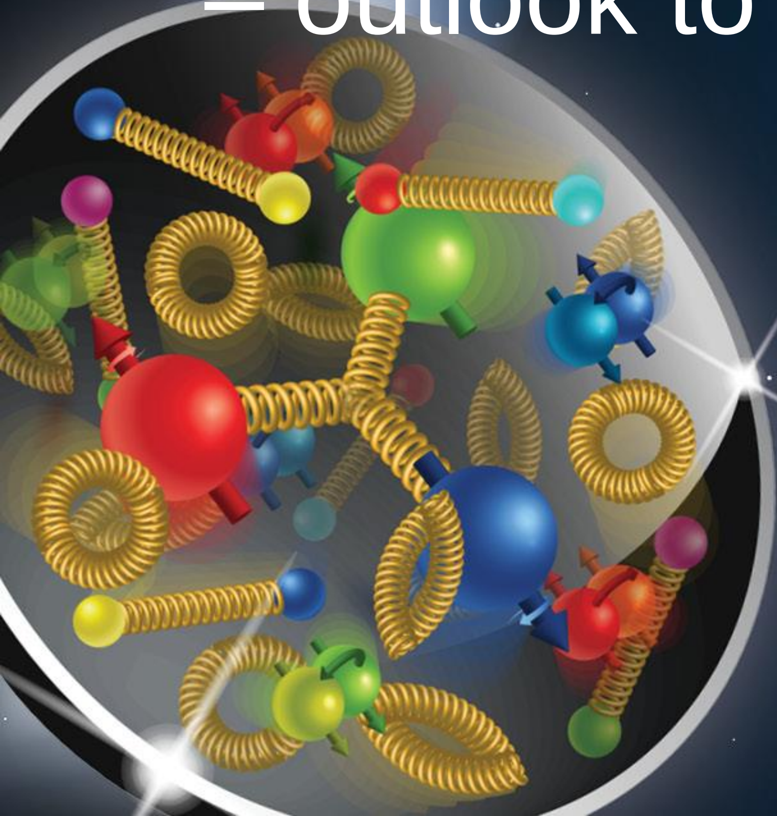
The quest to understand the fundamental structure of nuclear matter – outlook to an Electron-Ion Collider

Rolf Ent (Jefferson Lab)

Electron Ion Collider



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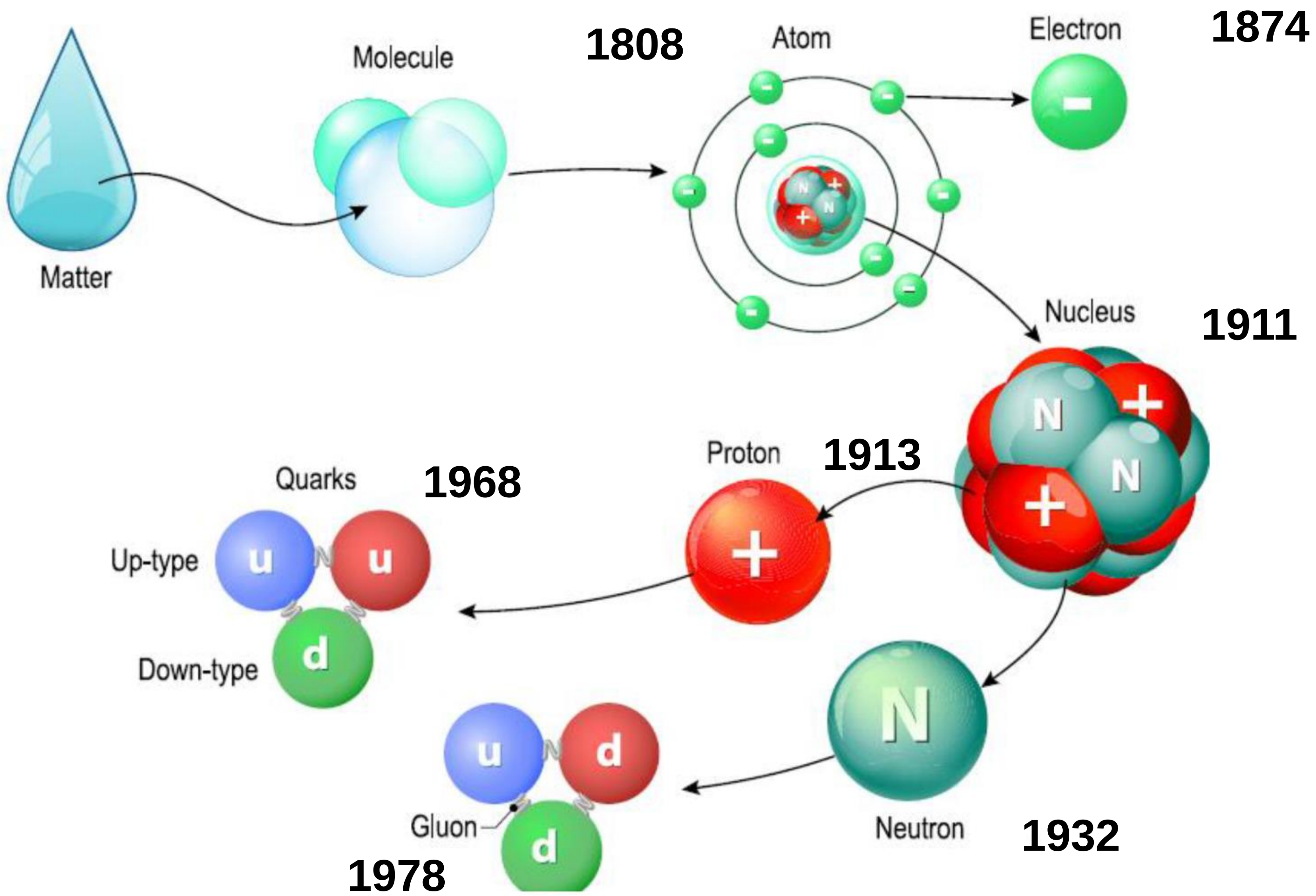
Outline

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

The Quest to Understand the Fundamental Structure of Matter



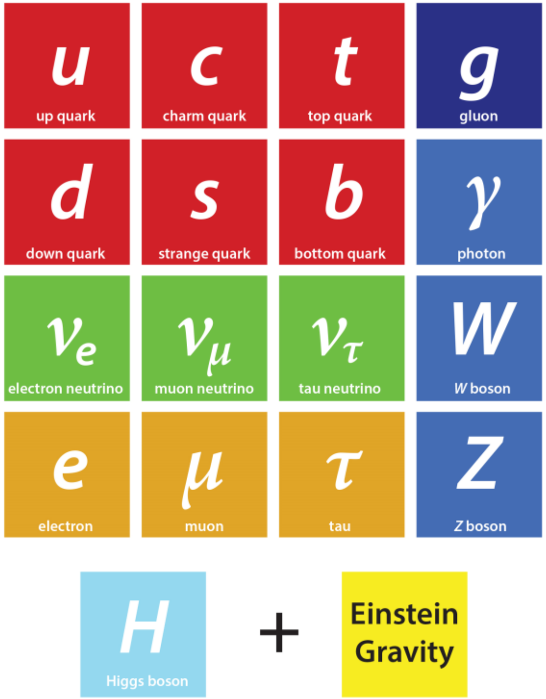
*EIC: Understanding the Glue that Binds Us All - **Without gluons, there would be no nucleons, no atomic nuclei… no visible world!***

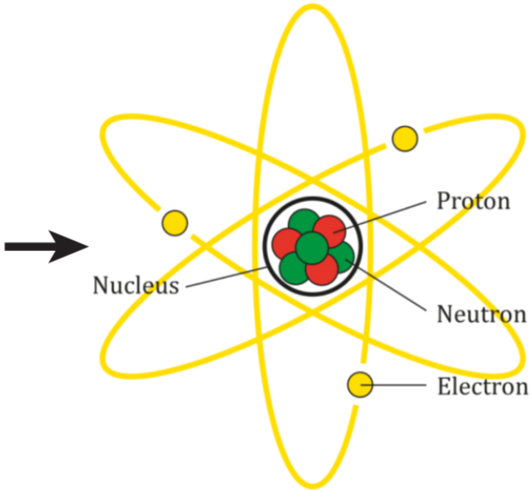
What is the World Made of?

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

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

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

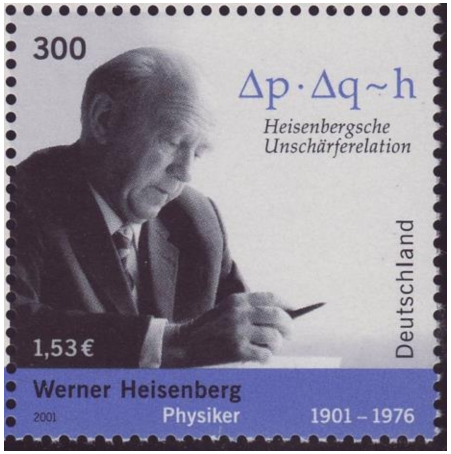




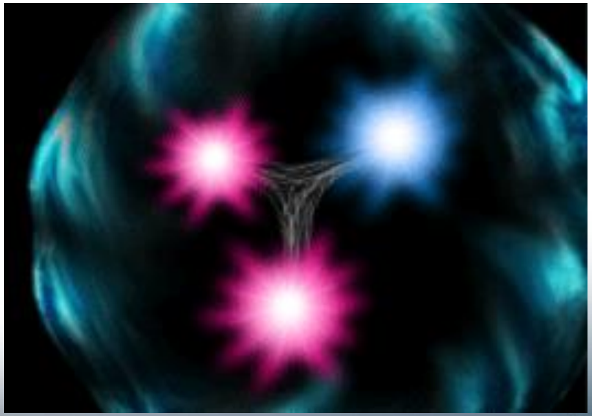
However, the mass of the quarks is much less than the mass of the proton.
The gluons are massless.
How can this make sense?

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



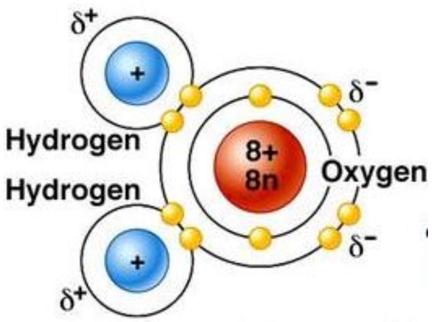
- Consequences:
  1. Particles that are bound or confined to small volumes will reach near-relativistic velocities
     - ❑ Protons inside atomic nuclei move with ~1/5 the speed of light, and quarks inside protons move at relativistic speeds.
  2. Pairs of virtual matter and anti-matter are continuously 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

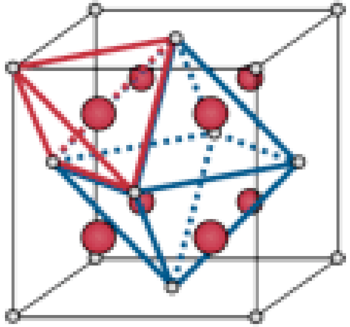
Most known matter has localized mass and charge centers – vast "open" space

Molecule:



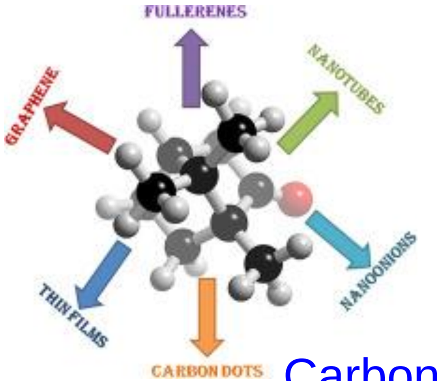
"Water"

Crystal:



Rare-Earth metal

Nanomaterial:



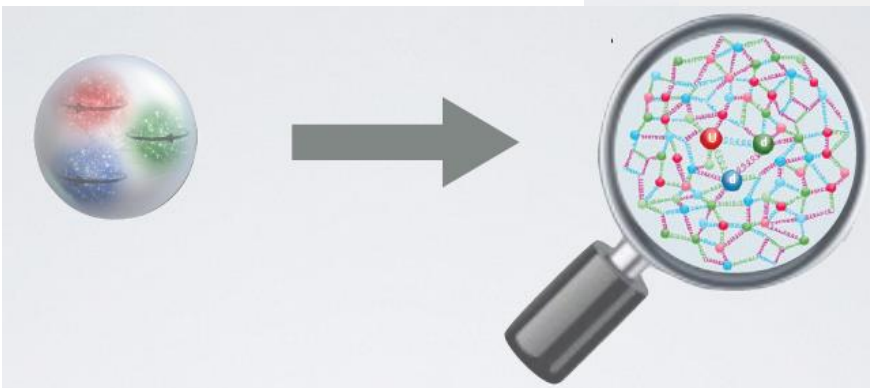
Carbon-based

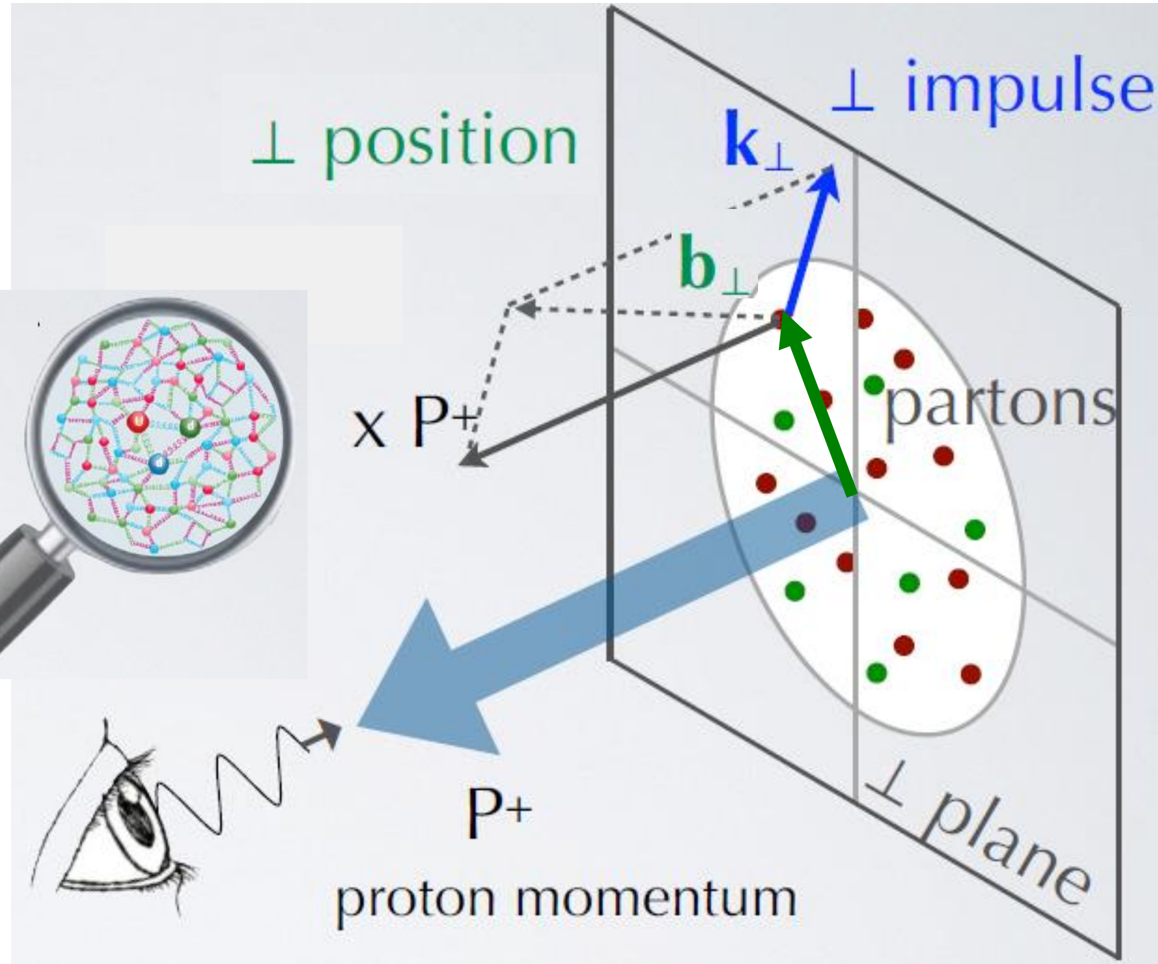
Not so in nuclear matter! – unlike the more familiar molecular and atomic matter, the interactions and structures are inextricably mixed up in protons and other forms of nuclear matter, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

Imaging Physical Systems is Key to New Understanding

Nuclear Femtography - Imaging

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





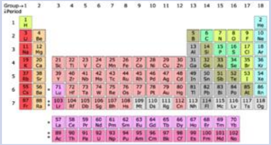
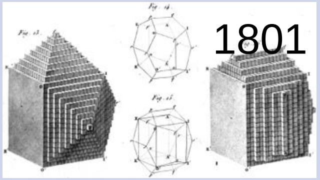
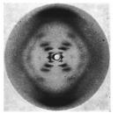
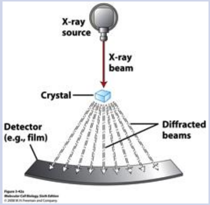
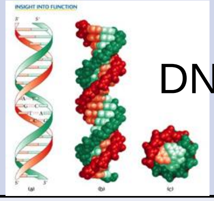
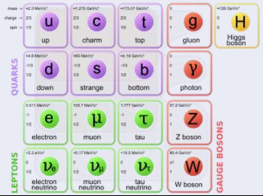
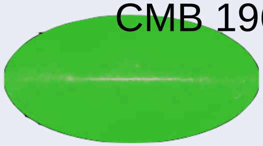
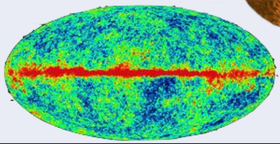
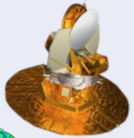
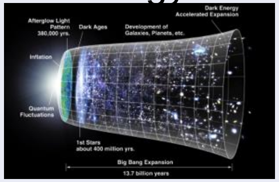
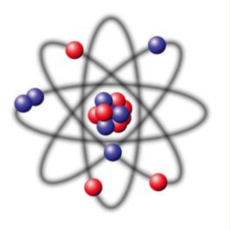
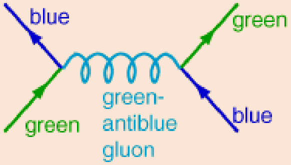
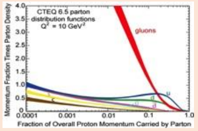
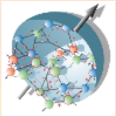
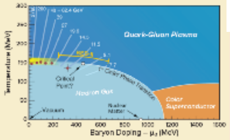
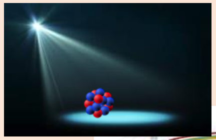
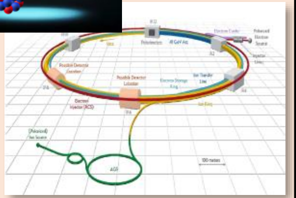
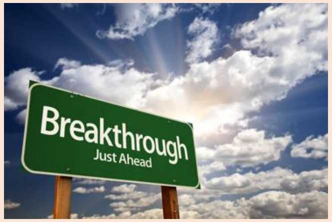
Structure mapped in terms of

$\mathbf{b}_T$ = transverse position

$\mathbf{k}_T$ = transverse momentum

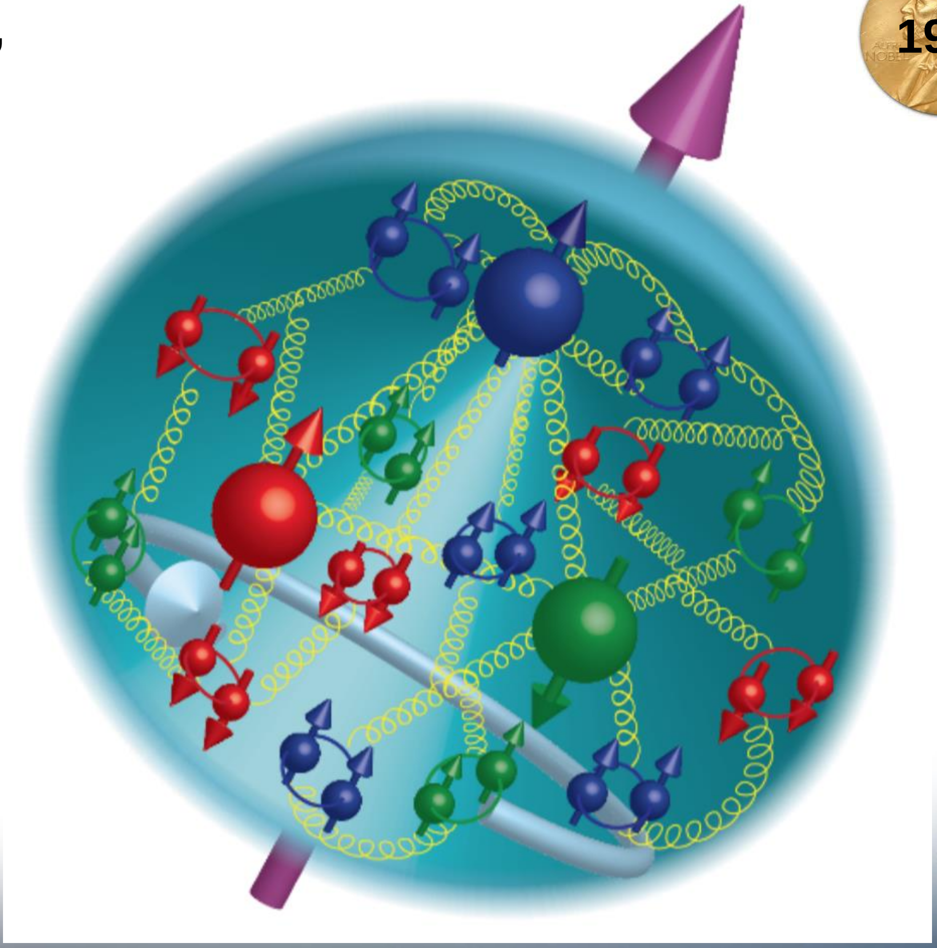
Also information on orbital angular momentum: **r** x **p**

Imaging Physical Systems is Key to New Understanding

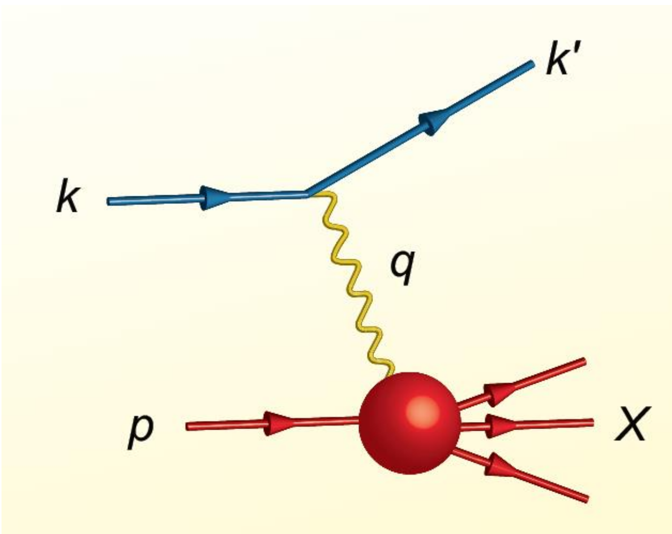
Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920)  	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark 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 

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) well mapped out.
- The proton spin and mass have large contributions from the quark-gluon dynamics.



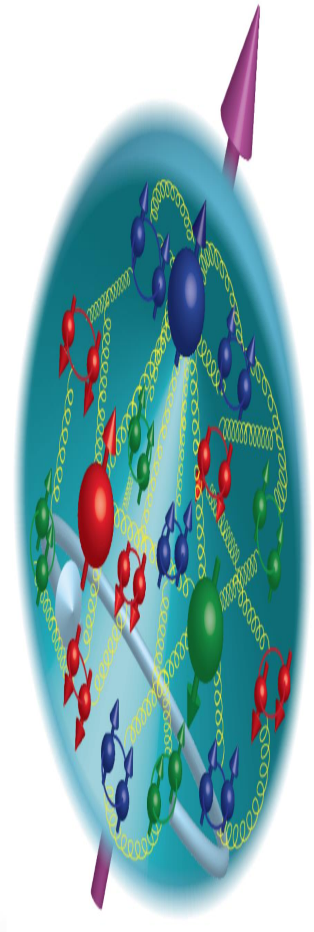
Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



Lorentz Invariants

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

R. Milner



- Viewed from boosted frame, length contracted by

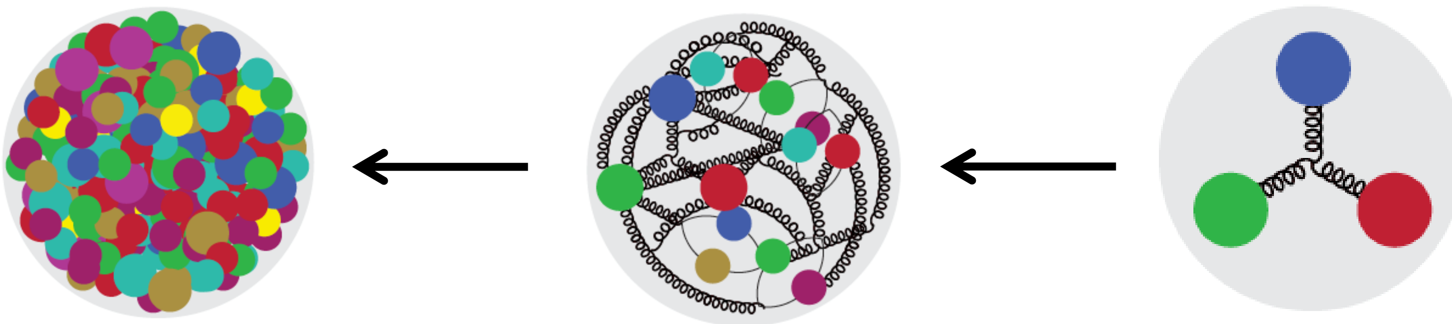
$$\gamma_{Breit} = \sqrt{1 + \frac{Q^2}{4M^2}}$$

- 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

High Energy Electron Scattering

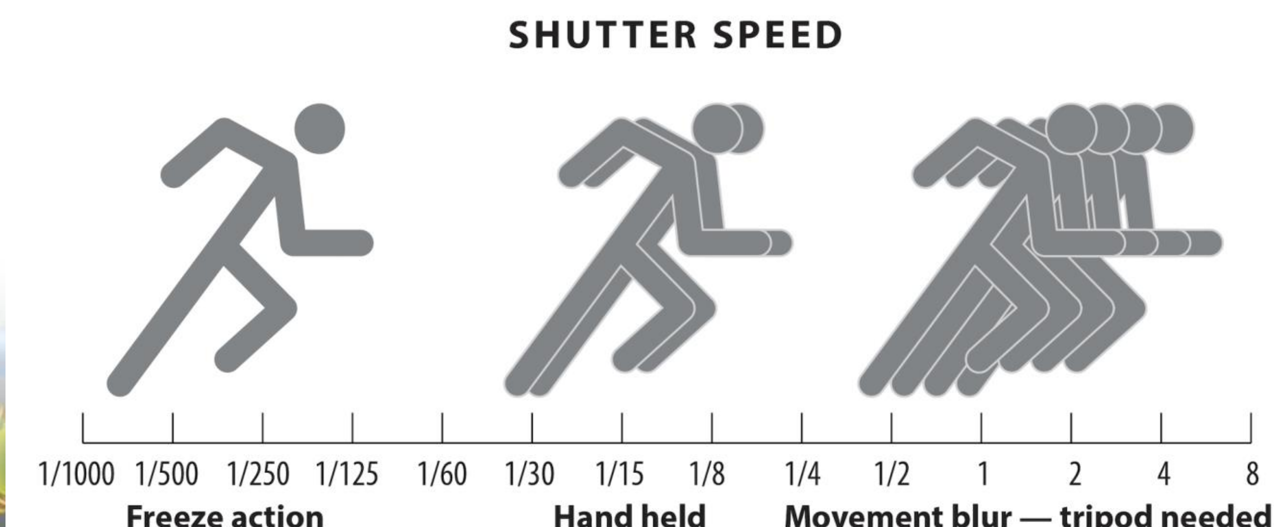
Snapshots where $0 < x < 1$ is the shutter exposure time



$x \approx 10^{-4}$
Probe non-linear dynamics
short exposure time

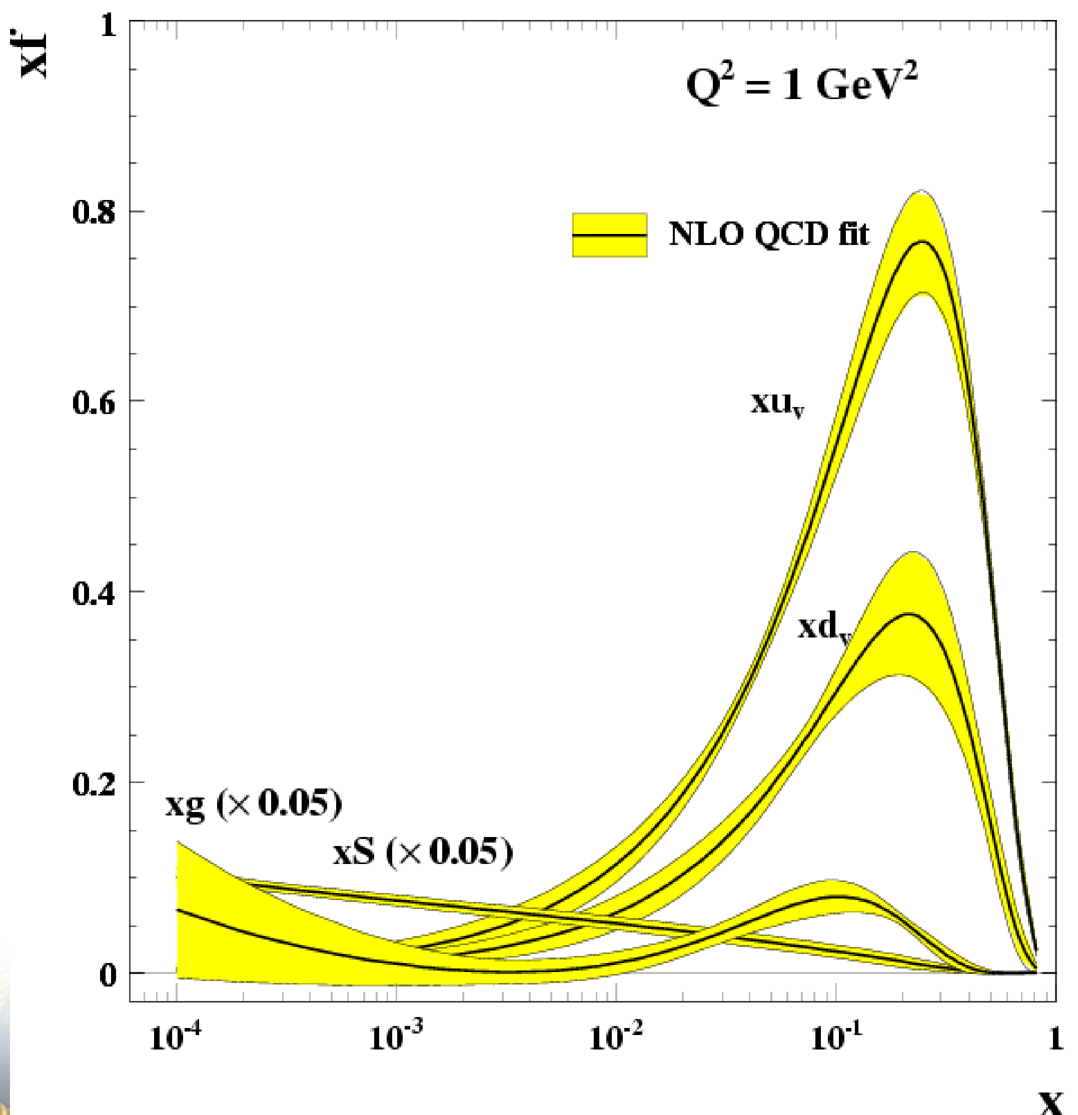
$x \approx 10^{-2}$
Probe rad. dominated
medium exposure time

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



R. Milner

1 Longitudinal Momentum Distributions

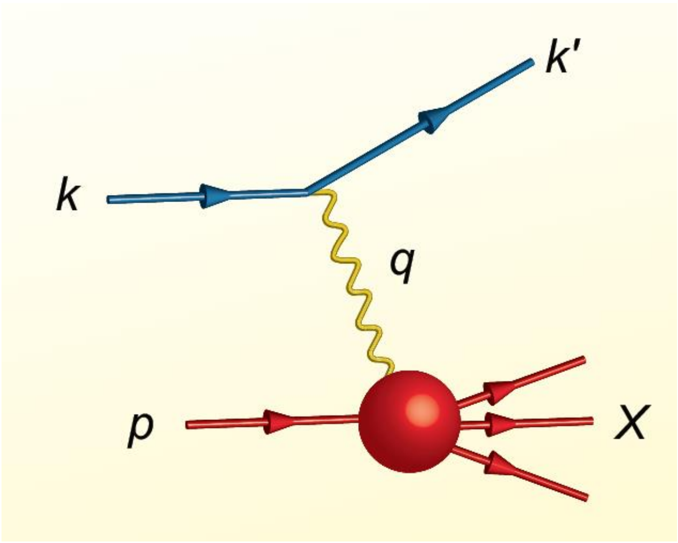


1/Q ~ spatial resolution

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

R. Yoshida
C. Gwenlan

Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



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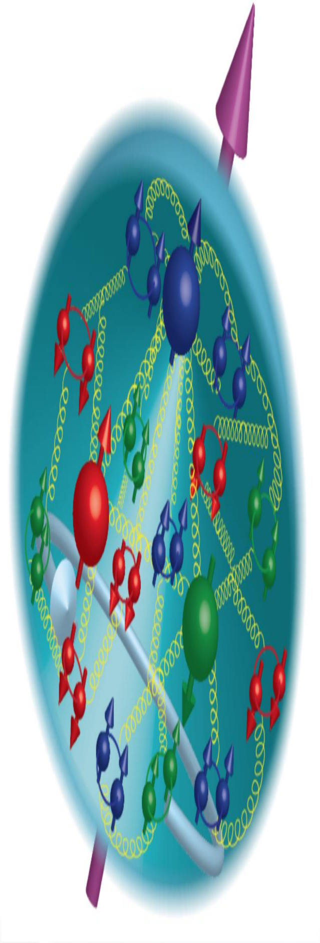

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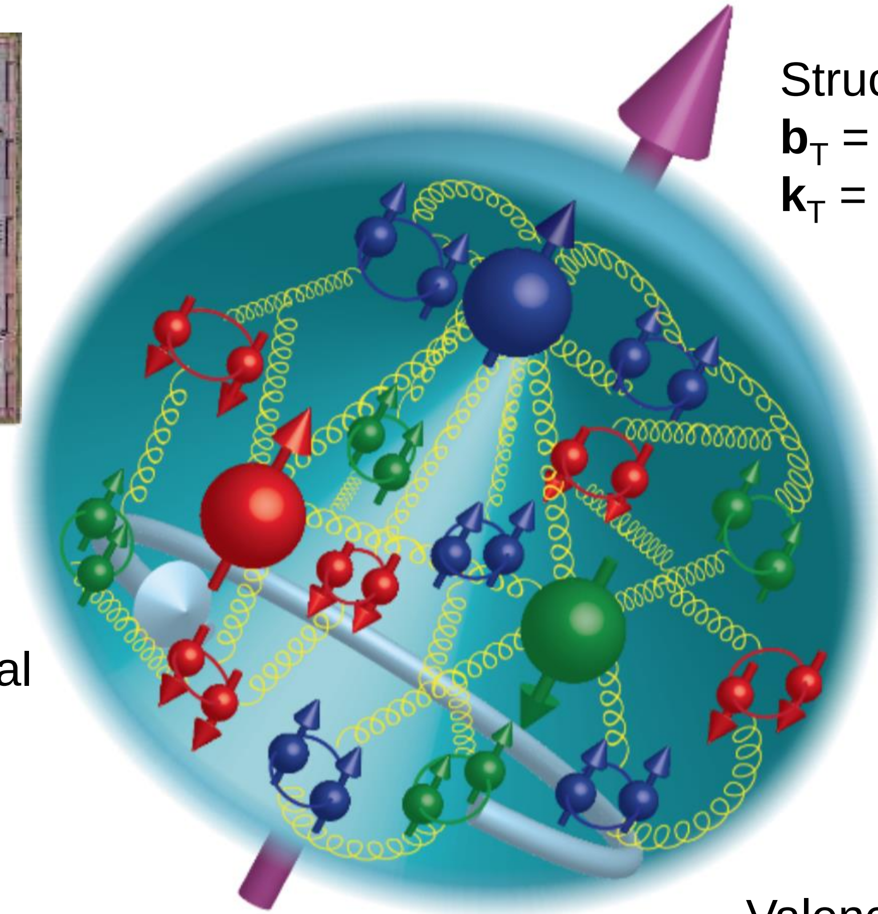
March 1969

Nuclear Femtography: 2 New Dimensions Transverse to Longitudinal Momentum



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

Spin!
Nuclei!

Goal:
Unprecedented
21st Century Imaging
of Hadronic Matter

Direction of longitudinal momentum normal to plane of slide

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

Exploring the 3D Nucleon Structure

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

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

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

Nuclear Femtography

What is Needed Experimentally?

experimental measurements categories to address EIC physics:

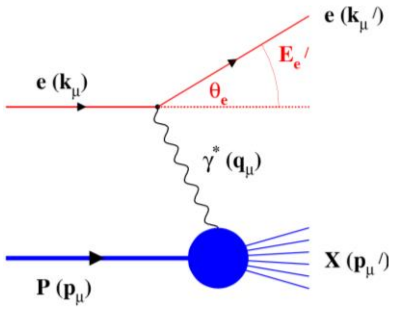
Parton Distributions in nucleons and nuclei

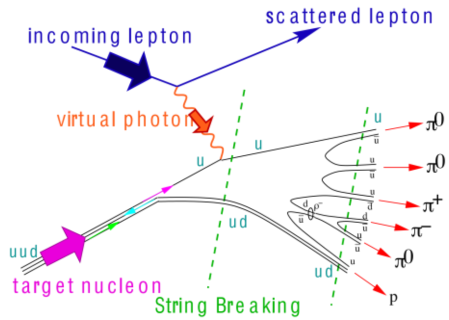
Spin and Flavor structure of nucleons and nuclei

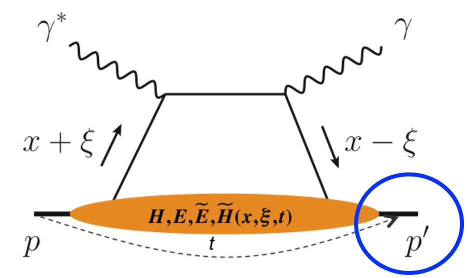
Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging







inclusive DIS

- measure scattered 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}

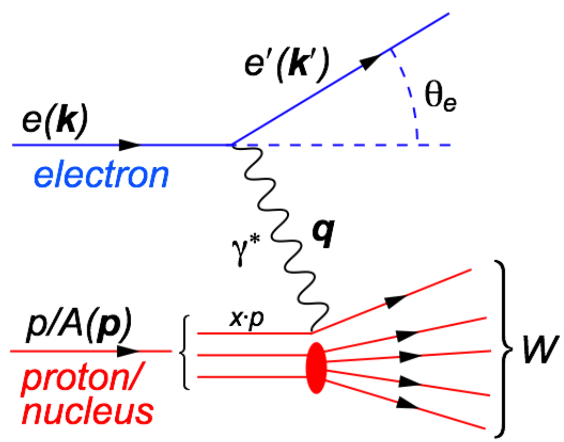
machine & detector requirements

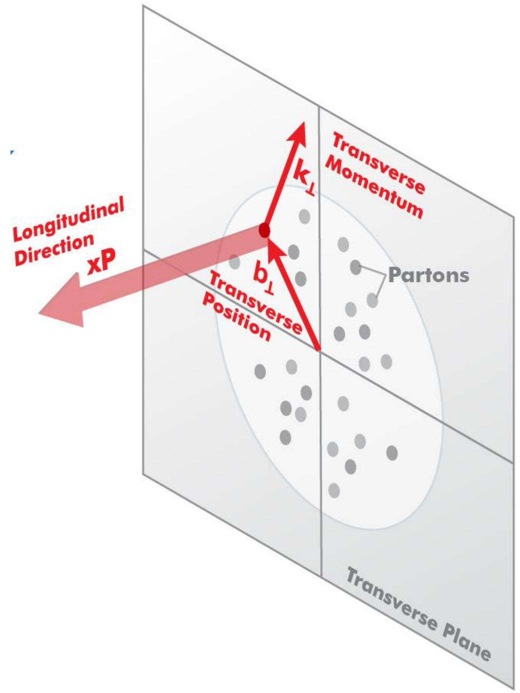
3D Structure of Nucleons and Nuclei

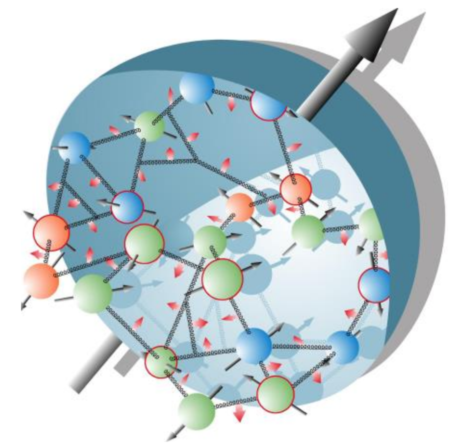
$s = xyQ^2$,

$s = 4E_eE_p$

- ***s:*** center-of-mass energy squared
- ***x***: the fraction of the nucleon's momentum carried by the struck quark (0 < x < 1)
- ***Q²***: resolution power
- ***y:*** inelasticity







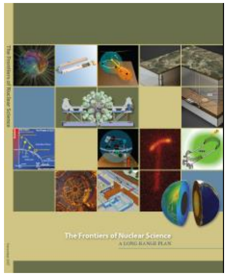
need energy range to unambiguously resolve partons over wide range in x and Q^2 → versatile center-of-mass energy energy $\sqrt{s}$: 20 – 140 GeV

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)

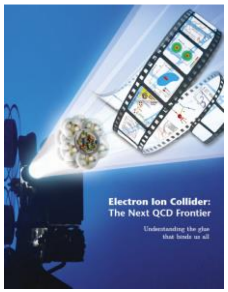
Proton and Ion Beam ~100 GeV

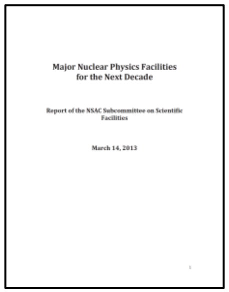
U.S. Electron-Ion Collider Planning 2007-18



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

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



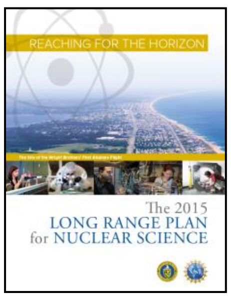

Major Nuclear Physics Facilities for the Next Decade

Report of the NSAC Subcommittee on Scientific Facilities

March 14, 2013

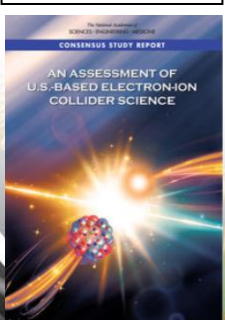
2013 Electron Ion Collider White Paper
(Writing committee convened by Jefferson Lab and BNL)

2013 NSAC Subcommittee on Future Facilities
Identified EIC as **absolutely central** to the nuclear science program of the next decade



2015 NSAC Long-Range Plan

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

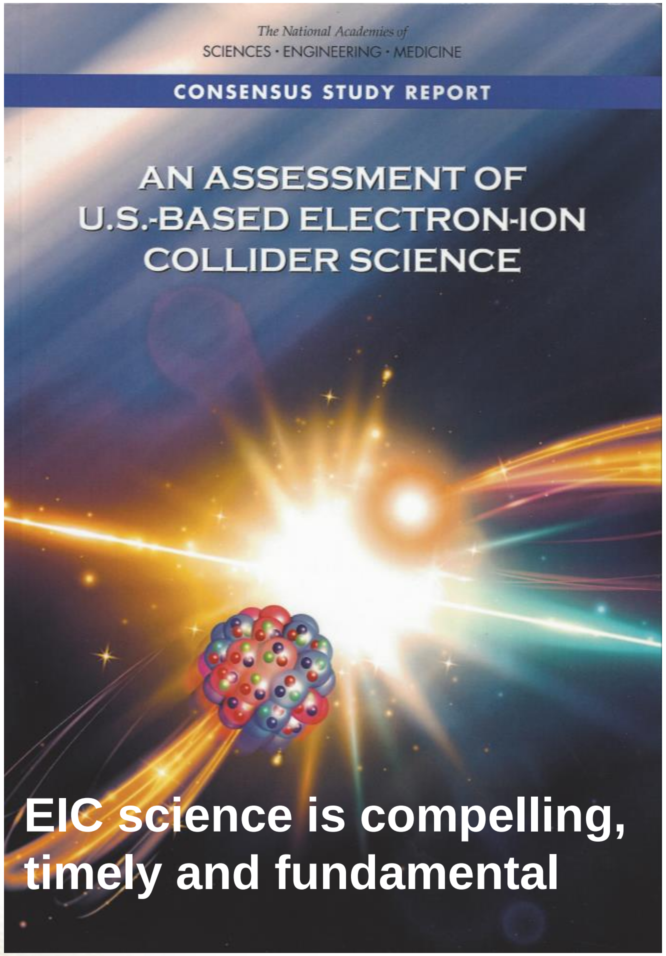


2018 National Academy of Sciences (NAS) – Assessment of U.S. Based Electron-Ion Collider Science

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

EIC Science – Findings of the NAS Committee

The National Academies of
SCIENCES · ENGINEERING · MEDICINE



EIC science is compelling, timely and fundamental

Developed by NAS committee with broad science perspective

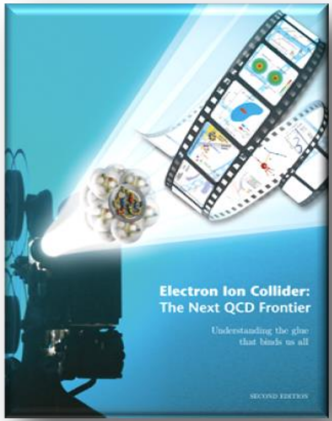
- **Finding 1:** An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:
  - How does the **mass** of the nucleon arise?
  - How does the **spin** of the nucleon arise?
  - What are the **emergent properties**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

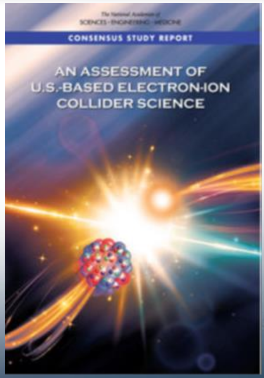
- **Finding 2:** These three high-priority science questions can be answered by an EIC with **highly polarized beams** of electrons and ions, with sufficiently **high luminosity** and sufficient, and **variable**, center-of-mass **energy**.

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:

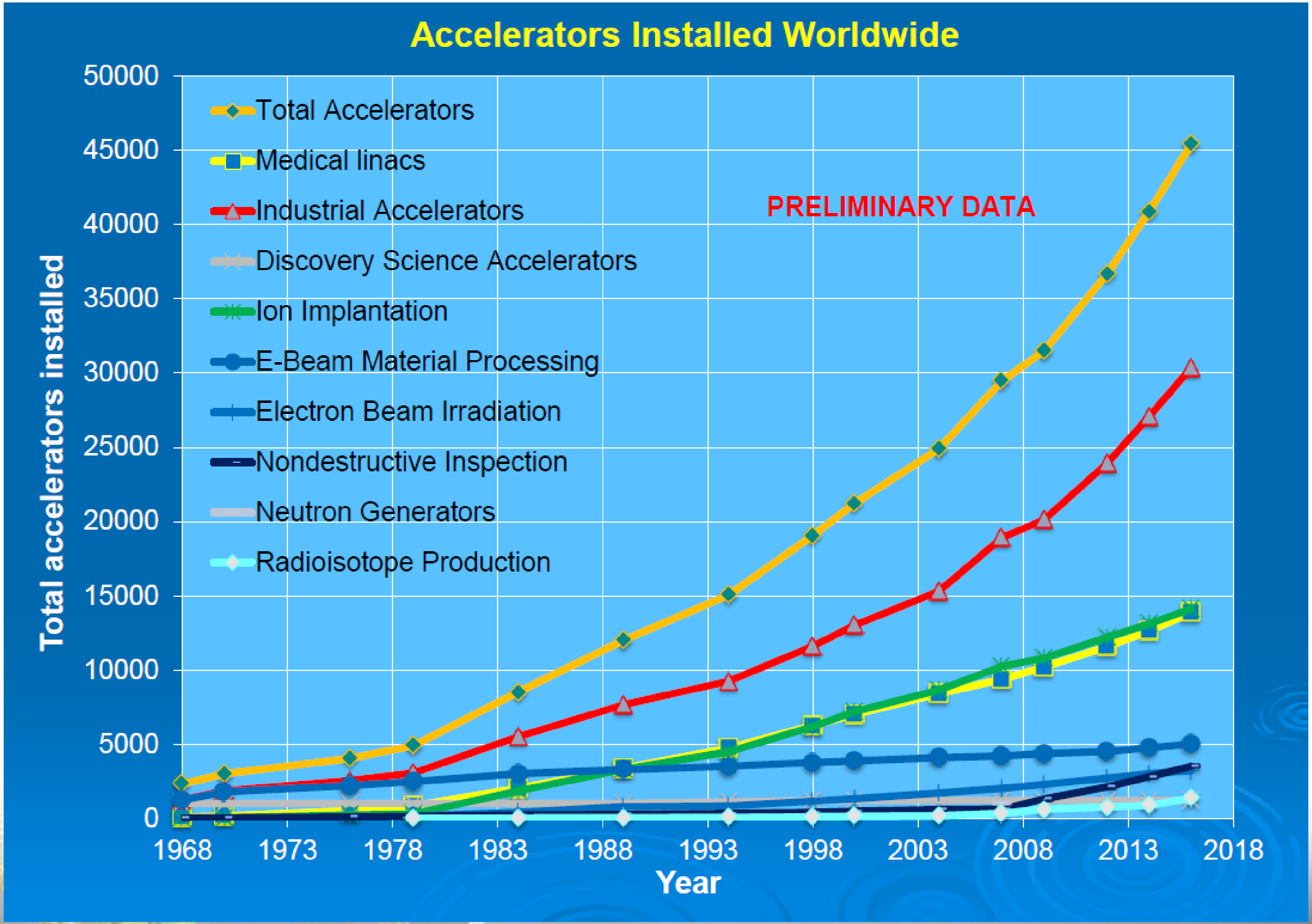
- Extensive center-of-mass energy range, from ~20-~100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times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





Note: consistent with 2013 white paper and 2015 NSAC Long Range Plan

Growing Relevance of Accelerators Worldwide



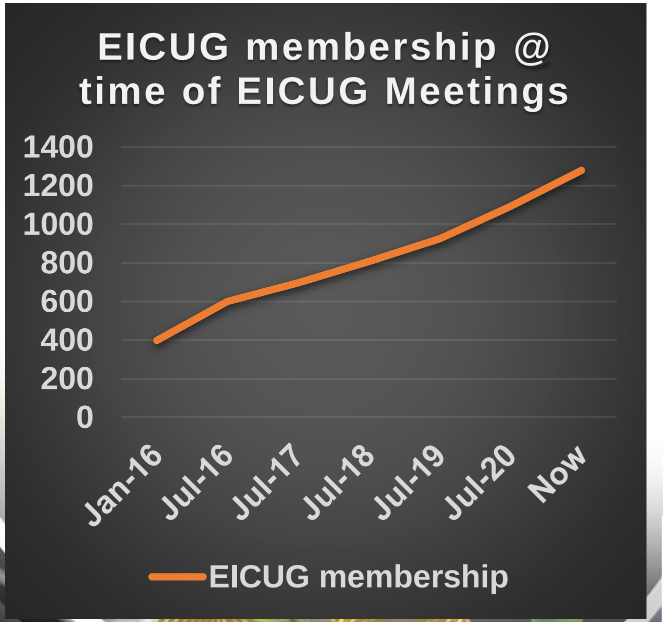
From: Dr. Robert W. Hamm

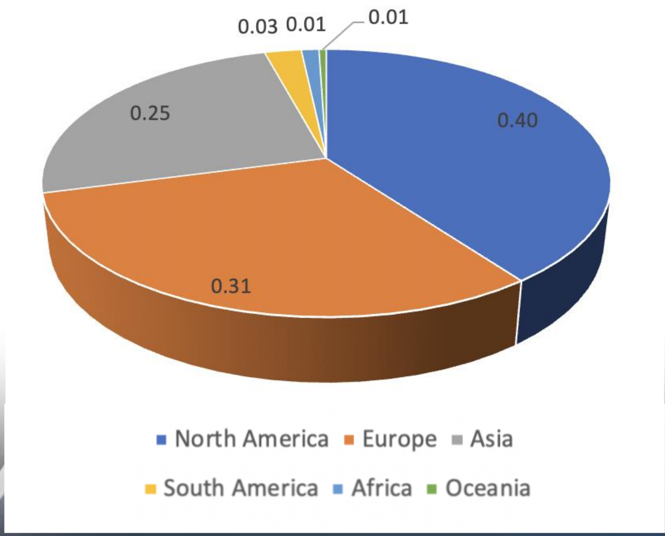
Worldwide Interest in EIC Physics

The EIC Users Group:
EICUG.ORG

Formed 2016 –
- **1282 collaborators,**
- **35 countries,**
- **258 institutions**

as of June 8, 2021.
Strong and Growing International Participation.

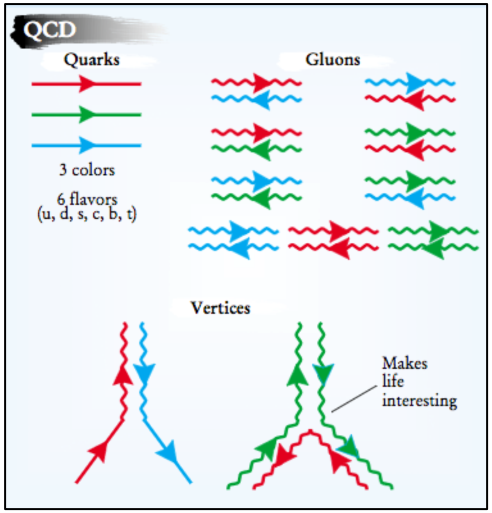


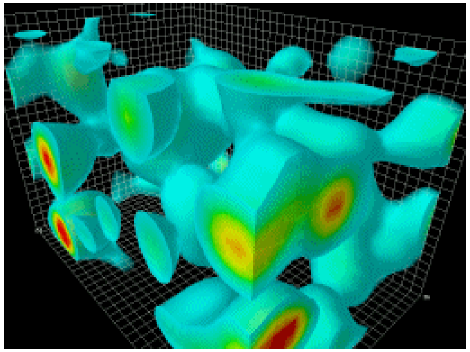


Annual EICUG meeting
2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 Washington, DC
2019 Paris, France
2020 Miami, FL
2021 VUU, VA & UCR, CA
2022 Warsaw, Poland

EIC: 21st Century Laboratory of Emergent Dynamics in QCD

- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% of the proton's momentum, a significant fraction of the nucleon's spin, and are essential for the dynamics of confinement
- Properties of hadrons – composite systems of quarks and gluons – are emergent phenomena and inextricably tied to the properties of the QCD vacuum. Striking examples besides confinement are spontaneous symmetry breaking and anomalies
- The nucleon-nucleon forces emerge from quark-gluon interactions: how this happens remains a mystery

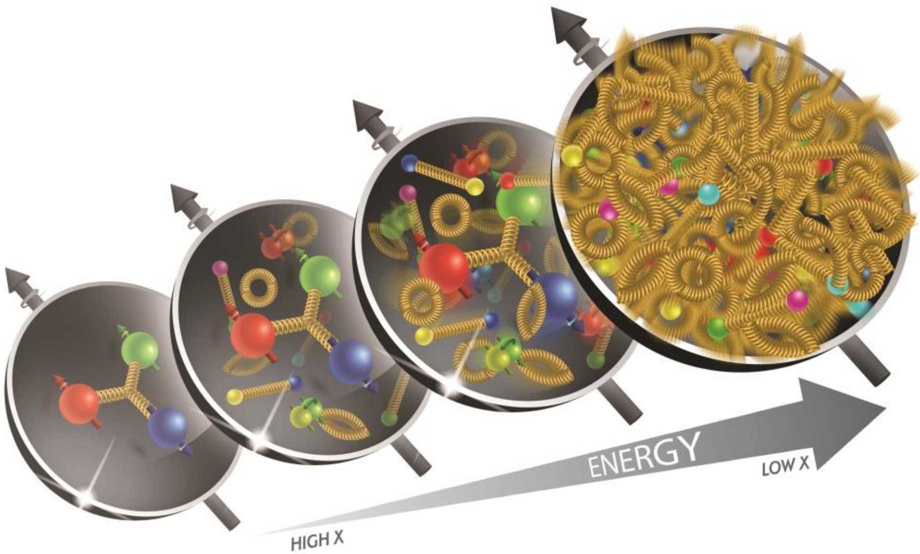


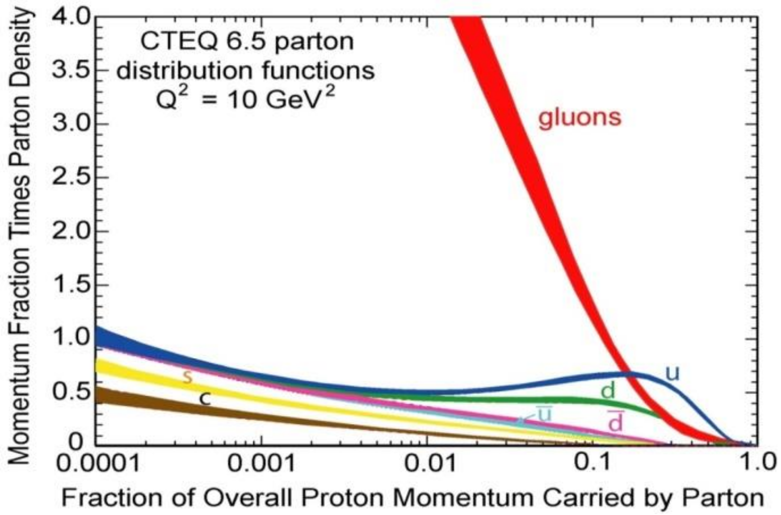


- The goal of the EIC is to provide us with an understanding of the internal structure of the proton and more complex atomic nuclei that is comparable to our knowledge of the electronic structure of atoms, which lies at the heart of modern technologies

QCD Landscape Explored by EIC

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



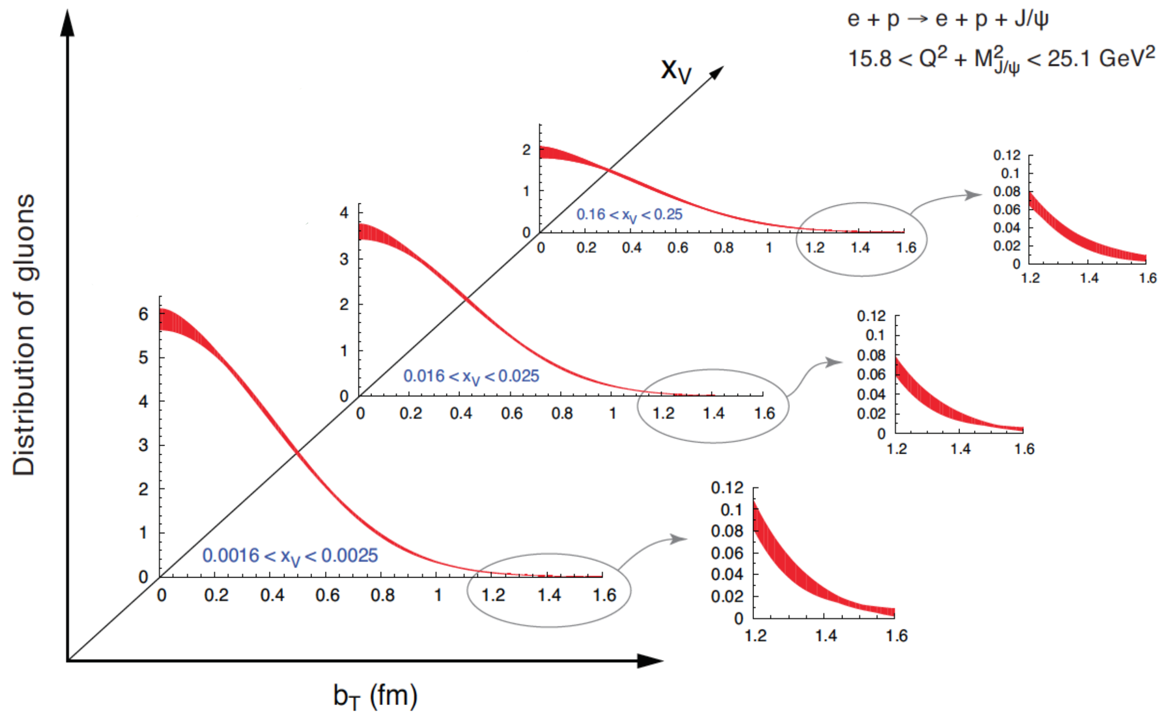


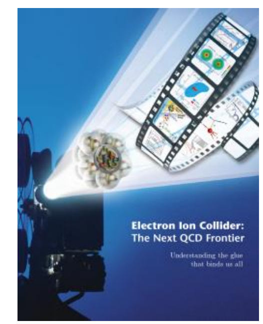
Longitudinal (1D) Momentum Fraction x

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.

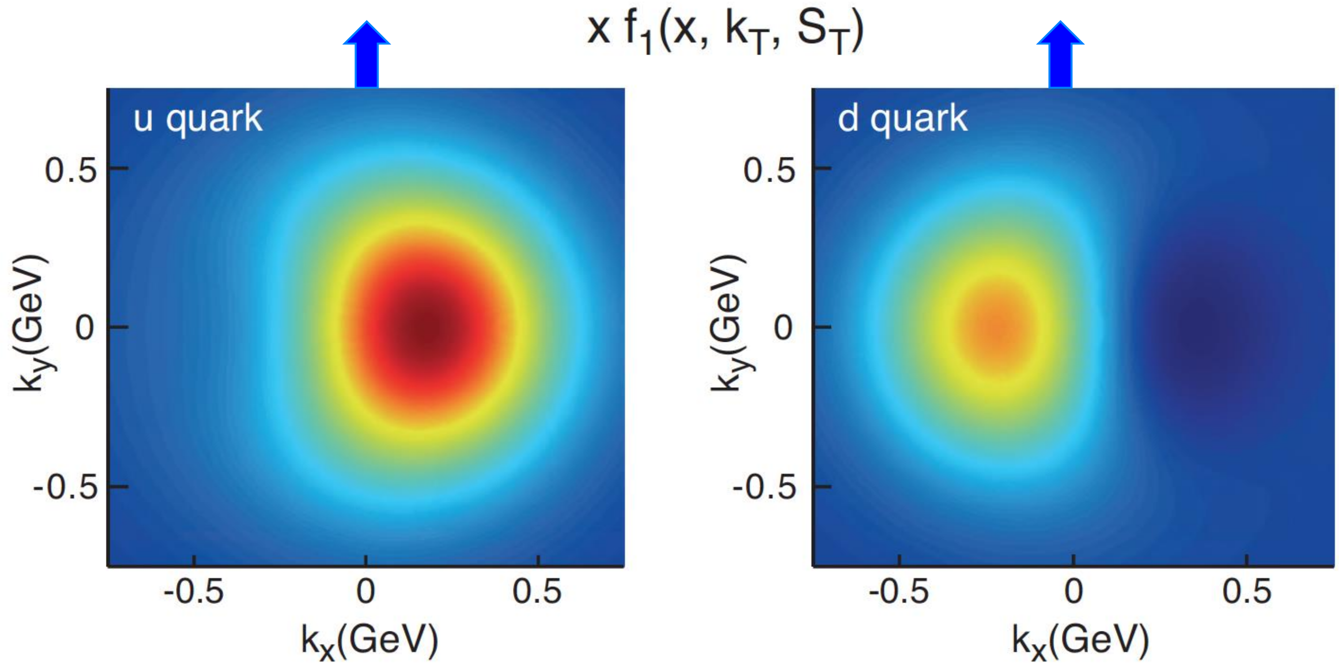
Confined Spatial Correlations: Transverse Spatial Distribution of Gluons

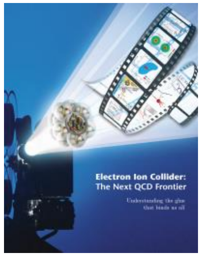




- How are gluons spatially distributed in a proton or a nucleus?
- Is the distribution smooth?
- How does it differ from the charge distribution?
- **First ever tomographic images of ocean of gluons within matter !**

Confined Motion: Transverse Momentum Distributions of Quarks & Gluons



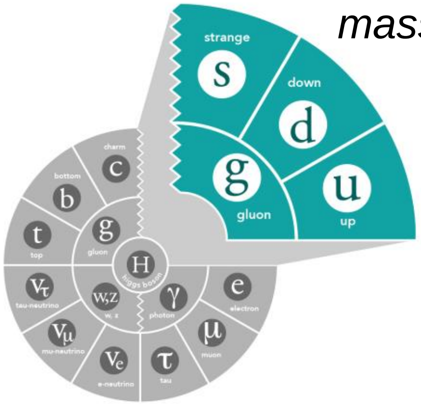


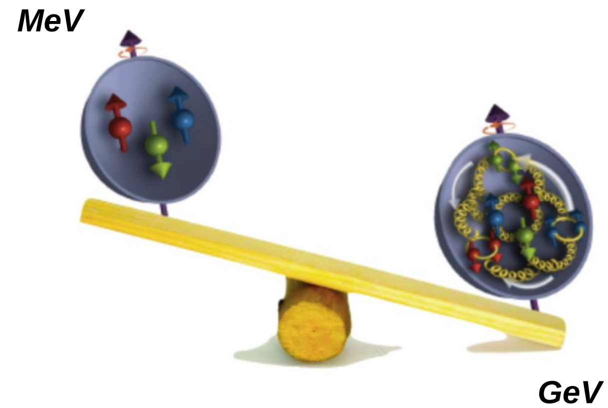
- Spin and the ability to look at transverse momentum together give a powerful new window into QCD
- Transverse Momentum Distributions directly related to orbital motion
- For example, we can explore for the first time **interference in quantum phases due to the color force – impossible with previous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





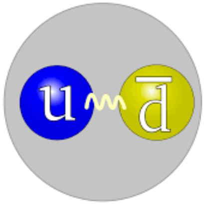
Proton

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

Gluon rise discovered by HERA e-p

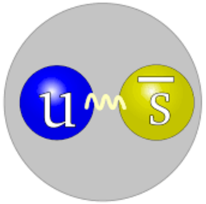
Pion

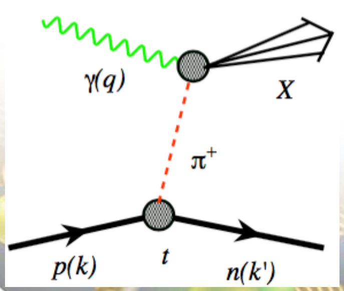
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



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.

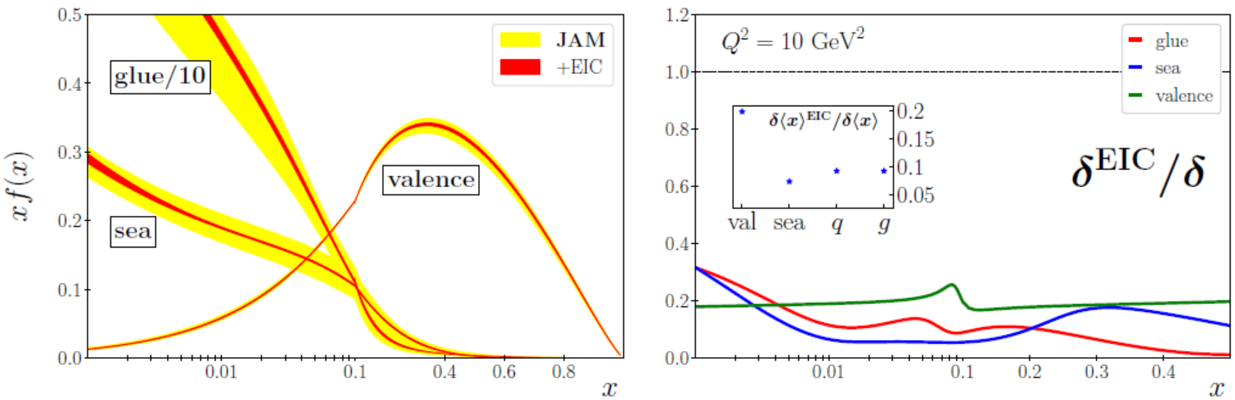
Emergent Mass and Structure Studies at the EIC

- Protons, neutrons, pions and kaons are the main building blocks of nuclear matter

> If we really want to claim we understand hadron structure as relevant for the visible world, we HAVE to understand at least the pion, kaon, proton, neutron (and likely the Lambda) at the same level.

- Paradoxically, the lightest pseudoscalar mesons appear to be the key to the further understanding of the emergent mass and structure mechanisms.
  - These mesons, namely the pion and kaon, are the Nambu-Goldstone boson modes of QCD.
- Unraveling their exact partonic structure and interplay with the Higgs mass mechanism is a common goal of three independent methodologies – phenomenology with continuum QCD based approaches, Lattice QCD, and the global analysis of parton distributions – linked to experimental measurements of hadronic structure.
- The unique role of EIC is its access to pion and kaon structure over a versatile large CM energy range, ~20-140 GeV. With this, the EIC will have the final word on the contributions of gluons in pions and kaons as compared to protons, settle how many gluons persist as viewed with highest resolution, and vastly extend the x and Q^2 range of pion and kaon charts, and meson structure knowledge.

Reduction of Pion 1-D Structure Information by EIC



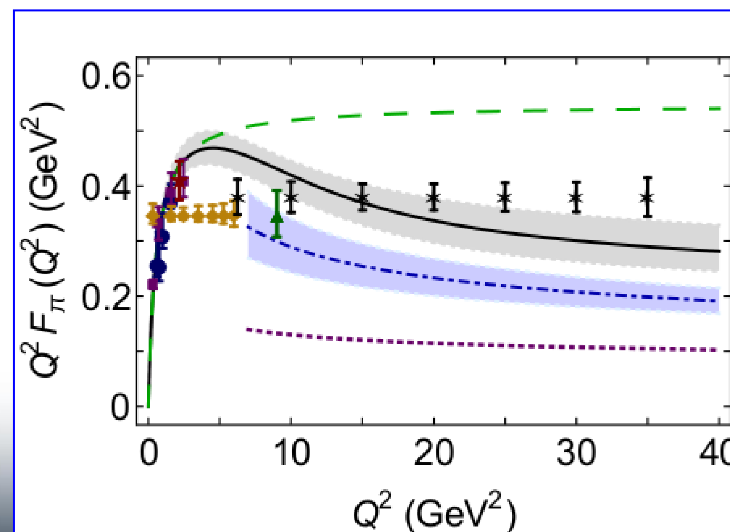
From EIC Yellow Report, P. Barry, W. Melnitchouk, N. Sato et al.

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,

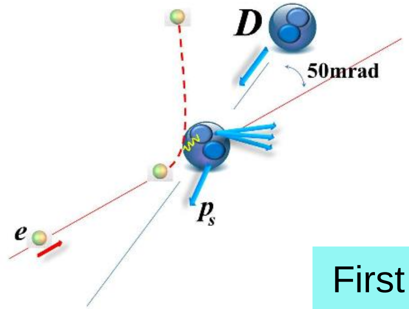
Pion form factor measurement projections at EIC

- 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*



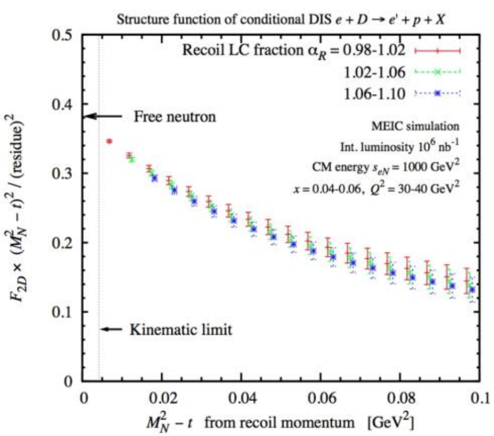
EIC Science: Deuterons and neutron targets



Studies ongoing to enable polarized (vector and tensor) deuteron beams (>80% polarization).

Collider → allows a *precision measurement* of the spectator nucleon.

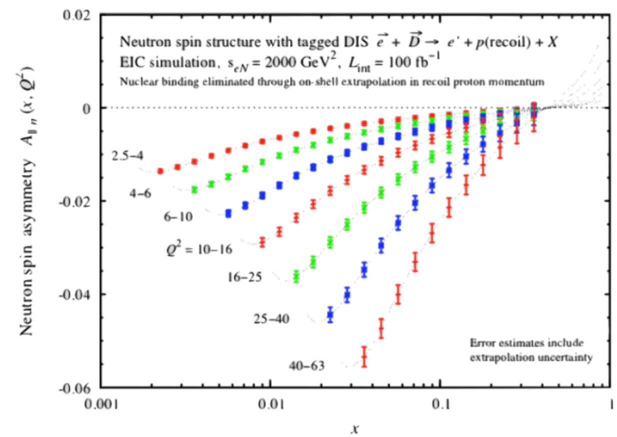
First precision measurement of *polarized* (and unpolarized) neutron is possible at EIC



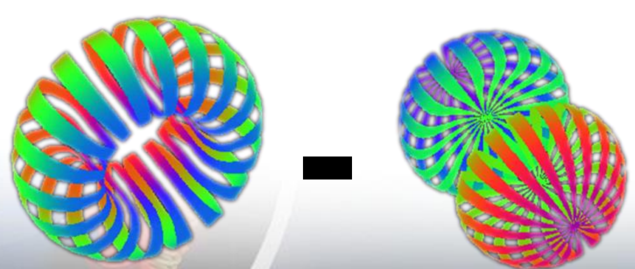
Extrapolation from bound to free neutron under control

F_2^n can be extracted at % level accuracy

Polarized Neutron Structure



Investigate nuclear effects at the level of partons with Tensor Polarization Observables



Polarized Deuteron Structure Function b_1

Are quarks sensitive to the shape of the nucleus?

Similar studies to map out polarized 3He nuclear structure in detail, from both nucleon-meson and parton level point of view

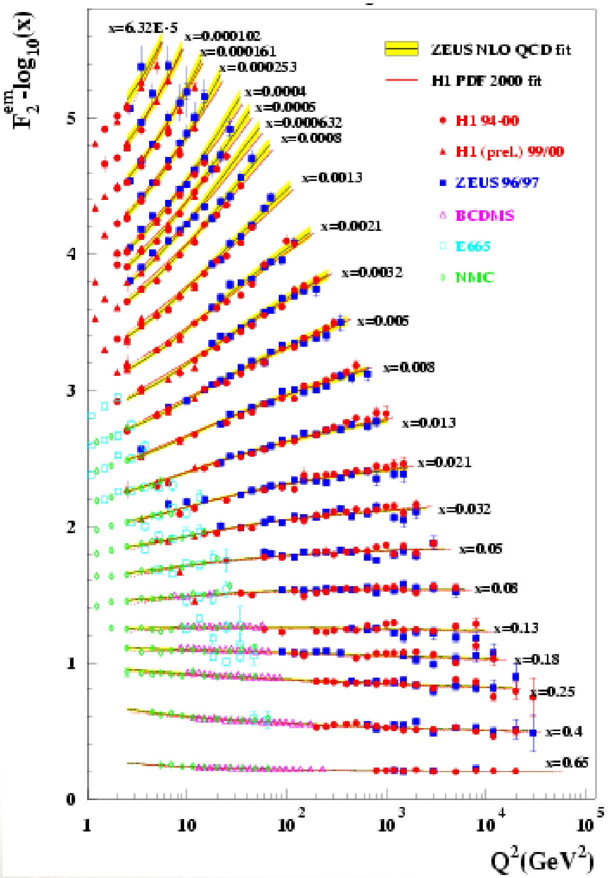
World Data on F_2^p   *World Data on g_1^p*   *World Data on h_1^p*

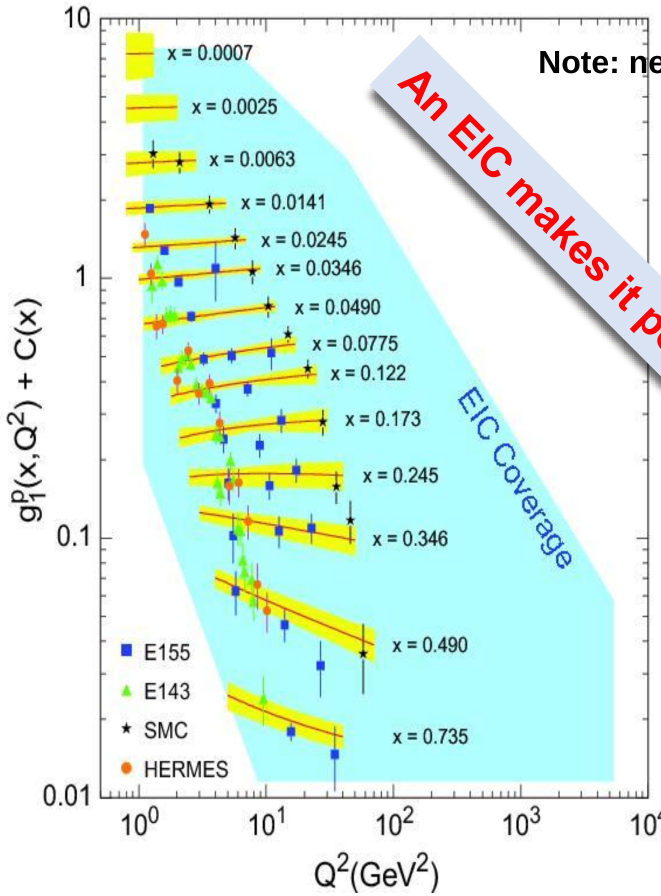
Similar for F_2^n

Similar for g_1^n, g_2^p, g_2^n (and b_1^d)

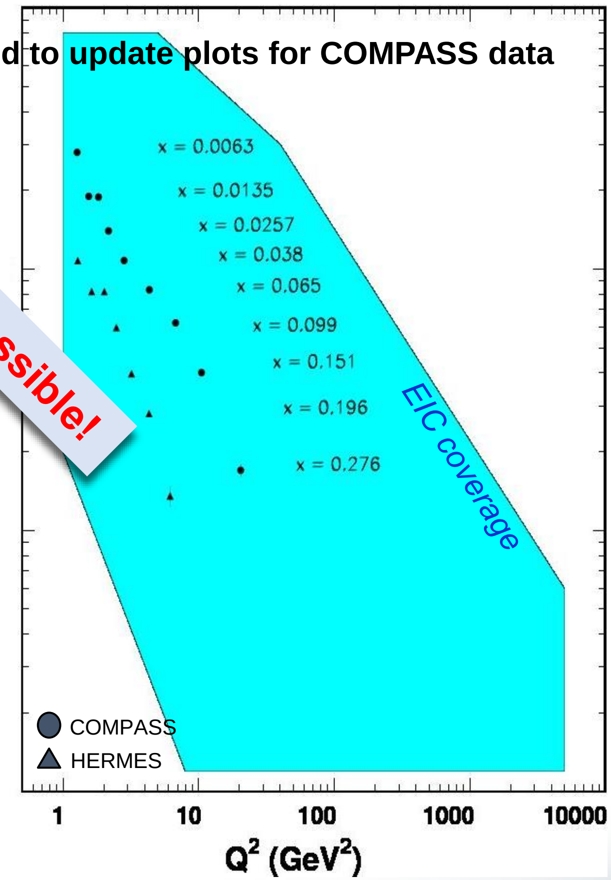
Similar for h_1^n

$F_{UT}^{\sin(\phi_h+\phi_s)}(x,Q^2) + C(x) \propto h_1$





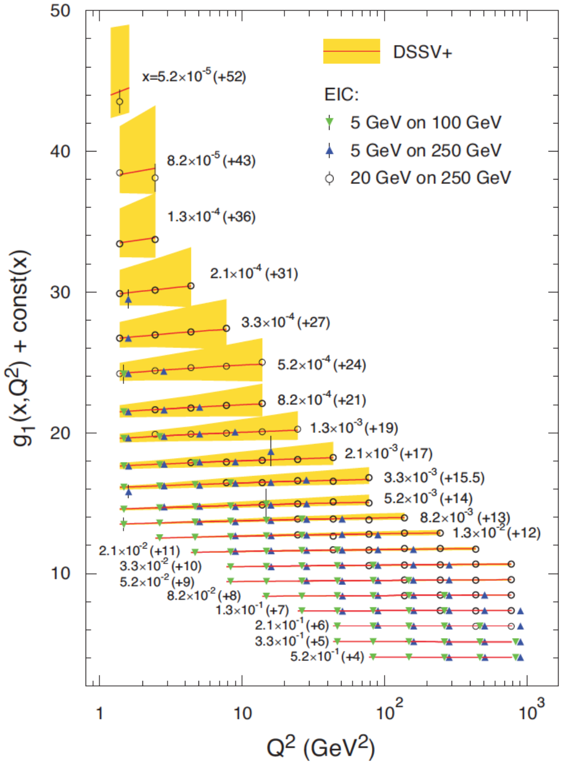
Note: need to update plots for COMPASS data



momentum   **spin**   **transverse spin ~ angular momentum**

EIC will be a real game changer

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 $L_q + L_g$

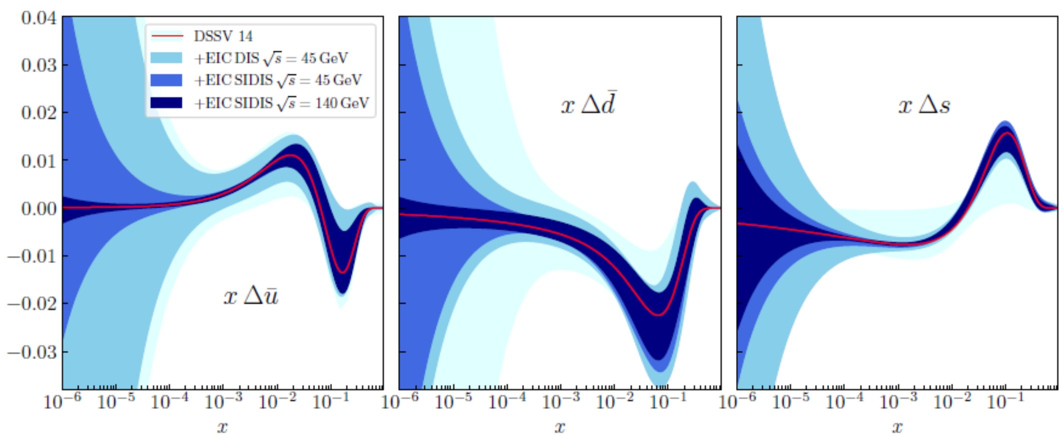


Figure 7.19: Impact of the EIC semi-inclusive measurements on the sea quark helicities $x\Delta\bar{u}(x,Q^2)$, $x\Delta\bar{d}(x,Q^2)$ and $x\Delta s(x,Q^2)$ as a function of x at $Q^2 = 10\,\text{GeV}^2$.

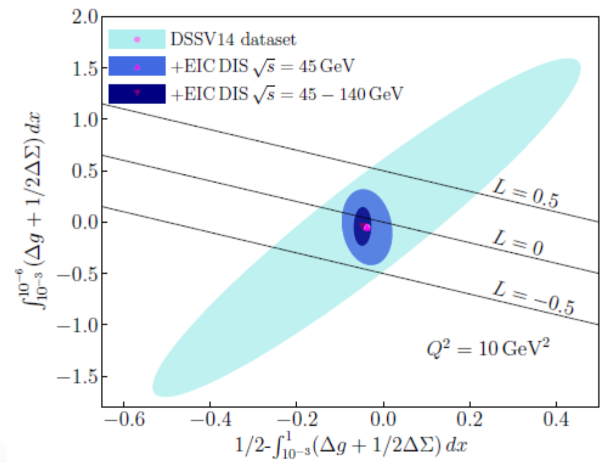
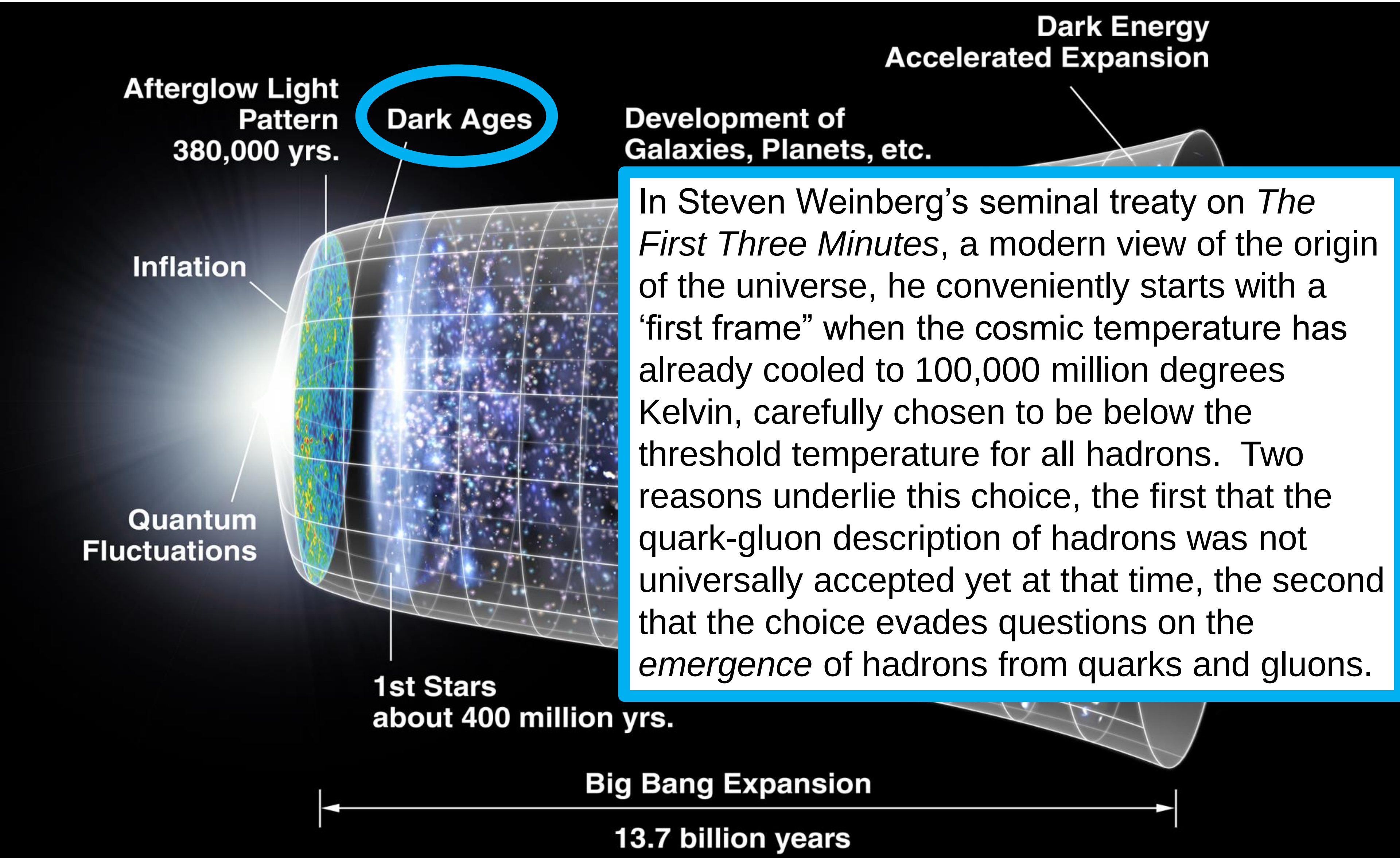


Figure 7.17: Room left for potential orbital angular momentum contributions to the proton spin at $Q^2 = 10\,\text{GeV}^2$, according to present data and future EIC measurements.

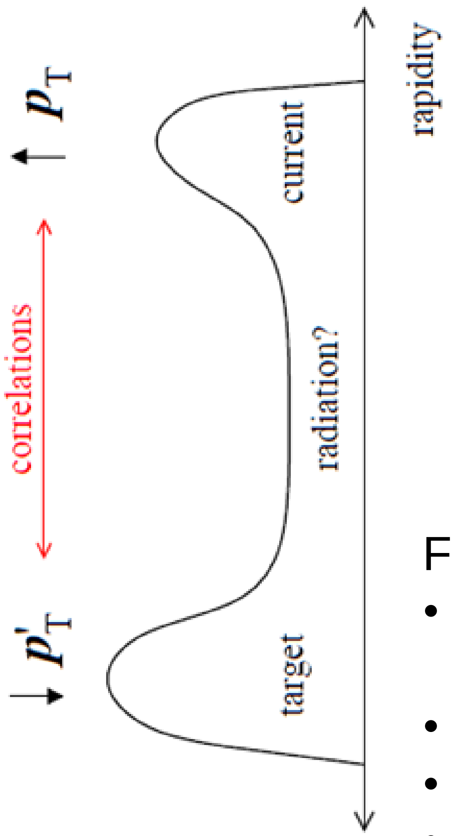
Timeline of the Universe

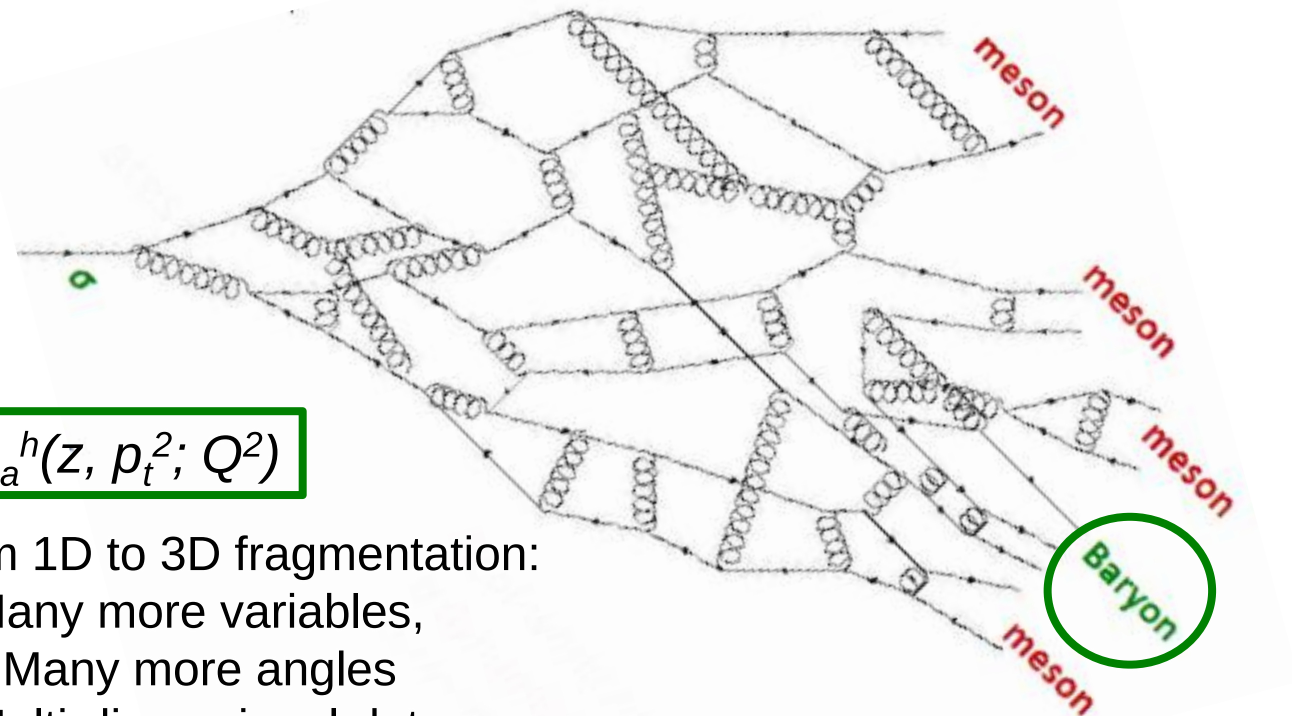


In Steven Weinberg's seminal treaty on *The First Three Minutes*, a modern view of the origin of the universe, he conveniently starts with a 'first frame" when the cosmic temperature has already cooled to 100,000 million degrees Kelvin, carefully chosen to be below the threshold temperature for all hadrons. Two reasons underlie this choice, the first that the quark-gluon description of hadrons was not universally accepted yet at that time, the second that the choice evades questions on the *emergence* of hadrons from quarks and gluons.

Towards a QM Description of the Final State

Balancing the transverse momentum (and spin) – candles of space-time





$D_a^h(z, p_t^2; Q^2)$

From 1D to 3D fragmentation:

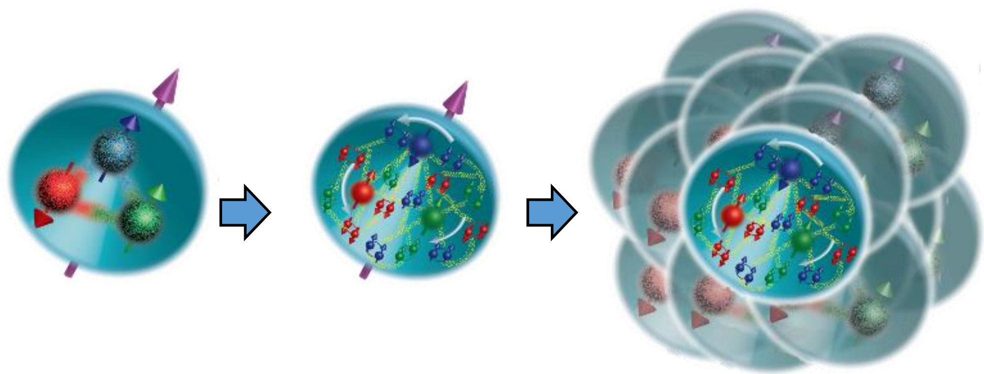
- Many more variables,
  Many more angles
- Multi-dimensional data
- Fine binnings
- Many spin correlations

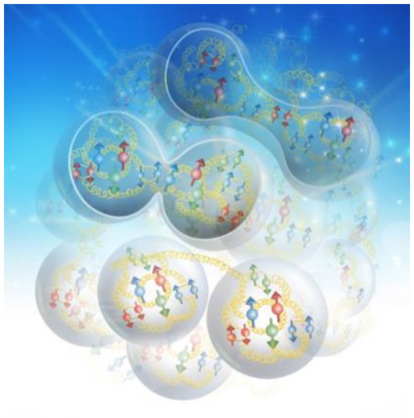
Understanding of the 3D structure of fragmentation into a hadron requires studies of transverse momentum, spin and hadron species dependence

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

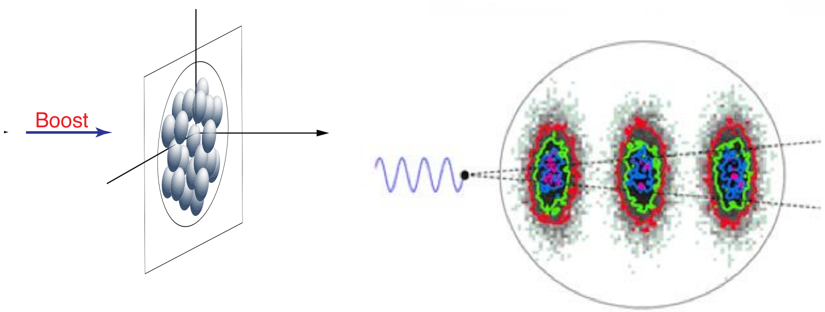
The EIC will, for the first time, provide a complete view of the nucleus:

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

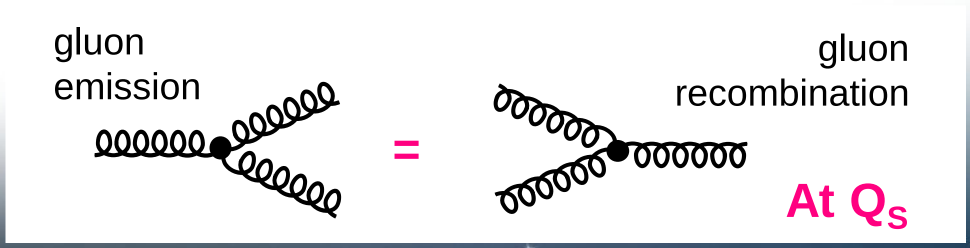


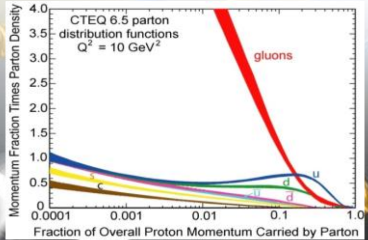


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

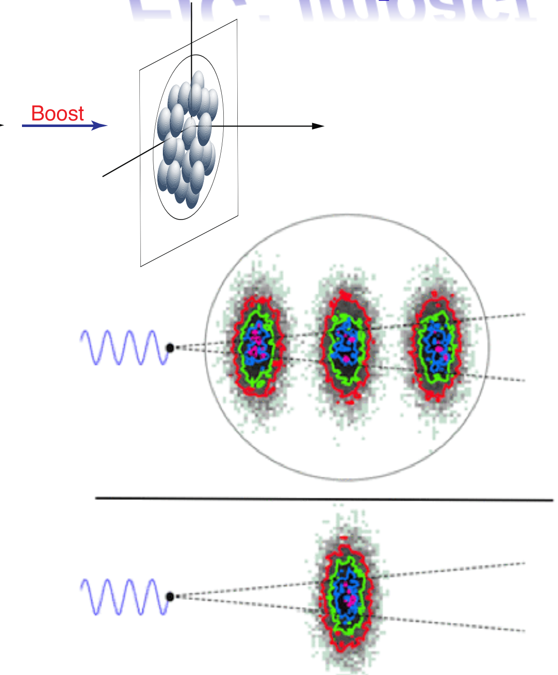


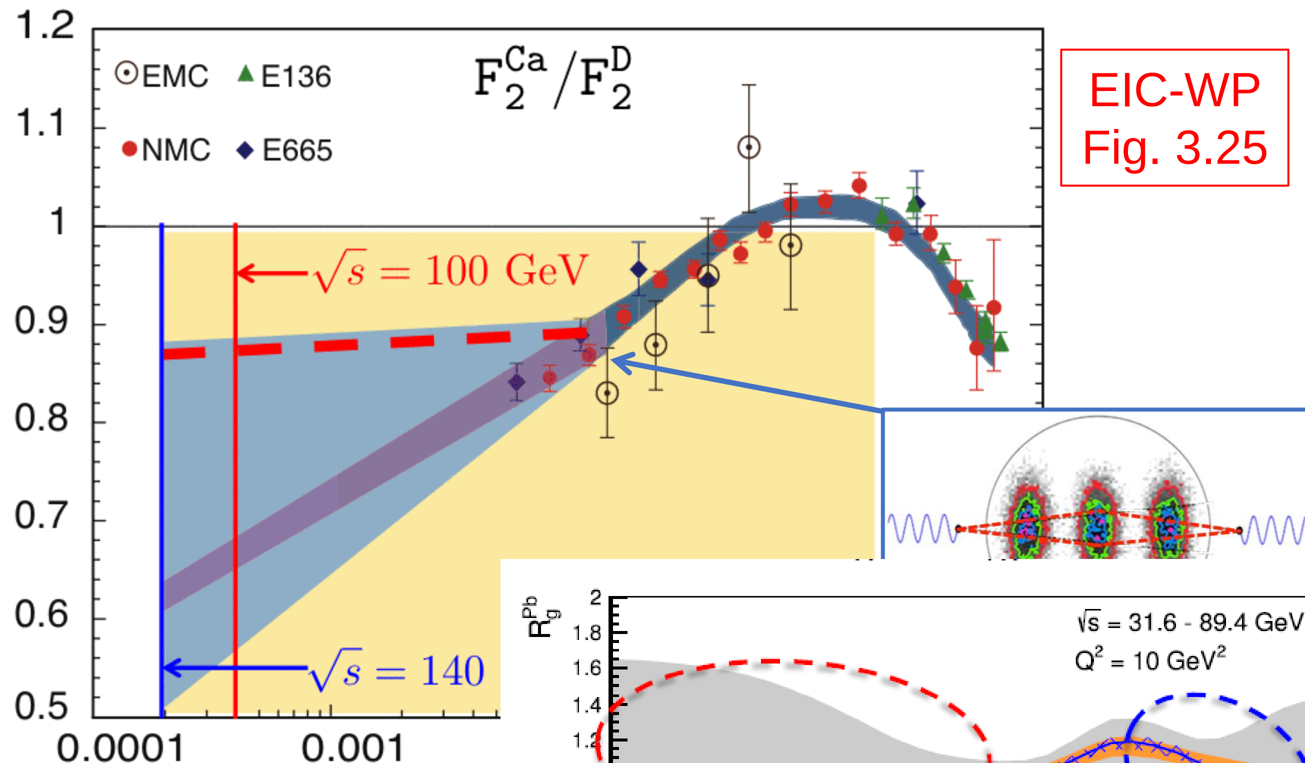
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclear matter?



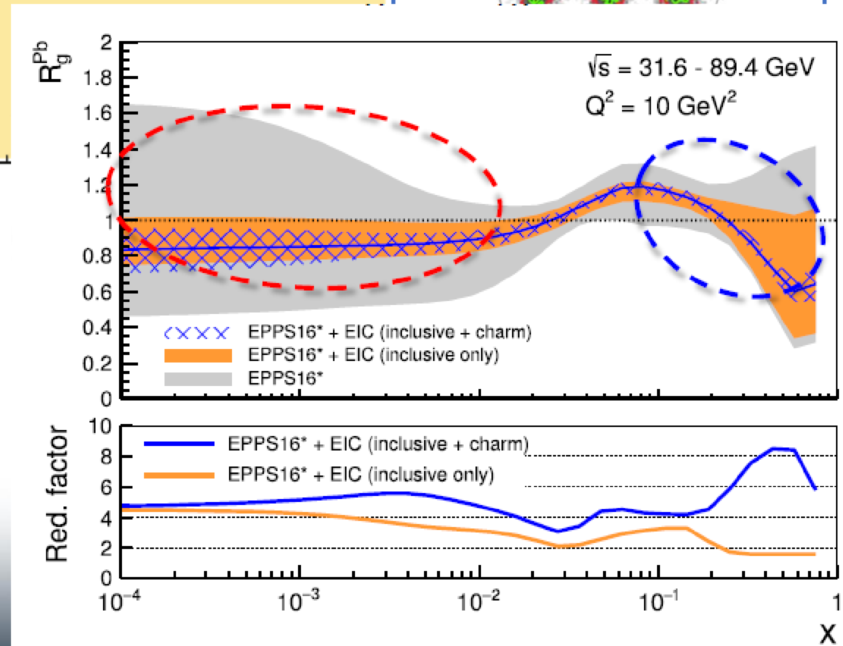


EIC: impact on the knowledge of 1D Nuclear PDFs





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

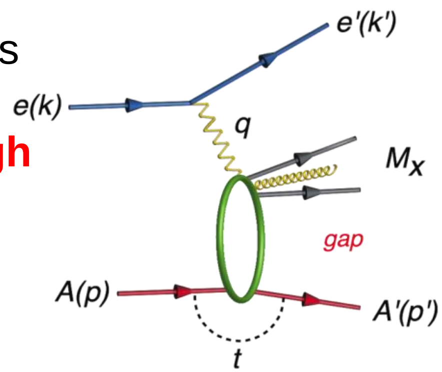
Diffraction for the 21st Century

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

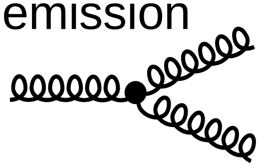
HERA surprise: A 7 TeV equivalent electron bombarding the proton … but nothing happens to the proton in 10-15% of cases

Diffractive event

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

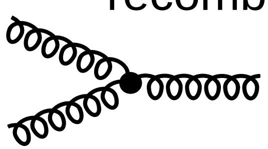


gluon emission



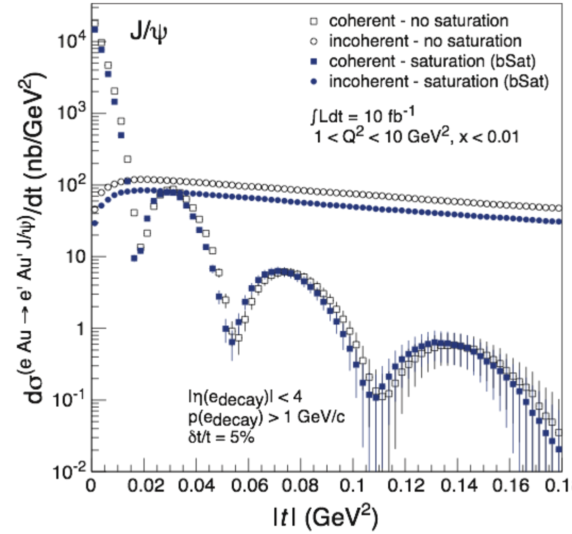
=

gluon recombination



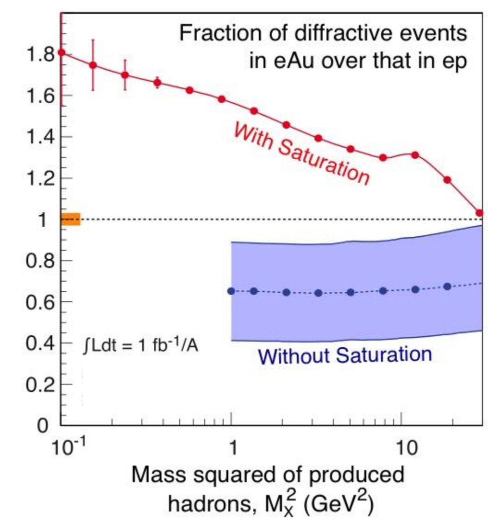
At Q_S

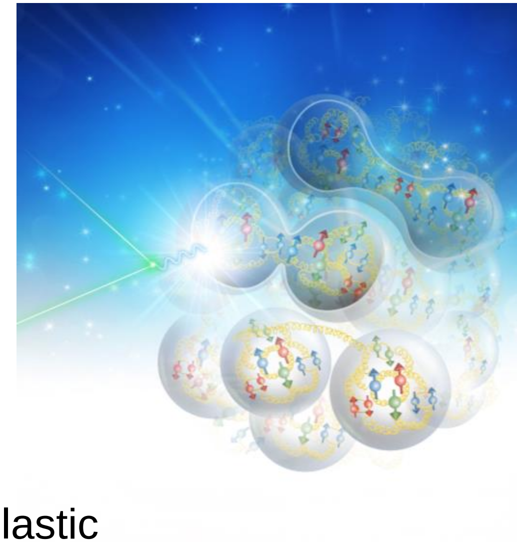
Extracting the gluon distribution $\rho(b_T)$ of nuclei via Fourier transformation of $d\sigma/dt$ in diffractive J/ψ production



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

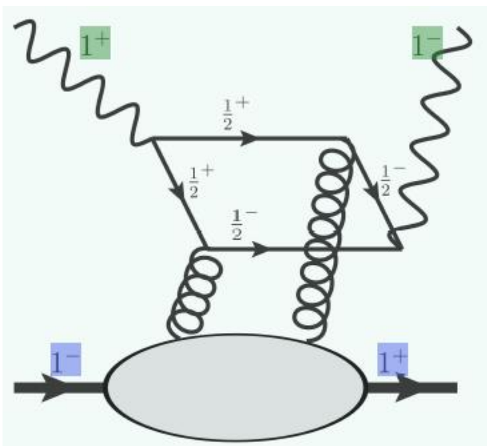




Exotic Glue in Nuclei =

- gluons **not** associated with individual nucleons in nucleus
- operator in nucleon = 0 & operator in nuclei ≠ 0

Targets with J ≥ 1 have leading twist gluon contribution
$\Delta(x,Q^2)$: double helicity flip (Jaffe and Manohar, 1989)
Changes both photon and target helicity by two units…



$$\Delta(x,Q^2) = A_{+-,-+}$$

Measurable in unpolarized Deep Inelastic Scattering with a **transversely polarized J ≥ 1 target like the deuteron** as azimuthal variation.

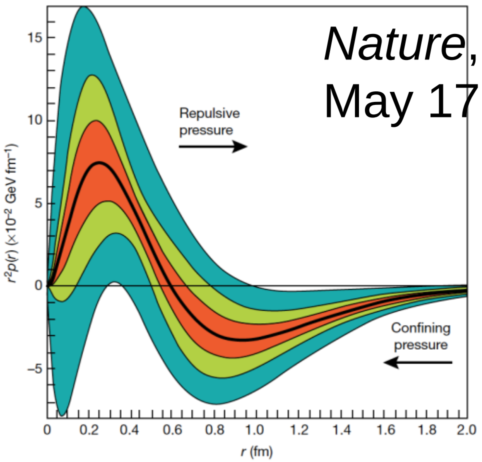
Parton model interpretation:
$\Delta(x,Q^2)$ informs how much more momentum of a transversely polarized particle is carried by a gluon with spin aligned rather than perpendicular to it in the transverse plane.

Shanahan, Detmold, et al.

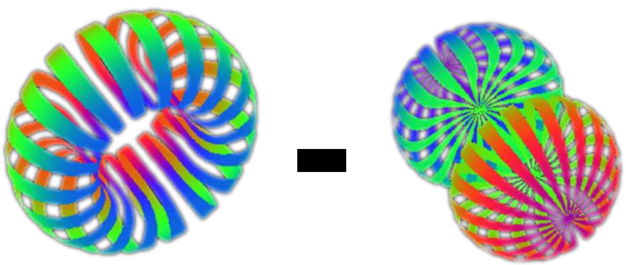
LQCD calculation: gluon transversity distribution in the deuteron, m_π = 800 MeV
→ **First evidence for non-nucleonic gluon contributions to nuclear structure**

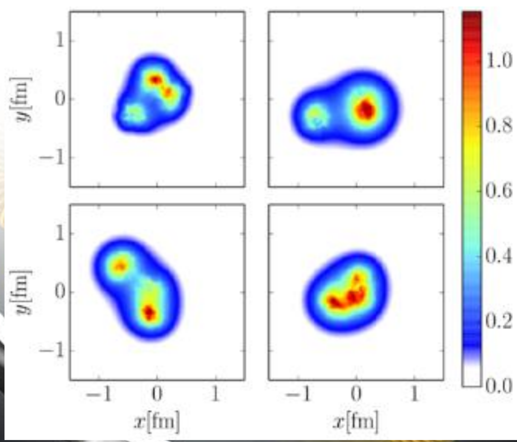
Expected soon: results at m_π = 300 MeV and at the physical pion mass!

New Avenues



Nature, **557**, May 17, 2018





- **Pressure in the Proton**
  - First determination using DVCS (Deeply Virtual Compton Scattering) data
  - Interior pressure in proton is > pressure inside a neutron star! ***Who knew that!***
  - Lattice calculation motivates determination of gluon GPDs at EIC

- **Polarized Deuteron Structure**
  - Inclusive Deep Inelastic Scattering on a Tensor-Polarized Deuteron Beam
  - Map the Structure Function b1
  - Are quarks sensitive to the doughnut or dumbbell shape of the nucleus?

- **Hot Spots in the Nucleus**
  - Simulated proton density fluctuations $x = 10^{-3}$
  - Accessible with 3D tomography
  - Responsible for ridge behavior found in Heavy-Ion reactions at high energies?

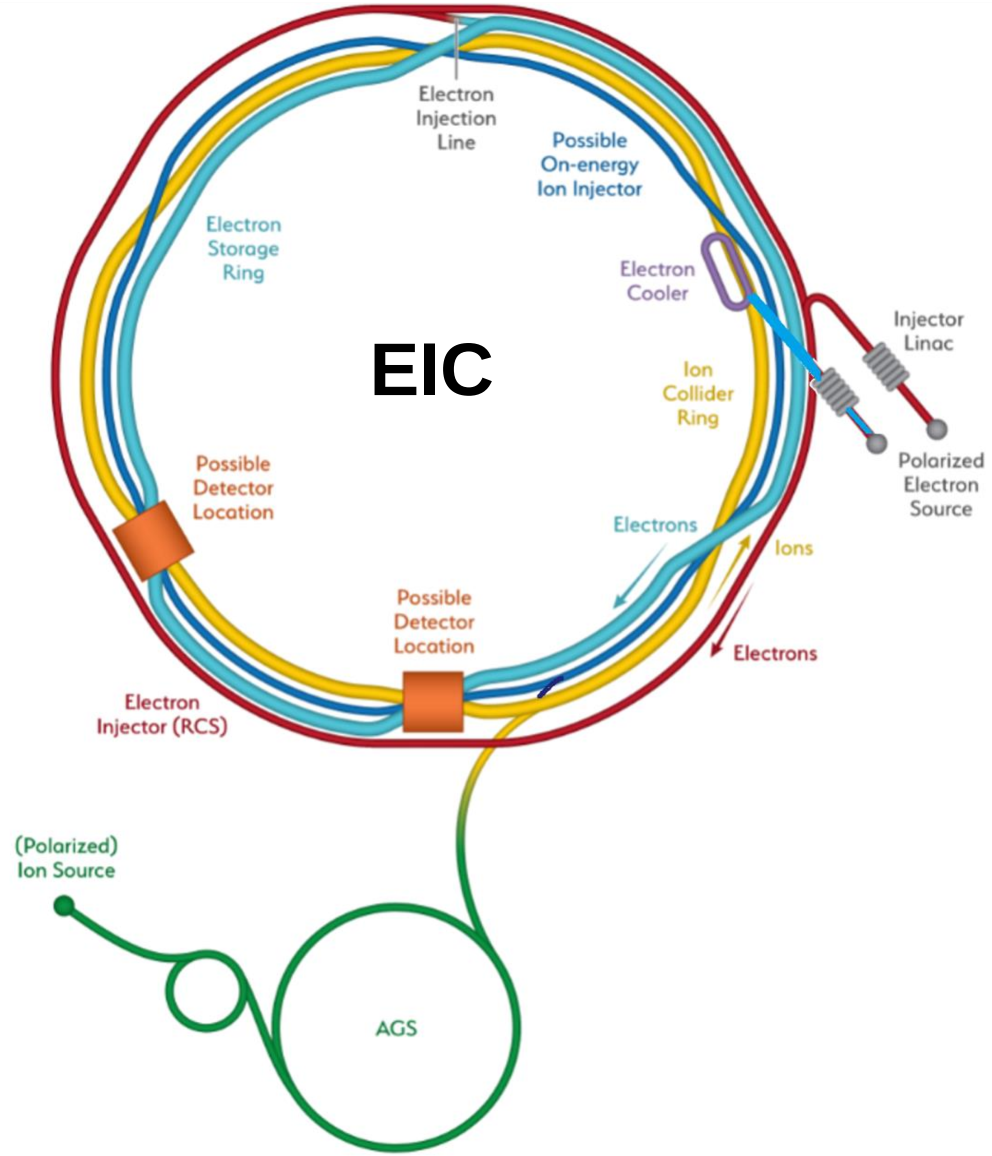
EIC Recent History

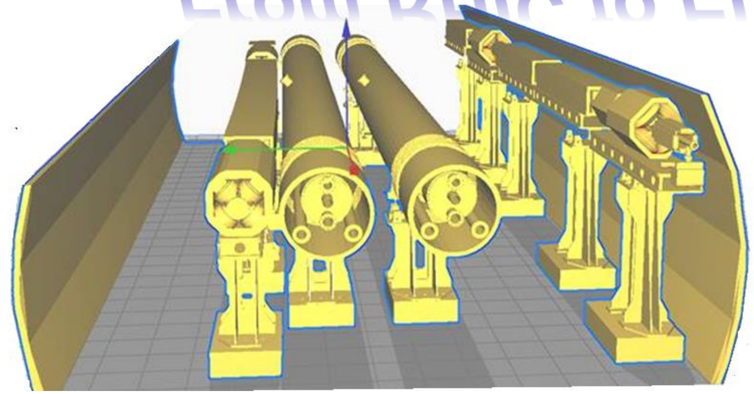
Event	Date
DOE Mission Need Statement Approved	January 22, 2019
DOE Independent Cost Review	July 2019
DOE Electron Ion Collider Site Assessment	October 2019
Critical Decision – 0 (CD-0) Approved	December 19, 2019
DOE Site Selection Announced	**January 9, 2020**
BNL TJNAF Partnership Agreement	May 7,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

* DOE Project Management Risk Committee (PMRC) blessed CD-1 – June 1, 2021
DOE CD-1 Energy Systems Acquisition Advisory Board (ESAAB) meeting – June 28

Electron-Ion Collider

From RHIC to EIC





The strong hadron cooling facility completes the facility

- Hadron Storage Ring (yellow)
- Electron Storage Ring (light blue)
- Electron Injector Synchrotron (red)
- Possible on-energy Hadron injector ring (dark blue)
- Hadron injector complex (green)

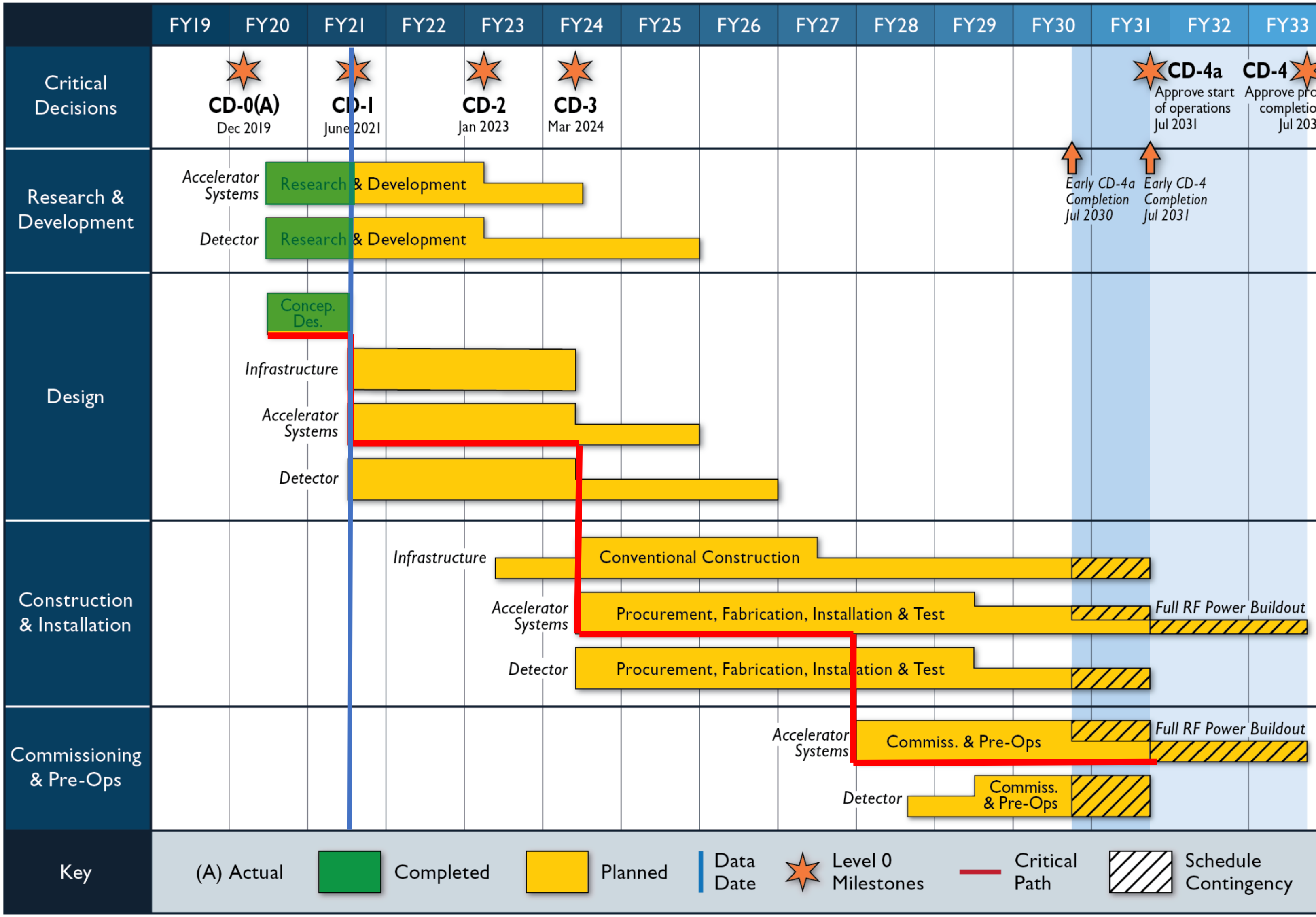
EIC Design per NSAC and NAS Requirements

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

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

Schedule

EIC Total Project Cost of order 2B$



Detector Planning

- The **EIC facility is capable of supporting a science program that includes two detectors and two interaction regions**.

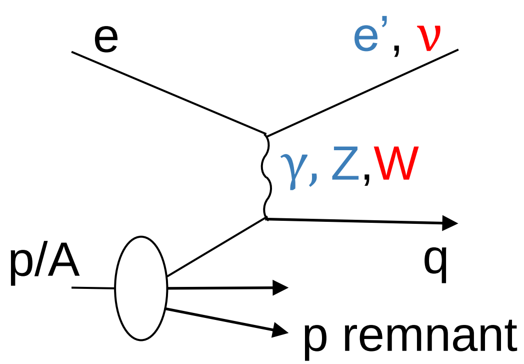
- The DOE-NP supported **EIC Project includes one detector and one Interaction Region** in the reference costing.
  - The reference cost for the detector (~$300M) assumes in-kind contributions (non-DOE or reused equipment) of order $100M
    - This corresponds to a rough presumed 70%-30% split of US project and in-kind contributions (international commitments or reuse of equipment)
    - This assumption seems valid based on assessment of a recent call for Expression of Interest.
    - In the cost book, this is reflected by having always two columns, for in-project and assumed contributions based on best estimate to date, both for materials and for labor.

  - Yellow Report Initiative spearheaded by the EIC User Group (http://www.eicug.org/web/content/yellow-report-initiative)
    - *The purpose of the Yellow Report Initiative is to advance the state and detail of the documented physics studies (White Paper, INT program proceedings) and detector concepts (Detector and R&D Handbook) in preparation for the realization of the EIC. The effort aims to provide the basis for further development of concepts for experimental equipment best suited for science needs, including complementarity of two detectors towards future Technical Design Reports (TDRs).*

EIC User Group Driven Yellow Report Activity

- Detector requirements and design as driven by EIC Physics program defined by Community
- EICUG Yellow Report activity http://www.eicug.org/web/content/yellow-report-initiative
- Provides critical input for detector proposals – handoff between Physics & Detector Working Groups in "**interactive detector matrix**": Collects physics requirements "real time", lists all technologies for a given region, and links to studies that established the numbers
- Different Physics (5) and Detector (8) Working Groups
- Timeline:
  - December 2019 Kick-off meeting at MIT
  - March 2020 1st meeting at Temple
  - May 2020 2nd meeting at Pavia/Italy
  - July 15-17, 2020 remote EIC-UG Meeting (at Miami)
  - September 2020 3rd meeting at CUA
  - November 2020 4th meeting at UCB/LBL
  - January 12, 2021 completion Yellow Report
    → sent to external reviewers
  - February 2021 Yellow Report volumes on arXiv:2103.05419

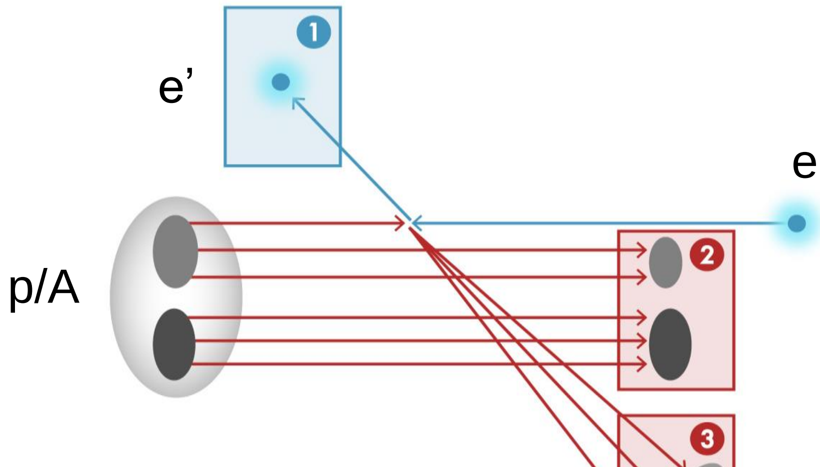
Detector Challenge of the EIC



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)

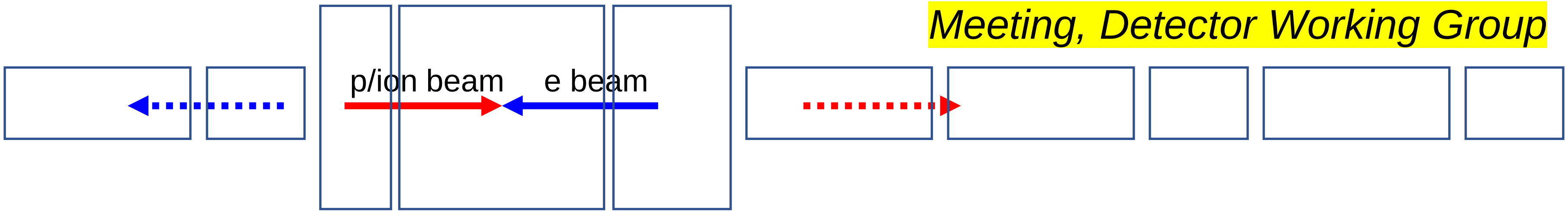
Ion remnant is particularly challenging

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

Cartoon/Model of the Extended Detector and IR

- EIC physics covers the entire region (backward, central, forward)
- Many EIC science processes rely on excellent and fully integrated forward detection scheme

Adapted from 2nd Yellow Report Meeting, Detector Working Group



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

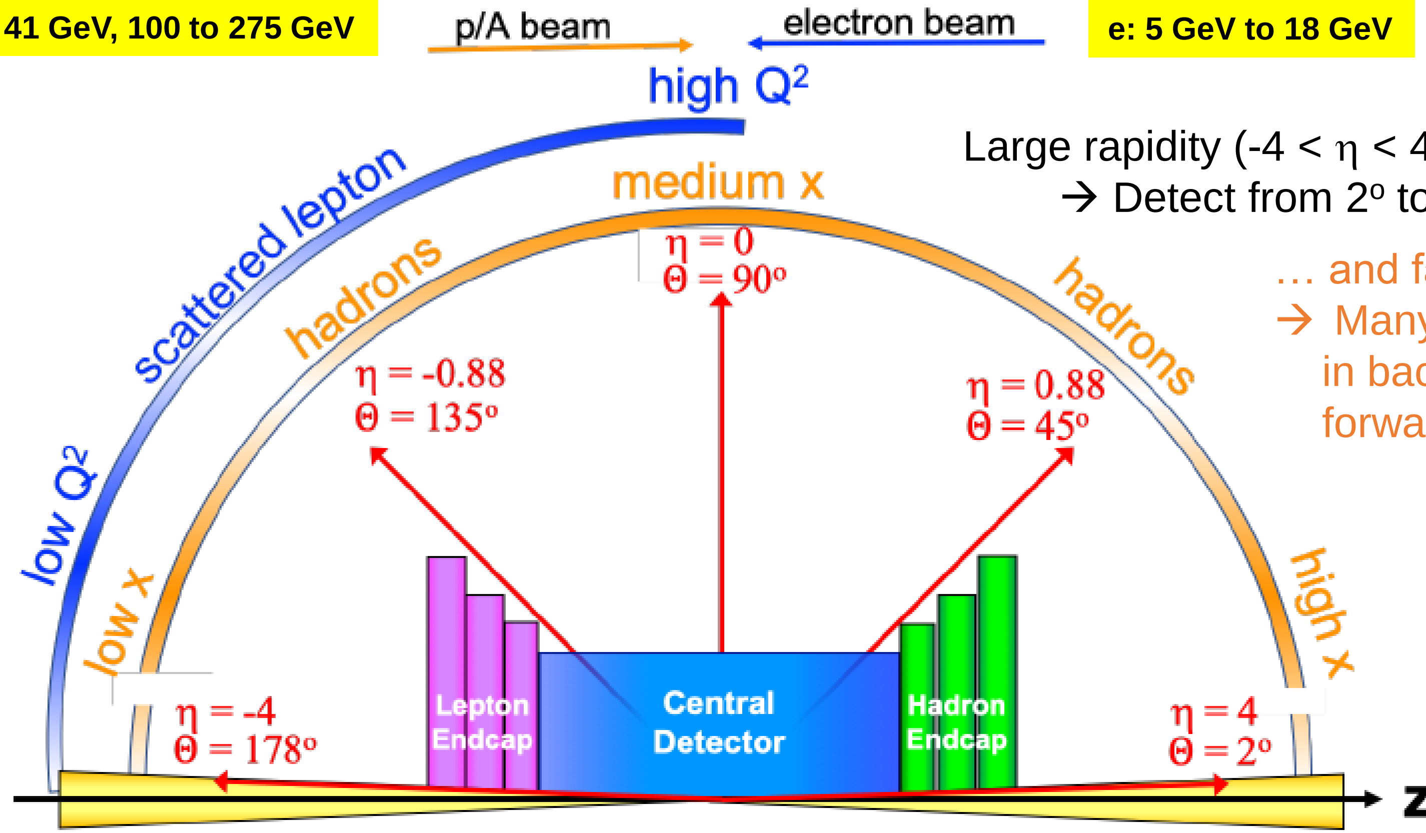
physics examples

detector examples

Detector Nomenclature

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV



Large rapidity ($-4 < \eta < 4$) coverage
→ Detect from 2^o to 178^o…

… and far beyond
→ Many detectors in backward + forward region

low Q^2 scattered electrons
Bethe-Heitler photons
for luminosity

Main detector =
Barrel +
Lepton Endcap +
Hadron Endcap

particles from nuclear breakup, i.e. neutrons, scattered protons, and ions from diffractive reactions

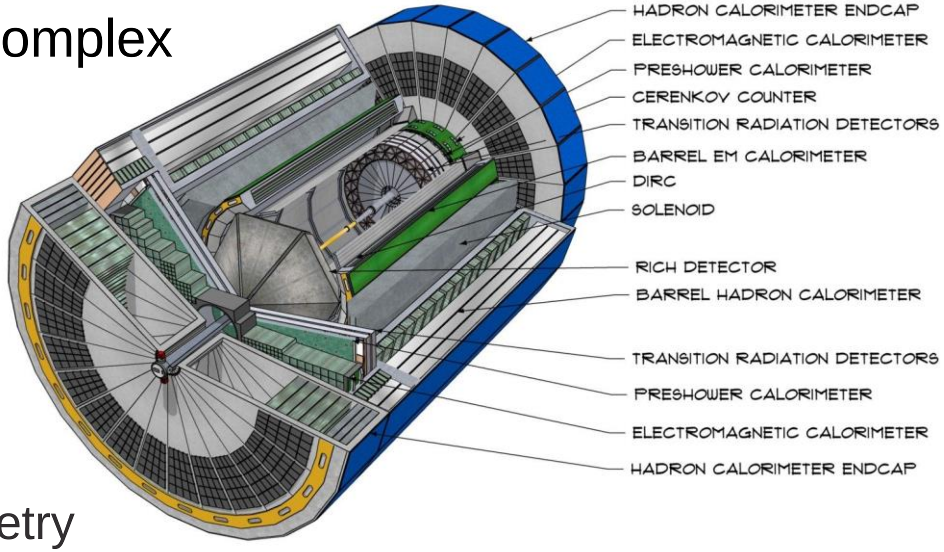
Backward

Forward

Endcaps critical because of largely asymmetric beam energies (with different beams).
Similar large impact on IR/accelerator.

EIC Experimental Equipment Requirements

Any general purpose EIC Detector is complex



Overall detector requirements:

- Large rapidity ($-4 < \eta < 4$) coverage; and far beyond in especially far-forward detector regions
- 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/π separation for electron-scattering
- 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 monitors, electron & hadron Polarimetry

Integration into Interaction Region is critical

Highly integrated detector system

Highly Integrated detector system: ~75m

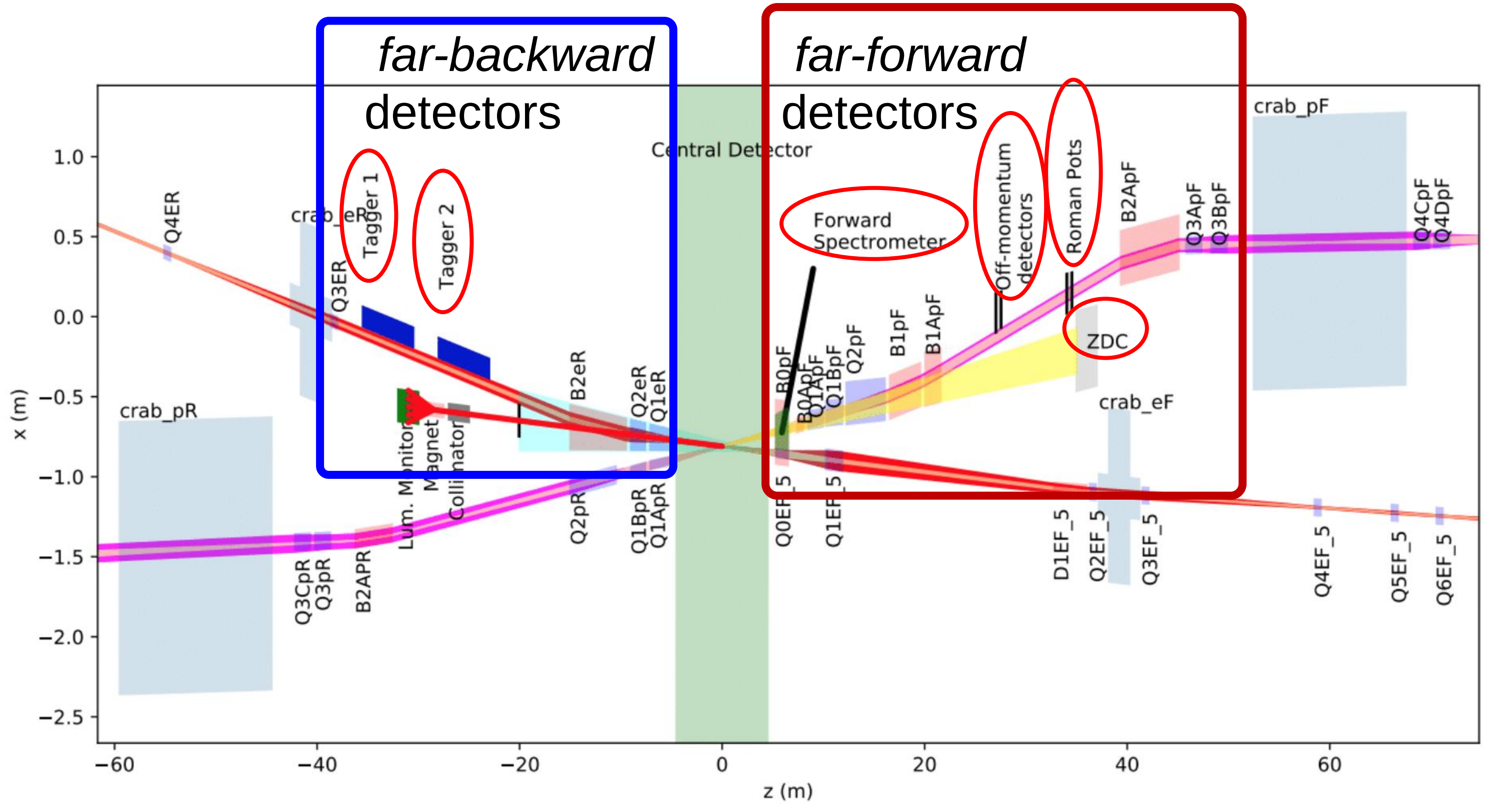
1. Central detector: ~10m
2. Backward electron detection: ~35m
3. Forward hadron spectrometer: ~40m

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

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

6.10.11 IR integration and ancillary detectors

Luminosity detector scope in 6.06.03 (as are electron and hadron polarimetry)



Experimental Program Preparation

- Call for Collaboration Proposals for Detectors launched after extensively soliciting input from DOE and EIC User community
- Jointly developed between EIC Project, JLab and BNL
- Appeared in the same week as the community Yellow Report (https://arxiv.org/abs/2103.05419)!

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

EICUG Activities towards Collaboration Formation

EIC user community efforts on detector collaboration formation have started:

- The ECCE consortium had its first organizational meeting February 12th. ECCE is investigating a detector based on an existing 1.5T solenoid in both EIC interaction regions, ready for the beginning of EIC accelerator operation: https://www.ecce-eic.org

- ATHENA had its organizational meeting March 12-13. ATHENA is investigating a new EIC experiment at IP6 based on a 3 T magnet and the Yellow Report Reference Detector: https://sites.temple.edu/eicatip6/

- CORE had a "Kick-Off" Workshop on March 29-30 for an open collaboration for an EIC Detector proposal based on a new 2-4 T compact magnet at IP8: https://userweb.jlab.org/~hyde/EIC-CORE/

There is in addition a 2nd IR EIC Workshop series with a focus on Detector and IR complementarity (https://indico.bnl.gov/event/10677/timetable/) – First workshop had 400+ attendants, 2nd and 3rd workshop planned. They plan to submit a (draft) White Paper to the Proposal Detector Advisory Panel.

Proto-Collaborations at a Snapshot

- ECCE
  - Contacts: Or Hen (MIT), Tanja Horn (CUA), John Lajoie (Iowa State)
  - ~80 collaborating institutions
  - Includes institutions from Armenia, Chile, China, Czech, France/IN2P3, Germany, Israel, Japan, Korea, Russia, Taiwan, UK

- ATHENA
  - Coordinating Committee: Abhay Deshpande (BNL/SBU), Silvia Dalla Torre (INFN Trieste), Olga Evdokimov (UIC), Yulia Furletova (JLab), Barbara Jacak (LBL/UCB), Alexander Kiselev (BNL), Franck Sabatie (Saclay), Bernd Surrow (Temple)
  - ~100 collaborating institutions
  - Includes institutions from Canada, China, Czech, France, Italy, India, Poland, Rumania, UK

- CORE
  - Contacts: Charles Hyde (ODU) and Pawel Nadel-Turonski (SBU)
  - Smaller-scale effort, ~20-30 active collaborators

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 & 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 **world-wide interest** in collaborating on the EIC
- Accelerator scientists at RHIC and JLab, in collaboration with many outside interested accelerator groups, will provide the **intellectual and technical leadership to realize the EIC**, a frontier accelerator facility.
- **Call for EIC detector proposals** released in **March 2021, deadline December 1.**

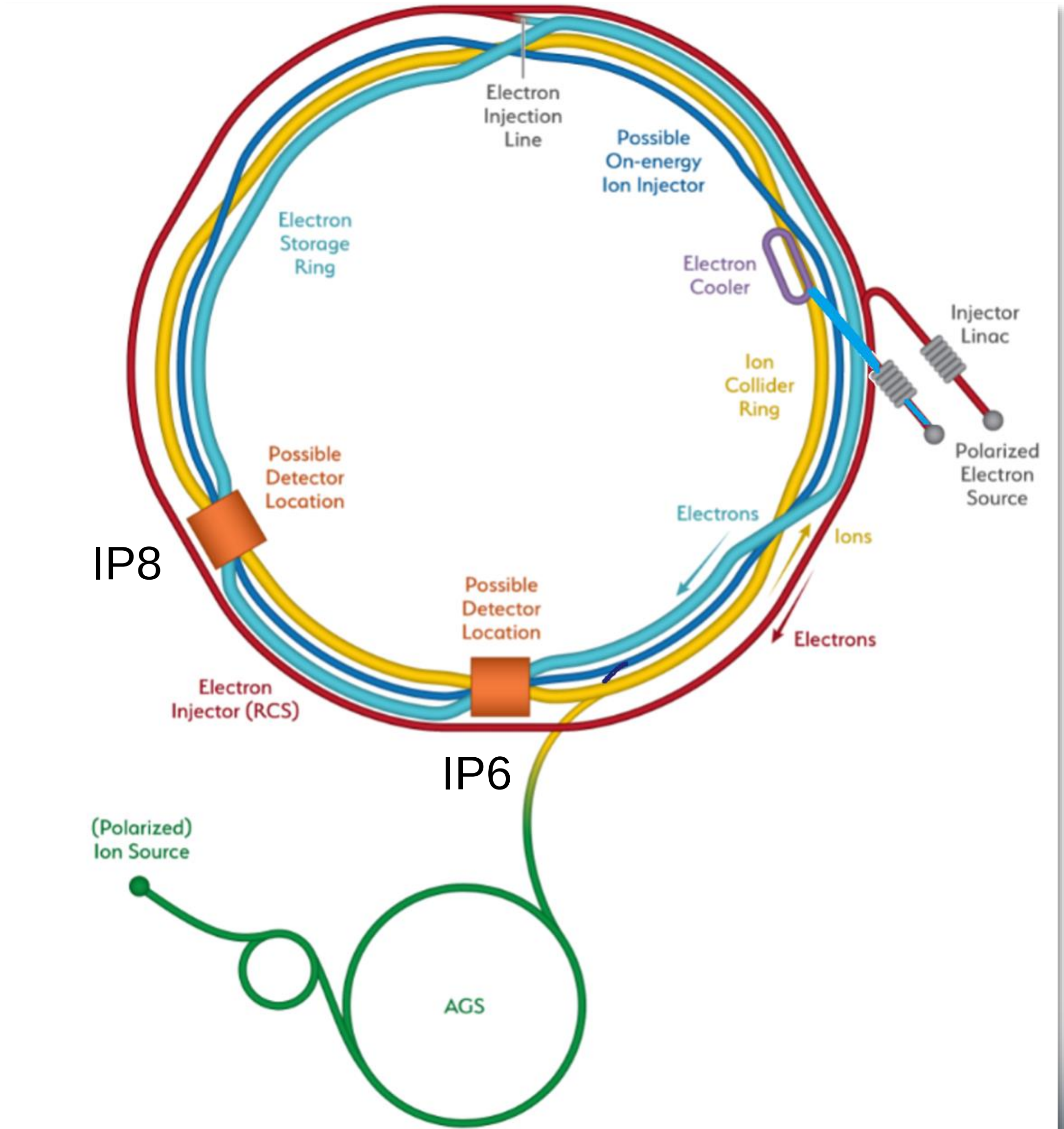
The future of QCD-based nuclear science demands an Electron Ion Collider (and the wind seems in our sails!)

Backup

International Engagement

Country	Interest and Important Facts
Canada	Establish EIC in ongoing LRP; Interest in Compton Polarimetry, Electromagnetic Calorimetry and Software
China	University groups also members in STAR; Interest in Electromagnetic Calorimetry and Silicon tracker
Czech	Working with funding agency; Interested in eECal and Silicon
India	Consortium is working with Funding agency; Interested in Software and PID - ToF
Italy	Working with INFN since a while; Interested in PID – RICH, Silicon, Electronics, DAQ
Japan	Need both bottom-up and top-down approach, are interested in a US-Japan agreement; Interested in Hadron calorimetry and Si-tracking
Korea	Starting to work with funding agency as for Japan a Gov-Gov contract will be critical; Interested in Calorimetry and Silicon tracking as well as 2^{nd} IR
Poland	Actively working with funding agency; Interested in detectors along the beam line
IRFU / Saclay	Funding agency engaged, Providing design work for Solenoid as in-kind, Interested in electronics, tracking
UK	Submitted proposal to funding agency; Well integrated in CERN R&D program, interested in MAPS tracker, polarimetry and detectors along the beams;

Detector Location Assumption



Two possible locations – IP6 and IP8 – for detectors and Interaction Regions.

IP6 is the assumed detector location from project risk view (mainly schedule).

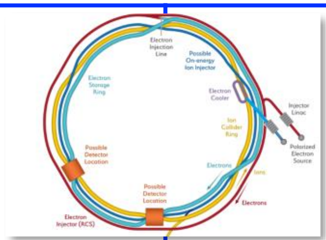
- IP8 is also suitable.

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

Complementarity for 1st IR and 2nd IR

Following CD-1 progress on the design for the 2nd IR with a focus on complementarity

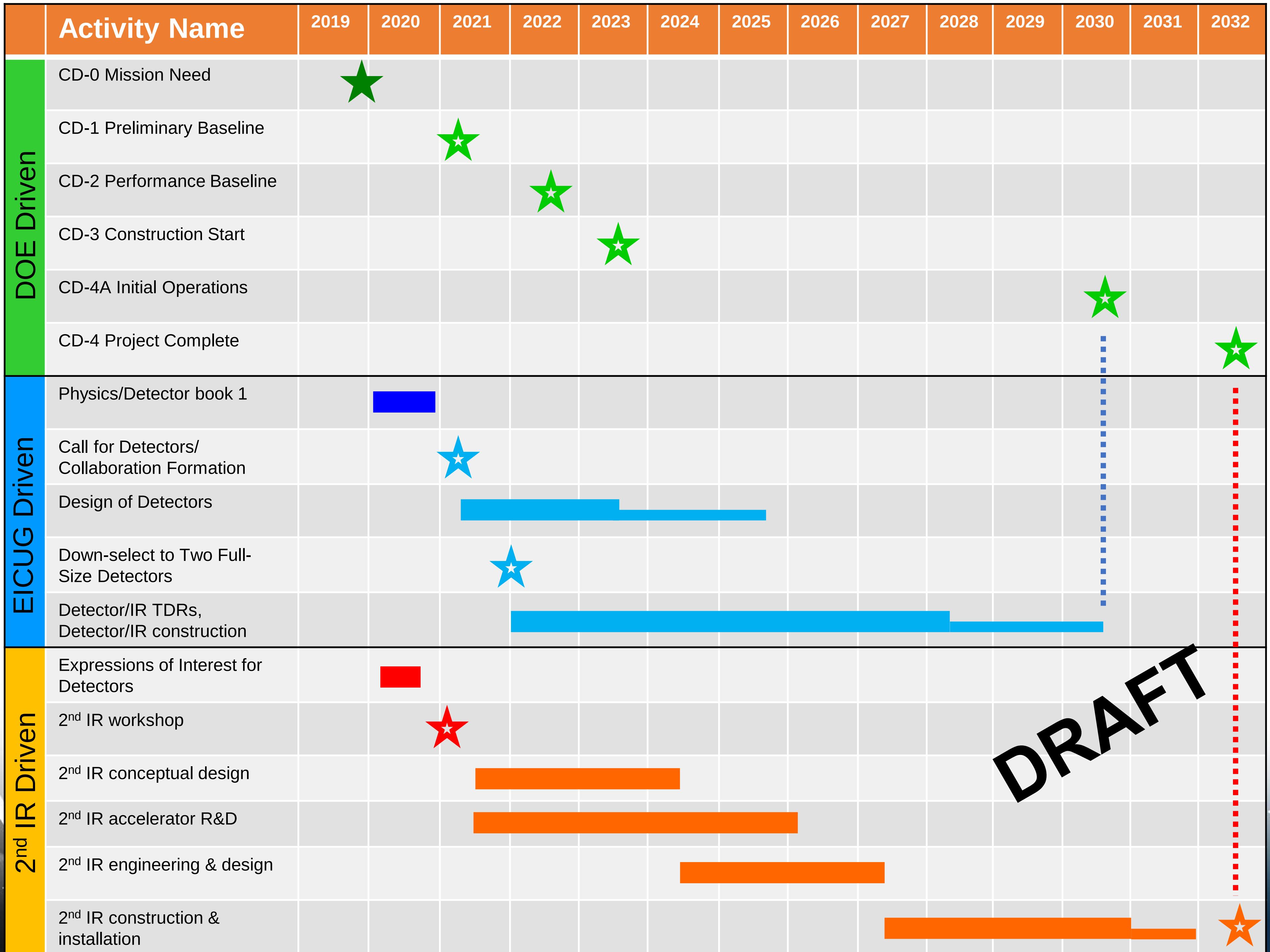
	1st IR (IP-6)	2nd IR (IP-8)
Geometry:	ring inside to outside	ring outside to inside
	tunnel and assembly hall are larger Tunnel: ⃠ 7m +/- 140m	tunnel and assembly hall are smaller Tunnel: ⃠ 6.3m to 60m then 5.3m
Crossing Angle:	25 mrad	35 mrad secondary focus



different blind spots
different forward detectors and acceptances
different acceptance of central detector

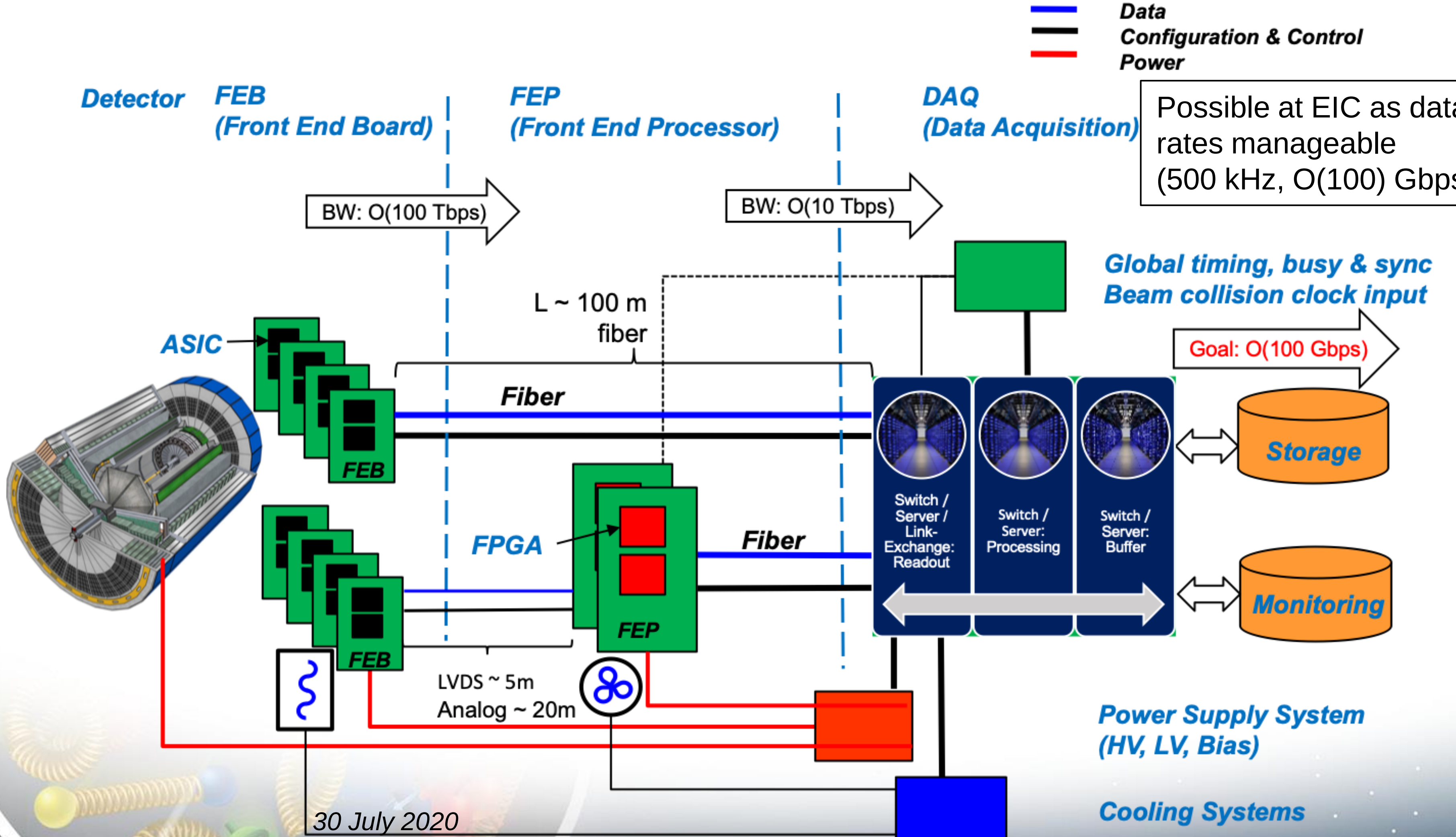
Luminosity:
more luminosity at lower E_{CM}
optimize doublet focusing DF vs. triplet FDF
→ impact of far forward p_T acceptance

Experiment:
1.5 Tesla or 3 Tesla
different subdetector technologies


Activity Name
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
DOE Driven
CD-0 Mission Need
CD-1 Preliminary Baseline
CD-2 Performance Baseline
CD-3 Construction Start
CD-4A Initial Operations
CD-4 Project Complete
EICUG Driven
Physics/Detector book 1
Call for Detectors/
Collaboration Formation
Design of Detectors
Down-select to Two Full-
Size Detectors
Detector/IR TDRs,
Detector/IR construction
2nd IR Driven
Expressions of Interest for
Detectors
2nd IR workshop
2nd IR conceptual design
2nd IR accelerator R&D
2nd IR engineering & design
2nd IR construction &
installation
DRAFT

Reference Detector – Streaming Readout Architecture

6.10.08 & 6.10.09 Electronics & DAQ/Computing

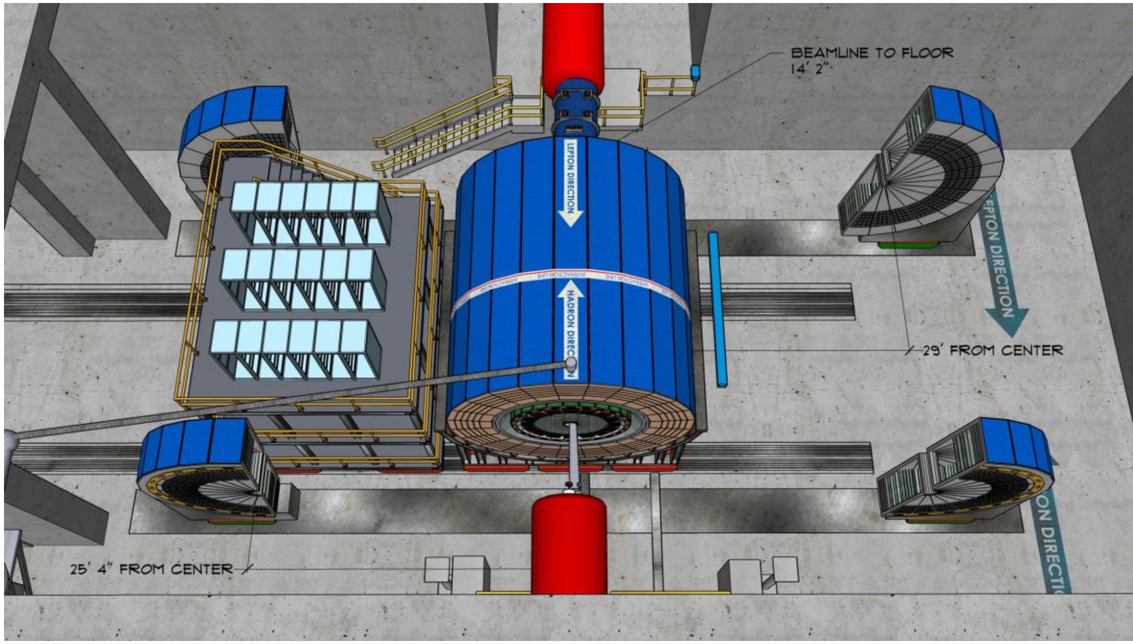


Possible at EIC as data rates manageable (500 kHz, O(100) Gbps)

Reference (Central) Detector – Maintenance

Correlated with 6.10.11 Detector Infrastructure

- **Short access** (hours) - actions without major disassembly
  - Electronics trailer
  - Hadronic calorimeter frontend electronics
  - Cryocan



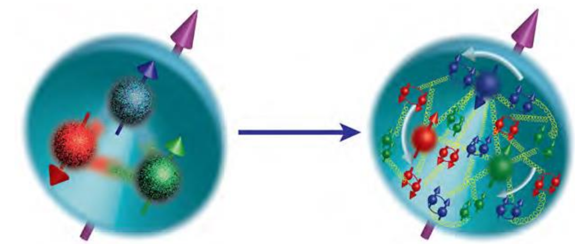
- **Longer access** (days) – endcaps rolled out in halves
  - e/m calorimeter frontend electronics
  - B0 magnet detectors (silicon tracker and e/m calorimeter)
  - Outer part of the central detector (planar trackers, perhaps the gaseous RICH electronics, perhaps DIRC electronics – if installed)

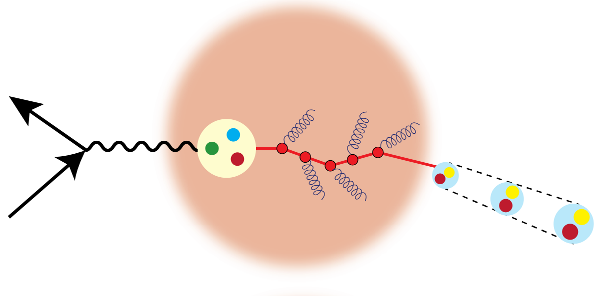
- **Scheduled maintenance** (months) – detector moved to the assembly hall
  - The only option to access the central tracker and the forward / vertex / backward silicon trackers

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?

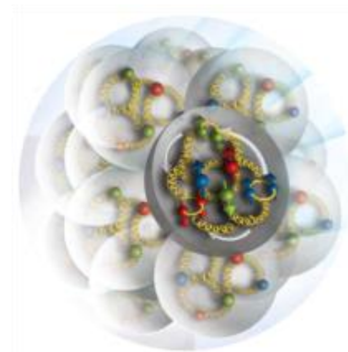




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

How do the quark-gluon interactions create nuclear binding?

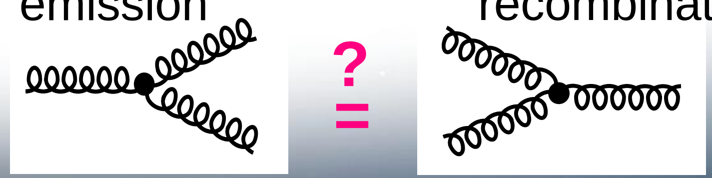


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

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

gluon recombination



Rapid acquisition of mass is effect of gluon interactions

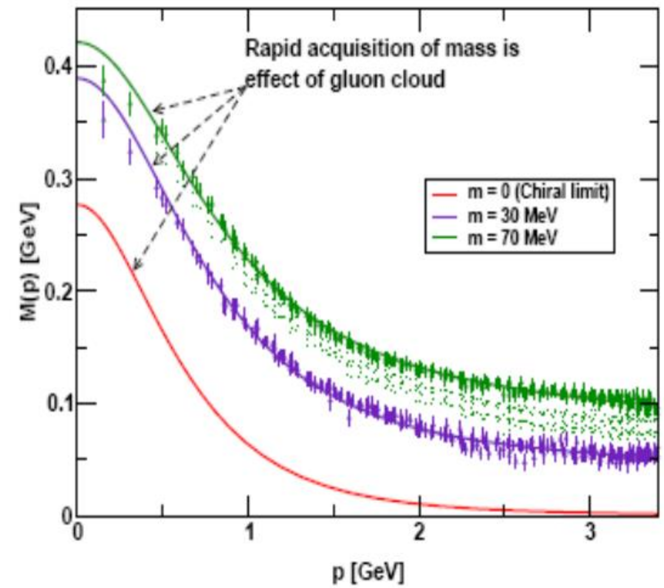
$$S_F(p) = \frac{\mathcal{F}(p)}{\not p - \mathcal{M}(p)}$$

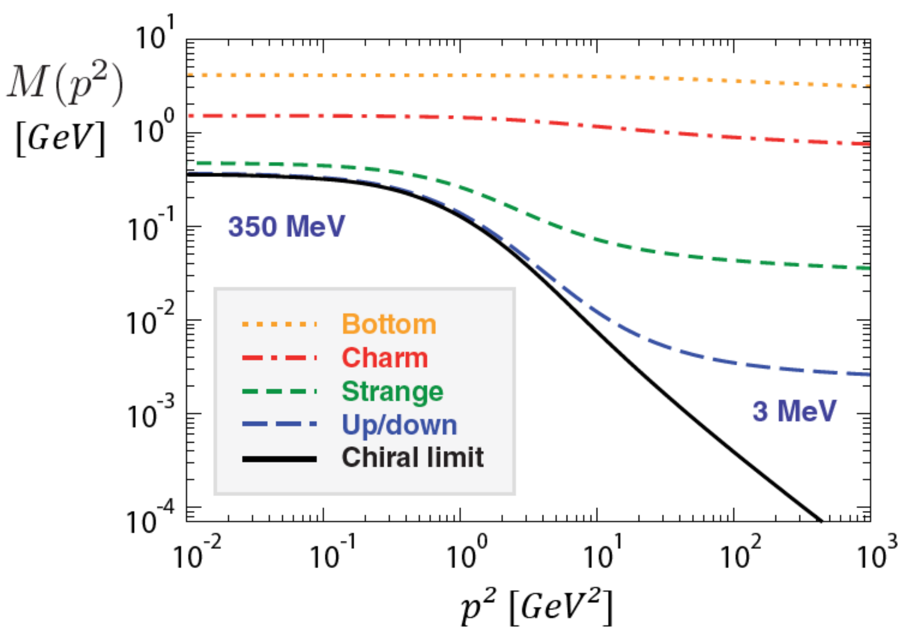
wavefunction renormalisation

mass function

$$S_F(p)^{-1} = \not p - m_0 - \frac{\alpha}{4\pi}\int d^4k\, \gamma_\mu S_F(k)\Gamma_\nu(k,p)\Delta^{\mu\nu}(q)$$

DSE and Lattice Results

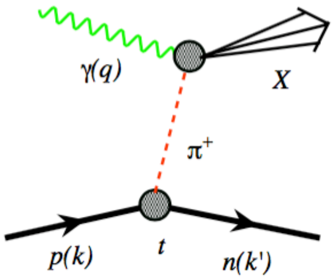




Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions. Higgs mechanism hardly plays a role.

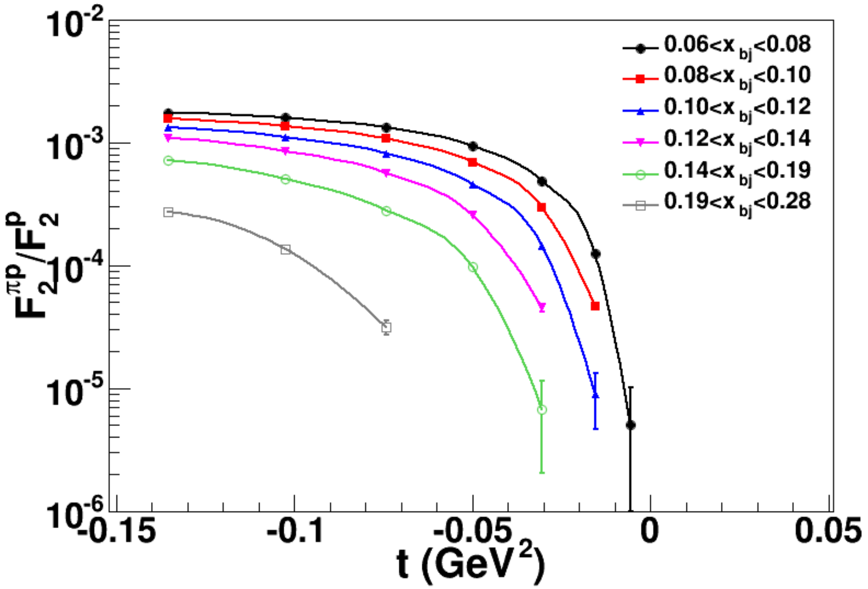
The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.

EIC – Versatility and Luminosity is Key



Why would pion and kaon structure functions, and even measurements of pion structure beyond (pion GPDs and TMDs) be feasible at an EIC?

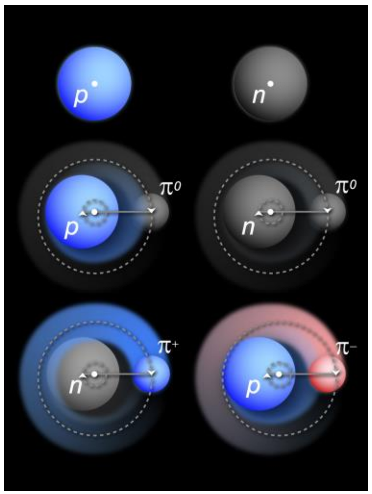
- $L_{EIC} = 10^{34} = 1000 \times L_{HERA}$
- Detection fraction @ EIC in general much higher than at HERA
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small –t bin (0.02).
- Hence, pion data @ EIC should be comparable or better than the proton data @ HERA, or the 3D nucleon structure data @ COMPASS
- If we can convince ourselves we can map pion (kaon) structure for –t < 0.6 (0.9) GeV^2, we gain at least a decade as compared to HERA/COMPASS.



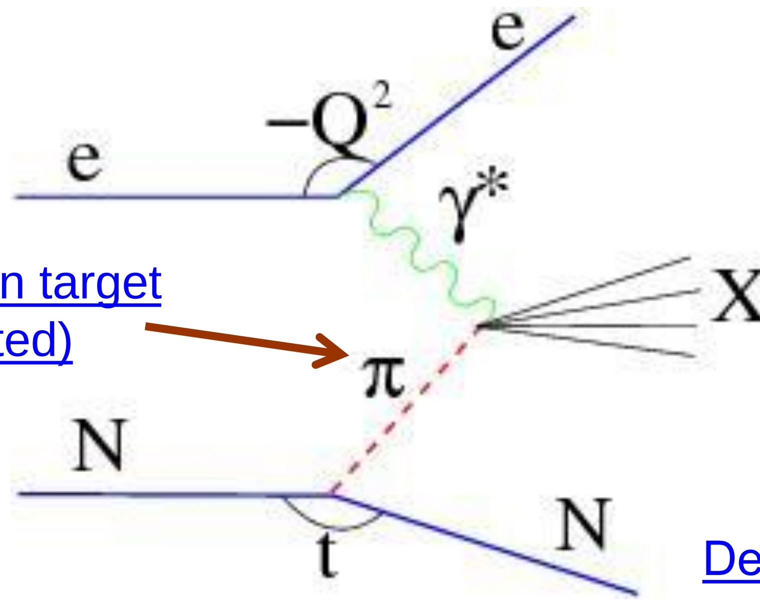
Ratio of the F_2 structure function related to the pion Sullivan process as compared to the proton F_2 structure function in the low-t vicinity of the pion pole, as a function of Bjorken-x (Jefferson Lab TDIS Collaboration, JLab Experiment C12-15-005)

Physics Objects for Pion/Kaon Structure Studies

Sullivan process – scattering from nucleon-meson fluctuations



Detect scattered electron



Pion/Kaon target (undetected)

DIS event – reconstruct x, Q^2, W^2, also M_X (W_π) of undetected recoiling hadronic system

Detect “tagged” neutron/lambda

$$F_2^{LP(3)} = \sum_i \left[\int_{t_0}^{t_{min}} f_i(z,t)\,dt \right] F_2^i(x_i, Q^2)$$

i = π, ρ, …

“Flux factor”