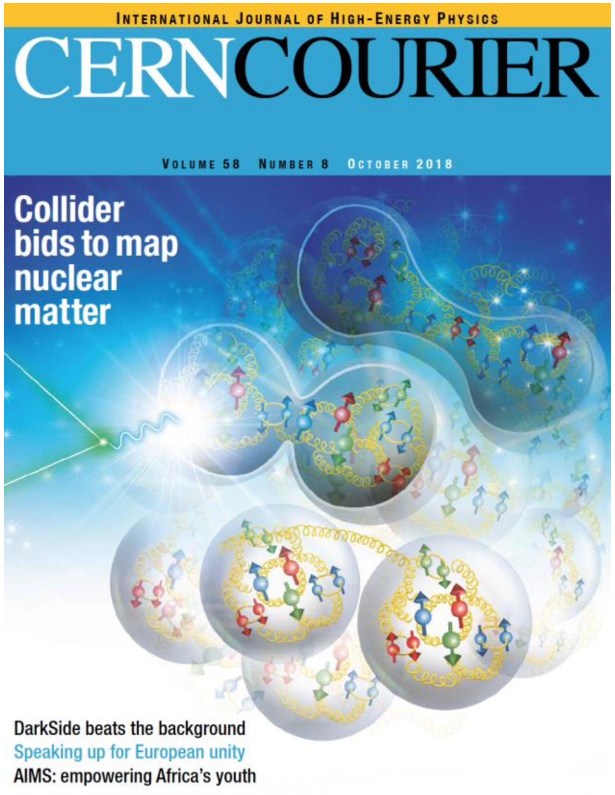
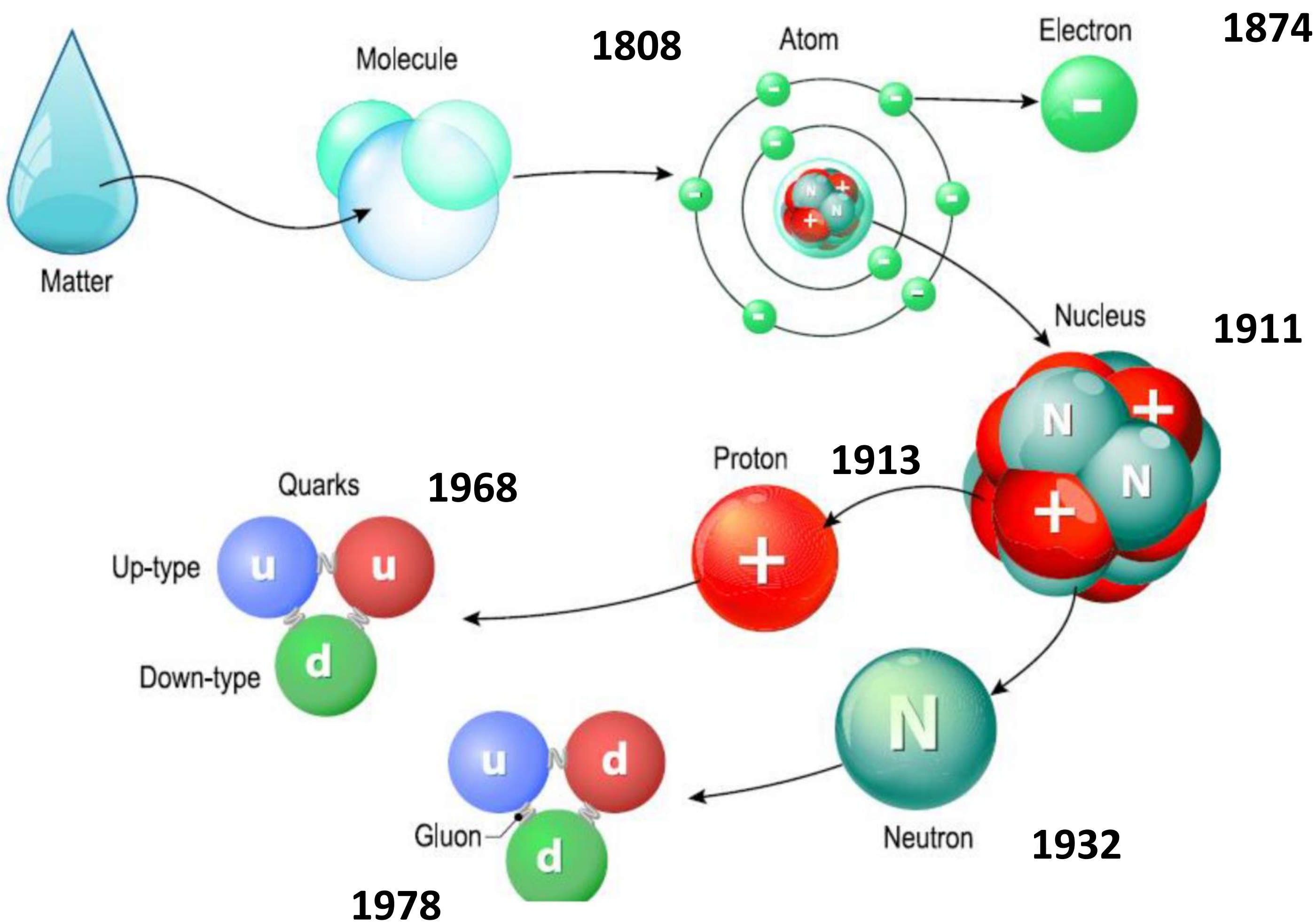
Physics Case for
The Electron-Ion Collider



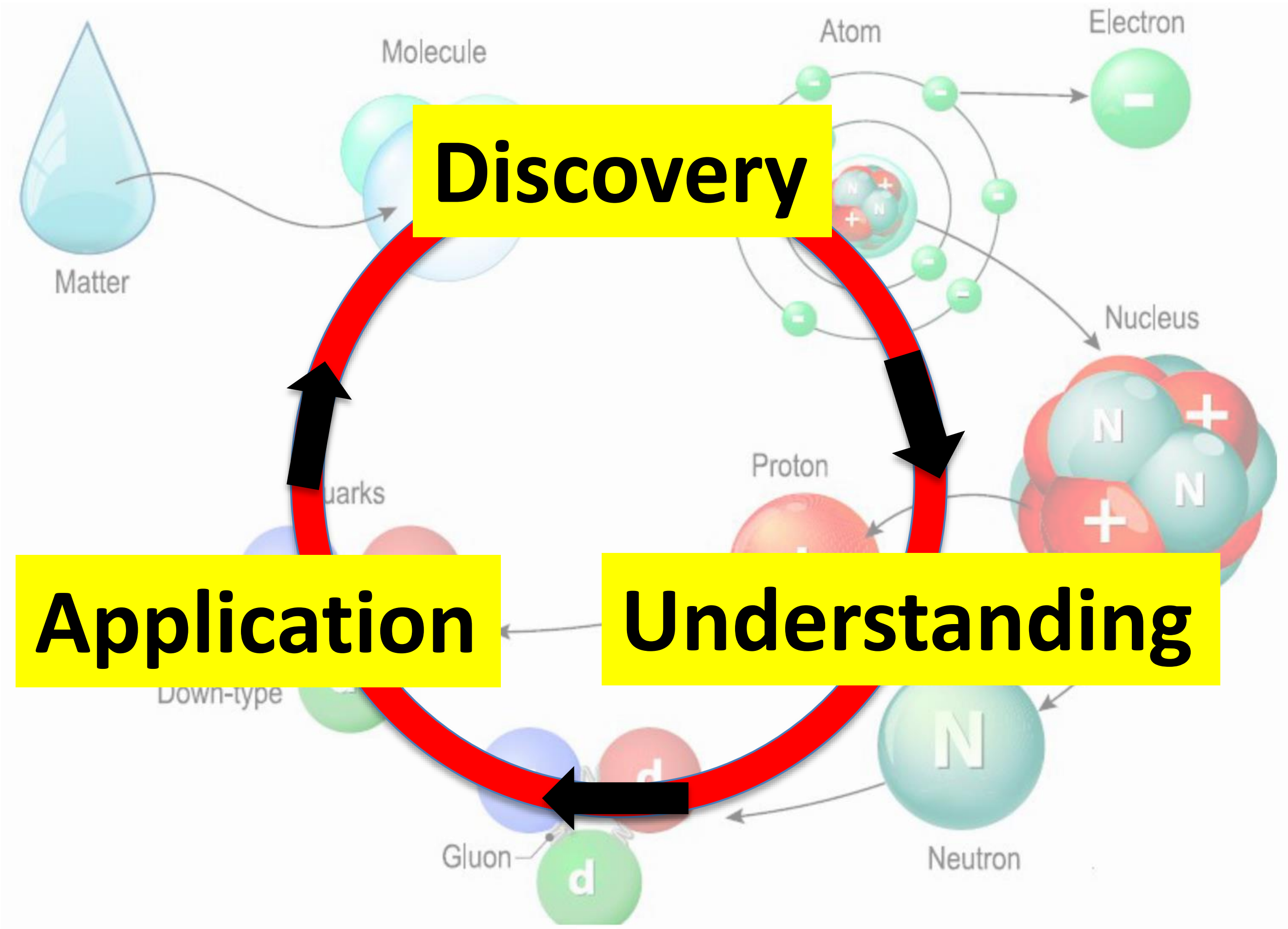
E. Aschenauer and R. Ent

- Introduction
- Physics Case
  - Femtography
  - Mass
  - Spin
  - Dense gluon states
  - New avenues
- Accelerator Concepts
  - eRHIC, JLEIC
  - R&D (M. Farkhondeh)
- EIC Users Group
- Detector R&D (T. Ullrich)
- Summary

The Quest to Understand the Fundamental Structure of Matter

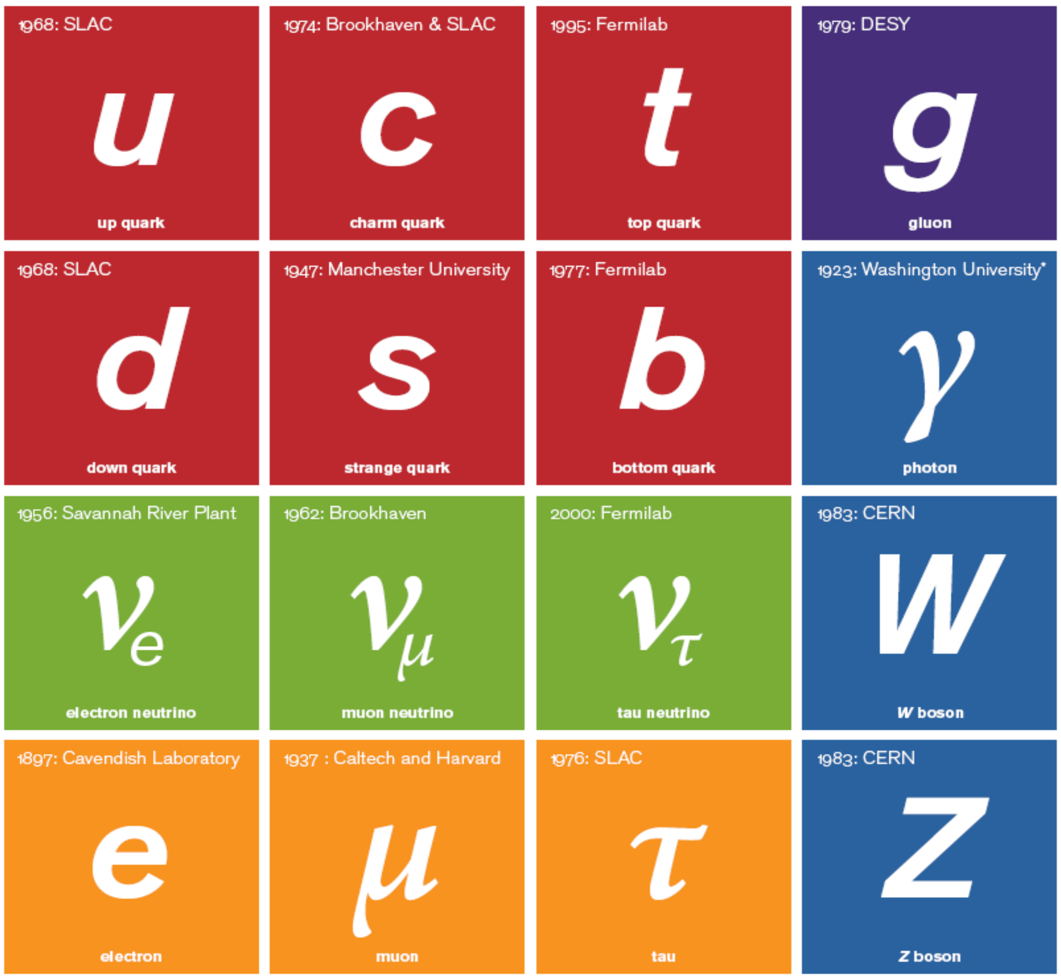


The Quest to Understand the Fundamental Structure of Matter



Fundamental Building Blocks of Matter 2018

The Standard Model of Physics



18 Physics Nobel Prizes since 1950

2012: CERN

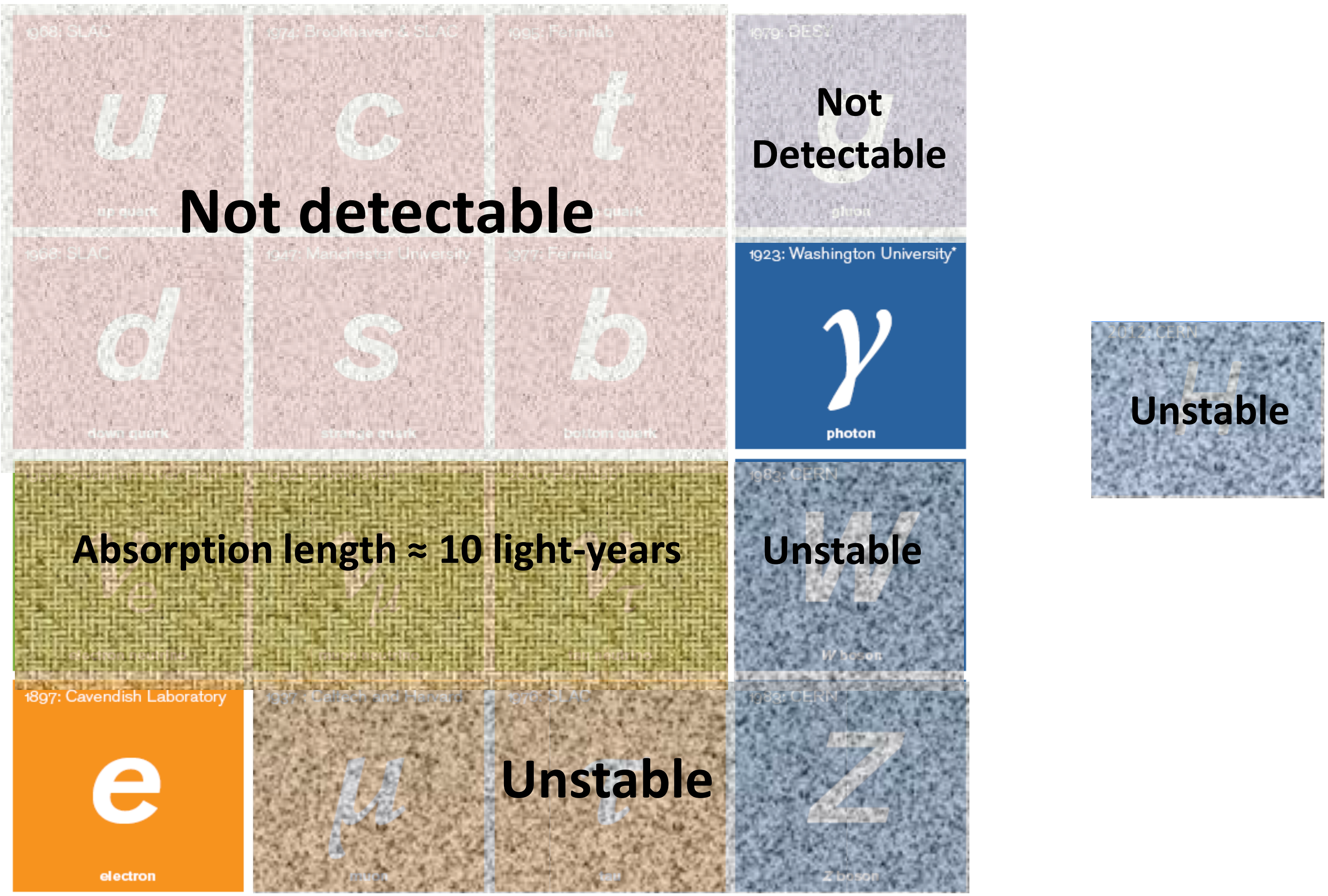
H

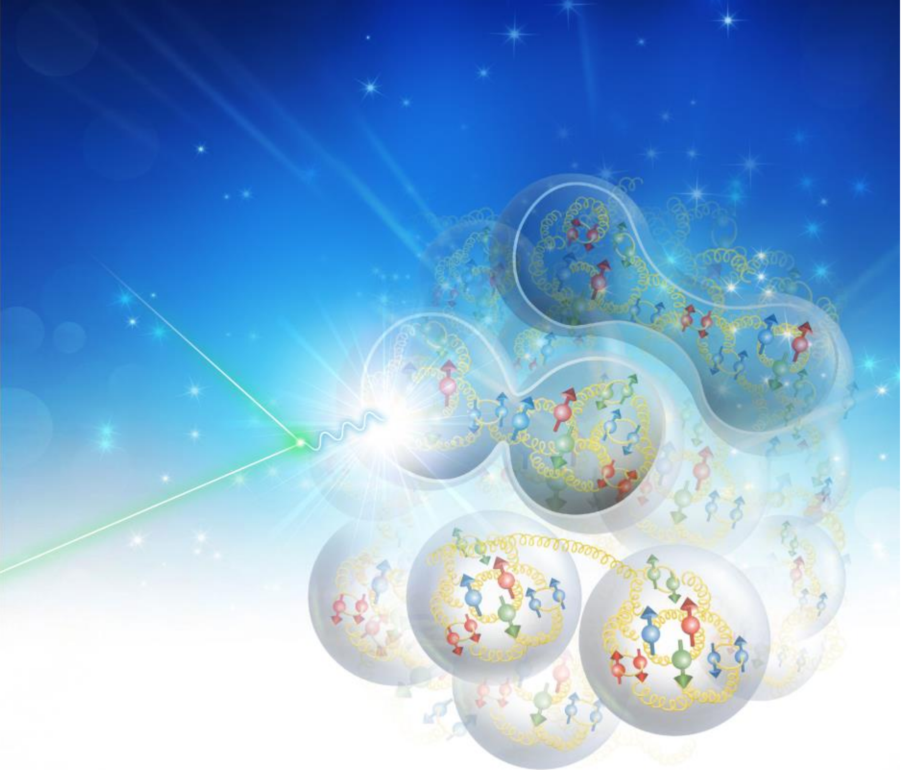
+

2015: Gravitational waves

Einstein gravity

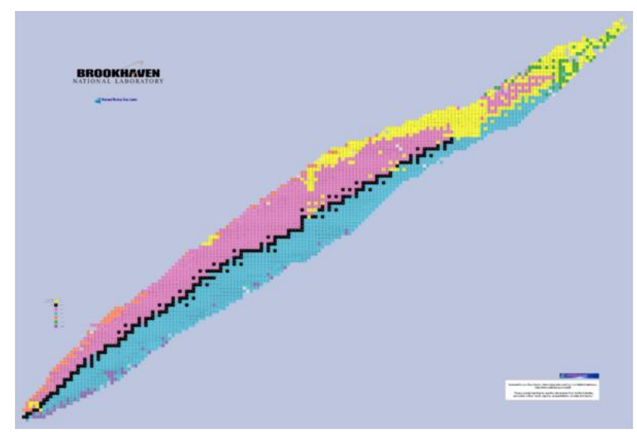
Not directly useful for understanding the visible matter in the universe





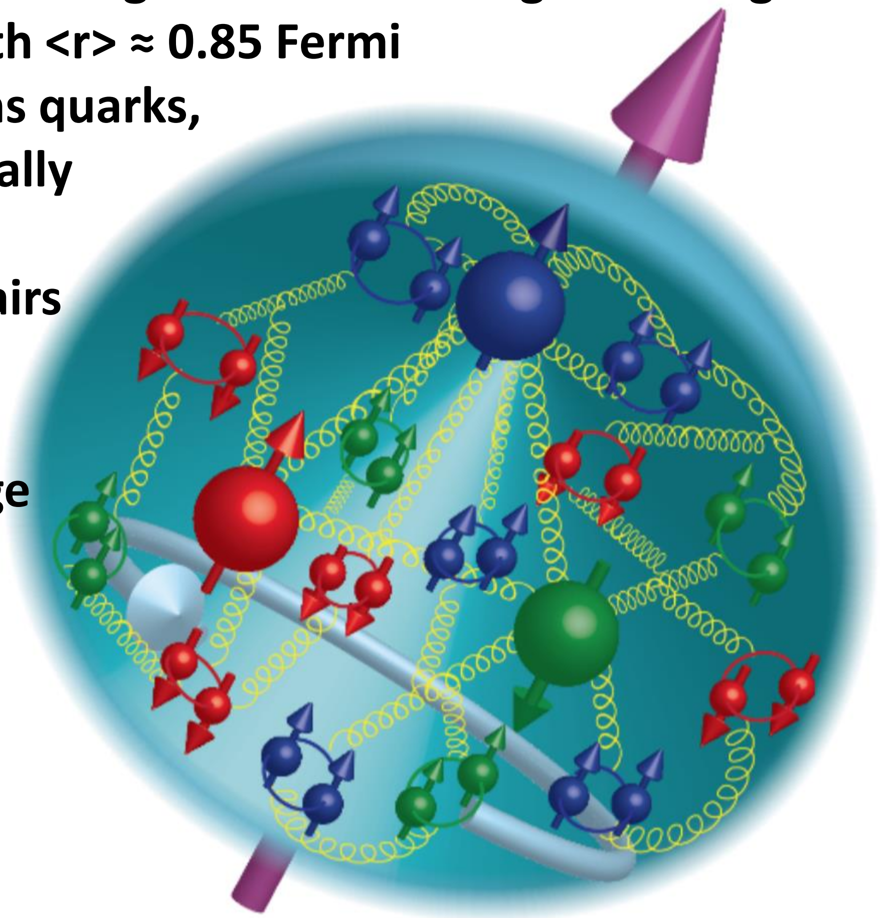
Understanding The Nucleus

- Reality: experiments deal with hadrons
- How do we relate the successful hadronic description of the nucleus to the fundamental quarks and gluons?
- How does the nucleon with its structure and properties emerge from quarks and gluons of QCD?
- What role does QCD play in the structure and properties of nuclei?

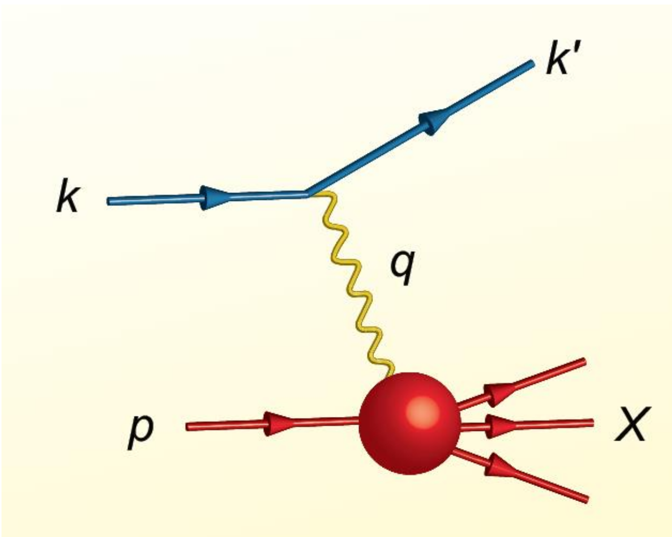


21^{st} Century View of the Fundamental Structure of the Proton

- 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.
- The proton spin and mass have large contributions from the quark-gluon dynamics.

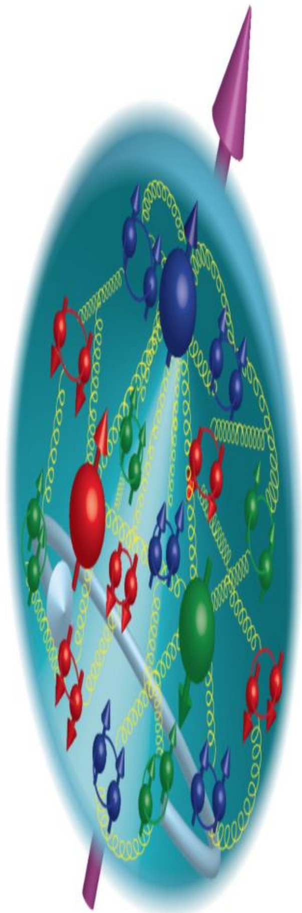


Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



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 instantaneous charge distribution of the proton is seen.
- In boosted frame x is understood as the longitudinal momentum fraction

valence quarks: $0.1 < x < 1$

sea quarks: $x < 0.1$

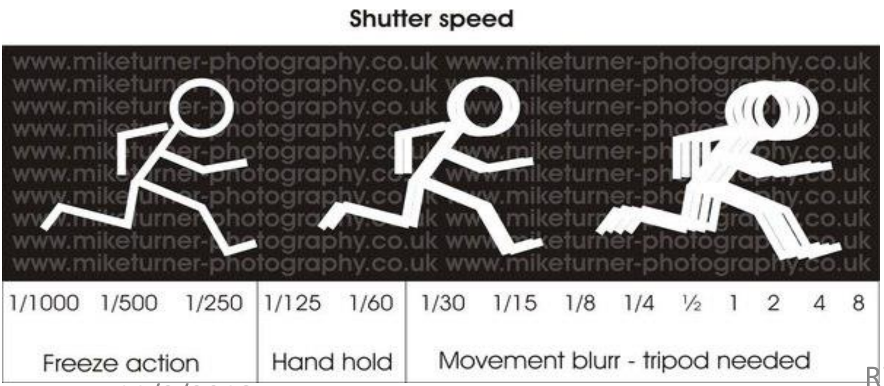
J. Bjorken, SLAC-PUB-0571
March 1969

Visualization

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

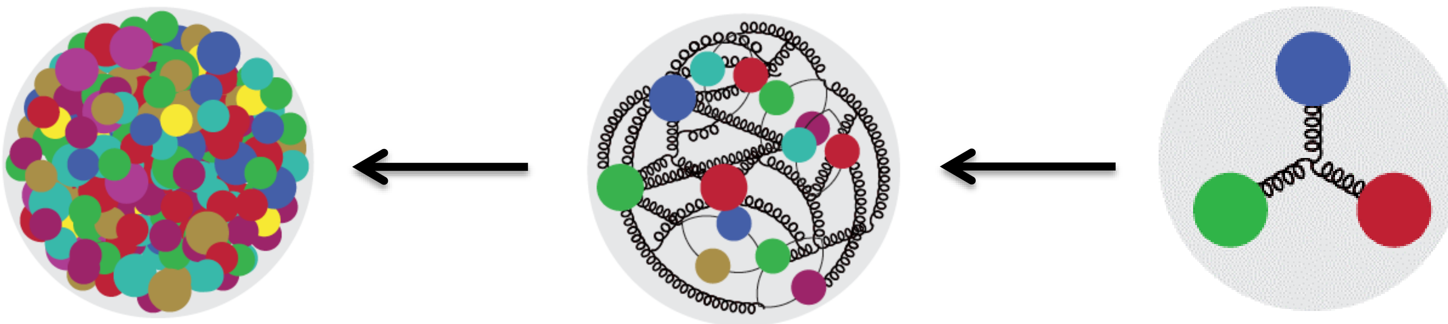
  - the focus which uses a lens to gather light from a selected image

  - the shutter which is a door that opens for a definite time to allow selected light to reach the medium.



High Energy Electron Scattering

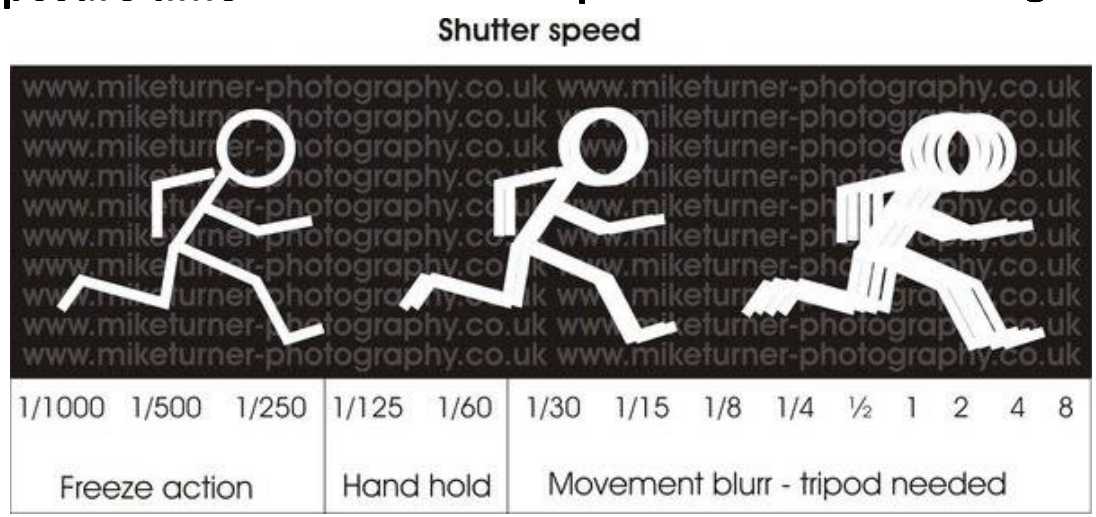
Snapshots where 0 < x < 1 is the shutter exposure time

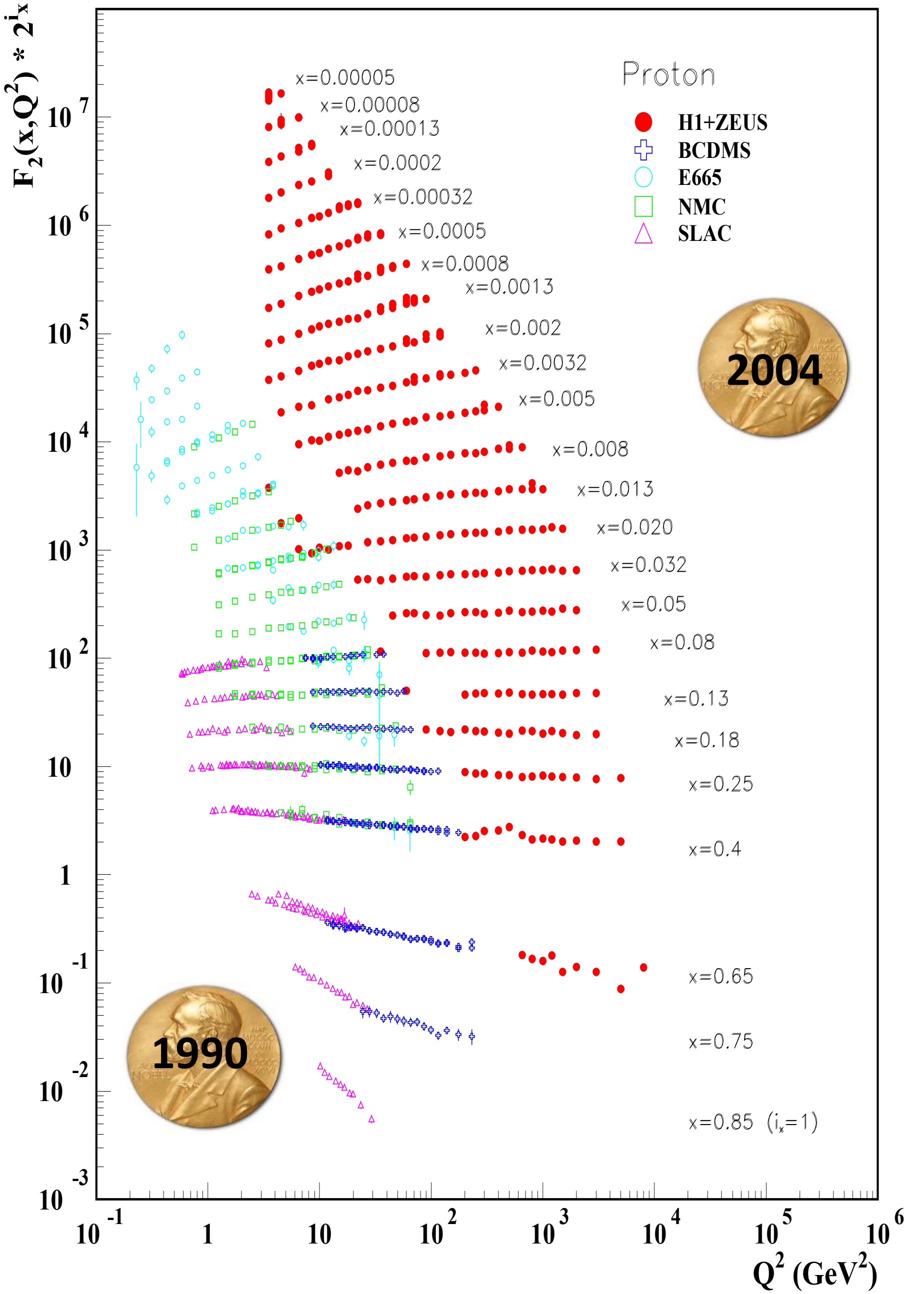


$x \approx 10^{-4}$
Probe non-linear dynamics
short exposure time

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

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



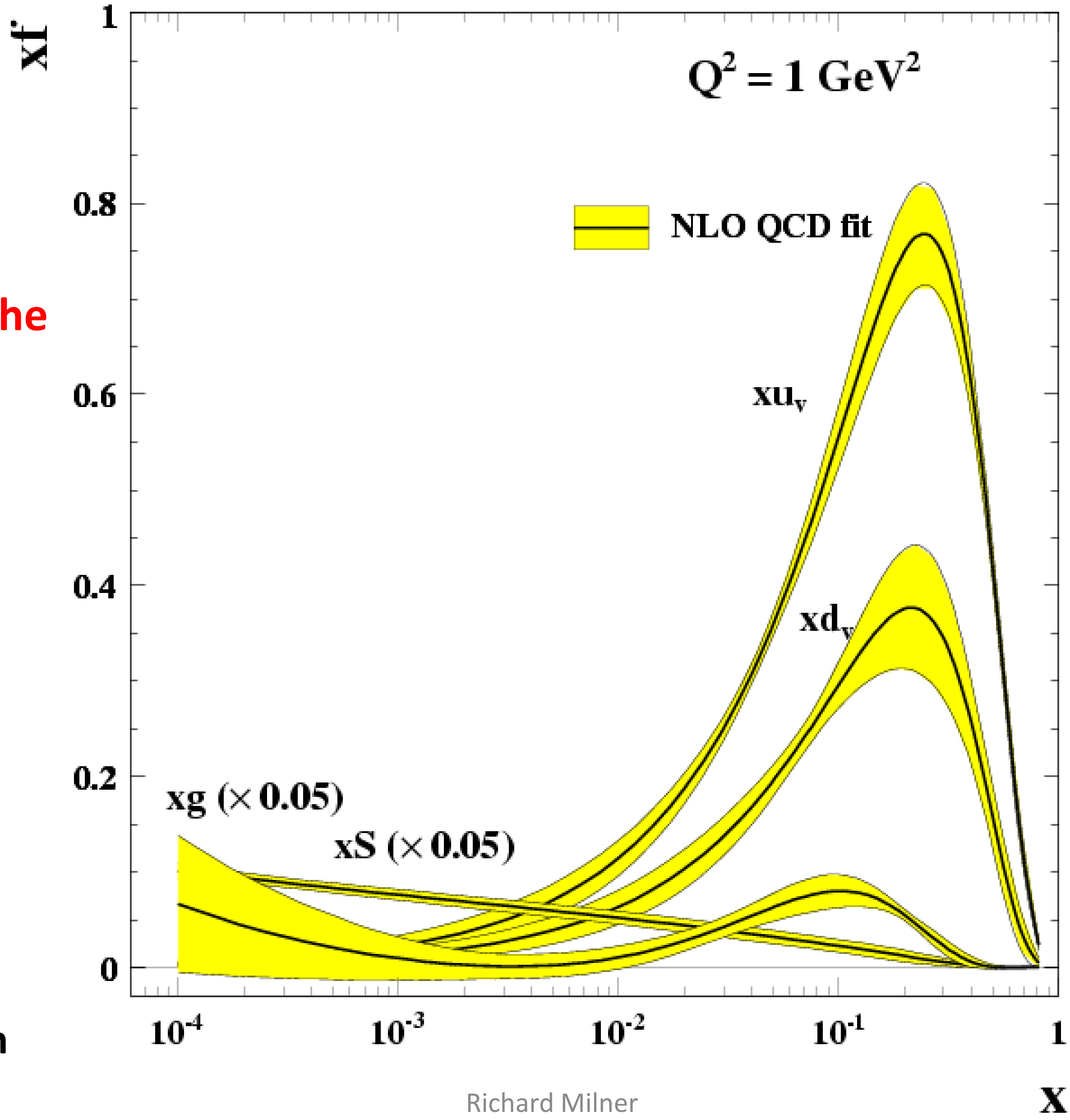


Quark Structure of Proton from High-Energy Lepton Scattering

e-p cross section ≈ $\sigma_{Mott} \bullet F_2(x,Q^2)$

- Snap shots of the charged structure of the proton taken in the boosted frame
- *1/Q* spatial resolution
- *x* exposure time
- QCD prescribes evolution with Q^2 which connects quarks and gluons

What about the Nucleus?



R. Yoshida
C. Gwenlan

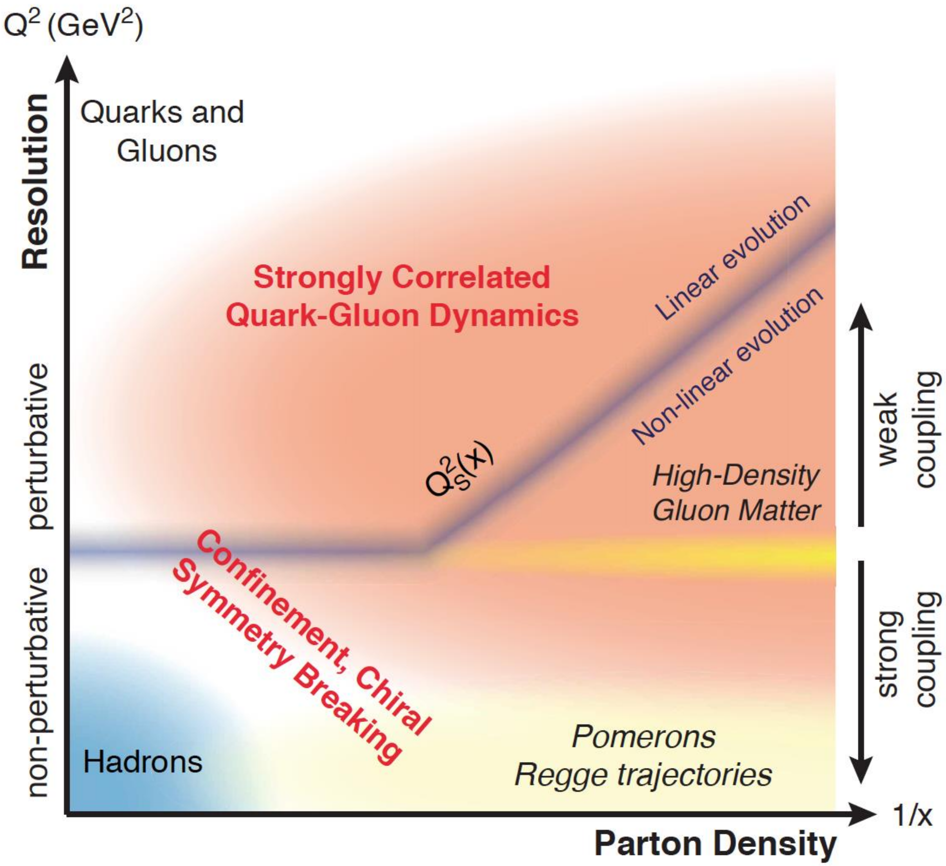
EIC: 21st Century QCD Laboratory

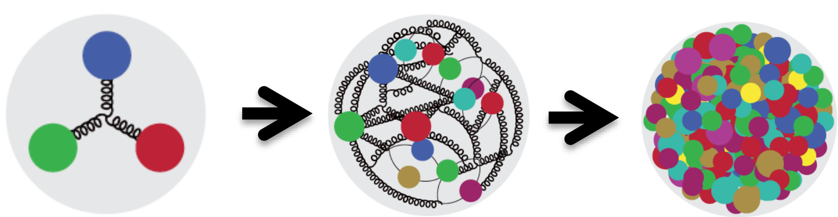
- To explore the fundamental structure and dynamics of the matter in the visible world

$$\mathcal{L}_{QCD} = \sum_{j=1}^{n_f} \bar{\psi}_j \left(i D_\mu \gamma^\mu - m_j \right) \psi_j - \frac{1}{4} \mathrm{Tr}\, G^{\mu\nu} G_{\mu\nu}$$

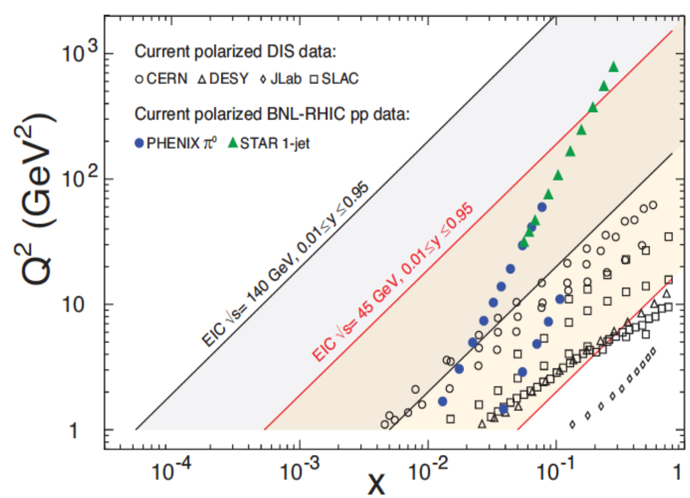
- Interactions arise through fundamental symmetry principles
- Properties of the visible universe emerge through complex structure of the QCD vacuum
- The proton is a highly relativistic system described by QCD, a fully relativistic quantum field theory.
- Lattice QCD is an increasingly powerful means 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.

QCD Exploration

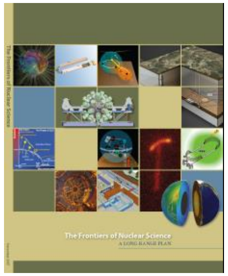




- EIC will allow us to explore the QCD landscape over a wide range in *x* and *Q²*.
- Study high-density gluon matter
- Different coupling regimes
- Nuclei are *terra incognita*
- Study modifications of gluons in nuclear environment complementing heavy ion programs at RHIC and LHC

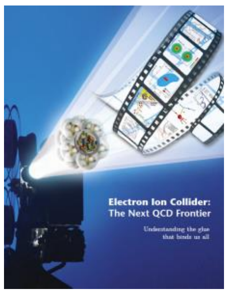


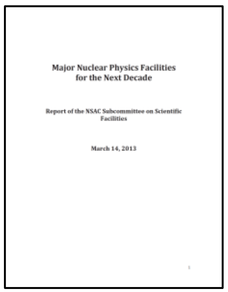
U.S. Electron-Ion Collider Planning 2007-18



2007 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

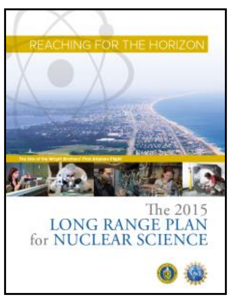
March 14, 2013

2013 Electron Ion Collider White Paper

(Writing committee convened by Jefferson Lab and BNL)

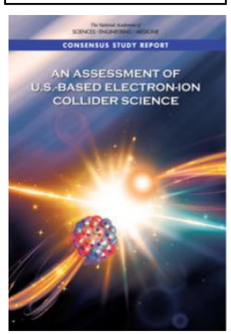
2013 NSAC Subcommittee on Future Facilities

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



2015 NSAC Long Range Plan

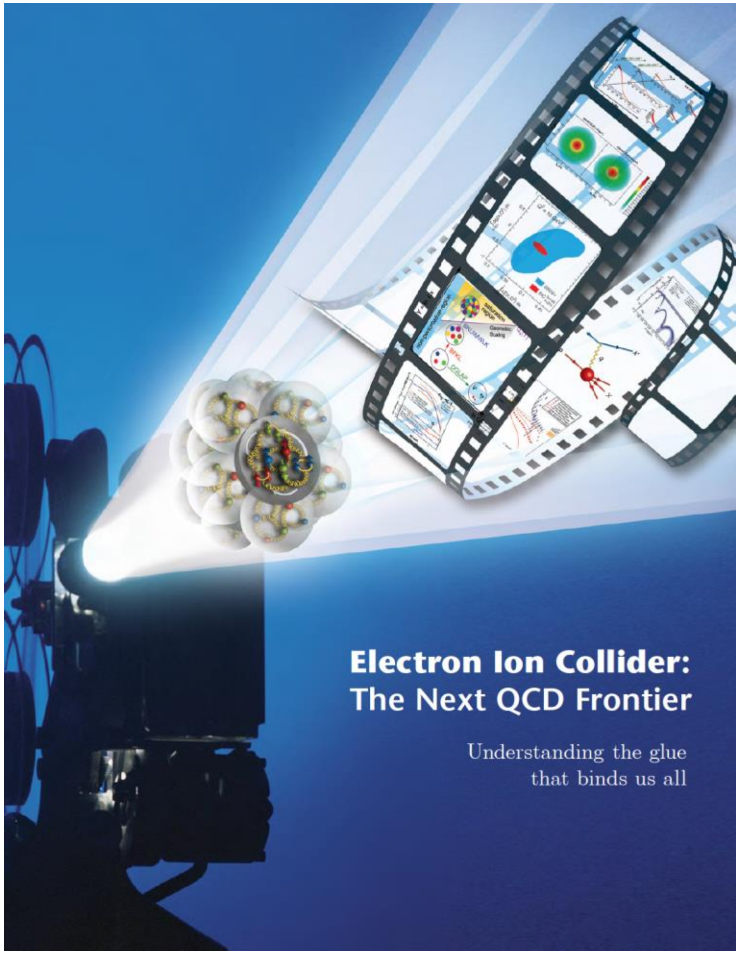
"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."



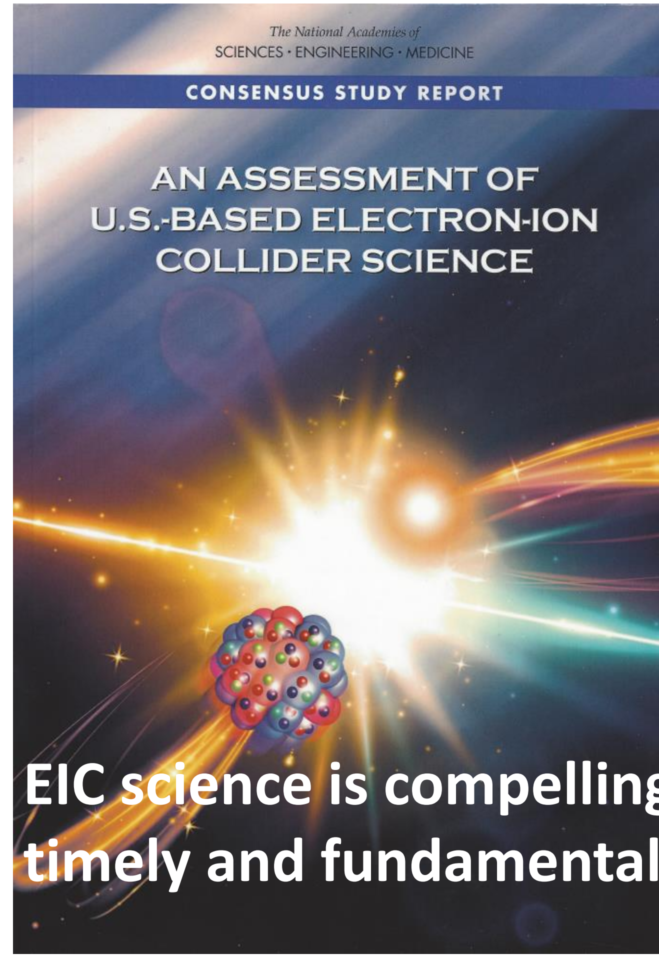
2018 National Academy of Sciences – Assessment of U.S. Based Electron-Ion Collider Science

"…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 Physics Case



Developed by US QCD community over two decades



EIC science is compelling timely and fundamental

Developed by NAS committee with broad science perspective

NAS Committee Statement of Task

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

In particular, the committee will address the following questions:

- What is the merit and significance of the science that could be addressed by an electron ion collider facility and what is its importance in the overall context of research in nuclear physics and the physical sciences in general?
- What are the capabilities of other facilities, existing and planned, domestic and abroad, to address the science opportunities afforded by an electron-ion collider?
- What unique scientific role could be played by a domestic electron ion collider facility that is complementary to existing and planned facilities at home and elsewhere?
- What are the benefits to U.S. leadership in nuclear physics if a domestic electron ion collider were constructed?
- What are the benefits to other fields of science and to society of establishing such a facility in the United States?

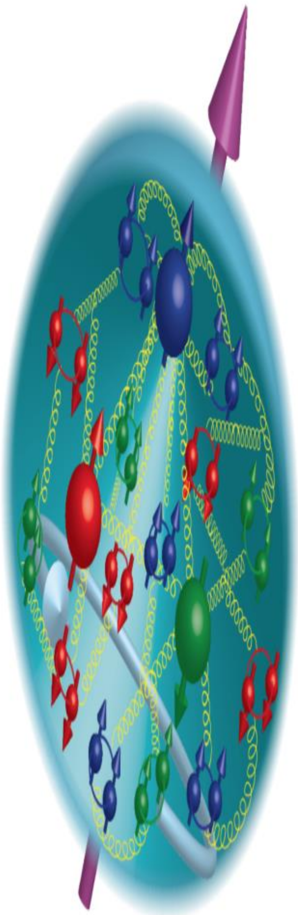
Findings of the NAS committee

- **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.**
- **Finding 5:** Taking advantage of **existing accelerator infrastructure** and accelerator expertise would make development of an **EIC cost effective and would potentially reduce risk.**
- **Finding 6:** The current accelerator R&D program supported by DOE is crucial to addressing outstanding design challenges.

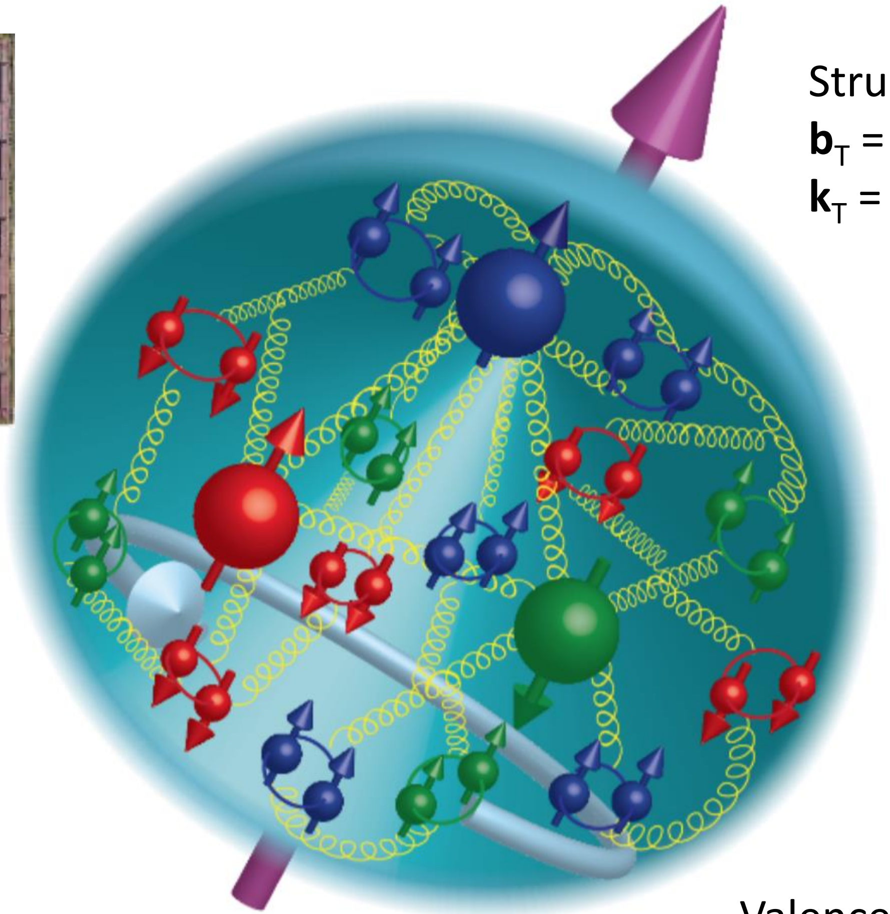
Findings of the NAS Committee (II)

- **Finding 7:** To realize fully the scientific opportunities an EIC would enable, **a theory program** will be required to predict and interpret the experimental results within the context of QCD, and furthermore, to glean the fundamental insights into QCD that an EIC can reveal.
- **Finding 8:** The U.S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high-luminosity polarized EIC as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.
- **Finding 9:** **The broader impacts of building an EIC in the United States are significant in related fields of science**, including in particular the accelerator science and technology of colliders and workforce development.

Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



Proton Tomography: 2 New Dimensions Transverse to Longitudinal Momentum



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

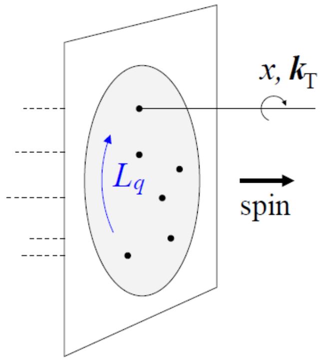
Nuclei!

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

3D Partonic Picture



Theorists have developed a powerful formalism for studying the 3D partonic picture of the nucleon and the nucleus. It is encoded in **Generalized Parton Distributions** and **Transverse Momentum Dependent Distributions**

Wigner distribution

$$W(\mathbf{p}, \mathbf{x})$$

Transverse Momentum Dependent distributions

d^3r

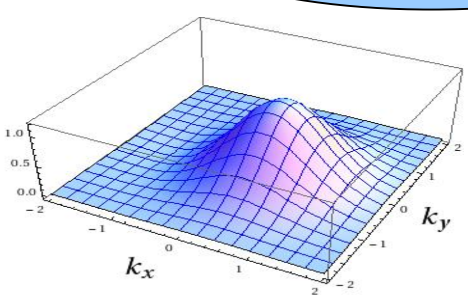
Orbital motion accessible!

d^3p

Generalized Parton Distributions

$$f(x, \mathbf{k}_\perp)$$

$$H(x, \xi, t)$$



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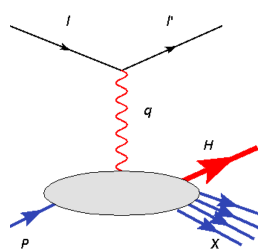

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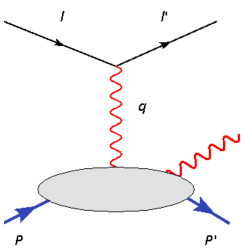
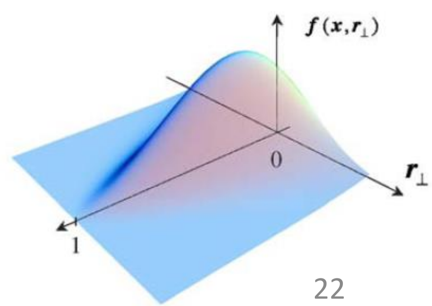
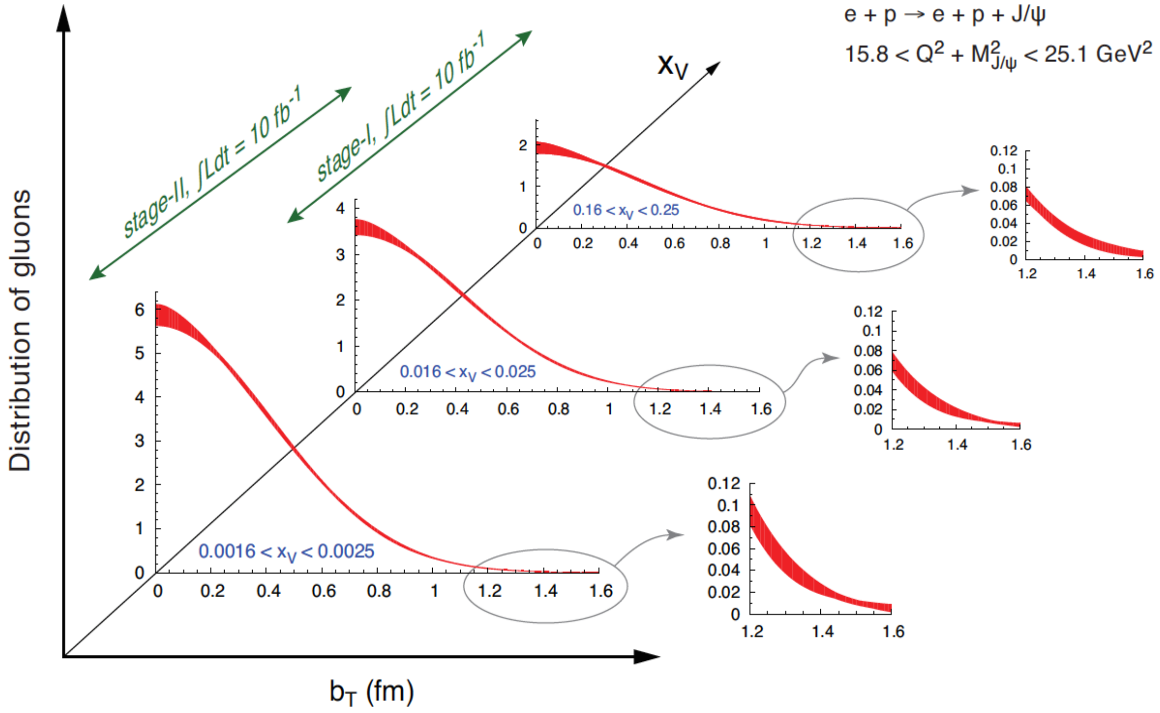
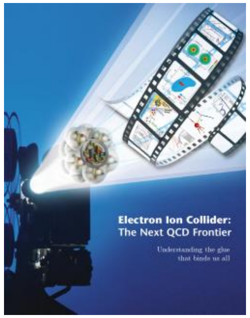




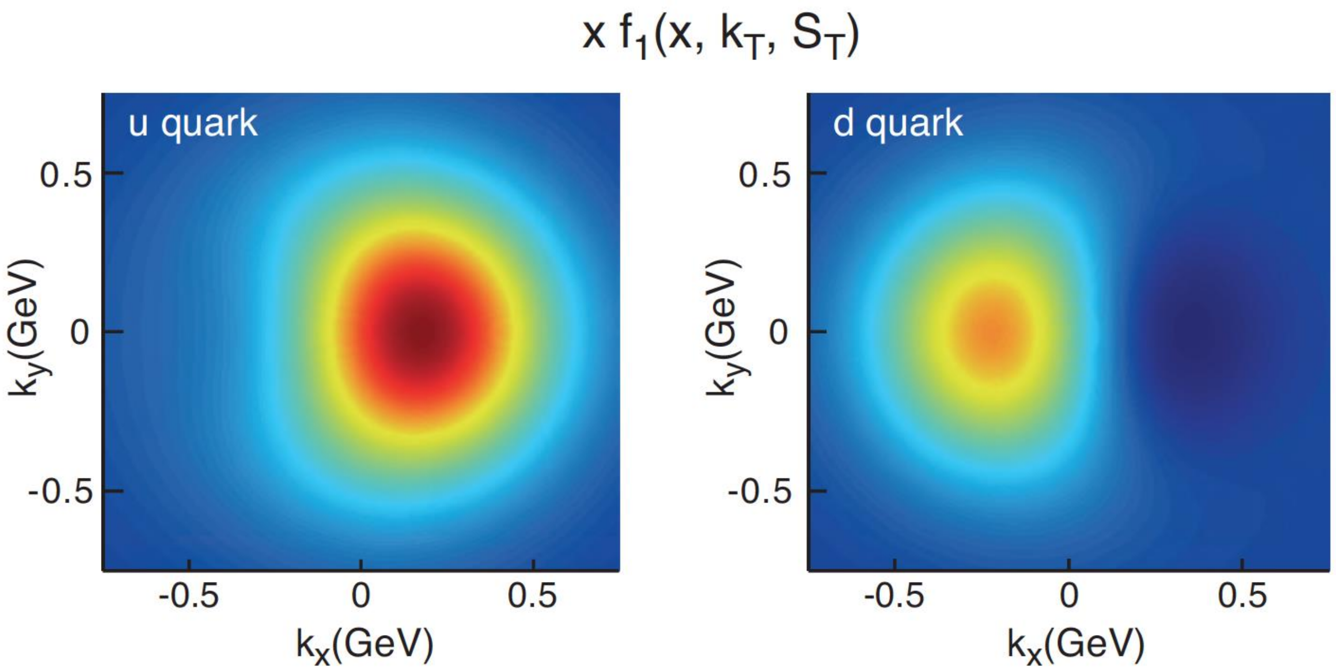
Transverse Spatial Distribution of Gluons

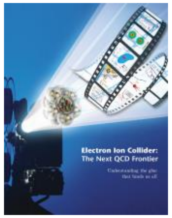




- How are gluons spatially distributed in a proton or a nucleus?
- Is the distribution smooth?
- How does it differ from the charge distribution?
- **First ever tomographic images of ocean of gluons within matter !**

Transverse Momentum Distributions



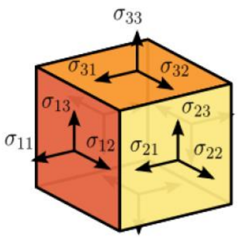


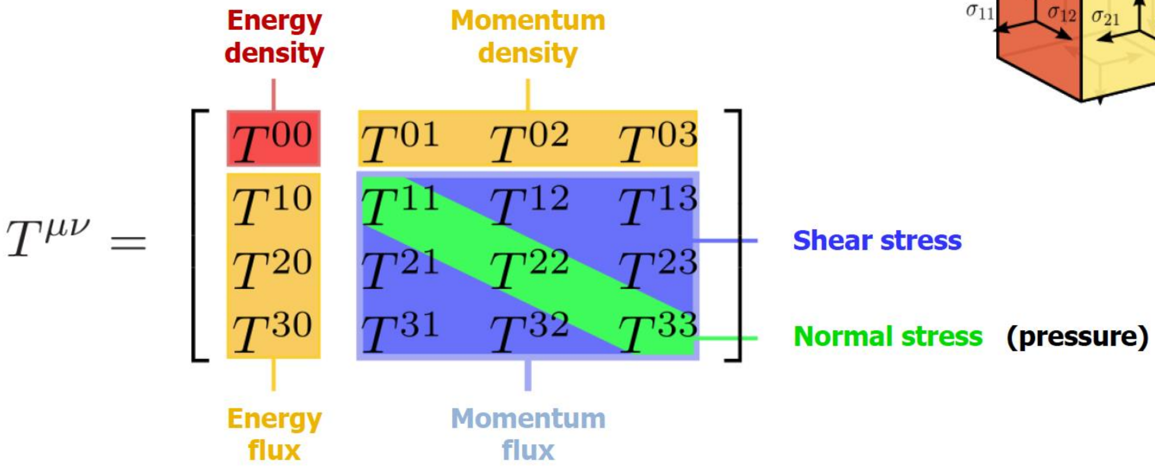
- Spin and the ability to look at transverse momentum together give a powerful new window into QCD
- TMDs directly related to orbital motion
- For example, we can explore for the first time interference in quantum phases due to color force – impossible with purely longitudinal experiments

Energy Momentum Tensor (EMT)

Mass, spin and pressure all encoded in

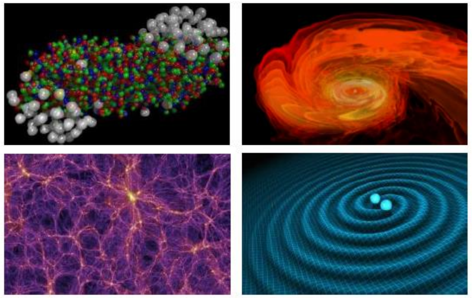
C. Lorcé



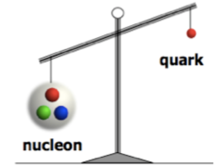


Key concept for

- **Nucleon mechanical properties**
- **Quark-gluon plasma**
- **Relativistic hydrodynamics**
- **Stellar structure and dynamics**
- **Cosmology**
- **Gravitational waves**
- **Modified theories of gravitation**
- **...**



Mass of the Nucleon



"The mass is the result of the equilibrium reached through dynamical processes." **X. Ji**

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" ***The 2015 Long Range Plan for Nuclear Science***

Relativistic Motion | *Chiral Symmetry Breaking* | *Quantum Fluctuations*

$$M = E_q + E_g + \chi_{m_q} + T_g$$

X. Ji, PRL 74 1071 (1995)

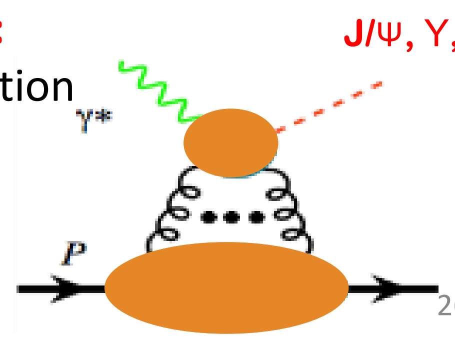
Quark Energy | Gluon Energy | Quark Mass | Trace Anomaly

- Criticisms: not scale-invariant, decompositions: Lorentz invariant vs. rest frame
- Great interest at workshops: Temple U., March 2016; ECT, April 2017
- Community wide consensus on how to determine the different contributions not yet reached
- Lattice QCD providing estimates

E_q ~30% E_g ~40% χ_{m_q} ~10% T_g ~ 25%

arXiv: 1710.09011

Trace anomaly:
Upsilon production near threshold

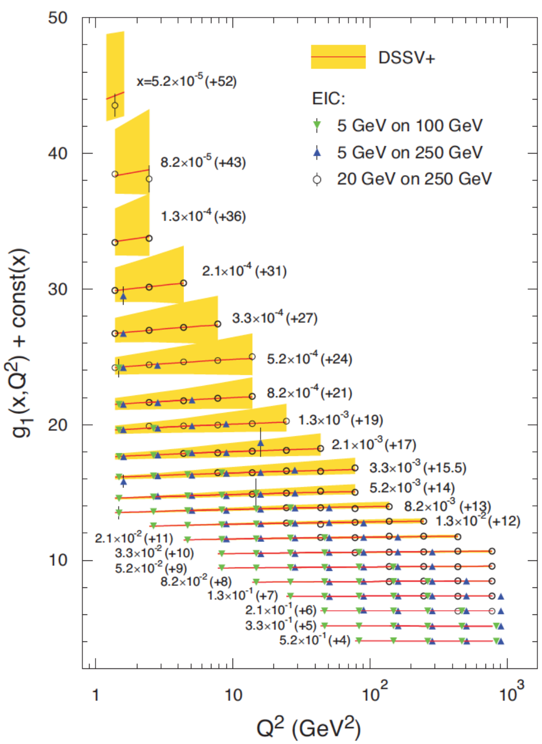


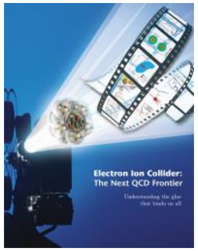
Spin of the Nucleon

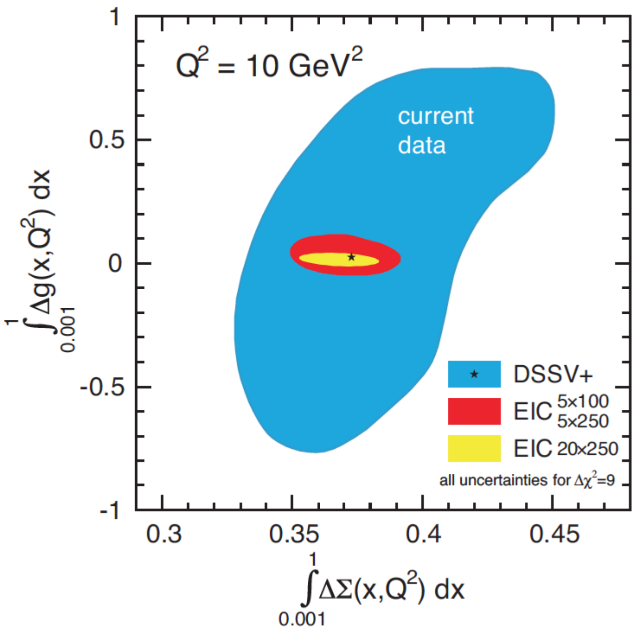
"Helicity sum rule"

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

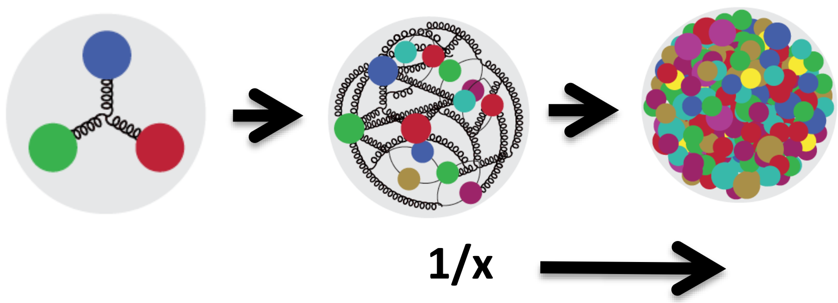
EIC projected measurements:
Precise determination of polarized PDFs of quark sea and gluons ➔ precision ΔG and ΔΣ
➔ Determination of $\Sigma\, L_q+L_g$





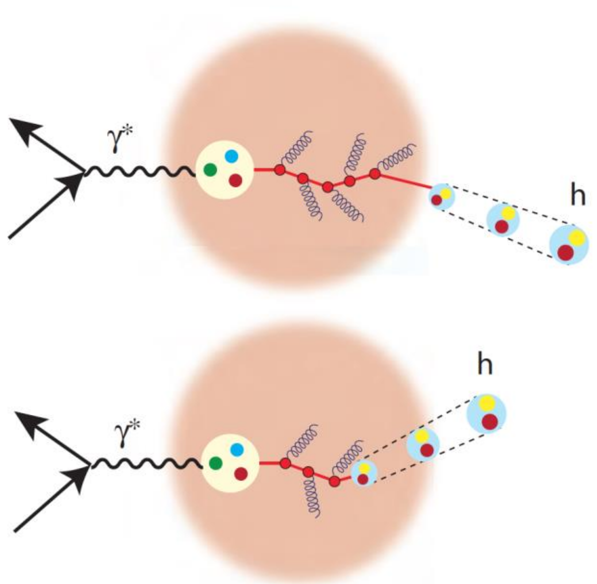


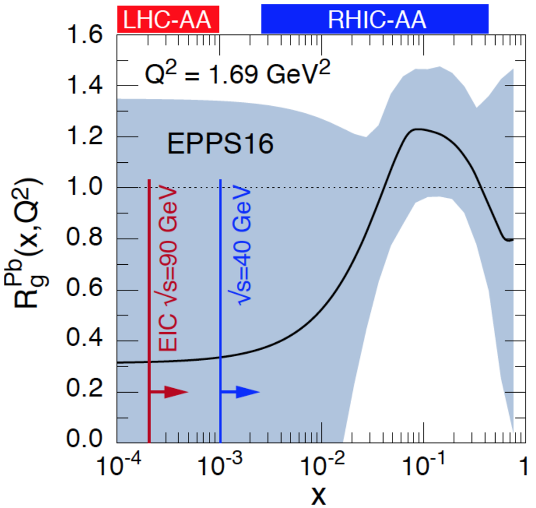
QCD Dynamics in Nuclei

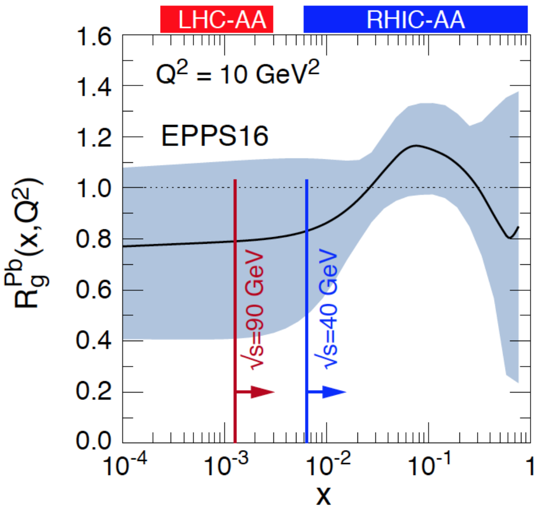


- Hadronization: the process that connects QCD with experiment
- Nuclear PDFs
- Color neutralization and propagation
- Diffraction: no net color exchange
- Jets

Hadronization

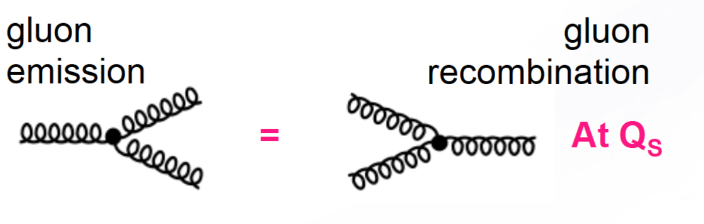




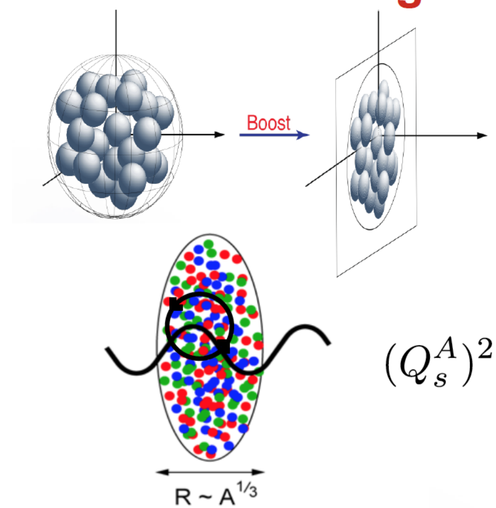


What tames the low-x rise of the gluons?

- New evolution equations at low x and moderate Q^2
- **Saturation scale $Q_s(x)$** where gluon emission and recombination become comparable

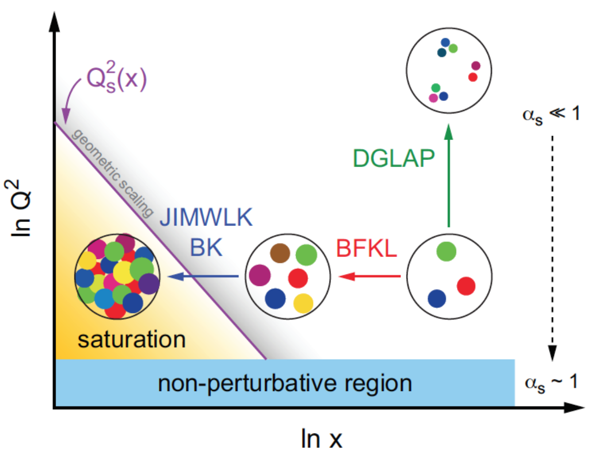


Advantage of nucleus



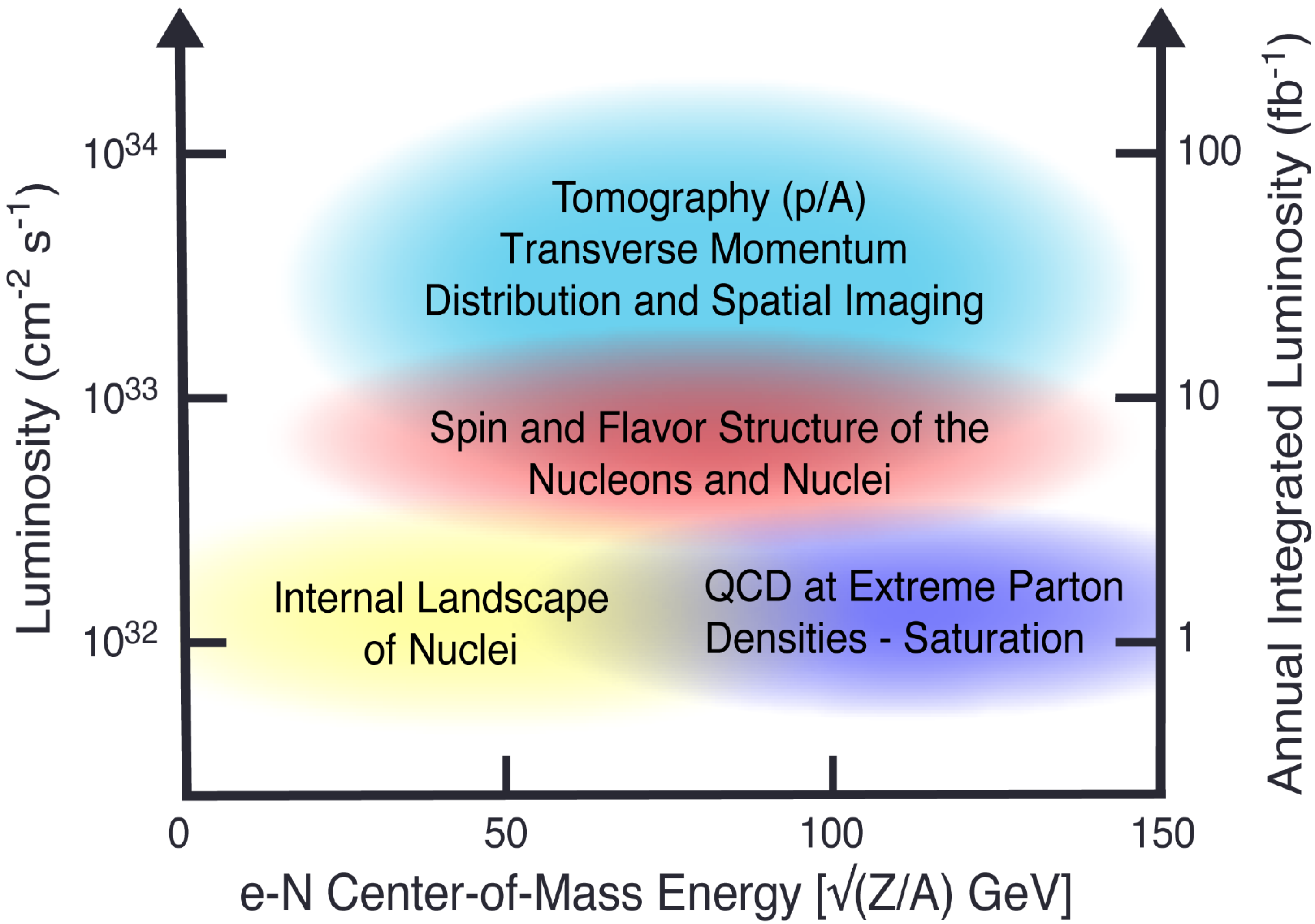
$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

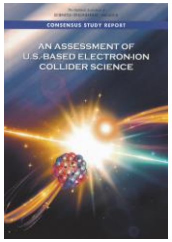
$L \sim (2m_N x)^{-1} > 2\,R_A \sim A^{1/3}$



- First observation of gluon recombination effects in nuclei
- Is this a universal property?
- What is the new effective theory in this regime?

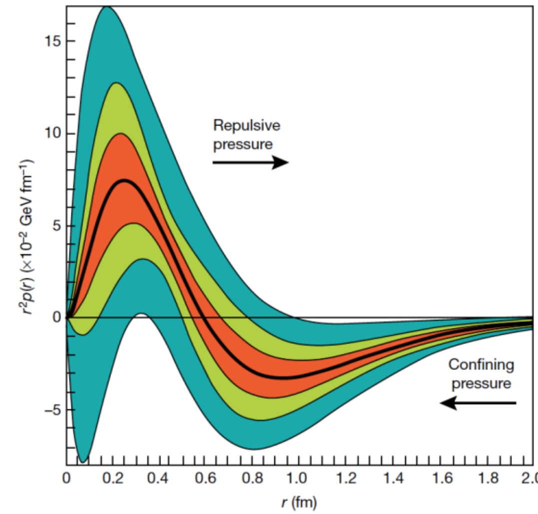
Collider Specifications from Science





New Avenues

(personal selection)



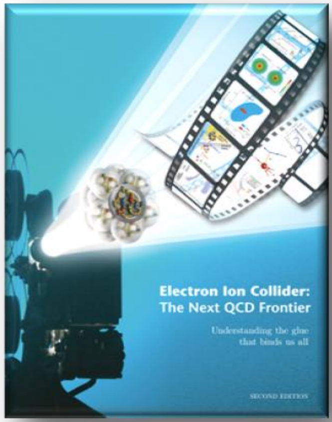
Nature, **557**, May 17, 2018

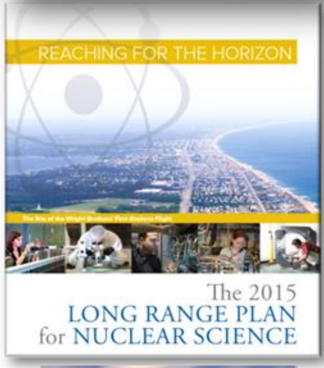
- **Pressure in the Proton**
  - First determination using DVCS data
  - Interior pressure in proton is > pressure inside a neutron star! ***Who knew that!***
  - Lattice calculation motivates determination of gluon GPDs at EIC
- **Exotic Gluons** (i.e. gluons not associated with individual nucleons)
  - Inclusive DIS on transversely polarized nucleus with J≥1
  - Lattice calculations hint at non-zero effects
- **Quark-gluon nature of short-range NN interaction**
  - Extract gluon transition GPD from NN pairs with high relative momenta
  - Estimates indicate that EIC will provide precision data out to relative transverse NN momentum of at least 3 GeV

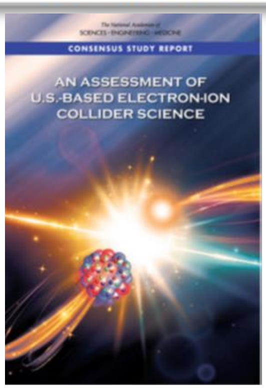
NAS Report on EIC Requirements

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).

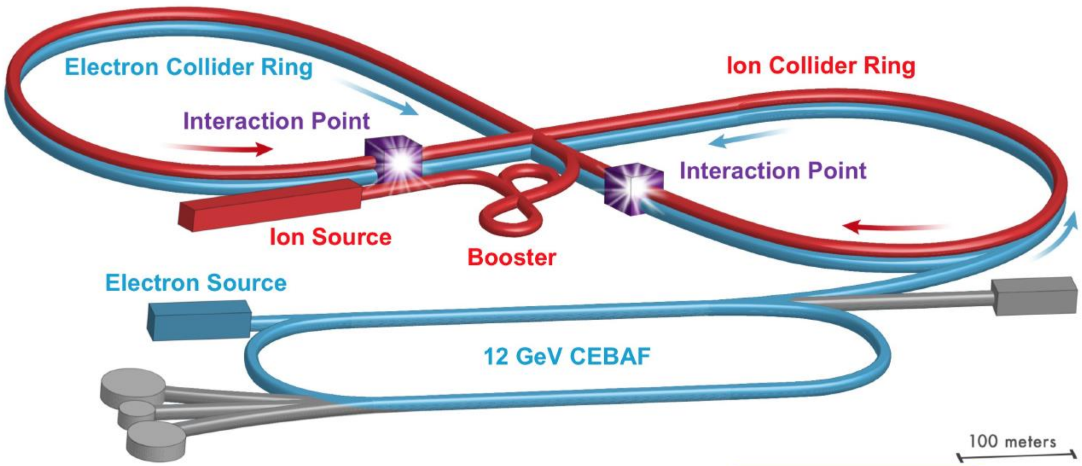






Note: consistent with 2013 white paper and 2015 NSAC Long Range Plan

JLEIC Layout: A Ring-Ring Collider



Update History

This Update

arXiv:1504.07961

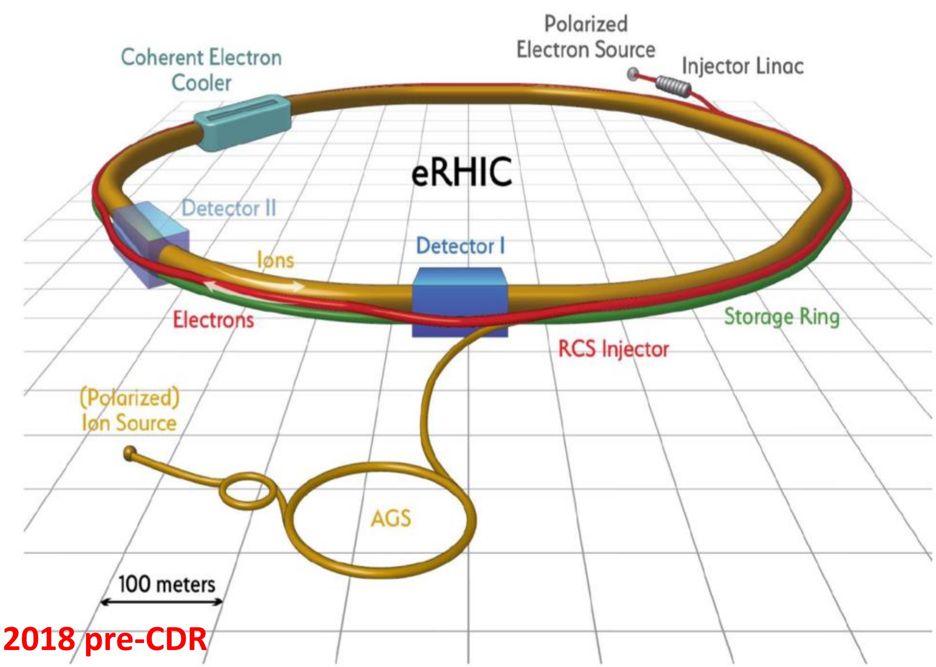
Document
Under development

- **Electron complex**
  - CEBAF full energy injection
  - Collider ring
- **Ion complex**
  - Ion source/Linac
  - Booster (8 GeV)
  - Collider ring
- **IP/detectors**
  - Two, full acceptance
  - Hori. crab crossing
- **Polarization**
  - Figure-8 shape

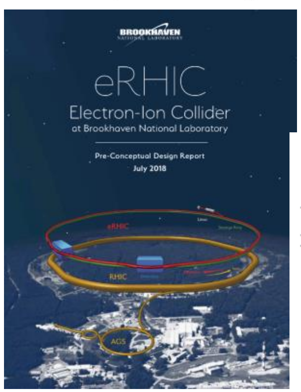
Oct 2018 Update

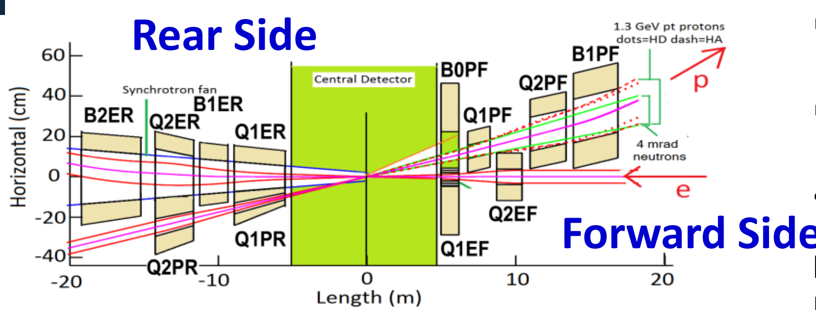
- Increasing √s range by increasing ion ring dipoles from 3T to 6T
- √s = 20 to 100 GeV upgradable to 140 GeV

eRHIC Layout: Ring-Ring Collider



2018 pre-CDR





Hadron Beam

- entirely re-uses infrastructure, injection chain and one of RHIC storage-rings (yellow)
- eRHIC beam parameters equal or close to parameters routinely used in RHIC
- This includes polarized proton beam operation
- Extension to operation with polarized light ions

Electron Accelerator

added inside the existing RHIC tunnel
→ minimal civil construction

- 5-18 GeV storage ring
- On-energy injector: Rapid Cycling Synchrotron
- Polarized electron source and 400 MeV injector linac: 10nC, 1 Hz
- Beam-Beam performance similar to HERA

IR-Region and Detectors:

- 2 IR regions
- Design of IR and Detectors incorporates EIC physics requirements
- 25 mrad horizontal crossing angle utilizing crab cavities
- Required detector acceptance

Polarization:

high polarization for light ions (p, D, He-3) and leptons 80%

Jones Panel Priority Table:

Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

February 13, 2017

2017

The **key EIC machine parameters** identified in the LRP were:

- Polarized (~70%) electrons, protons, and light nuclei,
- Ion beams from deuterons to the heaviest stable nuclei,
- Variable center of mass energies ~20-100 GeV, upgradable to ~140 GeV,
- High collision luminosity ~10^{33}-10^{34} $cm^{-2}sec^{-1}$, and
- Possibly have more than one interaction region.

Technical Challenges for EIC

EIC will be one of the most complex collider accelerators ever to be built. It will push the envelope in many fronts including high degrees of beam polarizations, high luminosity, beam cooling, beam dynamics, crab cavities for both beams, and an interaction region with complex magnets.

Required Accelerator R&D Advances for EIC (list from the Jones panel report)

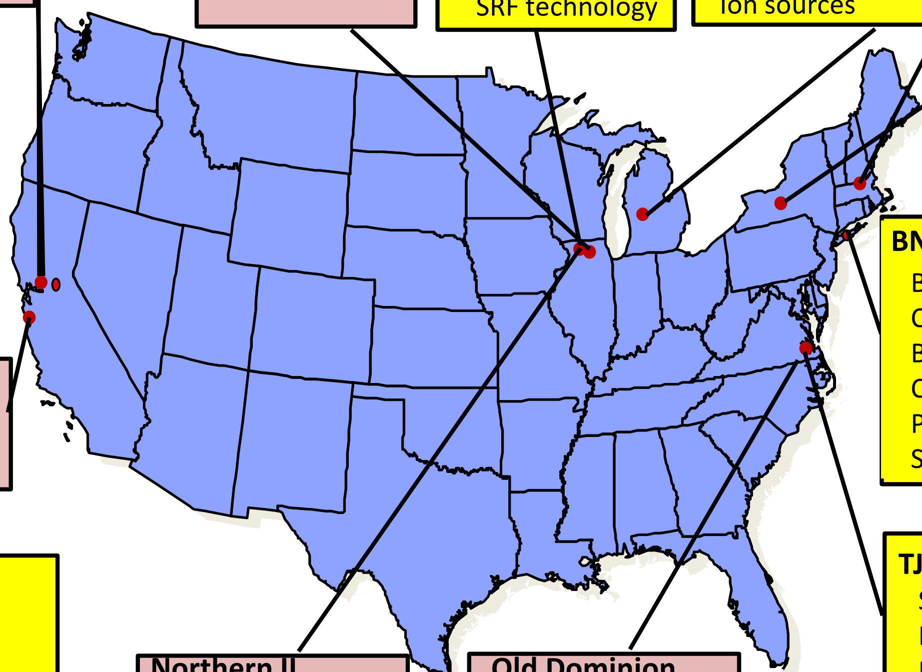
- Hadron cooling techniques
- Polarized electron sources
- Ring magnet demonstrations
- Interaction region magnet design and prototyping
- Machine-detector interfaces
- Superconducting RF technology
- Large scale cryogenics technology
- High current ERL linacs
- Crab cavity design, fabrication and testing (with beam)
- Beam and spin dynamics and benchmarking of simulation tools
- Electron cloud mitigation techniques

State of the Art Accelerator Technology for EIC

- **Beam Cooling:** Beam cooling is one of the highest priority R&D for EIC. The challenge is to achieve the high collision luminosity of order ~10^{33}-10^{34} $cm^{-2}sec^{-1}$.
  - High current multi-pass energy Recovery Linac (ERL)
  - High current unpolarized electron injectors for ERL
- **Interaction Region**
  - **Magnets:** Challenging magnet designs to meet required high fields and field free regions for passage of primary beams.
  - **Crab cavities:** Achieve maximized collision rates between bunches. No operational experience yet exists for crab cavities in hadron beams.
- **Storage ring Magnets**: Challenging high field storage ring magnets are needed.
- **Polarized electron Sources**: **H**igh bunch charges for the ring-ring concept
- **Simulation Codes:** Benchmarking of realist EIC simulation tools against available data needs to be aggressively pursued.

Core Competencies for EIC at NP Labs and Universities

FY18 funding: $ 8.8 M



LBNL
Next Gen. ion source

LBNL
Beam simulation

FNAL
Beam Cooling

ANL
Beam simulation
SRF technology

Michigan State U. (FRIB)
SRF technology
Ion sources

MIT
High current polarized electron sources
Polarized ^{3}He target

Cornell University
High current e. sources
SRF technology

BNL (RHIC)
Beam cooling
Crab Cavity design
Beam simulations
Colliders
Polarized ion sources
SC magnet design

SLAC
Beam simulation

Northern IL University
Beam simulation

Old Dominion University
Crab cavity design

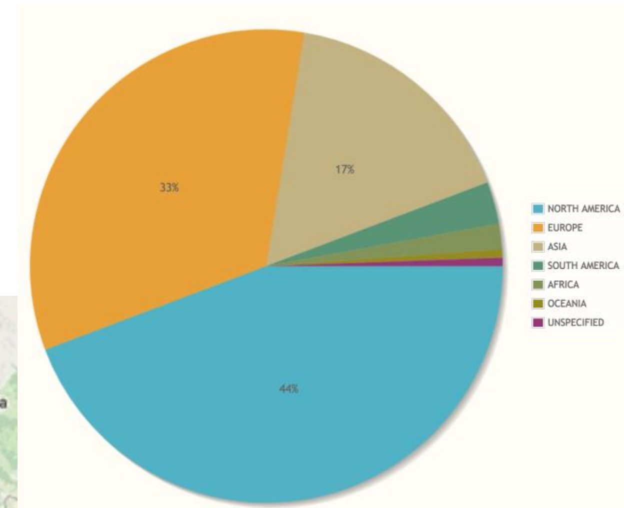
TJNAF
SRF technology
ERL
Polarized electron sources
Beam simulations
SC magnet design

NP core competency

With NP EIC awards

EIC Users Group and International Interest

Formed 2016, currently:
824 Ph.D. members in
174 institutions from 30 countries



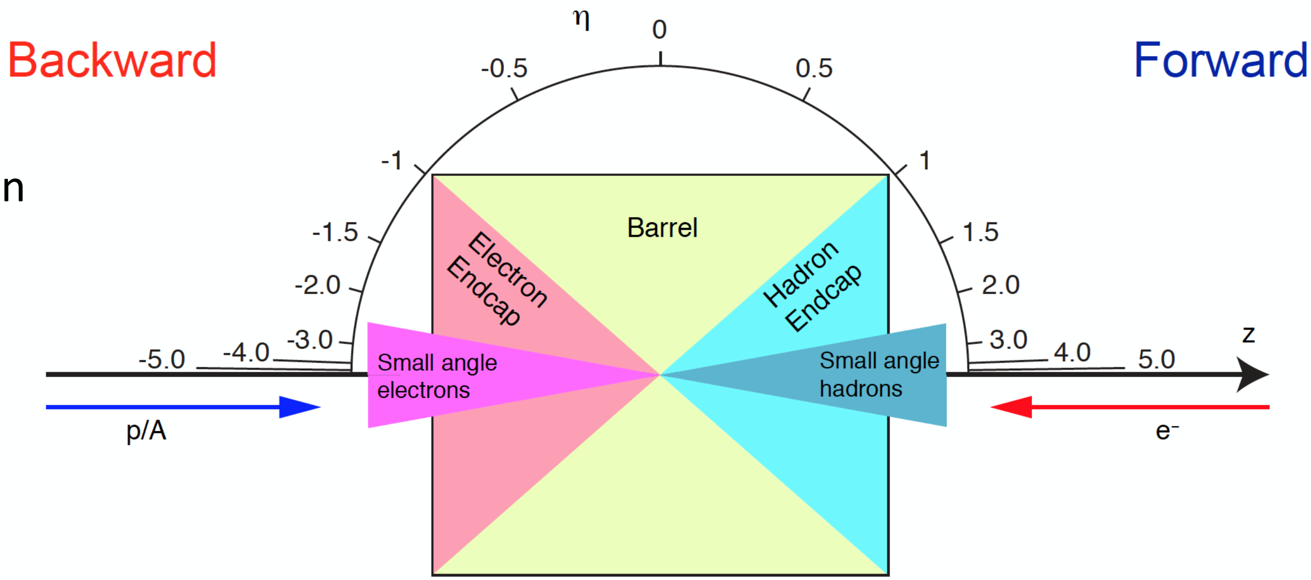
Annual EICUG meeting
2017 Trieste, Italy
2018 Washington, DC
2019 Paris, France

New!
Center for Frontiers in Nuc. Sc., Stony Brook U.
EIC² at Jefferson Lab

EIC Detectors

- Consensus within EIC community
  - At least 1 general purpose detector
  - Needs for a second detector – majority favors a second general purpose detector instead of a more specialized detector
  - Arguments for 2 detectors similar as for every collider
  - The 2 detectors should be complementary
- Both eRHIC and JLEIC include at least 2 IRs

Challenges:
Hermiticity } IR design
Compactness } IR design
Precision
PID: 250 MeV/c -> 50 GeV
Calorimetry



R&D Efforts

- Laboratory Directed Research & Development Programs (LDRDs) at National Labs in the US (BNL, JLAB, ANL)
- R&D at Belle-II and Panda has some overlap with EIC
- CERN/LHC
  - No R&D on key EIC challenges (PID, ECal)
  - R&D for phase-I upgrades ended, phase-II focus on radiation hardness and rate
- Generic EIC Detector R&D Program
  - Started in 2011 by BNL, in association with JLab and DOE NP
  - Funded by DOE NP, through RHIC operations
  - Program explicitly open to international participation
  - Standing EIC Detector Advisory Committee with internationally recognized detector experts

Current: Marcel Demarteau (ANL, Chair), Carl Haber (LBNL), Peter Krizan (Ljubljana), Ian Shipsey (Oxford), Rick Van Berg (UPenn), Jerry Va'vra (SLAC), Glenn Young (JLab)

Generic EIC Detector R&D Program

- Typical 10-11 projects supported at any time
- Attempt to merge projects in larger consortia when related (calorimetry, tracking, PID, Si-Vertex)
- Participation:
  - 46 institutions (13 non-US), 6 Natl. Labs
  - 187 participants
  - Important seed for formation of EIC collaborations
  - Since 2016 budget flat at $1M/year
- Requested funds exceed available funds by factor 2.5 (FY18)
- Despite being underfunded projects make steady and excellent progress.
- Need for increased R&D to meet challenges as recommended in 2015 LRP
  - Funding is spread too thin
  - Funding fewer would discourage many & excludes groups with expertise that want to get involved

N.B.: *Generic* RHIC detector funding was ~$4M in 2018$

Briefings to U.S. Government

National Academy of Sciences Assessment

- July 12: ***Office of Nuclear Physics, DOE***
  Timothy Hallman, Jehanne Gillo, Manouchehr Farkhondeh
- July 18: ***OMB, OSTP***
  Avital Bar-Shalom
- July 18: ***Staff on House Science Committee***
  Adam Rosenberg, Emily Domenech, Hillary O'Brien
- August 7: ***Undersecretary for Science, DOE***
  Paul Dabbar
- October 30: ***House Appropriations (Energy & Water)***
  Perry Yates

December 4: Visits to *Capitol Hill* by EICUG members

Summary

- Over two decades, the U.S. nuclear physics community has developed the scientific and technical case for a new 21st century instrument, the Electron-Ion Collider, to push the frontiers of human understanding of the fundamental structure of matter.
- The U.S. National Academy of Sciences judges the physics case to be

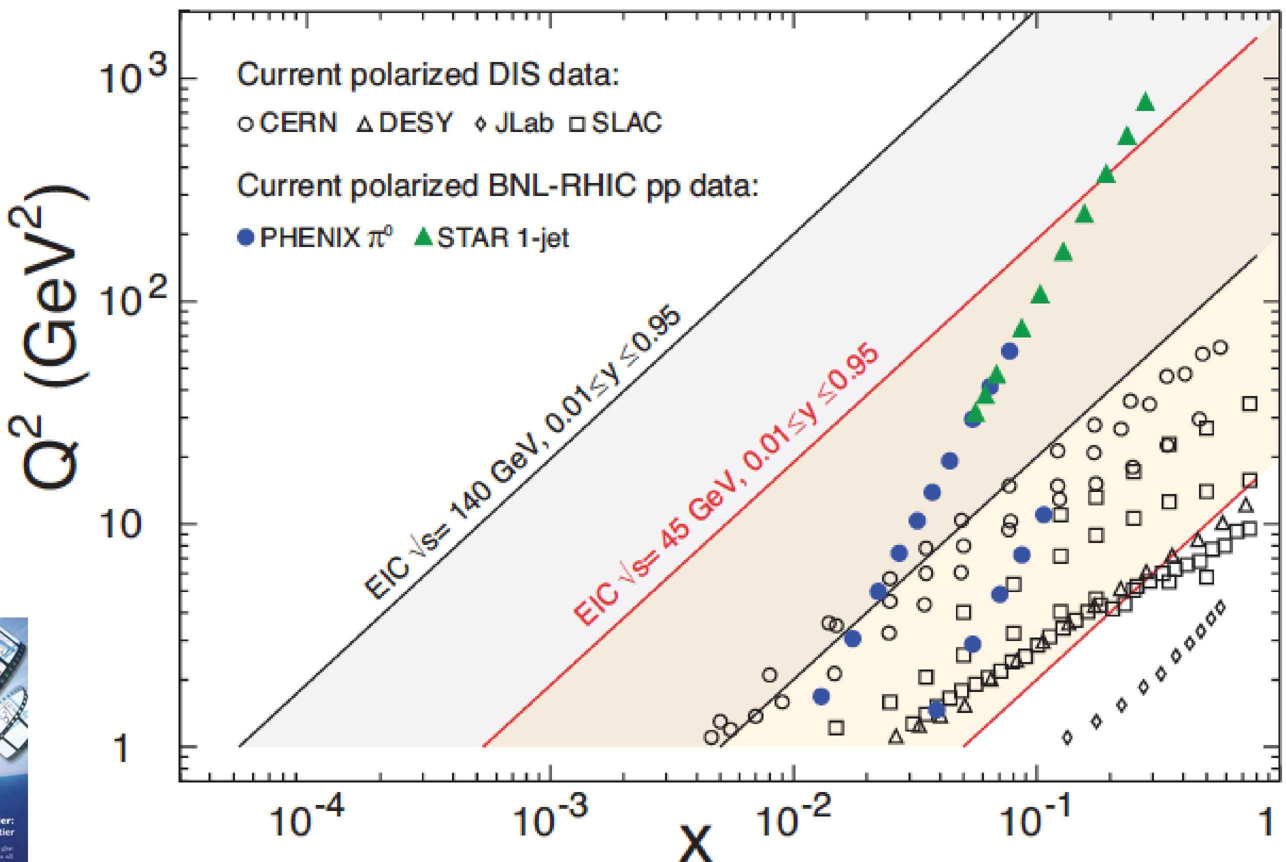
  "**compelling, fundamental and timely**."
- This compelling EIC physics case continues to sprout vigorous new branches.
- FRIB, together with EIC, will probe the visible matter in the universe well into the 21st century.
- The parameters of the EIC accelerator are well defined and will drive innovations in accelerator technology well beyond state of the art.
  - Accelerator R&D a high priority
  - Expertise and scientific thrusts of current flagship NP facilities BNL and Jefferson Lab are well aligned with EIC.
- Realization of EIC will demand that DOE NP, BNL and JLab lead the U.S. to the frontiers of collider technology.
- There is substantial interest worldwide in EIC and clear opportunities for foreign investment in U.S. nuclear physics.

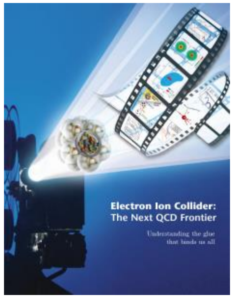
  - Accelerator R&D - Detector R&D - Theory/Lattice
- We await the launch of EIC on the DOE Critical Decision Management process.

BACKUP

EIC Reach

Collider delivers high E_{CM} with final-state particles distributed over a large angular range
e.g. for E_{CM} = 100 GeV, $E_{fixed\ target}$ = 5 TeV ➔ all final-state particles are very forward

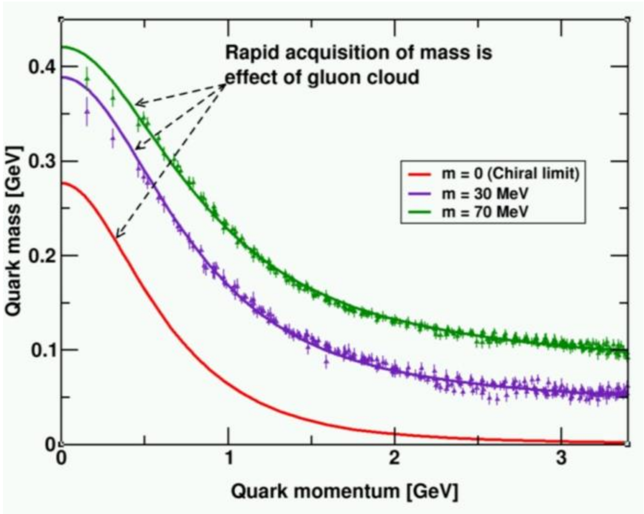




The Incomplete Hadron: Mass Puzzle

"Mass without mass!"

Bhagwat & Tandy/Roberts et al



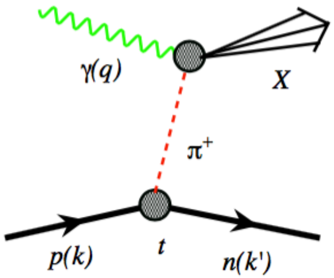
Proton: Mass ~ 940 MeV
constituents acquire mass by DχSB,
most of mass generated by dynamics

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 π and K with Sullivan process



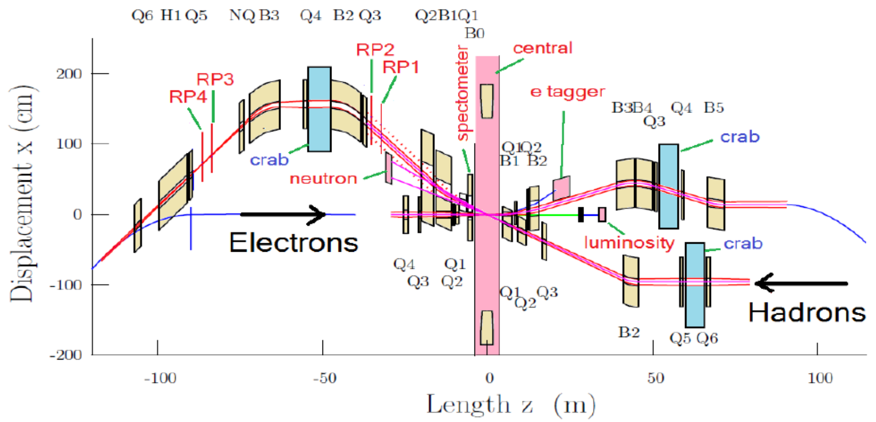
In chiral limit (m_π -> 0), matrix element of EMT for pion vanishes.

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

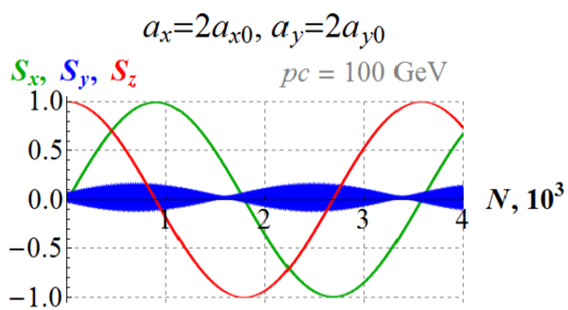
State of the Art Accelerator Technology for EIC

Schematic layout of IR



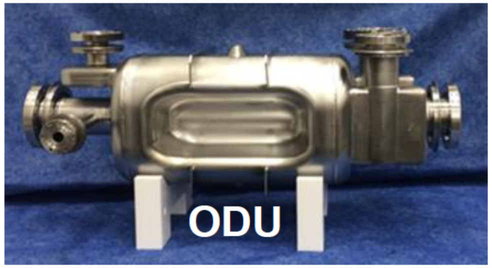
V. Ptitsyn *et al.*

Spin: Nonlinearity of orbital motion-



V. Morozov *et al.*

Crab Cavity

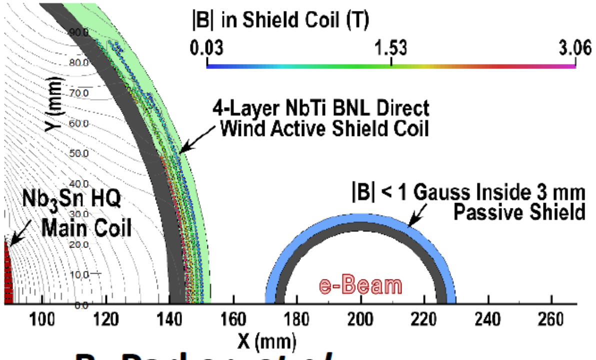


S. De Silva *et. Al*

952.6 MHz cooler ERL (SCRF)

B. Rimmer, *et al.*

IR quadrupole magnet



B. Parker, *et al.*

Core Competencies for EIC at NP Labs and Universities