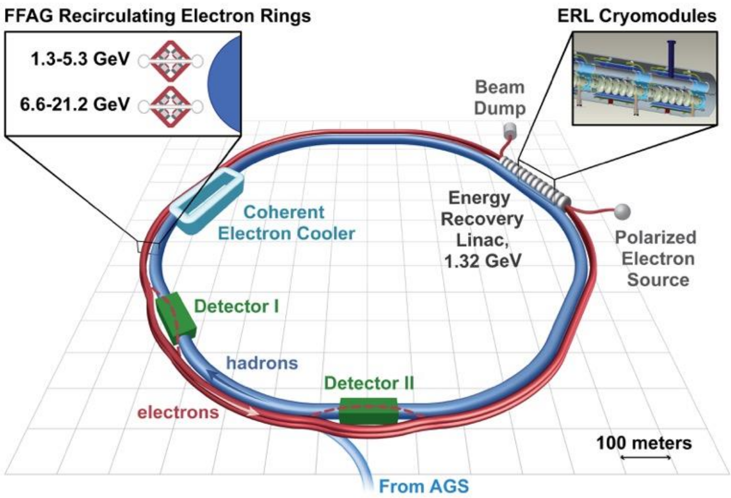
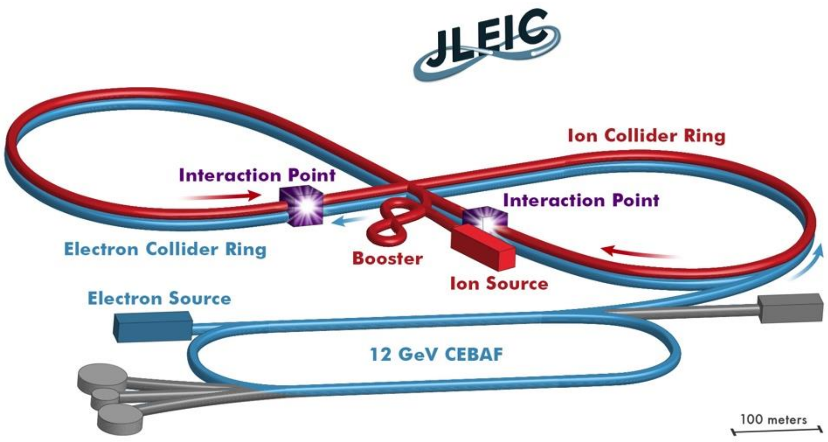
Accessing Quarks and Gluons at a Future EIC

Cynthia Keppel
HADRON 2017





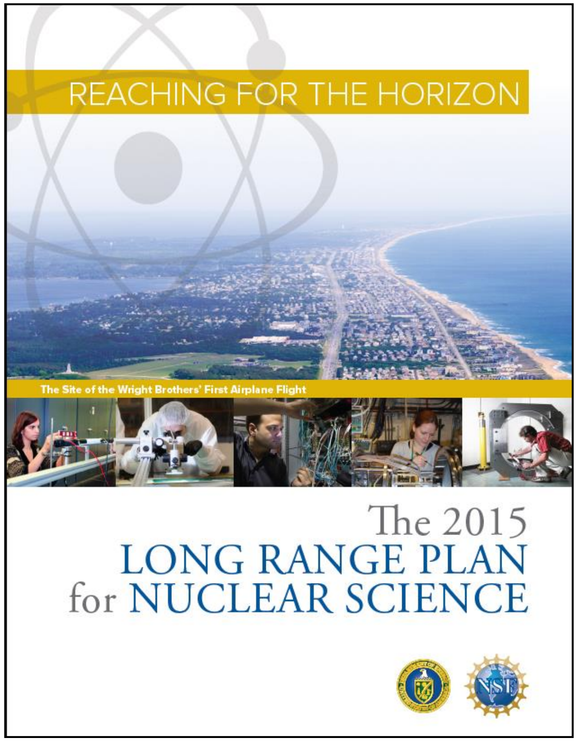
25-29 September 2017
Salamanca, Spain

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Nuclear Science Long-Range Planning

Every 5-7 years the US Nuclear Science community produces a Long-Range Planning (LRP) Document

2015



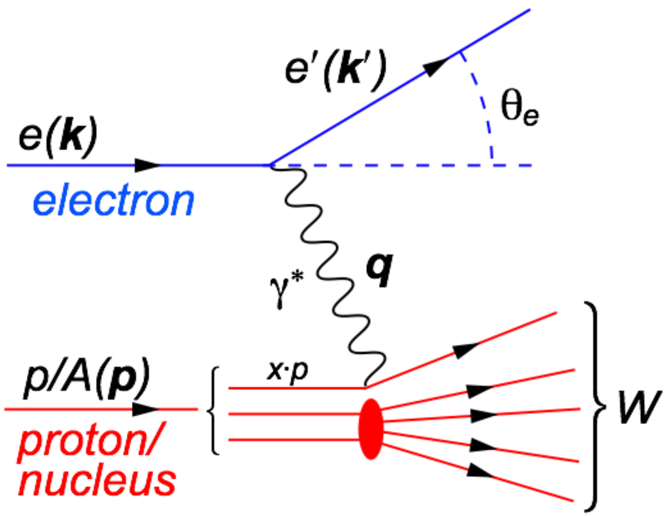
"We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB."

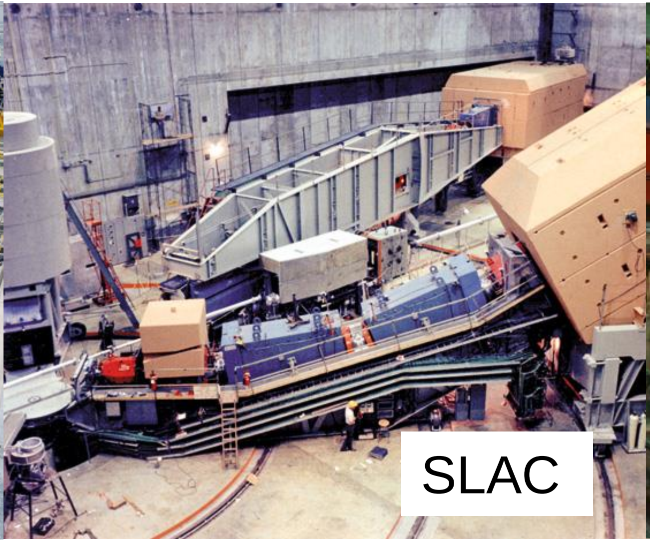
Outline

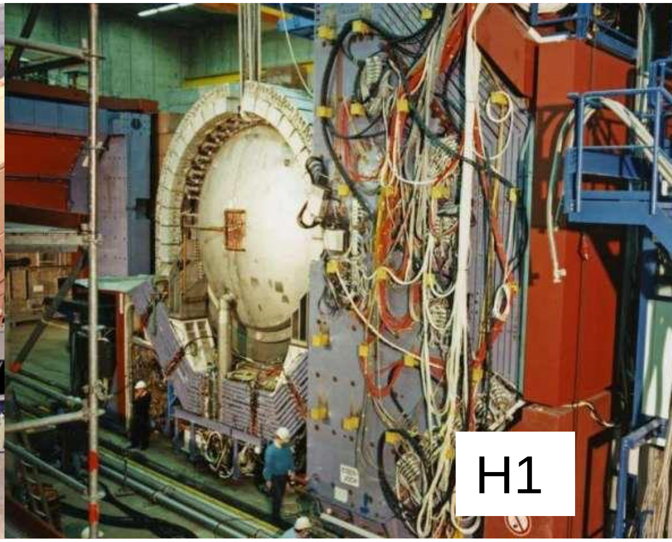
- Why an Electron-Ion Collider (EIC)?
- Design requirements/considerations for an EIC
- Path to possible EIC realization

The EIC is a Deep Inelastic Scattering (DIS) Collider

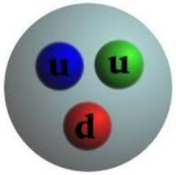
- Point-like electron probe interacts with p/A
- 30+ years of charged lepton DIS at <u>*multiple*</u> laboratories
- So why is EIC the highest priority for new construction for US Nuclear Physics?.....



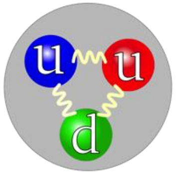




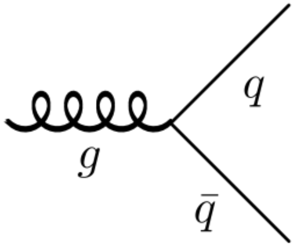
A Brief History of DIS: QCD and Nucleons



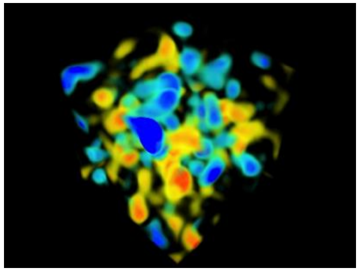
Quark Model: hadrons are made of quarks.



Quantum Chromodynamics: theory of quark and gluon interaction.



QCD is a strongly interacting theory except at short distances: asymptotic freedom and perturbative QCD.

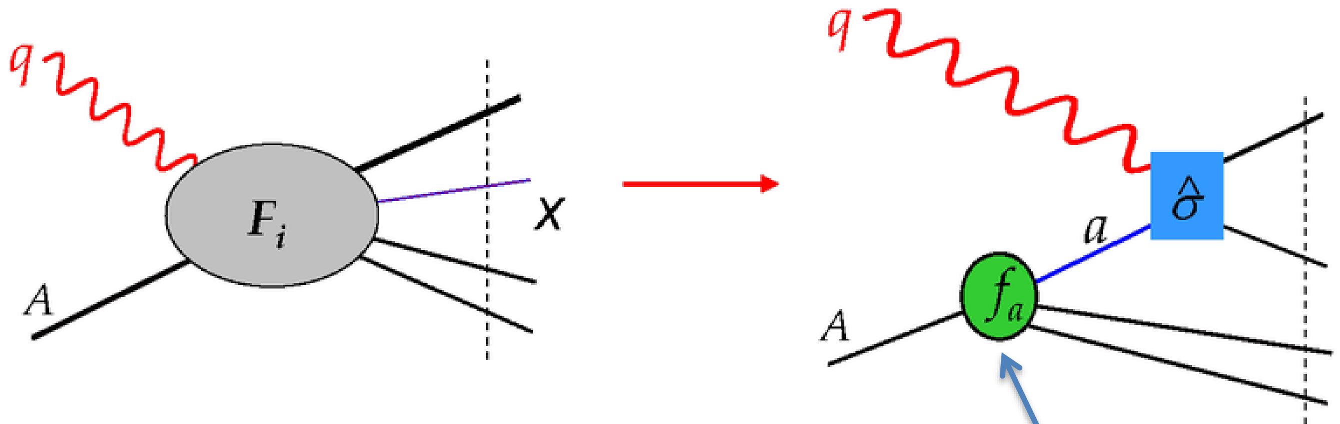


Nucleon size is long-distance in this scale: perturbative theory.

Collinear Factorization

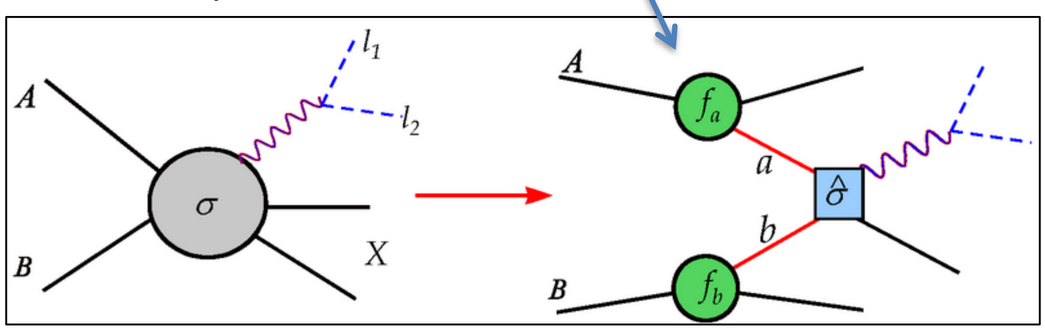
QCD-Factorization

$$\lim_{Q^2\to\text{large},\, x\text{ fixed}} F_i(x,Q^2) = f_a \otimes \hat{s}$$



Same Parton Distributions

Different process

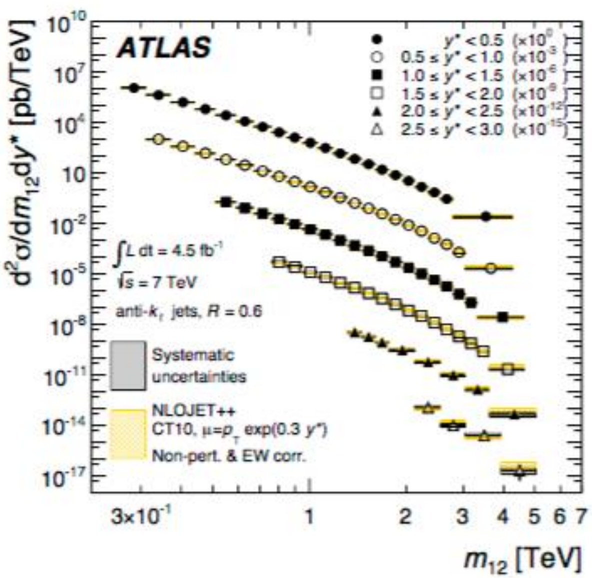


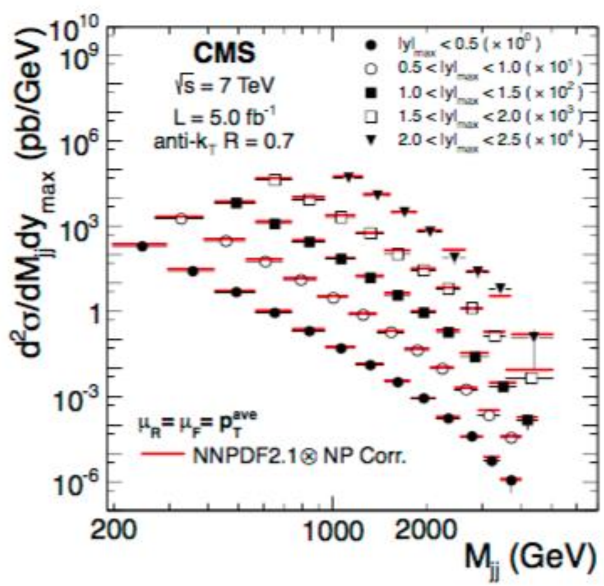
Parton distributions are process independent!

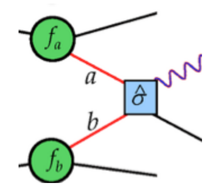
Using pQCD to Understand Protons: *so far*

- Protons at high momentum can be treated as a beam of partons— now identified as free quarks and gluons (Asymptotic Freedom)
- QCD nature of quark and gluons dictates that their densities "evolve" with Q^2.
- This evolution is calculable and the partons behave incoherently.
- You can measure DIS (and other) cross-sections -> extract pdfs -> predict cross-sections for other processes. (Factorization)

Jet cross-sections at the LHC predicted and measured



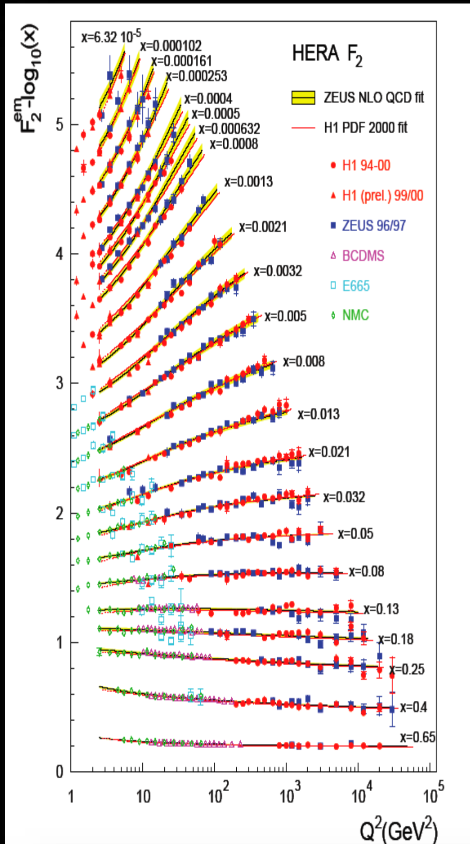




This is great if you are interested in studying the hard interaction (LHC physics)

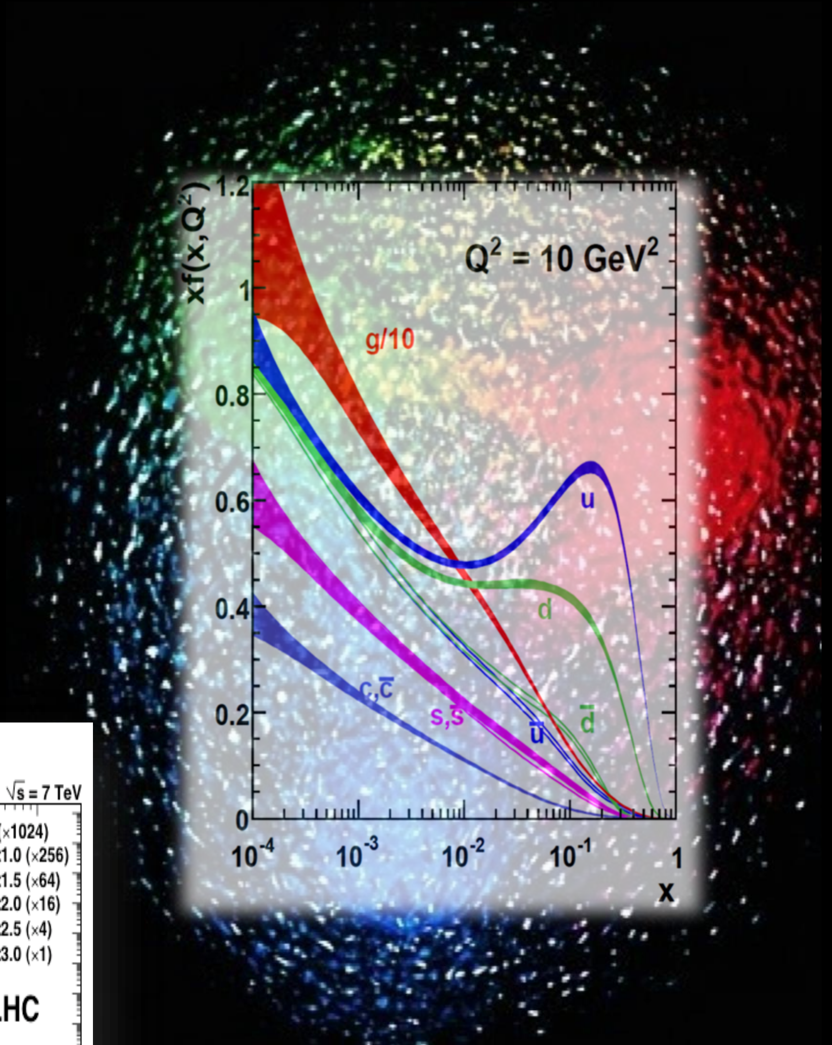
Jefferson Lab

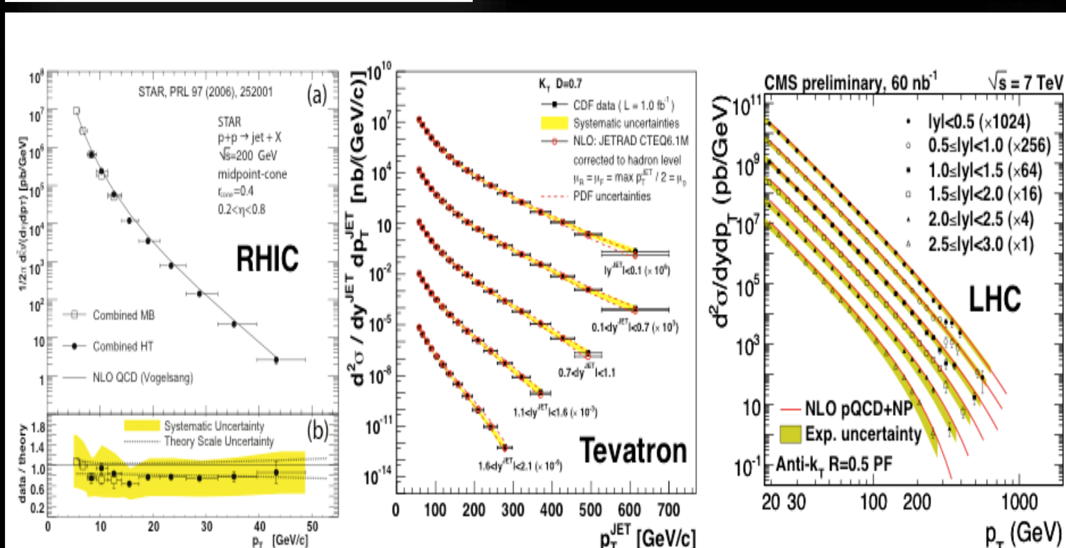
QCD Success !



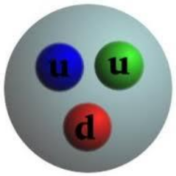
Measure e-p @ 0.3 TeV (HERA)

p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV

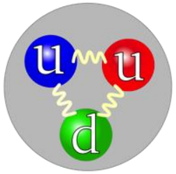


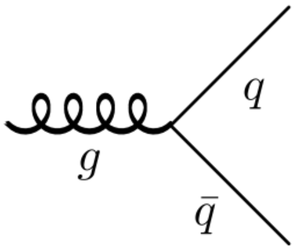


✓ We’ve discovered that (nearly) massless quarks and gluons make up the nucleon/nucleus and that QCD governs their interactions. Rigorous calculations possible.



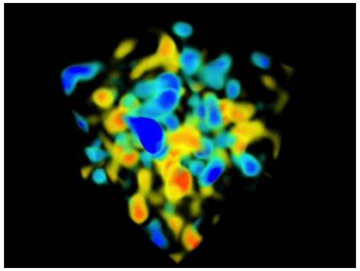
- *So what’s missing?*
- We had hoped….
  - to find out how quarks and gluons and their interactions give rise to the characteristics of the nucleons.
    - Spin
    - Mass
    - Bulk
  - to find out how NN interactions work in terms of QCD.
    - How nuclear forces arise
    - How nuclear characteristics come about
- We were able to do these kinds of things with EM and atoms.
- *<u>So far we have failed…</u>*





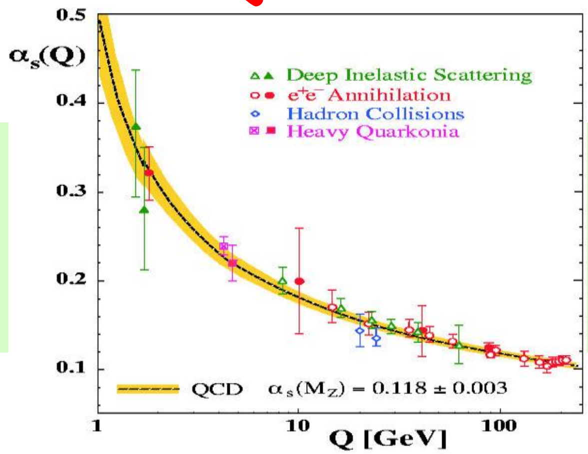
perturbative QCD
at short distances

<u>QCD still unsolved in non-perturbative region</u>
Insights into soft phenomena exist through qualitative models and quantitative numerical (lattice) calculations



perturbative theory

QCD



Confinement

Large Distance
Low Energy

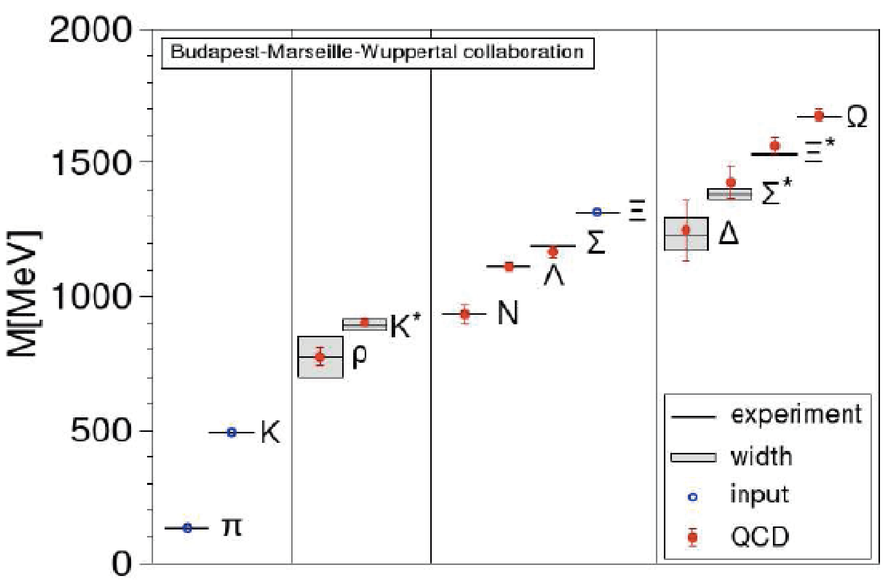
Strong QCD

Asymptotic Freedom

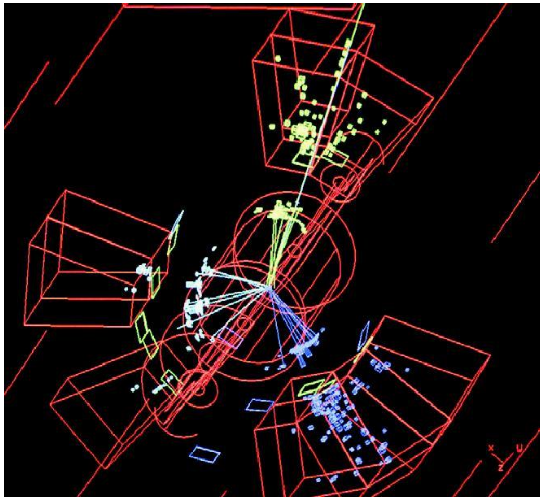
Small Distance
High Energy

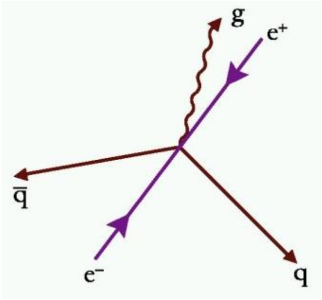
Perturbative QCD

Hadron Spectrum - no signature of gluons?



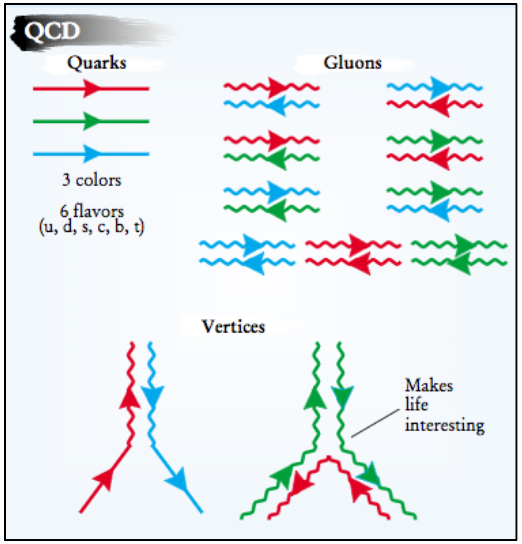
High Energy Scattering



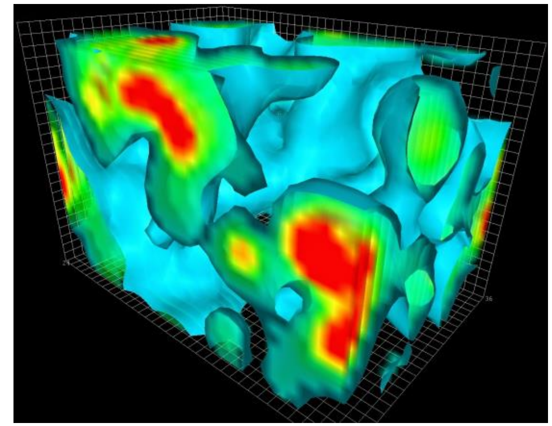


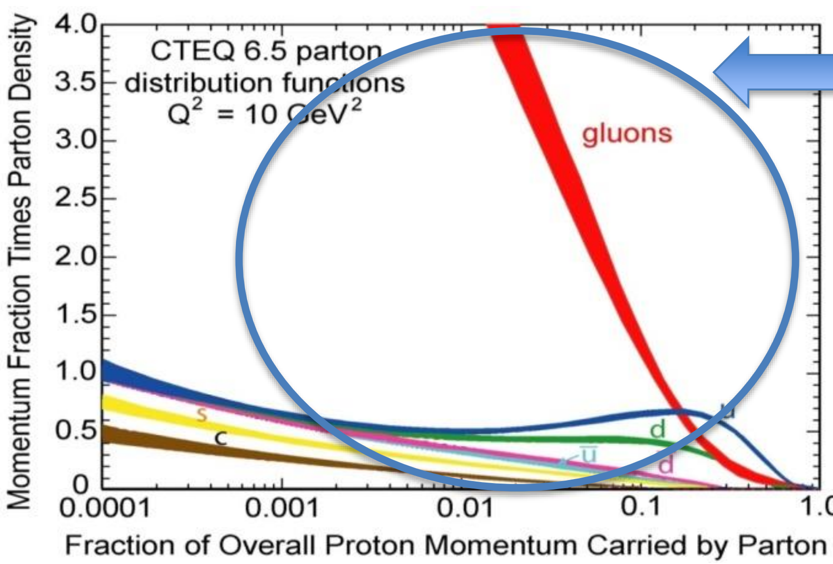
Gluon Jets
Observed

QCD is Unique



Structure and **Interaction** are entangled because of gluon self-interaction.

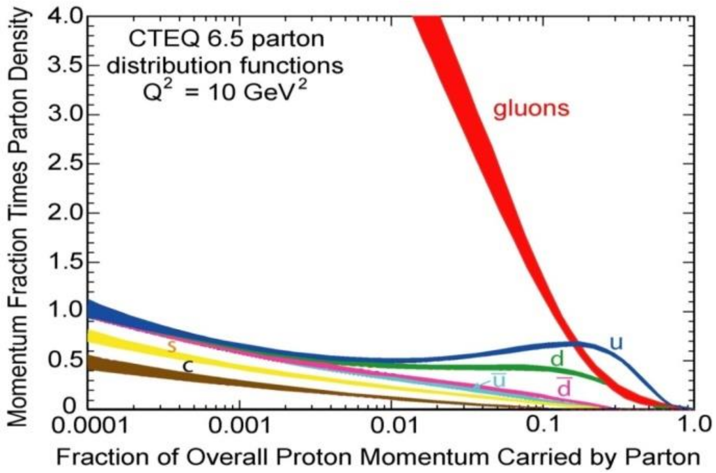




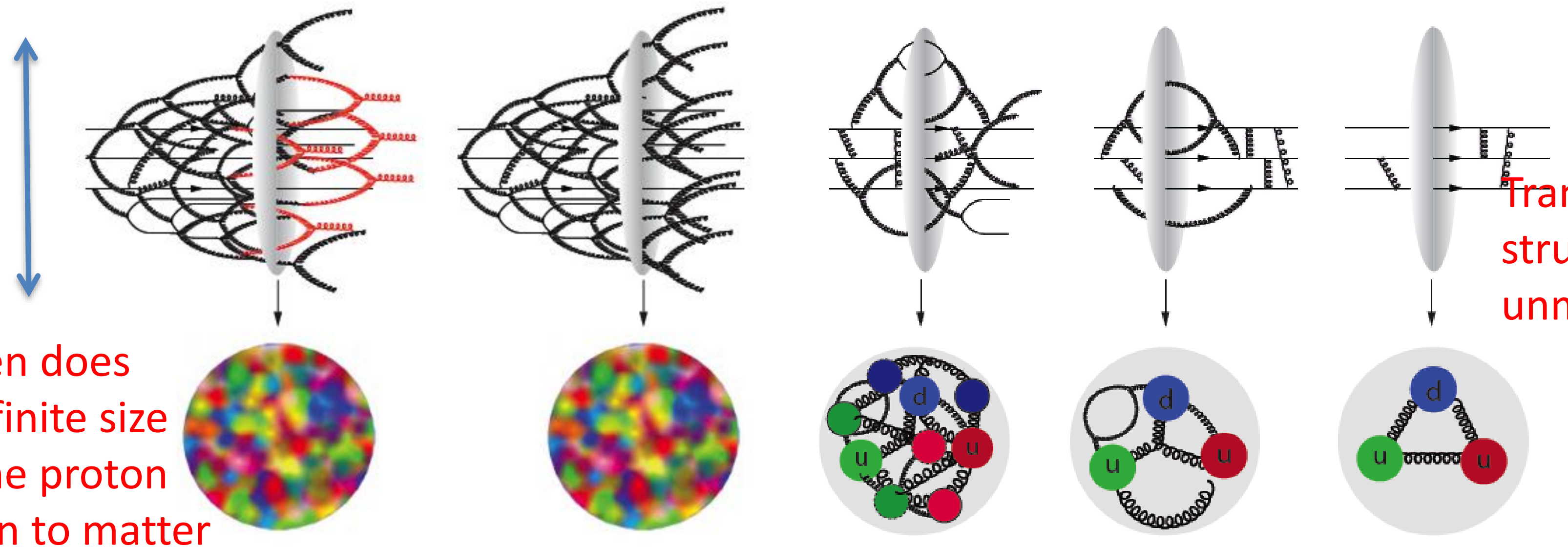
EIC is needed to explore both the region of non-perturbative effects and the gluon dominated region.

The origin of nucleon spin and the distributions of quarks and gluons in nuclei remain mysteries after decades of study.

Proton Structure



- Proton structure is embedded in the quark and gluon distributions.
- Gluons dominate below x of 0.1
- We imagine a proton looks something like the cartoon below..
- But we so far only have longitudinal information…



Transverse structure unmeasured

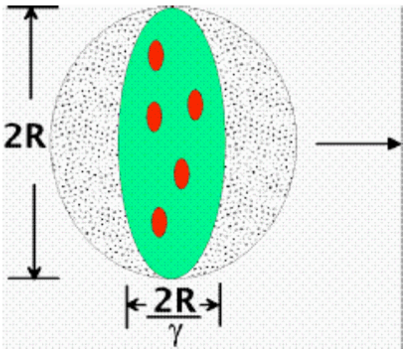
When does the finite size of the proton begin to matter (saturation! confinement!)

X (longitudinal) structure measured

Limits of Longitudinal Information

infinite
momentum
frame

What we know



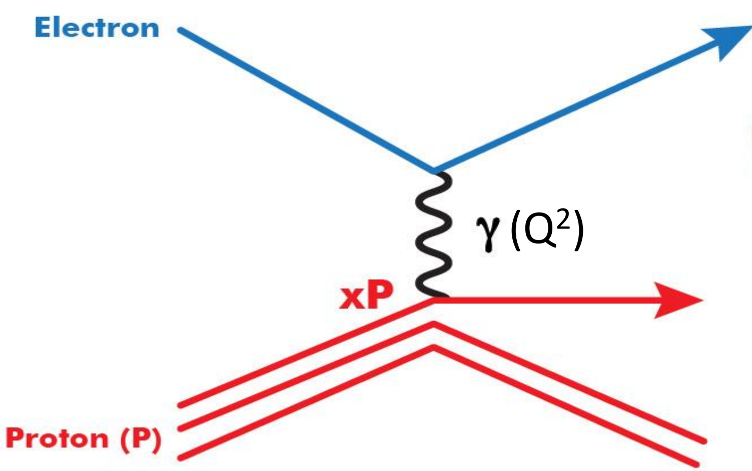
What is the quark and gluon ***structure*** of the proton?
- orbital motion?
- color charge distribution?
- spin?
- how does the mass come about?
- origin of nucleon-nucleon interaction?

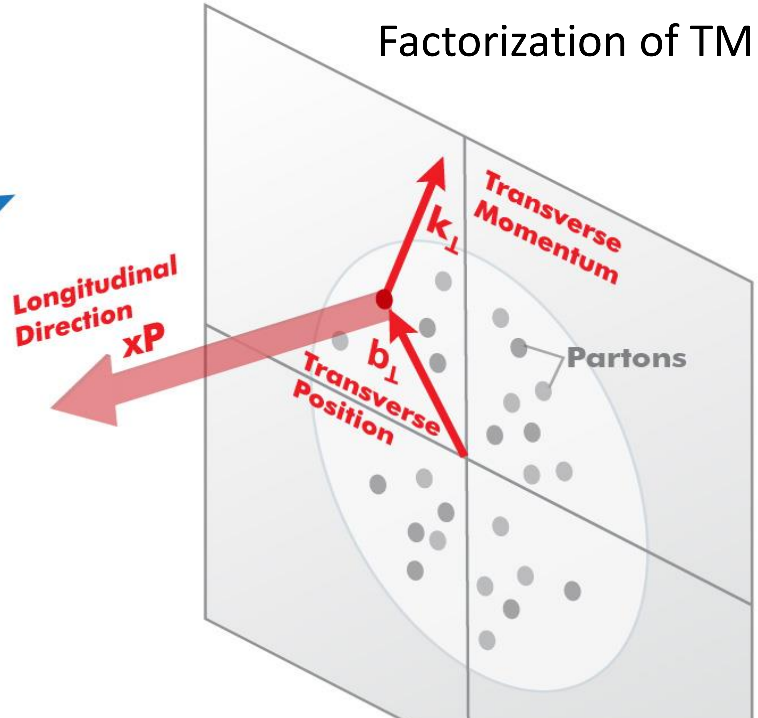
Parton frozen transversely. Framework does not incorporate any transverse information.

This ***was*** the only way to define quark-gluon structure of proton in pQCD….

Progress in pQCD Theory (~1980 - )

Factorization of TMD, GPD





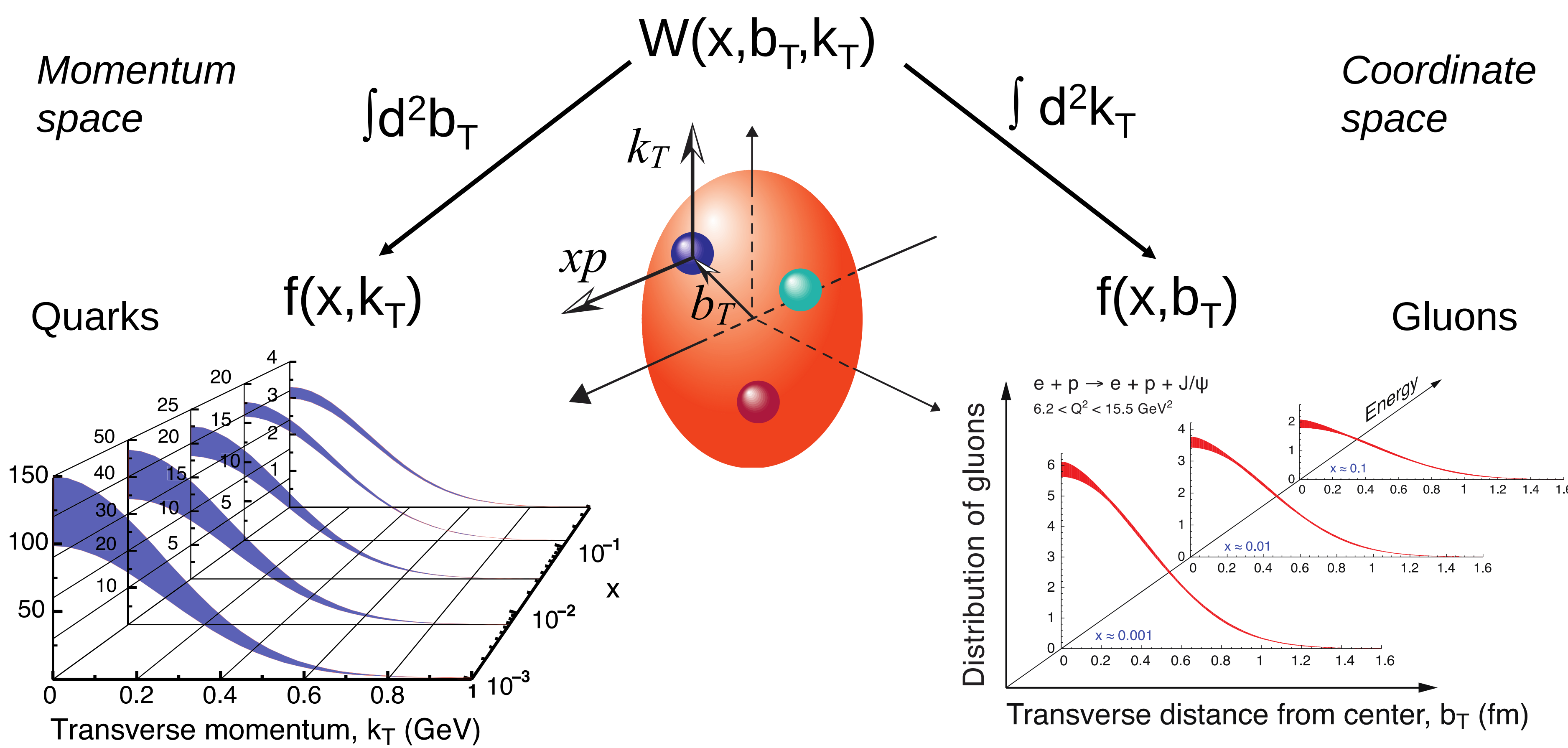
Parton Distribution Functions:
Longitudinal only—
Pert. quarks and gluons can only be thought of longitudinally making up p.

3D (Transverse) Structure
TMD's, GPD's—
Now we know what to measure to understand the 3D structure of nucleons

Transverse Momentum Dependent Distributions (TMD): k_t
Generalized Parton Distributions (GPD): b_t

HERMES,
COMPASS,
JLAB 12

3D Imaging of Quarks and Gluons

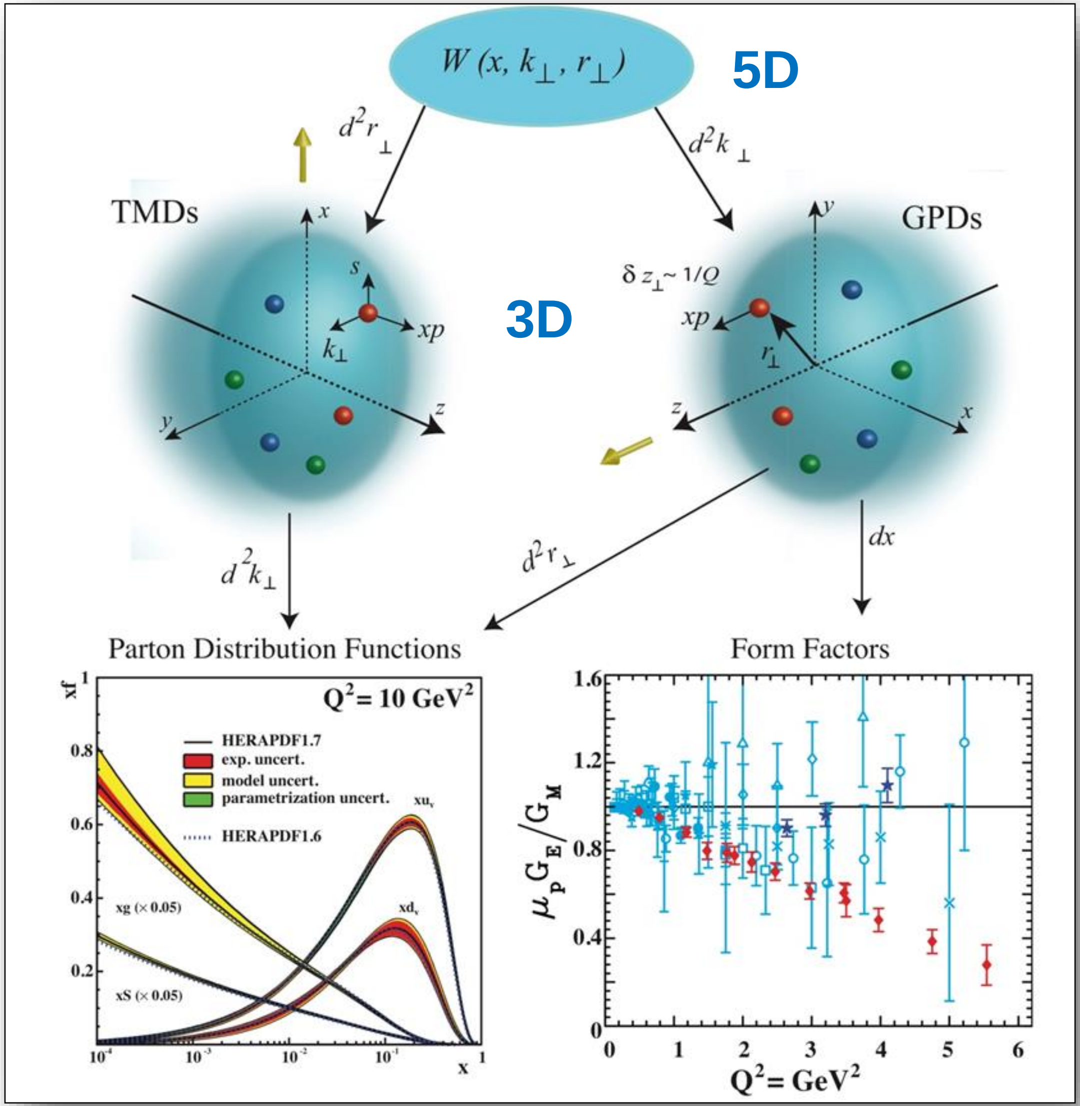


Spin-dependent 3D momentum space images from semi-inclusive scattering

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

Position *r* X Momentum *p* → Orbital Motion of Partons

New Paradigm for Nucleon Structure

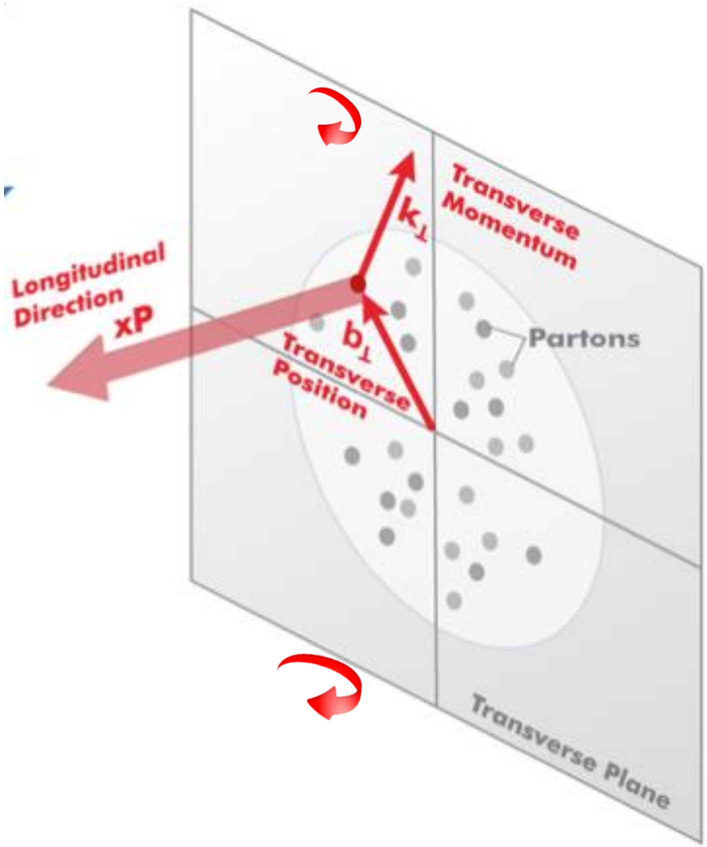


- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets

Map 3D Structure of Nucleons and Nuclei

Experimental Challenge

- We need to measure positions and momenta of the partons transverse to the direction of motion.
- Also their polarization!
- <u>*On one hand:*</u> need high beam energies to resolve partons in nucleons: Q^2 needs to be up to ~1000 GeV^2
- <u>*On the other hand:*</u> (k_T, b_T) are of the order of a few hundred MeV.



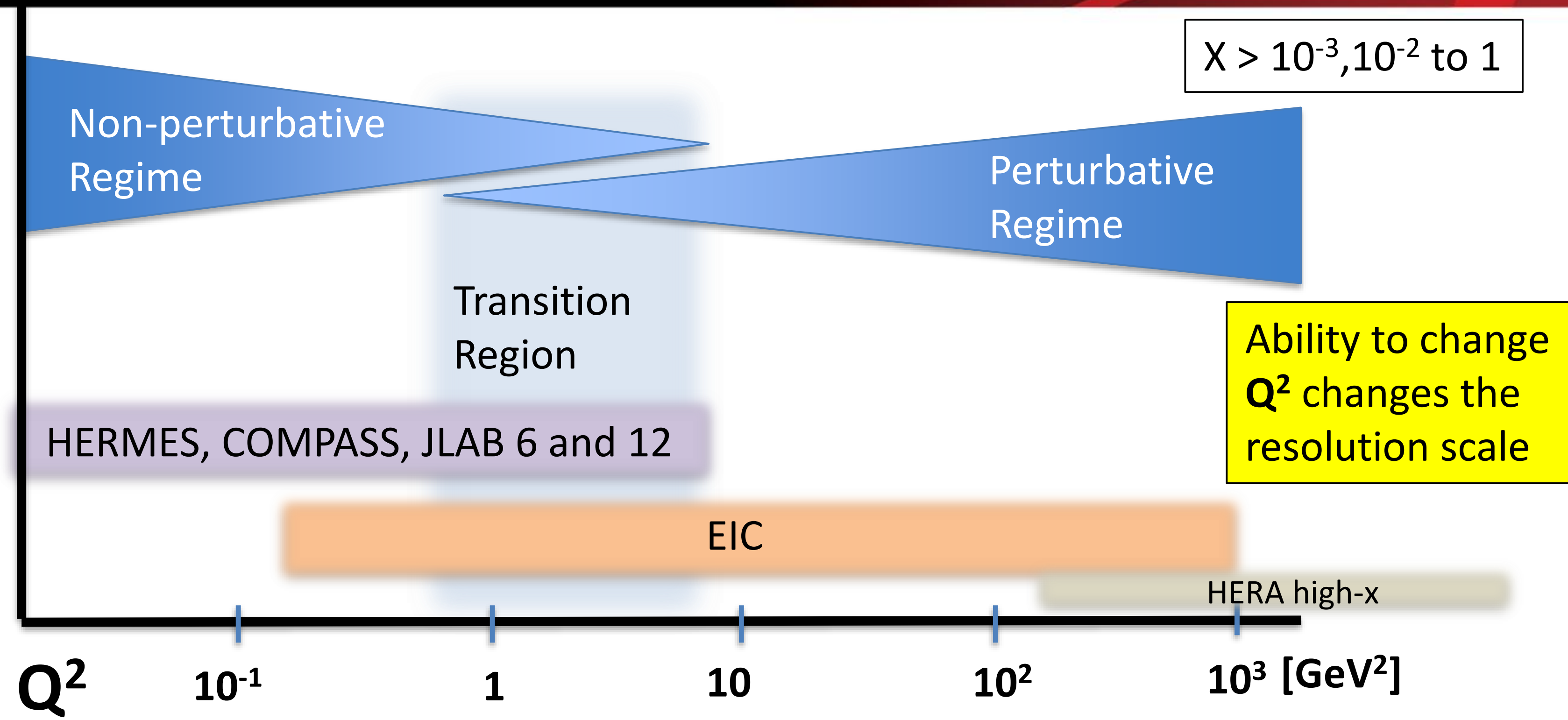
k_T, b_T (~100 MeV)

Proton and Ion Beam

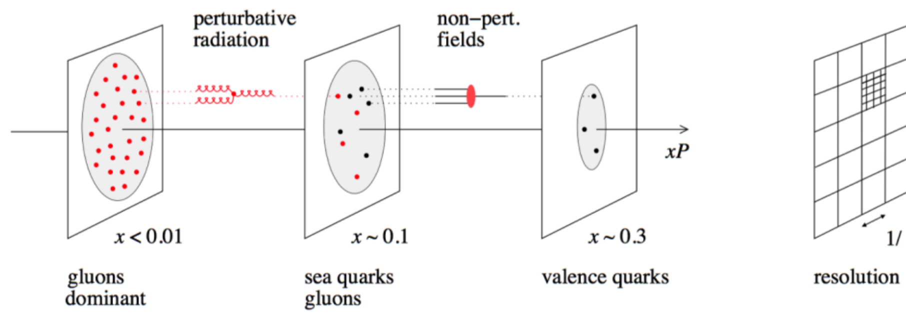
Need to keep $[100\ MeV]_T/E_{proton,Ion}$ manageable (~ >10^{-3}) ➔ E_{proton} ~< 100 GeV

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high

Where EIC needs to be in Q^2 (Q_1^2)



- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements



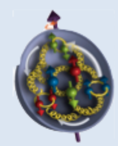
Where EIC Needs to be in x (Nucleon)

Measure in the Multi-Body regime:
- Region of quantum fluctuation + non-perturbative effects → dynamical origin of mass, spin.

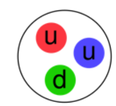
Saturation Regime: Needs to be Accessed via Ions (see later)

Collective Regime

Many-body Regime



Few-body Regime



Ability to change **x** projects out different configurations where different dynamics dominate

10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 X (for proton)

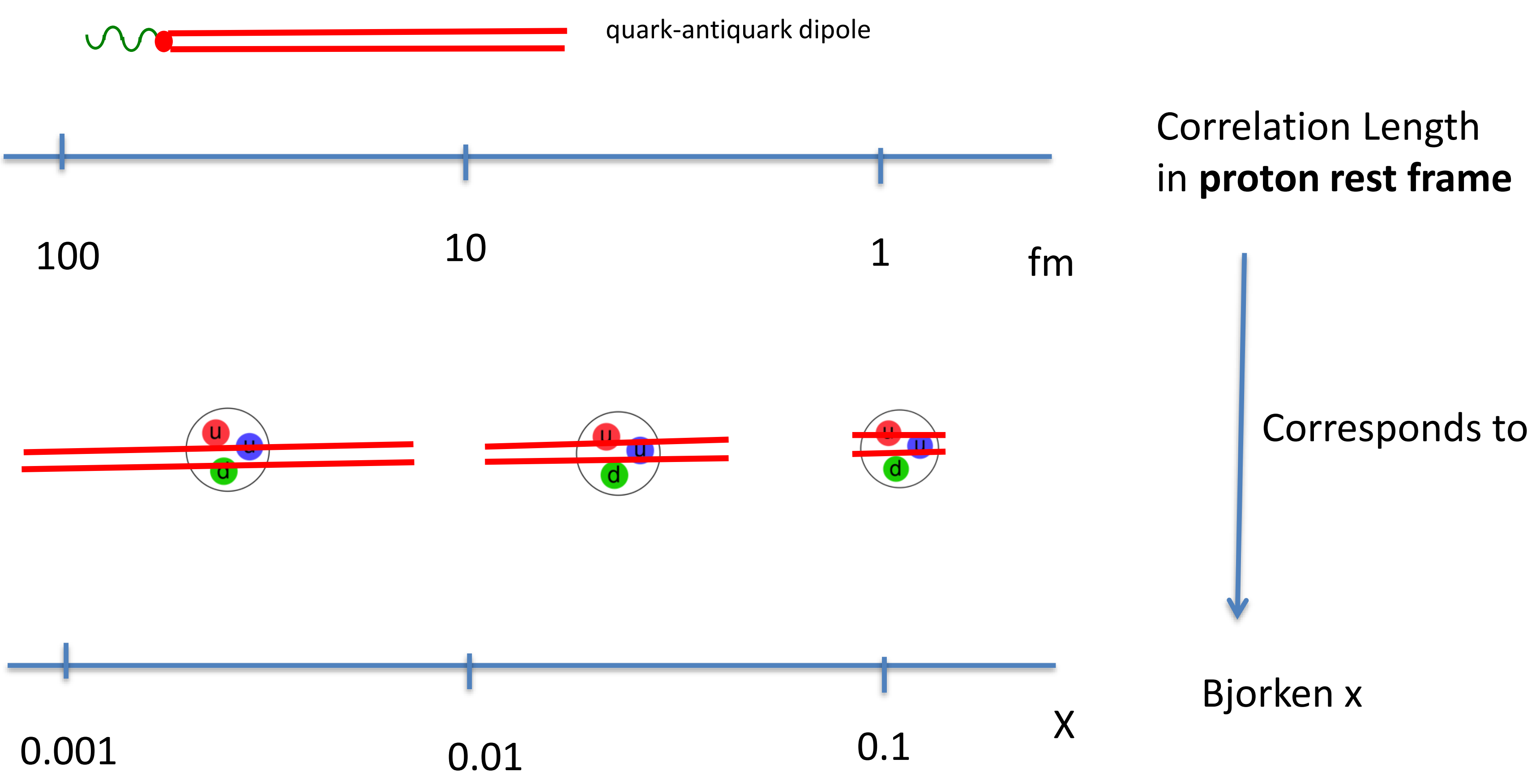
QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Main interest for EIC Nucleon/Nuclear Program

Spin,TMD, GPD…

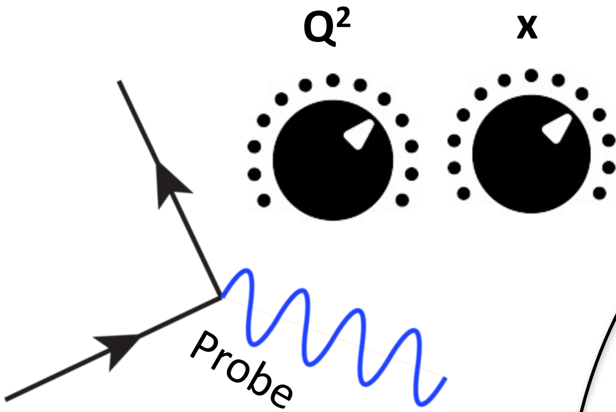
Bjorken x and Length Scale

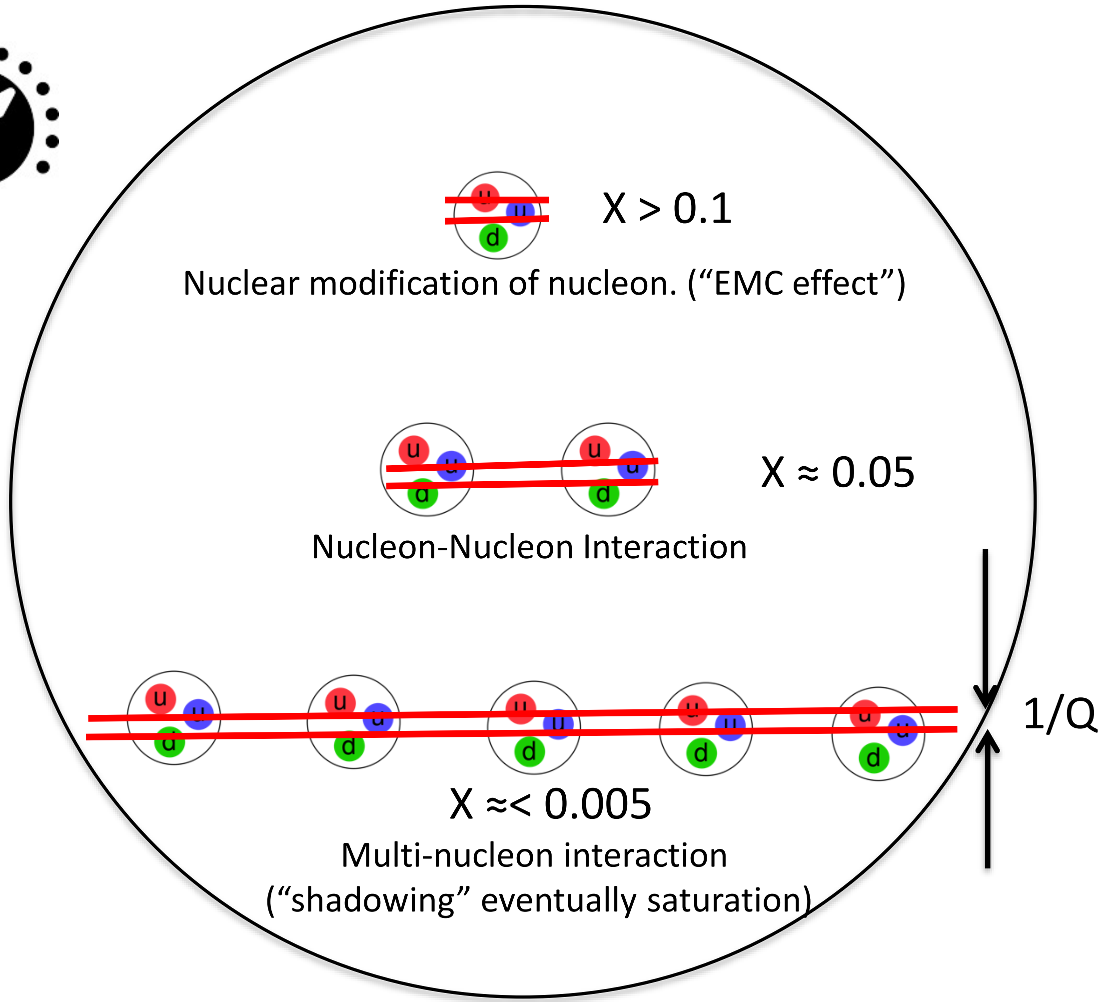


In the proton rest frame, dipole lifetime ($x < 0.1$) extends far beyond the proton charge radius

Parameters of the Probe (Nuclei)

[Cosyn, Armesto, Fazio]

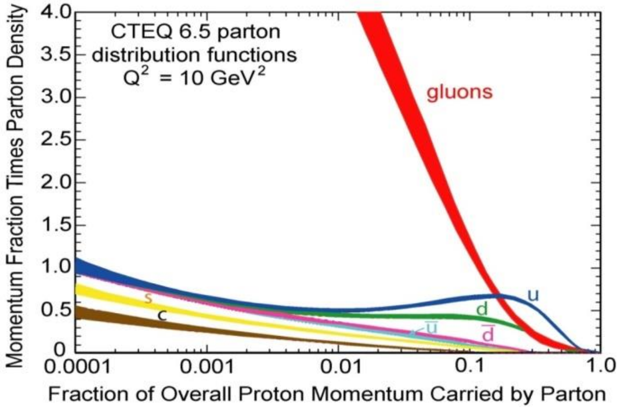




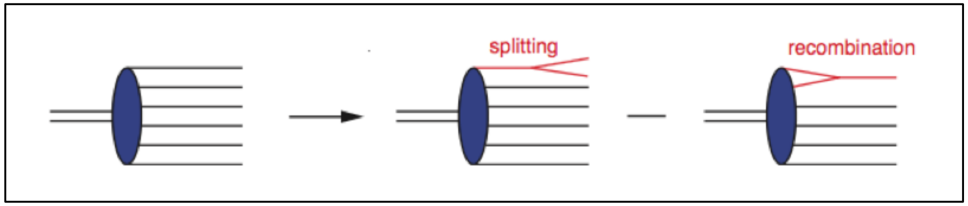
Probing the nucleon interaction in nuclei (note this is different from correlation measurements)

Note: the x range for nuclear exploration is similar to the nucleon exploration

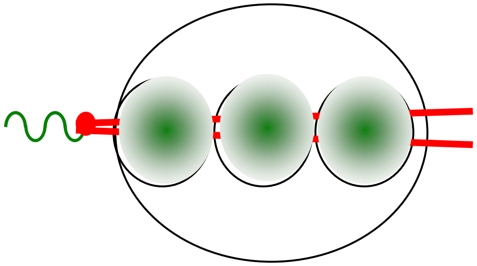
QCD at Extremes: Parton Saturation



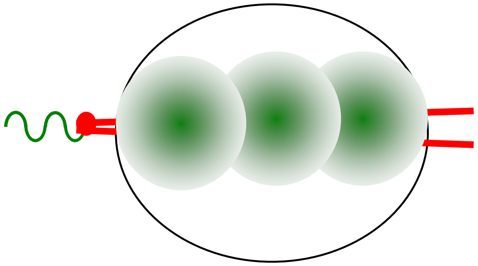
HERA discovered a dramatic rise in the number of gluons carrying a small fractional longitudinal momentum of the proton (i.e. small-x).



This cannot go on forever as x becomes smaller and smaller: parton recombination must balance parton splitting.
i.e. Saturation—unobserved at HERA for a proton. (expected at extreme low x)

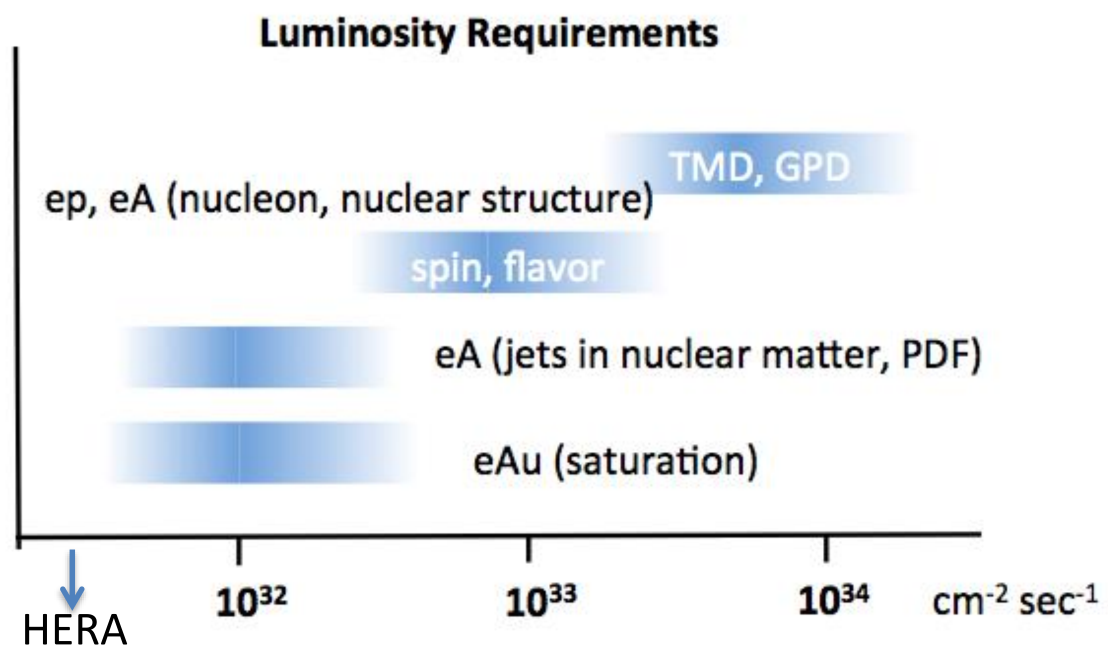


In nuclei, the interaction probability enhanced by $A^{1/3}$



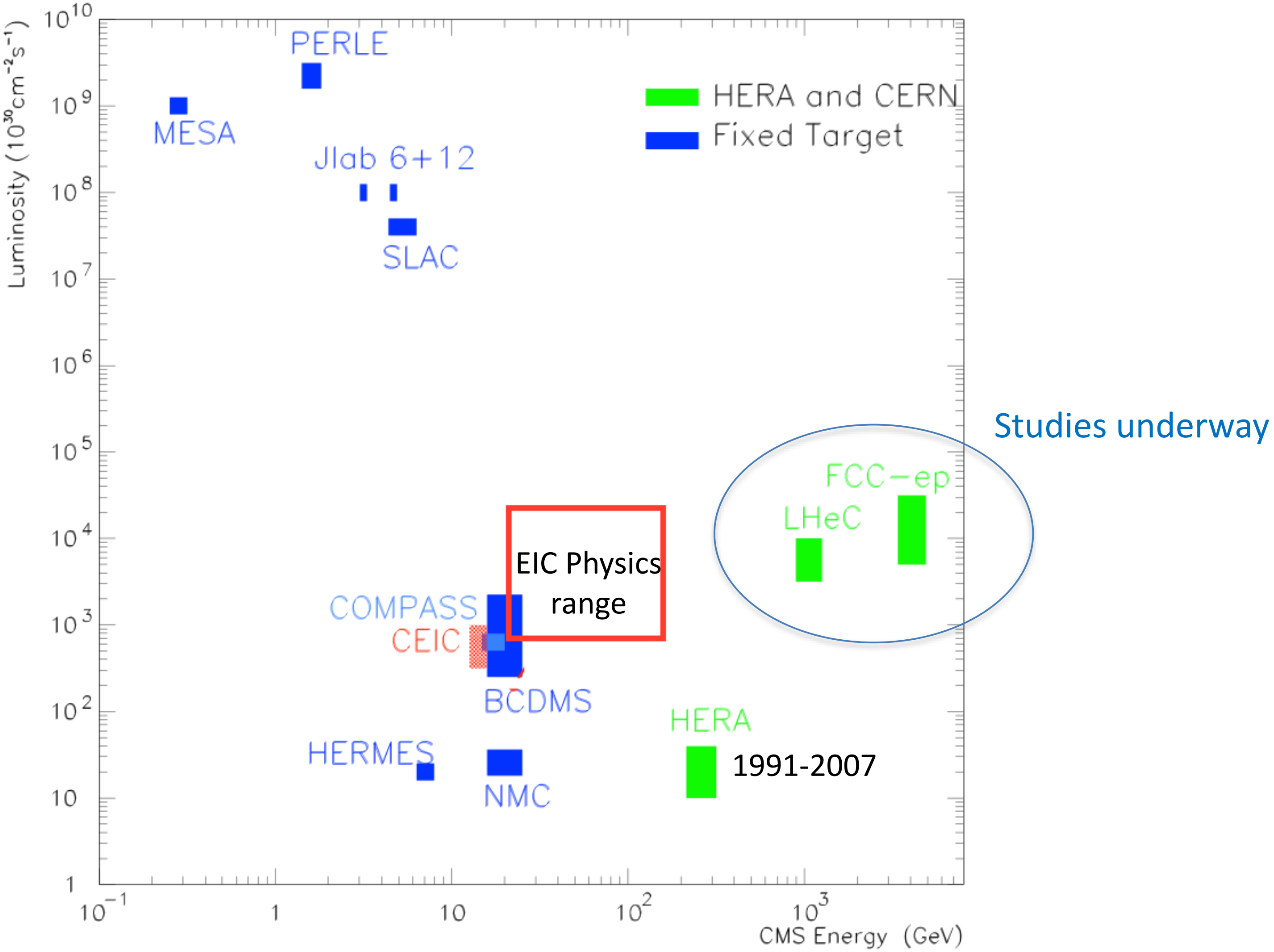
Will nuclei saturate faster as color leaks out of nucleons?

Luminosity/Polarization Needed



Central mission of EIC (nuclear and nucleon structure) requires high luminosity and polarization (>70%).

Past, Existing and Proposed DIS Facilities



The Electron Ion Collider

For e-N collisions at the EIC:

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

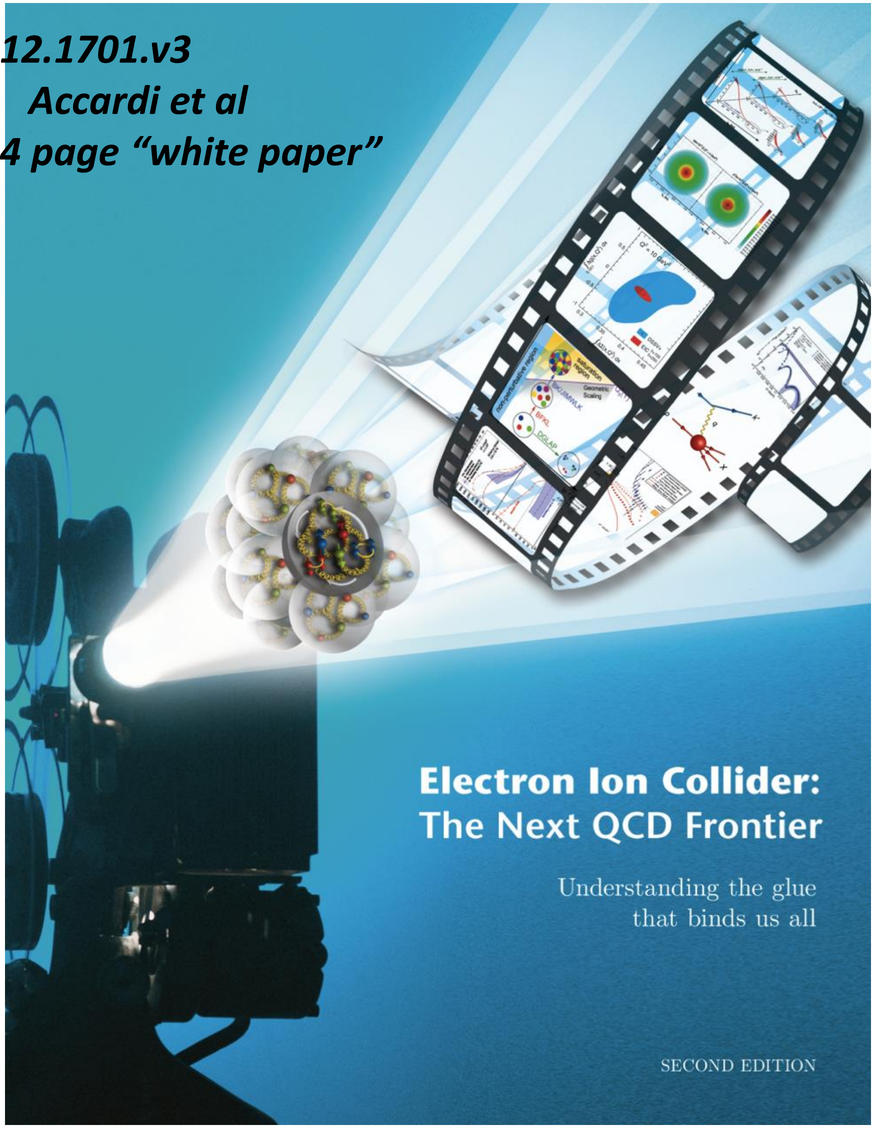
For e-A collisions at the EIC:

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

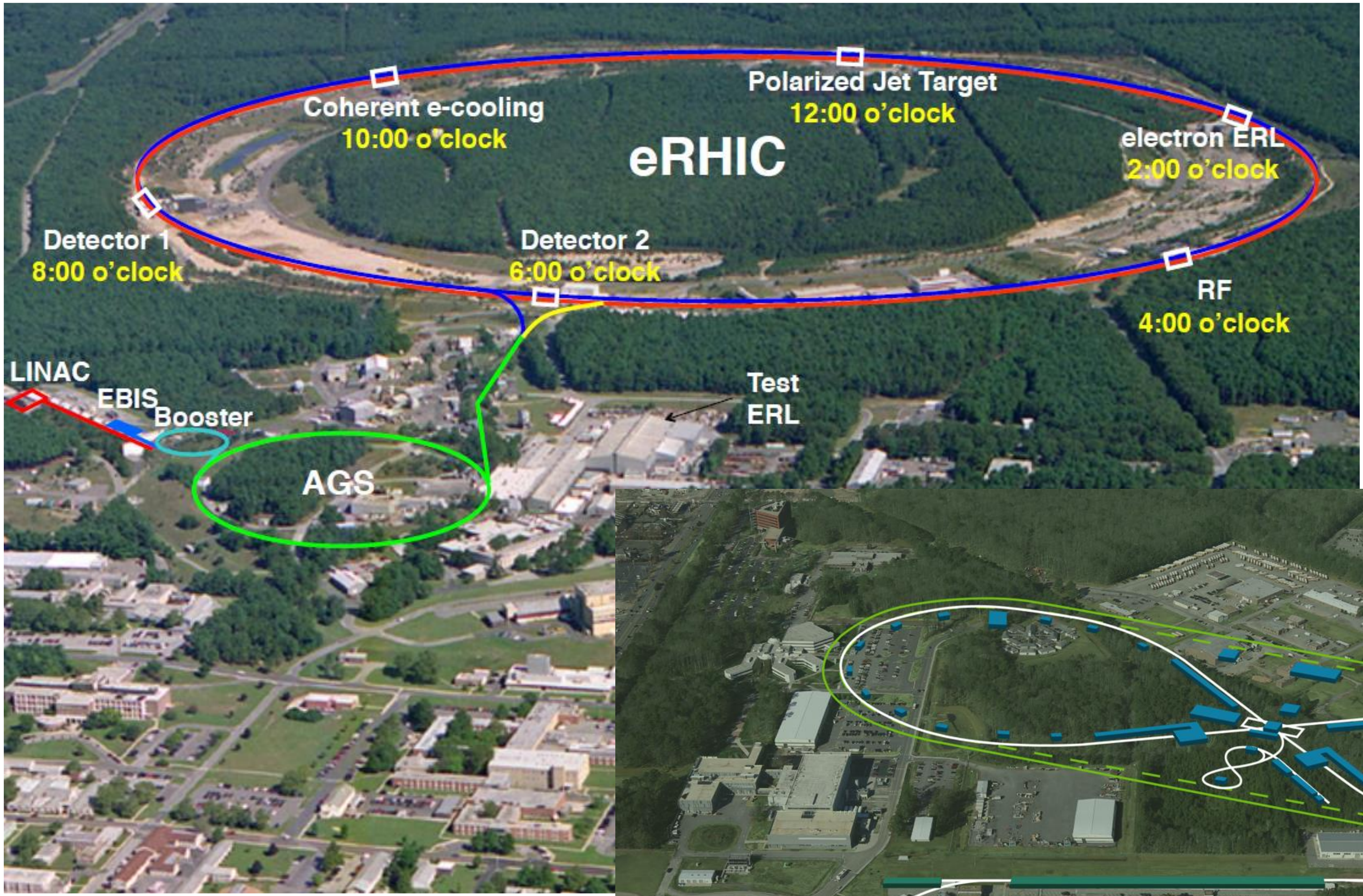
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Two proposals for realization of the science case -
both designs use DOE's significant investments in infrastructure

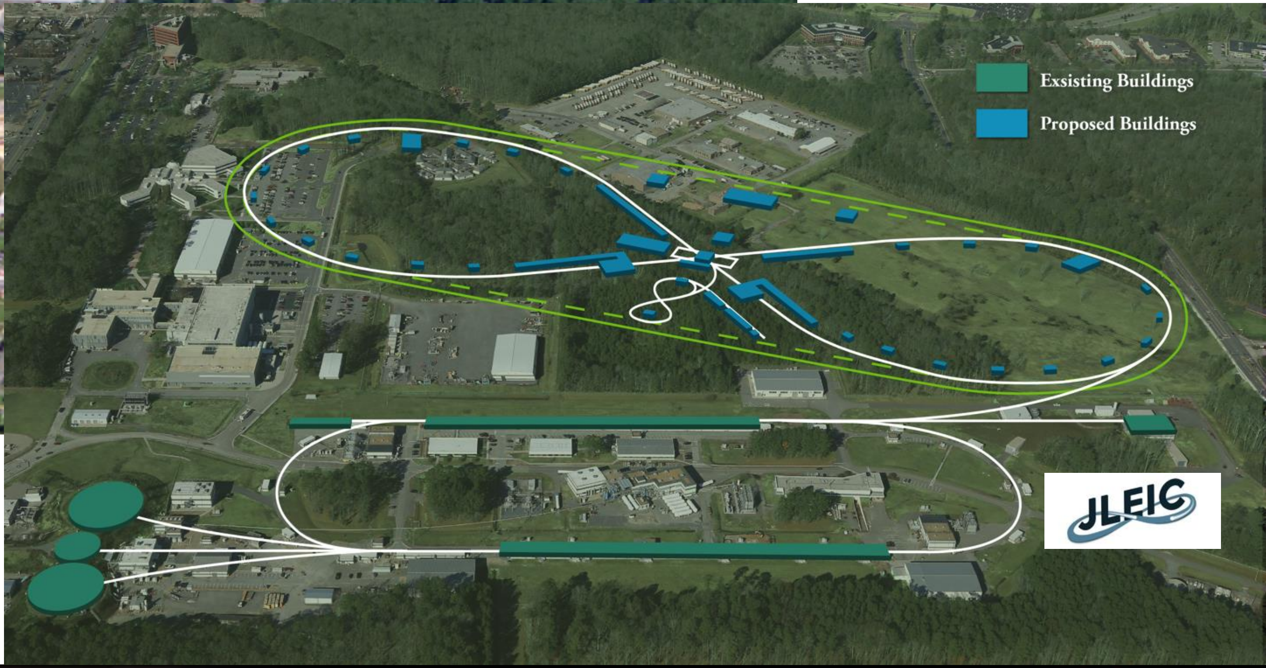
1212.1701.v3
A. Accardi et al
164 page "white paper"



(US-Based) EIC Proposals

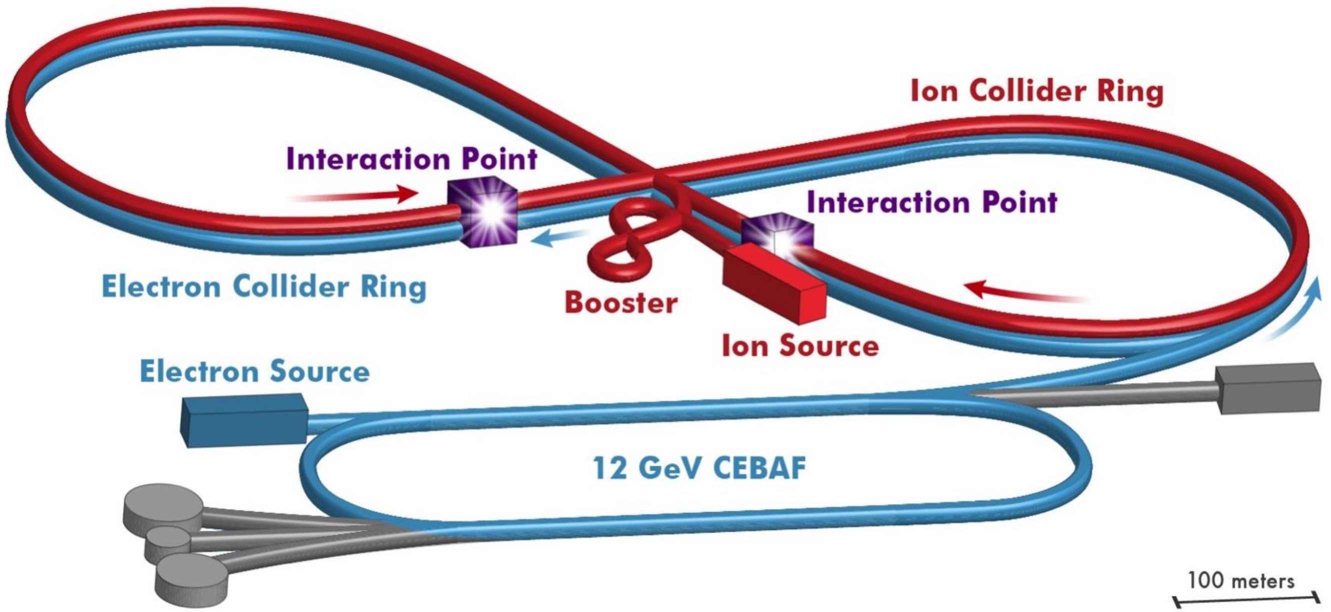


Brookhaven Lab
Long Island, NY



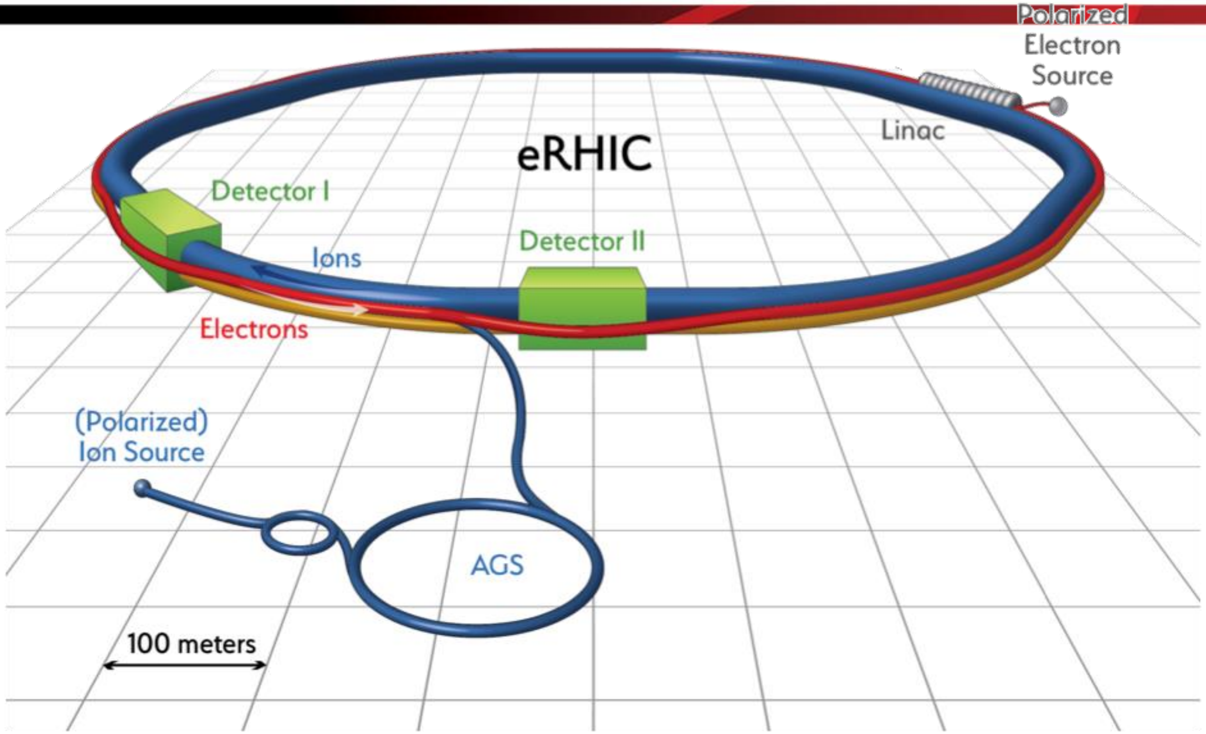
Jefferson Lab
Newport News, VA

JLEIC Proposal



- 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 Proposal



- 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

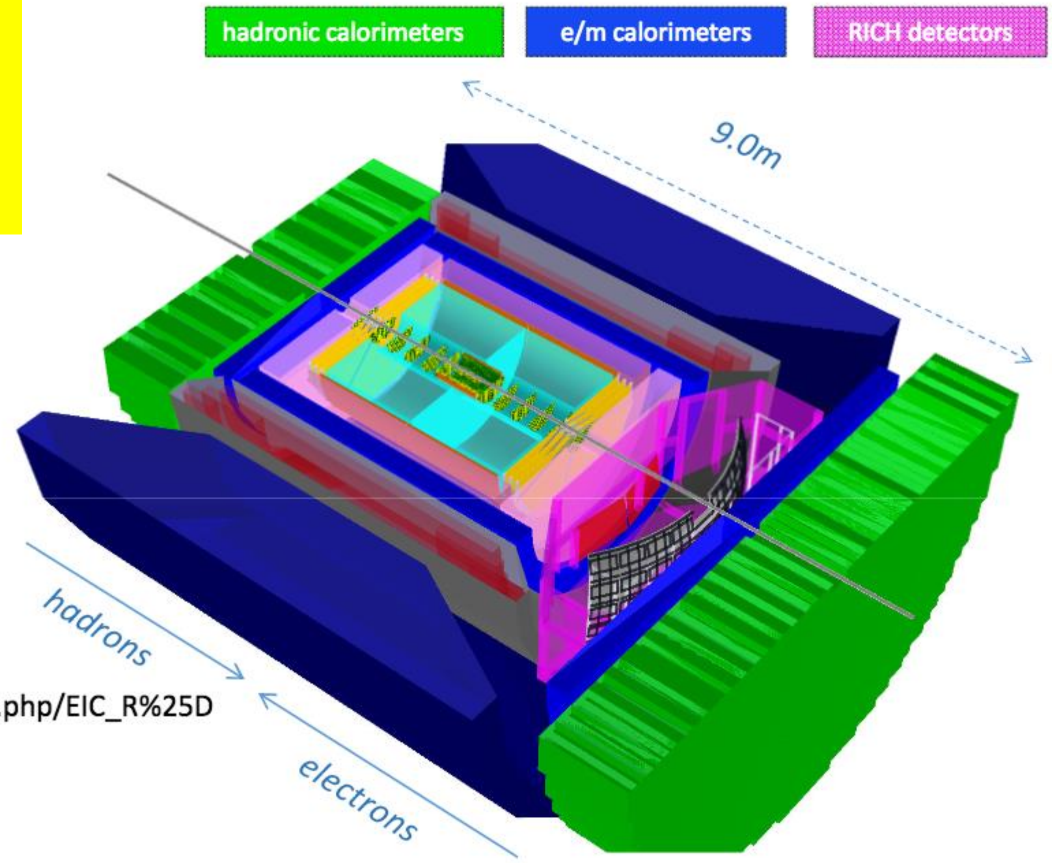
BNL Reference Detector

Reference detector layout: BeAST

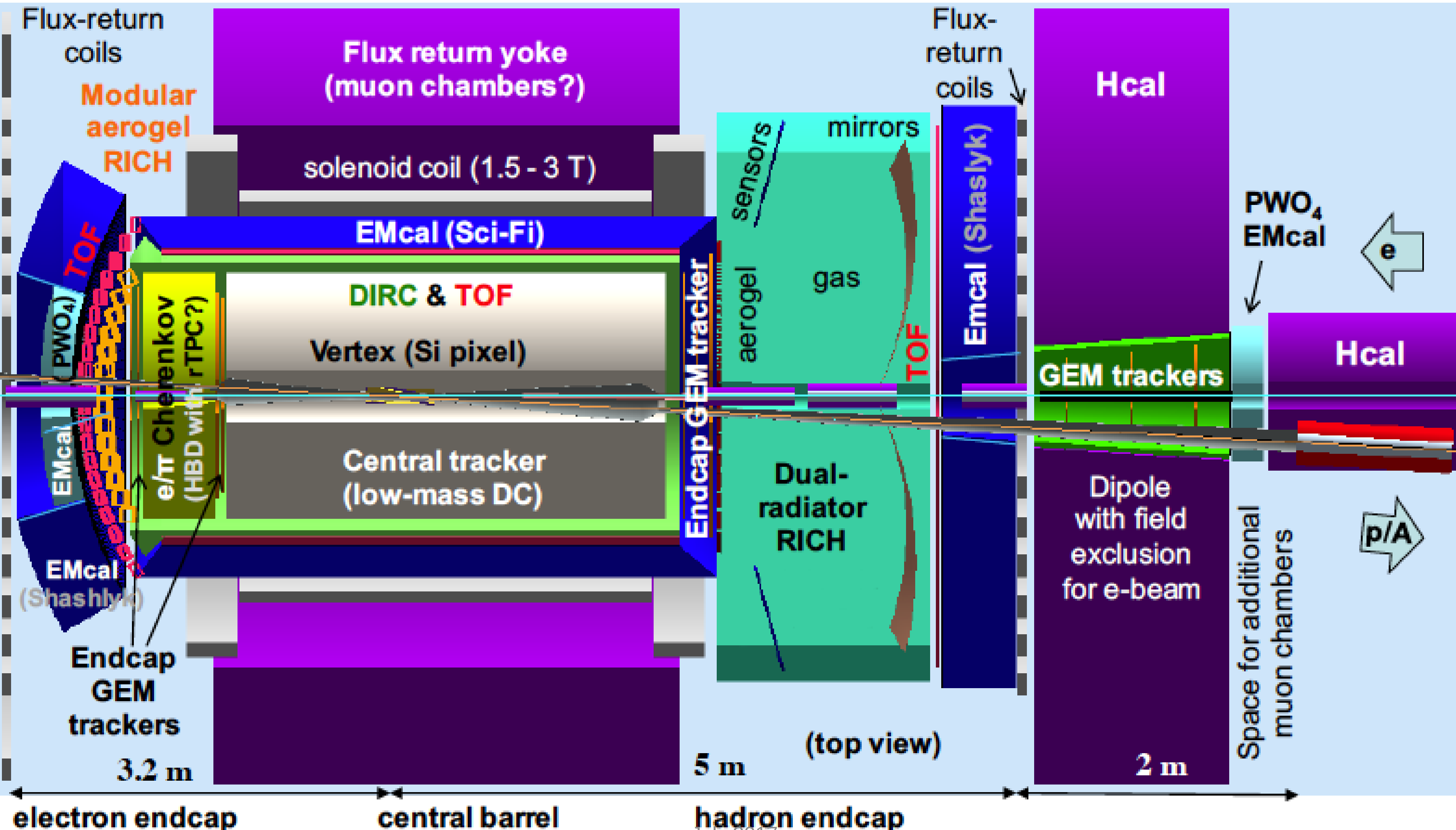
EIC Physics demands ~100% acceptance for all final state particles (including particles associated with initial ion)

- BeAST: Brookhaven eA Solenoidal Tracker
- Hermetic coverage
- Tracking and e/m calorimetry in the range $|\eta| < 3.5$
- Active R&D for detector components

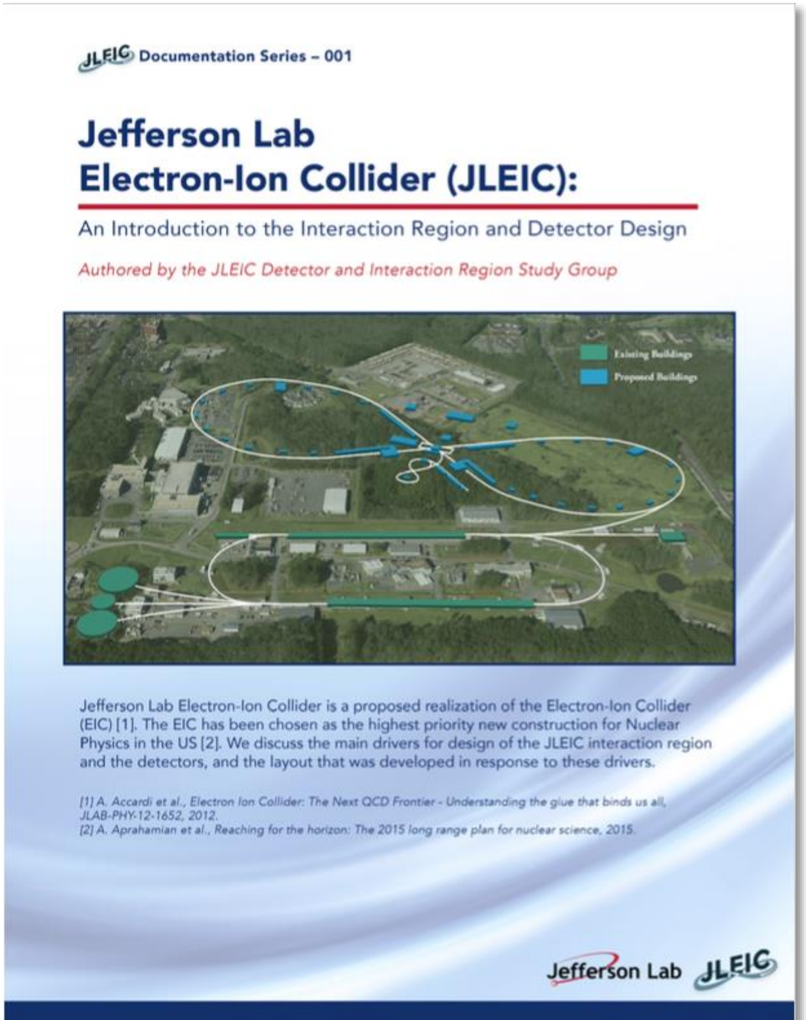
https://wiki.bnl.gov/conferences/index.php/EIC_R%25D



Current JLEIC Concept



JLEIC Detector and IR Document



JLEIC Documentation Series – 001

Jefferson Lab
Electron-Ion Collider (JLEIC):

An Introduction to the Interaction Region and Detector Design

Authored by the JLEIC Detector and Interaction Region Study Group

Jefferson Lab Electron-Ion Collider is a proposed realization of the Electron-Ion Collider (EIC) [1]. The EIC has been chosen as the highest priority new construction for Nuclear Physics in the US [2]. We discuss the main drivers for design of the JLEIC interaction region and the detectors, and the layout that was developed in response to these drivers.

[1] A. Accardi et al., *Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all*, JLAB-PHY-12-1652, 2012.
[2] A. Aprahamian et al., *Reaching for the horizon: The 2015 long range plan for nuclear science*, 2015.

Jefferson Lab JLEIC

Can be found at the JLEIC Public Wiki page at: https://eic.jlab.org/wiki

This a short 9-page general introduction for people new to JLEIC.

More specific and detailed documents to follow.

EIC Realization Imagined

What can we (or I) speculate about any EIC timeline?

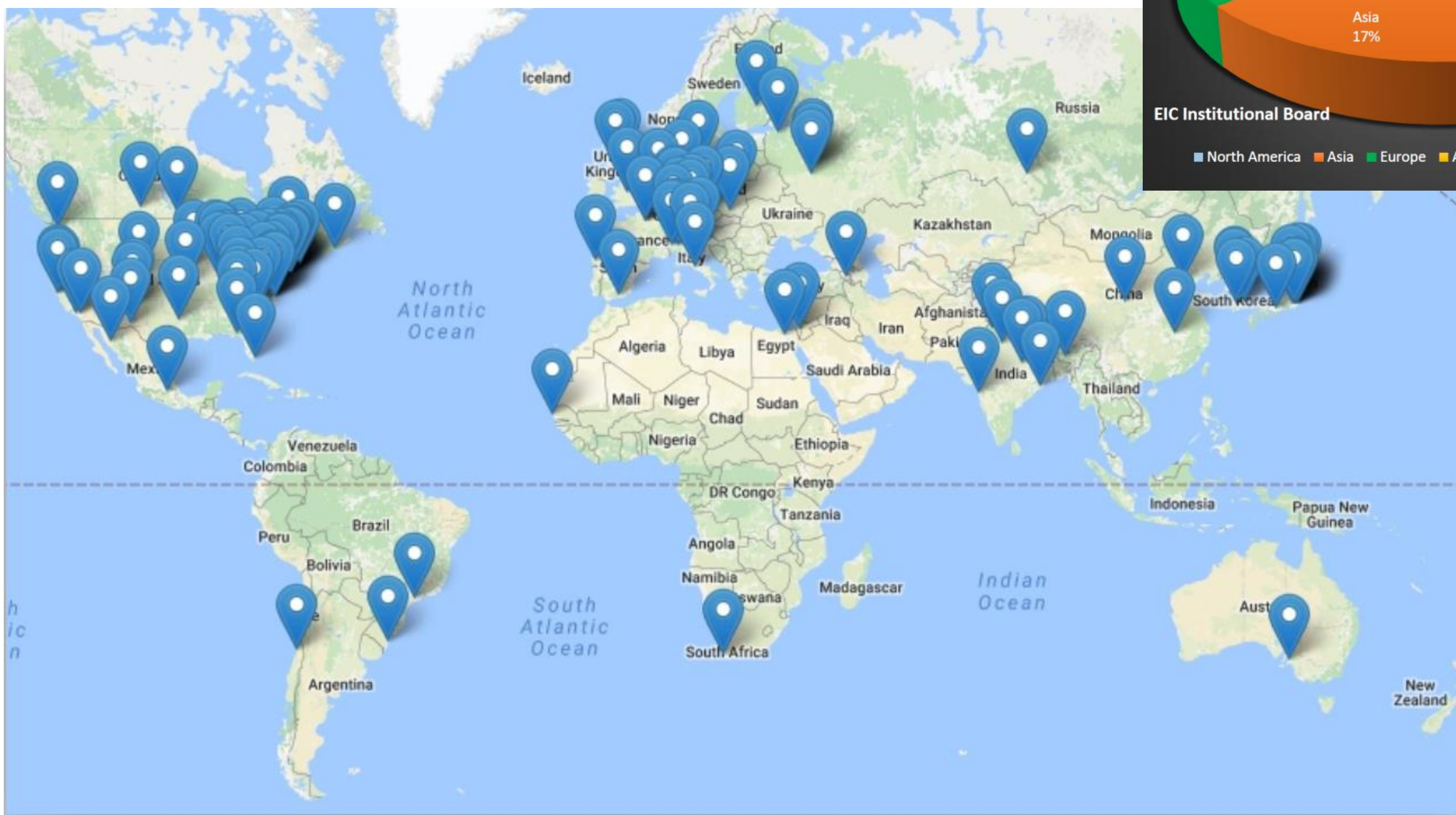
- A National Academy of Sciences study has been initiated. Charge: “assess the scientific justification for a U.S. domestic electron ion collider facility,“ (Wider Science Community)
  - 1st meeting February, 2nd meeting April, 3rd meeting September 2017
  - Report anticipated early 2018 … assuming positive …
  - This would/could imply CD-0 Late 2018
- (critical) EIC accelerator R&D questions will not be answered until ~2019?
- Site selection may occur perhaps around 2019/2020?
- EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20

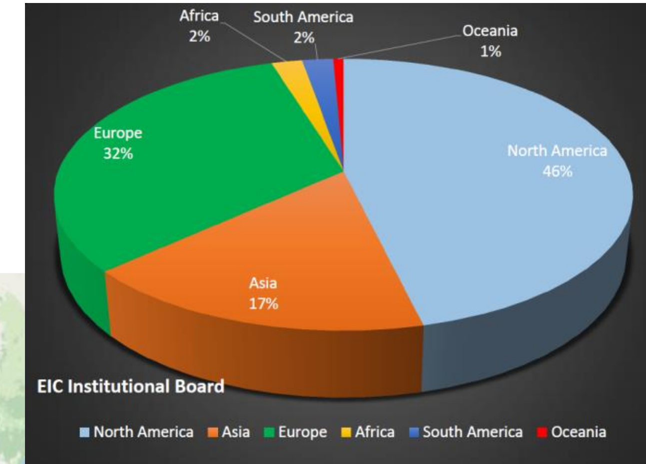
→ <u>Most optimistic</u> scenario would have EIC funds start in FY20, perhaps more realistic (yet optimistic) construction starts in FY22-23 timeframe

→ *(My) Best guess for EIC completion assuming NAS blessing would be 2025-2030 timeframe*

EIC Users Group and International Interest

Formed 2016, currently: 708 members
162 institutions, 29 countries (9/2017)





EIC UG Meeting, Trieste

Opening Session

Welcome		09:00 - 09:05
EIC Science Case	DESHPANDE, Abhay	09:05 - 09:35
EIC project / EICUG and US NAS review status	SURROW, Bernd	09:40 - 10:10
DOE NP Perspectives on a Possible Future Electron Ion Collider	HALLMAN, Tim J.	10:15 - 10:45
Coffee Break		10:50 - 11:25
The 2017 NuPECC Long Range Plane	BRACCO, Angela	11:25 - 11:45
Eu Integrating Activity in Hadron Physics	ERAZMUS, Barbara	11:50 - 12:05
The IN2P3 visions and plans for nuclear and particle physics	VERDIER, Patrice	12:10 - 12:30
the CEA/IRFU visions and plans for nuclear and particle physics	ETIENVRE, Anne-Isabelle	12:35 - 12:55
The INFN vision and plans for nuclear and particle physics	NAPPI, Eugenio	13:00 - 13:20

DOE NP

NUPECC

EU

IN2P3

CEA/IRFU

INFN

18-22 July 2017

Next Meeting:
Washington DC
Catholic University of America
July-August 2018

New Users → New Physics → Lots of activities

Programs related to EIC

physical masses

Highly Active EIC Community has evolved

- ...ia production with 10...
- In view of new discoveries of multi-quark XY...

Conclusion

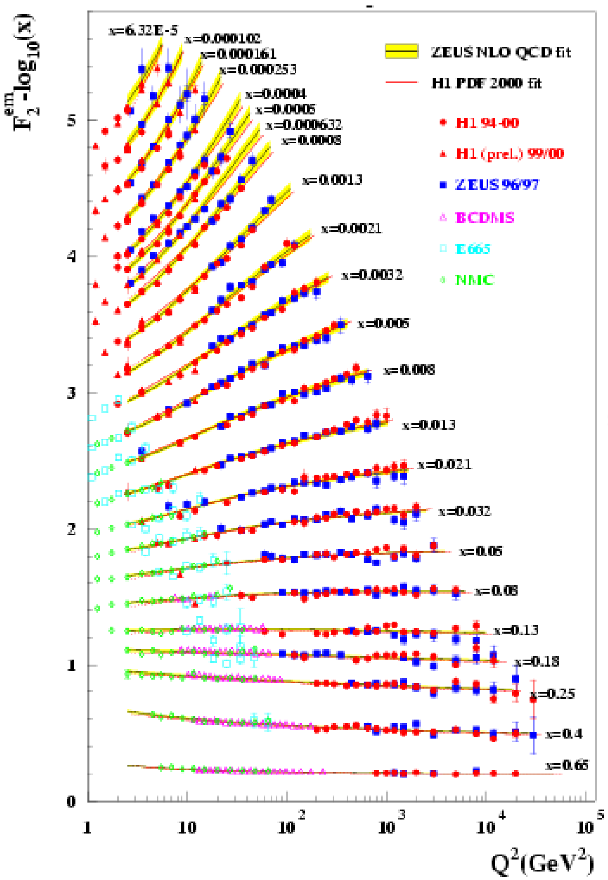
- EIC Program aim: Revolutionize the understanding of nucleon and nuclear structure and associated dynamics.
- For the first time, EIC will enable us to study the nucleon and the nucleus at the scale of quarks and gluons, over (arguably) the entire kinematic range that is relevant for exploring the QCD dynamics of nuclear and nucleon structure.
- Outstanding questions raised both by the science at RHIC/LHC and at HERA/COMPASS/Jefferson Lab, have **naturally led to the science and design parameters of the EIC.**
- There exists **worldwide interest** in collaborating on the EIC – *please join the effort!*

In the next decades, with the advent of the EIC, a new window will open to the quark gluon structure of ordinary QCD matter.

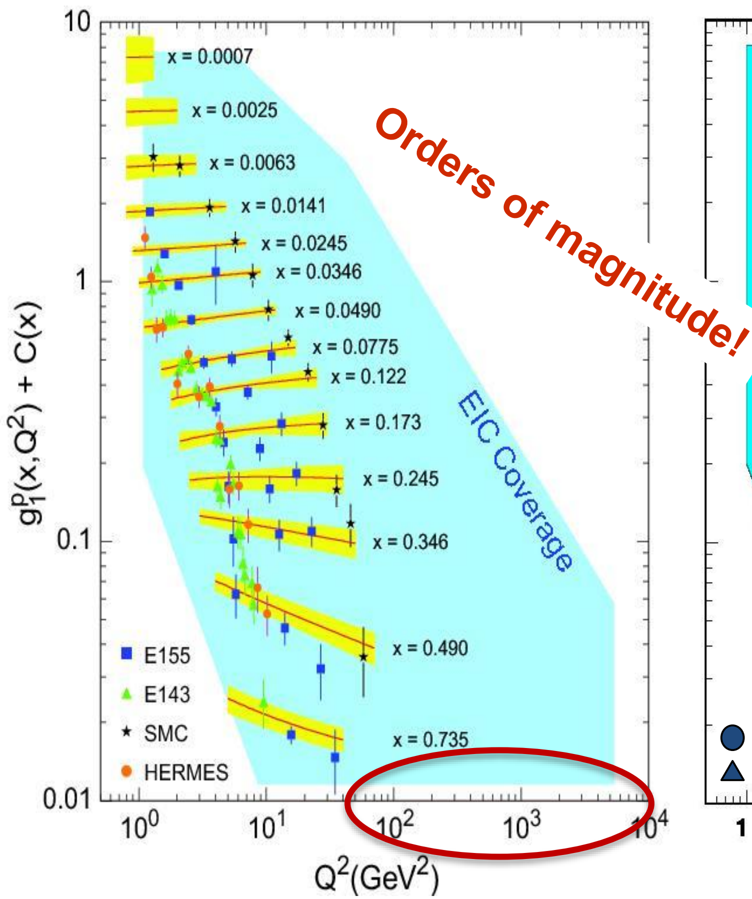
Backups (Check these out… projected results!....)

World Data on F_2^p World Data on g_1^p World Data on h_1^p

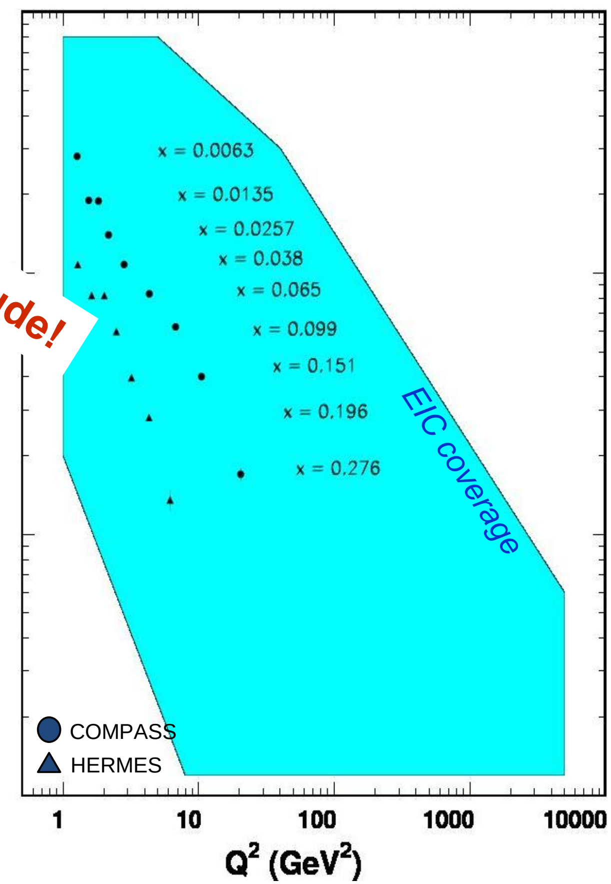
$$F_{UT}^{\sin(\phi_h+\phi_s)}(x,Q^2) + C(x) \propto h_1$$



momentum



spin



transverse spin ~ angular momentum

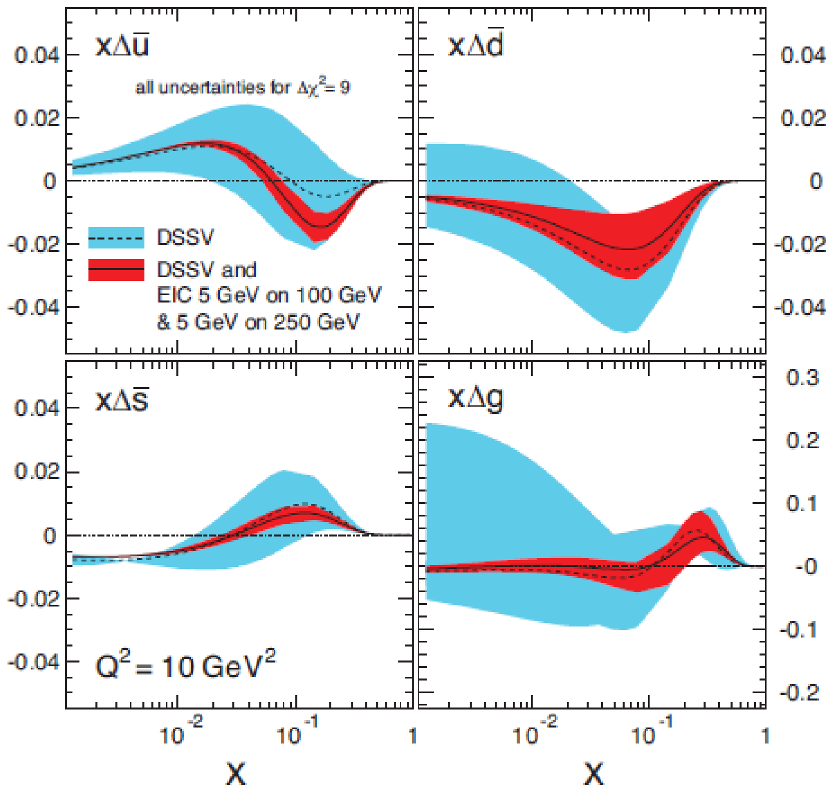
Helicity PDFs at an EIC

A Polarized EIC:

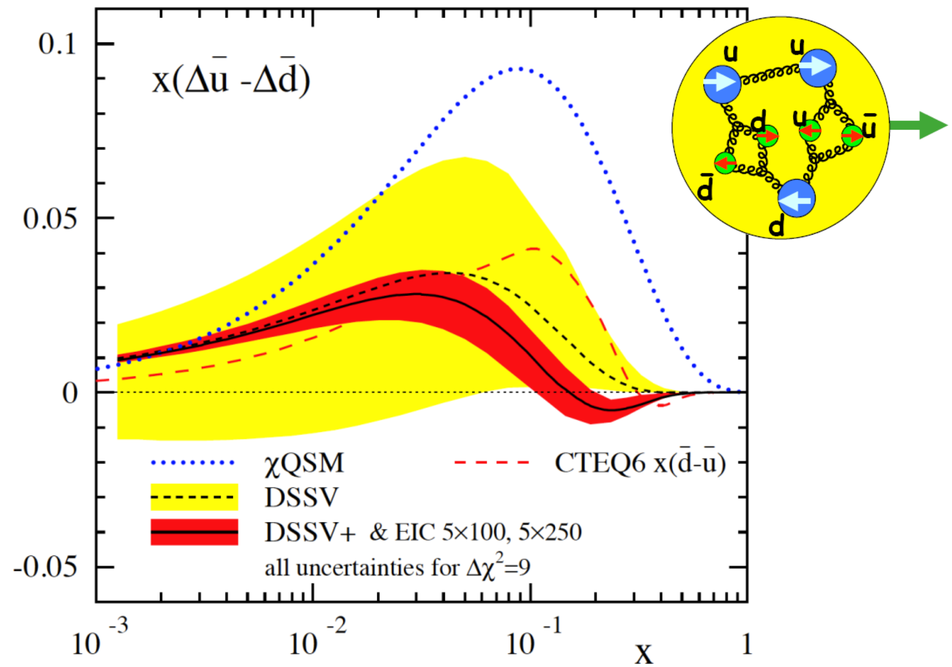
- Tremendous improvement on $x\Delta g(x)$
- Good improvement in $\Delta\Sigma$
- Spin Flavor decomposition of the Light Quark Sea

Many models predict $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

Needs range of √s, here from ~ 45 to ~ 70

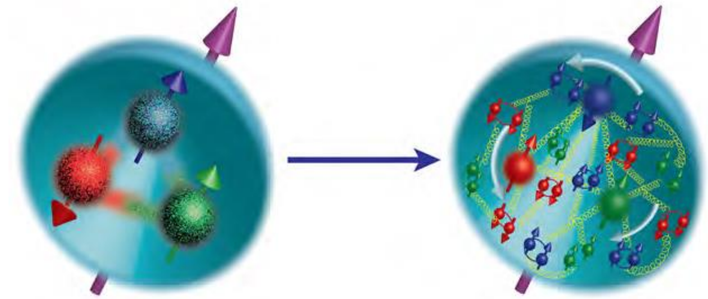


Needs range of √s ~ 30-70 (and good luminosity)

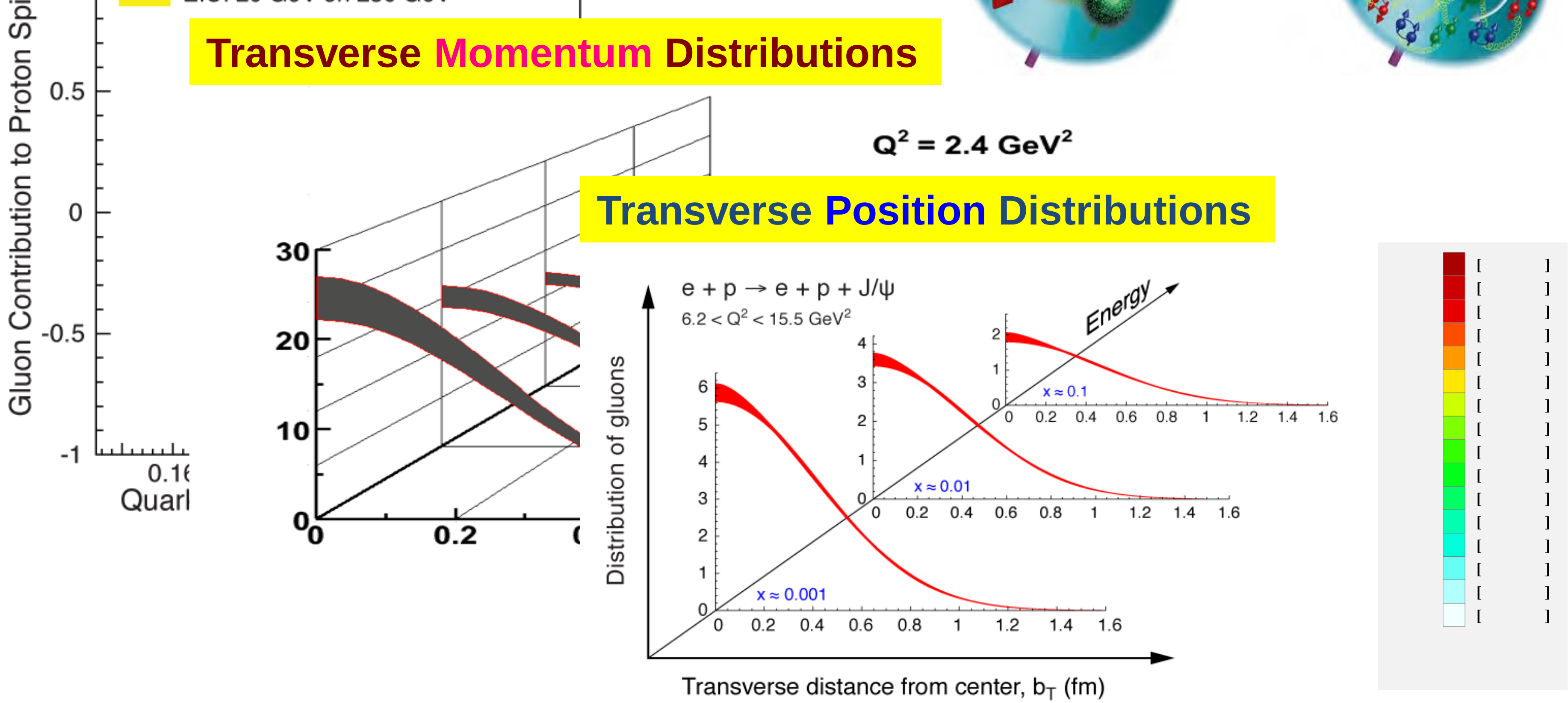


2+1 D partonic image of the proton

Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum



Helicity Distributions: ΔG and ΔΣ

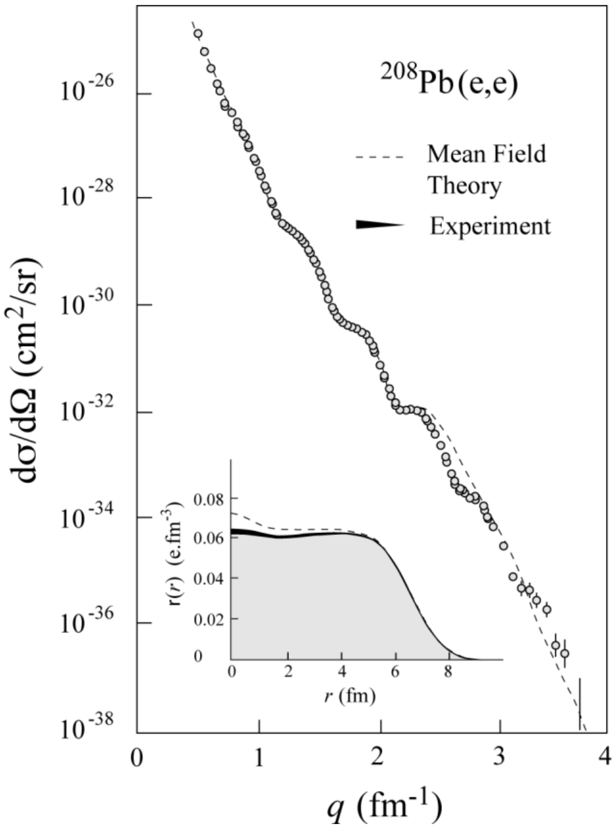


Exposing different layers of the nuclear landscape with electron scattering

History:

Electromagnetic

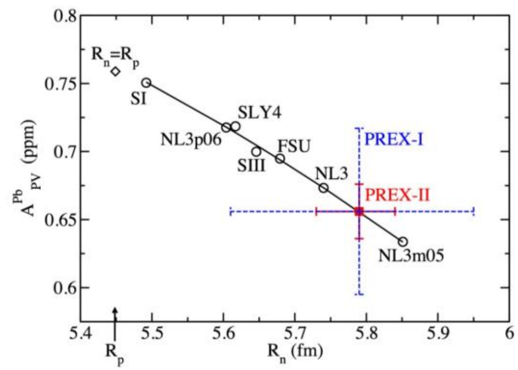
Elastic electron-nucleus scattering → charge distribution of nuclei

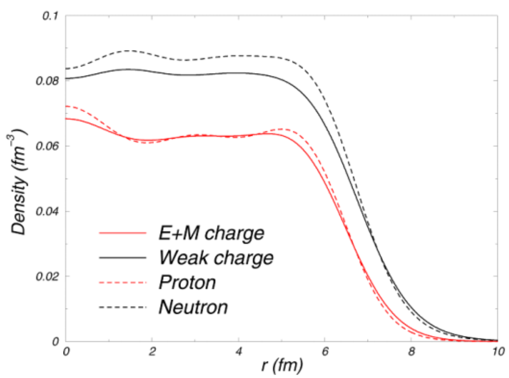


Present/Near-future:

Electroweak

Parity-violating elastic electron-nucleus scattering (or hadronic reactions *e.g.* at FRIB) → neutron skin

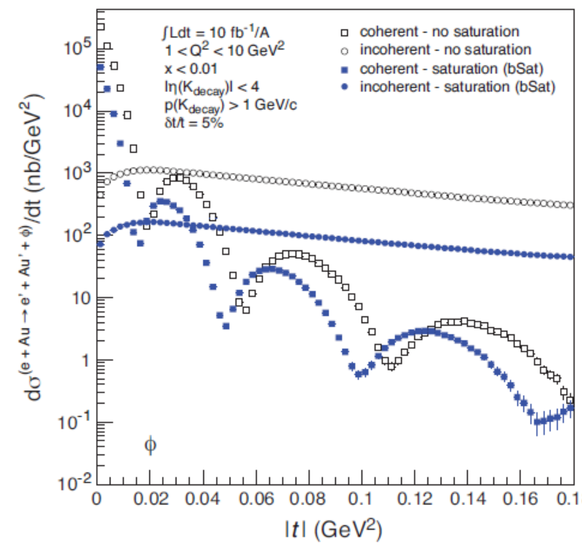




Future:

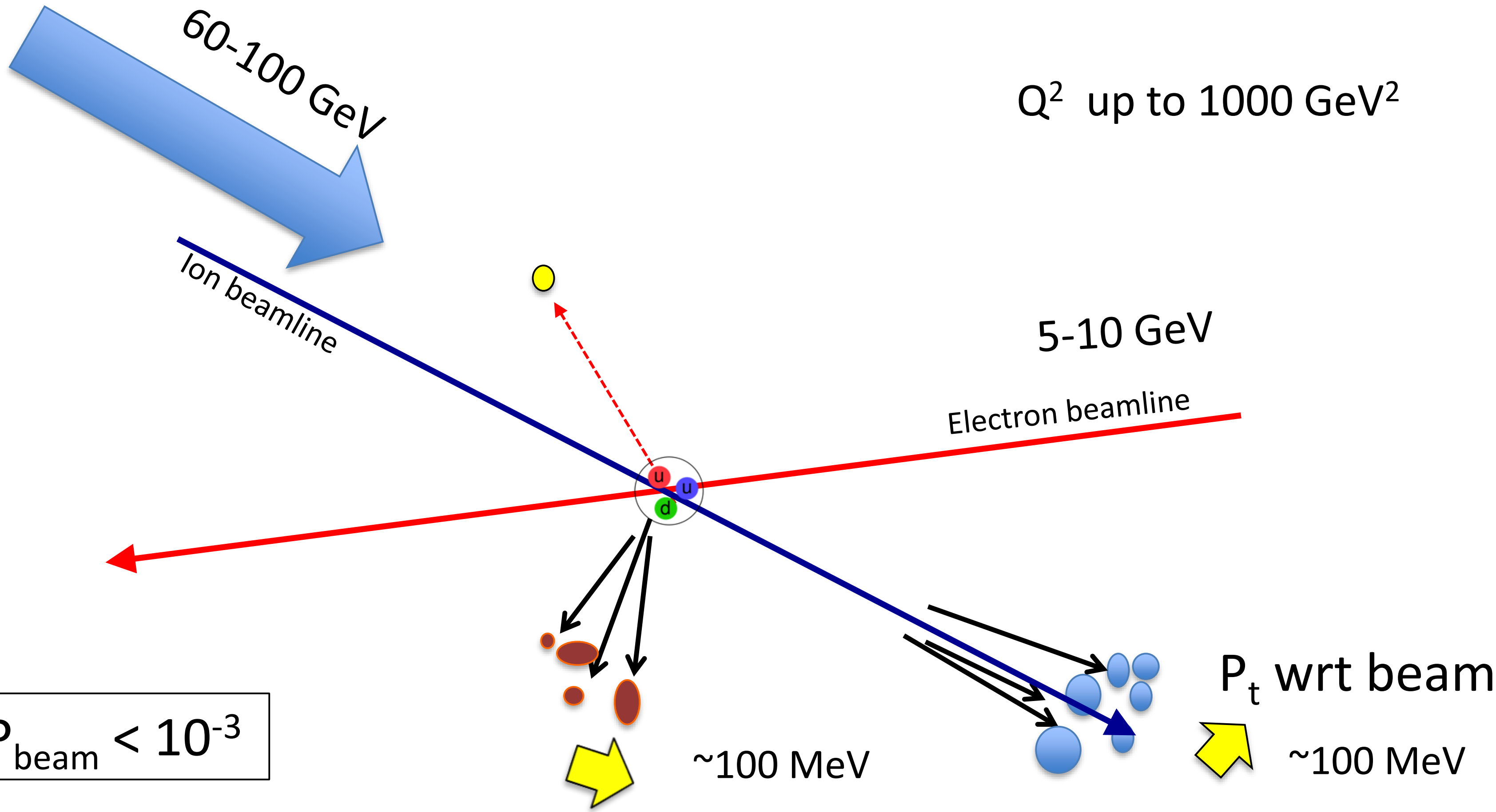
Color dipole

ϕ Production in coherent electron-nucleus scattering → gluon spatial distribution of nuclei



Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

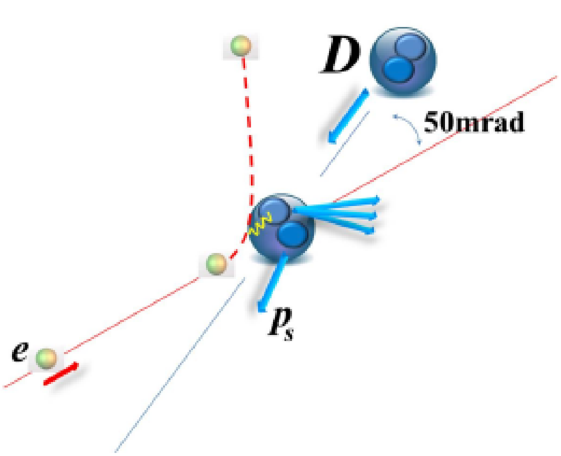
Measuring k_t and b_t

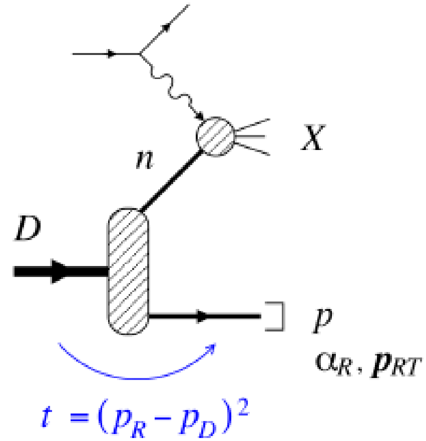


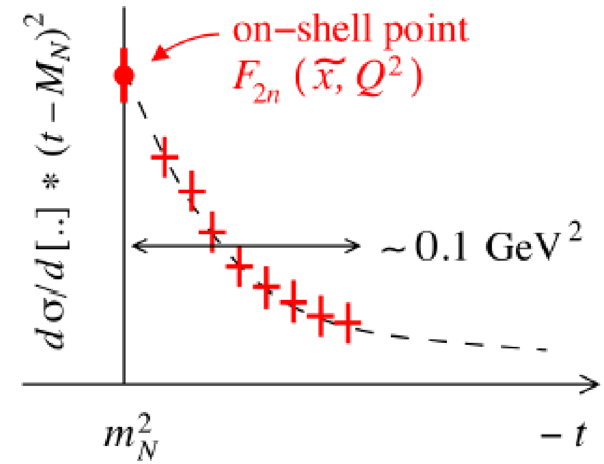
$P_t/P_{beam} < 10^{-3}$

P_t wrt scattering plane.
+ particle ID

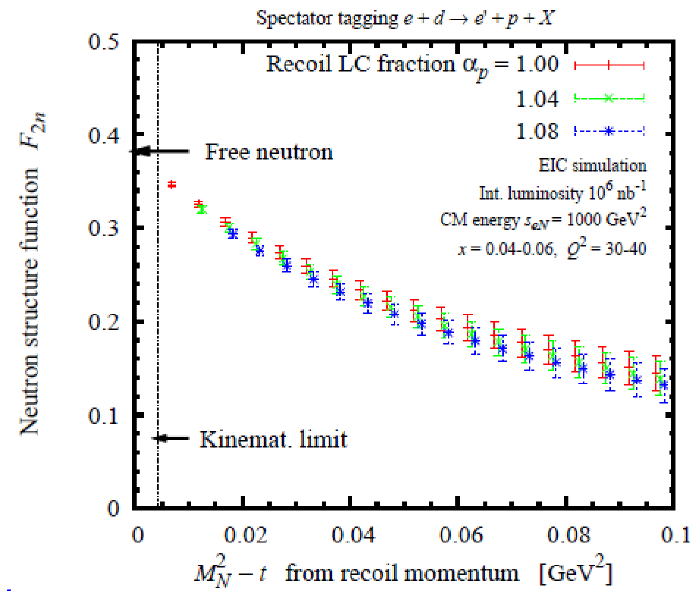
(Tagged) Neutron Structure Extrapolation in t





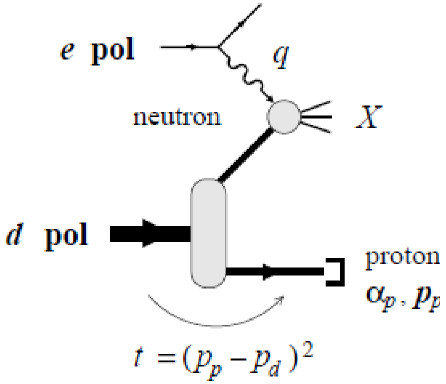


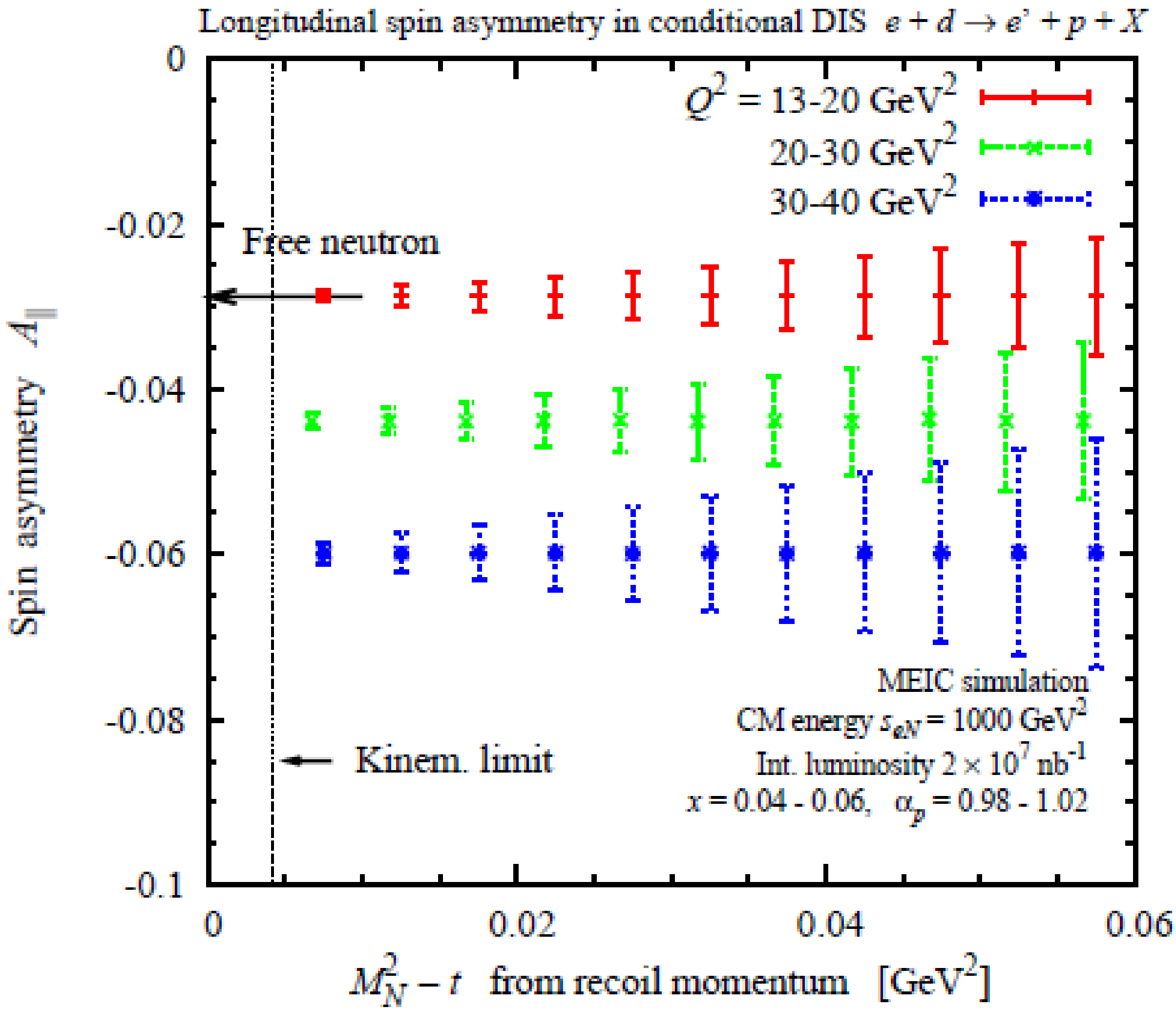
- t resolution better than 20 MeV, < fermi momentum
- Resolution limited/given by ion momentum spread
- Allow precision extraction of F_2^n neutron structure function



C. Weiss et al, see https://www.jlab.org/theory/tag/

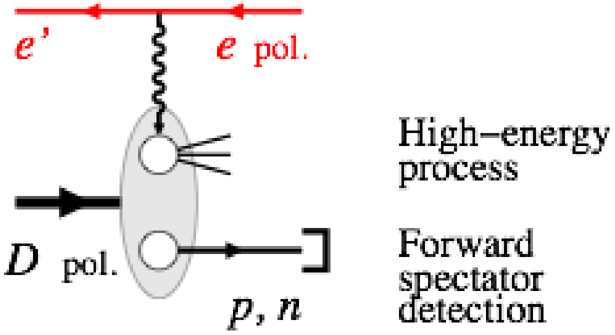
(Tagged) Polarized Neutron Structure





C. Weiss et al, see https://www.jlab.org/theory/tag/

Tagging → Neutron spin structure



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

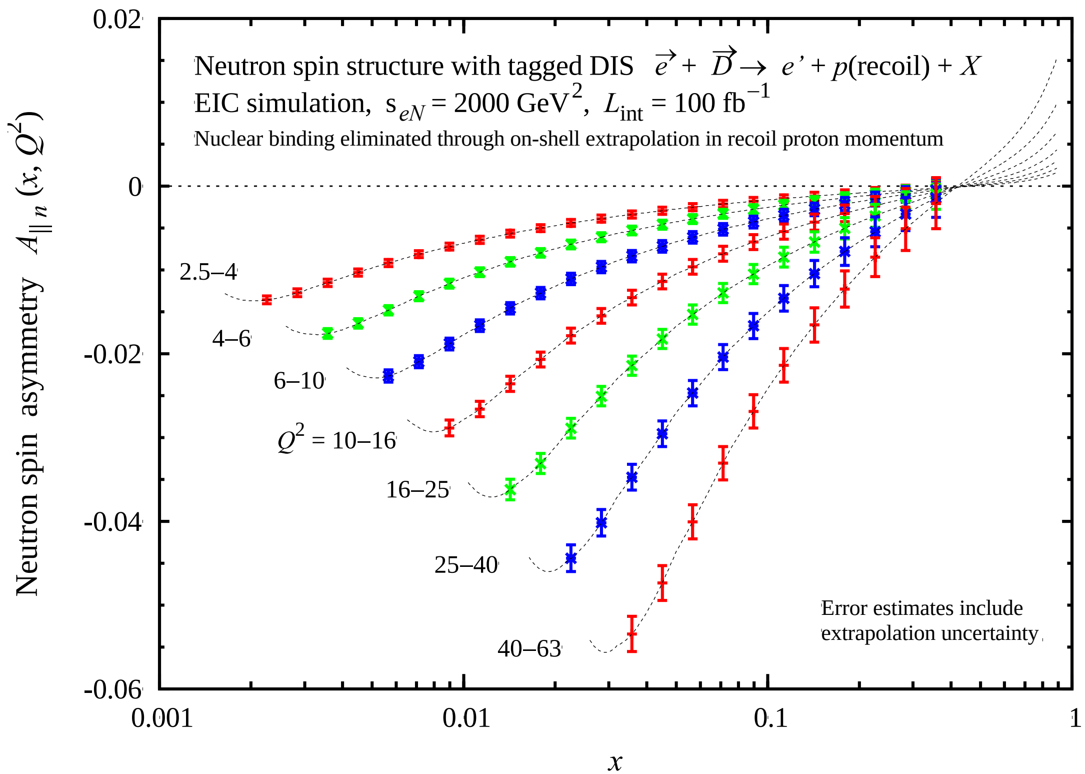
$$A_{\parallel n} = \frac{\sigma(+-) - \sigma(++)}{\sigma(+-) + \sigma(++)}$$

$$= D\,\frac{g_1}{F_1} + \ldots$$

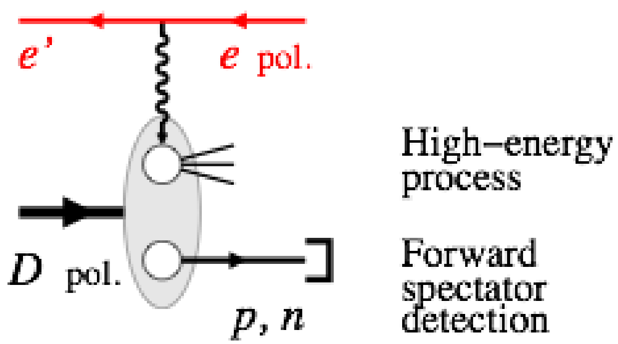
$$D = \frac{y(2-y)}{2 - 2y + y^2}$$

depolarization factor

$$y = \frac{Q^2}{x\, s_{eN}}$$



Tagging → study of nuclear binding



- Another area of interest: 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):

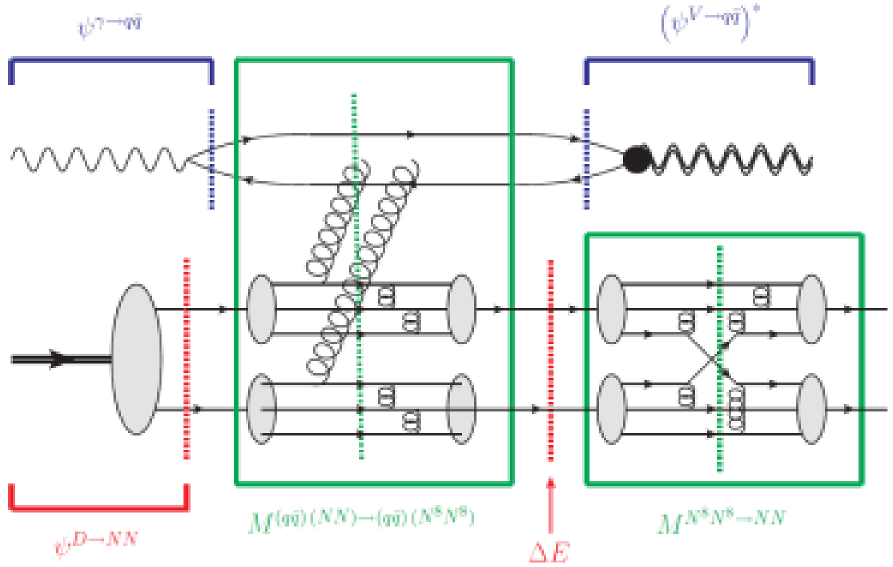
  → quark-gluon origin of the nuclear binding

(also for other light nuclei: ^{3,4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{12}C)

Alternatively, also with e-d:

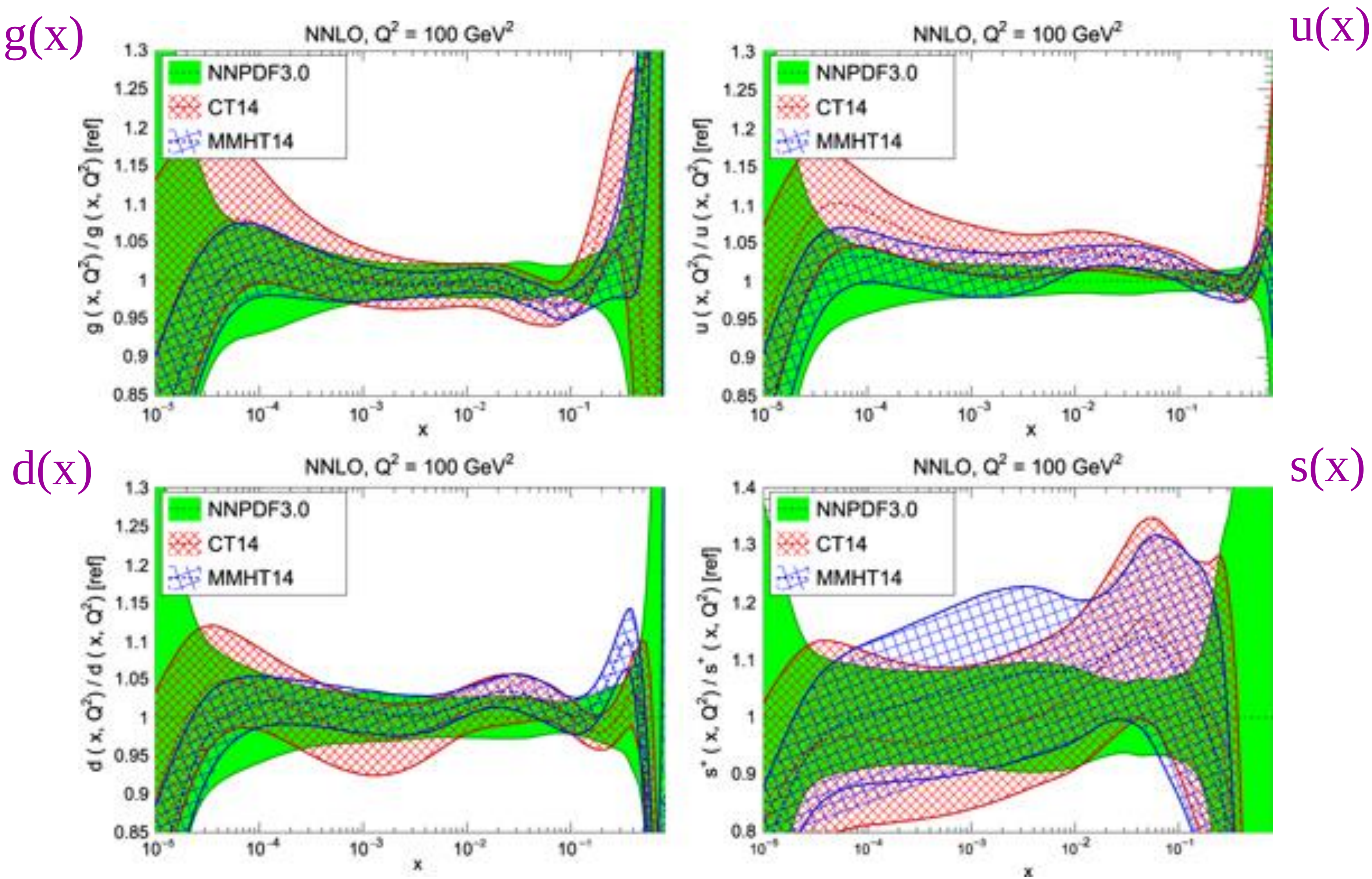
e + D → e' + p + n + J/Ψ

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



Miller, Sievert and Venugopalan,
Phys. Rev. C 93 (2016) 045202

Large Uncertainties on Large x Valence pdfs



Determining large-x Parton Distributions with EIC

Procedure: use projected EIC data in CTEQ-Jefferson Lab “CJ” PDF Fits

So far, have used JLEIC 10x100 GeV^2 projections in bins 0.1 < x < 0.9 for:

- ✓ F_2^p
- ✓ F_2^n from deuterium with tagged proton spectator
- • F_2^d

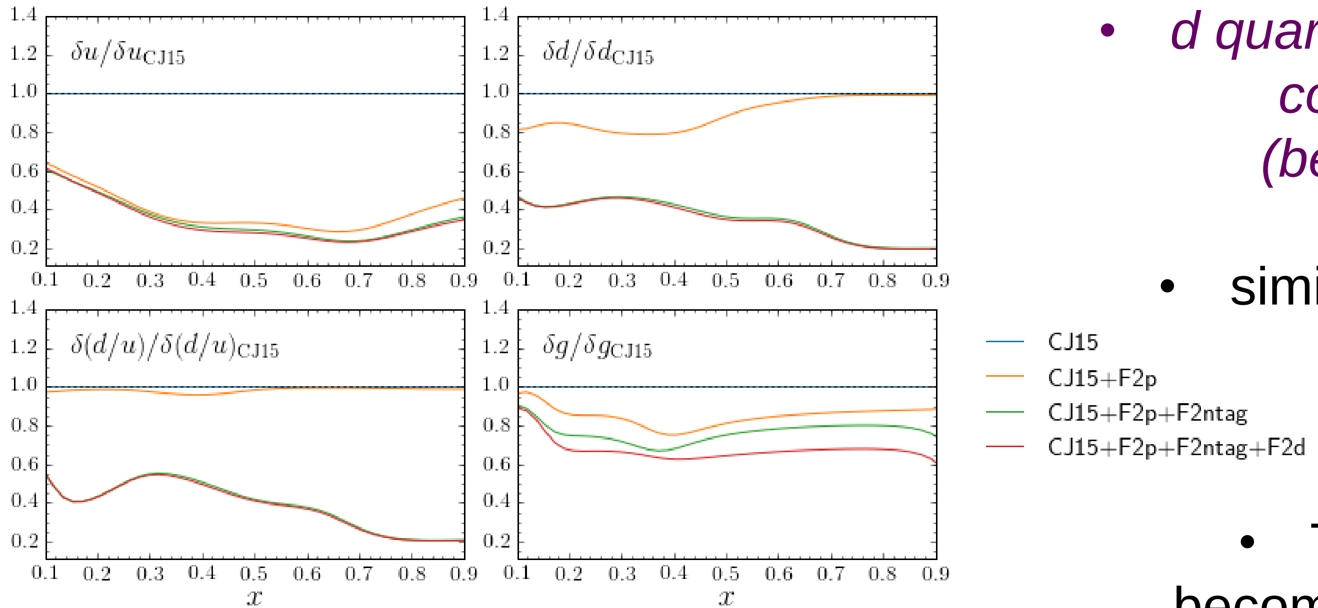
Measurements ranging to high (up to a few 1000 GeV2) will enable studies of target mass, higher twist, pert/nonpert. studies)

Can check on-shell extrapolation by measuring F_2^p from deuterium with tagged neutron spectator, comparing to proton target data

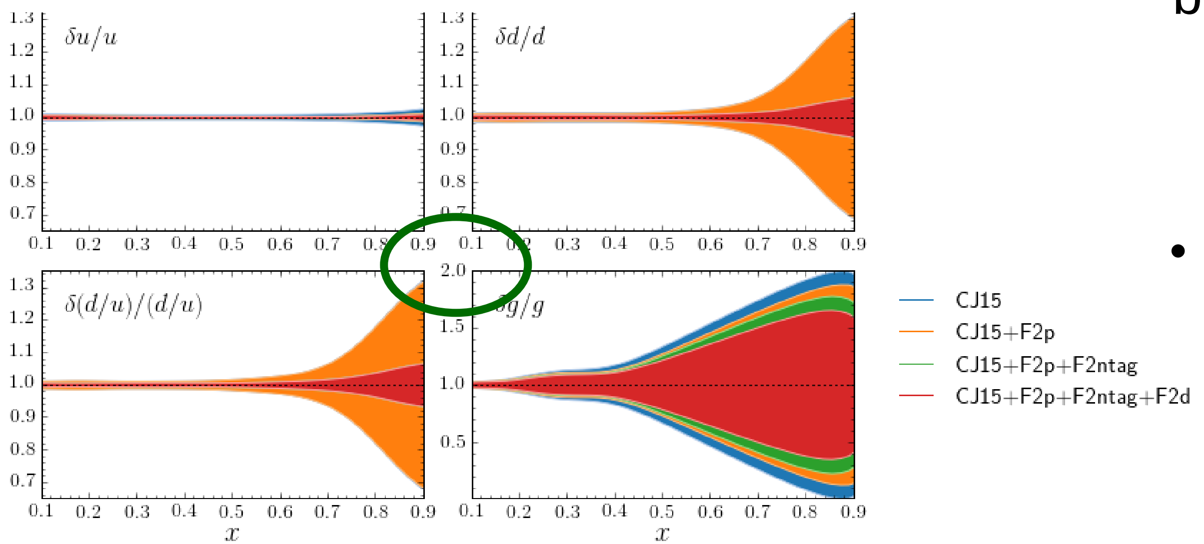
Can check nuclear corrections to F_2^d against $F_2^{n\ (tagged)}$

A. Accardi (Hampton),
R. Ent, J. Furletova,
C. Keppel, K. Park,
R. Yoshida (JLab),
M. Wing (UC London)

EIC e-d (with n_{tag}) projection with 100/fb luminosity

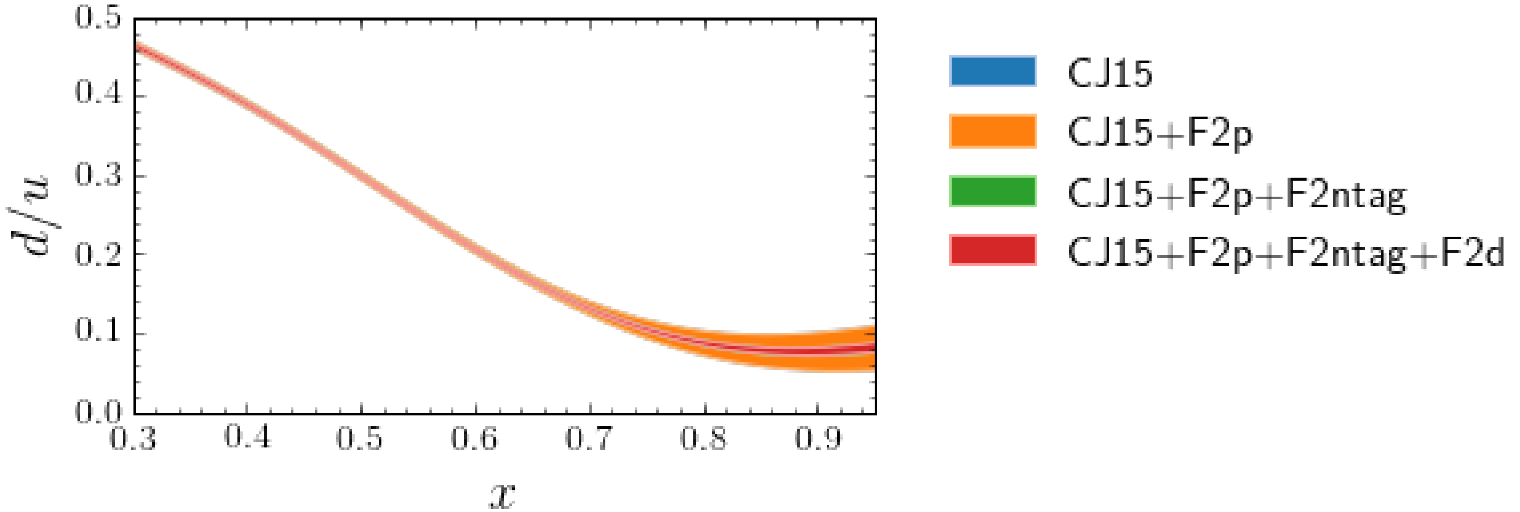


- *d quark precision will become comparable to current u!! (becomes ~5% at x = 0.9)*
- similar improvement in g(x)



- The u quark uncertainty becomes less than ~1%; may be important for large mass BSM new particles.
- With d quark nailed by F_2^n, fitting F_2^d data will explore details of nuclear effects

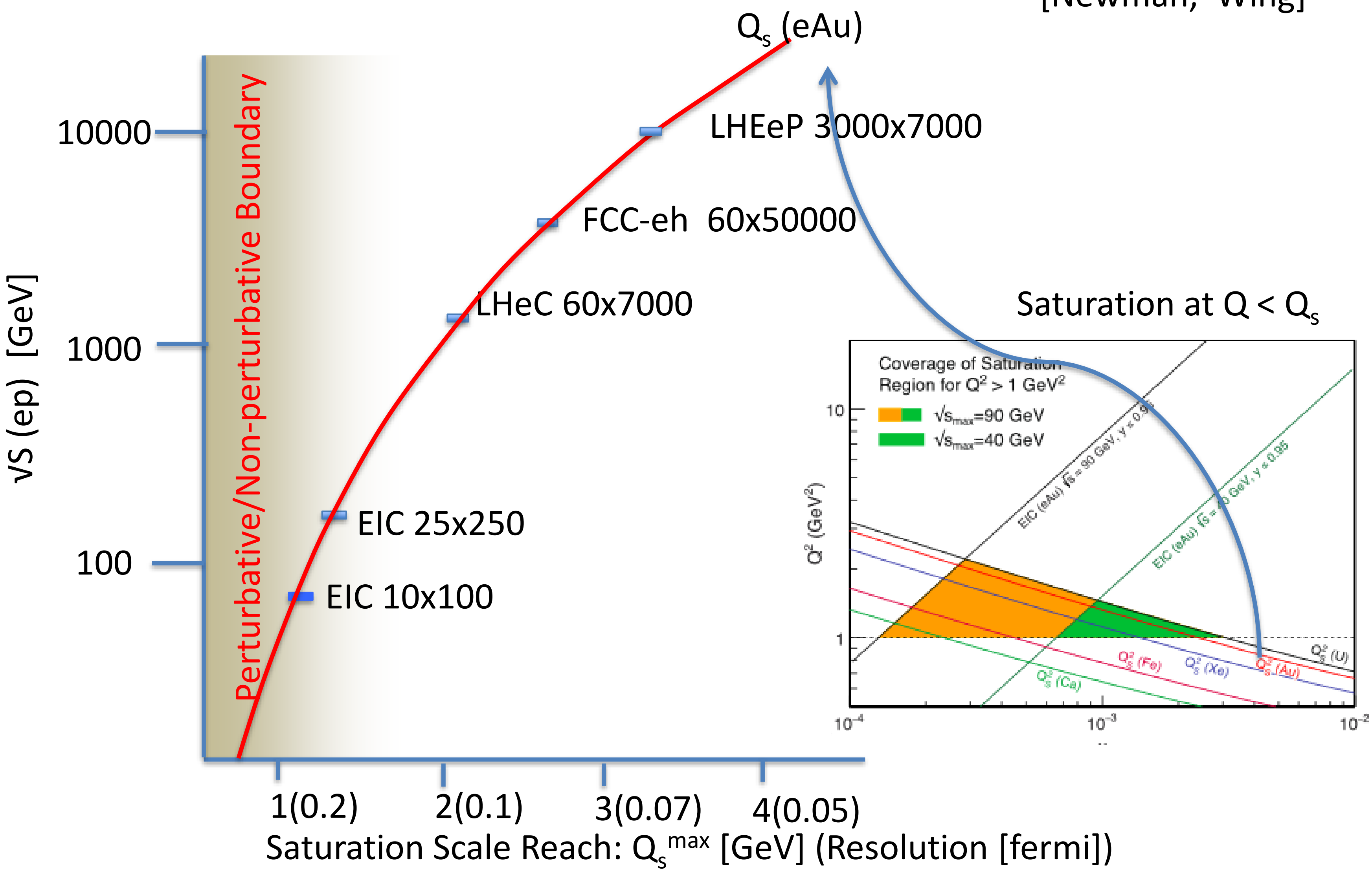
Improved d(x) precision is good news



- The d-quark goes from a few 10% to ~few% percent level
- Resolve long-standing mystery of d/u at large x, bell-weather for fundamental models of nucleon structure
- D/(p+n) in one experiment for the first time – unprecedented handle on nuclear medium modifications
- Facilitate accurate neutron excess/isoscalar corrections
  - Important also for neutrino physics and nuclear PDFs

Parton Saturation at eA colliders

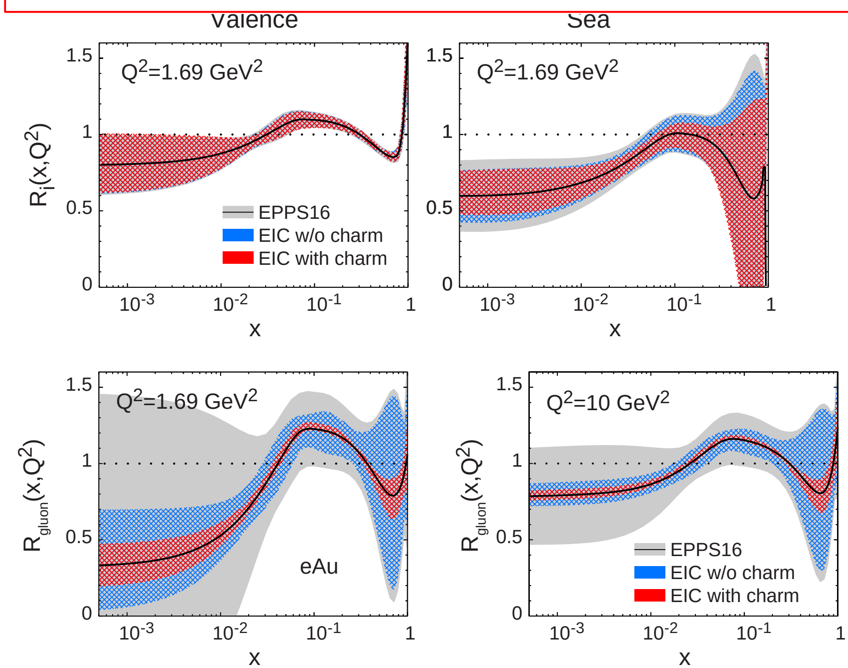
[Newman, Wing]

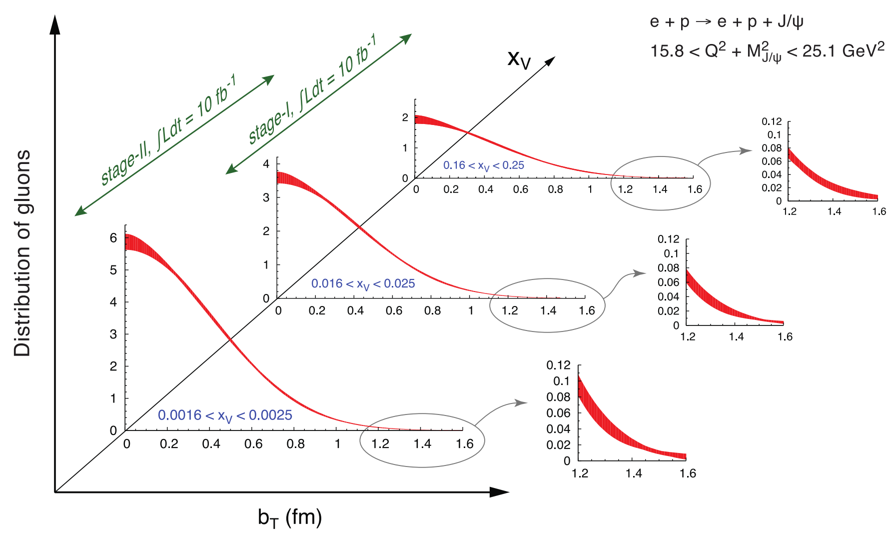


Quark-Gluon Plasma

Our understanding of fundamental properties of the Glasma, sQGP and Hadron Gas depend on our knowledge of the initial state!

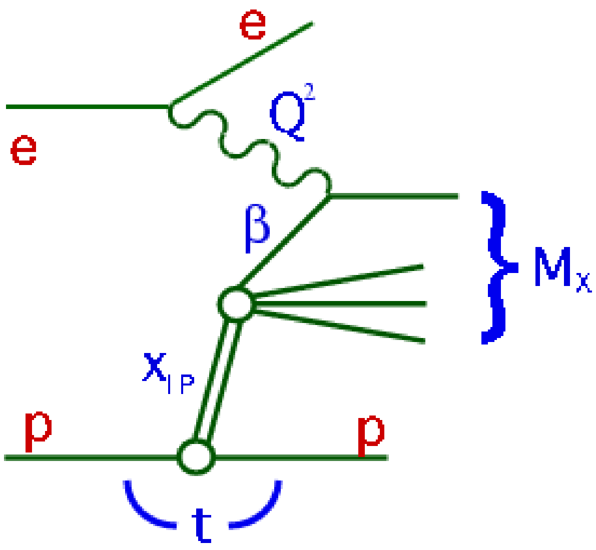
EIC: Measure nuclear PDFs and map out quark and gluon structure in 3D.

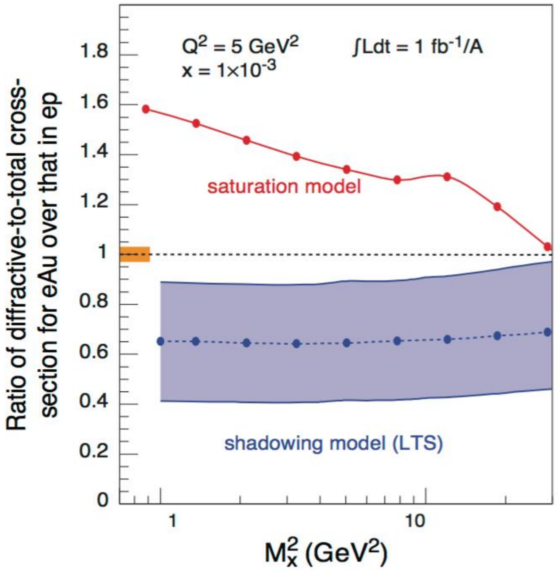


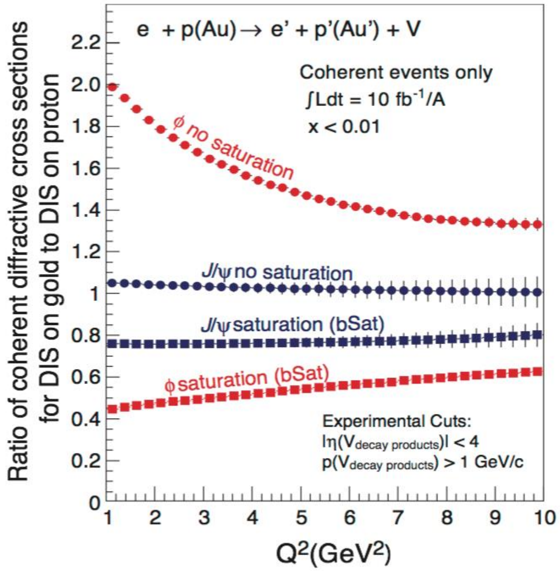


An Example: Diffractive DIS

Signature for Saturation (among other things)



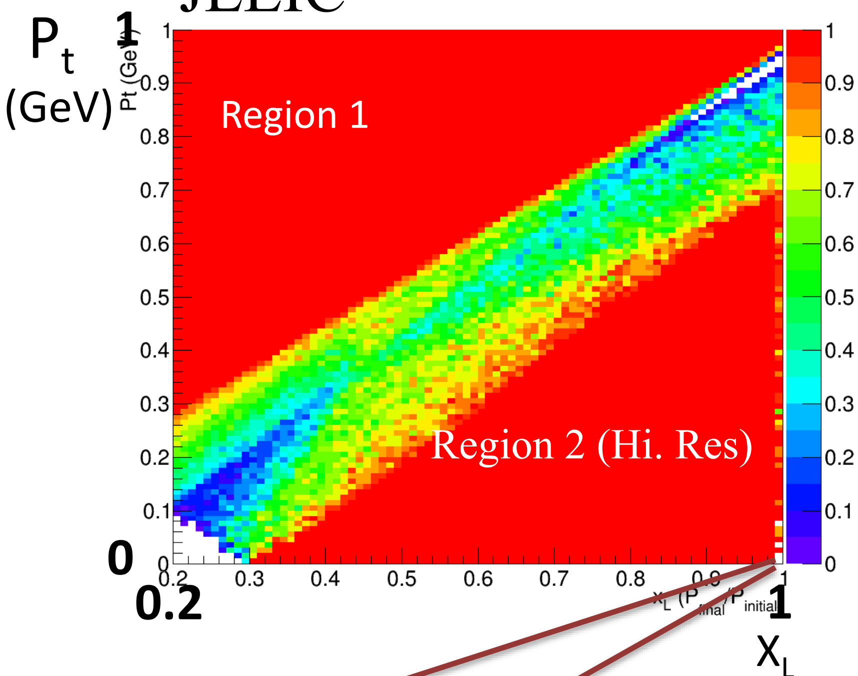


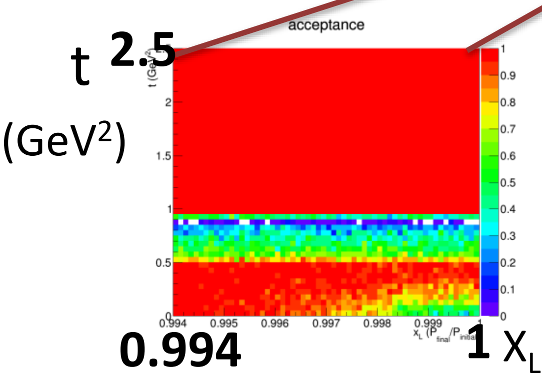


Identify the scattered proton: distinguish from proton dissociation
Measure $\mathbf{X_L= E_p'/E_p}$, and $\mathbf{P_t}$ (or **t**) (equiv. to measuring M_X)

Acceptance for p' in DDIS

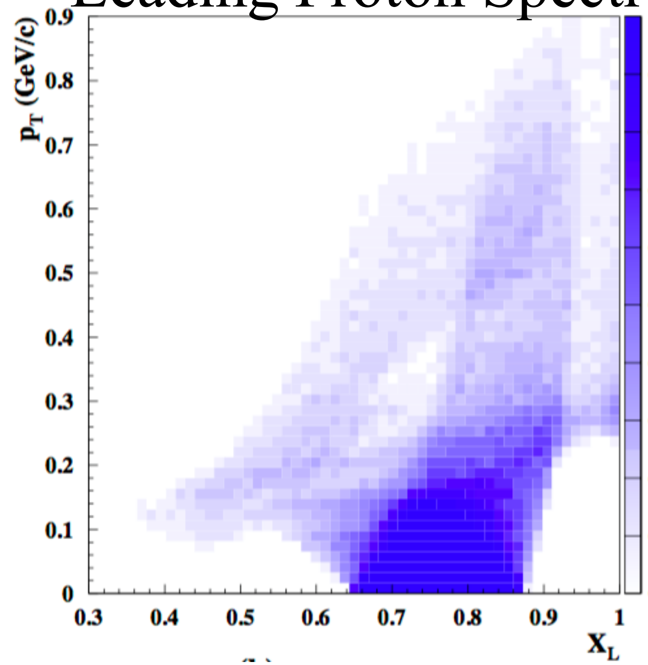
JLEIC





ZEUS

Leading Proton Spectrometer



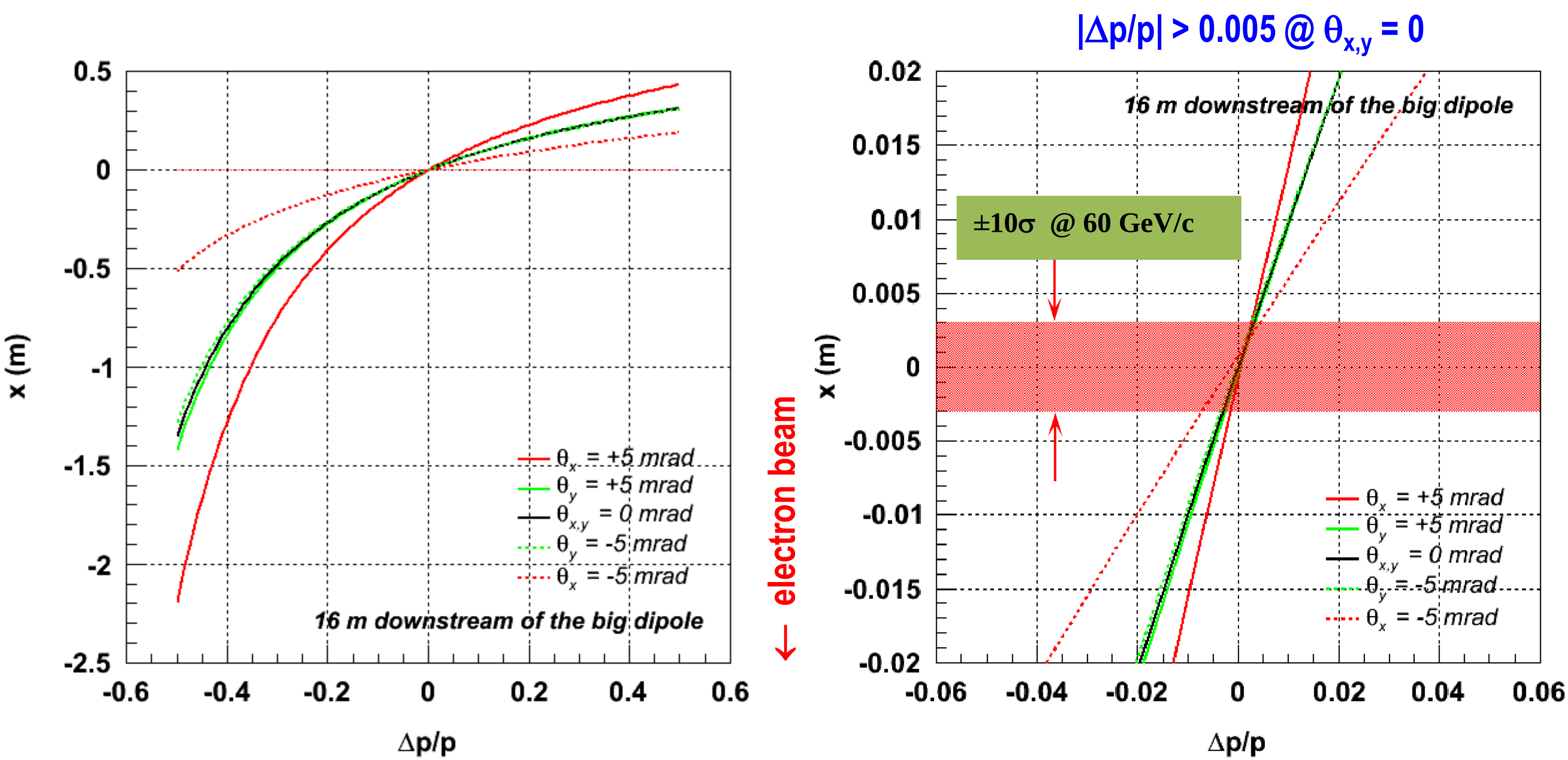
Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

JLEIC: ~100%

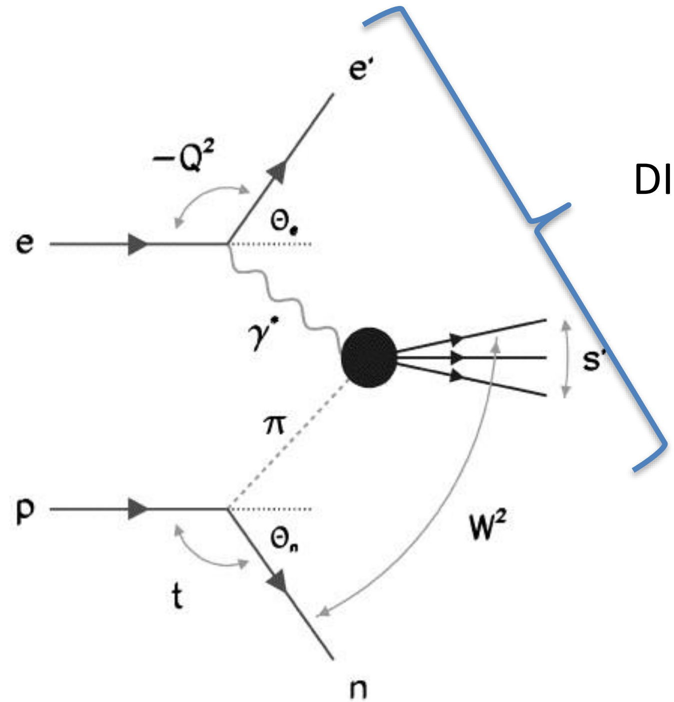
Forward Ion Momentum & Angle Resolution

- **Protons with Δp/p spread launched at different angles to nominal trajectory**

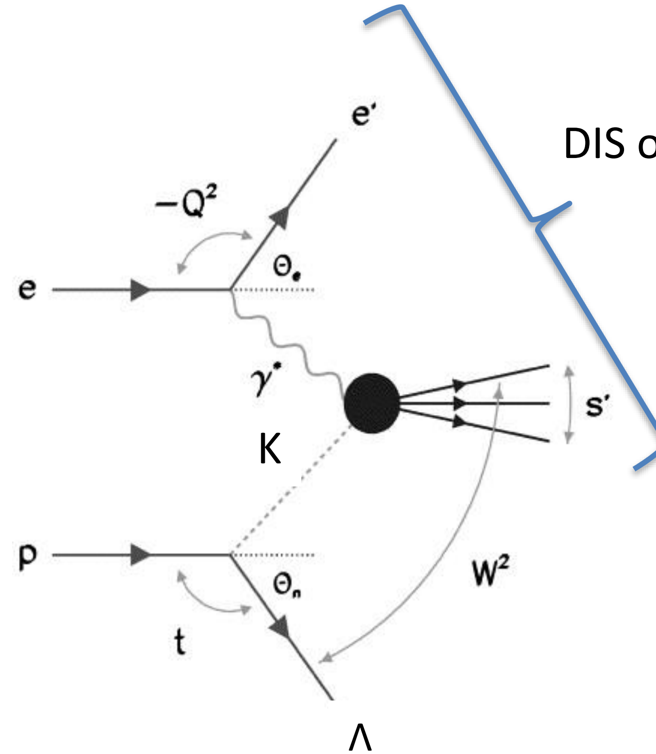


For ZEUS LPS: resolution in X_L was about 0.5% and Pt resolution was 5 MeV

Another example: Kaon and Pion Structure at an EIC



DIS on pion



DIS on Kaon

Need to measure these

Detection of $^1H(e,e'K^+)\Lambda$

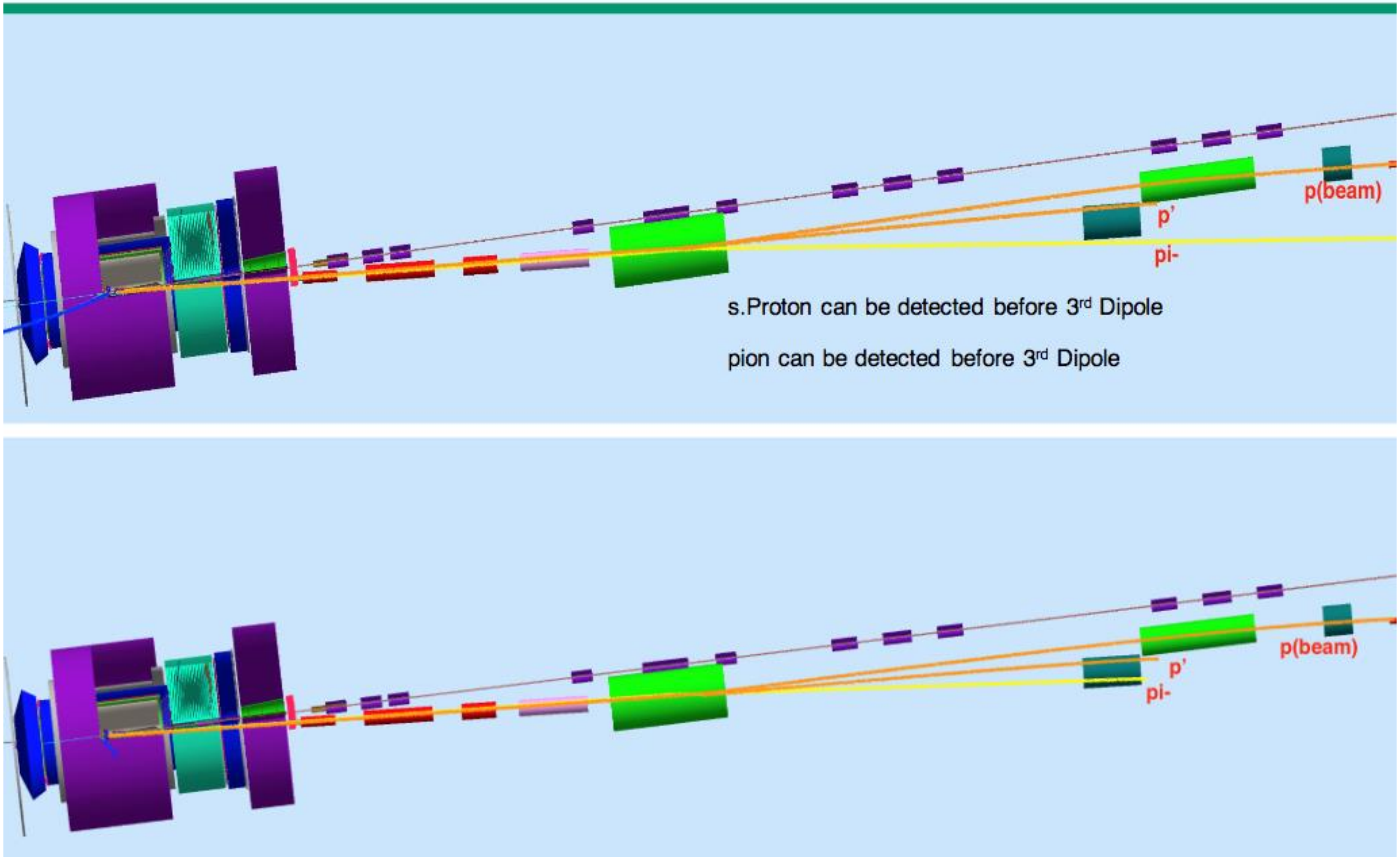
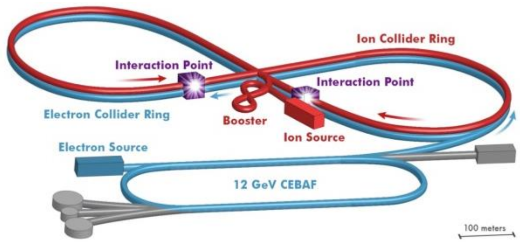


Figure from K.Park

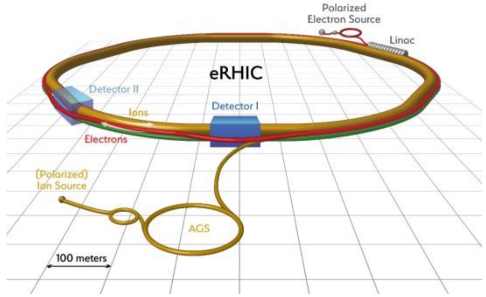
12

How efficiently can we do this?

BNL and JLAB working together



Adapted from
F. Willeke (BNL)



Complementary expertise

JLab expertise:

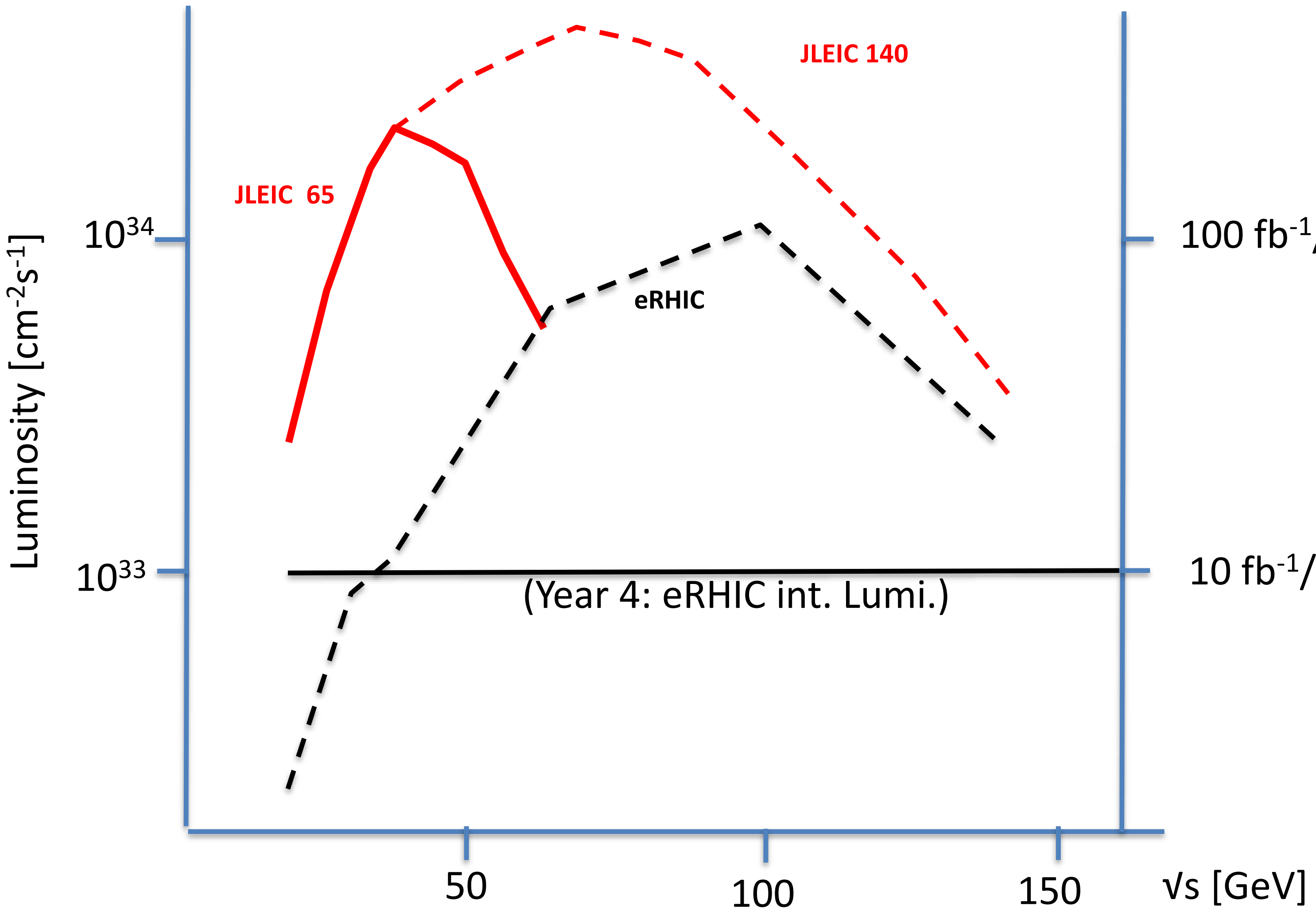
- Polarized electron sources
- Superconducting RF development
- Superconducting RF production and industrialization
- Superconducting LINAC technology
- Energy-recovery LINACs
- Superconducting LINAC beam physics
- Acceleration and transport of polarized electron beams

BNL expertise:

- Ion/proton beam sources
- Ion acceleration
- Ion spin preservation
- Hadron beam dynamics
- RF for hadron beams
- Hadron beam instrumentation
- Superconducting magnets
- Storage beam ring physics
- Electron cooling

Accelerator R&D going on with strong cooperation
between BNL an JLAB under DOE NP guidance

Comparison JLEIC and eRHIC (Apr. 2017)



JLEIC parameters can be found at eic.jlab.org/wiki (January, 2017 update)