Jefferson Lab's Pursuit of Nuclear Femtography – from 12 GeV to EIC

aka "From JLab12 to EIC"

aka "Prospective Science and Status of the EIC – JLab View"

Rolf Ent

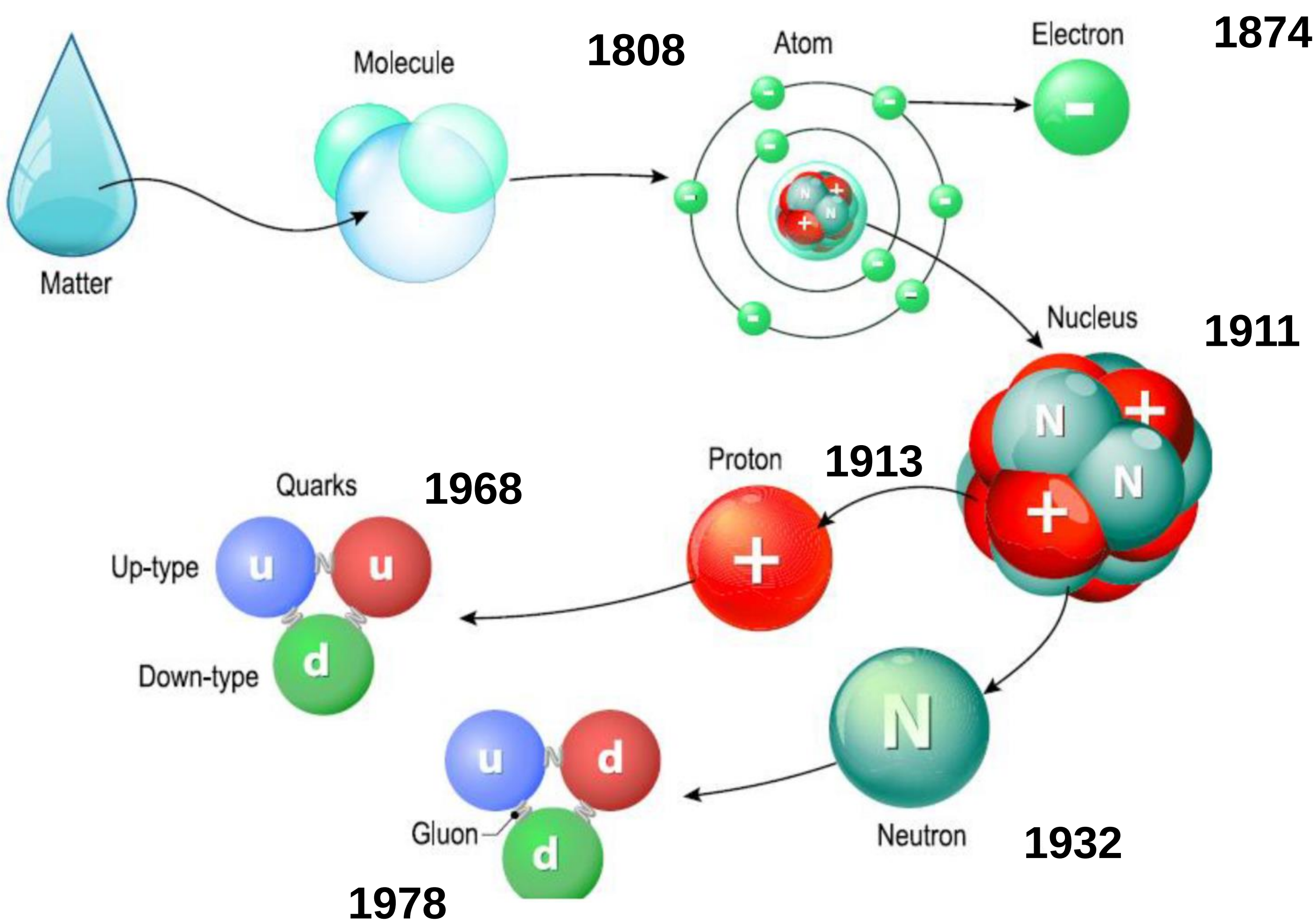
QCD with Electron-Ion Collider (QEIC)

IIT Bombay, January 4-7, 2020, Mumbai, India

Outline

- The Quest to Understand the Fundamental Structure of Matter
- Towards 3D Sub-Atomic Structure: Nuclear Femtography
- Nuclear Femtography starts at Jefferson Lab 12-GeV
- The US-Based Electron-Ion Collider (EIC)
  - Why an EIC?
  - Why its Parameters?
- EIC Science Examples
  - Femtography
  - Mass
  - Spin
  - Hadronization
  - Dense Gluon States
- EIC Status – A Portal to a New Frontier

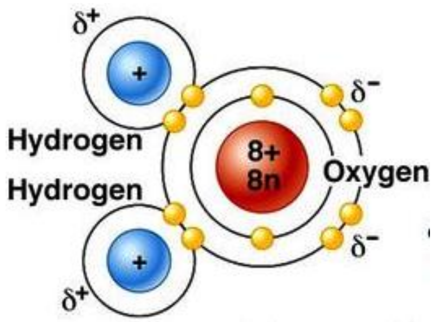
The Quest to Understand the Fundamental Structure of Matter



Nuclear Femtography – Subatomic Matter is Unique

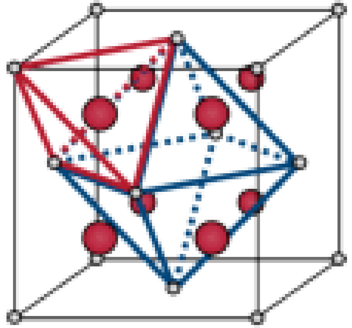
- ❑ Localized mass and charge centers – vast "open" space:

Molecule:



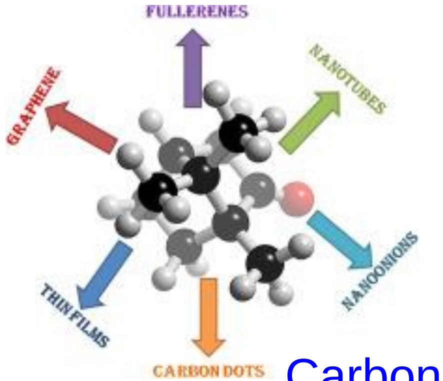
"Water"

Crystal:



Rare-Earth metal

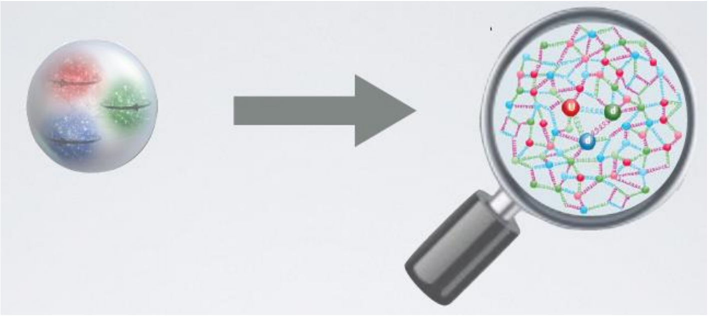
Nanomaterial:



Carbon-based

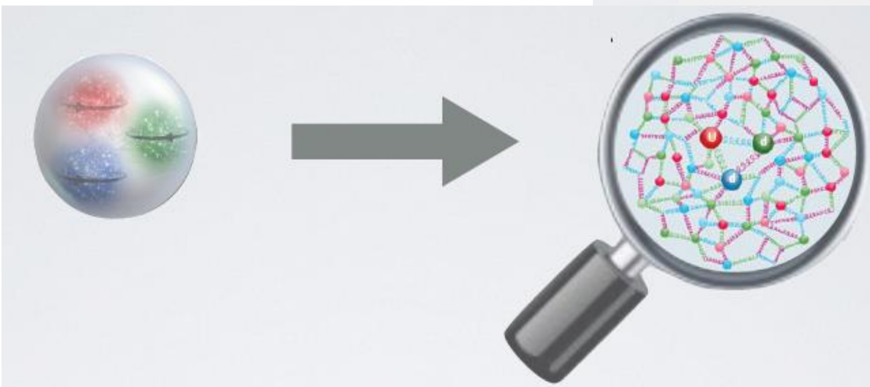
Interactions and structure are mixed up in nuclear matter: Nuclear matter is made of quarks that are bound by gluons that also bind themselves. Unlike with the more familiar atomic and molecular matter, the interactions and structures are inextricably mixed up, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

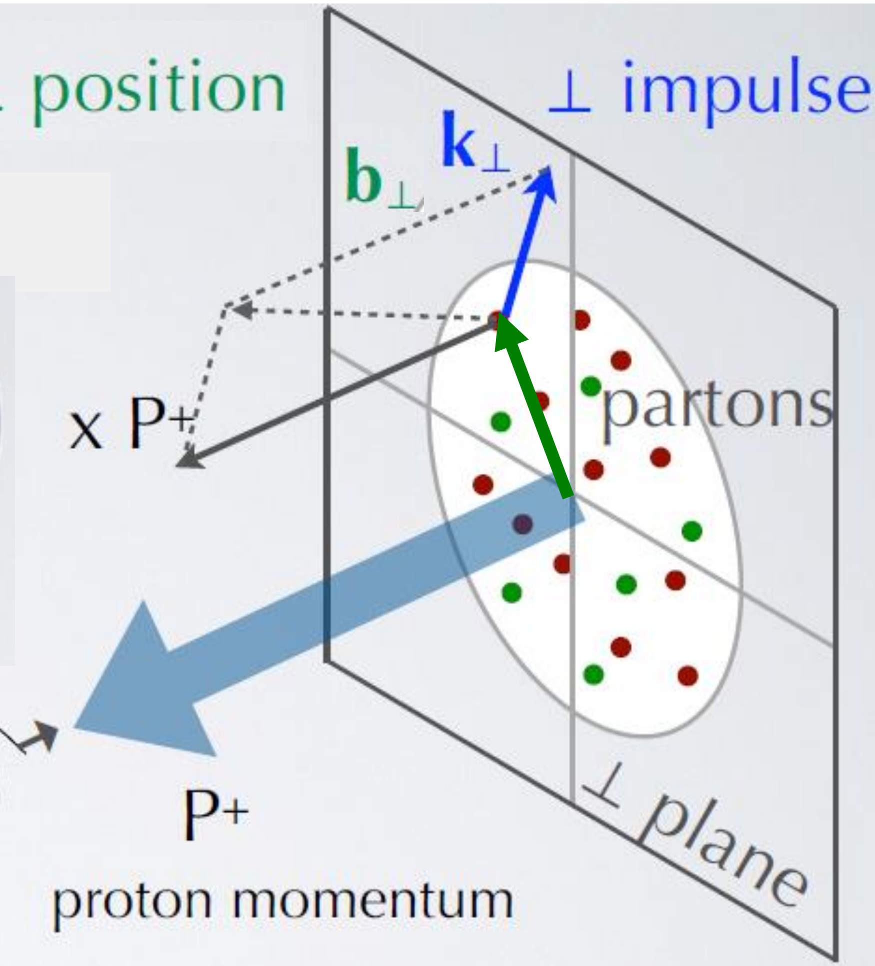
- ❑ Not so in proton structure!



NUCLEAR FEMTOGRAPHY - IMAGING

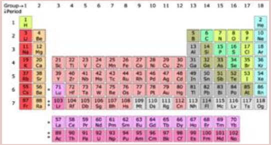
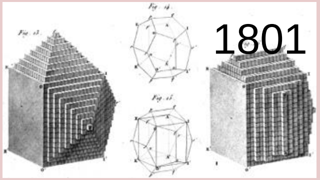
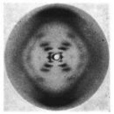
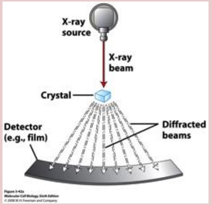
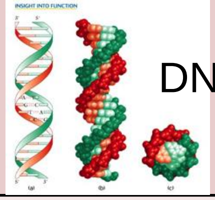
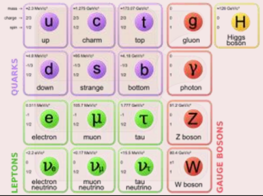
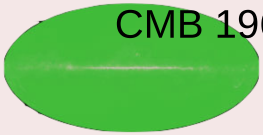
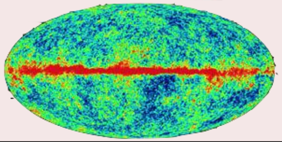
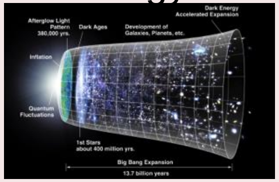
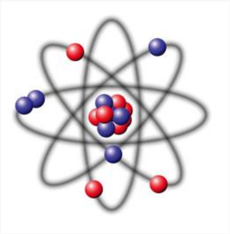
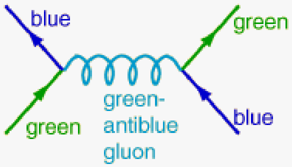
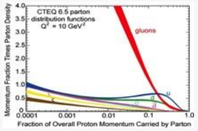
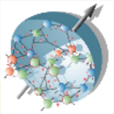
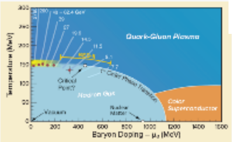
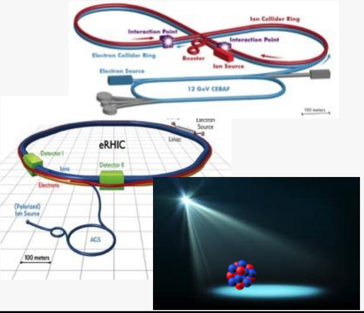
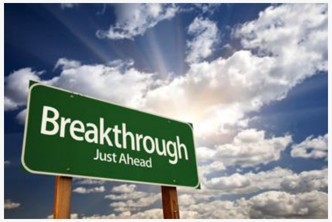
In other sciences, imaging the physical systems under study has been key to gaining new understanding.





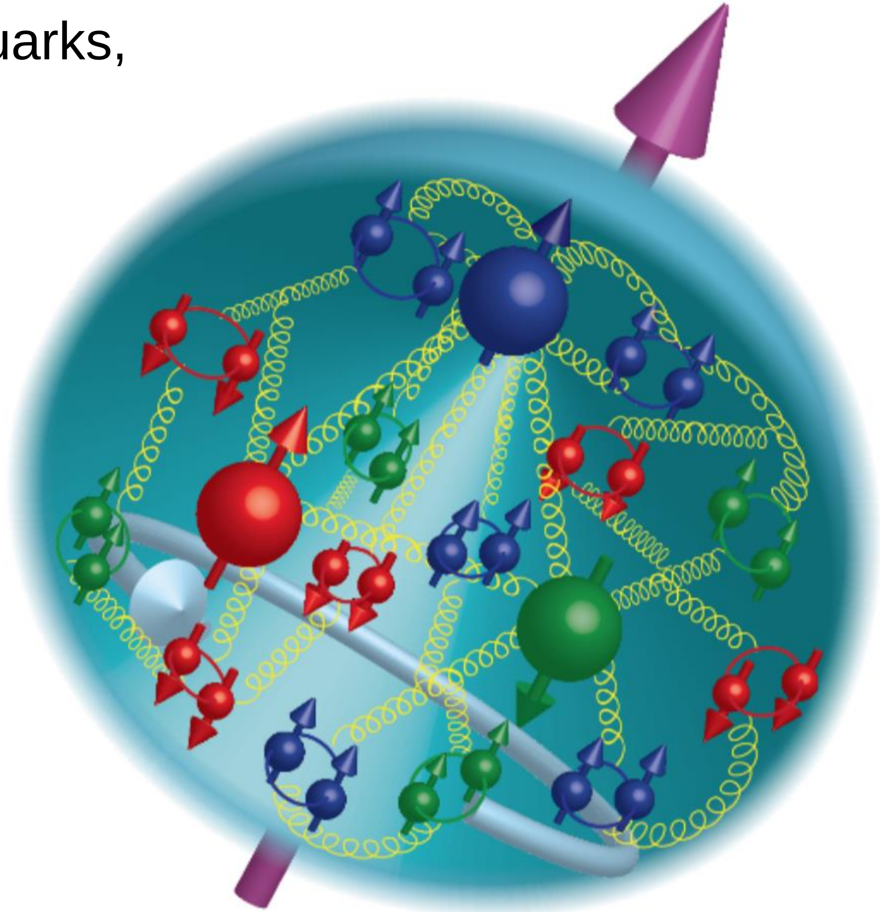
Structure mapped in terms of
b$_T$ = transverse position
k$_T$ = transverse momentum

Imaging Physical Systems is Key to New Understanding

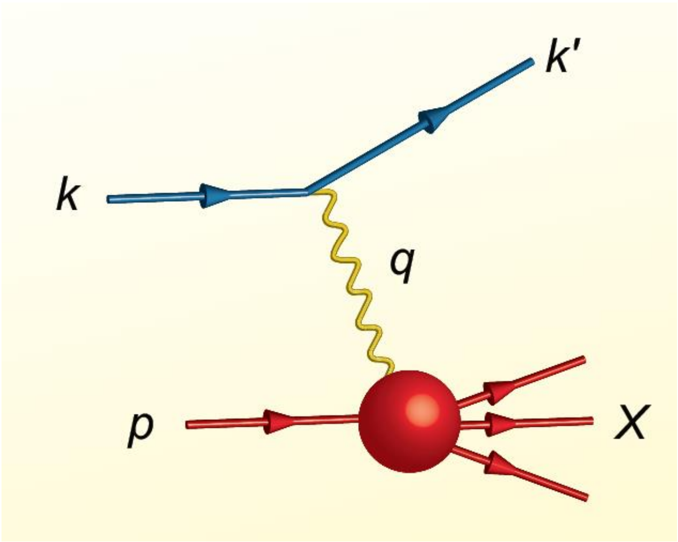
Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920)  	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark 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 (2025+) 	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.

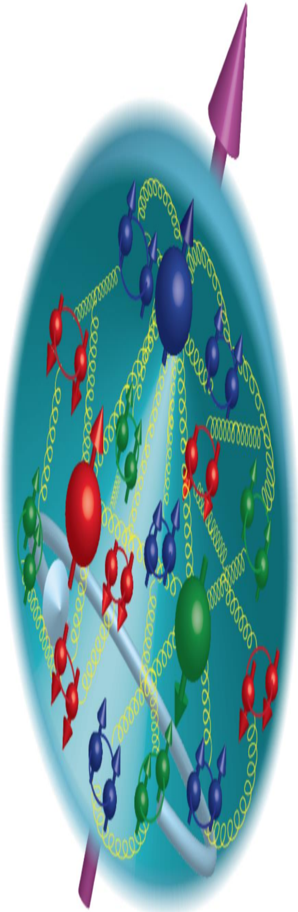


Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



Lorentz Invariants

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



- Viewed from boosted frame, length contracted by

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

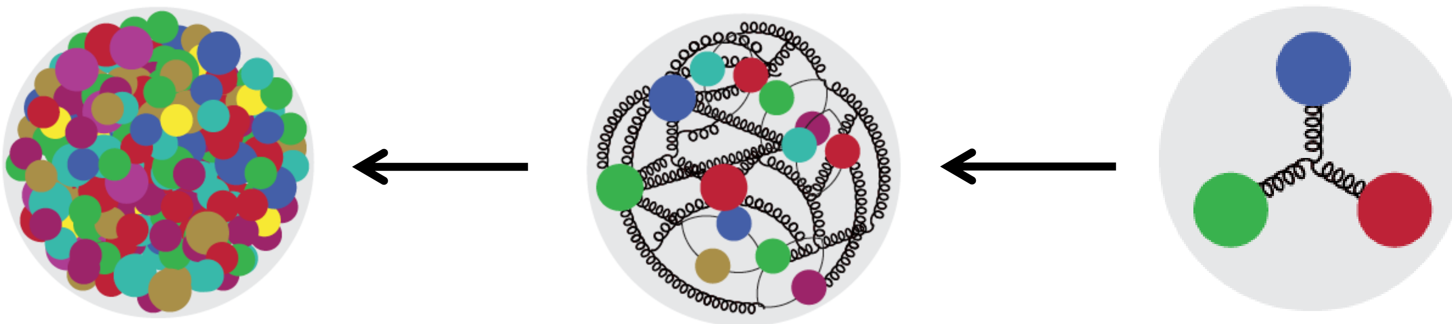
- Internal motion of the proton's constituents is slowed down by time dilation – the <u>instantaneous</u> charge distribution of the proton is seen.
- In boosted frame *x* is understood as the <u>longitudinal momentum fraction</u>
  valence quarks: $0.1 < x < 1$
  sea quarks: $x < 0.1$

J. Bjorken, SLAC-PUB-0571
March 1969

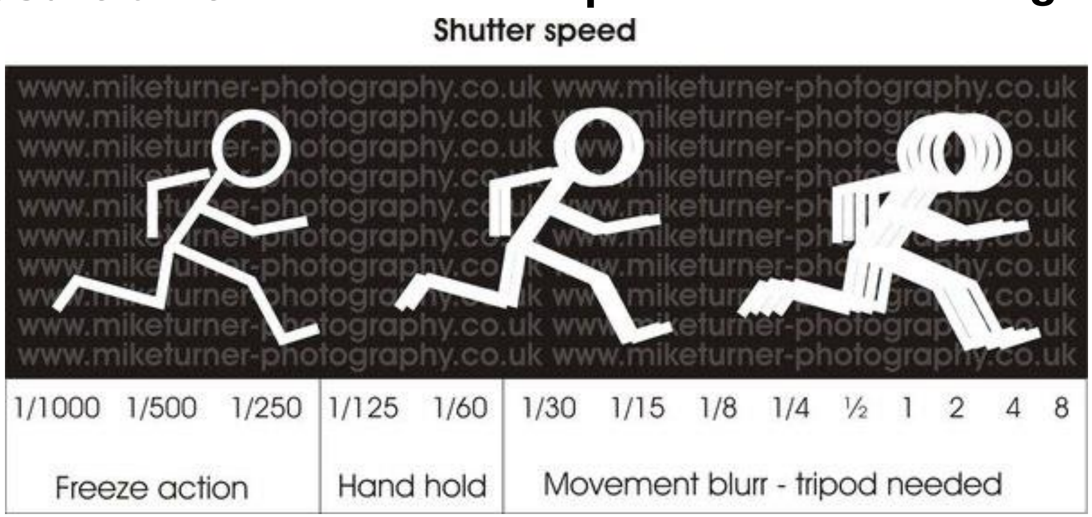
Jefferson Lab

High Energy Electron Scattering

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



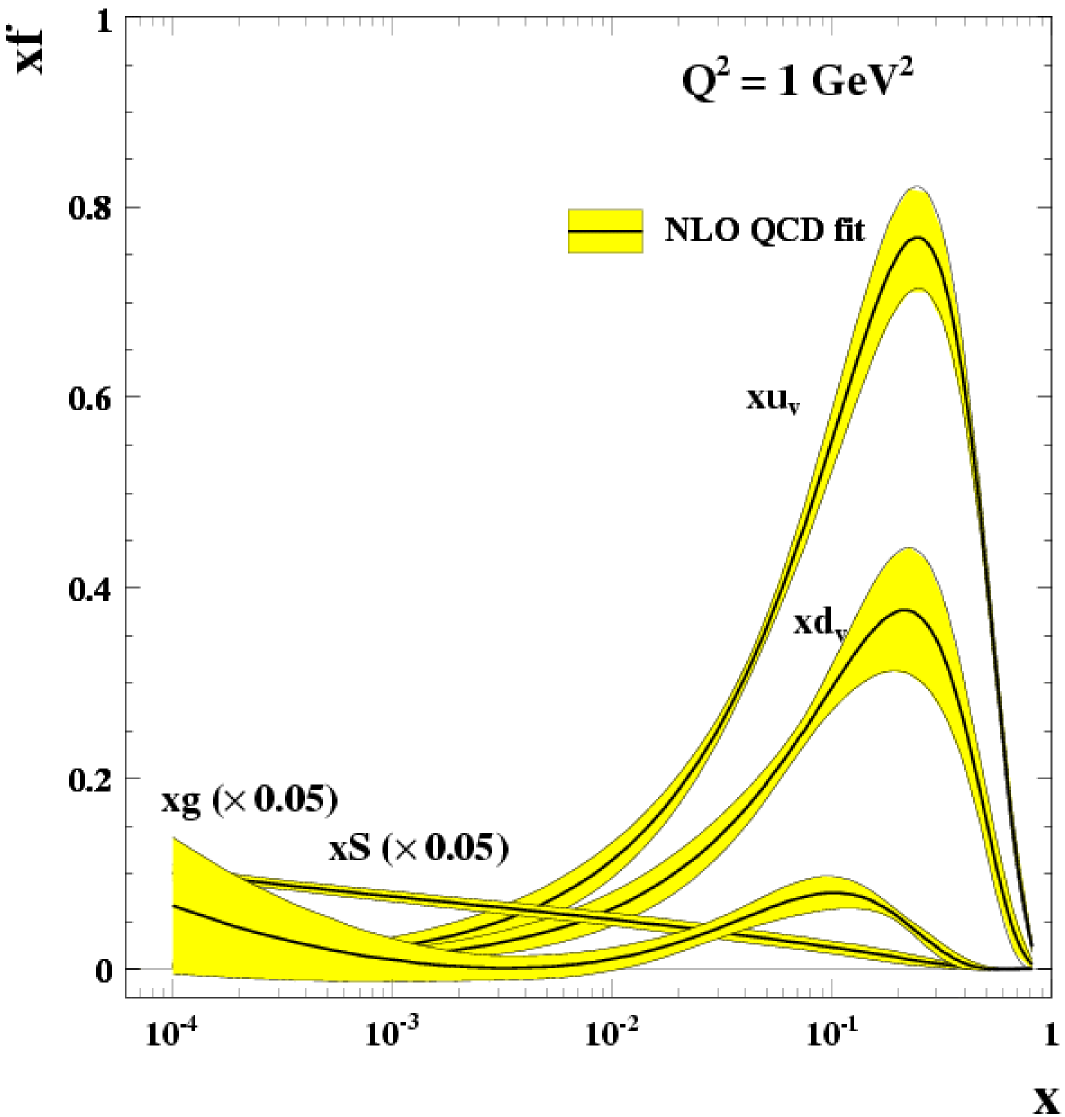
$x \approx 10^{-4}$	**$x \approx 10^{-2}$**	**$x \approx 0.3$**
Probe non-linear dynamics short exposure time	**Probe rad. dominated medium exposure time**	**Probe valence quarks long exposure time**



R. Milner

1 Longitudinal Momentum Distributions

What about the Nucleus?

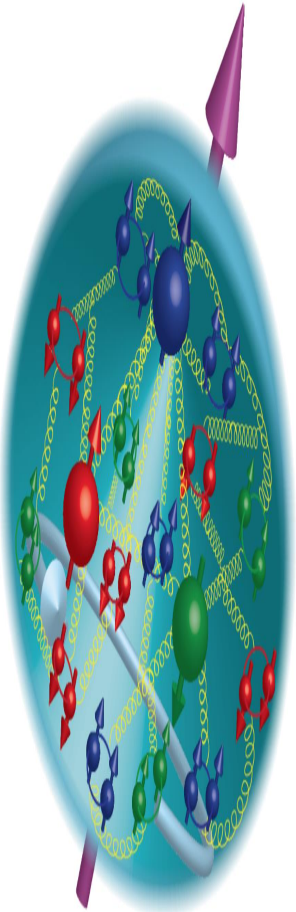


1/Q ~ spatial resolution

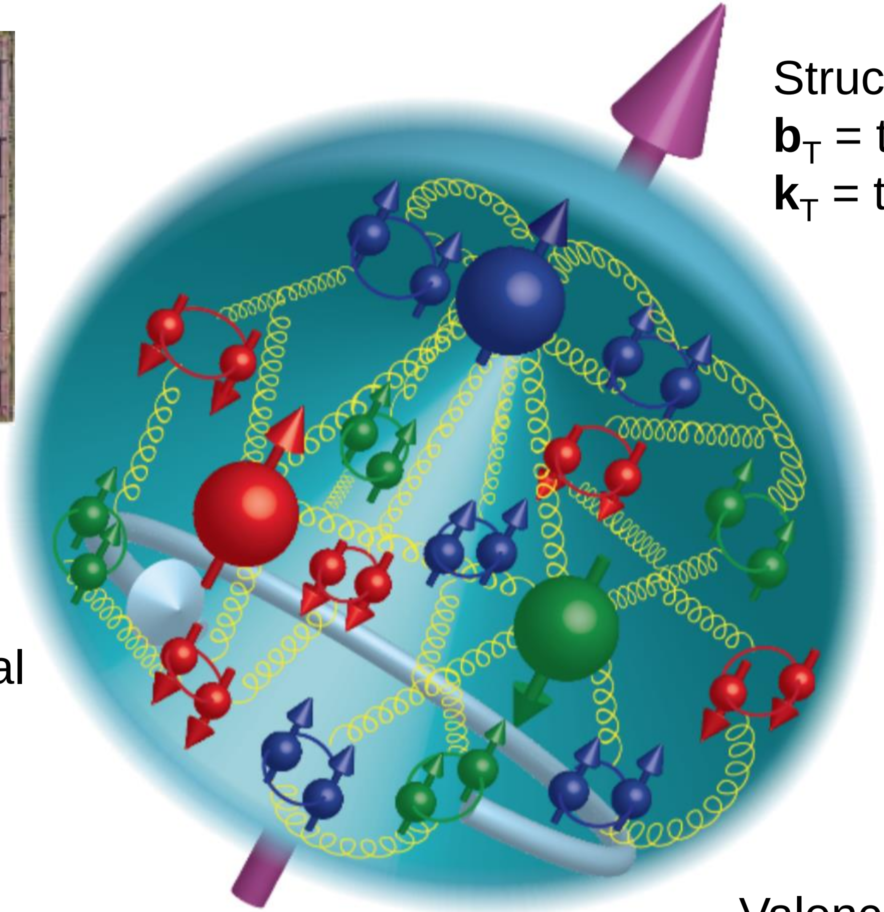
g – gluons
S – quark sea
u, d – up, down
valence quarks

R. Yoshida
C. Gwenlan

Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



Nuclear Femtography: 2 New Dimensions Transverse to Longitudinal Momentum



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

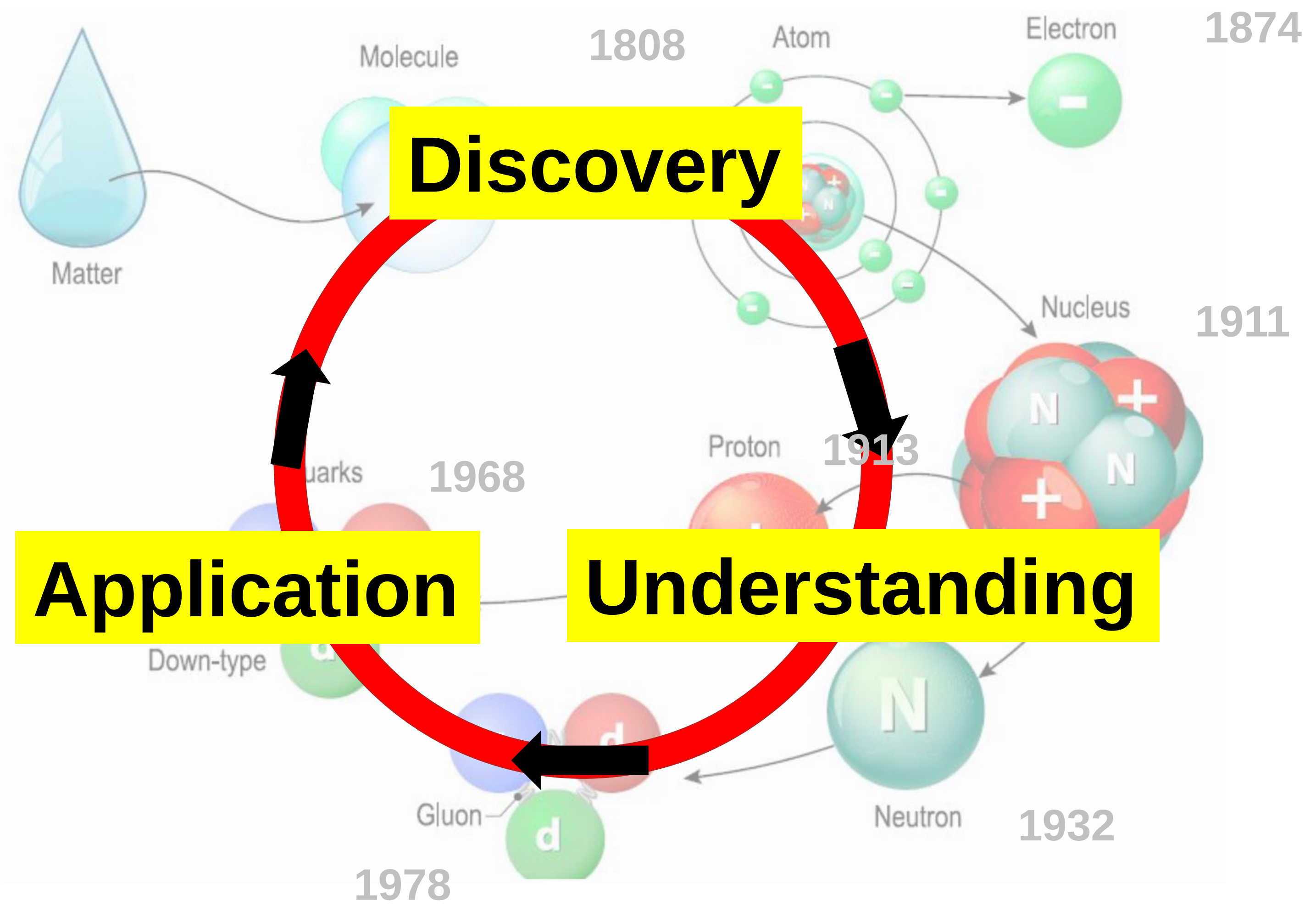
Spin!
Nuclei!

Goal:
Unprecedented
21st Century Imaging
of Hadronic Matter

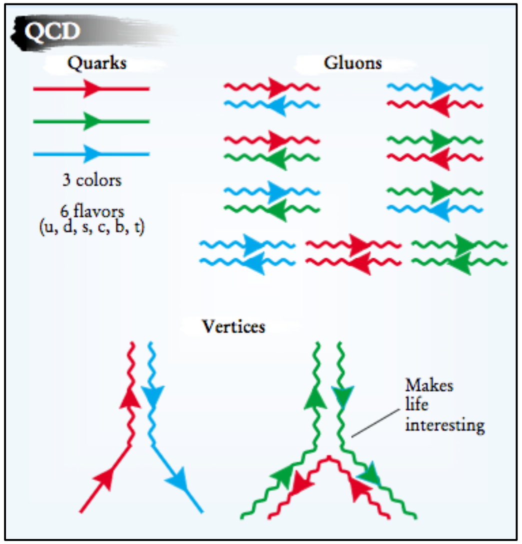
Direction of longitudinal momentum normal to plane of slide

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

The Quest to Understand the Fundamental Structure of Matter

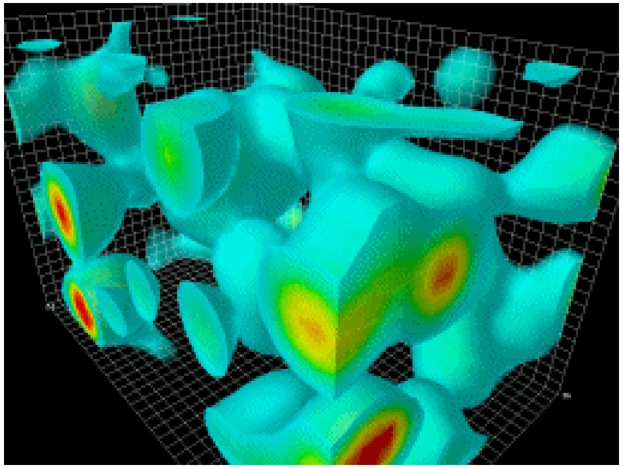


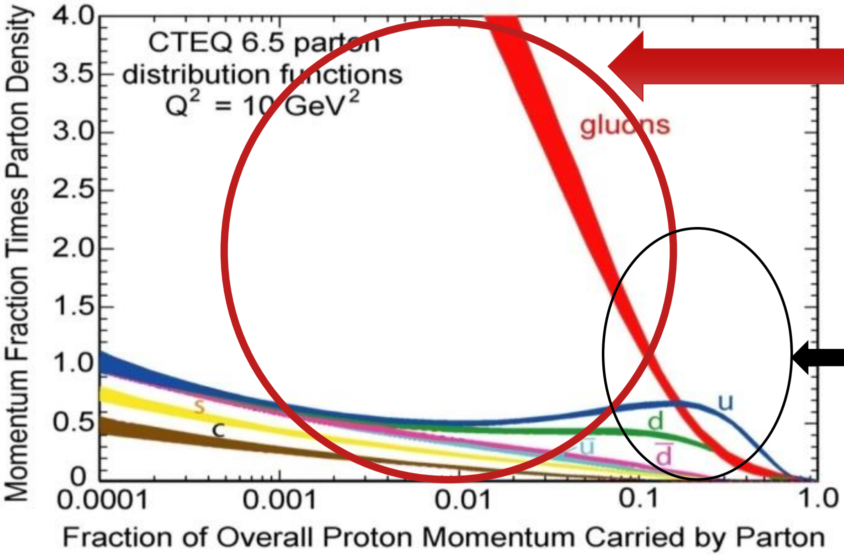
Subatomic Matter is Unique



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

Overview of Jefferson Lab

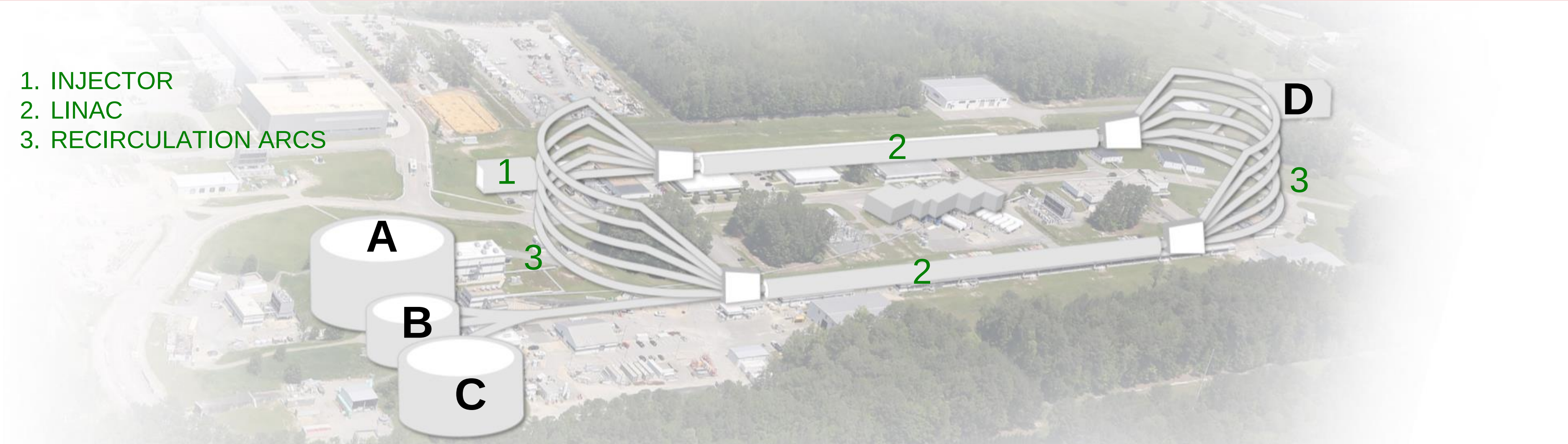
Created to build and operate the Continuous Electron Beam Accelerator Facility (CEBAF), world-unique user facility for Nuclear Physics

Jefferson Lab Stats:

- Located in Newport News, Virginia
- 169 acre site
- In operation since 1995
- ~700 employees
- 1,691 Active Users (FY19)
- 1/3 of Users are from non-US Institutions, from 37 countries
- >650 PhDs granted to-date
- On average 30% of US PhDs in nuclear physics
- FY2016 Costs: $184.1M (~2/3 operations, ~1/3 new construction)

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of confinement?
- **Can we reveal a novel landscape of nucleon and nuclear substructure through measurements of new multidimensional distribution functions?**
- Can we discover evidence for new physics beyond the Standard Model?

CEBAF at Jefferson Lab



- CEBAF Upgrade completed in September 2017
  - CW electron beam
  - E_{max} = 12 GeV
  - I_{max} = 90 μA
  - Pol_{max} = 90%
- Commissioning:
  - April 2014: hall A
  - October 2014: hall D
  - February/March 2017: halls C & B

CEBAF World-leading Capabilities

- Nuclear experiments at ultra-high luminosities, up to 10^{39} electrons-nucleons /cm^2/ s
- World-record polarized electron beams
- Highest intensity tagged photon beam at 9 GeV
- Ability to deliver a range of beam energies and currents to multiple experimental halls simultaneously
- Unprecedented stability and control of beam properties under helicity reversal

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 b.

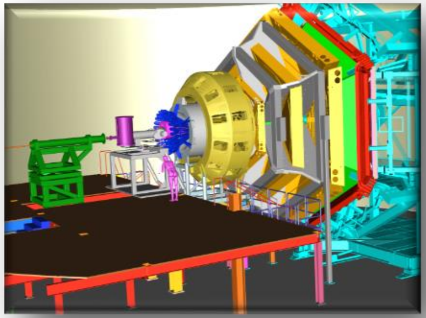
- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum (k_T) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

Nuclear Femtography

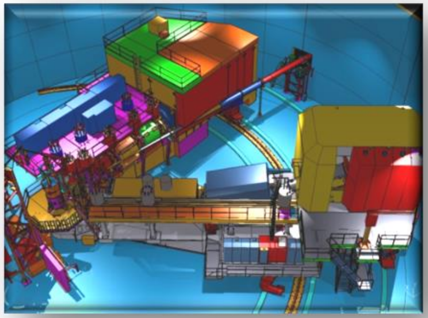
3D Imaging With JLab @ 12 GeV

Generalized Parton Distributions (GPDs) and Transverse Momentum Distributions (TMDs)

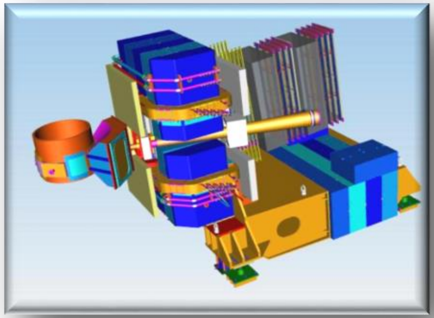
- CEBAF Large Acceptance Spectrometer (CLAS12) in Hall B: general survey experiments, large acceptance and medium luminosity



- SHMS, High Momentum Spectrometer (HMS) and Neutral-Particle Spectrometer (NPS) in Hall C: precision cross sections for L-T studies and ratios, small acceptance and high luminosity



- Super Bigbite Spectrometer (SBS) in Hall A : dedicated large-x TMD study medium acceptance and high luminosity



- Future: Solenoidal Large Intensity Device (SoLID) in Hall A: large acceptance and high luminosity

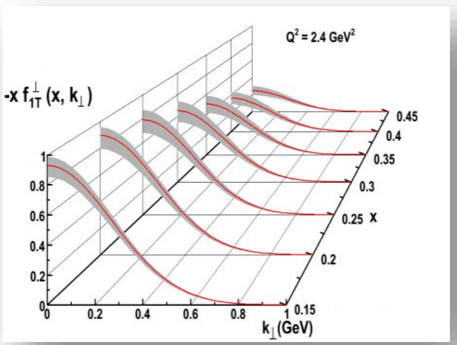
12 GEV: 3D IMAGING OF THE NUCLEON

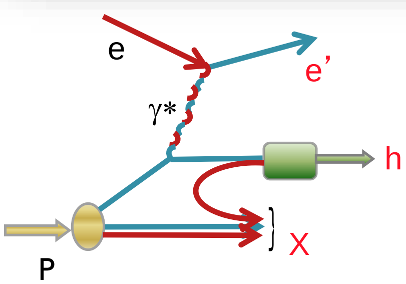
TMDs: Longitudinal momentum fraction x and transverse momentum k

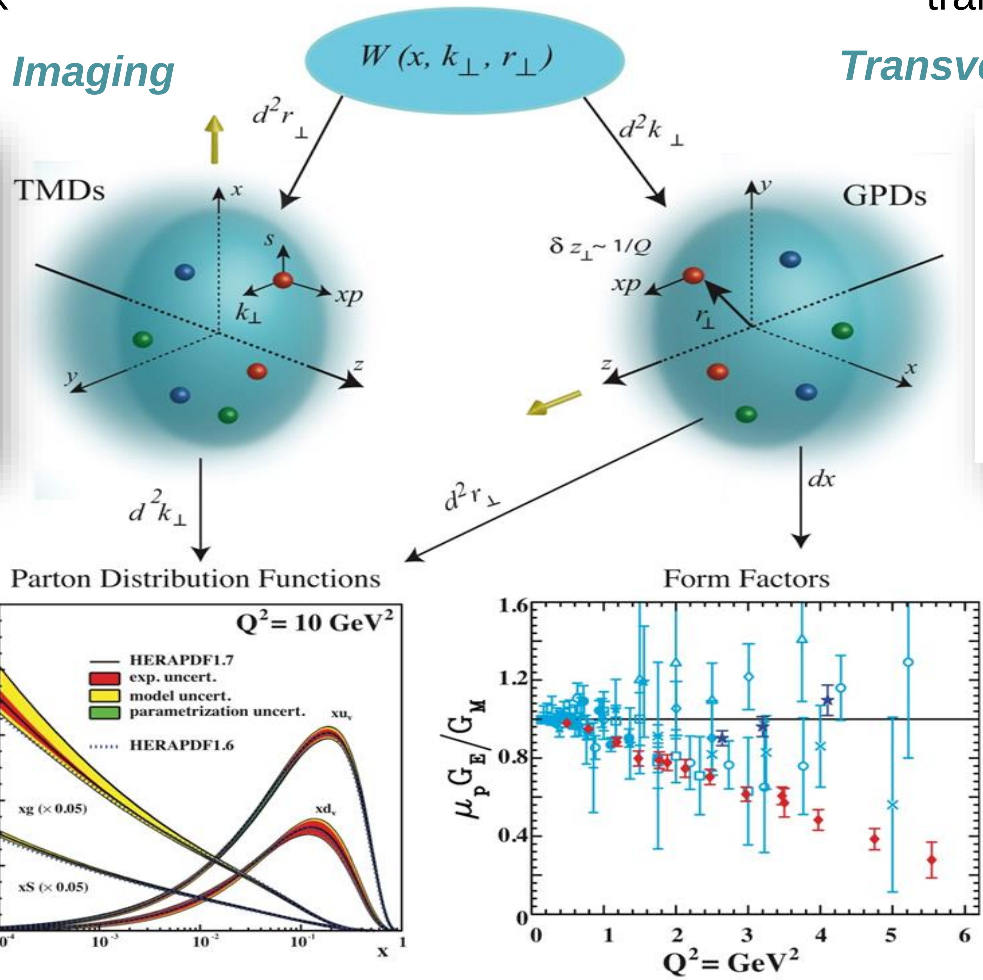
GPDs: Longitudinal momentum fraction x at transverse location b

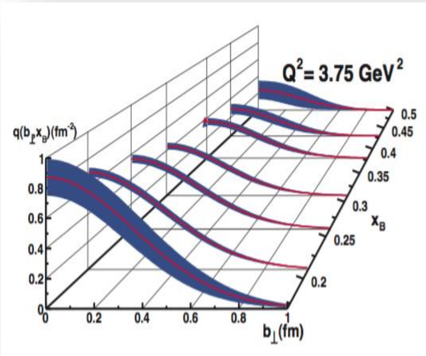
Transverse Momentum Imaging

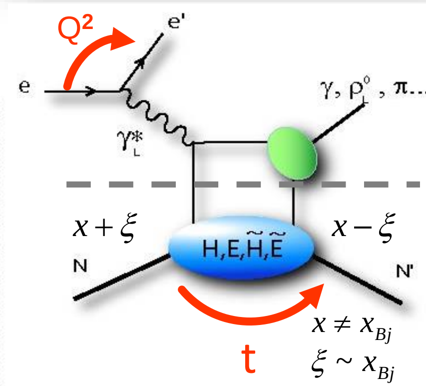
Transverse Spatial Imaging



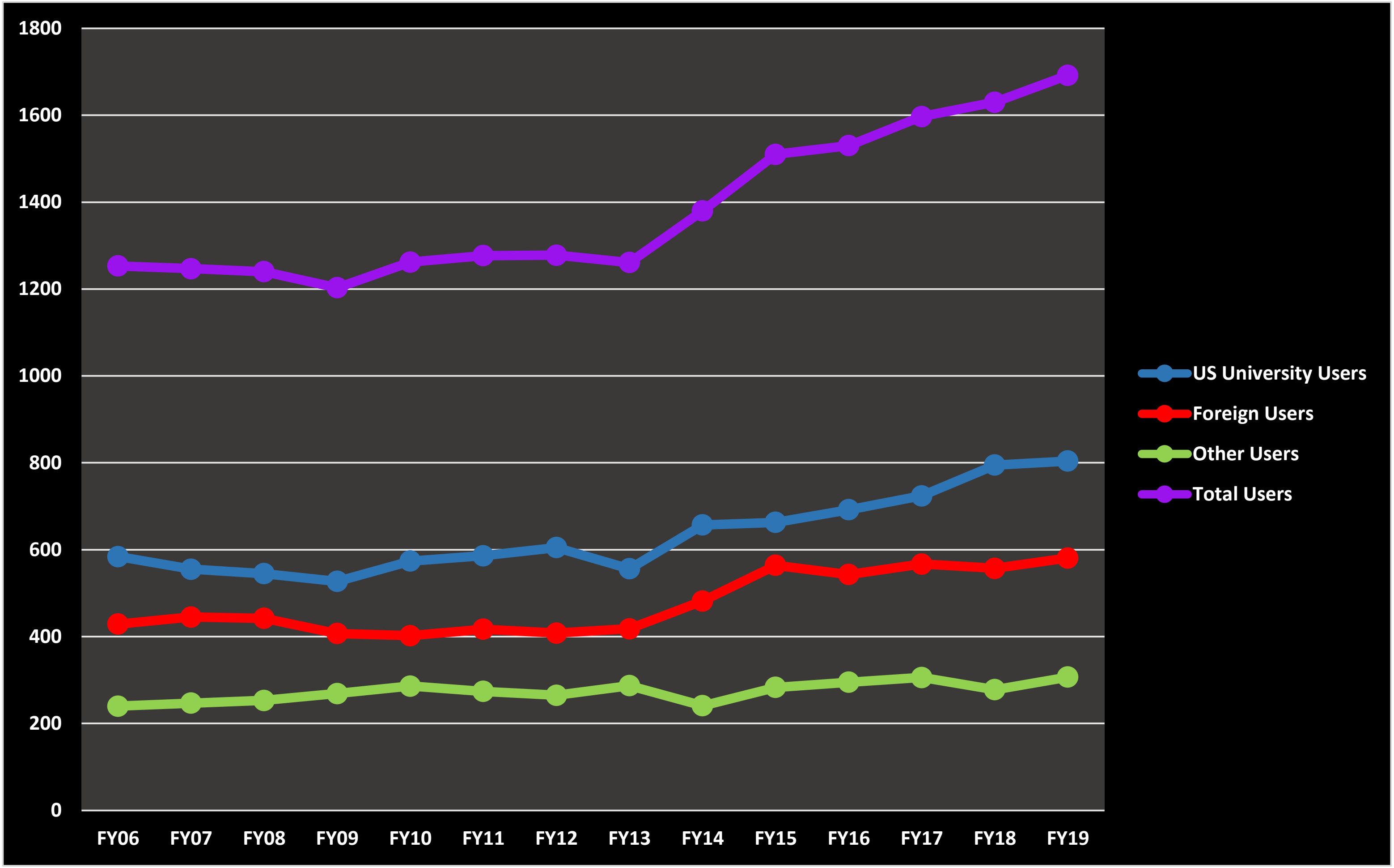








JEFFERSON LAB USER GROWTH

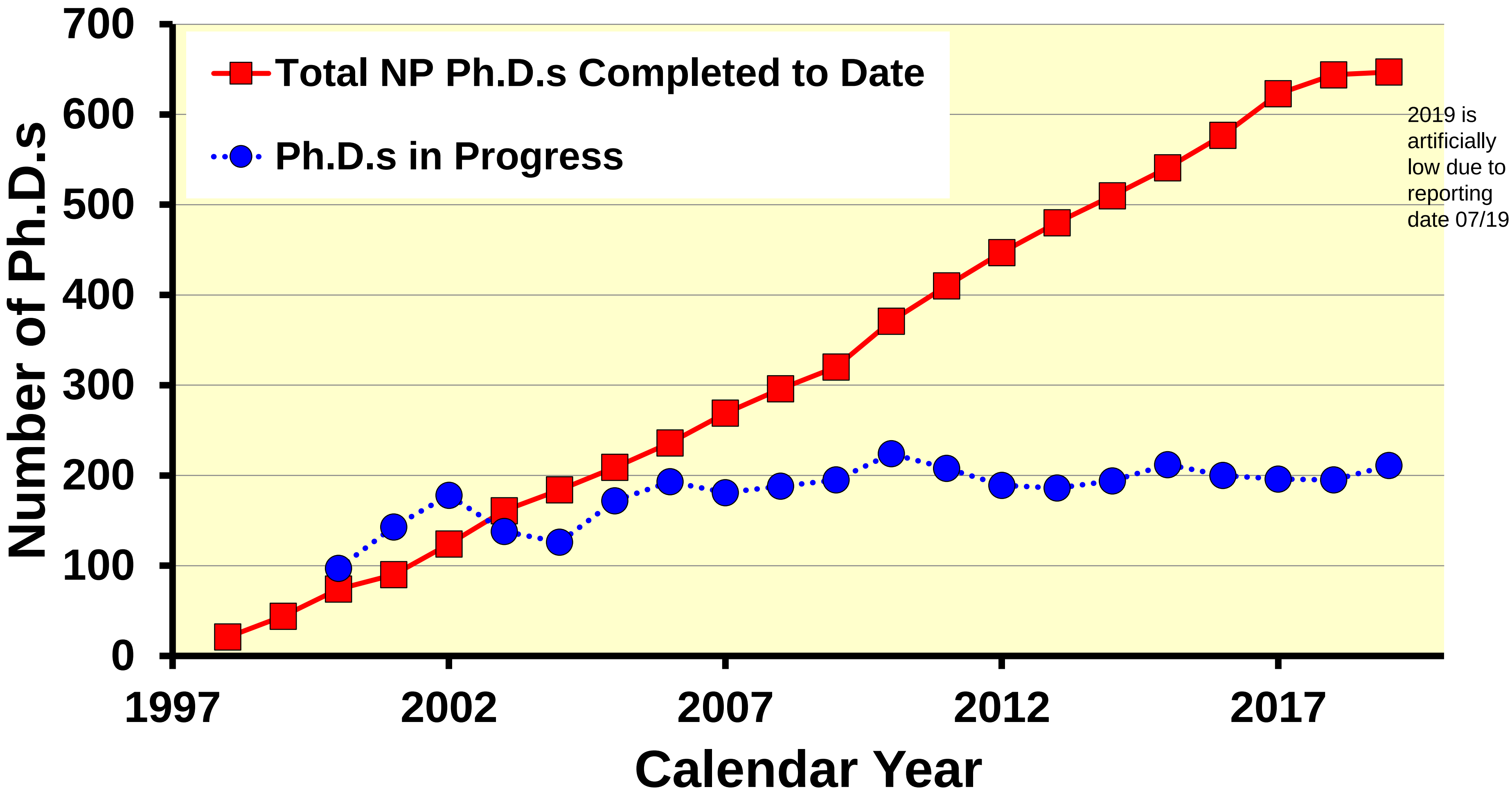


“Other Users” include US National Labs and Industry

1691 users in 278 institutions from 38 countries worldwide

PhDs based on Jefferson Lab Research

On average: 30 PhDs/year. Last few years average: 35 PhDs/year.
Typically 200 PhD students annually engaged in Jefferson Lab research.



Jefferson Lab

Introduction: Why an Electron-Ion Collider

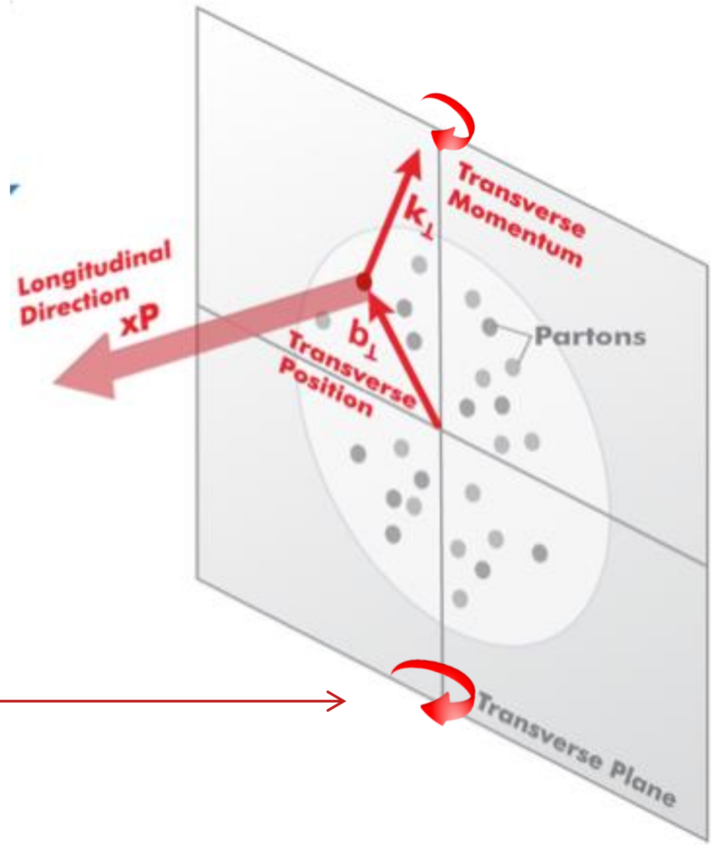
- **Interactions and structure are mixed up in nuclear matter:** Nuclear matter is made of quarks that are bound by gluons that also bind themselves. Unlike with the more familiar atomic and molecular matter, the interactions and structures are inextricably mixed up, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

- **Gaining understanding of this dynamic matter is transformational:** Gaining detailed knowledge of this astonishing dynamical system at the heart of our world will be transformational, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.

- **The Electron Ion Collider is the right tool:** A new US-based facility, EIC, with a versatile range of beam energies, polarizations, and species, as well as high luminosity, is required to precisely image the quarks and gluons and their interactions, to explore the new QCD frontier of strong color fields in nuclei – to *understand* how matter at its most fundamental level is made.

3D Structure of Nucleons and Nuclei

- EIC is a machine to completely map the 3D structure of the nucleons and nuclei
- We need to measure positions and momenta of the partons transverse to its direction of motion.
- These quantities (k_T, b_T) are of the order of a few hundred MeV.
- Also their polarization!



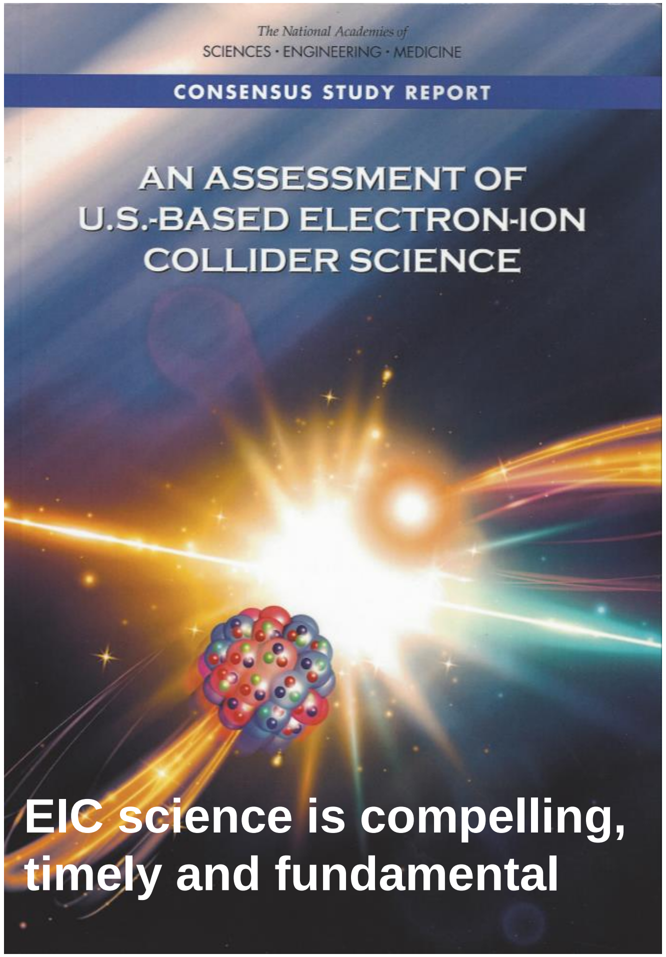
k_T, b_T (~100 MeV)

Proton and Ion Beam

Need to keep [100 MeV]$_T$/$E_{proton,Ion}$ manageable (~ >10^{-3}) ➔ E_{proton} ~< 100 GeV

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high

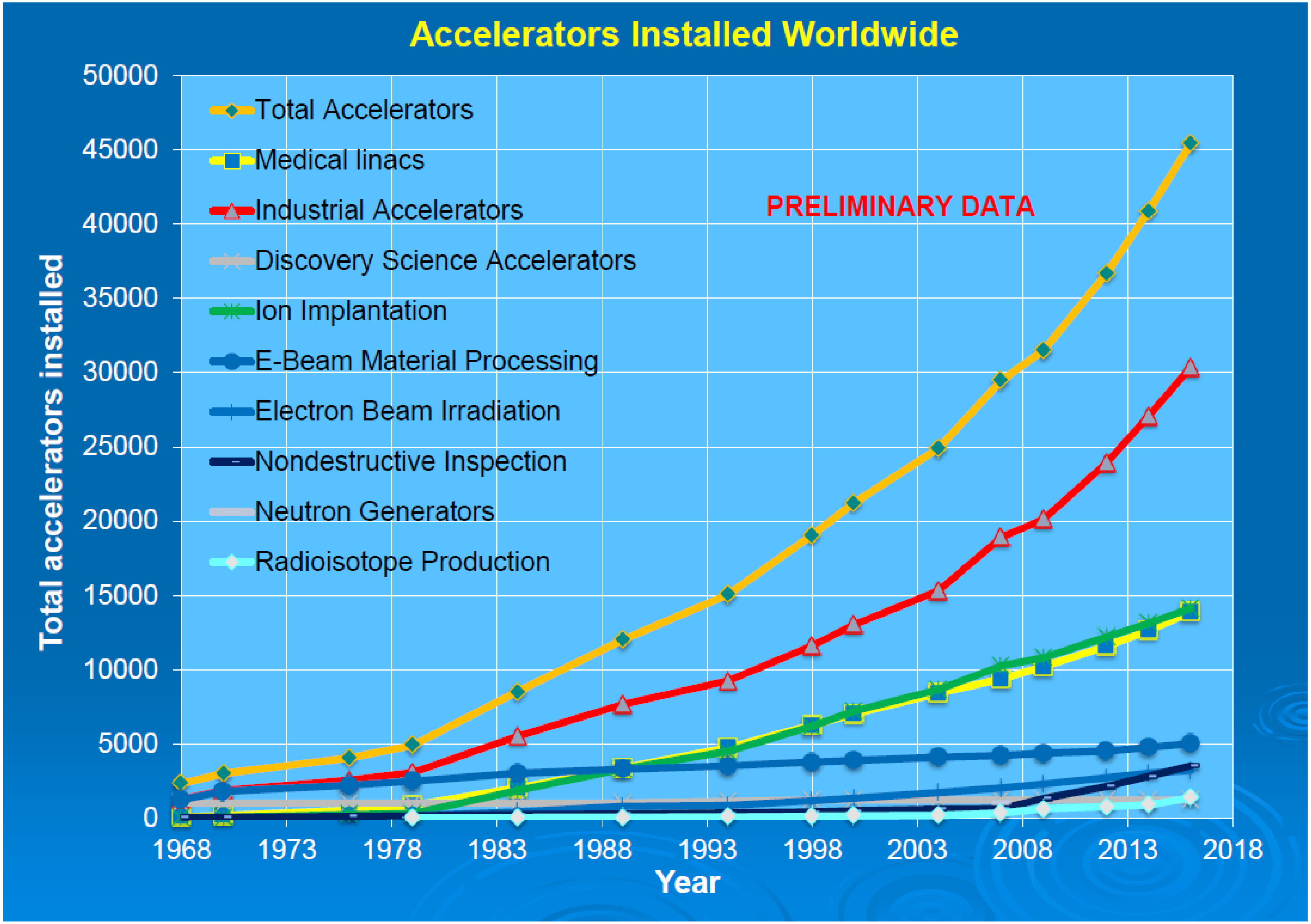
Findings of the NAS committee



Developed by NAS committee with broad science perspective

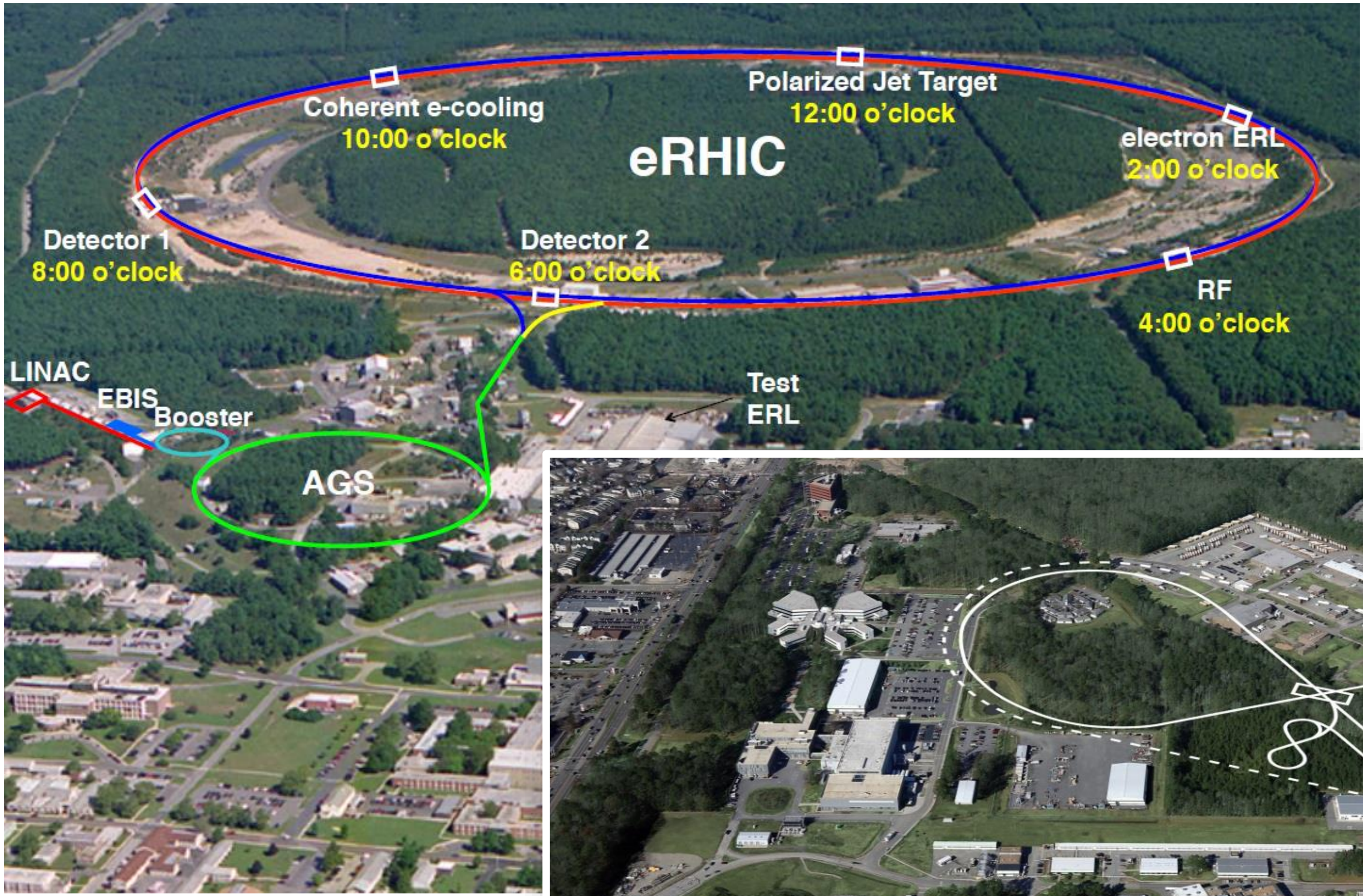
- **Finding 1:** An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:
  - How does the **mass** of the nucleon arise?
  - How does the **spin** of the nucleon arise?
  - What are the **emergent properties**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

Growing Relevance of Accelerators Worldwide

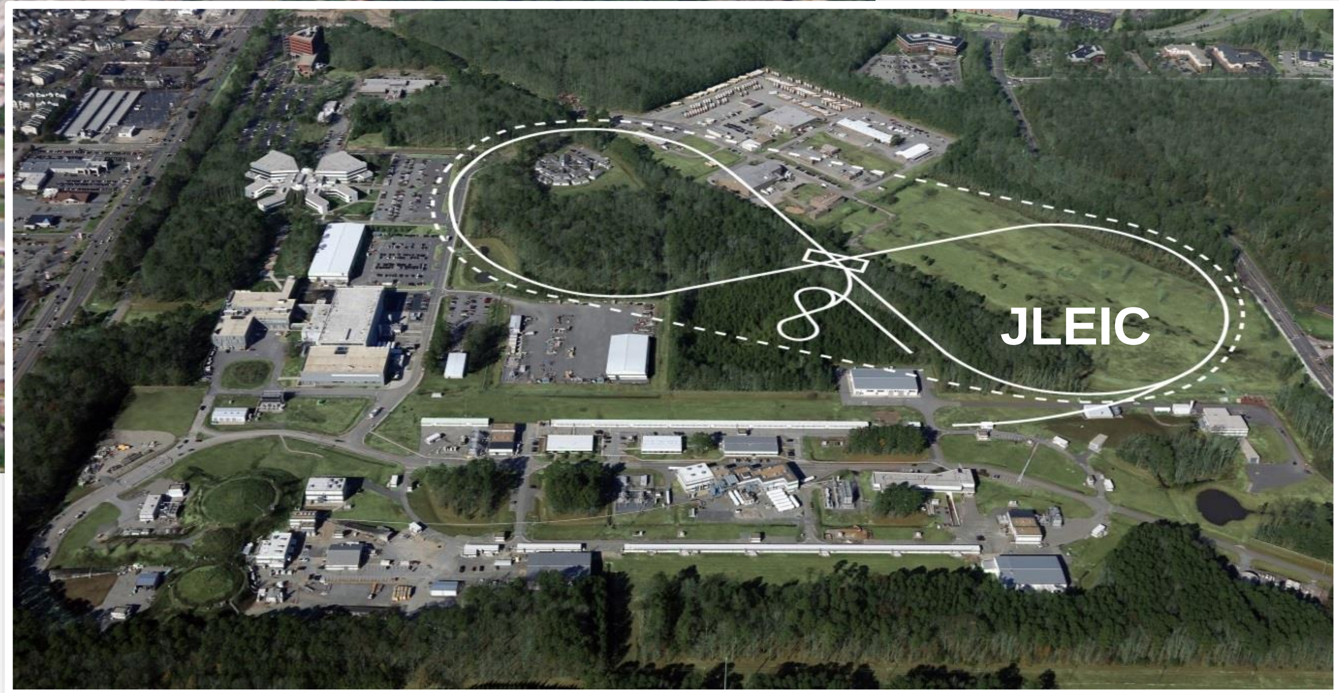


From: Dr. Robert W. Hamm

US-BASED EIC PROPOSALS



Brookhaven Lab
Long Island, NY



Jefferson Lab
Newport News, VA

Key EIC Machine Parameters

as required by the NSAC LRP & NAS

Parameter	Unit	JLEIC	eRHIC
Center of Mass Energies	[GeV]	20-100 a)	20-140
Ion Species		p to U	p to U
Number of Interaction Regions		2	2
Hadron Beam Polarization		85%	80%
Electron Beam Polarization		80%-85%	80%
Maximum Luminosity	$[10^{34} cm^{-2} s^{-1}]$	1.55	1.3

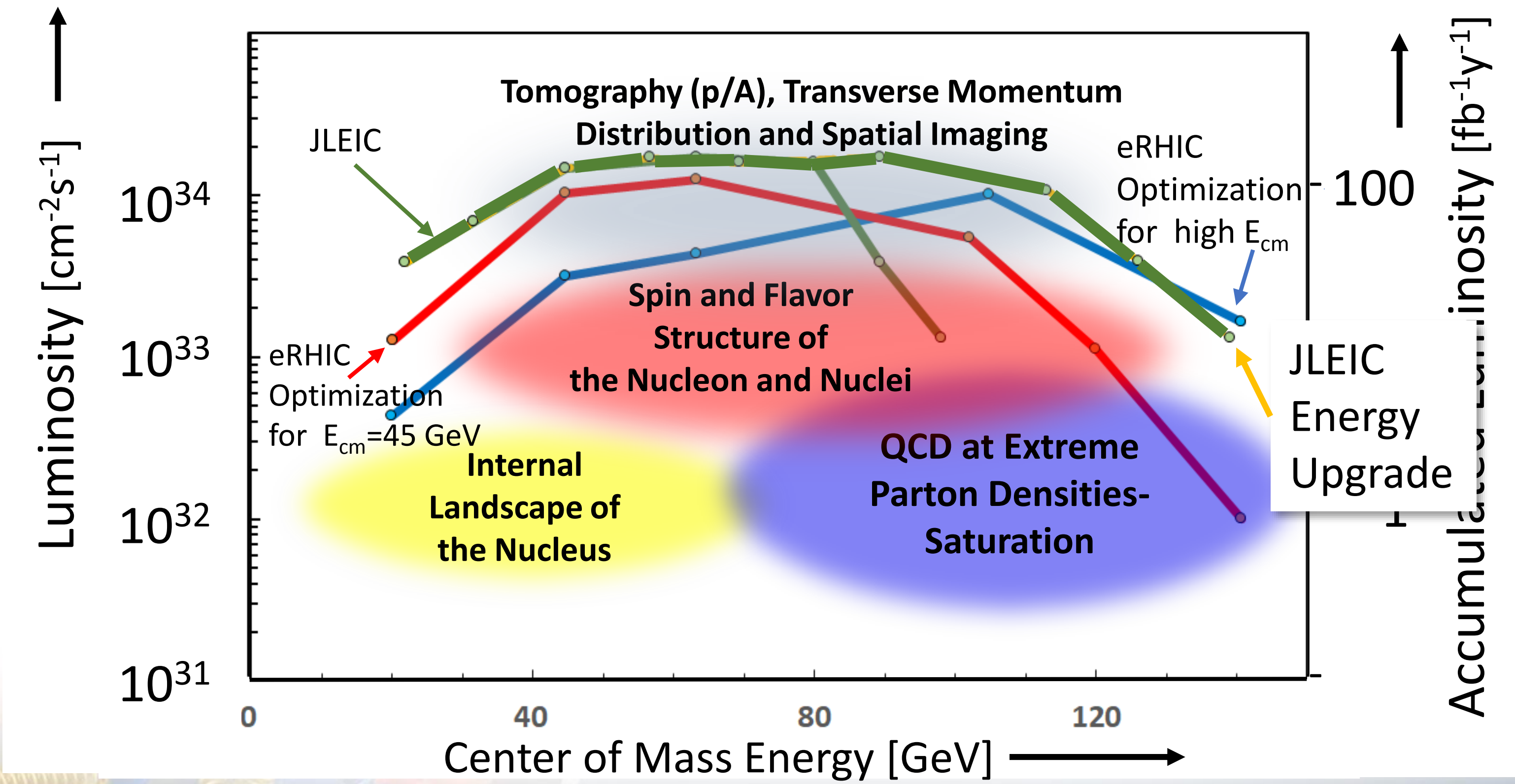
a) upgradable to 140 GeV

F. Willeke, BNL, July 2019

F. Willeke, BNL, July 2019

EIC Luminosity

IR Designs can be adjusted to obtain peak luminosity at different center of mass energies. The curves below show luminosity vs E_{cm} with IRs optimized for high or low center of mass energy. With two IRs, in principle both optimization can coexist in the same machine



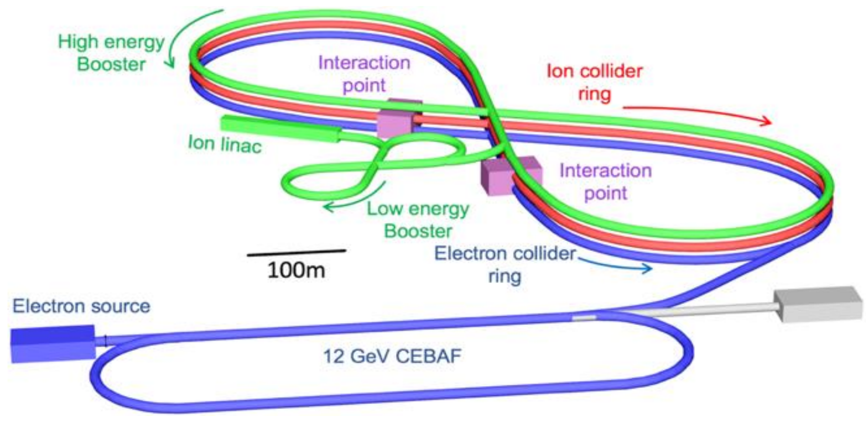
Note: For electron ion collisions, the E_{cm} scale needs to be reduced by a factor $(Z/A)^{1/2}$

Jefferson Lab Electron Ion Collider

- JLEIC Design Concept:
  - Existing CEBAF serves as a full-energy electron injector
  - Optimized for **high luminosity** and high polarization, well-matched to luminosity requirements
  - Innovative figure-8 design guarantees **high polarization, including deuteron**
  - **Full acceptance** detector and interaction region
  - Energy Range:

    $\sqrt{s}$: 20 to 100 - 140 GeV
    (magnet technology choice,
    6T (NbTi) vs 12 T (Nb_3Sn) field)
  - Cut-and-cover tunnel configuration compatible with future upgrade to E_{CM} = 140 GeV

- JLEIC offers an appropriate balance between performance and risk



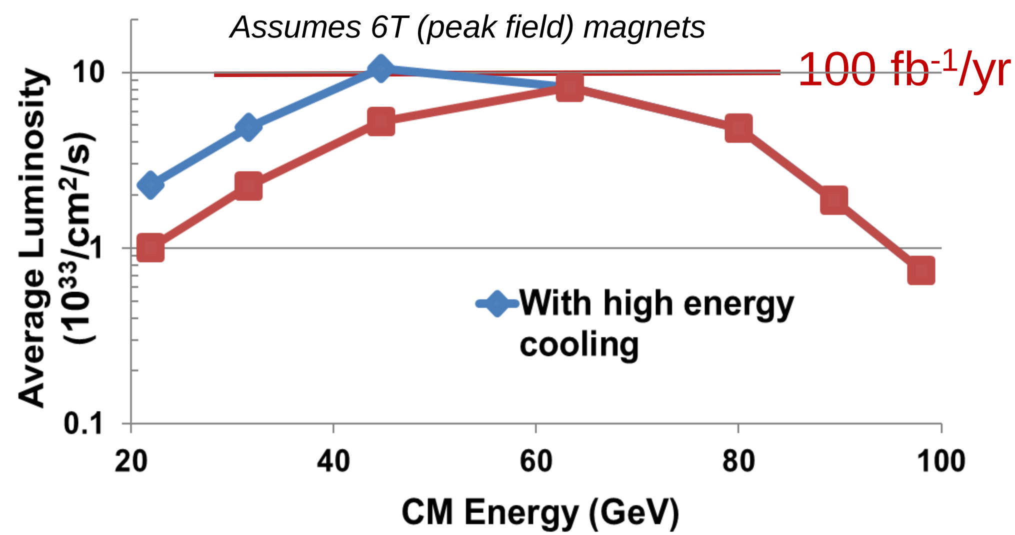
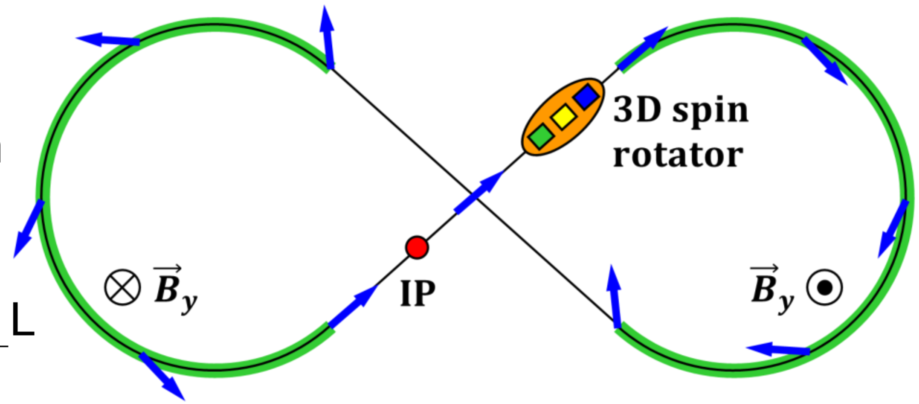


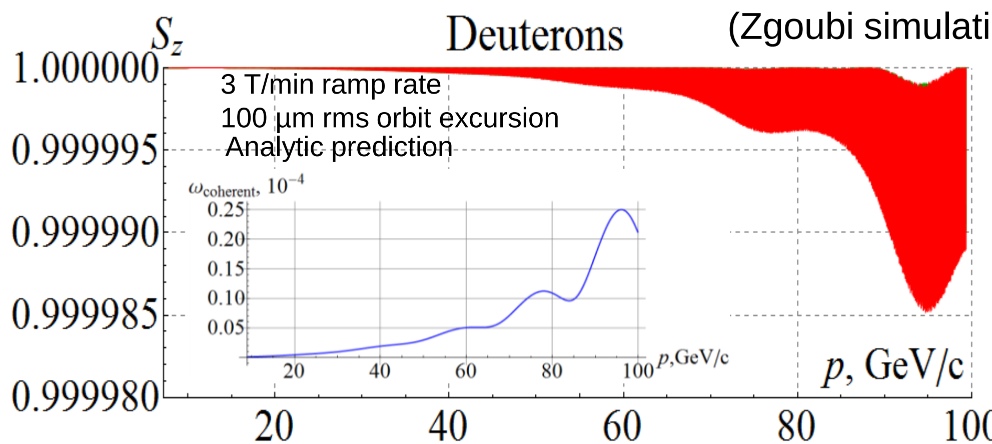
FIGURE 8 DESIGN ENSURES HIGH ION POLARIZATION

- Properties of a figure-8 structure enables preservation of injected 85% polarization
  - Spin precessions in the two arcs are exactly cancelled
  - In an ideal structure (without perturbations) all solutions are periodic
  - The spin tune is zero independent of energy
- A figure-8 ring provides unique capabilities for polarization control
  - Local spin rotator determines spin tune and local spin direction
  - $B_{||}L$ of only 3 Tm provides deuteron polarization stability up to 100 GeV
  - A conventional ring at 100 GeV would require $B_{||}L$ of 1200 Tm or $B_{\perp}L$ of 400 Tm



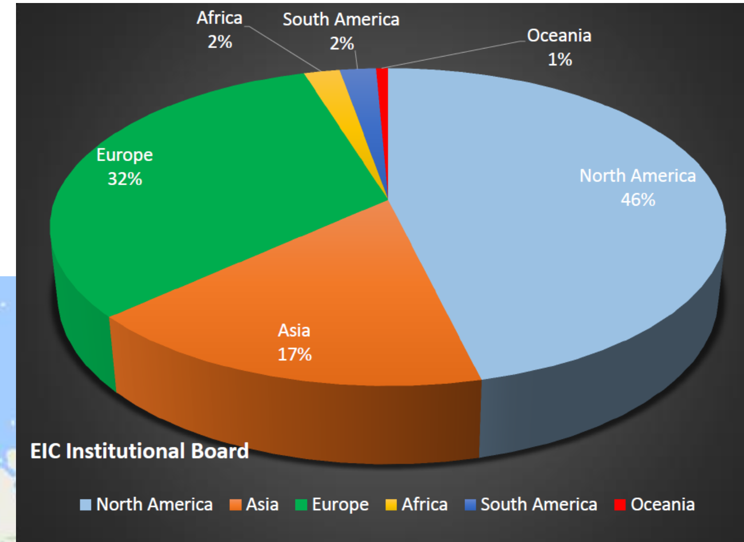
- Recent progress:
  - Start-to-end deuteron acceleration (folding in analytic-calculated spin tune requirement and orbit excursion due to magnet misalignments)
  - Deuteron spin is highly stable in figure-8 rings

(Zgoubi simulation)



Worldwide Interest in EIC Physics

The EIC Users Group: EICUG.ORG



Formed 2016 – 969 collaborators, 30 countries, 197 institutions as of Dec. 31, 2019

Map of institution's locations

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

EIC: 21st Century QCD Laboratory

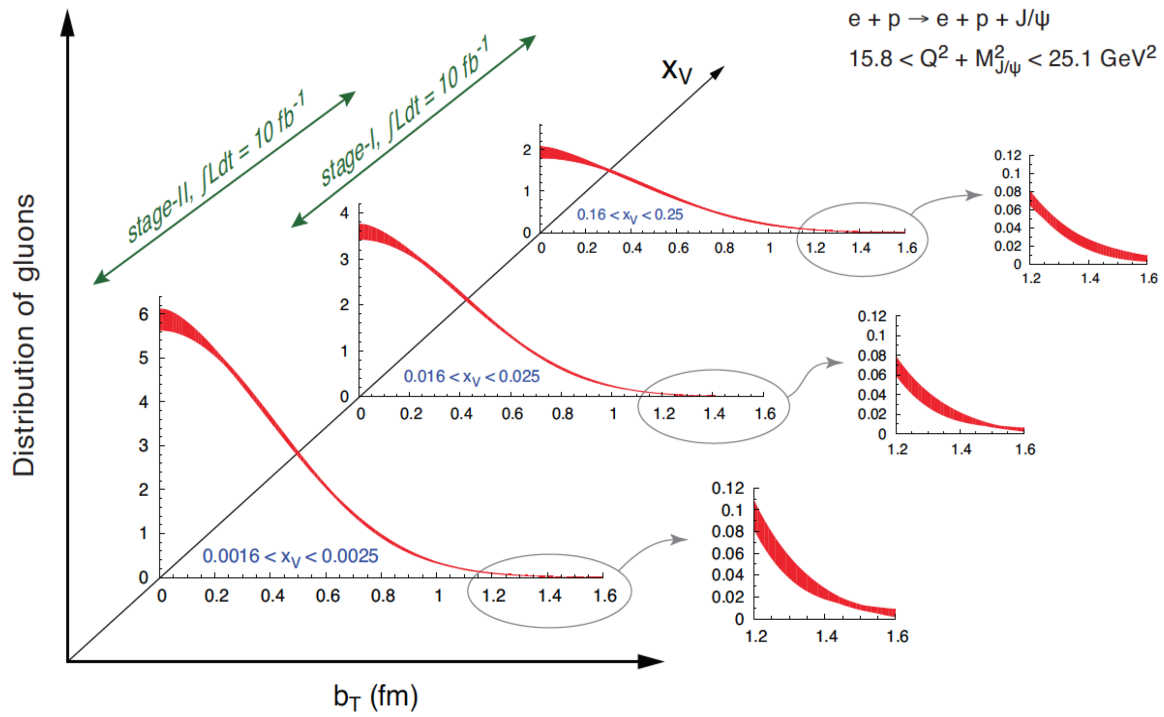
- To explore the fundamental structure and dynamics of the matter in the visible world

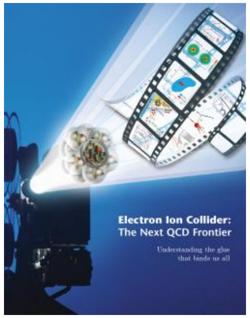
$$L_{QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j \left[i\gamma^{\mu} D_{\mu} - m_j \right] q_j - \frac{1}{4} G^{a}_{\mu\nu} G^{a\mu\nu}$$

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

- Interactions arise through fundamental symmetry principles
- Properties of the visible universe emerge through complex structure of the QCD vacuum
- The proton is a highly relativistic system described by QCD, a fully relativistic quantum field theory.
- Lattice QCD is an increasingly powerful means to carry out *ab initio* QCD calculations of hadron structure in the rest frame.
- 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 themselves, which lies at the heart of modern technologies.

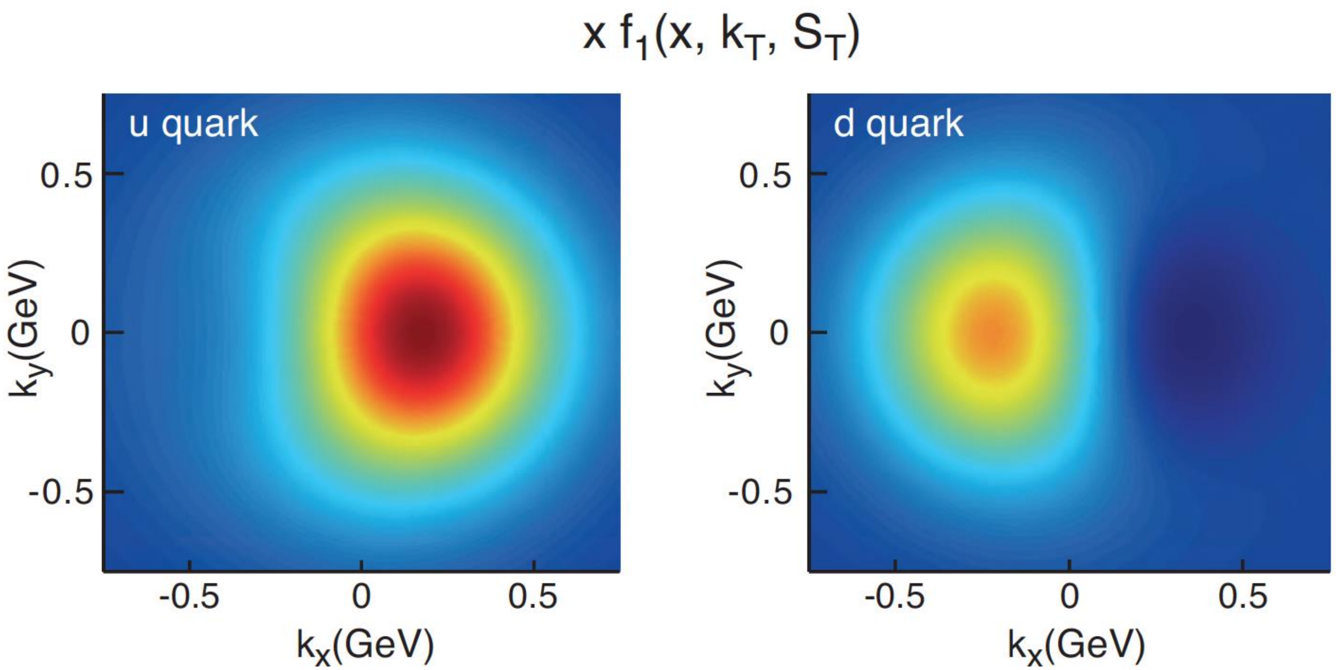
Transverse Spatial Distribution of Gluons

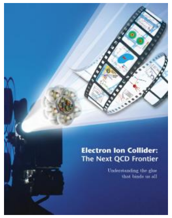




- How are gluons spatially distributed in a proton or a nucleus?
- Is the distribution smooth?
- How does it differ from the charge distribution?
- **First ever tomographic images of ocean of gluons within matter !**

Transverse Momentum Distributions



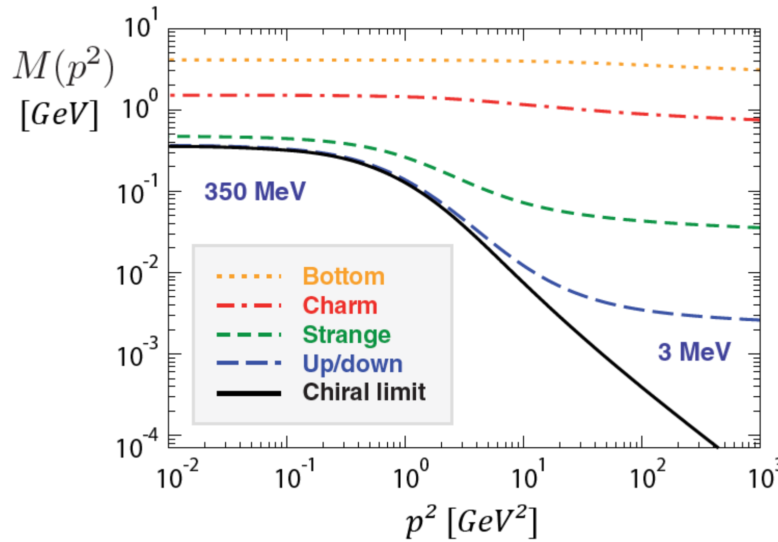


- Spin and the ability to look at transverse momentum together give a powerful new window into QCD
- TMDs directly related to orbital motion
- For example, we can explore for the first time **interference in quantum phases due to color force – impossible with purely 1D/longitudinal experiments**

THE INCOMPLETE HADRON: MASS PUZZLE

"Mass without mass!"

Proton: Mass ~ 940 MeV
constituents acquire mass by DχSB,
most of mass generated by dynamics
Kaon: Mass ~ 490 MeV
boundary between emergent-mass and
Higgs-mass generation mechanisms
Pion: Mass ~ 140 MeV
exists only if mass is dynamically generated

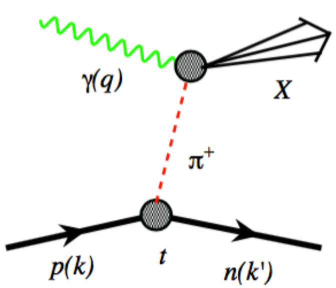


- **EIC's expected contribution in:**

✧ Quark-gluon energy:
$\propto$ *quark-gluon momentum fractions*

In the chiral limit, for the pion (m_π = 0):

$$\langle \pi(q)|\Theta_0|\pi(q)\rangle = -q_\mu q_\mu = m_\pi^2 = 0$$




EPJ A
Hadrons and Nuclei

Eur. Phys. J. A (2019) 55: 190 DOI 10.1140/epja/i2019-12885-0

Pion and kaon structure at the electron-ion collider

Sometimes interpreted as that in the chiral limit the gluons disappear and thus contribute nothing to the pion mass: **is the pion empty or full of gluons?**

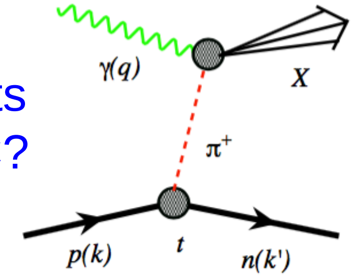
On the other hand, from phenomenological view, at a given scale, **there is far less glue in the kaon than in the pion. All measurable at EIC.**

For π and K with Sullivan process

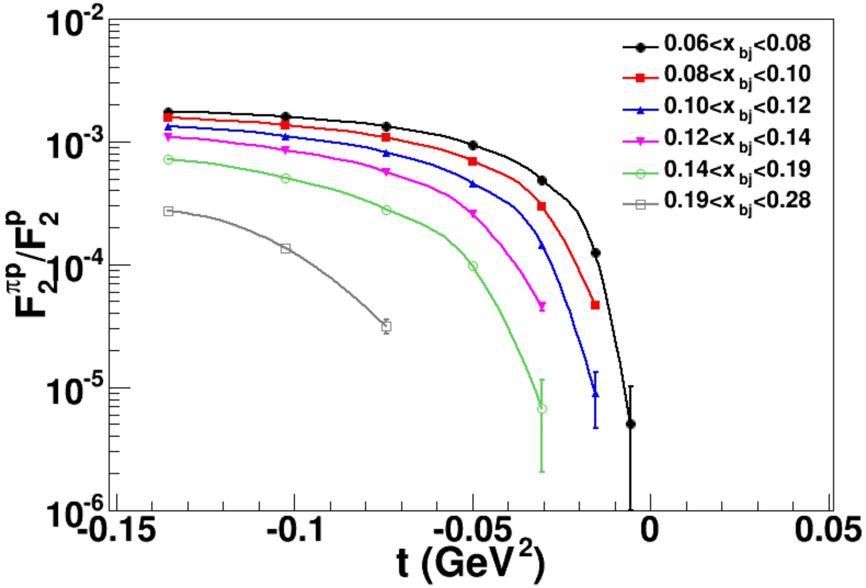
A.C. Aguilar et al., Pion and Kaon structure at the EIC, arXiv:1907.08218, EPJA 55 (2019) 190.

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 another decade.



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 (for JLab kinematics)

EIC SCIENCE: DEUTERONS AND NEUTRON TARGETS

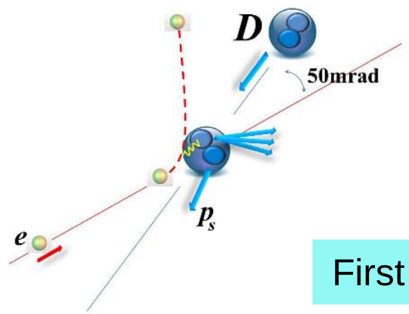
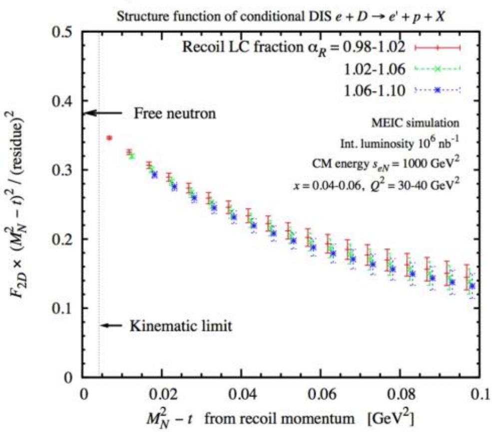


Figure-8 design enables polarized (vector and tensor) deuteron beams (>80% polarization).

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

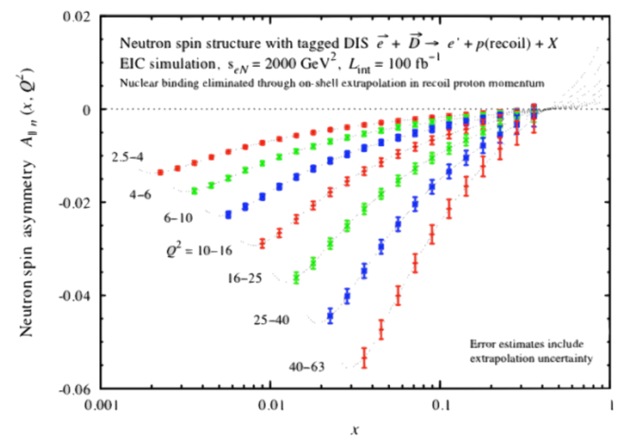
First precision measurement of *polarized* (and unpolarized) neutron is possible at EIC



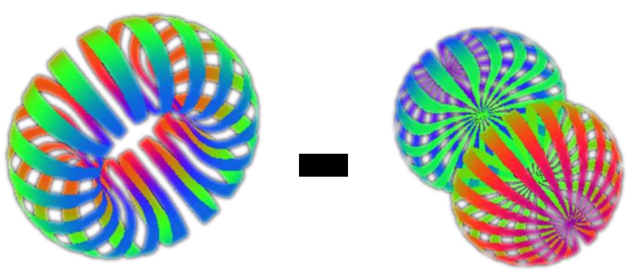
Extrapolation from bound to free neutron under control

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?

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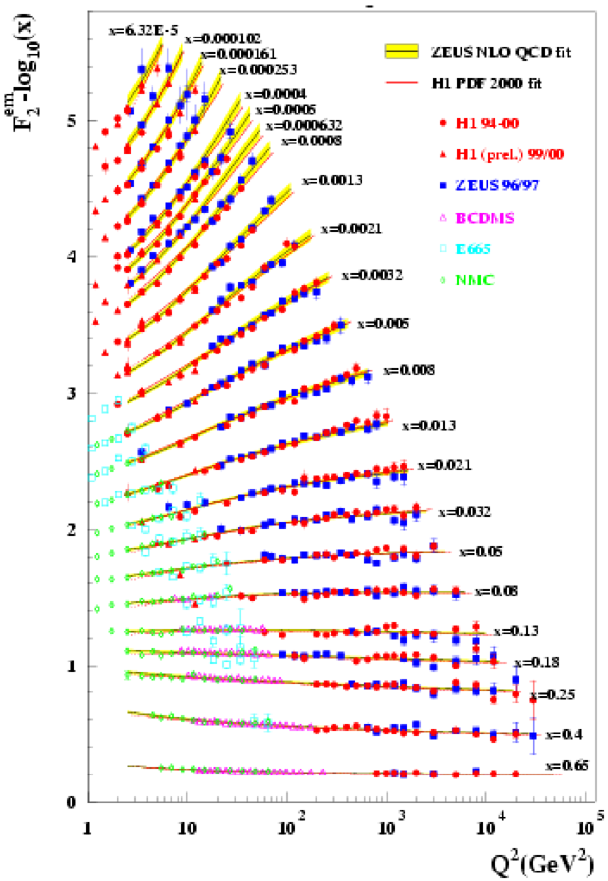
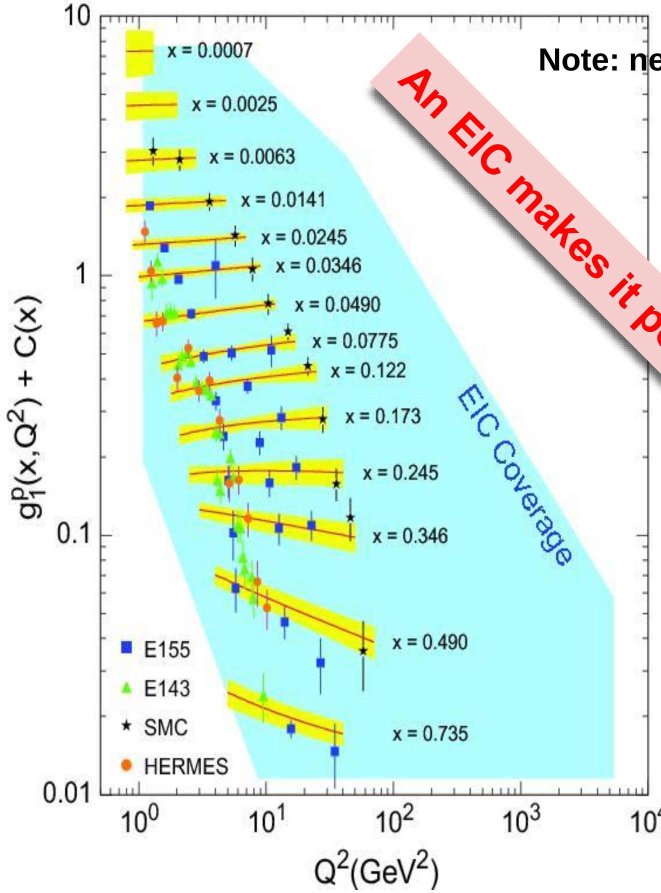
World Data on F_2^p World Data on g_1^p World Data on h_1^p

Similar for F_2^n



momentum

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

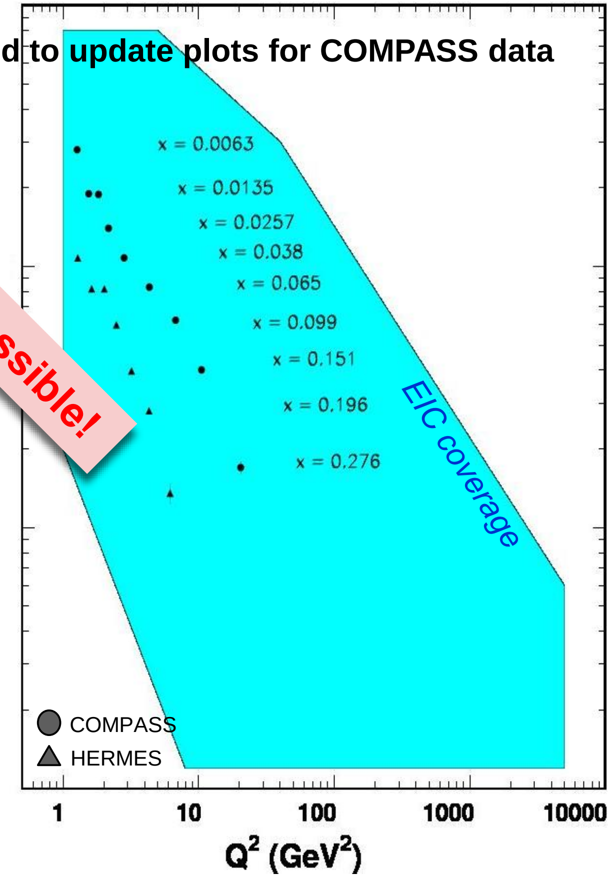


spin

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



transverse spin ~ angular momentum

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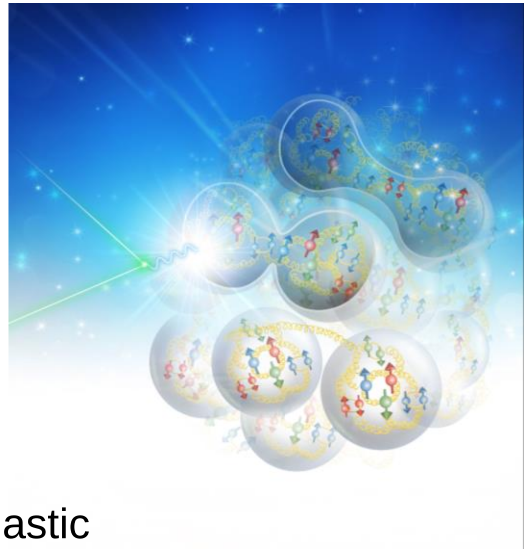
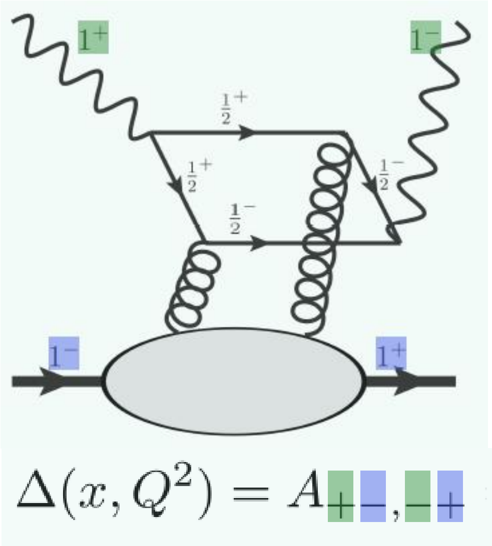
Exotic Glue in Nuclei



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…



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**

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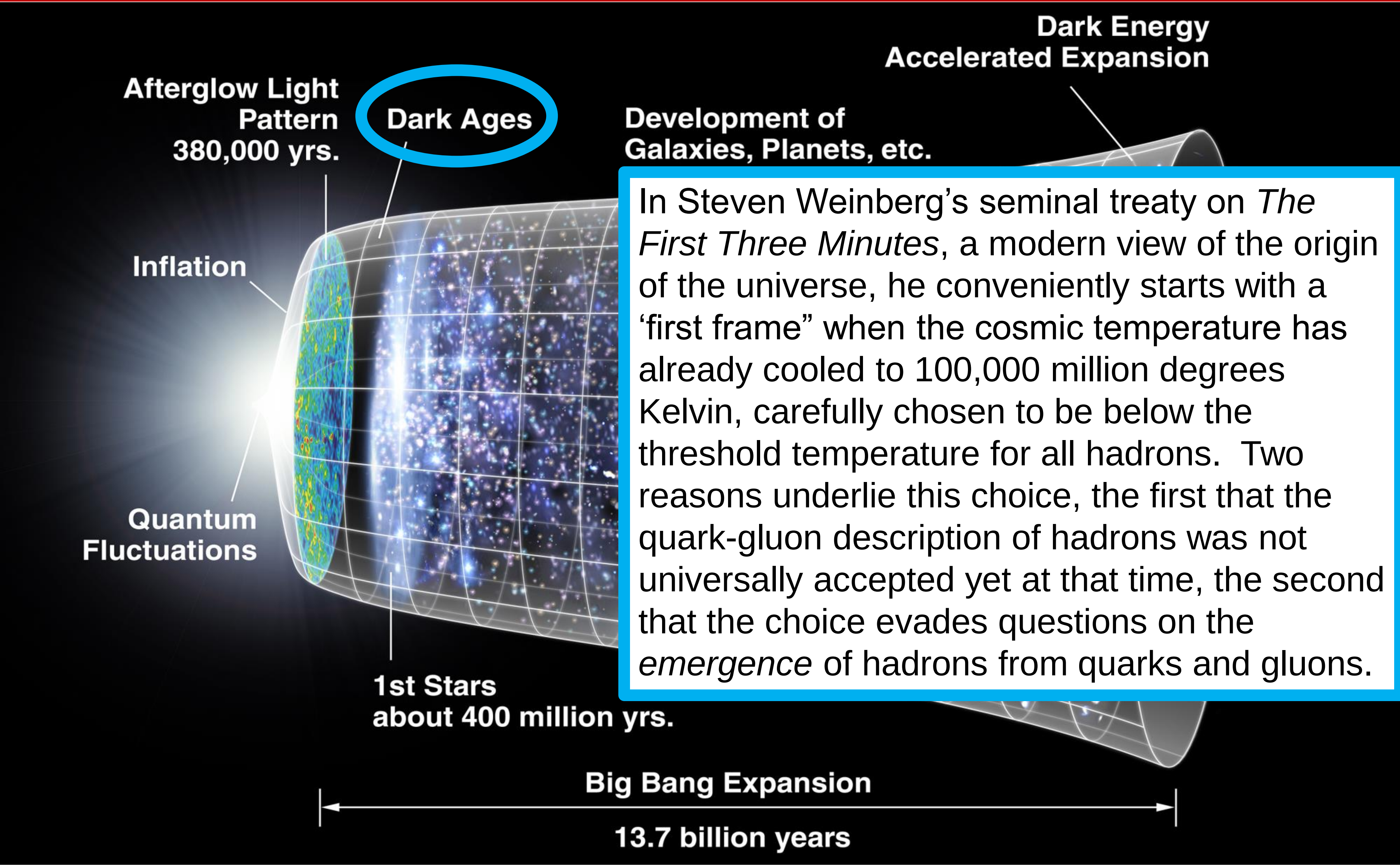
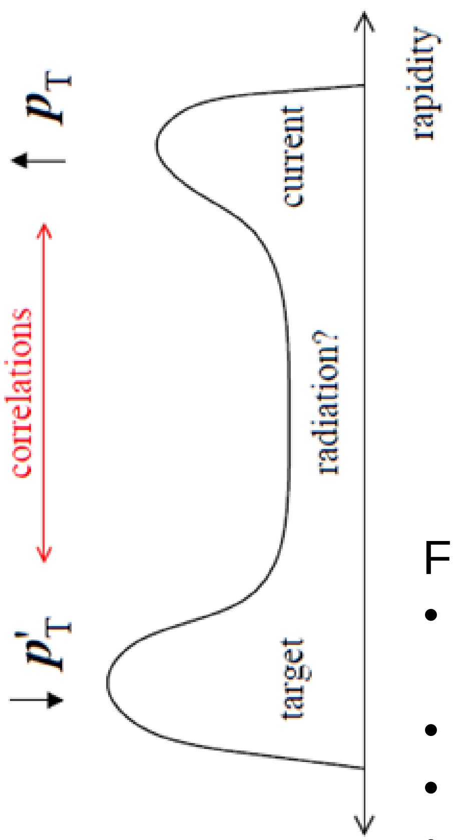
Timeline of the Universe

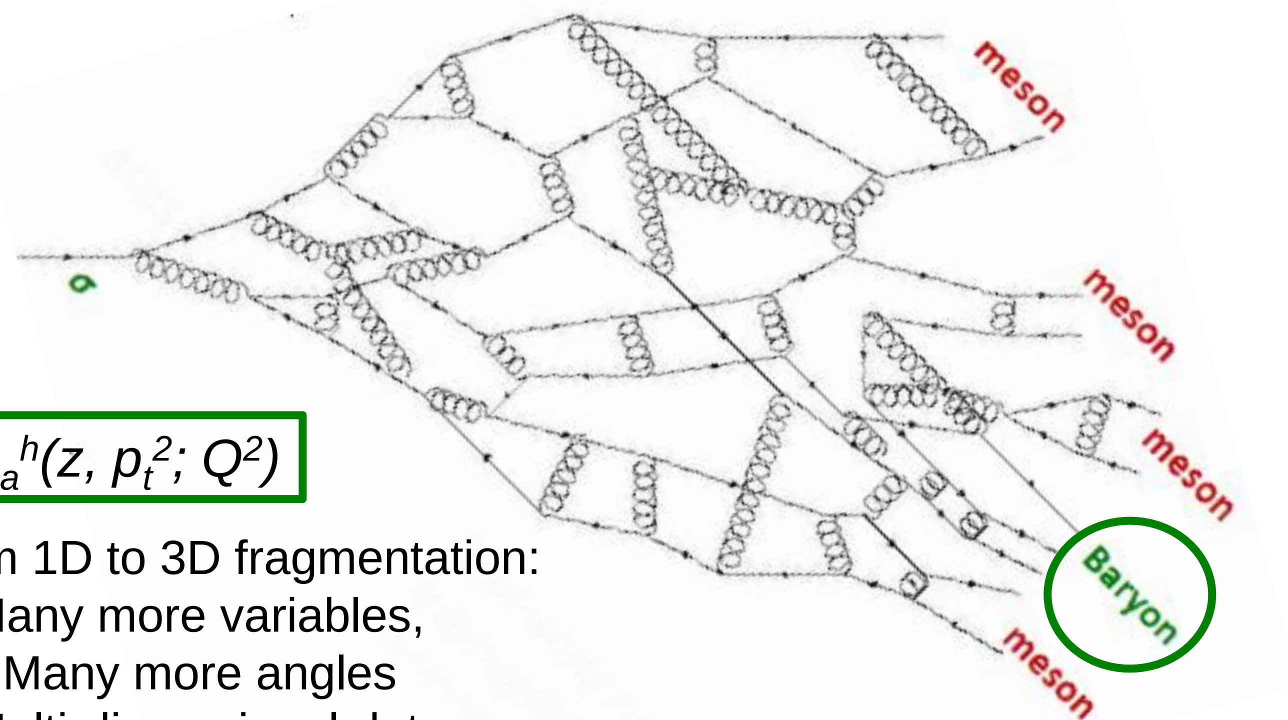


In Steven Weinberg's seminal treaty on *The First Three Minutes*, a modern view of the origin of the universe, he conveniently starts with a 'first frame" when the cosmic temperature has already cooled to 100,000 million degrees Kelvin, carefully chosen to be below the threshold temperature for all hadrons. 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 – candles of space-time





$\boxed{D_a^h(z, p_t^2; Q^2)}$

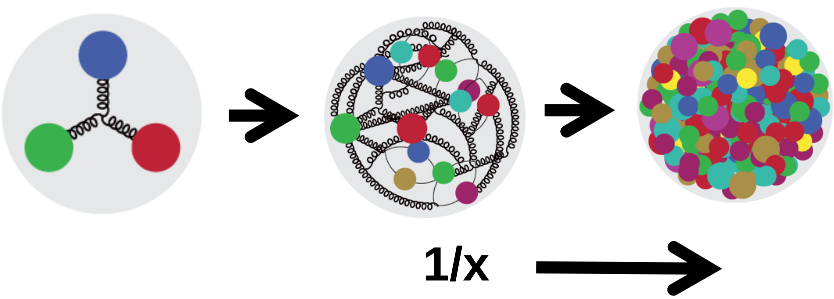
From 1D to 3D fragmentation:

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

First step is always unpolarized cross sections
→ JLab/12 GeV (but limited in kinematics)

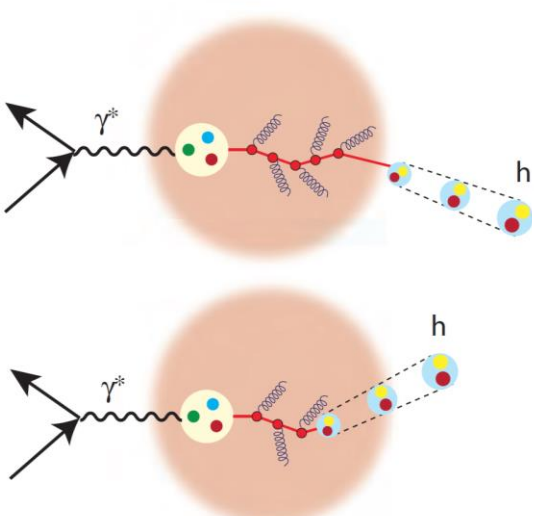
Understanding of the 3D structure of fragmentation into a hadron requires studies of transverse momentum, spin and hadron species dependence

QCD Dynamics in Nuclei

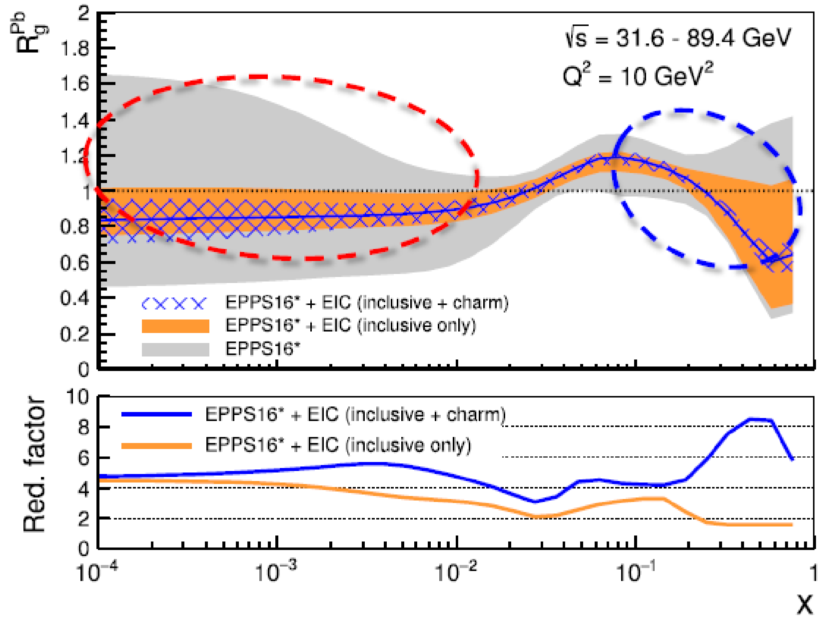


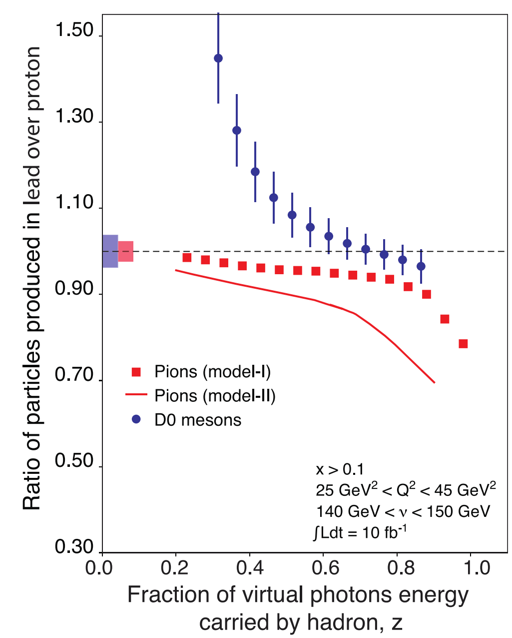
- Hadronization: the process that connects QCD with experiment
- Nuclear PDFs: we know ~nothing about gluons in nuclei
- Particle transport, color neutralization and propagation
- Diffraction: no net color exchange
- Jets

Hadronization



Salvatore Fazio, arXiv:1709.00076





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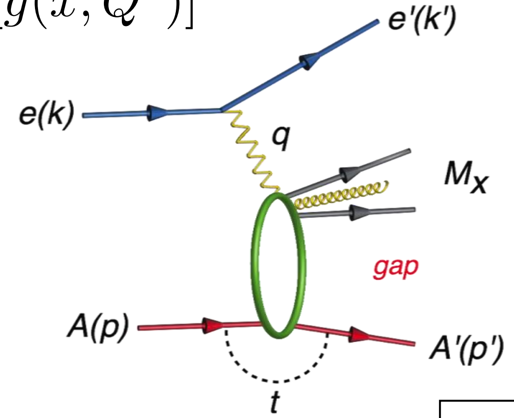
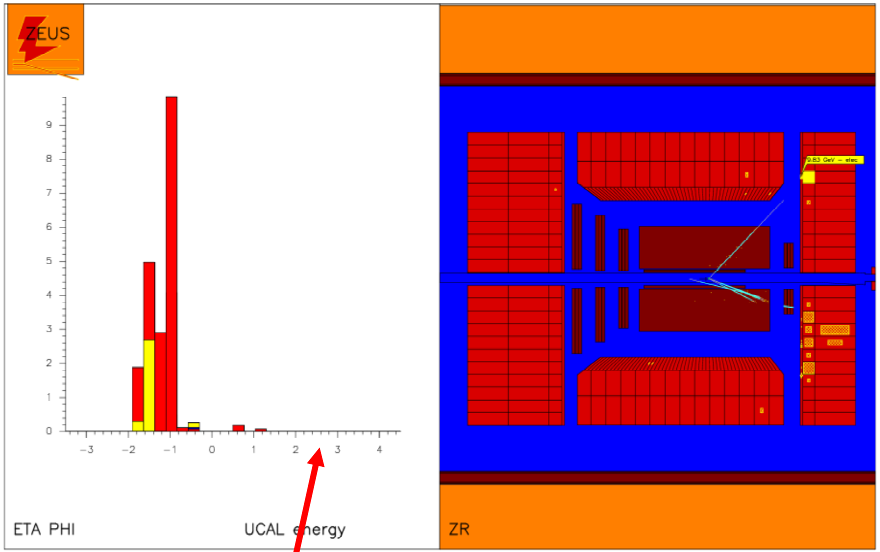
GLUON SATURATION – WHAT TO MEASURE?

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

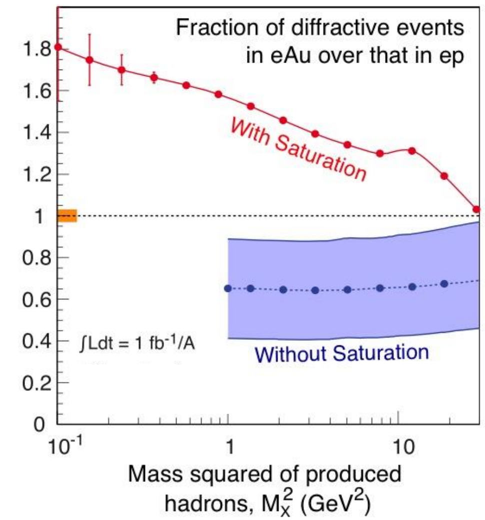
Diffractive event

$$\sigma_{\text{diff}} \propto [g(x,Q^2)]^2$$





No activity in proton direction



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

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

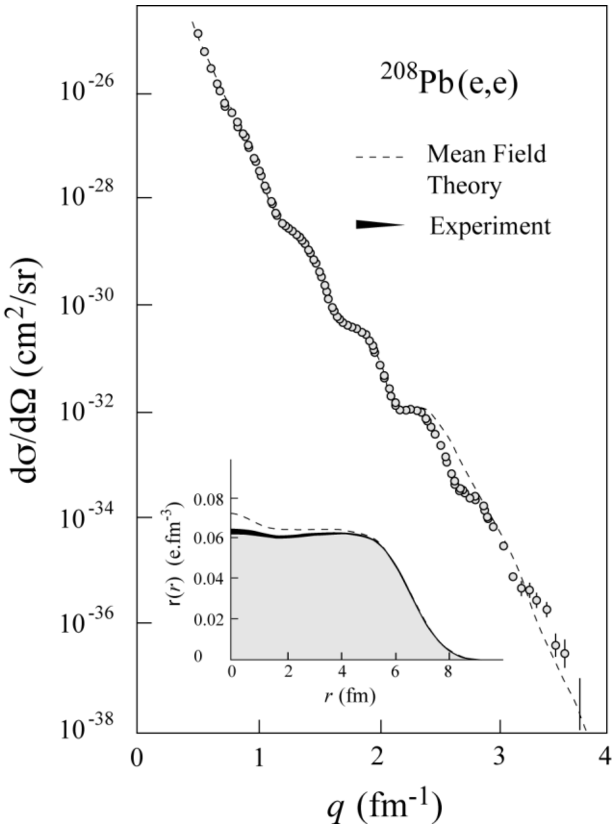
(EIC: utilize g ~ $A^{1/3}$ x $s^{0.3}$ to hunt for c.q. map onset of saturation)

Exposing different layers of the nuclear landscape with electron scattering

History:

Electromagnetic

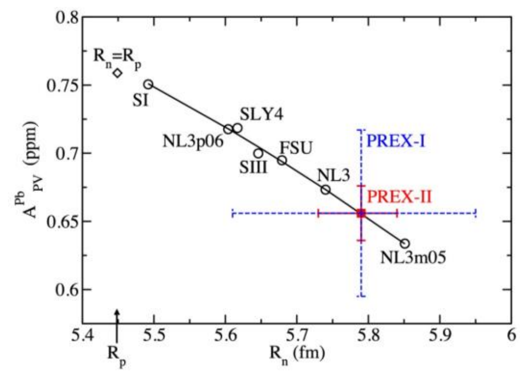
Elastic electron-nucleus scattering → charge distribution of nuclei

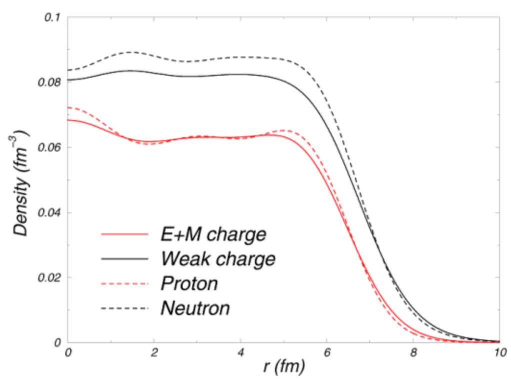


Present/Near-future:

Electroweak

Parity-violating elastic electron-nucleus scattering (or hadronic reactions *e.g.* at FRIB) → neutron skin

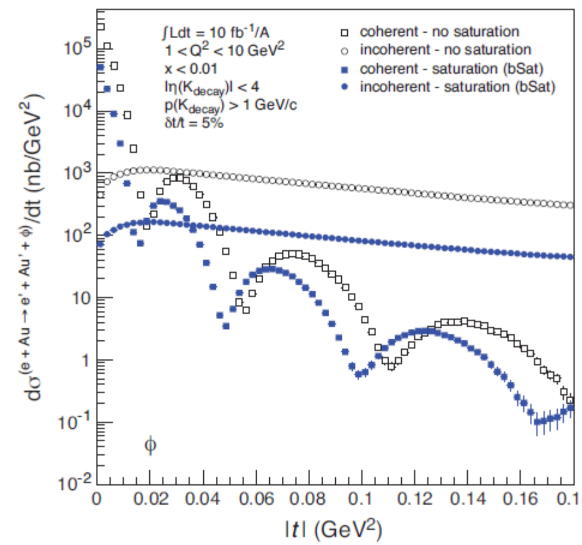




Future:

Color dipole

ϕ Production in coherent electron-nucleus scattering → gluon spatial distribution of nuclei



Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

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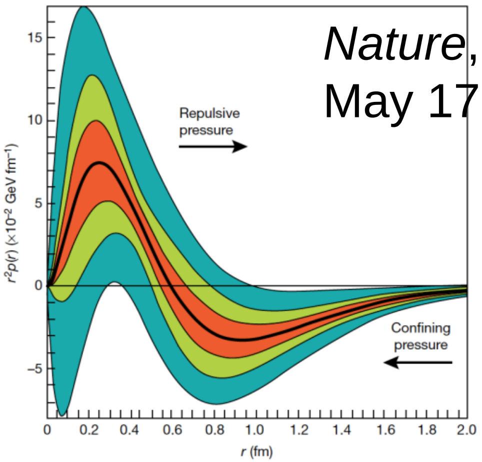
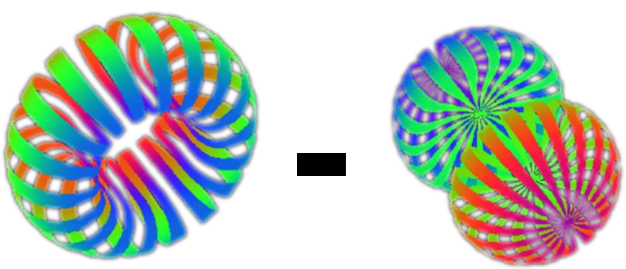
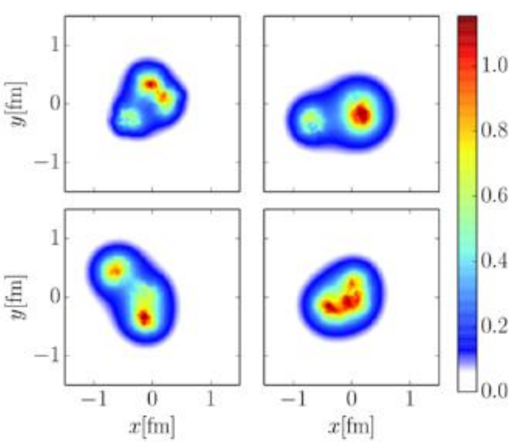
New Avenues



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



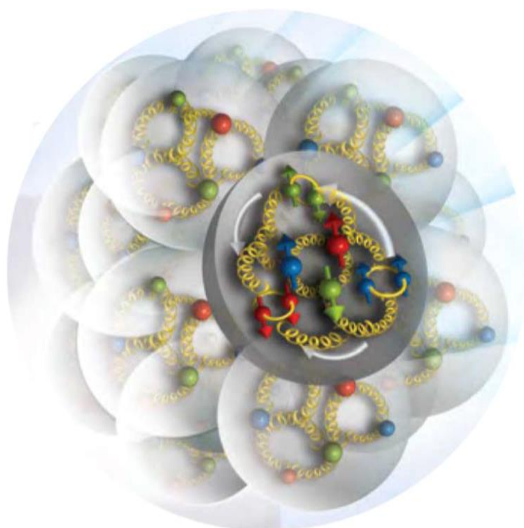


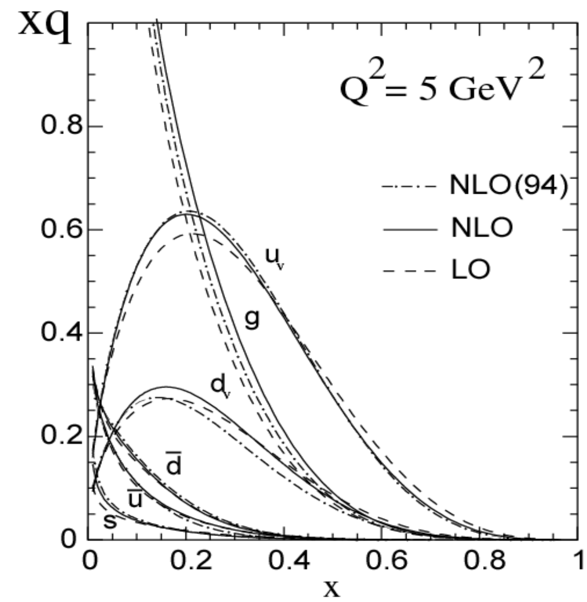
- **Pressure in the Proton**
  - First determination using DVCS (Deeply Virtual Compton Scattering) data
  - Interior pressure in proton is > pressure inside a neutron star! ***Who knew that!***
  - Lattice calculation motivates determination of gluon GPDs at EIC
- **Polarized Deuteron Structure**
  - Inclusive Deep Inelastic Scattering on Vector- and Tensor-Polarized Deuterons
  - Leading-twist gluon contribution $\Delta(x,Q^2)$: Is there exotic glue in nuclei?
  - Structure fn b_1: 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?

Nuclear Femtography

Science of mapping the position and motion of quarks and gluons in the nucleus.

Artist's Conception
of Quark and Gluons
in a proton and nucleus





12 GeV

.. is just beginning → **EIC**

REQUIRES:

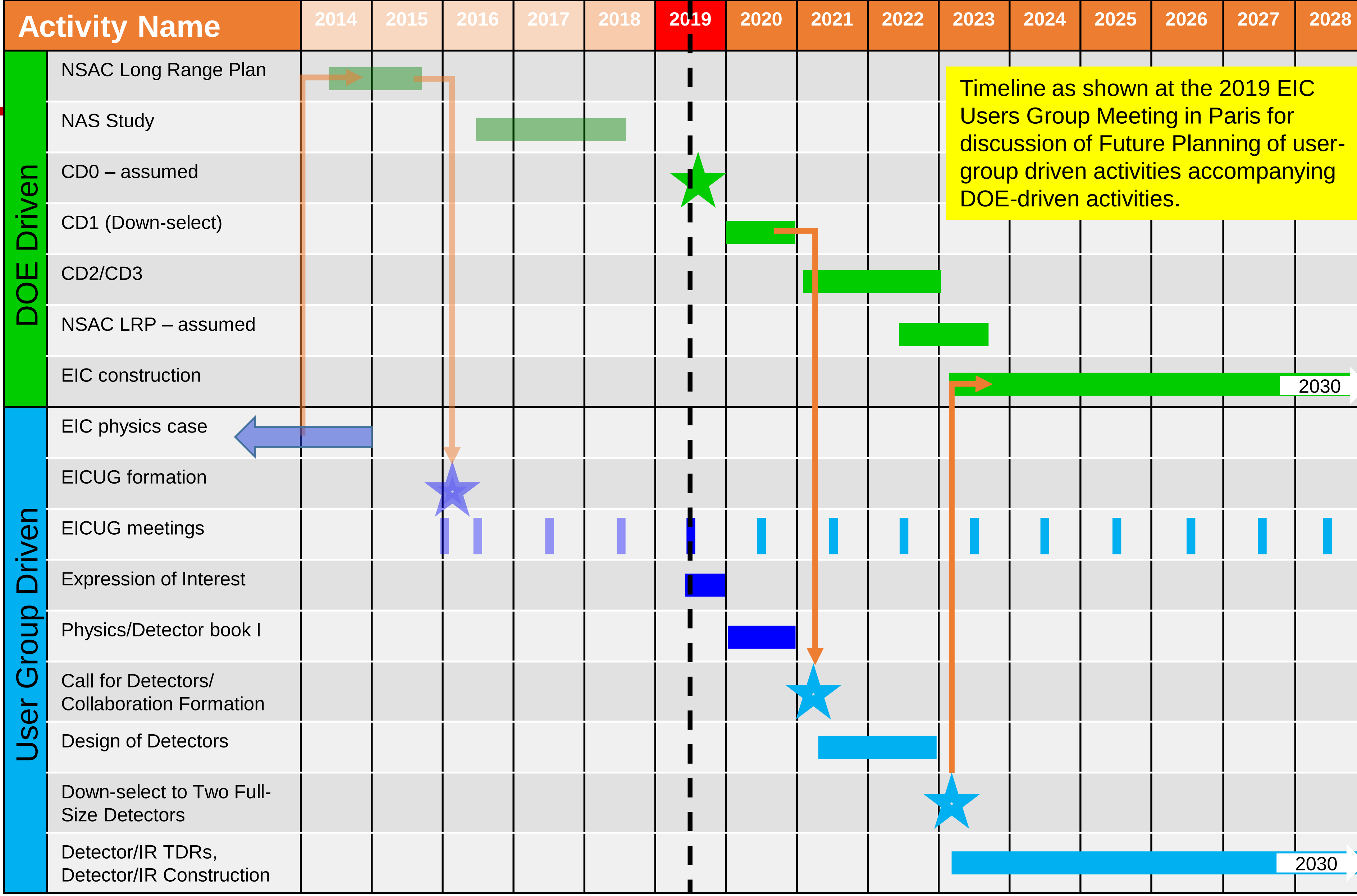
- *High beam polarization*
- *High electron current*
- *High target polarization*
- *Large solid angle spectrometers*

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 **world wide interest** in collaborating on the EIC
- Accelerator scientists at RHIC and JLab, in collaboration with many outside interested accelerator groups, can provide the **intellectual and technical leadership to realize the EIC**, a frontier accelerator facility.

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

EIC TIMELINE AND
EICUG YELLOW REPORT ACTIVITIES



CD0 = DOE “Mission Need” statement; **CD1** = design choice and site selection

CD2/CD3 = establish project baseline cost and schedule

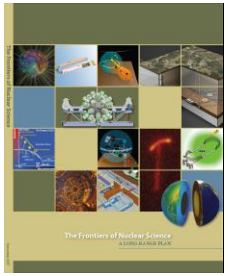
PHYSICS AND DETECTOR CONCEPTUAL DEVELOPMENT STUDY

"EIC Yellow Report(s) Exercise"

- **Initiated by the EICUG Steering Committee**
- **Purpose**
  - Advance state of documented physics studies and detector concepts in preparation for the EIC.
  - Provide basis for further development of concepts for experimental equipment best suited for science needs, including complementarity of two detectors
  - Input towards future Technical Design Reports (TDRs)
- **Approach**
  - Two WG: *Physics* requirement and *Detector* concepts - 4 conveners each
  - Several sub-groups each, ~2 conveners/sub-group
  - Time limited effort: ~1 year
- **Meetings**
  - December 12-13, 2019, MIT: Kick-off organizational meeting
  - Workshops
    - March 19-21, 2020, Temple U., Philadelphia
    - May 22-24, 2020, U. of Pavia, Pavia, Italy
    - September 17-19, 2020, CUA, Washington D.C.
    - November 19-21, 2020, UCB/LBNL, Berkeley, CA

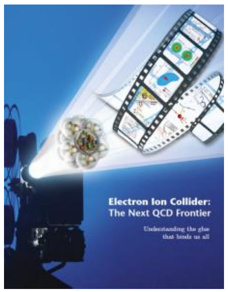
It is essential, EIC activities in DOE seem to proceed fast. Let's get going !!!

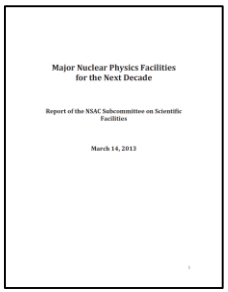
U.S. Electron-Ion Collider Planning 2007-18



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

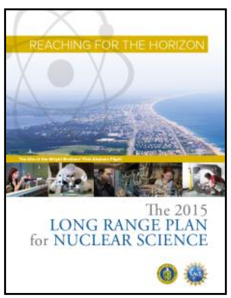
March 14, 2013

2013 Electron Ion Collider White Paper

(Writing committee convened by Jefferson Lab and BNL)

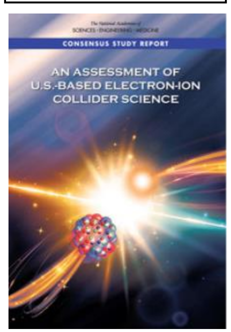
2013 NSAC Subcommittee on Future Facilities

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



2015 NSAC Long-Range Plan

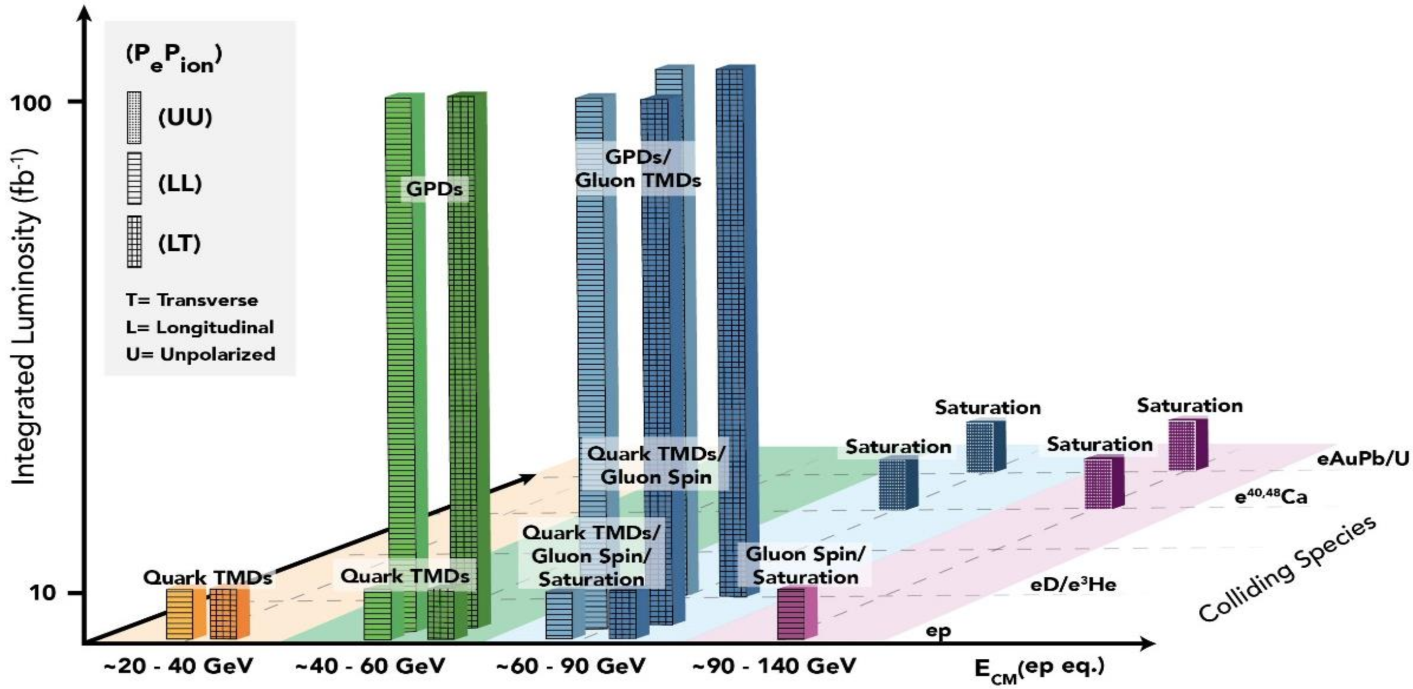
"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."

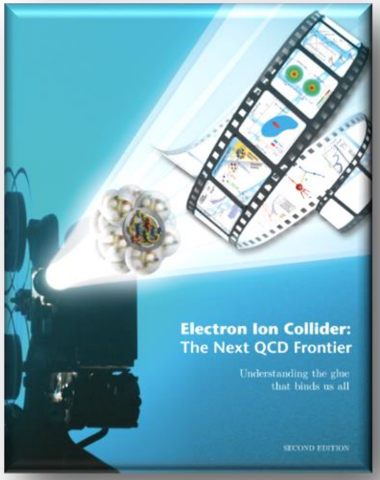


2018 National Academy of Sciences (NAS) – Assessment of U.S. Based Electron-Ion Collider Science

"…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 Scientific Program: White Paper Science Goals





- The total integrated luminosity to complete whitepaper program is ~700 fb^{-1}
- This made some assumptions, e.g., that wherever the EIC White Paper assumed spin-polarized runs with e-p, there likely also would be similar spin-polarized e-d or e-^{3}He runs, both longitudinal and transverse.
- At $\mathcal{L}_{avg}$ = 10^{34} $cm^{-2}s^{-1}$ this program requires 7 years of operation.
- **Luminosity, polarization and versatility of the EIC is key**

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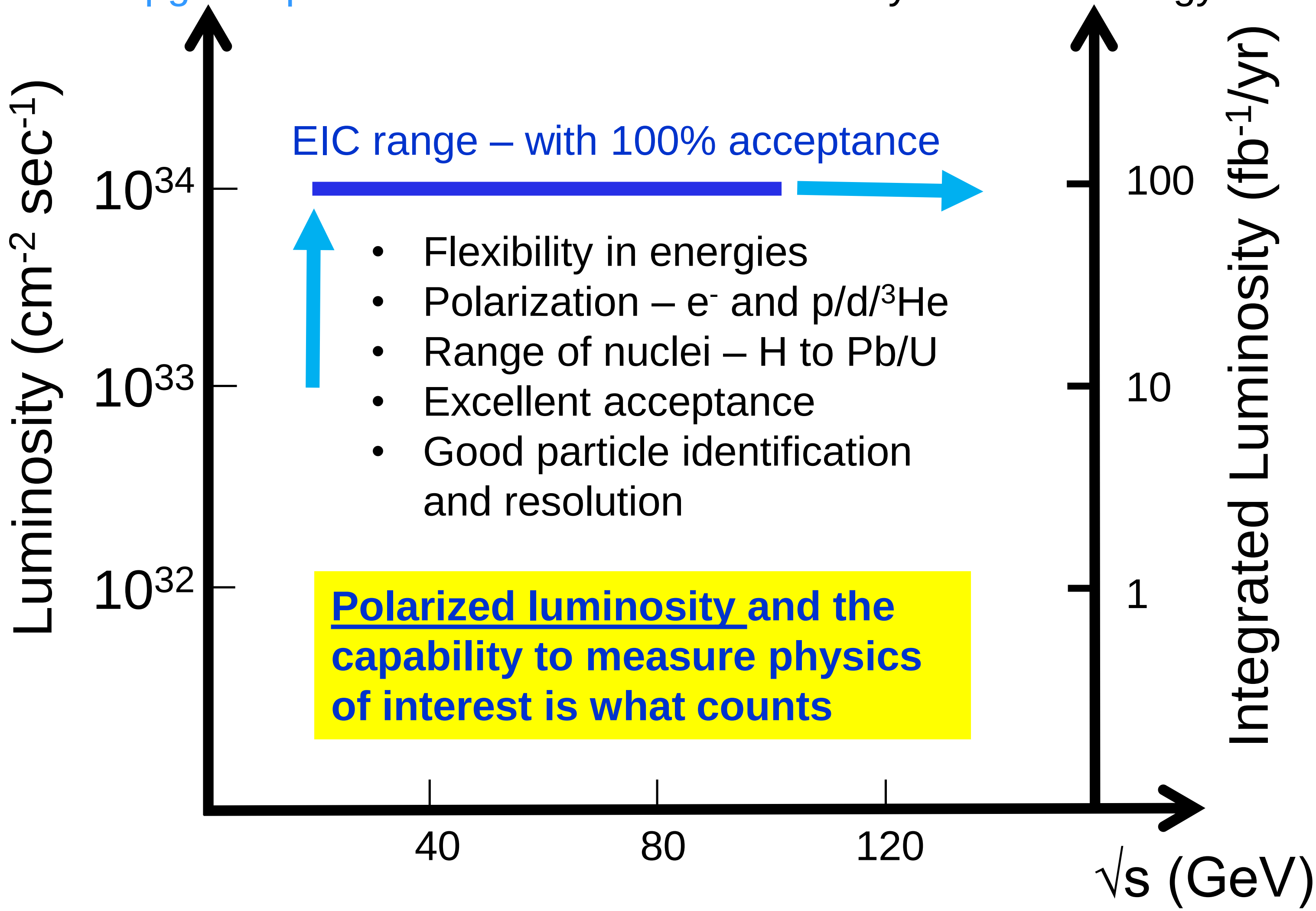
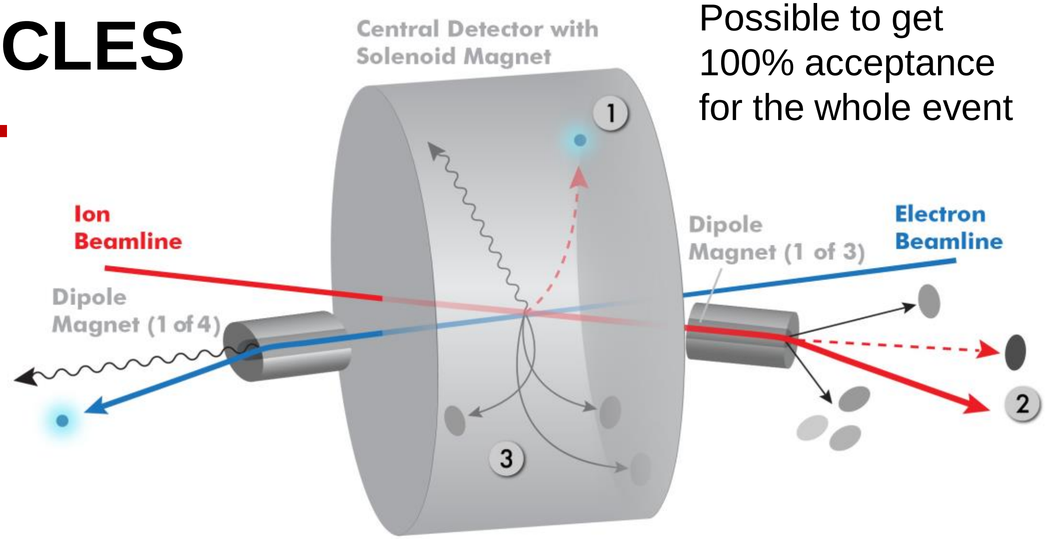
PHYSICS VS. EIC DESIGN REQUIREMENTS

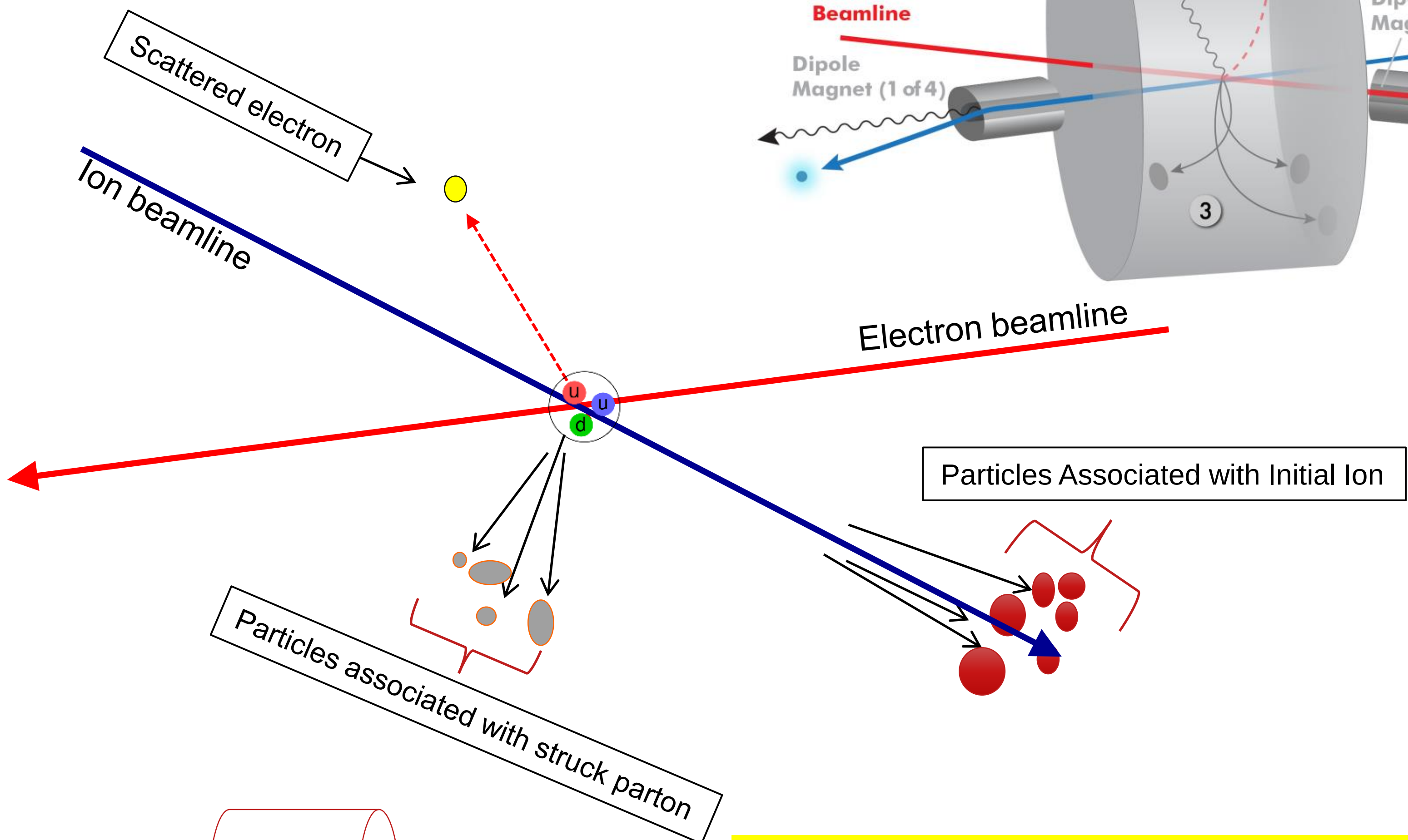
What the nuclear physicists dream off and drives the EIC designs, with upgrade paths included either in luminosity or in CM energy

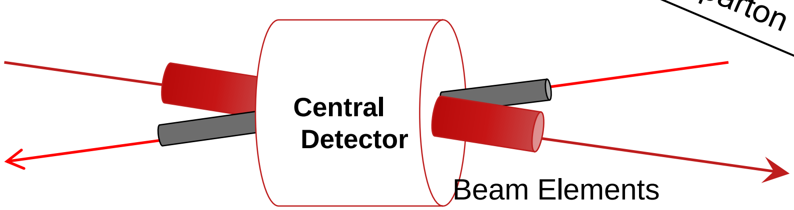


EIC FINAL STATE PARTICLES

Possible to get 100% acceptance for the whole event







Beam elements limit forward acceptance
Central Solenoid not effective for forward

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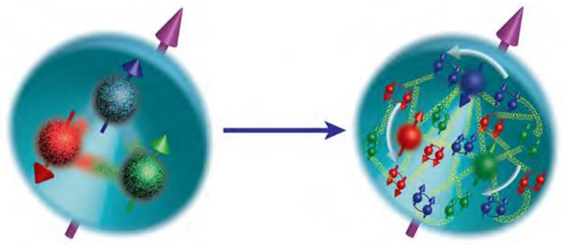
EIC – World's First Polarized eN Collider



A spin factory of polarized electrons and polarized protons/light nuclei: imaging the quarks and gluons

- 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?

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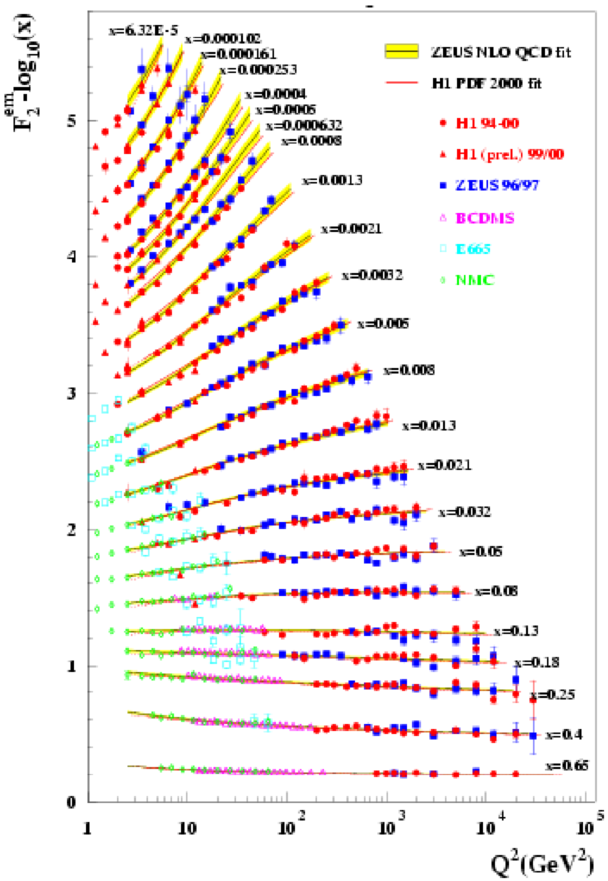
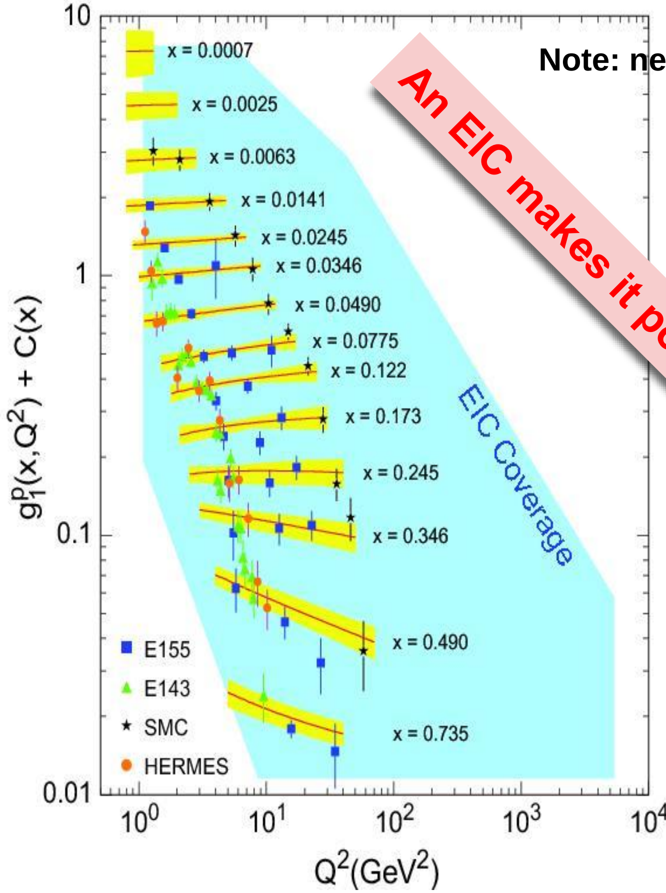
World Data on F_2^p World Data on g_1^p World Data on h_1^p



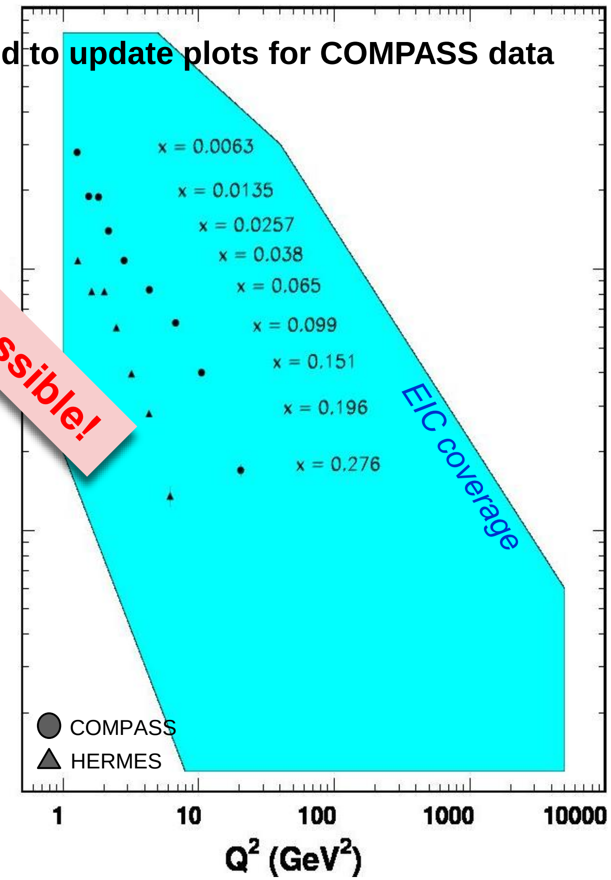
momentum



spin

An EIC makes it possible!

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



transverse spin ~
angular momentum

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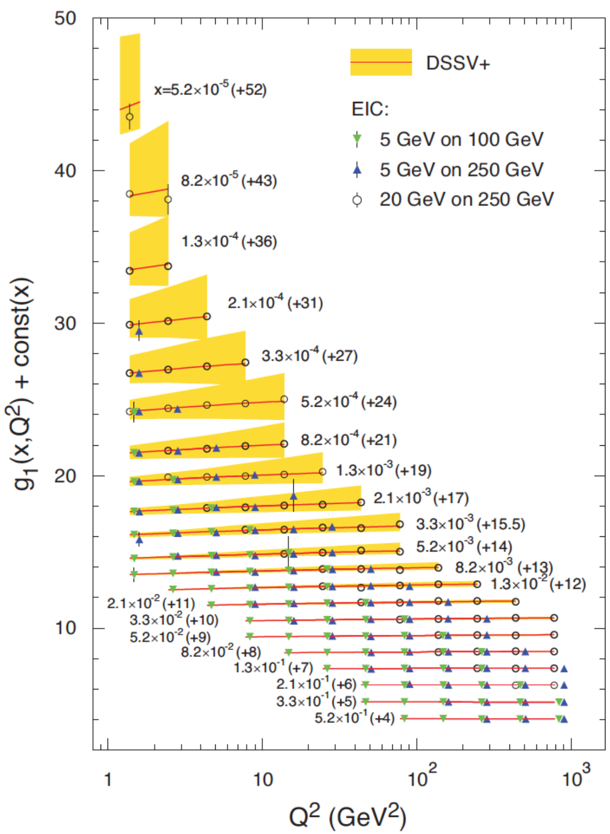
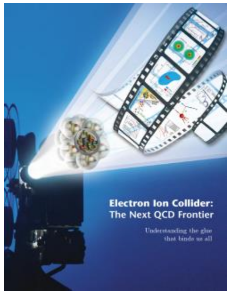
THE INCOMPLETE HADRON: SPIN PUZZLE

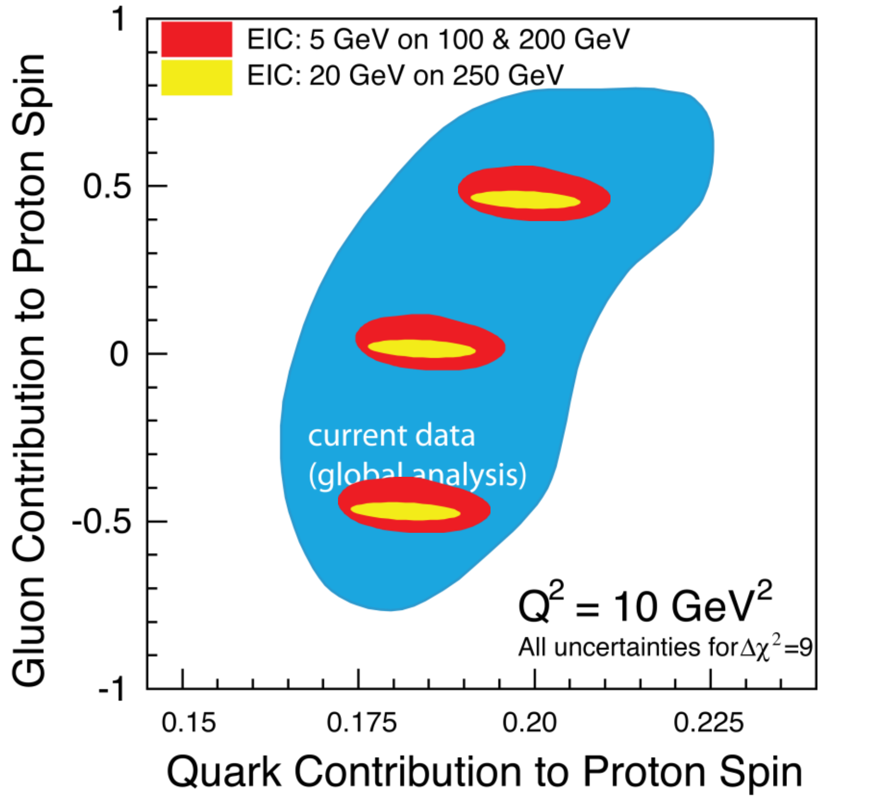
"Helicity sum rule"

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

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







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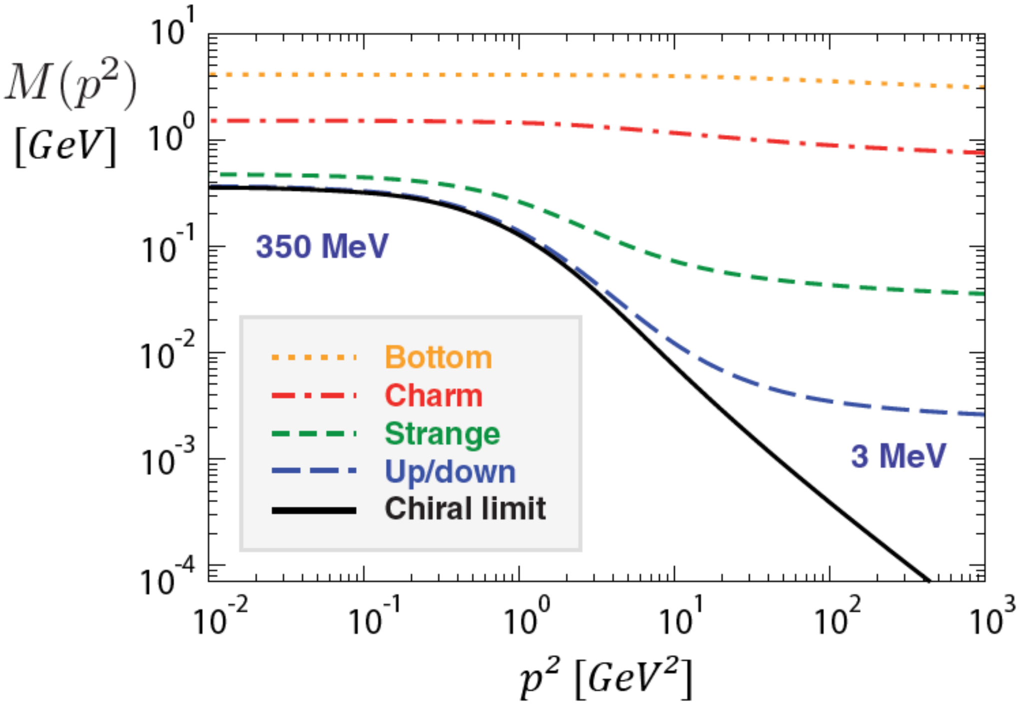
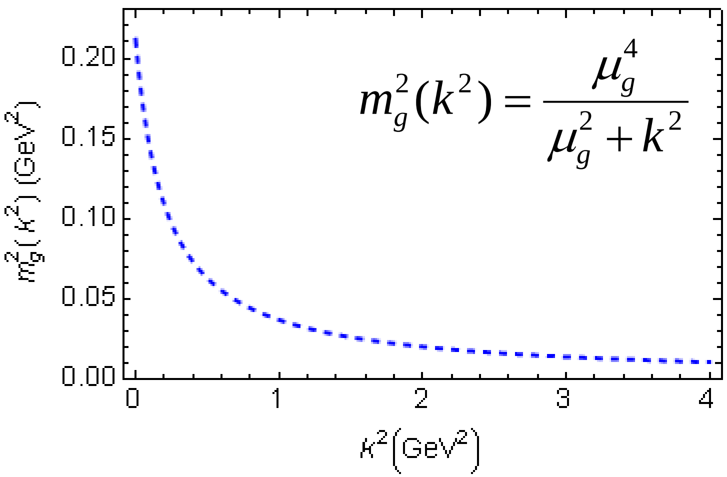
MASS OF THE VISIBLE UNIVERSE

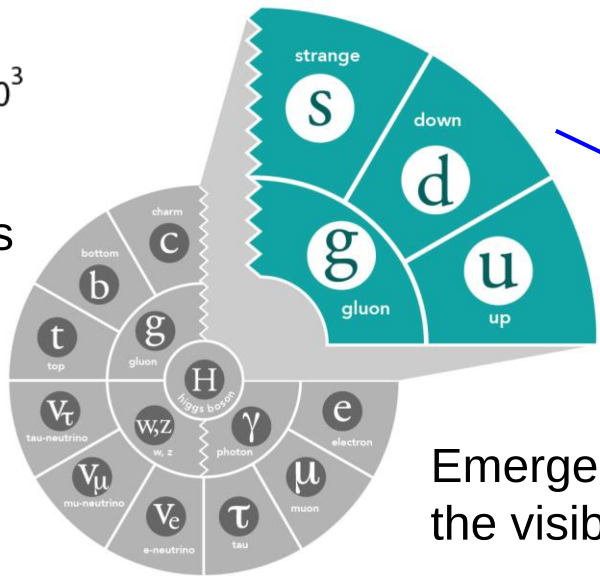


Gluon mass-squared function



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.

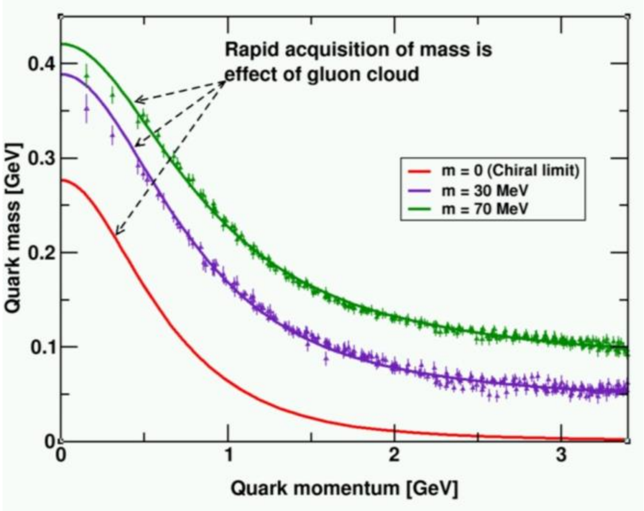


Emergent mass of the visible universe

THE INCOMPLETE HADRON: MASS PUZZLE

"Mass without mass!"

Bhagwat & Tandy/Roberts et al



Proton: Mass ~ 940 MeV
constituents acquire mass by DχSB,
most of mass generated by dynamics

Kaon: Mass ~ 490 MeV
boundary between emergent-mass and
Higgs-mass generation mechanisms

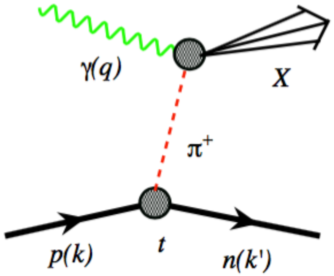
Pion: Mass ~ 140 MeV
exists only if mass is dynamically generated

- **EIC's expected contribution in:**
  - Quark-gluon energy:
    $\propto$ *quark-gluon momentum fractions*

In the chiral limit, for the pion (m_π = 0):

$$\langle \pi(q)|\Theta_0|\pi(q)\rangle = -q_\mu q_\mu = m_\pi^2 = 0$$

For π and K with Sullivan process

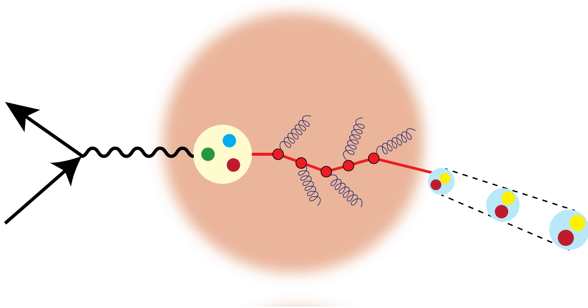


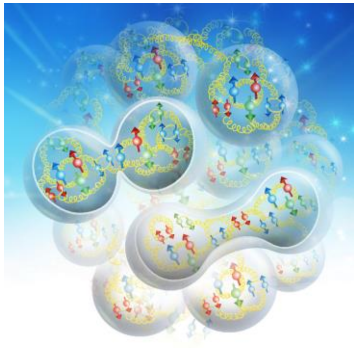
Sometimes interpreted as that in the chiral limit the gluons disappear and thus contribute nothing to the pion mass: **is the pion empty or full of gluons?**

On the other hand, from phenomenological view, at a given scale, **there is far less glue in the kaon than in the pion. All measurable at EIC.**

A.C. Aguilar et al., Pion and Kaon structure at the EIC, arXiv:1907.08218, EPJA 55 (2019) 190.

EIC – Versatility is Key





EIC: A Versatile Collider with a Hermetic Detector

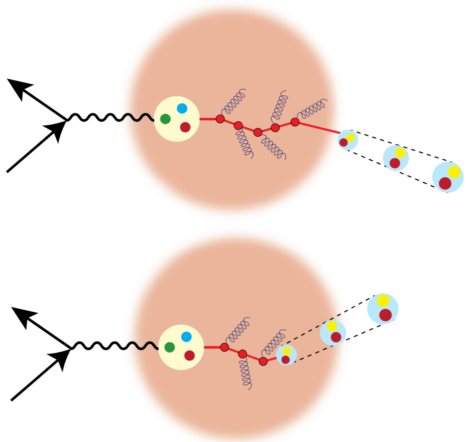
- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
- How do the confined hadronic states emerge from these quarks and gluons?
- How do the quark-gluon interactions create nuclear binding?

EMERGENCE OF HADRONS FROM PARTONS

Nucleus as a Femtometer sized filter

Unprecedented ν, the virtual photon energy range @ EIC : *precision & control*

$$\nu = \frac{Q^2}{2mx}$$

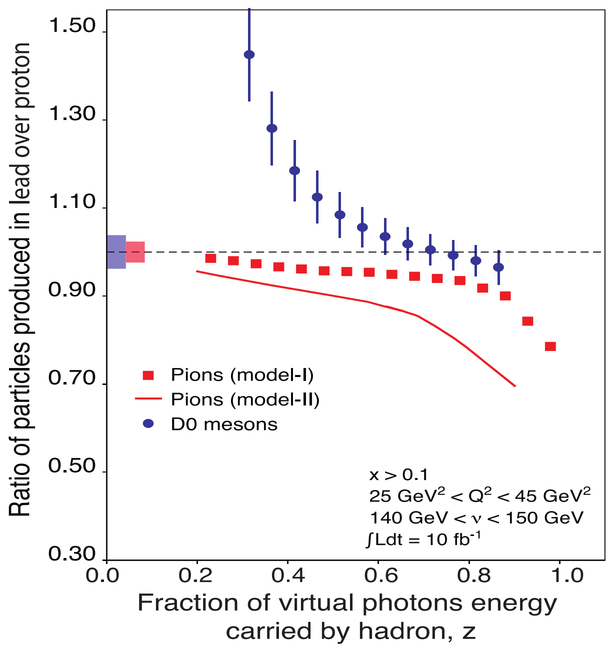


Control of ν by selecting kinematics;

Control the medium by selecting ions

Colored quark emerges as color neutral hadron ➔ What is nature telling us about confinement?

Energy loss by light vs. heavy quarks:



Identify π vs. D^0 **(charm)** mesons in e-A collisions: Understand energy loss of light vs. heavy quarks traversing nuclear matter

Need the collider energy of EIC and its control on parton kinematics

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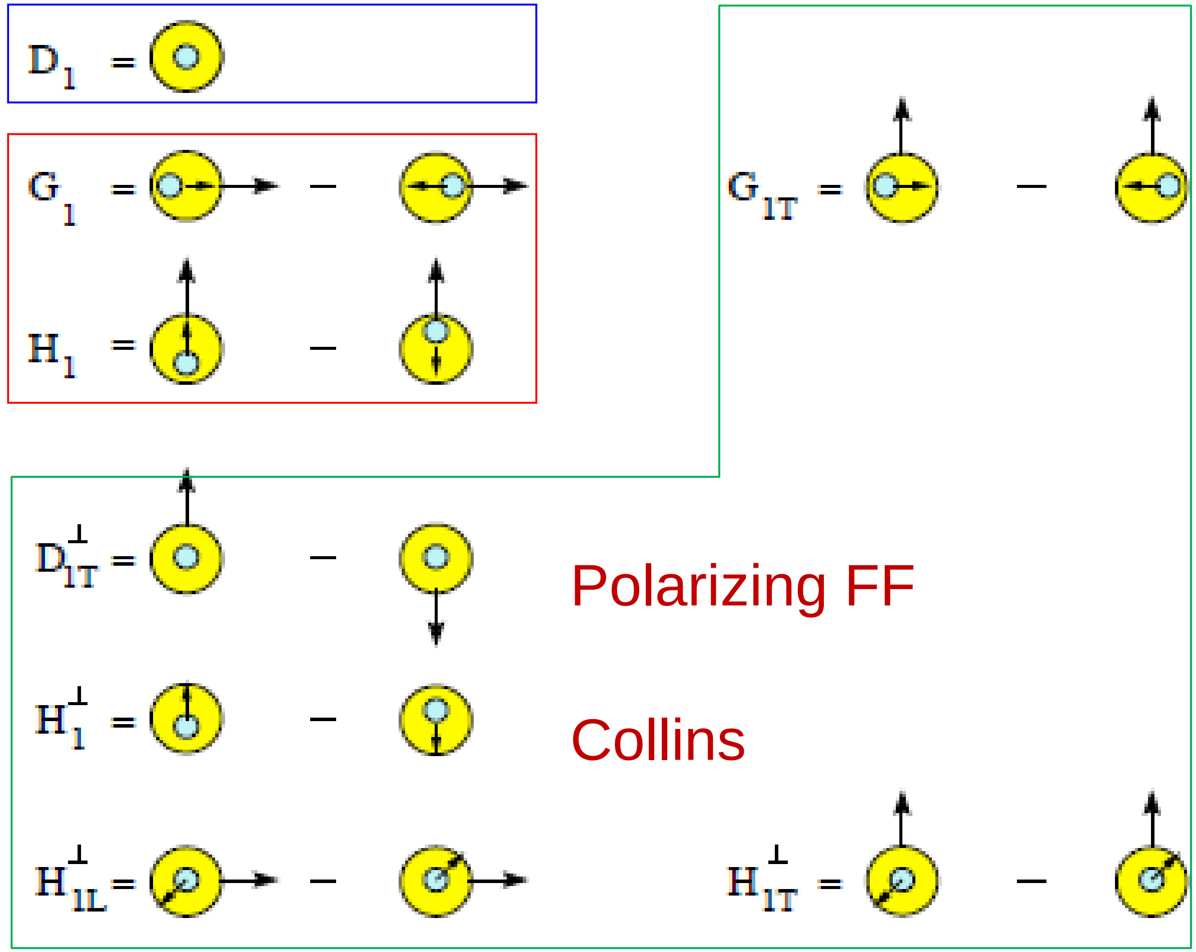
TWIST-2 3D FRAGMENTATION FUNCTIONS

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

Unpolarized

Spin-spin correlations

Spin-momentum correlations



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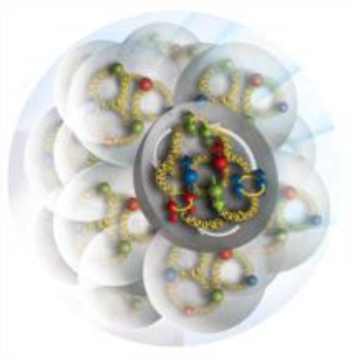
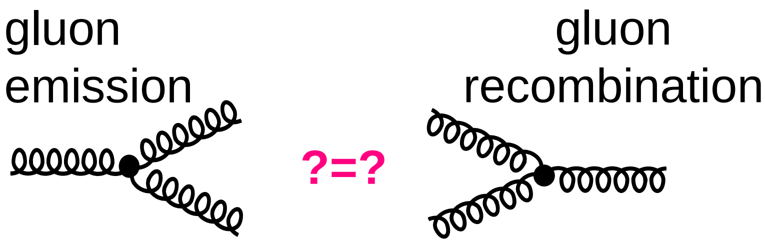
EIC – World's First eA Collider





The Nucleus:
A laboratory for QCD

- 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?

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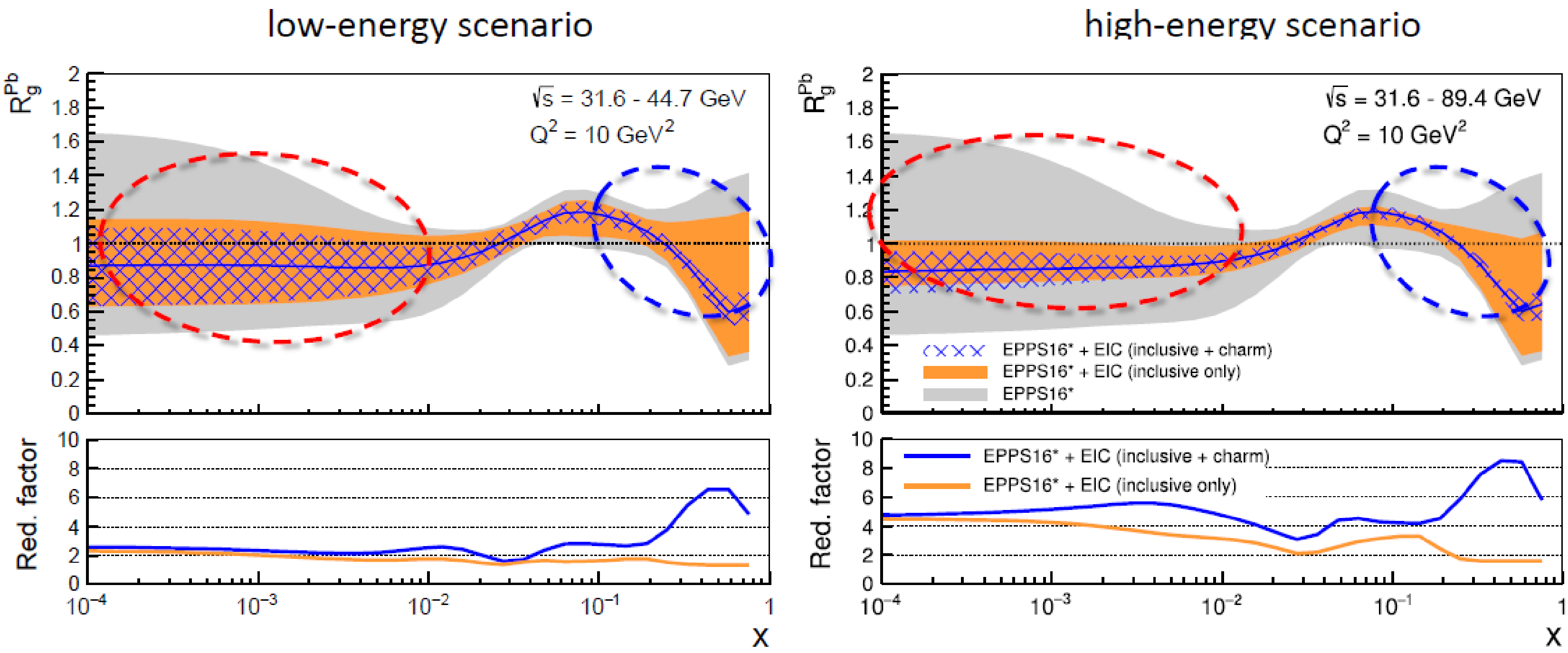
NUCLEAR PARTON DISTRIBUTIONS

What do we know of gluons in nuclei? Essentially nothing!



Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear (light) sea quarks and gluons**
- An EIC with projected F_L **and** $F_L^{C\bar{C}}$ will significantly reduce uncertainties
- Impossible for current and future pA data at RHIC & LHC data to achieve

From: Salvatore Fazio talk at INT 2017-3 program, also arXiv:1709.00076

Similar findings for impact of charm at large x by Weiss et al, arXiv:1610.08536

The Technical Foundations for EIC: Accelerator R&D

The EIC will be one of the most complex and sophisticated collider accelerators ever built. The machine requirements push the state-of-the-art on many fronts including the high degree of beam polarization, high luminosity, beam cooling, beam dynamics, crab cavities for both beams, and an interaction region with complex magnets. **EIC will be unique facility in the world and will maintain leadership in accelerator science and technology of colliders.**

- **NP Community Panel Review:** Panel review charged with identifying high priority accelerator R&D aimed at technical risk reduction. Dr. Kevin Jones of SNS chaired this international panel. Panel Report published February 2017 (https://science.energy.gov/np/community-resources/reports/)
- **Bi-Annual FOA :** Competitive accelerator R&D based on priorities established in EIC panel report. **Funding level**: ~$9-11 M per year for FY18 and FY19.
- Strong collaborations formed at the labs and with universities to advance different EIC concepts with collaborative common R&D effort.

T. Hallman – DOE Nuclear Physics
EICUG meeting, July 2019

The International Foundation for EIC: Meeting at IUPAP

- DOE encourages international cooperation in EIC activities, including nuclear and accelerator sciences, detector and accelerator R&D, computing, engineering and construction efforts.

- DOE-led EIC meeting with international funding agency and government representatives during the 5th IUPAP nuclear science symposium has been scheduled on August 3 at the University of Notre Dame London.

Attending are representatives of Australia, Brazil, Canada, France, Germany, Japan, Korea, India, Italy, Russia, UK and South-Africa.

Invitations are also being sent to CERN, Poland, Sweden, Romania

T. Hallman – DOE Nuclear Physics
EICUG meeting, July 2019

Current Status and Path forward for the EIC

The "wickets" are substantially aligned for a major step forward on the EIC

- A Mission Need Statement for an EIC has been approved by DOE
- An Independent Cost Review (ICR) Exercise mandated by DOE rules for projects of the projected scope of the EIC has been completed
- DOE is moving forward towards a request for CD-0 (approve "Mission Need")
- DOE convened a panel to assess options for siting between two proposed concepts.
- The Deputy Secretary is the Acquisition Executive for this level of DOE Investment
- The FY 2020 President's Request includes $ 1.5 million OPC. The FY 2020 House Mark identifies $ 10 million OPC and $ 1 million TEC. Senate Mark identifies $ 10 million OPC and $ 1 million TEC.

T. Hallman – DOE Nuclear Physics
NSAC meeting, October 2019