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
Virtual photon serves as a microscopic probe of the nucleon:

Larger $Q^2$ probe smaller distances – DGLAP evolution

Plot from EIC whitepaper
Virtual photon serves as a microscopic probe of the nucleon:

Larger $Q^2$ probe smaller distances – DGLAP evolution

Plot from EIC whitepaper
Global analysis of helicity PDFs

Pedro Jimenez-Delgado  Alberto Accardi  Wally Melnitchouk

collaboration with CTEQ

\[ \Delta u + \Delta \bar{u} \]
\[ \Delta d + \Delta \bar{d} \]

Jimenez-Delgado et al. (2013)
Virtual photon serves as a microscopic probe of the nucleon:

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

Plot from EIC whitepaper
Virtual photon serves as a microscopic probe of the nucleon:

Non perturbative region is difficult and interesting.

Christian Weiss
Unified View of Nucleon Structure

Wigner Distribution

\[ W(x, k_\perp, b_\perp) \]

5D

Transverse Momentum Dependent distributions

\[ f(x, k_\perp) \]

3D

\[ f(x) \]

1D

\[ H(x, \xi, t) \]

Generalized Parton Distributions

\[ F(Q^2) \]

\[ \int d^2 b_\perp \]

\[ \int d^2 k_\perp \]

\[ \int dx \]
Unified View of Nucleon Structure

Particular processes to study. Polarization is required!
Unified View of Nucleon Structure

Particular processes to study. Polarization is required!

Authors: Anatoly Radyushkin, Alexei Prokudin, Christian Weiss

Mathematical expressions:
- $W(x, k_\perp, b_\perp)$
- $f(x, k_\perp)$
- $H(x, \xi, t)$
Tomographic scan of the nucleon

Data

Results

Global analysis of the data
The Incomplete Nucleon: Spin Puzzle

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

[Xiandong Ji, 1997]

Relation to GPDs

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

- DIS $\rightarrow \Delta \Sigma \cong 0.25 \rightarrow L_q$
- RHIC + DIS $\rightarrow \Delta G \ll 1$
- Clear indication that OAM is important
GPDs are measured in DVCS

\[ e p \rightarrow e p \gamma \]

High luminosity and large acceptance allows wide coverage in \( Q^2 < 8 \text{ GeV}^2 \), \( x_B < 0.65 \), and \( t < 1.5 \text{ GeV}^2 \)

Polarised target and polarised electron beam are required
Only my collaborators are listed

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  - Francesco Murgia

**NETHERLANDS**
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**GERMANY**
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- Marc Schlegel

**PENN STATE**
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**BNL**
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**NCU**
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- Xin Qiang

**BERNARDINO D’ALESSIO**
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**JEFFERSON LAB**
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- Alberto Accardi
- Harut Avakian
  - etc

**LANL**
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- Xin Qiang

**Stony Brook**
- Ted Rogers

**China**
- Bo-Qiang Ma
  - etc
What will be achieved? Example:

Expected result for tensor charge extraction:

\[ \delta q = \int dx \left( h^q(x) - h^{\bar{q}}(x) \right) \]

A. Prokudin (2012) contribution

To JLab12 white paper

JLab 12 Proton and He\(^3\) targets

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

Statistical errors only
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

Current data for Sivers asymmetry:
- COMPASS $h^\pm$: $P_{hT} < 1.6 \text{ GeV}$, $z > 0.1$
- HERMES $\pi^{0,\pm}$, $K^\pm$: $P_{hT} < 1 \text{ GeV}$, $0.2 < z < 0.7$
- JLab Hall-A $\pi^\pm$: $P_{hT} < 0.45 \text{ GeV}$, $0.4 < z < 0.6$

Planned:
- JLab 12

$Q^2 (\text{GeV}^2)$

$X$

NEW FRONTIER
Physics driven design

Spin and 3D quark/gluon structure 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
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”