Questions in Hadron Physics

The future: Electron Ion Collider (EIC)

July 4, 2014

Paris, France

Lecture 2 B

Stony Brook University

Abhay Deshpande

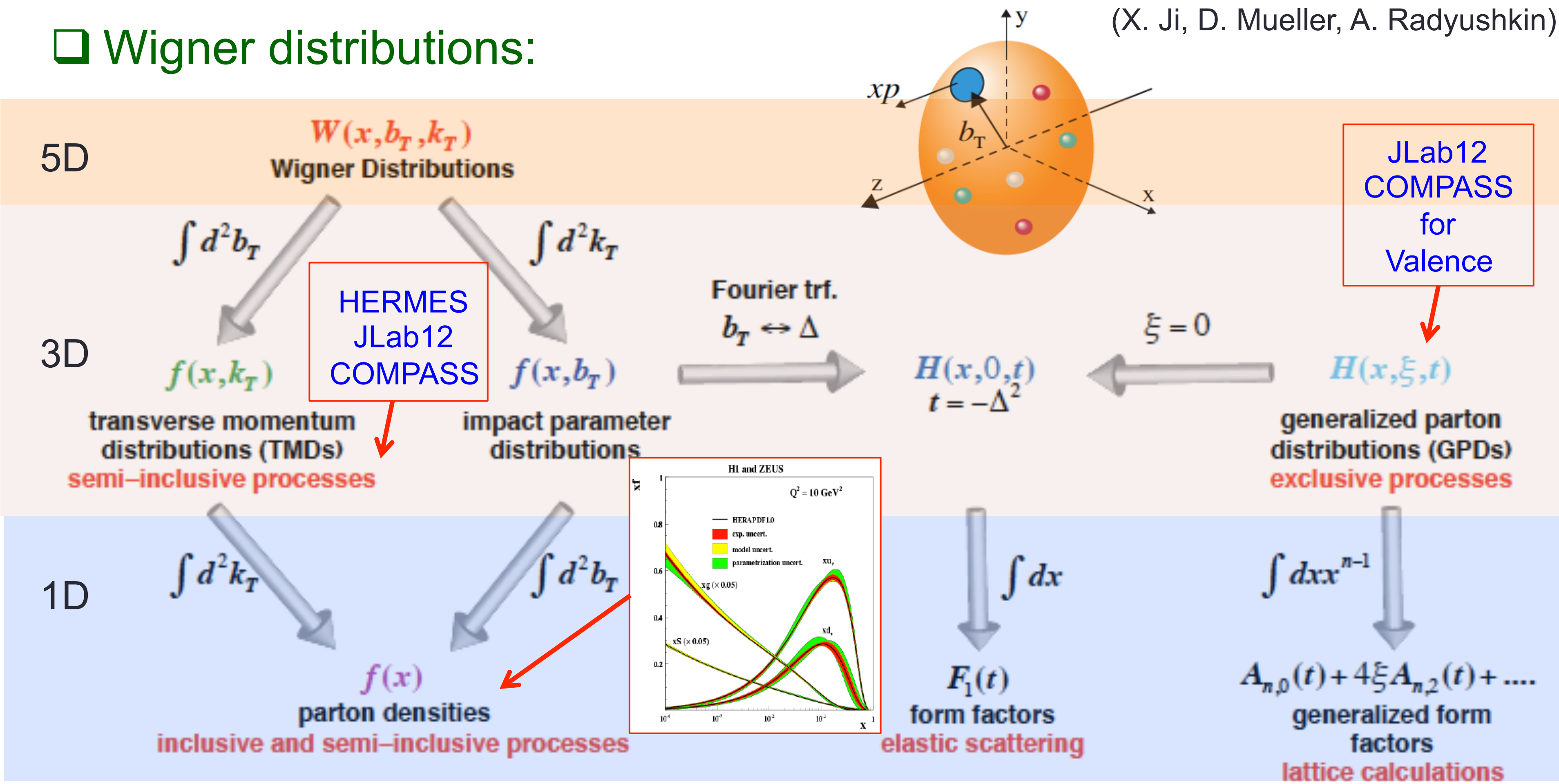
But a more complete picture of the nucleon structure including its spin has emerged over ….

Aided by theoretical developments & data from fixed target polarized DIS at COMPASS & JLab and p-p at RHIC experiments

We aspire to complete this unified picture of the nucleon structure and the parton dynamics

Unified view of the Nucleon Structure

❑ Wigner distributions:



❑ EIC – 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)

Why a collider?

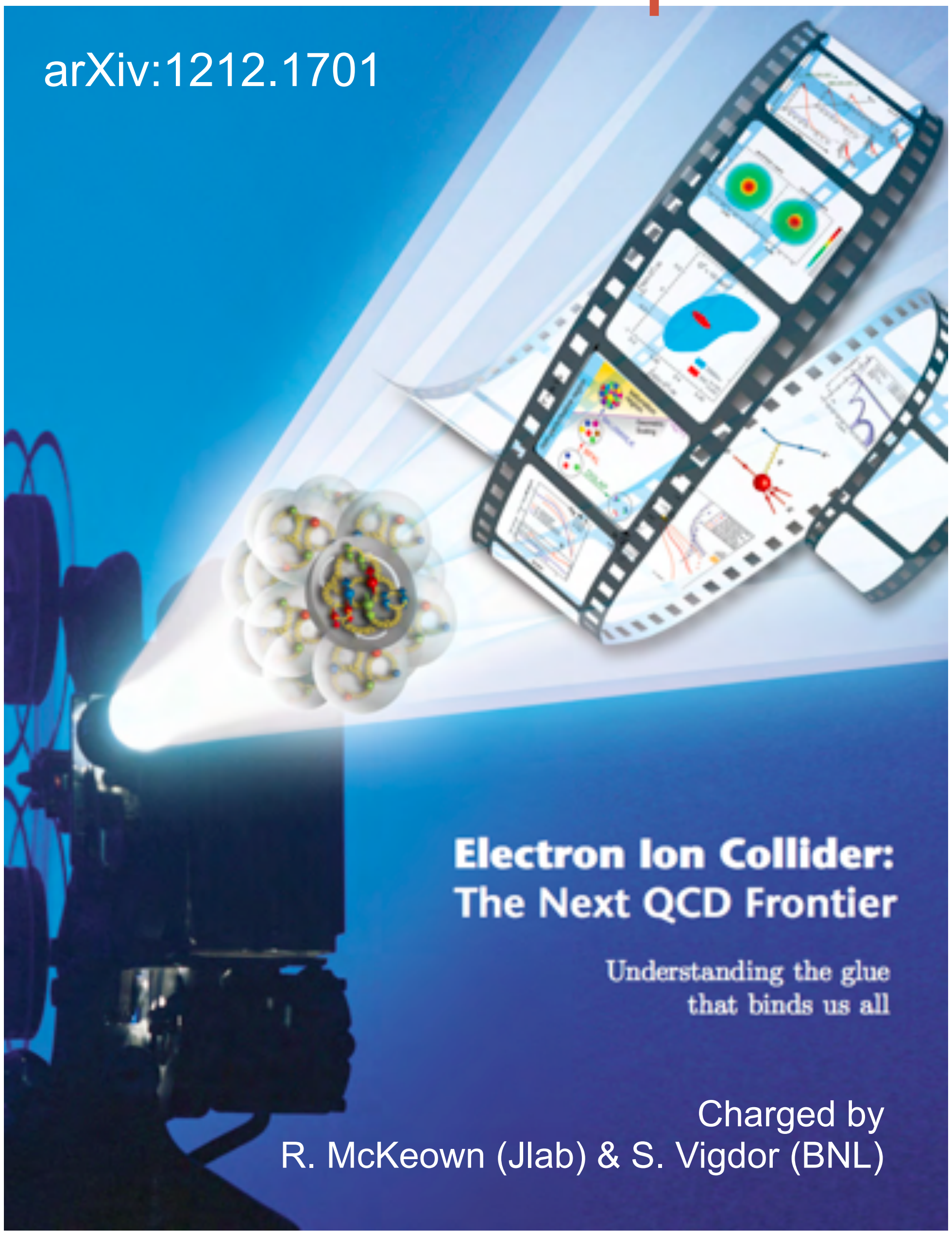
- A collider brings a very wide kinematic range in the observables in their measurable coordinates

- A high energy collider brings access to low-x and high Q^2
  - Low x ➔ largest uncertainties since no spin measurements there
  - Large Q^2 ➔ large arms to see and test Q^2 evolution in variables

- Compared to solid state fixed target experiments, the target and beam fragments in a collisions fly in different directions

- Rapid “target” and “beam” spin “flips” helps brings experimental systematics under control

White Paper: EIC Science Case



Overall Editors:
A. Deshpande (Stony Brook), Z-E. Meziani (Temple), J. Qiu (BNL)

Gluon Saturation in e+A:
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:
W. Brooks (TSFM) and J. Qiu(BNL)

Electroweak physics:
K. Kumar (U Mass) and M. Ramsey-Musolf (Wisconsin)

Accelerator design and challenges:
A. Hutton (JLab) and T. Roser (BNL)

Detector design and challenges:
E. Aschenauer (BNL) and T. Horn (CUA)

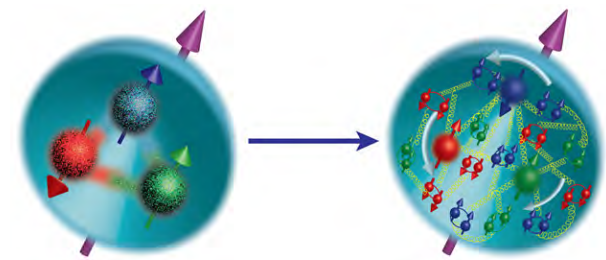
Senior Advisors:
A. Mueller (Columbia) and R. Holt (ANL)

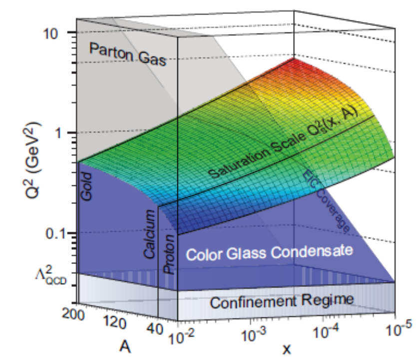
Successful thanks to many other co-authors and contributions

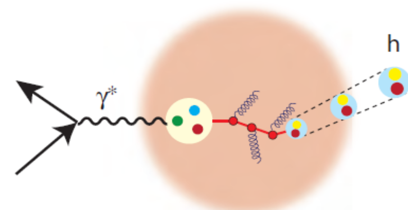
EIC – The Physics Highlights

- **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

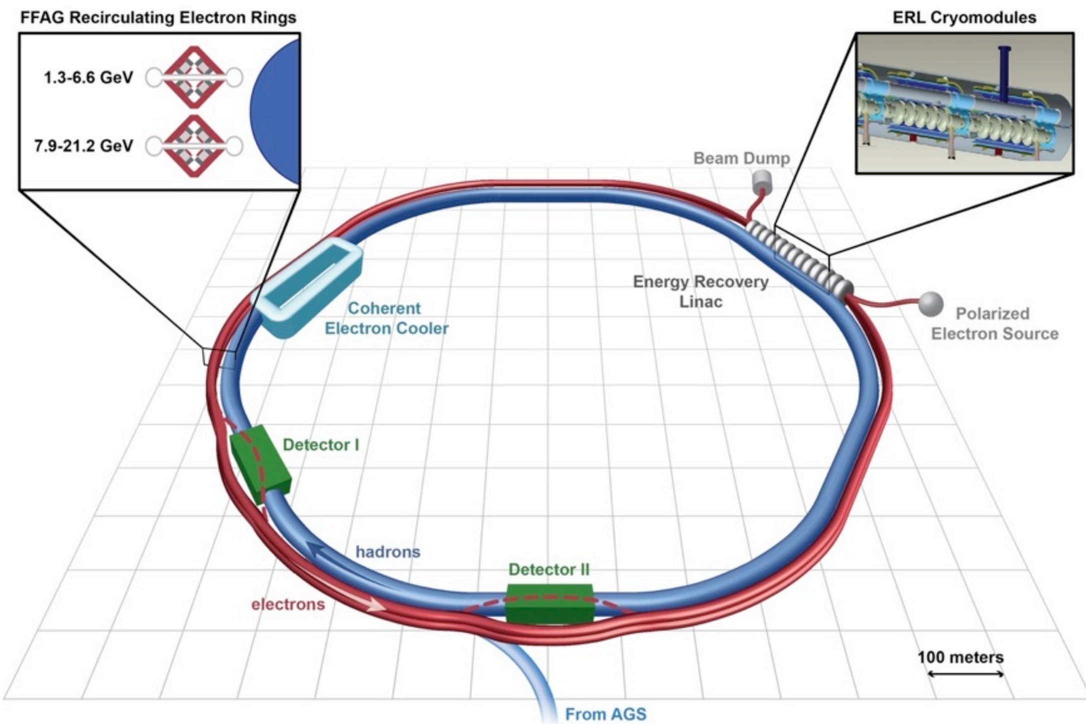




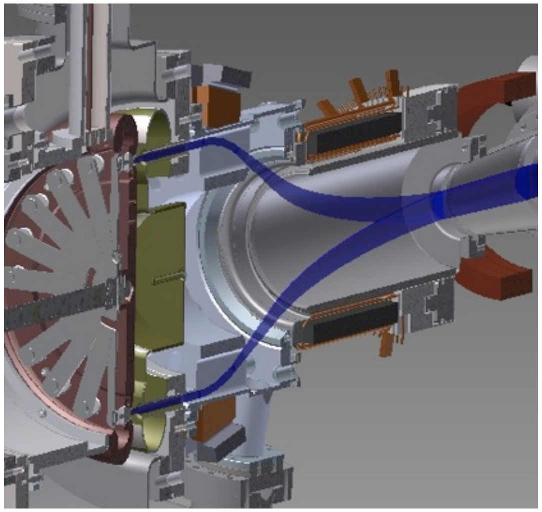


eRHIC Machine Design

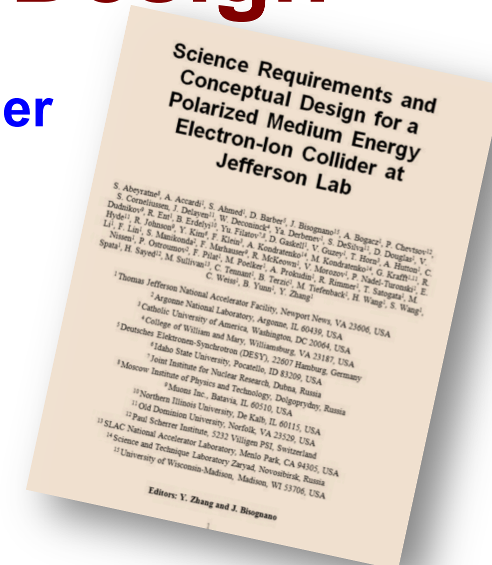
- ✓ Up to 21.2 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside the RHIC tunnel collides with existing 250 GeV polarized protons and 100 GeV/n HI RHIC beams
- ✓ ERL with 1.32 GeV SRF Linac and two FFAG recirculating rings (1.33 – 6.62 GeV; 7.94 – 21.16 GeV) allow for full luminosity (> 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


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

Editors: Y. Zhang and J. Bisognano

- **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**

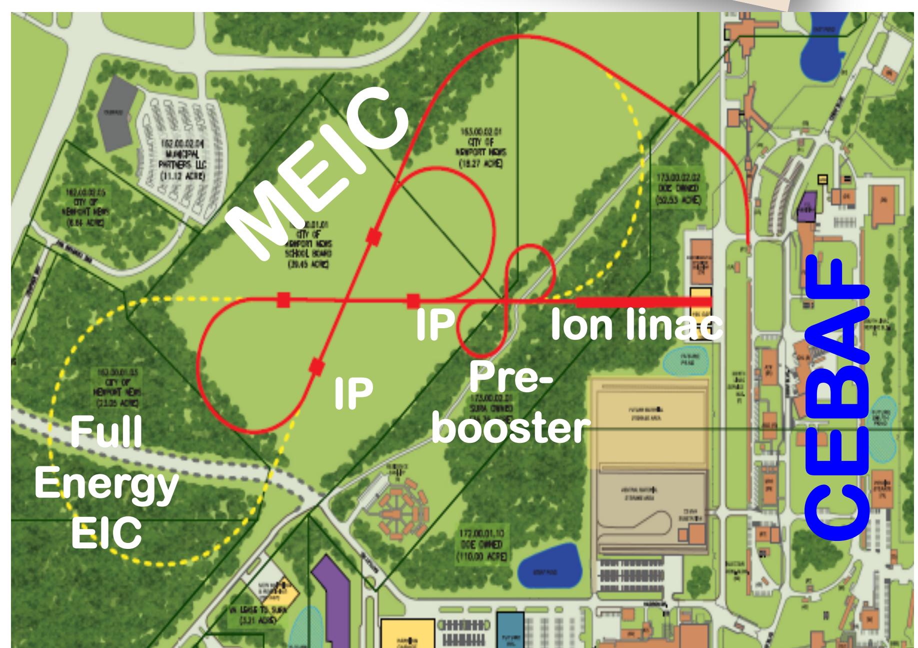
  1) cooling studies – evolutionary approach

  2) dynamical aperture – 1st order o.k.

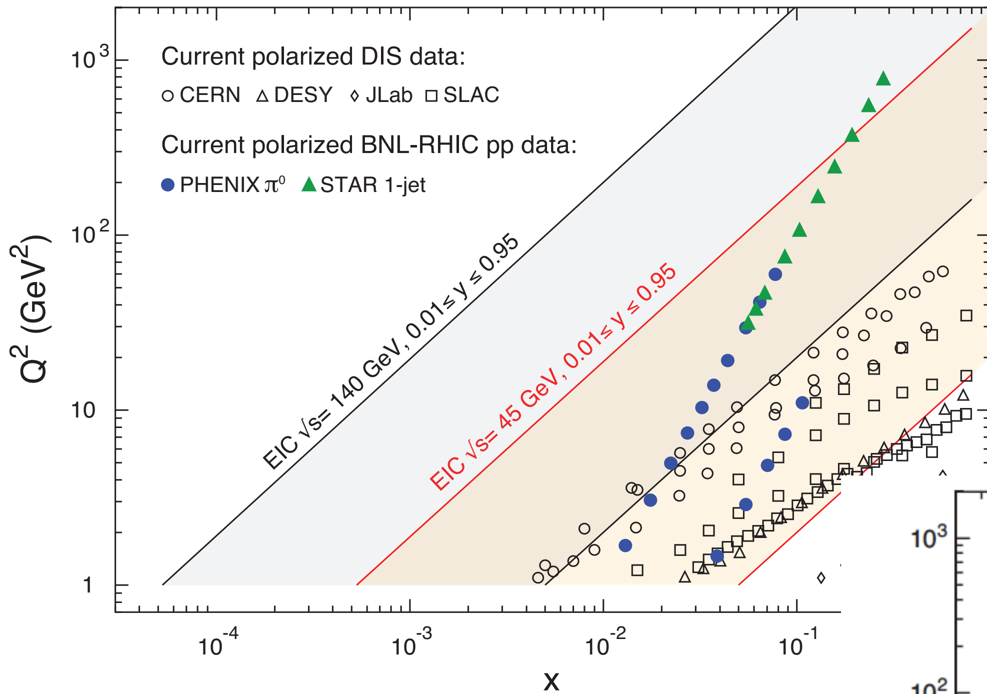
  3) polarization – tracking & optimization

  4) collective beam effects – deemed o.k.

Will add sections on cooling and polarization to existing design report

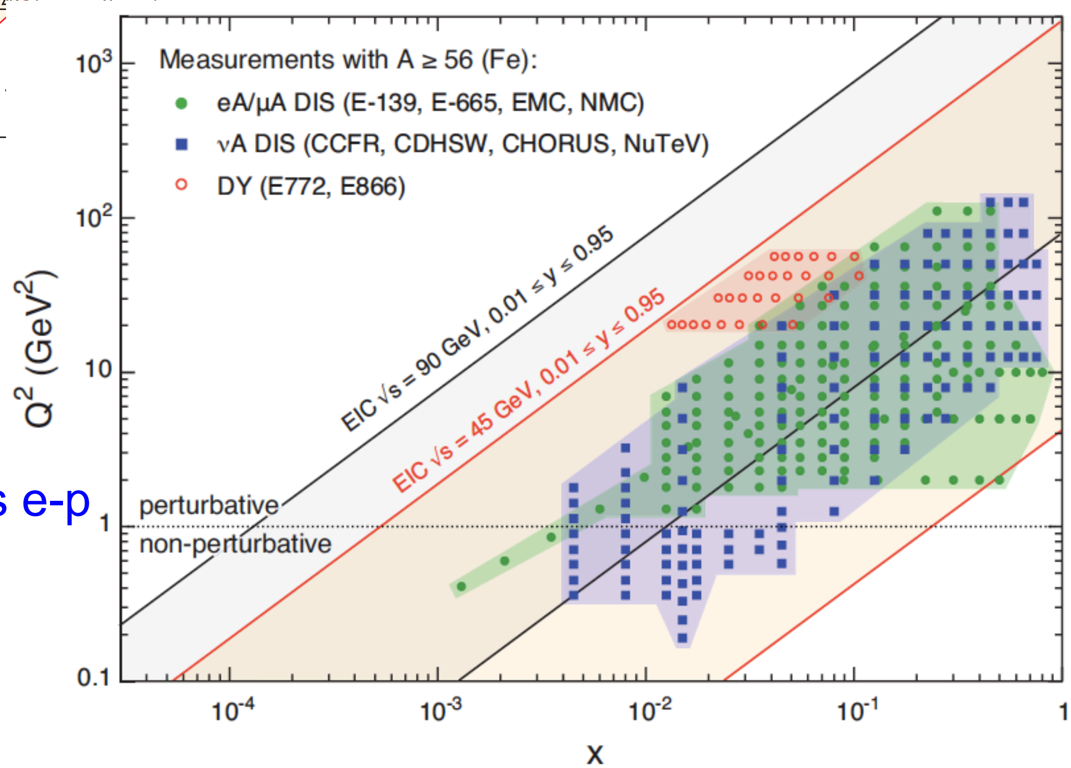


US EIC: Kinematic reach & properties



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



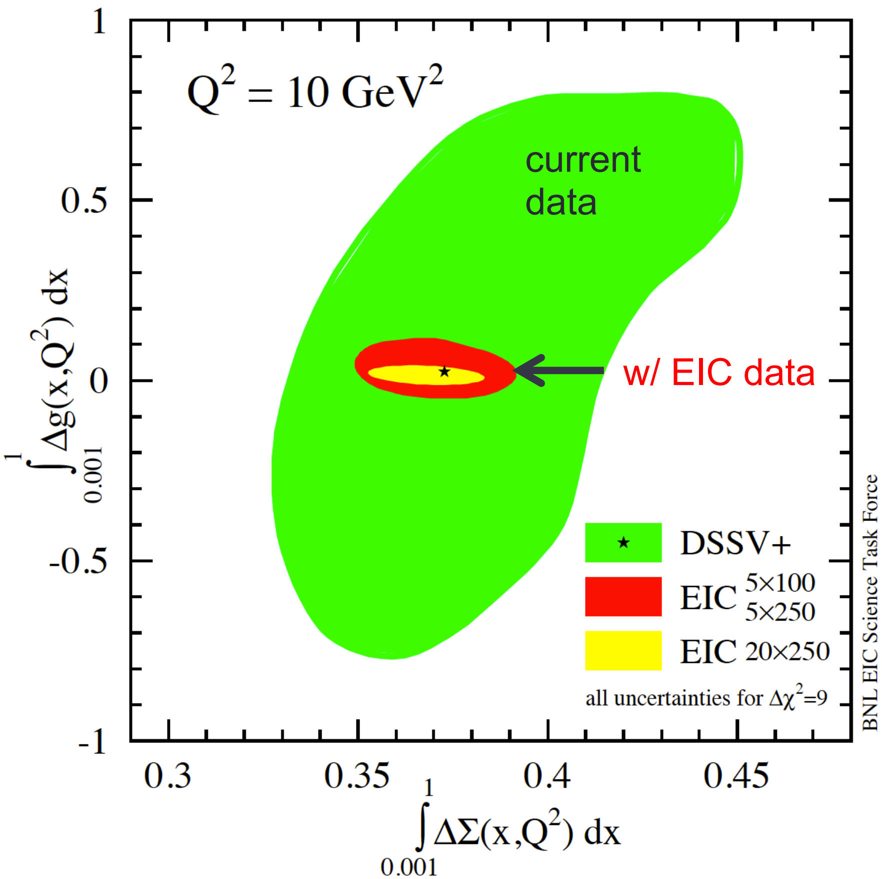
For e-A collisions at the EIC:

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

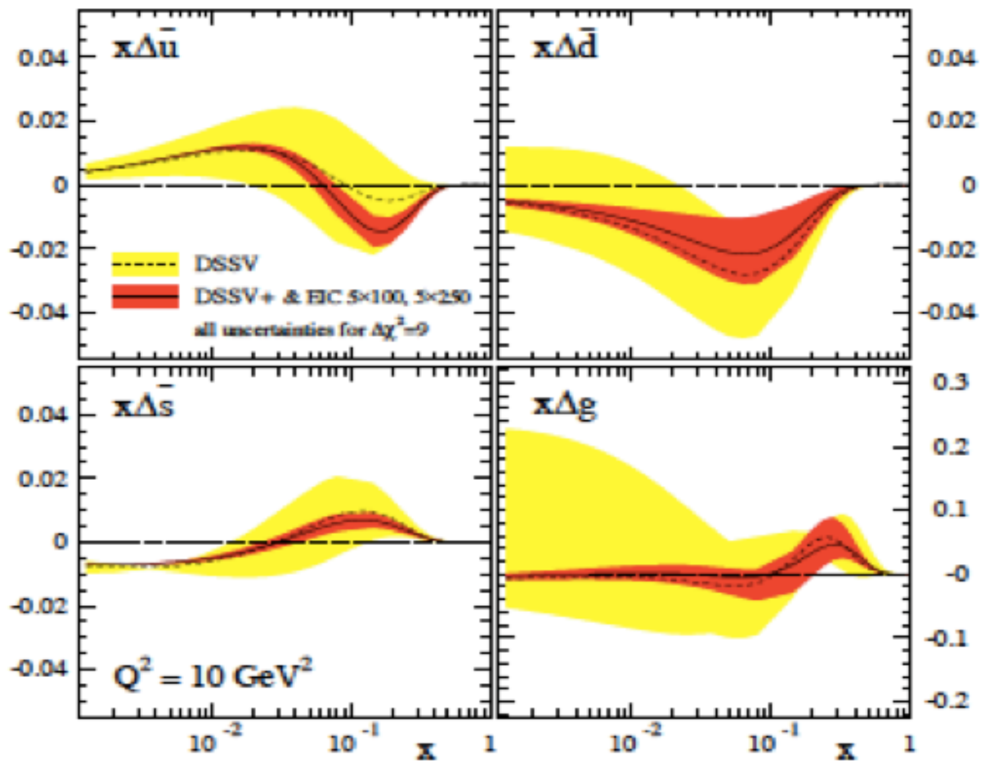
Precision: Gluon & Sea Quark *polarization:*

--Beyond the current experimental capabilities!

ΔG and ΔΣ in helicity sum

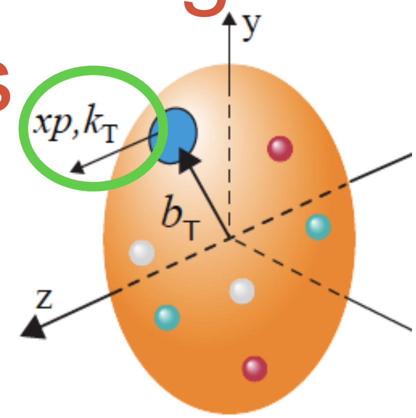


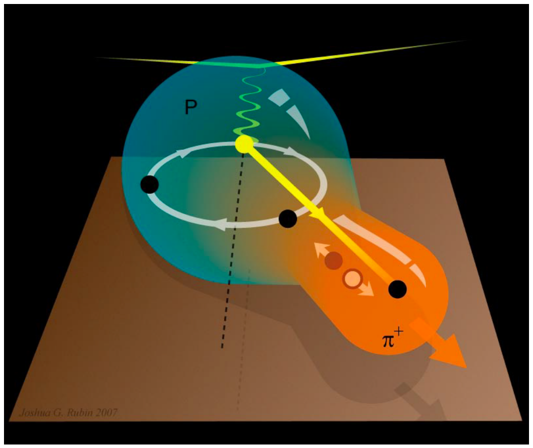
Are the sea quark polarizations different?



EIC White Paper: arXive:1212.1701

Semi-Inclusive DIS → Best for measuring Transverse Momentum Distributions





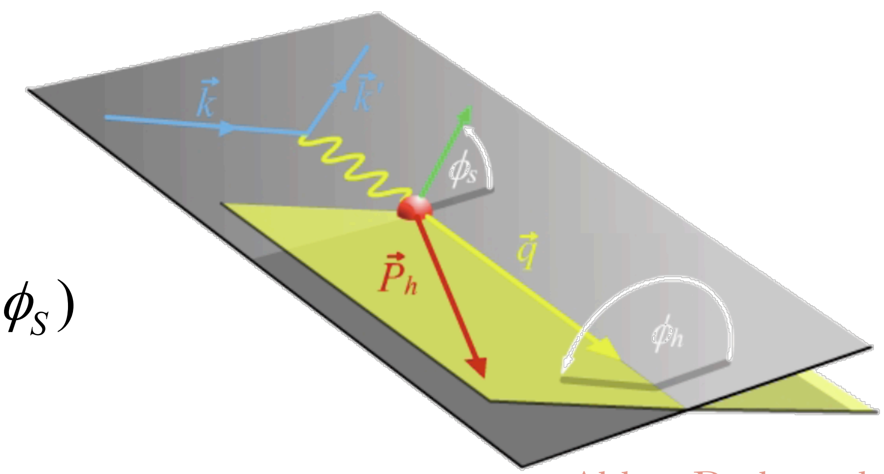
- Naturally, two scales:
  - ✧ high Q – localized probe
    To "see" quarks and gluons
  - ✧ Low p_T – sensitive to confining scale
    To "see" their confined motion
  - ✧ *Theory – QCD TMD factorization*

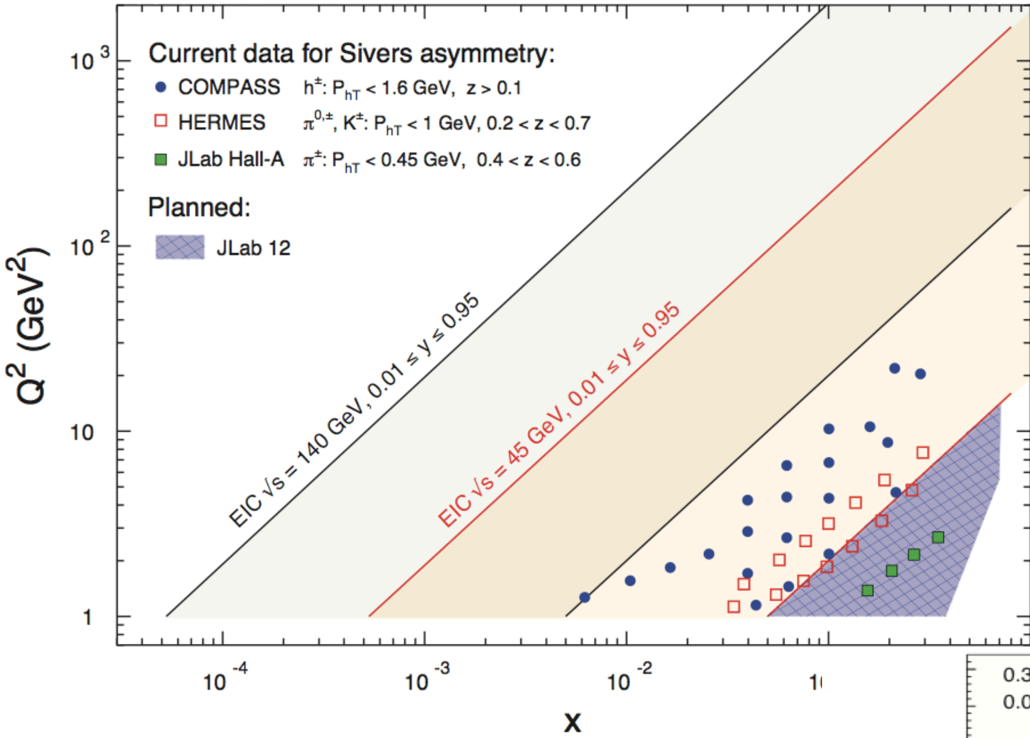
- Naturally, two planes:

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

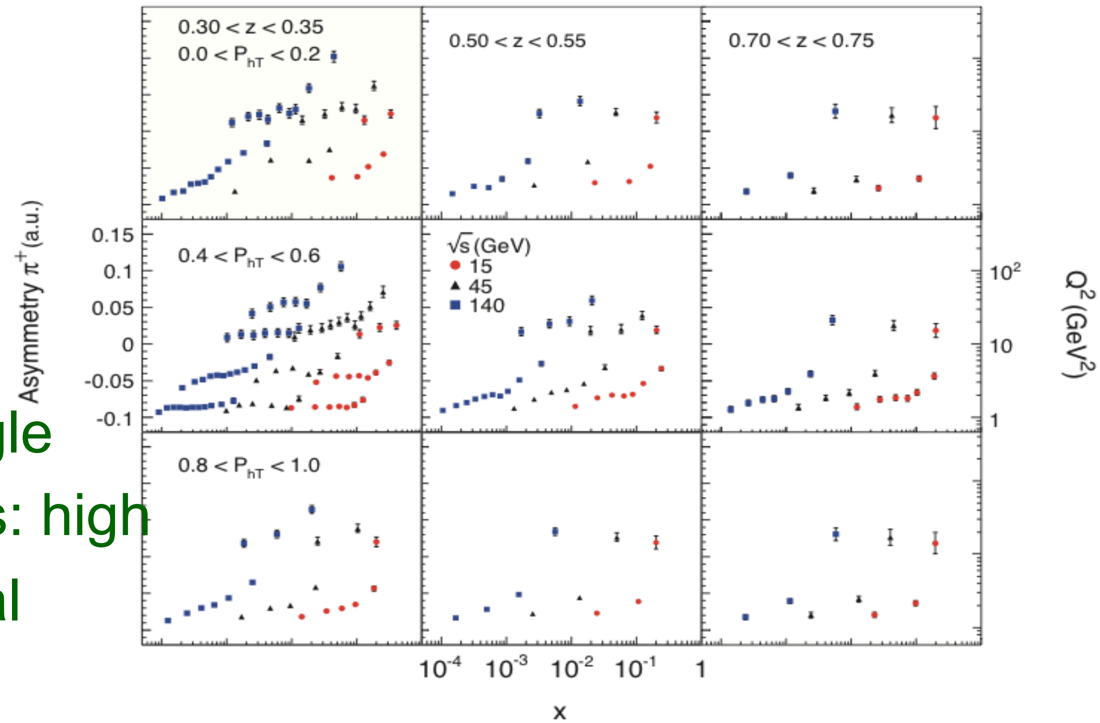
$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

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





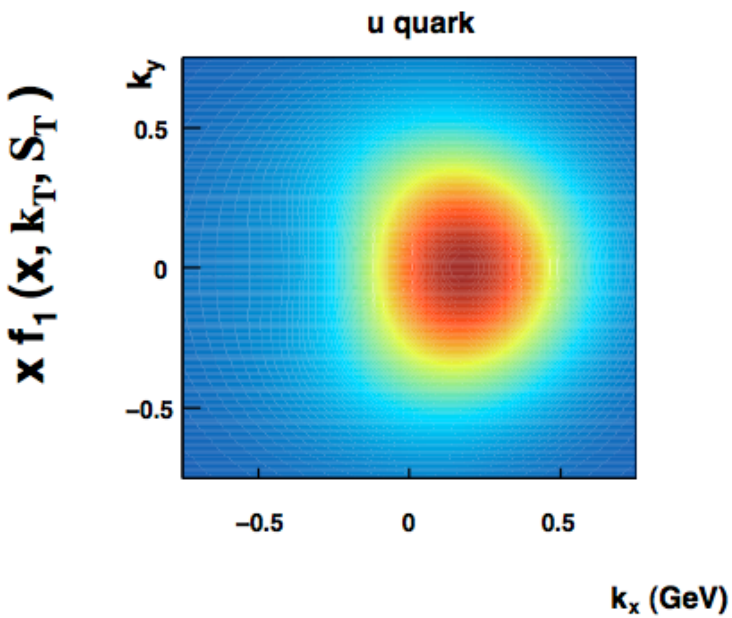
First, maybe the only, measurement of polarized sea and gluon TMDs

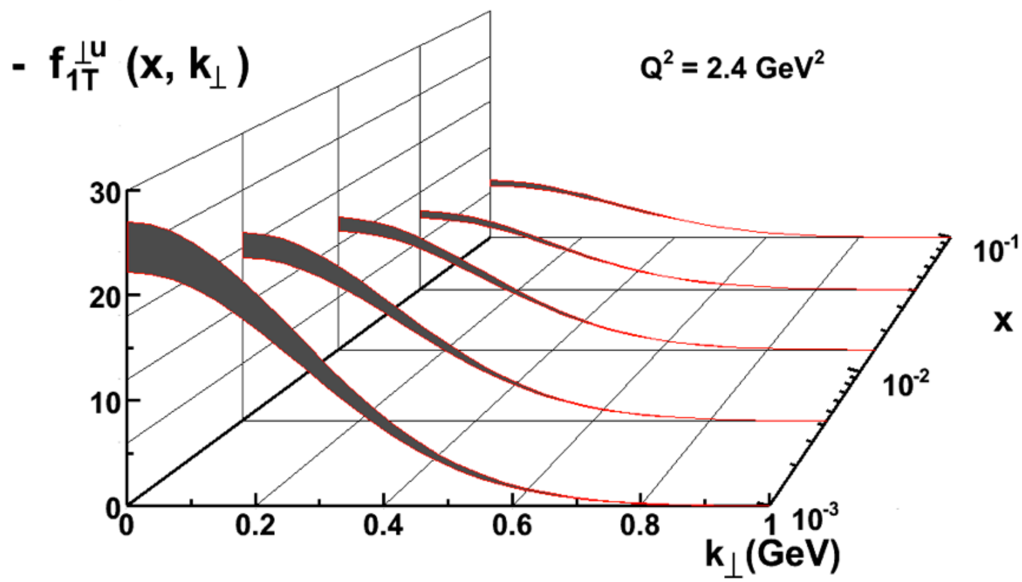


- High luminosity implies: Single transverse-spin asymmetries: high resolution & multidimensional

Momentum tomography of the nucleon

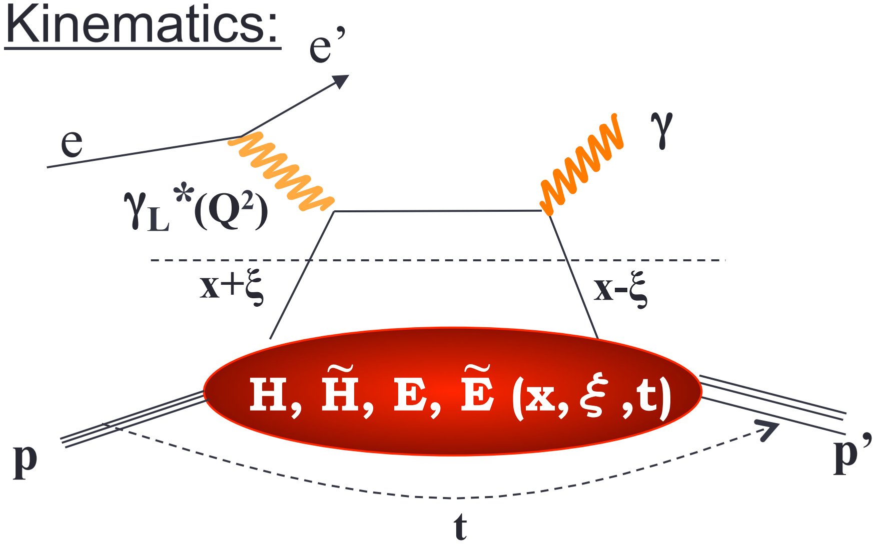
- Tomographic images of K_X/K_y of partons as functions of Bjorken-x: u quark distribution for transversely polarized proton.
- ***With EIC: low x partonic plots like these possible!***





Exclusive DIS

Kinematics:



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

Measure of resolution power

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

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

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

Allow access to the spatial distribution of partons in the nucleon

Fourier transform of spatial distributions → GPDs

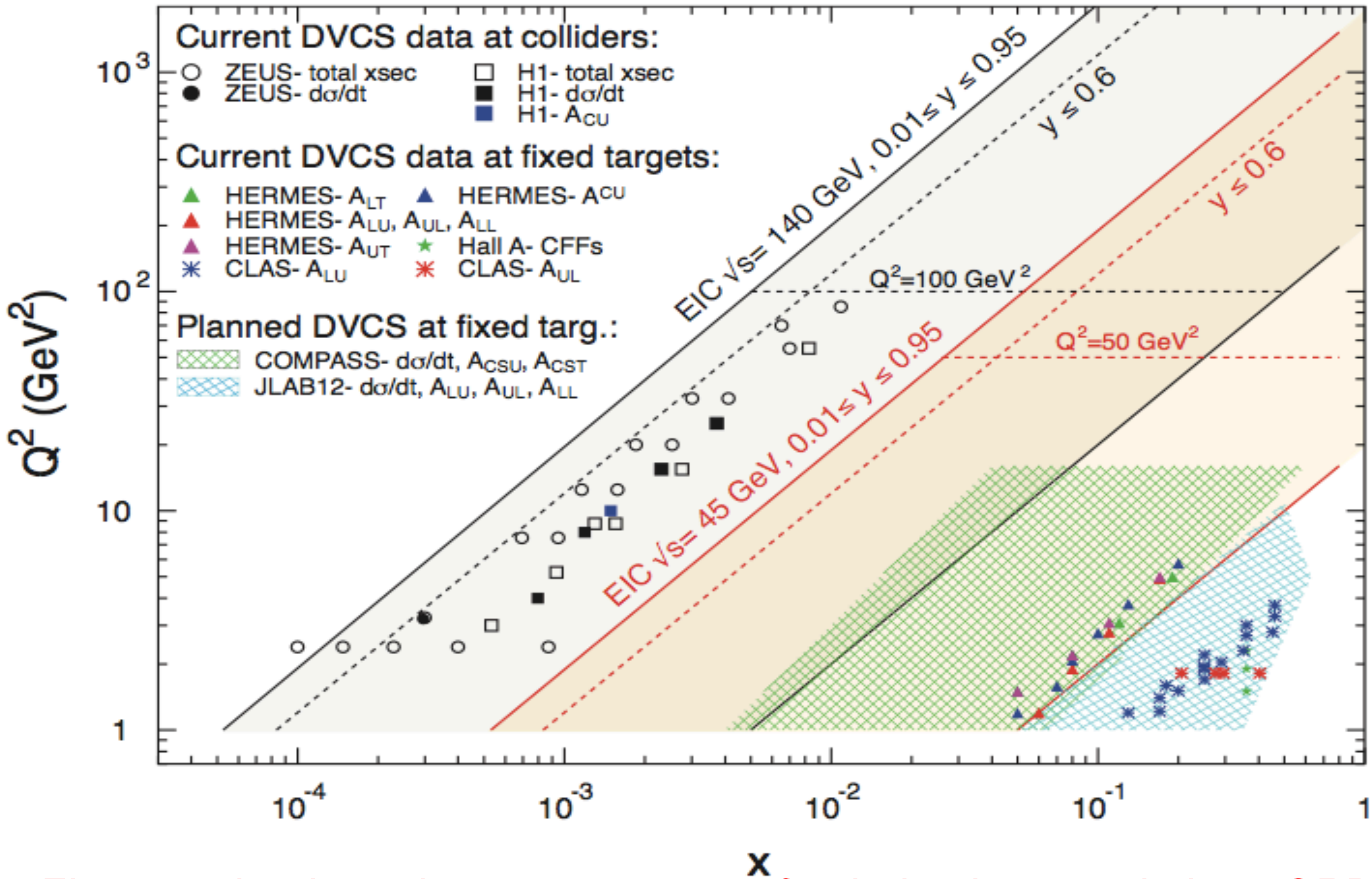
GPDs → Orbital Angular Momenta!

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

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

$$J_G = \Delta G + L_G$$

EIC coverage for GPDs



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

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

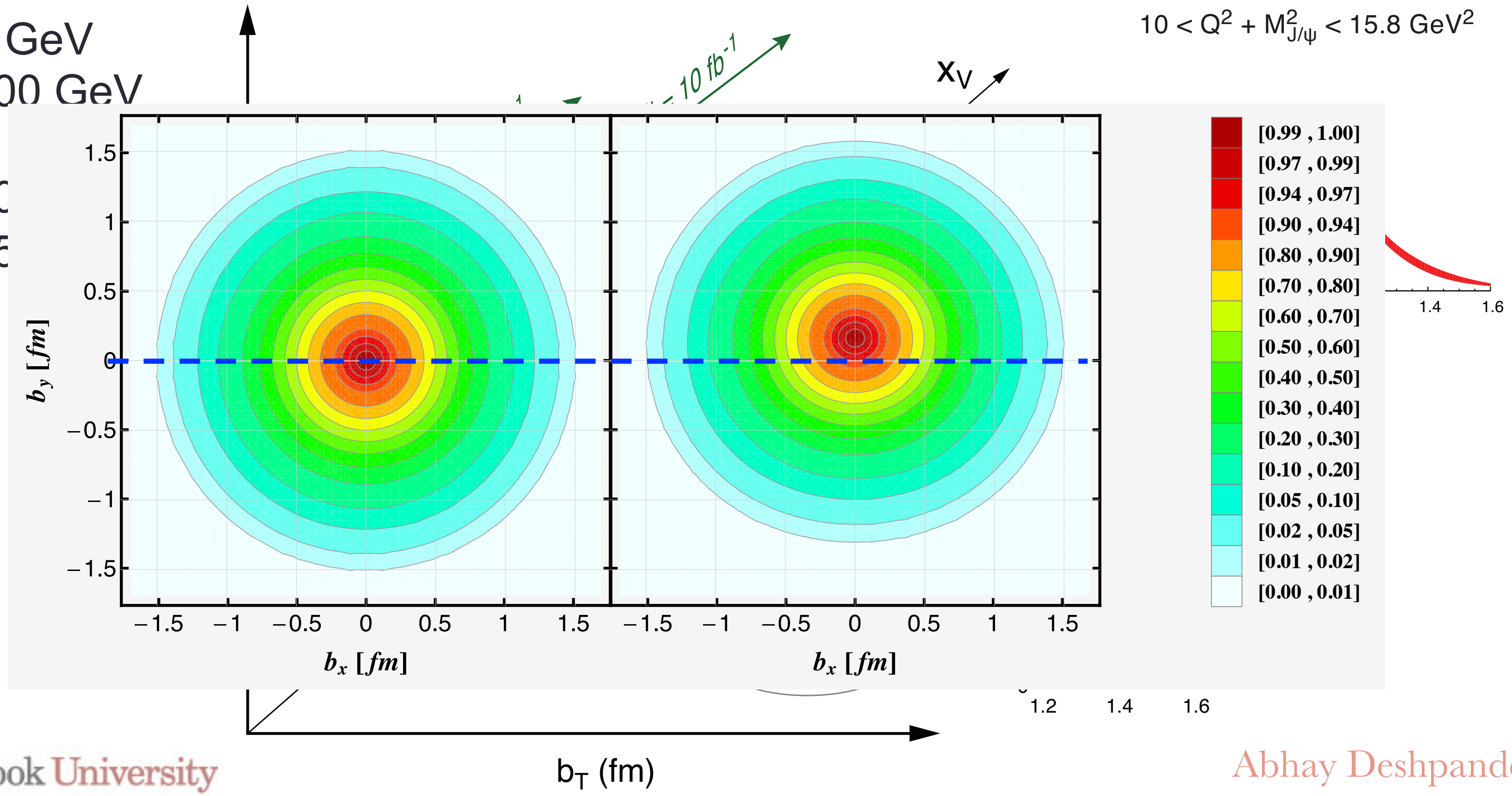
$$x_V = \frac{M_{J/\psi}^2 + Q^2}{W^2 + Q^2 + M_N^2}$$

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

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

E_e = 5 GeV
E_p = 100 GeV

E_e = 20
E_p = 25



Abhay Deshpande

An immediate check/impact:

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

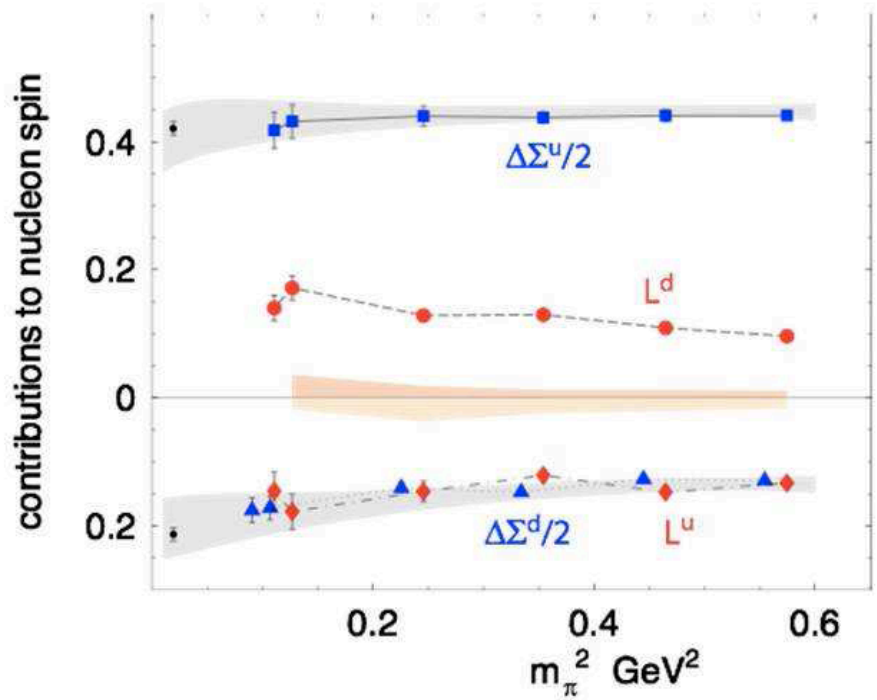
$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)] = \frac{1}{2}\Delta q + L_q$$

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

$L_u + L_d \sim 0$?

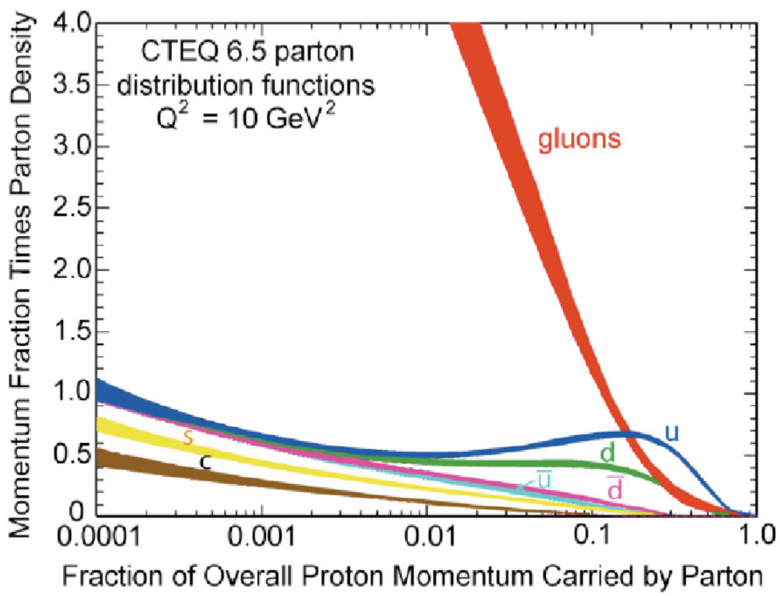
There are also more recent ideas Of calculating parton distribution functions on Lattice:
X. Ji et al. arXiv 1310.4263; 1310.7471; 1402.1462
& Y.-Q. Ma, J.-W. Qiu 1404.6860

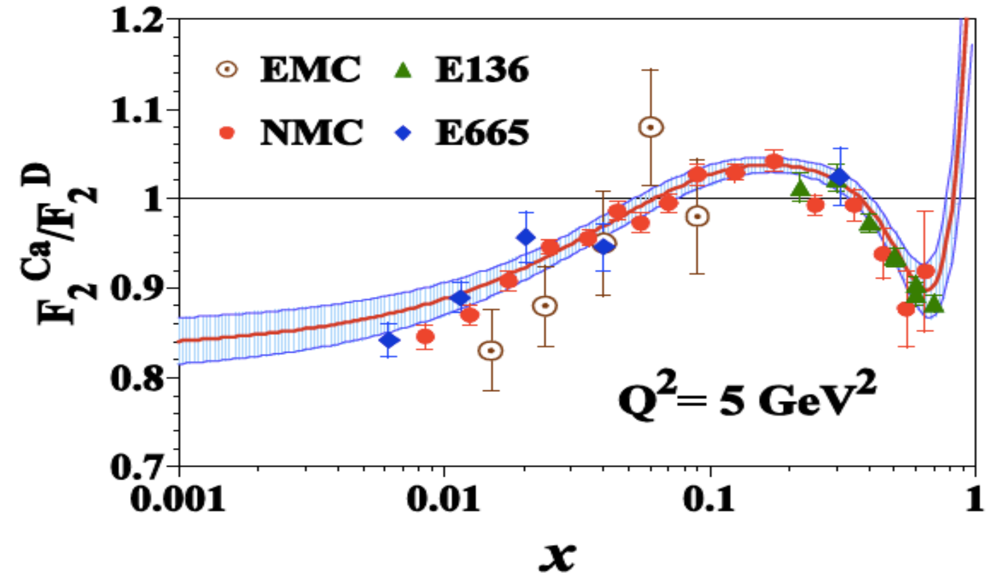


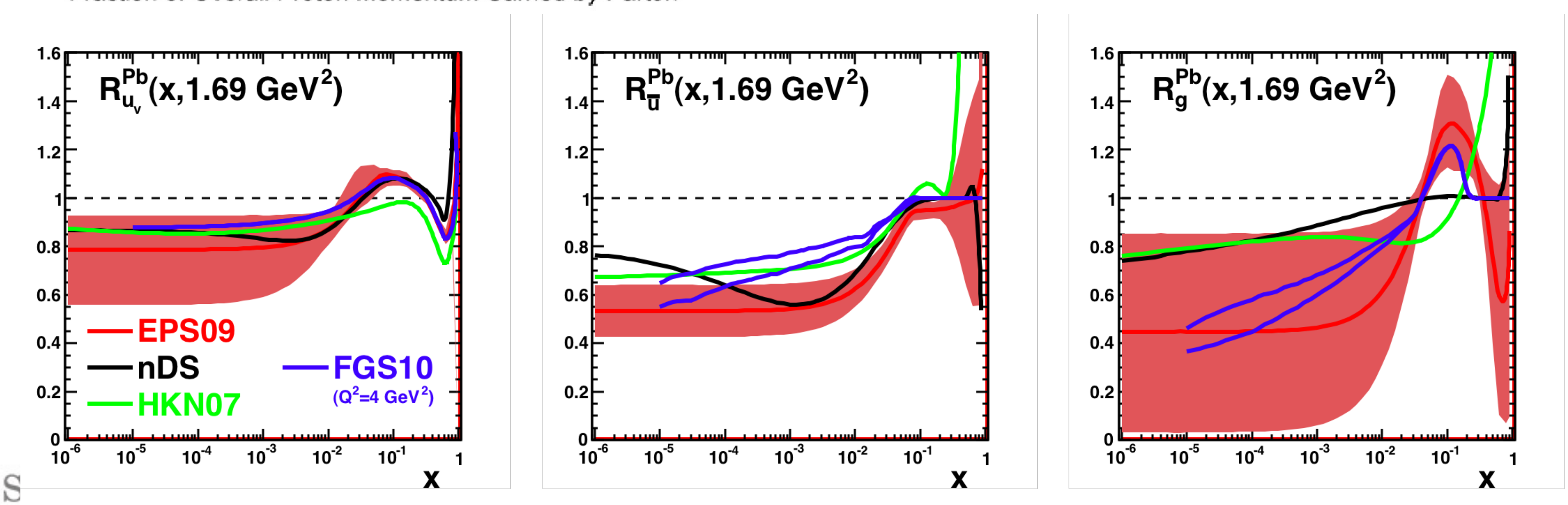
A now for something completely different! But a most exciting topic:

Physics with nuclei at the EIC!

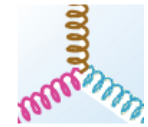
Low-x in proton (puzzle) and nuclei (unmeasured)







Gluon self-interaction in QCD

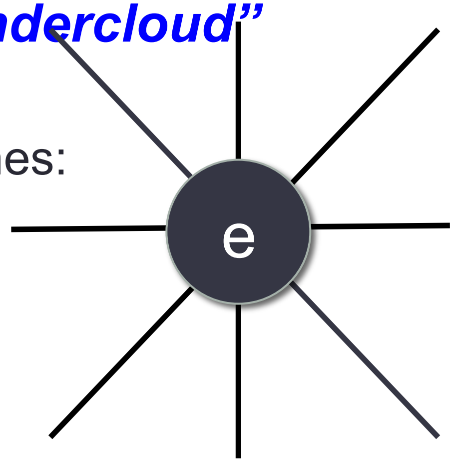


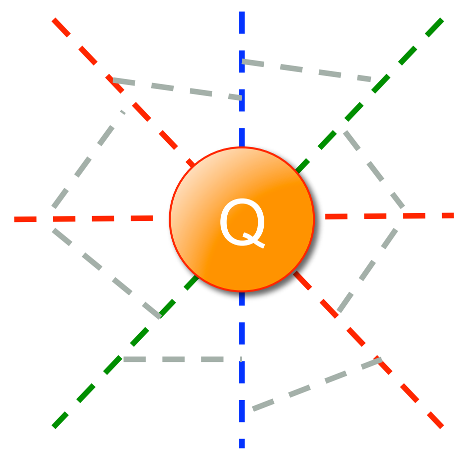
Dynamical generation & self-regulation of hadron masses

F. Wilczek in "Origin of Mass"

Its enhanced coupling to soft radiation… means that a 'bare" color charge, inserted in to empty space will start to surround itself with a cloud of virtual color gluons. These color gluon fields themselves carry color charge, so they are sources of additional soft radiation. The result is a self-catalyzing enhancement that leads to a ***runaway growth****. A small color charge, in isolation builds up a big color thundercloud….****theoretically the energy of the quark in isolation is infinite… having only a finite amount of energy to work with, nature always finds a way to short cut the ultimate thundercloud"***

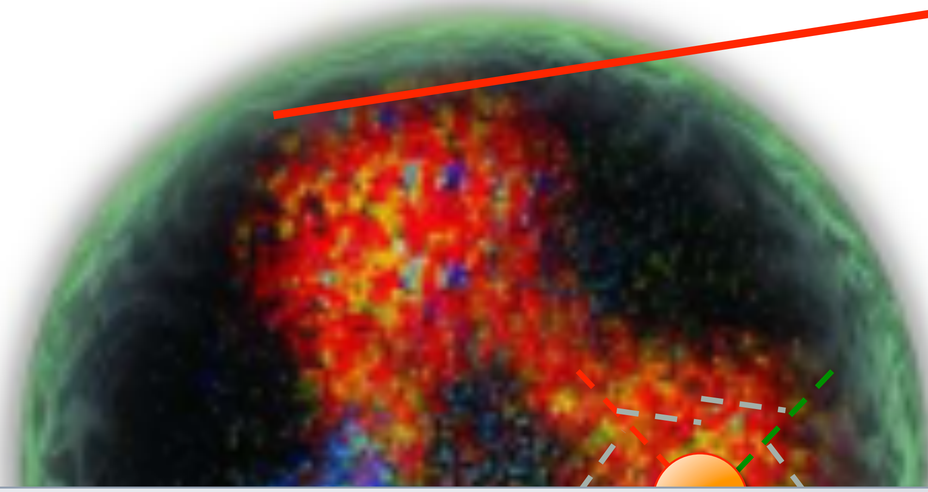
Electric charge, lines: photons

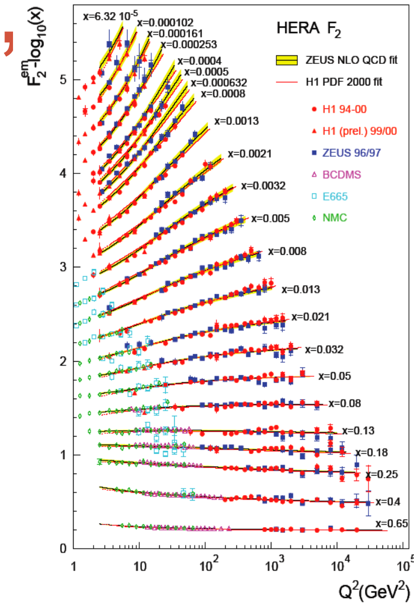




Color charge gluons

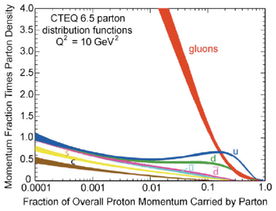
What limits the "thundercloud"





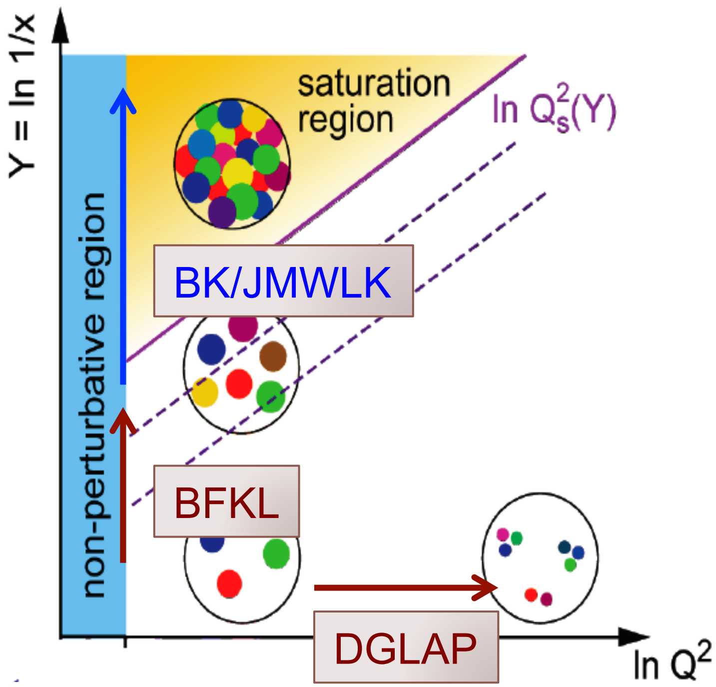
- Partial cancellation of quark-color-charge in color neutral finite size of the hadron (confinement) is responsible, ***but***
- **Saturation of gluon densities due to gg→ g (gluon recombination) must also play a critical role regulating the hadron mass**

Need to experimentally explore and study ***many body dynamics***
a) regions of ***quark-hadron transition*** and
b) non-linear QCD regions of extreme ***high gluon density***



Physics at Low x?

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

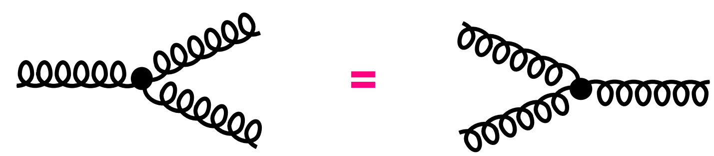


Method of including **non-linear** effects (McLerran, Venugopalan)

- 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



At Q_S

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?

A comment about study of QCD in the EIC era:

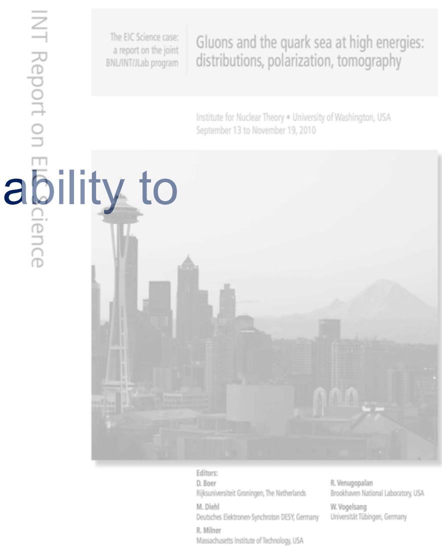
- QED: understanding the interactions of electric & magnetic charges + including quantum mechanics + relativity
  - Condense Matter Physics IS "*QED of many body system*"
  - Complicated, but extremely important and rich!
  - We learnt much about nature through the study of these collective phenomena, many Nobels!

- QCD: understanding the interactions of color charge leading to fundamental understanding of strong interactions….
  - *The EIC is essential for understanding the MANY BODY INTERACTIONS, including the parton dynamics in QCD, both in nucleons and nuclei.*
  - ***EIC Physics is the "Condense Matter Physics of QCD"***

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:**

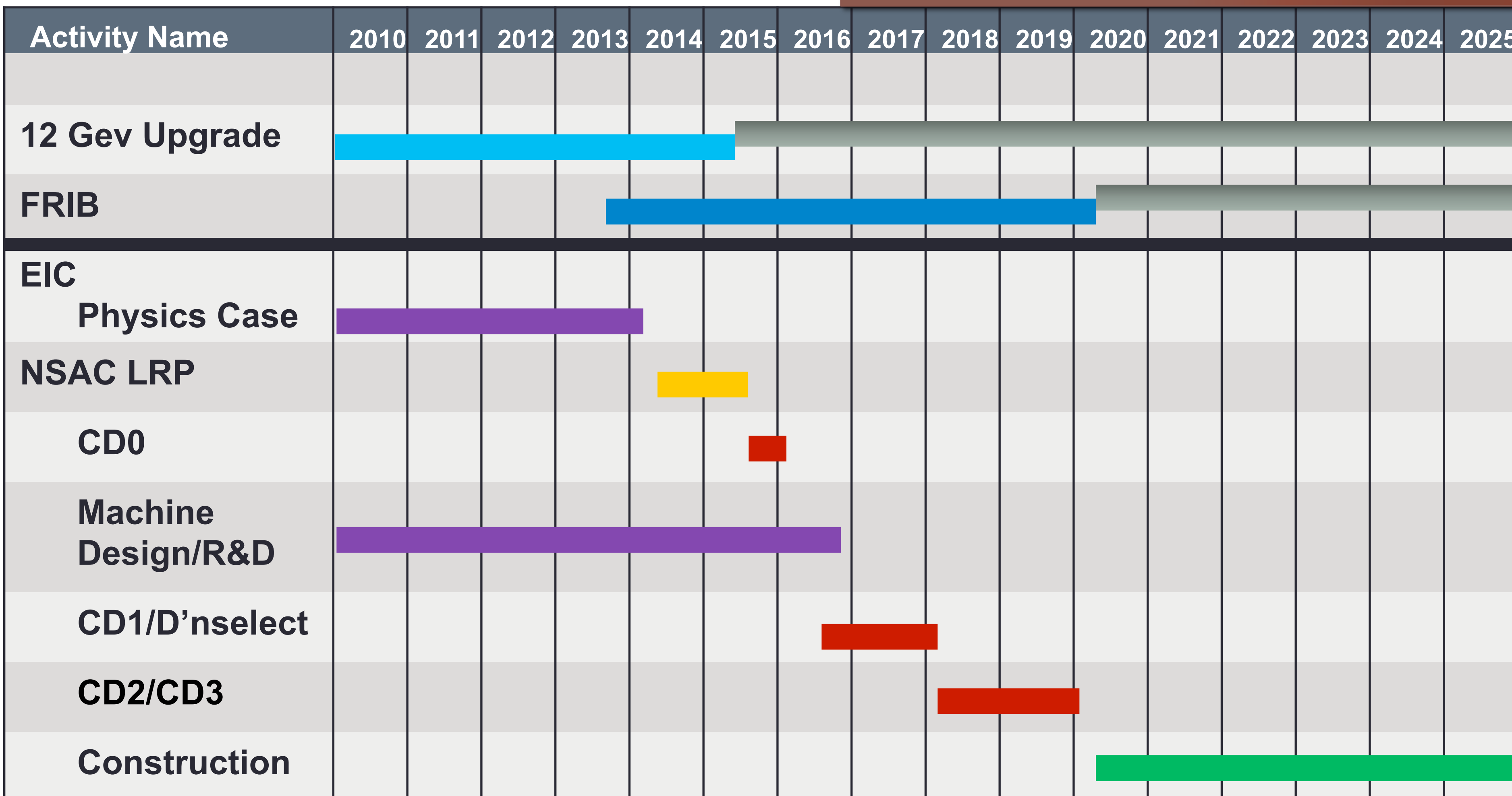
  Officially started! Final report due on October 15, 2015
  EIC needs to be a high recommendation in this report!

EIC User Group Meeting at Stony Brook (June 24-27, 2014)
http://skipper.physics.sunysb.edu/~eicug/meetings/SBU.html

H. Montgomery, Jeff. Laboratory Director

EIC Realization Possible Time Line

B. Mueller, BNL ALD's time line similar



Construction Schedule Highly Site Dependent

Summary & Outlook:

RHIC, the first polarized collider, has been a huge success: high impact results on gluon and anti-quark polarizations and emergent transverse spin phenomena

The Electron Ion Collider will further bring new "dimension" to our understanding of nucleon spin: from 1D → 2+1D tomographic images of nucleon may be possible… (and an exciting program with nuclei)

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

- ***Precision studies of the role of GLUONS & SEA QUARKS in QCD***

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 approved through the LRP.***

Development of the Standard Model of Physics 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** to study QCD