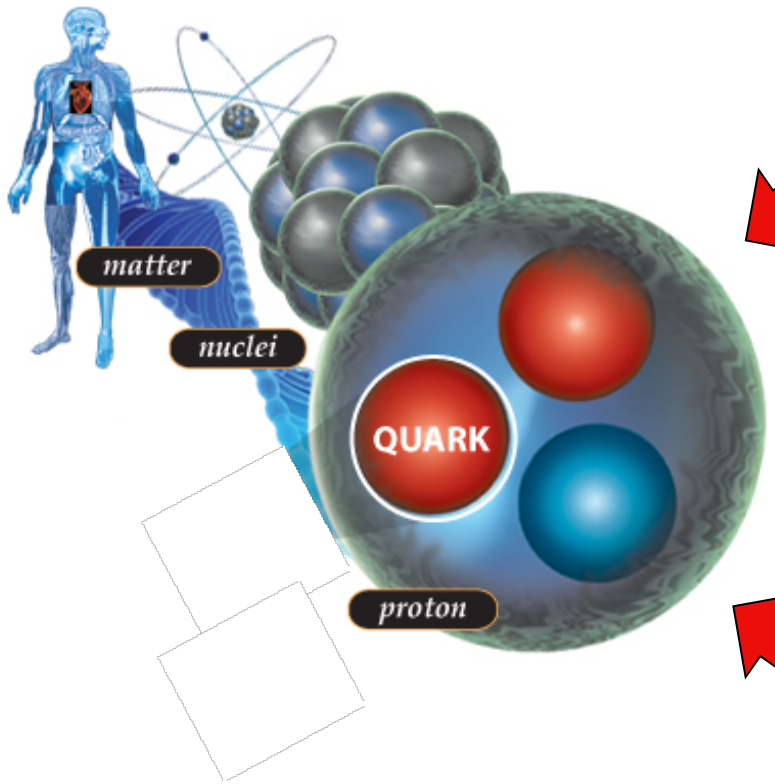
Hadron Structure
Jefferson Lab 12 and beyond

Alexei Prokudin

February 8, 2013

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Exploring the nucleon: a fundamental quest

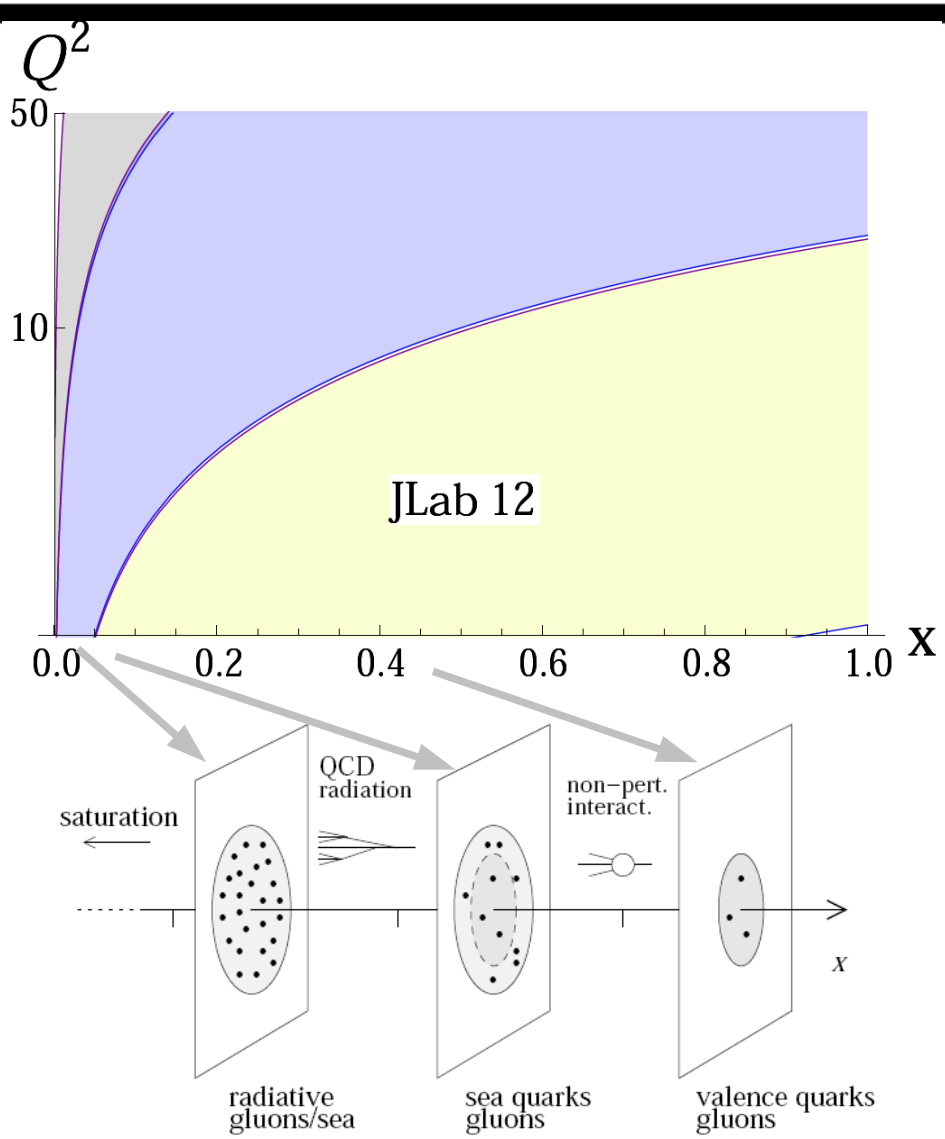


Know what we are made of !

Understand the strong force: "QCD"

Use protons as tool for discovery (e.g. LHC)

Nucleon landscape



Nucleon is a many body dynamical system of quarks and gluons

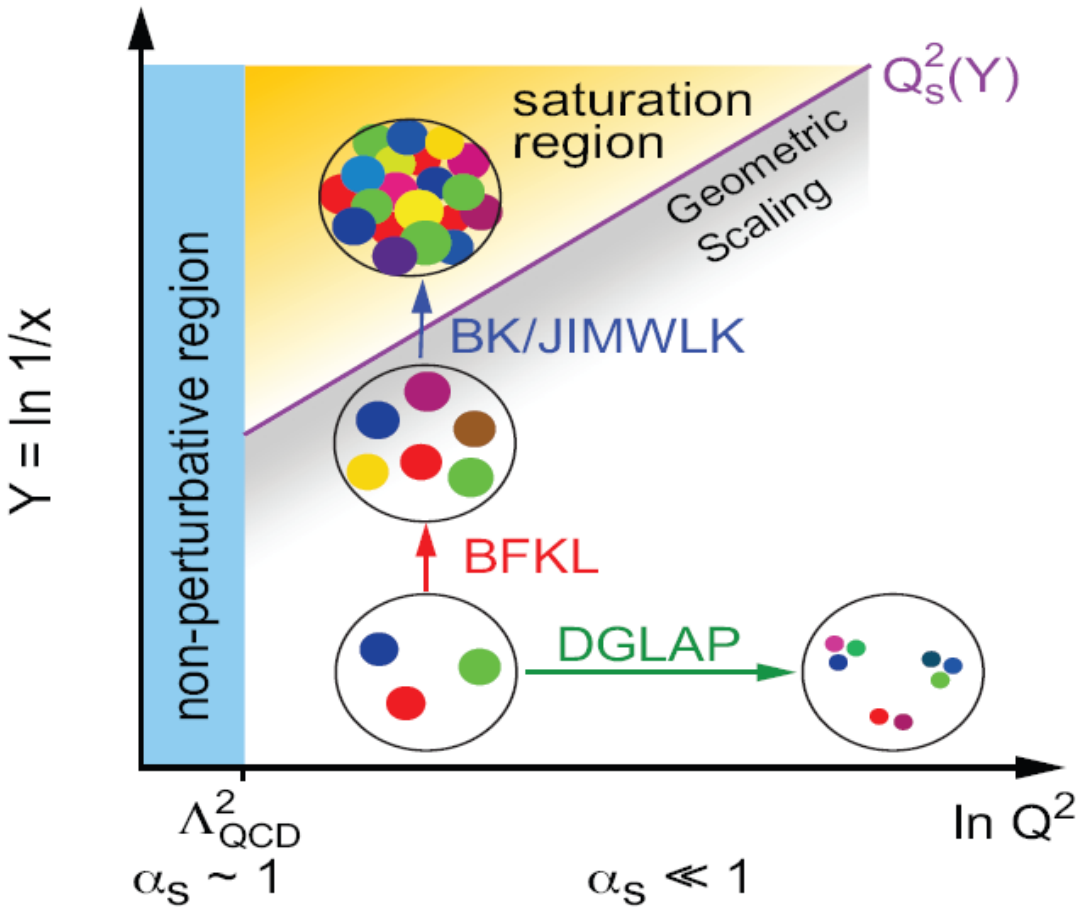
Changing x we probe different aspects of nucleon wave function

How **partons move** and how they are distributed in **space** is one of the future directions of development of nuclear physics

Technically such information is encoded into Generalised Parton Distributions and Transverse Momentum Dependent distributions

These distributions are also referred to as **3D (three-dimensional) distributions**

Nucleon landscape



Virtual photon serves as a microscopic probe of the nucleon:

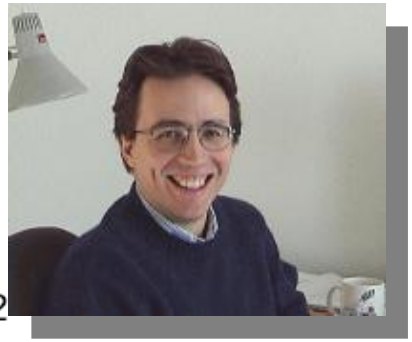
Larger Q^2 probe smaller distances – DGLAP evolution

Plot from EIC whitepaper

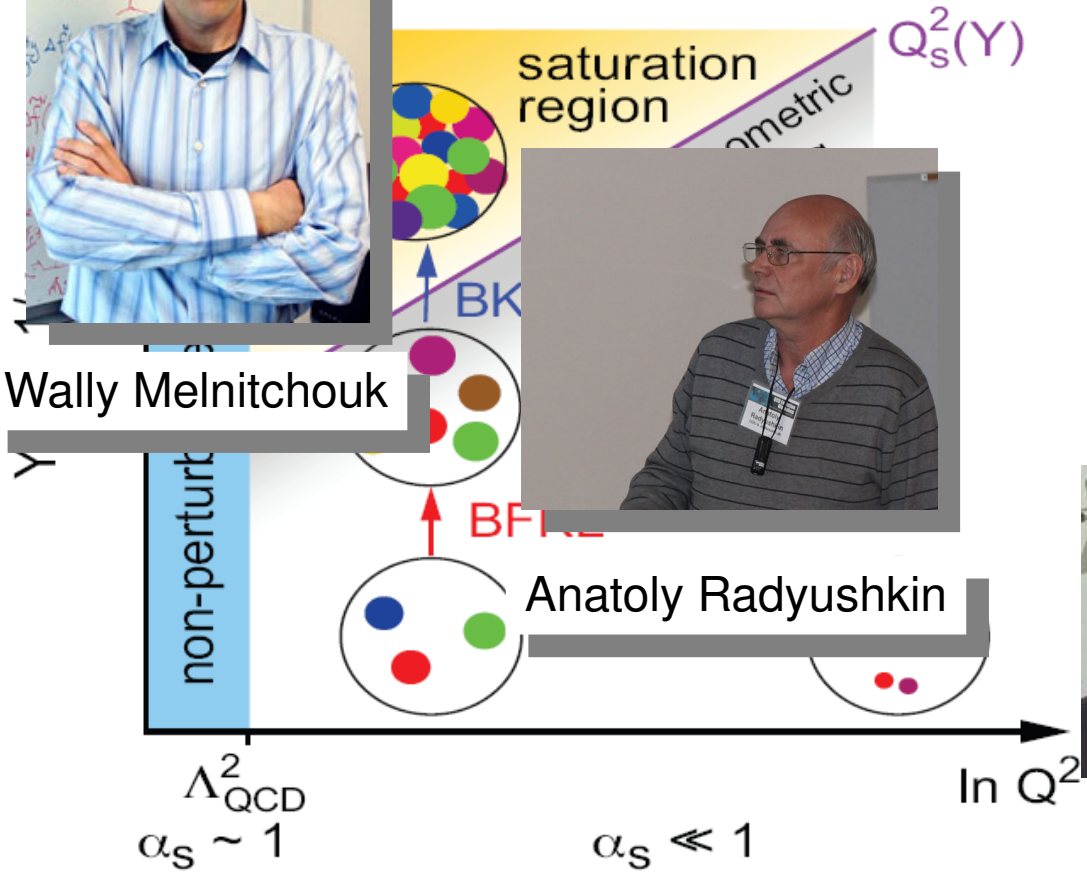
Nucleon landscape

Wally Melnitchouk

Anatoly Radyushkin



Alberto Accardi



Virtual photon serves as a microscopic probe of the nucleon:

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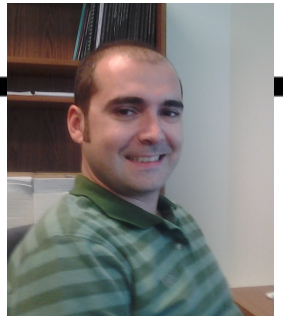
JAM



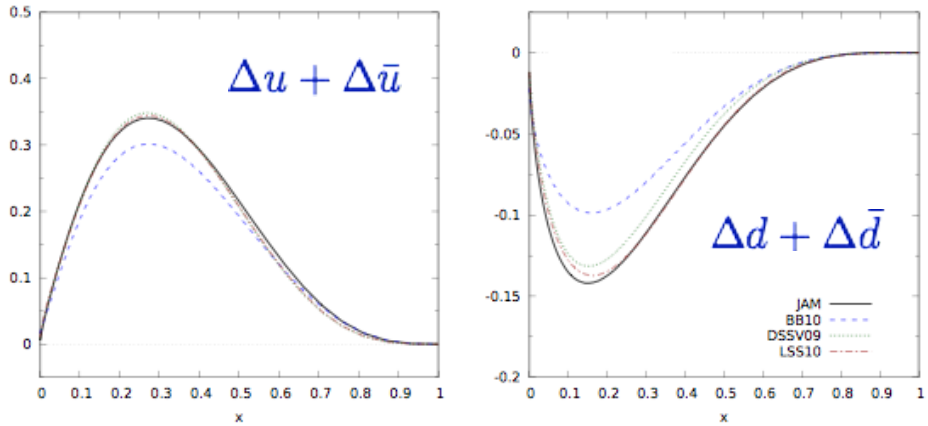
Global analysis of helicity PDFs

Pedro Jimenez-Delgado

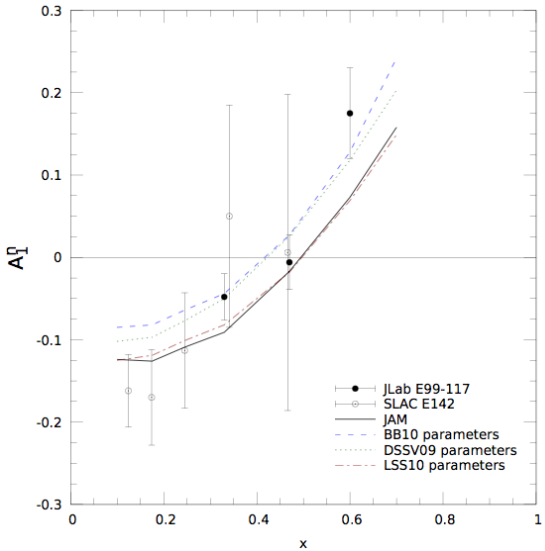
Alberto Accardi

Wally Melnitchouk

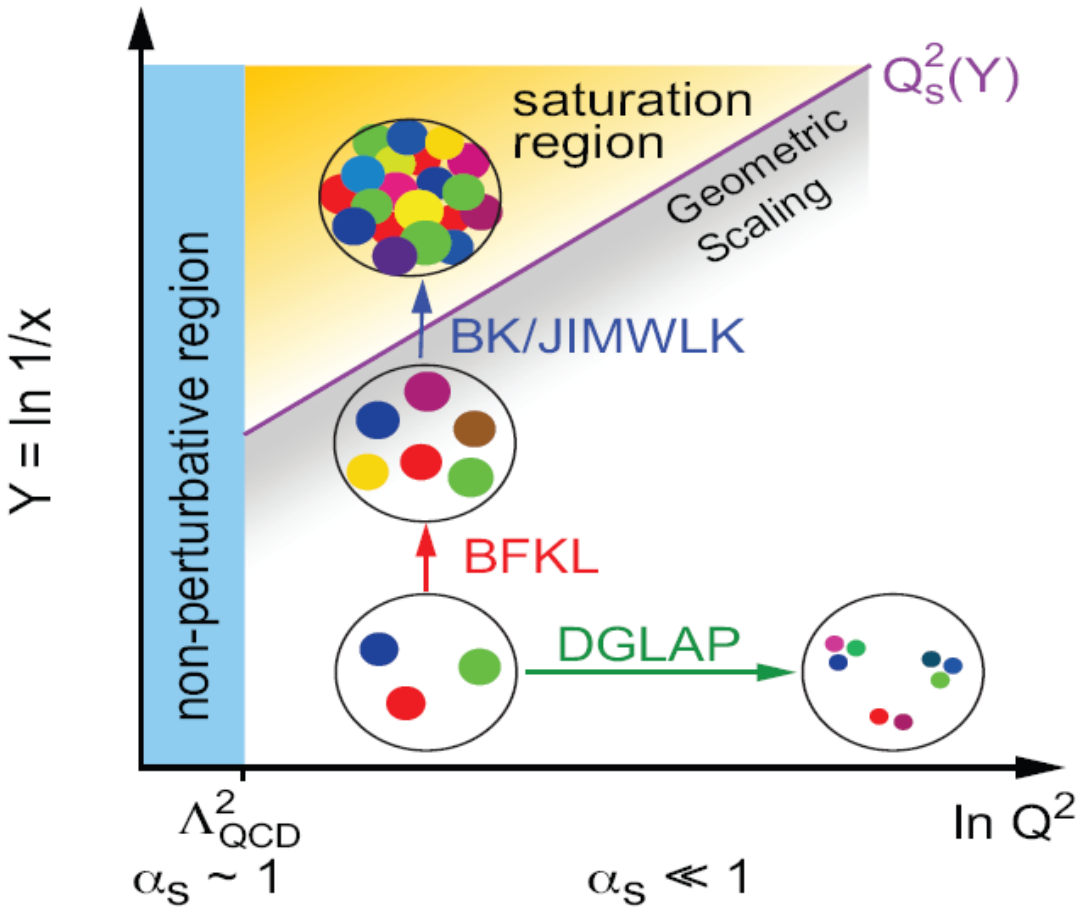
collaboration with CTEQ



Jimenez-Delgado et al. (2013)



Nucleon landscape



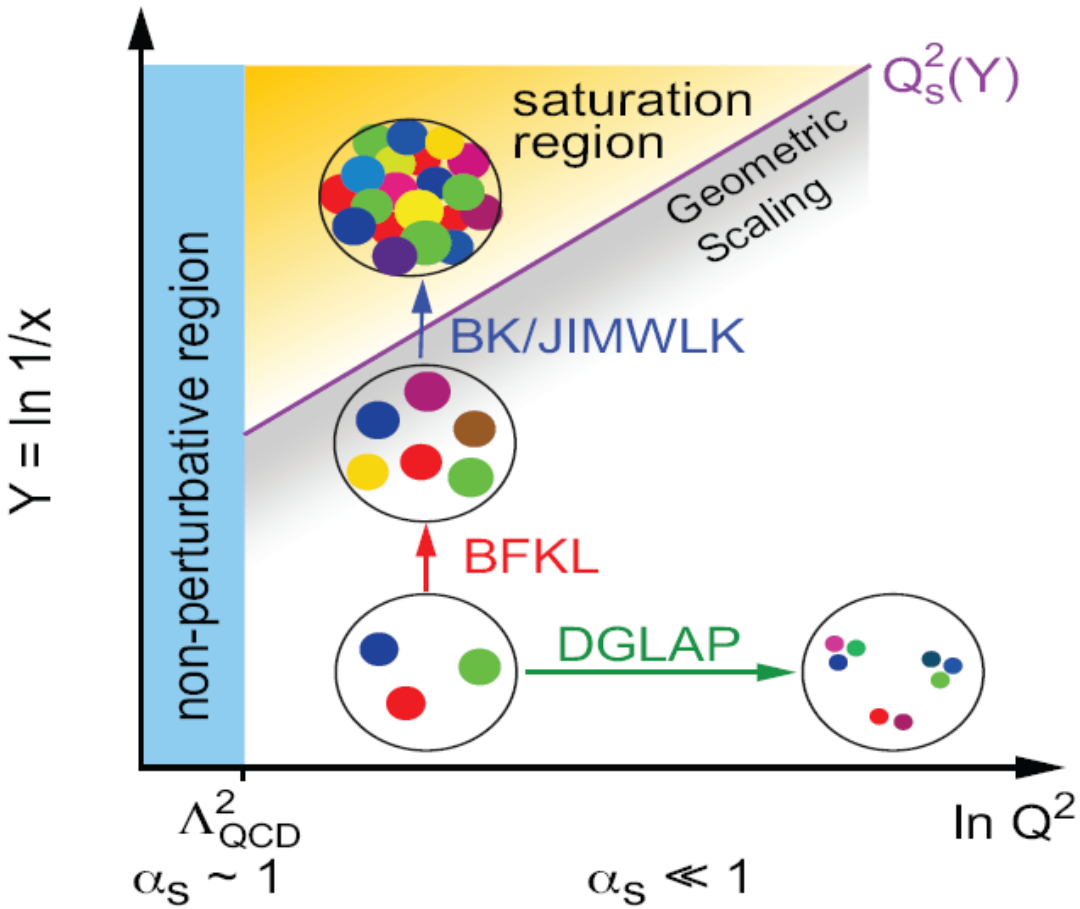
Virtual photon serves as a microscopic probe of the nucleon:

Fixing Q^2 and changing the energy we probe **BFKL** evolution

Ian Balitsky

Plot from EIC whitepaper

Nucleon landscape



Virtual photon serves as a microscopic probe of the nucleon:

Non perturbarive region is difficult and interesting.

Christian Weiss

Plot from EIC whitepaper

Unified View of Nucleon Structure

Wigner Distribution

5D

$$W(x, \mathbf{k}_\perp, \mathbf{b}_\perp)$$

Tansverse Momentum Dependent distributions

$$\int d^2\mathbf{b}_\perp$$

$$\int d^2\mathbf{k}_\perp$$

Generalized Parton Distributions

$$f(x, \mathbf{k}_\perp)$$

3D

$$H(x, \xi, t)$$

$$\int d^2\mathbf{k}_\perp$$

Parton Distribution Functions

Form Factors

$$\int dx$$

$$f(x)$$

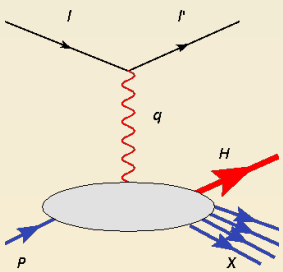
1D

$$F(Q^2)$$

JSA Jefferson Lab

Unified View of Nucleon Structure

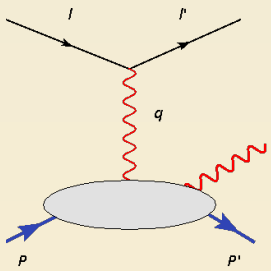
TMD



5D

$$W(x, \mathbf{k}_\perp, \mathbf{b}_\perp)$$

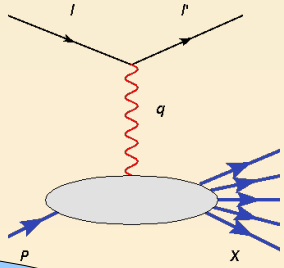
GPD

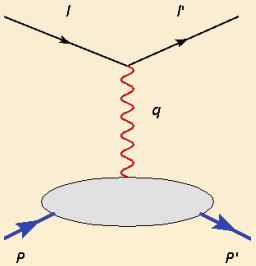


$$f(x, \mathbf{k}_\perp)$$

3D

$$H(x, \xi, t)$$





PDF

FF

$$f(x)$$

1D

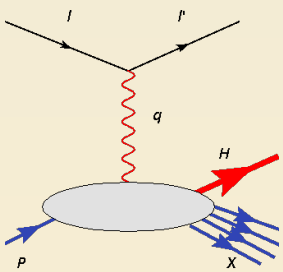
$$F(Q^2)$$

Particular processes to study. Polarization is required!

JSA
Jefferson Lab

Unified View of Nucleon Structure

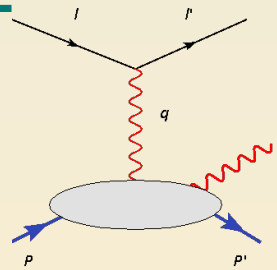
TMD



$$W(x, \mathbf{k}_\perp, \mathbf{b}_\perp)$$

5D

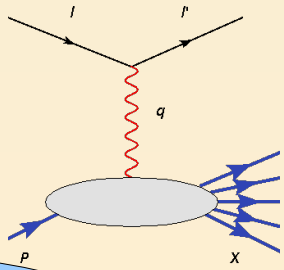
GPD



$$f(x, \mathbf{k}_\perp)$$

3D

$$H(x, \xi, t)$$



PDF

Alexei Prokudin

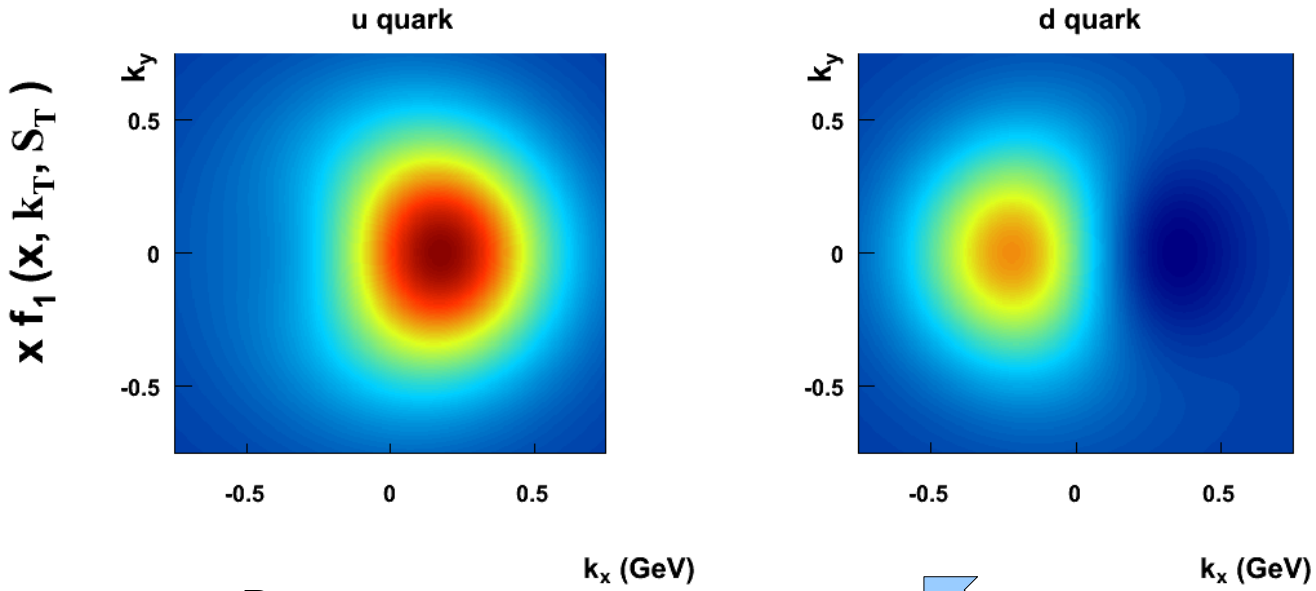
1D

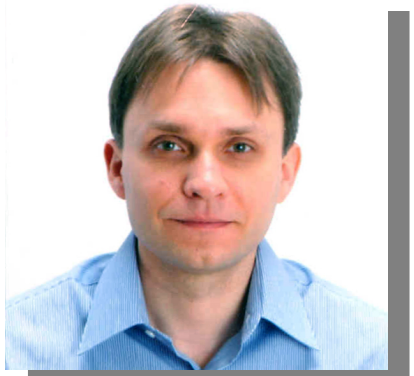
Anatoly Radyushkin

Christian Weiss

Particular processes to study. Polarization is required!

Tomographic scan of the nucleon





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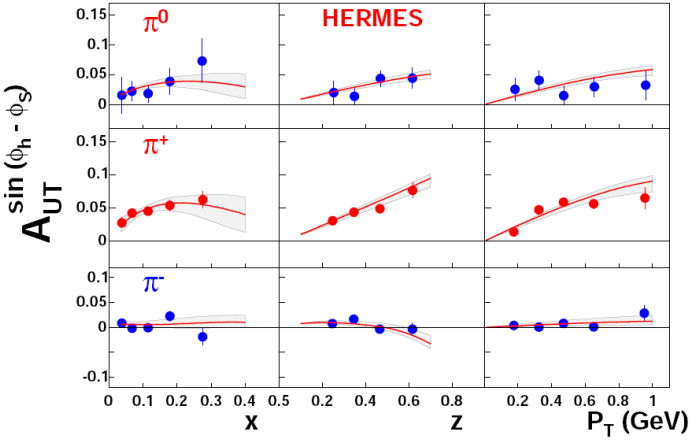
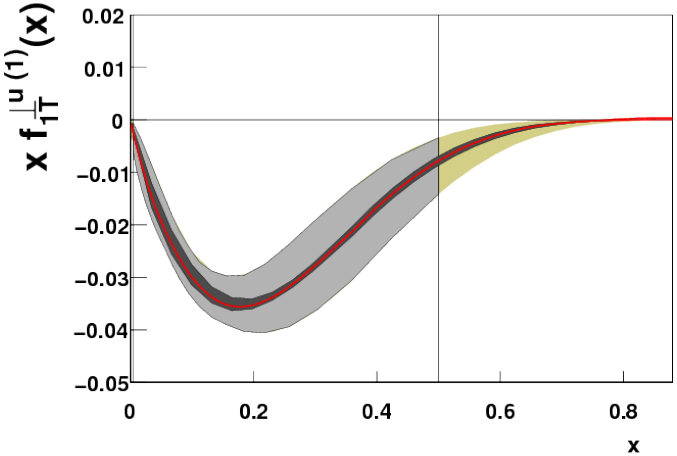
Data

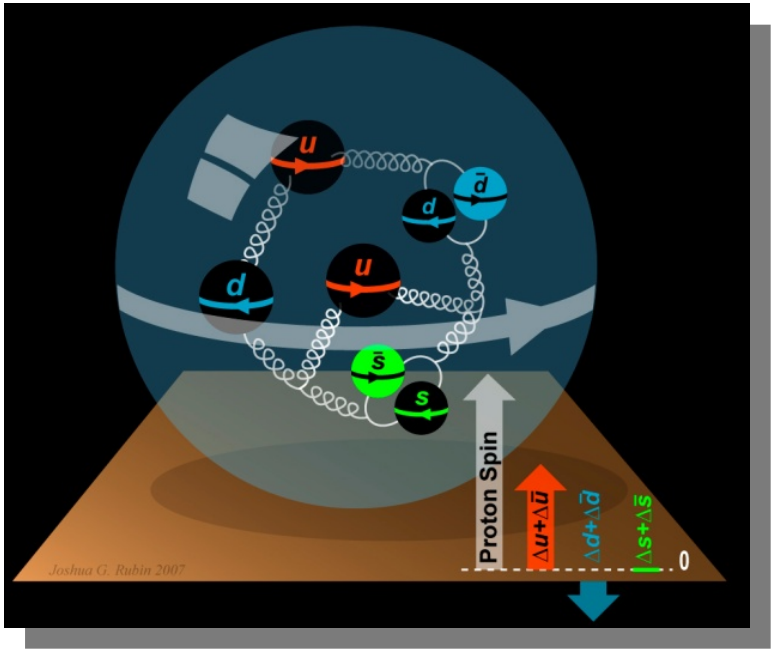


Global analysis of the data

Results



The Incomplete Nucleon: Spin Puzzle

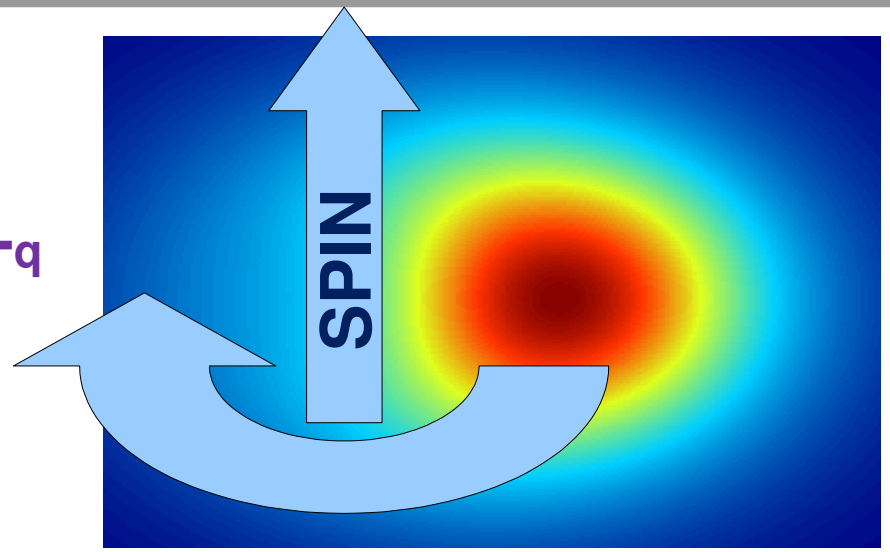


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

[Xiandong Ji, 1997]

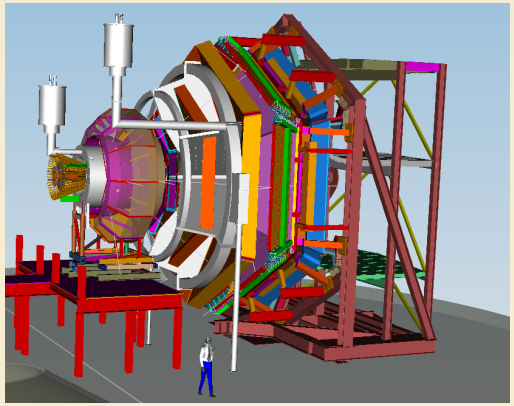
Relation to GPDs

$$J^q = \frac{1}{2}\int_{-1}^{+1} dx\, x\, [H^q(x,\xi,t) + E^q(x,\xi,t)] = \Delta\Sigma^q / 2 + L^q$$



- DIS → $\Delta\Sigma \cong 0.25$ → L_q
- RHIC + DIS → $\Delta G \ll 1$
- Clear indication that OAM is important

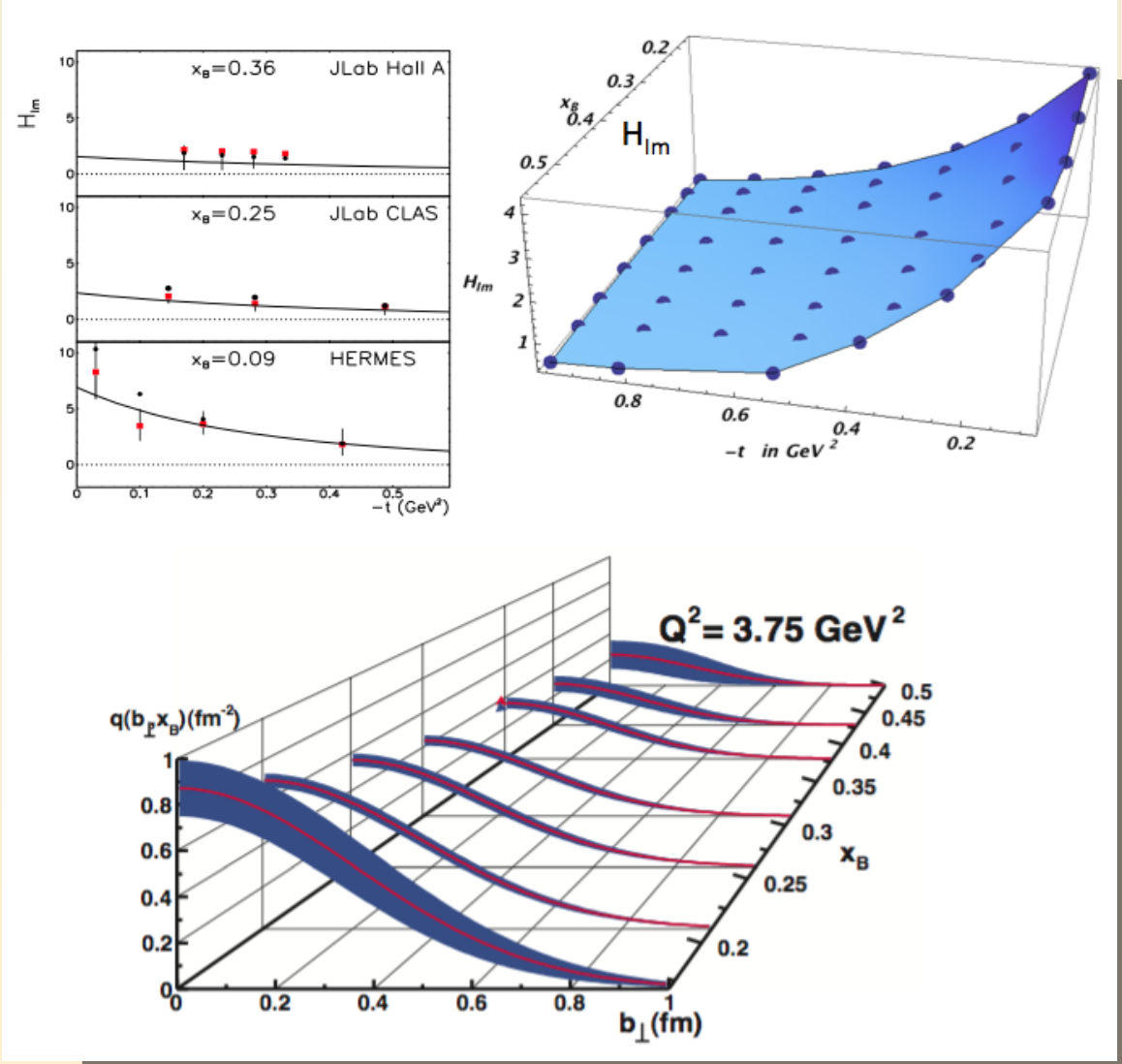
GPDs are measured in DVCS



$\vec{e}p \rightarrow ep\gamma$

High luminosity and large acceptance allows wide coverage in $Q^2 < 8$ GeV^2, $x_B < 0.65$, and $t < 1.5$GeV^2

Polarised target and polarised electron beam are required



Only my collaborators are listed

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Alberto Accardi
Harut Avakian
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Stony Brook
Ted Rogers

China
Bo-Qiang Ma

NETHERLANDS
Daniel Boer

GERMANY
Werner Vogelsang
Marc Schlegel

ITALY
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Mauro Anselmino
Stefano Melis
Elena Boglione
Vincenzo Barone
University of Cagliari
Umberto D'Alesio
Franceso Murgia
etc

What will be achieved? Example:

Expected result for tensor charge extraction:

1 - JLab 12
2 - Anselmino et al., Nucl.Phys.Proc.Suppl. (2009)
3 - Cloet, Bentz and Thomas, Phys.Lett.B (2008)
4 - Wakamatsu, Phys.Lett.B (2007)
5 - Gockeler et al., Phys.Lett.B (2005)
6 - He and Ji, Phys. Rev. D (1995)
7 - Pasquini et al, Phys. Rev. D (2007)
8 - Gamberg and Goldstein, Phys. Rev. Lett. (2001)
9 - Hecht, Roberts and Schmidt Phys. Rev. C (2001)

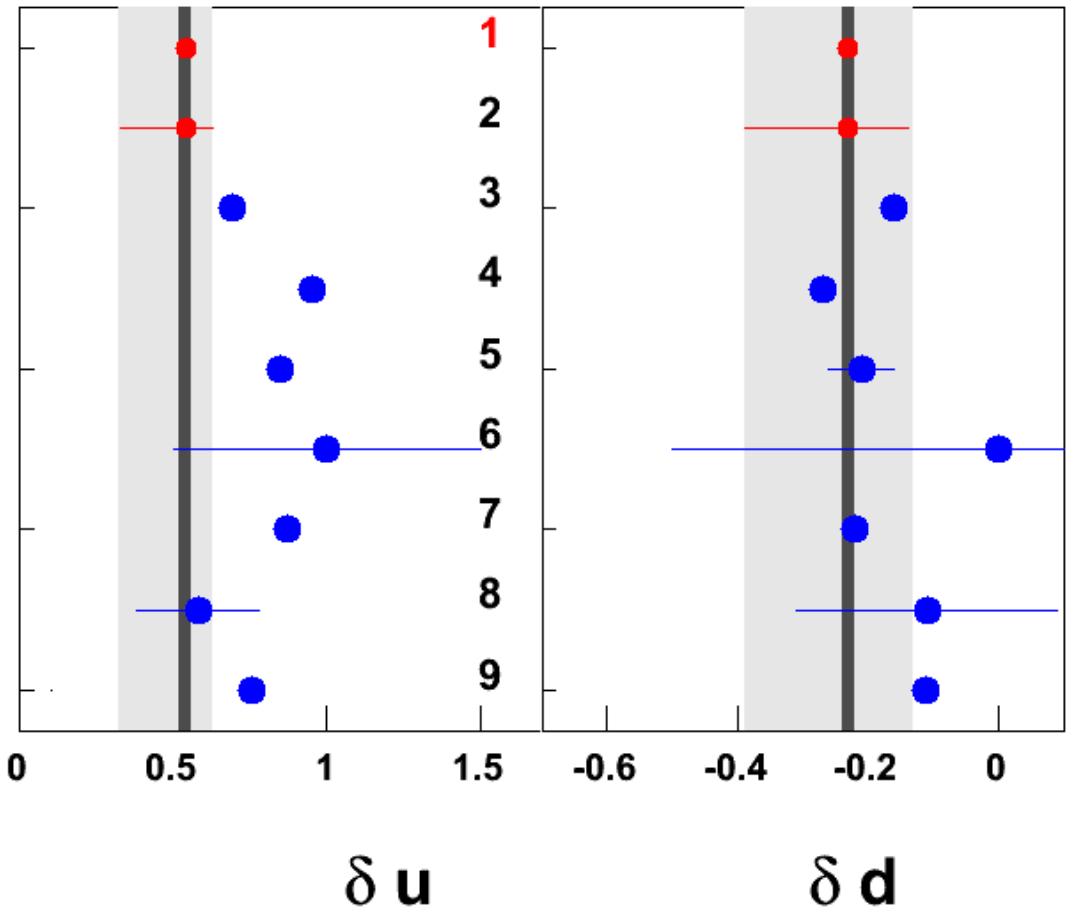
$$\delta q = \int dx \, (h^{q}(x) - h_1^{\bar{q}}(x))$$

$$\delta u = 0.54^{+0.09}_{-0.22}, \; \delta d = -0.23^{+0.09}_{-0.16}$$

JLab 12 Proton and He^3 targets

$$\delta u = 0.54^{+0.02}_{-0.02}, \; \delta d = -0.23^{+0.01}_{-0.01}$$

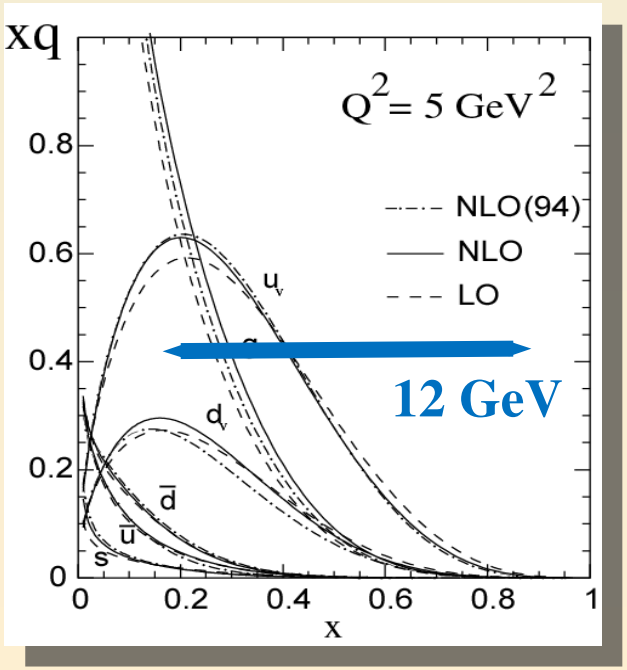
Statistical errors only



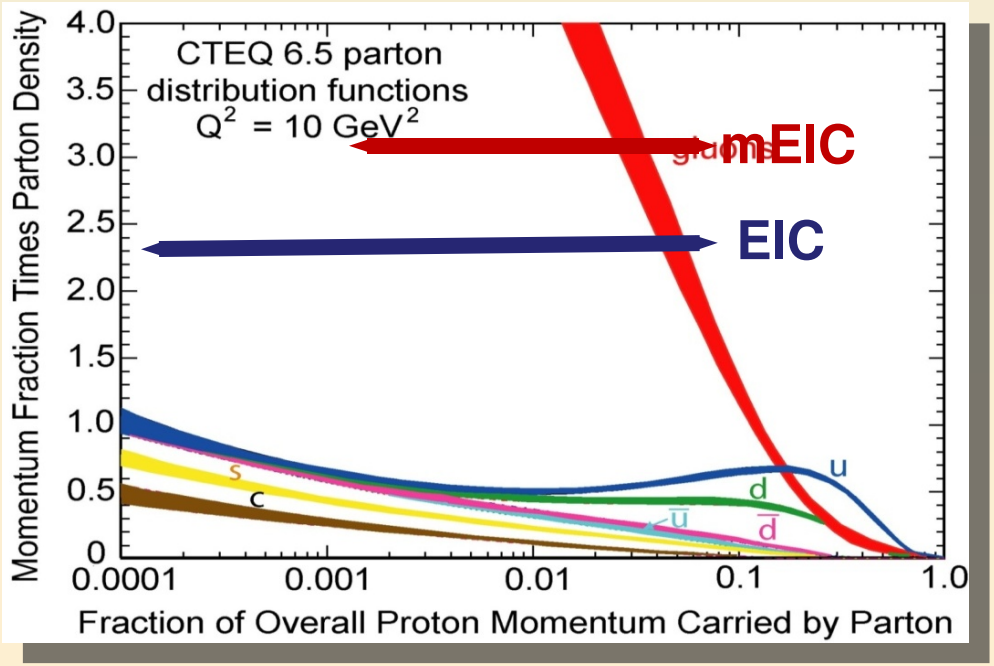
A. Prokudin (2012) contribution To Jlab12 white paper

Into the "sea": Electron Ion Collider

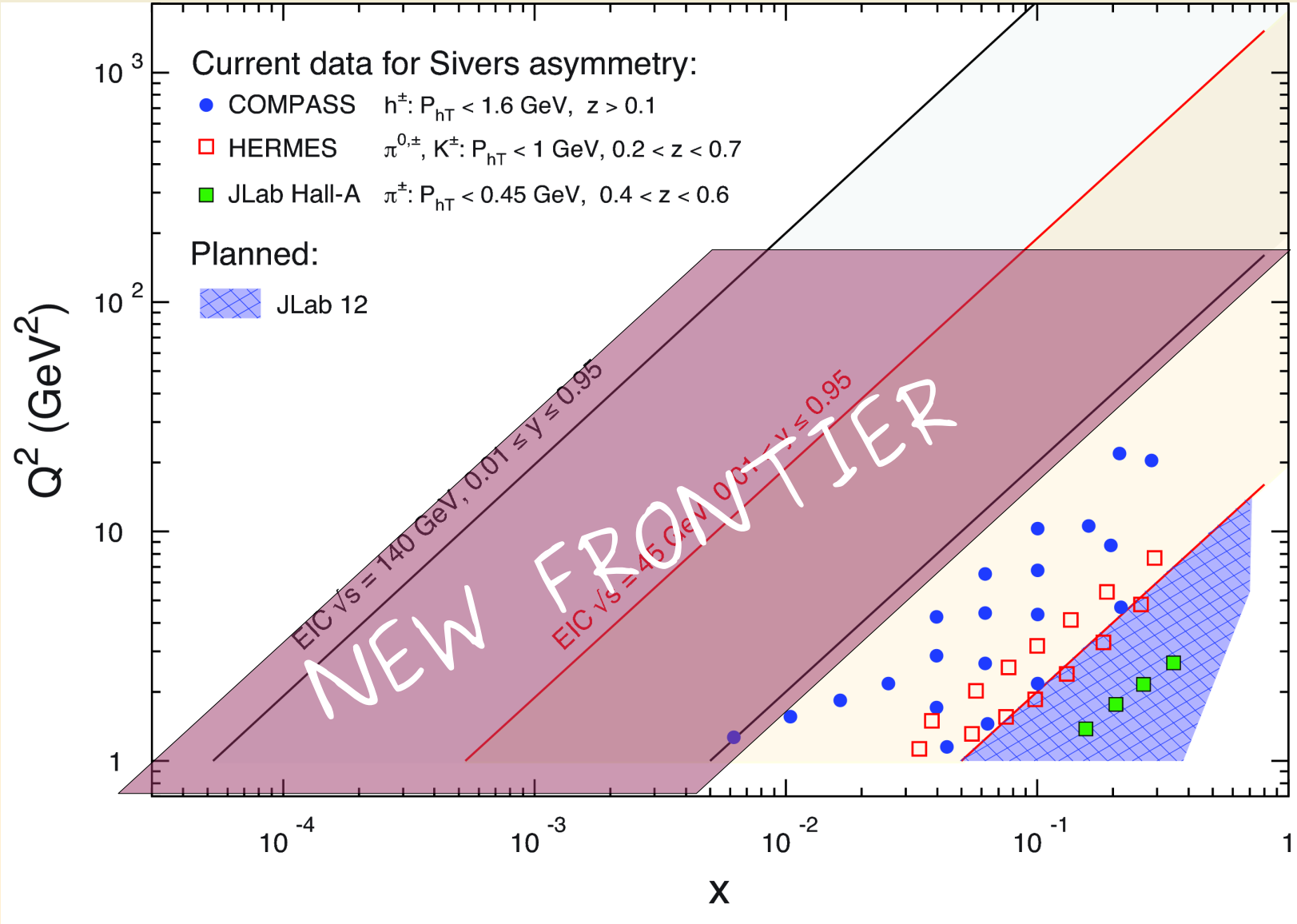
- With 12 GeV we study mostly the valence quark component



An EIC aims to study the sea quarks, gluons, and scale dependence.



Into the "sea": Electron Ion Collider



Medium Energy EIC@JLab

Physics driven design

Spin and 3D quark/gluon structute of the hadron

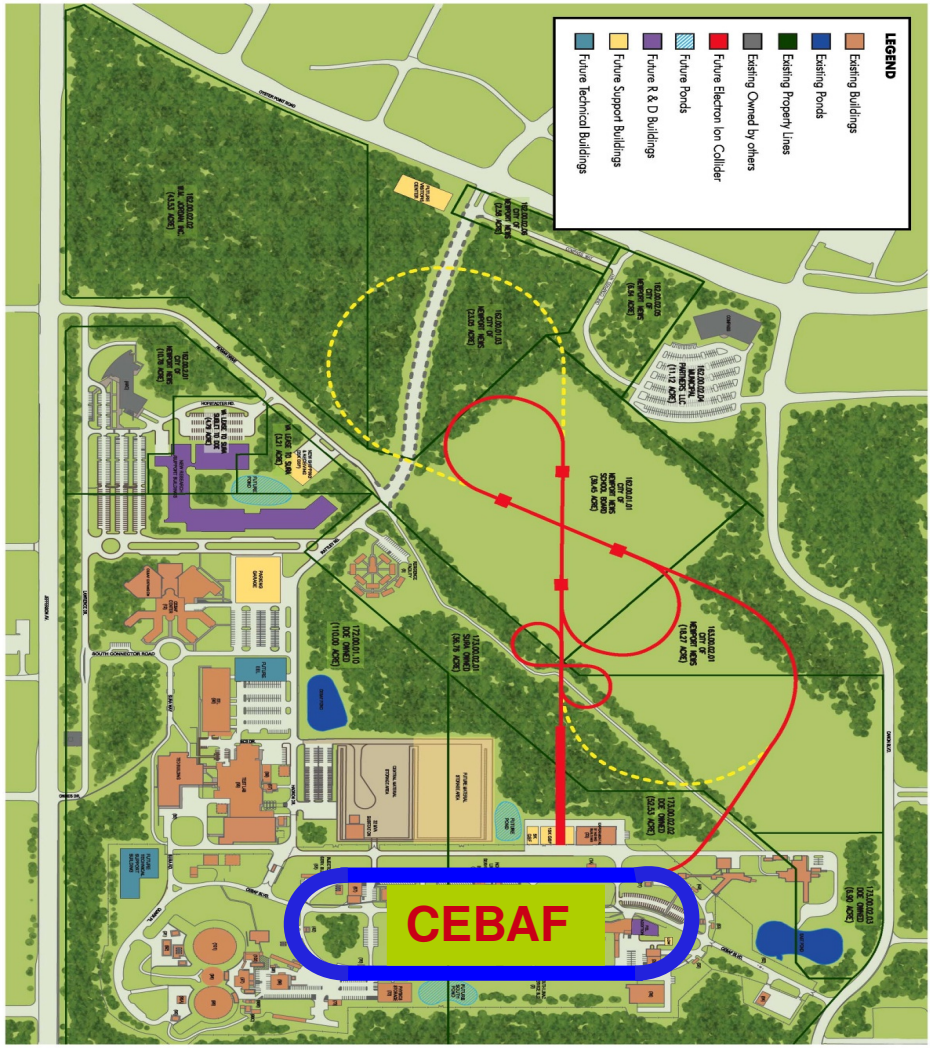
Dynamics of color fields in nuclei

Emergence of hadrons from color charge

JLab Concept

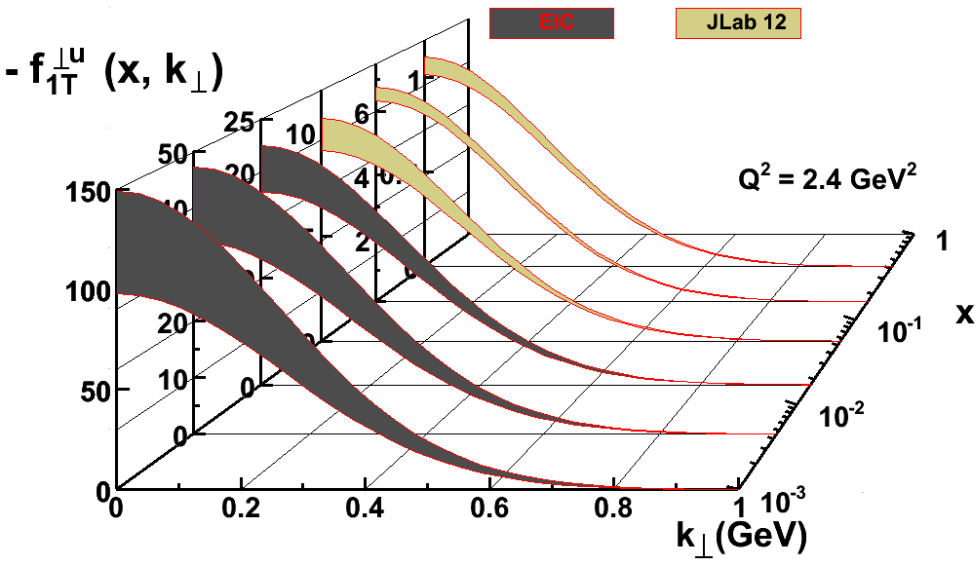
Initial configuration (MEIC):
3-12 GeV on 20-100 GeV ep/eA collider
fully-polarized, longitudinal and transverse
luminosity: few x 10^{34} e-nucleons cm^{-2} s^{-1}

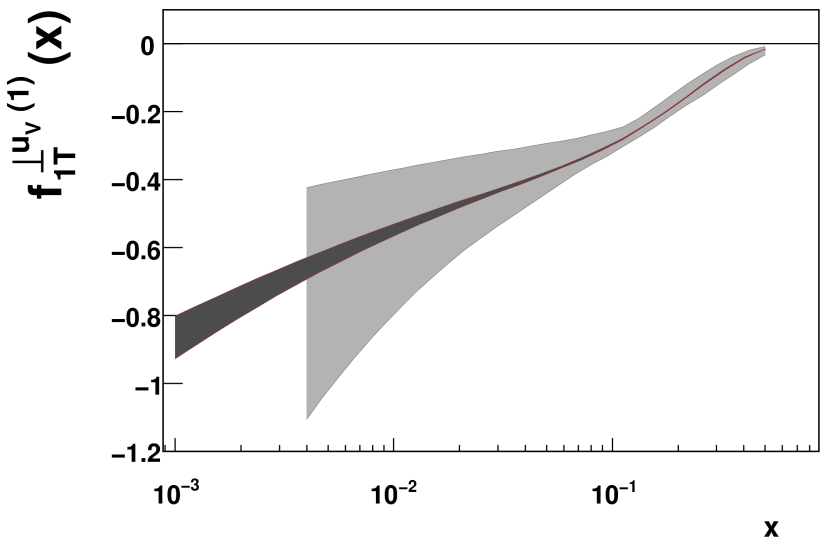
Upgradable to higher energies (250 GeV)



What will be achieved? Example:

Expected result for an individual function:





Expected accuracy of TMD profile

A. Prokudin (2012) contribution to EIC white paper

A Laboratory for Nuclear Science

- The Jefferson Lab electron accelerator is a unique world-leading facility for nuclear physics research and related applications

- 12 GeV Upgrade ensures at least a decade of excellent opportunities for hadron structure studies
  - New vistas in QCD
  - A lot of unique data

- EIC moving forward:
  - Strong science case, much builds on JLab 12 GeV program
  - MEIC design well developed – time scale following 12 GeV program is "natural"