Exploring the 3D Partonic Structure of Neutron with BONuS12

M. Hattawy

- Physics Motivations
- Recent Results.
- Proposed Measurements.

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Most of what we know today about hadrons’ structure has come from the electromagnetic probes which give access to measure structure functions that quantify the properties of partons in hadrons.

● Form Factors (FFs)
  → Provide the charge and magnetization distributions inside a hadron.
  → Accessible via Elastic Scattering (ES).

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{exp}} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Motl}} \frac{E'}{E} \left( \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2\left(\frac{\theta_e}{2}\right) \right)
\]

Quick reminder about the Hadron Structure

Structure functions that quantify the properties of the partons in a hadron:

- **Form Factors (FFs)**
- **Parton Distribution Functions (PDFs)**
  - Provide partons longitudinal momentum distributions
  - Measurable via Deep Inelastic Scattering (DIS).

  - For nucleons, the unpolarized DIS cross section is parametrized by two PDFs: $F_{1,2}(x)$, with
    
    \[
    F_1(x) = \frac{1}{2} \sum_q e_q^2 f_1(x) \quad \text{and} \quad F_2(x) = x \sum_q e_q^2 f_2(x)
    \]

  - Proton structure:
    
    \[\text{Large } x, \; u_v(x) \sim 2 \; d_v(x)\]
    
    \[\text{Low } x, \; \text{more gluons radiated and splitting producing sea quarks}\]

Generalized Parton Distributions

- **Contain information on:**
  - Correlation between quarks and anti-quarks
  - Correlation between **longitudinal momentum** and **transverse spatial** position of partons

- **Can be accessed via** hard exclusive processes such as deeply virtual Compton scattering (DVCS):

  \[
  t = \left( p - p' \right)^2 = \left( q - q' \right)^2
  \]

  \[
  \xi \approx x_B \left( 2 - x_B \right)
  \]

  \[
  x_B = \frac{Q^2}{2p.q}
  \]

  \[
  \delta_{\perp} \sim \frac{1}{Q}
  \]

  \[
  \delta_{\parallel} \sim \frac{1}{v}
  \]

  \[
  \xi \approx \frac{x_B}{2 - x_B}
  \]

- **Experimentally,** the **measured** photon-electroproduction cross section (ep → epγ) is:

  \[
  d\sigma \propto |\tau_{\text{BH}}|^2 + \left( \tau_{\text{DVCS}}^* \tau_{\text{BH}} + \tau_{\text{BH}}^* \tau_{\text{DVCS}} \right) + |\tau_{\text{DVCS}}|^2
  \]

  \[
  \frac{1}{2}
  \]

- The **DVCS** signal is enhanced by the interference with BH.

* At leading order in \(1/Q^2\) (**twist-2**) and in the coupling constant of QCD (\(\alpha_s\)).
GPDs links to FFs and PDFs

GPDs: $H, E, \tilde{H}, \tilde{E}$
Fully correlated quark distributions in both coordinate and momentum space

Form factors:
transverse quark distribution in coordinate space

\[
\int H(x,\xi,t)dx = F_1(t) \quad (\forall \xi)
\]
\[
\int E(x,\xi,t)dx = F_2(t) \quad (\forall \xi)
\]

Parton distributions:
longitudinal quark distribution in momentum space

\[
\int H(x,0,0)dx = q(x), \quad \tilde{H}(x,0,0) = \Delta q(x)
\]
Proton Tomography via DVCS

- Local fit of all the JLab data
  - Jlab Hall A (σ, Δσ)
  - CLAS (σ, Δσ, ITSA, DSA)

- Enough coverage to explore the t and $x_B^\rightarrow\xi$ dependence of $H_{\text{Im}}$.

- Obtaining the tomography of the proton
  - Represented is the mean square charge radius of the proton for slices of $x$.

- The nucleon size is shrinking with $x$.

Why Do We Need to Measure Neutron GPDs

- First free proton 3D tomography has been extracted within the GPDs framework.

- Much less is known about the neutron structure, unavailability of free neutron target.

- First dedicated nDVCS measurement at CLAS12, E12-11-003

\[ \gamma^* + d \rightarrow n + \gamma + (p), \] looking for the flavor separation of GPDs:

\[
(H, E)_u(\xi, \xi, t) = \frac{9}{15} \left[ 4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t) \right]
\]

\[
(H, E)_d(\xi, \xi, t) = \frac{9}{15} \left[ 4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t) \right]
\]

What do we propose to measure here? Why? ...
Two nDVCS channels are accessible with BONuS12:

◊ **Tagged-proton nDVCS:** $\text{e}^- \text{D} \rightarrow \text{e}^- \text{p} \gamma (\text{n})$
  → Study the partonic structure of the neutron via measuring the $A_{LU}$

\[
A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B} \frac{N^+ - N^-}{N^+ + N^-}
\]

◊ **Fully exclusive nDVCS:** $\text{e}^- \text{D} \rightarrow \text{e}^- \text{n} \gamma \text{p}$
  → Study the Fermi motion effect on $A_{LU}$
  → Measure the size of the FSI on $A_{LU}$
  → Explore the size of the systematic uncertainty on RG-B measurement.
RG-F Approved Experimental Setup

- **CLAS12 Forward Detector:***
  - Superconducting **Torus** magnet.
  - 6 independent sectors:
    - **HTCC:** identifying $\pi^-$ ($p > 5.0 \text{ GeV}/c$).
    - **LTCC:** $\pi^-$ identification ($p > 3.0 \text{ GeV}/c$).
    - **FTOF Counters:** identifying hadrons.
    - **PCAL and Ecs:** detecting $\gamma$, $e^-$ and n ($5^\circ, 40^\circ$).
    - **FT:** detecting $\gamma$, $e^-$ [$2.5^\circ, 4.5^\circ$]

- **Central Detector:**

  - **Target:** D gas @ 7.5 atm, 293 K
  - **BONuS12 RTPC:** Detects low energy spectator protons.
  - **Solenoid:** Shields the detectors from Møller electrons.
  - **Additional detectors to be used:** CTOF, CND, and FMT

We are asking for the electron beam to be highly polarized

- **$e^- D \rightarrow \ldots$**

- **35 days on D**
- **5 days on H$_2$**
- **with** $L = 2 \cdot 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
BONuS12 RTPC

- Design:
  ♦ 100% azimuthal coverage
  ♦ 400 mm long, 160 mm Ø
  ♦ 50 μm target's Kapton wall
  ♦ 4 μm cathode foil @ 4.3 kV
  ♦ 40 mm drift region, uniform $|E| = 500 \, \text{V/cm}$, $|B| = 5 \, \text{T}$
  ♦ 3 GEMs layers, gain of 1000/layer
  ♦ 17280 readout elements (2.7 mm x 3.9 mm).

- Work principle:
  Charged particle ionizes the gas atoms
  → Under EM field, released electrons follow their drift paths at a certain drift speed
  → Amplifications via the 3 GEM layers
  → Readout board, record electrons' charges (ADCs units) in time bins (TDCs units).

- Offline reconstruction:
  $\langle \frac{dE}{dX} \rangle = \frac{\sum_i ADC_i}{G_i vtl}$

PID $p/q$
nDVCS Generation, Simulation, & Reconstruction

- nDVCS event generation: GENEPI DVCS/DVMP Generator
- Simulation: CLAS12 official simulation (GEMC 4.3.0)
- Reconstruction: COATJAVA 5b.7.4
Tagged-proton nDVCS Events Selection

Events which have:
◊ Events with:
  - One good electron
  - One high-energy photon ($E_\gamma > 2$ GeV)
  - One proton in BONuS12.
◊ $Q^2 > 1$ GeV$^2$ and $W > 2$ GeV/c$^2$
◊ Exclusivity cuts.
Tagged-proton nDVCS Phase-Space

\[ A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B} \frac{N^+ - N^-}{N^+ + N^-} \]

3D bins: \( x^* \) vs. \( t \) vs. phi

\[ x^* = \frac{Q^2}{2M_N E_y(2 - \alpha_{sp})} = \frac{x_B}{2 - \alpha_{sp}}, \]

\[ \alpha_{sp} = \frac{E_s - p_s^z}{M_N} \]
Tagged-proton nDVCS $A_{LU}$ Projections

◊ 9M expected events.
◊ Total of 108 bins in $x^*$ vs. t vs. phi
◊ 20% conservative sys. Uncertainties.
◊ Exploring the neutron’s CFF via the BSA.
◊ Compare the nDVCS to Free proton DVCS.
Fully exclusive nDVCS Events Selection

Events which have:
◊ Events with:
  - One good electron
  - One high-energy photon
    \((E_\gamma > 2 \text{ GeV})\)
  - One proton in BONuS12.
  - One neutron in FD or CD
◊ \(Q^2 > 1 \text{ GeV}^2\) and \(W > 2 \text{ GeV}/c^2\)
◊ Exclusivity cuts.
Fully exclusive nDVCS Phase-Space & binning

- a. Initial bin in $x^*$ vs. $t$

- b. 6 bins in the spectator proton $p$ vs. $\theta$

- c. Binning in $\phi$
Fully Exclusive nDVCS $A_{LU}$ Projections

◊ 9M tagged nDVCS events (black) ~ 0.8M fully exclusive nDVCS (blue).

◊ 20% conservative sys. uncertainties.

◊ Exploring the Fermi motion and FSI effects on BSA.
Other Physics Opportunities

The proposed nDVCS measurements is only a fraction of the physics that can be achieved by successfully analyzing the polarized beam data from RG-F.

- **π^0** production off D
  - Coherent and incoherent production.
  - Measure BSA, leading to chiral-odd CFFs.
  - Also as a DVCS background.

- **Coherent DVCS off D**
  - Access to new GPDs, H_3, with relationships to deuteron charge form factors.

- **Coherent DVMP off D**
  - π^0, φ, ω and ρ mesons.

- **Semi-inclusive reaction p(e,e'p)X**
  - Study the π^0 cloud of the proton.

- **D(e, e'pp_{s})X**
  - Study the π^- cloud of the neutron.

- **Incoherent p DVCS & DVMP**

- **More Physics:**
  - Transverse momentum distributions (TMDs) on the neutron (twist-3).
  - The medium modification of the transverse momentum dependent parton distributions.
  - Final state interactions through the 5th structure function in D(e, e0p n).

- **Transverse momentum distributions (TMDs)**
  - The medium modification of the transverse momentum dependent parton distributions.
  - Final state interactions through the 5th structure function in D(e, e0p n).
Polarizing the electron beam during the approved RG-F will allow us to investigate in a unique way many aspects of QCD within the GPD framework.

Complementary to the approved E12-11-003 experiment, \( \gamma^* + d \rightarrow n + \gamma + (p) \).

We intend to measure the neutron DVCS beam-spin asymmetry by:
- tagging the spectator slow-recoiling proton
- measuring the fully exclusive neutron DVCS channel.

Additional physics topics to be investigated, increasing the physics outcome of the approved beam time.
Hadronic Structure Functions

Structure functions that quantify the properties of the partons in a hadron:

\[ f(k, P) \text{ parton correlation function} \]

\[ W(x, k, b) \text{ Wigner distribution} \]

\[ f(x, z) \leftrightarrow f(x, b) \text{ impact parameter distribution} \]

\[ f(x) \text{ PDF} \]

\[ F_n(b) \leftrightarrow F_n(\Delta^2) \text{ form factor} \]

\[ \sum_{k=0}^{n} A_{nk}(\Delta^2) (2\xi)^k \text{ GFFs} \]

\[ H(k, P, \Delta) \text{ parton correlation function} \]

\[ H(x, k, \xi, b) \leftrightarrow H(x, k, \xi, \Delta) \text{ GTMD} \]

\[ H(x, \xi, b) \leftrightarrow H(x, \xi, \Delta^2) \text{ GPD} \]

\[ f dk^- \]

\[ \int d^2k \]

\[ \int dx x^{n-1} \]