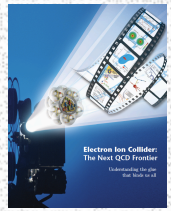


The Science and Status of Of the US Electron Ion Collider: "The EIC"

WHY EIC?

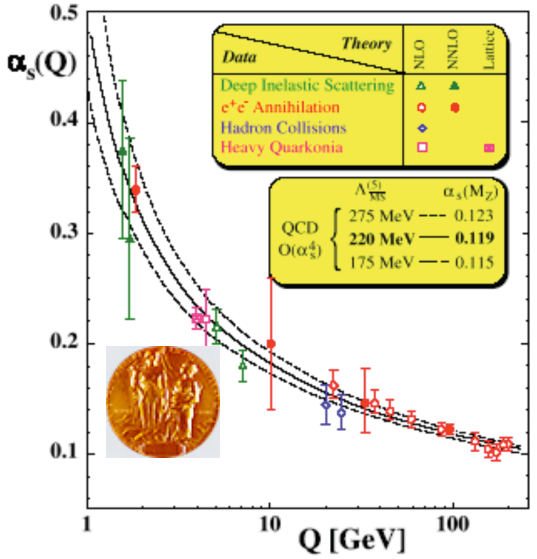
TO STUDY AND UNDERSTAND THE ROLE OF GLUONS AND SEA QUARKS IN QCD

DIS 2013

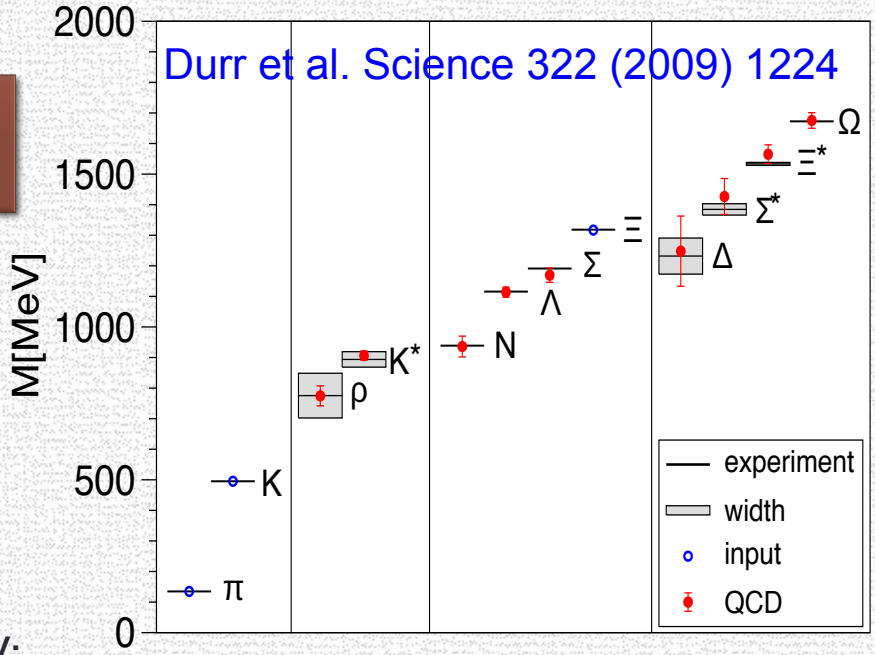
Marseille, France

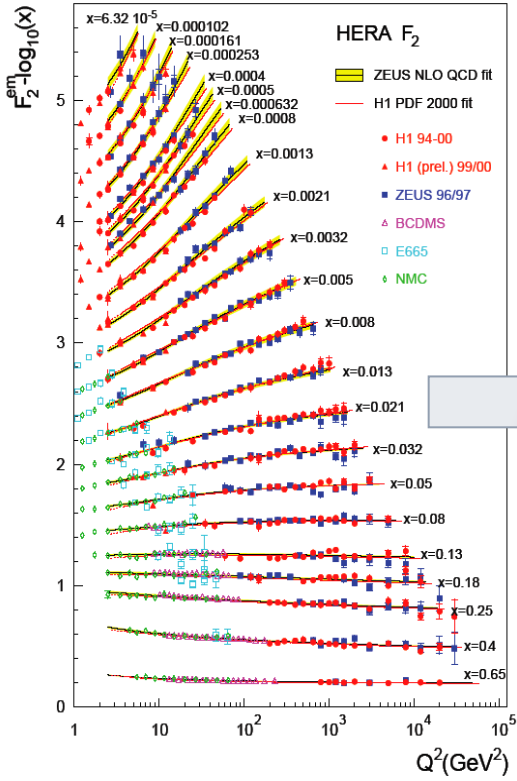
Stony Brook University

Abhay Deshpande
April 23, 2013



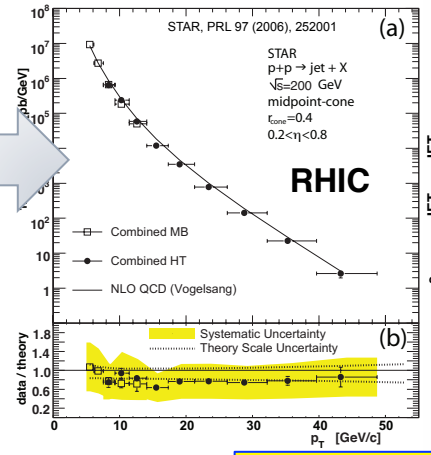
Successes of QCD

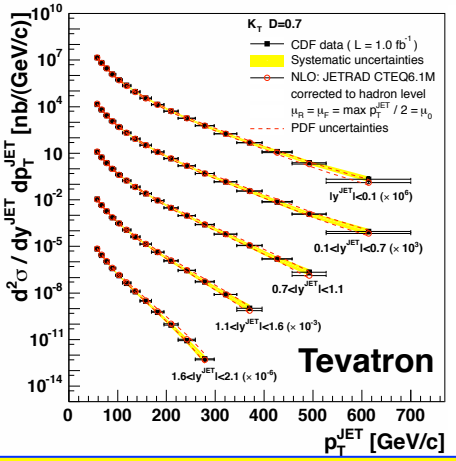


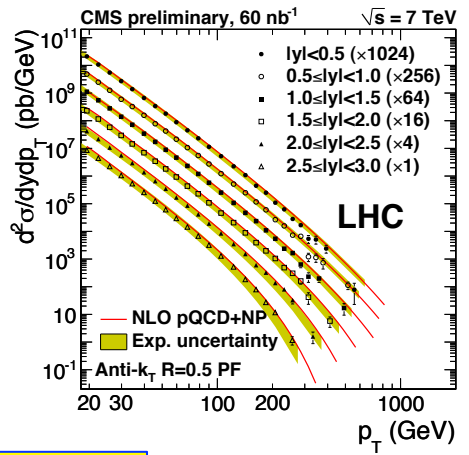


Measure **e-p** 0.3 TeV:

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







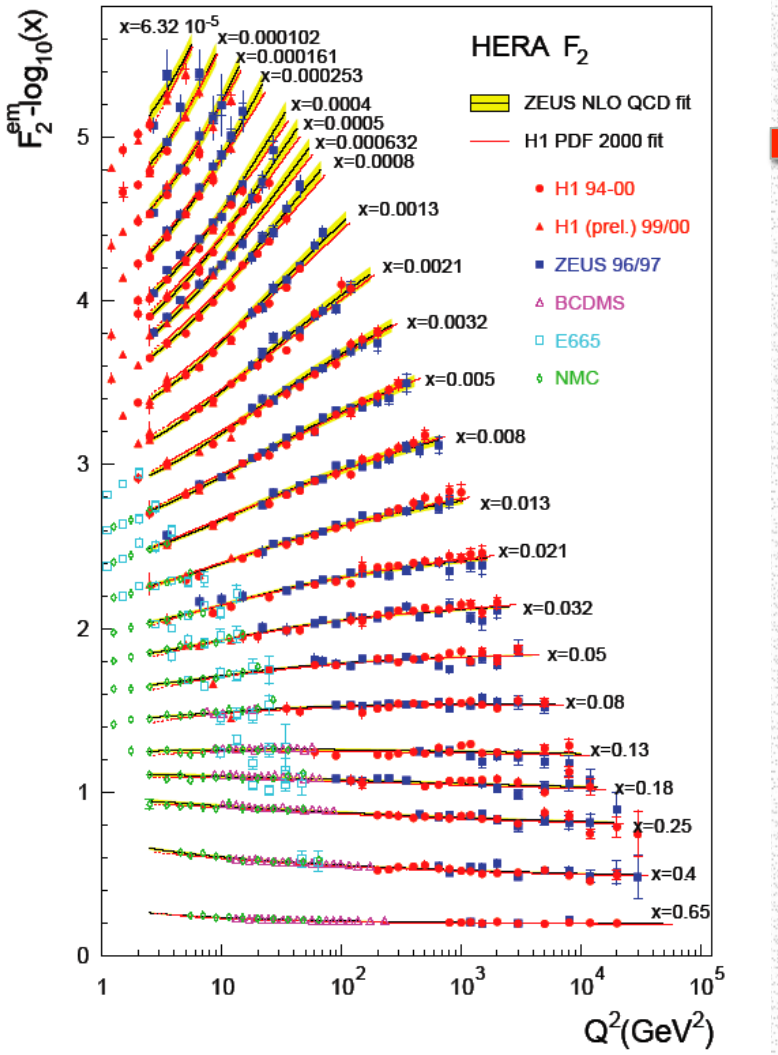
Precision QCD: Talks by O. Behnke, P. Lenzi

"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 and seq quarks in QCD?

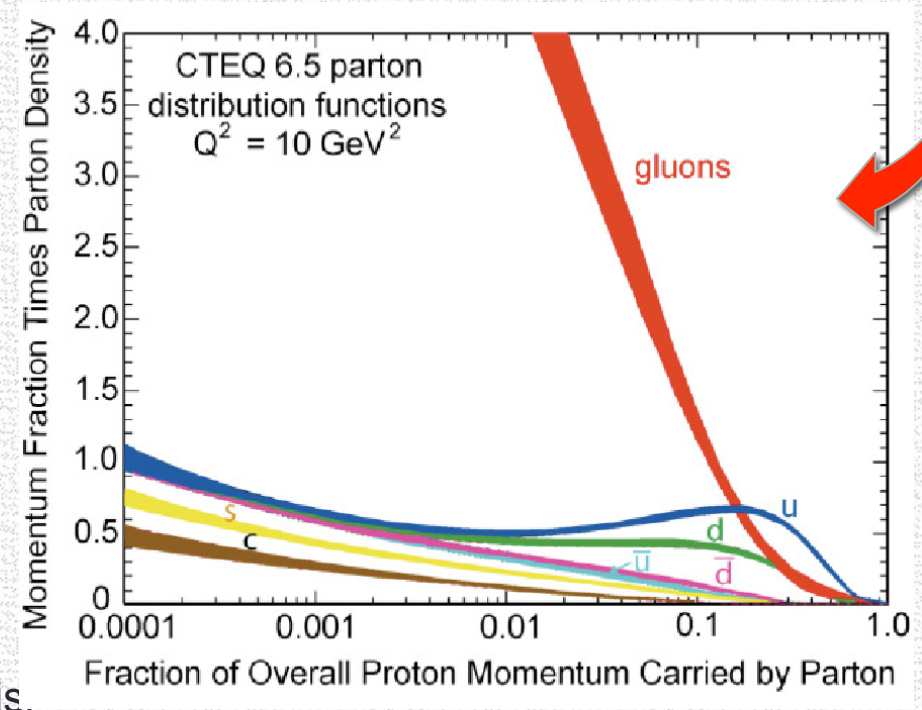
Measurement of Glue at HERA



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

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

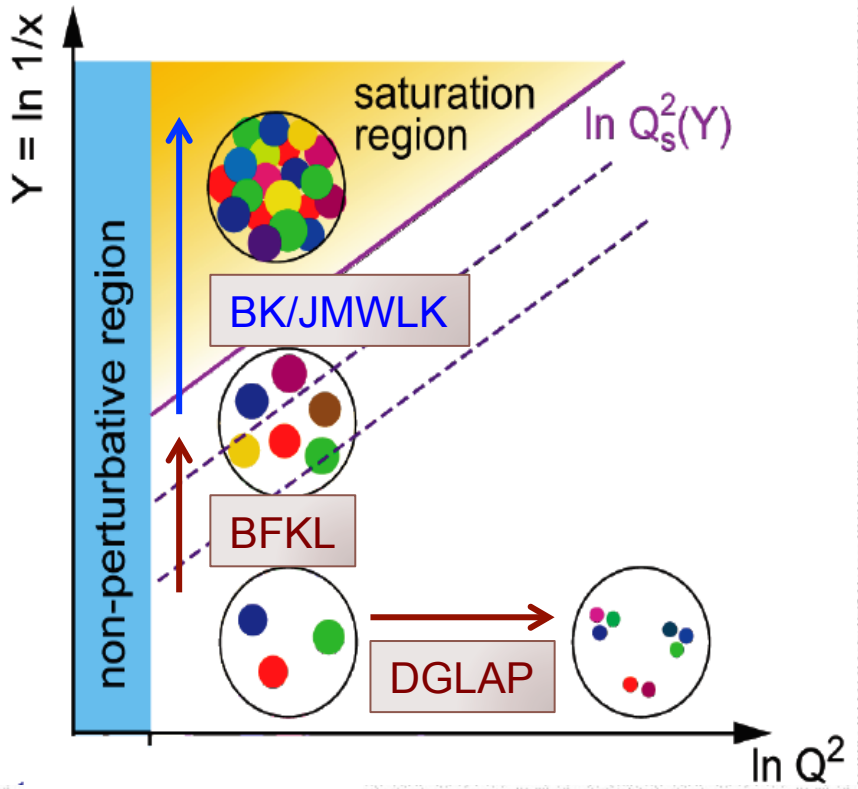
- NLO pQCD analyses: fits with **linear** DGLAP* equations



*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Physics at Low x ➔ Color Glass Condensate?

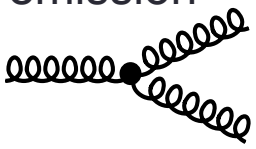
See Ann. Rev. Nucl Part (60) 2010 F. Gelis et al., , arXiv:1002.0333)



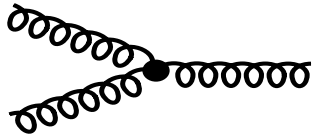
Method of including **non-linear** effects (McLerran, Venugopalan)

- 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



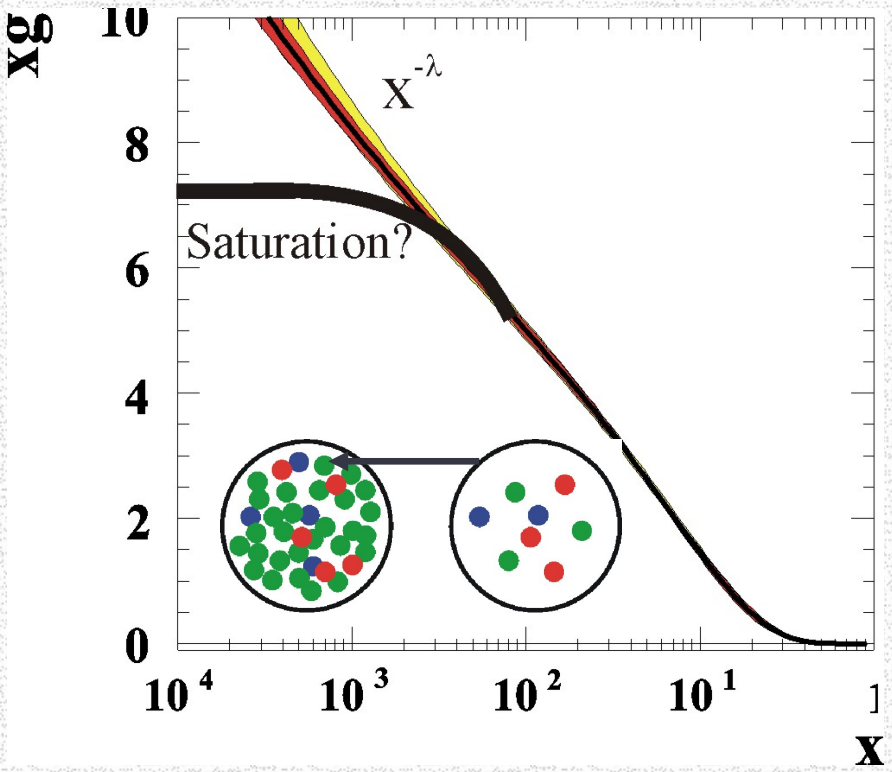
At Q_S gluon emission balances the recombination

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

Color Glass Condensate ??

B. Erazmus' talk

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!

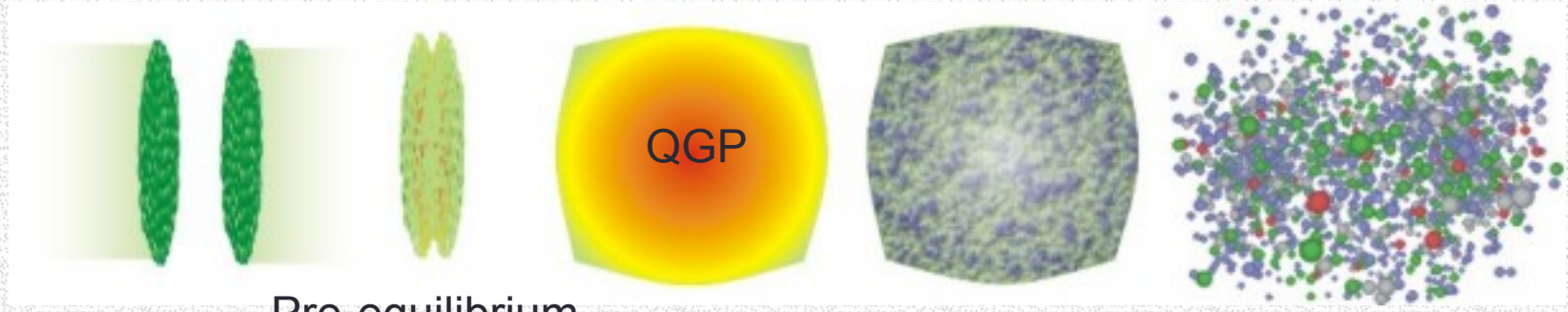
➔Large Hadron electron Collider (LHeC) M. Klein et al

➔ Nuclei: naturally enhance the densities of partonic matter

Why not use Nuclear DIS at high energy?

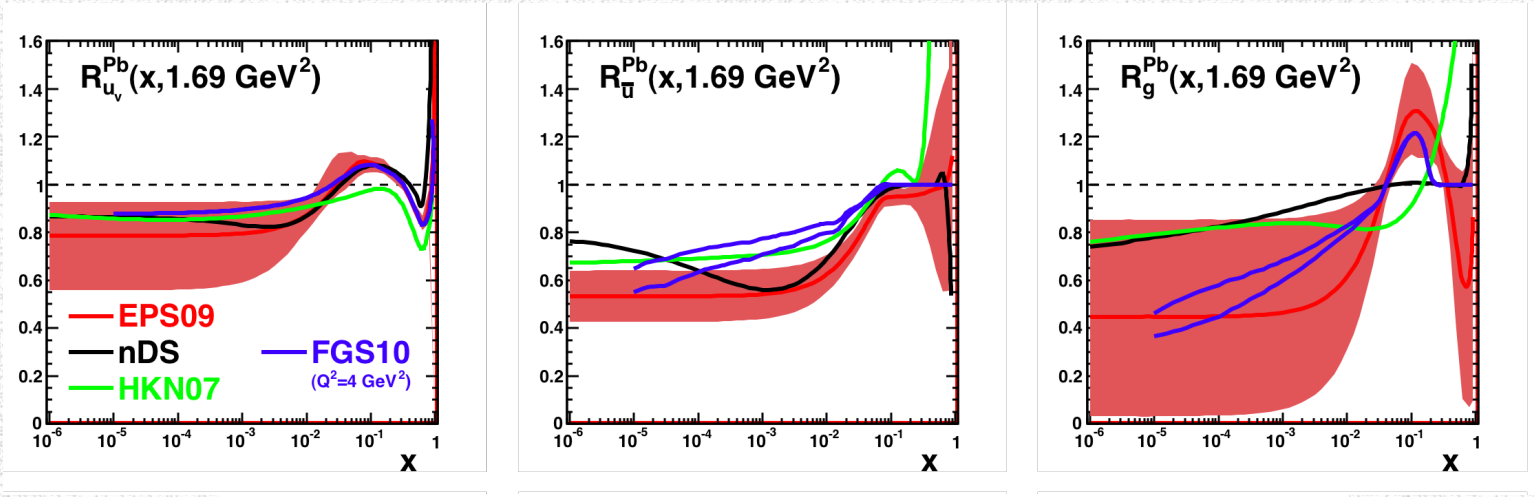
EIC & RHIC/LHC (Heavy Ion)

B. Erazmus

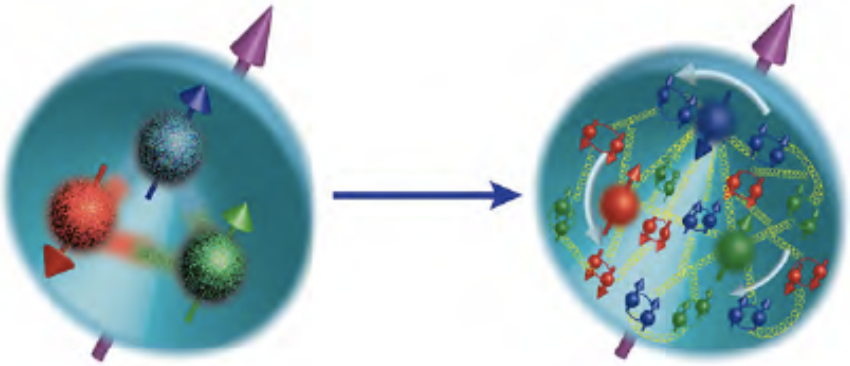


To understand "QGP" fully, we need to understand:

The initial state PDFs in the nucleus & hadronization



R_i = Nuclear PDF i / (A * proton PDF i)

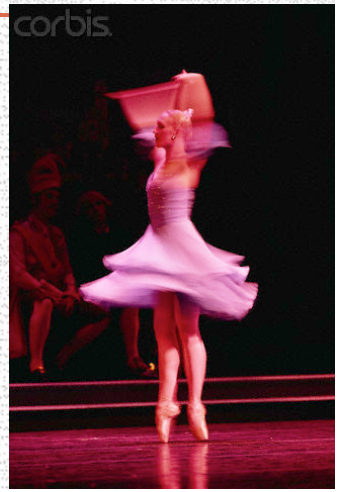


Evolution In Our Understanding Of Nucleon "Spin"

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?



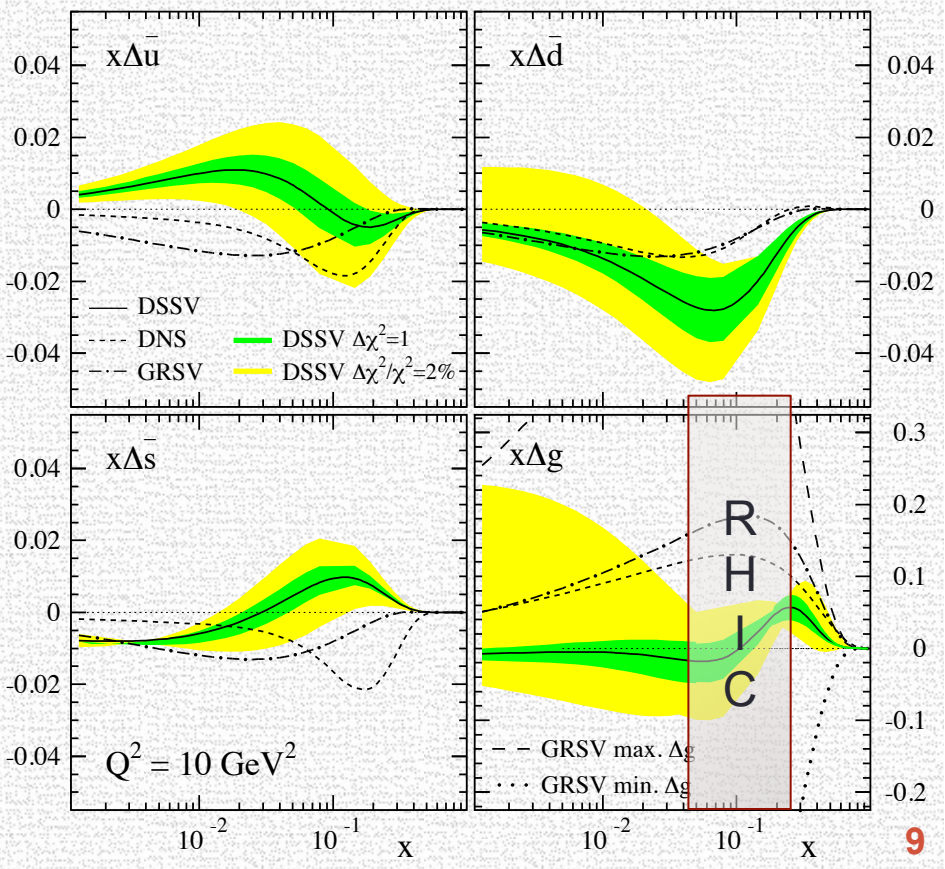
Nucleon Spin Puzzle

M. Stratmann's talk

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

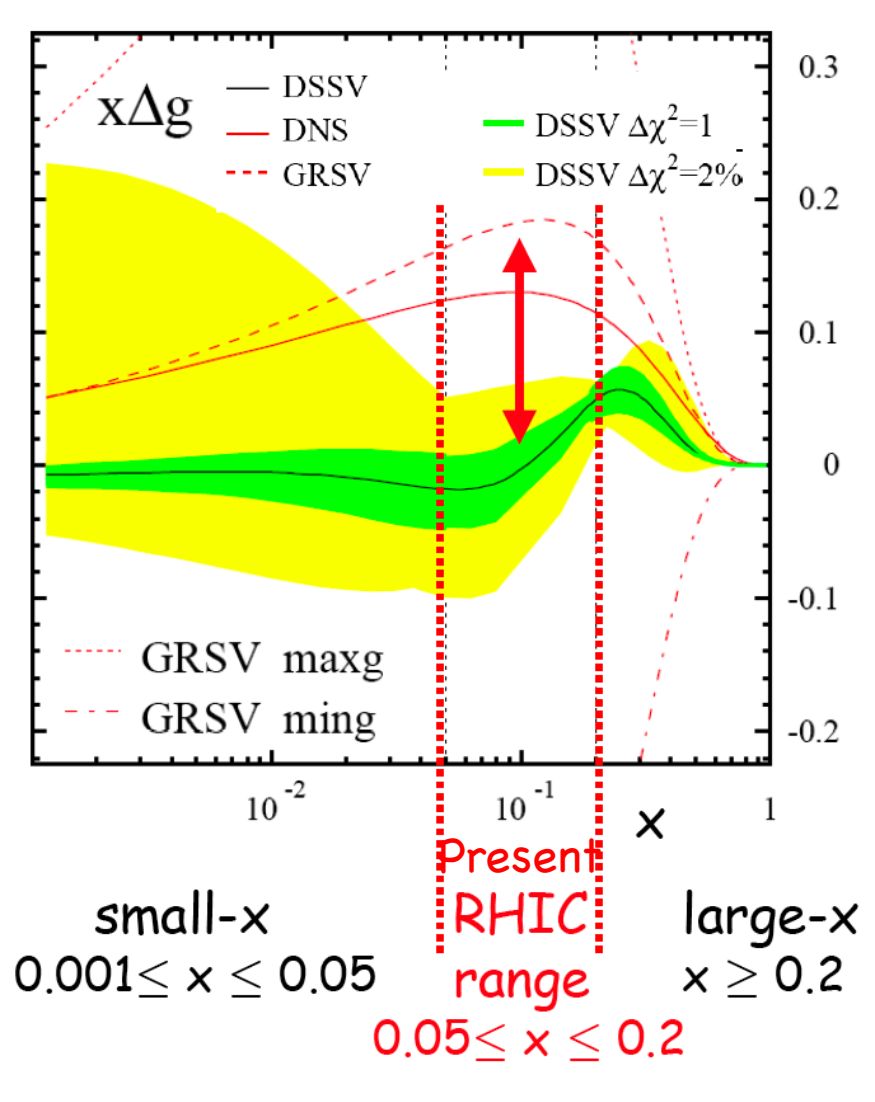
- ½ ($\Delta\Sigma$) ~ 0.15 : From fixed target pol. DIS experiments performed in 1990s
- Recent RHIC-Spin: (2000s)
  - *Δg ~0.1 +/- 0.1*
  - *Not as large as anticipated in the 1990s but seems to be non-zero (currently with large uncertainty)*
- ***Precision needed***
- ***Low-x coverage needed***

DSSV, arXiv:0804.0422



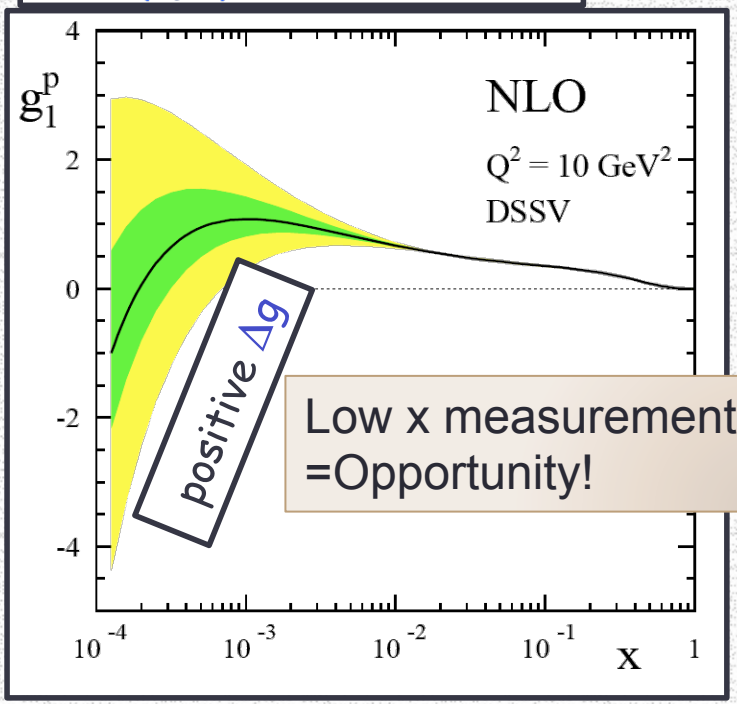
Current knowledge of Polarized Glue:

de Florian, Sassot, Stratmann & Vogelsang



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

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

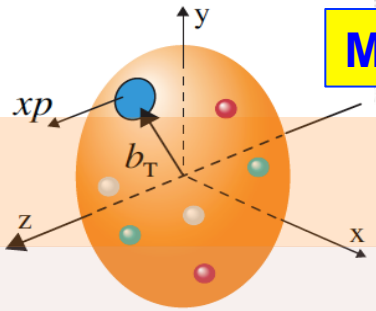


Low x measurements =Opportunity!

Unified view of the Nucleon Structure

❑ Wigner distributions:

M. Diehl, M. Stratmann



JLab12 COMPASS for Valence

5D

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

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

3D

HERMES JLab12 COMPASS

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

Fourier trf. $b_T \leftrightarrow \Delta$

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

$\xi=0$

$H(x,\xi,t)$

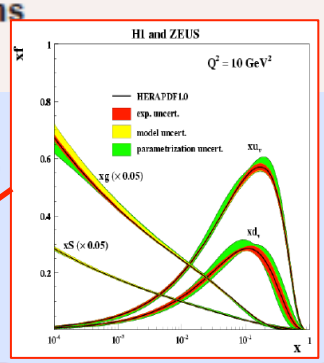
transverse momentum distributions (TMDs)
semi–inclusive processes

impact parameter distributions

generalized parton distributions (GPDs)
exclusive processes

1D

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



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

$\int dx$

$F_1(t)$
form factors
elastic scattering

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

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

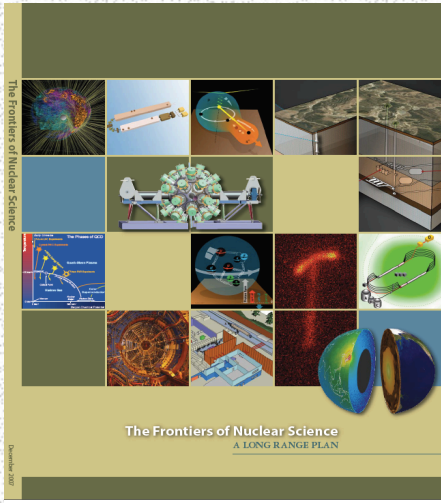
❑ EIC – 3D imaging of sea and gluons:

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

Community effort and commitments

- 2007 Nuclear Physics Long Range Plan

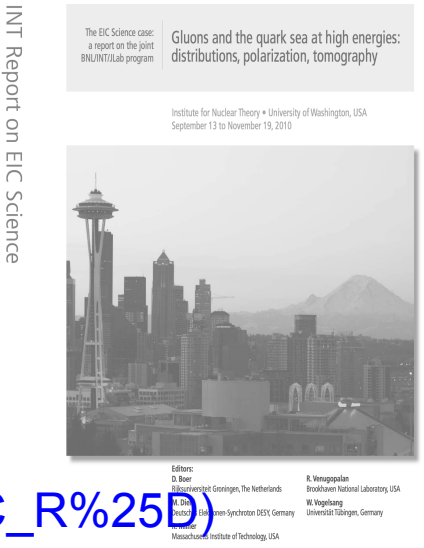
  Designated Electron-Ion Collider (EIC) as "embodying the vision for reaching the next QCD frontier"



- Many workshops on EIC physics:

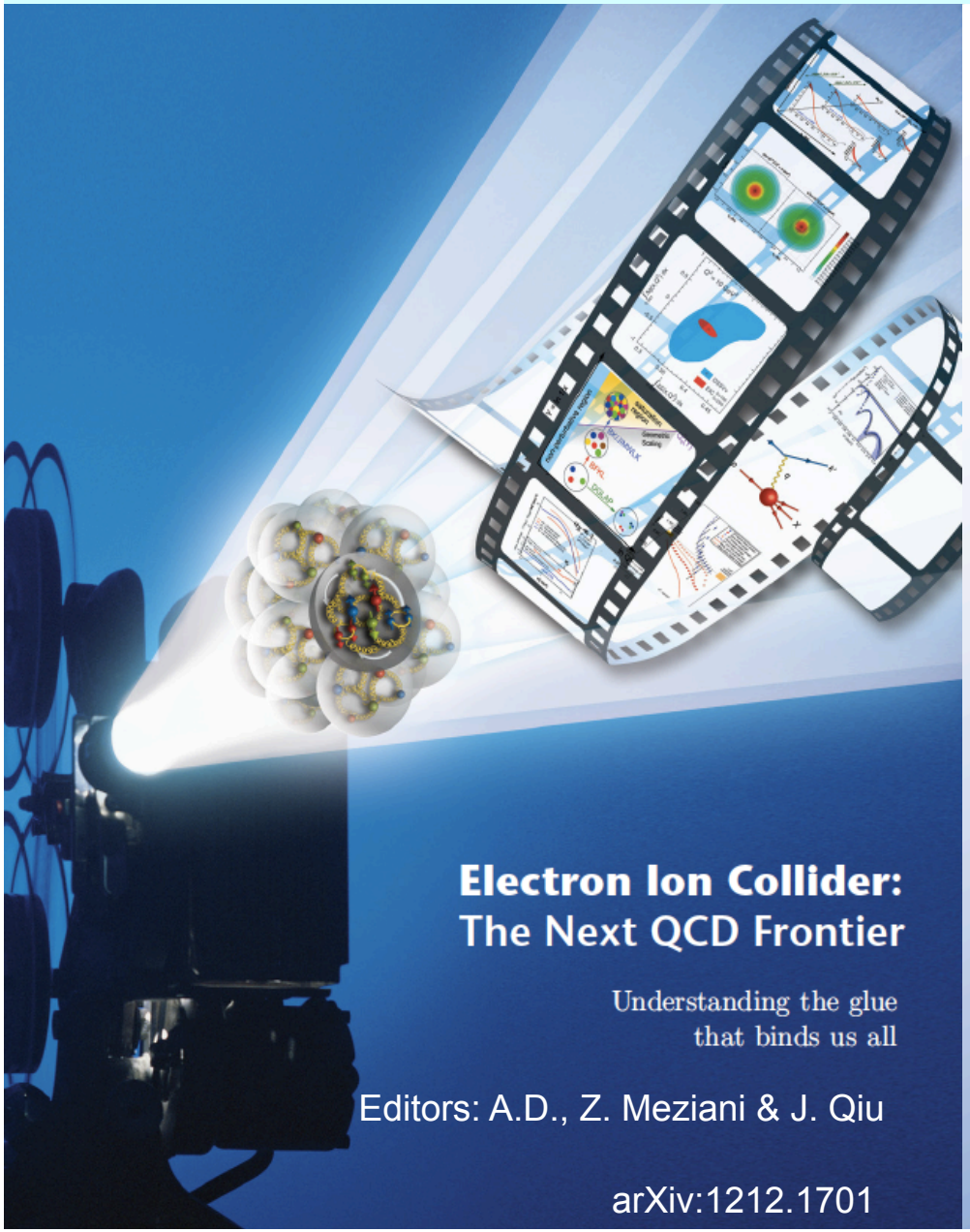
  Ten-week program (9/13–11/19, 2010)
  at Institute for Nuclear Theory

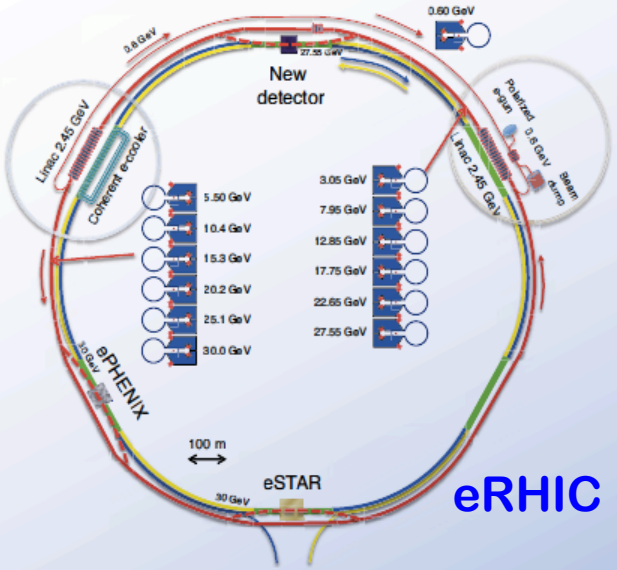
  (INT Report: arXiv:1108.1713v2, 500+ pages)



- 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 – appointed jointly by BNL and JLab

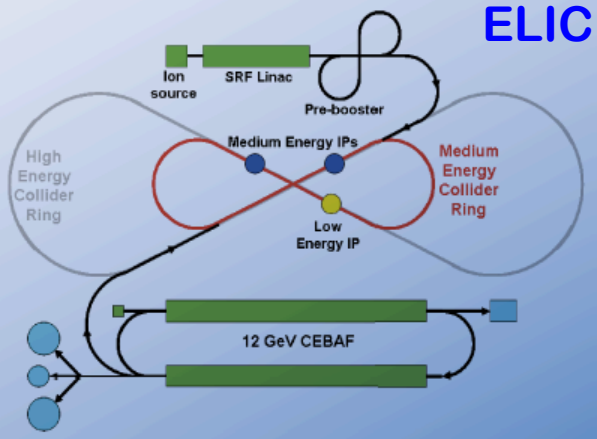
White Paper for the Electron-Ion Collider



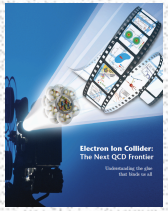


eRHIC (BNL)

ELIC (JLab)



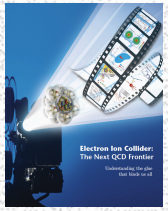
Science of EIC



- **How are sea quarks, gluons and their spins 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?

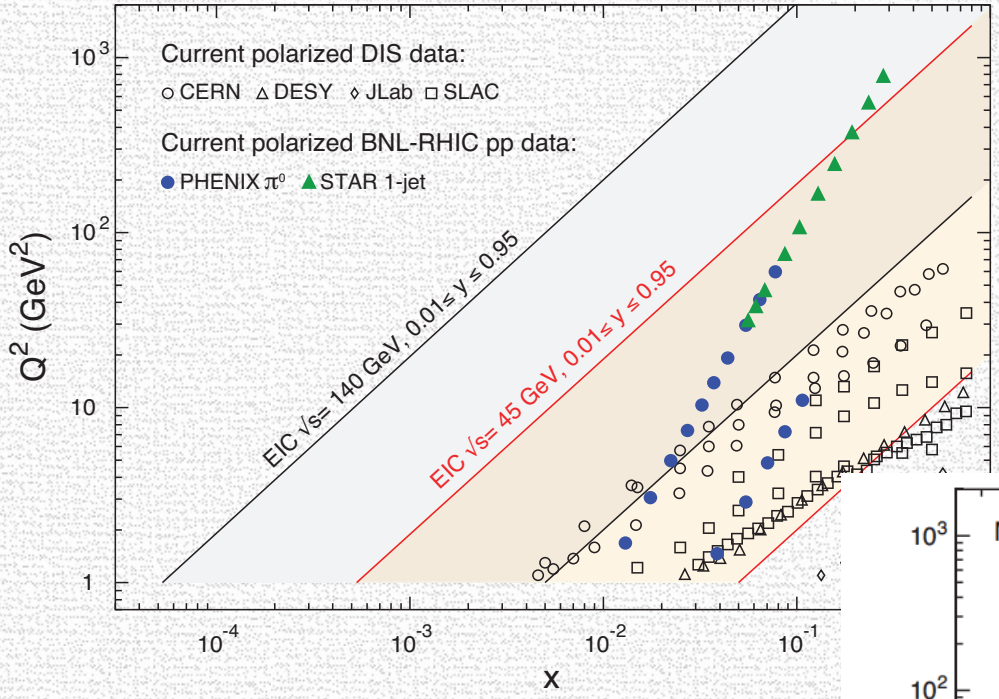
Science of EIC… (continued)



- **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?

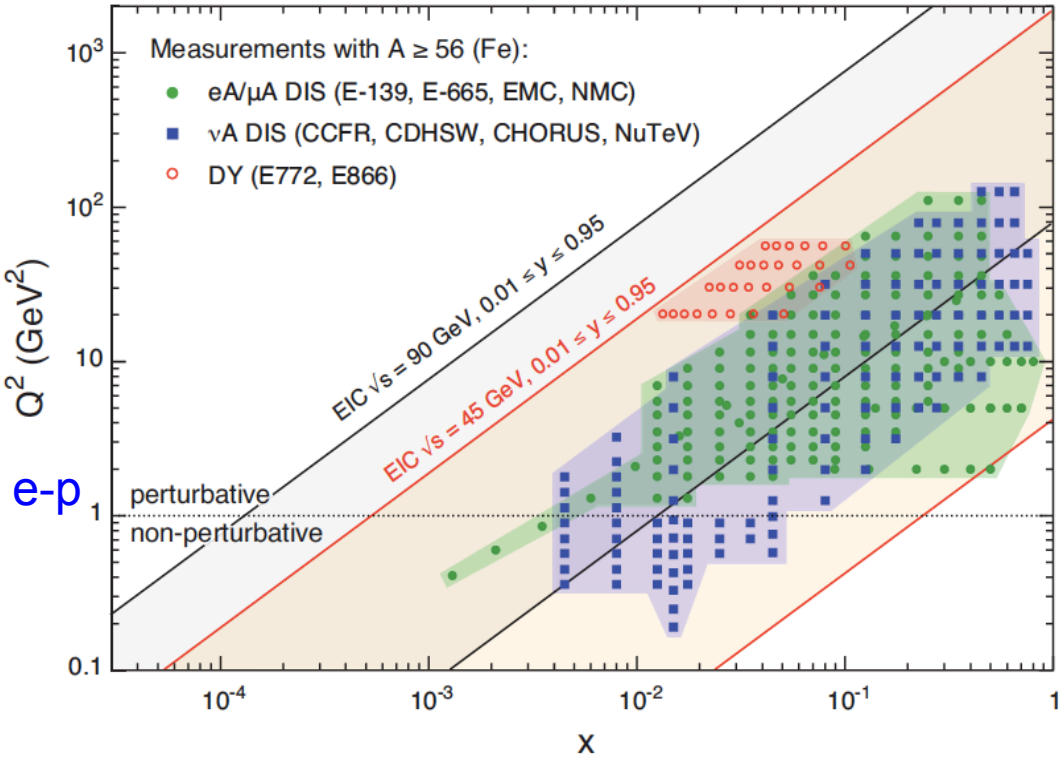
- Since (a) the collider will provide high luminosity, high energy and polarized beams and (b) there may eventually be a very comprehensive large acceptance detector: **Why not explore topics in Electroweak Physics and possible impact on searches for physics beyond the SM?**

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
  range ~50-140 GeV

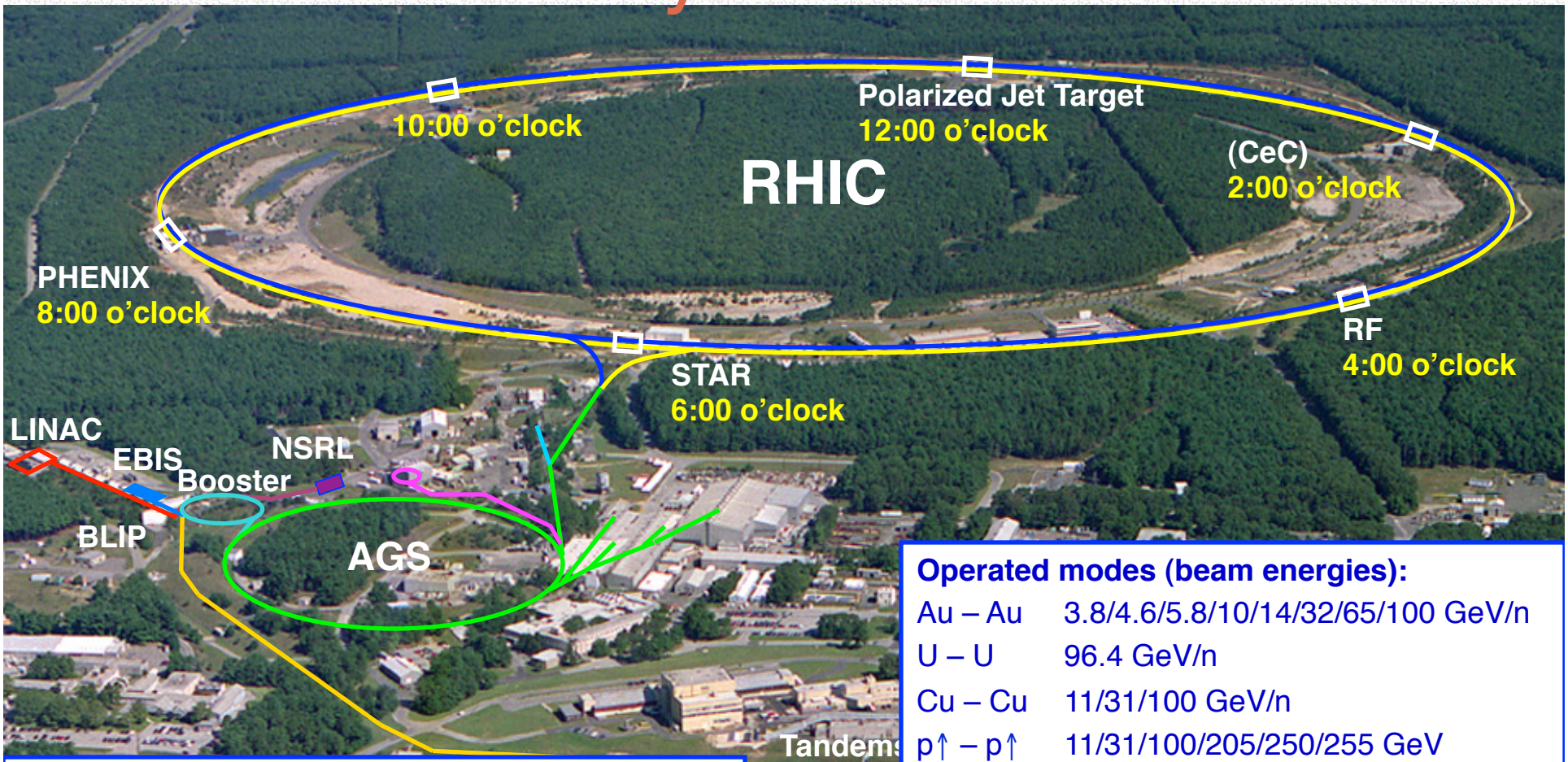


For e-A collisions at the EIC:

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

Stony Brook University

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):

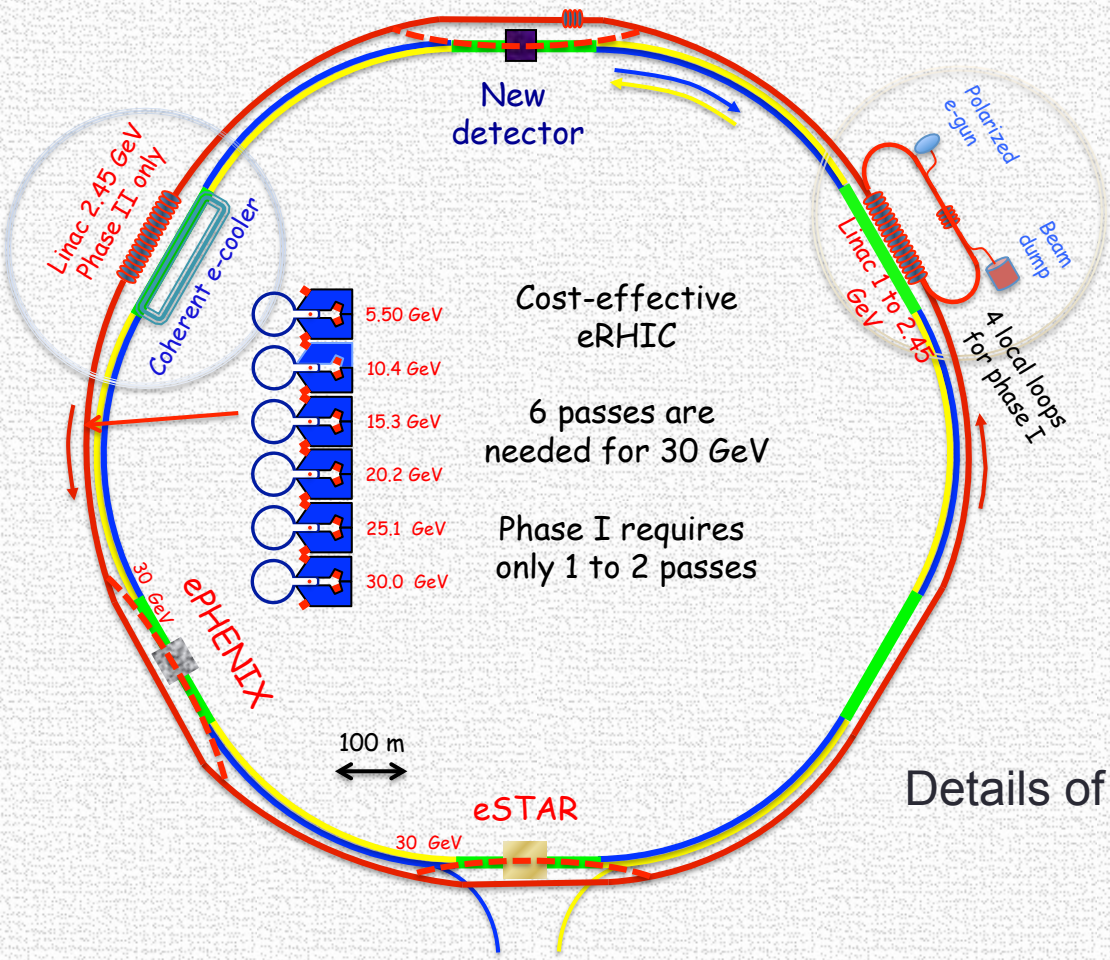
Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

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



Stage I:
5-10 GeV e beam
$\sqrt{s}$ ~ 50-100 GeV
Stage II:
20-30 GeV e beam
$\sqrt{s}$ > 100 GeV

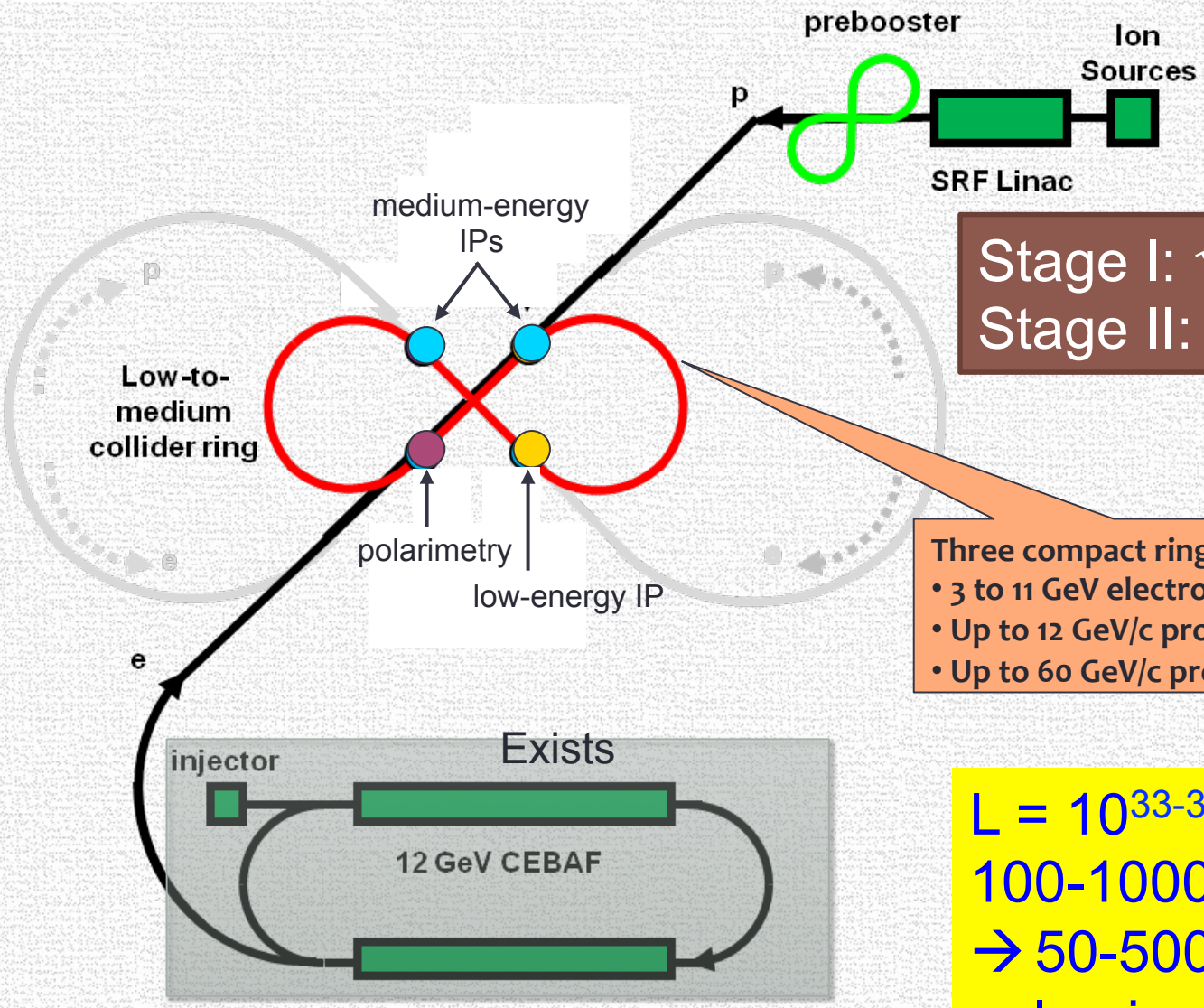
$L = 10^{33\text{-}34}$ cm^{-2}sec^{-1}
100-1000 times HERA
→ 50-500 fb^{-1} integrated in ~10 yrs

Details of eRHIC design, detector IR design :
Talk by E. Aschenauer

Evolution of existing detectors:
Talk by K. Dehmelt, Y. Goto

MEIC : Medium Energy EIC at JLab

Y. Zhang's talk

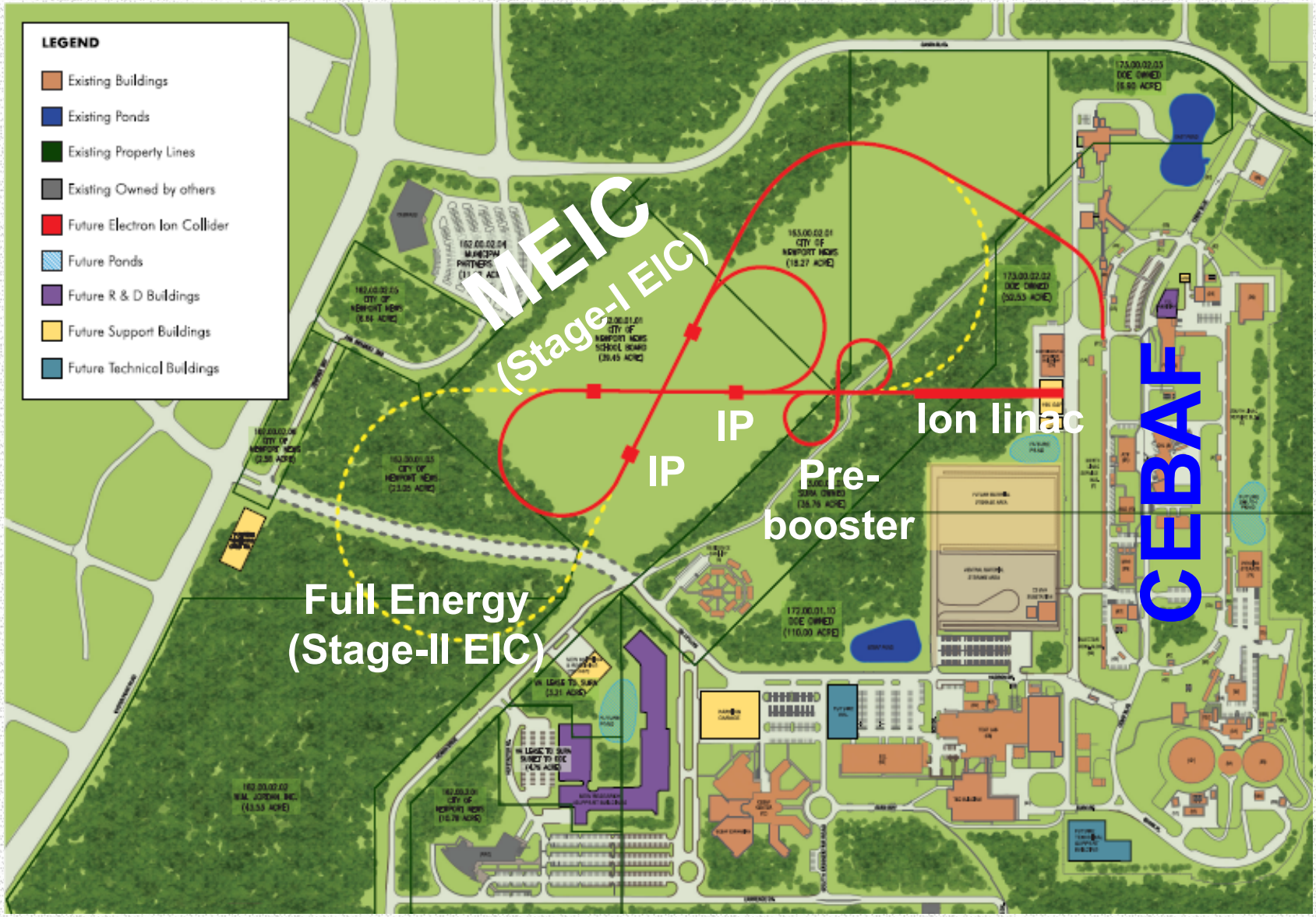


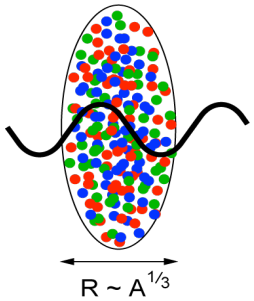
Stage I: √s ~ ~50 GeV
Stage II: √s > 100 GeV

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

MEIC/EIC Layout

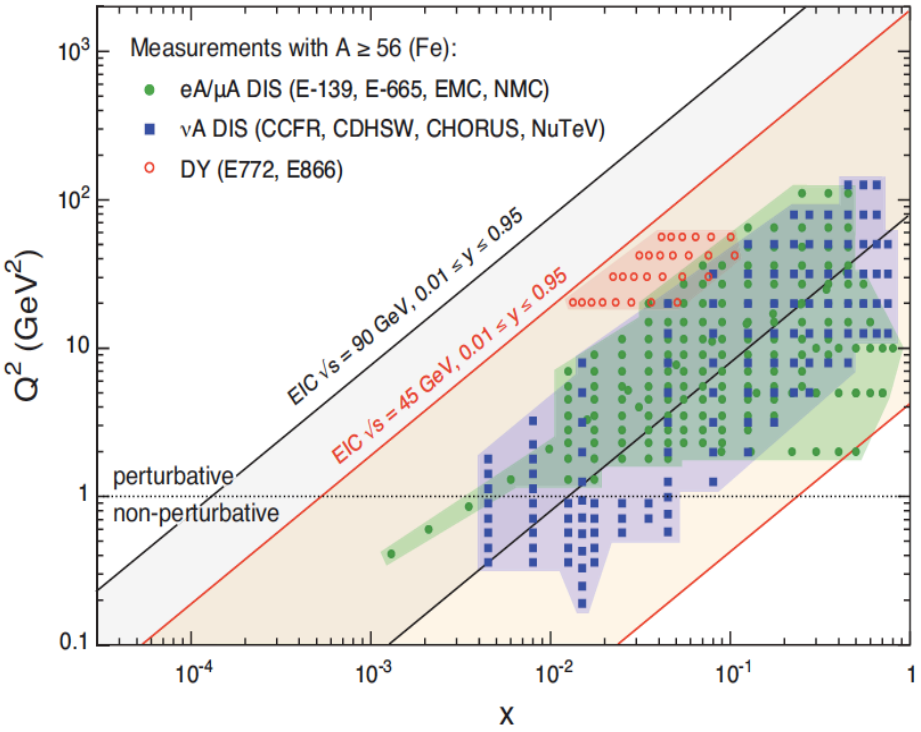




$L \sim (2m_N x)^{-1} > 2\,R_A \sim A^{1/3}$

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

Kowalski Teaney



Nucleus: A laboratory for QCD

Parton propagation and interaction in nuclei (vs. protons)

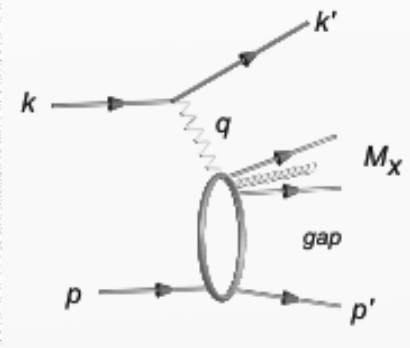
Does gluon density saturate? Does it produce a unique and universal state of matter?

Talks by: M. Lamont, N. Armesto

Saturation/CGC: What to measure?

- F_2 (quark+ antiquark) & F_L(gluons) at low x (classic inclusive measurement)
  - F_L requires change in the center of mass energy in operation of collider

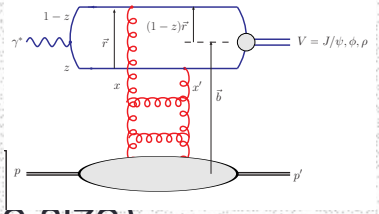
Diffraction:



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

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.
  (See E. Aschenauer's & P. Nadel-Turonski's Talk)

Diffractive vector meson production in eA

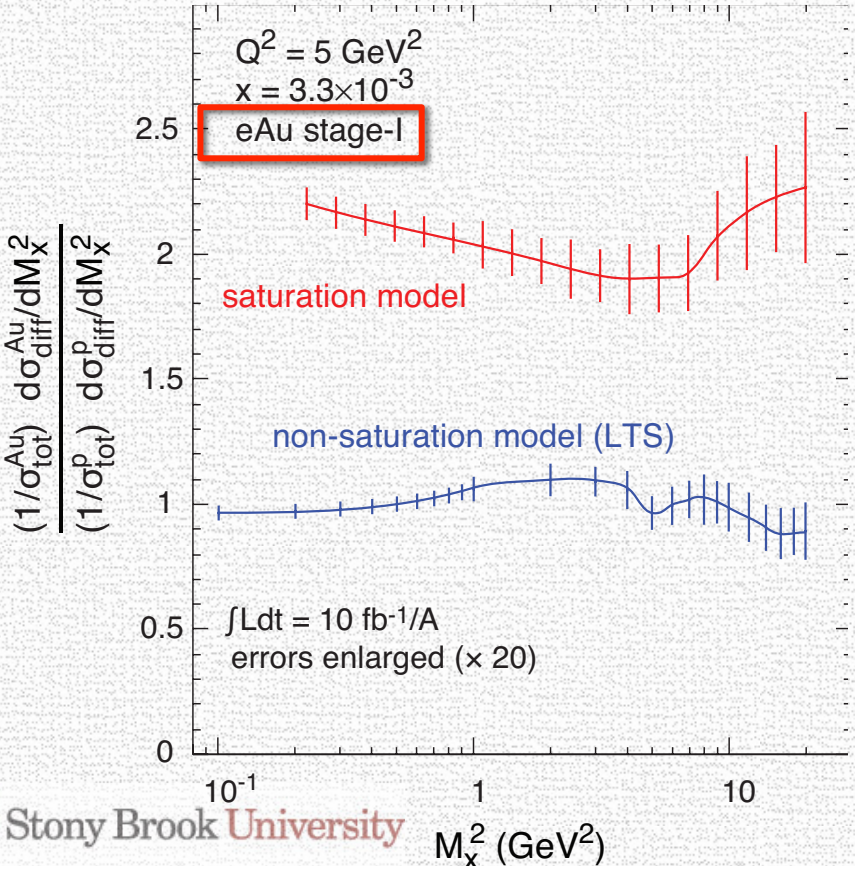
Precise transverse imaging of the gluons in nuclei

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

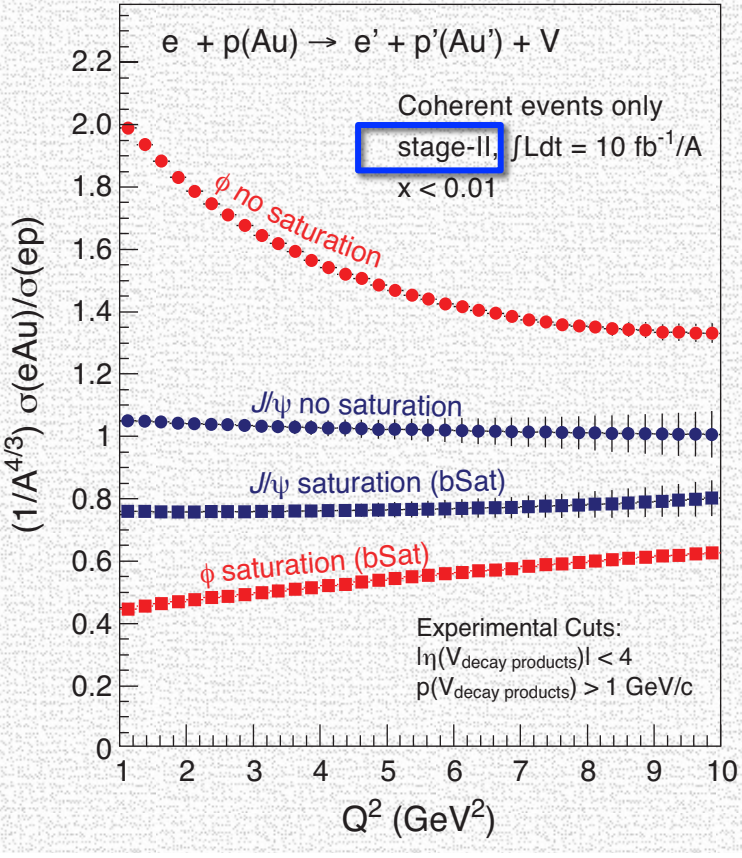
b) **Coherent diff. ratio of eA/ep for J/Ψ and ϕ production with/without saturation**

M. Lamont's talk

Diffractive/Total Cross Section



Coherent diffraction ratios eA/ep



What will *polarized EIC* do for you?

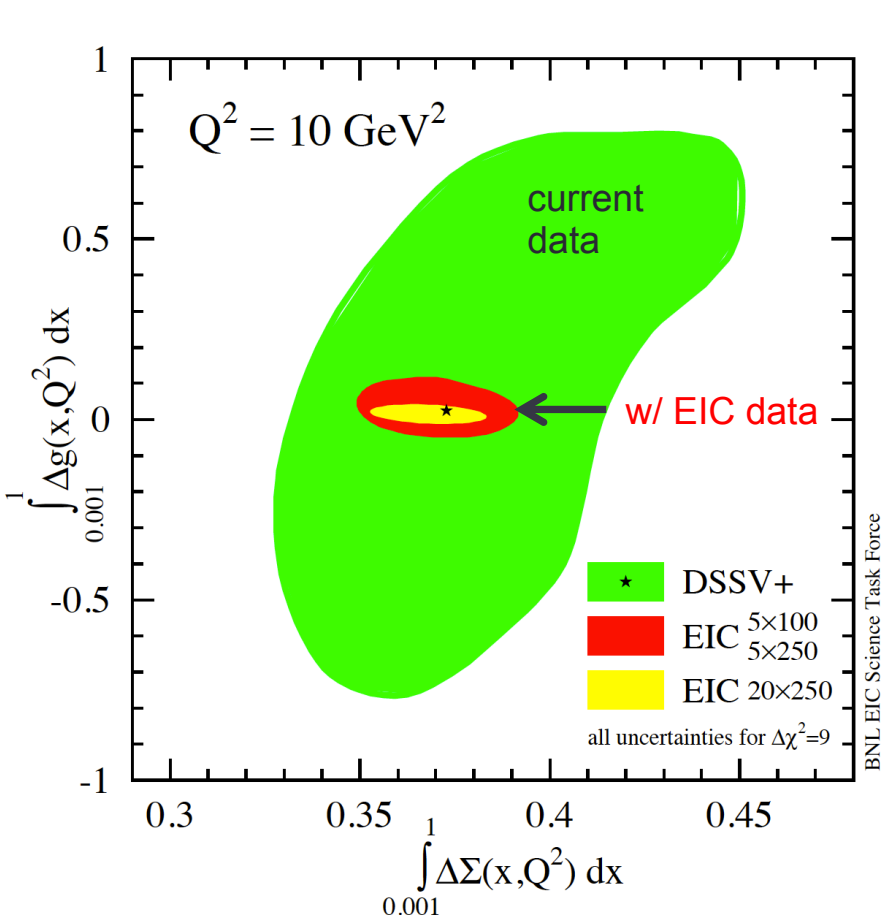
Nucleon Spin:
A precision tool for studying QCD

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

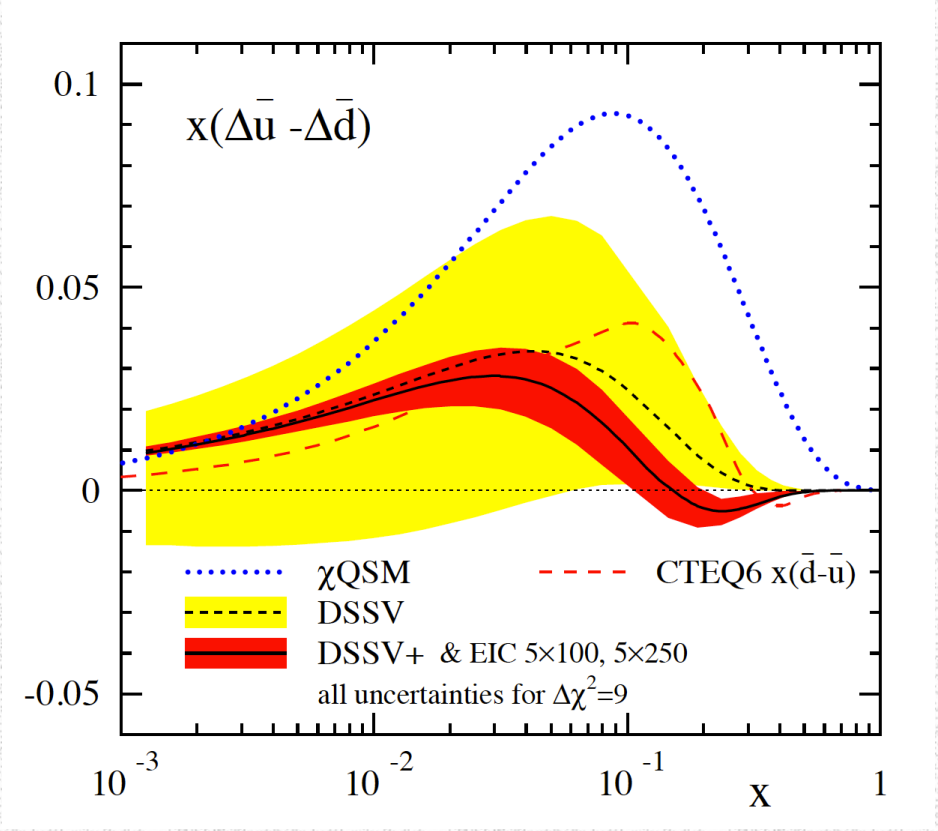
Precision: Gluon & Sea Quark *polarization!*

--Beyond the current experimental capabilities!

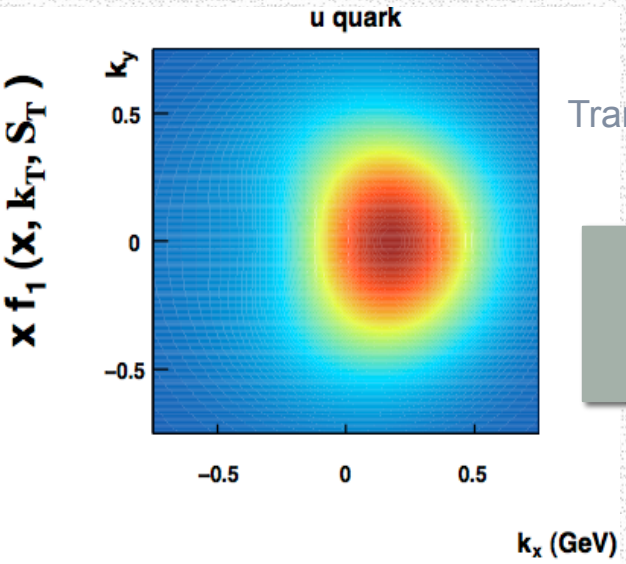
ΔG and ΔΣ in helicity sum



Are the sea quark polarizations different?



2+1D scans of the proton in momentum and position space

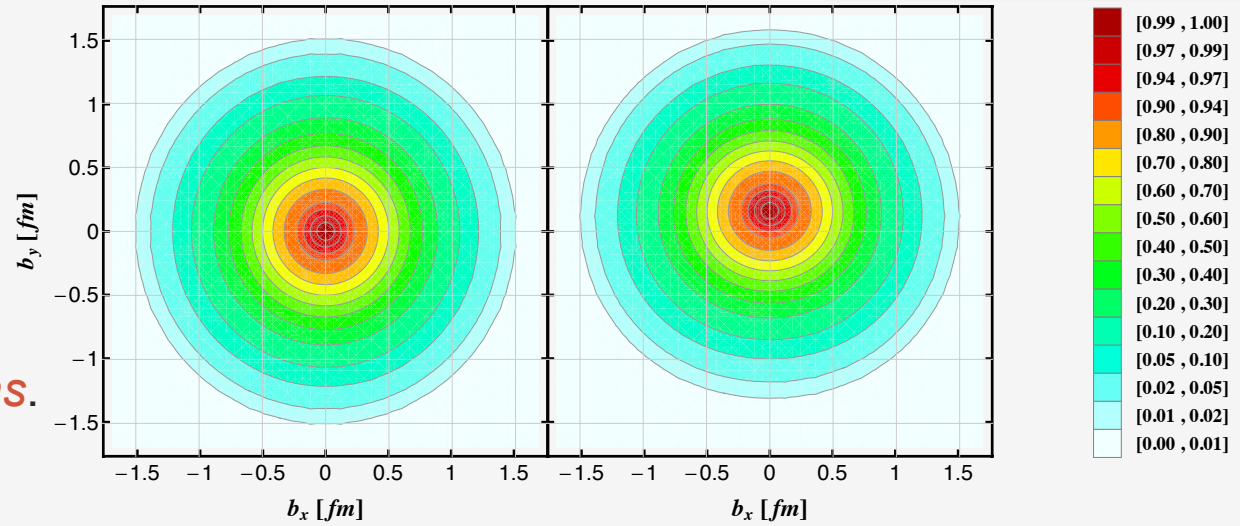


Semi-Inclusive DIS
Transverse Momentum Distributions

Parton's k_x/k_y momenta transversely polarized Proton (z direction)

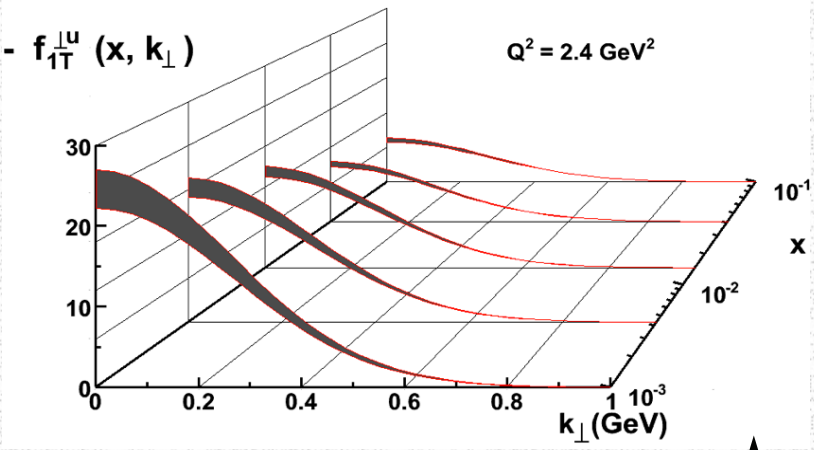
Exclusive J/Ψ production

Parton's position: Distance b from Center for polarized protons



Connections to Orbital motion of Partons JLab12 will explore *valence quarks, EIC would be essential for measurements associated with sea and gluons*.

2+1D scans of the proton in momentum and position space



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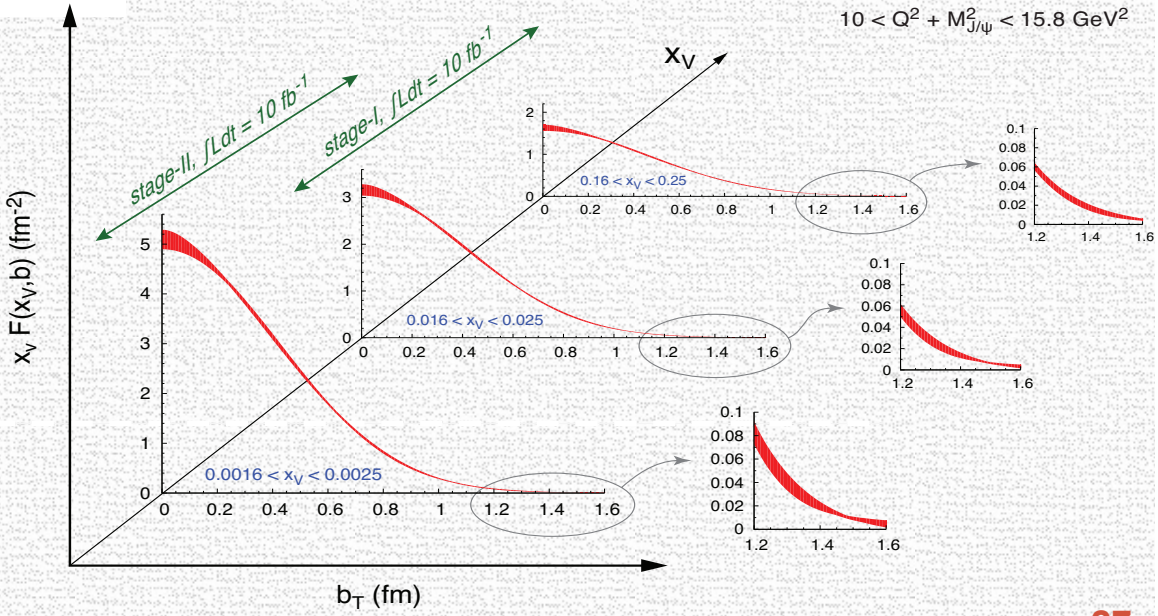

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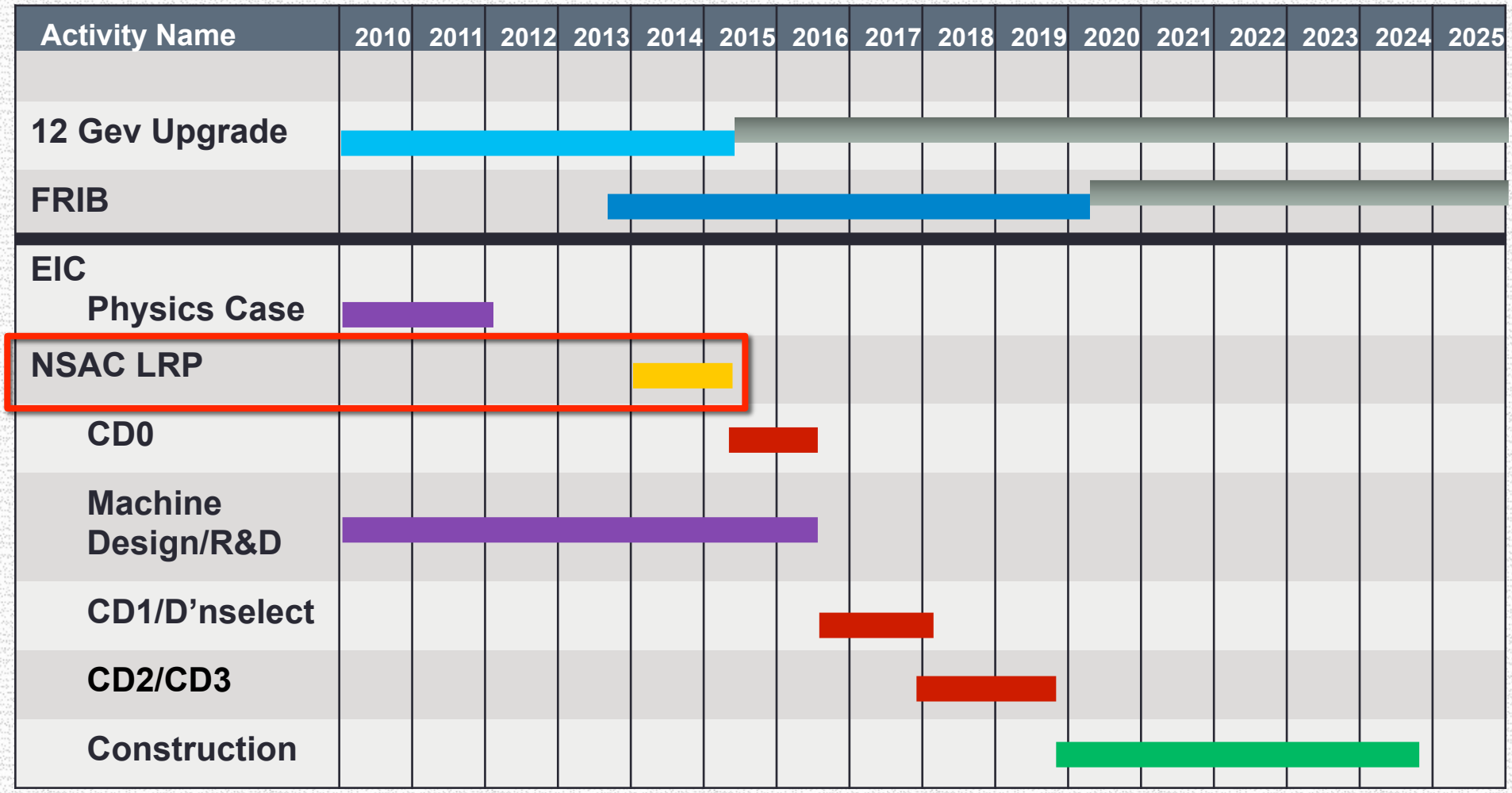
EIC Realization Possible Time Line



Accelerator & Detector R&D & Collaboration

See Details in E. Aschenaur's & Y. Zhang's & P. Nadel-Turonski's talks

- **Accelerator R&D:** Significant level of activity since 2008
- Detector designs ideas being developed: @BNL & @JLab
- 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 June 2013]
- Collaborative groups formed across the US Universities and some European institutions: Tracking, PID, Calorimetry R&D proposals

- **Invitation: Collaboration welcome on all fronts: accelerator, detector, and detailed physics simulation/studies for the EIC**

Summary & Outlook:

The EIC will profoundly impact our understanding of QCD with its energy variability , high luminosity (e-A) and *polarized* e-p/D collisions

EIC: 1st *polarized* DIS collider, 1st nuclear DIS collider, ***Focus: QCD***

- ***Precision studies of the role of sea quarks and gluons in QCD***

- Historically **p-p, e-e, e-p** collisions have played a complimentary and essential role in the development of the SM
  - **EIC's** will add "**spin**" and "**nuclei**" to this list: A-A, p/d-A, **e-A**

Next milestones for US EIC: Long Range Plan of the NSAC 2014/5 for support & approval by the US NP community

Thank you!

EIC White Paper Writing Group and Contributors

EIC-Task Force and WG s at BNL and JLab

Electroweak & beyond….(?)

BNL LDRD: Deshpande, Marciano, Kumar & Vogelsang

- High energy collisions of polarized electrons and protons and nuclei afford a unique opportunity to study electro-weak deep inelastic scattering
  - **Electroweak structure functions (including spin)**
  - Significant contributions from W and Z bosons which have different couplings with ***quarks and anti-quarks***

- **Parity violating DIS**: a probe of beyond TeV scale physics
  - Measurements at higher Q^2 than the PV DIS 12 GeV at Jlab
  - Precision measurement of $Sin^2\Theta_W$

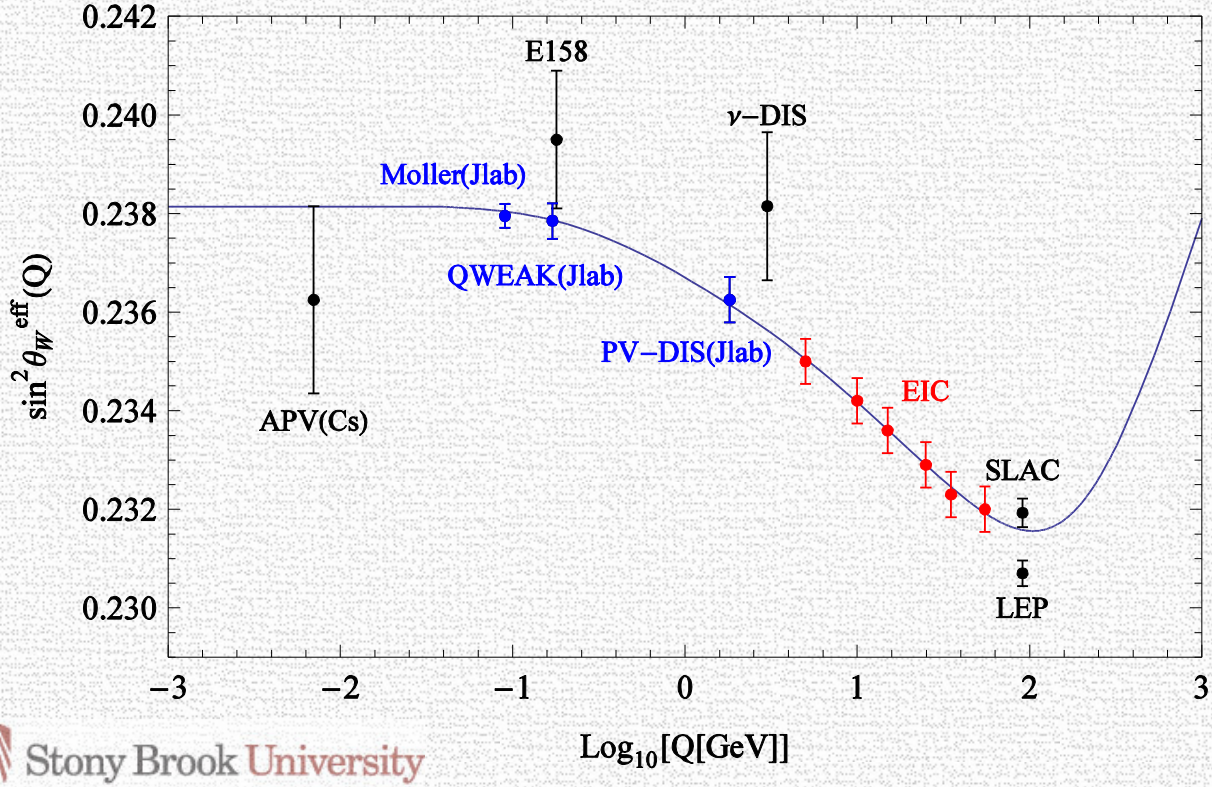
- **New window for physics beyond SM**
  - Lepton flavor violation search

arXiv: 006.5063v1 [hep-ph]
M. Gonderinger et al.

$$e^- + p \rightarrow \tau^- + X$$

$Sin^2\Theta_W$ with the EIC: Physics Beyond SM

- Precision parity violating asymmetry measurements e/D or e/p
- Deviation from the "curve" may be hints of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, E_6/Z' based extensions of the SM



Black: measurements

Blue: near future measurements

Red: US EIC projections

eRHIC Technically Driven Schedule

Roser @ BNL