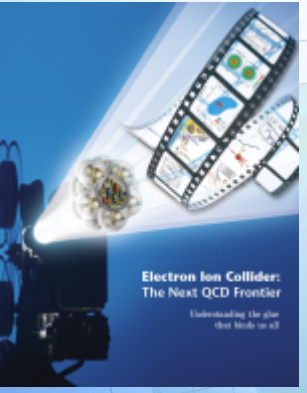
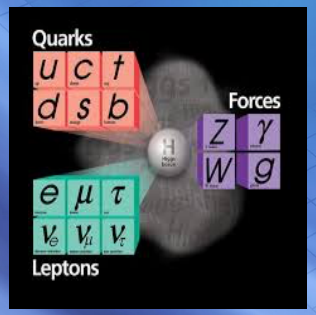


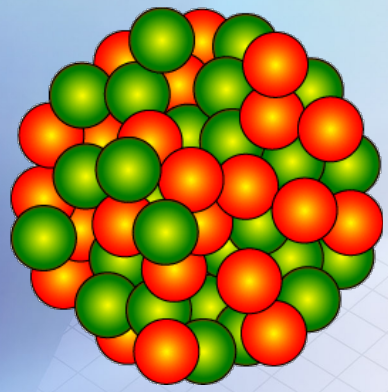
arXiv 1212.1701.v3
Eur. Phy. J. A52, 9 (2016)

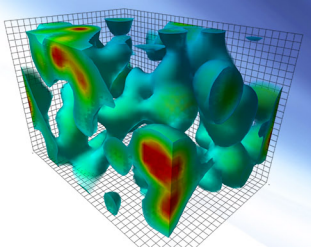
Electron Ion Collider: The next QCD frontier

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

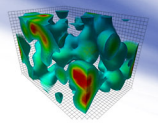
Stony Brook University

Why an Electron Ion Collider

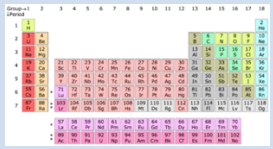
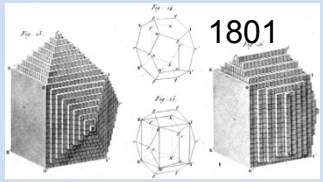
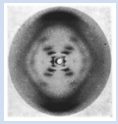
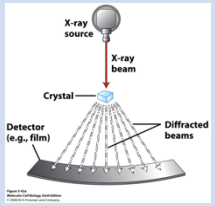
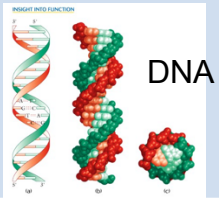
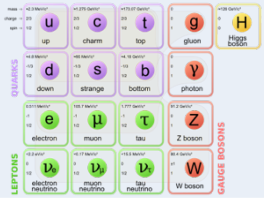
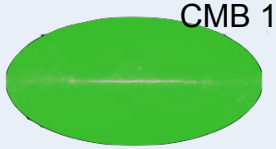
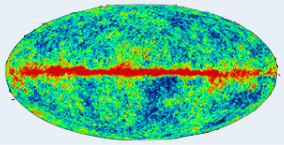
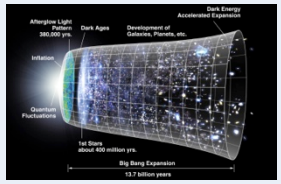
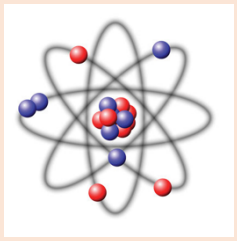
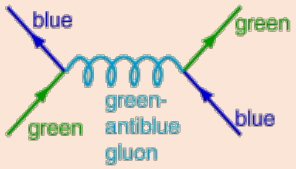
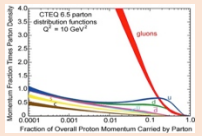
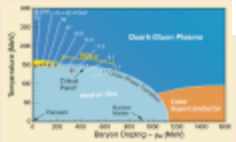
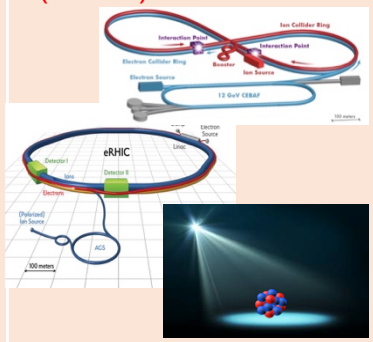
- **Interactions and structure are inseparable in nuclear matter:** Nuclear matter is made of quarks that are bound by gluons that also bind themselves. Unlike with the more familiar atomic and molecular matter, the interactions and structures are inseparable, and the **observed properties** of nucleons 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, and as dramatic as 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 **in situ**, to explore the new QCD frontier of **strong color fields** in nuclei – to *understand* how matter at its most fundamental level is made.

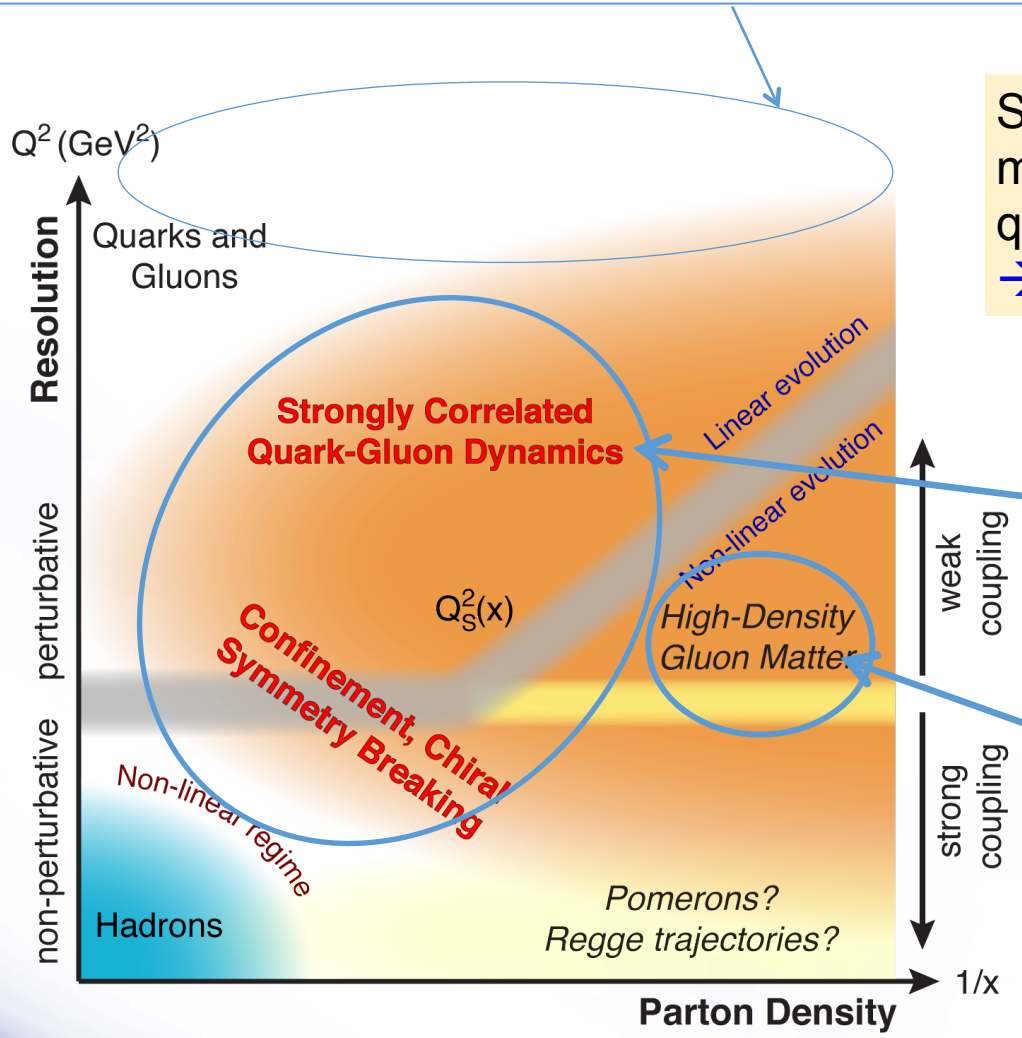


EIC: A Portal to a New Frontier

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes (Date)	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure 	X-ray Diffraction (~1920)  	Solid state physics Molecular biology 
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure 	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{\text{QCD}} = \overline{\psi}(i\partial\!\!\!/ - g\mathcal{A}\!\!\!/)\psi - \frac{1}{2}\text{tr}\, F_{\mu\nu}F^{\mu\nu}$ 	Non-perturbative QCD Structure  2017  	Electron-Ion Collider (2025+) 	Structure & Dynamics in QCD 

QCD Landscape explored by EIC

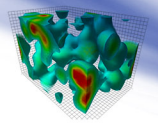
QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described



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

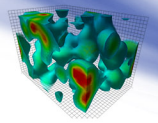
EIC systematically explores correlations in this region.

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?



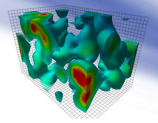
Emergent Dynamics in QCD

***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

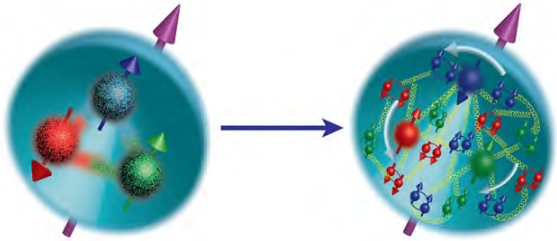
Experimental insight and guidance crucial for complete understanding of *how* hadrons & nuclei emerge from quarks and gluons

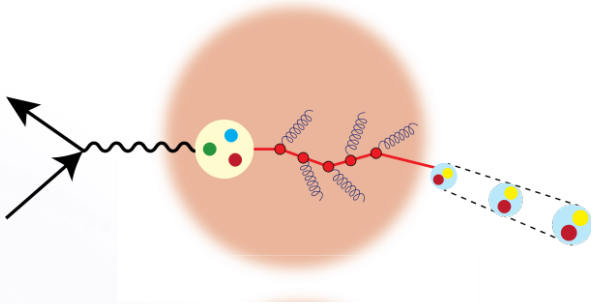


A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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?





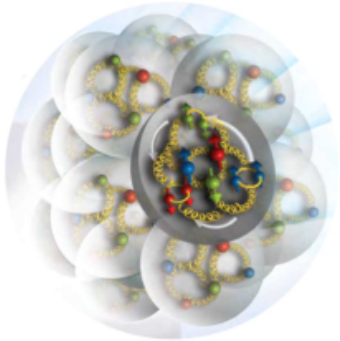
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

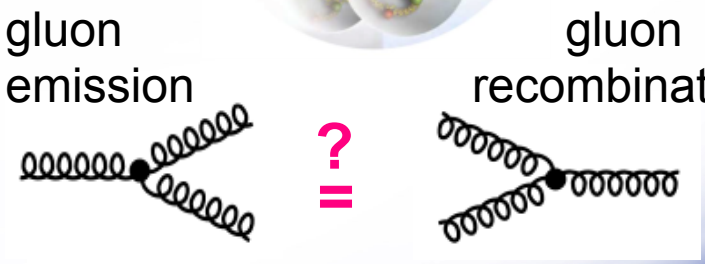
How do the confined hadronic states emerge from these quarks and gluons?

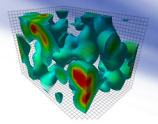
How do the quark-gluon interactions create nuclear binding?

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

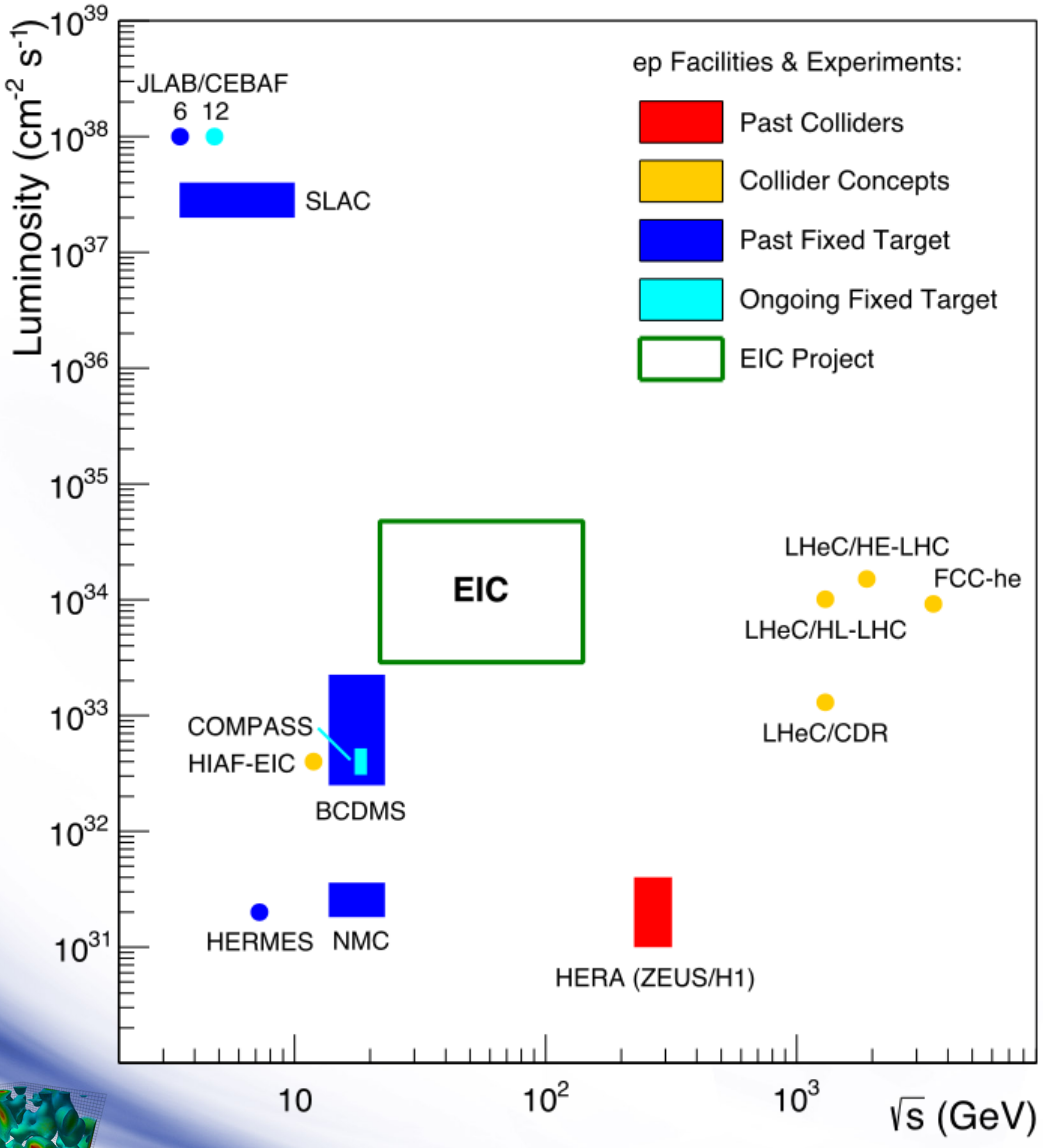
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?







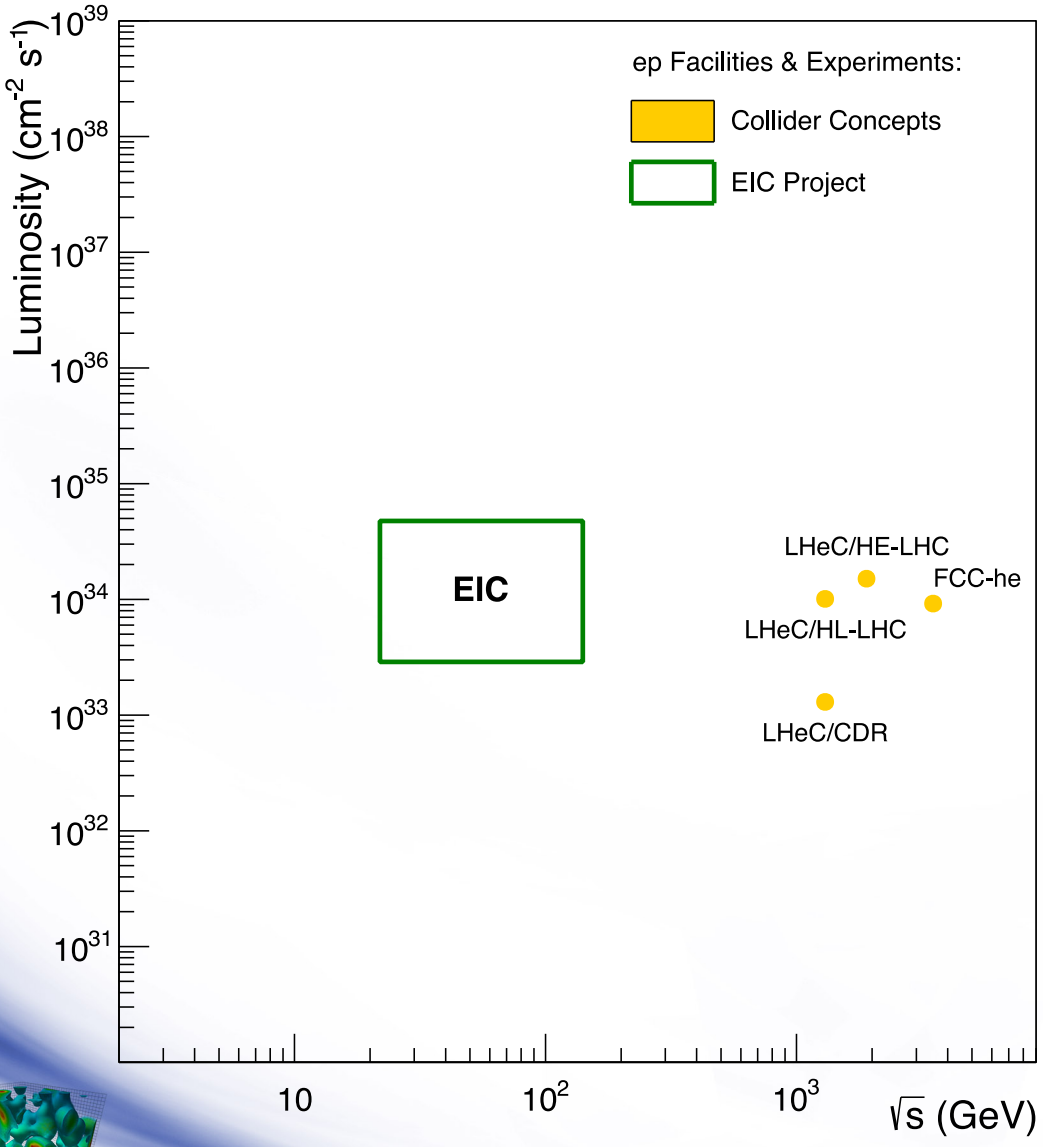
Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

However,
if we ask for:

Uniqueness of EIC among all DIS Facilities

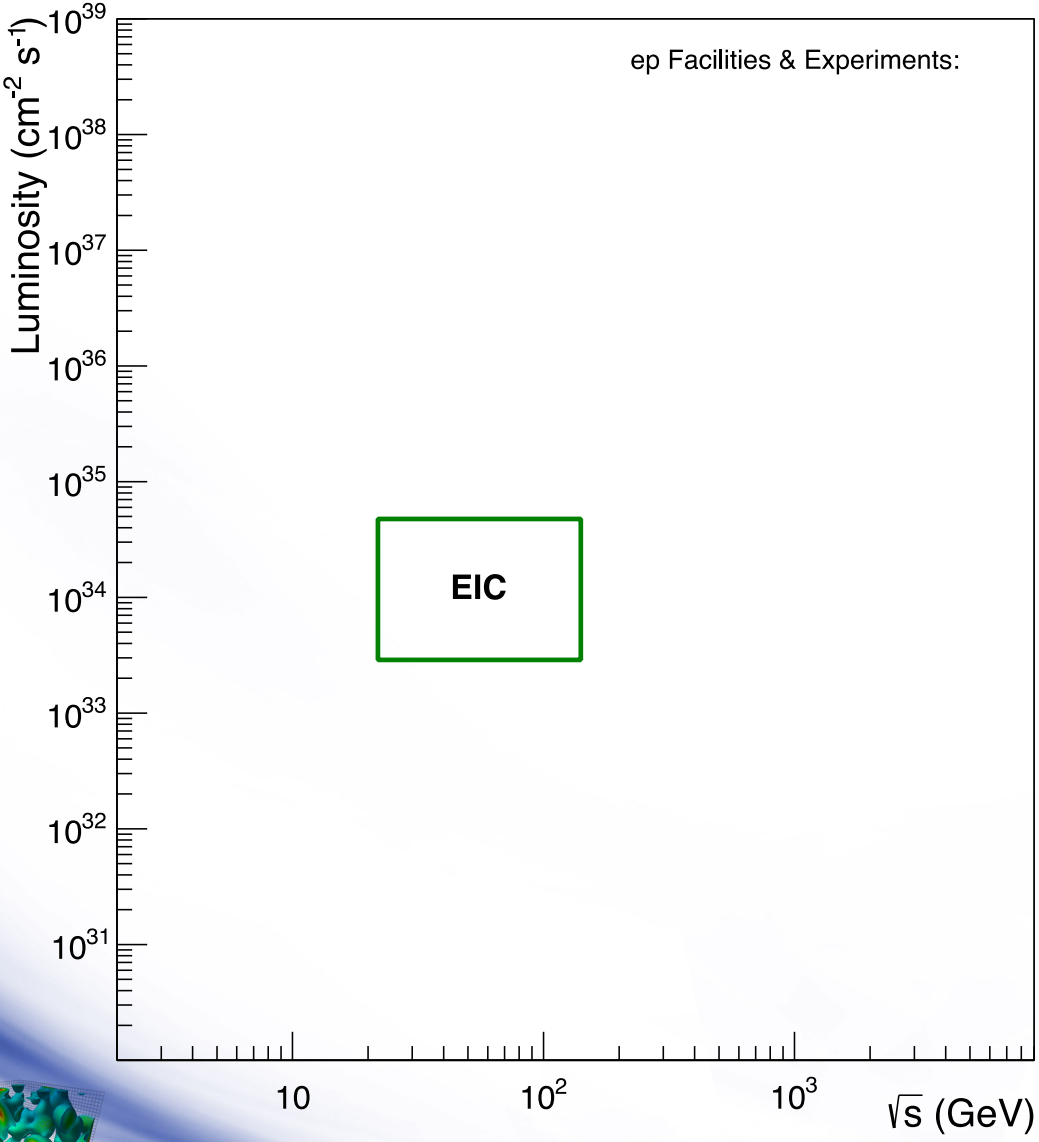


All DIS facilities in the world.

However,
if we ask for:

- high luminosity &
  wide reach in √s

Uniqueness of EIC among all DIS Facilities



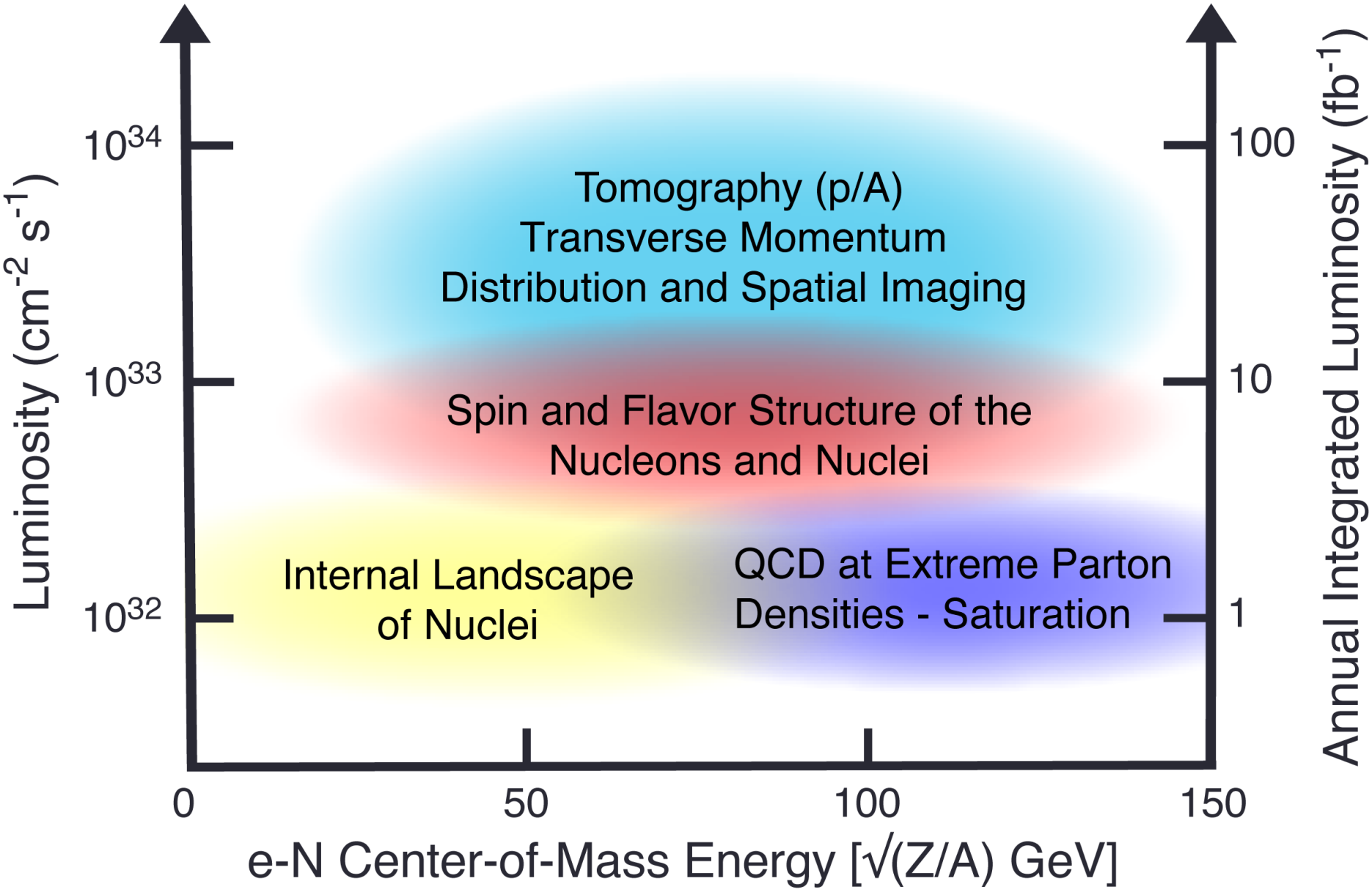
All DIS facilities in the world.

However,
if we ask for:

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

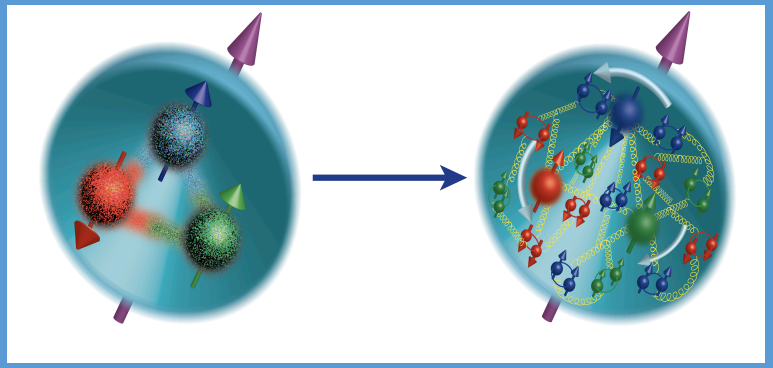
EIC stands out as unique facility …

Uniqueness of EIC among all DIS Facilities

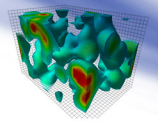


The world's first polarized electron-proton collider

Polarized proton as a laboratory for QCD



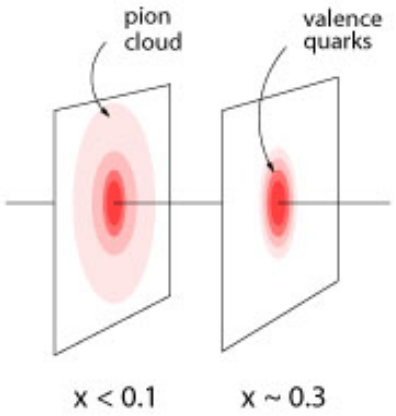
- How are the sea quarks and gluons, and their spins, *distributed in space and momentum* inside the nucleon?
- How do the *nucleon properties emerge* from them and their interactions?



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:

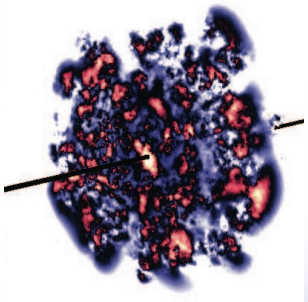
- $q\bar{q}$ pairs (sea quarks) generated at small(ish)-x are predicted to be unpolarized
- gluons generated from sea quarks are unpolarized

→ needed:

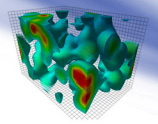
- ➢ high precision measurement of flavor separated polarized quark and gluon distributions as functions of x
- ➢ high precision spatial imaging: Gluon radius ~ sea-quark radius ?

What happens in the gluon dominated small-x regime?

- ➢ possible scenario: lumpy glue



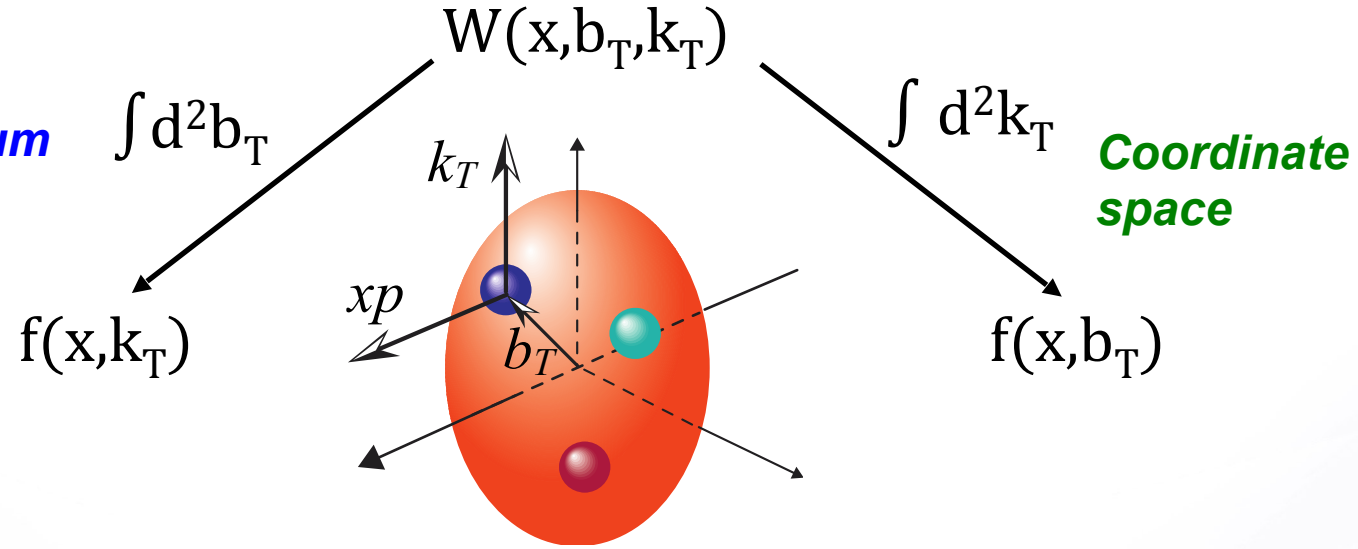
EIC will explore the dynamical spatial structure of hadrons



3-Dimensional Imaging Quarks and Gluons

Wigner functions $W(x,b_T,k_T)$

offer unprecedented insight into confinement and chiral symmetry breaking.

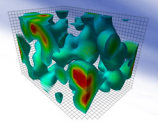


Spin-dependent 3D momentum space images from semi-inclusive scattering
→ **TMDs**

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

Position and momentum → Orbital motion of quarks and gluons

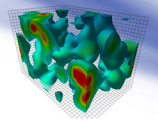
Recent theoretical work indicates possible direct access to gluon Wigner function through diffractive di-jet measurements at an EIC



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

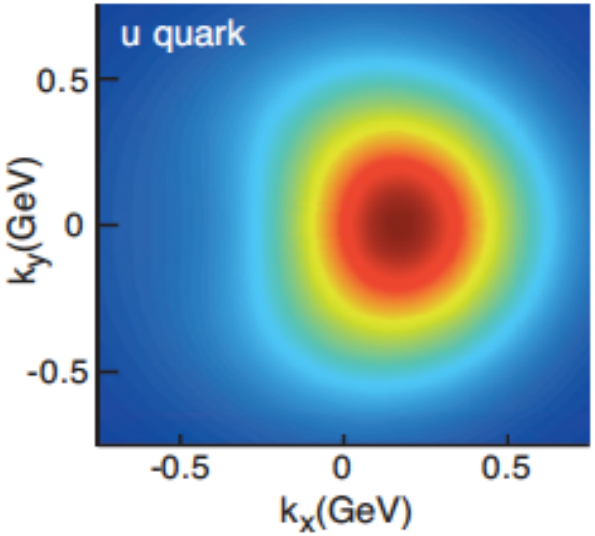


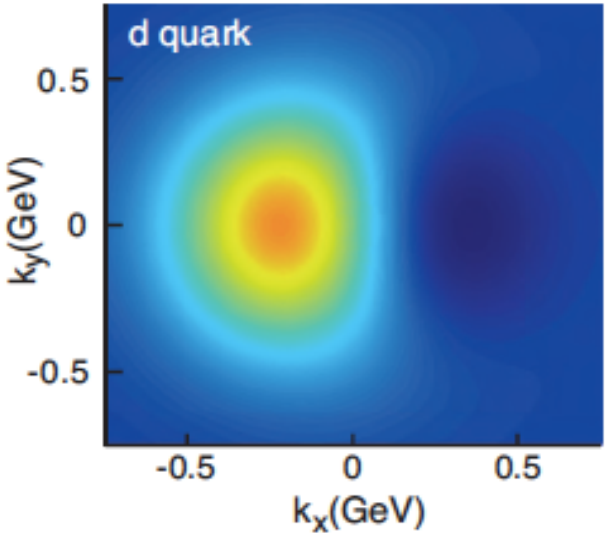
2+1 D partonic image of the proton with the EIC

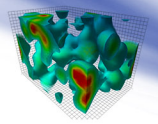
Spin-dependent 3D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions

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







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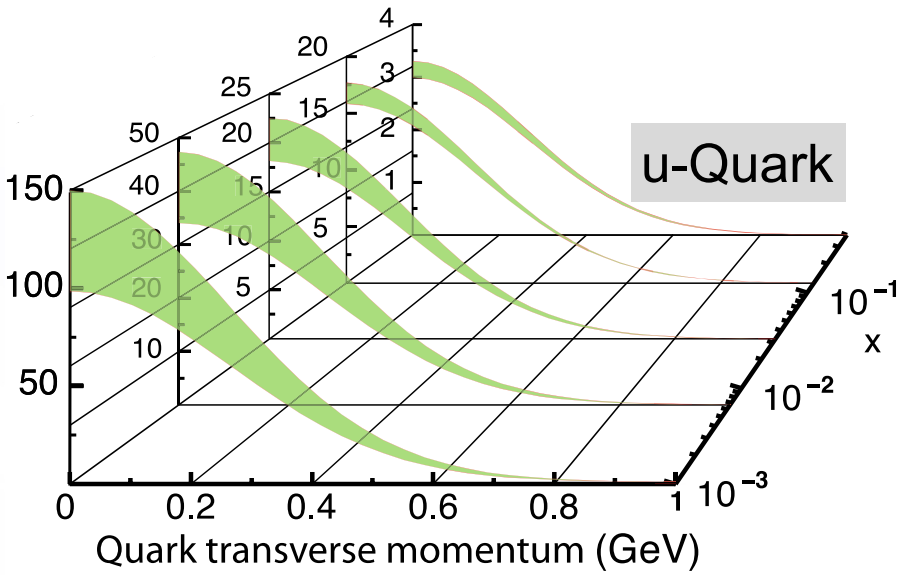
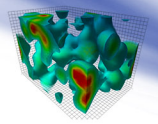
Spin-dependent 3D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions



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



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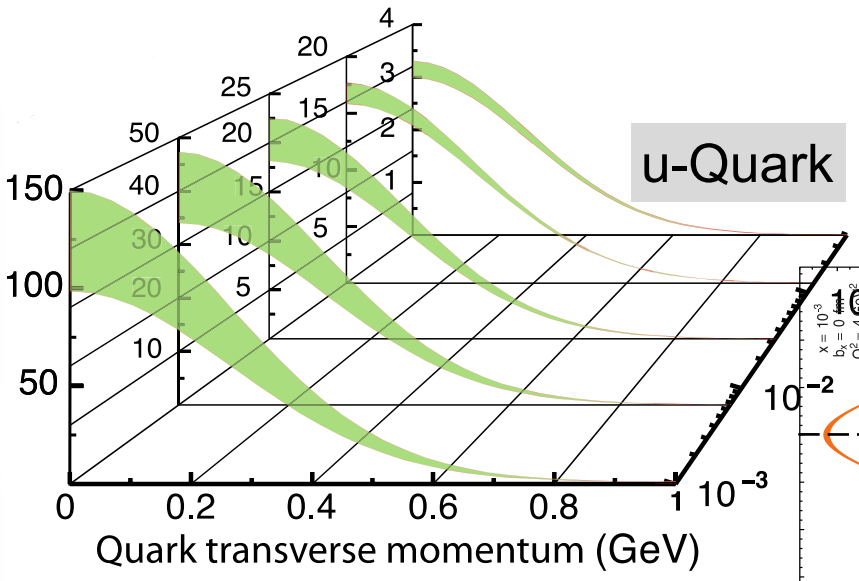
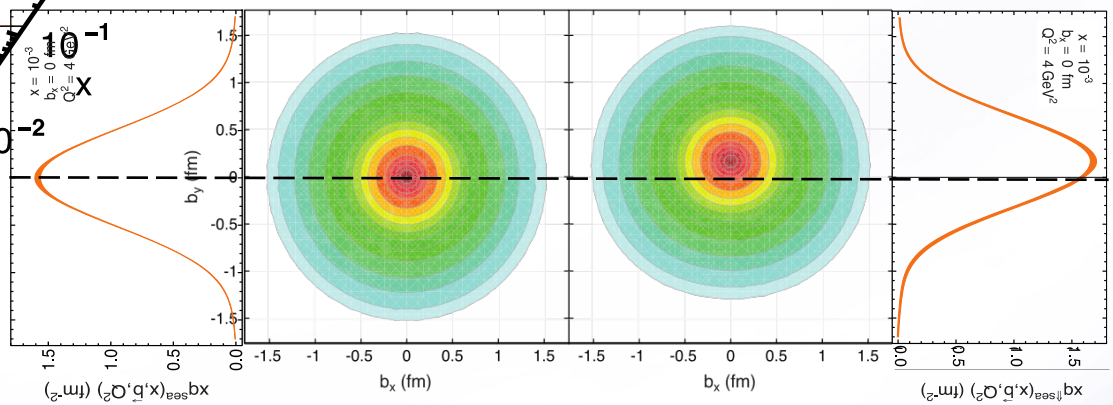


Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

sea-quarks

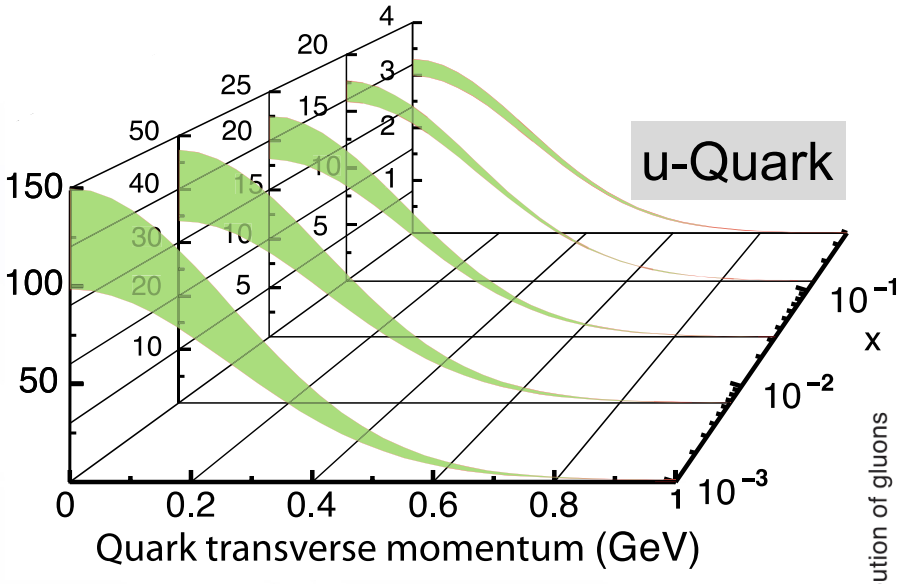
unpolarized polarized



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

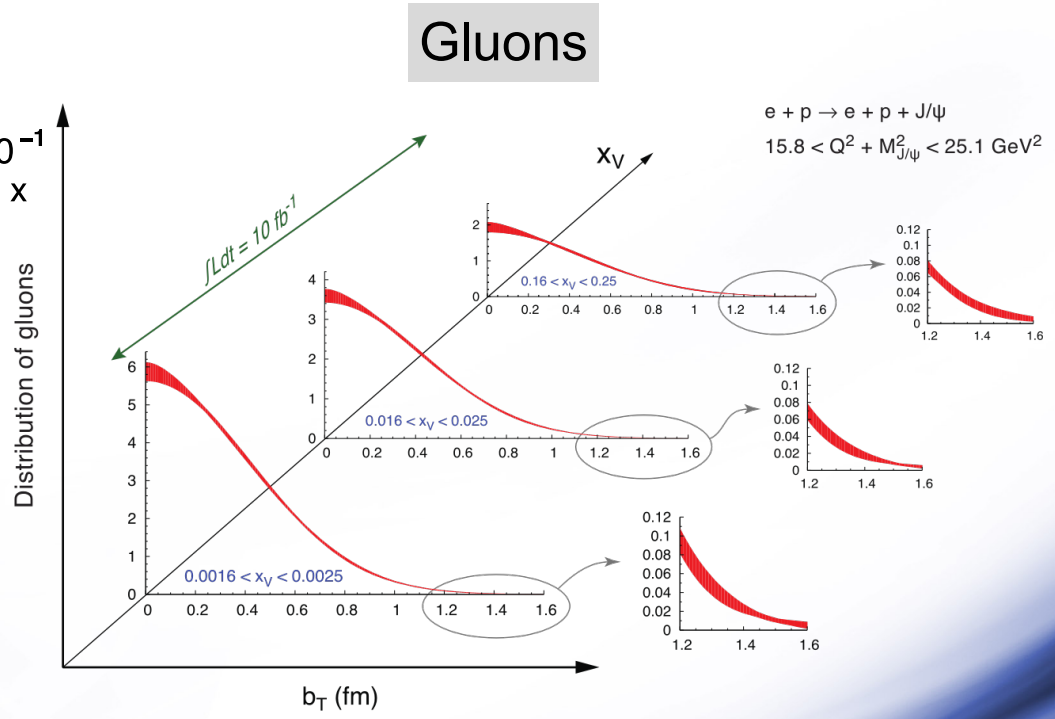
Spin-dependent 3D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions

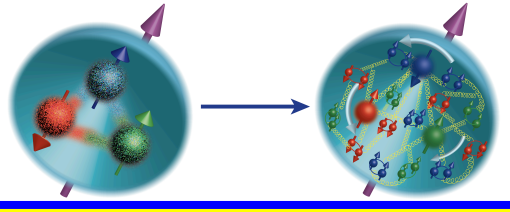


Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions



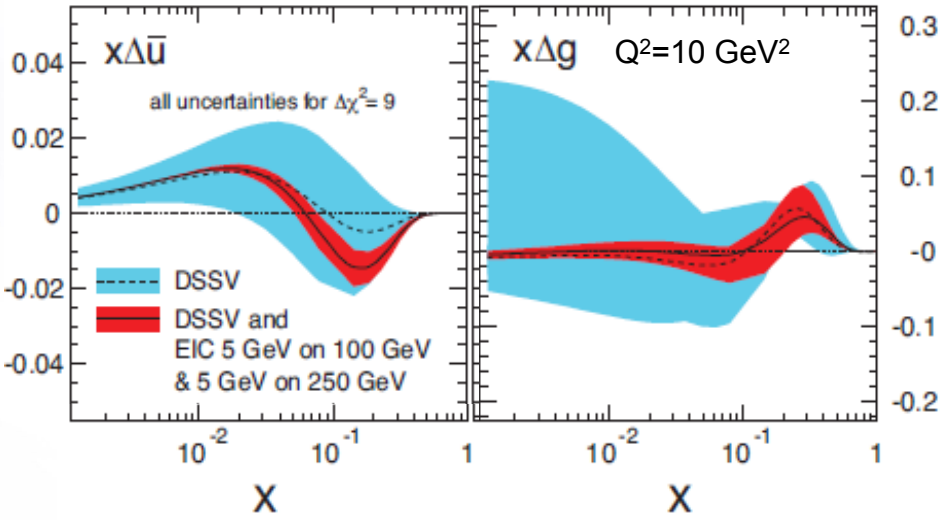
Understanding Nucleon Spin

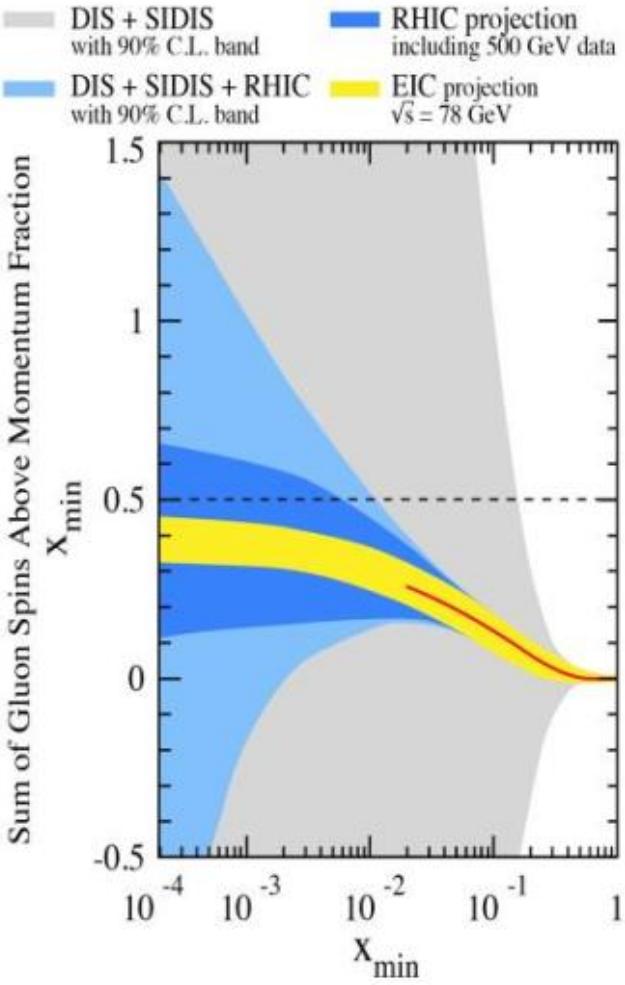


"Helicity sum rule"

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

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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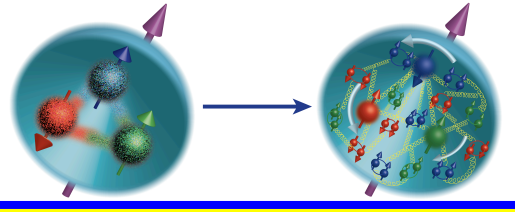

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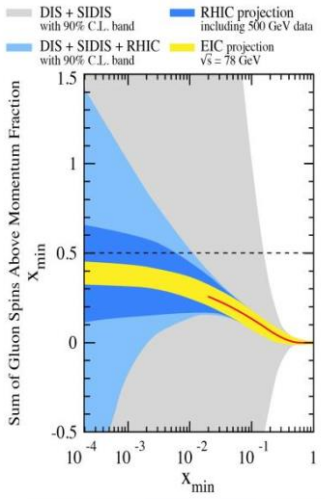
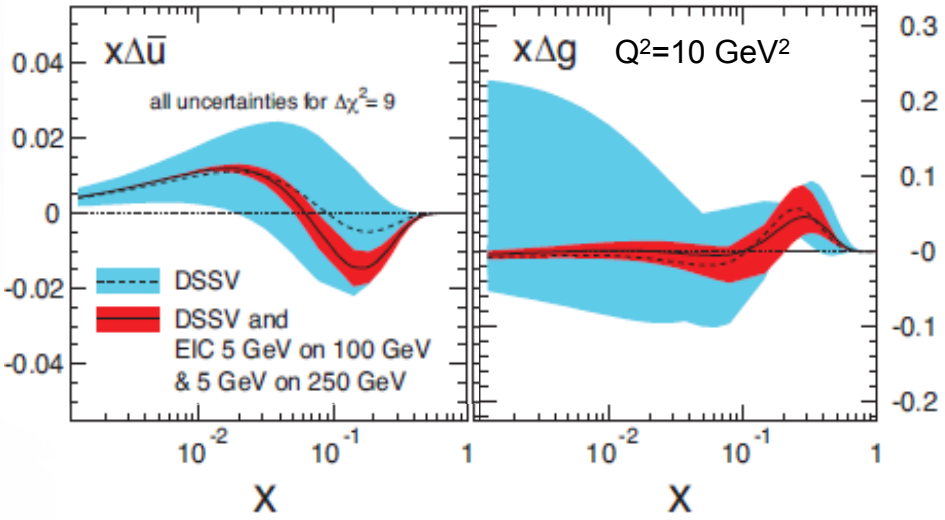
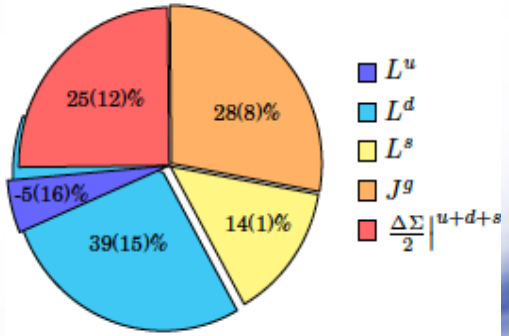


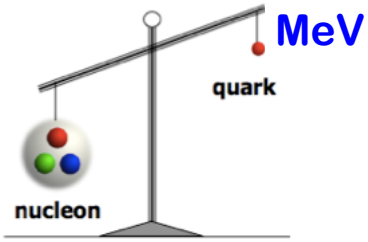


Spin and Lattice: Recent Activities

- **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:**
  [redacted]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

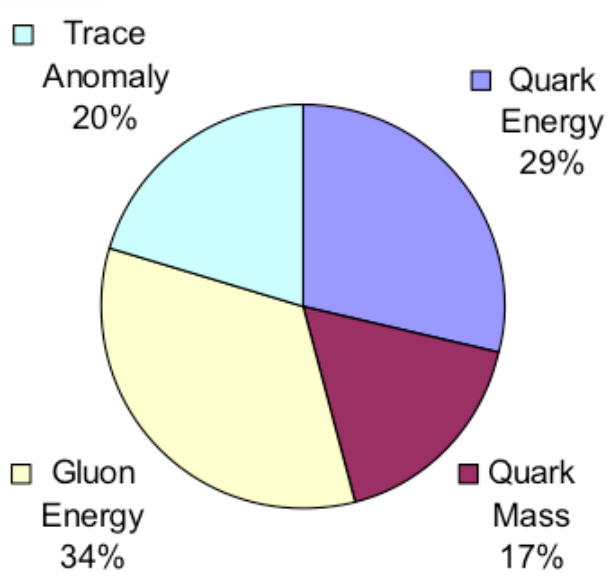
Quark Mass

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

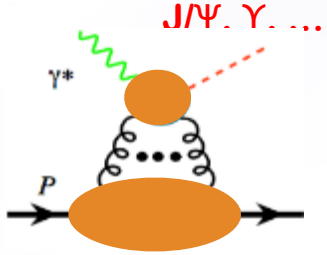
❑ Preliminary Lattice QCD results:



❑ EIC's expected contribution in:

◇ Trace anomaly:

Upsilon production near the threshold

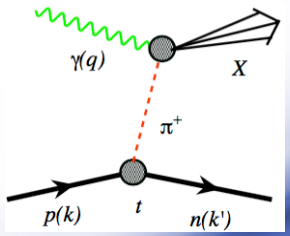


◇ Quark-gluon energy:

$\propto$ *quark-gluon momentum fractions*

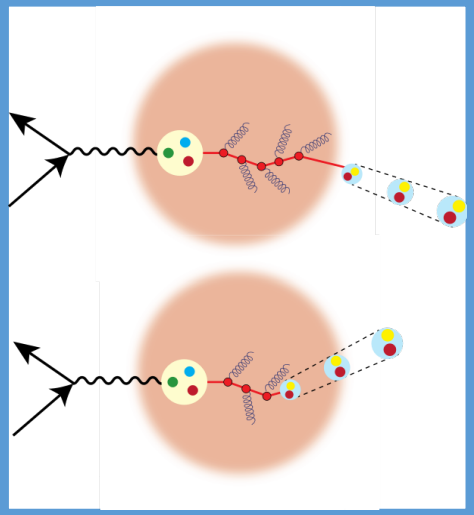
In nucleon with DIS and SIDIS

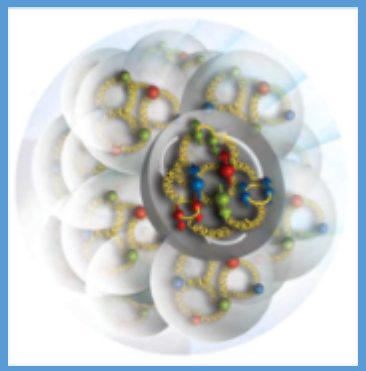
In pions and kaons with Sullivan process

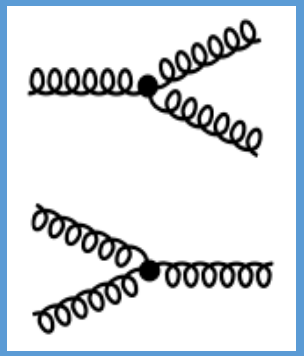


The world's first electron-nucleus collider

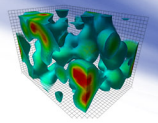
The Nucleus as a laboratory for QCD







- 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 does the quark-gluon interaction *create nuclear binding*?

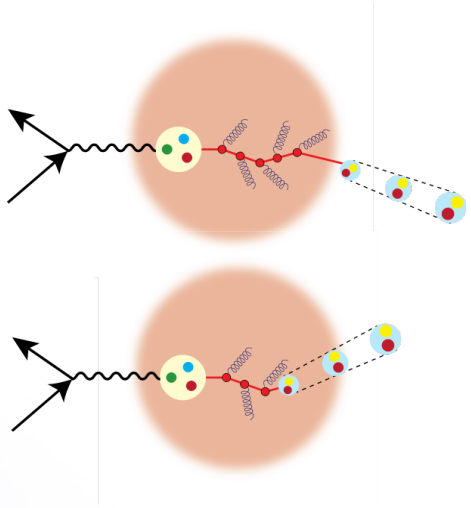


Emergence of Hadrons from Partons

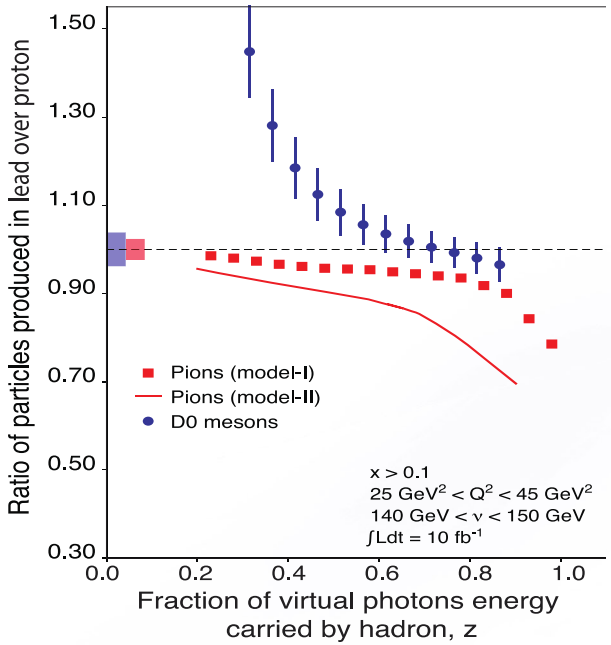
Nucleus as a Femtometer sized analyzer

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

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



Energy loss by light vs. heavy quarks:



Control of ν by selecting kinematics;

Also under control the nuclear size.

Colored quark emerges as color neutral hadron ➔ What is the impact of colored media on confinement?

Identify light vs. charm hadrons in e-A: Understand energy loss of light vs. heavy quarks in cold nuclear matter. *Provides insight into energy loss in the Quark-Gluon Plasma*

DIS at collider energies enables control of parton/event kinematics

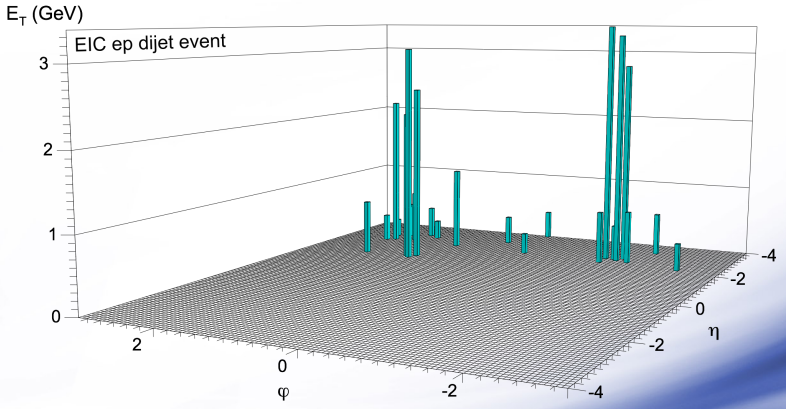
Jets: A Window to Partons

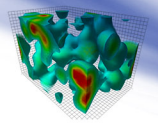
- Jet: transition process from a parton to hadrons and as such fundamentally encodes hadronization and dynamic confinement.
- Jets are golden tools to study quarks and gluons at RHIC and LHC
- Jets probe the interaction with the medium using the well understood jet shower evolution to extract the space-time dynamics of hadronization.

Jets in eA Collisions

- Jet showers, their correlations and attenuation shed light on hadronization and dynamical nature of confinement in extended colored media
- Determine the transport properties in cold QCD medium
- Gluon distribution from dijets

Many opportunities for jet physics in polarized ep



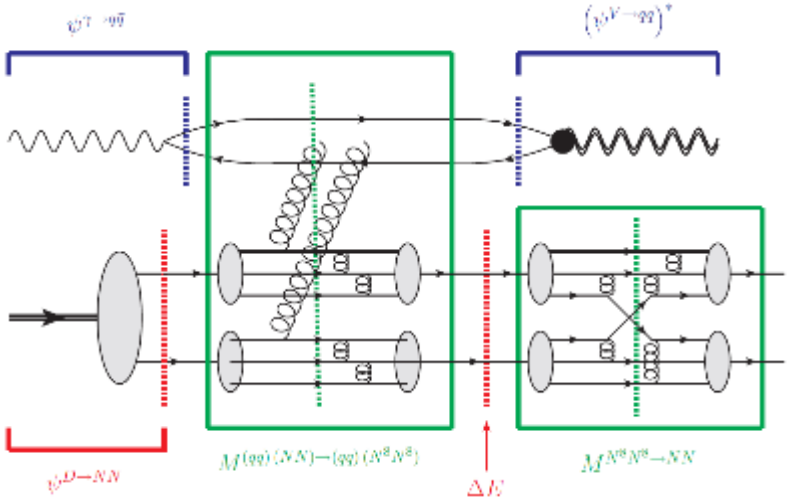


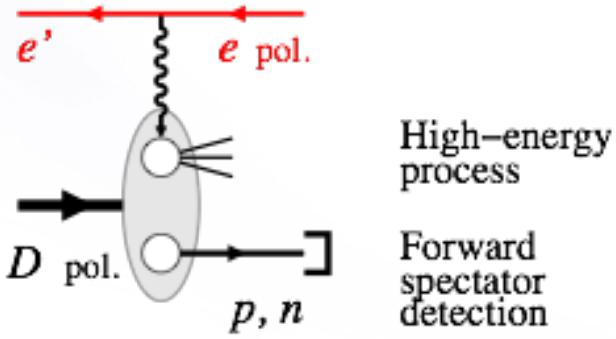
Short range correlations & physics with light nuclei

Exciting area of interest:

e + D → e' + p + n + J/Ψ

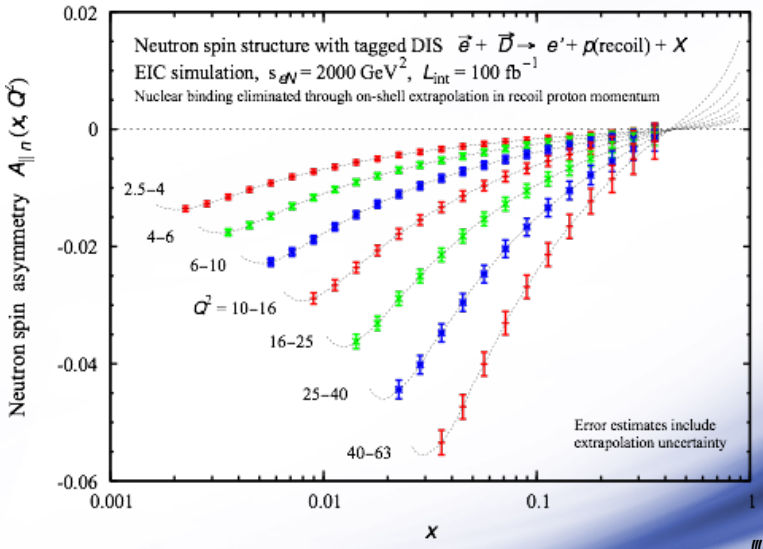
Exclusive measurements of tagged (polarized) protons and neutrons in coincidence with vector mesons probe the short-range quark-gluon nature of nuclear forces





Tag the recoil proton → Study the neutron's spin structure function.

Other possibilities: Polarized EMC effect with polarized light nuclei



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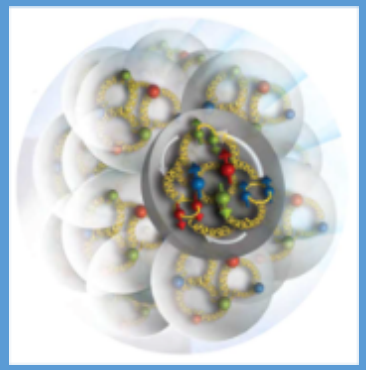
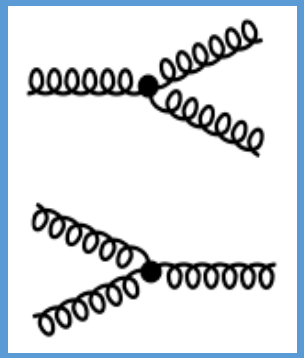
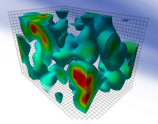
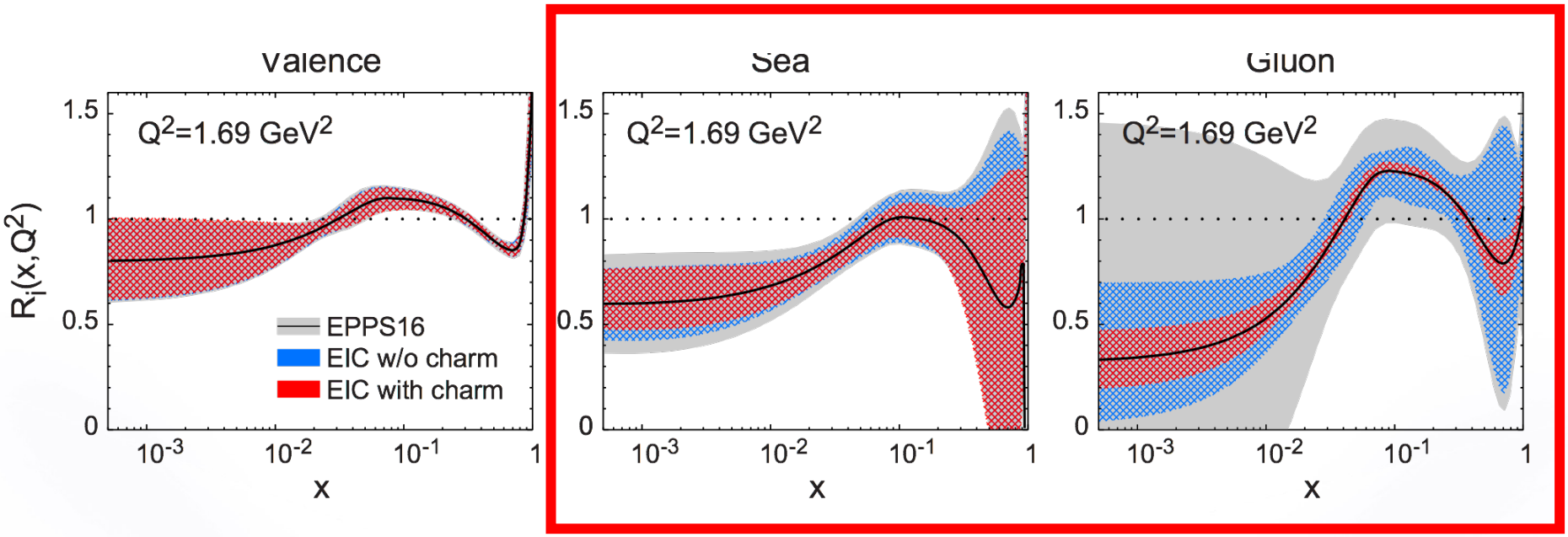




- How does a *dense nuclear environment* affect the quarks and gluons, their correlations, and their interactions?
- What happens to the *gluon density in nuclei*? Does it *saturate at high energy*, giving rise to a gluonic matter with *universal properties* in all nuclei, even the proton?

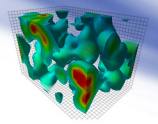


EIC: impact on the knowledge of 1D Nuclear PDFs

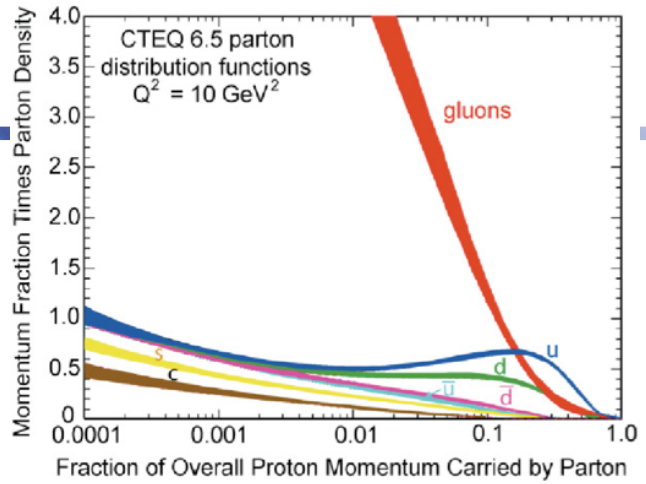


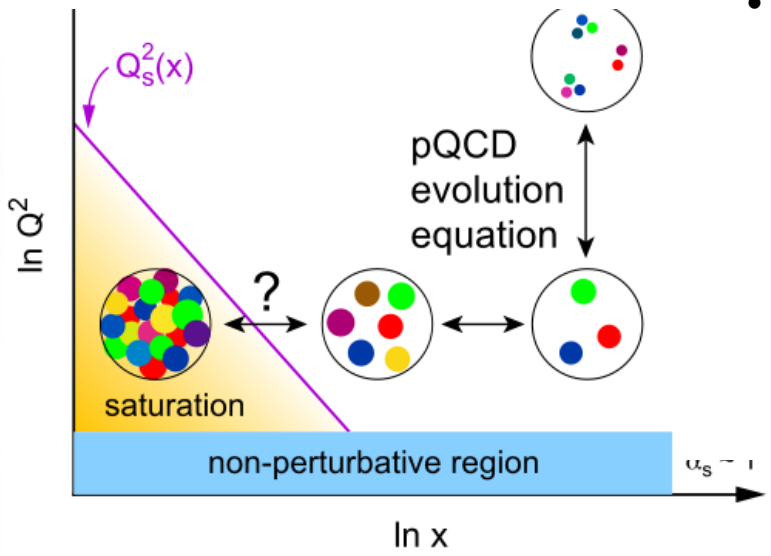
Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
  ➔With EIC significantly reduced uncertainties
- Complementary to RHIC and LHC pA data. Provides information on initial state for heavy ion collisions.
- Does the nucleus behave like a proton at low-x? ➔ such color correlations relevant to the understanding of astronomical objects



Gluon saturation at low-x





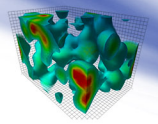
What tames the low-x rise?

- 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

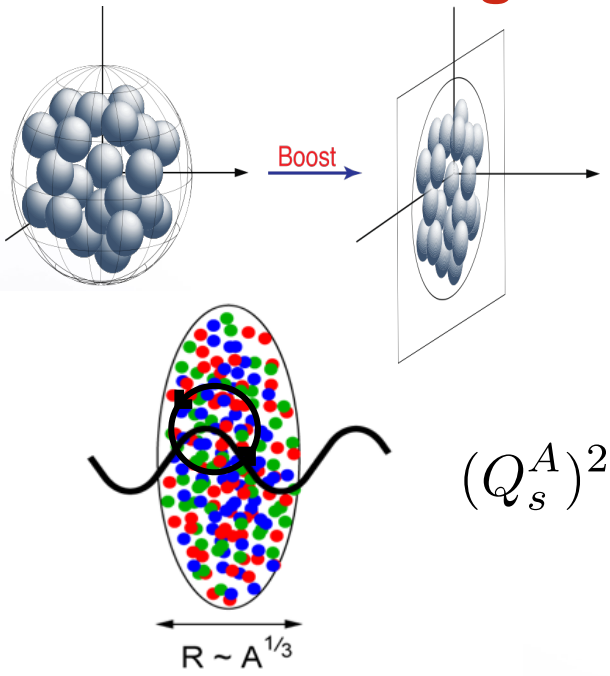
First observation of gluon recombination effects in nuclei:
→ leading to a collective gluonic system
First observation of gluon recombination in different nuclei
→ Is this a universal property?
What is the new effective theory in this regime?



How to explore/study this new phase of matter?

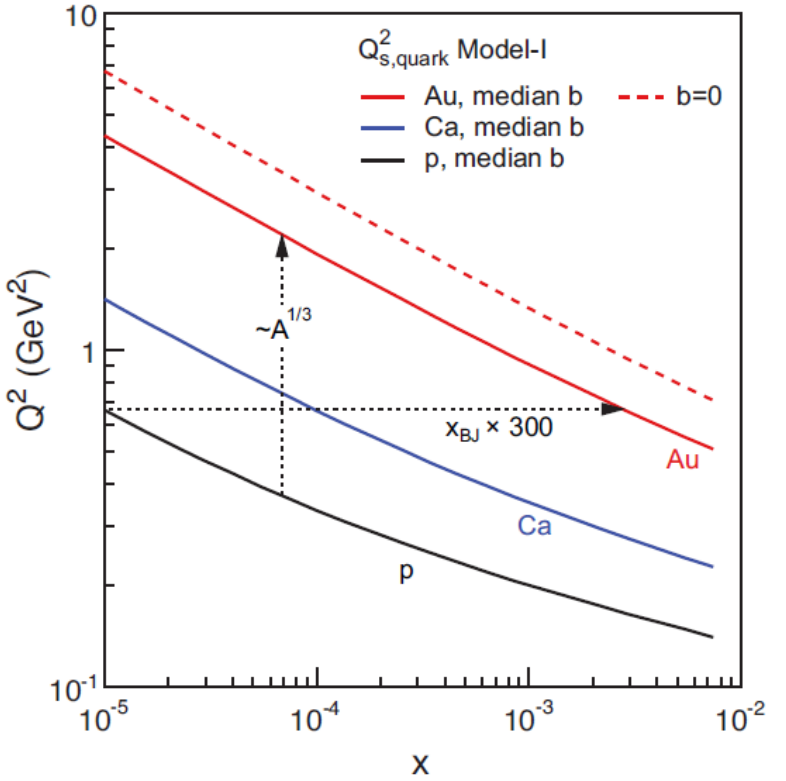
(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

Advantage of nucleus →



$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

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



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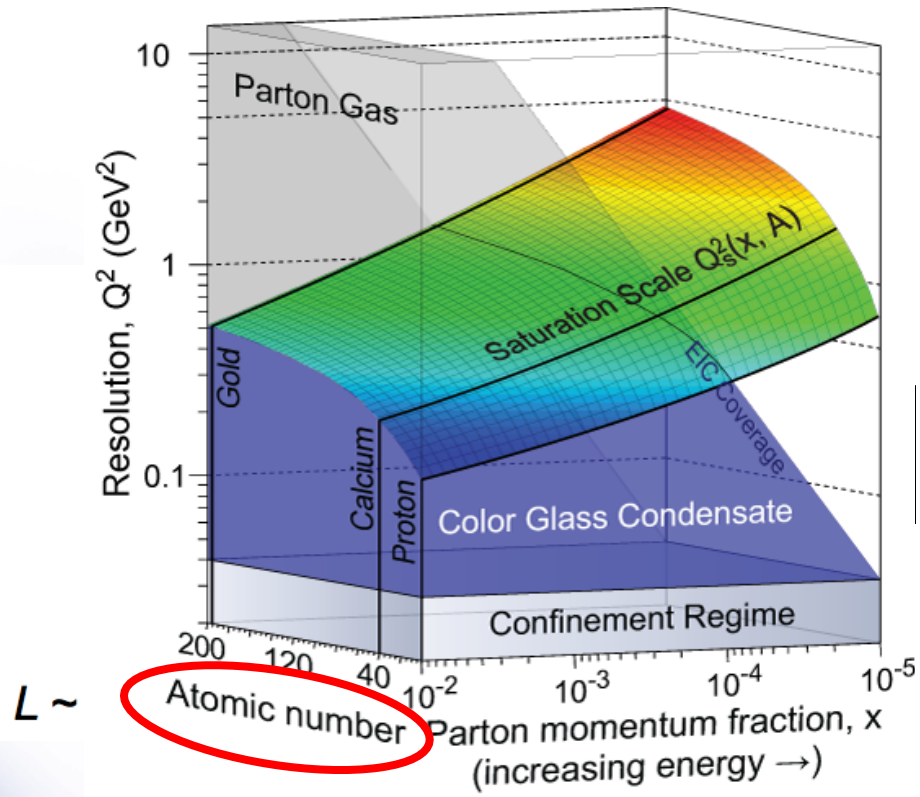
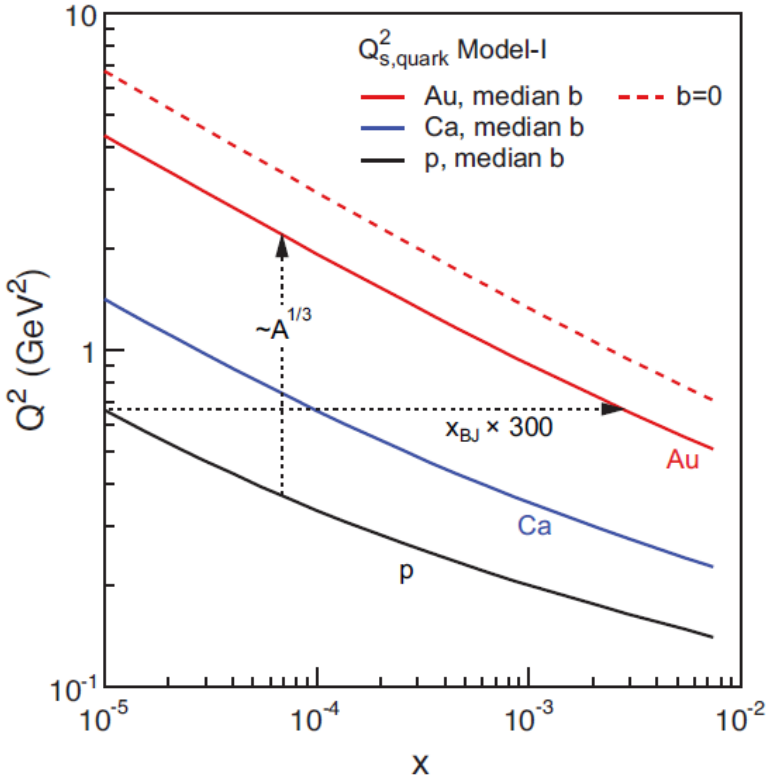




Enhancement of Q_S with A:

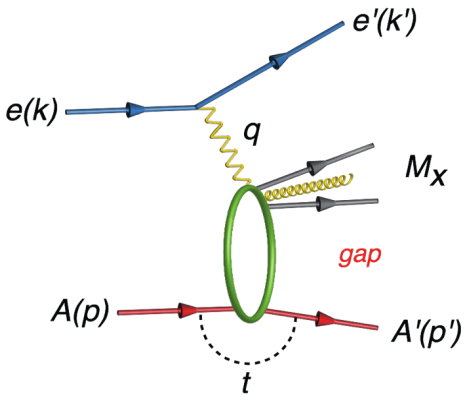
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

Diffraction for the 21st Century

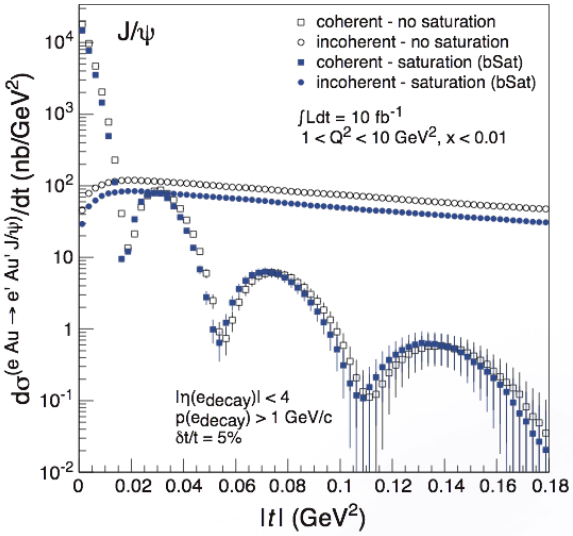
Diffraction cross-sections have strong discovery potential:

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

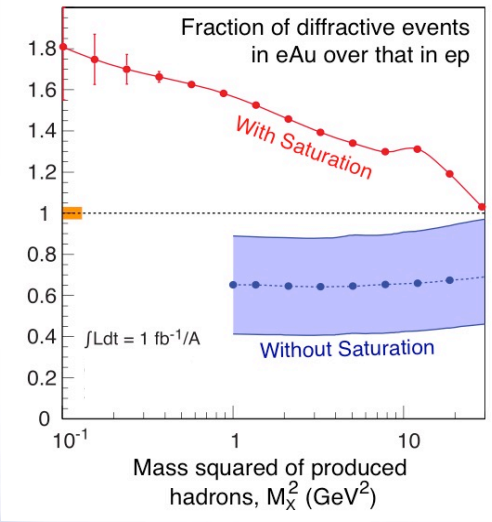
Dramatic changes in cross-sections with onset of non-linear strong color fields



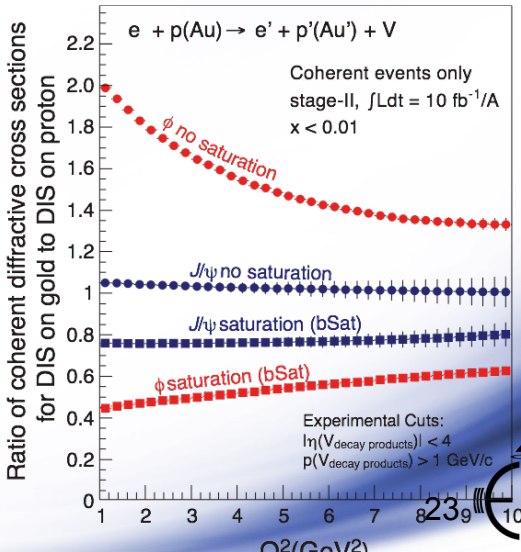
Extracting the gluon distribution $\rho(b_T)$ of nuclei via Fourier transformation of $d\sigma/dt$ in diffractive J/ψ production



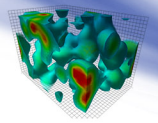
Probing gluon saturation through measuring $\sigma_{diff}/\sigma_{tot}$



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

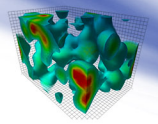


EIC Science and Connections



Connections to other areas of physics

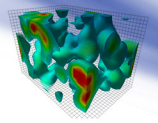
- Explorations of the stringy dynamics of hadrons led to the string theory of Gravity. A weakly coupled regime of 10-d gravity is conjectured to be dual to strongly coupled 4-d QCD-like theory. *Further profound connections may emerge from deeper investigations of the QCD landscape.*
- The dynamics *of strongly coupled cold atom gases and QCD (non-Abelian gauge fields but also strong nuclear fields) show strikingly common features*. Cold atom scientists are actively engaged in engineering cold atoms simulators of gauge field mechanism.
- Strong connections have emerged between studies of strongly correlated condensed matter systems and QCD: *topological effects arising from chiral anomaly*
- Strong field QED explores the breakdown of the QED vacuum and its nonlinear optical response in e^+e^- pair creation. *Reaching this regime is a major goal in developing high powered lasers.*



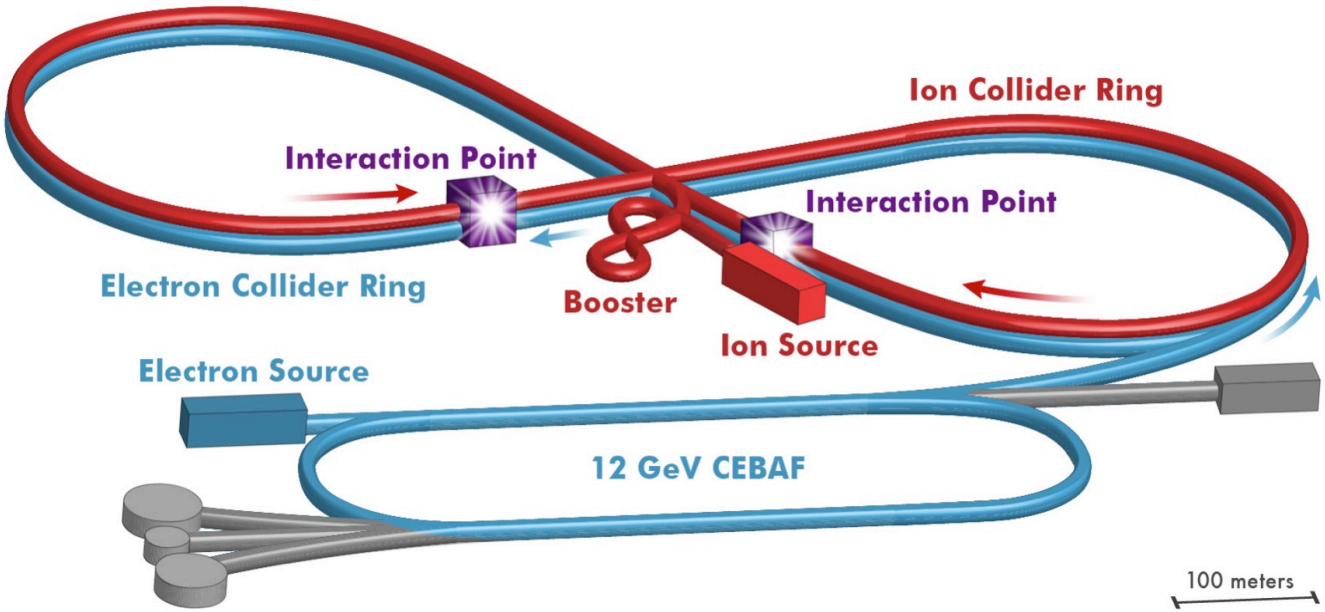
Collider Realization & US leadership in Accelerator Science

Collider requirements: High luminosity & energy, variable CM energy, all- A nuclear beams, polarization in e- and light ions of the EIC poses unique & attractive challenges to the accelerator physicists

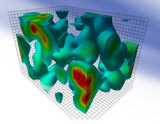
➔ *EIC demands frontier ideas and technologies in accelerator physics*



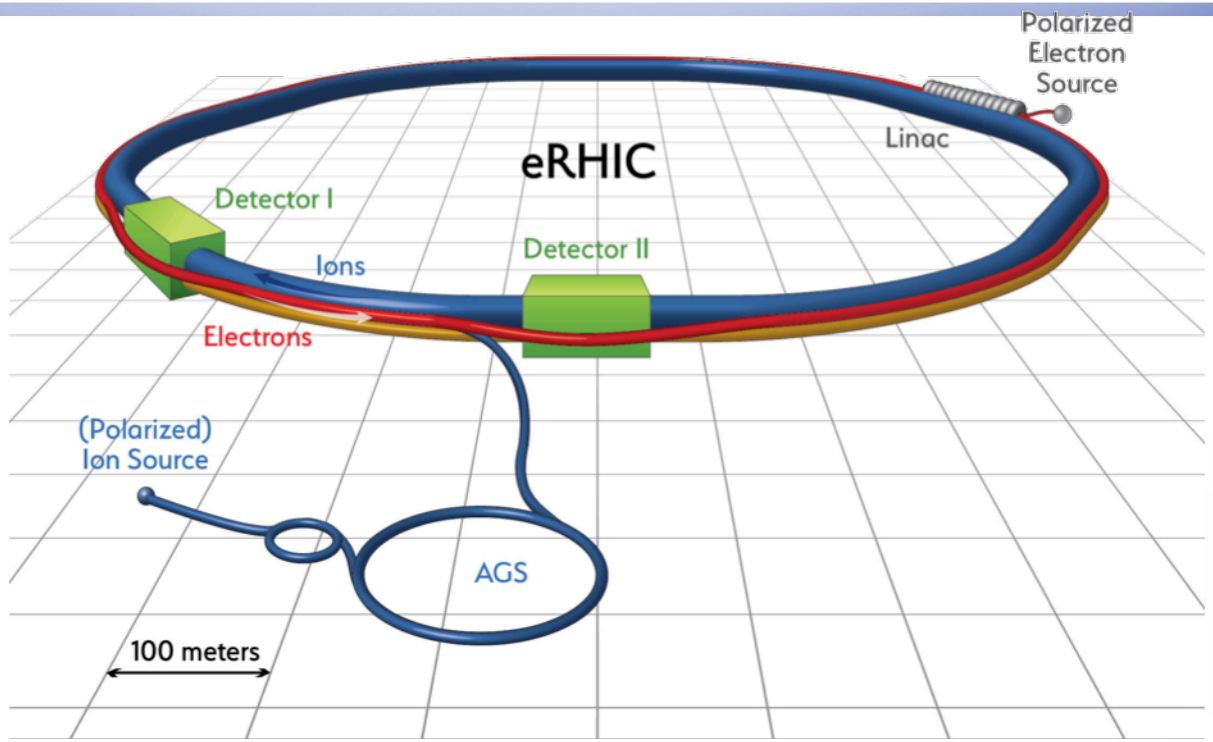
JLEIC Realization



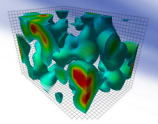
- Use existing CEBAF for polarized electron injector
- Figure 8 Layout: Optimized for high ion beam polarization ➔ polarized deuterons
- Energy Range: √s : 20 to 65 - 140 GeV (magnet technology choice)
- Fully integrated detector/IR
- JLEIC achieves initial high luminosity, with technology choice determining initial and upgraded energy reach



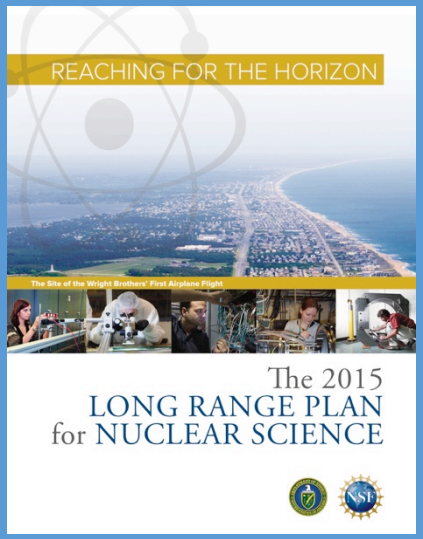
eRHIC Realization



- Use existing RHIC
  - Up to 275 GeV protons
  - Existing: tunnel, detector halls & hadron injector complex
- Add 18 GeV electron accelerator in the same tunnel
  - Use either high intensity Electron Storage Ring or Energy Recovery Linac
- Achieve high luminosity, high energy e-p/A collisions with full acceptance detector
- Luminosity and/or energy staging possible



EIC Users Group



"….This facility can lead to the convergence of the present world-leading QCD programs at CEBAF and RHIC in a single facility….."

EIC Users Group

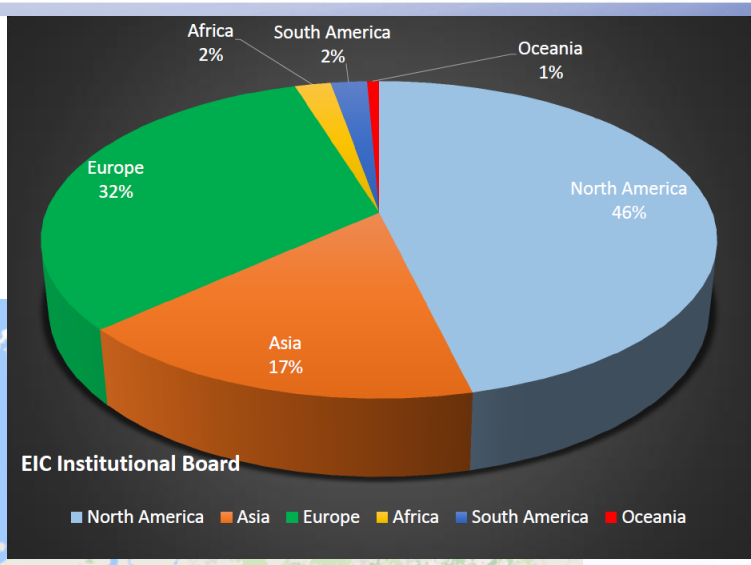
- Established, enthusiastic and active
- New physics ideas initiated with new influx of people….

The EIC Users Group: EICUG.ORG

(no students included as of yet)

685 collaborators, 28 countries, 151 institutions... (April, 2017)

Map of institution's locations



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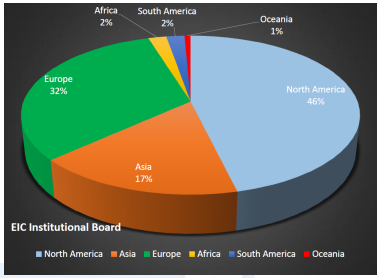


The EIC Users Meeting at Stony Brook, June 2014:

→ *http://skipper.physics.sunysb.edu/~eicug/meeting1/SBU.html*

The EIC UG Meeting at University of Berkeley, January 6-9, 2016

http://skipper.physics.sunysb.edu/~eicug/meeting2/UCB2016.html

Recent EICUG Argonne National Laboratory July 7-10, 2016

http://eic2016.phy.anl.gov

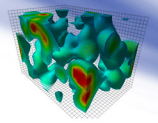
Remote/Internet: meeting: March 16th : For NAS Review preparation

Next meeting:

July 18-22, 2017 Trieste, Italy

New Users → New Physics → Lots of activities

- Jet studies at the EIC:
  - Systematic investigations of general issues in jet-finding at an EIC
  - Understanding of “micro-jets” – jets with only few hadrons
  - Understanding the jet structure modifications in nuclei vs. protons
  - Energy loss in cold QCD matter (Nuclei) vs. hot QCD matter at RHIC and LHC
- Precision measurements of the “initial state” for collisions leading to the QGP being studied at RHIC and LHC
- Precision PDF measurements in proton, neutron & photons at the EIC:
  - Study the free neutron PDFs through tagging and on-shell extrapolation
  - Study the gluon PDFs at large Bjorken x through evolution and open-charm production
  - Study of gluons TMDs
  - Study the potential impact on Higgs studies in the High-Luminosity LHC era
  - Study the impact of TMDs @ EIC on W-production at the LHC
  - Polarized and unpolarized photon PDFs
- Measurements of PDFs in pions and kaons through the Sullivan process
  - Theoretical studies of the equivalence of near-off-shell and on-shell pions and kaons
  - Study the extraction of, and expected differences of, quark and gluon PDFs in pions, kaons and nucleons, and the relation to their physical masses
- Nucleon structure with electroweak probes, and precision BSM physics (i.e. $Sin^2\Theta_W$)
- Heavy quark & quarkonia production with 100-1000 times HERA luminosity
- In view of new discoveries of multi-quark XYZ states: what could EIC contribute?



New Users → New Physics → Lots of activities

- M
- ...elation to their physica...
- ...onia production with ...
- In view of new discoveries of multi-quark ...

Highly Active EIC Community has evolved

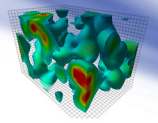
Summary

- The EIC will profoundly impact our understanding of QCD and its dyamics
  ➔ the **structure of nucleons and nuclei in terms of sea quarks & gluons**
- The EIC will enable **imaging** and provide **unprecedented kinematic reach** into **yet unexplored regions of phase spaces in QCD** with its high luminosity/energy, nuclei & beam polarization

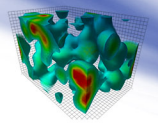
⇒***High potential for discovery within QCD with broad impact beyond***

- **O**utstanding questions raised by the science at RHIC/LHC and CEBAF, have **naturally led to the EIC Science & design parameters**
- **World wide interest** in collaborating on the EIC
- Accelerator scientists at BNLand JLab together with international accelerator community is ready to provide the **intellectual and technical leadership for to realize the EIC**, a frontier accelerator facility.

Future of nuclear science demands an Electron Ion Collider.
The U.S. must lead the way.



Thank you!



QCD: The Holy Grail of Quantum Field Theories

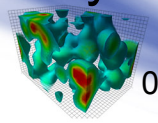
- QCD : "nearly perfect" theory that explains nature's strong interactions, is a fundamental quantum theory of quarks and gluon fields
- QCD is rich with symmetries

$$SU(3)_C \times \boxed{SU(3)_L \times SU(3)_R} \times \boxed{U(1)_A \times U(1)_B}$$

(1) (2) (3)

(1) Gauge "color" symmetry : unbroken but confined
(2) Global "chiral" flavor symmetry: exact for massless quarks
(3) Baryon number and axial charge (massless quarks) conservation
(4) Scale invariance for massless quarks and gluon fields
(5) Discrete C, P & T symmetries

- Chiral, Axial, Scale & P&T symmetries broken by quantum effects: Most of the visible matter in the Universe emerges as a result
- Inherent in QCD are the deepest aspects of relativistic quantum field theories: (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry) ➔ all depend on non-linear dynamics in QCD



The Electron Ion Collider

For e-N collisions at the EIC:

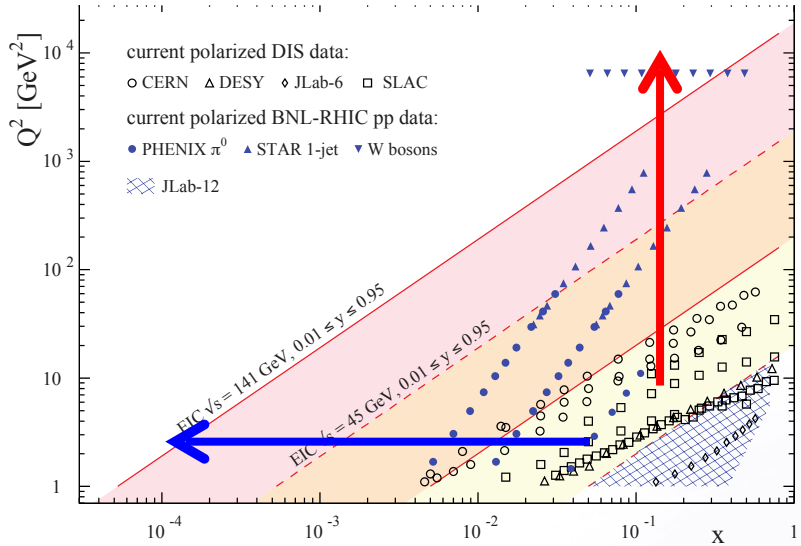
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

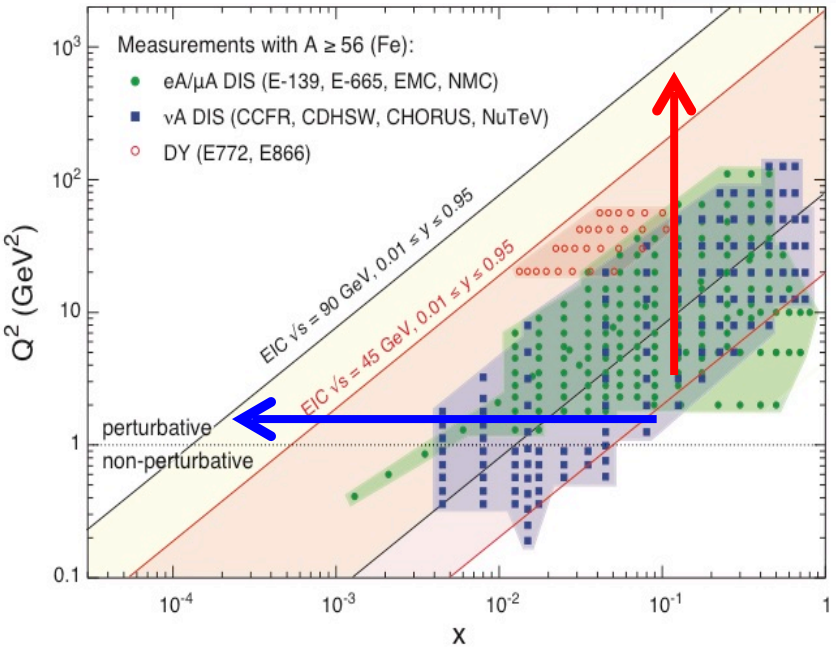
For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

EIC White Paper: 1212.1701.v3
A. Accardi et al Eur. Phy. J. A, 52 9(2016)



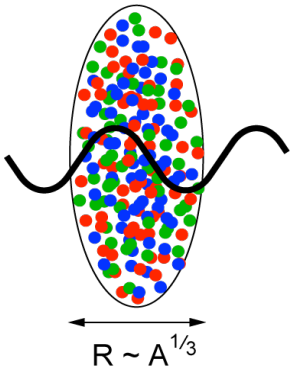


Gluon Saturation in Nuclei: The Oomph

Probes interact over distances
$L \sim (2m_N x)^{-1}$

Probe interacts coherently with

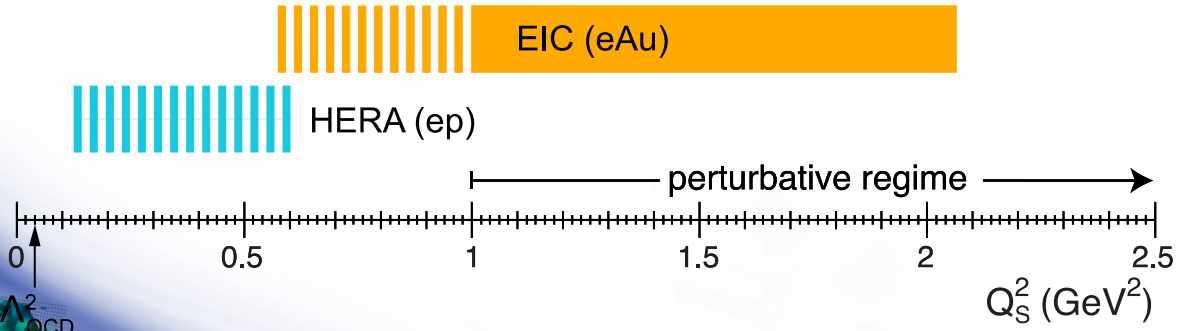
all nucleons for
$L > 2\,R_A \sim A^{1/3}$



$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A: saturation regime reached at significantly lower energy in nuclei (and lower cost)

x ≤ 0.01



Nucleus serves as **amplifier** of the saturation scale