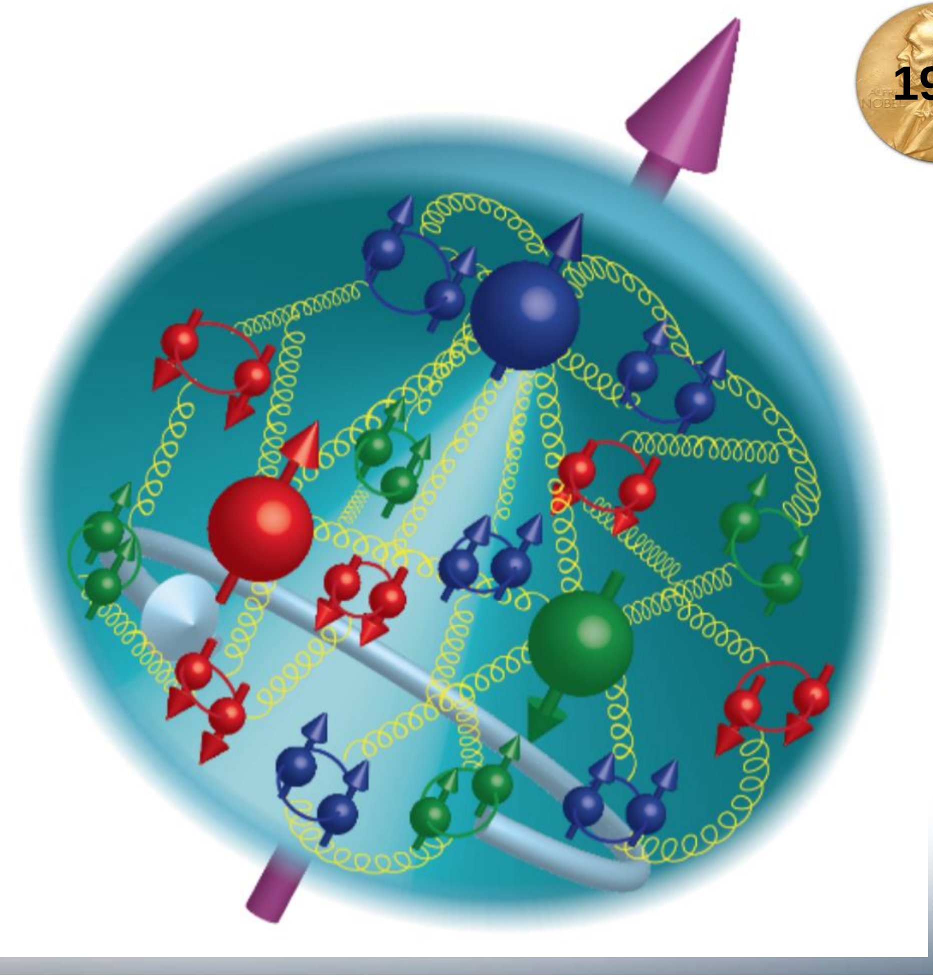
- **"Now is the time to realize the EIC in the U.S."** (LRP 2015).
  - The scientific foundation for an EIC was built over two decades, from an initiative in LRP 2002 through an unnumbered recommendation in LRP 2007 to a formal numbered recommendation in LRP 2015.
  - The 2018 NAS Report concluded: "EIC science is compelling, timely and fundamental."
  - The QCD community support for EIC remains broad and near-unanimous.
- The EIC User Group currently stands at **1405 members in 37 countries.**
  - This is a strong community that has delivered on the EIC Science White Paper(s), the EIC Yellow Report, and three detector proposals now culminating in ePIC.
  - Efforts towards the ePIC detector and a path to a 2nd detector are ongoing.
- **Recent IRA funding resulted 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 immediate focus of the EIC Project will be to reach CD-3A (Early 2024).
- **There will be one EIC with this high level of performance in the world.**
  - The EIC will be on the frontiers of nuclear science, accelerator, and detector technologies.
  - Strong support for the EIC with increasing international engagement – Various possible in-kind contributions to detector construction are maturing with funding agencies worldwide.

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.

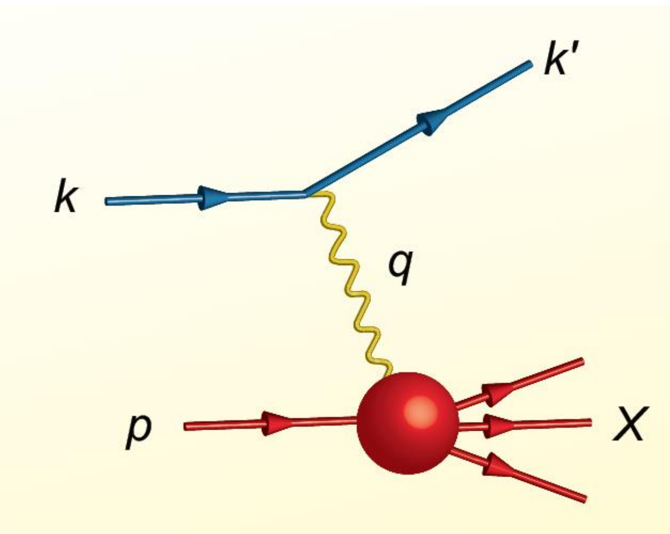
21st Century View of the Fundamental Structure of the Proton

- 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.



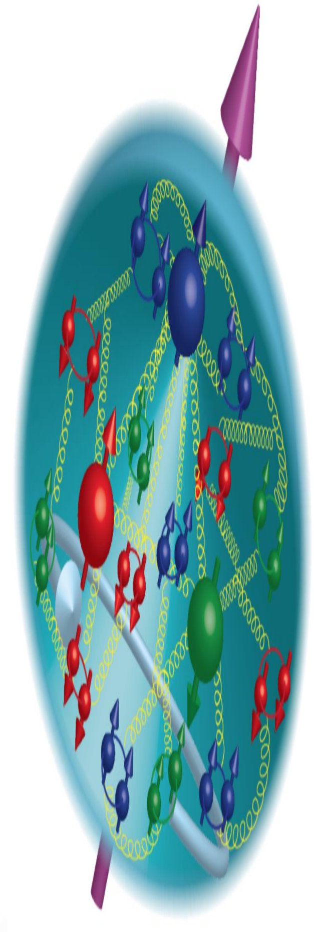
In fact, mass and structure emerge from the quark-gluon dynamics

Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



Lorentz Invariants

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



- Viewed from boosted frame, length contracted by

$$\gamma_{Breit} = \sqrt{1 + \frac{Q^2}{4M^2}}$$

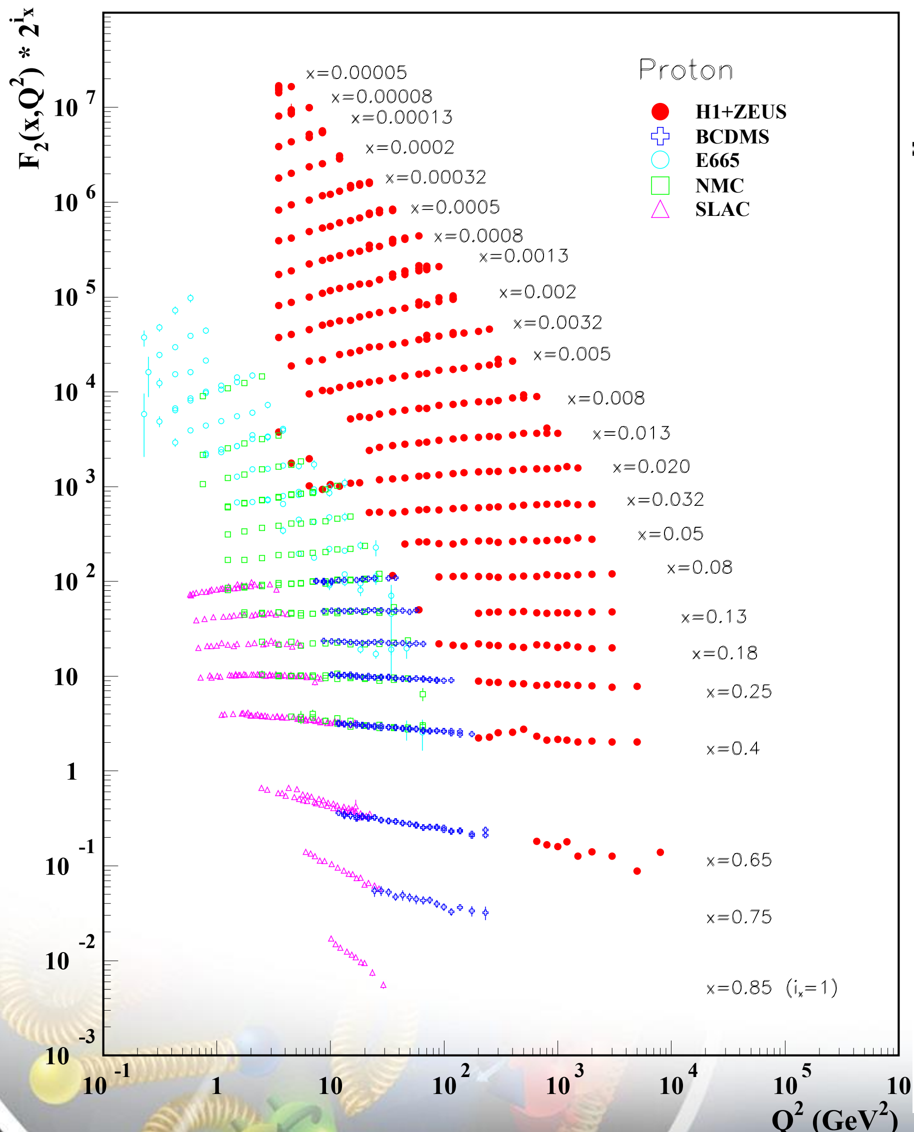
- Internal motion of the proton's constituents is slowed down by time dilation – the <u>instantaneous</u> charge distribution of the proton is seen.
- In boosted frame *x* is understood as the <u>longitudinal momentum fraction</u>

  valence quarks: $0.1 < x < 1$

  sea quarks: $x < 0.1$

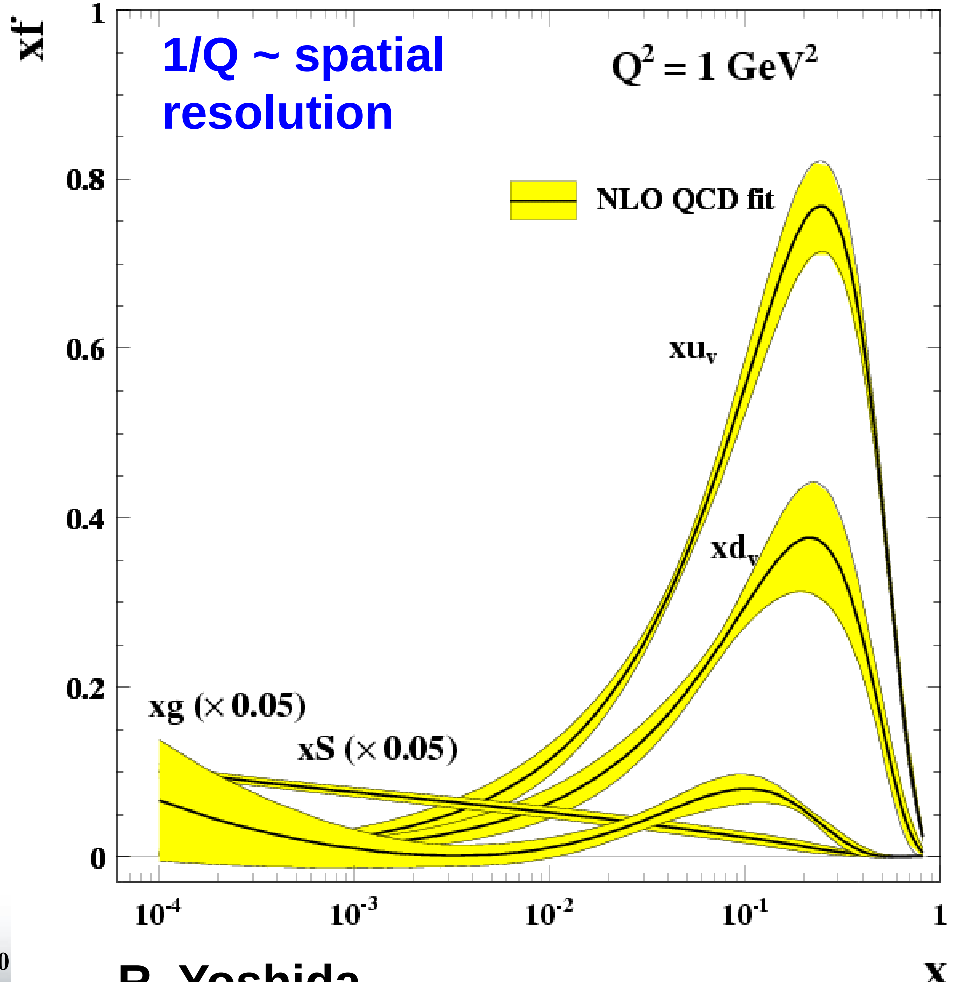
J. Bjorken, SLAC-PUB-0571
March 1969

Learn From Past: 1D Longitudinal Momentum Distributions



g – gluons
S – quark sea

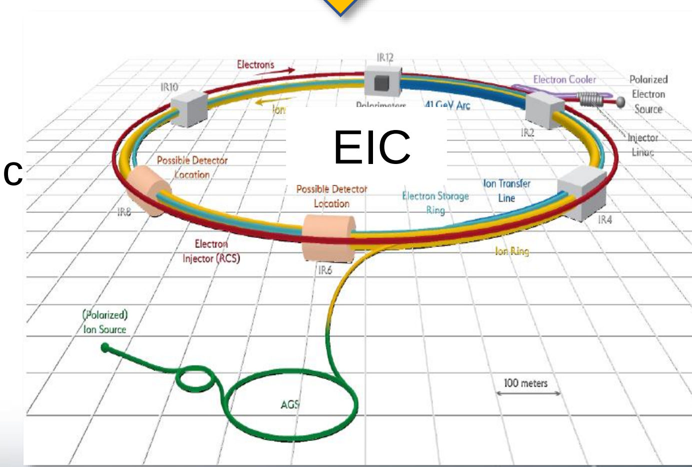
u, d – up, down
valence quarks



R. Yoshida
C. Gwenlan

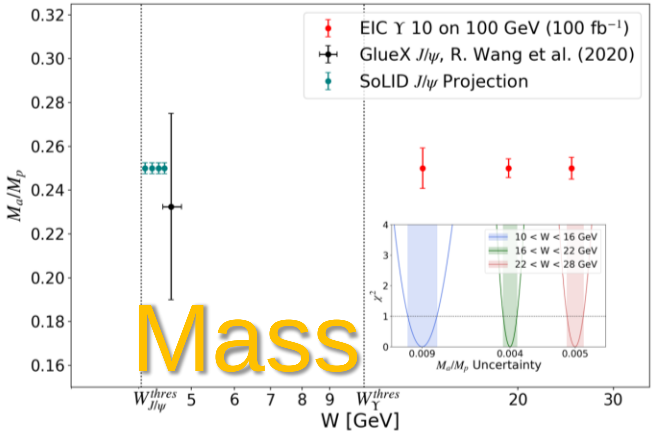
EIC Accelerator Design Overview

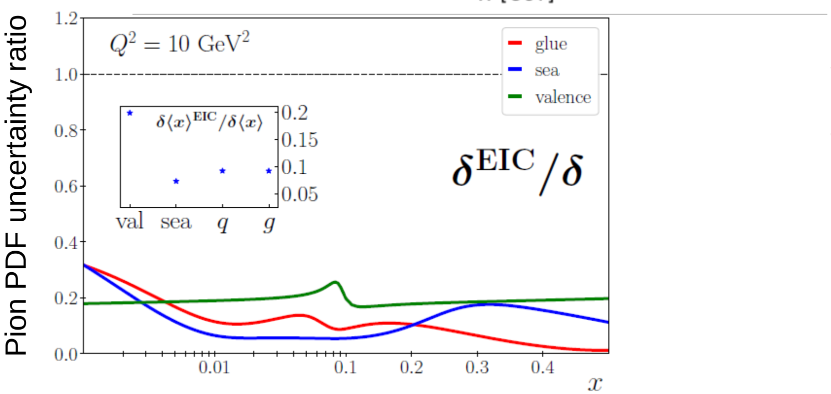
- **Hadron storage ring (HSR): 40-275 GeV** (existing)
  - up to 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance (1.5 nm)
  - strong cooling (coherent electron cooling, ERL)
- **Electron storage ring (ESR): 2.5–18 GeV** (**new**)
  - up to 1160 polarized bunches
    - high 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 periodic
- **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)

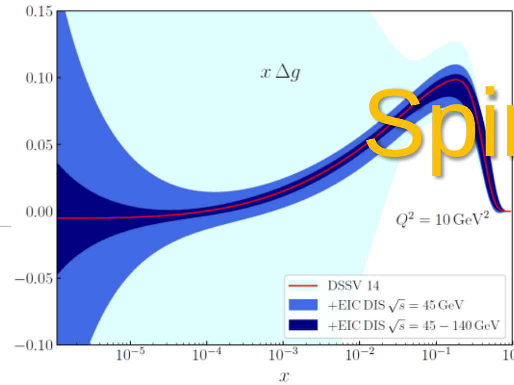


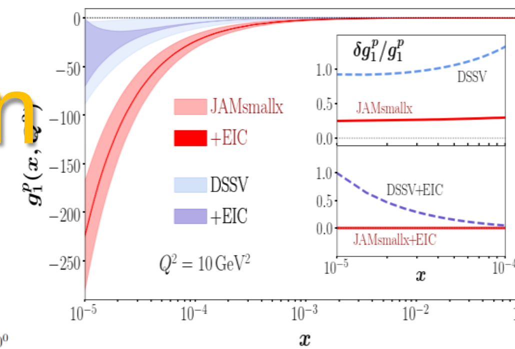
The EIC Will Deliver

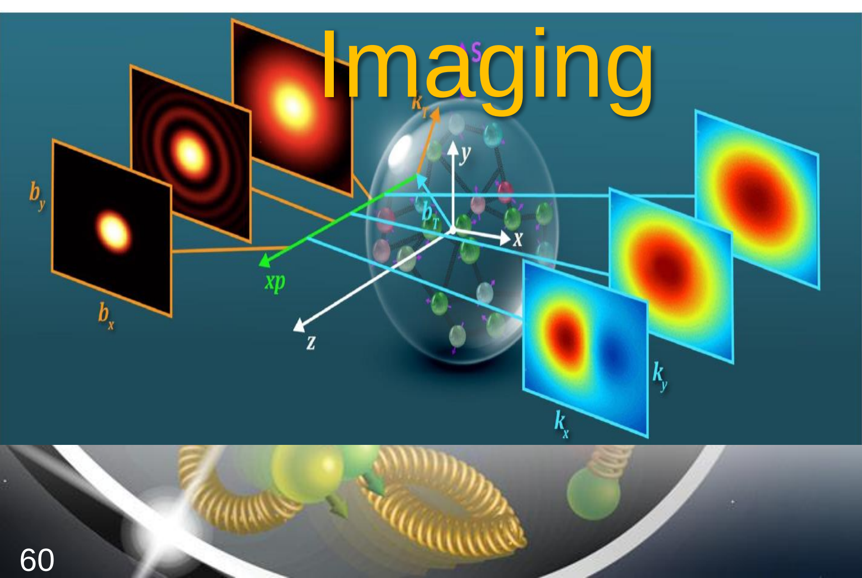
Some highlight plots from the submitted 2023 EIC White Paper

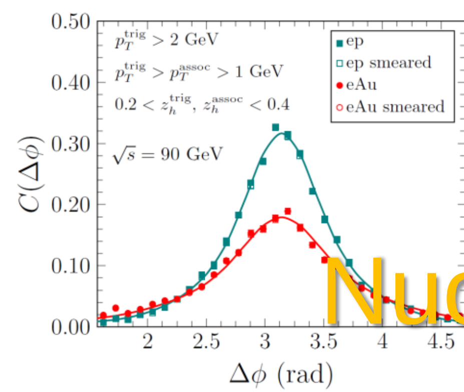


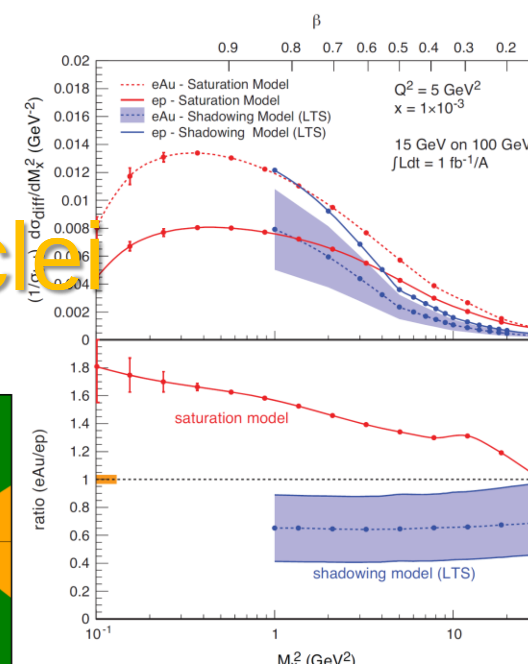


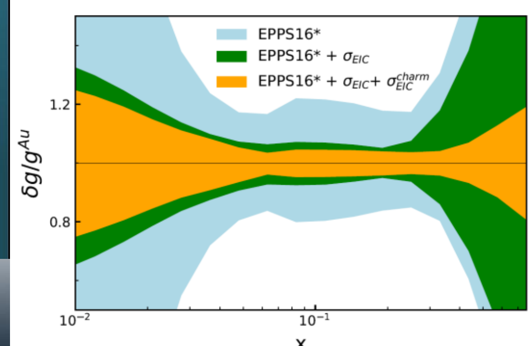










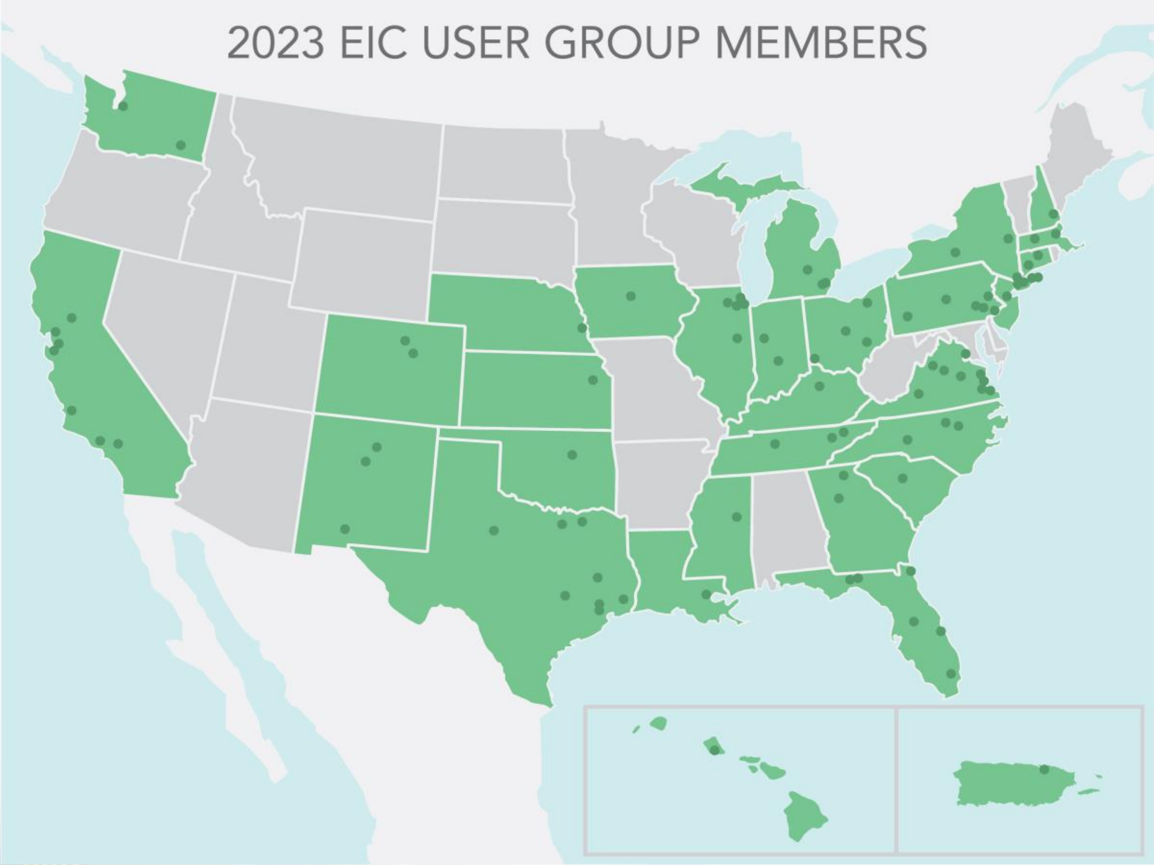


Non-DOE Interest & In-Kind – Updated 07/05/23

Entity	Interest and Important Facts
NSF	NSF-MSRI pre-proposal submitted by 10 US universities – aims at full scope of backward EM calorimetry (eECal). Armenia, Czech, France/IN2P3 as unfunded contributors. Invited to submit proposal. Final NSF review is ongoing.
CERN	MAPS sensor design developed by CERN/ITS-3 Group providing synergy with ALICE. Synergy of gaseous-based Cherenkov detectors and photon-sensors with ALICE & LHCb. Synergy of Forward AC-LGAD design with CMS endcap timing layer.
Armenia	Contributions, mainly labor to eECal and many EM calorimetry and particle id detectors component tests.
Canada	EIC included in 2022 Canadian Subatomic Physics Long-Range Plan; Interested in Compton Polarimetry, Barrel Electromagnetic Calorimetry and Software
China	Forward EM Calorimeter
Czech	Working with funding agency; Interested in eECal (PbWO4 crystals and glass) and Silicon
France/IRFU	Interested in MPGD/racking, electronics. Provided in-kind contributions to SC magnet design and interested to continue labor oversight during magnet construction.
France/IN2P3	International contribution to backward EM calorimetry (including in-kind design) and to readout electronics (two ASICs for AC-LGAD detectors and Calorimetry). IRFU & IN2P3 discussing together for higher-level contributions.
India	Consortium is working with Funding agency; Interested in detector software (non-project scientific contribution), contributions to DAQ/slow controls. Investigating further hardware contributions (including possible links with Si plants).
Italy/INFN	Aims at major scope of forward particle identification detector (dRICH), at (part of) the Si/MAPS tracker scope, and at photo-sensor contributions. Further investigating possible interest in EIC detector magnet scope.
Israel	B0 Detectors (Si tracking and PbWO4)
Japan	Interested in a US-Japan agreement; Aims at full scope of Zero-Degree Calorimeter in collaboration with Taiwan/Korea. Pursuit of full scope of barrel AC-LGAD detector as EIC-Asia consortium. Contribution to DAQ/streaming. Possible aerogel.
Korea	Aims at major scope for fiber-based barrel EM calorimeter, Also work packages for barrel AC-LGAD and Si-based hadronic calorimetry for ZDC.as part of EIC-Asia consortium (includes also Japan,Taiwan), Collaboration on Si tracking detector.
Poland	Actively working with ministry/funding agency; Interested in detectors along the beam line (luminosity detector, Roman Pots)
Taiwan	Pursuit of full scope of barrel AC-LGAD as part of EIC-Asia consortium. LYSO-based EM calorimeter for ZDC, Also optical readout/fiber. Possible later interest in PCBs. Computing.
UK	STFC seed funding for UK detector R&D (3M£). Interest in Si/MAPS tracker, polarimetry and detectors along the beams (Low-Q2/TimePix). Follow-up STFC/UKRI request for 5-7 years submitted early 2023 (includes accelerator part).

Domestic Interest in EIC and Diverse Workforce Development

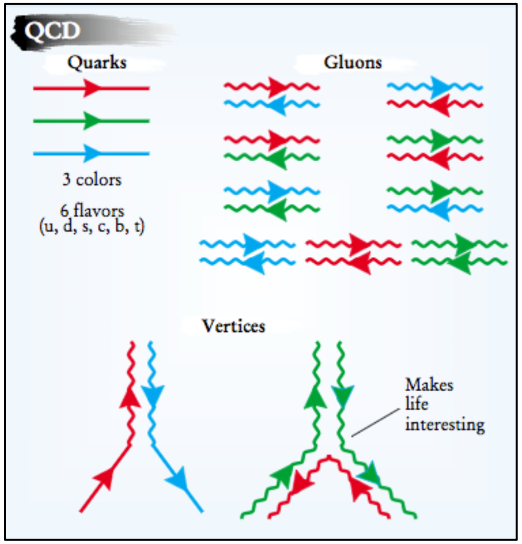
The EIC User Group:
https://eicug.github.io/



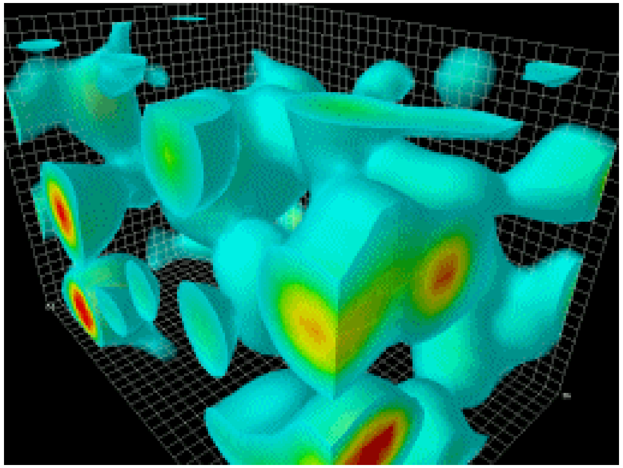
The broad US interest in EIC provides opportunities for further diverse workforce development

- The growing EIC user community currently comprises 276 institutions from 37 countries.
- 94 institutions (about 1/3) are based in the U.S.
- 12 of these are MSIs:
  - Dillard University
  - Florida A&M University
  - Florida International University
  - Georgia State University
  - Hampton University
  - New Mexico State University
  - University of Illinois Chicago
  - University of Houston
  - University of Puerto Rico, Rio Piedras
  - Virginia Union University
  - Univ. of CA, Riverside
  - Texas A&M

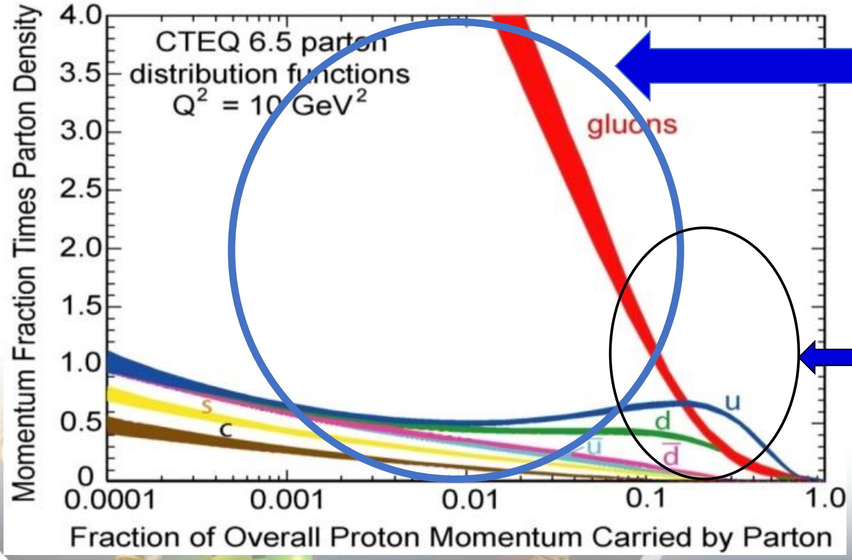
Subatomic Matter is Unique



Interactions and Structure are entangled
because of gluon self-interaction.



Observed properties such as mass and spin emerge from this complex system.



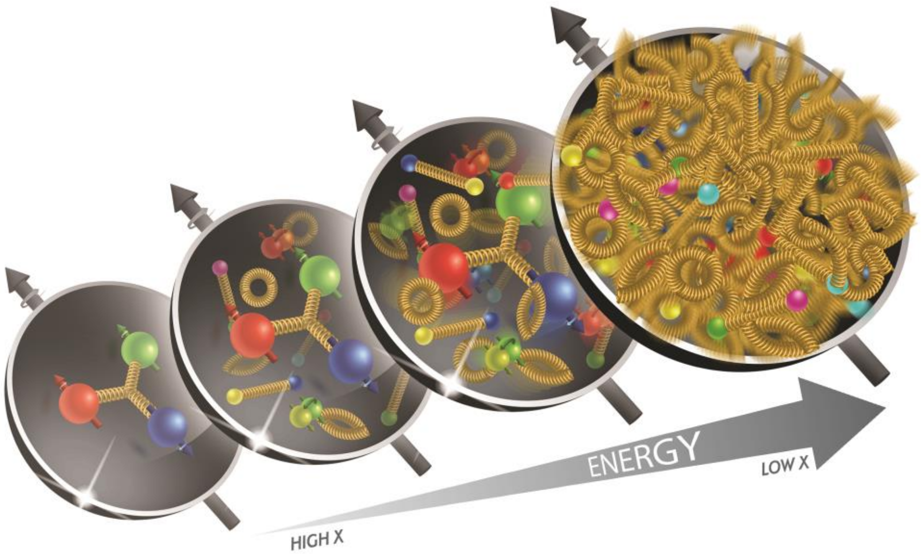
Longitudinal (1D) Momentum Fraction x

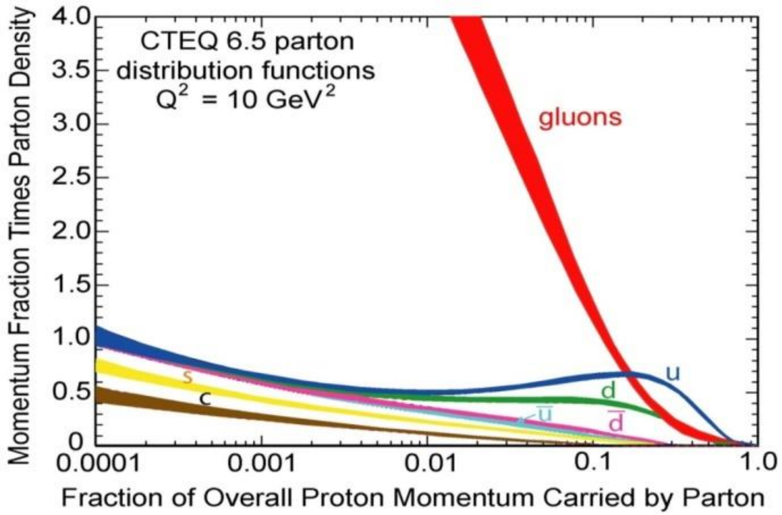
EIC needed to explore the gluon dominated region

JLAB 12 to explore the valence quark region

QCD Landscape Explored by EIC

Strong QCD dynamics creates many-body correlations between quarks and gluons
→ structure of nuclear matter emerges





Longitudinal (1D) Momentum Fraction x

Explore QCD landscape over large range of resolution (Q^2) and quark/gluon density (1/x)

- EIC needed as microscope to explore the region from where a proton is (mostly) an up-up-down quark system to the gluon dominated region.
- Heavy nuclei critical to explore high-density gluon matter.

3D Structure of Nucleons and Nuclei

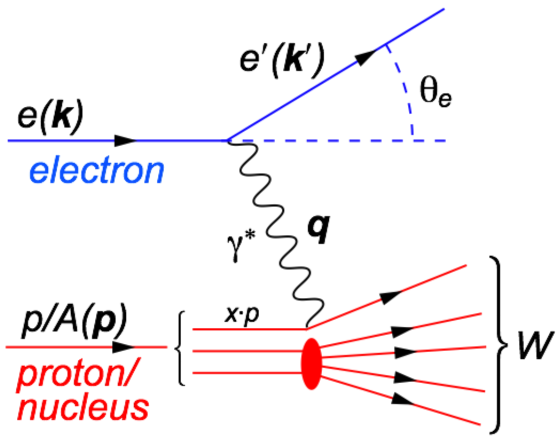
$s=xyQ^2$,
$s=4E_eE_p$

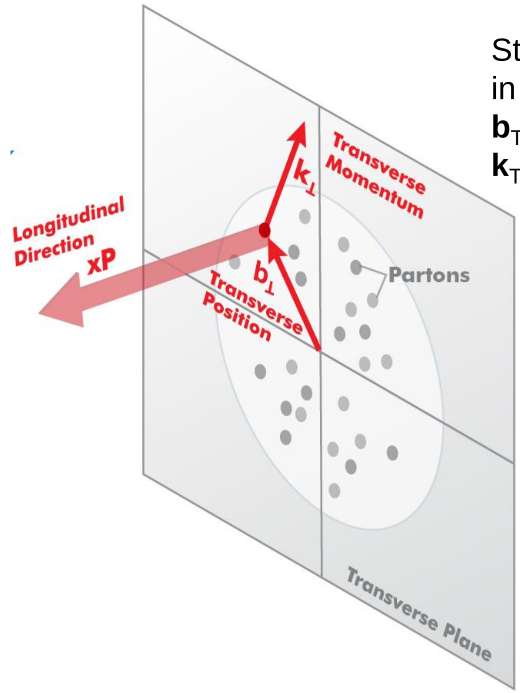
s: center-of-mass energy squared

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

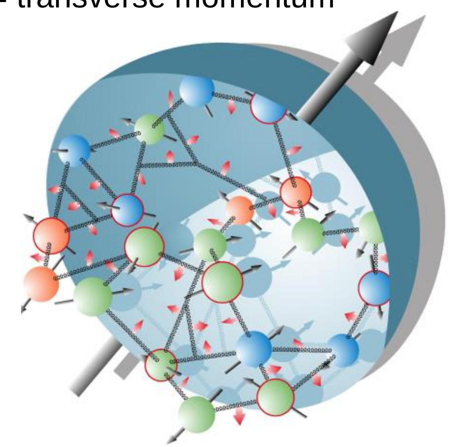
Q^2: resolution power

y: inelasticity





Structure mapped
in terms of
b_T = transverse position
k_T = transverse momentum



need energy range to unambiguously resolve partons over wide range in x and Q^2 → versatile center-of-mass energy energy √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 Revolution in Hadron and Nuclear Structure

Nuclear Physics in terms of protons, neutrons and pion exchange is a very good effective model. Resolution or Momentum transfer Q is negligible

Protons and Neutrons in terms of constituent (valence) quarks is a very decent effective model:

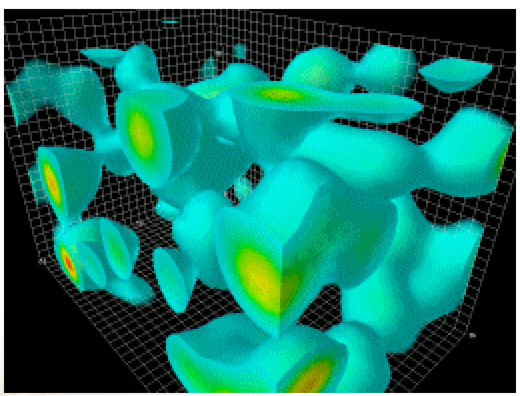
the Constituent Quark Model works surprisingly well.

Resolution or Momentum transfer Q is small

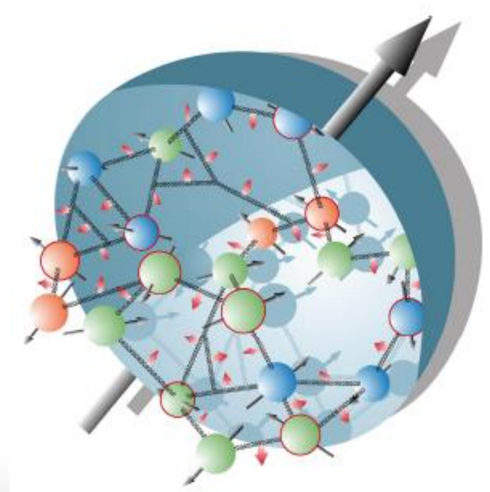
Looking deep inside protons and neutrons:

Quantum fluctuations + special relativity + $M = E/c^2$ gives rise to quark-gluon dynamics (structure and interactions).

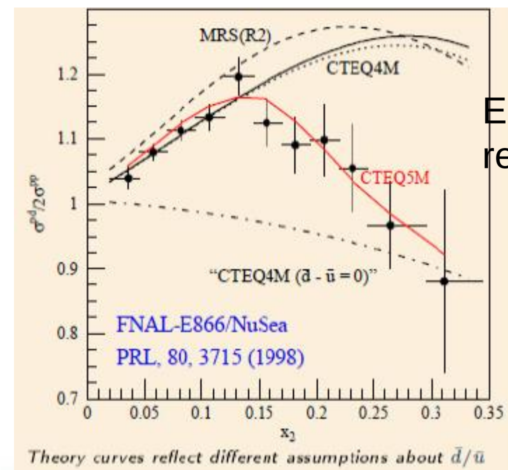
Resolution or Momentum transfer Q is “large”



The QCD vacuum is not empty, but full of gluon fluctuations: deep in the proton is a wall of gluons



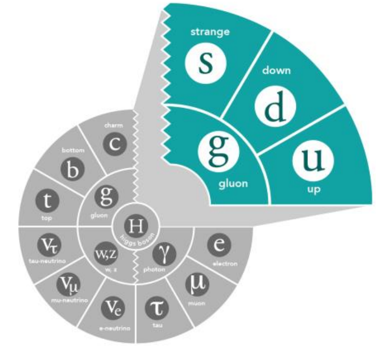
The proton is complex, mass and spin are emergent phenomena



E866 result

Quantum fluctuations play a role in nucleon structure:

$\bar{d}(x) \neq \bar{u}(x)$



Naïve Quark Model: proton = uud (valence quarks)

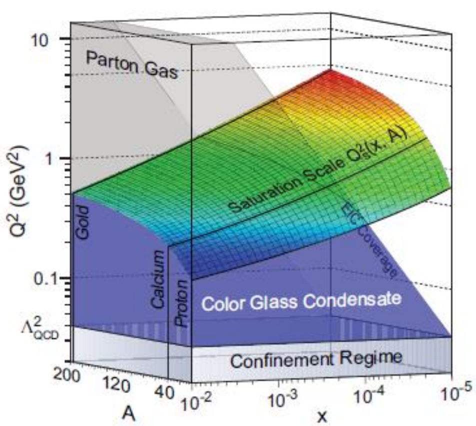
QCD: proton = uud + $u\bar{u}$ + $d\bar{d}$ + $s\bar{s}$ + …

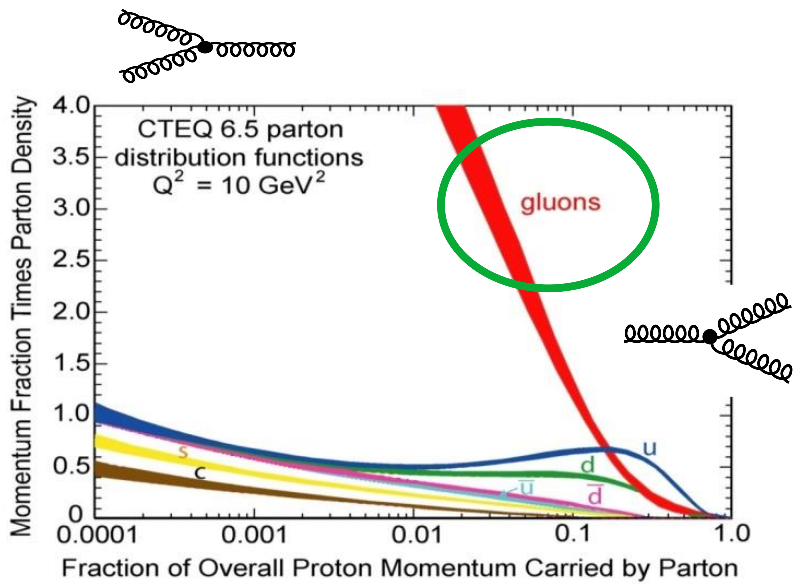
(90s) The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

(late 80s) & gluons are abundant

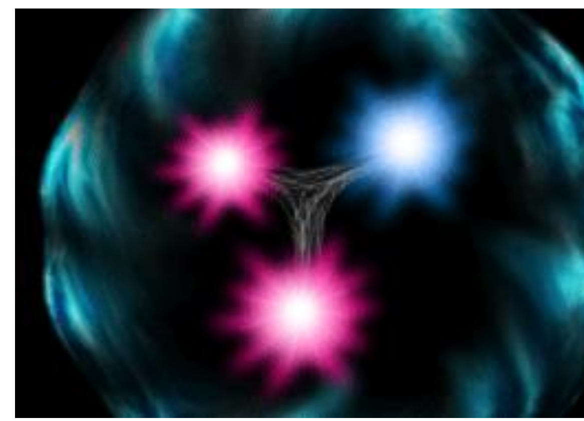
(early 2000s)

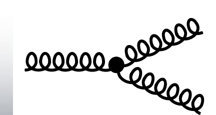
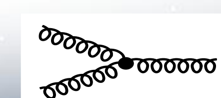
gluon dynamics



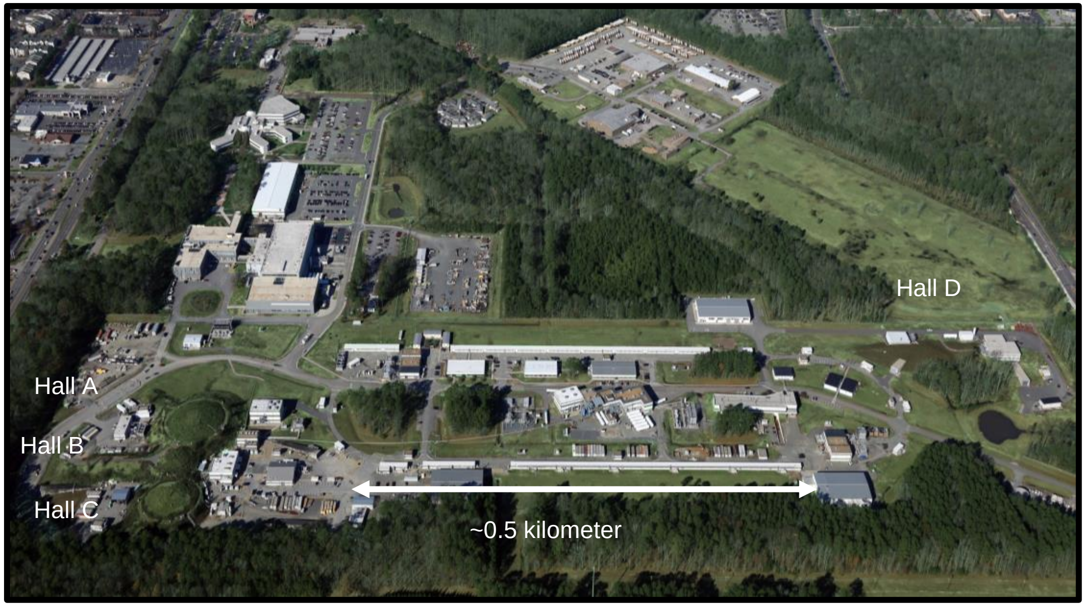


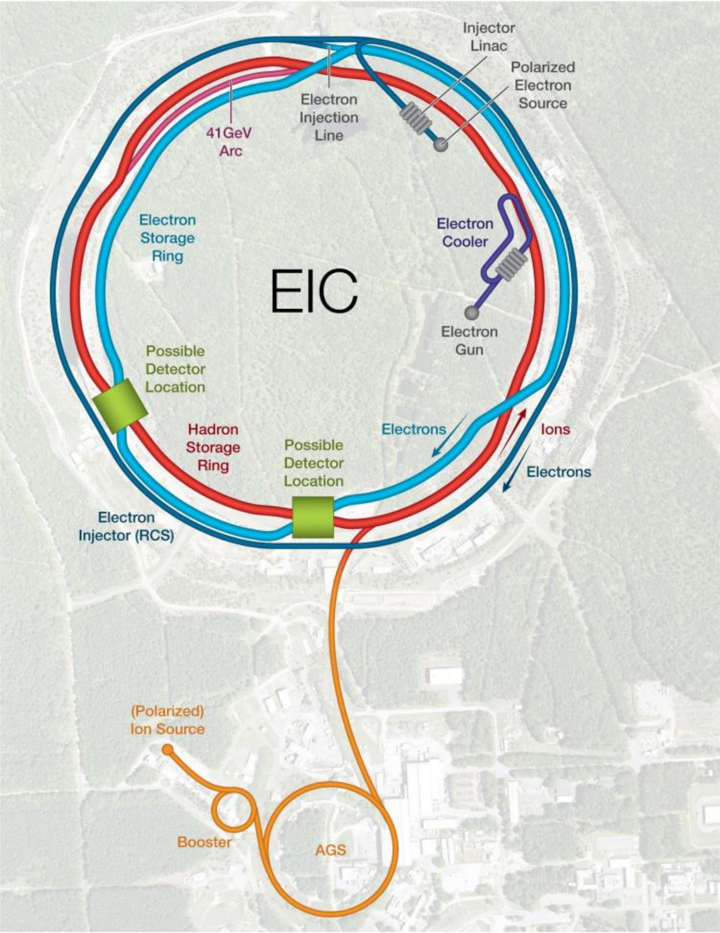
Non-trivial sea structure



- ❑ The proton is **far more** than just its up + up + down (valence) structure
- ❑ Gluon ≠ photon: Radiates  and recombines: 

Jefferson Lab and EIC – an exciting future lies ahead





Electron accelerator on fixed-targets

- 1995 start of 4 GeV science program
- 2000s evolutionary upgrade to 6 GeV
- 2017 formal start of 12-GeV program
- 2023 continue 12-GeV operations, decade-long science program on books
- Studying options to upgrade to 22 GeV

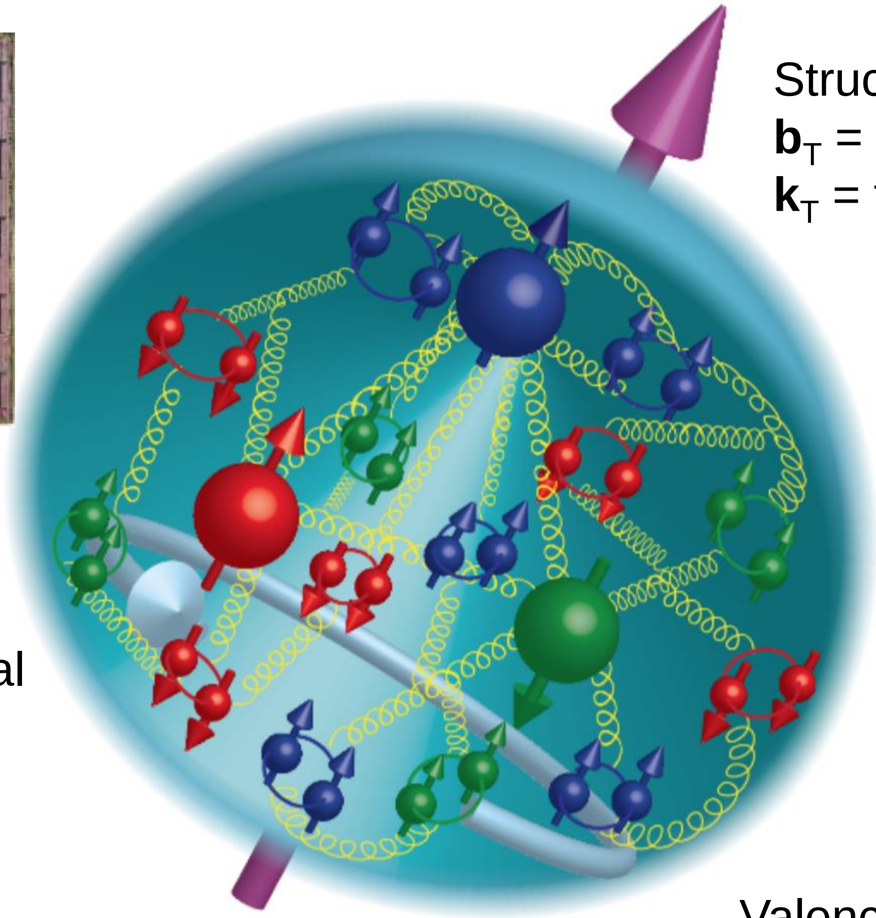
Electron-proton/ion collider

- Science operations phase in 2030s

~1900 scientific users

~1400 members of EICUG

Nuclear Femtography: 2 New Dimensions Transverse to Longitudinal Momentum



Structure mapped in terms of
$\mathbf{b}_T$ = transverse position
$\mathbf{k}_T$ = 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