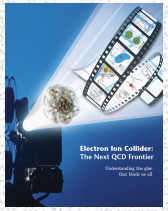


Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

Why EIC?

To understand the role of gluons & sea quarks in QCD

Jefferson Laboratory Users Meeting
June 2, 2014

Acknowledgement: Contribution from many in RHIC/JLab/HERA physics community and the EIC White Paper Writing Group assembled by the BNL/JLab Managements

Stony Brook University

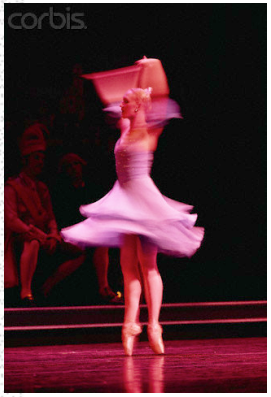
Abhay Deshpande

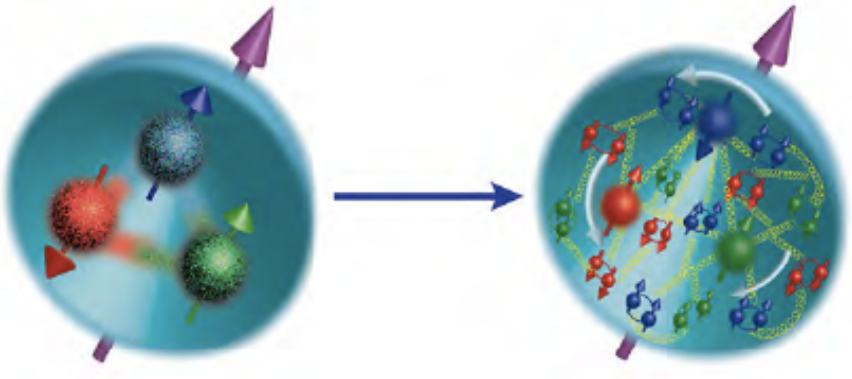
"Folks, we should stop testing QCD, and start understanding it." Yuri Dokshitzer (ICHEP'98, Vancouver)

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?





$$\text{Proton Spin} = \frac{1}{2} = \Delta Q + \Delta G + L_{Q,G}$$

Our Understanding Of "Nucleon Spin"

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

Theoretical tools and experiments to view the proton in 3D

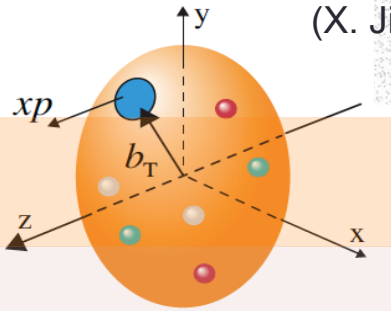
What are the ***position & momentum correlations*** amongst partons? Do they contribute to nucleon's spin?

Position & momentum tomography of the nucleon possible??

Unified view of the Nucleon Structure

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

❑ Wigner distributions:



5D

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

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

JLab12 COMPASS for Valence

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

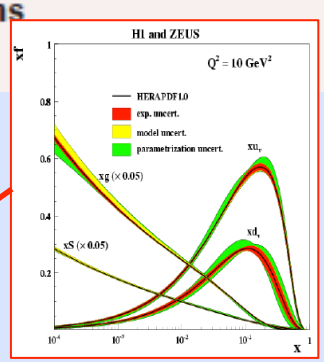
generalized parton distributions (GPDs)
exclusive processes

1D

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

$\int dx$

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



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

$F_1(t)$
form factors
elastic scattering

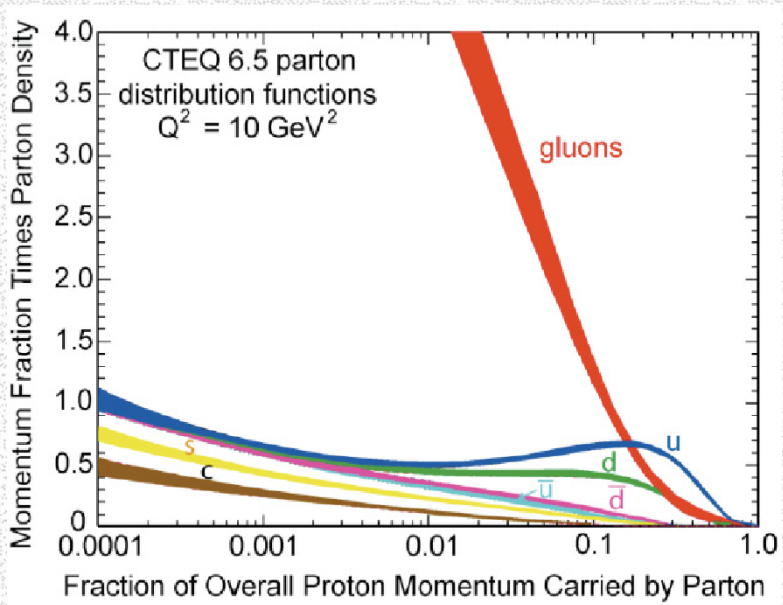
$A_{n,0}(t)+4\xi A_{n,2}(t)+....$
generalized form factors
lattice calculations

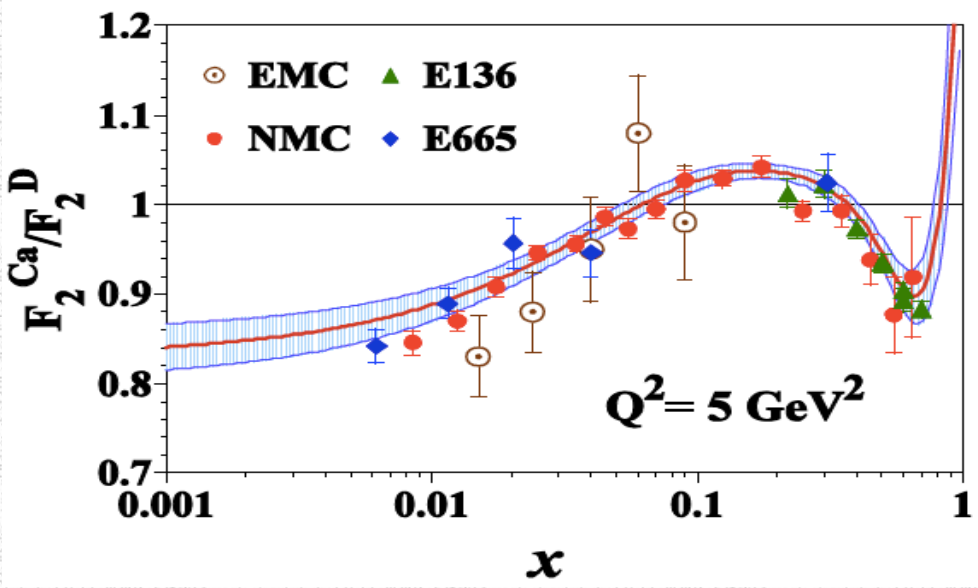
❑ 3D imaging of partons: Quarks (fixed target) , Gluons (collider)

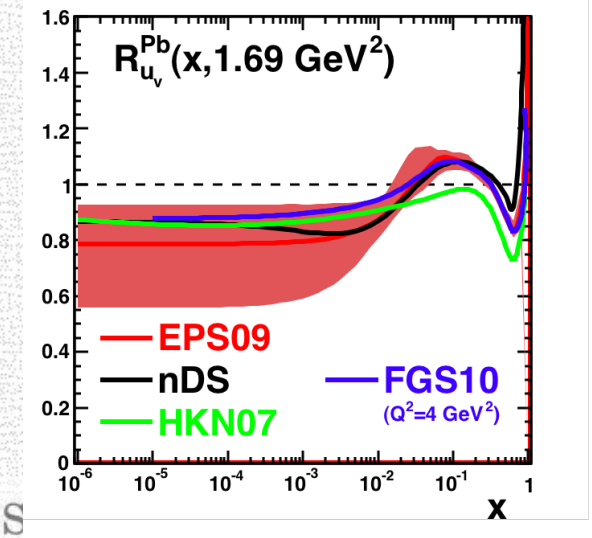
✧ TMDs – confined motion in a nucleon (semi-inclusive DIS)

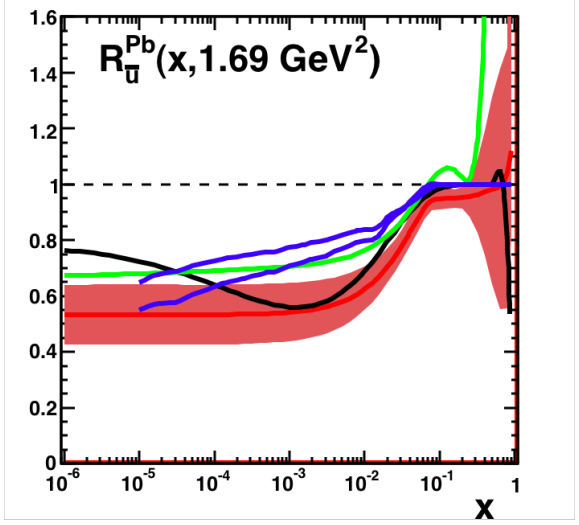
✧ GPDs – Spatial imaging of quarks and gluons (exclusive DIS & diffraction)

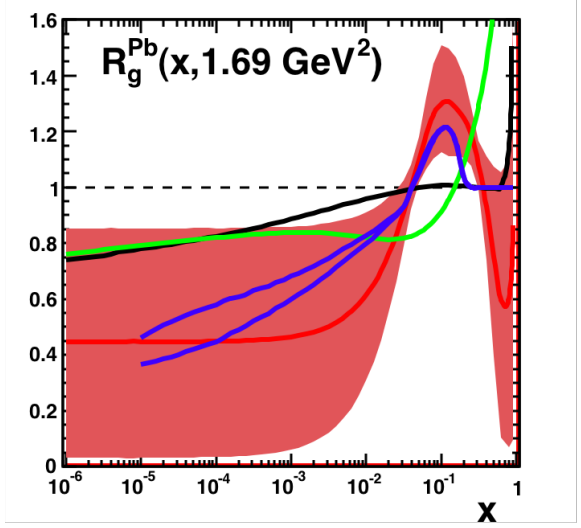
Low-x in proton (puzzle) and nuclei (unmeasured)

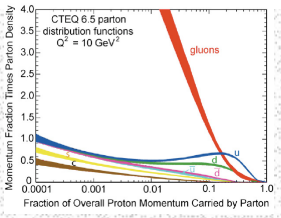






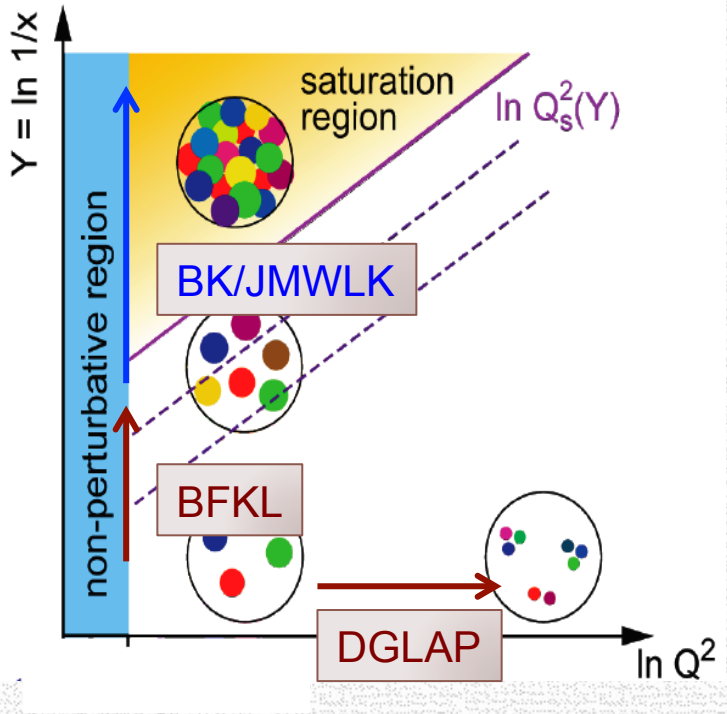






Physics at Low x?

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

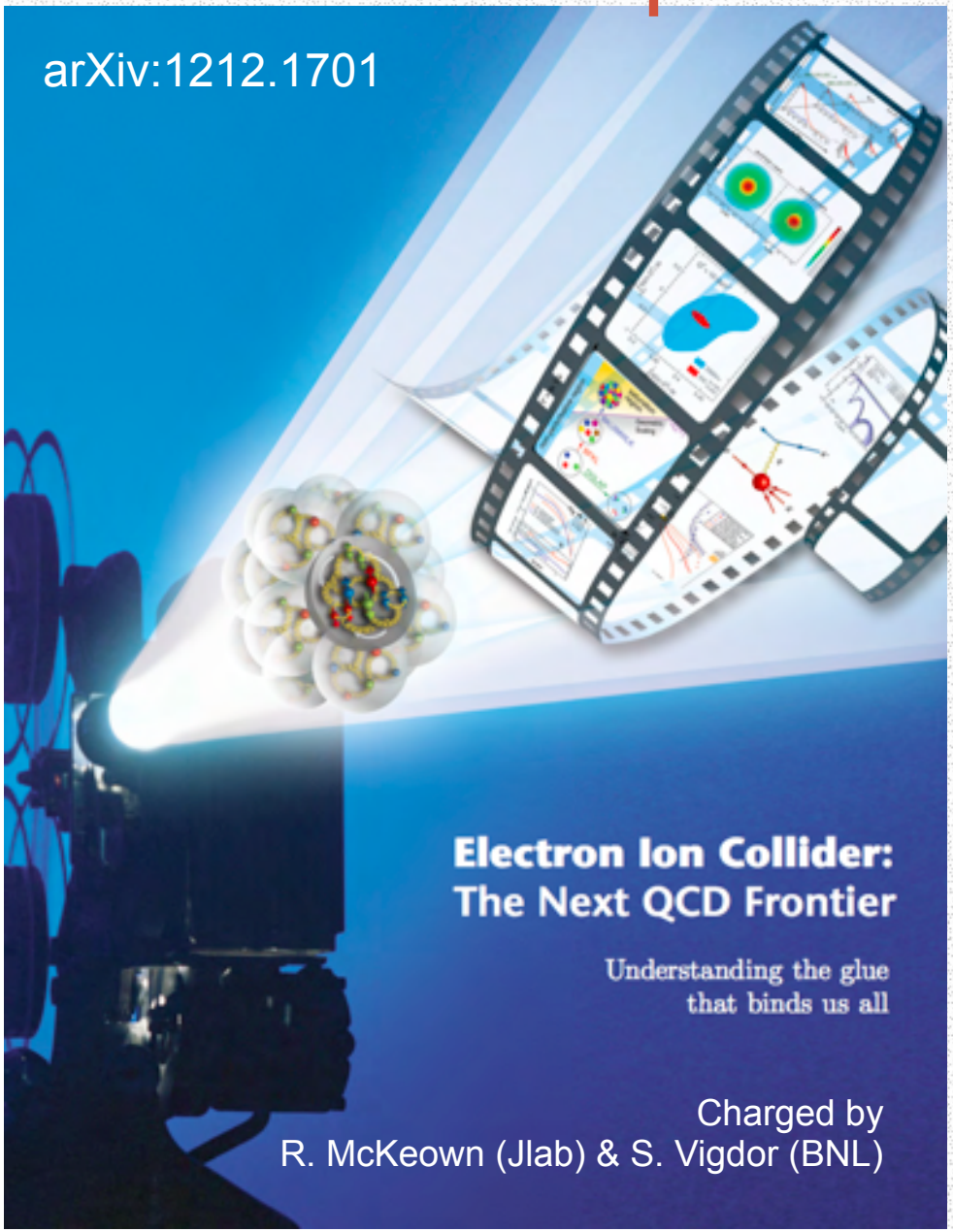
Strongly correlated gluonic system? Universal? Properties?

Need a higher energy e-p collider than HERA! ➔LHeC

Or ➔ Nuclei: naturally enhance the densities of partonic matter

Why not use Nuclear DIS at high energy?

White Paper: EIC Science Case



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T. Ullrich (BNL) and Y. Kovchegov (Ohio State)

Nucleon spin structure (inclusive e+N):
E. Sichtermann (LBNL) and W. Vogelsang (Tübingen)

GPD's and exclusive reactions:
M. Diehl (DESY) and F. Sabatie (Saclay)

TMD's and hadronization and SIDIS:
H. Gao (Duke) and F. Yuan (LBNL)

Parton Propagation in Nuclear Medium:
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Electroweak physics:
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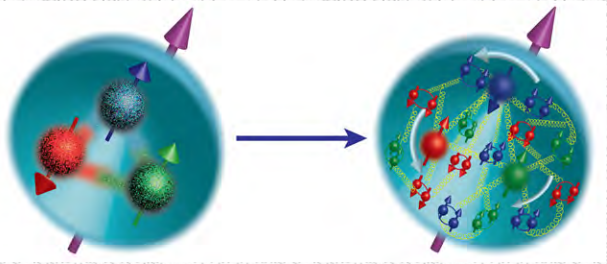
A. Mueller (Columbia) and R. Holt (ANL)

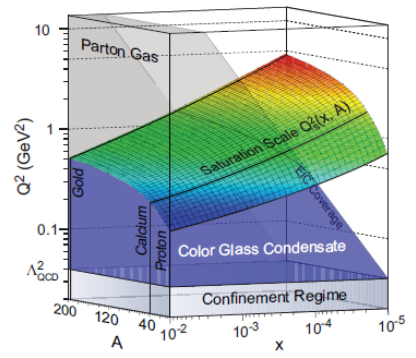
Successful thanks to many other co-authors and contributions

EIC – The Physics Highlights

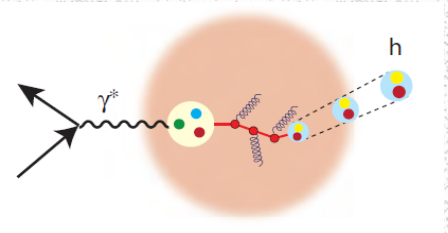
- **Explore and image the spin and 3D structure of the nucleon**
  Needs a machine with high polarized luminosity and variable energy range to cover valence to sea quarks and gluons, excellent acceptance/PID in detectors



- **Discover the role of gluons in structure and dynamics**
  Needs a machine capable of high energy capable of accelerating nuclei



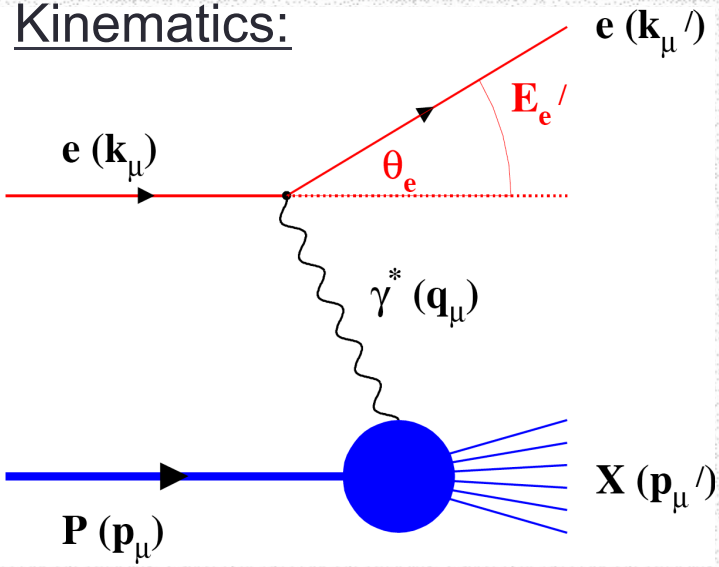
- **Understand the emergence of hadrons from color charge**
  Needs machine capable of accelerating large & small nuclei & special detectors for nuclear fragments



- **Investigations of physics beyond the Standard Model**
  Highest e-p luminosity, highest possible energy and at least one beam polarization

Deep Inelastic Scattering = Precision + Control

Kinematics:



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

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

Measure of resolution power

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

Measure of inelasticity

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

Measure of momentum fraction of struck quark

Hadron :

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

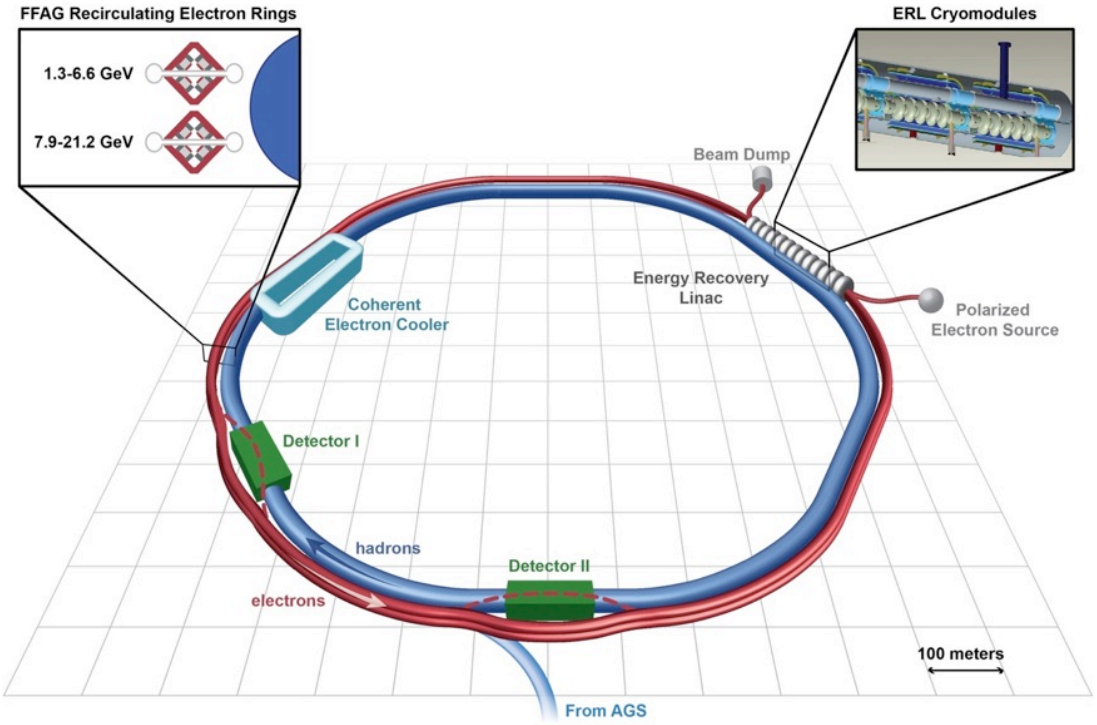
Inclusive events: e+p/A → e'+X
detect only the scattered lepton in the detector

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

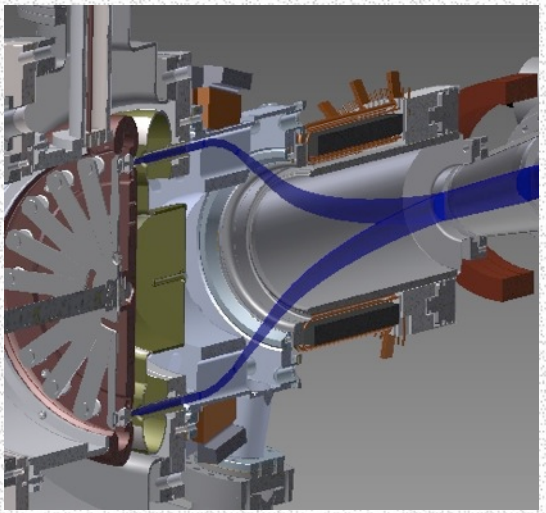
Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)
Detect every things including scattered proton/nucleus (or its fragments)

eRHIC Machine Design

- ✓ Up to 21.2 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside the RHIC tunnel collides with existing 250 GeV polarized protons and 100 GeV/n HI RHIC beams
- ✓ ERL with 1.32 GeV SRF Linac and two FFAG recirculating rings (1.33 – 6.62 GeV; 7.94 – 21.16 GeV) allow for full luminosity (> 10^{33} cm^{-2} s^{-1}) up to 15.9 GeV and reduced luminosity up to 21.2 GeV
- ✓ Single collision of each electron bunch allows for large disruption ➔ high luminosity and full electron polarization transparency
- ✓ *Accelerator R&D for highest luminosity: High current (50 mA) pol. electron gun (Gatling gun); High average current ERL with FFAG passes; Coherent electron cooling of hadron beam*



50 mA polarized electron gun (Gatling gun)



MEIC at JLab: Conceptual Design

- MEIC - a polarized medium energy electron-ion collider
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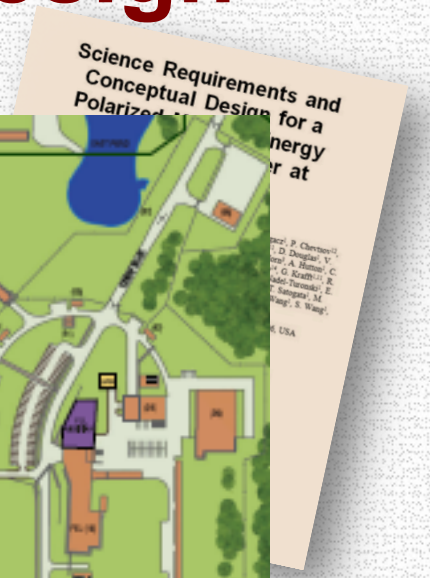
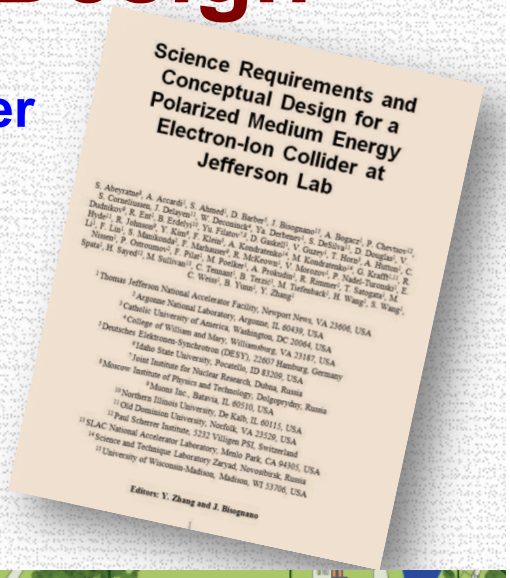


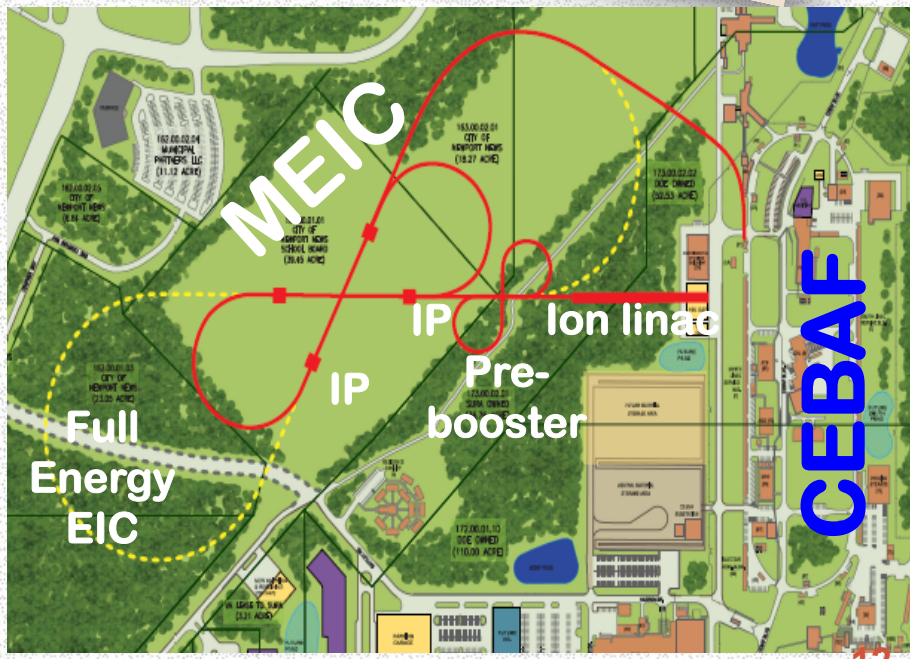
MEIC at JLab: Conceptual Design


Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

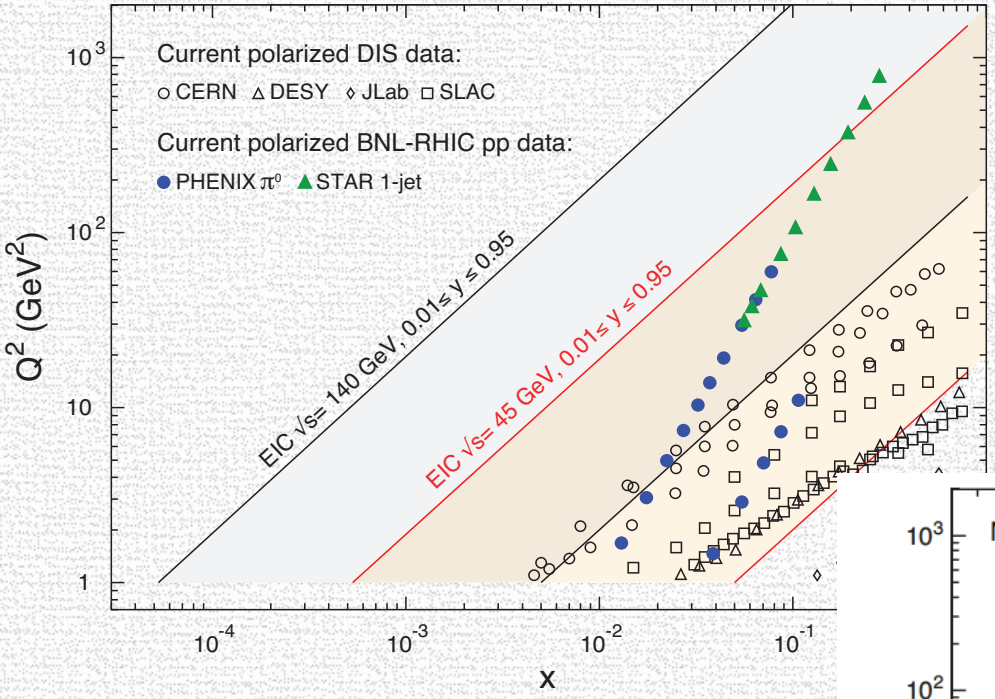
- **MEIC - a polarized medium energy electron-ion collider**
- **The MEIC baseline design**
  - A ring-ring collider, supporting 3 IPs, two for medium ion energies
  - Luminosity reaches 10^{34} $cm^{-2}sec^{-1}$ per interaction point
  - Highly polarized electron, proton, deuteron and helium-3 beams
  - 12 GeV CEBAF recirculating linac as a full energy electron injector
  - A new ion complex consisting of source, linac and two booster rings
- **Design report released last August (arXiv:1209.0757)**
- **Now focusing on specific R&D**

1) cooling studies – evolutionary approach
2) dynamical aperture – 1st order o.k.
3) polarization – tracking & optimization
4) collective beam effects – deemed o.k.

Will add sections on cooling and polarization to existing design report

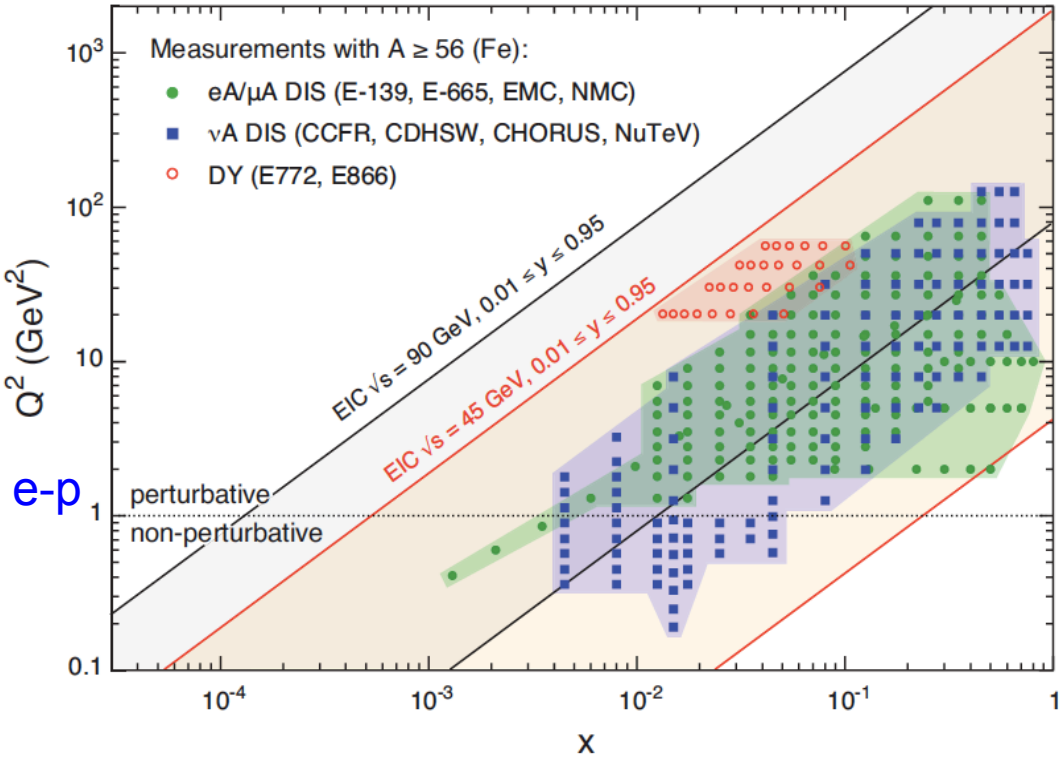


US EIC: Kinematic reach & properties



For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ **e beam 5-10(20) GeV**
- ✓ 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:

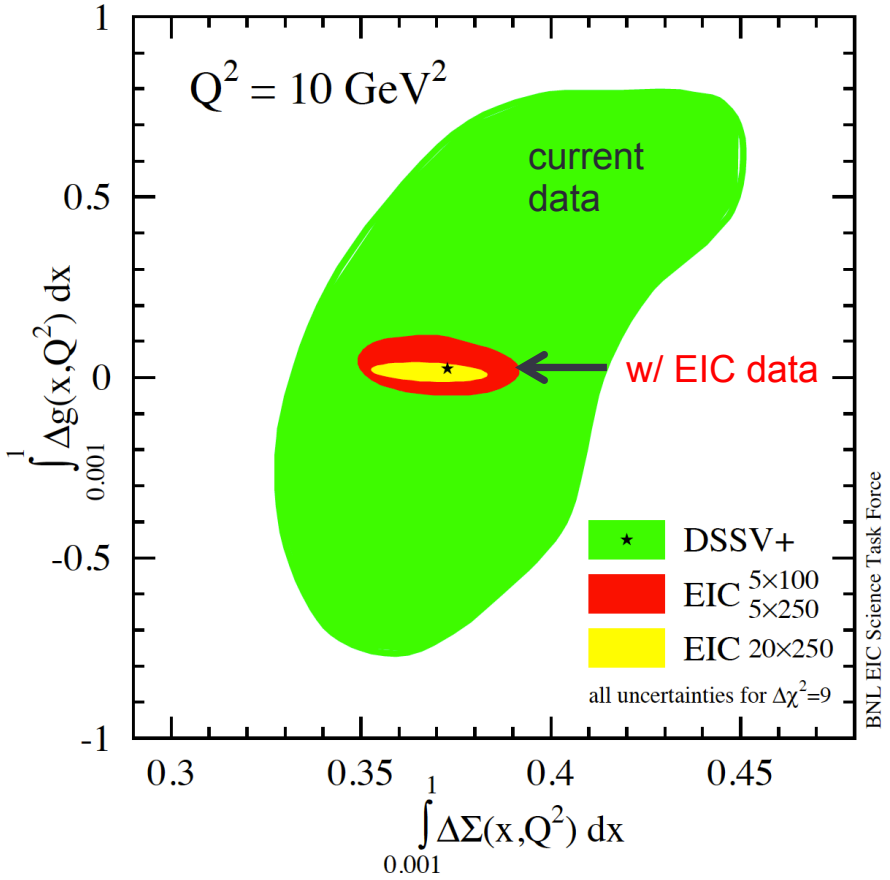
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

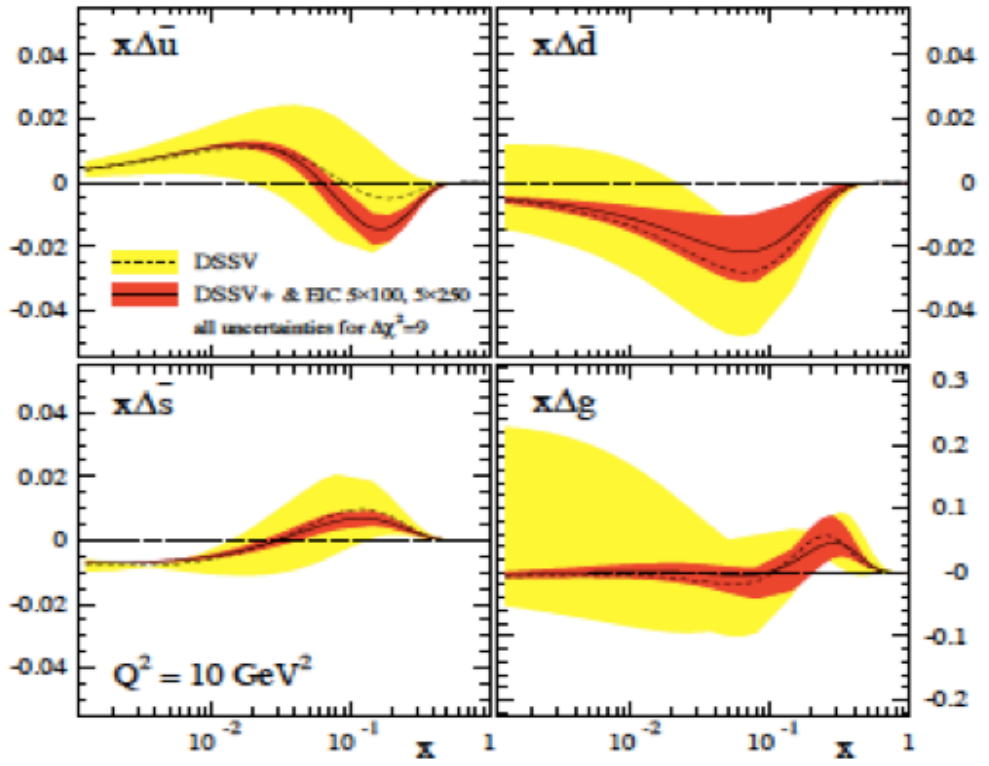
Precision: Gluon & Sea Quark *polarization!*

--Beyond the current experimental capabilities!

ΔG and ΔΣ in helicity sum

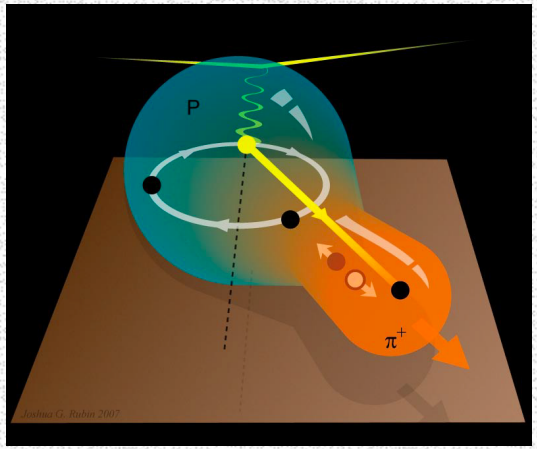
Are the sea quark polarizations different?

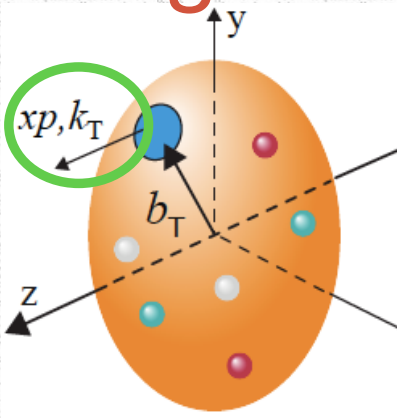




EIC White Paper: arXive:1212.1701

Semi-Inclusive DIS ➔ Best for measuring Transverse Momentum Distributions





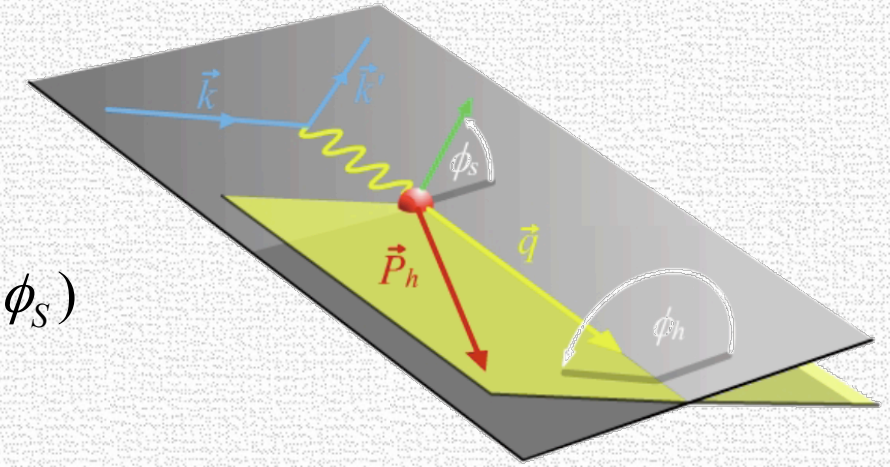
- Naturally, two scales:
  - ✧ high Q – localized probe
    To "see" quarks and gluons
  - ✧ Low p_T – sensitive to confining scale
    To "see" their confined motion
  - ✧ *Theory – QCD TMD factorization*

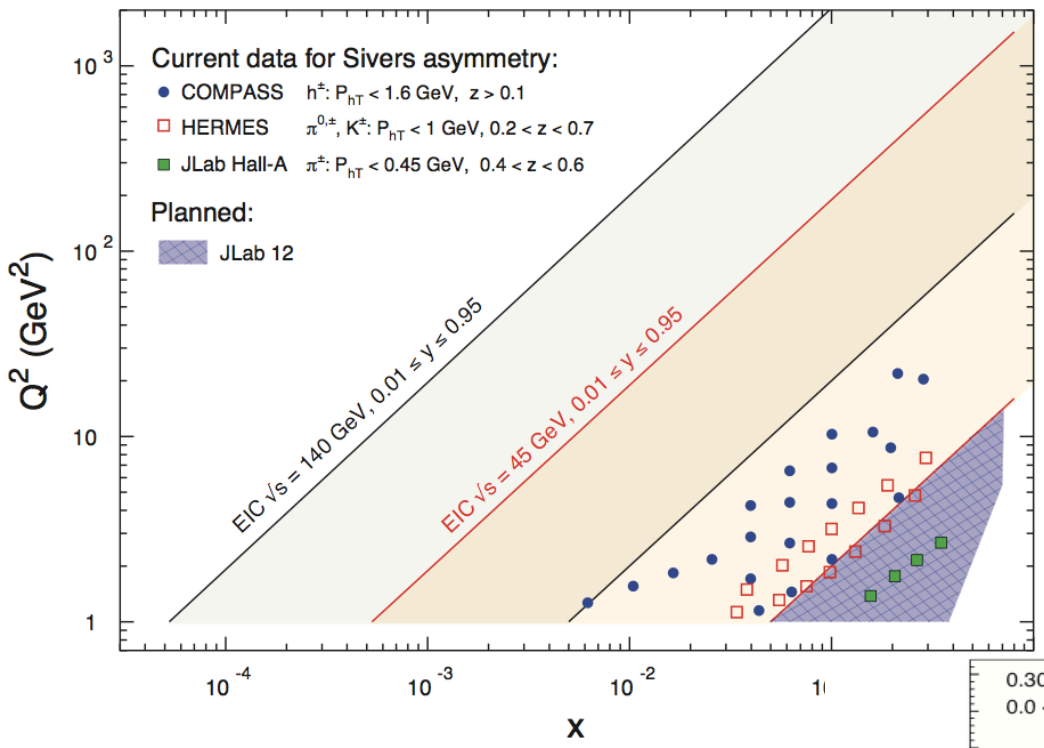
- Naturally, two planes:

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

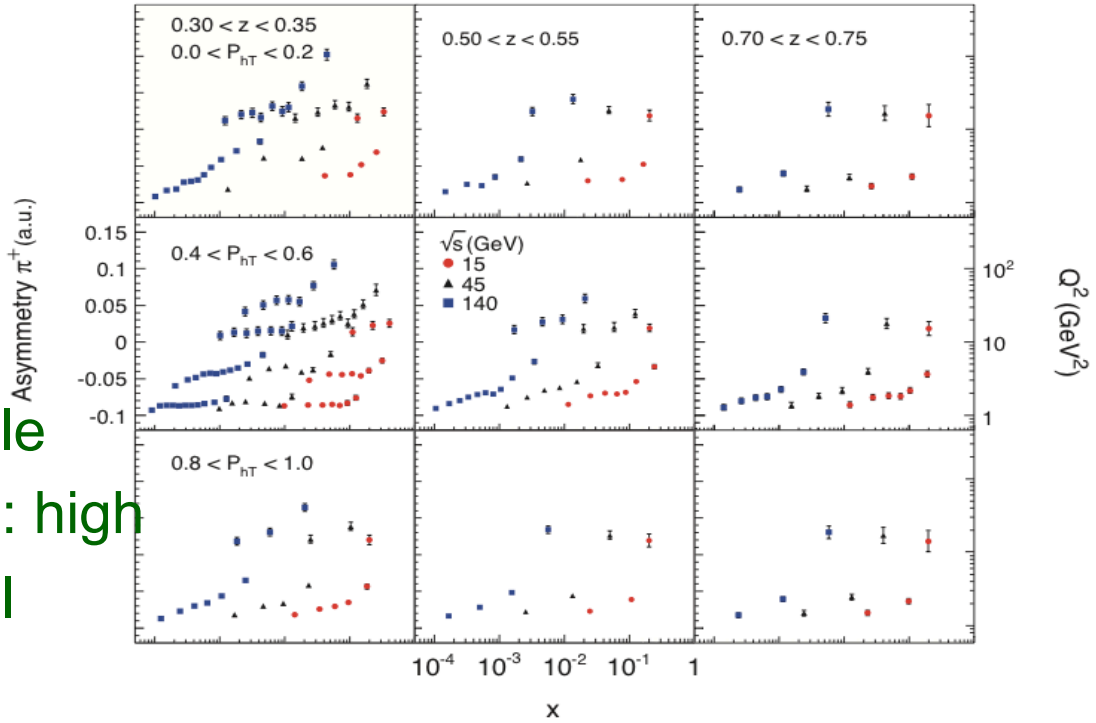
$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$





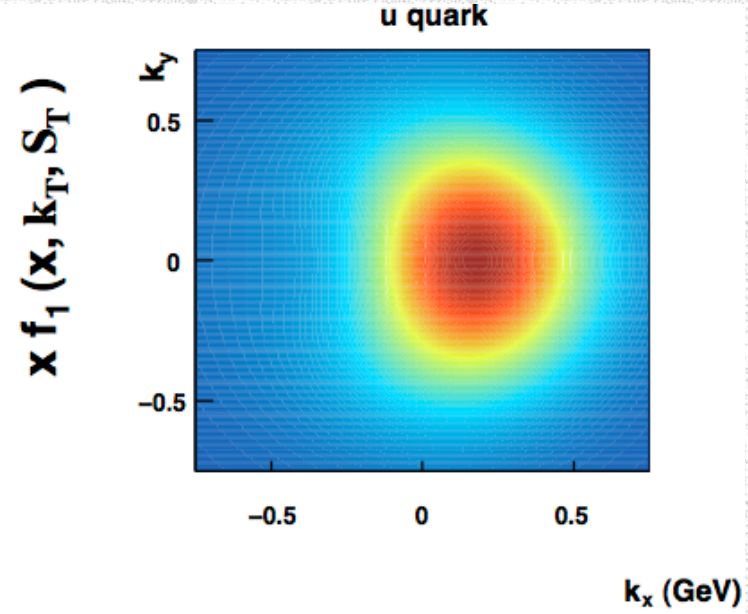
First, maybe the only, measurement of polarized sea and gluon TMDs

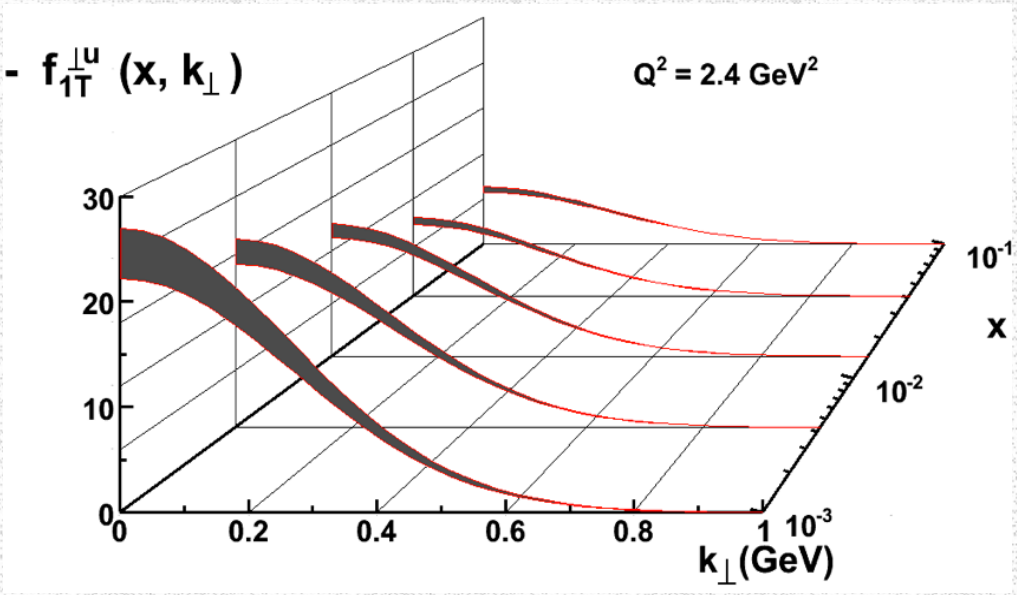


- High luminosity implies: Single transverse-spin asymmetries: high resolution & multidimensional

Momentum tomography of the nucleon

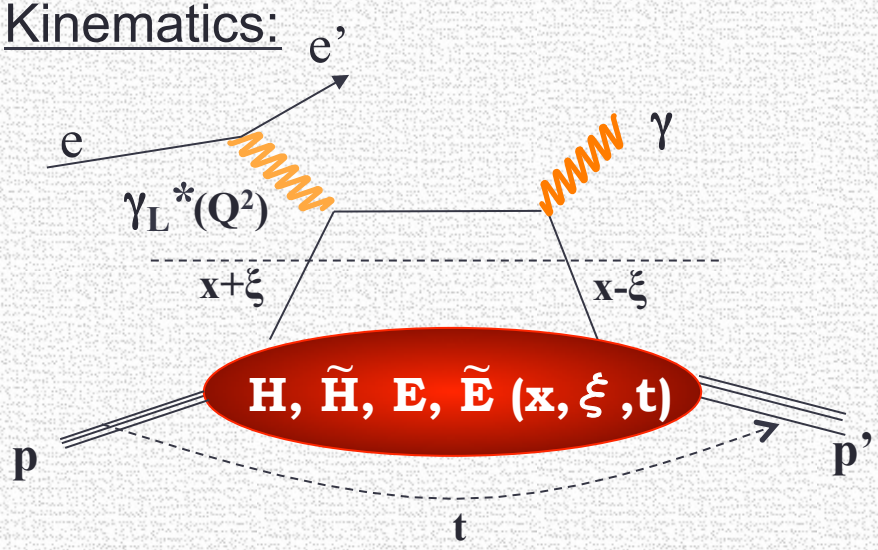
- Tomographic images of K_X/K_y of partons as functions of Bjorken-x: u quark distribution for transversely polarized proton.
- ***With EIC: low x partonic plots like these possible!***





Exclusive DIS

Kinematics:



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

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

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

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

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

$$\frac{1}{2} = J_Q + J_G$$

$$J_Q = \frac{1}{2}\Delta\Sigma + L_Q$$

$$J_G = \Delta G + L_G$$

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

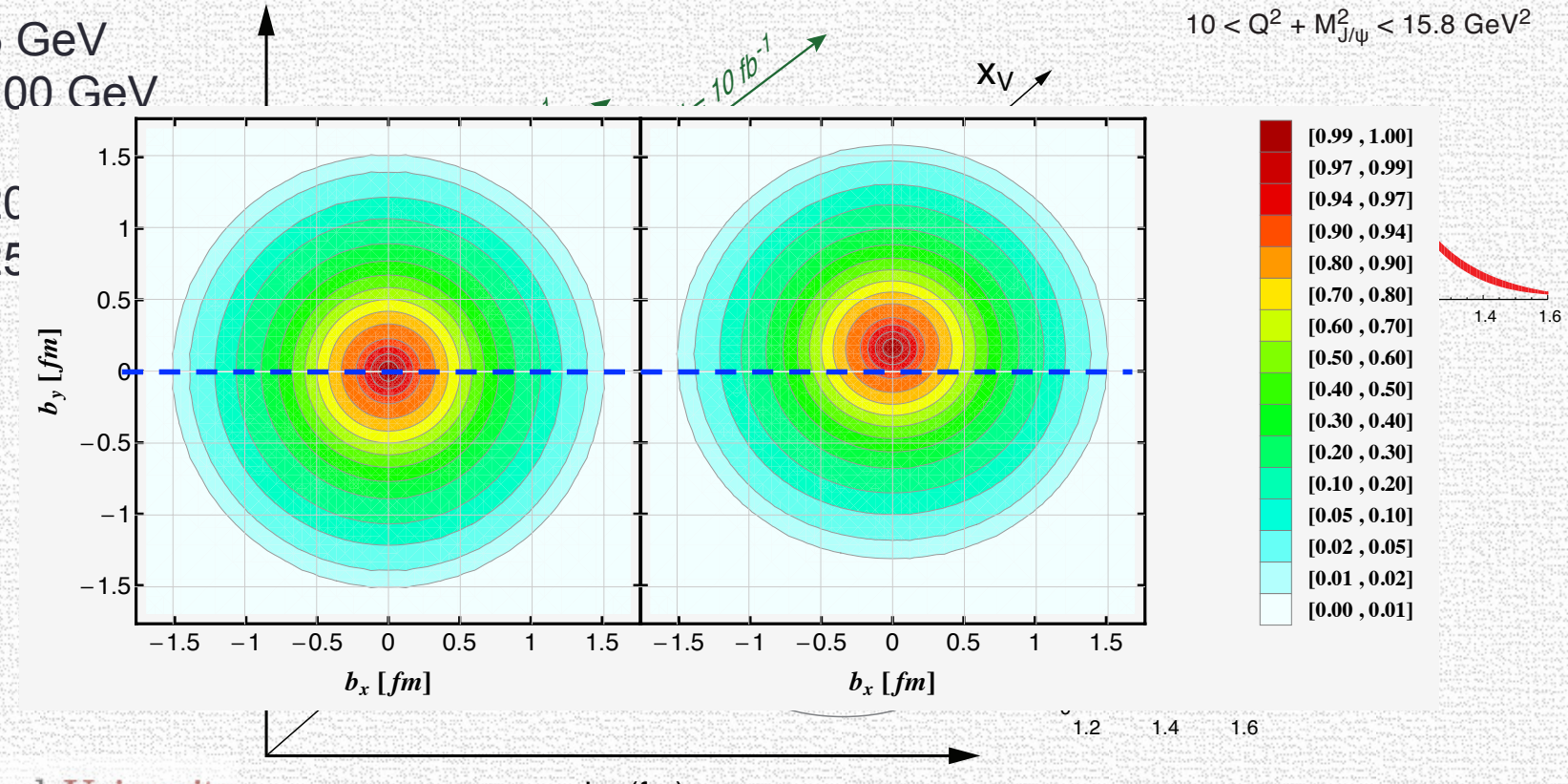
b_T is the distance of the gluon from the center of the proton
x_V determines the gluon momentum fraction

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

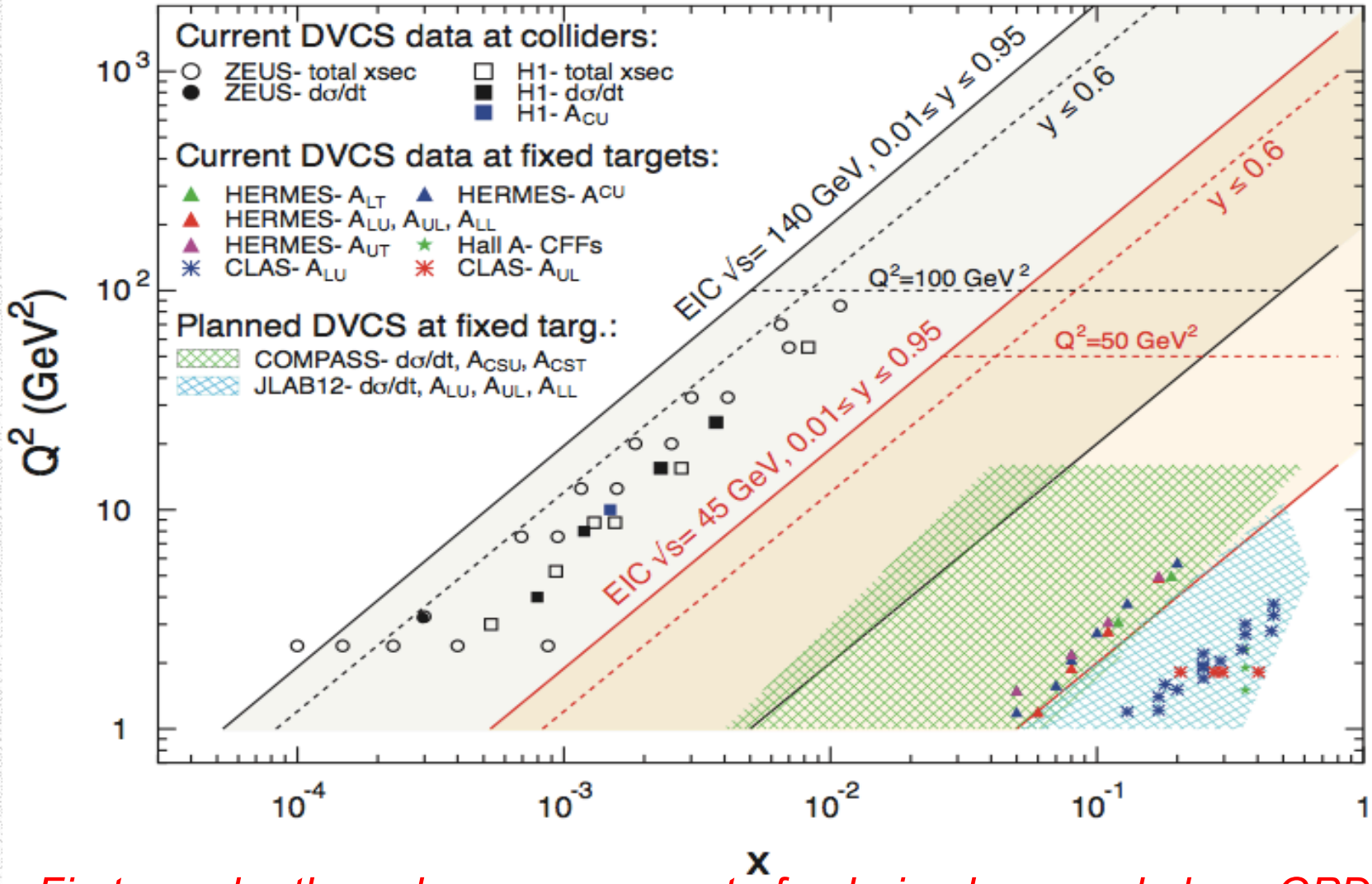
$$W^2 = (p+q)^2; \qquad M_N^2 = p^2$$

E_e = 5 GeV
E_p = 100 GeV

E_e = 20
E_p = 25



EIC coverage for GPDs



First, maybe the only, measurement of polarized sea and gluon GPDs

An immediate check/impact:

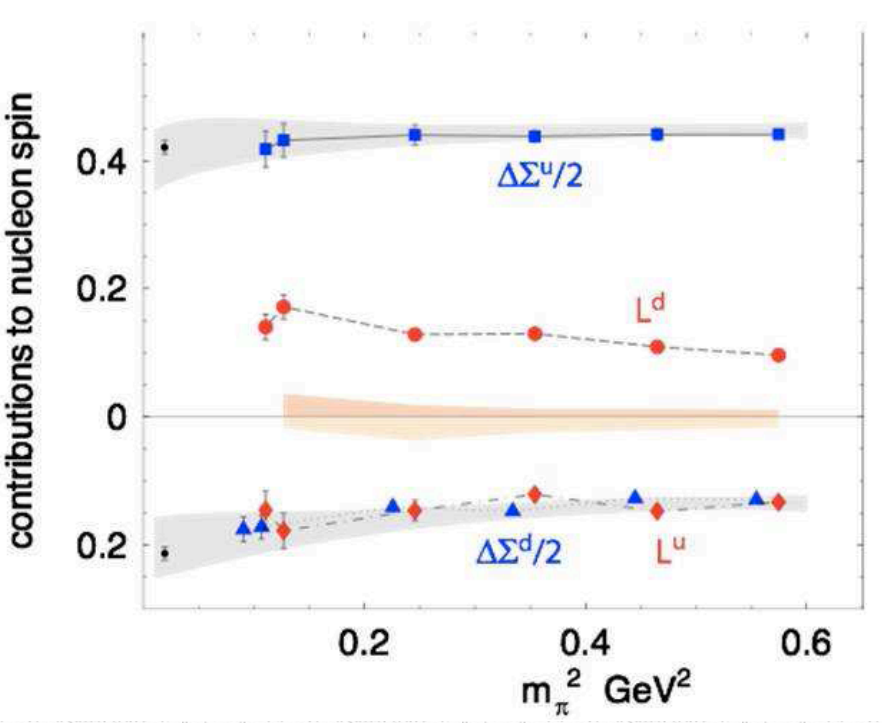
❑ Quark GPDs and its orbital contribution to proton's spin:

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] = \frac{1}{2}\Delta q + L_q$$

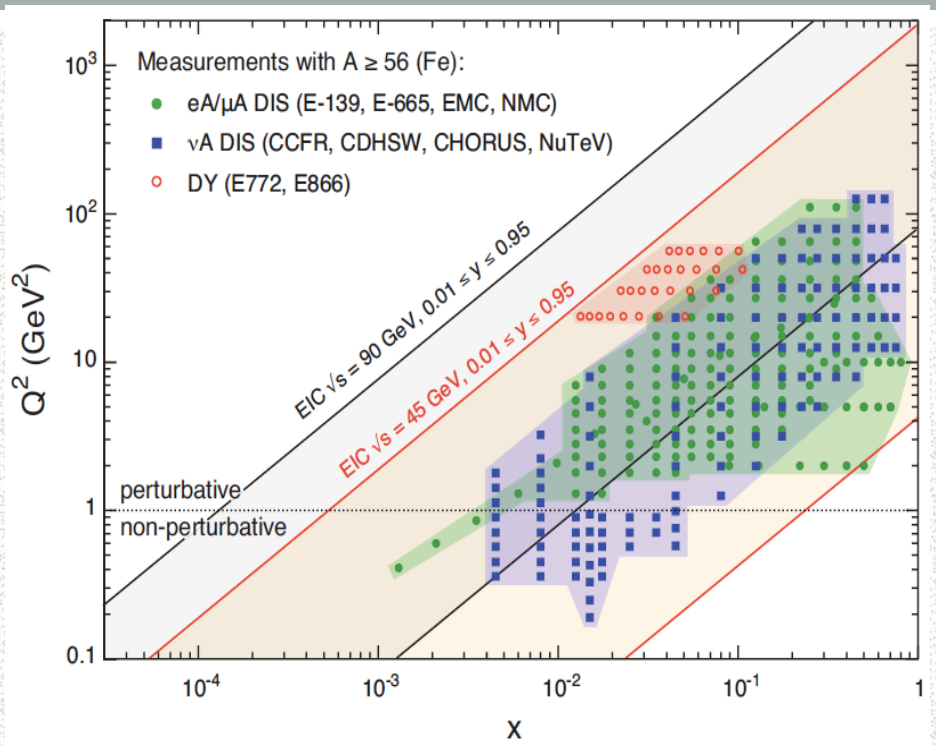
The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab 12

This could be checked by Lattice QCD

$L_u + L_d \sim 0$?



There are also more recent ideas Of calculating parton distribution functions on Lattice:
X. Ji et al. arXiv 1310.4263; 1310.7471; 1402.1462
& Y.-Q. Ma, J.-W. Qiu 1404.6860



Nucleus: A laboratory for QCD

What do we know about the gluons in nuclei? Very little!

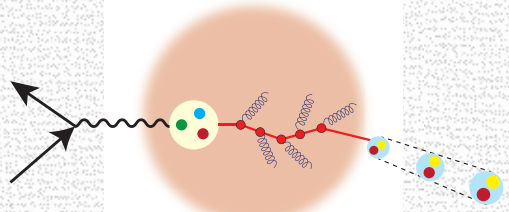
Parton propagation and interaction in nuclei (vs. protons)

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

Hadronization & Energy Loss in cold QCD matter

How hadrons emerge from quarks and gluons?

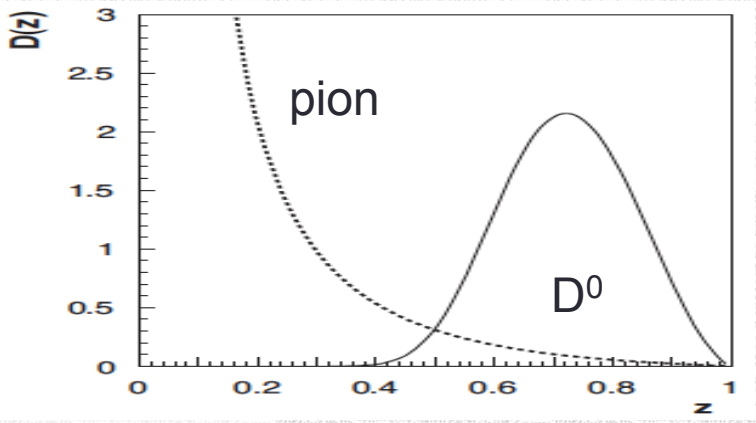
- **Unprecedented** ν range at EIC:

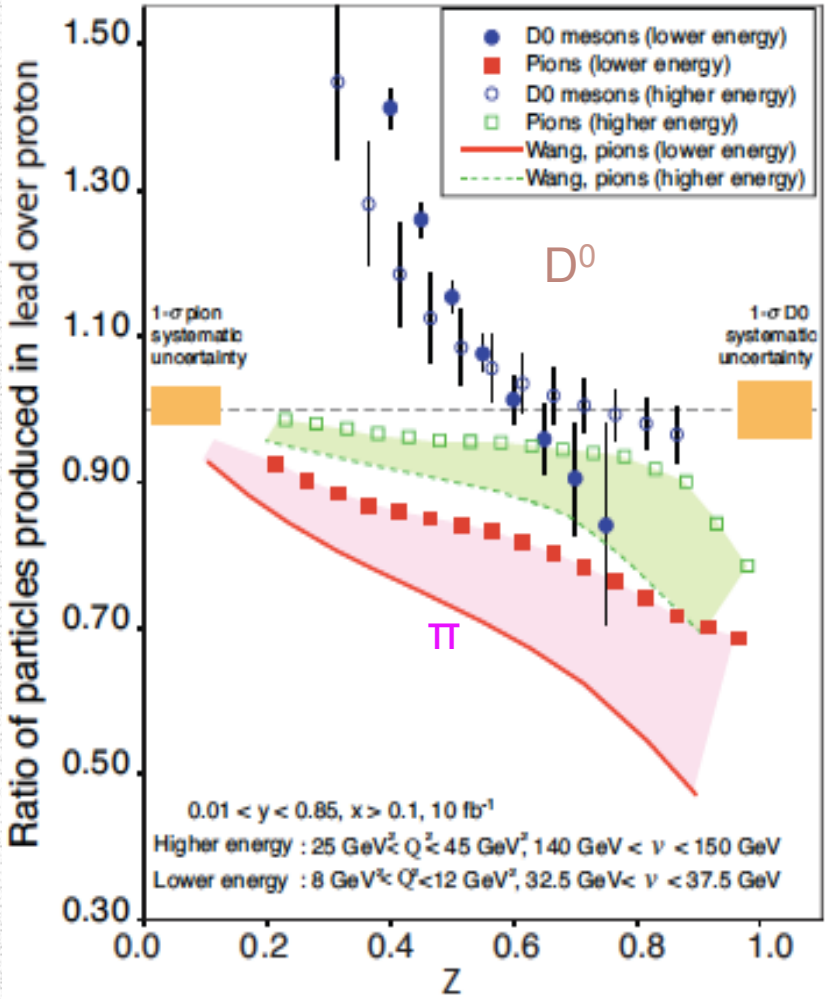


$$\nu = \frac{Q^2}{2mx}$$

Control of ν and length in the Medium

- Heavy quark energy loss:
  - Mass dependence of fragmentation

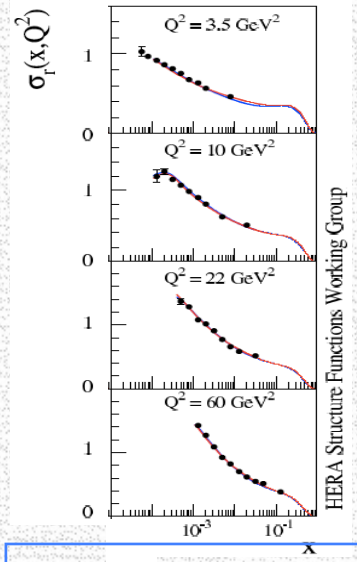




Need the collider energy of EIC and its control on parton kinematics

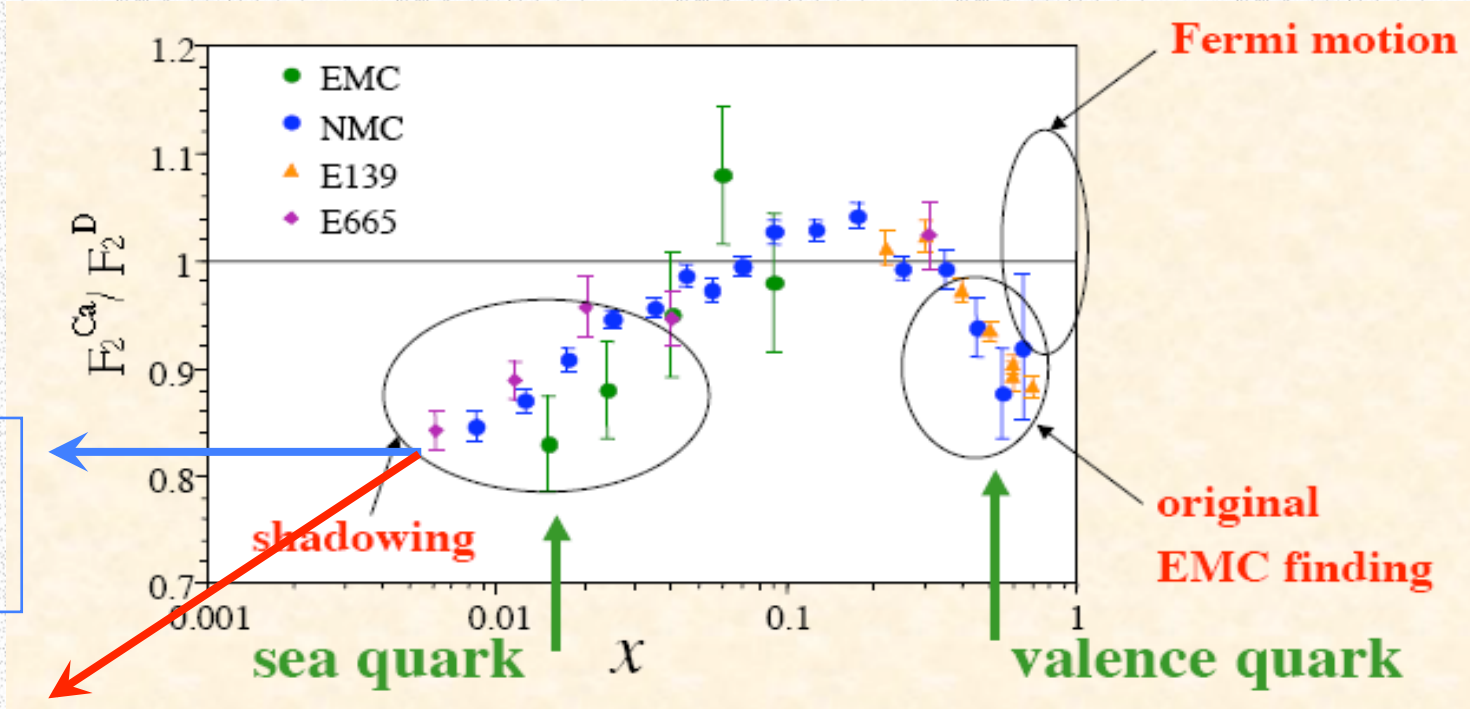
Stony

Nuclear Landscape: What do we know at low x?



Saturation in R_{F2}
≠
Saturation in F_2

- EMC effect, Shadowing and Saturation:



Saturation in $F_2(A) = R_{F2}$ decreases until saturation in $F_2(D)$

- Questions:

Is (if so why is) nuclear structure function suppressed at small x?

Will the suppression continue fall as x decreases?

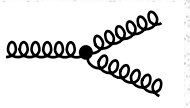
Range of color correlation – could impact the center of neutron stars!

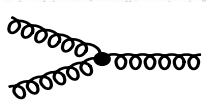
Exploring a new phase of matter:

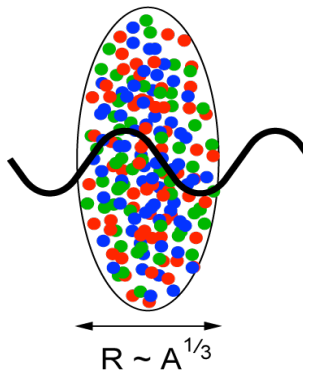
Probe the ***NUCLEI*** with the:
Electron Ion Collider (EIC)

Probe high gluonic density matter, find what "Q_s" is!

Balance between



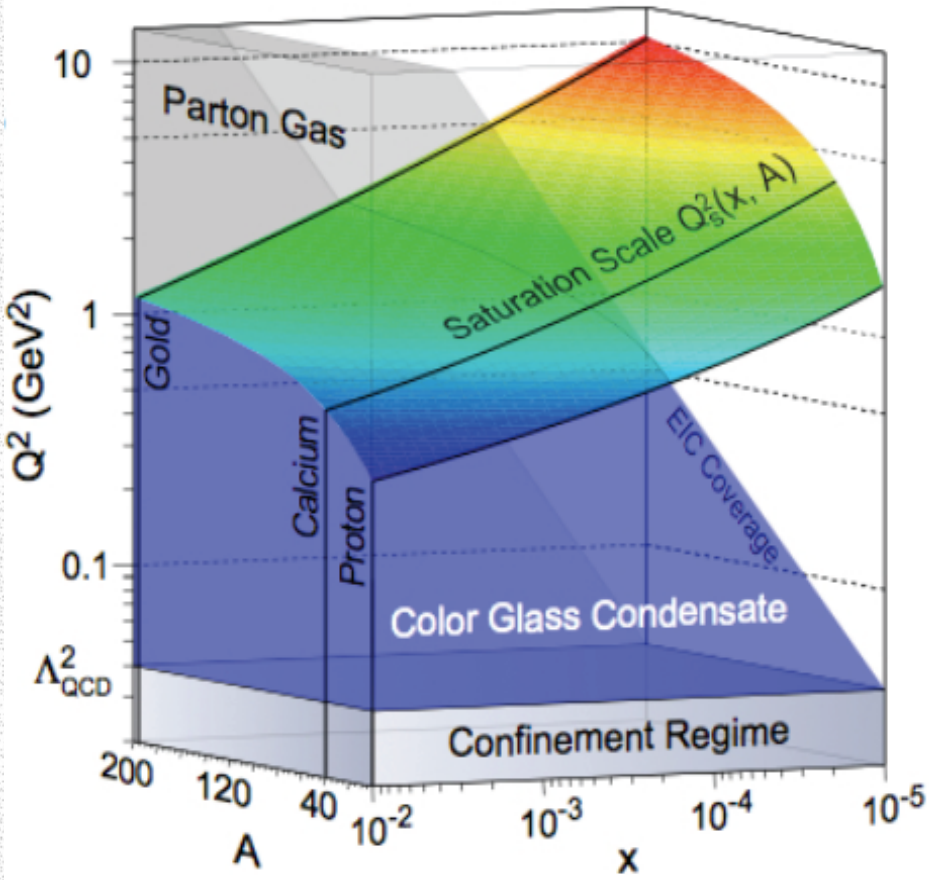




Kowalski, Teany
PRD 68:114005

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

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



Enhancement of Q_S with A, not energy

Saturation/CGC: What to measure?

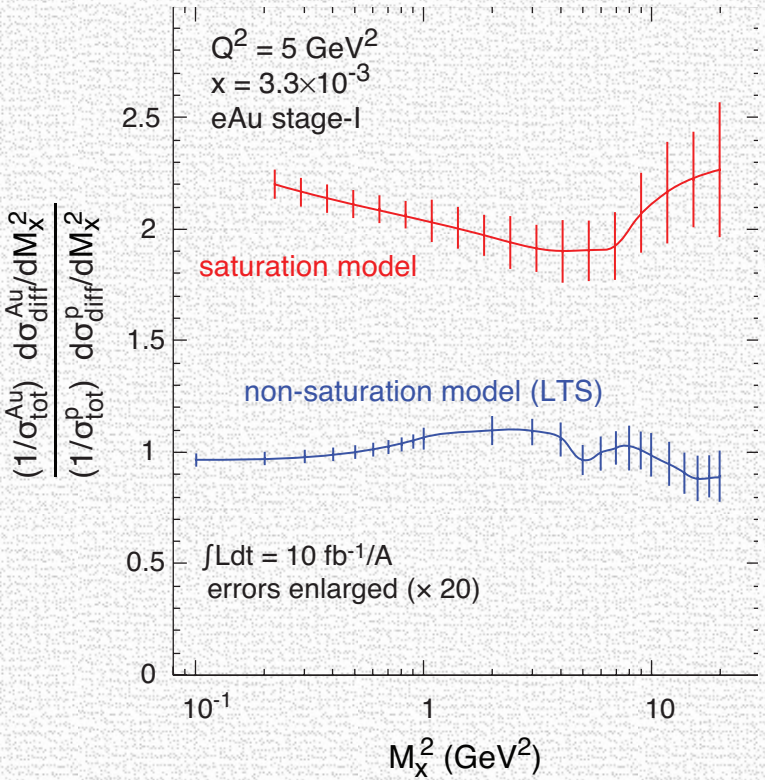
- F_2 (quark+ antiquark) & F_L(gluons) at low x (classic inclusive measurement)
  - $$g(x,Q^2) \propto \frac{\delta F_2}{\delta \ln Q^2} \qquad F_L(x,Q^2) \propto g(x,Q^2)$$
  - F_L requires change in the center of mass energy in operation of collider

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



Experimental challenges in diffractive measurements drive the detector and IR design.

Physics Beyond The SM, Through Precision PV Measurements

Next generation SOLID/PVDIS Experiment at JLab12

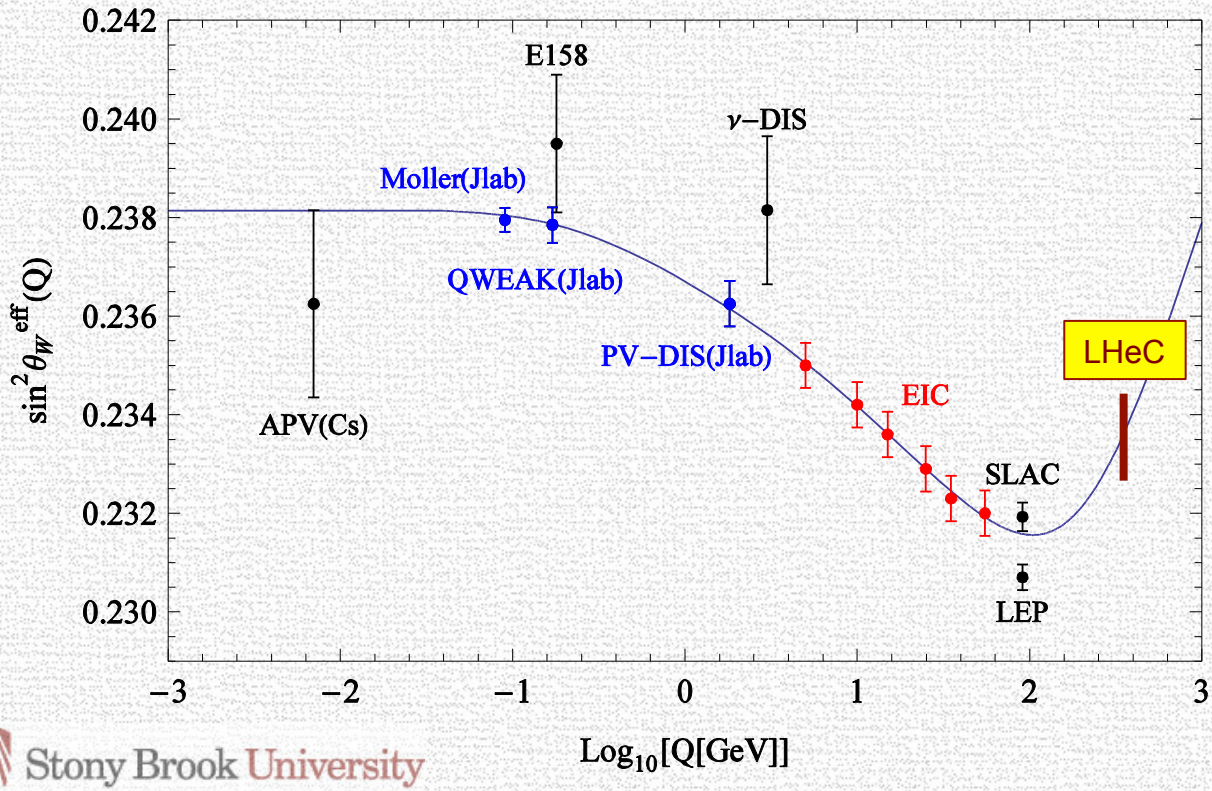
Will need the highest possible luminosity for the collider & a great control of systematics… will have to be learnt.

-- $Sin^2\Theta_W$

-- Searches of leptoquarks and other such exotics

$Sin^2\Theta_W$ 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

Maroon: LHeC Projection

Accelerator/Detector R&D & Collaboration

- **Accelerator R&D:** Significant level of activity since 2008
- Detector designs ideas being developed: @BNL & @Jlab
  - BNL ALD asked to evaluate the feasibilities with ePHENIX and eSTAR
  - Studies of MEIC detector & IR lay out ongoing at Jefferson Lab

NEW since 2010:

- Detector R&D supported by DOE through BNL (Dr. T. Ullrich)
  - 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 July 2014]
- Collaborative groups formed across the US Universities and some European & Asian institutions: Tracking, PID, Calorimetry R&D proposals

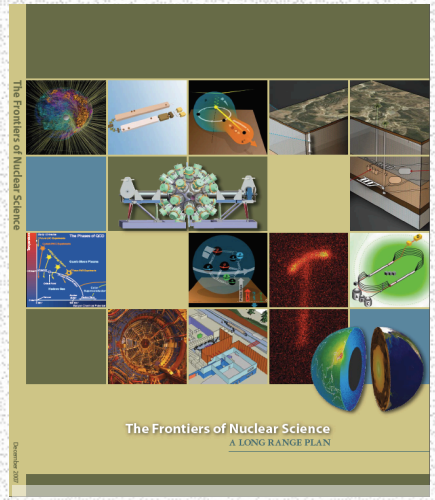
Invitation: NEXT EIC Users Meeting at Stony Brook University, June 23-27, 2014. All are welcome to attend and participate!

http://skipper.physics.sunysb.edu/~eicug/meetings/SBU.html

Evolving status of EIC in the US:

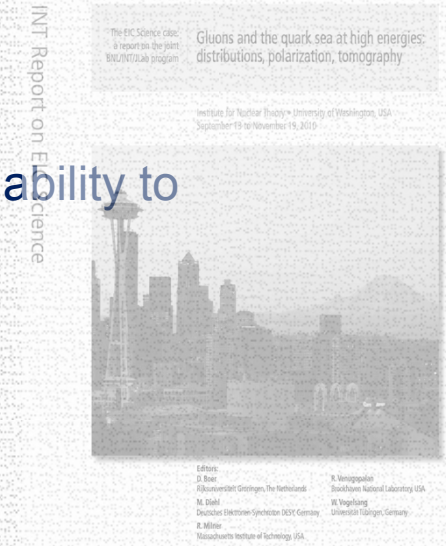
❑ NSAC 2007 Long-Range Plan:

"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."



❑ NSAC Facilities Subcommittee (2013):

The Subcommittee ranks an EIC as **Absolutely Central** in its ability to contribute to world-leading science in the next decade."



❑ NSAC NEXT Long-Range Process:

Officially started! Final report due on October 15, 2015

EIC needs to be a high recommendation in this report!

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

It will lead to a 2+1 D view of nucleons and nuclei: Color distributions! And study the transition from low to high density QCD matter

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

- *Precision studies of the role of sea quarks and gluons in QCD*
- Precision always leads to discoveries…

Development of the Standard model needed: **p-p/p-bar, e-e, e-p** collisions
→**complimentary** but **essential** role

- **EIC's** will add "**spin**" and "**nuclei**" to this list: A-A, p/d-A, **e-A**

Currently two designs: JLab & BNL both use upgrades of existing facilities**.**

Next milestones for US EIC: Long Range Plan of the NSAC 2014/5 for support & approval by the US NP community. ***Its critical that both JLab and RHIC user communities work closely together with our international collaborators to get this through the LRP.***

World Wide Interest in the EIC

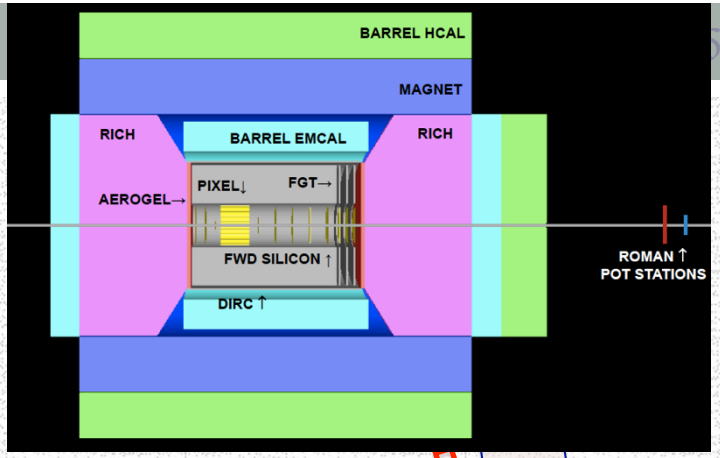
	HERA@DESY	LHeC@CERN	eRHIC@BNL	MEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
L [$cm^{-2}\ s^{-1}$]	2×10^{31}	10^{33}	10^{33-34}	10^{33-34}	$10^{32-33} \rightarrow 10^{35}$	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2022 (?)	2025	Post-12 GeV (2025)	2019 → 2030	upgrade to FAIR

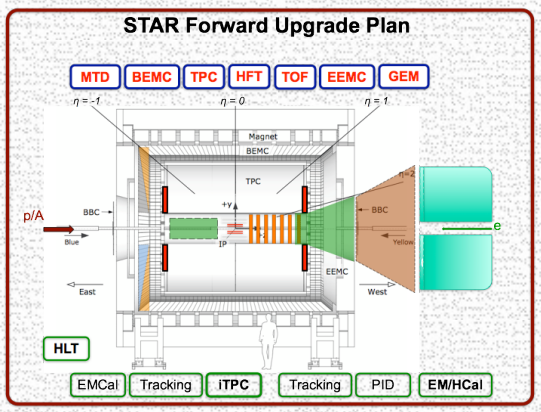
High Energy

Medium Energy

Low Energy

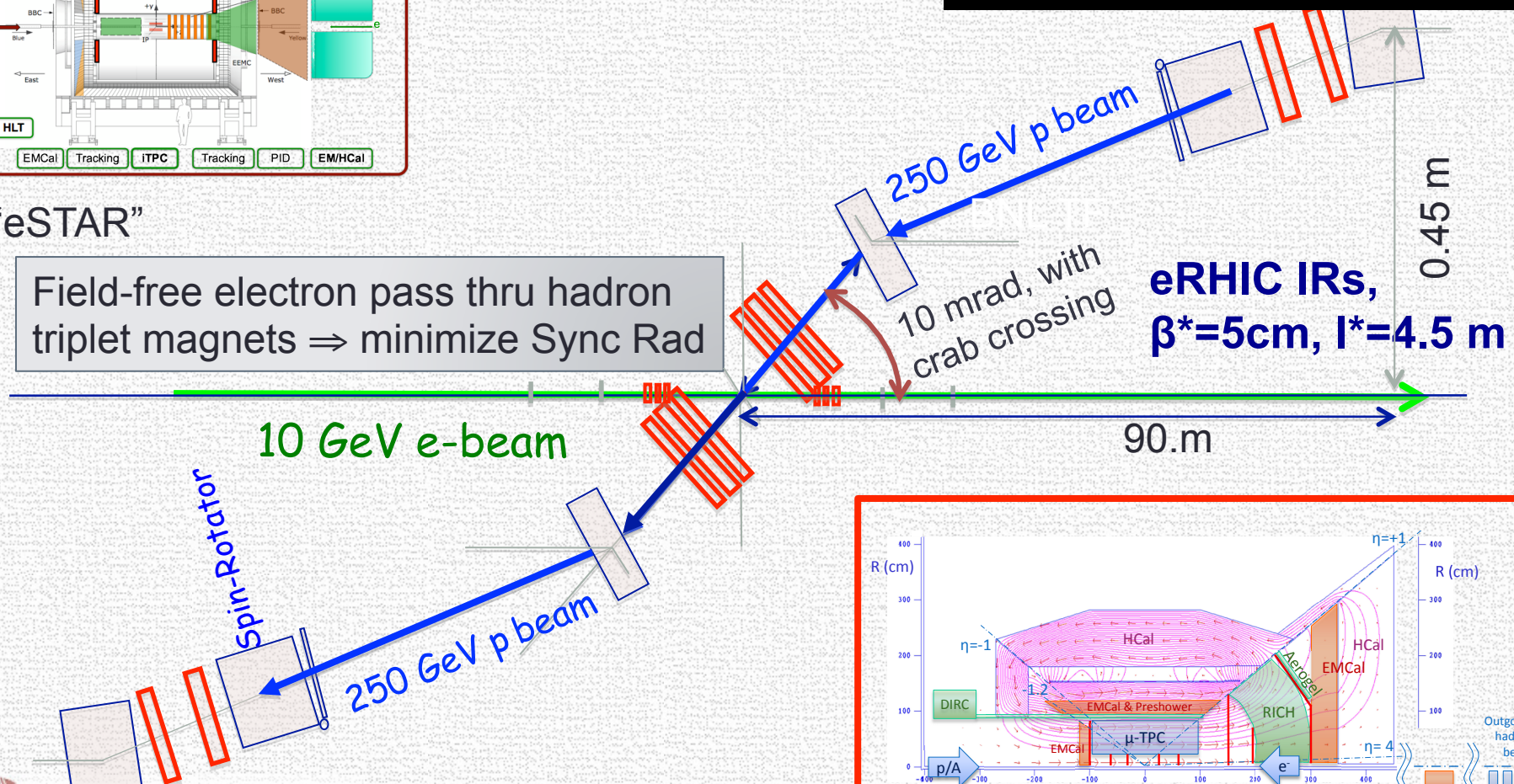
EIC Detectors & IR

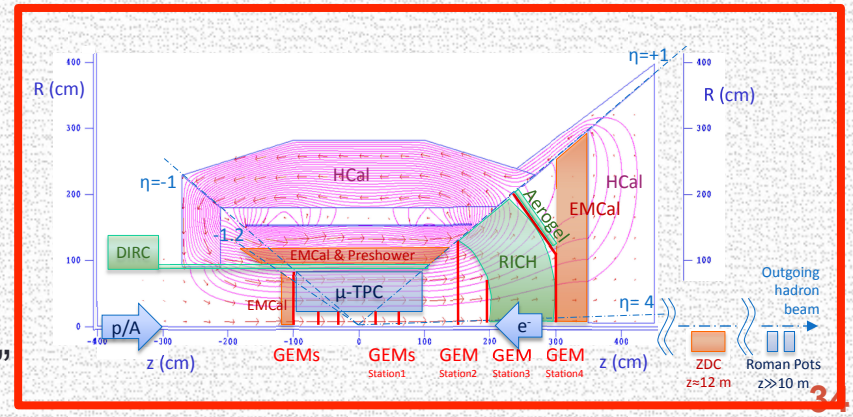




"eSTAR"

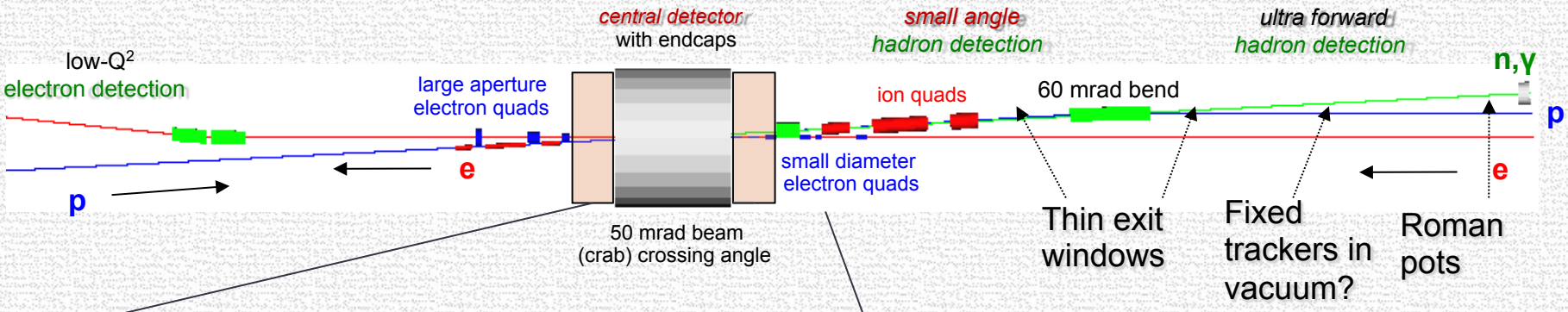
Field-free electron pass thru hadron triplet magnets ⇒ minimize Sync Rad

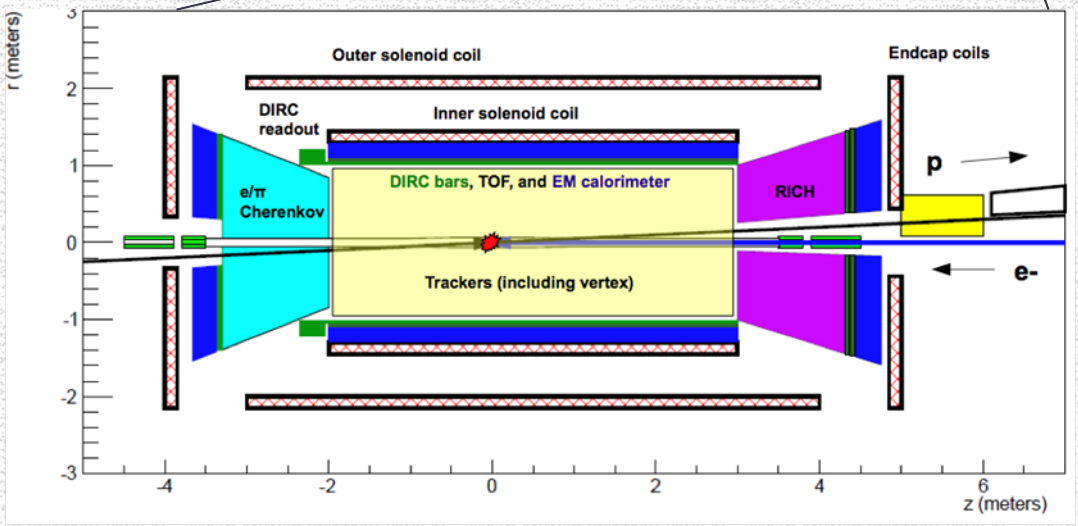




"ePHENIX"

EIC at JLab: Integrated IR & Detector

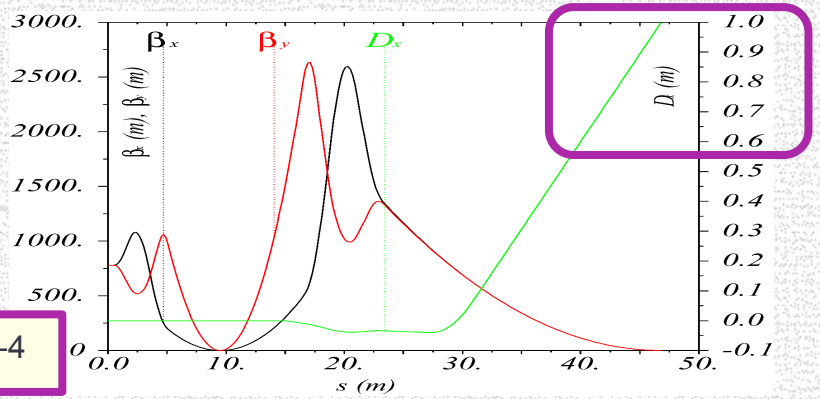




Cartoon of central detector based on dual solenoid a la ILC4 detector, but using the previous iteration interaction region design.

Hadron/Ion detection in 3 stages

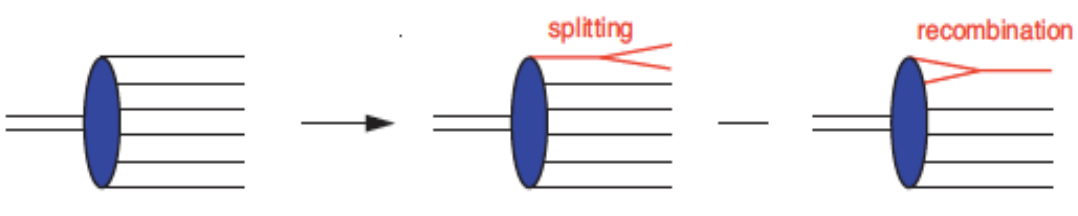
- Endcap with 50 mrad crossing angle
- Small dipole covering angles to a few degrees
- Ultra-forward up to one degree, for particles passing accelerator quads

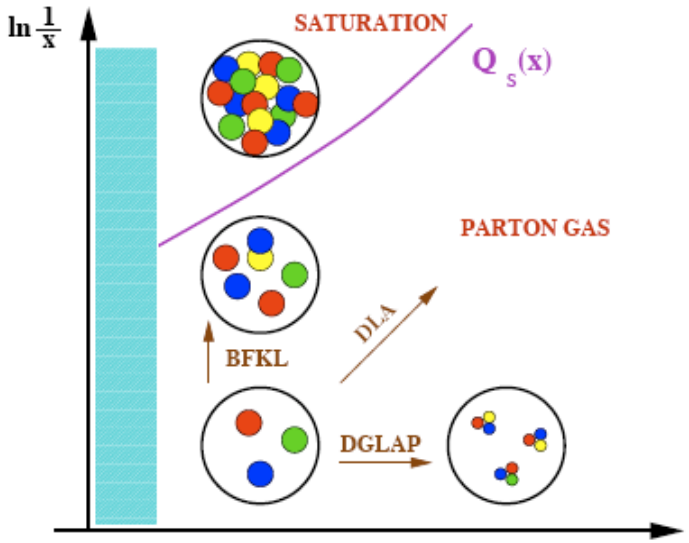


Beamline functions as spectrometer: dp/p < 3×10^{-4}

Non-linear evolution and saturation in QCD

❑ Gluon recombination:





❑ Modified DGLAP:

$$\frac{\partial}{\partial \ln Q^2} x g(x,Q^2) \approx \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dx'}{x'} x' g(x',Q^2)$$

$$- \frac{K}{Q^2 R^2} \left[\frac{\alpha_s N_c}{\pi}\right]^2 \int_x^1 \frac{dx'}{x'} [x' g(x',Q^2)]^2 + \mathcal{O}\left[\left(\frac{Q_s^2}{Q^2}\right)^2\right]$$

Power corrections

Saturation: All power correction terms are equally important

➡ Saturation scale: $Q_s^2(x) \sim \frac{\alpha_s(Q_s)}{\pi R^2} x g(x,Q_s^2) \sim \frac{1}{x^\lambda}$

Counting single parton is not effective! ➡ Scattering amplitude, Effective fields, …

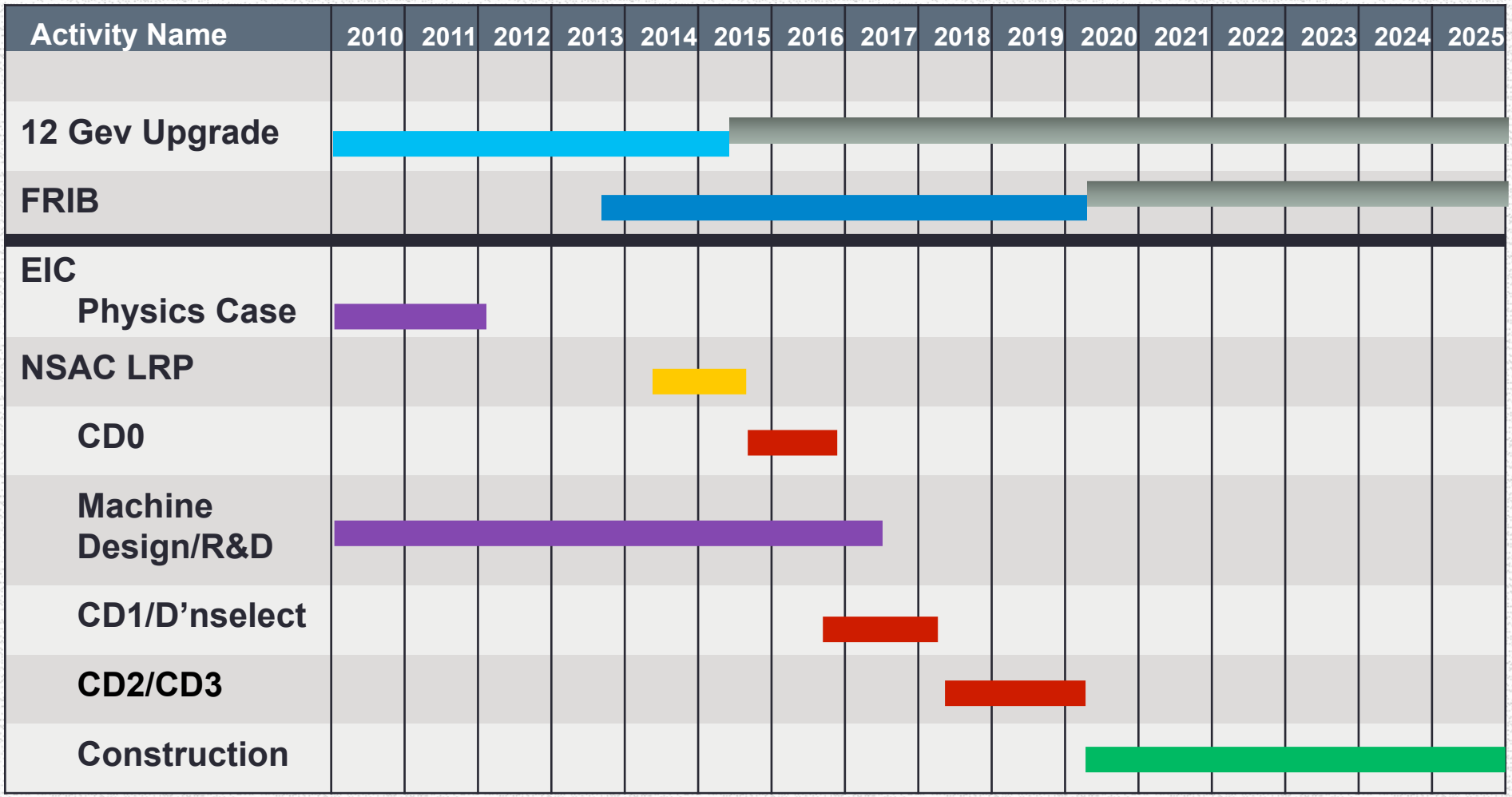
❑ Modified BFKL – BK equation:

$$\frac{\partial N(x,r_T)}{\partial \ln(1/x)} = \alpha_s K_{\rm BFKL} \otimes N(x,r_T) - \alpha_s [N(x,r_T)]^2$$

➡ *JIMWLK - equation*

EIC @ Realization Possible Time Line

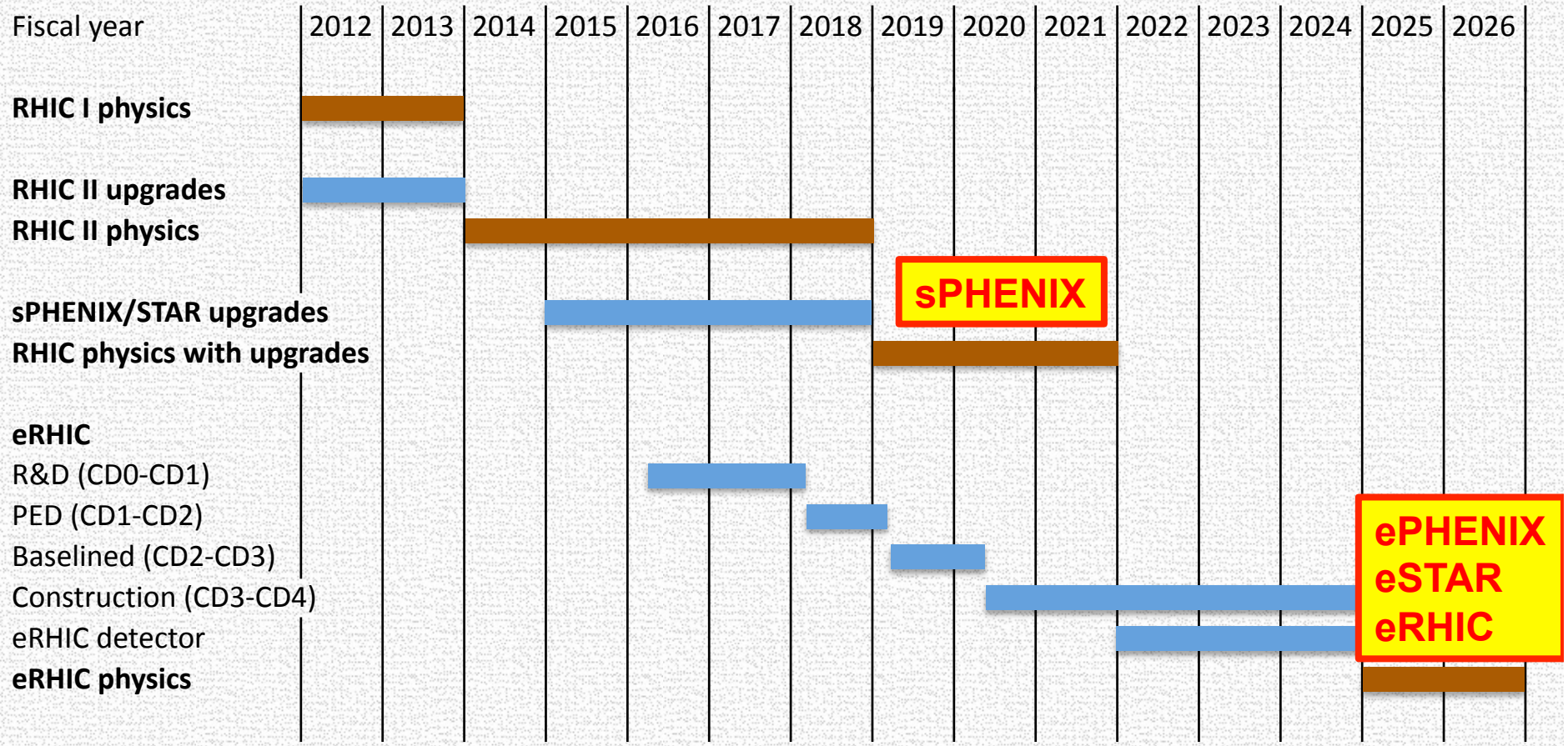
Modified by AD Based on H. Montgomery, JLab Director



Time line not too different that BNL's plan

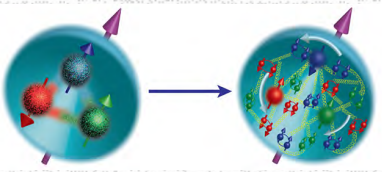
eRHIC Technically Driven Schedule

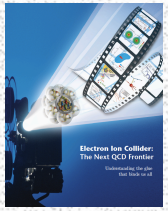
Mueller, BNL ALD



Time-line for MEIC at JLab not too different than this.

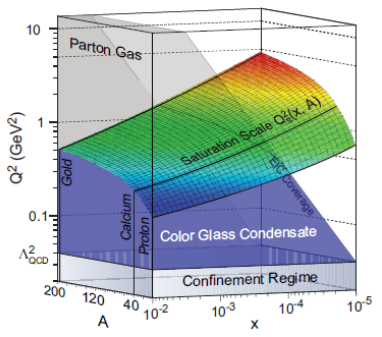
Science of EIC



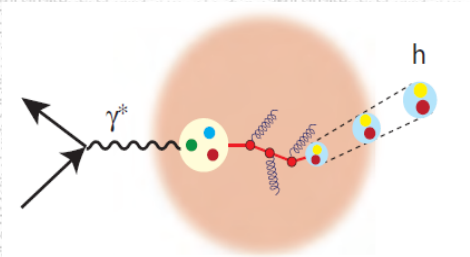


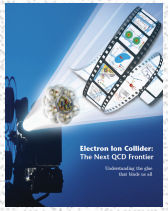
- **How are sea quarks/gluons and their spins distributed in space and momentum inside the nucleon?**
  - How are these quark and gluon distributions correlated with the over all nucleon properties, such as spin direction?
  - What is the role of the motion of sea quarks and gluons in building the nucleon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

- **Where does the saturation of gluon density 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 saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?



Science of EIC…





- **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?

- **Electro-Weak Physics and possible searches for physics beyond the SM:**
  - Precision measurement of evolution of the $Sin^2\Theta_W$
  - Precise limits on charged lepton flavor violation ($e \rightarrow \tau$) transition(?)

Will need the highest energy and luminosity of the collider.