Electron Ion Collider: Physics and Prospects

We will give an outline of the anticipated physics program for a future electron ion collider. The status and prospects for construction of such a device will be discussed.

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QCD Evolution 2016

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Outline

Deep Inelastic and Parton Structure

- The next ten years
- The Electron Ion Collider
  - The Physics
  - The Collider
    - e-RHIC
    - Jefferson Lab EIC
  - Detector Design
  - The NSAC 2015 Long Range Plan and Path Forward
- Conclusions

The Next Ten Years

Compass

Jefferson Lab 12 GeV

RHIC

Drell-Yan/Sea Quest

Mainz, Bonn

Medium Energy Physics in The Next Decade

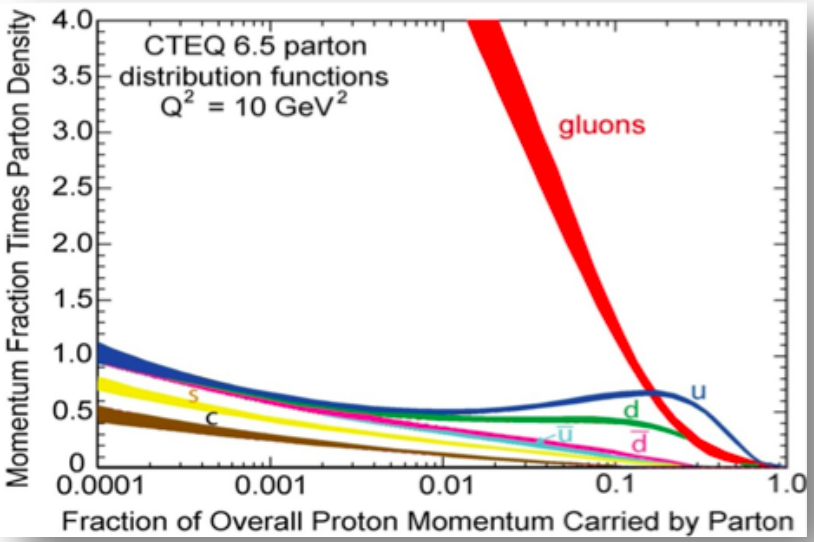
- Meson and Baryon Spectroscopy
- Valence Structure of the Hadrons
  - Form Factors, Charge Radius of the Proton
  - Spin Distributions
  - 3 Dimensional Structure, Transverse Momentum Structures
  - Orbital Angular Momentum
- Anti-quark sea
- Gluon Spin
- Nuclear Structure
  - Short Range nuclear forces
  - Neutron skin in nuclei
- Fundamental Symmetries
  - $\sin^2\Theta_W$ at low Q^2
  - Heavy photons?

Need for an Electron Ion Collider

In 2025, our ignorance in hadron physics will be related almost exclusively to the gluon.

- The Electron Ion Collider with:
  - high luminosity
  - high and controllable polarization
  - moderate and flexible energy
  - and the availability of nuclear beams

- Will enable the sophisticated studies of the nucleon from x_{Bj}~0.1 to x~0.0001, a regime in which the content of the nucleon and its interactions are dominated by the gluon.



Gluons and Hadronic Structure

- Since ~1970 we have known that gluons must carry 50% of the momentum of the nucleon, this fact is the origin of the gluon concept.

- Massless gluons & almost massless quarks, through their interactions, seem to generate more than 98% of the mass of the nucleons:

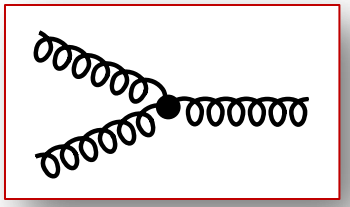
  Without gluons, there would be no nucleons,

  no atomic nuclei,… no visible world!

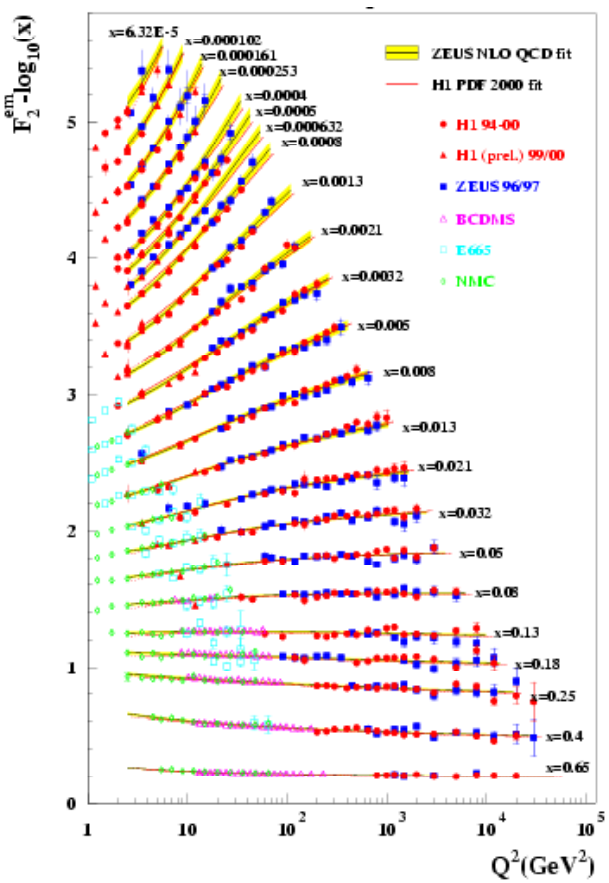
- We do not know, but suspect that the gluons carry a finite fraction of the spin of the nucleon.

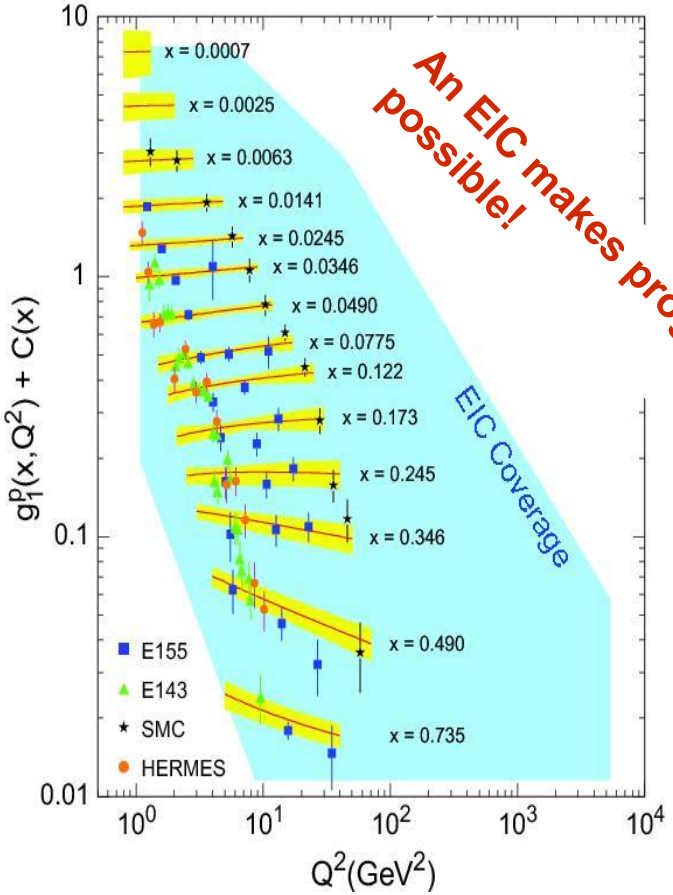
- We believe that the residual component of the gluon interaction, the strong "van der Waals", is the nucleon-nucleon force which controls the internal structure of the nucleus.

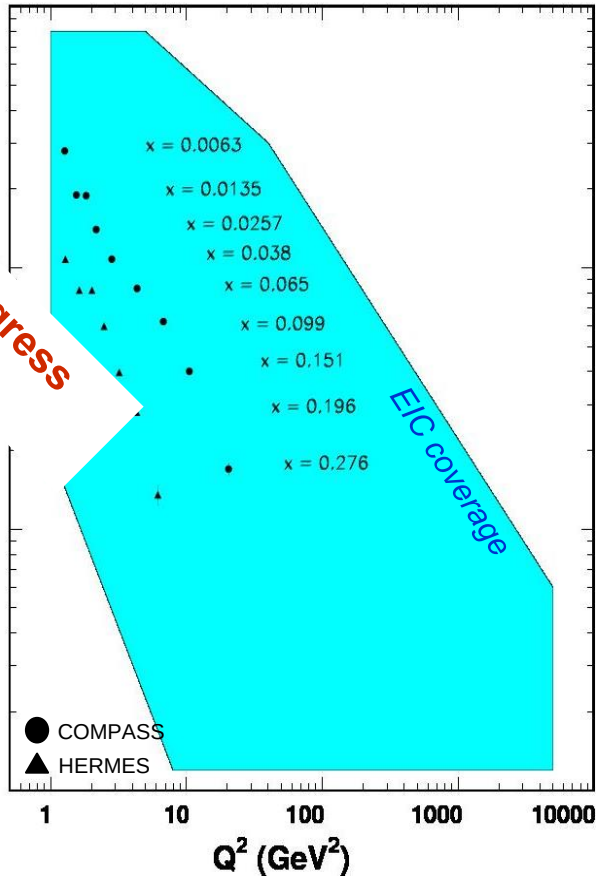
- The plots suggest divergence, however, QCD has recombination as well as splitting, it is non-Abelian so, presumably a balance is reached, and "saturation" occurs. Where?



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







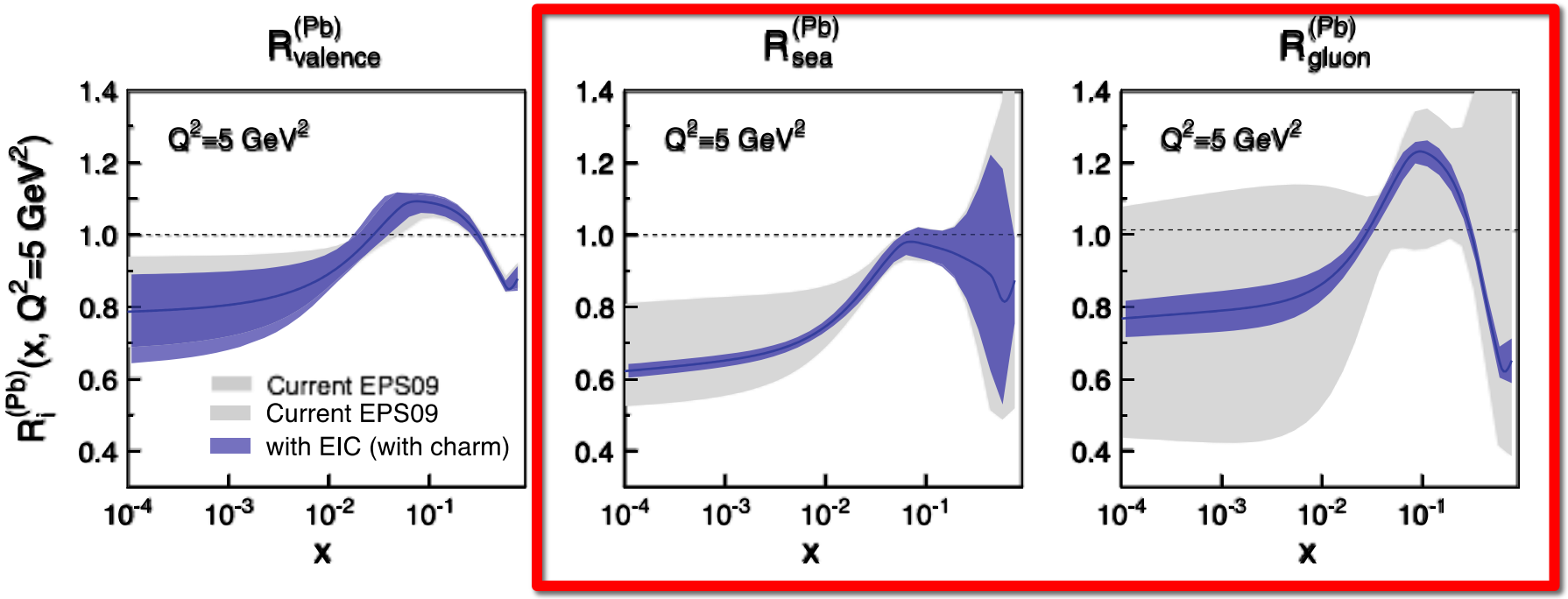
momentum

spin

transverse spin ~ angular momentum

EIC: sea quarks and gluons in nuclei

What do we know of gluons in nuclei? Essentially nothing!



Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
- An EIC will significantly reduce uncertainties

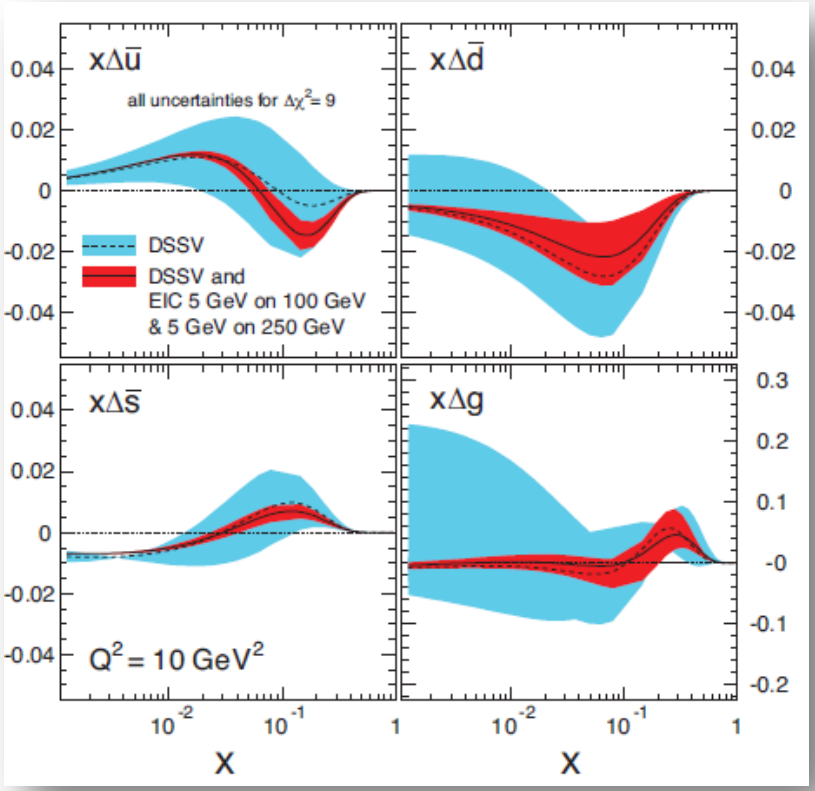
- Impossible for current and future pA data at RHIC & LHC data to achieve

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

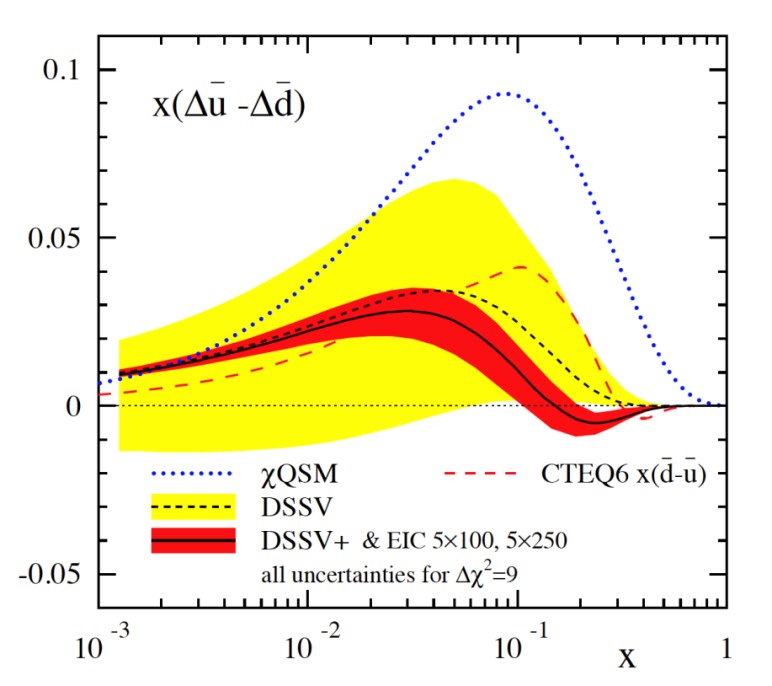
Needs range of $\sqrt{s}$, from ~ 45 to ~ 70 GeV^2



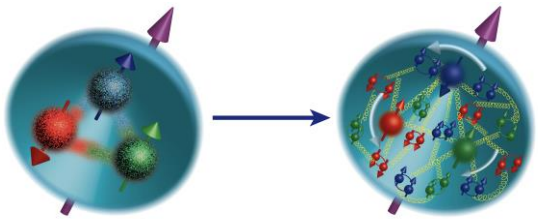
Many models predict

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

Needs range of $\sqrt{s}$ ~ 30-70 (and good luminosity)



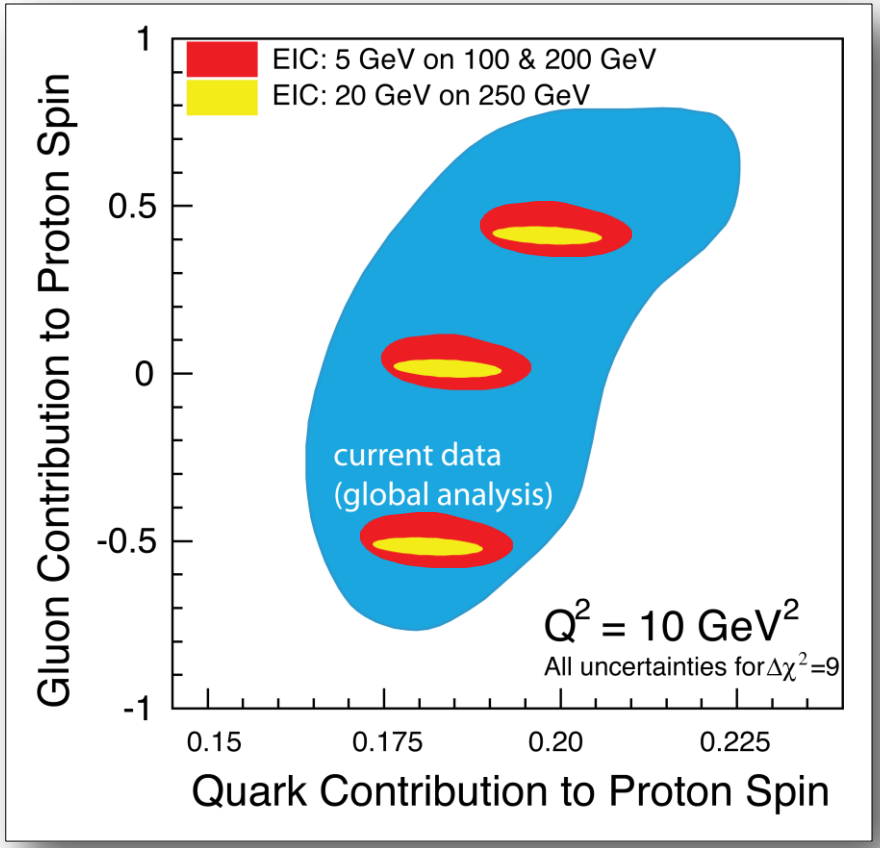
Nucleon Spin



$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

Precision in $\Delta\Sigma$ and Δg ➔ A clear idea of the magnitude of L_Q+L_G



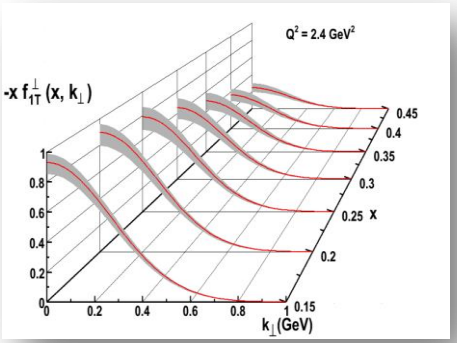
3D Mapping of the Nucleon

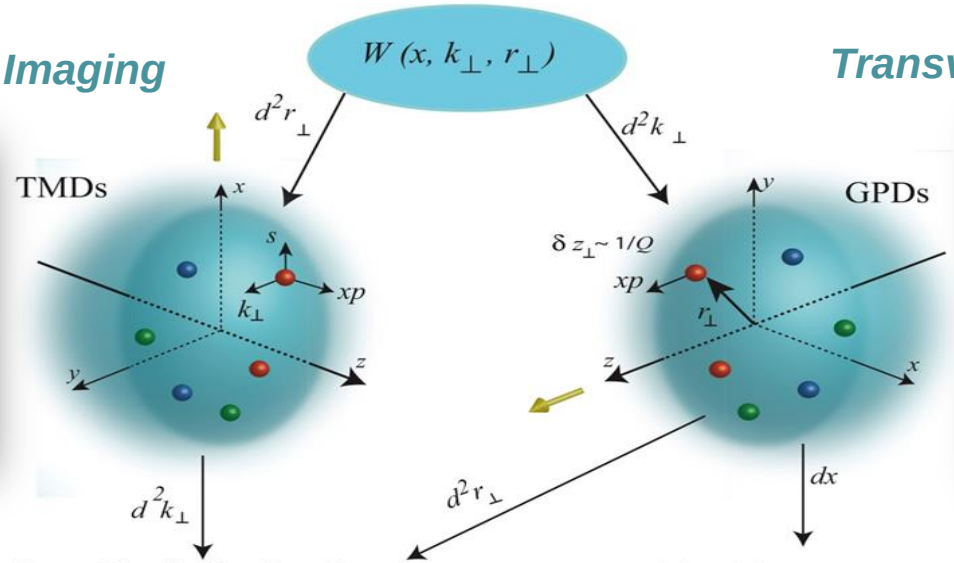
TMDs: Longitudinal momentum fraction x and transverse momentum k

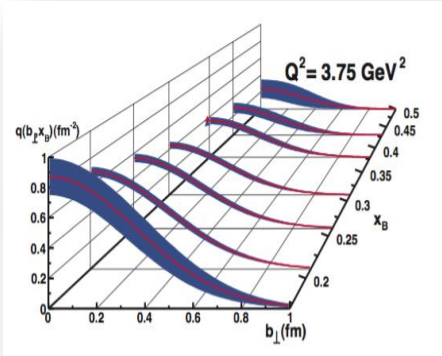
GPDs: Longitudinal momentum fraction x at transverse location b

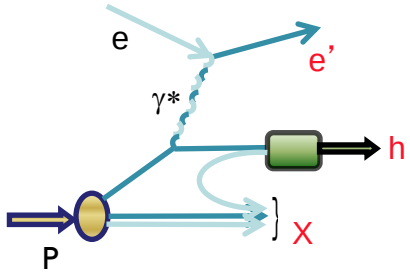
Transverse Momentum Imaging

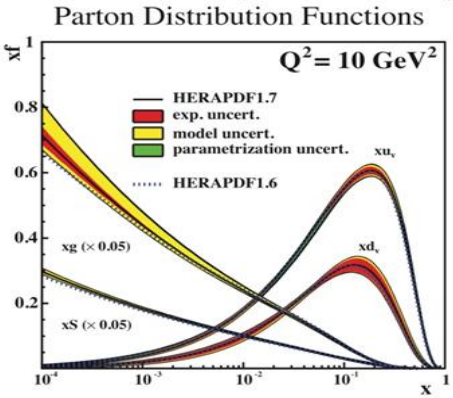
Transverse Spatial Imaging

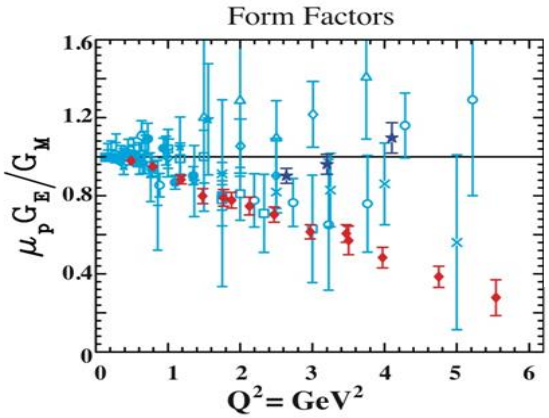


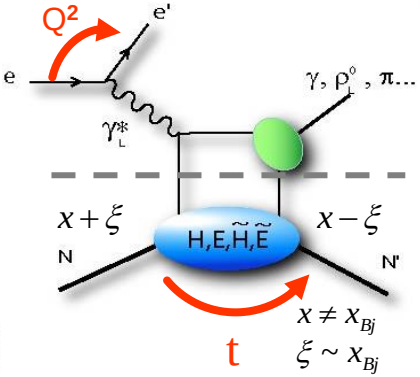








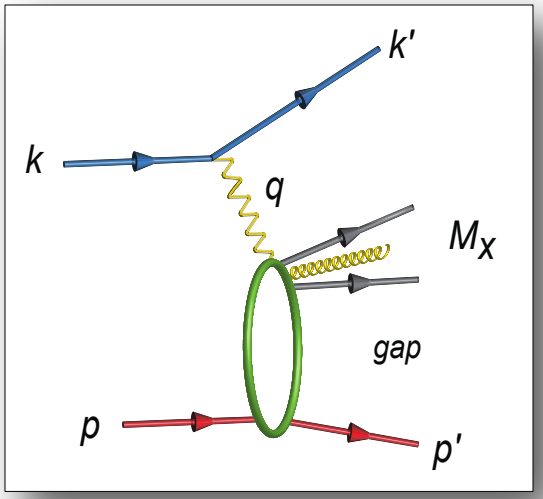


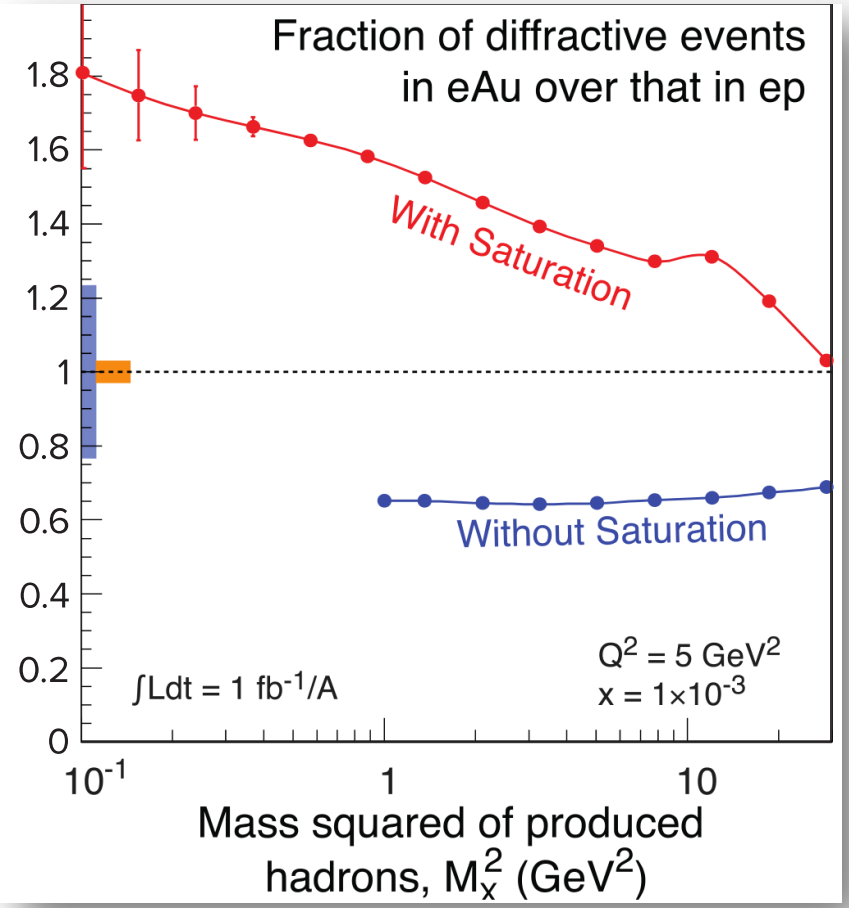


Saturation???

Many ways to get to gluon distribution in nuclei, but diffraction most sensitive:

$$\sigma_{\rm diff} \propto [g(x, Q^2)]^2$$





At HERA

ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

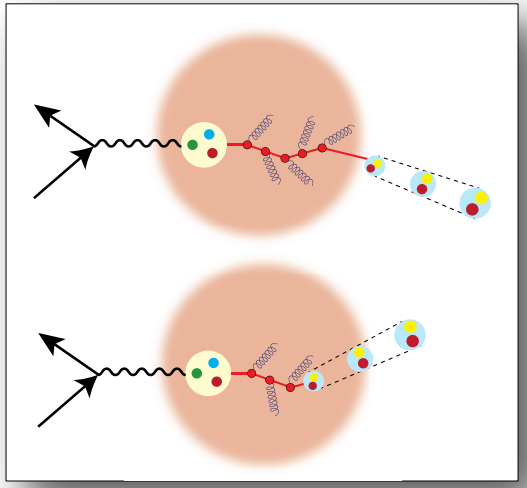
eA: 25-30% diffractive

Partons to Hadrons

Nucleus as a Femtometer sized filter

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

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

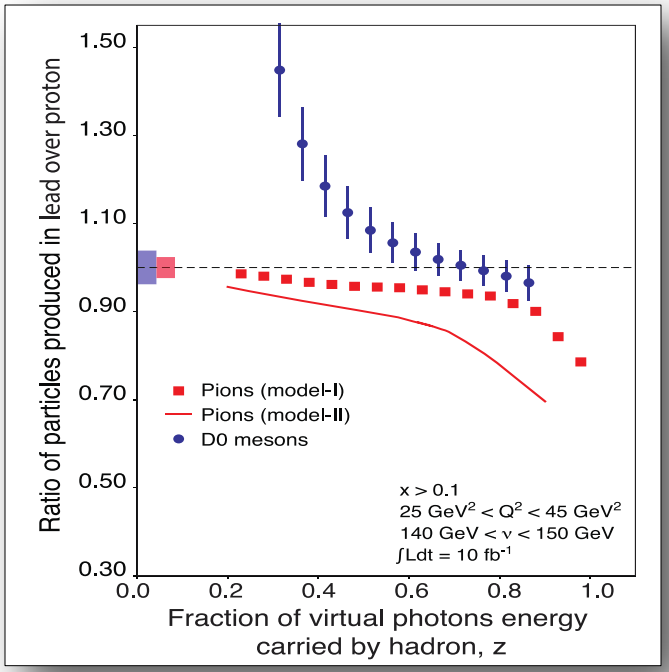


Control of $\{$ by selecting kinematics;

Also under control the nuclear size.

Colored quark emerges as color neutral hadron ➔ What is nature telling us about 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

Electron Ion Collider Design Parameters

Electron Nucleus(p, d, …) Collider

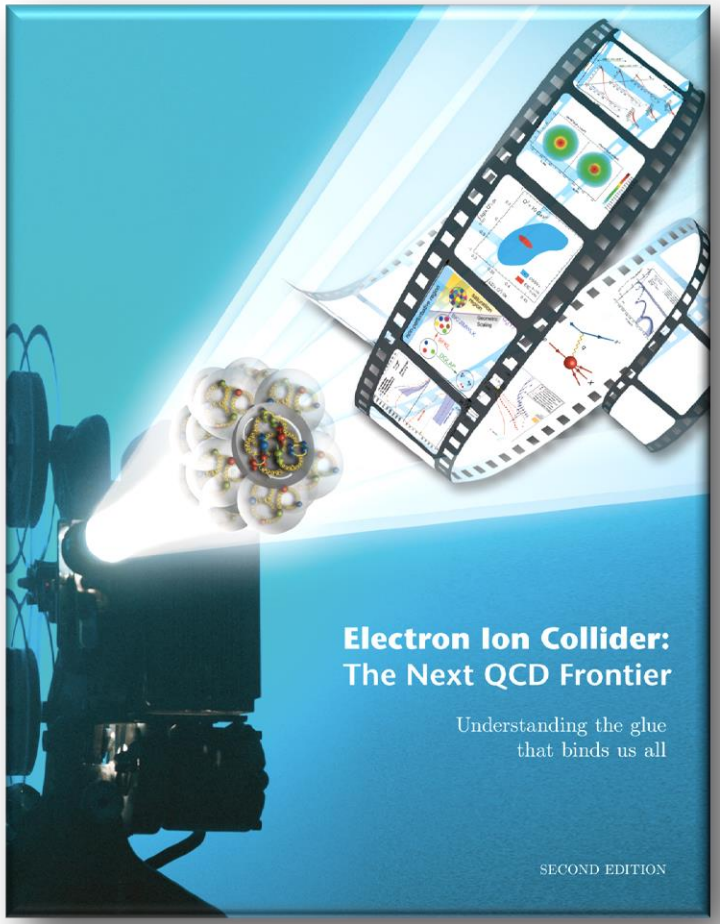
Collider Energy 20 – ~100 GeV

High Luminosity → 10^{33} - 10^{34} cm^2s^{-1}

Low x regime x → 0.0001

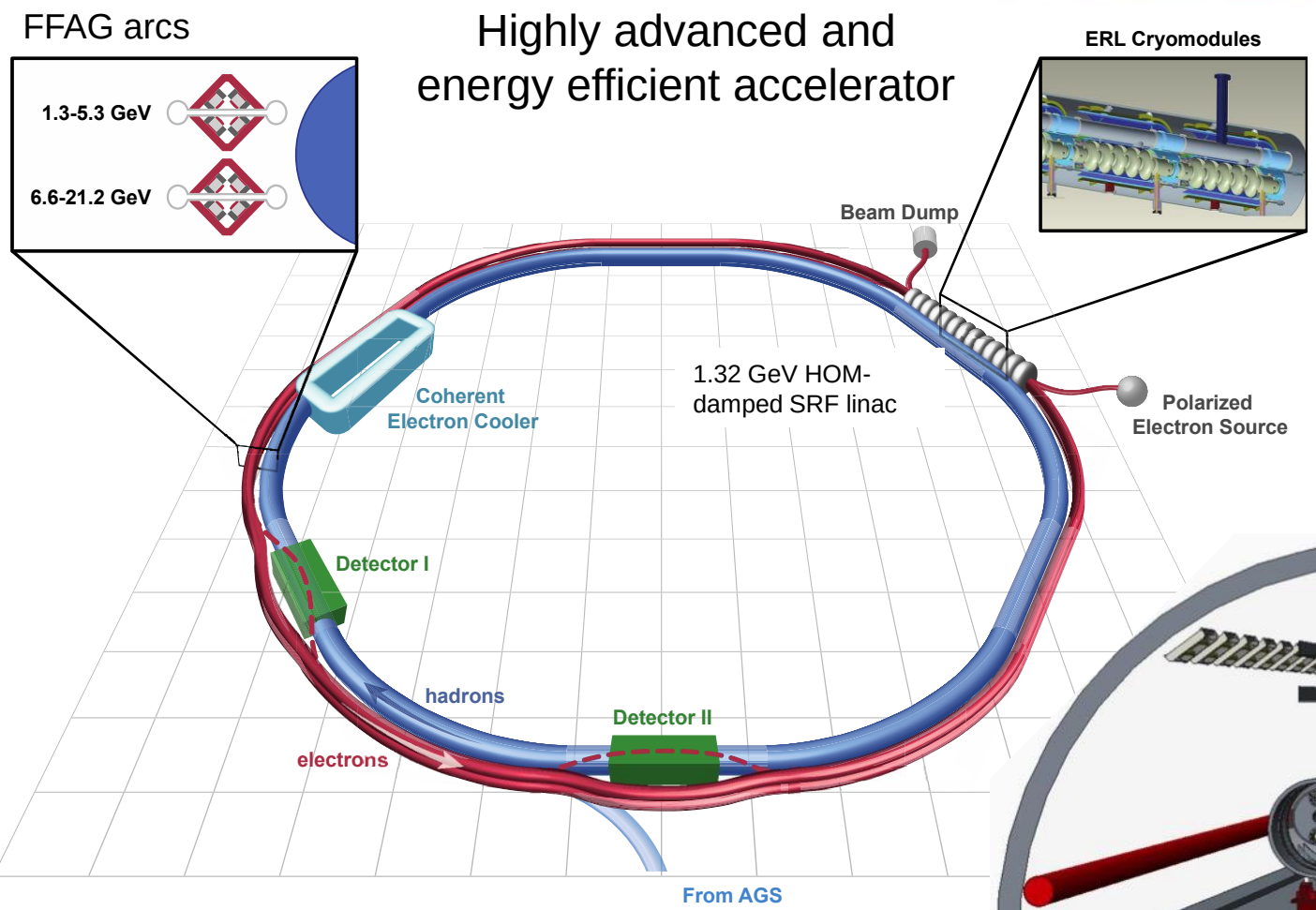
High polarizations 70%

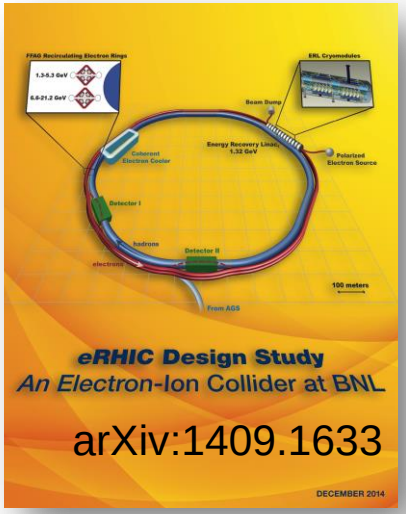
Ion beams up to U or PB

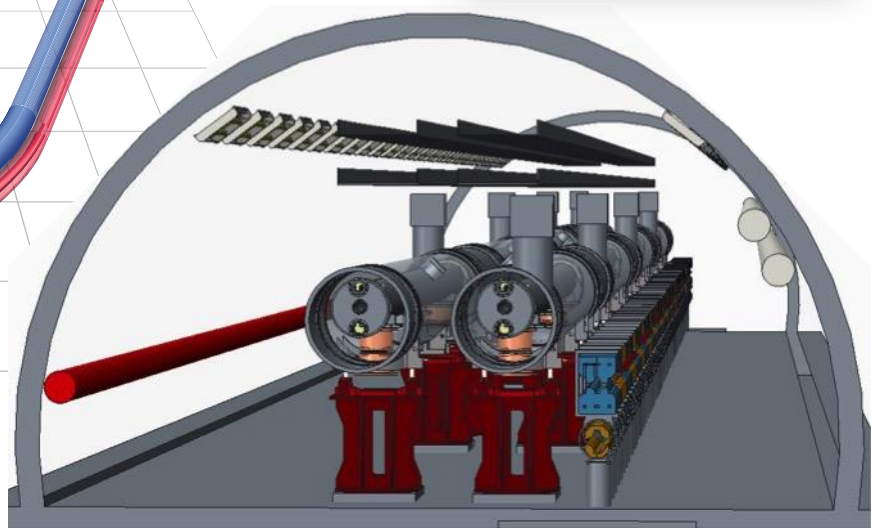


eRHIC Baseline Design

Highly advanced and energy efficient accelerator







- Peak luminosity 2×10^{34} cm^{-2} s^{-1} for $\sqrt{s}$ ~ 70-105 GeV (250 GeV p↑)
- Low-risk luminosity ~ $5\text{-}9 \times 10^{32}$ cm^{-2} s^{-1}

Jefferson Lab Electron Ion Collider

arXiv:1209.0757 (Sept. 2012)
arXiv:1504.07961 (April 2015)

Features:

- Collider ring circumference: ~2100 m
- Electron collider ring and transfer lines: PEP-II magnets, RF (476 MHz) and vacuum chambers
- Ion collider ring: super-ferric magnets (3T)
- Booster ring: super-ferric magnets
- SRF ion linac

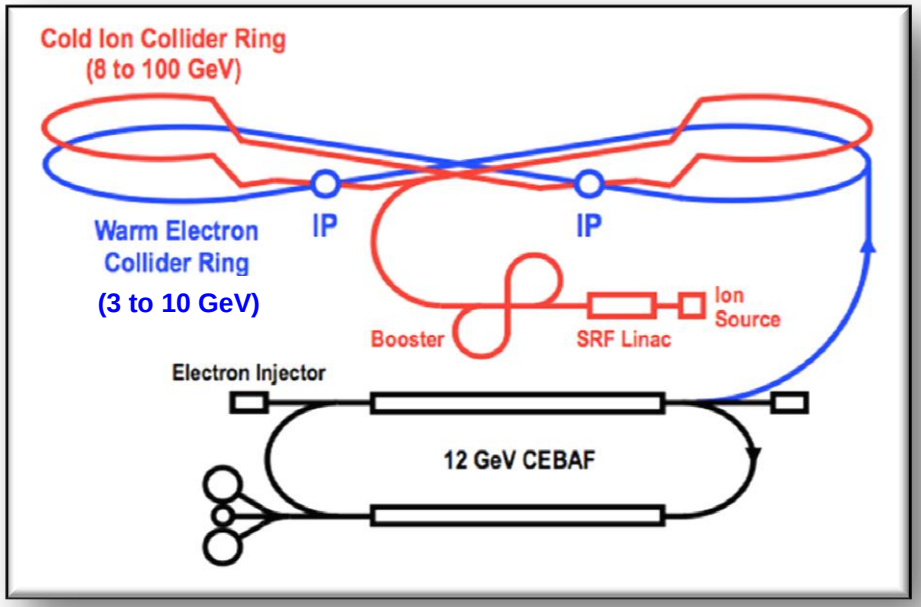
Low-risk luminosity ~ 5-10 × 10^{33} cm^{-2} s^{-1}

Goals:

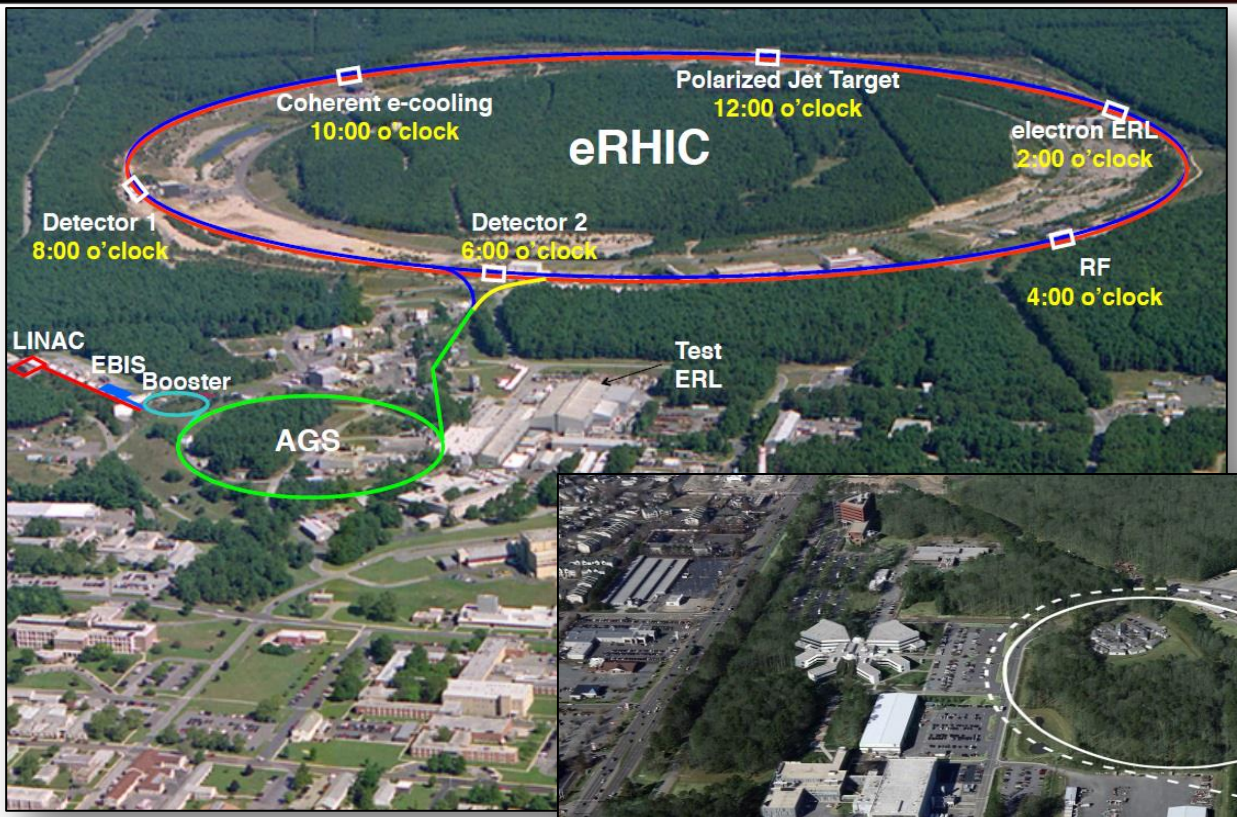
- Balance of civil construction versus magnet costs and risks
- Aim overall for low technical risks

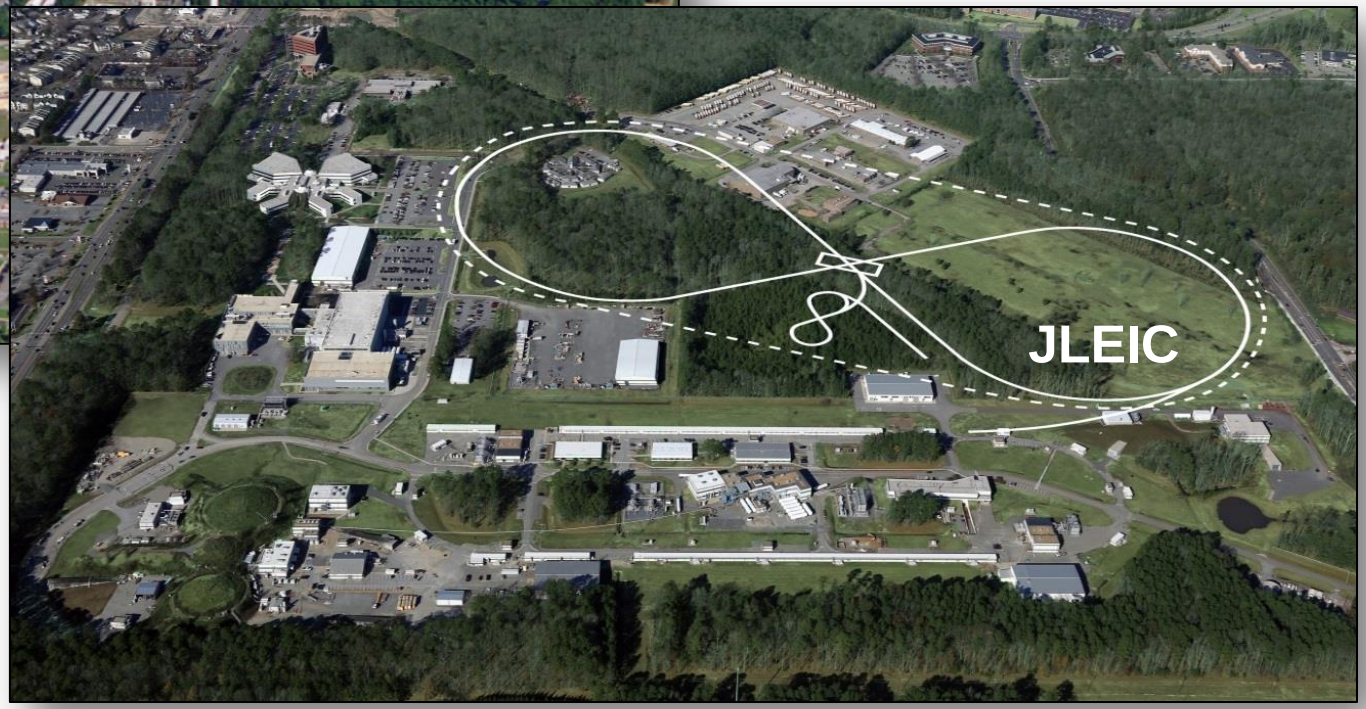
Collaborators:

- ANL, LBNL, Fermilab, SLAC, Texas A&M
  Also DESY, Dubna



US-Based Electron Ion Collider





EIC Electron-(backward) Direction Detection

- Low Q^2 Tagger (Photoproduction)
- Luminosity Measurement
- Compton Polarimetry

Each puts a premium on detection close to the electron beam direction

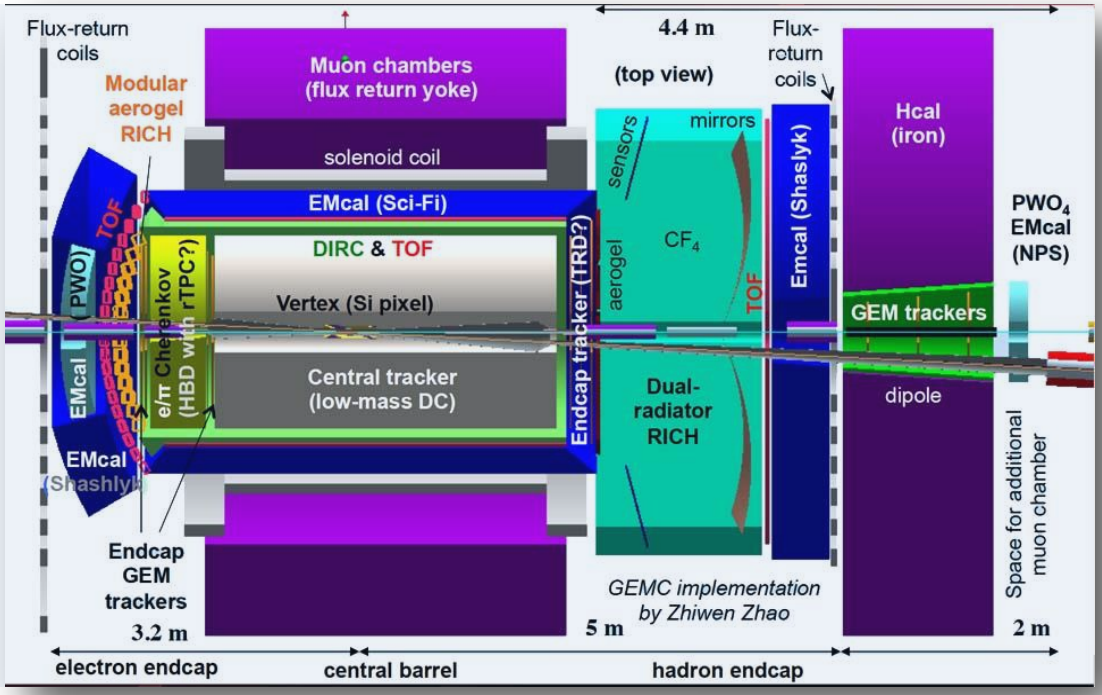
EIC Ion-(forward) Direction Detection

- Good acceptance for recoil nucleons (rigidity close to beam)
  - **Diffractive processes on nucleon, coherent nuclear reactions**
  - Small beam size at detection point (to get close to the beam)
    Secondary focus on roman pots, small beam emittance (cooling)
  - Large dispersion (to separate scattered particles from the beam)

- Good acceptance for fragments (rigidity different than beam)
  - **Tagging in light and heavy nuclei, nuclear diffraction**
  - Large magnet apertures (low gradients)
  - Detection at several points along a long, aperture-free drift region

- Good momentum- and angular resolution
  - **Free neutron structure through spectator tagging, imaging**
  - Both in roman pots and fixed detectors

Detector Design



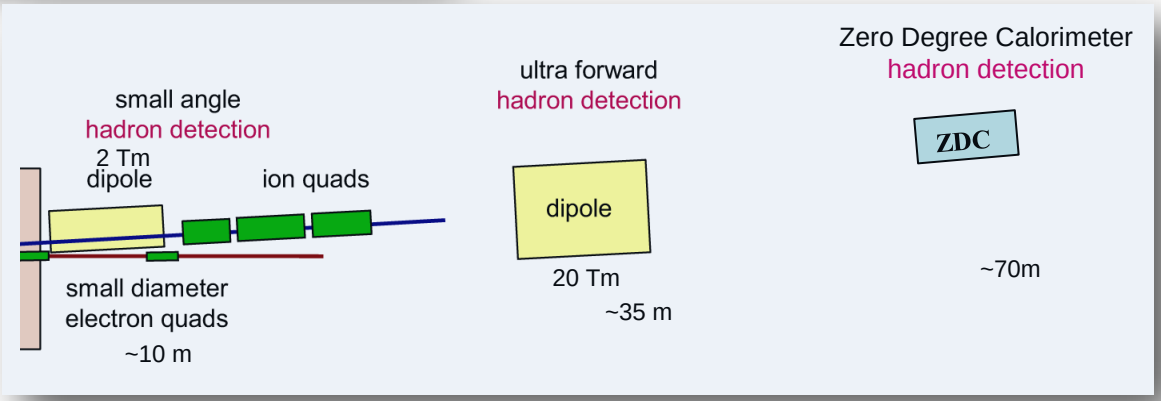
Detector

Backward (e Direction),

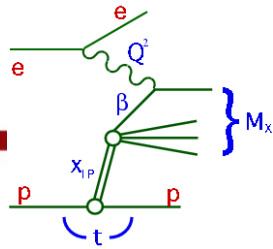
Central,

Forward, (ion direction) and
Very Forward

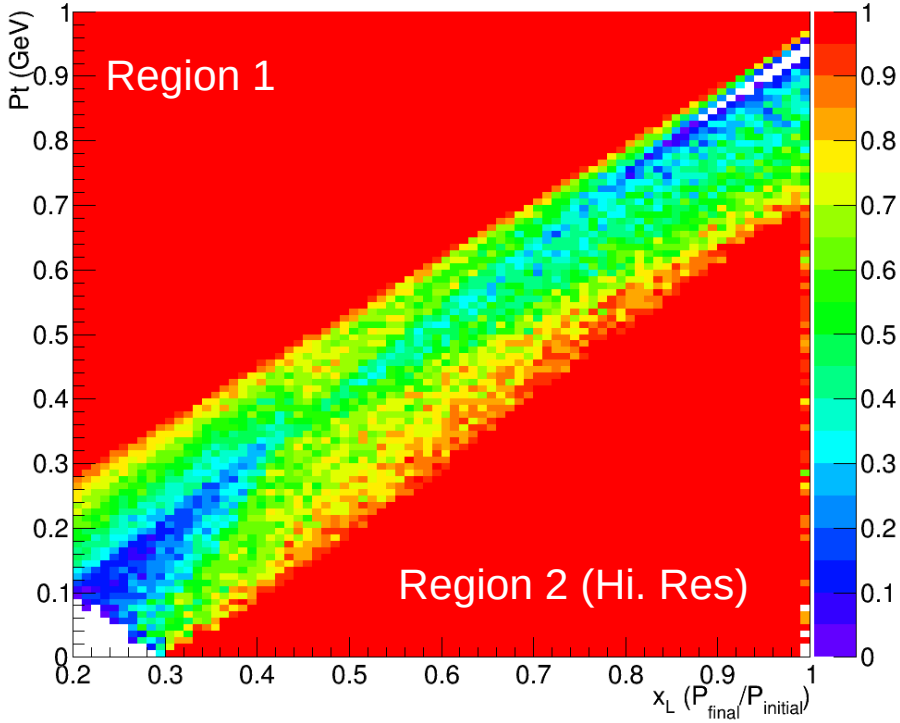
ALL Important!



Acceptance for p' in ep->e'Xp'



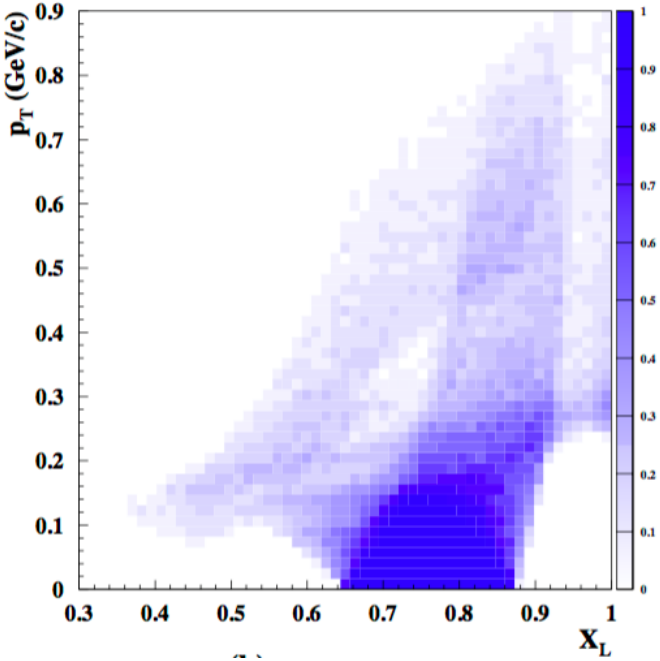
JLEIC acceptance



Zhiwen Zhao

ZEUS

Leading Proton Spectrometer



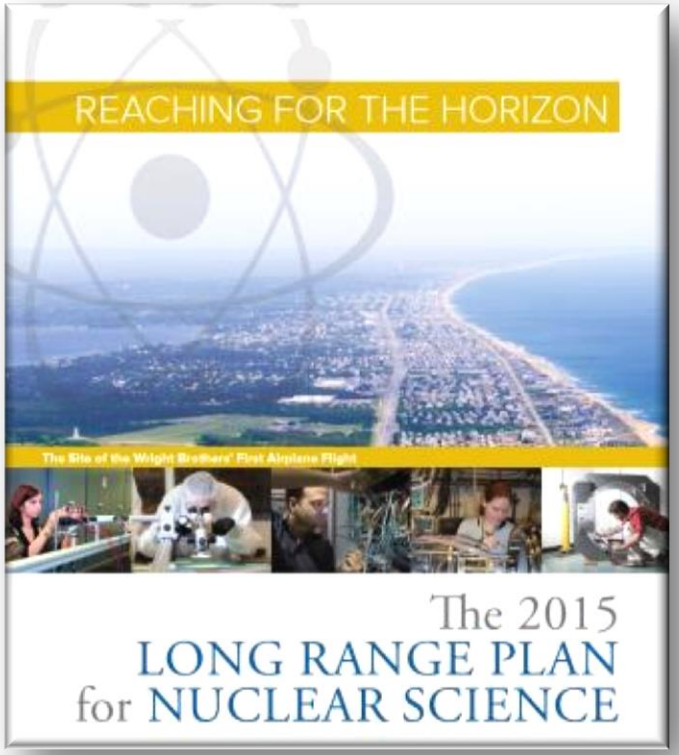
X_L= Ep'/Ep

Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

JLEIC: ~100% (also covers much higher X_L than at HERA)

NSAC 2015 LRP



Manifest impact on Electron Ion Collider
Users Organization/Meetings

National Academy Study

Enhanced explicit EIC Accelerator R&D

Increased interest in collaboration with Jefferson Lab

RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

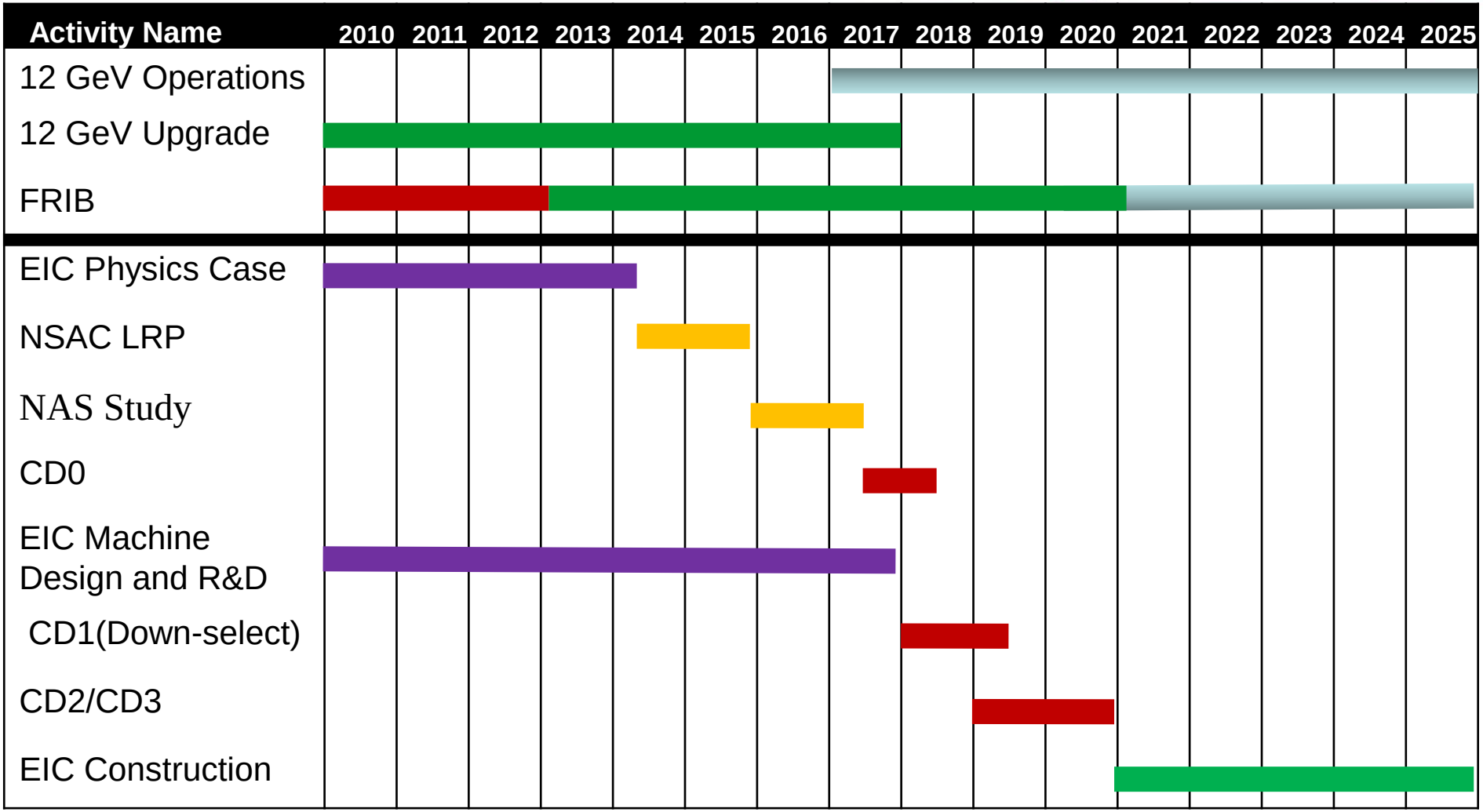
RECOMMENDATION III

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

RECOMMENDATION IV

We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

EIC Timeline



CD0 = DOE “Mission Need” statement; CD1 = technology and site selection
CD2/CD3 = establish project baseline cost and schedule

The EIC Users Group: EICUG.ORG

600+ collaborators, 26 countries, 104 institutions..
(April, 2016)

Conclusion

- Concept of Electron Ion Collider and the Physics Case
  - Embraced by US Nuclear Physics Community
  - Supported by the international nuclear physics community
  - Treated Seriously by US-DOE
  - To be considered by broader physics (NAS) community
- Facility Designs, collaborative efforts
  - Making palpable progress
  - Addressing Risk
  - Addressing Cost
- Detector Designs advancing
  - Expect dramatic improvements vis-à-vis HERA

There is a movement afoot!!!! It is very exciting!!!