Electron–Ion Collider
A major new scientific facility to probe the heart of nuclear matter

Garth Huber

University of Regina

Physics Department Seminar
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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?
- Canadian and URegina involvement

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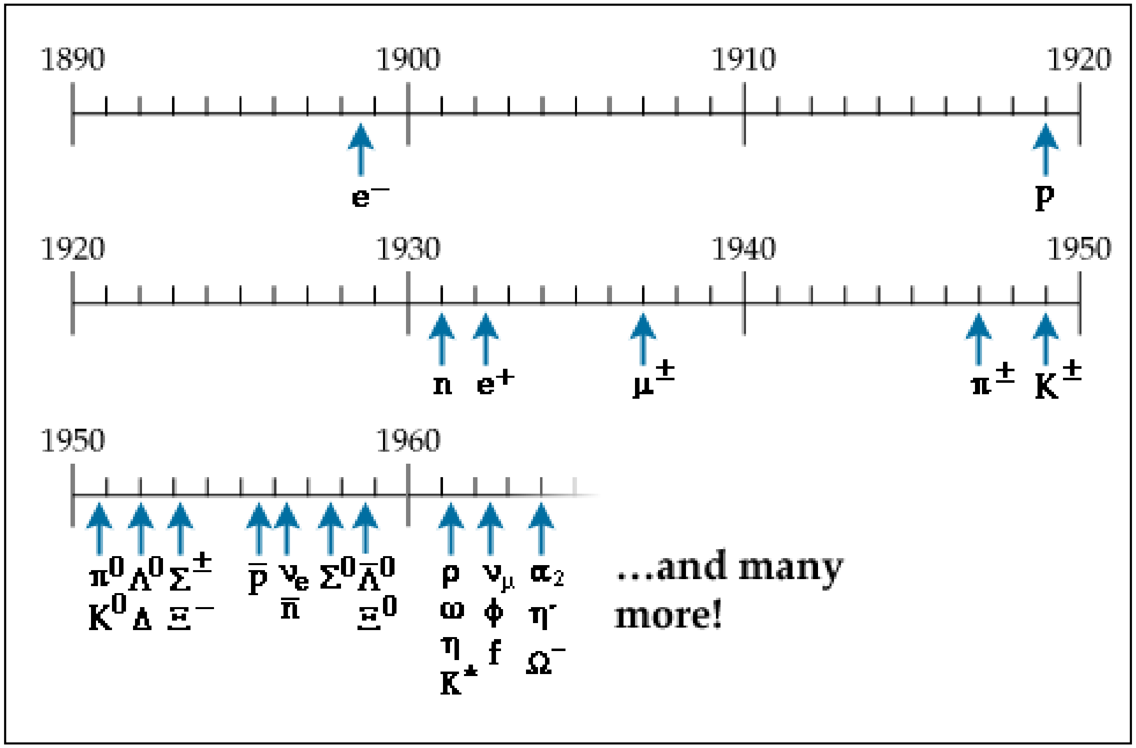
The Particle Zoo

- 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

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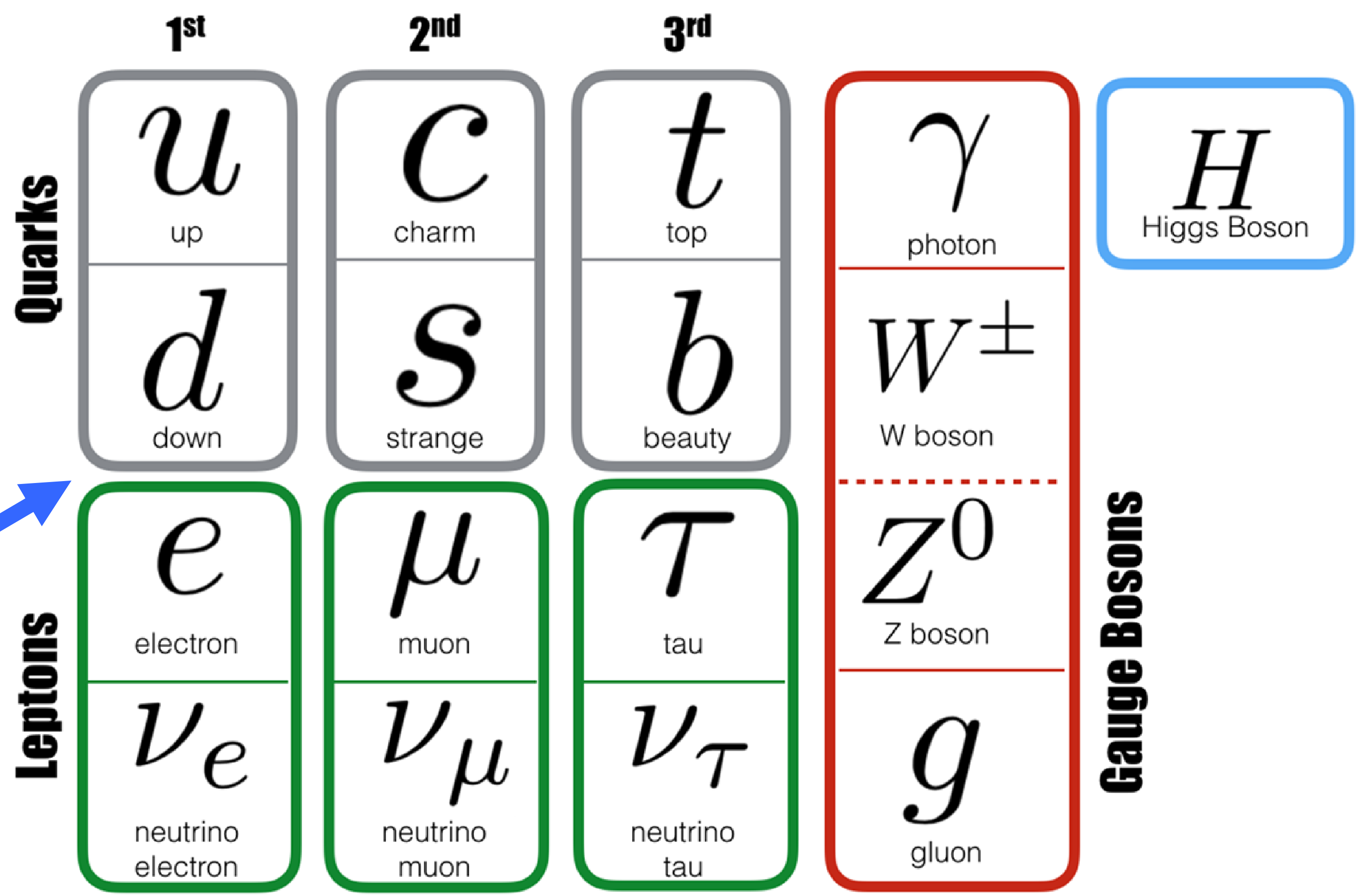

The ground state of matter

Quantum Electrodynamics
Quantum Chromodynamics

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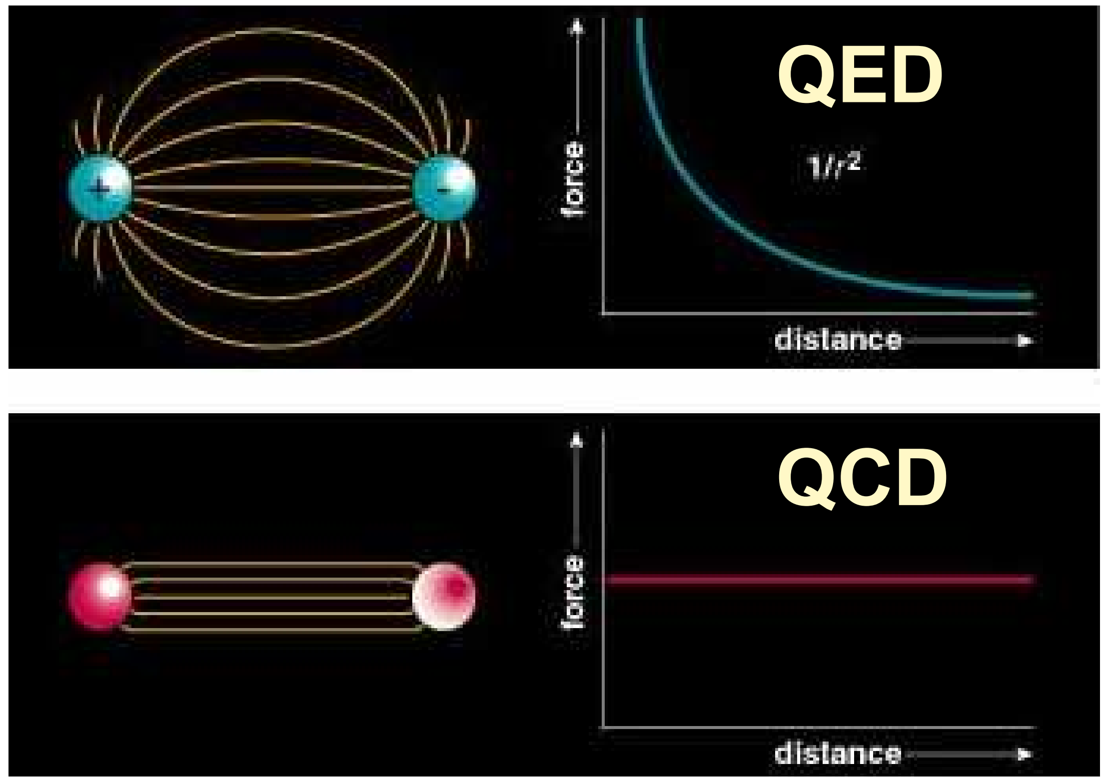
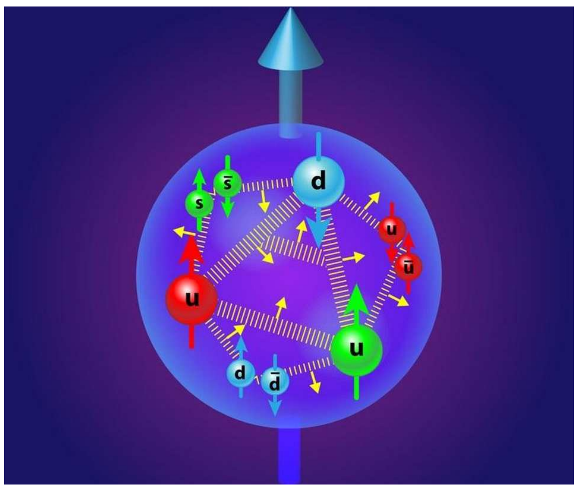
The gluons of QCD carry color charge and interact strongly (in contrast to the photons of QED)

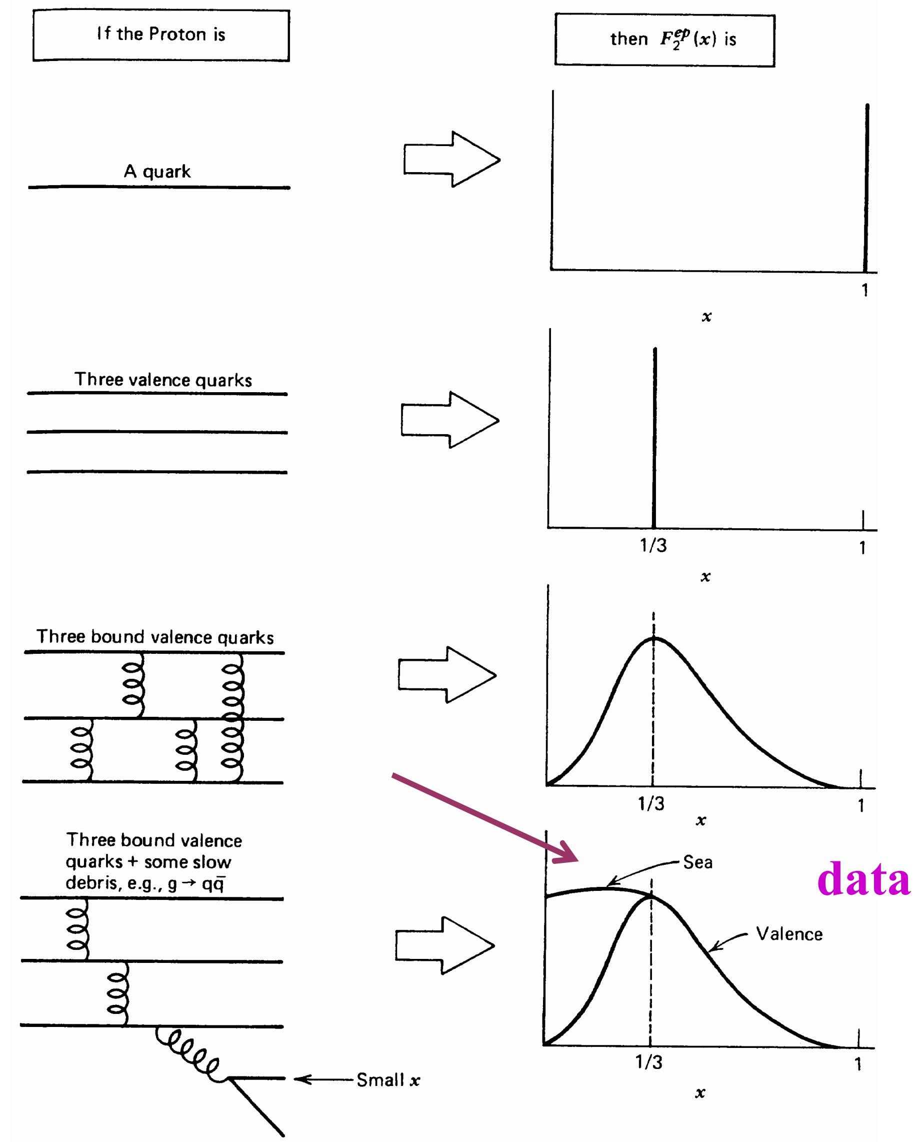


Quarks (and their color charge) are confined inside strongly–interacting particles called hadrons

Quark & Gluon Momenta within Proton

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.

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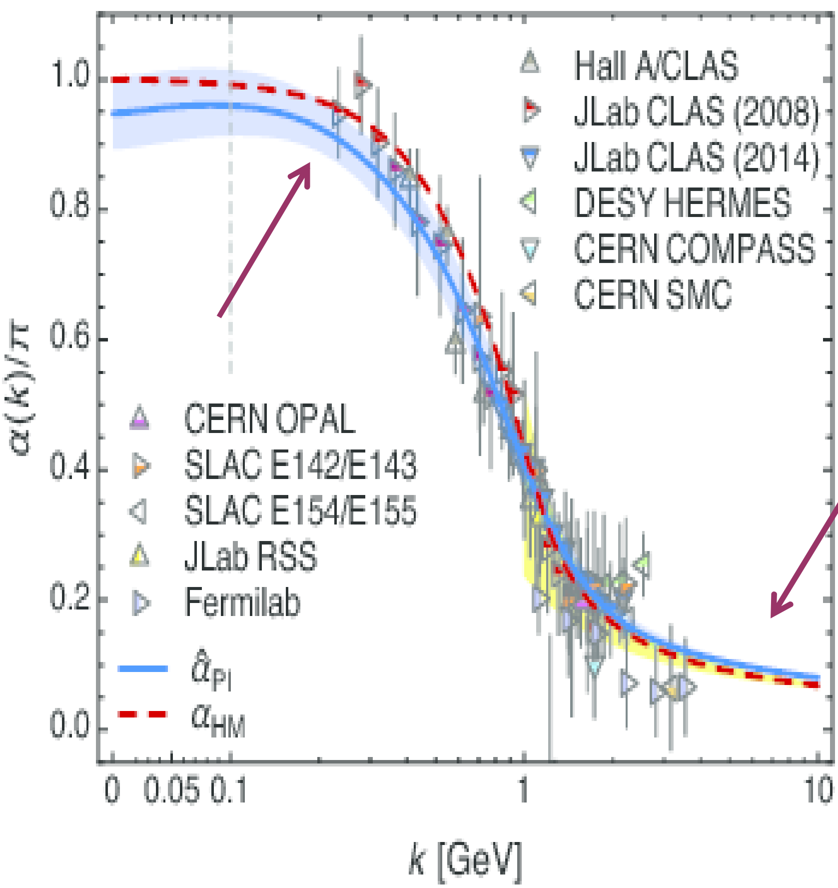
QCD's Dual Nature



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 **~ 938 [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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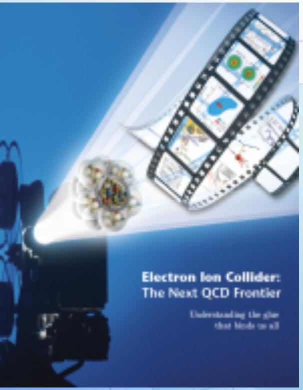
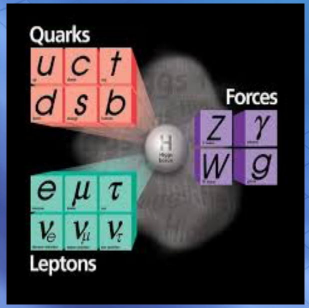


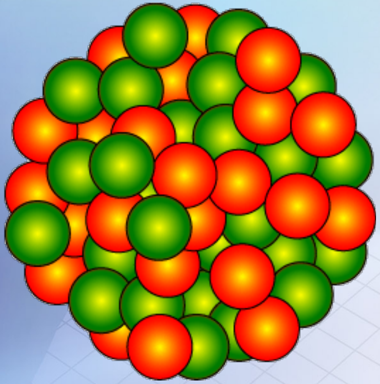
arXiv 1212.1701.v3
Eur. Phy. J. A52, 9 (2016)

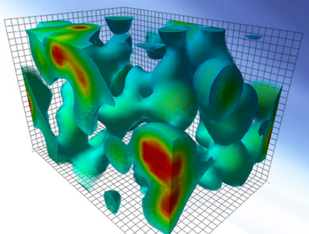
Electron Ion Collider: The next QCD frontier

*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







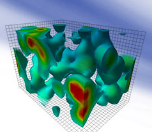
Abhay Deshpande

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.

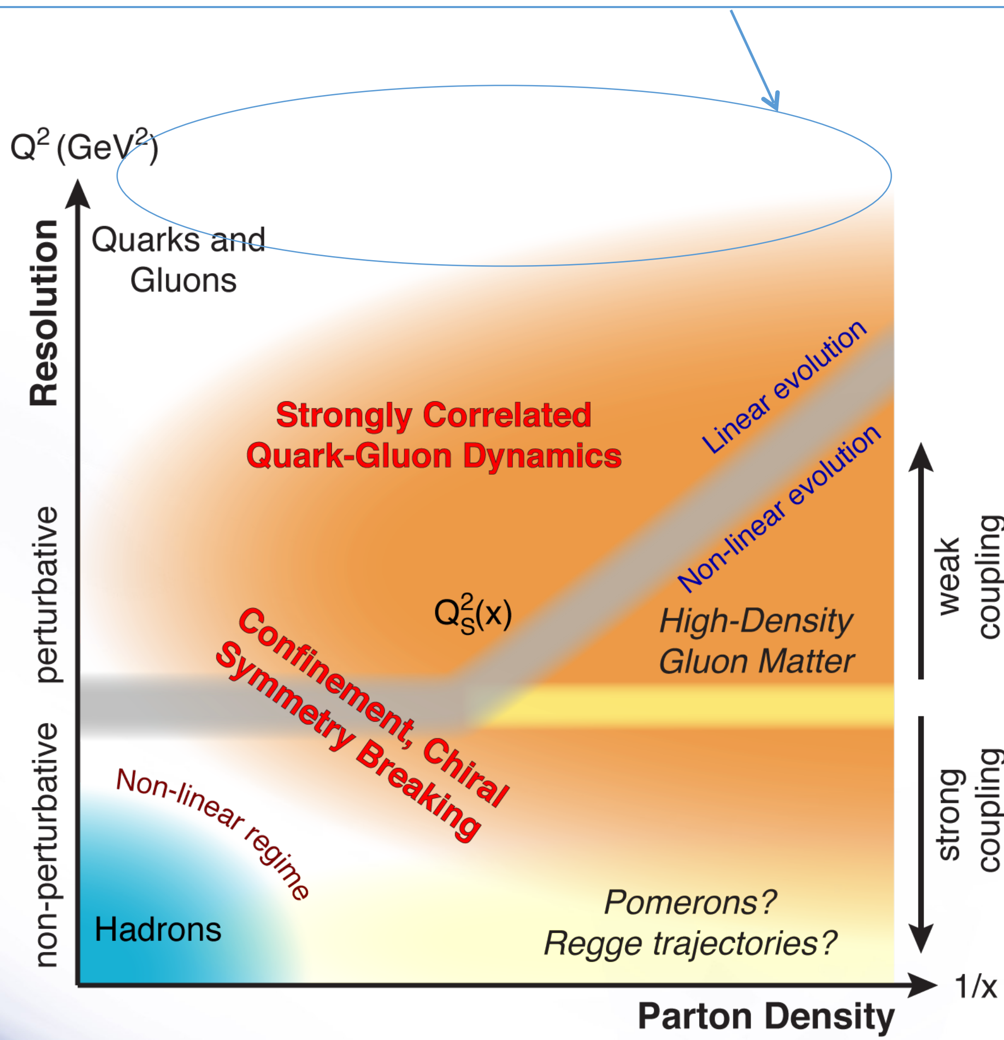
- **Gaining understanding of this dynamic matter → transformational:** Gaining detailed knowledge of this astonishing dynamical system at the heart of our world **could be transformational**, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter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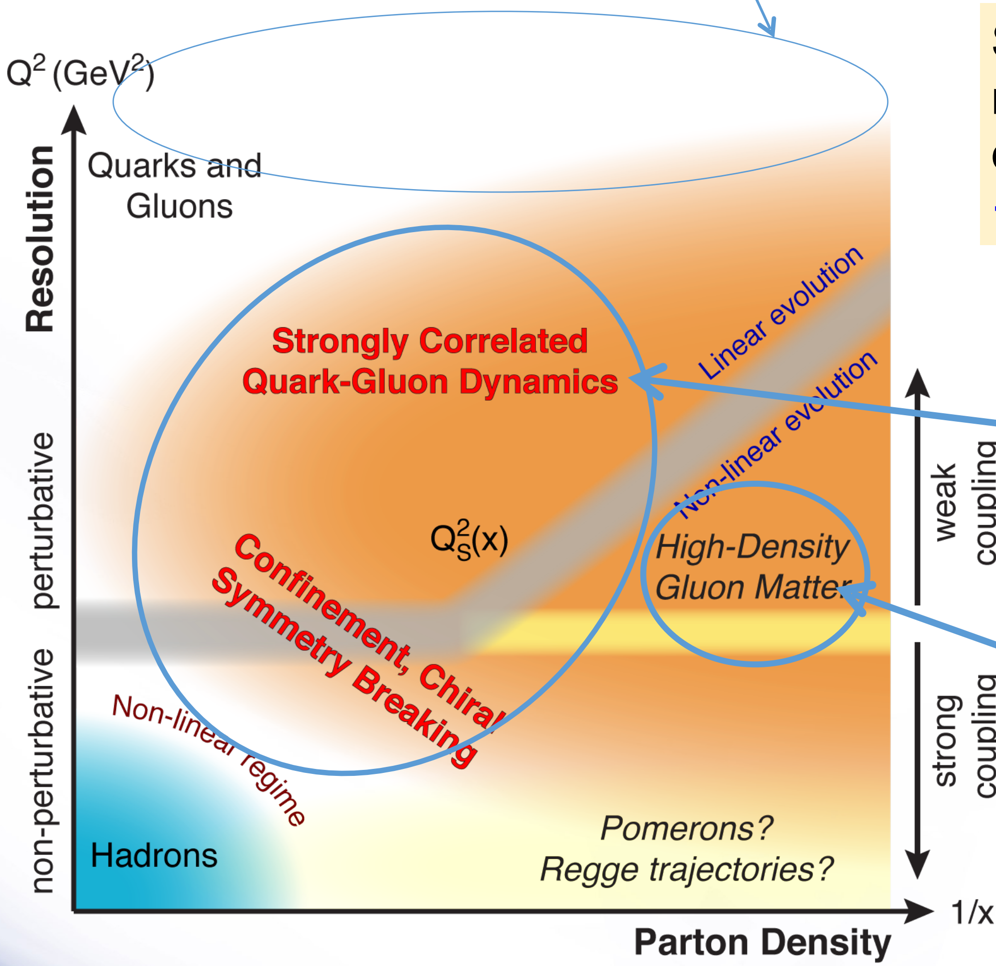


Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

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!

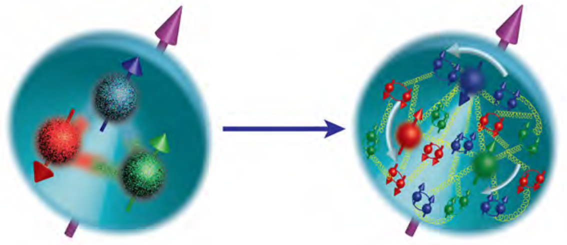
- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% of the proton's momentum, a significant fraction of the nucleon's spin, and are essential for the dynamics of confined partons
- Properties of hadrons are emergent phenomena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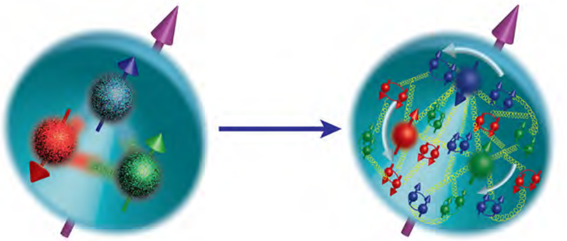

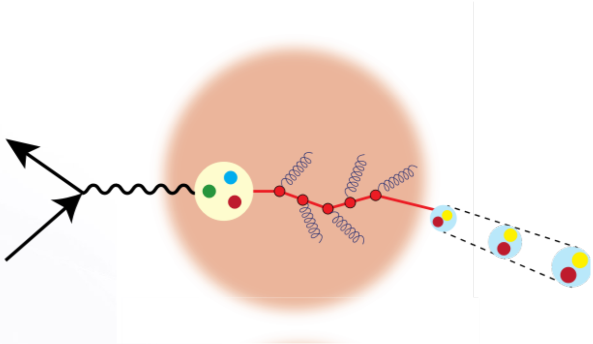

How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

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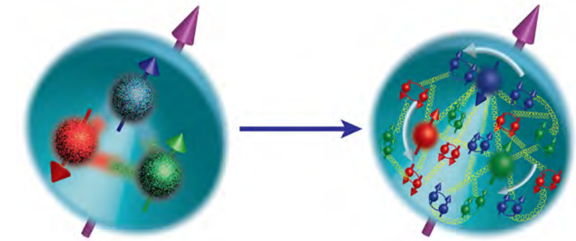

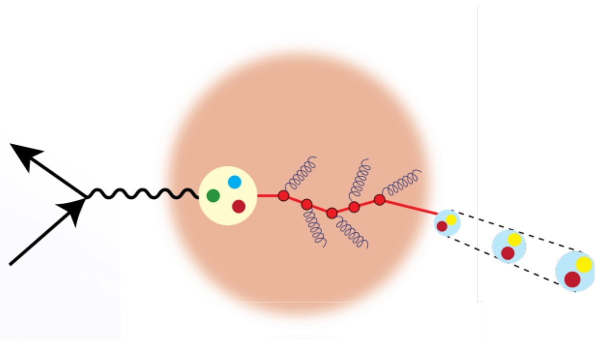

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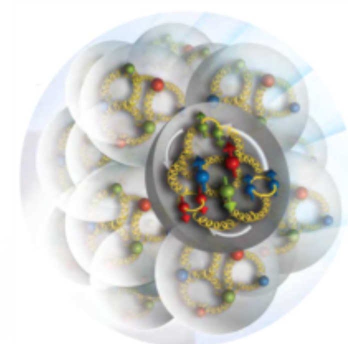
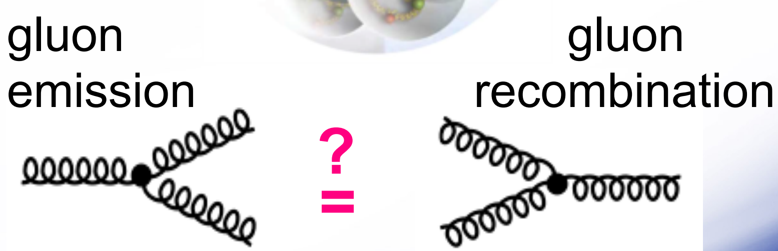
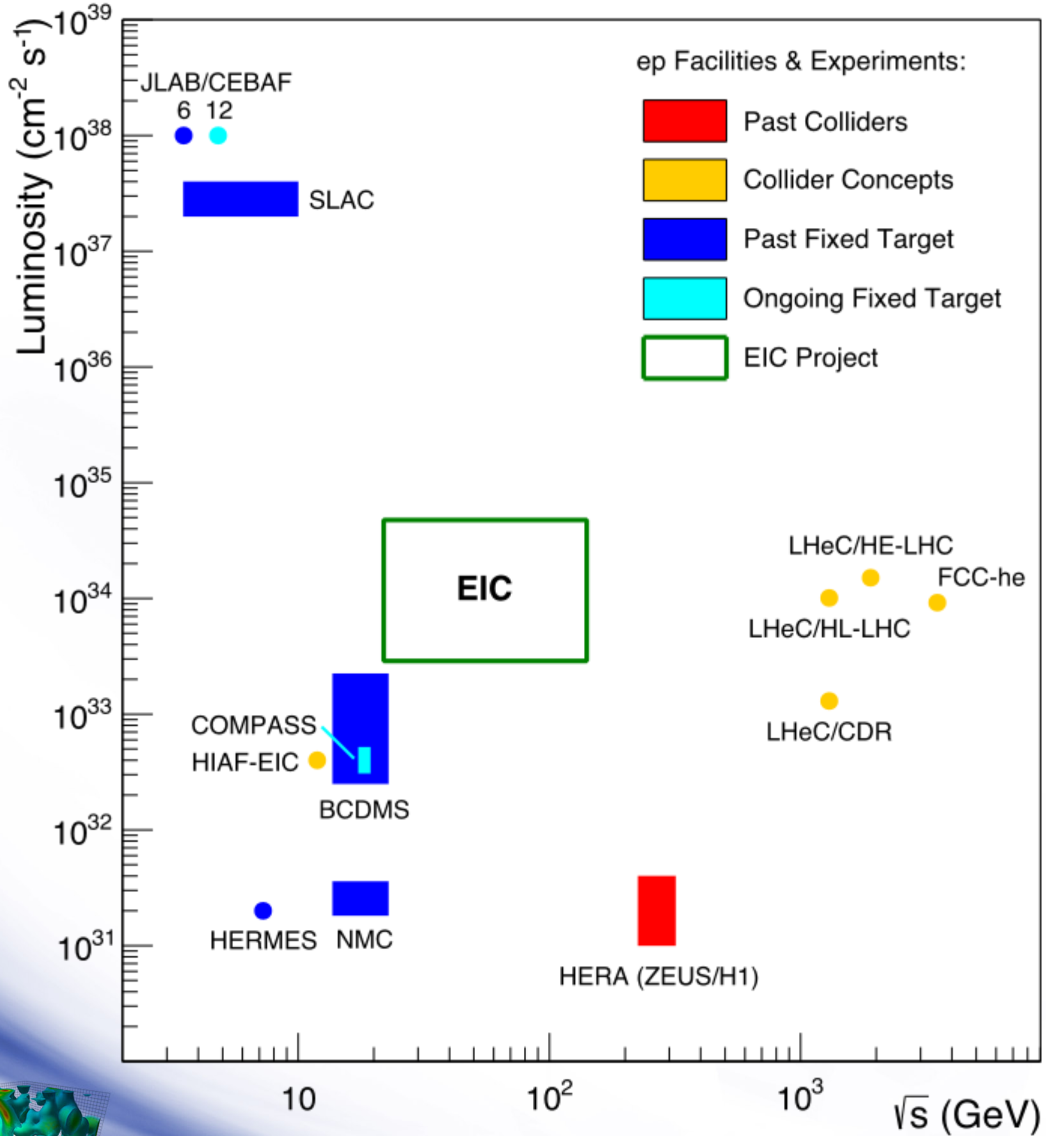


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

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?



Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

However,
if we ask for:

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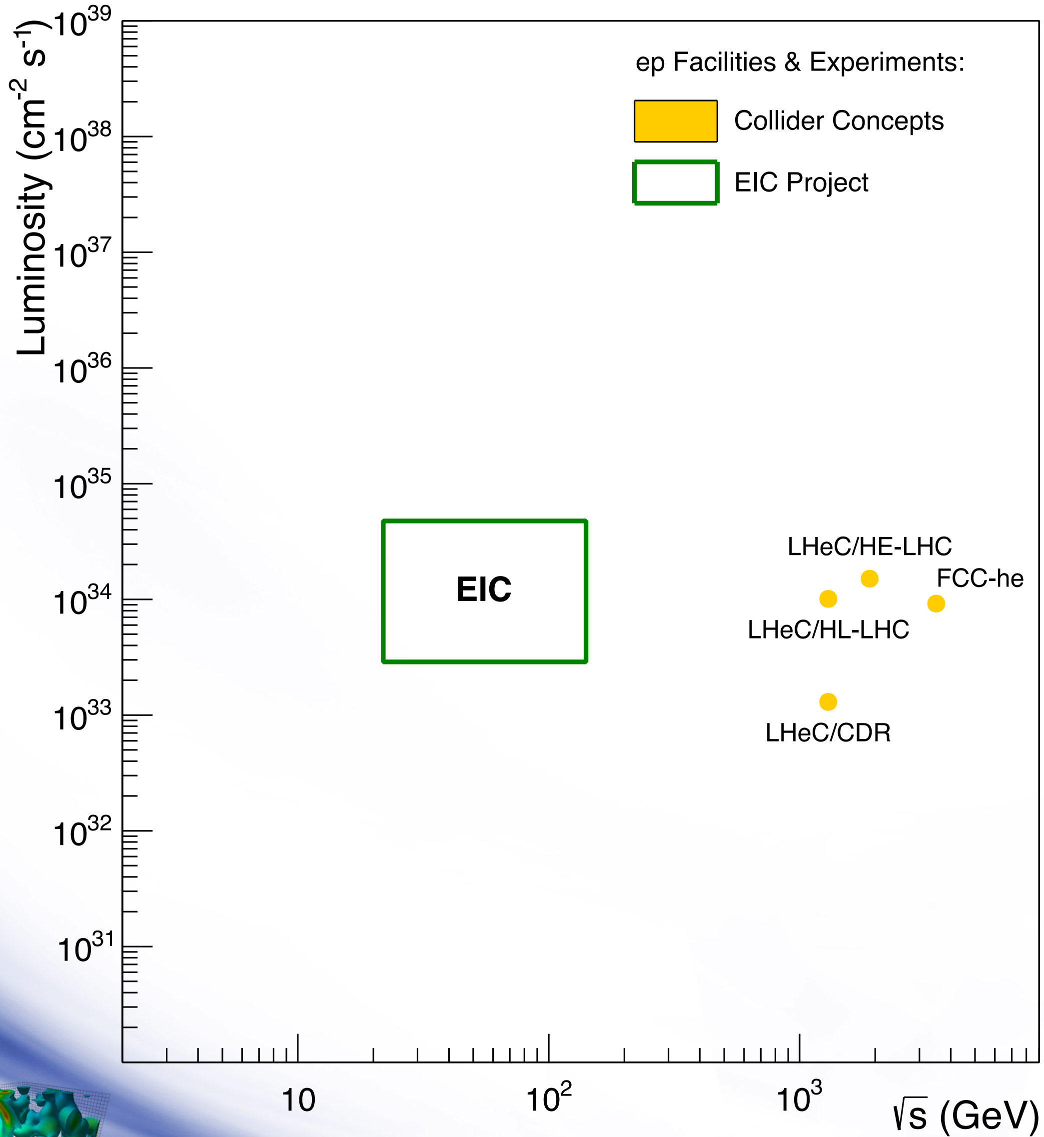

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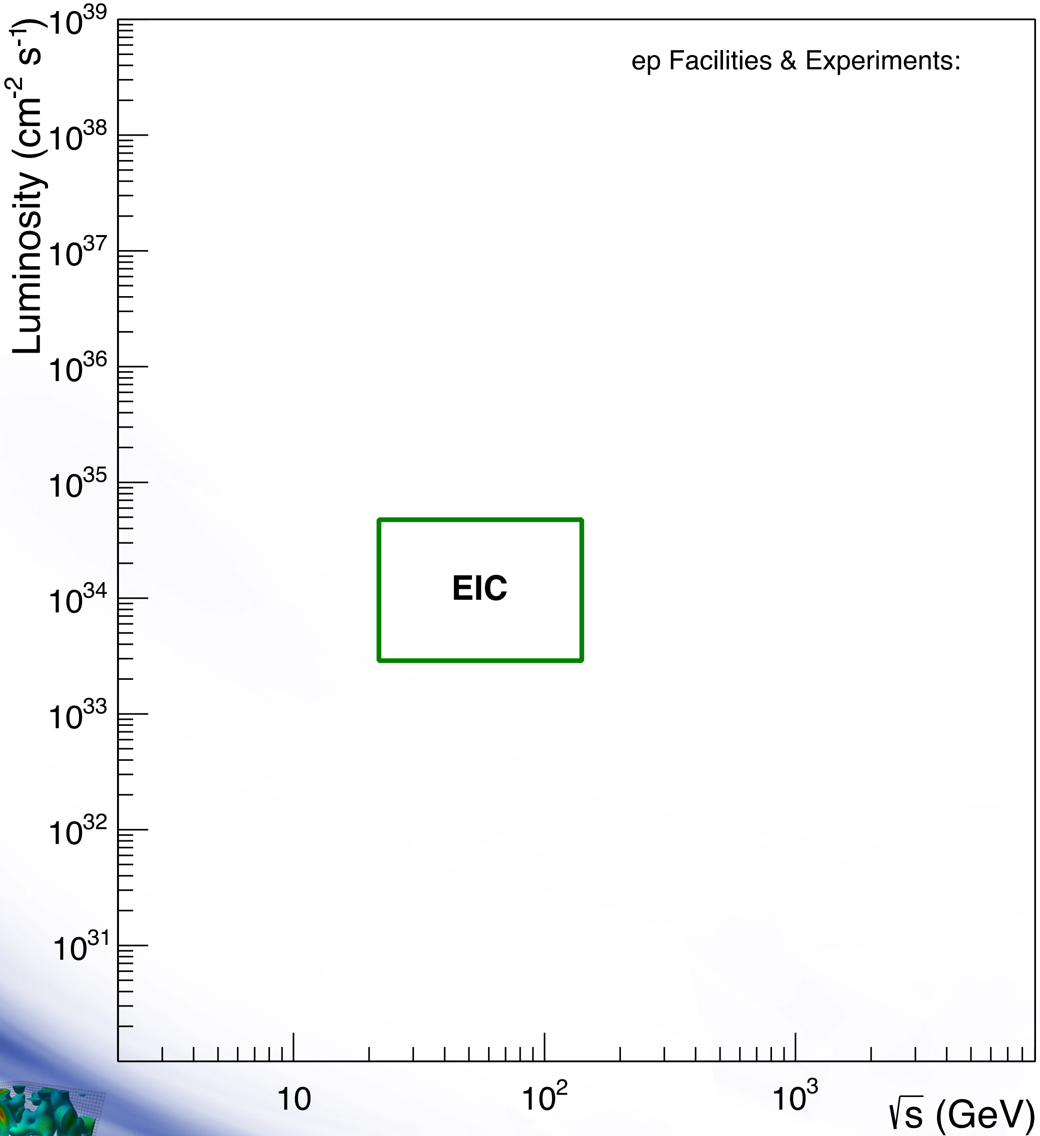

All DIS facilities in the world.

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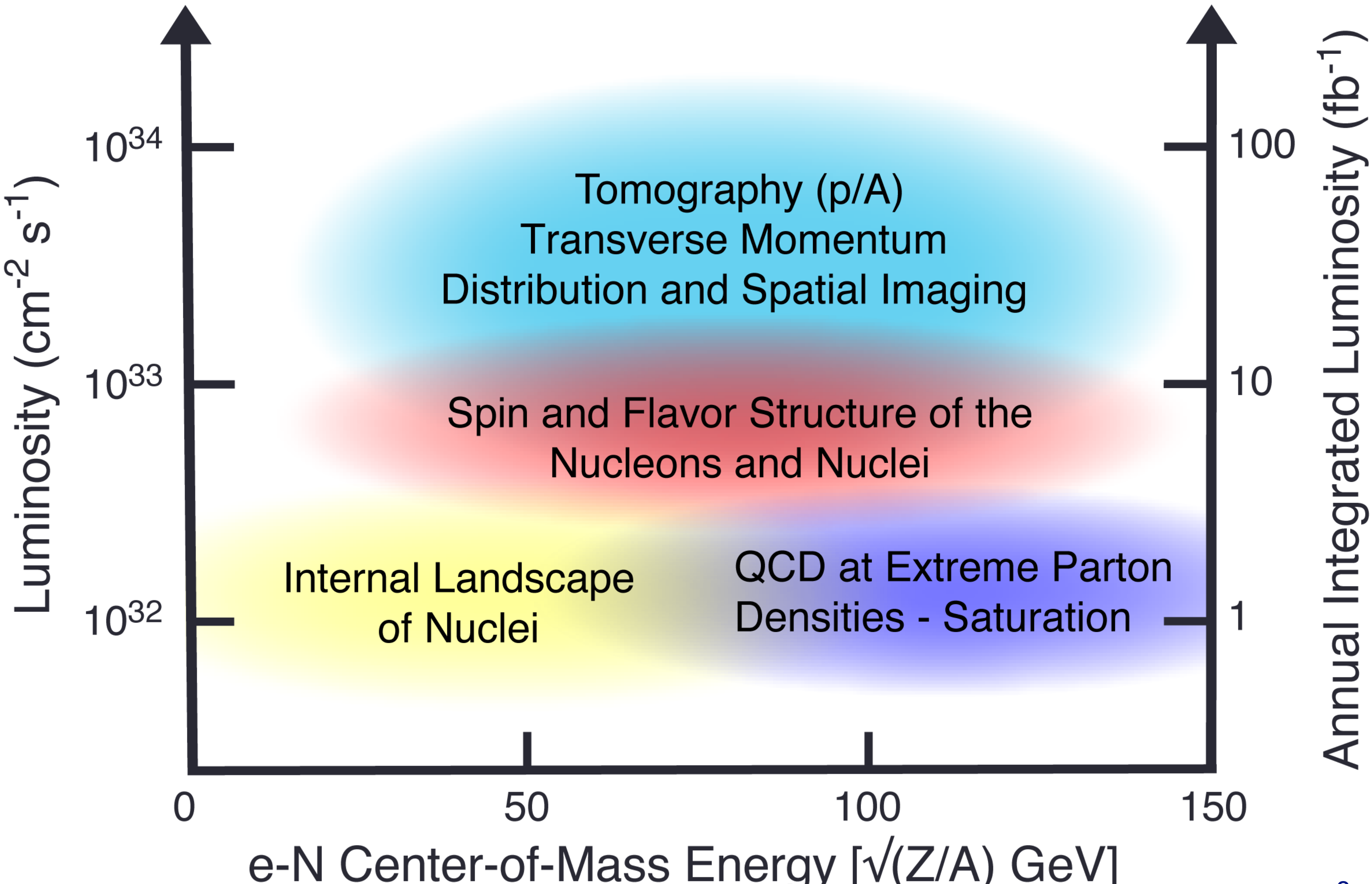
- high luminosity & wide reach in √s
- polarized lepton & hadron beams
- nuclear beams

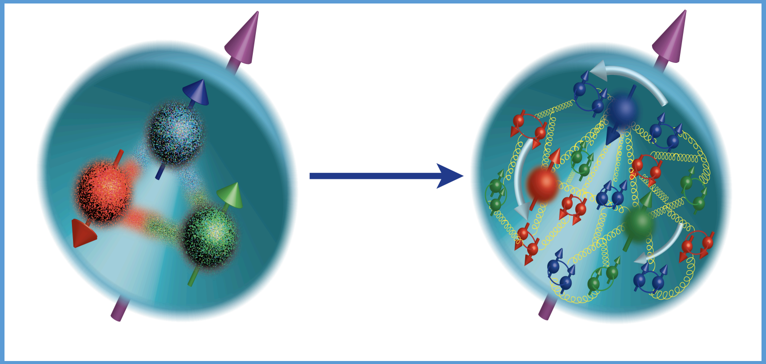
EIC stands out as unique facility …

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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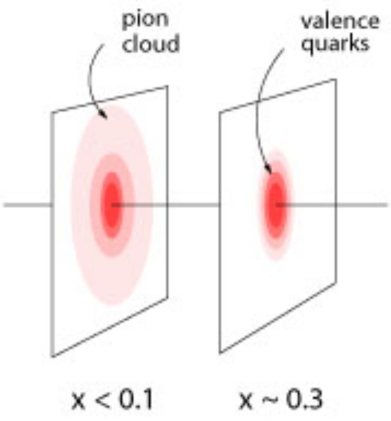
What does a proton look like with increasing energy?



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:

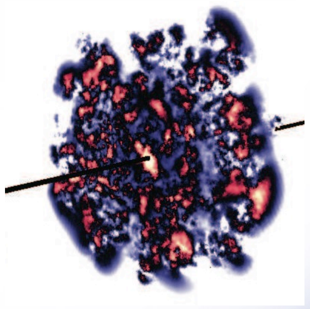
- ❑ $q\bar{q}$ pairs (sea quarks) generated at small(ish)-x are predicted to be unpolarized
- ❑ gluons generated from sea quarks are unpolarized

→ 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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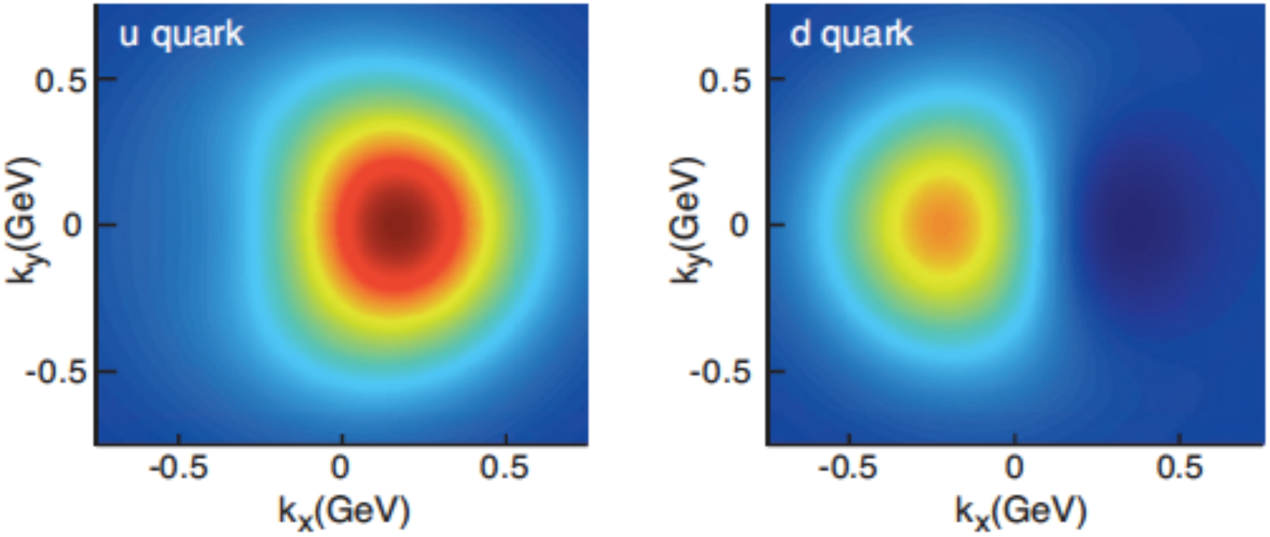

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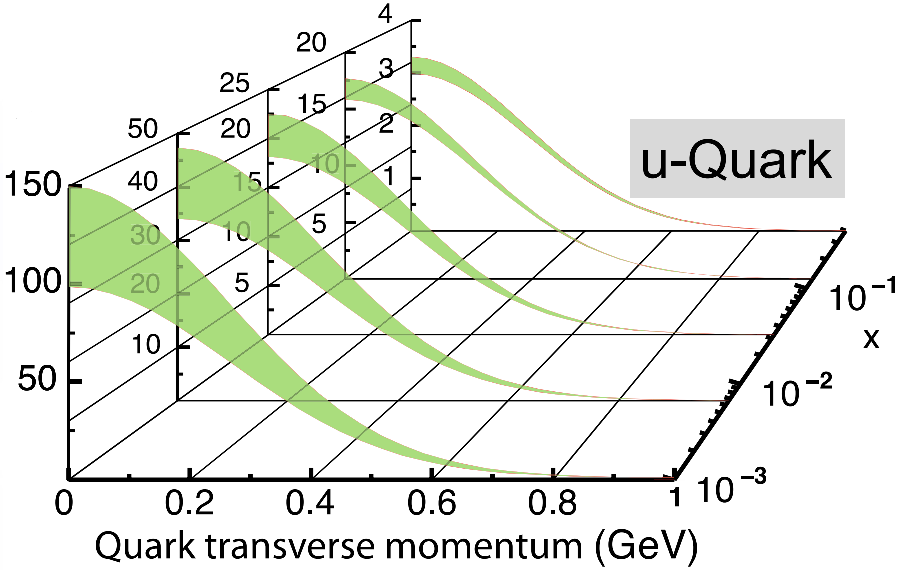

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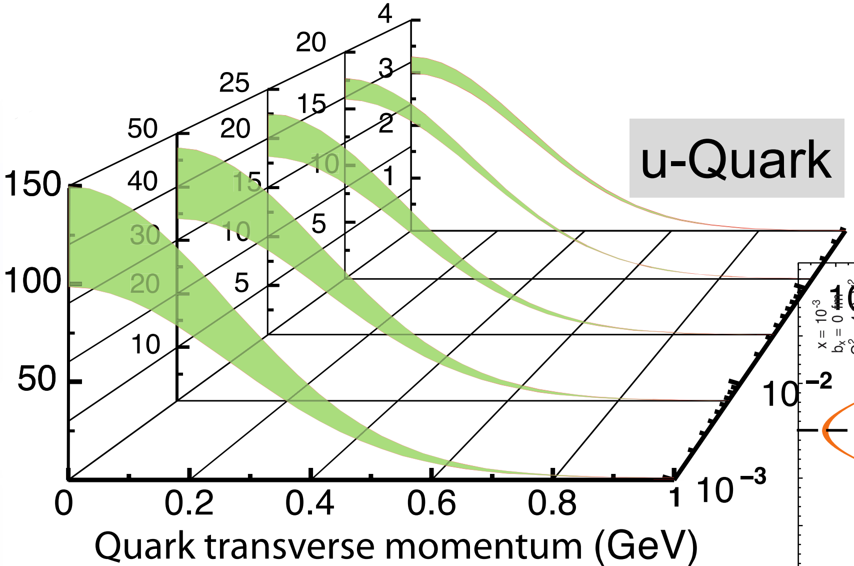

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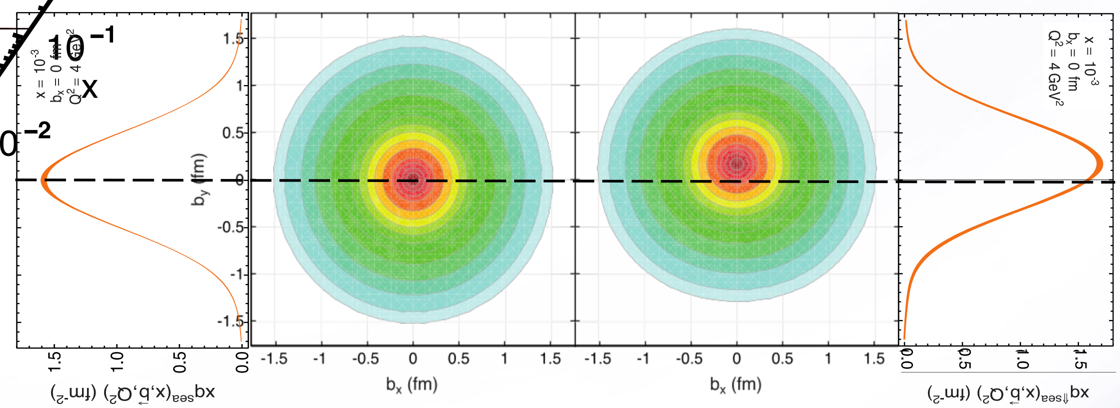
Transverse Position Distributions

sea-quarks
unpolarized polarized



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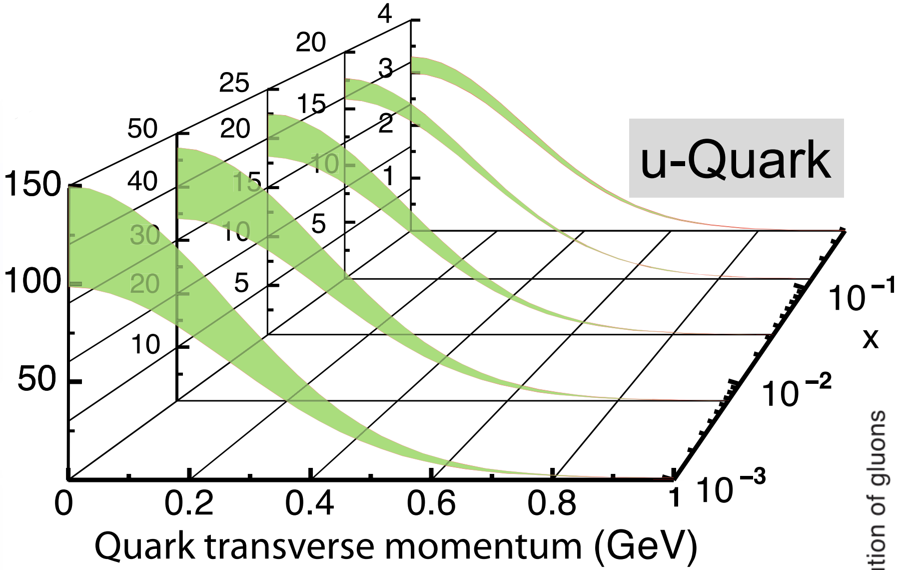

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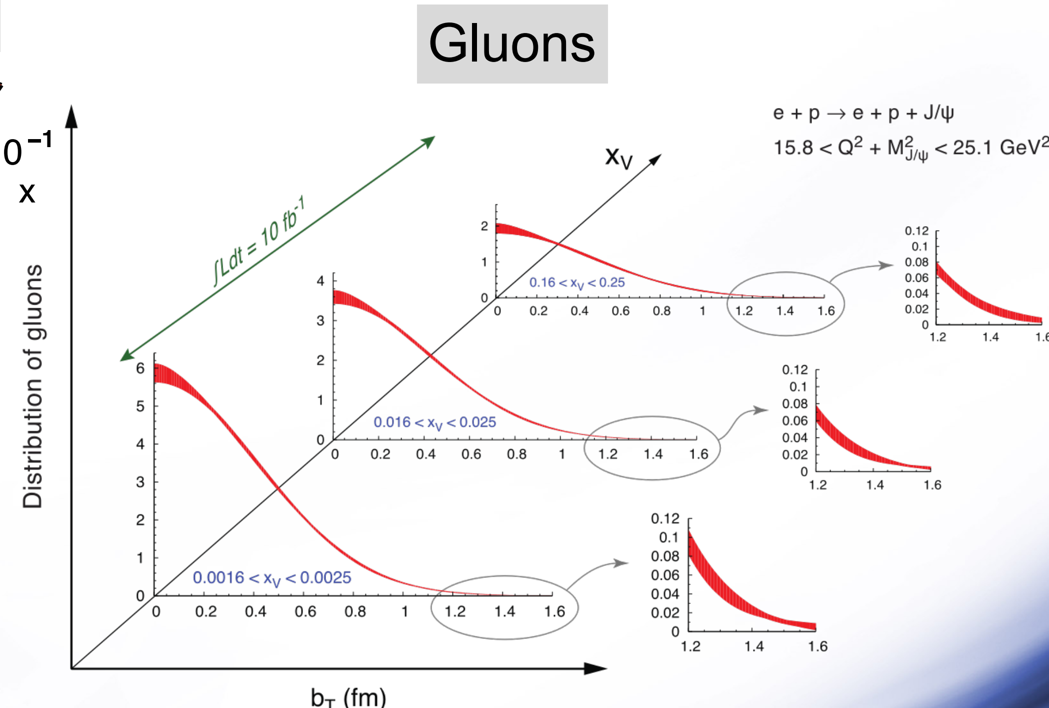
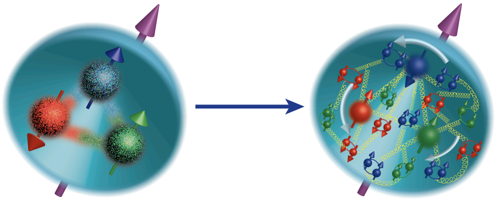


Understanding Nucleon Spin

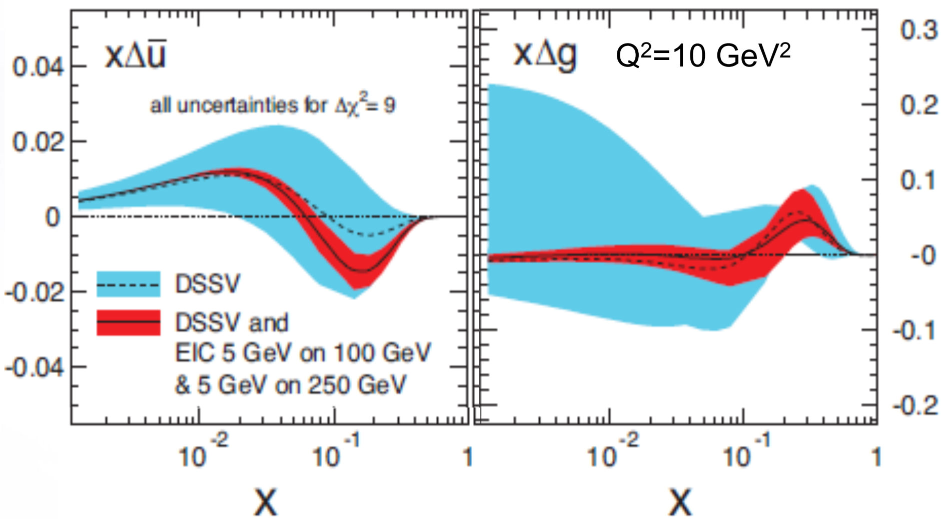


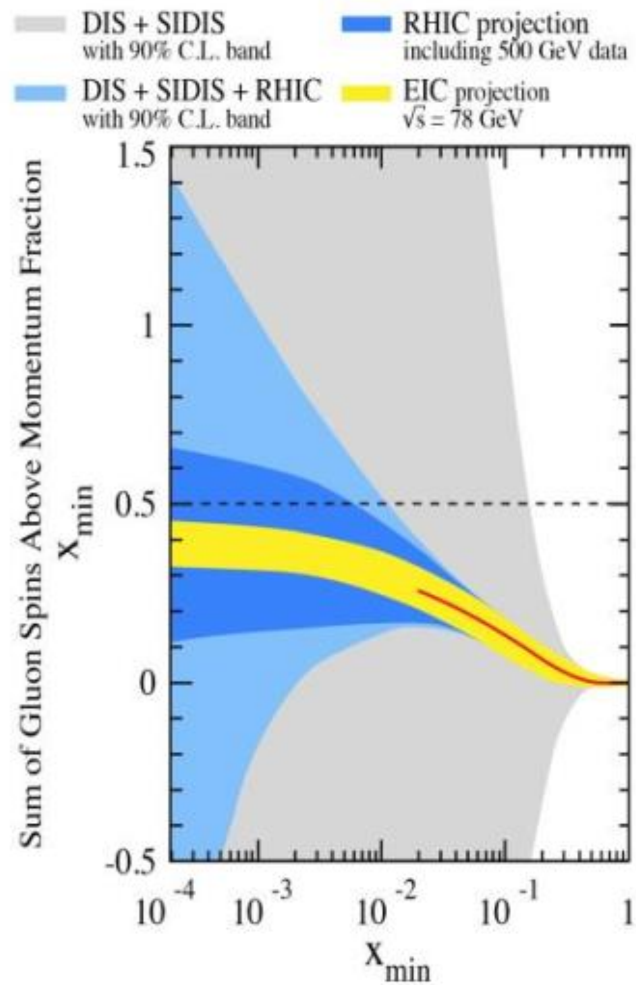
"Helicity sum rule"

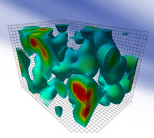
$$\frac{1}{2}\hbar = \frac{1}{2}\Delta\Sigma + \Delta G + \sum_q L_q^z + L_g^z$$

quark contribution — gluon contribution — 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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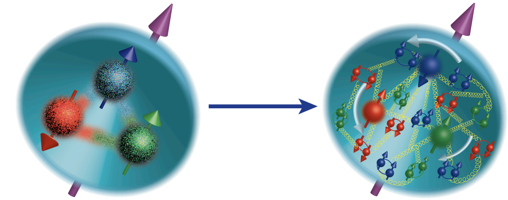

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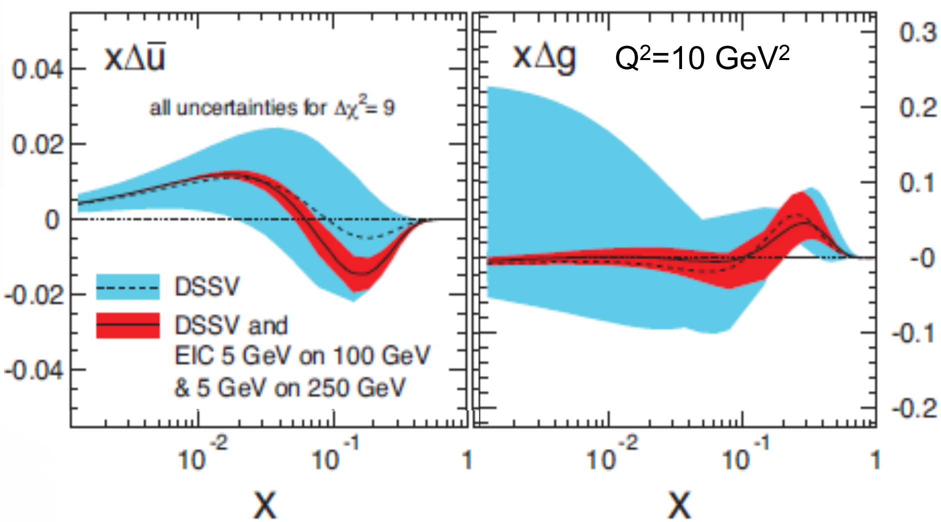
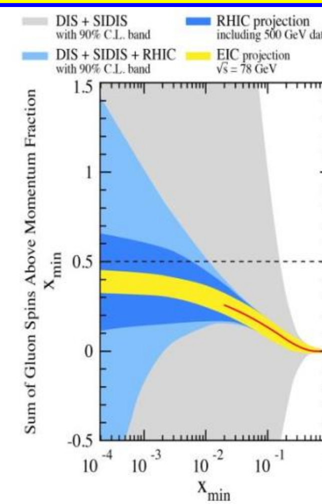
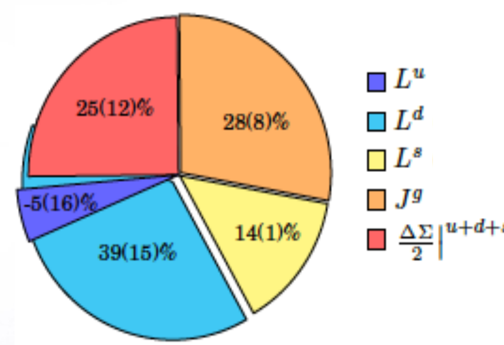
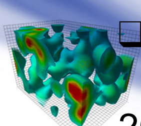




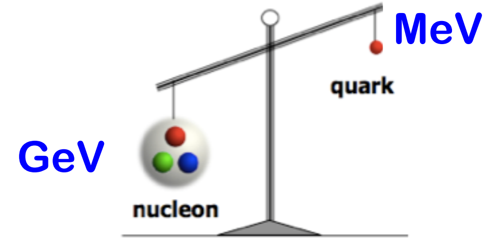
Spin and Lattice: Recent Activities

- **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:**
  ◻◻QCD Collaboration, PRD91, 014505, 2015





Understanding Nucleon Mass



Relativistic motion

χ Symmetry Breaking

Quantum fluctuation

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

Quark Energy

Gluon Energy

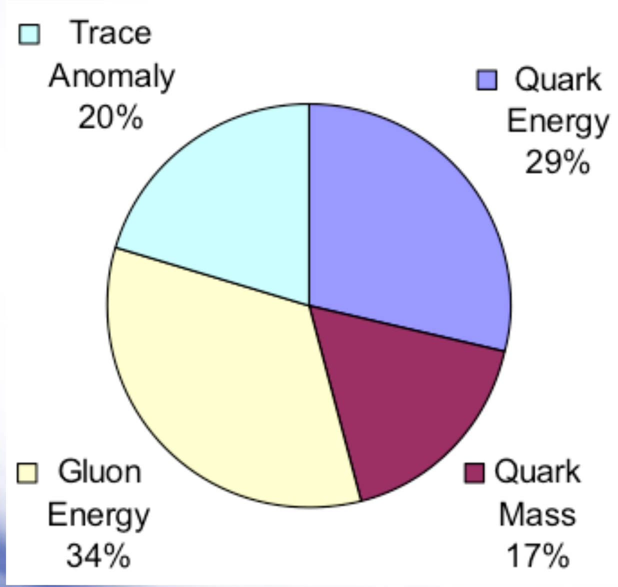
Quark Mass

Trace Anomaly

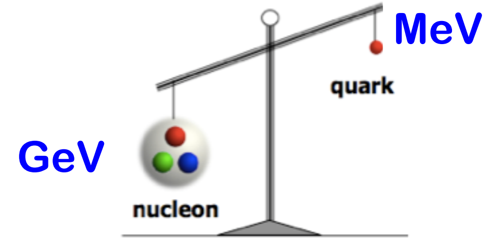
"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

The 2015 Long Range Plan for Nuclear Science

- **Preliminary Lattice QCD results:**



Understanding Nucleon Mass



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

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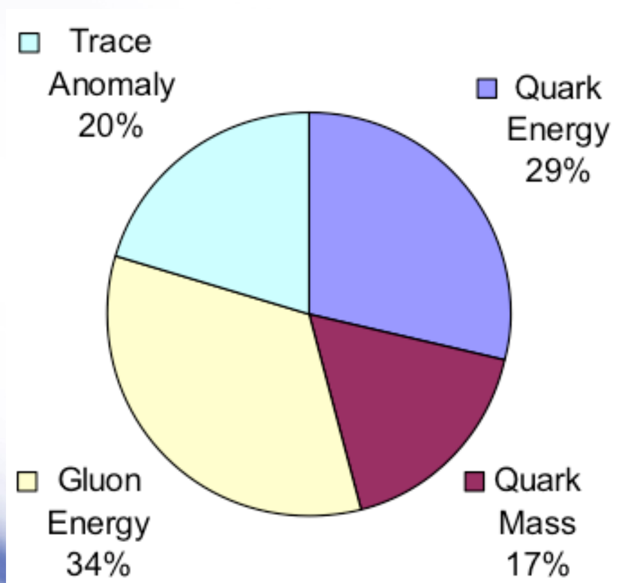
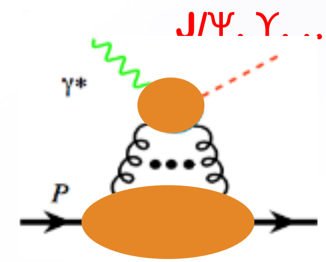


❑ EIC's expected contribution in:

◇ Trace anomaly:

Upsilon production near the threshold

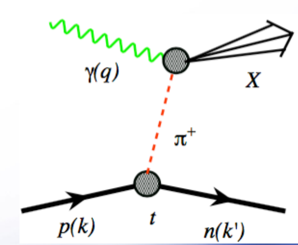


◇ Quark-gluon energy:

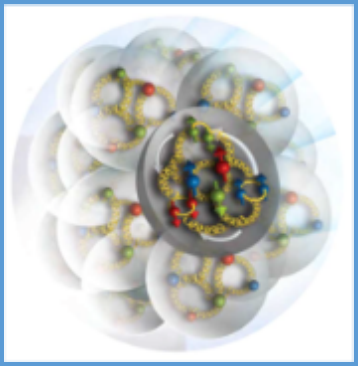
$\propto$ *quark-gluon momentum fractions*

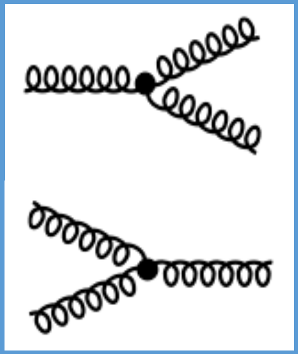
In nucleon with DIS and SIDIS

In pions and kaons with Sullivan process



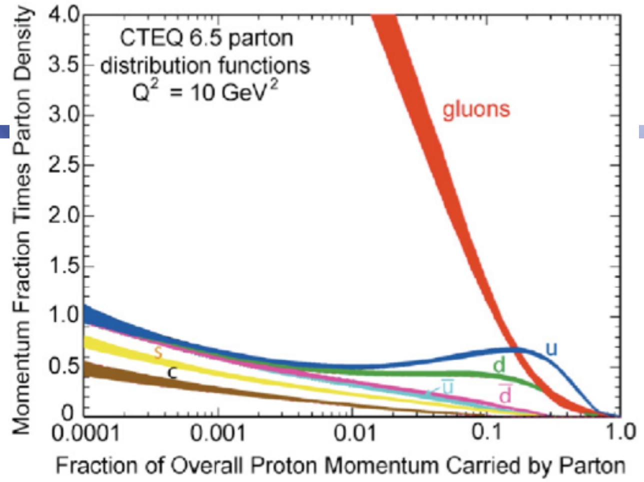
The Nucleus as a laboratory for QCD

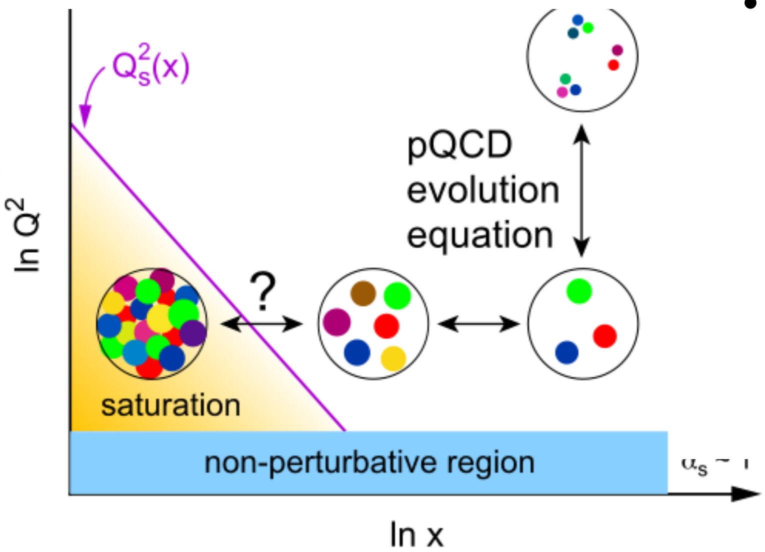




- How does a *dense nuclear environment* affect the quarks and gluons, their correlations, and their interactions?
- What happens to the *gluon density in nuclei*? Does it *saturate at high energy*, giving rise to a gluonic matter with *universal properties* in all nuclei, even the proton?

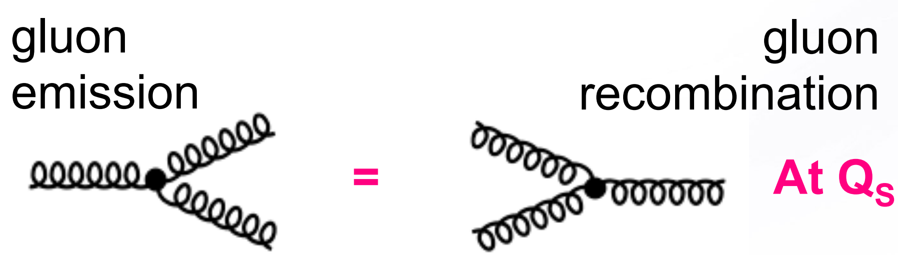
Gluon saturation at low-x



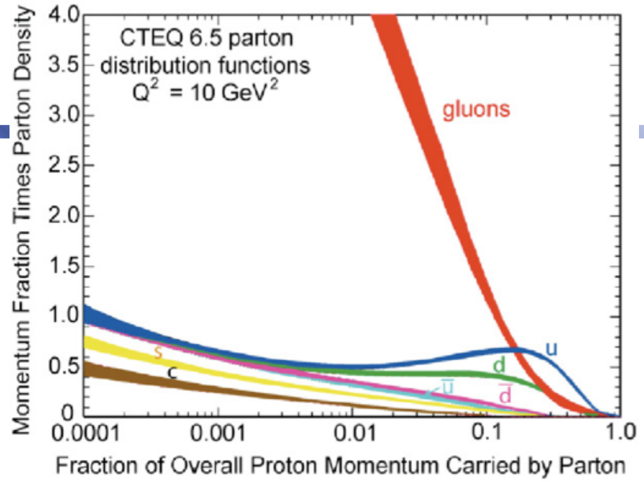


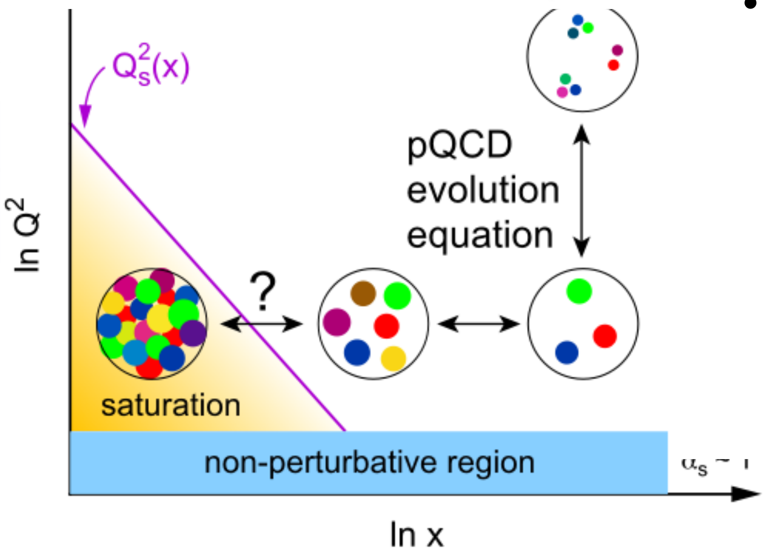
What tames the low-x rise?

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



Gluon saturation at low-x





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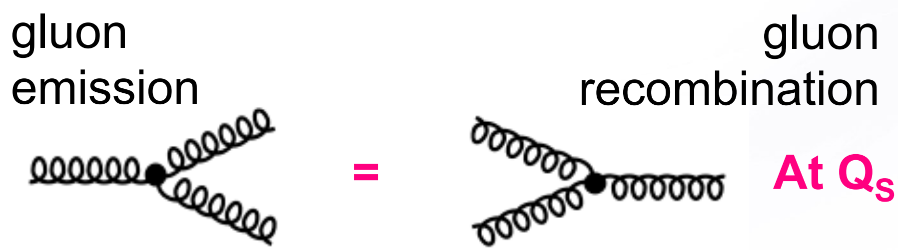


First observation of gluon recombination effects in nuclei:

➔ leading to a collective gluonic system

First observation of gluon recombination in different nuclei

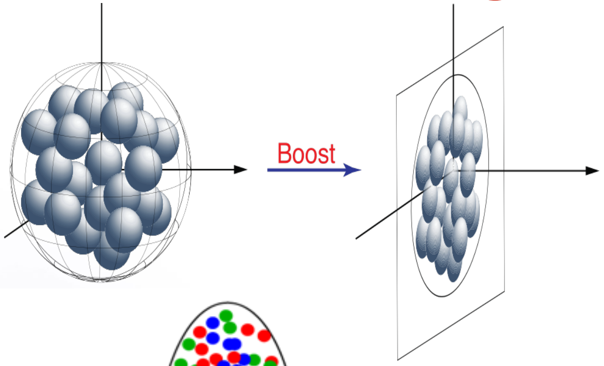
→ Is this a universal property?

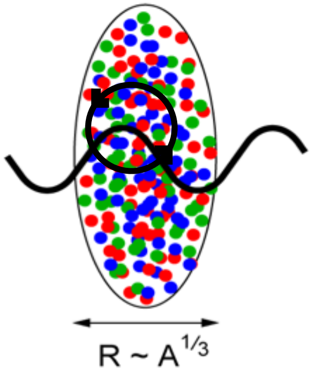
What is the new effective theory in this regime?

How to explore/study this new phase of matter?

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

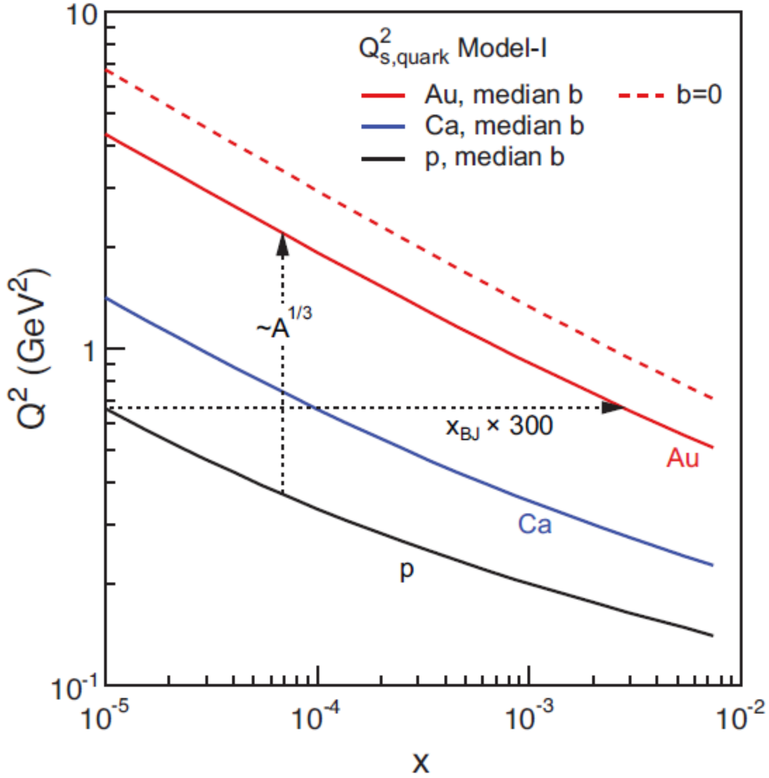
Advantage of nucleus →





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

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



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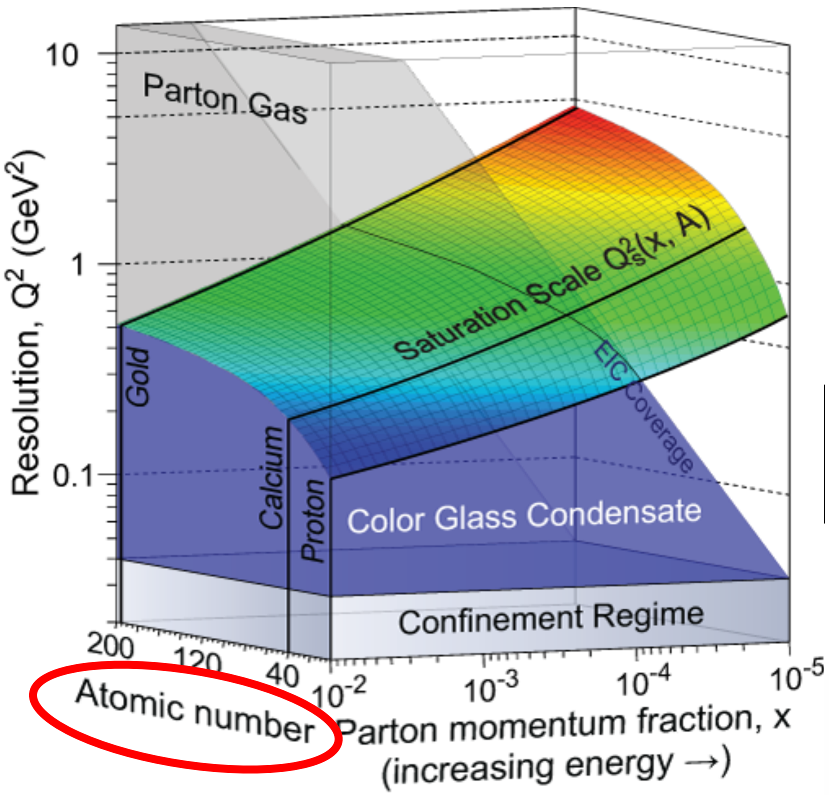
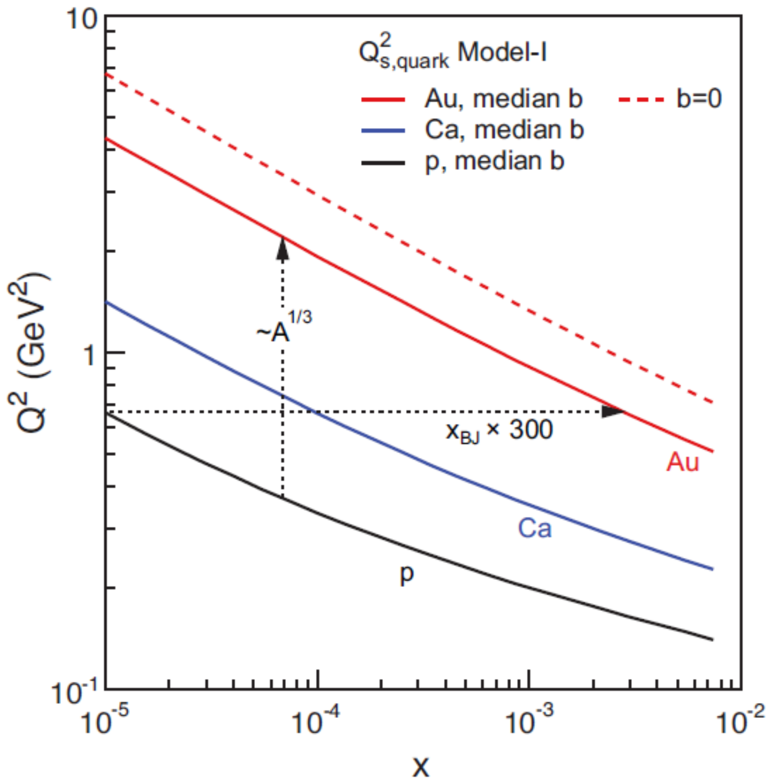


$L \sim$ $A^{1/3}$



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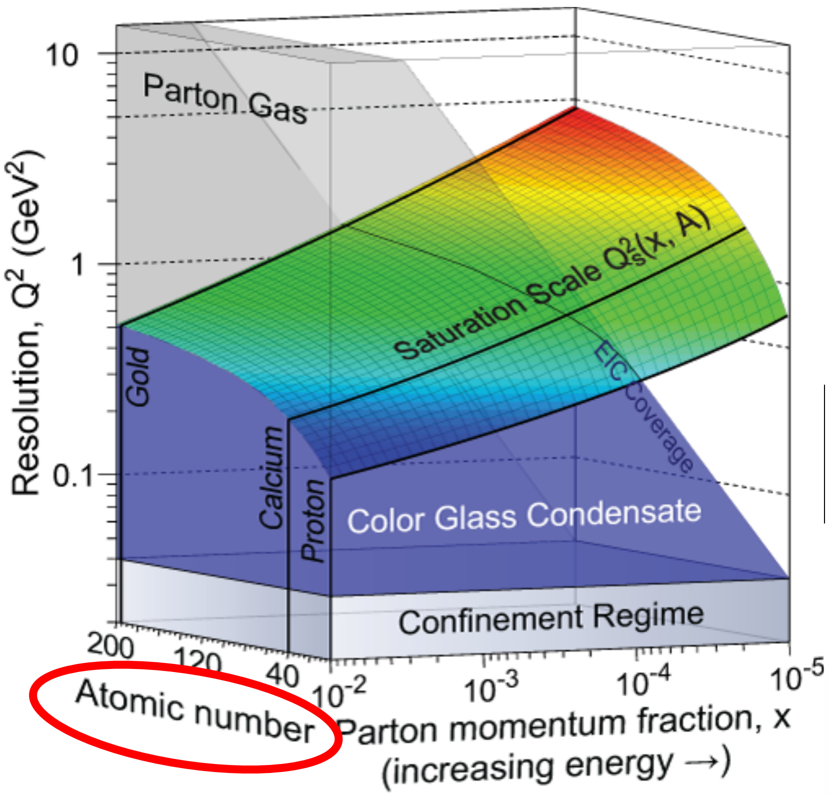
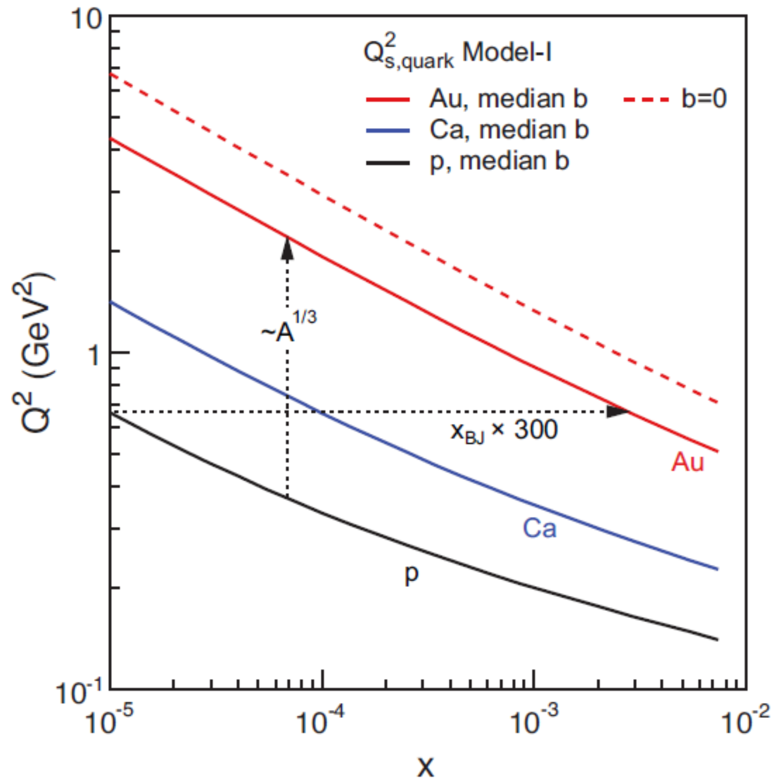


$L \sim$ $1/3$



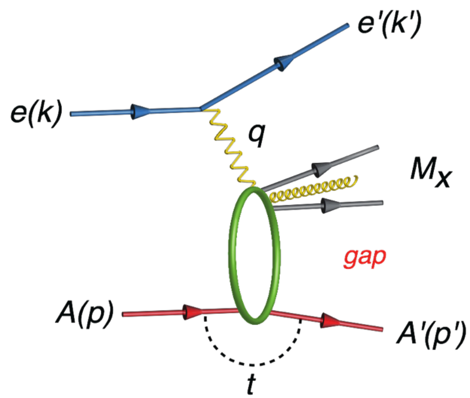
Enhancement of Q_S with A:
Saturation regime reached at significantly lower energy (read: “cost”) in nuclei

Diffraction for the 21st Century

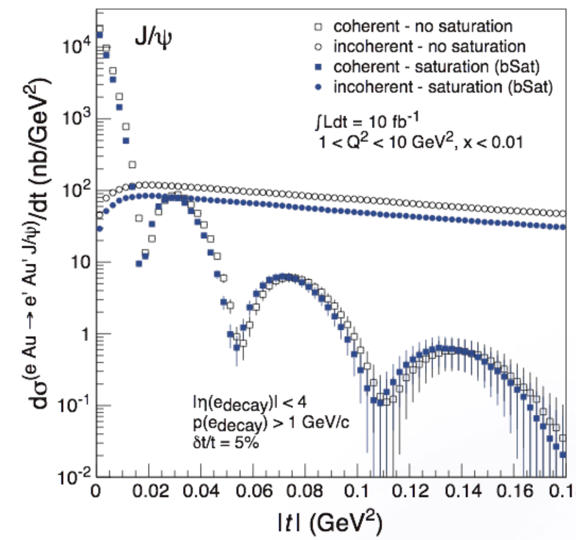
Diffraction cross-sections have strong discovery potential:

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

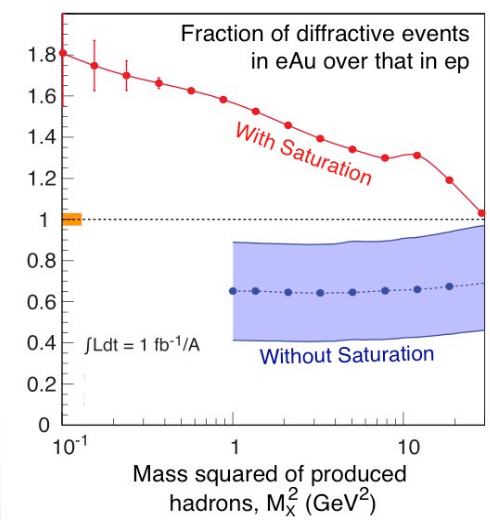
Dramatic changes in cross-sections with onset of non-linear strong color fields



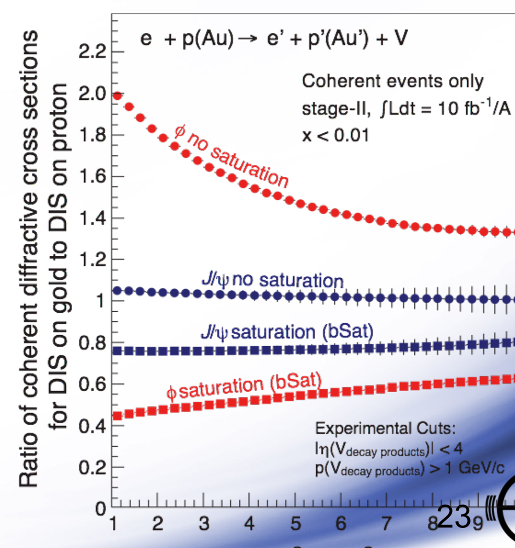
Extracting the gluon distribution $\rho(b_T)$ of nuclei via Fourier transformation of $d\sigma/dt$ in diffractive J/ψ production



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

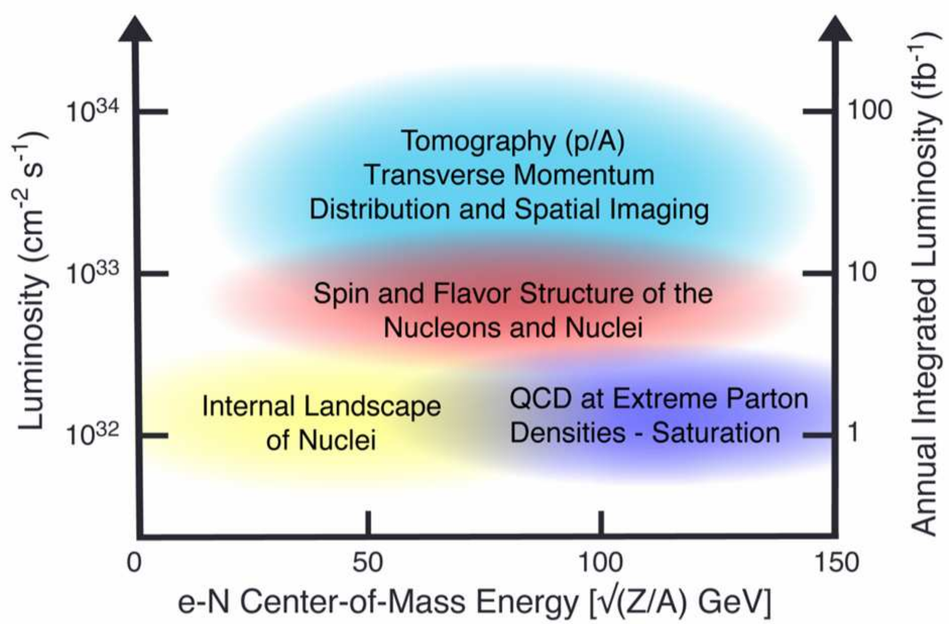


Probing Q^2 dependence of gluon saturation in diffractive vector meson production



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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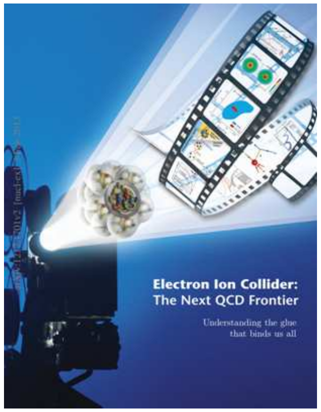
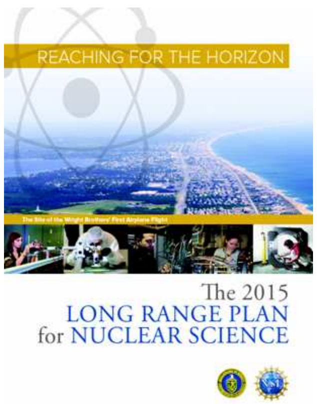
A long journey to get here…



EIC White Papers (2012,14,16)

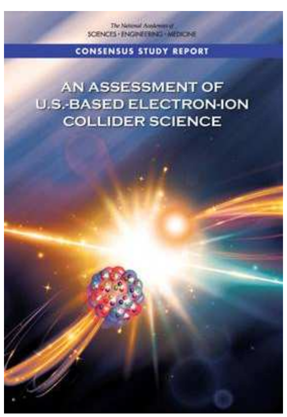
Development of EIC science case: *"The next QCD frontier: Understanding the glue that binds us all".* arXiv: 1212.1701

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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Major Announcement: 2020–Jan–08

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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 at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

"The EIC promises to keep America in the forefront of nuclear physics research and particle accelerator technology, critical components of overall U.S. leadership in science," said **U.S. Secretary of Energy Dan Brouillette**. "This facility will deepen our understanding of nature and is expected to be the source of insights ultimately leading to new technology and innovation."

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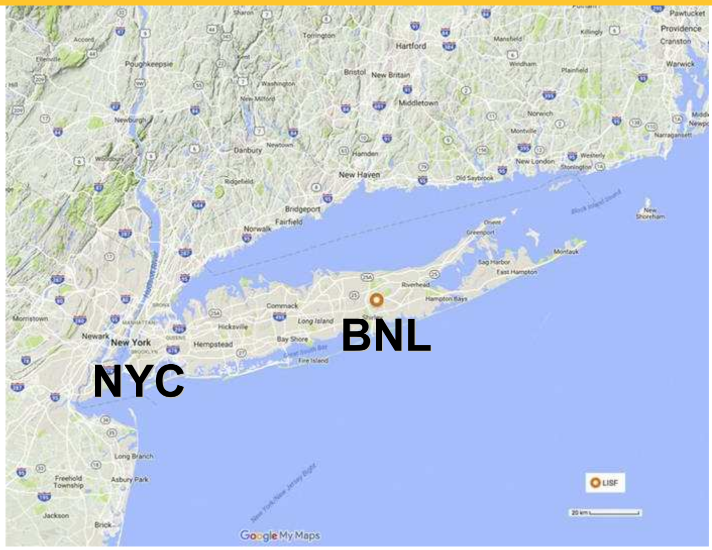
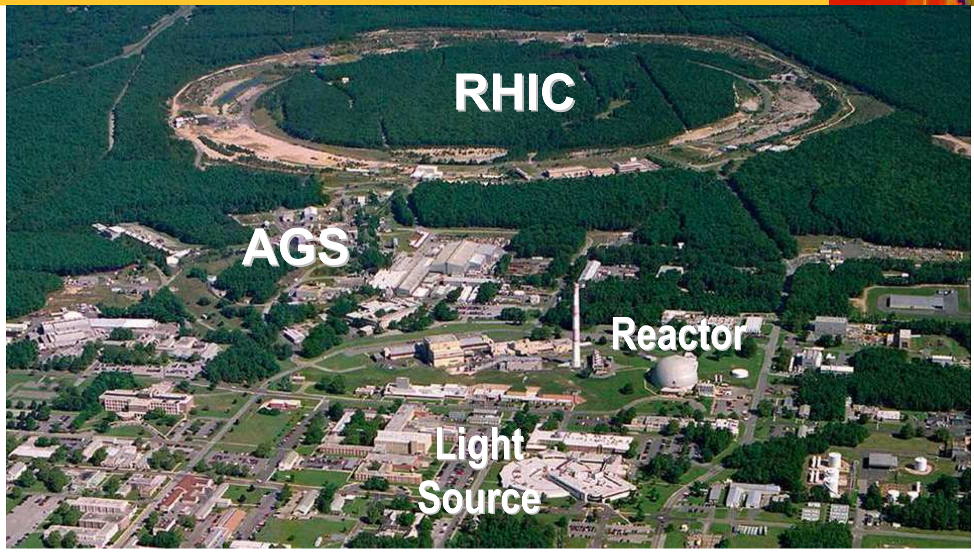
Brookhaven National Laboratory





BNL Researchers Awarded Five Nobel Prizes in Physics

- **1957**: T.D. Lee & C.N. Yang, discovery of Parity Violation at BNL's Cosmotron Accelerator
- **1976**: Sam C.C. Ting, discovery of J/Ψ particle at BNL's AGS, proving existence of charmed quark
- **1980**: J.W. Cronin & V.L. Fitch, discovery of CP violation at AGS
- **1988**: L. Lederman, M. Schwartz, J. Steinberger, discovery of muon neutrino at BNL's AGS
- **2002**: R. Davis, first observation of cosmic neutrinos

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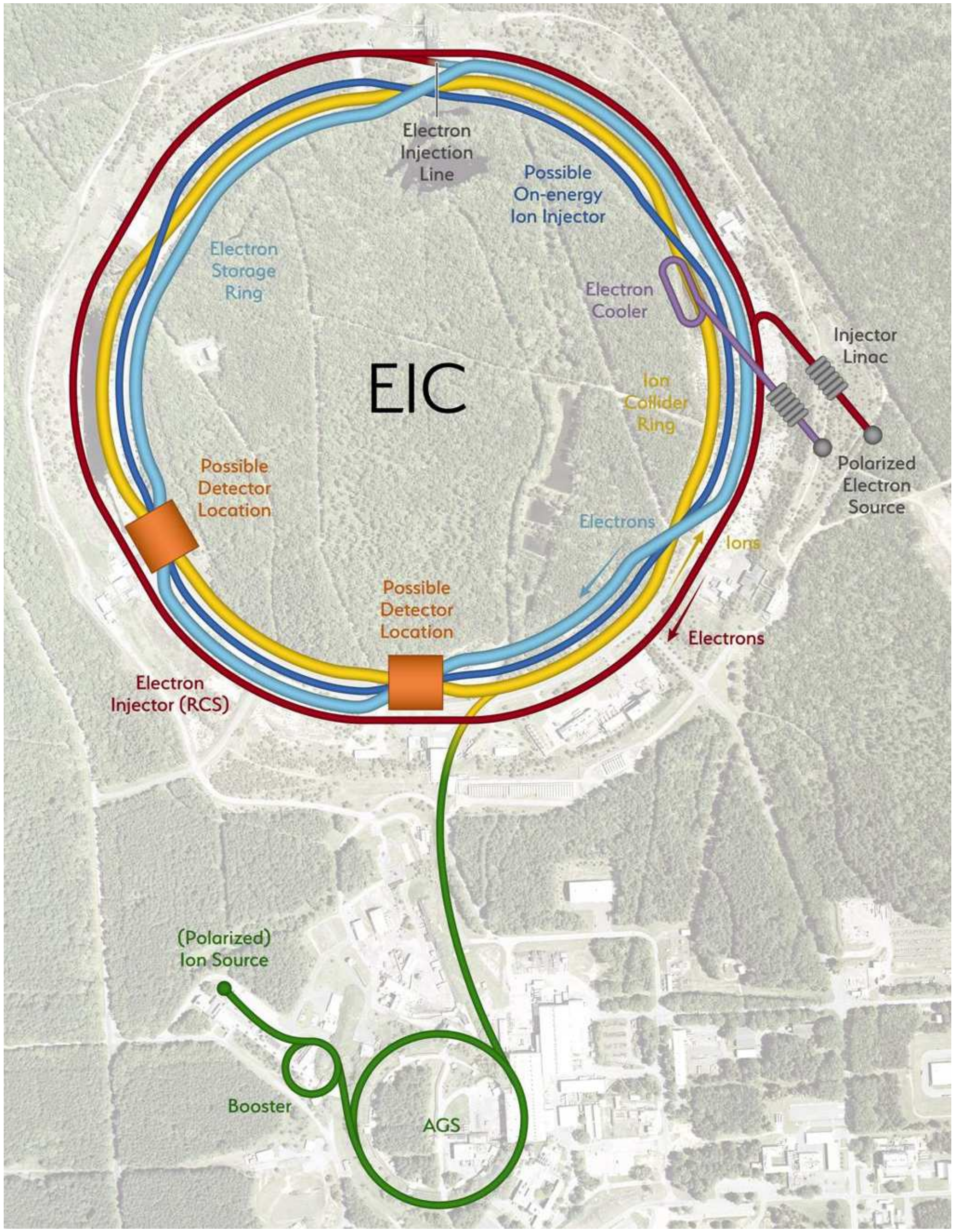
eRHIC Realization @ BNL

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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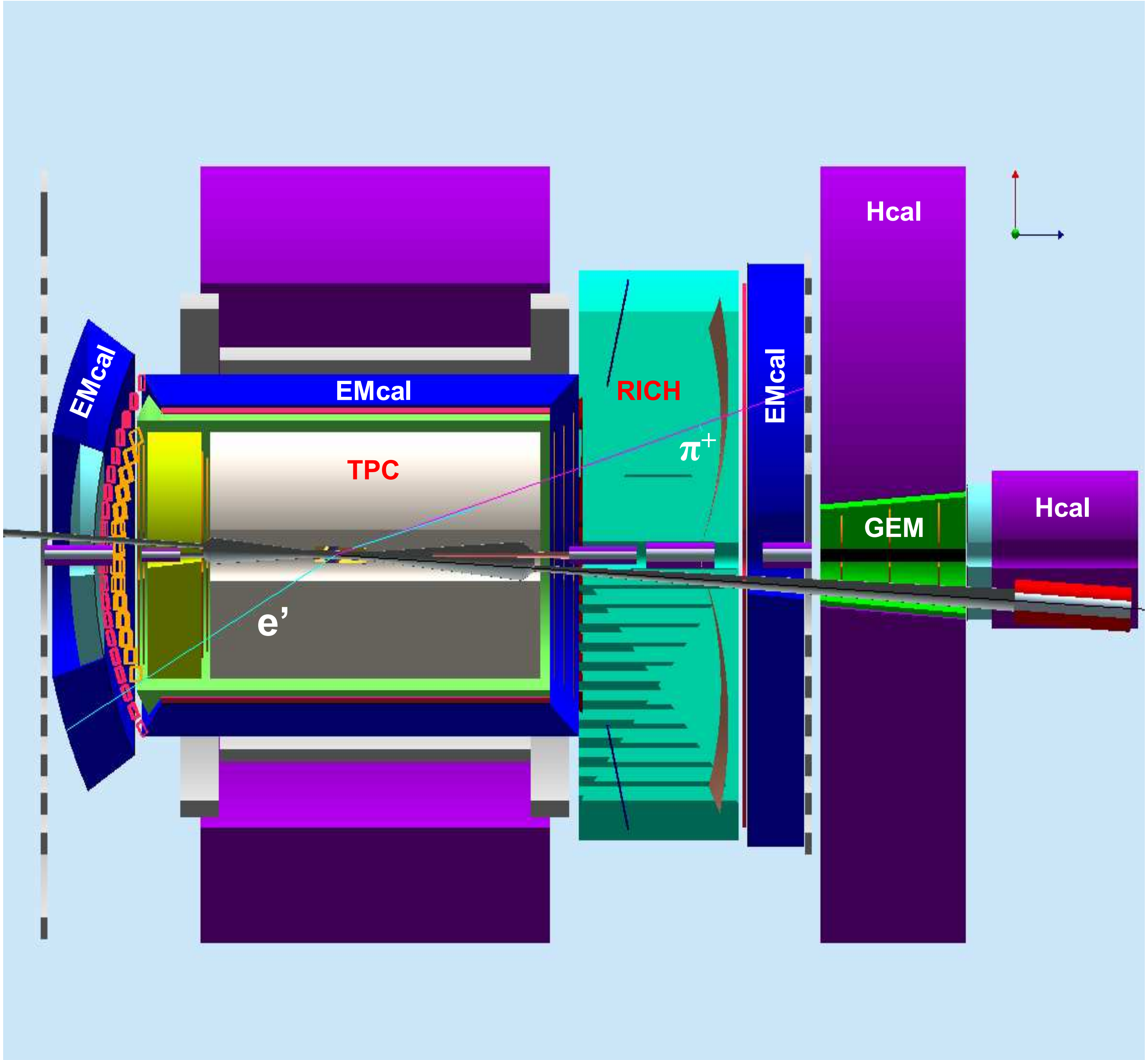
EIC Conceptual Detector Design

100 GeV proton beam



5 GeV electron beam

n

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EIC Users Group: EICUG.ORG

- **1052 collaborators, 31 countries, 215 institutions** (2020 Mar 05)
- Map of institution's locations

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Canadian members of EICUG

- **22 collaborators, 8 institutions** (2020 Mar 05)

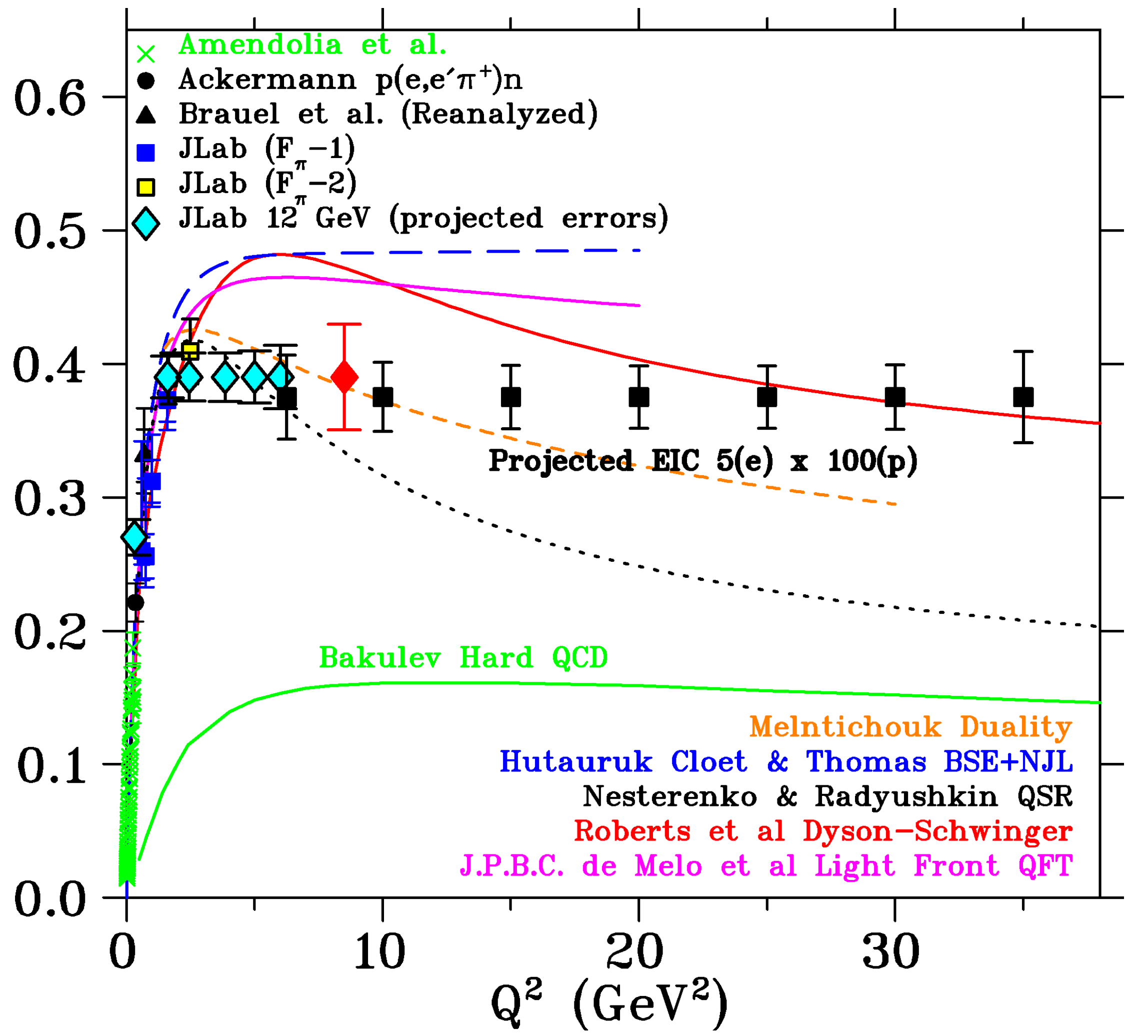
First name	Last Name	E-mail address	Institution	Country	Area
Mohammad	Ahmady	mahmady@mta.ca	Mount Allison University	CANADA	Theory
Aleksandrs	Aleksejevs	aaleksejevs@grenfell.mun.ca	Memorial University of Newfoundland, Grenfell Campus	CANADA	Theory
Mauricio	Barbi	mdsbarbi@gmail.com	University of Regina	CANADA	Experiment
Svetlana	Barkanova	sbarkanova@grenfell.mun.ca	Memorial University of Newfoundland, Grenfell Campus	CANADA	Theory
Thomas	Brunner	thomas.brunner@physics.mcgill.ca	McGill University	CANADA	Experiment
Wouter	Deconinck	wouter.deconinck@umanitoba.ca	University of Manitoba	CANADA	Experiment
Charles	Gale	gale@physics.mcgill.ca	McGill University	CANADA	Experiment
Michael	Gericke	mgericke@physics.umanitoba.ca	University of Manitoba	CANADA	Experiment
David	Hornidge	c [illegible]	[illegible]	[illegible]	Experiment
Garth	Huber	h [illegible]	[illegible]	[illegible]	Experiment
Sangyong	Jeon	jeon [illegible]	[illegible]	[illegible]	Experiment
Muhammad	Junaid	junai [illegible]	[illegible]	[illegible]	Experiment
Stephen	Kay	Stephen.Kay@uregina.ca	University of Regina	CANADA	Experiment
Vijay	Kumar	vkb135@uregina.ca	University of Regina	CANADA	Experiment
Juliette	Mammei	jmammei@physics.umanitoba.ca	University of Manitoba	CANADA	Experiment
Philippe	Martel	martel@uni-mainz.de	Mount Allison University	CANADA	Experiment
Wim van	Oers	vanoers@jlab.org	University of Manitoba	CANADA	Experiment
Zisis	Papandreou	zisis@urengina.ca	University of Regina	CANADA	Experiment
Ken	Ragan	ragan@physics.mcgill.ca	McGill University	CANADA	Experiment
Ruben	Sandapen	ruben.sandapen@acadiau.ca	Acadia University	CANADA	Theory
Swadhin	Taneja	swadhin.taneja@gmail.com	Dalhousie University	CANADA	Experiment
Ali	Usman	auu001@uregina.ca	University of Regina	CANADA	Experiment

Formation of EIC Canada Collaboration in progress

EIC Yellow Report

- **Highest EIC–UG priority for 2020**
- **Purpose:** advance the state and detail of the documented physics studies and detector concepts in preparation for the realization of the EIC.
  - Aims to further develop concepts for experimental equipment best suited for science needs, including complementarity of two detectors towards future Technical Design Reports (TDRs).
- Upcoming Yellow Report Workshops:
  - March 19–21, 2020, Temple University, Philadelphia
  - May 22–24, 2020, U. of Pavia, Pavia , Italy
  - **September 17–19, 2020, CUA, Washington DC**
  - **November 19–21, 2020, UCB – Berkeley, CA**
- **U.Regina 2020 EIC effort: physics simulations for Yellow Report**

Pion Form Factor @ EIC (2018 study)



A significant extension in kinematic reach beyond our JLab program

Understanding the structure of the pion is essential to unraveling the origin of nucleon mass (Dynamical Chiral Symmetry Breaking)

Craig Roberts (2016):

"No understanding of confinement within the Standard Model is practically relevant unless it also explains the connection between confinement and DCSB, and therefore the existence and role of pions."

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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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