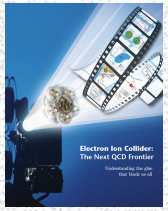


The Science and Status of Of the US Electron Ion Collider: "The EIC"

PHENIX workshop on Physics Opportunities with Accelerator and Detector Upgrades at RHIC

RIKEN, Japan

Credits to the EIC White Paper Writing Group, The EIC collaborators and Accelerator Developers

Stony Brook University

Abhay Deshpande
August 1, 2013

Why EIC?

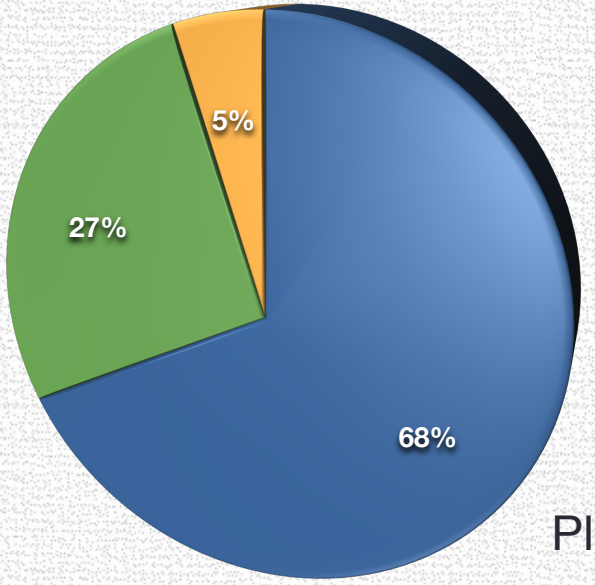
To study and understand the role of gluons and sea quarks in QCD

Understanding Gluons ➔ Understanding QCD

Also emphasized by Tetsuo Hatsuda, this meeting

Our Universe:

- 68% Dark energy
- 27% Dark matter
- 5% Visible matter



Planck 2013 Results

- What makes up the mass of the **visible universe?**

  Atomic mass (visible matter): 99.9% from nuclear mass

  Nuclear Mass: all of it from **nucleon mass**

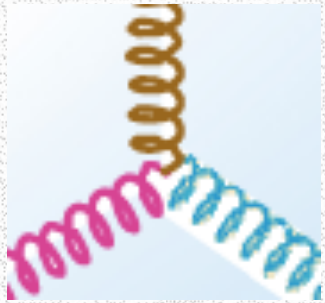
  Nucleon mass? ➔ **energy of massless *gluons* and almost massless up & down quarks**

  ➔ *"Mass without mass" – John Wheeler*

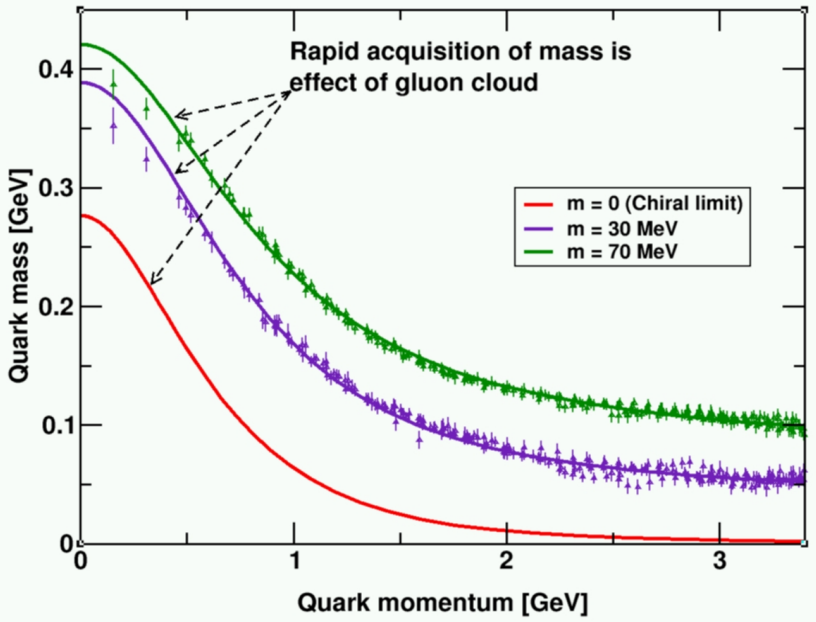
Gluon & quark interactions & dynamics make up the entire mass of the visible universe!

Generation of mass in QCD

- 99% of the nucleon mass: self-generated gluon fields
- Similarity between p, n mass indicates ➔ **gluon self interactions** are identical & overwhelmingly important:



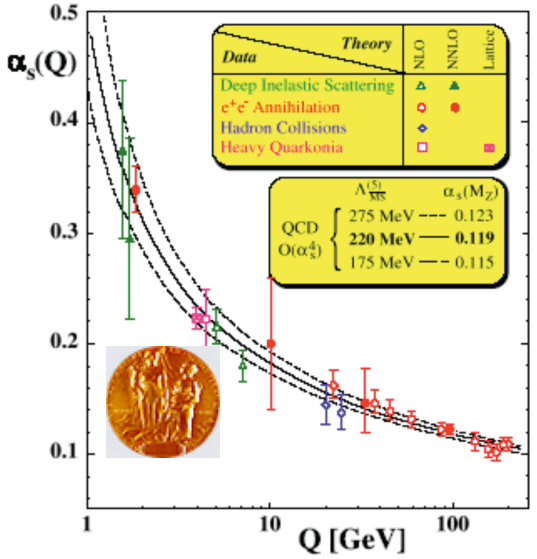
Bhagwat et al. arXiv:0710.2059 [nucl-th]



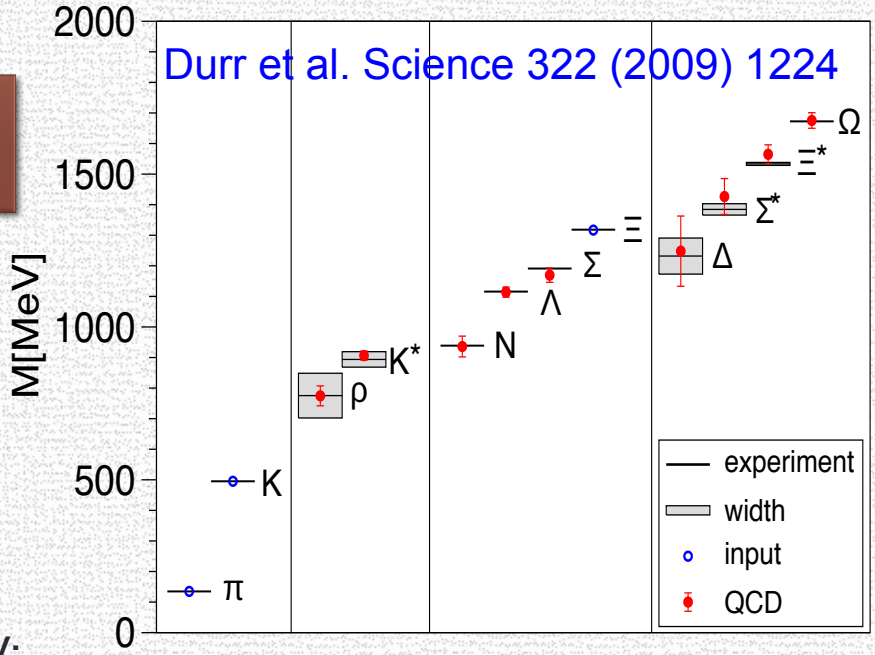
Success of QCD!

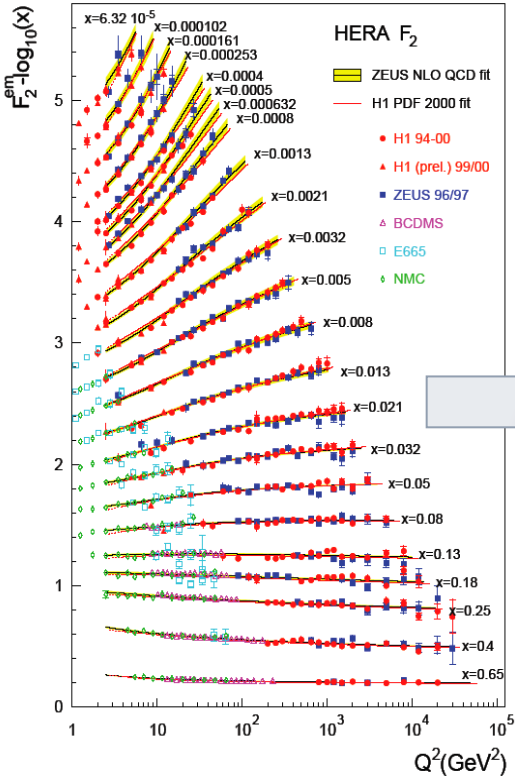
Higgs boson plays no role here.

Other successes of QCD: ➔



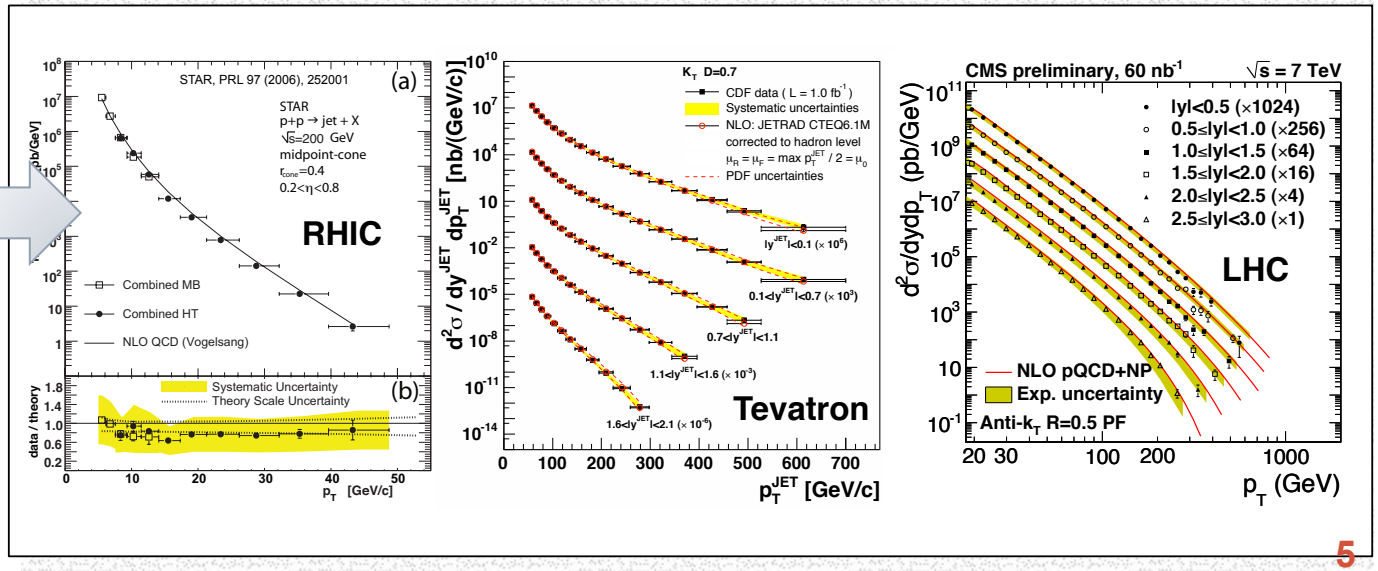
Successes of QCD





Measure **e-p** 0.3 TeV:

➔ Use pQCD Calculate **p-p, p-pbar Jet x-sctn** at 0.2, 2, 7 TeV



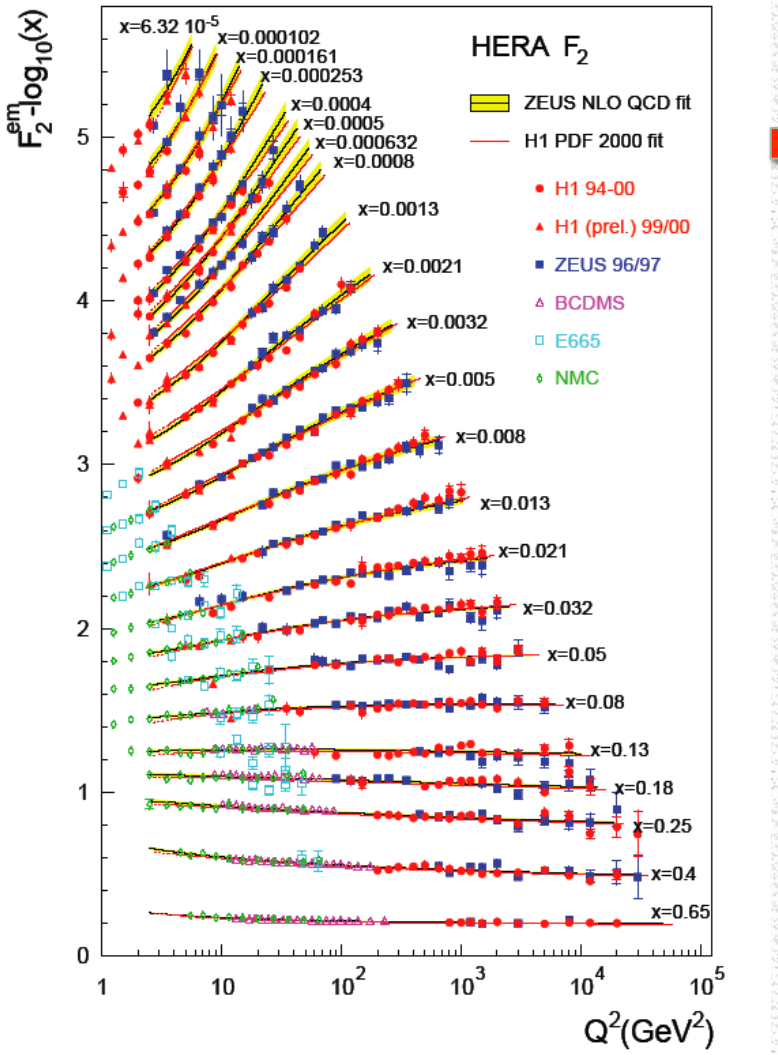
"Folks, we should stop testing QCD, and start understanding it." Yuri Dokshitzer (ICHEP'98, Vancouver)

QCD is the correct theory of strong interactions, but do we understand it?

How well do we understand the role of gluons in QCD?

How well do we understand the sea quarks?

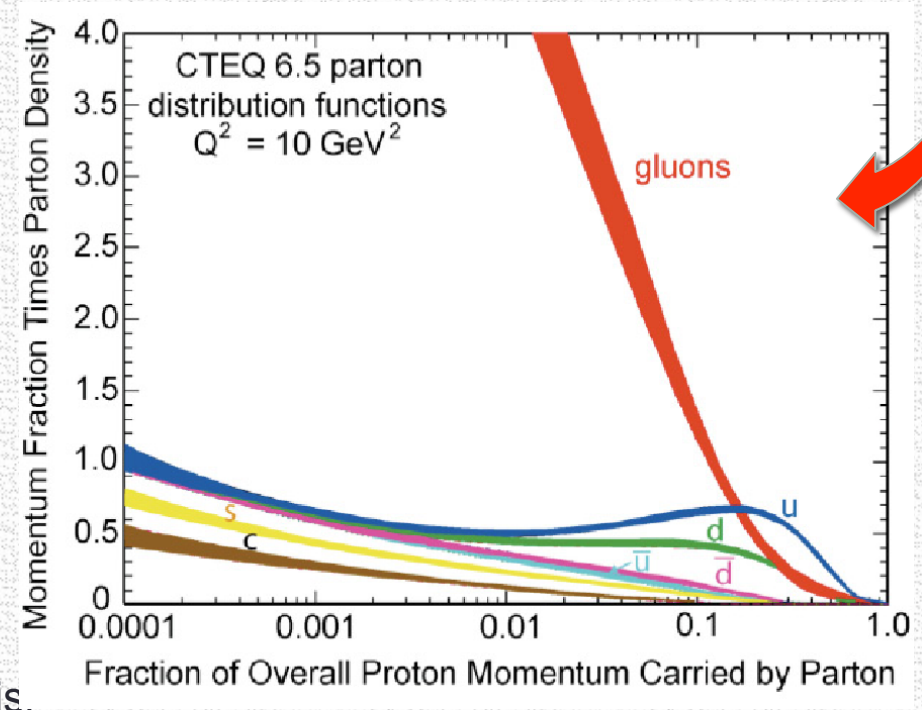
Measurement of Glue at HERA



- Scaling violations of $F_2(x,Q^2)$

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

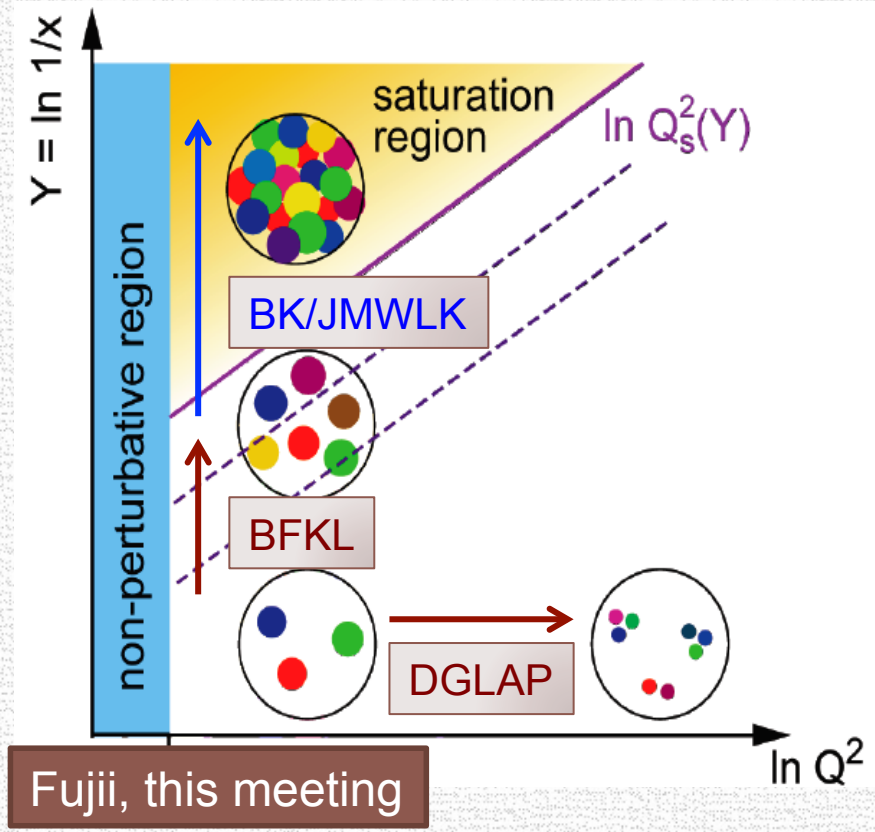
- NLO pQCD analyses: fits with **linear** DGLAP* equations



*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Physics at Low x ➔ Color Glass Condensate?

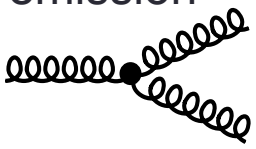
See Ann. Rev. Nucl Part (60) 2010 F. Gelis et al., , arXiv:1002.0333)



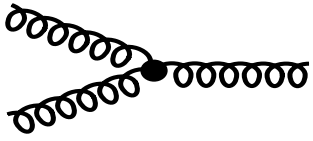
Method of including **non-linear** effects (McLerran, Venugopalan)

- Small coupling, high gluon densities
- BK/JMWLK equations lead to a Saturation Scale $Q_S(Y)$

Linear QCD BFKL: gluon emission



Nonlinear QCD BK/JMWLK gluon recombination

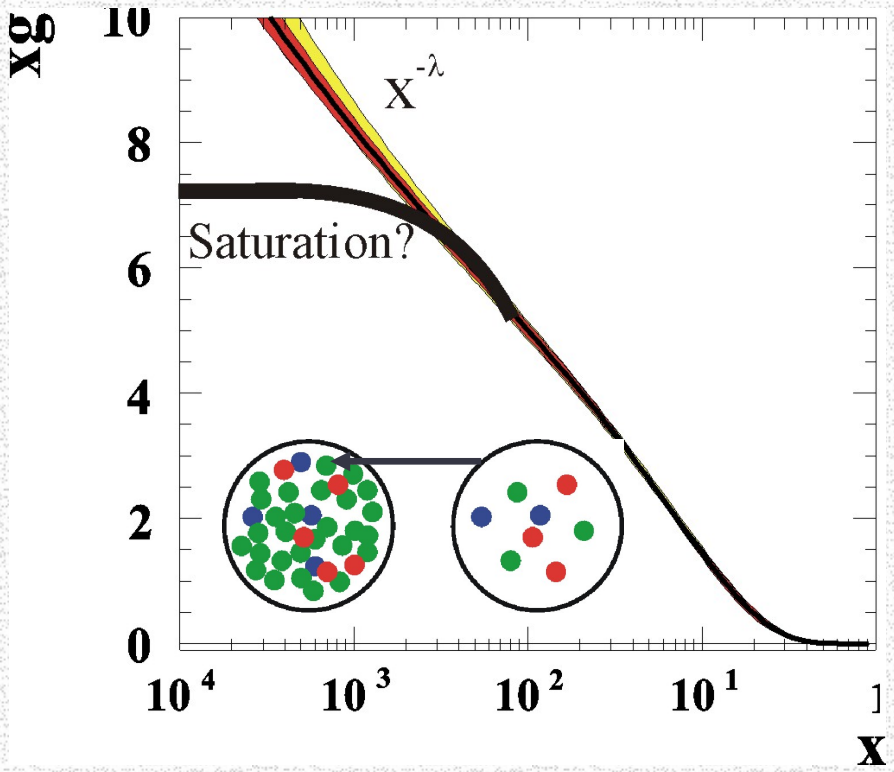


At Q_S gluon emission balances the recombination

Strongly correlated gluonic system at high energy (low-x)

Color Glass Condensate ??

Gluon distribution at low-x understood?



- Indefinite rise: Infinite high energy hadron cross section?
  - An **artifact** of using of **linear** DGLAP in gluon extraction?
- Somewhere, some how the low x rise of the gluon should be tamed! How? Where?
- How would we find out?
  - Need theory development &

Need a higher energy e-p collider than HERA!

➔Large Hadron electron Collider (LHeC)

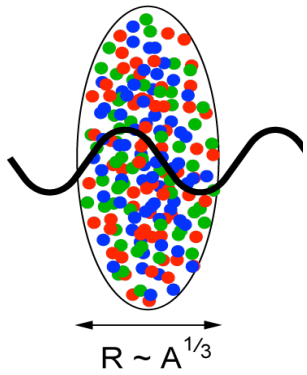
➔ Nuclei: naturally enhance the densities of partonic matter

Why not use Nuclear DIS at high energy?

How to reach the high gluon density?

More powerful e-p collider than HERA (300 GeV) →
Large **H**adron **e**lectron **C**ollider

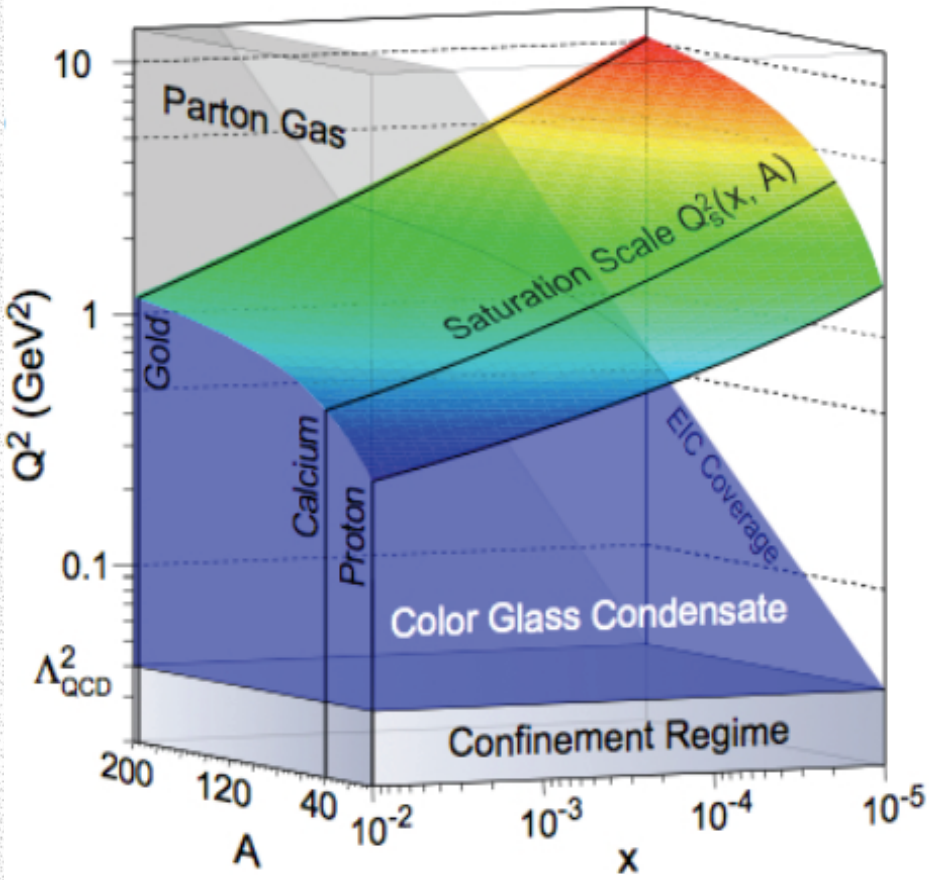
Alternatively,
Probe the nucleons in ***NUCLEI***
US Electron Ion Collider (EIC)



Kowalski, Teany
PRD 68:114005

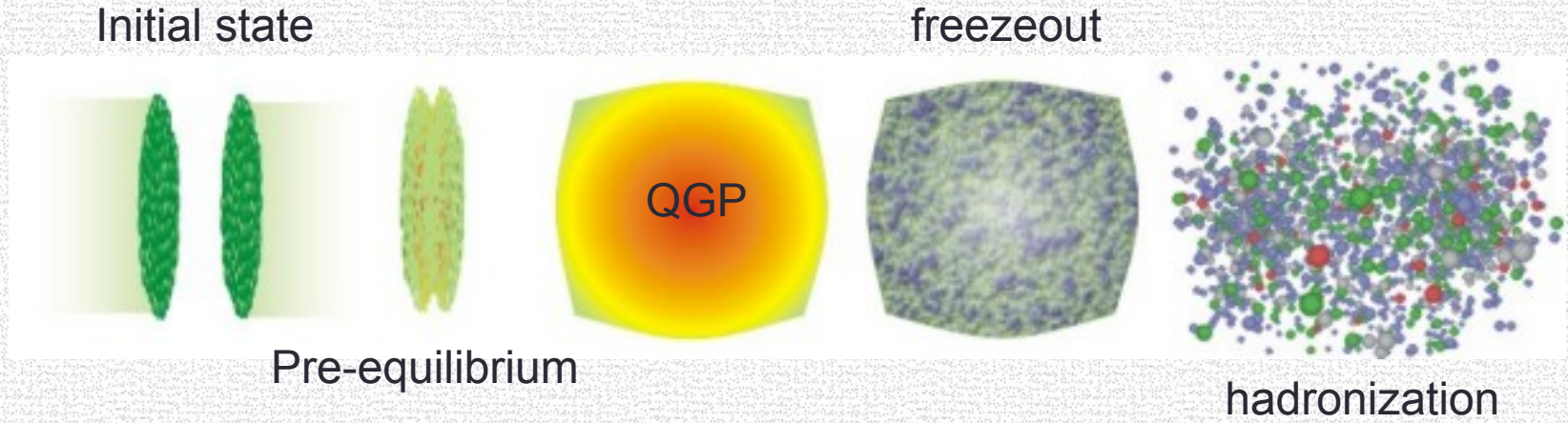
$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

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

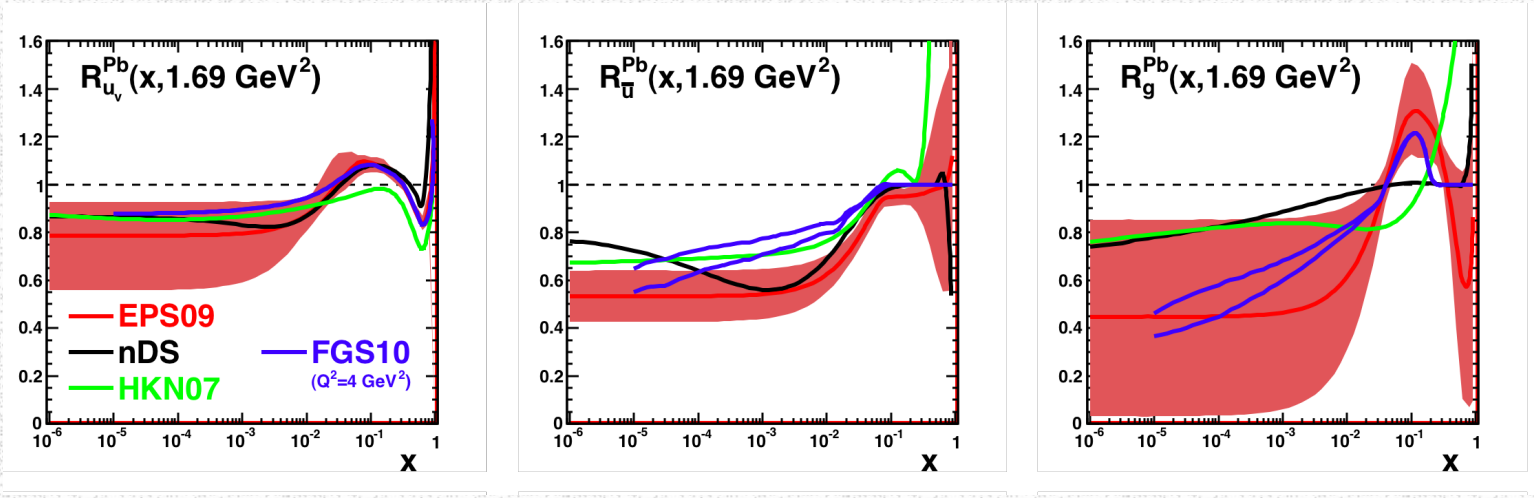


Enhancement of Q_S with A, not energy

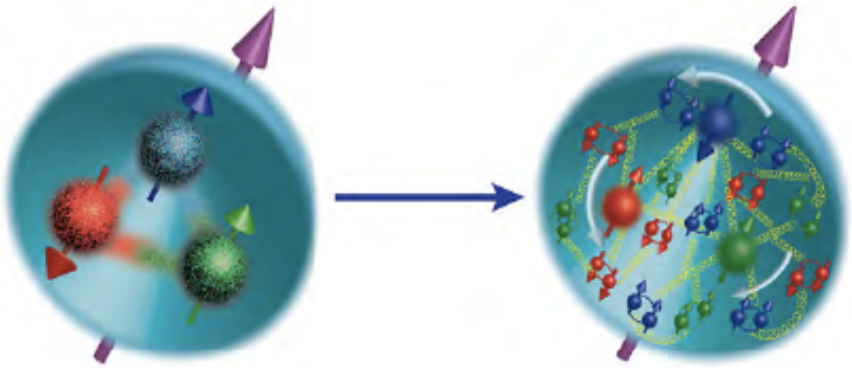
EIC & RHIC/LHC (Heavy Ion)



To understand "QGP" fully, we need to understand:
The initial state PDFs in the nucleus & hadronization



R_i = (nuclear PDF_i)/(A*proton PDF_i)

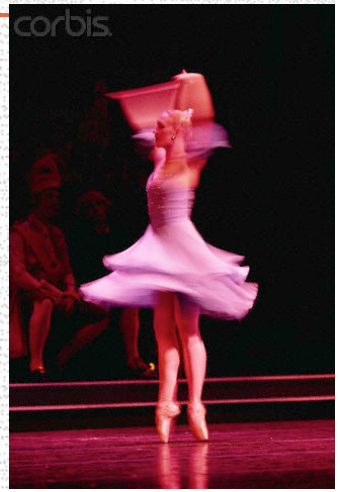


Evolution In Our Understanding Of Nucleon "Spin"

What are the ***quark, gluon intrinsic spin*** contributions to the nucleon's spin? → *Treat proton as a 1D object*

More recently: *Admit that proton is a (2+1)D object!*

What are the ***position & momentum correlations*** amongst partons? How do they contribute to spin?



Nucleon Spin Puzzle

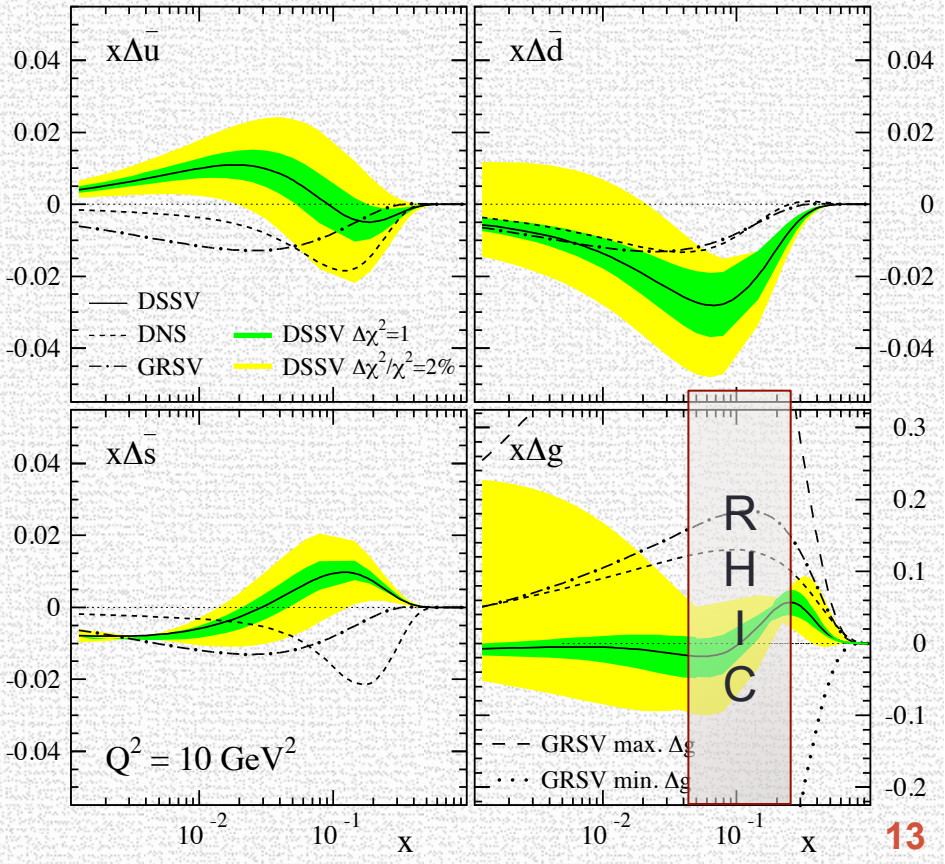
X. Ji & T. Izubuchi's talks
Potential from Lattice QCD

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta g + L_g$$

Hatta, this meeting

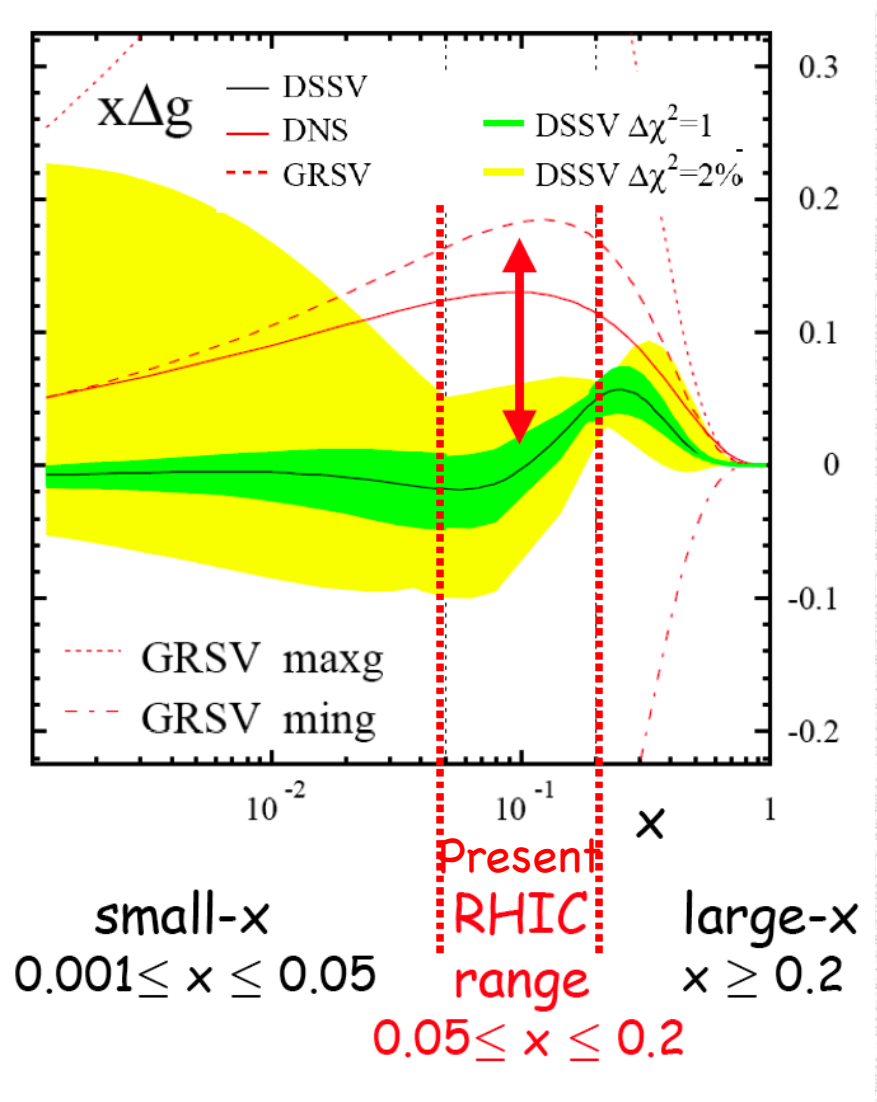
- ½ ($\Delta\Sigma$) ~ 0.15 : From fixed target pol. DIS experiments performed in 1990s
- Recent RHIC-Spin: (2000s)
  - *Δg ~ 0.10 +/- 0.07 (x = 0.05→0.2) at Q^2=10 GeV^2*
  - *Not as large as anticipated in the 1990s but seems to be non-zero (currently with large uncertainty)*
- *Precision needed*
- *Low-x coverage needed*

DSSV, arXiv:0804.0422



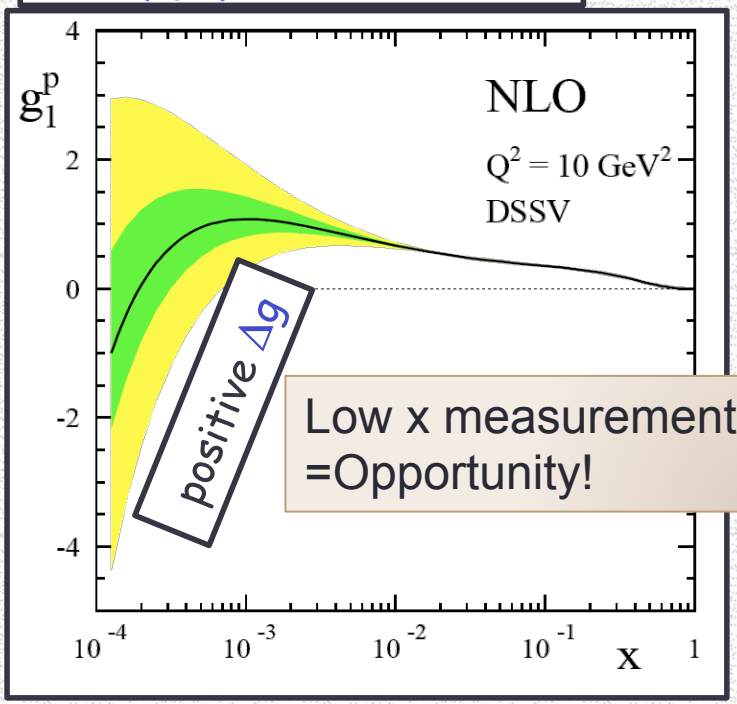
Current knowledge of Polarized Glue:

de Florian, Sassot, Stratmann & Vogelsang



- **Global analysis: DIS, SIDIS, RHIC-Spin**
- **Uncertainly on ΔG large at low x**

$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$

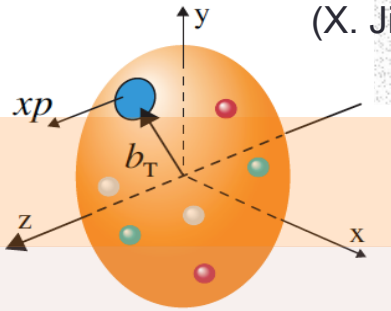


Low x measurements =Opportunity!

Unified view of the Nucleon Structure

(X. Ji, D. Mueller, A. Radyushkin)

❑ Wigner distributions:



5D

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

$\int d^2b_T$ $\int d^2k_T$

3D

HERMES
JLab12
COMPASS

JLab12
COMPASS
for
Valence

$f(x,k_T)$ $f(x,b_T)$

Fourier trf.
$b_T \leftrightarrow \Delta$

$H(x,0,t)$
$t=-\Delta^2$

$\xi=0$

$H(x,\xi,t)$

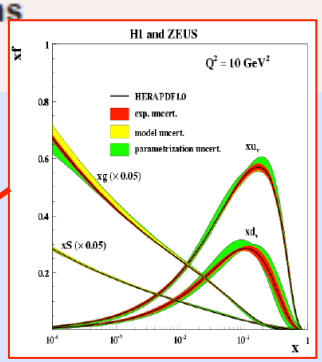
transverse momentum distributions (TMDs)
semi–inclusive processes

impact parameter distributions

generalized parton distributions (GPDs)
exclusive processes

1D

$\int d^2k_T$ $\int d^2b_T$



$\int dx$

$\int dx x^{n-1}$

$f(x)$
parton densities
inclusive and semi–inclusive processes

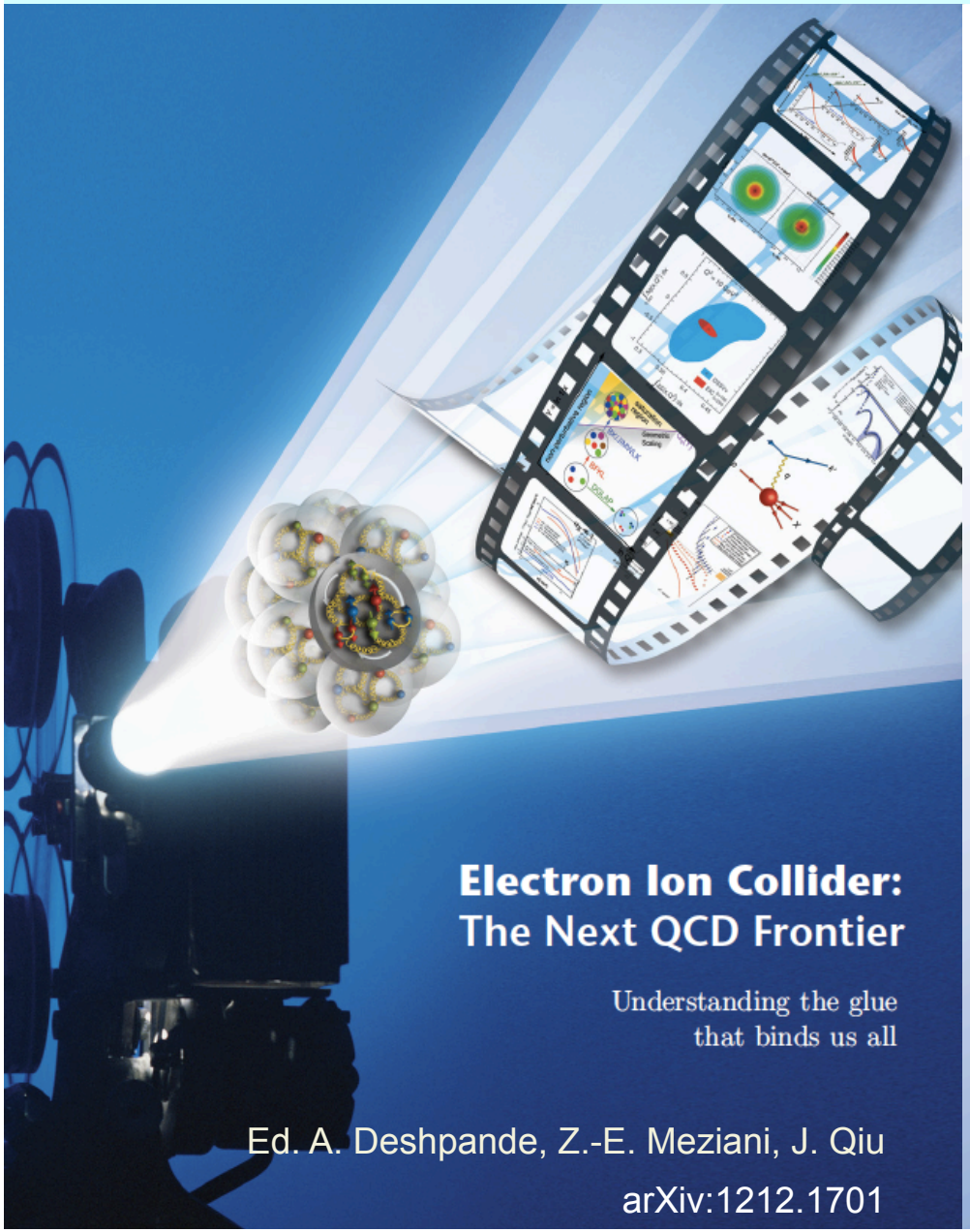
$F_1(t)$
form factors
elastic scattering

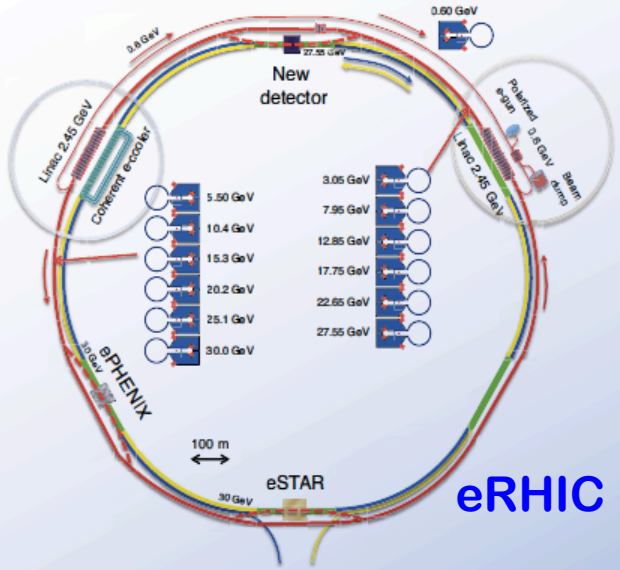
$A_{n,0}(t)+4\xi A_{n,2}(t)+....$
generalized form factors
lattice calculations

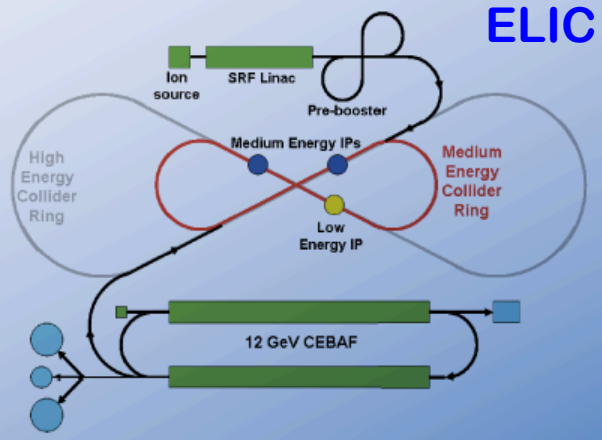
❑ EIC – 3D imaging of sea and gluons:

- ✧ TMDs – confined motion in a nucleon (semi-inclusive DIS)
- ✧ GPDs – Spatial imaging of quarks and gluons (exclusive DIS)

White Paper for the Electron-Ion Collider





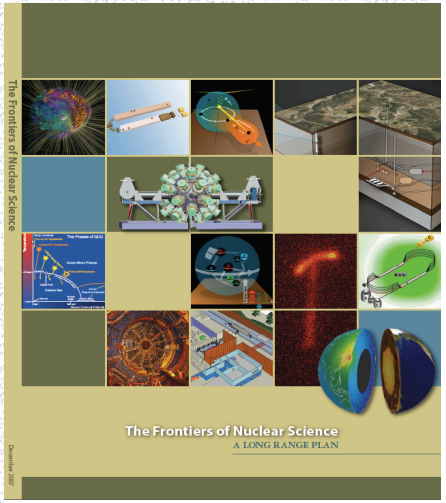


Jefferson Lab Thomas Jefferson National Accelerator Facility
BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

Community effort and commitment

- 2007 Nuclear Physics Long Range Plan

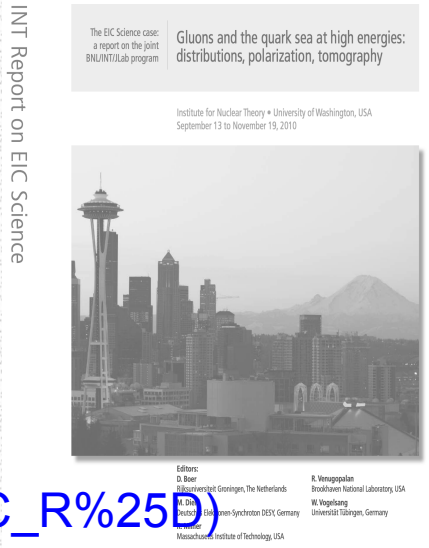
  Designated Electron-Ion Collider (EIC) as "embodying the vision for reaching the next QCD frontier"



- Many workshops on EIC physics:

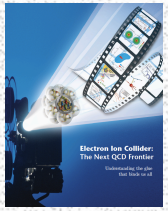
  Ten-week program (9/13–11/19, 2010)
  at Institute for Nuclear Theory

  (INT Report: arXiv:1108.1713v2, 500+ pages)



- Commitment from BNL and JLab:
  - BNL EIC Task force (https://wiki.bnl.gov/eic/index.php/Main_Page)
  - EIC@JLab (https://eic.jlab.org/wiki/index.php/Main_Page)
  - Detector R&D (https://wiki.bnl.gov/conferences/index.php/EIC_R%25D)
  - EIC International Advisory Committee – jointly appointed by BNL & JLab

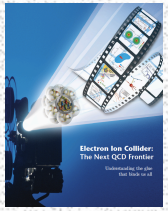
Science of EIC



- **How are sea quarks and gluons and their spin distributed in space and momentum inside the nucleon?**
  - How are these quark and gluon distributions correlated with the over all nucleon properties, such as spin direction?
  - What is the role of the motion of sea quarks and gluons in building the nucleon spin?

- **Where does the saturation of gluon densities set in?**
  - Is there a simple boundary that separates the region from the more dilute quark gluon matter? If so how do the distributions of quarks and gluons change as one crosses the boundary?
  - Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

Science of EIC… (continued)

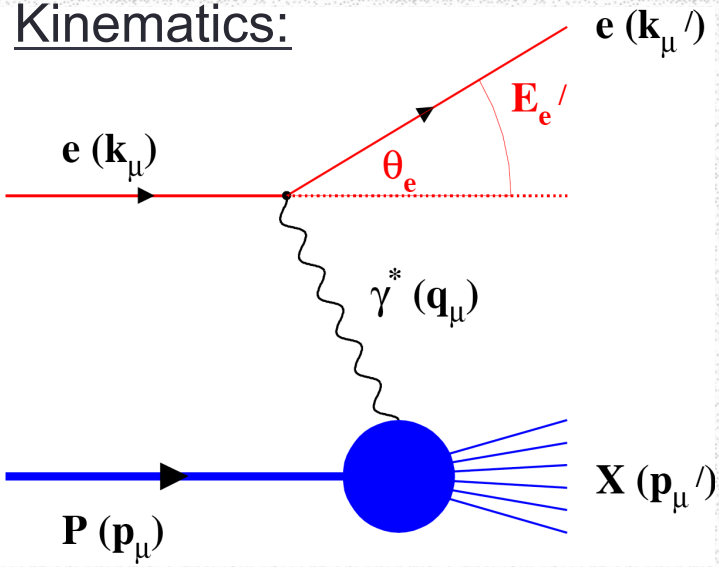


- **How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?**
  - How does the transverse spatial distribution of gluons compare to that in the nucleon?
  - How does matter respond to fast moving color charge passing through it? Is this response different for light and heavy quarks?

- Since (a) the collider will provide high luminosity, high energy and polarized beams and (b) there may eventually be a very comprehensive large acceptance detector: **Why not explore topics in Electroweak Physics and possible impact on searches for physics beyond the SM?**

Deep Inelastic Scattering = Precision + Control

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

Measure of resolution power

$$Q^2 = 2E_e E'_e(1 - \cos\Theta_{e'})$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

Hadron :

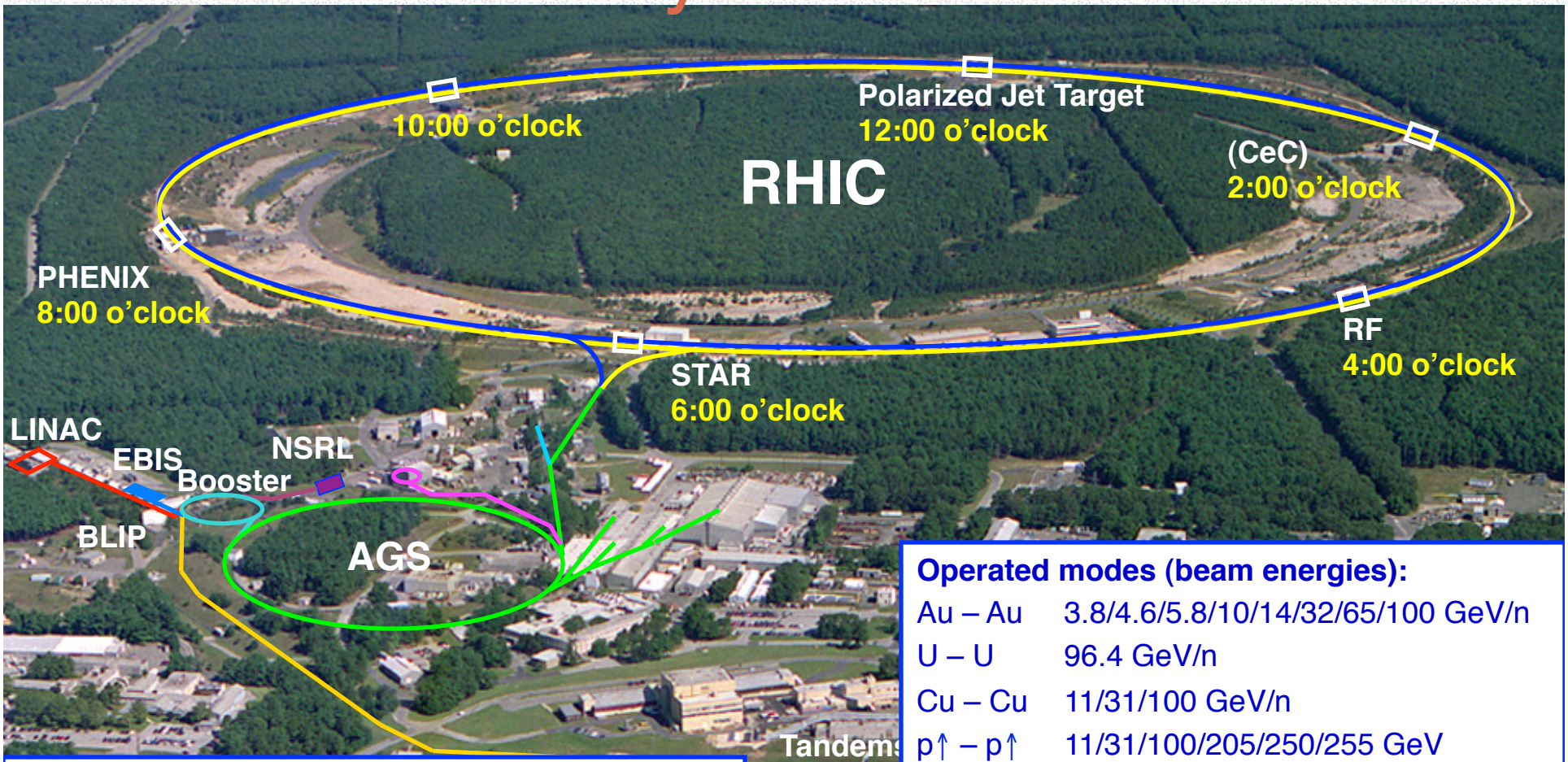
$$z = \frac{E_h}{\nu}; p_t$$ with respect to γ

Inclusive events: e+p/A → e'+X
detect only the scattered lepton in the detector

Semi-inclusive events: e+p/A → e'+h(π,K,p,jet)+X
detect the scattered lepton in coincidence with identified hadrons/jets in the detector

Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)
Detect every things including scattered proton/nucleus (or its fragments)

RHIC – The Only Polarized Collider



Achieved peak luminosities:

Au – Au (100 GeV/n)	195×10^{30} cm^{-2} s^{-1}
p↑ – p↑ (255 GeV)	165×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 255 GeV):

Tevatron (p – pbar)	110×10^{30} cm^{-2} s^{-1}
LHC (p – p)	430×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

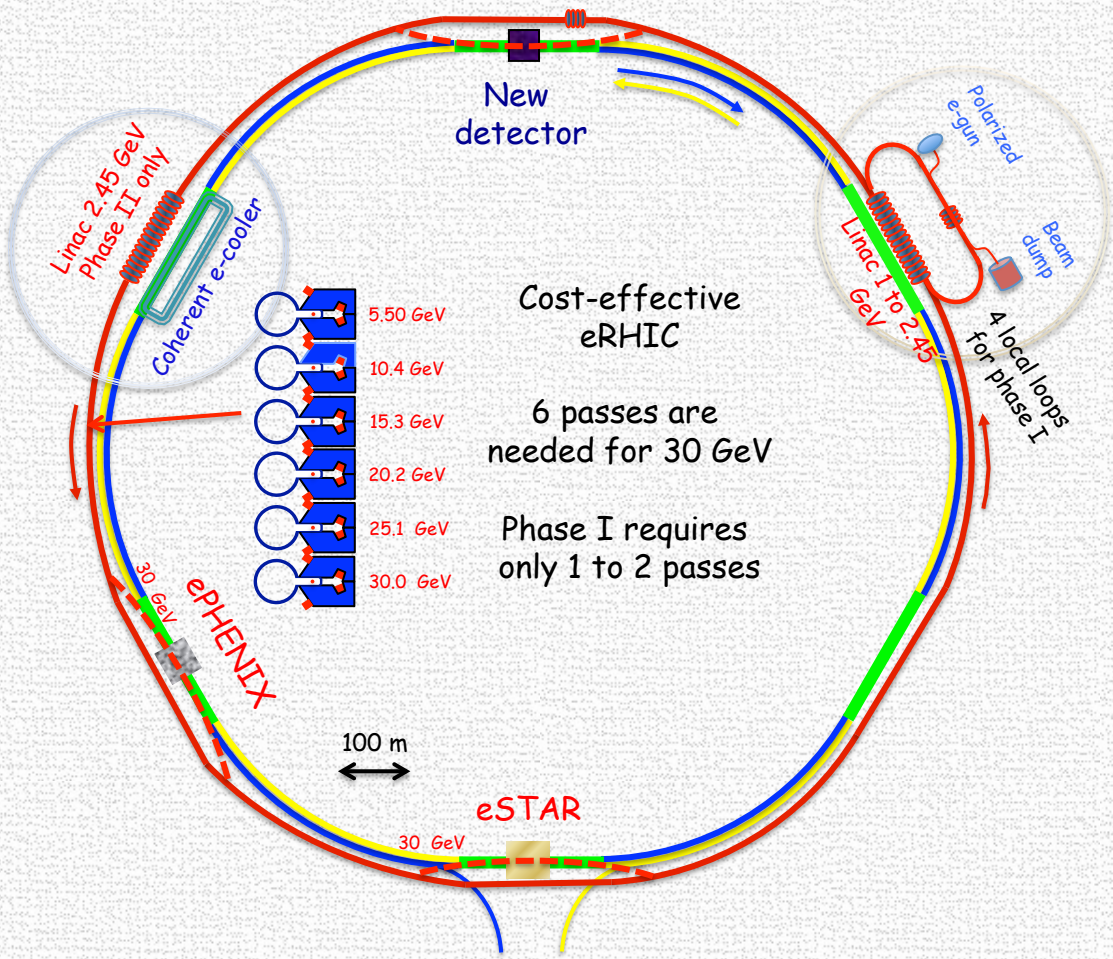
Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

Planned or possible future modes:

Au – Au	2.5 GeV/n
p↑ – Au*	100 GeV/n
p↑ – ^{3}He↑*	166 GeV/n

(*asymmetric rigidity)

eRHIC at Brookhaven National Laboratory



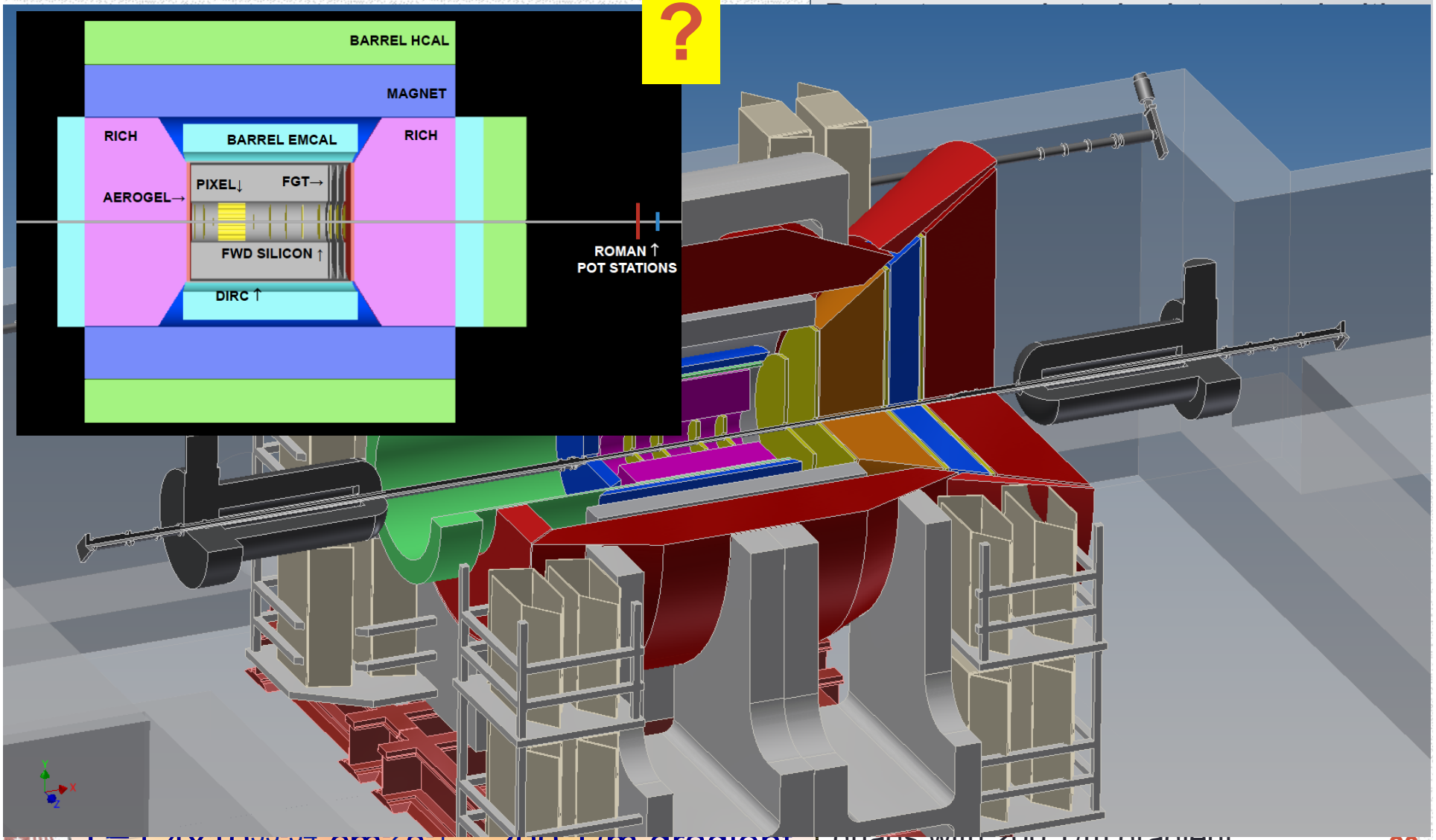
Current Plan (Stage I)
$\sqrt{s}$ ~ 60-100 GeV
Possible with 10 GeV Electron beam

Future Upgrade (Stage II)
$\sqrt{s}$ > 100 GeV

$L = 10^{33\text{-}34}$ cm^{-2}sec^{-1}
100-1000 times HERA
→ 50-500 fb^{-1} integrated luminosity in 10 yrs

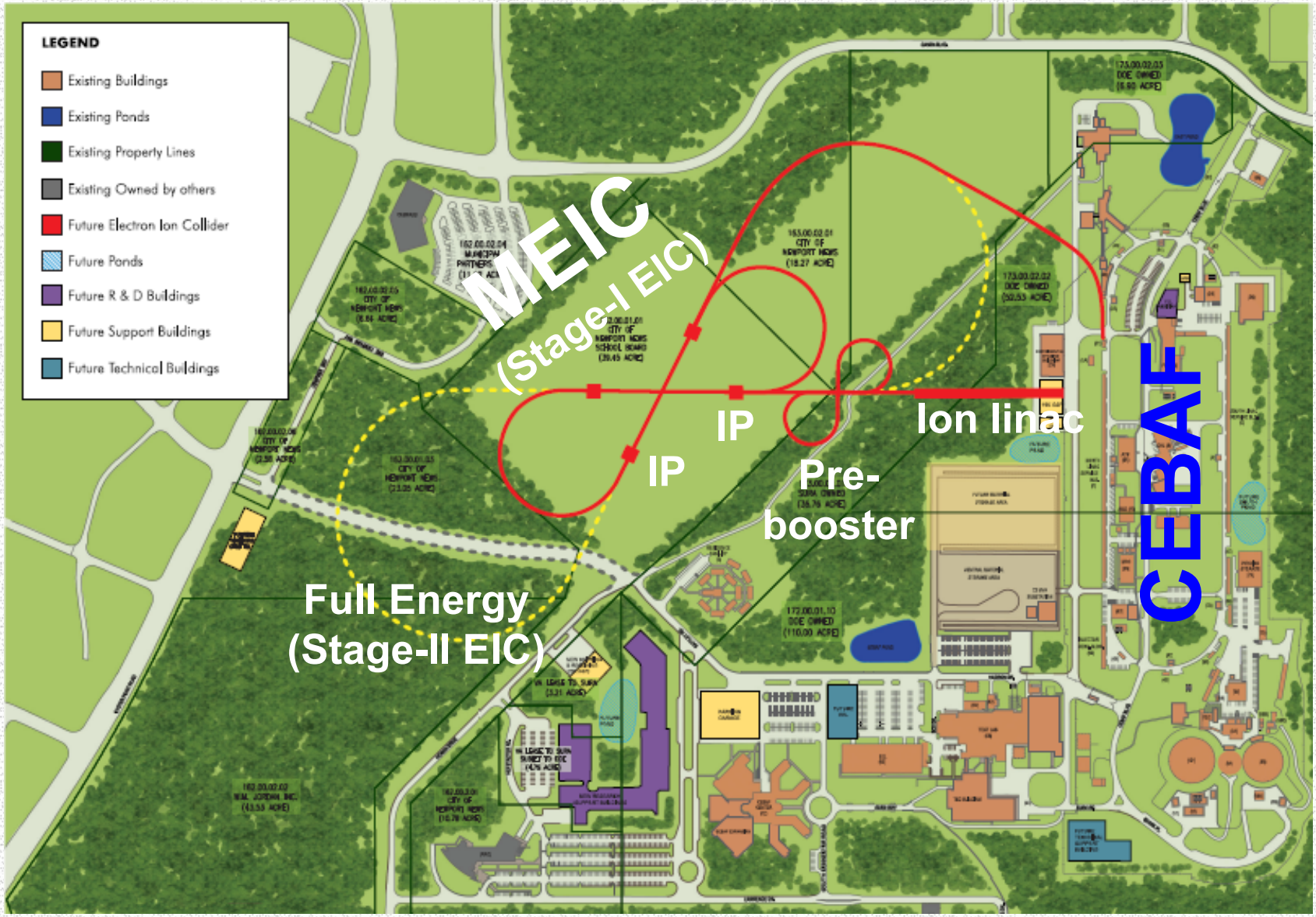
Discussions this week here

EIC-ePHENIX Detector & IR

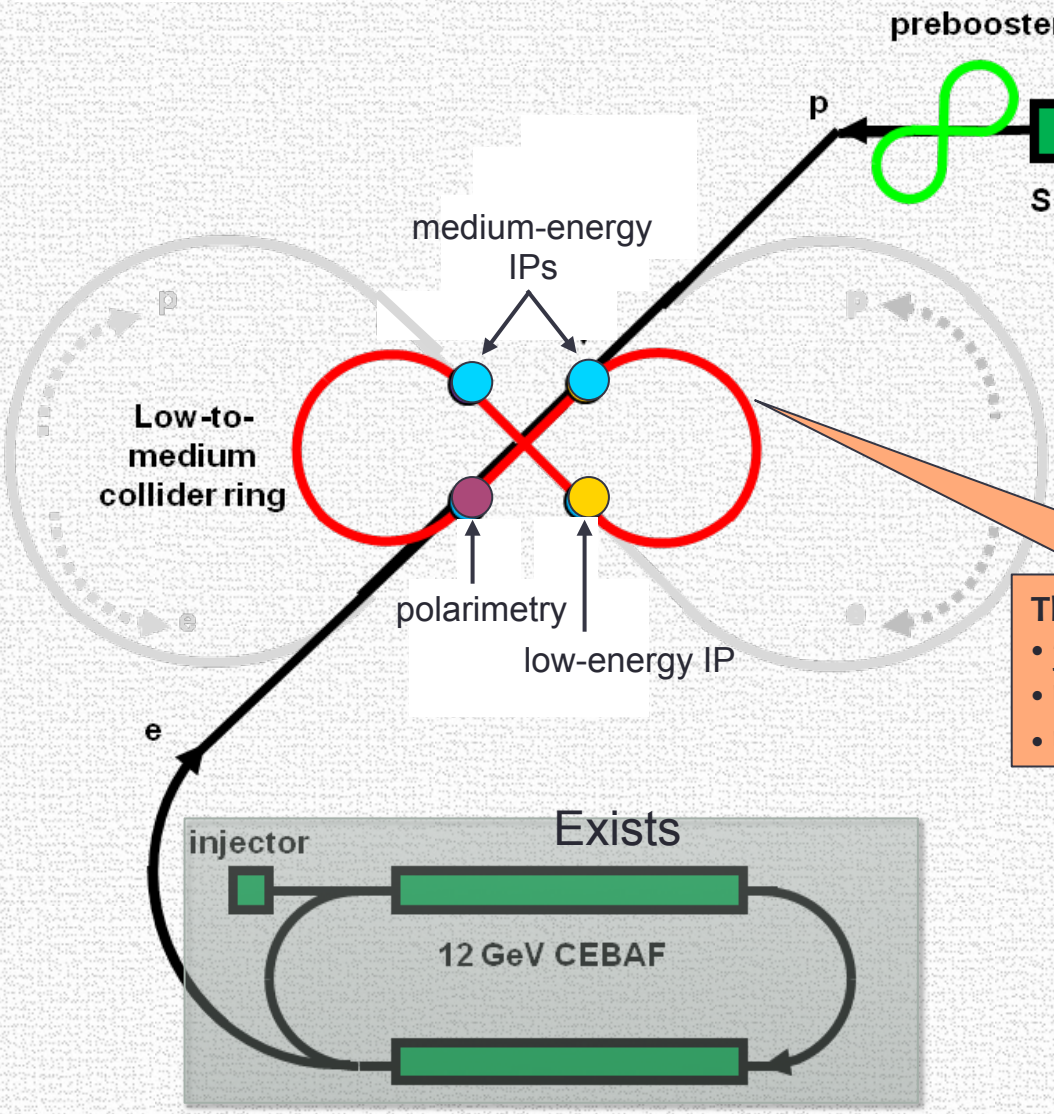


L= 1.4x10[illegible] cm⁻²s⁻¹, 200 T/m gradient | quads with 200 T/m gradient

MEIC/EIC Layout



MEIC : Medium Energy EIC at JLab

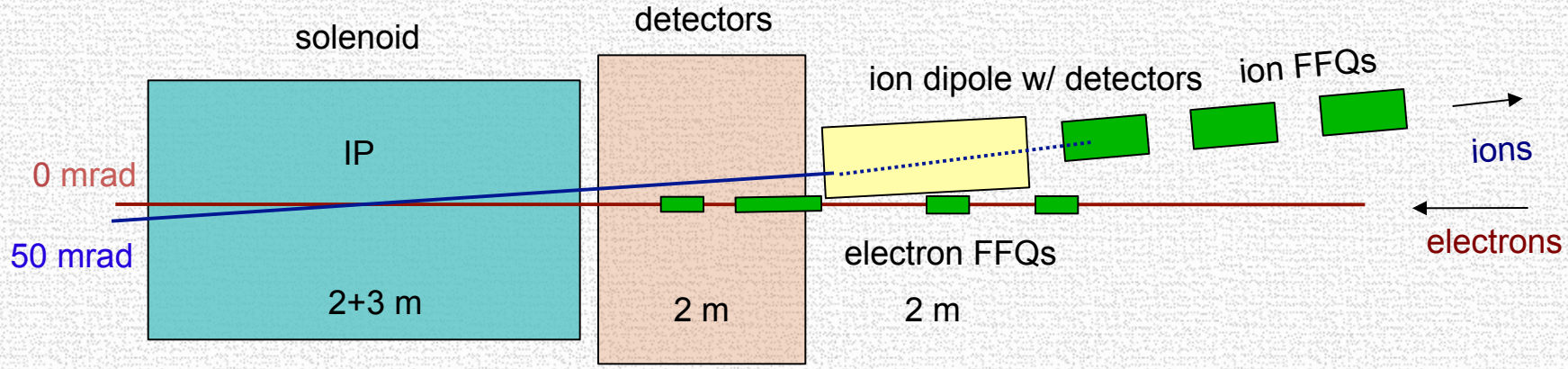


Plan: √s ~ ~50 GeV
Future Upgrade:
√s > 100 GeV

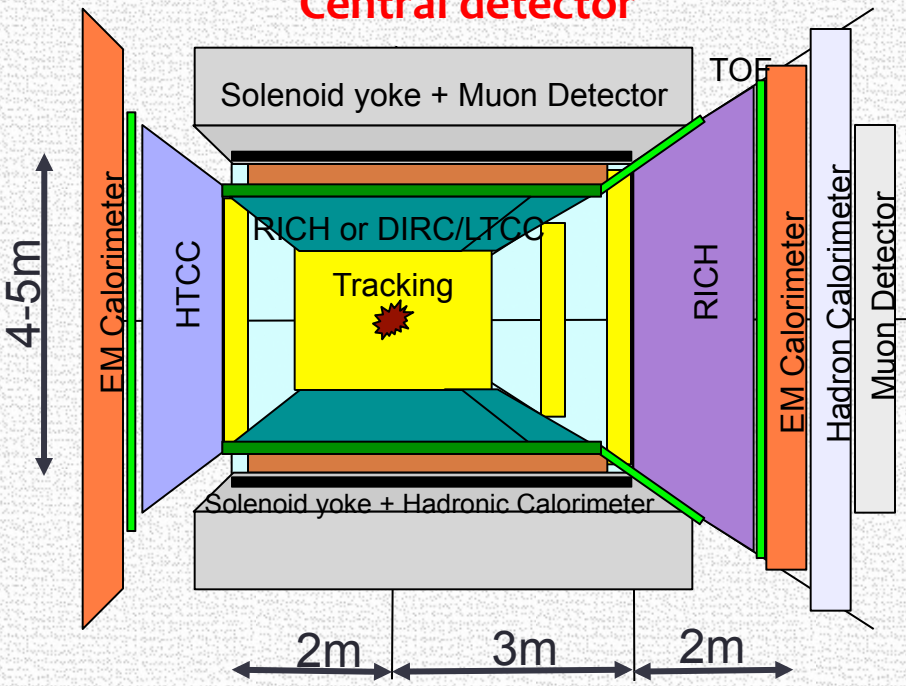
Three compact rings:
- **3 to 11 GeV electron**
- **Up to 12 GeV/c proton (warm)**
- **Up to 60 GeV/c proton (cold)**

$L = 10^{33\text{-}34}$ cm^{-2}sec^{-1}
100-1000 times HERA
→ 50-500 fb^{-1} integrated luminosity in 10 yrs

Detector & IR Design: ELIC



Central detector



Detect particles with angles down to 0.5° before ion FFQs. Need 1-2 Tm dipole.

Detect particles with angles below 0.5° beyond ion FFQs and in arcs.

Very-forward detector

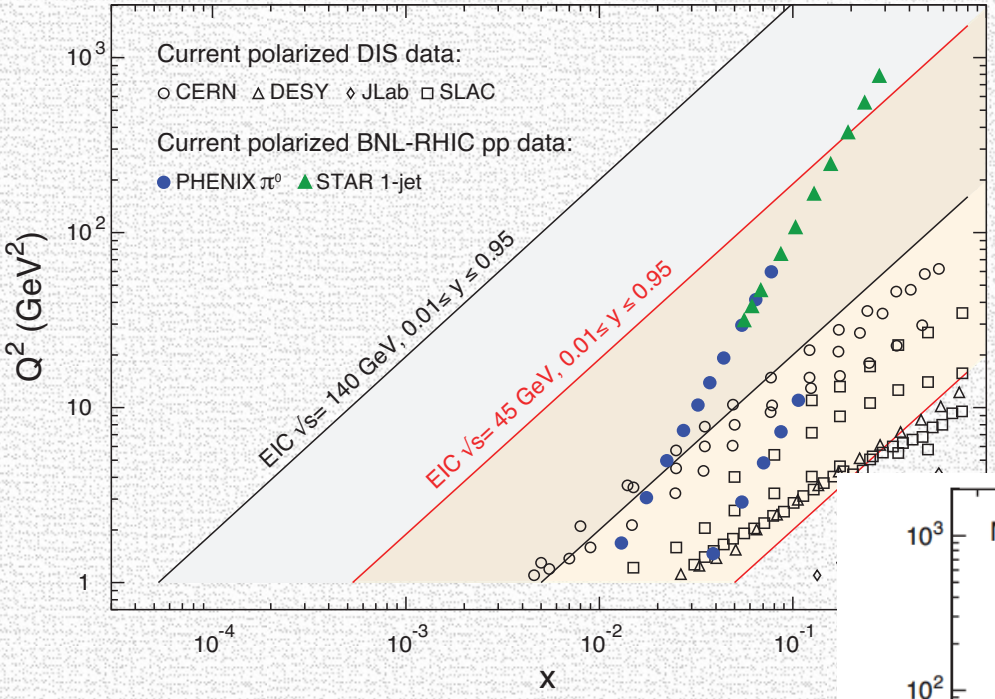
Large dipole bend @ 20 meter from IP

(to correct the 50 mr ion horizontal crossing angle)

allows for **very-small angle detection (<0.3°)**

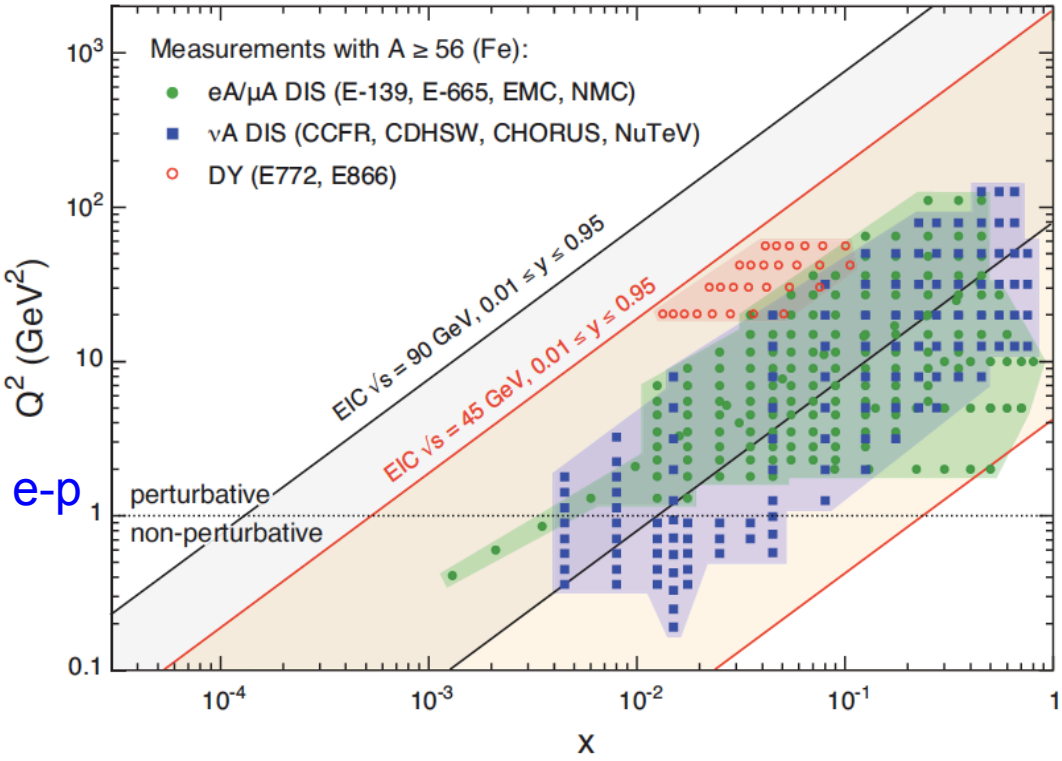
Jlab EIC WG

US EIC: Kinematic reach & properties



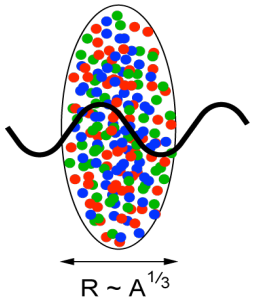
For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ Variable center of mass energy



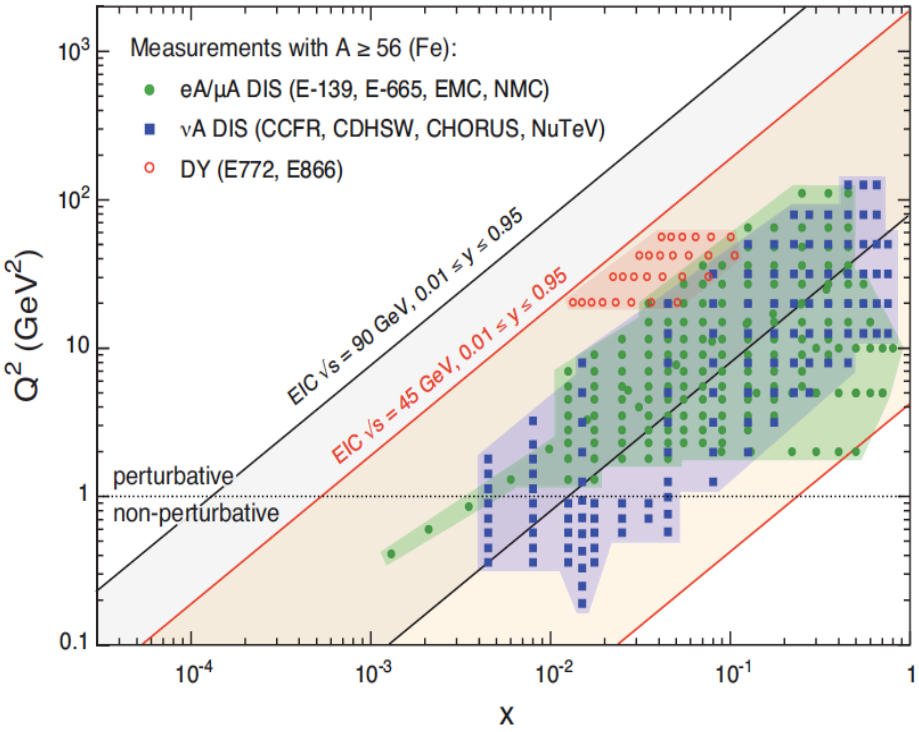
For e-A collisions at the EIC:

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



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

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



Nucleus: A laboratory for QCD

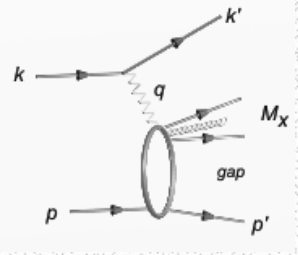
Parton propagation and interaction in nuclei (vs. protons)

Does gluon density saturate? Does it produce a unique and universal state of matter?

Saturation/CGC: What to measure?

- F_2 (quark+ antiquark) & F_L(gluons) at low x (classic inclusive measurement)
  - $$g(x,Q^2) \propto \frac{\delta F_2}{\delta \ln Q^2} \qquad F_L(x,Q^2) \propto g(x,Q^2)$$
  - F_L requires change in the center of mass energy in operation of collider

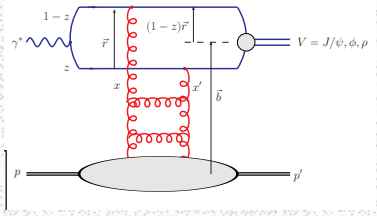
Diffraction:



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

At HERA: ep observed 10-15%
If CGC/Saturation: then
Diffraction eA expect ~25-30%

- Diffractive to Total cross section ratio for eA/ep
  - Models predict very different behavior with/without saturation
- Coherent diffraction cross section ratio for eA/ep: J/Ψ and ϕ
  - Very different behaviors predicted for J/Ψ and ϕ (different transverse size)



- Experimental challenges in diffractive measurements demand close attention, and drive the detector and IR design.

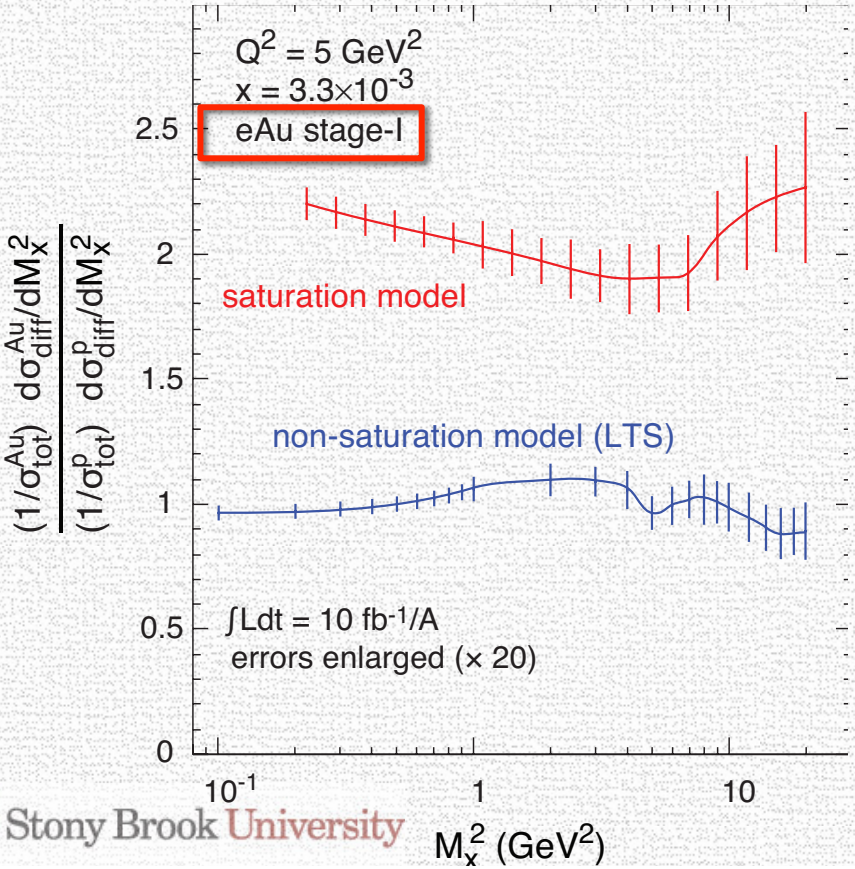
Diffractive vector meson production in eA

Precise transverse imaging of the gluons in nuclei

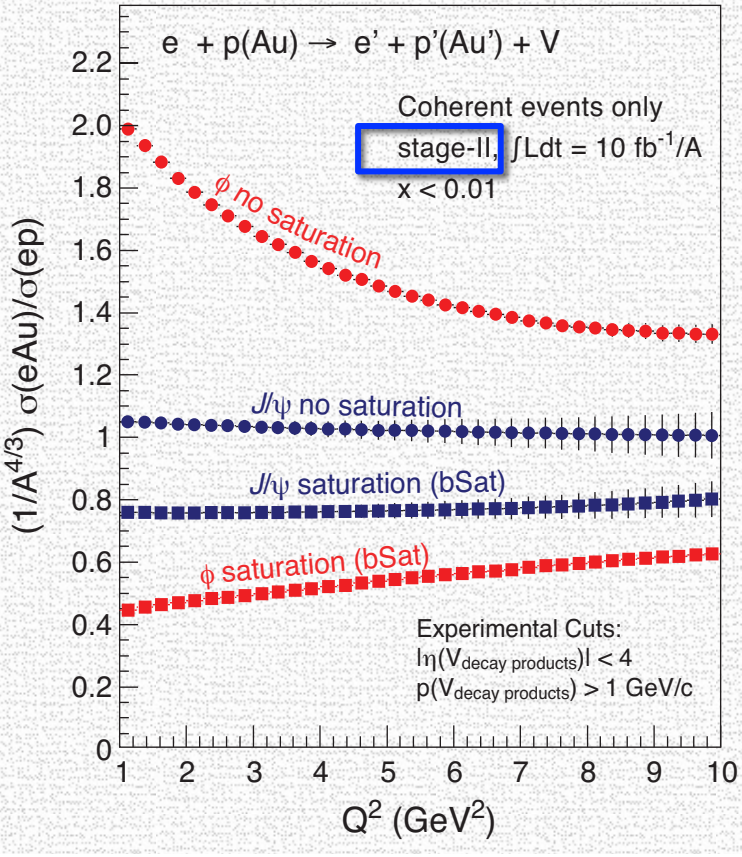
a) **Diffractive/total cross section eA/ep with/without saturation**

b) **Coherent diff. ratio of eA/ep for J/Ψ and ϕ production with/without saturation**

Diffractive/Total Cross Section

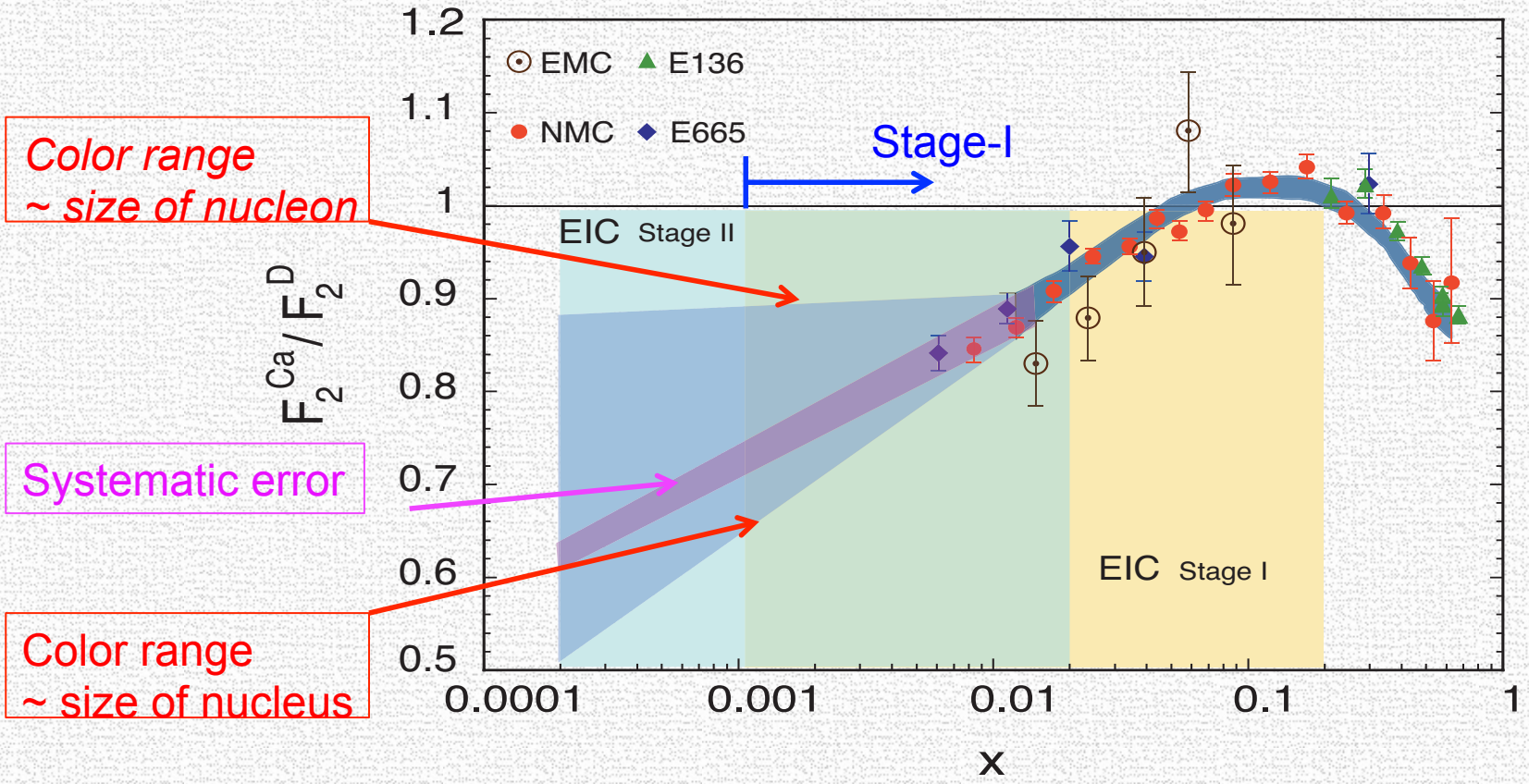


Coherent diffraction ratios eA/ep

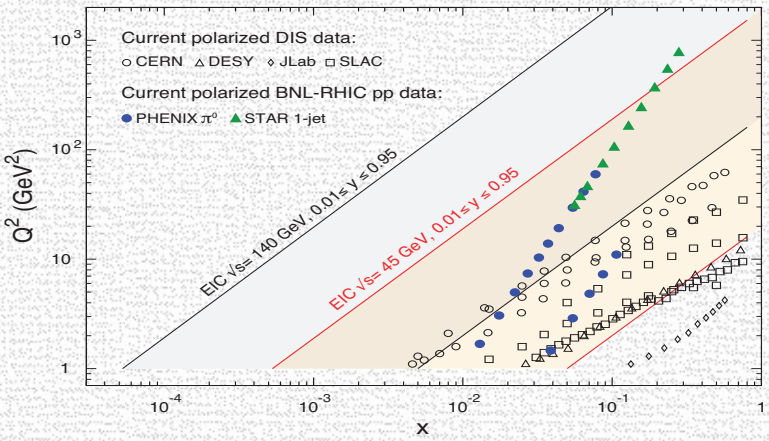


Range of color correlation inside a nucleus?

- Ratio of DIS F_2 structure functions:



A clean stage-I measurement at EIC (statistical error < systematic error)



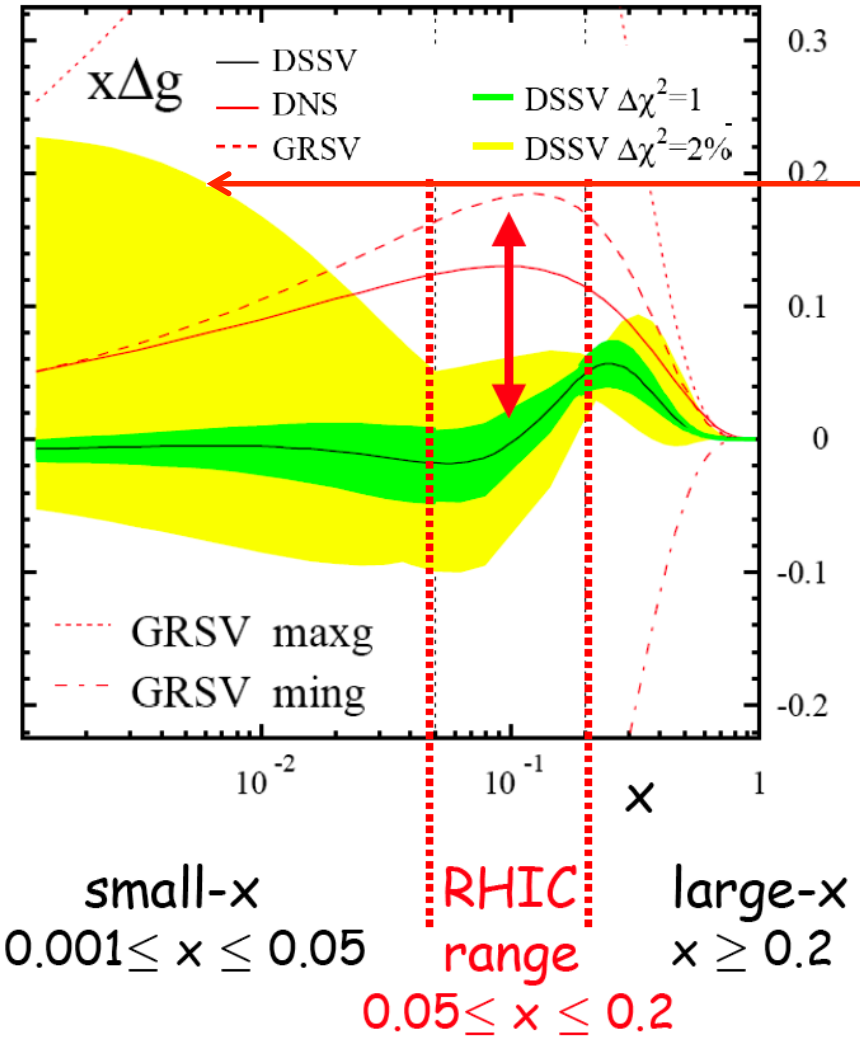
What will *polarized EIC* do for you?

Nucleon Spin:

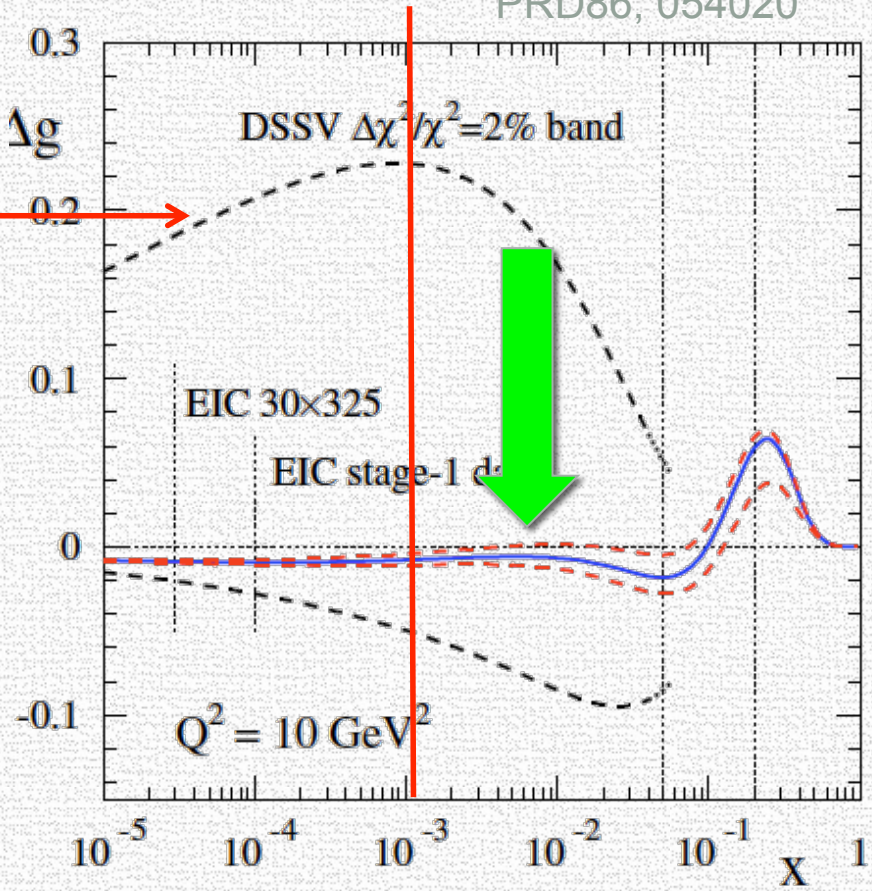
A precision tool for studying QCD

3D structure of the proton and resolution of the spin puzzle!

Nucleon Spin: Precision measurement: ΔG



PRD86, 054020

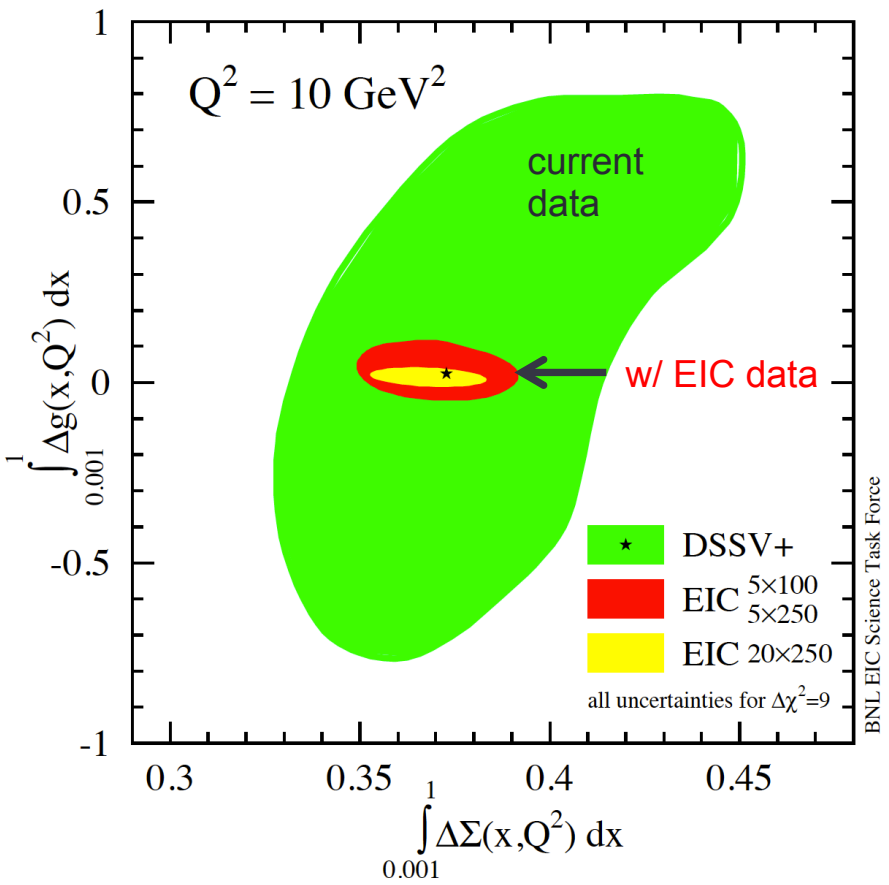


Yellow band (left) reduces to the band shown with **red dashed line** (right)

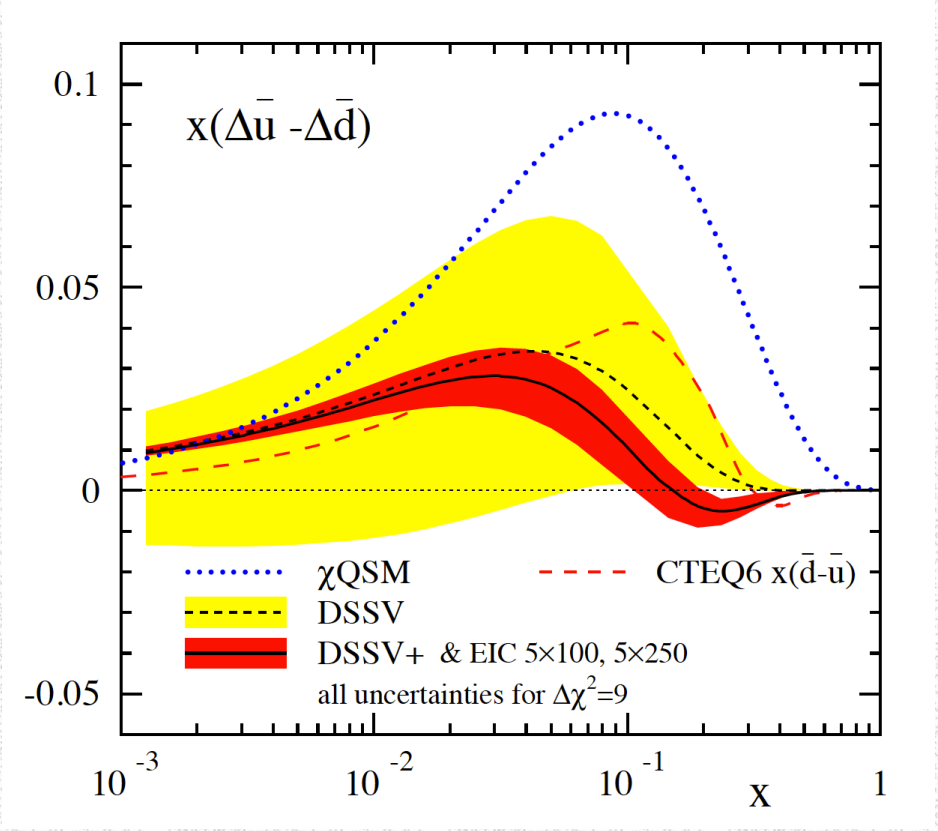
Precision: Gluon & Sea Quark *polarization!*

--Beyond the current experimental capabilities!

ΔG and ΔΣ in helicity sum



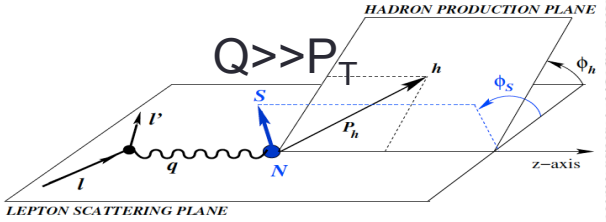
Are the sea quark polarizations different?



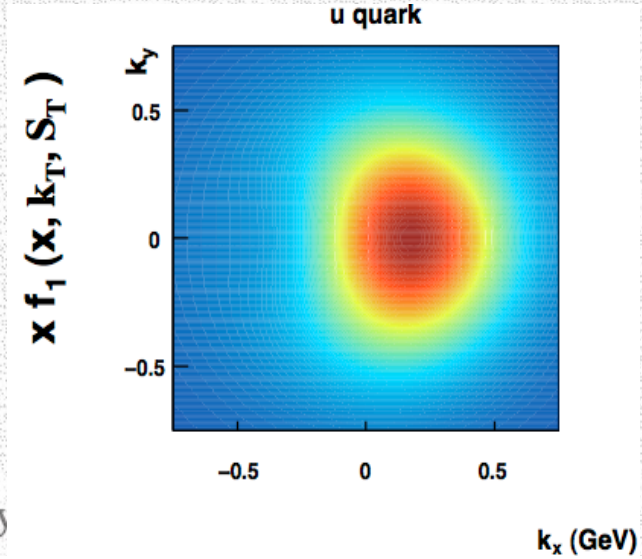
EIC White Paper: arXive:1212.1701

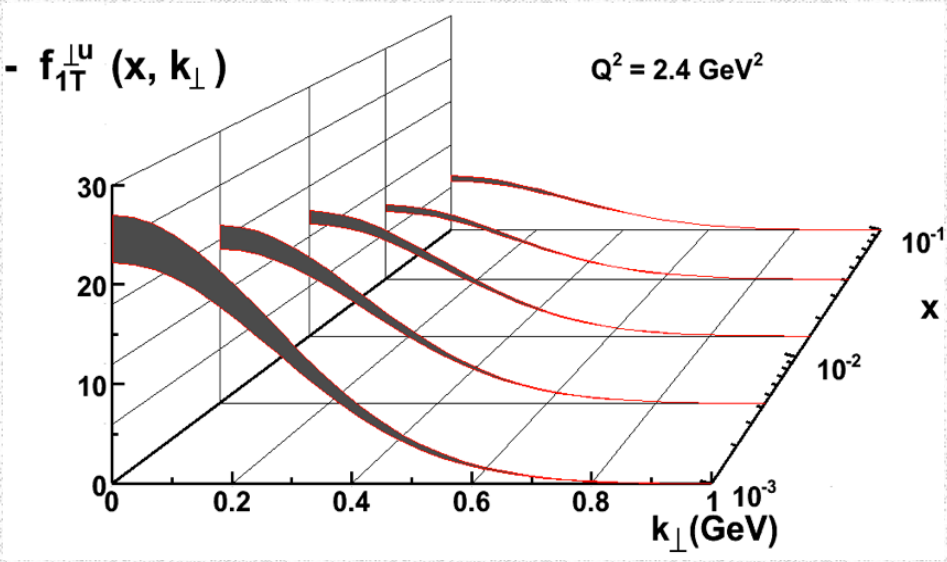
Momentum tomography of the nucleon

- Going beyond the PDFs: 2D motion of quarks and gluons in the nucleon
- *DIS with high resolution but still sensitive to the parton's transverse momentum: Semi-Inclusive DIS:*
  - QCD Quantum Correlations: momentum space



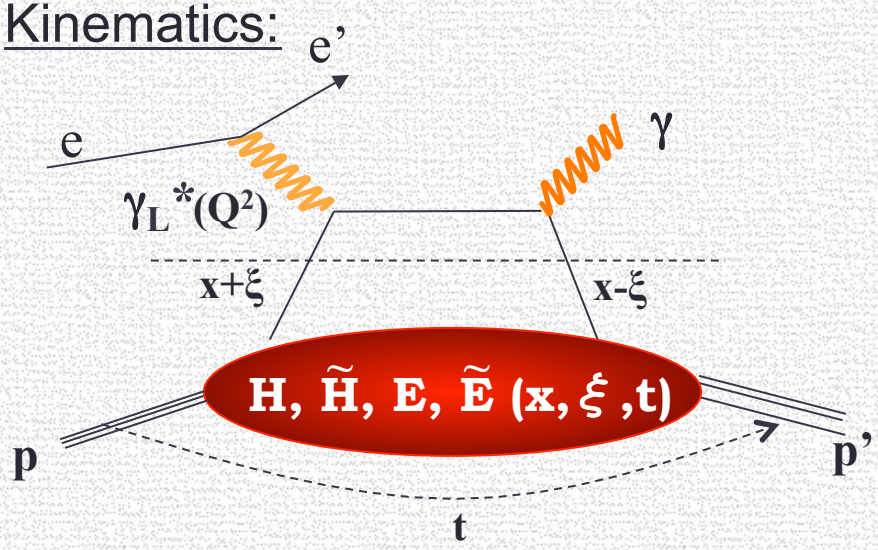
- Tomographic images of K_X/K_y of partons as functions of Bjorken-x: u quark distribution for transversely polarized proton.
- ***With EIC: low x partonic plots like these possible!***





Exclusive DIS

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

Measure of resolution power

$$Q^2 = 2E_e E'_e(1 - \cos\Theta_{e'})$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x_B = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

$$t = (p - p')^2, \xi = \frac{x_B}{2 - x_B}$$

Exclusive events:
e + **(p/A)** → e'+ **(p'/A')**+ γ / J/ψ / ρ / ϕ
detect **all** event products in the detector

Special sub-event category rapidity gap events
e + **(p/A)** → e' + γ / J/ψ / ρ / ϕ / jet
Don't detect **(p'/A') in final state**

Allow access to the spatial distribution of partons in the nucleon
Fourier transform of spatial distributions ➔ *GPDs*
GPDs ➔ Orbital Angular Momenta!

GPDS: Transverse spatial gluon distribution from exclusive J/Ψ production

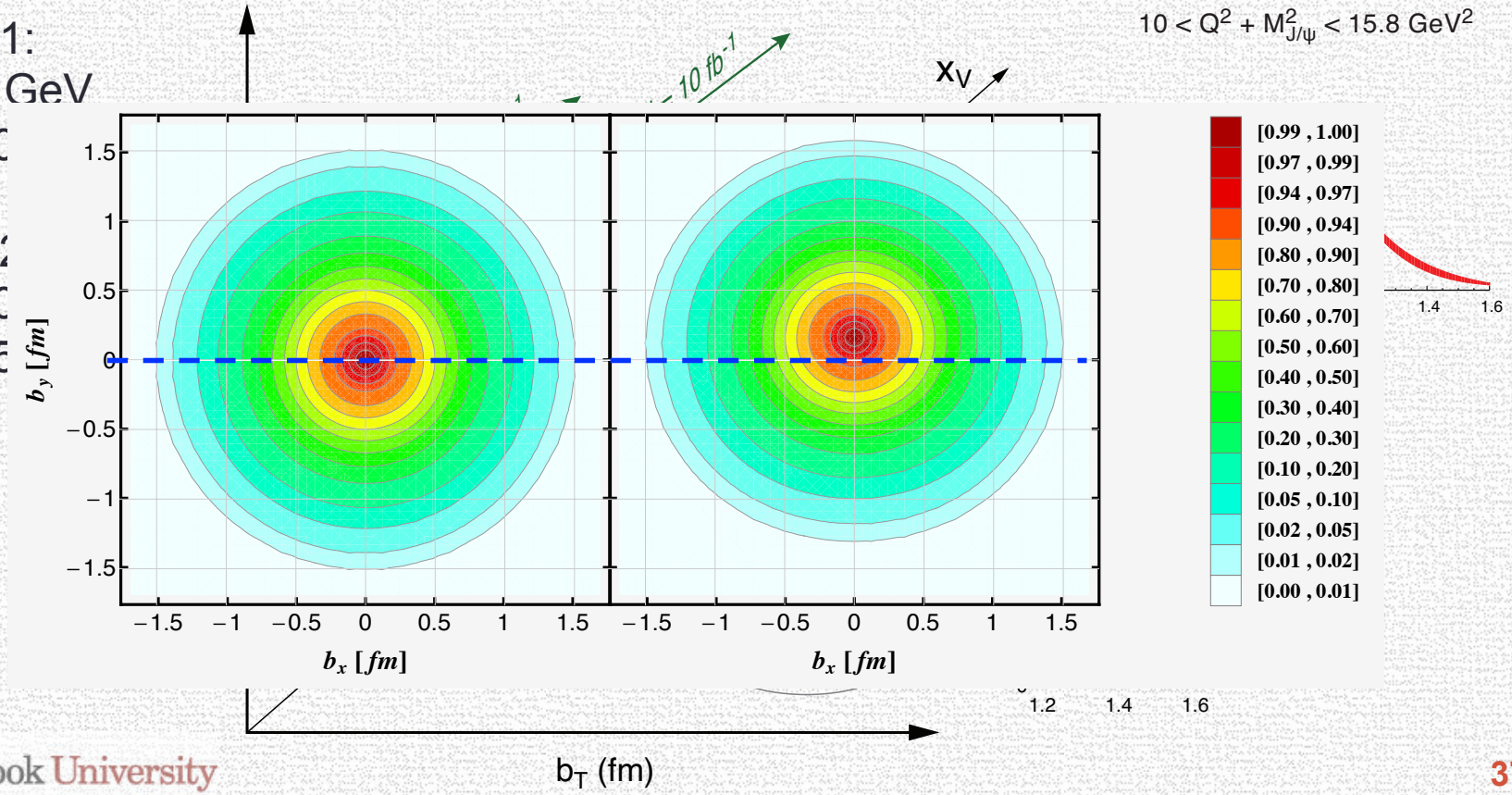
b_T is the distance of the gluon from the center of the proton
x_V determines the gluon momentum fraction

$$x_V = \frac{M_{J/\psi}^2 + Q^2}{W^2 + Q^2 + M_N^2}$$

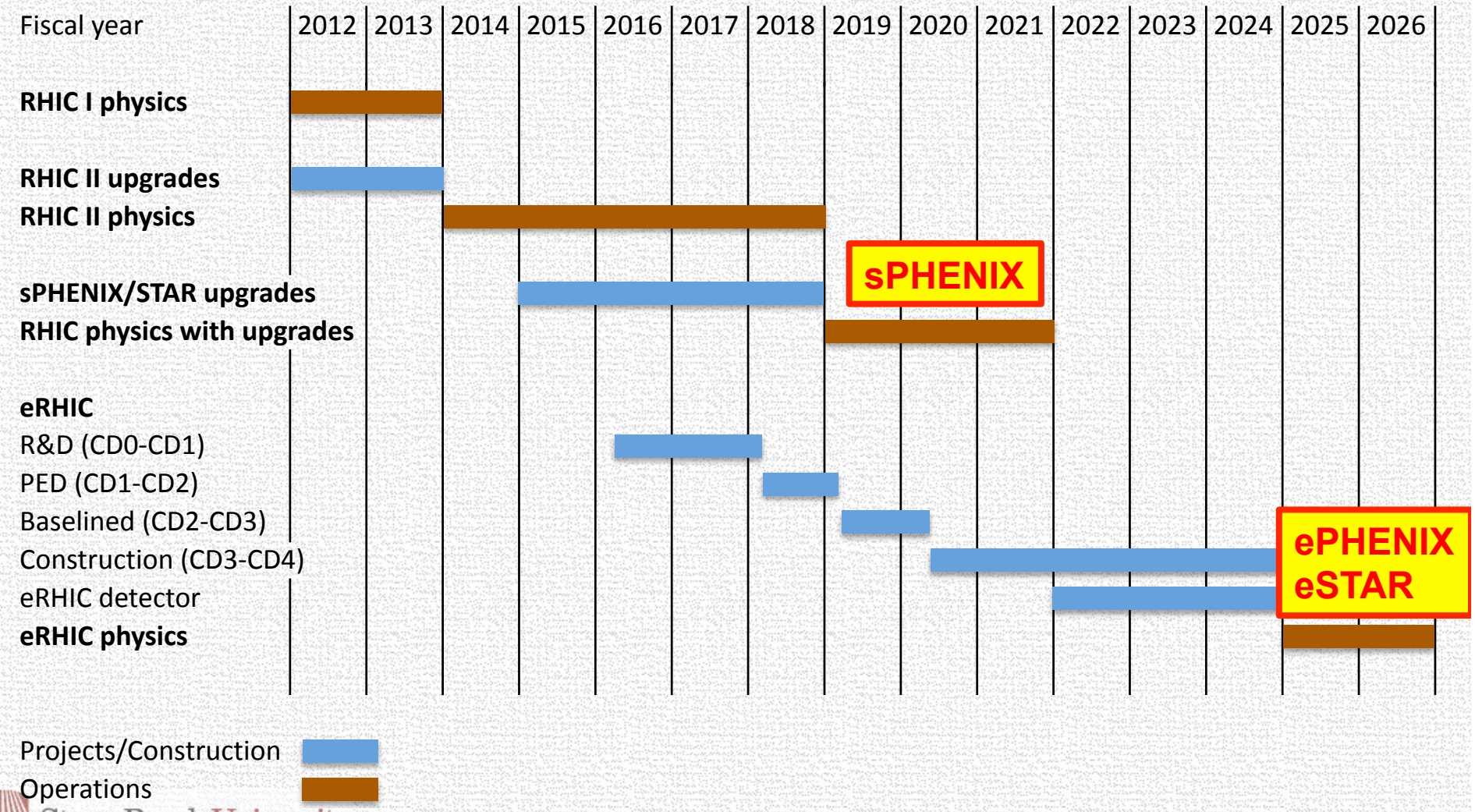
$$W^2 = (p+q)^2; \qquad M_N^2 = p^2$$

Stage 1:
E_e = 5 GeV
E_p = 10

Stage 2
E_e = 20
E_p = 25



eRHIC Technically Driven Schedule



Accelerator & Detector R&D & Collaboration

- **Accelerator R&D:** Significant level of activity since 2008
- Detector designs ideas being developed: @BNL & @Jlab
  - ALD asked to evaluate the feasibilities with ePHENIX and eSTAR
- Integration with the machine an integral part of all future EIC designs

NEW since 2010:

- Detector R&D supported by DOE through BNL (Dr. T. Ludlam)
  - https://wiki.bnl.gov/conferences/index.php/EIC_R%25D
  - An external committee evaluates: new proposals and progress on funded ones every ~6 months. [Next review December 2013]
- Collaborative groups formed across the US Universities and some European institutions: Tracking, PID, Calorimetry R&D proposals

- **Invitation: Collaboration with Japanese physicists would be welcome on all fronts: accelerator, detector, other physics of EIC**

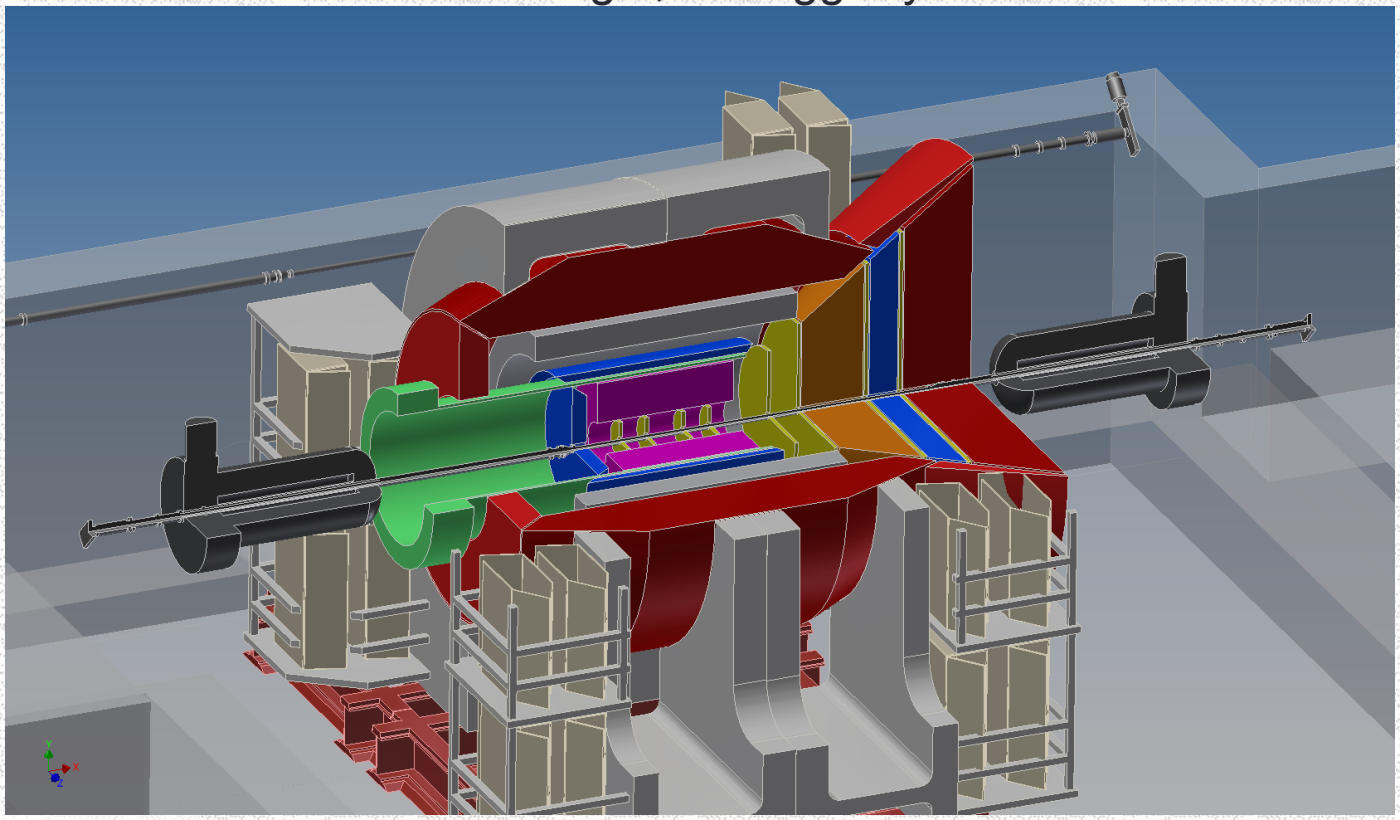
PHENIX → sPHENIX → ePHENIX

(BaBar Magnet + Many modification) and a 10 GeV e- beam of eRHIC

Talks tomorrow: Kieran. Boyle, Jin Huang, Itaru Nakagawa

For the ePHENIX Task Force:

A. Bazilevsky, K. Boyle, A. Deshpande, T. Hemmick, J. Huang, I. Nakagawa, C. Woody + J. Nagle, J. Haggerty



Summary

The EIC will enable an *unprecedented* study of "QCD at a new frontier" through use of protons and nuclei as "laboratories for QCD"

It will enable understanding of the role of gluons and sea quarks in the hadrons (visible universe!) as no other current or future planned experimental facility will.

Two US proposals: eRHIC at BNL, MEIC/ELIC at JLab

- Electron & hadron beam polarization and all nuclei ➔ *luminosity and polarization frontier, variable center of mass energy*
- *Staged realization will* ***include upgrades of existing detectors*** *for the early studies of e-A/p at RHIC.*
- *Both plan to make use of existing NP facilities and infrastructure: most effective use of current and past DOE investments.*

- Next milestone: Approvals by the US NP community **(NSAC LRP 2014)**