GPD PROGRAM WITH JEFFERSON LAB 12 GEV UPGRADE AND THE CENTER FOR NUCLEAR FEMTOGRAPHY

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Jefferson Lab

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What is inside the proton/neutron?

1933: Proton’s magnetic moment

1960: Elastic e-p scattering

1969: Deep inelastic e-p scattering

1974: QCD Asymptotic Freedom

"for ... and for his discovery of the magnetic moment of the proton".

\[ g \neq 2 \]

"for ... and for his thereby achieved discoveries concerning the structure of the nucleons"

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons ...".

"for the discovery of asymptotic freedom in the theory of the strong interaction".
QCD Science Questions

How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon?

What is the role of orbital motion?

What are Pressure & Forces distributions??

Color confinement & its origin?

Jefferson Lab
Elastic form factors $\rightarrow$ Transverse charge & current densities $F_1(t), F_2(t)$.

DIS structure functions $\rightarrow$ Longitudinal parton momentum & helicity densities, $F_2(x), g_1(x)$.

Deeply exclusive processes $\rightarrow$ GPD’s and 3D images in transverse space and longitudinal momentum. 4 GPDs $H, E, H, \bar{E}$ ($x, \xi, t$).
The Generalized Parton Distributions (GPDs) provide the theoretical framework to interpret the experimental data.

Breakthrough in theory of \textbf{QCD} (1990s): developing \textbf{Deeply Virtual Compton Scattering (DVCS)} as a tool to characterize the structure of the nucleon within \textbf{QCD} and showing how its properties can be probed through experiments.

Deeply Virtual Compton Scattering (DVCS) and GPDs

DVCS and Generalized Parton Distributions

\[ \gamma^* p \rightarrow \gamma p' \]

Bjorken regime:
\[ Q^2 \rightarrow \infty, \quad x_B \text{ fixed} \]
\[ t \text{ fixed} \ll Q^2, \quad \xi \rightarrow \frac{x_B}{2 - x_B} \]

\[ \frac{P^+}{2\pi} \int dy^- e^{ixp^+y^-} \langle p' | \bar{\psi}_q(0) \gamma^+(1 + \gamma^5) \psi(y) | p \rangle \]

\[ = \tilde{N}(p') \left[ H^q(x, \xi, t) \gamma^+ + E^q(x, \xi, t) i\sigma^+ \Delta_\nu \frac{\Delta^+}{2M} \right. \]

\[ + \tilde{H}^q(x, \xi, t) \gamma^+ \gamma^5 + \tilde{E}^q(x, \xi, t) \gamma^5 \frac{\Delta^+}{2M} \left. \right] N(p) \]

- \( x \): average fraction of quark longitudinal momentum
- \( \xi \): fraction of longitudinal momentum transfer

H, E, \( \tilde{H}, \tilde{E} \): Generalized Parton Distributions (GPDs)

3-D Imaging conjointly in transverse impact parameter and longitudinal momentum
UNRAVELING CONFINEMENT FORCES IN PROTON

Nucleon matrix element of Energy Momentum Tensor (EMT) contains:

\[ M_2(t) : \text{Mass distribution inside the nucleon} \]
\[ J(t) : \text{Angular momentum distribution} \]
\[ d_1(t) : \text{Shear forces and pressure distribution} \]

Measure directly in graviton-proton scattering

\[ \int dx xH(x, \xi, t) = M_2(t) + \frac{4}{5} \xi^2 d_1(t) \]

\[ \text{Re}\mathcal{H}(\xi, t) \overset{\text{LO}}{=} D(\xi, t) \]
\[ + \mathcal{P} \int_{-1}^{1} dx \left( \frac{1}{\xi - x} - \frac{1}{\xi + x} \right) \text{Im}\mathcal{H}(\xi, t) \]

From measurement of D(t), we learn about confinement forces in the proton.
Elastic form factors → Transverse charge & current densities $F_1(t), F_2(t)$.

Deeply exclusive processes → GPD’s and 3D images in transverse space and longitudinal momentum. 4 GPDs $H, E, \tilde{H}, \tilde{E} (x,\xi,t)$

DIS structure functions → Longitudinal parton momentum & helicity densities, $F_2(x), g_1(x)$. 
Facilities and equipment to Explore Hadron Structure became possible with all the advancement in detector, Electronics and Computing technologies.

- **Unprecedented capabilities:**
  - High Intensity
  - High Duty Factor
  - High Polarization
  - Parity Quality Beams
  - Large acceptance detectors
  - State-of-the-art polarimetry and polarized targets
  - High luminosity

- Facilities and laboratories working together
Jefferson Lab Overview

• One of 17 U.S. Department of Energy National Laboratories
  – Single program focus on Nuclear Physics

• Created to build and operate the Continuous Electron Beam Accelerator Facility (CEBAF), world-unique user facility for Nuclear Physics

• Mission is to gain a deeper understanding of the structure of matter
  – Through advances in fundamental research in nuclear physics
  – Through advances in accelerator science and technology

• In operation since 1995

• Managed for DOE by Jefferson Science Associates, LLC (JSA)

Jefferson Lab by the numbers:

• 700 employees
• 169 acre site
• 1,600 Active Users
• 27 Joint faculty
• 608 PhDs granted to-date (211 in progress)
• K-12 programs serve more than 12,000 students and 950 teachers annually
12 GeV CEBAF Upgrade Project is Complete, On-time and On-Budget!

Project Completion Approved September 27, 2017
12 GeV CEBAF Upgrade Project is Complete, On-time and On-Budget!

Project Completion Approved September 27, 2017
RECOMMENDATION I
The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in the 2015 Plan is to capitalize on the investments made.

- With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.

→ Operate 12 GeV CEBAF – highest priority

RECOMMENDATION II
We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

RECOMMENDATION III
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

→ Jefferson Lab EIC (JLEIC) development
→ BNL (eRHIC) development
→ National Academy of Sciences report

RECOMMENDATION IV
We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.
Quantum phase-space distributions of quarks

\[ W_{p}^{q}(x,k_{T},r) \]

Wigner distributions

Probability to find a quark \( q \) in a nucleon \( P \) with a certain polarization in a position \( r \) & momentum \( k \)

\[ J_{q} = \frac{1}{2} \]

\[ + L_{q} = \lim_{t \to 0} \int \frac{dx}{x} \left[ H(x, t) + E(x, t) \right] \]

TMD PDFs: \( f_{p}^{u}(x,k_{T}), \ldots \)

GPDs: \( H_{p}^{u}(x,x,t), \ldots \)

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

PDFs \( f_{p}^{u}(x), \ldots \)
DVCS WITH POLARIZED E⁻ BEAM IN HALL A/C

$K=11$ GeV, $Q^2=9$ GeV², $x_B=0.6$, $\theta_e=30.23^\circ$, $\kappa=3$ GeV, $\theta_{\text{c.m.}}=-11^\circ$

Calo 13x16 Blocks at 3 meters $L_u=2.97 \times 10^{38}$ cm⁻² s⁻¹, 400 Hours

$-0.4 > t_1 > -0.67 > t_2 > -0.8 > t_3 > -0.93 > t_4 > -1.14 > t_5 > -1.6$ GeV²

Jefferson Lab
The CLAS12 Detector

Baseline equipments

**Forward Detector (FD)**
- TORUS magnet (6 coils)
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter

**Central Detector (CD)**
- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of-Flight

**Beamline**
- Polarized target (transv.)
- Moller polarimeter
- Photon Tagger

Upgrades to the baseline & under construction
- RICH detector (FD)
- Forward Tagger (FD)
- Neutron detector (CD)
- Micromegas (CD)
- Polarized target (long.)
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45 Institutions
A path towards extracting GPDs

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta \sigma}{2\sigma} \]

\[ \xi \sim x_B/(2-x_B) \]

\[ k = t/4M^2 \]

Polarized beam, unpolarized target:

\[ \Delta \sigma_{LU} \sim \sin \phi \left\{ F_1 H + \xi(F_1 + F_2)\tilde{H} + kF_2 E\right\} d\phi \]

Unpolarized beam, longitudinal target:

\[ \Delta \sigma_{UL} \sim \sin \phi \left\{ F_1 \tilde{H} + \xi(F_1 + F_2)(H + \xi/(1+\xi)E)\right\} d\phi \]

Unpolarized beam, transverse target:

\[ \Delta \sigma_{UT} \sim \cos \phi \sin(\phi_s - \phi) \{k(F_2 H - F_1 E)\} d\phi \]

Unpolarized total cross section:

Separates h.t. contributions to DVCS

\[ H(\xi,t) \]

\[ \tilde{H}(\xi,t) \]

\[ E(\xi,t) \]

\[ \text{Re}(T^{DVCS}) \]
GPDS KINEMATICS

Accessed by beam/target spin asymmetry

$H(x, \xi, 0)$

Accessed by cross sections

t=0
GPDS KINEMATICS

Mapping GPDs requires large kinematical coverage

Accessed by beam/target
spin asymmetry

Accessed by cross sections

$H(x, \xi, 0)$

$t=0$
$A_{LU}$ Projections for 12GeV

$$\Delta\sigma_{LU} \sim \sin\phi \left\{ F_1 H + \xi(F_1+F_2)H + kF_2 E \right\} d\phi$$

$\vec{e}p \rightarrow ep\gamma$
**$A_{LU}$ - Projections for protons**

$$e^p \rightarrow ep\gamma$$

$E_e = 11 GeV$

$$\Delta \sigma_{LU} \sim \sin \phi \{ F_1 H + \xi (F_1 + F_2) \bar{H} + kF_2E \} d\phi$$
Beam-spin asymmetry for nDVCS

CLAS12 Projection

$J_u = .3, J_d = .1$

$J_u = .1, J_d = .1$

$J_u = .3, J_d = .3$

$J_u = .3, J_d = -.1$
Broad science program at 11 GeV
- N* physics at short distances
- Imaging of nucleon quark structure
- GPDs, TMDs
- Exotic hadrons
- Strong interaction in nuclei
- Gravitational structure of the proton

=> Many talks at this conference
(sessions: EE- FE)
- High energy **electron**
  \[ E_{elec} > 2 \text{ GeV} \]

- High energy **photon**
  \[ E_{phot} > 3 \text{ GeV} \]

- **Proton**

- **Kinematical cuts**
  \[ Q^2 = -q^2 > 1 \text{ GeV}^2 \]
  \[ W^2 = (p + q)^2 > 4 \text{ GeV}^2 \]
FIRST LOOK AT BEAM-SPIN ASYMMETRY FROM CLAS12

Preliminary asymmetry:

\[ A_{LU} = \frac{1}{P} \frac{N^+(\phi_{trento}) - N^-(\phi_{trento})}{N^+(\phi_{trento}) + N^-(\phi_{trento})} \]

- Residual background not yet subtracted
- Only statistical errors
- Integrated over all kinematic domain
The Emergence of Confinement

History of the Universe

Dramatic events in the μsec old universe
- Chiral symmetry is broken
- Quarks attain masses dynamically
- Quark confinement occurs

QGP ➔ Hadron gas phase

With electron machines we explore these events to unravel the mechanisms of confinement
FROM THE H SPECTRUM TO THE N* SPECTRUM

Understanding the hydrogen atom requires understanding its spectrum of sharp energy levels
-> From the Bohr model to QED

Understanding the proton requires understanding its energy spectrum of broad energy levels
-> From the quark model to strong QCD

We have the theory and need to apply it to the excited states of the proton.

Niels Bohr, model of the hydrogen atom, 1913.
Resonances cannot be uniquely separated in inclusive scattering → exclusive processes

\[ Q^2 = -(e-e')^2; \quad W^2 = M_X^2 = (e-e'+p)^2 \]
Understand the physics of NΔ transition at the partonic level.

At leading twist in QCD: 3 vector N-Δ GPDs and 4 axial-vector N-Δ GPDs.

Expectation is that 3 GPDs dominate at small t.

\[
H_M(x, \xi, t) = \frac{2}{\sqrt{3}} \left[ E^u(x, \xi, t) - E^d(x, \xi, t) \right],
\]

\[
C_1(x, \xi, t) = \sqrt{3} \left[ \tilde{H}^u(x, \xi, t) - \tilde{H}^d(x, \xi, t) \right],
\]

\[
C_2(x, \xi, t) = \frac{\sqrt{3}}{4} \left[ \tilde{E}^u(x, \xi, t) - \tilde{E}^d(x, \xi, t) \right].
\]
Example: Access NΔ GPDs in ΔVCS

\[ \text{e}^- + \text{p} \rightarrow \text{e}^- + \Delta^+ + \gamma \ (\Phi = 0^\circ) \]

\[ Q^2 = 2.5 \text{ GeV}^2, x_B = 0.3 \]

\[ \frac{d\sigma}{dk_e d\Omega_e d\Omega_\gamma} \text{ (nb/GeV sr}^2) \]

\[ E_{e^-} = 6 \text{ GeV}, E_{e^-} = 8 \text{ GeV}, E_{e^-} = 12 \text{ GeV} \]

\[ \Theta_{\gamma} \text{ (deg)} \]

\[ \text{BH} \quad \text{DVCS} \]

\[ \text{DVCS} \quad \text{BH} \quad \text{C1} \]
Similar to elastic DVCS+BH, \( \Delta VCS + BH \) have a beam spin asymmetry.

In large \( N_c \) limit beam spin asymmetry can be computed using magnetic transition form factor \( G_M^\Delta \) of \( N\Delta \) as input.
Experimental Aspects

\[ \text{ep} \rightarrow e\pi^+(\gamma) \quad E_e = 4.2 \text{GeV}, \quad Q^2 \sim 1 \text{GeV}^2 \]

\( W > 2 \text{ GeV} \)

CLAS12 can access, \( Q^2 < 10 \text{ GeV}^2, \ x_B < 0.8 \)

N-N*(J=1/2, T=1/2) GPDs should have simpler structure than N-\( \Delta \) (J=3/2, T=3/2) GPDs.

- Need to develop transition GPD formalism for NN* transitions in N*DVCS.

- Channels of interest for experiments
  \( p(e,e'\gamma\rho\pi^0) \), \( p(e,e'\gamma\rho\eta) \), \( p(e,e'\gamma\eta\pi^+) \), \( n(e,e'\gamma\rho\pi^-) \) for low mass states, and \( p(e,e'\gamma\rho\pi^+\pi^-) \) for high mass states.
Precision multi-dimensional mapping of 3D PDFs using SoLID, CLAS12, EIC,...
Motivation
The science of imaging the interior of the atomic nucleus is in its infancy. With new tools at our disposal, we are poised to make major progress in the near future.

Notable events:
• Development of 3D formalism for nuclear structure
• New experimental tools becoming available
• Need for a multidisciplinary approach

→ Center for Nuclear Femtography
Proposal to Commonwealth of VA

- Initial request of $.5M for pilot study funded, future funding of ~$2M/year envisioned

- Consortium of VA universities, Jefferson Lab, others?

- Theoretical physics, experimental physics, computation, statistics, data science, visualization – interdisciplinary effort
FIRST STEP TOWARDS THE CENTER

• Symposium at the University of Virginia in December 2018. The symposium brought together scholars and researchers from universities and research institutes from around the world to discuss recent developments and future opportunities in the imaging and visualization of scientific data across a spectrum of disciplines and how these could be applied to advance Nuclear Femtography.

1. Collect interested parties, experts from nuclear physics and other disciplines

2. Exchange information on expertise, capabilities relevant to Nuclear Femtography

3. Identify areas of potential collaboration

4. Discuss the development of the Center and near-term activities
As the next step, we will be soliciting applications for near-term projects that can both seed future activities at the Center, and can contribute to a future proposal to the Commonwealth of Virginia aimed at the long-term establishment of a world-leading Center. These projects include, but are not restricted to:

1. The construction of a QCD-inspired reference model for the nucleon, including that of the Wigner Distribution, that can serve as synthetic input for the activities below.

2. The development of images of the nucleon through fitting to experimental data with theoretical input, reflecting constraints arising from limitations both in experiment and theory.

3. The use of Visualization both as a means of imaging the nucleon, and of refining our analysis methodology.

4. Applications of Machine Learning to data analysis, interpretation and classification.

5. The development and application of computational and mathematical methods, and the associated computational infrastructure.
SUMMARY

Theory
Phenomenology
Computer Science

Experiments:
CEBAF at 6 & 12 GeV, DESY, CERN, & EIC

CNF
Thank You

follow me on 

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