Electron–Ion Collider

A major new scientific facility to probe the heart of nuclear matter

Garth Huber

University of Regina

Prairie Universities Physics Seminars
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University of Regina

- Founded 1974
- 16,501 students, incl. 2,021 Grad Students (Fall 2019)
- Physics Dept. offers B.Sc., M.Sc. and Ph.D. degrees

Outline

- Brief introduction to quarks and gluons
- The science problem in brief
- Major scientific motivations for the Electron–Ion Collider (EIC)
- Where will it be built?
- EIC Canada and URegina involvement

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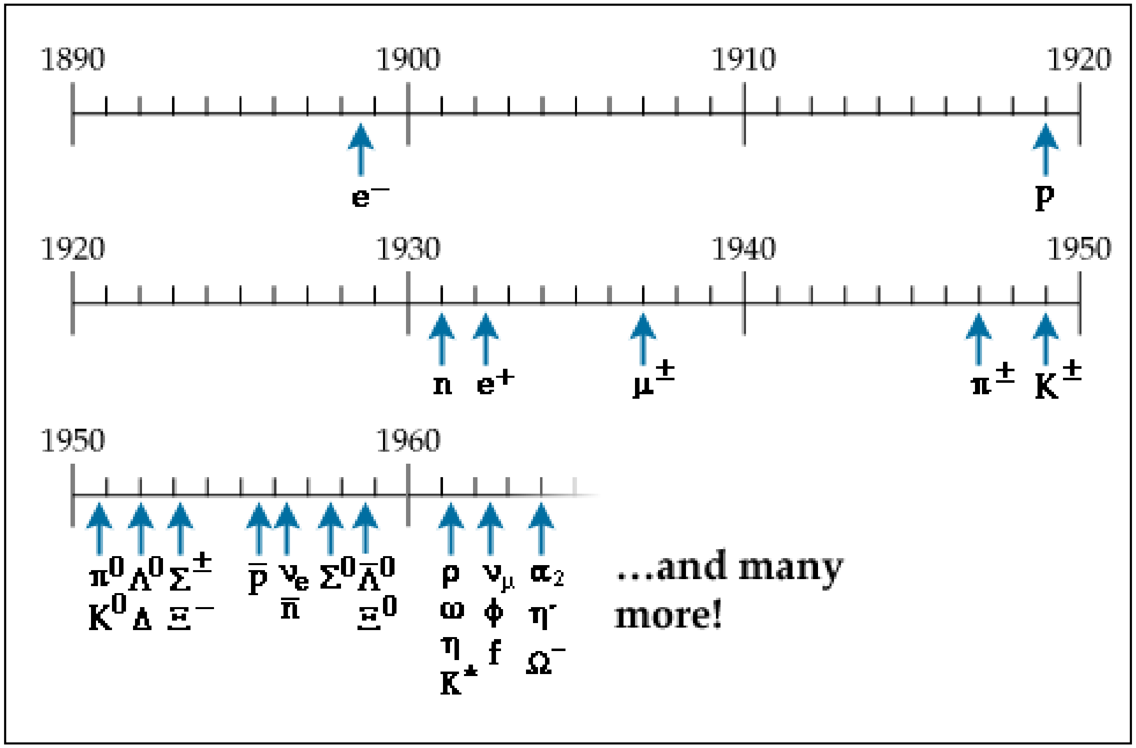
The Particle Zoo

- Circa 1950, the first particle accelerators began to uncover many new particles.
- Most of these particles are unstable and decay very quickly, and hence had not been seen in cosmic ray experiments.
- Could all these particles be fundamental?



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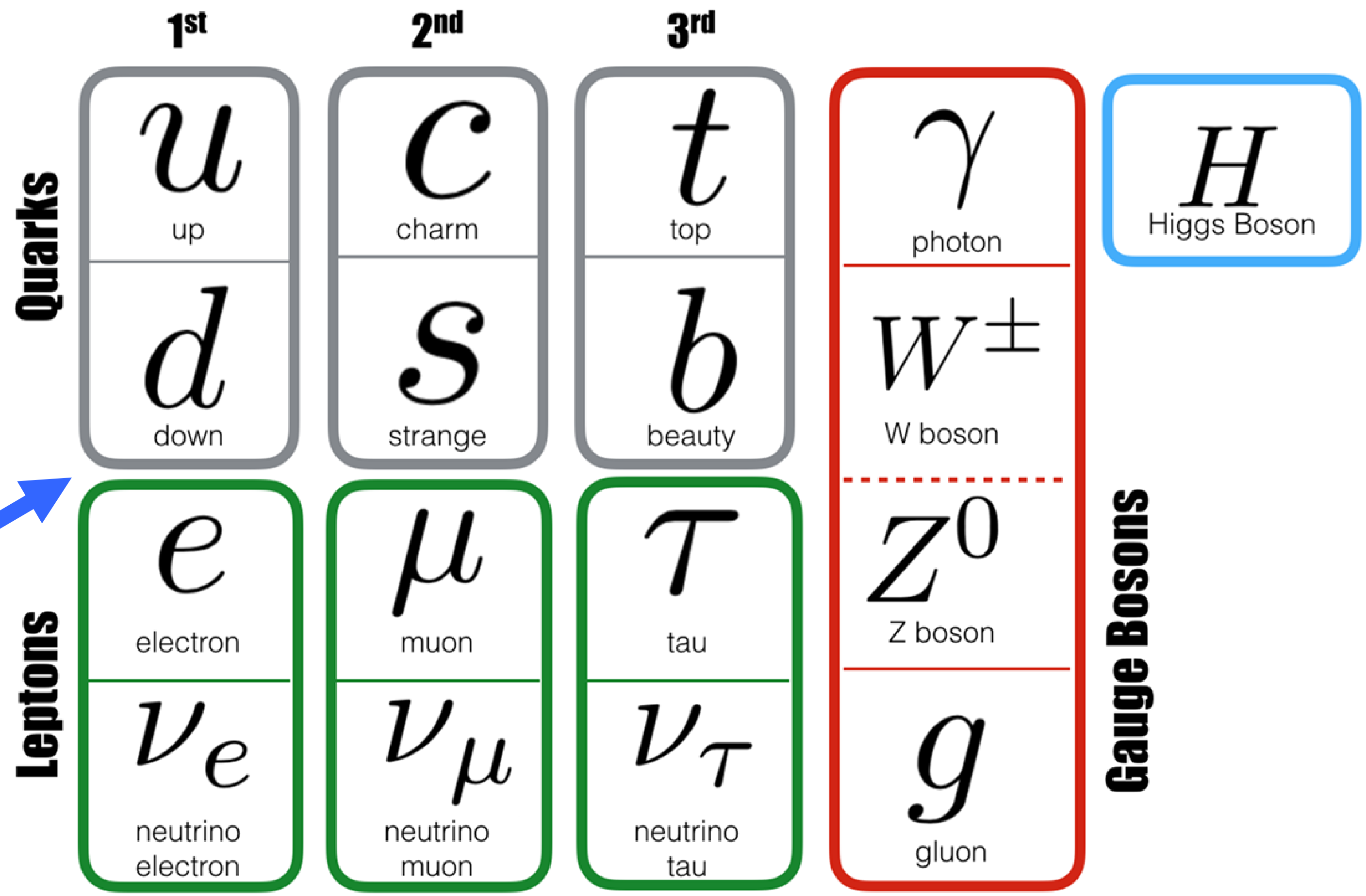
Quarks, Leptons and their Fundamental Interactions



The ground state of matter

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Quantum Electrodynamics
Quantum Chromodynamics

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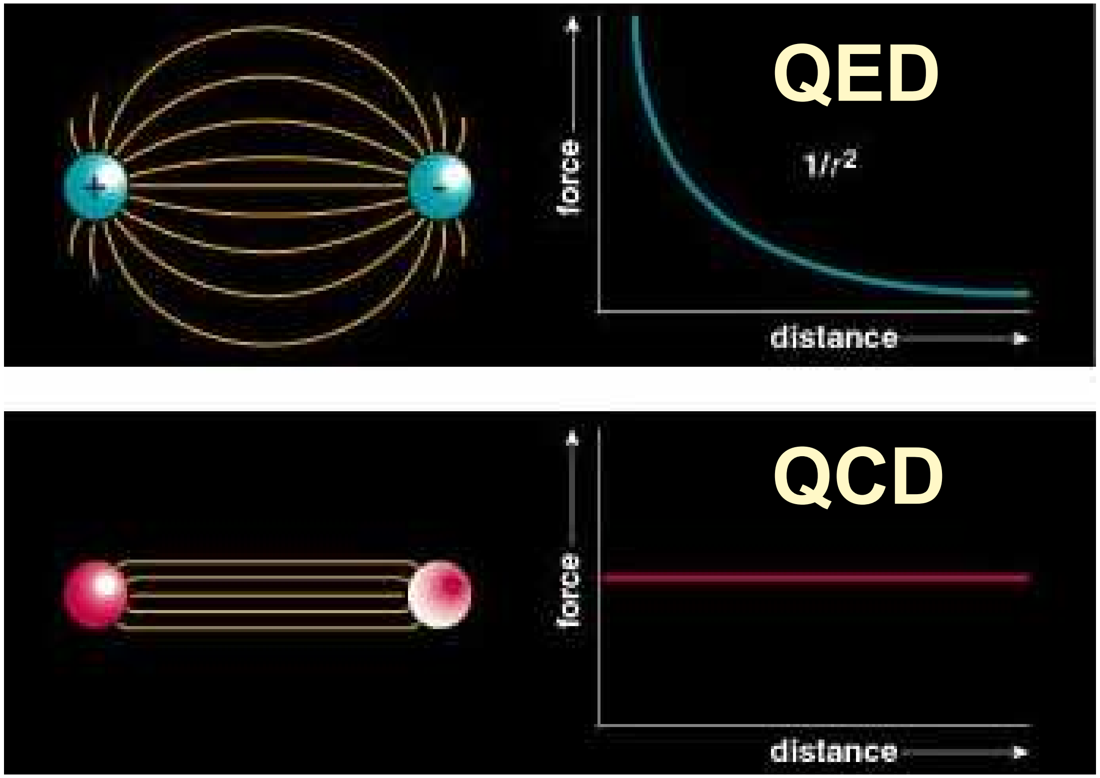
The gluons of QCD carry color charge and interact strongly (in contrast to the photons of QED)



Quarks (and their color charge) are confined inside strongly–interacting particles called hadrons

Quark & Gluon Momenta within Proton

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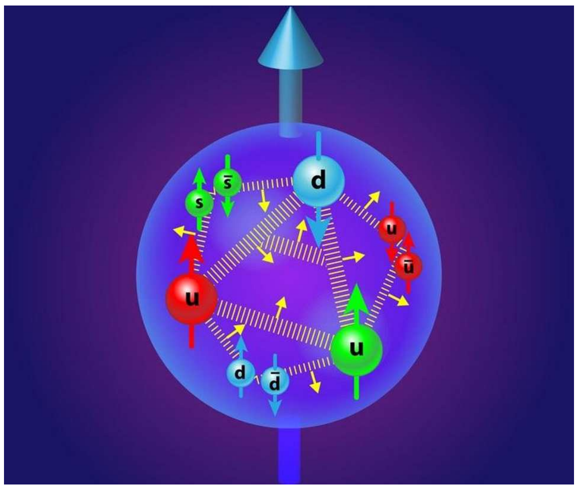
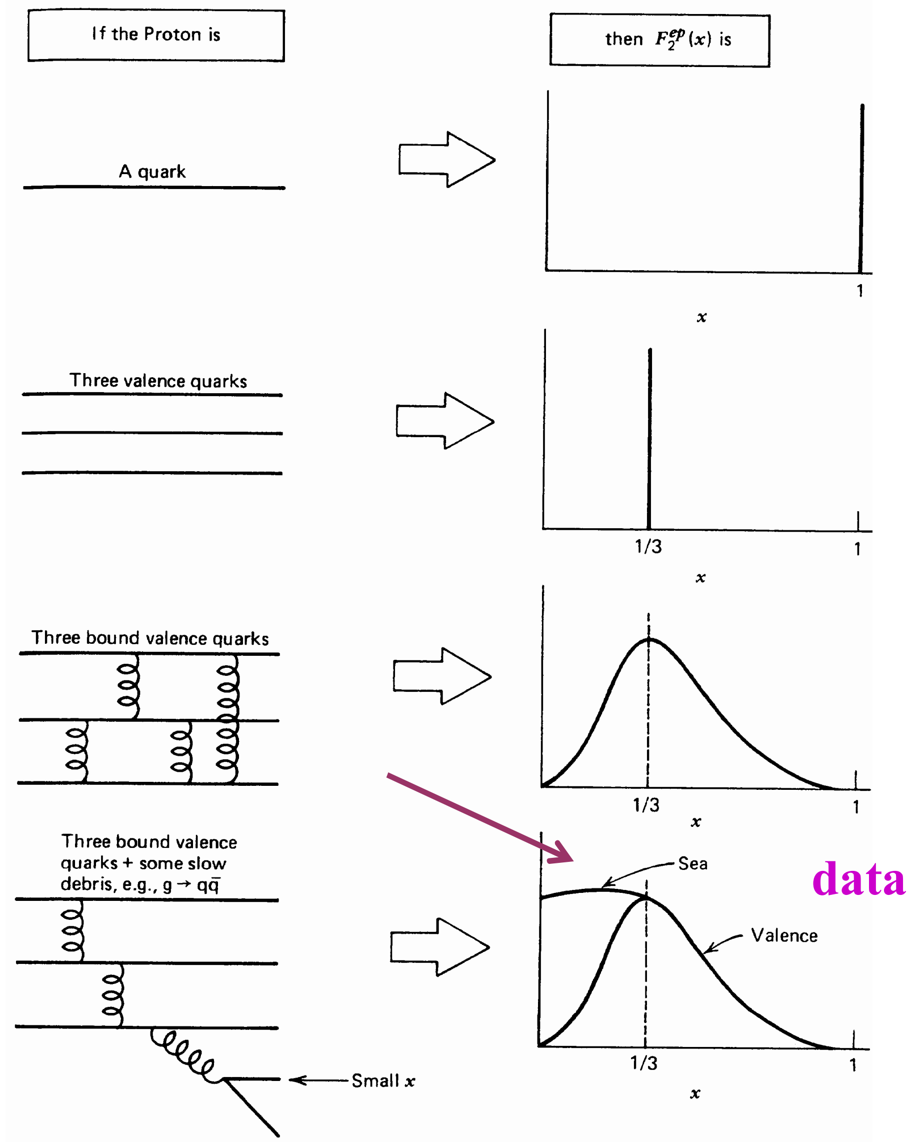
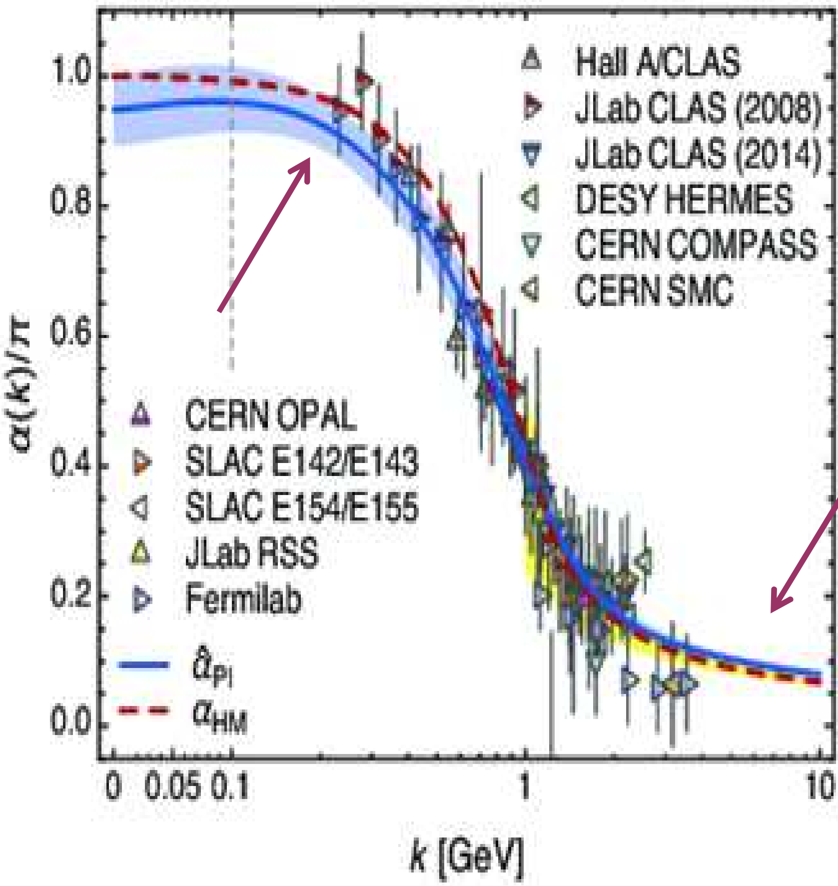
VALENCE QUARKS: qqq
required for correct proton quantum numbers.
SEA QUARKS: virtual $q\bar{q}$ pairs allowed by uncertainty principle.





- x represents fraction of proton momentum carried by struck parton (quark or gluon).
- Quarks inside proton have probability (P) distribution ($f(x)=dP/dx$) to have momentum fraction x.

QCD's Dual Nature



Binosi, Mezrag, Papavassiliou, C.D. Roberts, Rodriguez-Quintero,

PRD **96** (2017) 054026. arXiv:1612.04835

Short Distance Interaction:

- Short distance quark-quark interaction is feeble.
  - Quarks inside protons behave as if they are nearly unbound, pQCD.
  - Asymptotic Freedom.
  - Nobel prize: Friedman, Kendall and Taylor, 1990.

Long Distance Interaction:

- Quarks strongly bound within hadrons.
  - Color confinement (strong QCD).
  - Quantitative QCD description of nucleon's properties (i.e. understanding of the confinement regime) remains a puzzle!

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Food for thought

Recall: Mass of Proton $\sim 938\ [\text{MeV}/c^2]$

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Total quark mass in proton: ~ 12 [MeV/c^2]

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→ ~99% of our mass comes from quark–gluon interactions in the nucleon, which are very complex!

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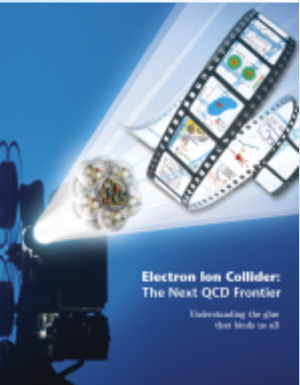
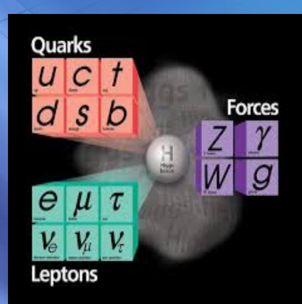


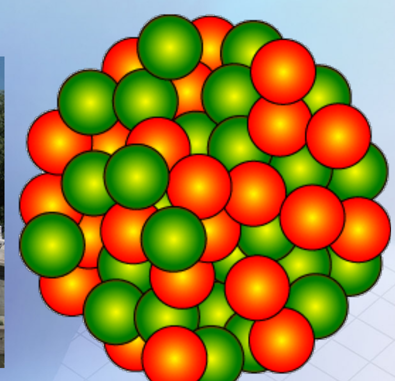
arXiv 1212.1701.v3
Eur. Phy. J. A52, 9 (2016)

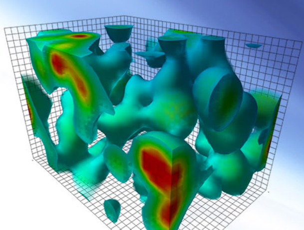
Electron Ion Collider: The next QCD frontier

*Understanding the **Glue** that Binds Us All*

This talk is based on the work of a large number of scientists, excited about the EIC science and involved in the EIC project, now organized as the EIC Users Group







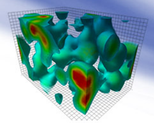
Abhay Deshpande

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.

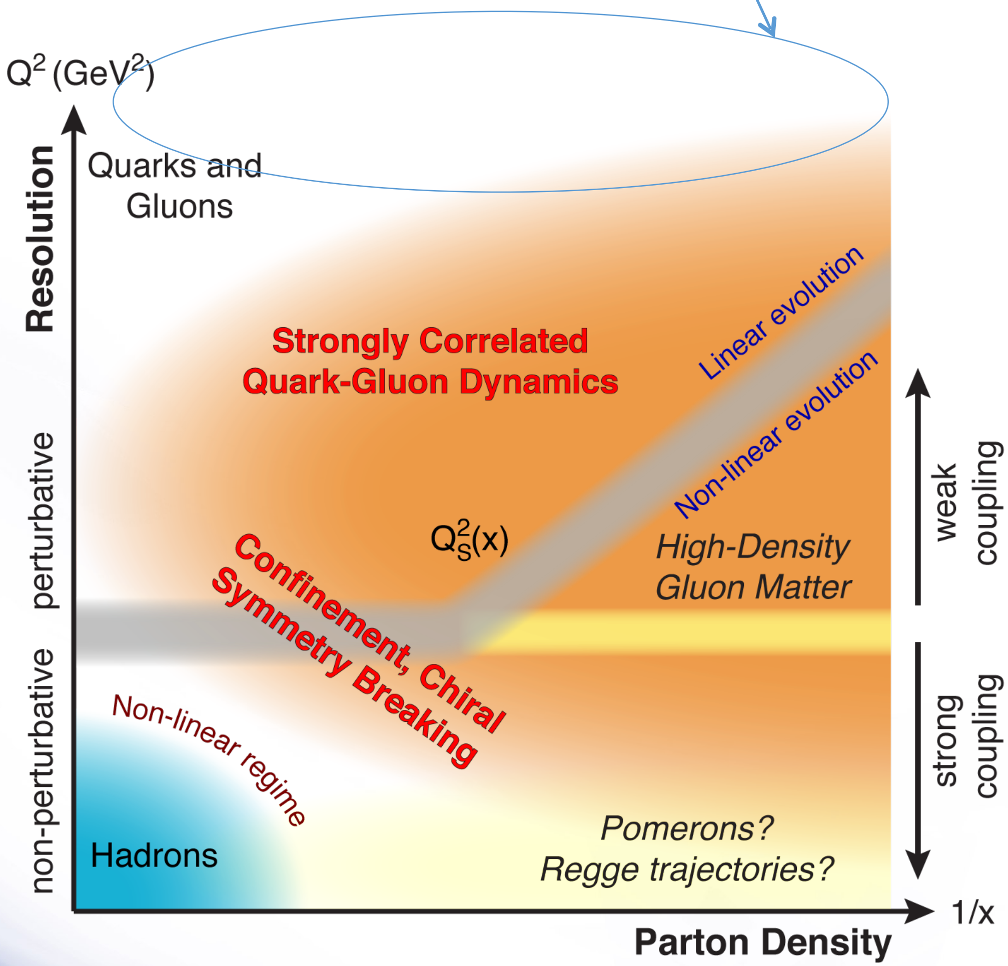
- **Gaining understanding of this dynamic matter → transformational:** Gaining detailed knowledge of this astonishing dynamical system at the heart of our world **could be transformational**, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter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

- **The Electron Ion Collider is the right tool:** A new US-based facility, high-energy, high-luminosity Electron Ion collider (EIC), capable of a versatile range of beam energies, polarizations, and species, 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.



QCD Landscape explored by EIC

QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described



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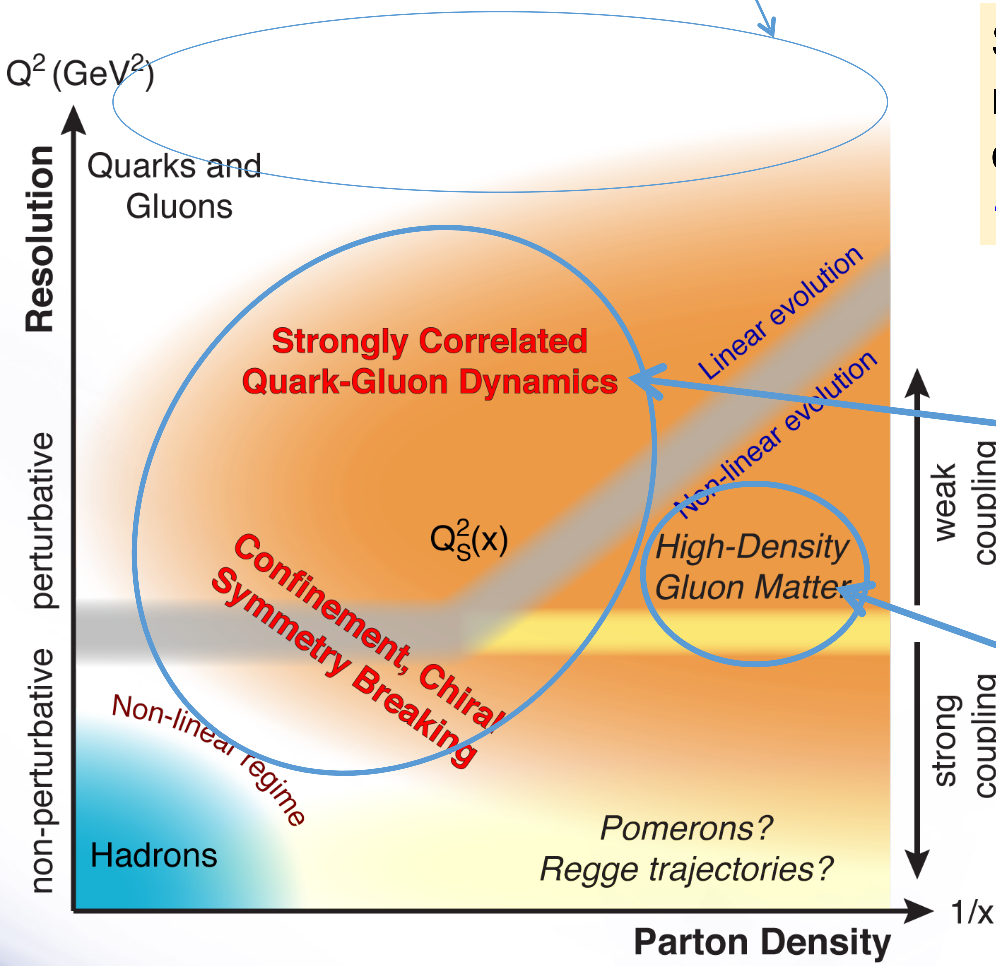


Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

EIC systematically explores correlations in this region.

An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter

Non-linear Structure of QCD: Fundamental Consequences

- Quark (Color) confinement:
  - Consequence of nonlinear gluon self-interactions
  - Unique property of the strong interaction

- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions – Generalized Parton Distributions (GPDs)

- Ultra-dense color (gluon) fields:
  - Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?

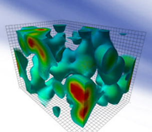
Emergent Dynamics in QCD

***Without gluons,* there would be no nucleons,**

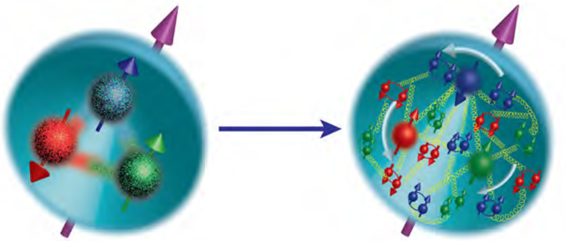
no atomic nuclei… no visible world!

- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% of the proton's momentum, a significant fraction of the nucleon's spin, and are essential for the dynamics of confined partons
- Properties of hadrons are emergent phenomena resulting not only from the equation of motion but are also inextricably tied to the properties of the QCD vacuum. Striking examples besides confinement are spontaneous symmetry breaking and anomalies
- The nucleon-nucleon forces emerge from quark-gluon interactions: how this happens remains a mystery

Experimental insight and guidance crucial for complete understanding of *how* hadrons & nuclei emerge from quarks and gluons



A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter



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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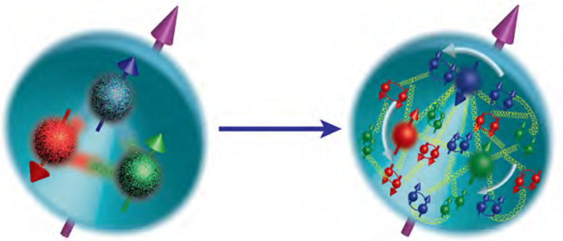

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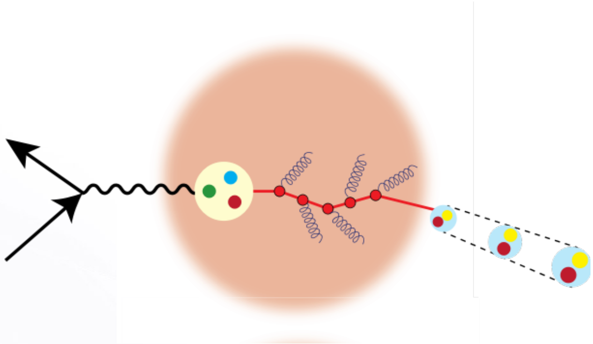

How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

How do the quark-gluon interactions create nuclear binding?

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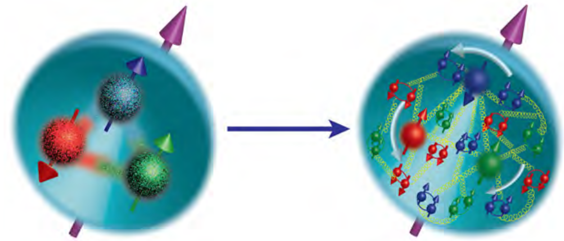

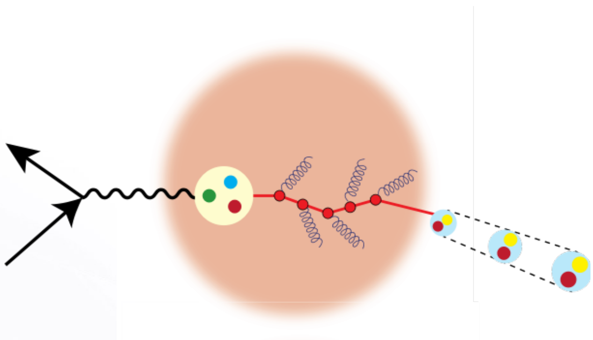

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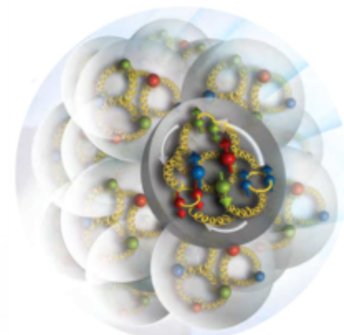
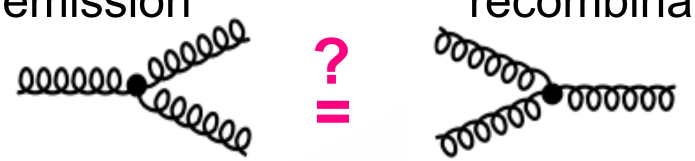


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

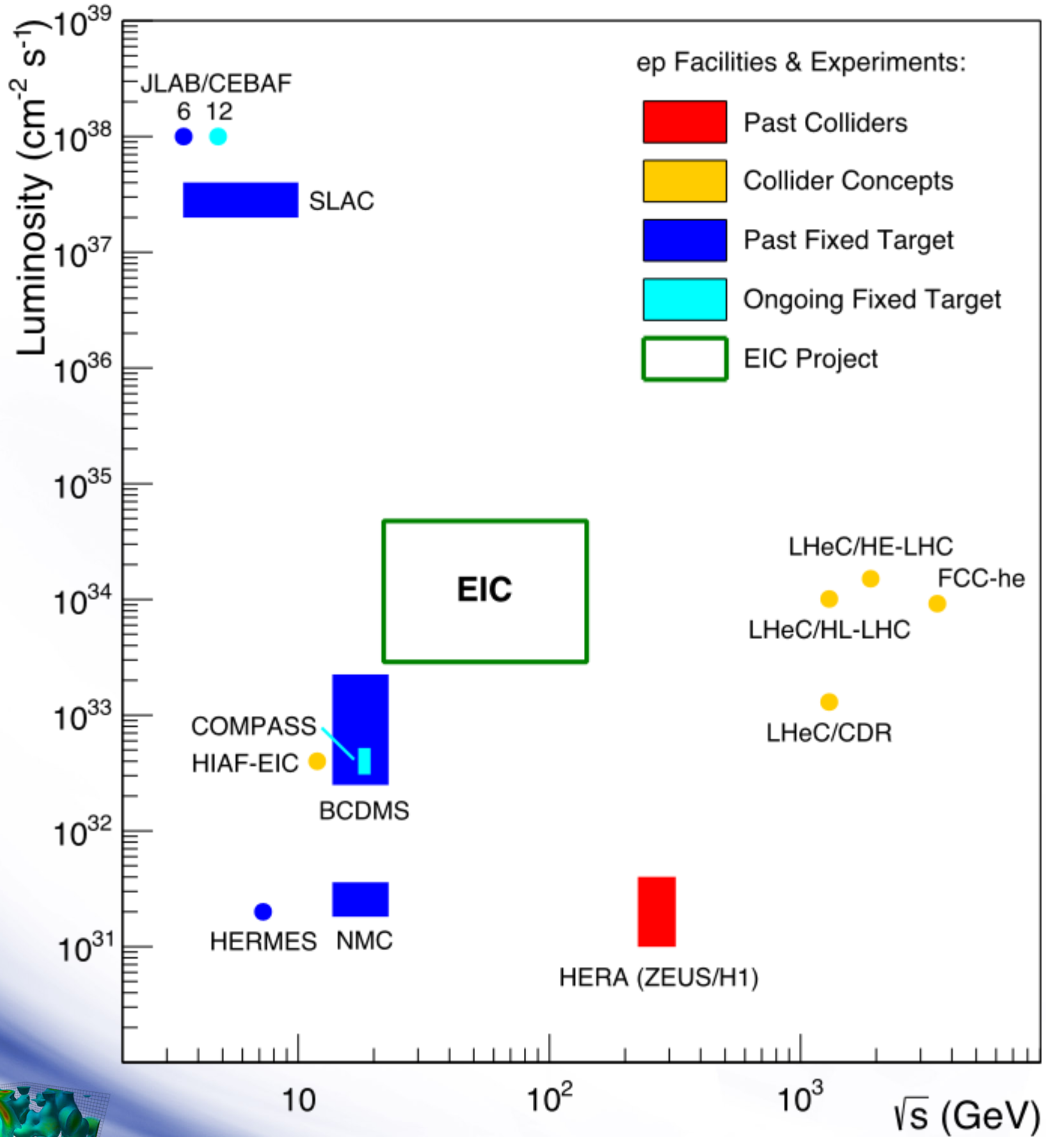
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission

gluon recombination



Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

However,
if we ask for:

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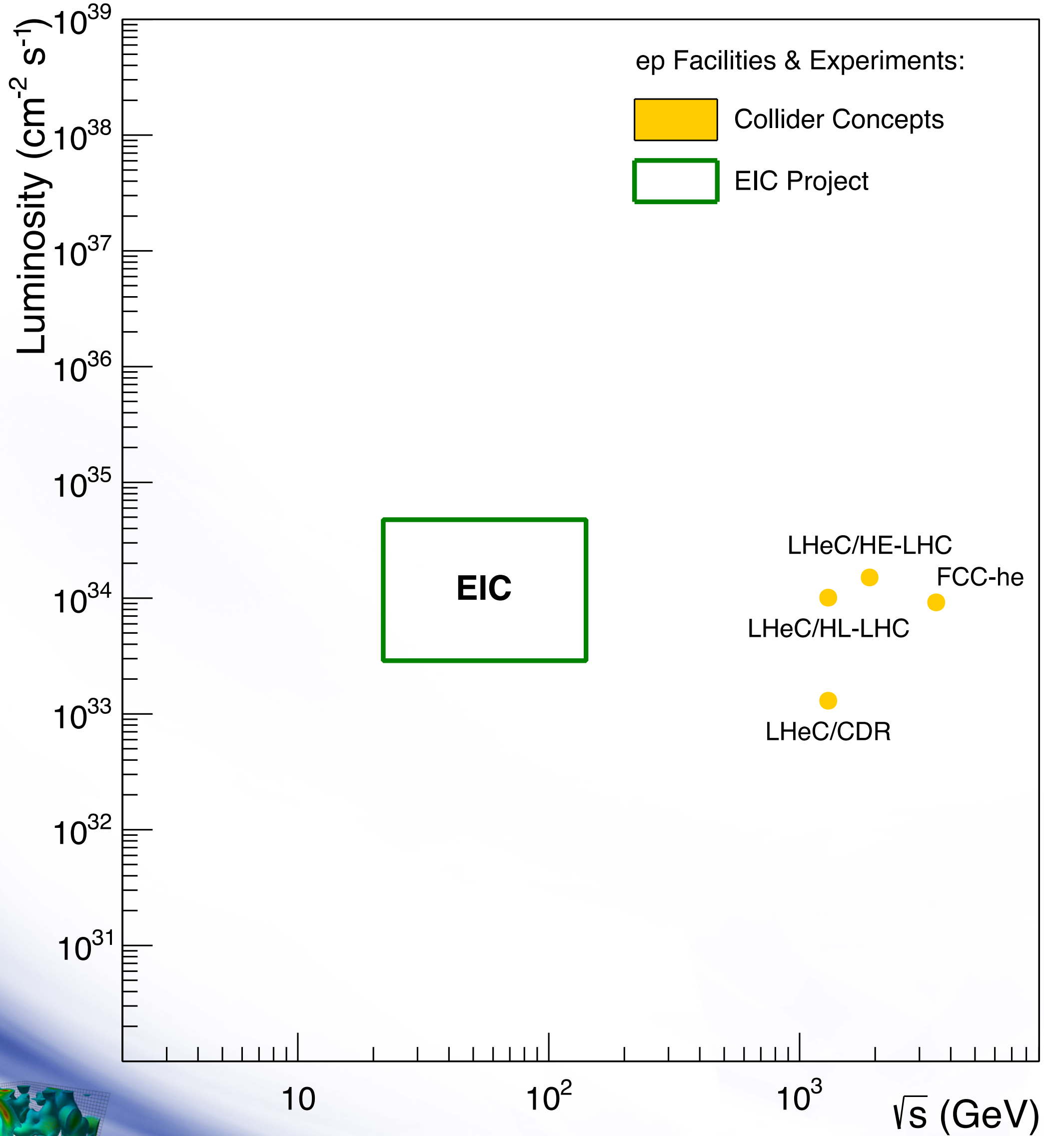

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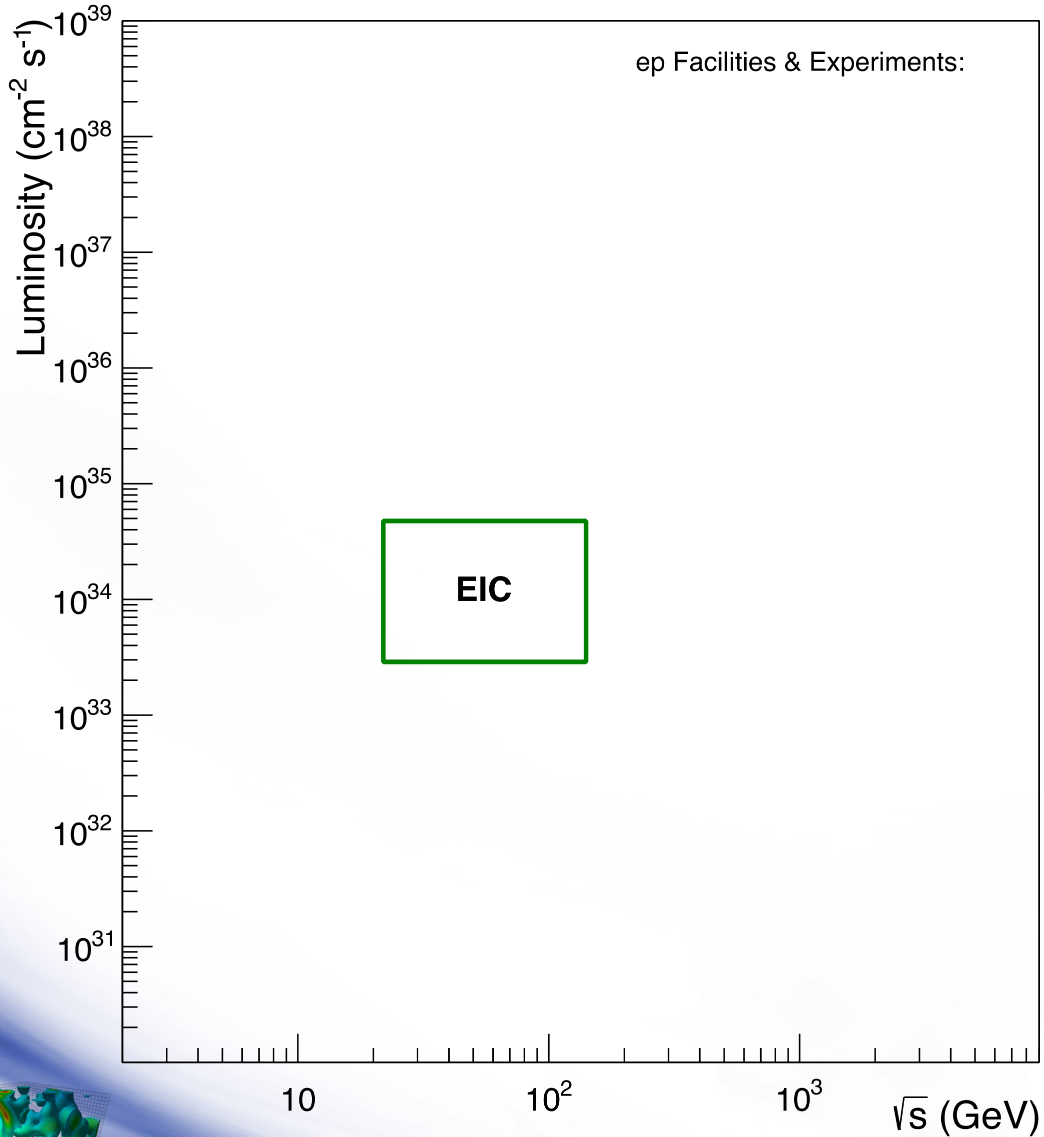

All DIS facilities in the world.

However,
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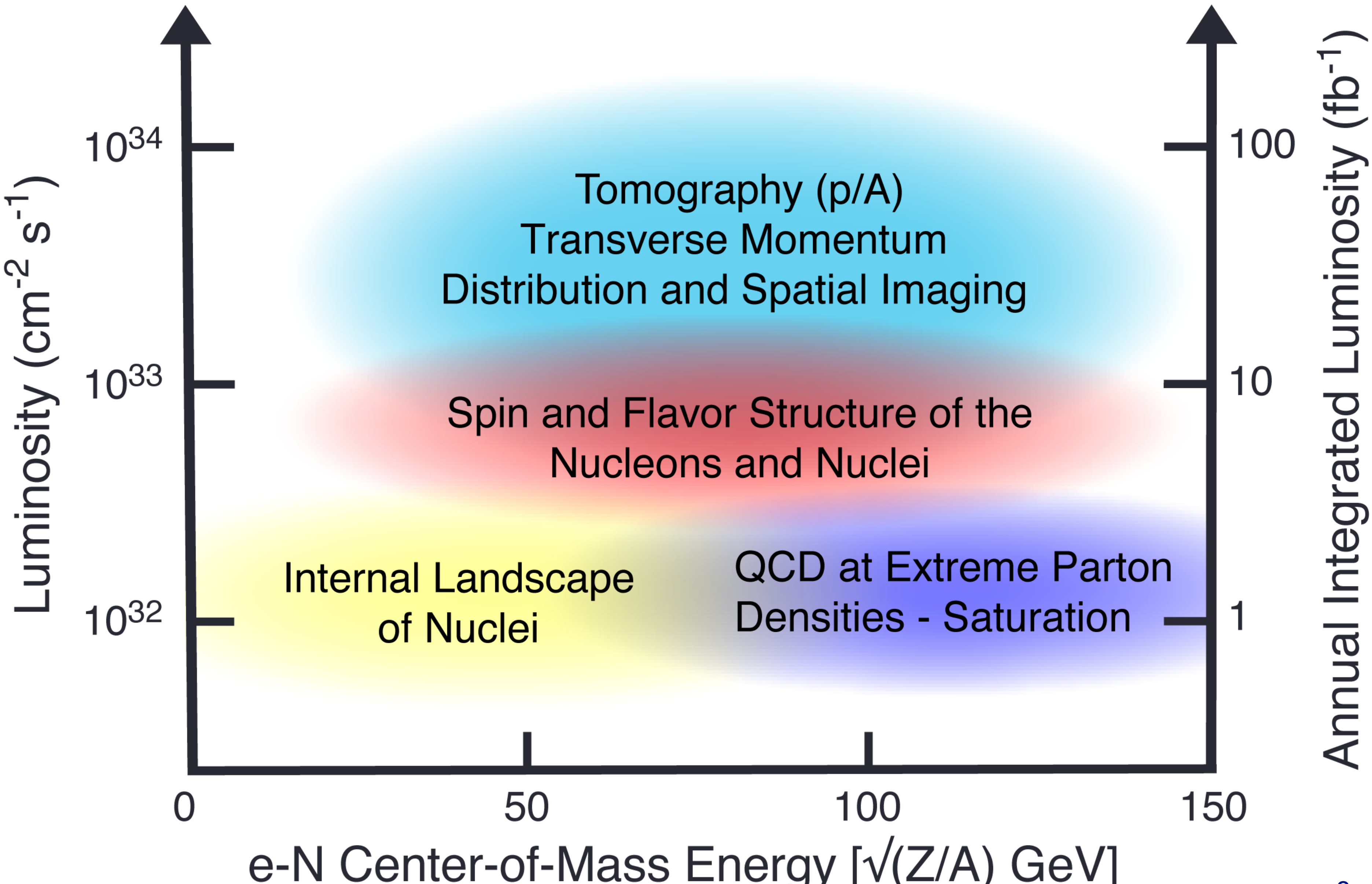
- high luminosity & wide reach in √s
- polarized lepton & hadron beams
- nuclear beams

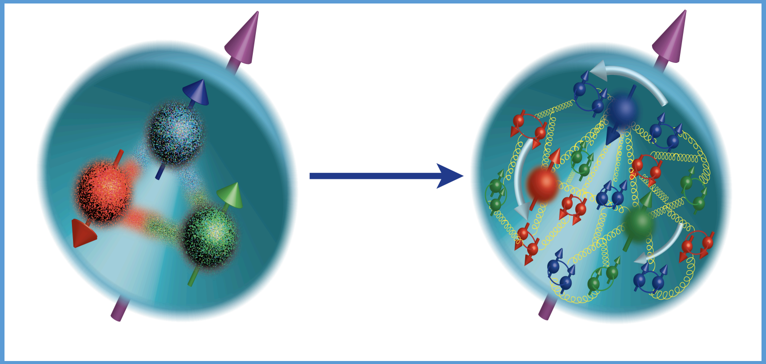
EIC stands out as unique facility …

Uniqueness of EIC among all DIS Facilities



The world's first polarized electron-proton collider

Polarized proton as a laboratory for QCD



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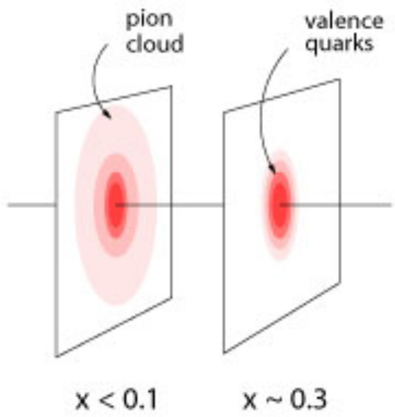
What does a proton look like with increasing energy?

One of several possible scenarios: a pion cloud model



A parton core in the proton gets increasingly surrounded by a meson cloud with decreasing x
→ large impact on gluon and sea-quark observables

What do we expect to see:

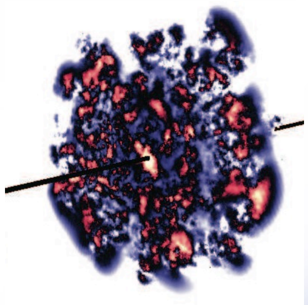
- ❑ $q\bar{q}$ pairs (sea quarks) generated at small(ish)-x are predicted to be unpolarized
- ❑ gluons generated from sea quarks are unpolarized

→ needed:

- ➢ high precision measurement of flavor separated polarized quark and gluon distributions as functions of x
- ➢ high precision spatial imaging: Gluon radius ~ sea-quark radius ?

What happens in the gluon dominated small-x regime?

- ➢ possible scenario: lumpy glue



EIC will explore the dynamical spatial structure of hadrons

2+1 D partonic image of the proton with the EIC

Spin-dependent 3D momentum space images from semi-inclusive scattering

Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

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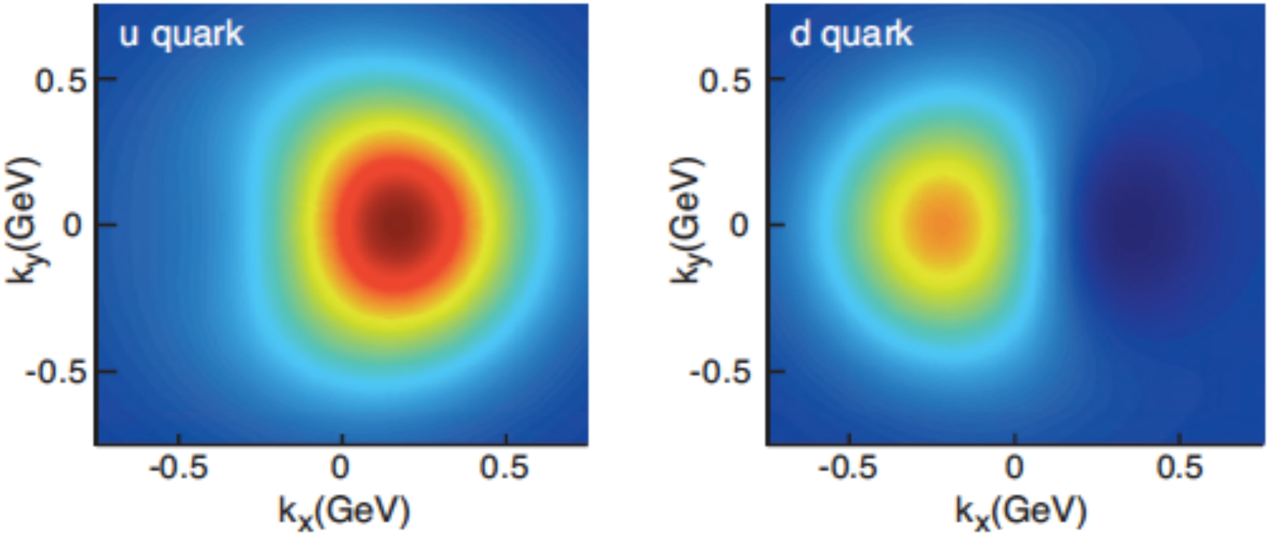

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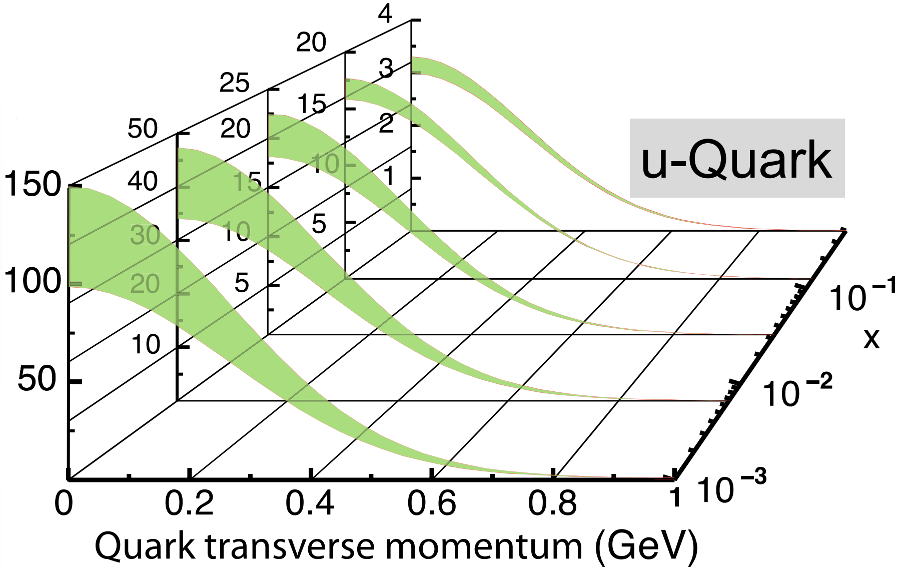

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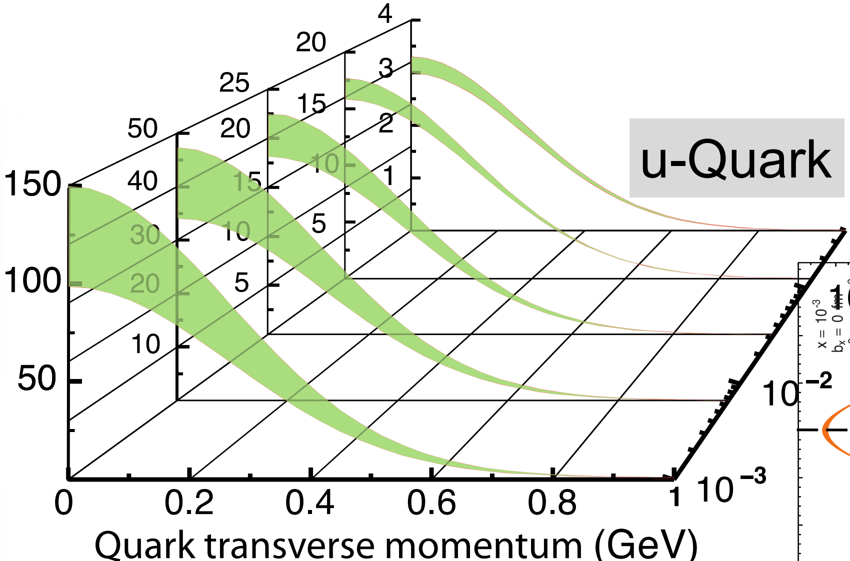

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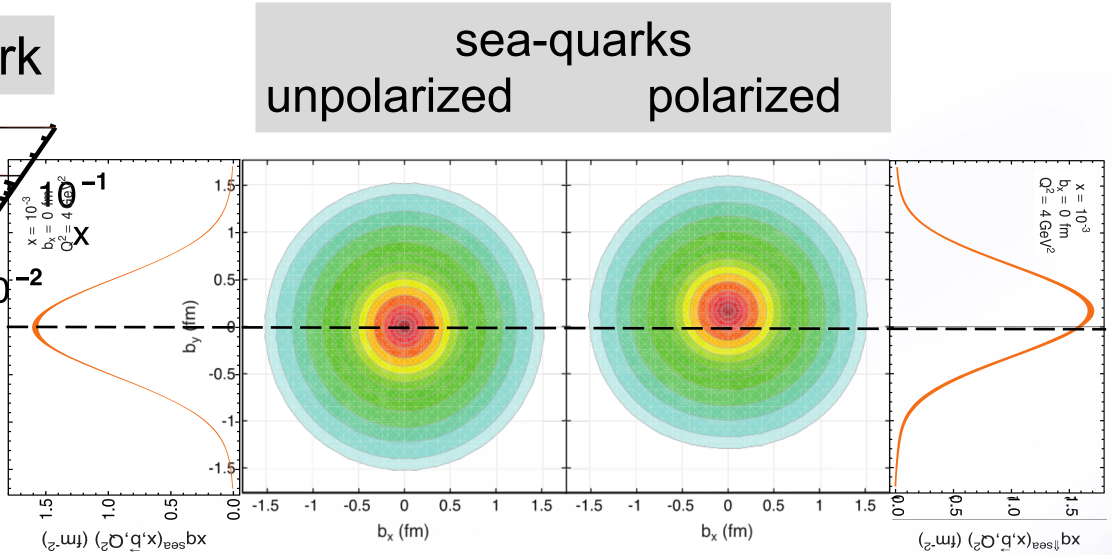
Transverse Position Distributions



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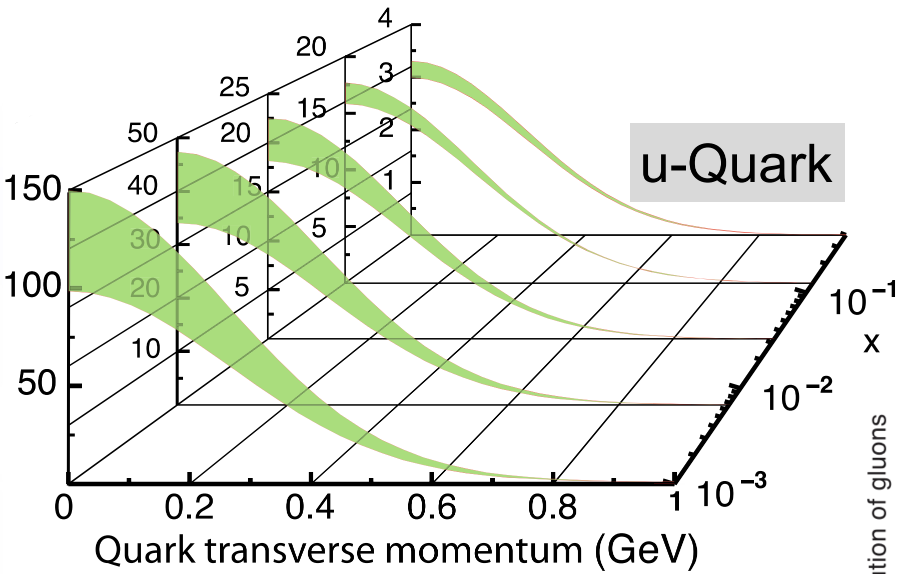

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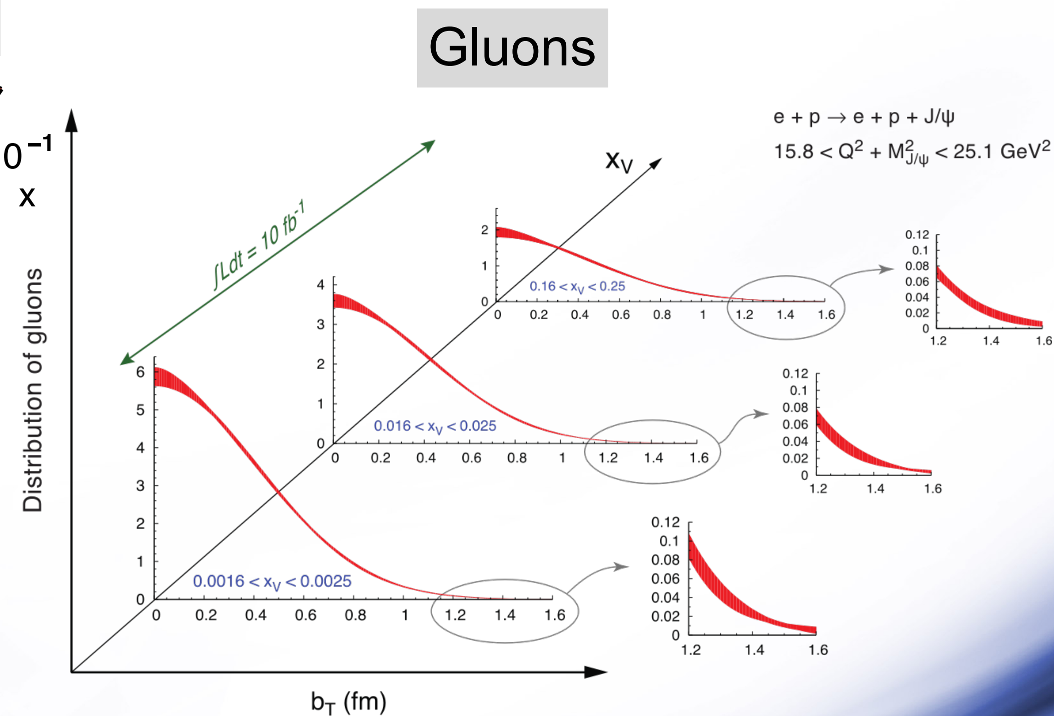
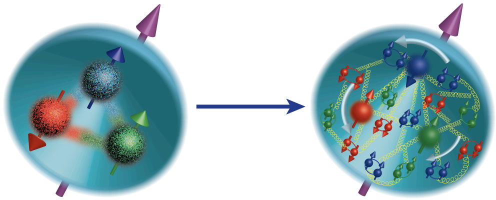


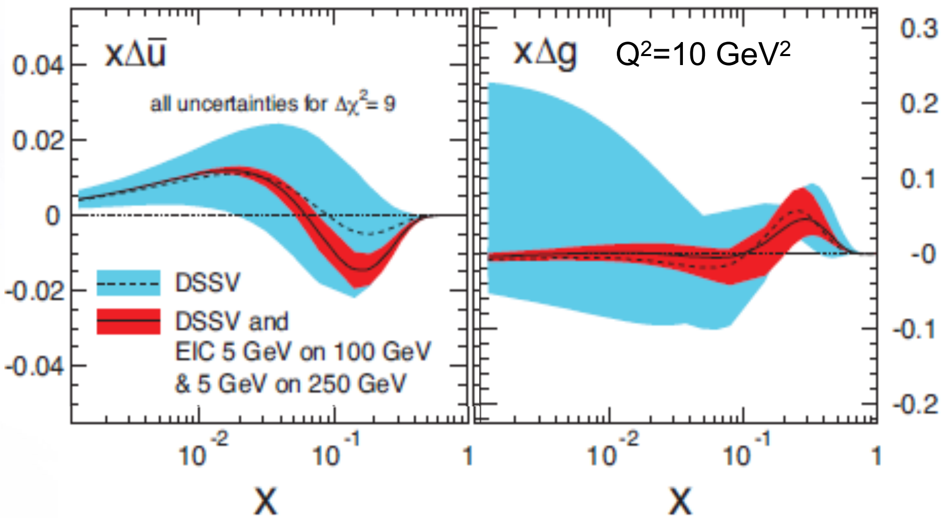
Understanding Nucleon Spin

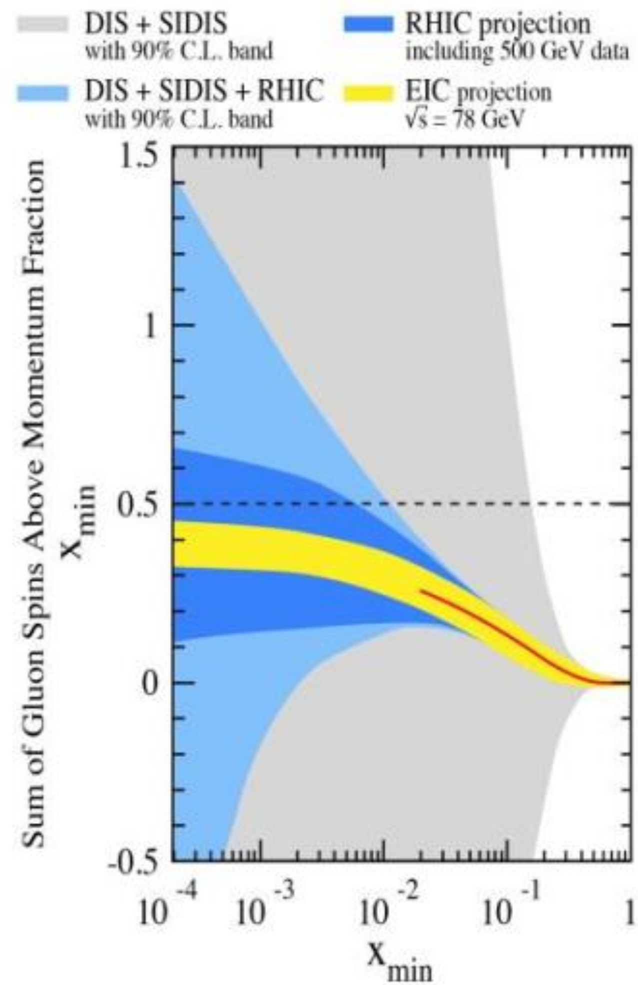


"Helicity sum rule"

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

EIC projected measurements:
precise determination of polarized PDFs of quark sea and gluons ➔ precision ΔG and $\Delta\Sigma$
→ A clear idea of the magnitude of $\sum L_q + L_g$





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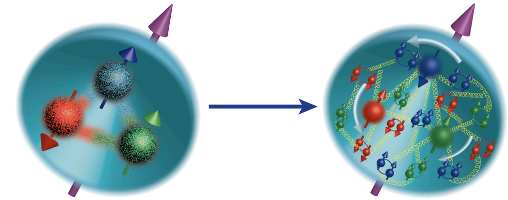

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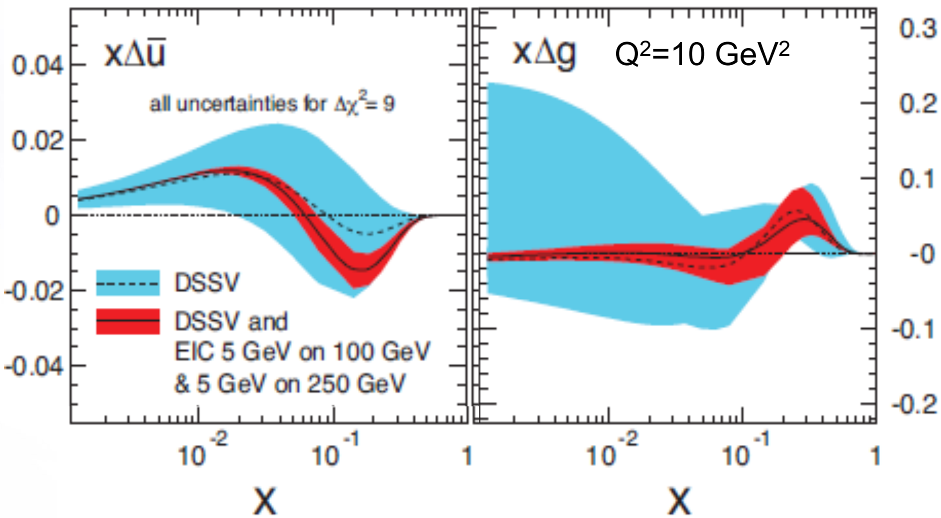
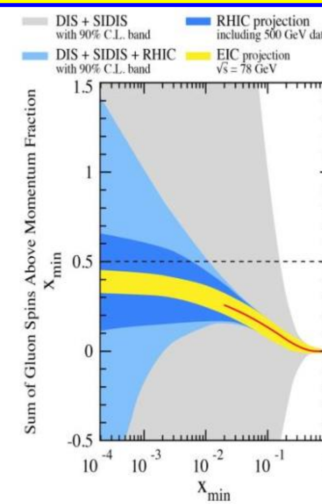
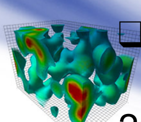
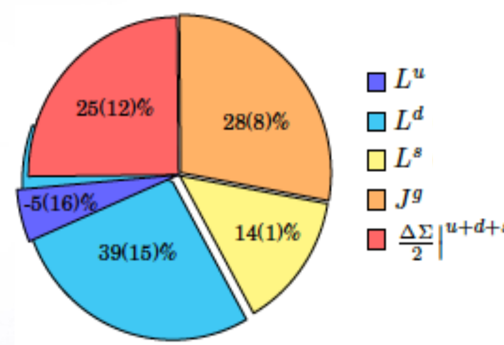




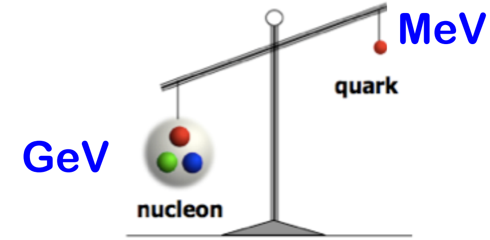
Spin and Lattice: Recent Activities

- ❑ **Gluon's spin contribution on Lattice: S_G = 0.5(0.1)**
  Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- ❑ **J_q calculated on Lattice QCD:**
  [illegible]QCD Collaboration, PRD91, 014505, 2015





Understanding Nucleon Mass



Relativistic motion

χ Symmetry Breaking

Quantum fluctuation

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

Quark Energy

Gluon Energy

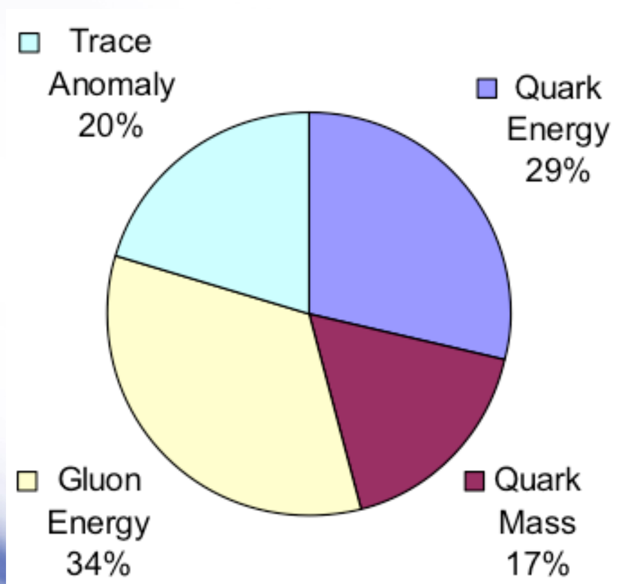
Quark Mass

Trace Anomaly

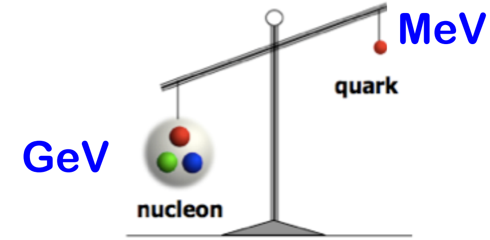
"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

The 2015 Long Range Plan for Nuclear Science

❑ Preliminary Lattice QCD results:



Understanding Nucleon Mass



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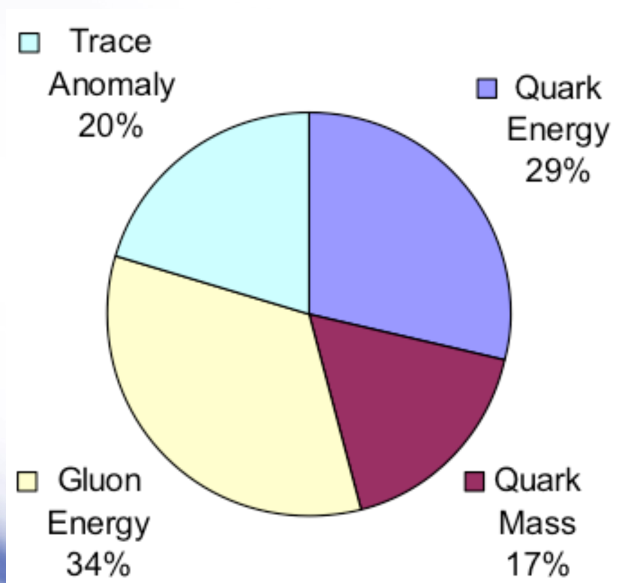
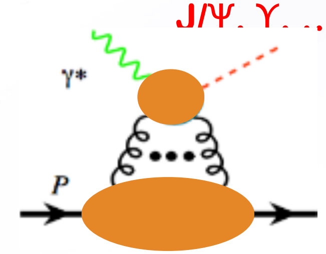


❑ EIC's expected contribution in:

◇ Trace anomaly:

Upsilon production near the threshold

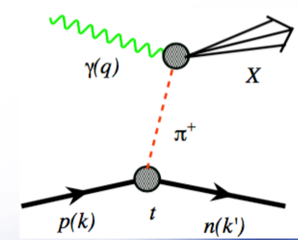


◇ Quark-gluon energy:

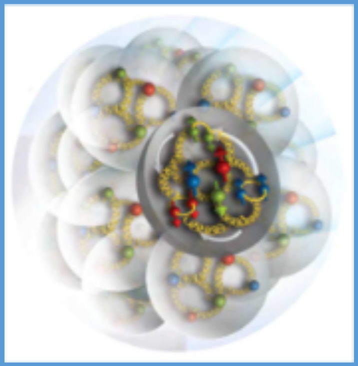
$\propto$ *quark-gluon momentum fractions*

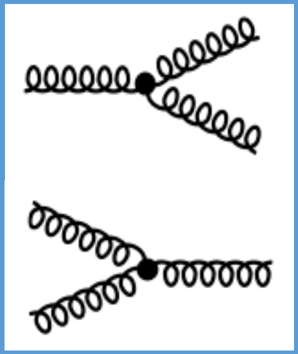
In nucleon with DIS and SIDIS

In pions and kaons with Sullivan process



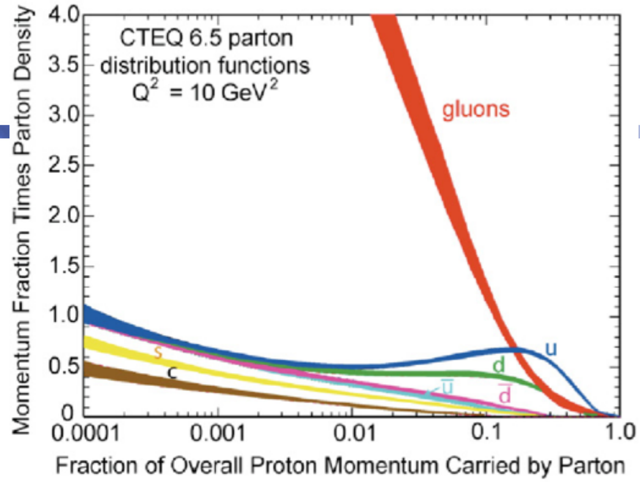
The Nucleus as a laboratory for QCD

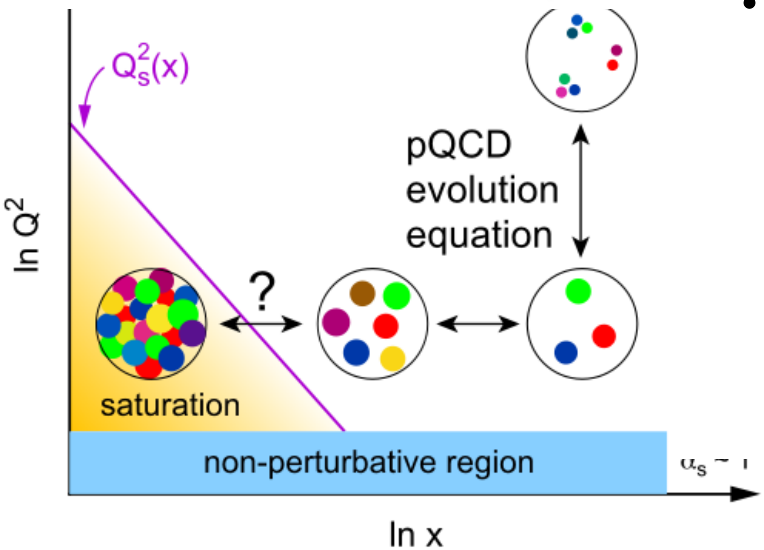




- How does a *dense nuclear environment* affect the quarks and gluons, their correlations, and their interactions?
- What happens to the *gluon density in nuclei*? Does it *saturate at high energy*, giving rise to a gluonic matter with *universal properties* in all nuclei, even the proton?

Gluon saturation at low-x



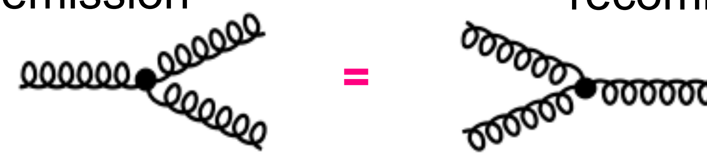


What tames the low-x rise?

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

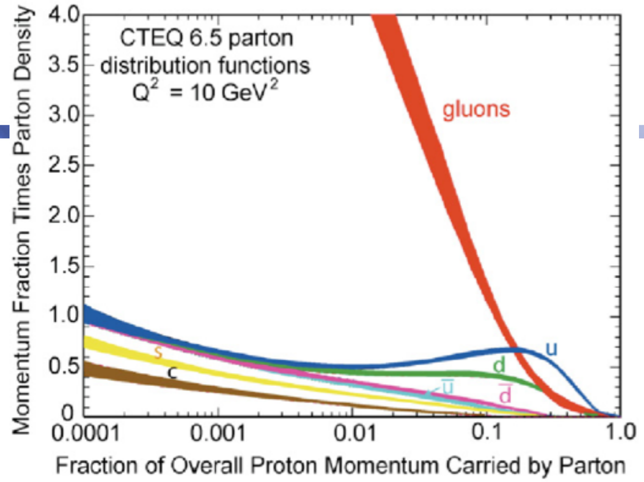
gluon emission

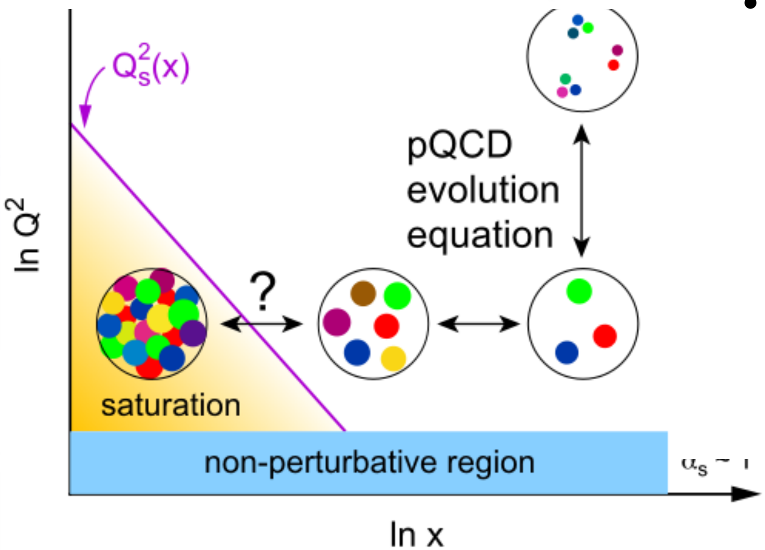
gluon recombination



At Q_S

Gluon saturation at low-x





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- New evolution equations at low x & moderate Q^2
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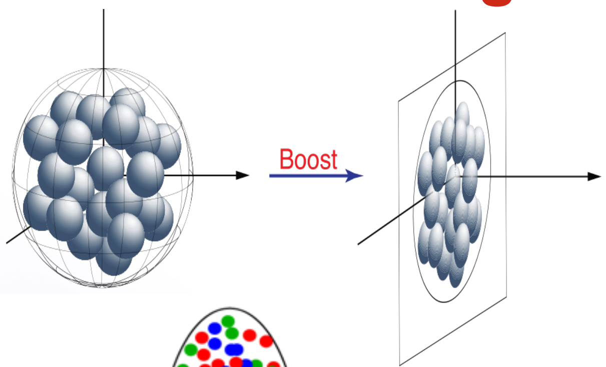
At Q_S

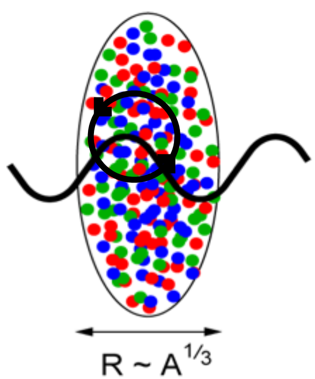
First observation of gluon recombination effects in nuclei:
➔ leading to a collective gluonic system
First observation of gluon recombination in different nuclei
→ Is this a universal property?
What is the new effective theory in this regime?

How to explore/study this new phase of matter?

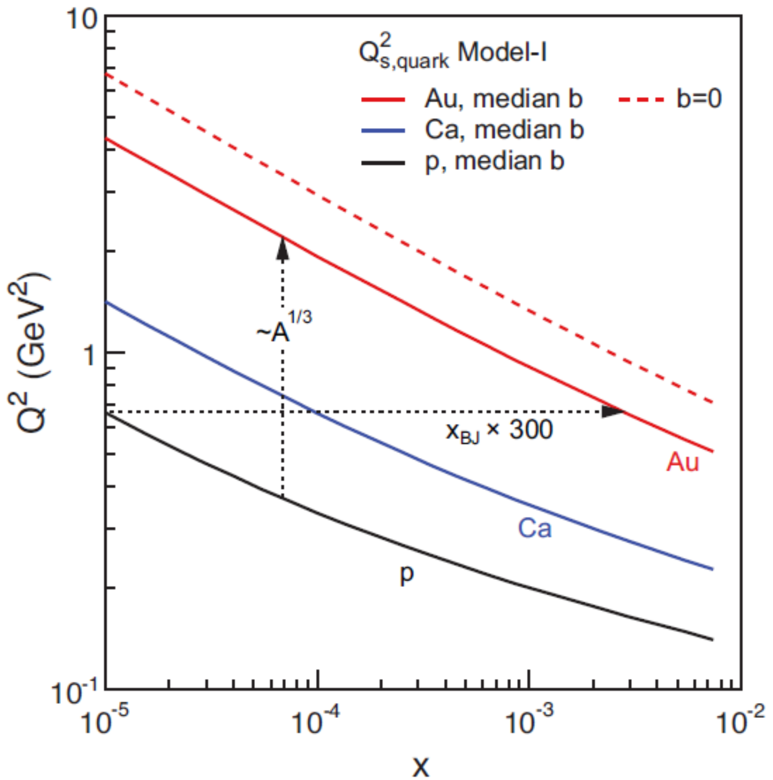
(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

Advantage of nucleus →





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

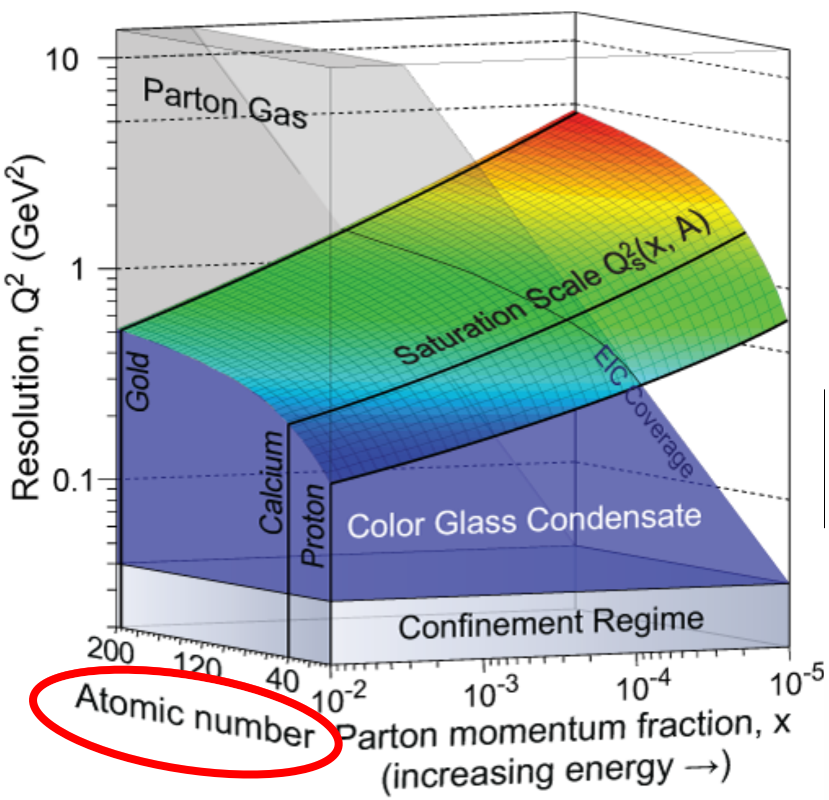


$L \sim (2m_N x)^{-1} > 2\, R_A \sim A^{1/3}$

How to explore/study this new phase of matter?

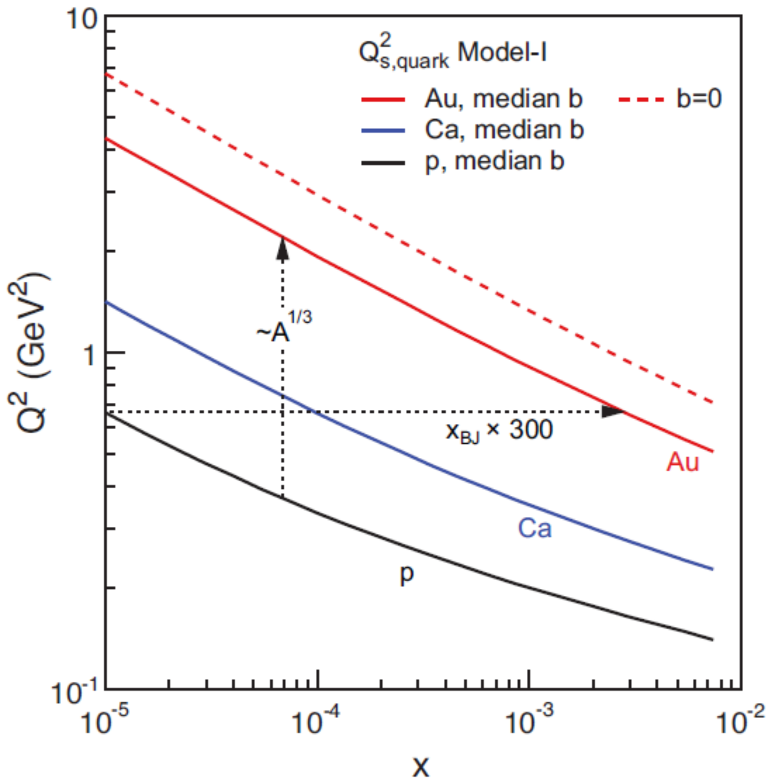
(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

Advantage of nucleus →



$L \sim$

$1/3$



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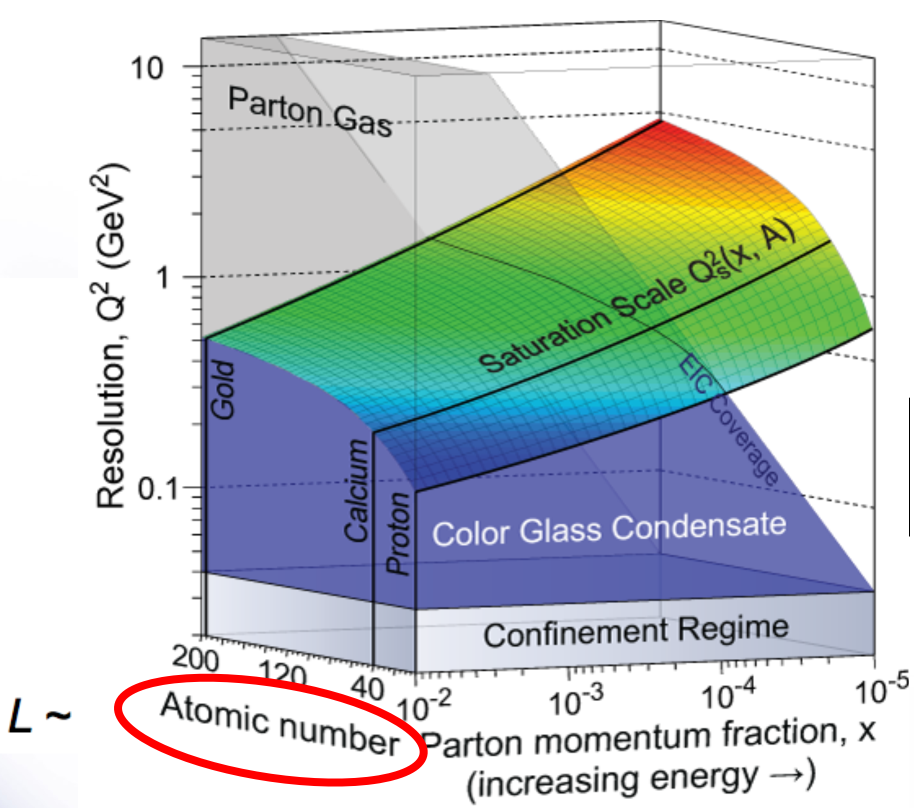
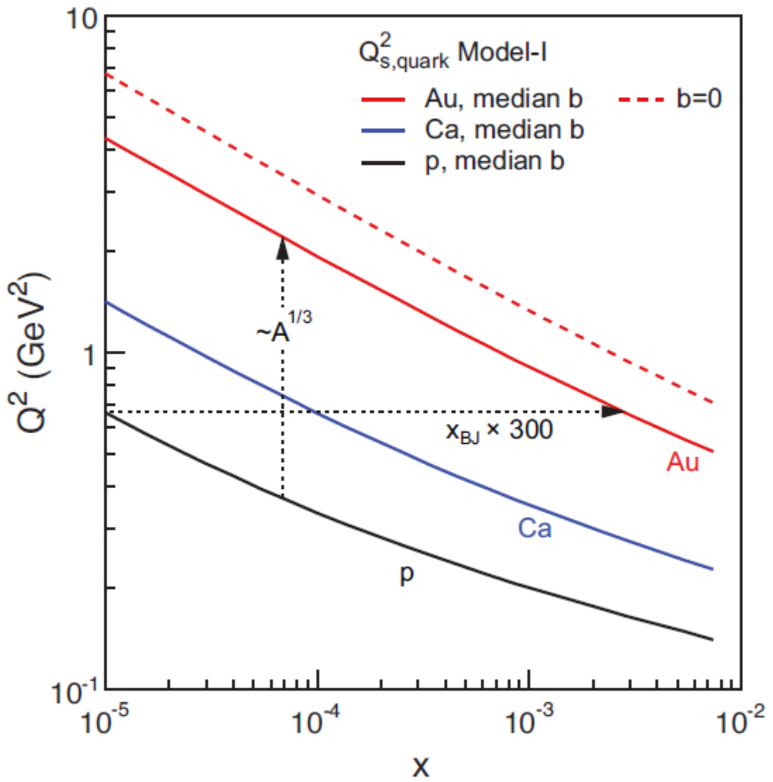


$1/3$



Enhancement of Q_S with A:

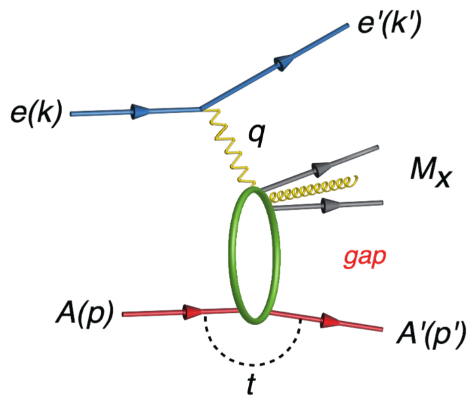
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

Diffraction for the 21st Century

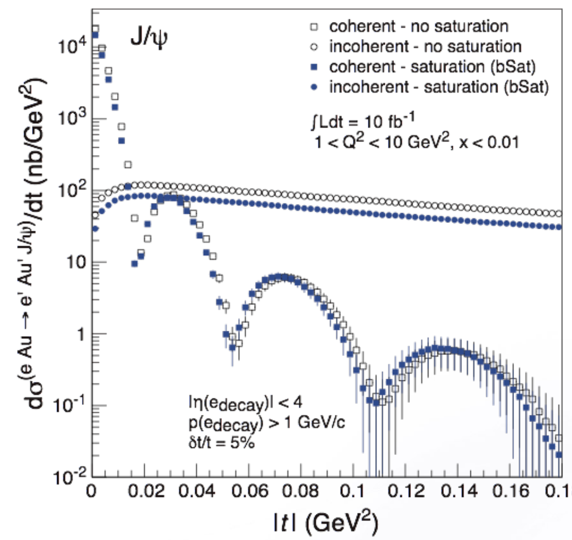
Diffraction cross-sections have strong discovery potential:

High sensitivity to gluon density in linear regime: $\sigma \sim [g(x,Q^2)]^2$

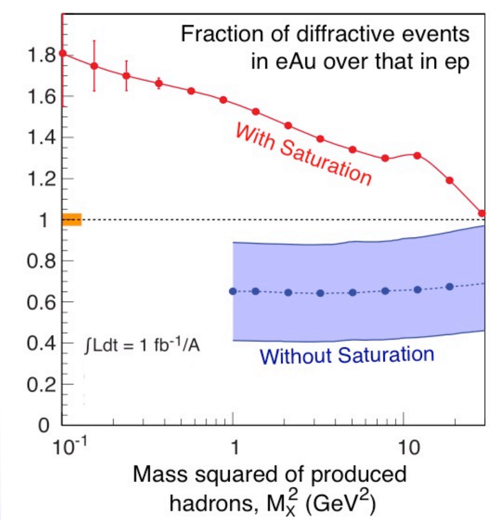
Dramatic changes in cross-sections with onset of non-linear strong color fields



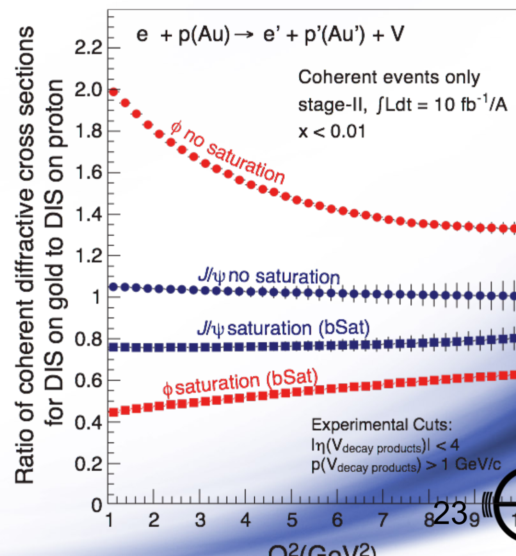
Extracting the gluon distribution $\rho(b_T)$ of nuclei via Fourier transformation of $d\sigma/dt$ in diffractive J/ψ production



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

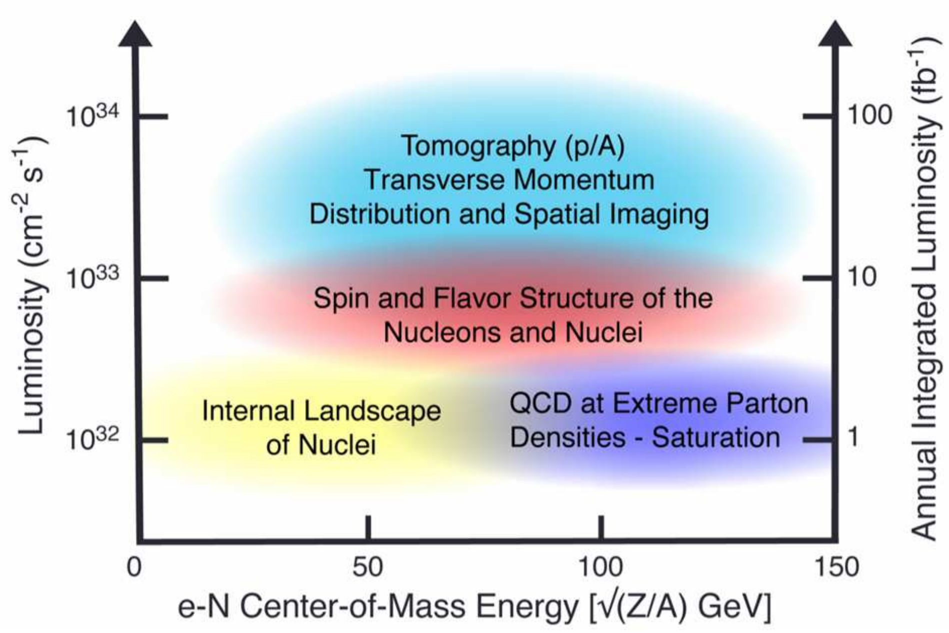


Probing Q^2 dependence of gluon saturation in diffractive vector meson production



Collider Requirements

- **Polarized electron and light ion beams (*p*,*d*,^{3}He)**
  - Double polarization absolutely required for nucleon tomography and spin structure studies
- **Wide variety of unpolarized nuclear beams (*A*)**
  - Needed for gluon saturation and other studies
- **High luminosity & energy**
- **Variable CM energy**
- **EIC demands frontier ideas and technologies in accelerator physics**



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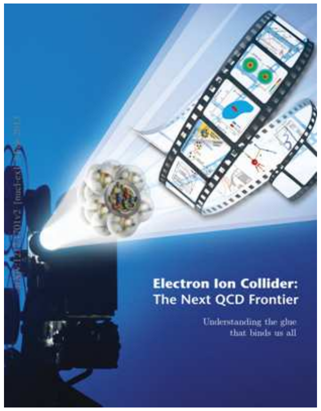
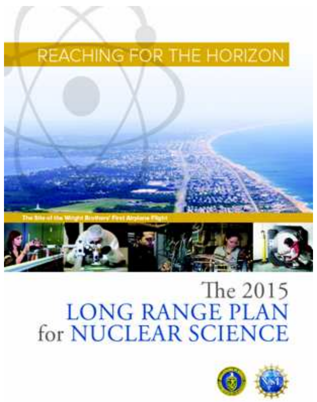
A long journey to get here…



EIC White Papers (2012,14,16)

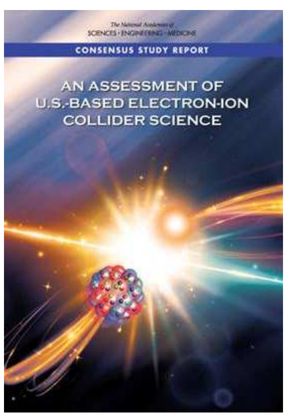
Development of EIC science case: *"The next QCD frontier: Understanding the glue that binds us all".* arXiv: 1212.1701

As science case matures and expands, white paper updated in 2014, 2016: Eur.Phys.J.A **52** (2016) 268



Nuclear Science Advisory Committee (2015)

"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction"



National Academy of Science Review (2018)

Asked by DOE to review EIC science case in light of the NSAC recommendation.

Very strong endorsement: *"questions to be addressed are profound… science case is compelling"*

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US Department of Energy: 2020 & 2021

- Lots of momentum in Washington and New York State for EIC
- Projected cost: US$1.7-2.8 billion
- Significant international contributions under negotiation
- 2030-2: First beam/operations

Department of Energy

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years cost between $1.6 and $2.6 billion, will smash electrons into protons and hea an effort to penetrate the mysteries of the "strong force" that binds the atom

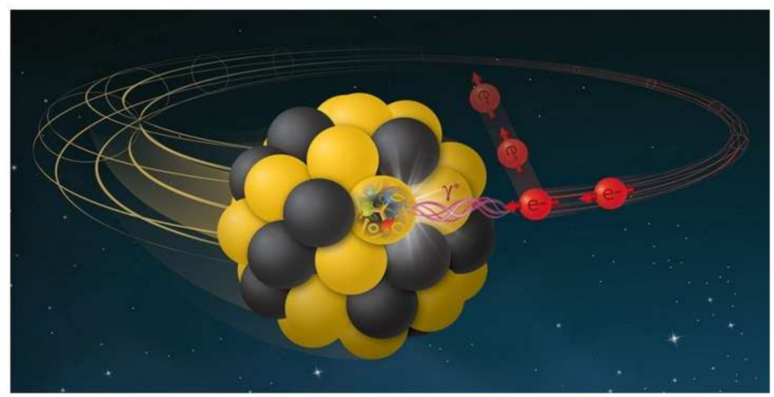
"The EIC promises to keep America in the forefront of nuclear physics resear accelerator technology, critical components of overall U.S. leadership in scie **Secretary of Energy Dan Brouillette.** "This facility will deepen our understan expected to be the source of insights ultimately leading to new technology a

Office of Science

Electron-Ion Collider Achieves Critical Decision 1 Approval

JULY 6, 2021

Office of Science » Electron-Ion Collider Achieves Critical Decision 1 Approval



UPTON, NY and NEWPORT NEWS, VA – The U.S. Department of Energy (DOE) has granted Critical Decision 1 (CD-1) for the Electron-Ion Collider (EIC), a one-of-a-kind nuclear physics research facility to be built at DOE's Brookhaven National Laboratory on Long Island. Following DOE's

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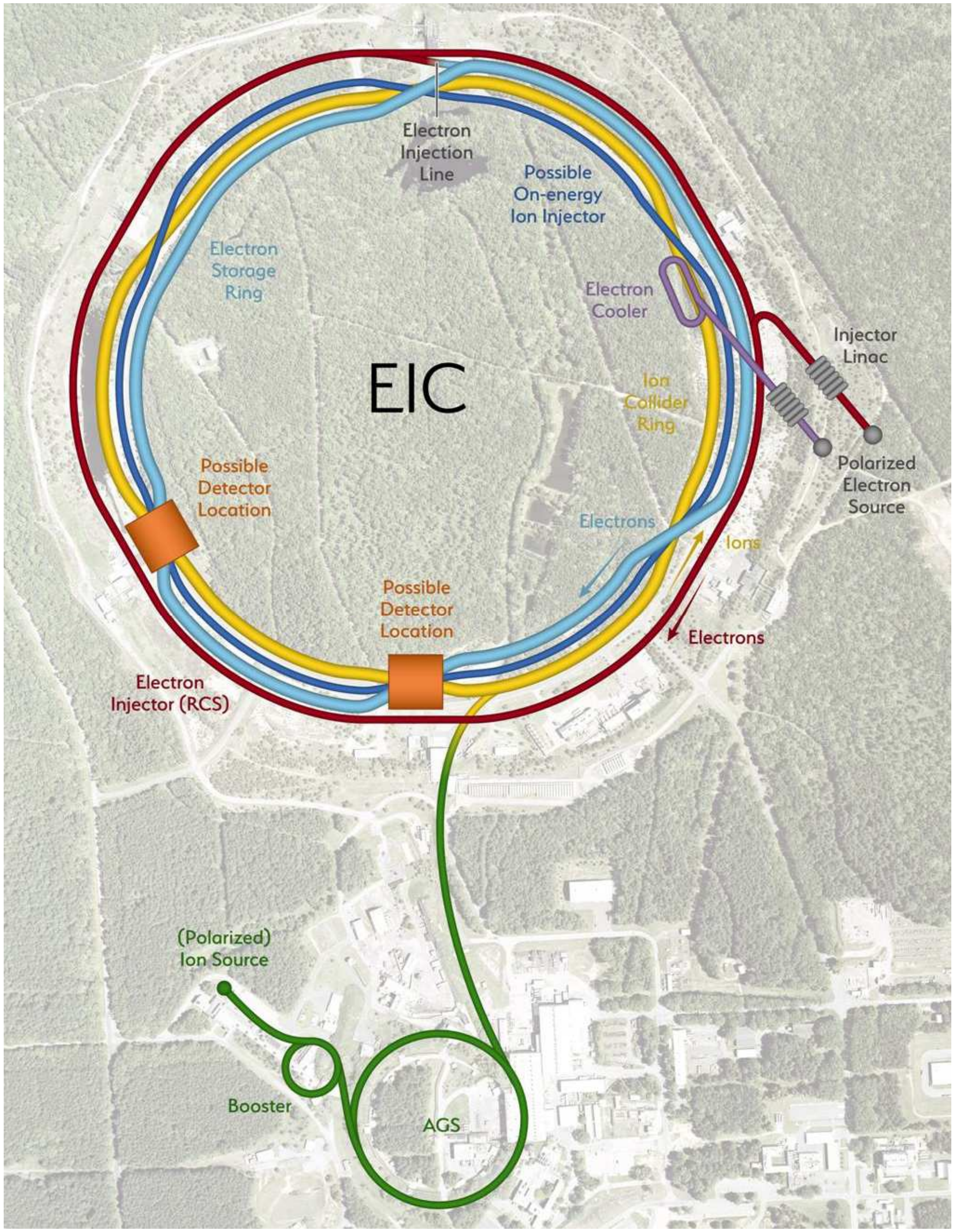
eRHIC Realization @ BNL

Use existing Relativistic Heavy Ion Collider (RHIC)

- Up to 275 GeV protons (polarized).
- Existing: tunnel, detector halls, hadron injector complex (AGS).
- Build new 18 GeV electron linac and add high intensity electron storage ring in same tunnel.
- Achieve high luminosity, high energy *e–p*/A collisions with full acceptance detectors.
- High luminosity achieved by extensions of state–of–the–art beam cooling techniques.



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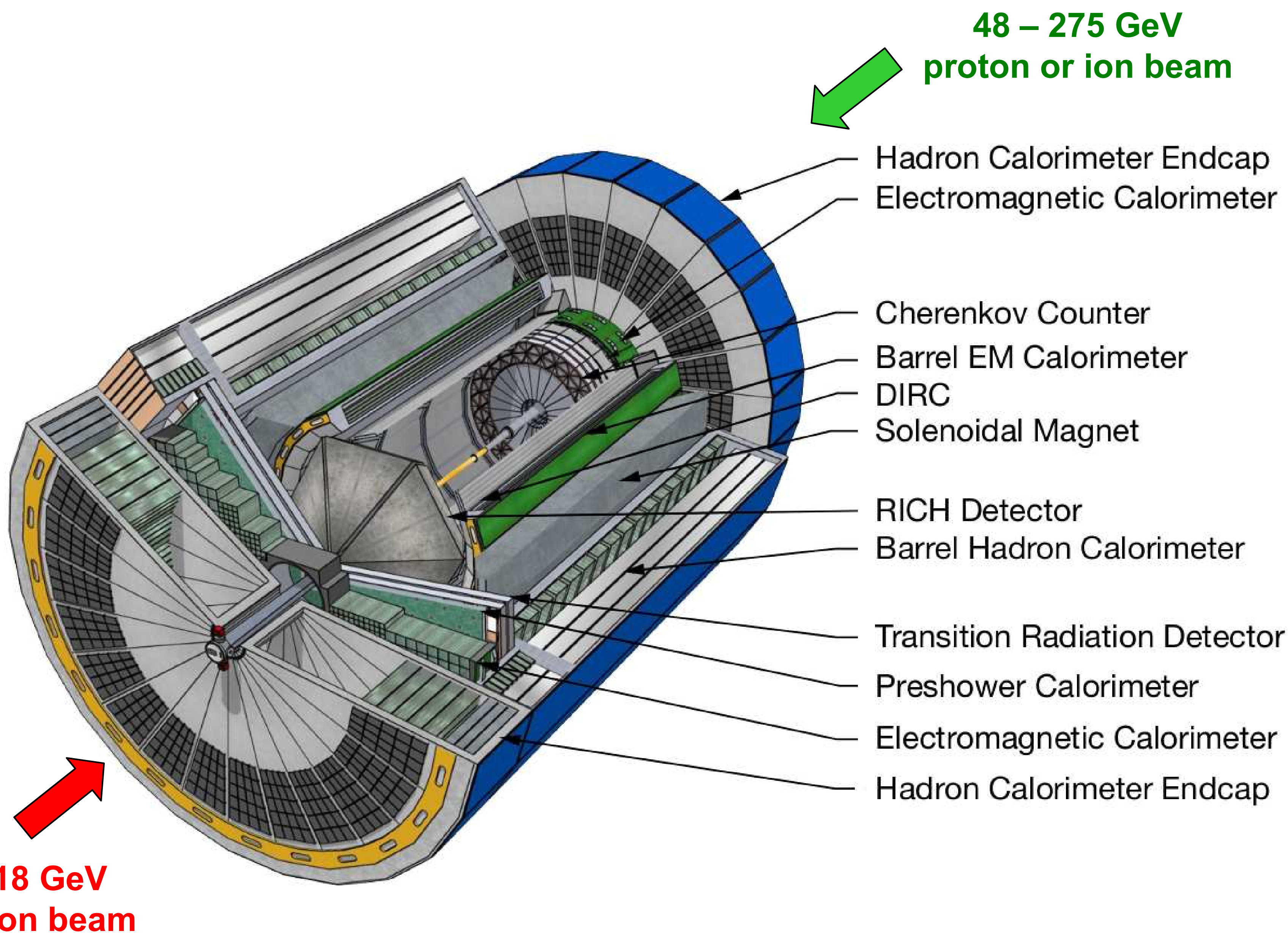
EIC Concept Detector (Central Barrel)



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EIC Canada: eic-canada.org

- **Coordinating the Canadian participation in the Electron Ion Collider**
- Chartered in 2020 after CD-0 decision and site selection for EIC Project
- Current initiatives:
  - Engagement with the 2022-2036 **Canadian Subatomic Physics Long Range Plan**
  - NSERC Subatomic Physics **Project Research Grants** (2021-2023: 8 funded grad/ugrads)
  - Interfacing with partner and funding organizations:
    - National funding agencies and research facilities (NSERC, CFI, TRIUMF)
    - International partners (EIC UG, BNL, JLab, working groups and consortia)
  - Participation in both **Detector Proposals** (**ATHENA**: Mt. A, U. Manitoba; **ECCE**: U. Regina)
- Current membership:
  - PIs at **U. Regina**, **U. Manitoba**, **Mt. Allison U.**
  - Associate memberships targeted at e.g. accelerator and theory communities
- Management plan, members, leadership and further details at eic-canada.org
- **New collaborators welcome!**

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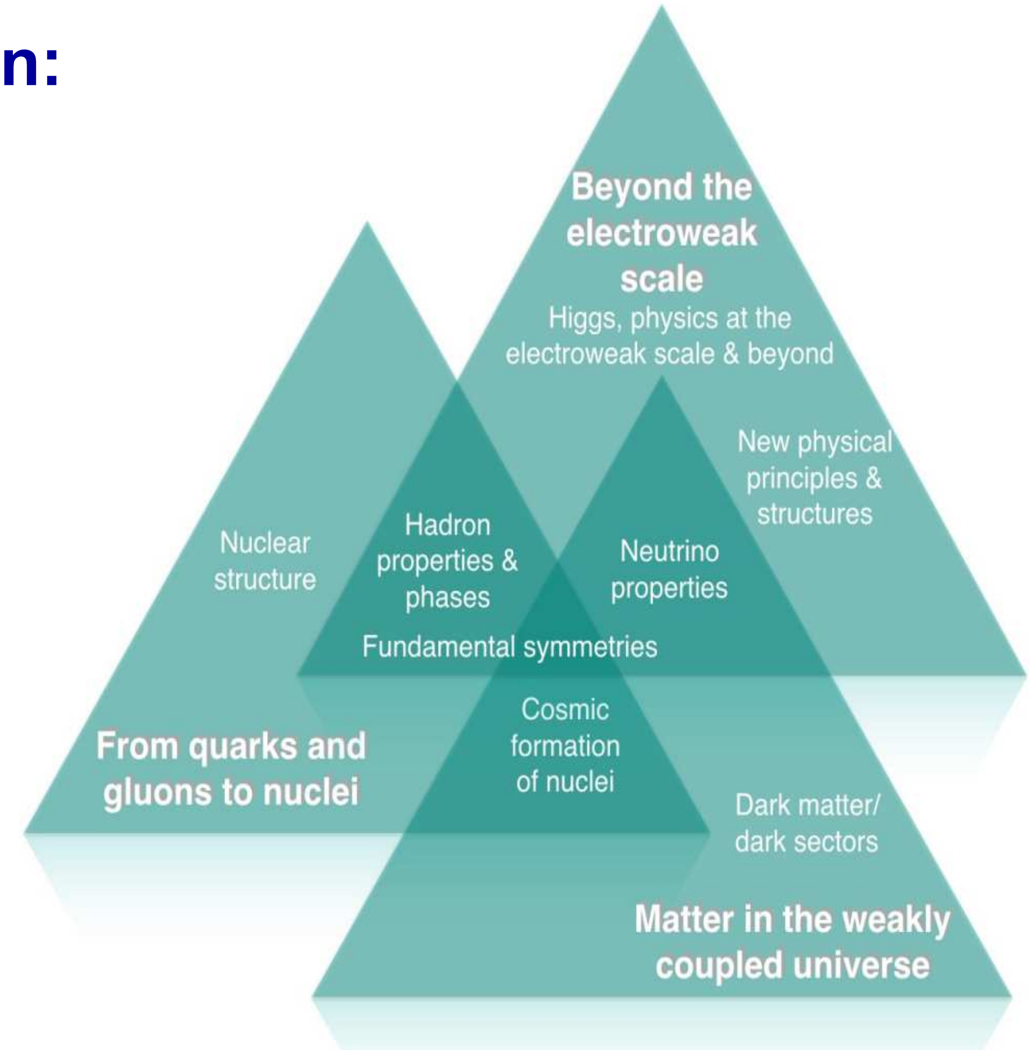
Canadian Subatomic Physics Long Range Plan

Excerpt from 2022-2036 Plan:

- **Hadron Properties and Phases**
  - How do quarks and gluons give rise to the properties of nucleons and other hadrons, and to the hadronic phases of matter in extreme conditions?
- **Nuclear Structure**
  - How does nuclear structure emerge from nuclear forces and ultimately from quarks and gluons?
- **Cosmic Formation of Nuclei**
  - How do the properties of nuclei explain the formation of the elements in the universe?



SubatomicPhysics.ca

EIC is listed as a flagship project for Canadian science!

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Canadian Involvement in EIC Detector Proposals

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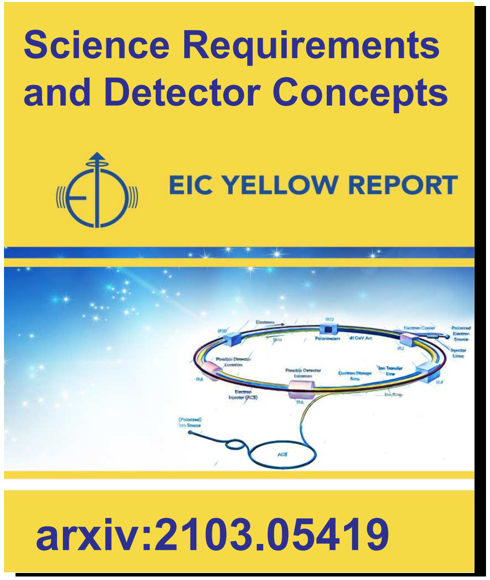

2021: From a community Yellow Report…

…**to two large collaboration detector proposals** with Canadian involvement

2022: Detector Proposal Review/Selection

2024: Construction/Installation

2030: First Beam/Operations

ATHENA: A Totally Hermetic Electron-Nucleus Apparatus

Key Characteristics:

- New 3T magnet
- Tracking: Si MAPS vertex, MicroMegas barrel, GEMs + µRWELL endcaps
- PID: hpDIRC, AC-LGAD ToF, dual radiator RICH, proximity-focused RICH
- Calo: Si-pixel imaging + SciFi hybrid barrel, PbWO + SciGlass hybrid endcaps
- Software: CERN-oriented (dd4hep, gaudi, ACTS)

EIC Canada involvement:

- U Manitoba (W. Deconinck: software WG convener)
- Mt Allison U (D. Hornidge)

Canadian resources:

- ComputeCanada full sims

ECCE *EIC Comprehensive Chromodynamics Experiment*

Key Characteristics:

- BaBar 1.5T magnet
- µRWell & Si tracker
- PID DIRC/mRICH/dRiCH
- Calo: Barrel, e-/Hadron endcap, Roman pots, ZDC, B0

EIC Canada involvement:

- U Regina: G. Huber (meson form factors at high Q^2); Z. Papandreou (spectroscopy of XYZ states)
- Event generators, Far forward detector studies
- Novel AI Work: Inner tracker design optimization; calo design using hierarchical density-based clustering

Canadian resources:

- JLab ifarm, Regina resources

Pion form factor as probe of emergent mass generation in hadrons

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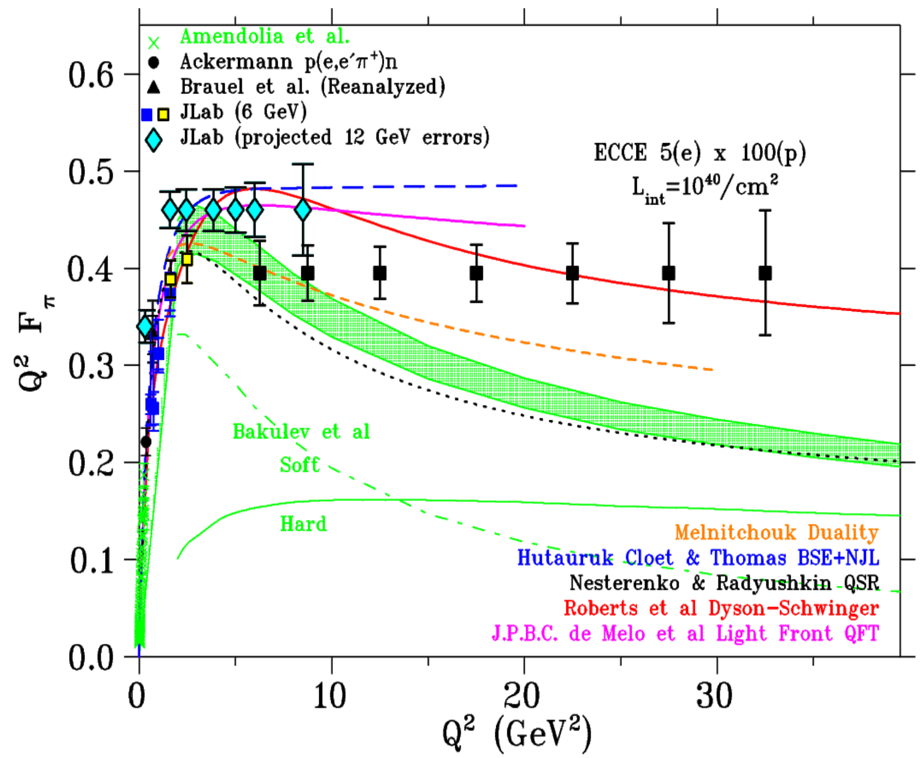
- Electromagnetic form factors of charged pion (F_π) and kaon (F_K) are rich source of insights into the roles played by confinement and Dynamical Chiral Symmetry Breaking in fixing the hadron’s size, mass, defining the transition from strong- to perturbative-QCD domains
- Regina group pion form factor feasibility simulations were instrumental in establishing importance of ECCE ZDC performance for *t* reconstruction resolution
- Extension to feasibility studies of kaon form factor utilizing far forward detectors is underway at URegina



Projections published in Eur.Phys.J. A **55** (2019) 190 and J.Phys.G **48** (2021) 075106.

Multi Objective Optimization

Role of AI

DWG's

Technology Selection
Baseline Design
Alternate Configuration(s)

PWG's

Physics Signal Selection
Physics Performance Evaluation

CWG's

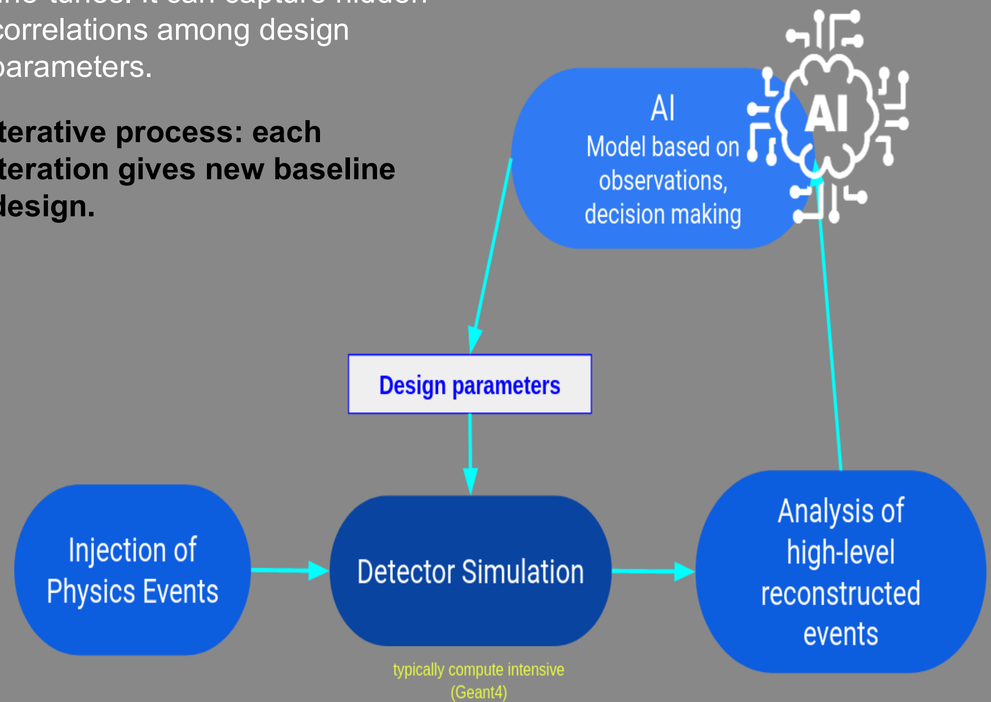
Simulation Campaign Support
AI Optimization

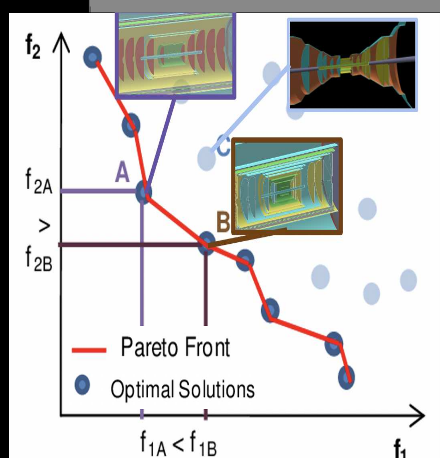
- Detector design optimization is challenging due to dimensionality & constraints.
- Multiple "objectives": weighted avg momentum resolution, resolution, KF efficiency, projected resolution at PID location; conflicting.
- Optimization pipeline with pymoo and "Fun4All" to simulate and analyze the detector response.

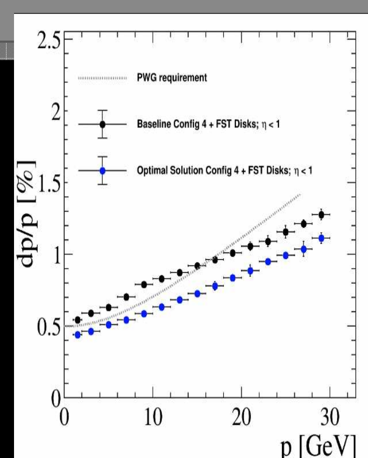
EIC Comprehensive Chromodynamics Experiment

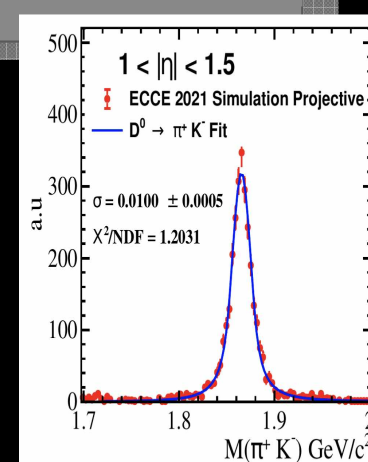
- AI can assist in designing more efficient detectors (performance, costs).
- Initially steers the design, then fine-tunes. It can capture hidden correlations among design parameters.
- **Iterative process: each iteration gives new baseline design.**

Detector Optimization Workflow









ATHENA Software: Alignment with Key4HEP

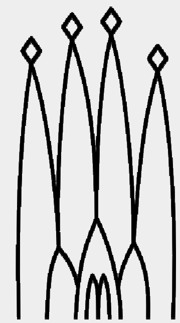
Philosophy:
- Modular & orthogonal
- Community-supported

Interface with:
- Data science toolkits
- HTC/HPC, GPU systems
- New AI/ML approaches

Open standards lead to modularity:
- HepMC3 and EDM4hep data models
- Flat data structures over structures

Core developed by EIC Canada (Manitoba)

DD4hep (CLiC, SLD): define active and passive geometry, readout segmentation



Gaudi (originally LHCb): connect geometry and data to algorithms

Flat output files (podio) enable flexible workflows (ROOT, python,…) without additional dependencies

Juggler: I/O, digitization, reconstruction, clustering and tracking algorithms

ACTS (ATLAS): provide general track reconstruction algorithms

Summary

- **The best summary is provided by the main findings of the National Academy of Sciences 2018 study:**
- 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?
- The committee concludes that an EIC is timely and has the support of the nuclear science community. The science that it will achieve is unique and world leading.
- **The EIC is an exciting opportunity for the next generation of physicists** (expected program: 2030-2060)

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