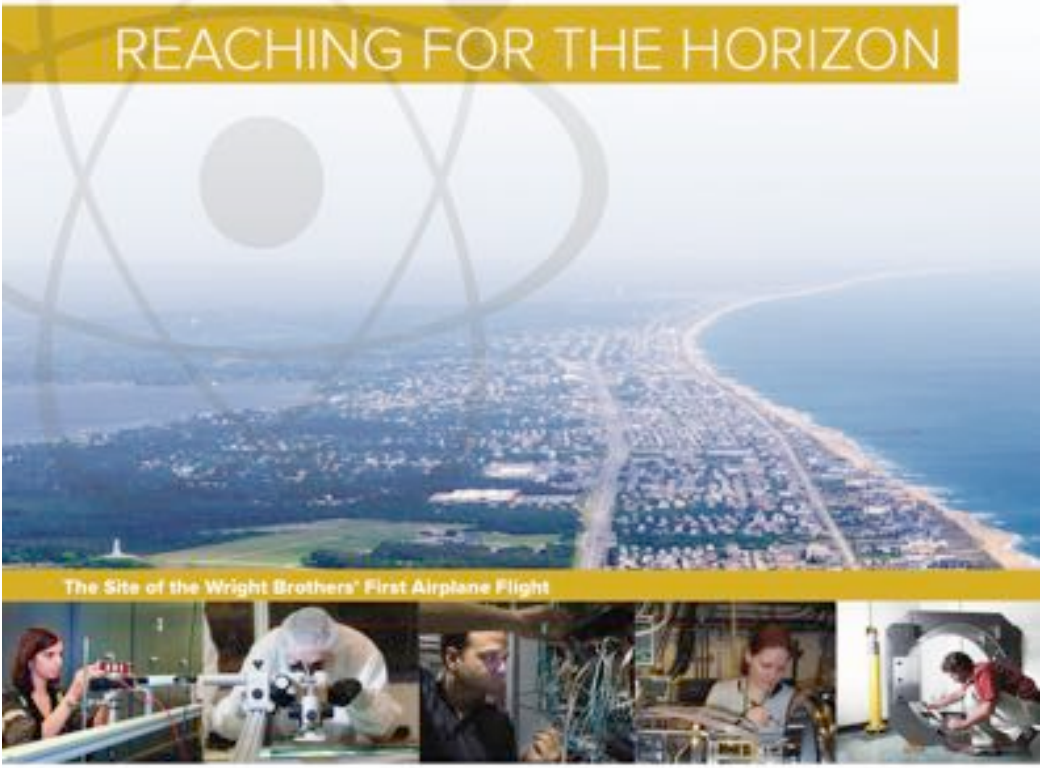


The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

http://science.energy.gov/np/reports

RECOMMENDATION:

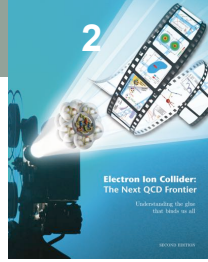
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:

Theory
Detector & Accelerator R&D

Detector R&D money ~1.3M/yr since 2011; significant increase anticipated soon.

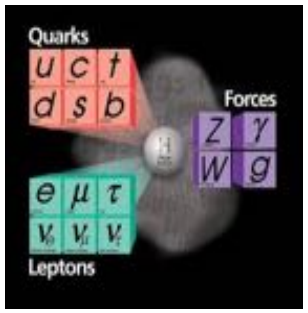
Anticipated Now:
NEW Money for EIC Accelerator R&D already assigned $7m/yr

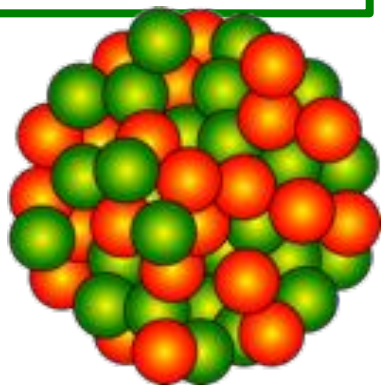


Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

Why the EIC? ➔ "Gluon Imaging"
To understand the role of gluons in binding quarks & gluons into Nucleons and Nuclei





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:

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

(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

Non-linear Structure of QCD: Fundamental Consequences

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

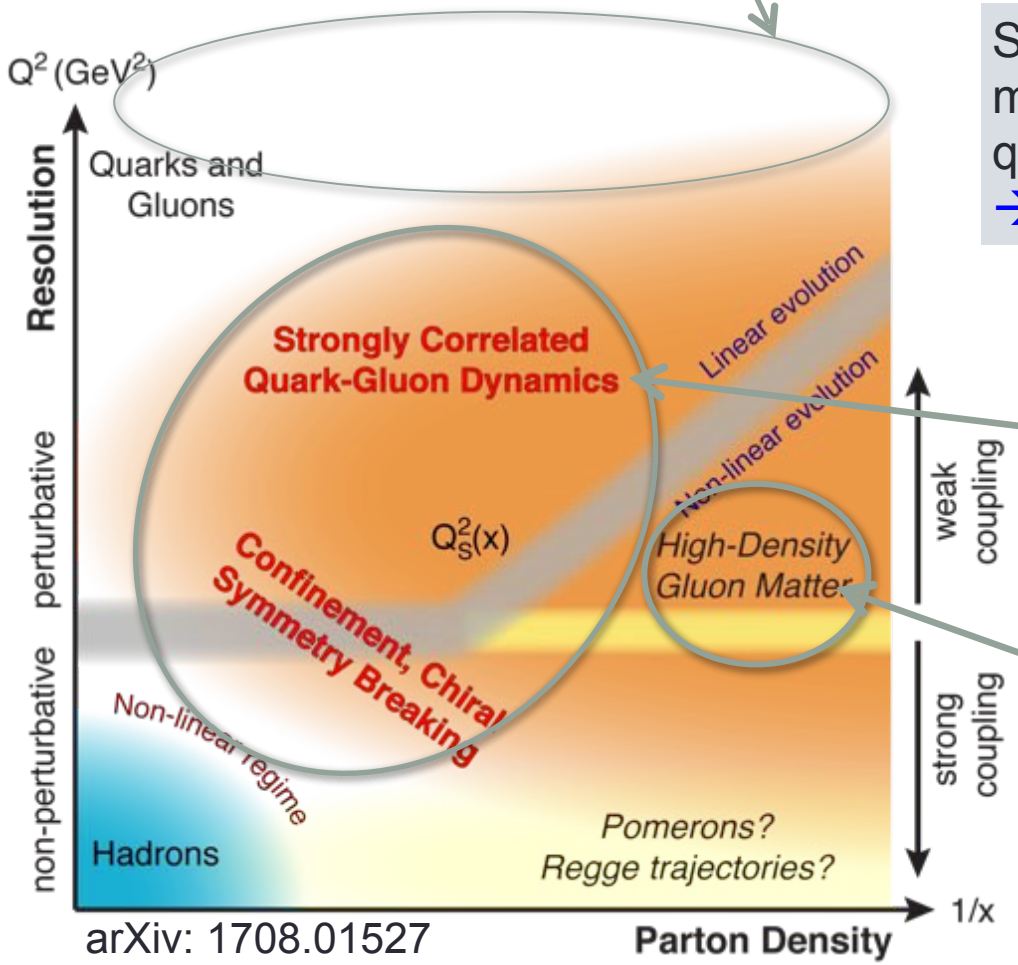
- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions – Generalized Parton Distributions (GPDs)

- 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?

All expected to be under the "femtoscope" called the EIC

QCD Landscape to be 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 will systematically explore correlations in this region.

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

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

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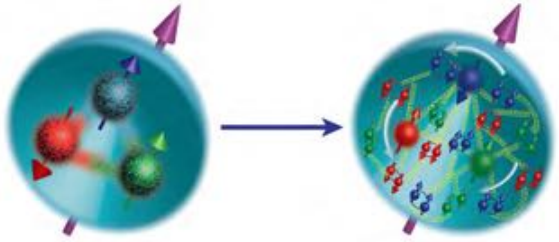
- The nucleon-nucleon forces emerge from quark-gluon interactions: how this happens remains a mystery

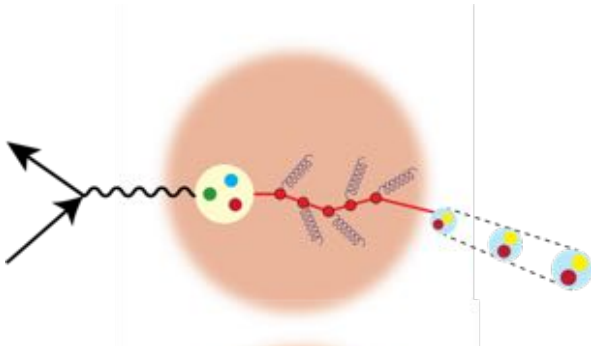
Experimental insight and guidance crucial for complete understanding of *how* hadrons & nuclei emerge from quarks and gluons

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?





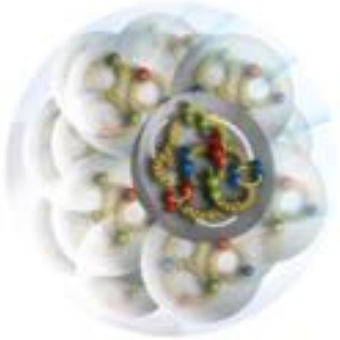
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

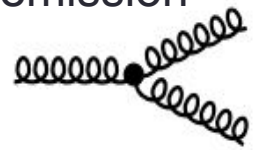
How do the quark-gluon interactions create nuclear binding?

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?



gluon emission

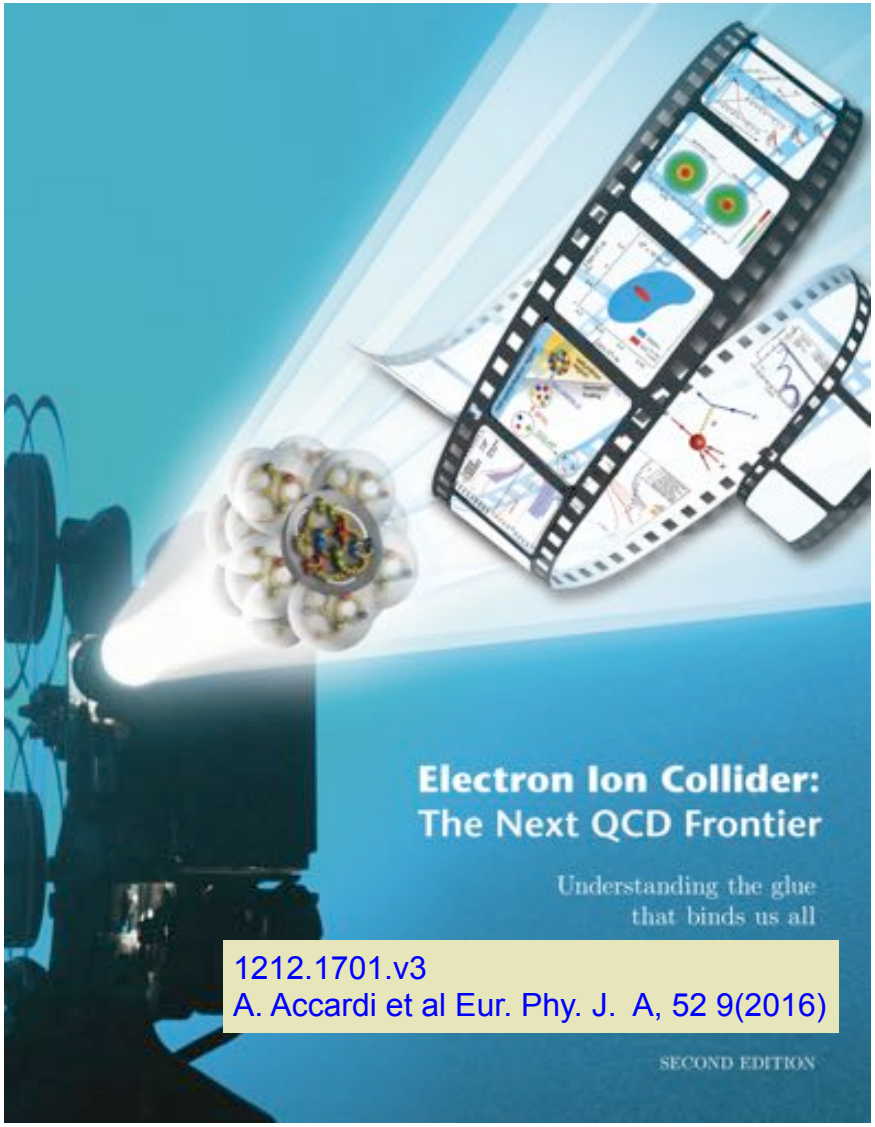


?=

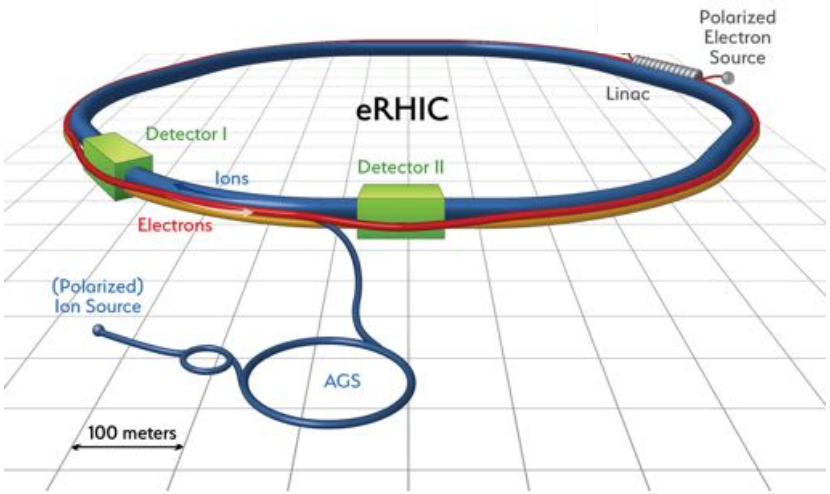
gluon recombination

The Electron Ion Collider

Two options of realization!

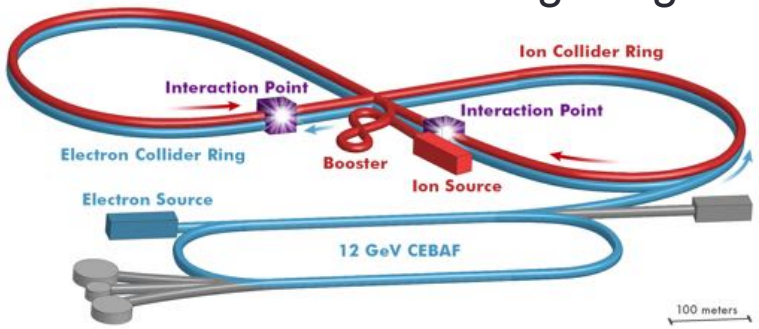


1212.1701.v3
A. Accardi et al Eur. Phy. J. A, 52 9(2016)



Not to scale

Ring-Ring



The Electron Ion Collider

Two options of realization!

For e-N collisions at the EIC:

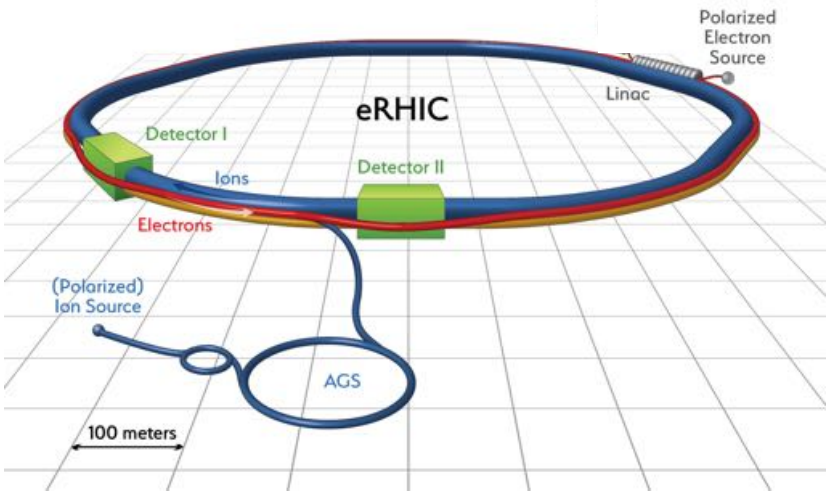
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

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

Both designs use DOE's significant investments in infrastructure



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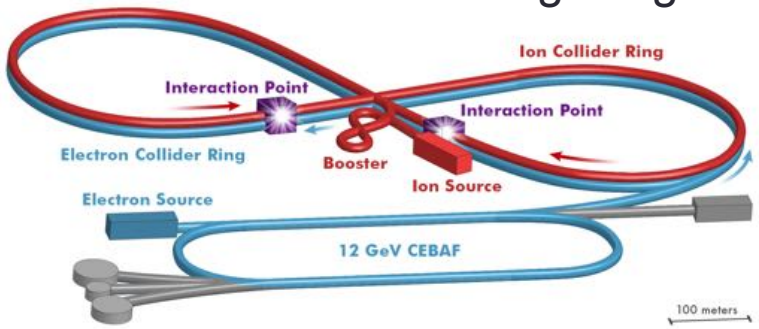
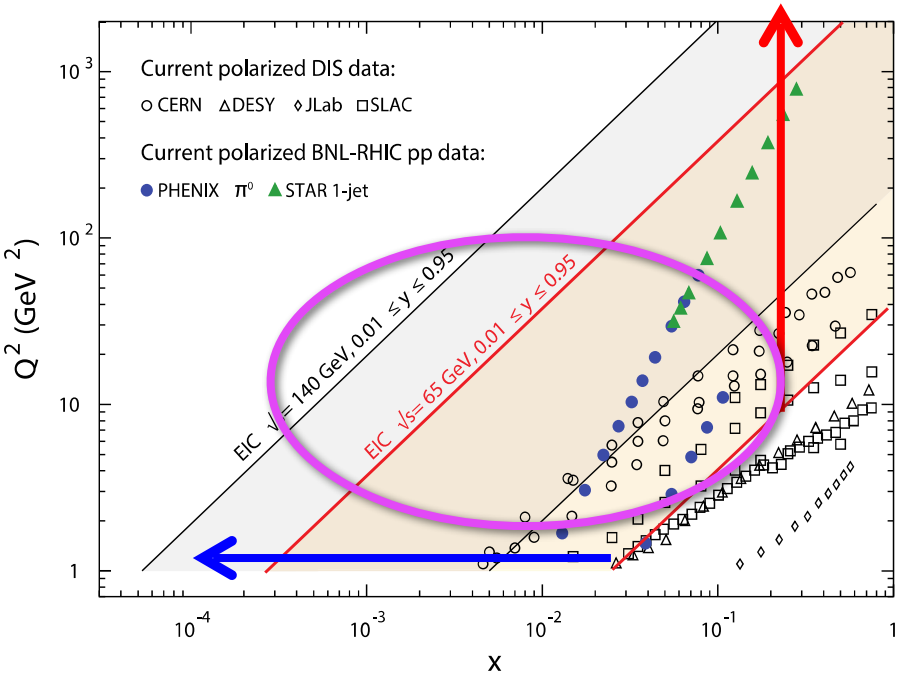
Ring-Ring



EIC: Kinematic reach & properties

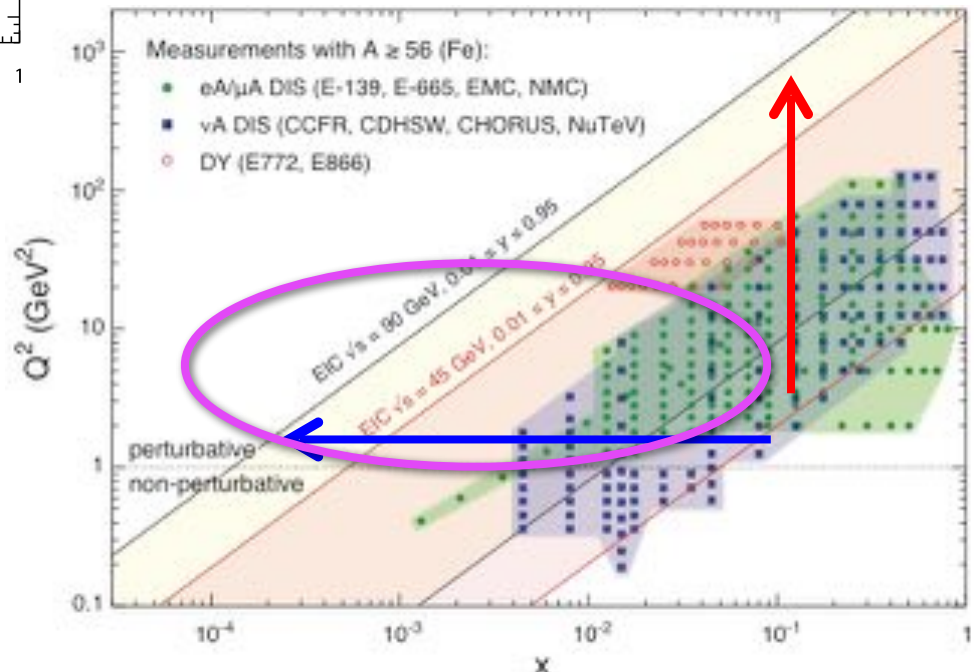


For e-N collisions at the EIC:

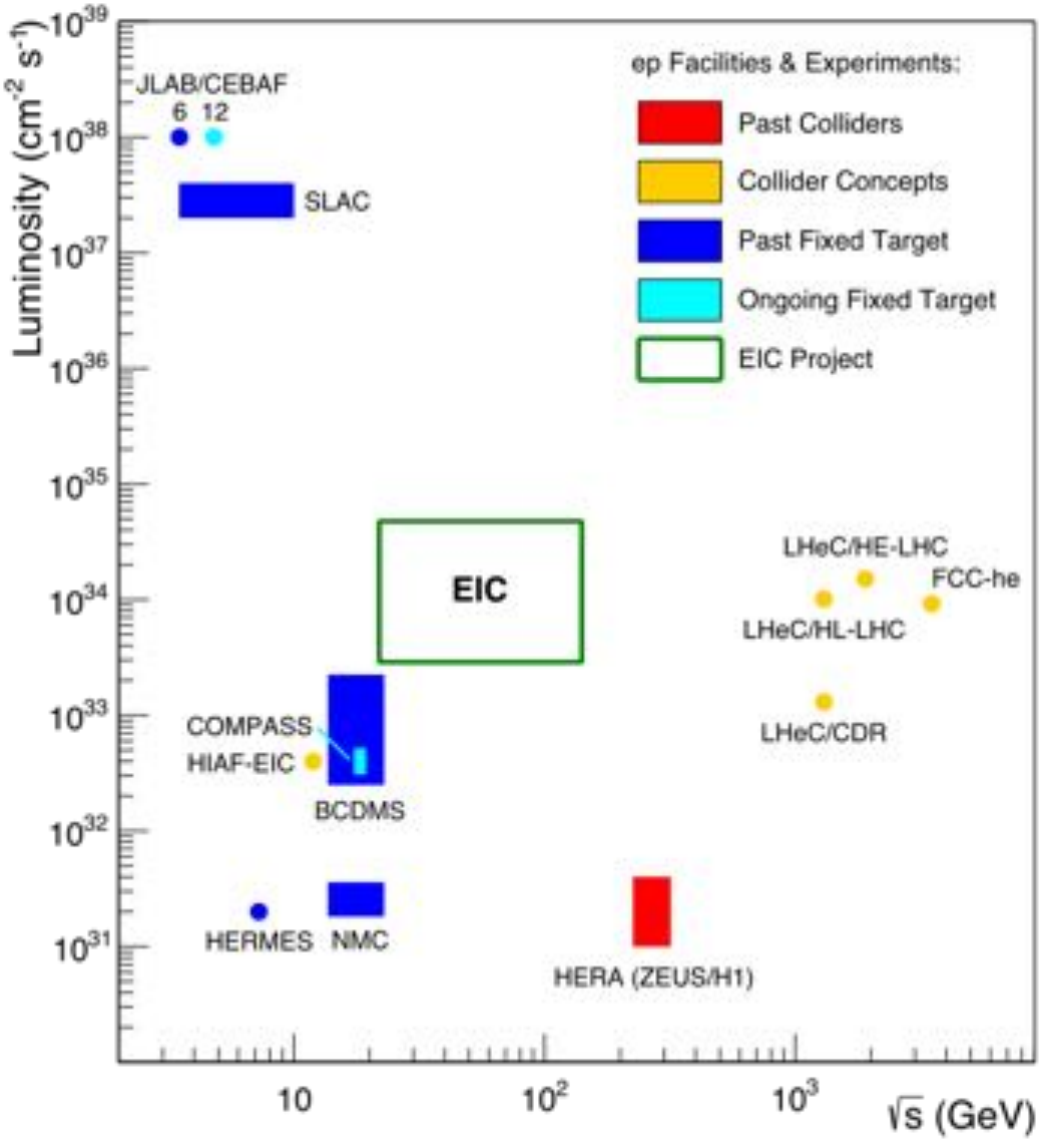
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



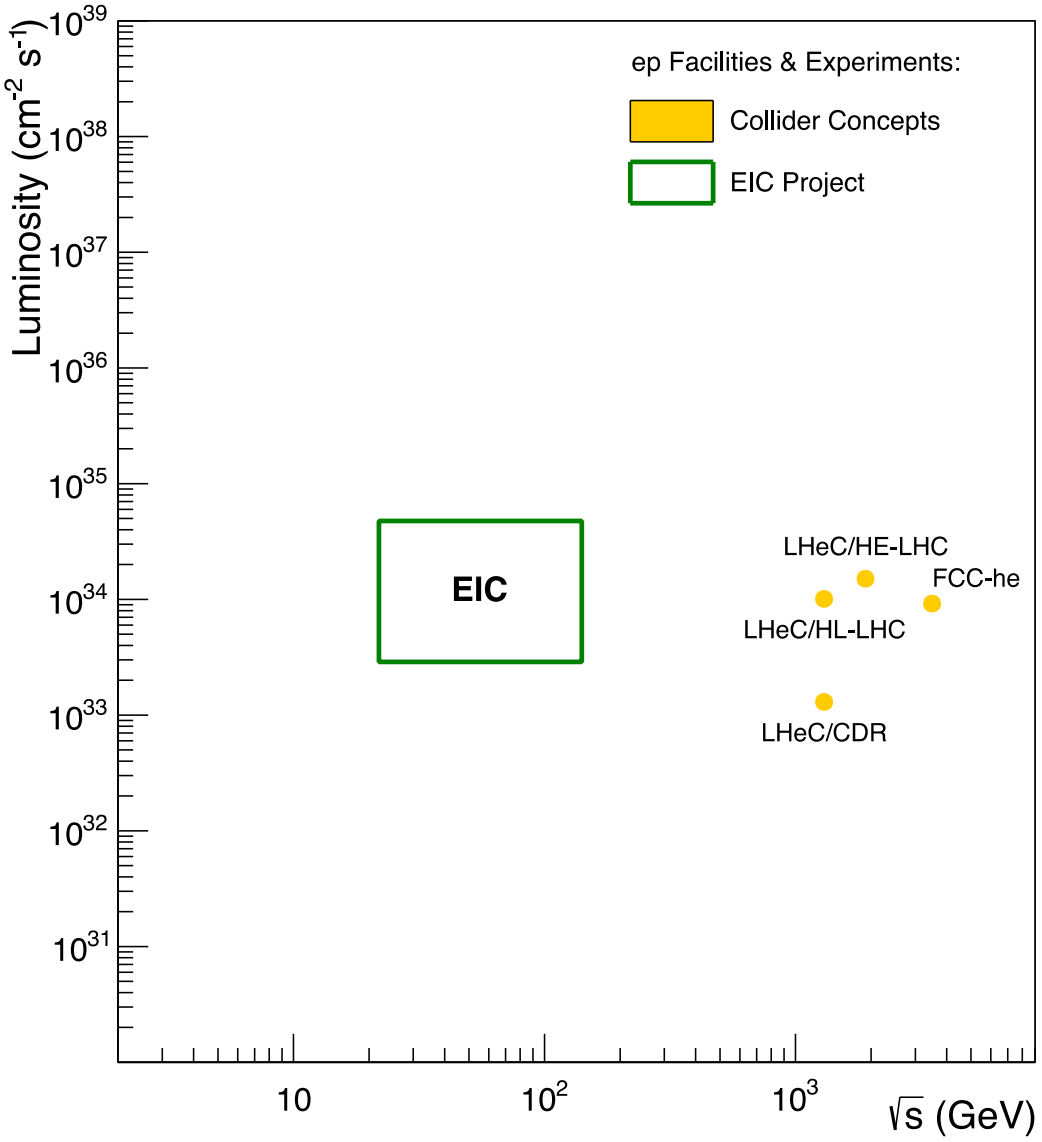
Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

However,
if we ask for:

Uniqueness of EIC among all DIS Facilities

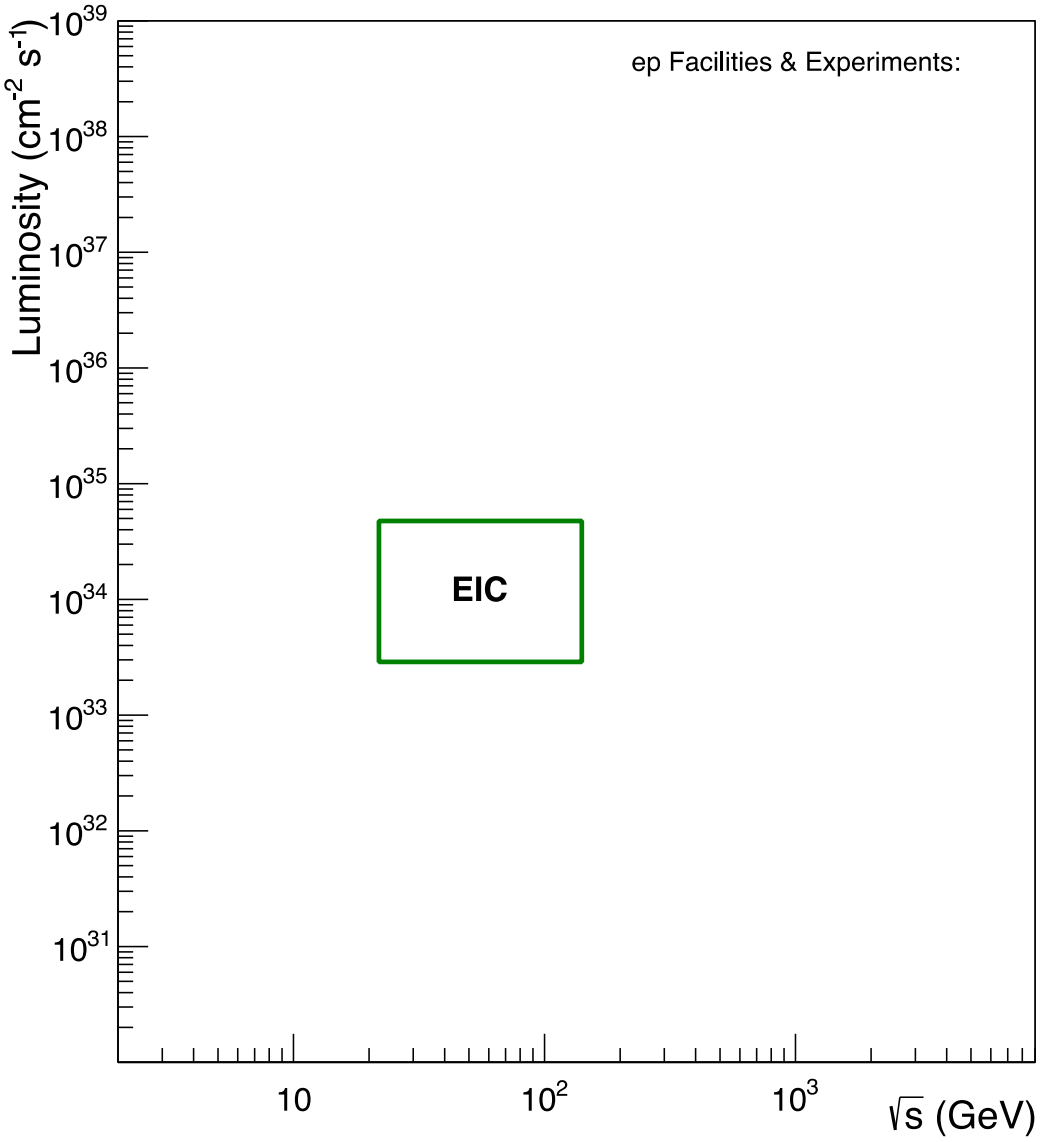


All DIS facilities in the world.

However,
if we ask for:

- high luminosity &
  wide reach in $\sqrt{s}$

Uniqueness of EIC among all DIS Facilities



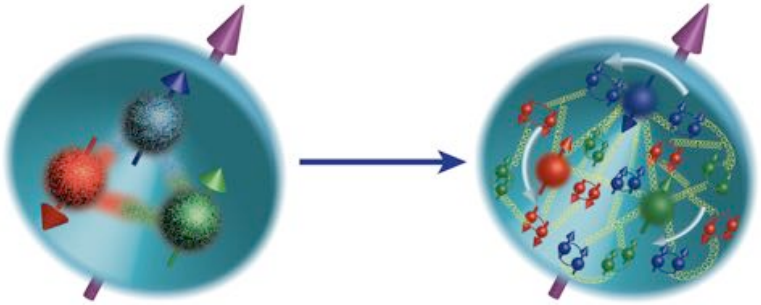
All DIS facilities in the world.

However,
if we ask for:

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

EIC stands out as unique facility …

Nucleon Spin: An emergent phenomena



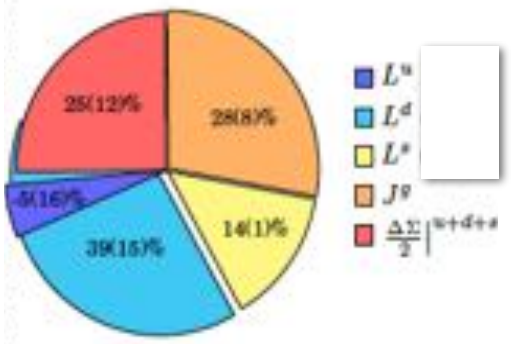
"Helicity sum rule"

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

(25 +/- 3%) + (25+/-25%) + ????

RECENT: Spin on the Lattice:

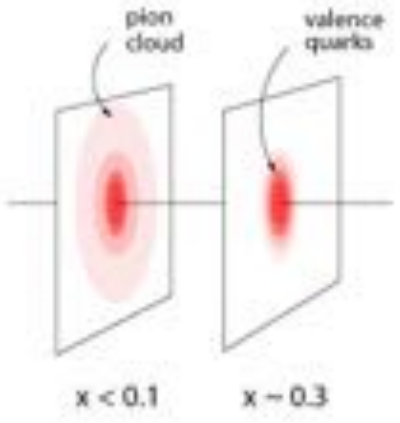
- **Gluon's spin contribution on Lattice: S_G = 0.5(0.1)**
  Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- **J_q calculated on Lattice QCD:**
  [redacted]QCD Collaboration, PRD91, 014505, 2015



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:

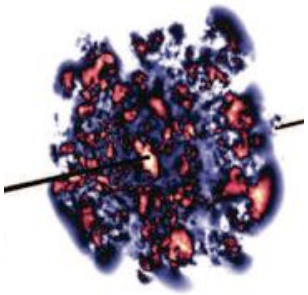
- ❑ $q\bar{q}$ pairs (sea quarks) generated at small(ish)-x are predicted to be unpolarized
- ❑ gluons generated from sea quarks are unpolarized

→ 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

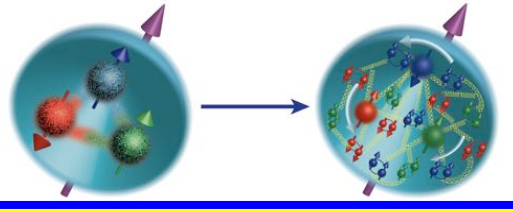


EIC needs to and will explore the dynamical spatial structure of hadrons

Proton as a laboratory for QCD

3D structure of hadrons in momentum and position space….

Understanding Nucleon Spin

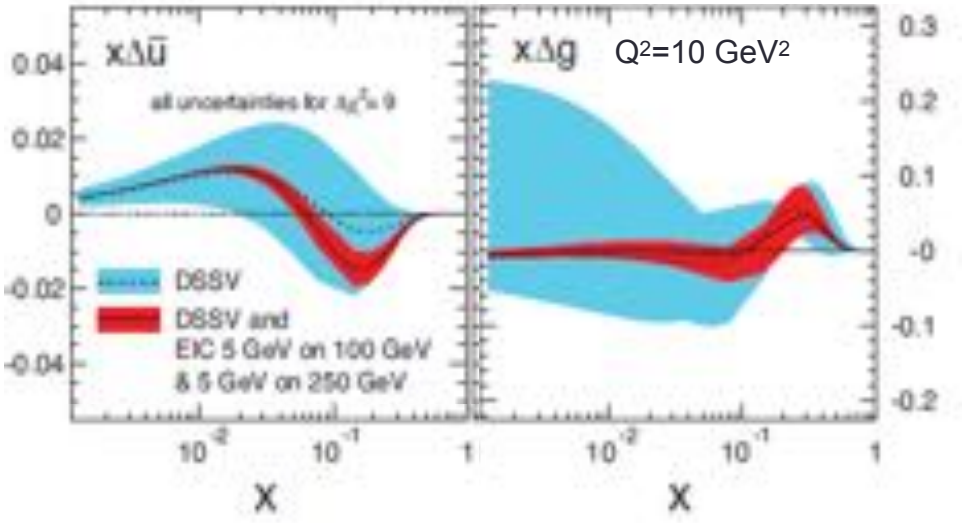


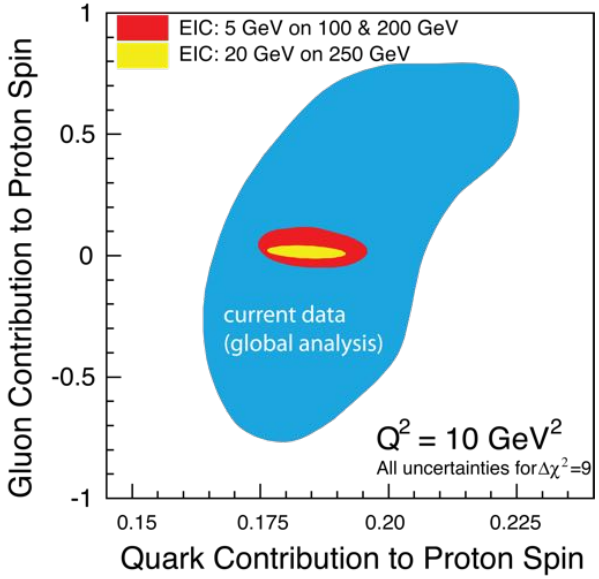
"Helicity sum rule"

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

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 $\sum L_q + L_g$





Spin and Lattice: Recent Activities

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  Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- **J_q calculated on Lattice QCD:**
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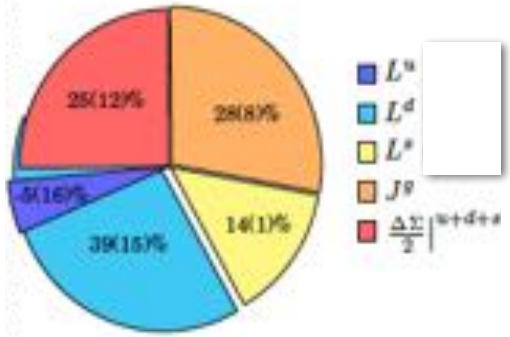
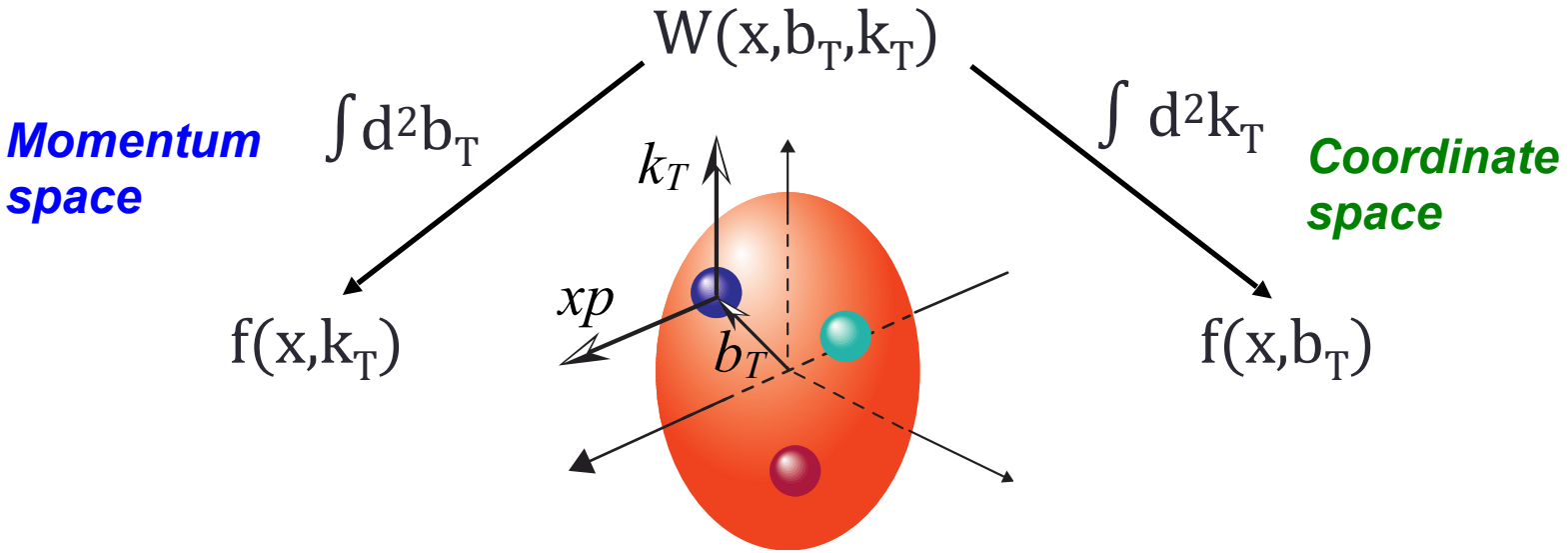


3-Dimensional Imaging Quarks and Gluons

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

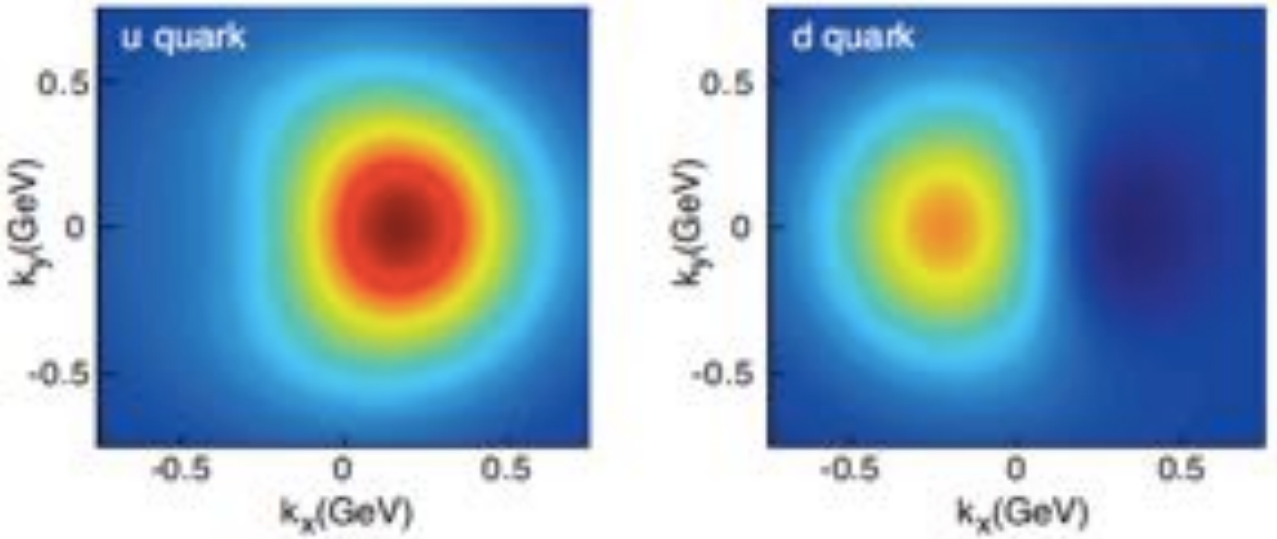
Possible direct access to gluon Wigner function through diffractive di-jet measurements at an EIC: Y. Hatta et al. PRL 16, 022301 (2016

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

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

Transverse Momentum Distributions

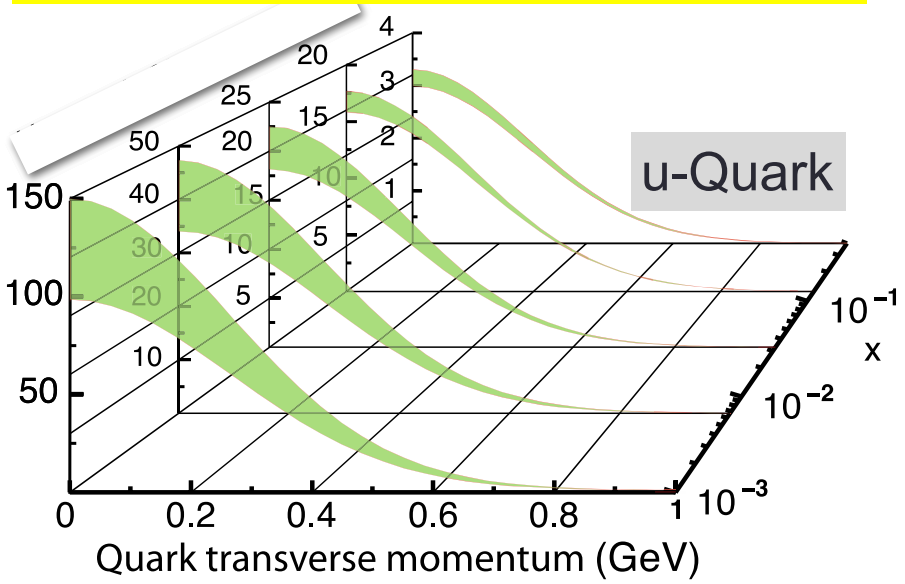
Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering



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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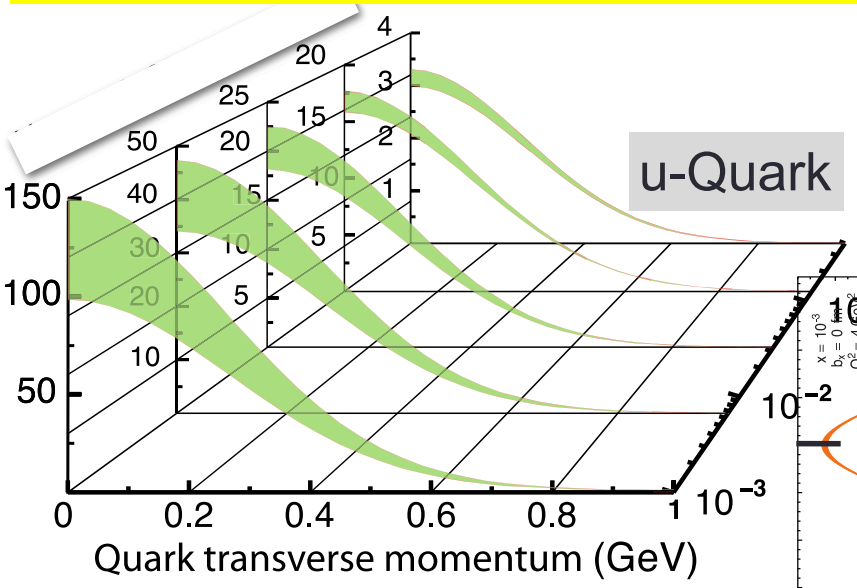
Transverse Momentum Distributions

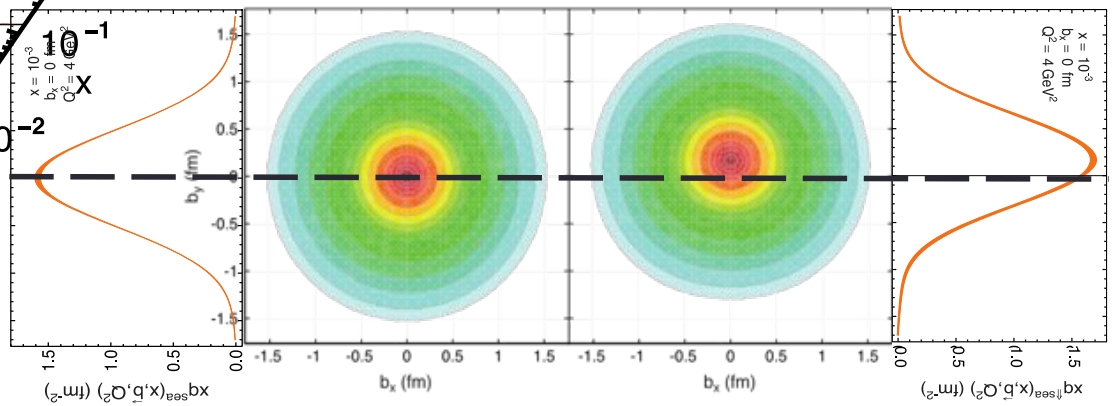


Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

sea-quarks

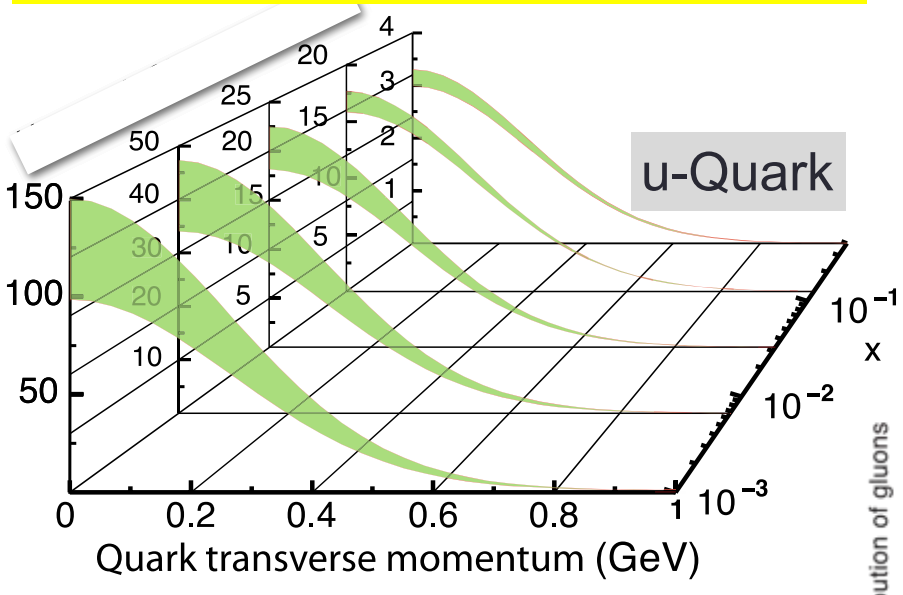
unpolarized polarized



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

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

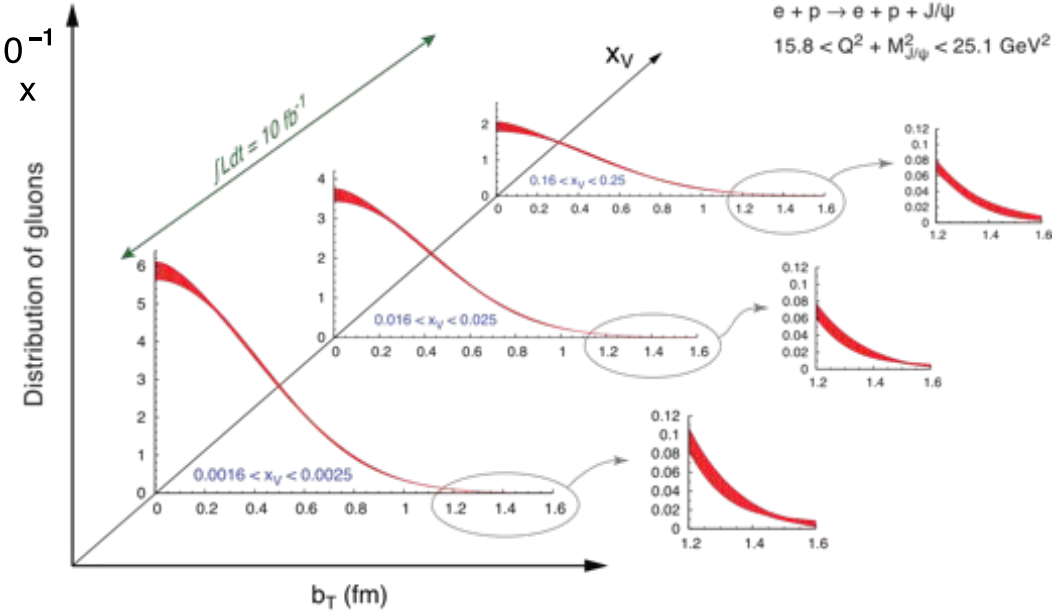
Transverse Momentum Distributions



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

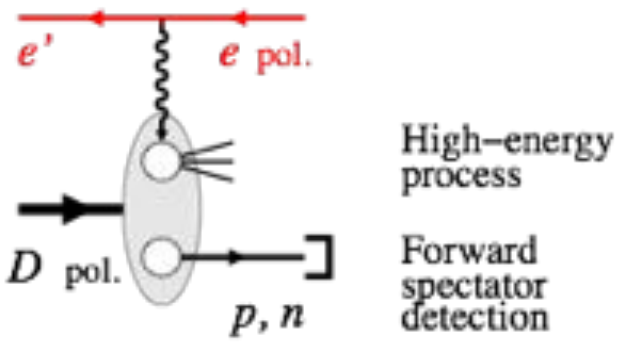
Transverse Position Distributions

Gluons



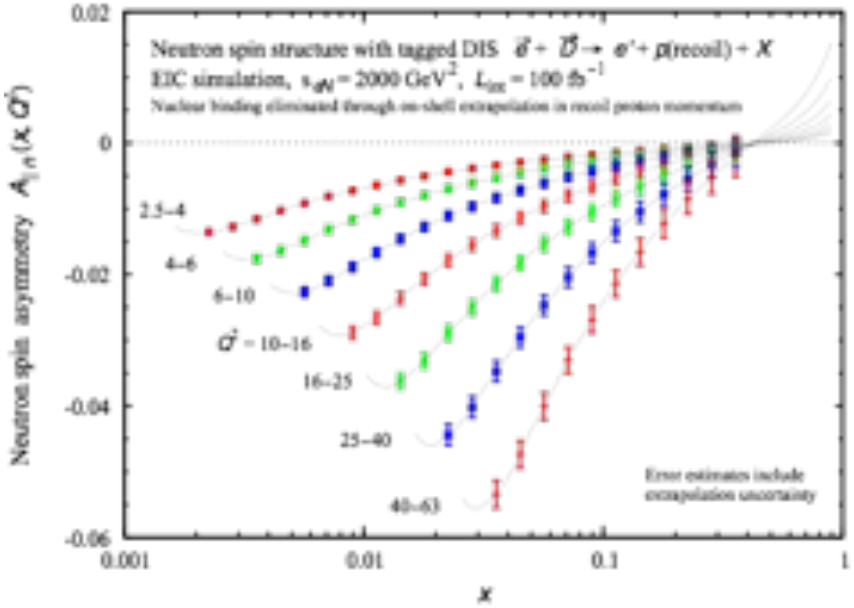
Use of Nuclei as a Laboratory for QCD :

Nuclear binding



- Measurement of the kinematics of the spectator nucleon indicator of the strength and (hence) the nature of its *binding* with the in-play nucleon(s):

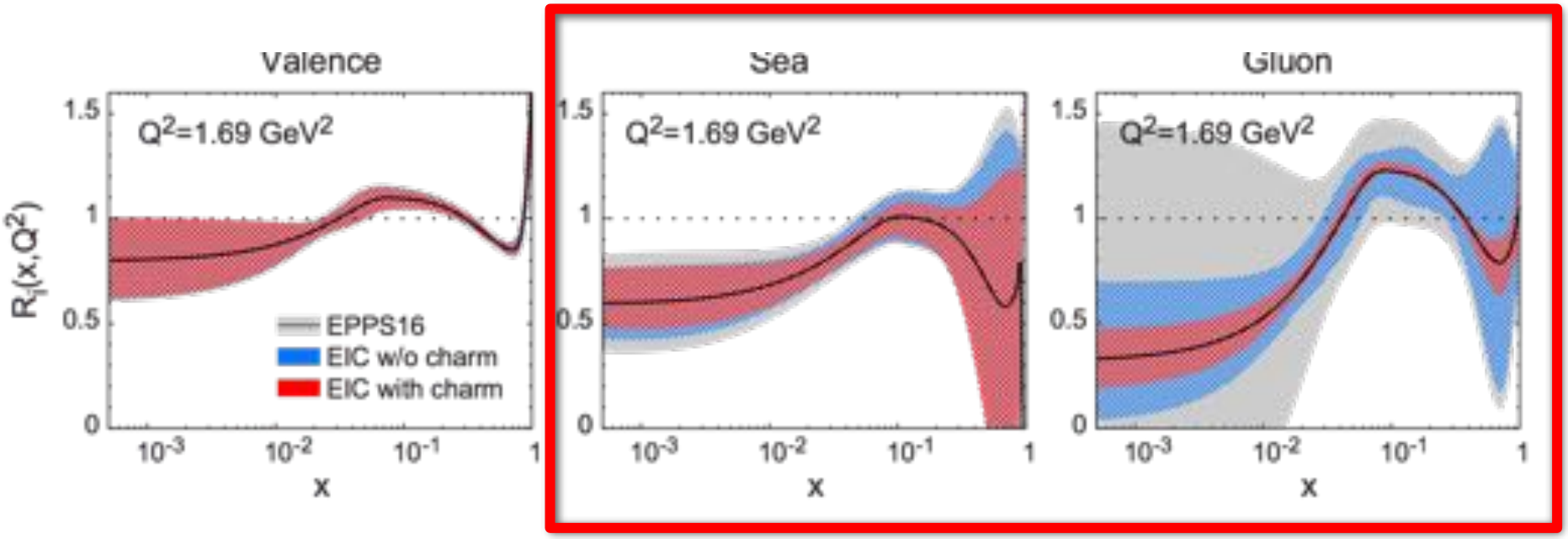
→ quark-gluon origin of the nuclear binding



Tag the recoil proton:
Study the neutron's q-g spin structure function.
Also for other few body nuclei

Neutron Spin Structure

EIC: impact on the knowledge of 1D Nuclear PDFs



Ratio of Parton Distribution Functions of Pb over Proton:

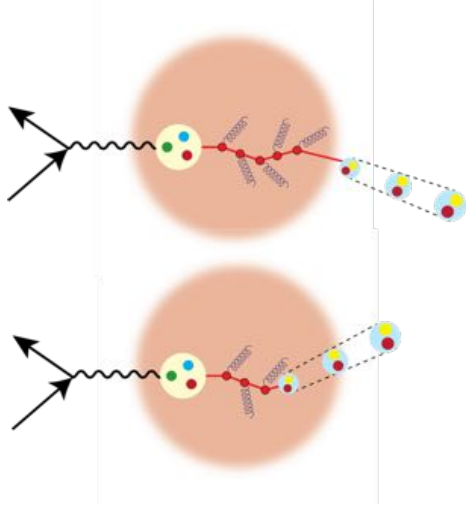
- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
  ➔With EIC significantly reduced uncertainties
- Complementary to RHIC and LHC pA data. Provides information on initial state for heavy ion collisions.
- Does the nucleus behave like a proton at low-x? ➔ such color correlations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

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

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

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

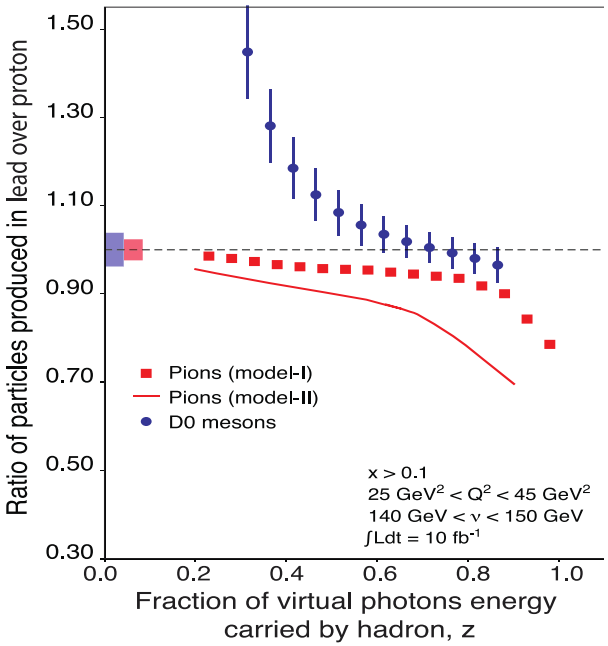


Control of ν by selecting kinematics;

Also under control the nuclear size.

(colored) Quark passing through cold QCD matter emerges as color-neutral hadron ➔ Clues to color-confinement?

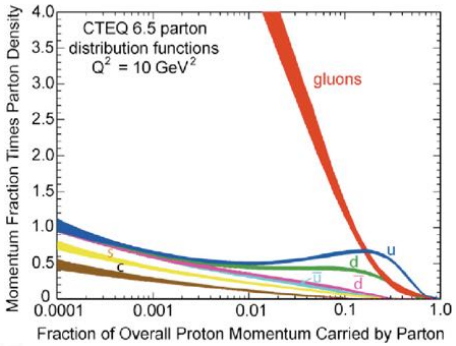
Energy loss by light vs. heavy quarks:



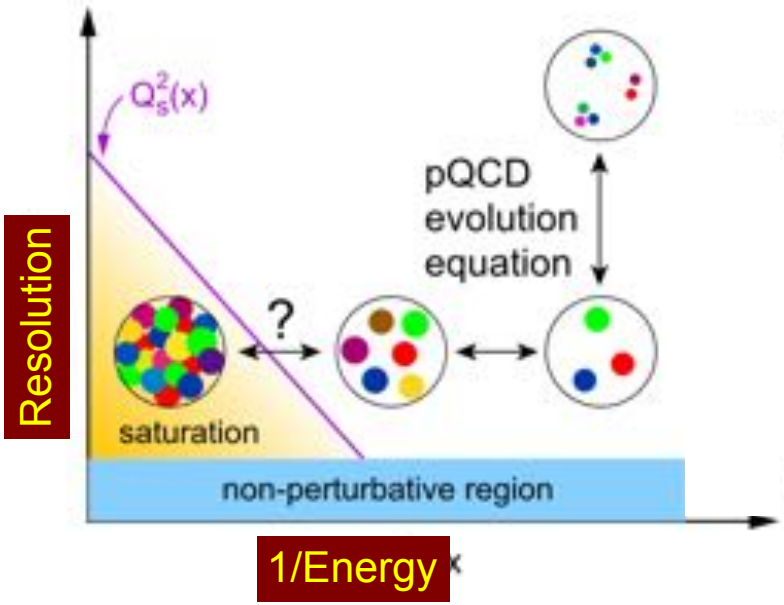
Identify π vs. D^0 **(charm)** mesons in e-A collisions: Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:

Connect to energy loss in Hot QCD

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



What do we learn from low-x studies?



What tames the low-x rise?

- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable

gluon emission = gluon recombination

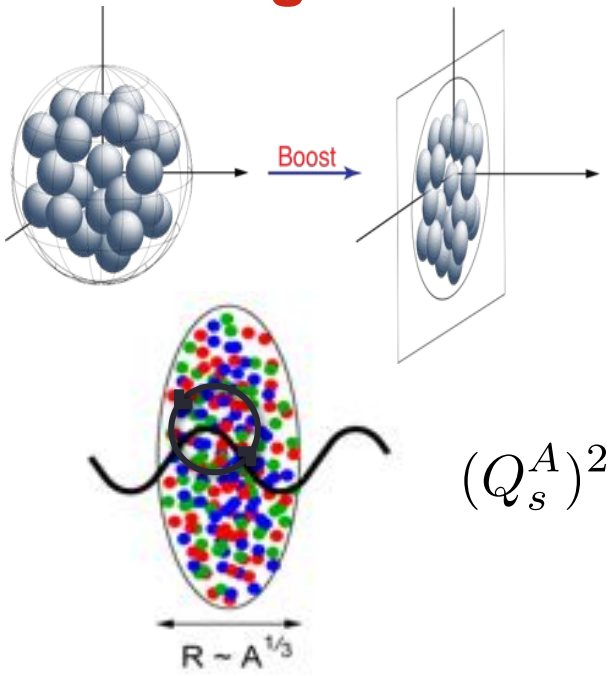
At Q_S

First observation of gluon recombination effects in nuclei:
➔leading to a *collective* gluonic system!
First observation of g-g recombination in *different* nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

How to explore/study this new phase of matter?

(multi-TeV) e-p collider 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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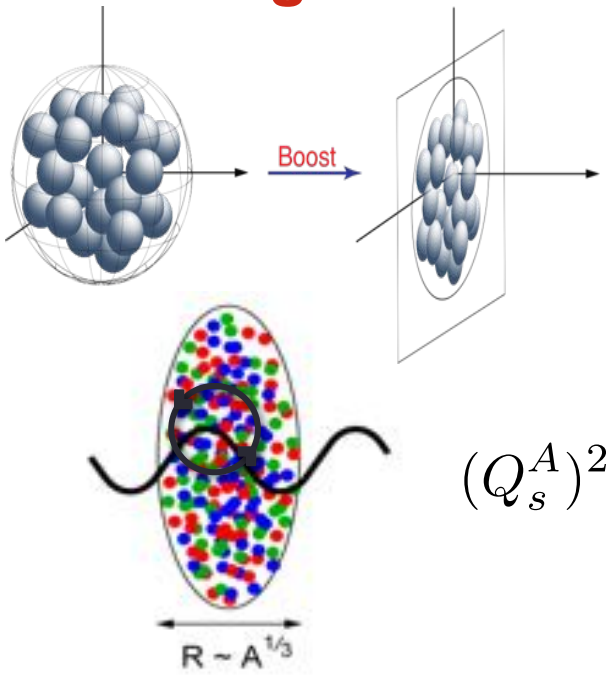

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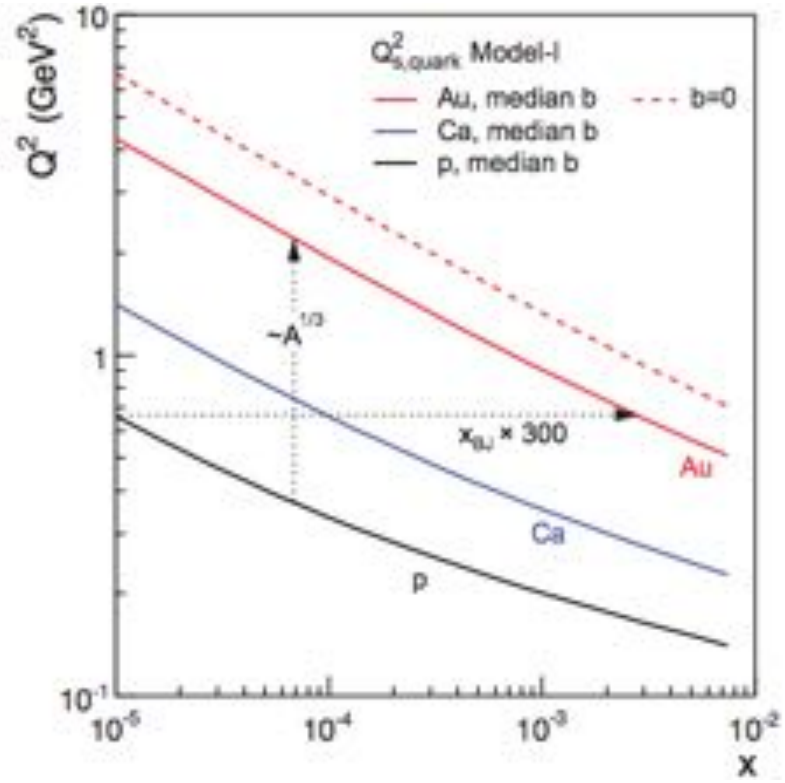
Teaney, Kowalski
Kovchegov et al.



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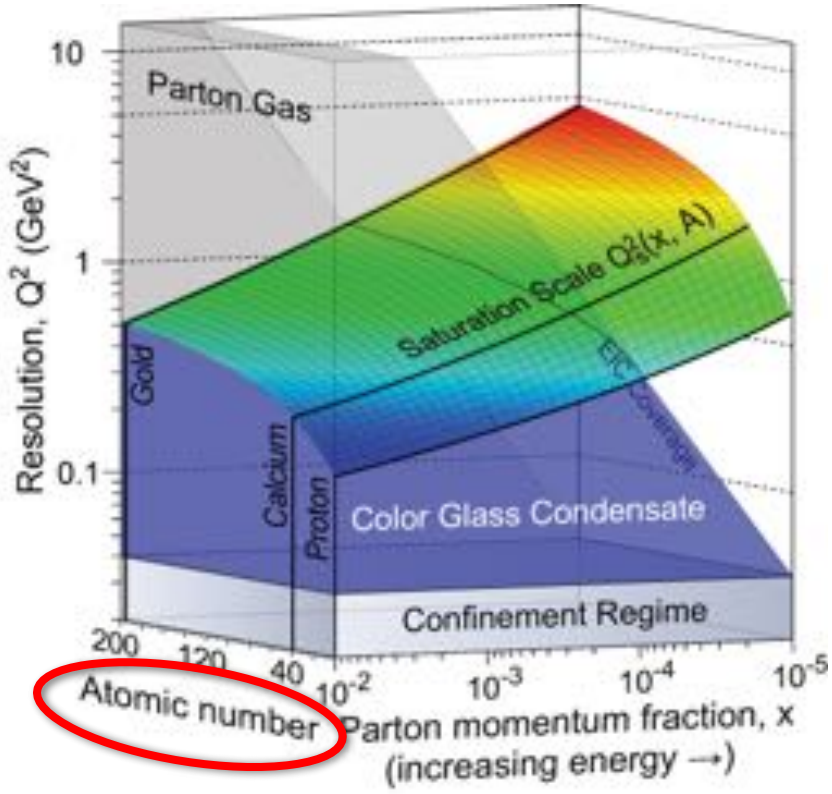

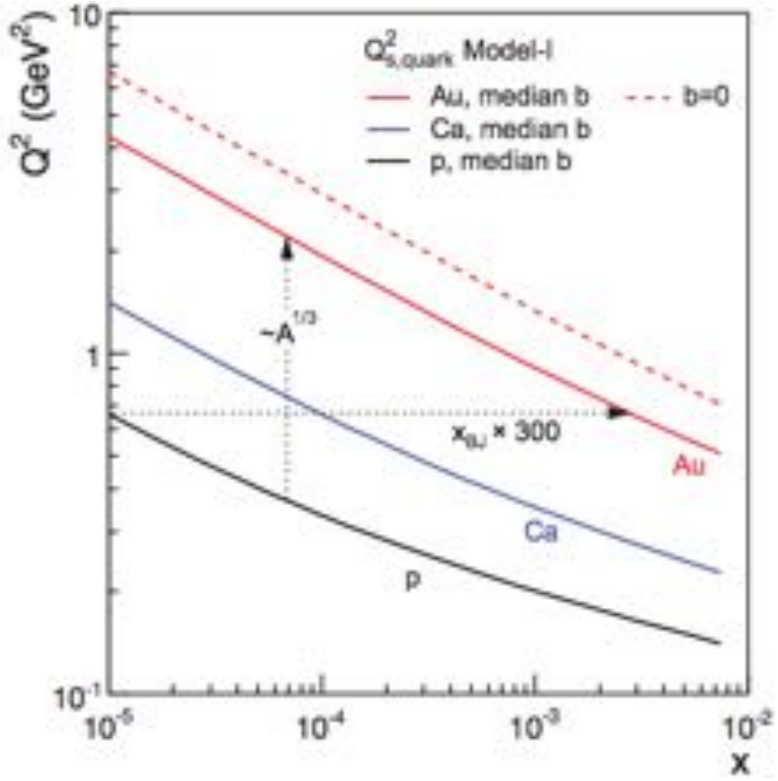

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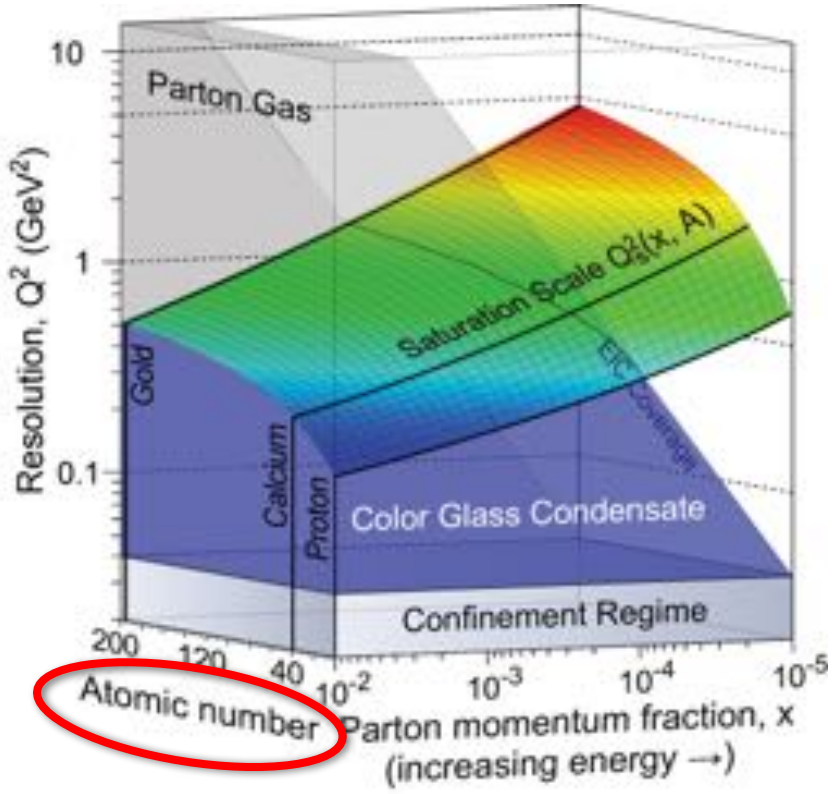
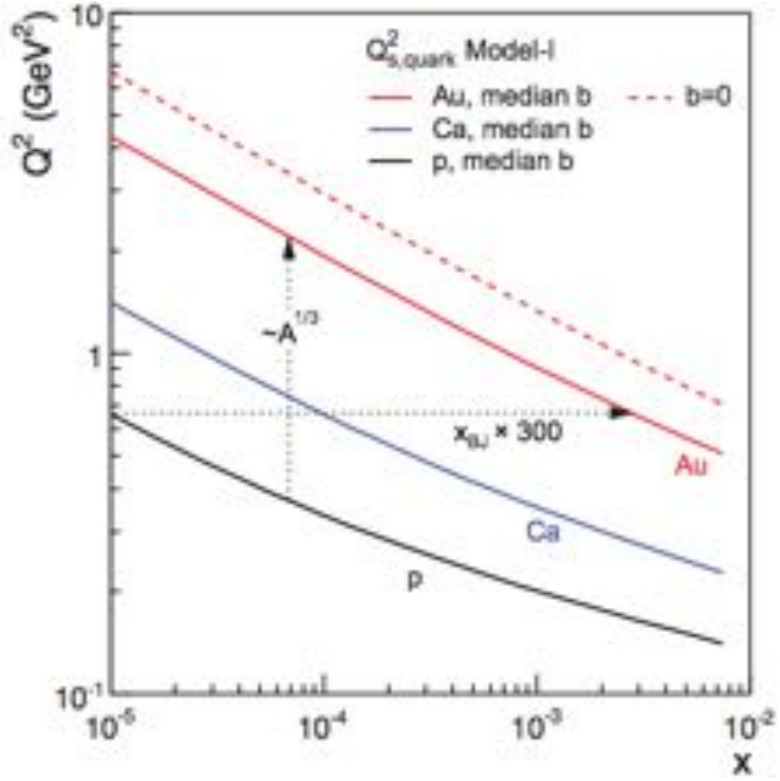




Enhancement of Q_S with A:

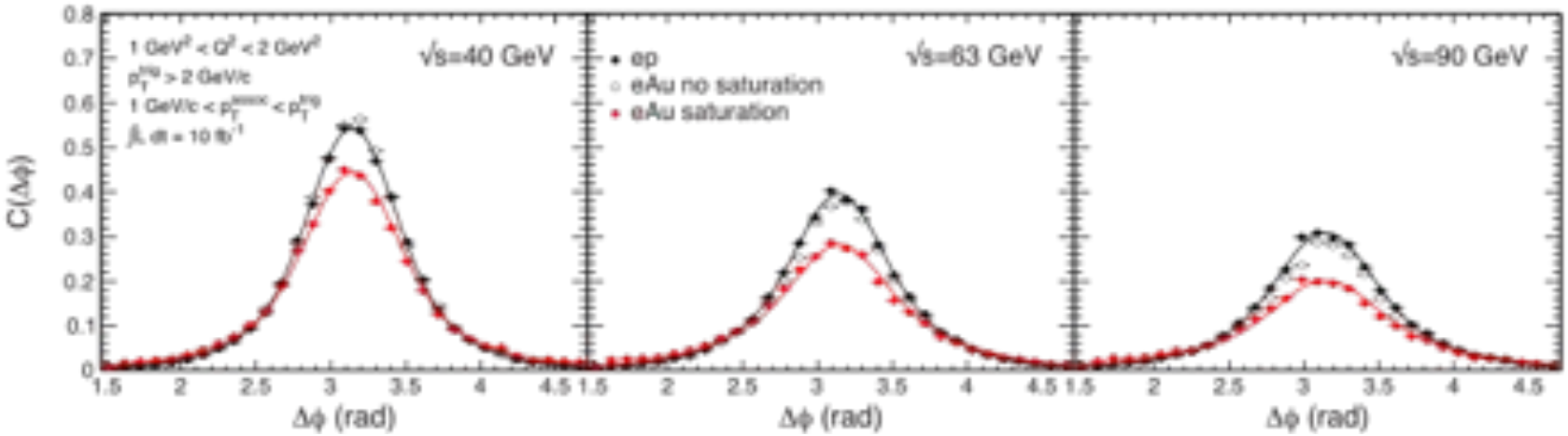
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

Exp. Signal for Saturation

Di-hadron Correlations: $e + A \rightarrow e' + h_1 + h_2 + X$

$\Delta\Phi$

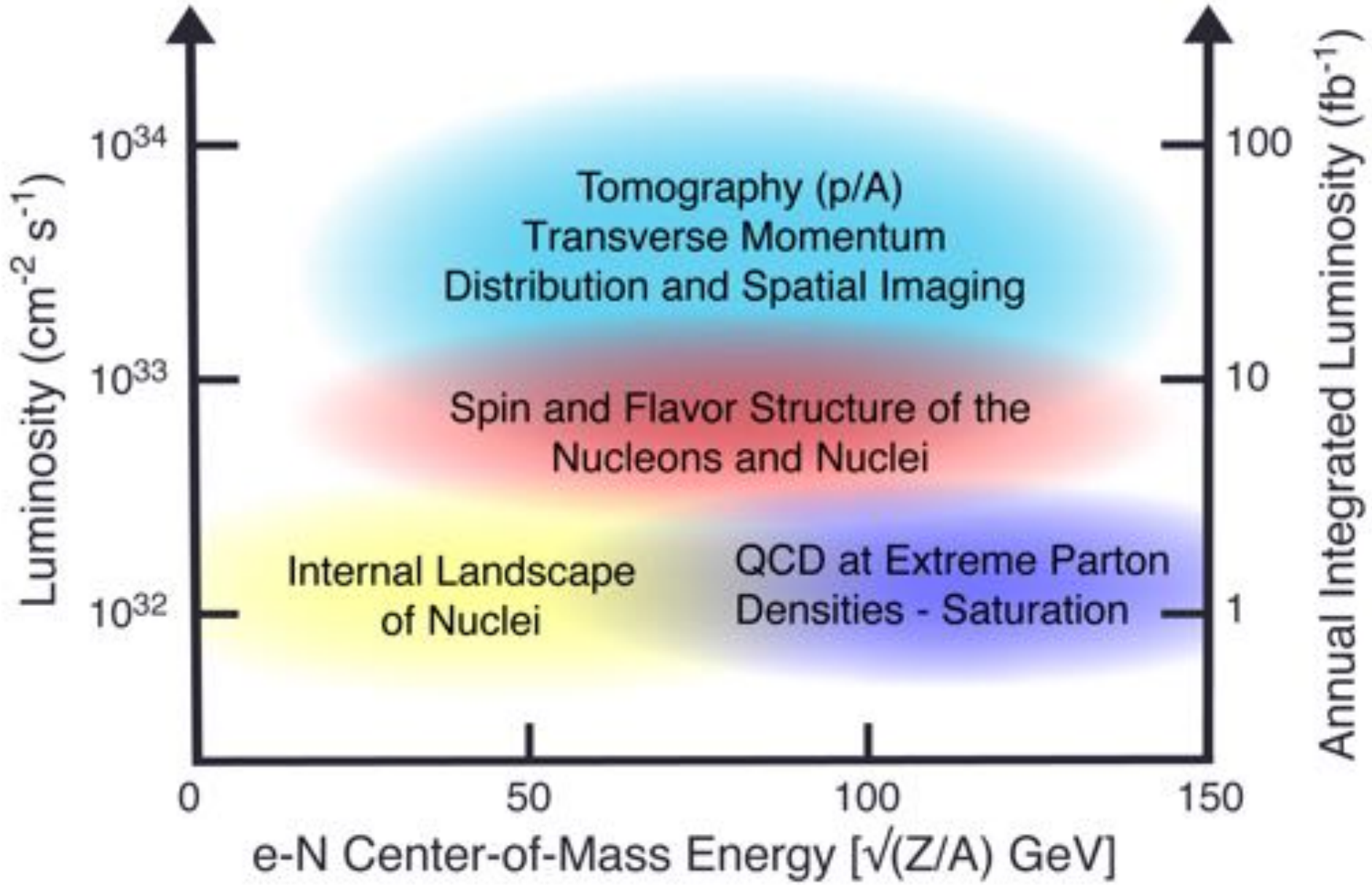
arXiv: 1708.01527



Comparison between

- e-A with saturation (red filled),
- e-p non-saturation (**black full points**) , and
- e-A non-Saturation model (black-hollow points)

Summary: EIC Physics: CM vs. Luminosity vs. Integrated luminosity



REALIZATION….

Detector R&D program + EIC User Group formation ➔ Seeds for future experimental collaboration

Current Detector Design Ideas

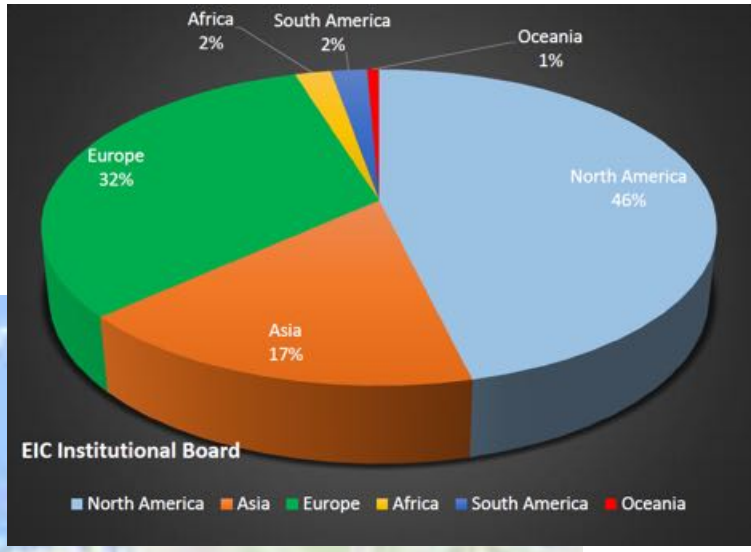
The National Academy of Science (NAS- NRC) Review

The EIC Users Group: EICUG.ORG

(no students included as of yet)

731 collaborators, 29 countries, 169 institutions... (January 2018)

Map of institution's locations



New physics for EIC beyond the White Paper:

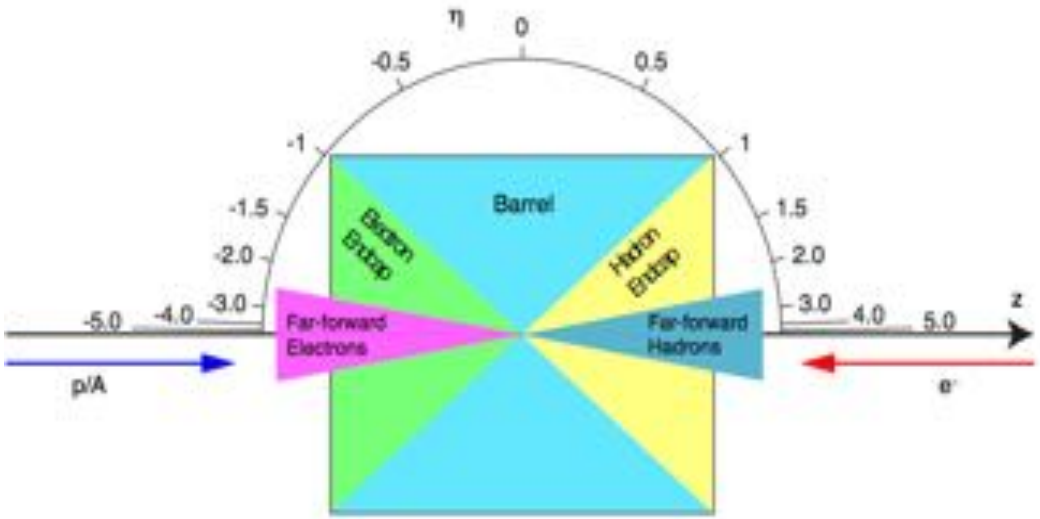
- Impact of super-precise PDFs in $x > 0.0$, $1 < Q^2 < 100$ GeV^2 for future Higgs studies (some insight through LHeC studies, but serious effort on EIC beginning now).
- What role would TMDs in e-p play in W-Production at LHC?
- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??) Does polarization of hadron play any role?
- Quark Exotica: 4,5,6 quark systems…?
- Internal structure of jets with variability of CM 50-140 GeV^2, in comparison with HERA, Tevatron & LHC energies, and with controlled electron & proton polarizations (jet fragmentation studies) aided by knowledge from e+e- physics at BaBar/Belle & in future Super-Belle (“Collins Functions”)
- Jet propagation in nuclei… energy loss in cold QCD medium: a topic interest
- Initial state affects QGP formation!….. p-A, d-A, A-A at RHIC and LHC: many puzzles
- Gluon TMDs at low-x!

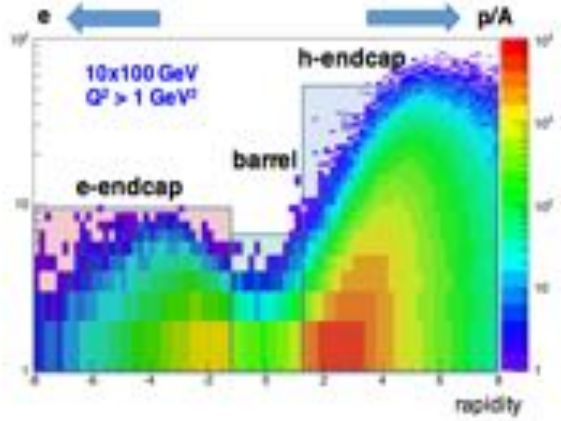
See: http://www.lnf.infn.it/conference/2016/3DPDF/scientific-topics.php

Requirement are mostly site-independent with some slight differences in the forward region (IR integration)

In Short:

- Hermetic detector, low mass inner tracking, good PID (e and π/K/p) in wide range, calorimetry
- Moderate radiation hardness requirements, low pile-up, low multiplicity

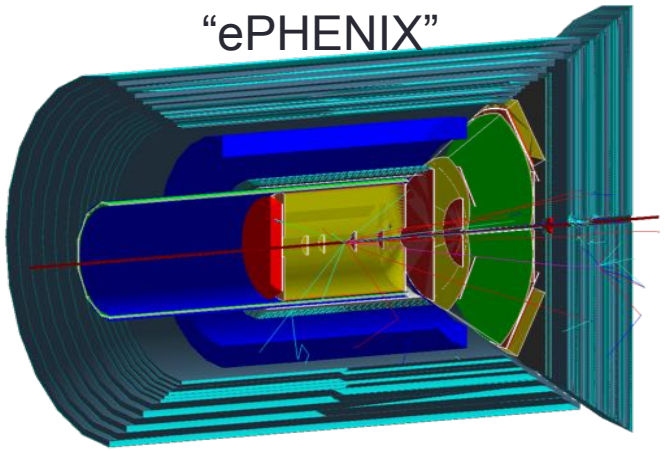




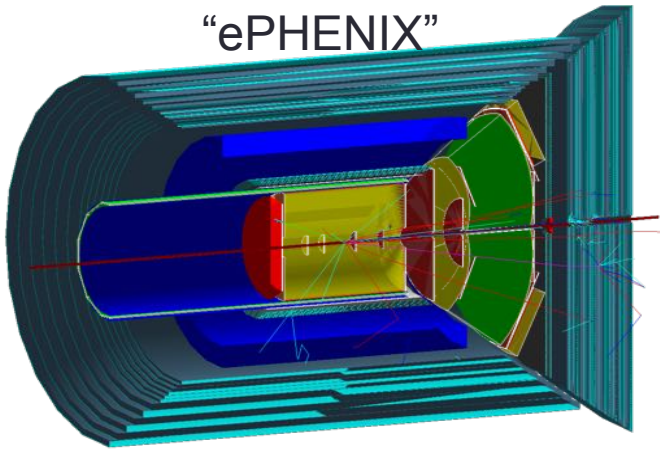
Curtsey of Thomas Ullrich

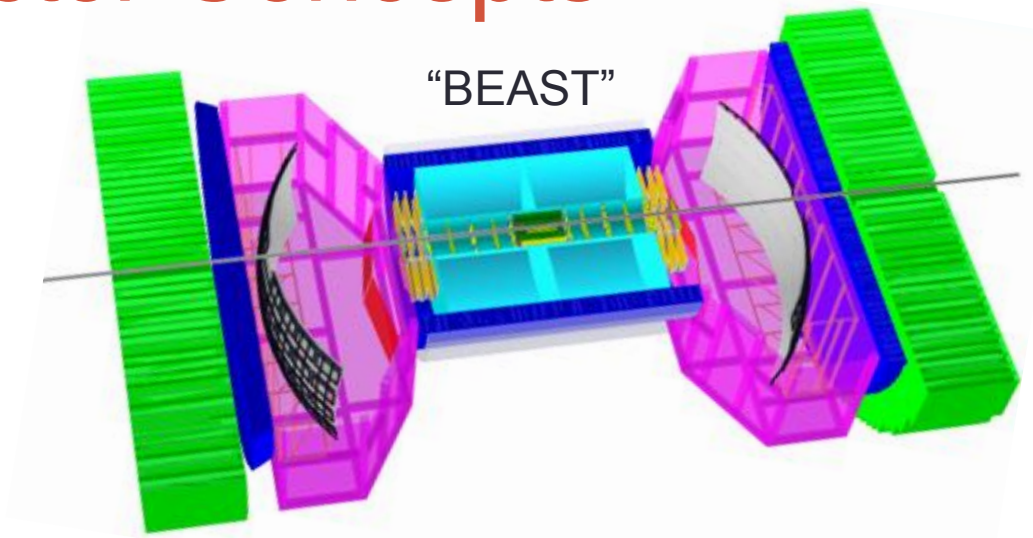
EIC Detector Concepts

“ePHENIX”



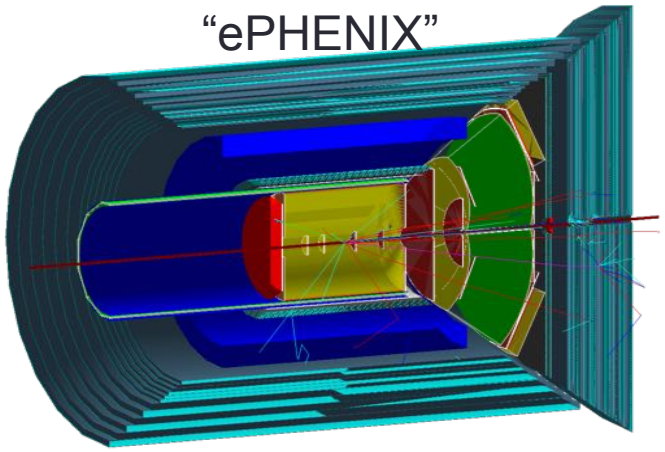
EIC Detector Concepts



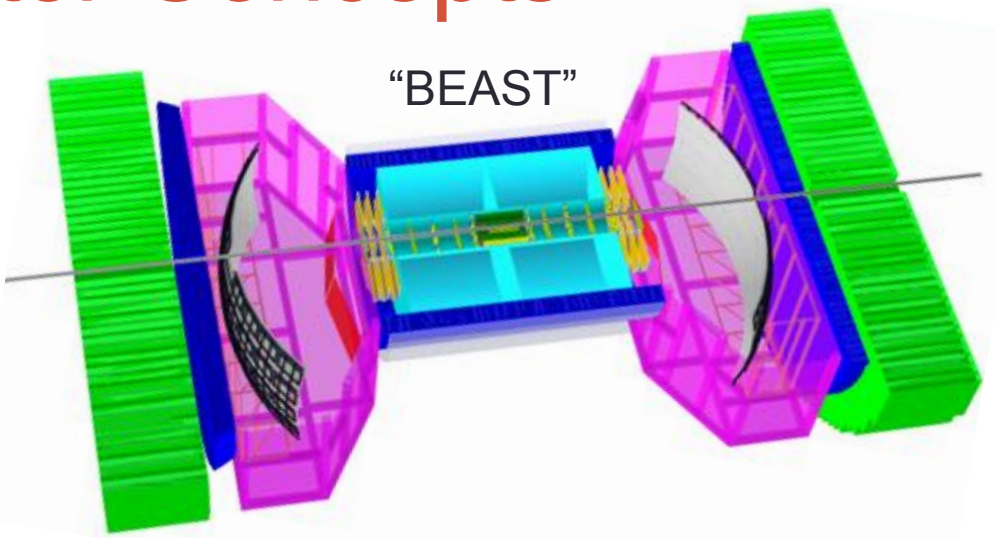


EIC Detector Concepts

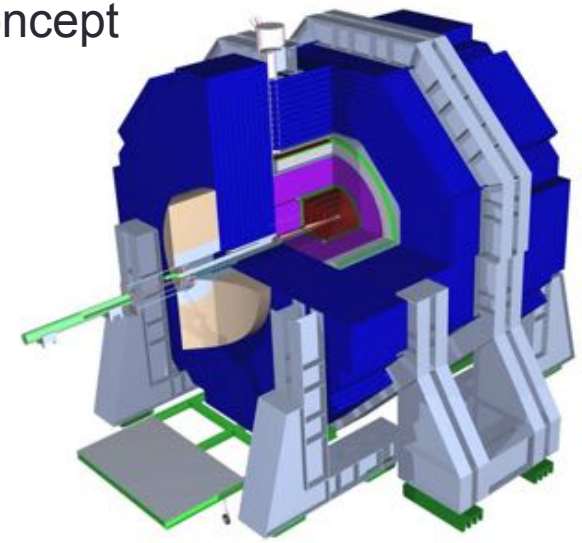
"ePHENIX"

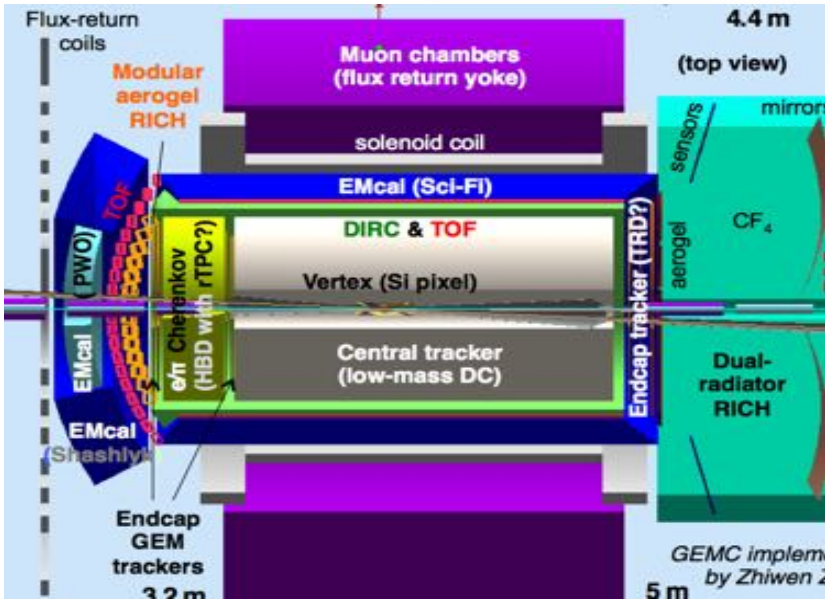


"BEAST"



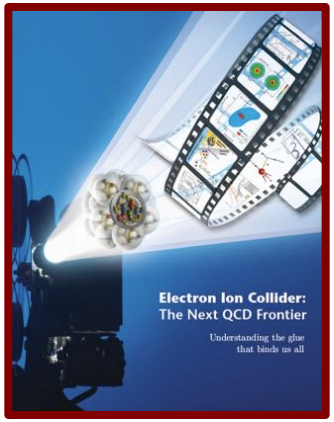
ANL's: "SiEIC Detector" Si-tracker & Precision calorimetry: particle flow detecor concept

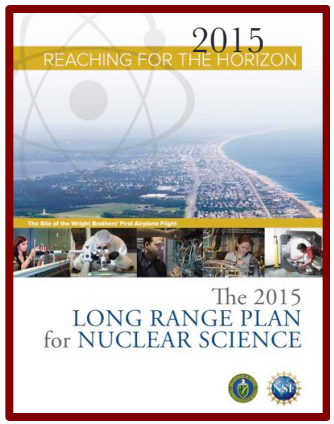




JLEIC

INT Program 2010 → EIC in the LRP2015





- 2010 INT workshop on the Science of EIC critical to making the case in the 2015 LRP. (500+ page document, 150+ participants and 500+ authors) : **arXiv:1108.1713**, D. Boer et al.

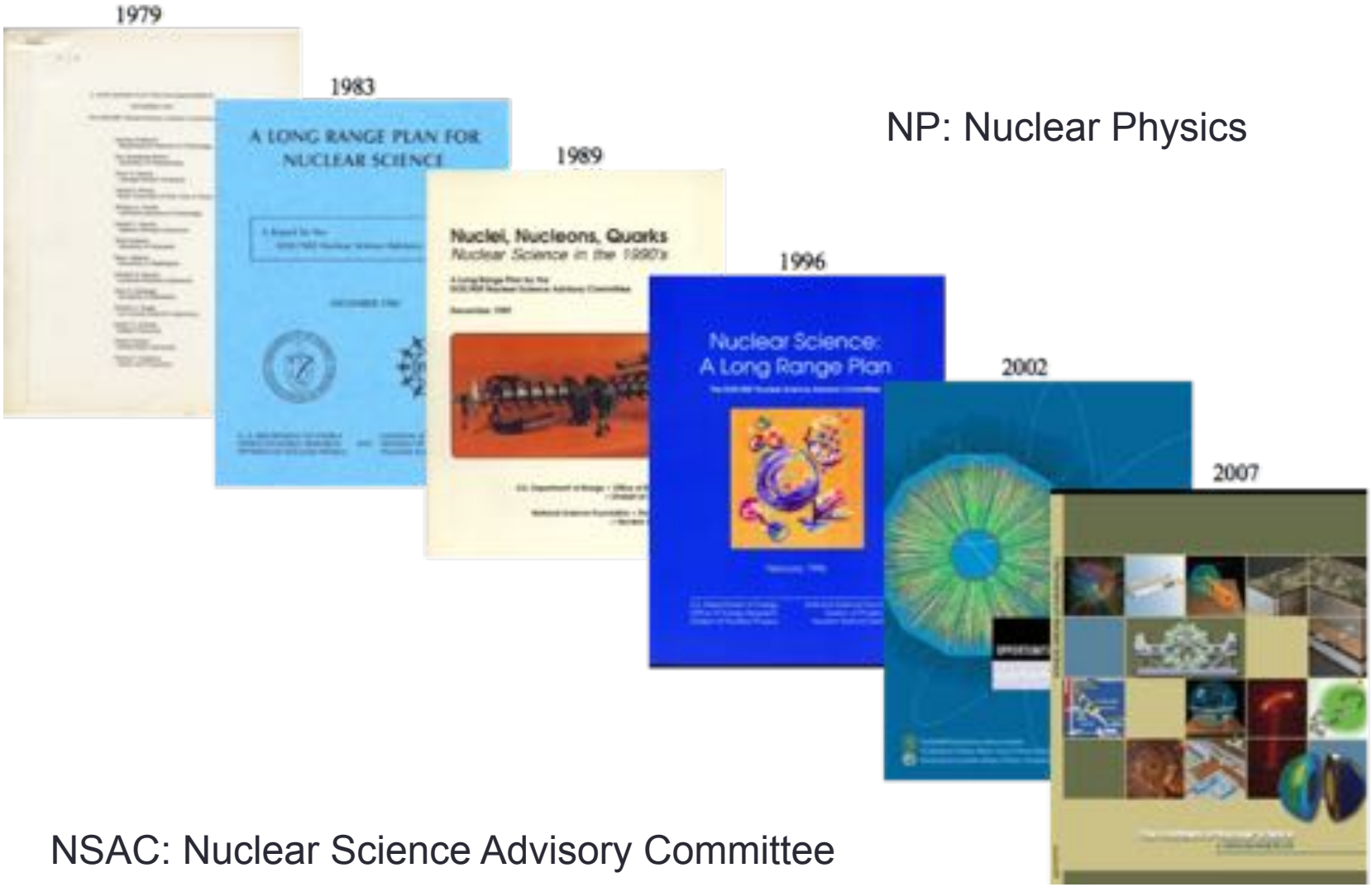
- Next LRP in ~2020/21, just before EIC Construction could begin → We need a updating of the EIC physics case for that, hopefully with additional details and new physics input….

INT Program Approved: 2018

A 7-week program "Probing Nucleons and Nuclei in High Energy Collisions" dedicated to the **physics of the Electron Ion Collider has been approved by the Institute for Nuclear Theory** in Seattle with the tentative dates of **October 1 - November 16, 2018**. The topics to be covered include Spin and Three-Dimensional Structure of the Nucleon (GPDs, TMDs, longitudinal spin) and QCD in a Nucleus (small-x physics and saturation, connections to heavy ions, large-x physics in a nucleus).

The program organizers will be **Yoshitaka Hatta, Yuri Kovchegov, Cyrille Marquet, and Alexei Prokudin.** They plan to have ample discussion time and lectures aimed at young researchers. Both **theorists and experimentalists** are welcome to participate in the program. Young researchers, women and underrepresented minorities are strongly encouraged to apply.

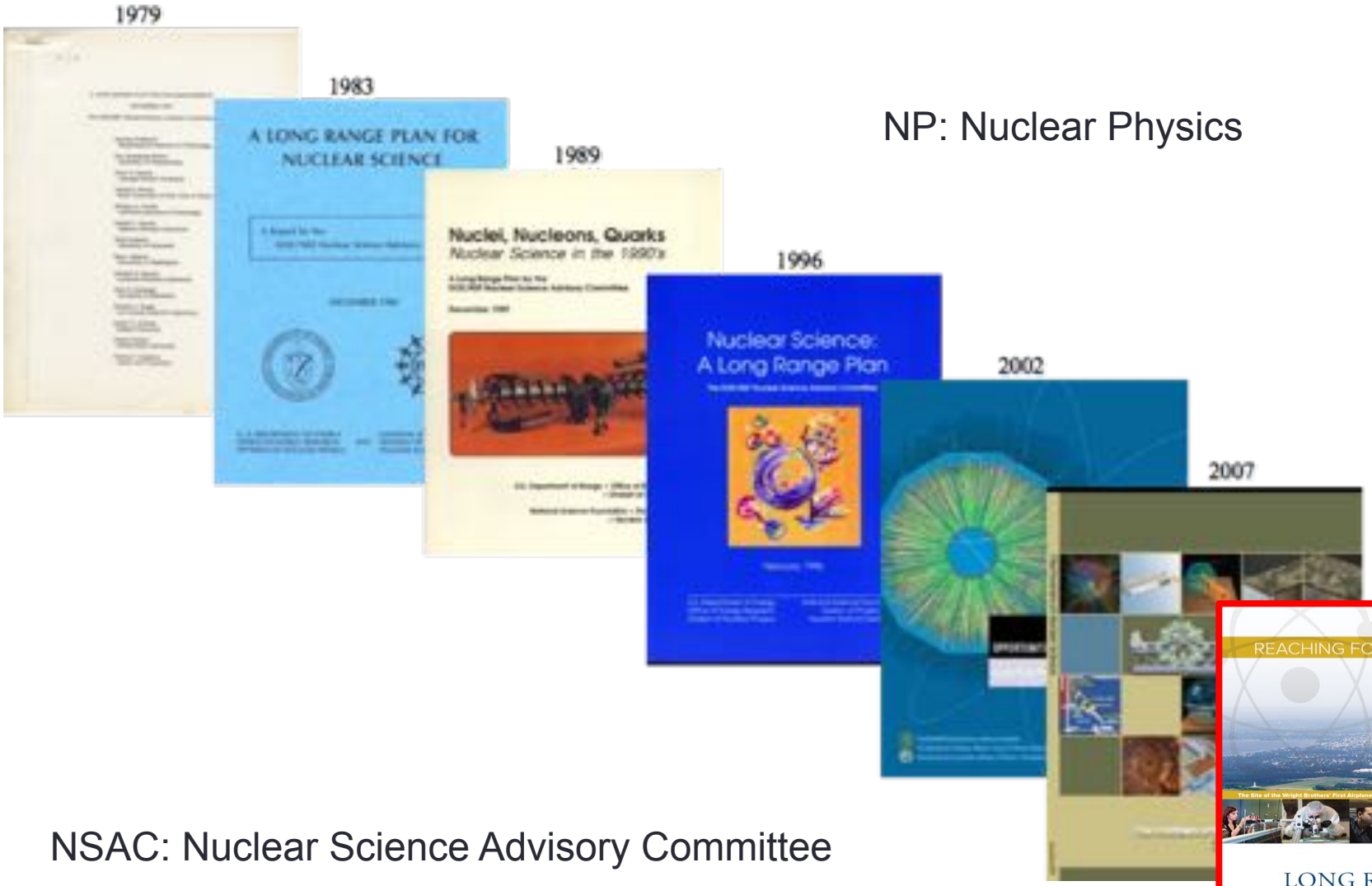
NP's long history of Long Range Plans (LRP)



NP: Nuclear Physics

NSAC: Nuclear Science Advisory Committee

NP's long history of Long Range Plans (LRP)



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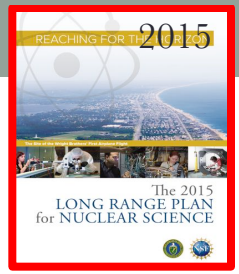


Assumption: "Modest Growth" → 1.6% growth/year above constant effort

The 2015 Long Range Plan for Nuclear Science

Not much time!

CD3

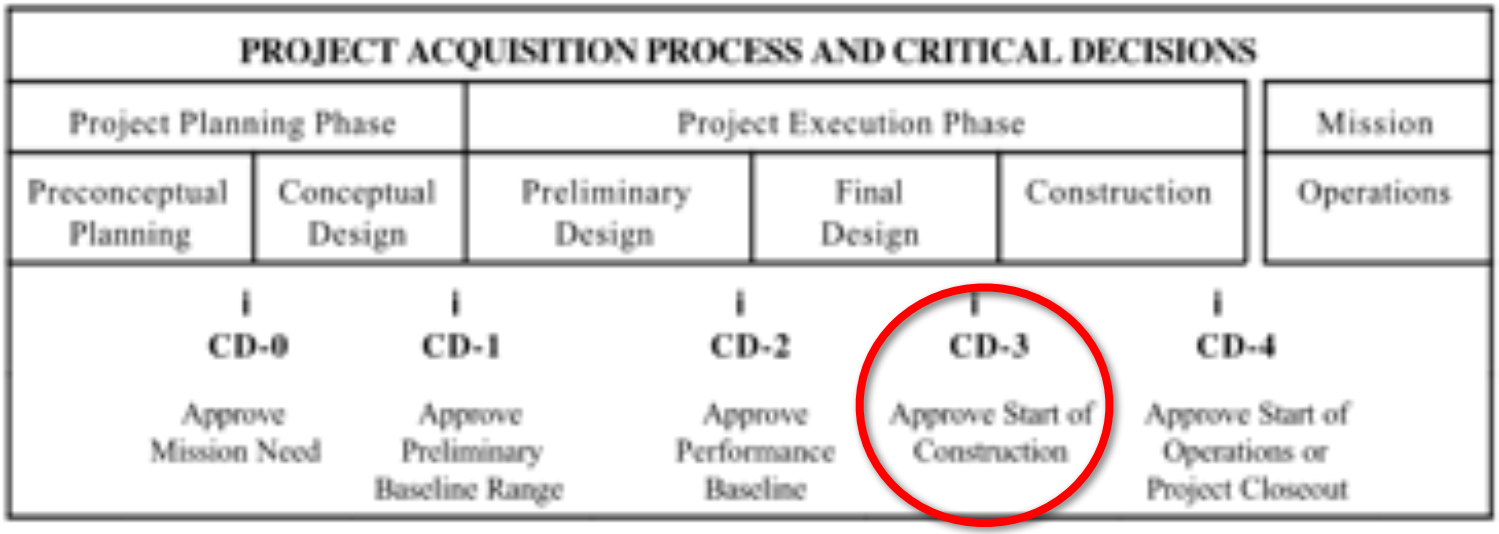
Figure 10.4: DOE budget in FY 2015 dollars for the Modest Growth scenario.

Path forward for the EIC:

- DOE sanctioned a science Review by National Academy of Science of EIC
  - Expect report **by April/May 2018**

- Positive NAS review will trigger the DOE's CD process
  - CD0 (acceptance of the critical need for science by DOE) FY19
  - EIC-Proposal's Technical & Cost review → FY20 (site selection)(/)
  - CD1 requires site selection
  - **Major Construction funds ("CD3") by 2022/23"**
    - Assuming 1.6% sustained increase over inflation of the next several years (Long Range Plan)
    - Consistent with the past 10 years of NP funding increases in the US

Critical Decision Process DOE



CD-0	CD-1	CD-2	CD-3	CD-4
Actions Authorized by Critical Decision Approval				
• Proceed with conceptual design using program funds • Request PED funding	• Allow expenditure of PED funds for design	• Establish baseline budget for construction • Continue design • Request construction funding	• Approve expenditure of funds for construction	• Allow start of operations or project closeout

PED: Project Engineering & Design

Concluding thoughts & perspective:

The EIC (with its precision and control) will profoundly impact our understanding of the many body structure of nucleons and nuclei in terms of sea quarks & gluons → *The bridge between sea quark/gluons to Nuclei*

The EIC will enable IMAGES of yet unexplored regions of phase spaces in QCD with its high luminosity/energy, nuclei & beam polarization
→ *High potential for discovery*

Positive National academy report → critical decision process at the DOE

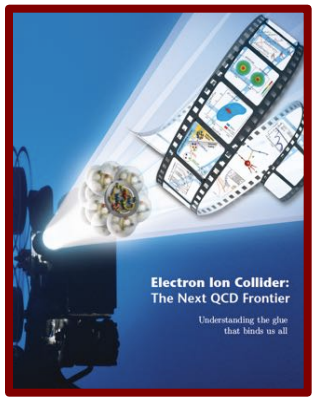
Many aspects of the physics more close attention: LIGHT ION BEAMS at EIC is one of them. → *Not just physics but also associated polarimetry, polarized source development. Pay attention and contribute!*

EIC Users Group has been formed: eicug.org

Please register yourself as a user of this group

Next *July 31-Aug 4, 2018 at Catholic American University, Washington DC*

THANK YOU



Thanks to many of my EIC Collaborators and Enthusiasts who led many of the studies presented in this talk
See: arXiv:1108.1713, D. Boer et al.

Without the EIC White Paper Writing Group the EIC White Paper would not have existed.
Special thanks to Dr. Jianwei Qiu and Prof. Zein-Eddine Meziani, my Co-Editors for the EIC White Paper
See: arXiv:1212.1701.v3 , A. Accardi et al.
Eur. Phy. J. A 52, 9 (2016)

The eRHIC and JLEIC machine design teams

Also gratefully acknowledge recent input from: M. Diefenthaler, R. Ent, R. Milner, R. Yoshida

Thank you.