Deeply Virtual Compton Scattering off the Neutron and Proton from deuterium with CLAS12 at Jefferson Lab

Adam Hobart
outline

• Motivations
• Data Samples and Event selection
• Exclusivity variables
• Refined neutron selection: The problem of mis-identified protons
• Partially reconstructed neutral pion background
• Beam Spin Asymmetries
• Conclusions
Motivations

Generalised Parton Distributions (GPDs):
Correlation of transverse position and longitudinal momentum of partons in nucleon & the spin structure

- Nucleon internal structure: DVCS gives access to 4 complex GPDs-related quantities: Compton Form Factors CFF
  
  \[ \bar{H}, \bar{E}, \tilde{H}, \tilde{E} (x, \xi, t) \]

- Experimentally: access combinations of CFF

  Polarized beam, unpolarized target:
  \[ \Delta \sigma_{UL} \sim \sin \phi \text{ Im}\{F_1 \bar{H} + \xi(F_1 + F_2 \bar{H} - k F_2 \bar{E} + \ldots) \} \]

  \[ \text{Im}\{\bar{H}_p, \tilde{H}_p, \bar{E}_p\} \]

  \[ \text{Im}\{H_n, \tilde{H}_n, \bar{E}_n\} \]

- Separation of CFFs: measure several observables

  Unpolarized beam, transverse target:
  \[ \Delta \sigma_{UT} \sim \cos \phi \sin(\phi_s - \phi) \text{ Im}\{k(F_2 \bar{H} - F_1 \bar{E}) + \ldots\} \]

  \[ \text{Im}\{\bar{H}_p, \bar{E}_p\} \]

  \[ \text{Im}\{H_n\} \]

- Measure GPDs on both nucleons: flavour separation of GPD

\[ (H,E)_u (x, \xi, t) = \frac{9}{15_1} \left[ 4(H,E)_p (x, \xi, t) - (H,E)_n (x, \xi, t) \right] \]

\[ (H,E)_d (x, \xi, t) = \frac{9}{15_1} \left[ 4(H,E)_n (x, \xi, t) - (H,E)_p (x, \xi, t) \right] \]
Motivations

• Physics observable: Beam Spin Asymmetry BSA
  • Scattering off neutron (nDVCS): GPD E
    • Determination of Ji sum rule
      • Contribution of orbital angular moment of quarks to the nucleon spin
        \[ J^q = \frac{1}{2} \int_{-1}^{1} x dx \left[ H^q(x, \xi, 0) + E^q(x, \xi, 0) \right] \]
  • Scattering off proton (pDVCS): GPD H
    • Quantify medium effects
      • Essential for the extraction of BSA of a “free” neutron (de-convoluting medium effect via comparison with DVCS on hydrogen target)

Model predictions (VGG) for different values of quarks’ angular momentum

\[ J_u = 3, J_d = -1 \]
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\[ J_u = 1, J_d = -1 \]
nDVCS with CLAS12

- Experimental configuration:
  - Baseline CLAS12 configuration + Central Neutron Detector
  - Highly polarized electron beam (~86% polarization) measured with 9 Moeller runs
  - Unpolarized liquid deuterium target (5 cm long)

- Run Dates considered in this talk for analysis:
  - Data taken during 3 periods in 2019 and early 2020: ~40% of the approved beamtime
  - Magnet inbending at 10.6 and 10.2 GeV beam energy (50% of all collected data)
  - Magnet outbending at 10.4 GeV beam energy (20% of all collected data)
  - Magnet inbending at 10.4 GeV beam energy (30% of all collected data)

Figure in V. Burkert et al., Nucl.Instrum.Meth.A 959 (2020) 163419
Channel selection for nDVCS and pDVCS

• Construct all the possible combinations of final state particles: ed→e’Nγ(N_{spec}) (N: nucleon)
  • Final states reconstructed using CLAS12 PID + a dedicated charged particle veto for neutron selection optimisation
  • Best candidate in event is selected based on best exclusivity criteria (a multi-dimensional $\chi^2$ with all exclusivity variables)

• When a distribution shows a gaussian behavior, estimate cut with +/- 5 standard deviations
• Fiducial cuts included for: electrons in PCAL and DC, photons in PCAL and protons in DC
Reconstruction of final states and exclusive selection

- The nDVCS (pDVCS) final state is selected with the following exclusivity criteria: (N:nucleon)
  - Missing mass
    - \( e\ d \rightarrow e\ N\ \gamma\ X \)
    - \( e\ N \rightarrow e\ N\ \gamma\ X \)
    - \( e\ N \rightarrow e\ N\ X \)
  - Missing momentum
    - \( e\ d \rightarrow e\ N\ \gamma\ X \)
  - \( \Delta\Phi, \Delta t, \theta(\gamma, X) \)
    - Difference between two ways of calculating \( \Phi \) and \( t \)
    - Cone angle between measured and reconstructed photon
- The optimization of the exclusivity cut is performed on the sum of the squares of \( \Delta\Phi, \Delta t, \theta(\gamma, X) \) and missing mass \( e\ N \rightarrow e\ N\ X \)
- Cuts informed by Monte Carlo simulations:
  - GPD-based event generator for DVCS/\( \pi^0 \) on deuterium
  - DVCS amplitude calculated according to the BKM formalism
  - Fermi-motion distribution evaluated according to Paris potential

<table>
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<th>Proton</th>
<th>Electron</th>
<th>Photon</th>
<th>Neutron</th>
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<td>0.35</td>
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<tr>
<td>Q2 &gt; 1 GeV2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W &gt; 2 GeV2</td>
<td></td>
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</table>

\( \theta(e, \gamma) > 5^\circ \) Remove radiative photons
Particle kinematics nDVCS

- From simulation:
  - nDVCS photons are mainly at low $\theta$ (FT)
  - nDVCS neutrons are mainly in high $\theta$ (CD)

The privileged topology for nDVCS final state particles is for neutron in CD and photons in FT
Particle kinematics pDVCS

- From simulation:

- pDVCS photons are mainly at low $\theta$ (FT)
- pDVCS protons are mainly in high $\theta$ (CD)

The privileged topology for pDVCS final state particles is for proton in CD and photons in FT
Exclusivity cuts applied

Red: MC (DVCS)
Blue: data (DVCS + \(\pi^0\) background - e n \(\rightarrow\) e n \(\pi^0\) (1\(\gamma\))

\[
\langle Q^2 \rangle = 2.27 \text{ GeV}^2, \\
\langle -t \rangle = 0.44 \text{ GeV}^2, \\
\langle x_B \rangle = 0.19
\]

Proton Contamination already removed
Exclusivity variables: pDVCS

Exclusivity cuts applied

Red: MC (DVCS)
Blue: data (DVCS + $\pi^0$ background - $e^+ p \rightarrow e^+ p \pi^0(1\gamma)$)

$\langle Q^2 \rangle = 2.35 \text{ GeV}^2$

$\langle t \rangle = 0.71 \text{ GeV}^2$

$\langle x_B \rangle = 0.21$

no kinematical corrections of final state particles momenta
Issue: protons are mis-identified as neutrons

• Tracking in the CVT is neither 100% efficient nor uniform
  • Efficacy drops down with increasing luminosity
  • Dead regions in the CVT where protons have no associated track and are identified as neutrons
  • At analysis level it was clear that protons roughly account for more than 20% contamination in the signal sample

• Current approach to remove misidentified protons:
  • Reconstruct nDVCS from RGA requiring neutron pid from event builder
  • Most of those neutron are actually misidentified protons
  • Use this sample to determine the caractéristiques of fake neutrons in high level reconstructed variables

• Steps:
  • Train a MultiVariate Algorithm to subtract the proton contamination as observed from the fake RGA neutron sample
  • Use high level reconstructed variables for training
  • Use as background fake neutrons from the fake nDVCS sample reconstructed using RGA
  • Use as signal protons from RGA (Assumption that pDVCS and nDVCS have similar kinematics)
nDVCS from RGA

n+p DVCS simulations  
nDVCS from RGA

Inefficient regions of the CVT
Training variables/ Signal efficiency vs. Background rejection

Tried different versions with different variables
Performance was stable

We are currently studying the options of either cutting at 90% signal efficiency and treating remaining background in analysis
OR
Cutting around 60% signal efficiency and suppressing all proton background
Validation on nDVCS from RGB

nDVCS from spring 2020 run period of RGB

Before cut

After cut

The Cut removes very well the proton contamination
How about BSAs? (raw BSAs)

- nDVCS from spring 2020
- nDVCS from RGB with proton contamination
- nDVCS from RGB without proton contamination

![Graphs showing nDVCS data with chi-squared and fit parameters. The left graph shows a chi-squared of 19.71/6 with a fit parameter of 0.07743 ± 0.00395. The right graph shows a chi-squared of 5.723/6 with a fit parameter of 0.04138 ± 0.00689.]
How about BSAs? (raw BSAs)

Fake nDVCS from RGA

Proton contamination in nDVCS from RGB: BDT cut inverted
π⁰ background subtraction

• Subtraction using simulations of the background channel

• Description of the method:
  • Estimate the ratio of partially reconstructed eN π⁰(1 photon) decay to fully reconstructed eN π⁰ decays in MC
  • This is done for each kinematic bin to minimize MC model dependence
  • Multiply this ratio by the number of reconstructed eN π⁰ in data to get the number of eN π⁰(1 photon) in data
  • Subtract this number from DVCS reconstructed decays in data per each kinematical bin

\[ R = \frac{N(eN\pi^0_{1\gamma})}{N(eN\pi^0)} \]
\[ N(eN\pi^0_{1\gamma}) = R \times N(eN\pi^0) \]
\[ N(DVCS) = N(DVCS_{recon}) - N(eN\pi^0_{1\gamma}) \]

Associate a systematic on the exclusive selection by varying the exclusive selection cuts and checking the corresponding effect on the background fraction
  • The induced effect on the BSA is taken as a systematic
nDVCS with RGB data

First-time measurement of BSA for nDVCS with exclusive final state selection:

Fit function: $a \sin \phi$

Background subtracted

BSA integrated over all kinematics and detection topologies

$\chi^2 / \text{ndf} = 3.517 / 6$

$a = 0.04336 \pm 0.00783$

$<Q^2> = 2.27 \text{ GeV}^2$

$<-t> = 0.44 \text{ GeV}^2$

$<x_B> = 0.19$
Variation of the nDVCS BSA amplitude
pDVCS with RGB data

First-time measurement of BSA for pDVCS with a deuterium target
• proton in a weakly bound state
  \( ed \rightarrow ep\gamma(n) \)

BSA integrated over all kinematics and detection topologies

Fit function:
\[
A_u = \frac{a \sin \varphi}{1 + b \cos \varphi}
\]

\(<Q^2> = 2.35 \text{ GeV}^2
\<t> = 0.71 \text{ GeV}^2
\<x_B> = 0.21

\(-\infty < t < -0.5 \text{ GeV}^2
\-0.5 < t < -0.3 \text{ GeV}^2
\-0.3 < t < 0 \text{ GeV}^2

Background subtracted
Variation of the pDVCS BSA amplitude

CLAS12 Preliminary

Xbj

Q2
Comparing analysis chains between RGA and RGB: also compare Free to bound protons

• I produce pDVCS from RGA inbending data set and check raw BSA
  • I apply the same cuts that I have for my analysis

Raw integrated BSA from spring 2019 RGB run period 10.6 GeV beam

Raw integrated BSA from fall 2018 RGA run period 10.6 GeV beam

Good compatibility

Fit function: \( \frac{a \sin \phi}{1 + b \cos \phi} \)
Summary

• Quite advanced in the analysis: promising results
• Analysis Note to be submitted soon for review

• Kinematical corrections on the way
• A global Neutron identification tool using informations from Central detectors is under study
On Fiducial cuts

• For electrons:
  • homogenous cut on the natural \(v\) and \(w\) coordinates of the PCAL to ensure enough distance between the cluster center and the edges
  • Ensure a homogenous response of DC: Reject not well reconstructed tracks from the sides; cut based on the position dependence of the \(\chi^2/NDF\) distribution

• For photons:
  • cut based on the position dependence of the sampling fraction in the PCAL

• For Protons:
  • Ensure a homogenous response of DC: Reject not well reconstructed tracks from the sides; cut based on the position dependence of the \(\chi^2/NDF\) distribution
Variable correlations

**Correlation Matrix (signal)**

<table>
<thead>
<tr>
<th></th>
<th>$\Delta(t)$</th>
<th>$\Delta(\phi)$</th>
<th>$p_{Nue}$</th>
<th>$\theta_{13}$</th>
<th>$\Delta(\phi_{j})$</th>
<th>$\Delta(\gamma)$</th>
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<td>$\Delta(\gamma)$</td>
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**Correlation Matrix (background)**

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Classifier output: BDT

TMVA overtraining check for classifier: BDT

Kolmogorov-Smirnov test: signal (background) probability = 0.325 (0.841)
nDVCS partial pi0 background fraction in data
pDVCS partial π0 background fraction in data