DVCS off the Neutron in Jlab Hall A
(6 GeV experiments)

Meriem BENALI

Faculte des Sciences de Monastir (Tunisia)
Generalized Parton Distribution GPDs

Elastic Scattering

Deep inelastic scattering

Deep exclusive scattering

Form Factors
(Transverse position of partons)

Parton Distribution Function (PDFs)
(Longitudinal momentum distribution of the partons in the nucleon)

Two independent informations about the nucleon structure

Correlate

3-D picture of the nucleon
Generalized Parton Distribution GPDs

At leading order, 8 GPDs for each flavor quark $f$:

- **4 chiral even GPDs**:
  \[ H_f^f(x, \xi, t), E_f^f(x, \xi, t), \tilde{H}_f^f(x, \xi, t), \tilde{E}_f^f(x, \xi, t) \quad \text{Conserves the parton helicity} \]

- **4 chiral odd (transversity) GPDs**:
  \[ H_T^f(x, \xi, t), E_T^f(x, \xi, t), \tilde{H}_T^f(x, \xi, t), \tilde{E}_T^f(x, \xi, t) \quad \text{Flips the parton helicity} \]

➢ Link to Parton distribution functions at $(\xi=t=0)$

\[ H^q(x,0,0) \begin{cases} = q(x) ; & x>0 \\ = -\bar{q}(x) ; & x<0 \end{cases} \]

\[ \tilde{H}^q(x,0,0) \begin{cases} = \Delta q(x) ; & x>0 \\ = \Delta \bar{q}(-x) ; & x<0 \end{cases} \]

\[ \tilde{H}_T^q(x,0,0) \begin{cases} = \delta q(x) ; & x>0 \\ = \delta \bar{q}(-x) ; & x<0 \end{cases} \]

➢ Link to Form Factors ( $\forall \xi$)

\[ \sum_q e_q \int_{-1}^1 dx H^q(x, \xi, t) = F_1(t) \]

\[ \sum_q e_q \int_{-1}^1 dx E^q(x, \xi, t) = F_2(t) \]

\[ \sum_q e_q \int_{-1}^1 dx \tilde{H}^q(x, \xi, t) = G_A(t) \]

\[ \sum_q e_q \int_{-1}^1 dx \tilde{H}_T^q(x, \xi, t) = G_p(t) \]

\[ \sum_q e_q \int_{-1}^1 dx \tilde{H}_T^q(x, \xi, t) = G_T(t) \]
At leading order, 8 GPDs for each flavor quark $f$:

- **4 chiral even GPDS**:
  \[ H^f(x, \xi, t), E^f(x, \xi, t), \tilde{H}^f(x, \xi, t), \tilde{E}^f(x, \xi, t) \]  
  Conserve the parton helicity

- **4 chiral odd (transversity) GPDs**:
  \[ H_T^f(x, \xi, t), E_T^f(x, \xi, t), \tilde{H}_T^f(x, \xi, t), \tilde{E}_T^f(x, \xi, t) \]  
  Flip the parton helicity

- **Access to quark angular momentum, via Ji sum rule [X. Ji 1997]**:
  \[
  \frac{1}{2} \int_{-1}^{+1} dx \, x \left[ H_q(x, \xi, t = 0) + E_q(x, \xi, t = 0) \right] = \frac{1}{2} \Delta \Sigma_q + L_q
  \]

- **Solving the problem of the "spin puzzle"**:
  \[
  \frac{1}{2} = \frac{1}{2} \Delta \Sigma_q + L_q + J_q
  \]
  quark spin contribution  
  (\sim 30\% of total spin)  
  quark orbital  
  angular momentum  
  ???
The deep exclusive processes in the Bjorken regime are the simplest process which can be described in terms of GPDs by measuring its cross section

\[
\begin{align*}
Q^2 &= -(k - k')^2 \to \infty \\
\nu &= (k_0 - k'_0) \to \infty
\end{align*}
\]

and fixed

\[
\frac{Q^2}{2M_\nu} = x_B
\]

Deeply Virtual Compton Scattering (DVCS)

Deeply Virtual Meson Production (DVMP)

Perturbative part (calculable)

Non perturbative part parameterized by GPDs
Deeply Virtual Compton Scattering

The unpolarized cross section accesses the real part of the interference and the $|T^{DVCS}|^2$ term which are sensitive to an integral of GPDs over $x$

$$d^4\sigma + d^4\bar{\sigma} = 2\mathfrak{Re}(T^{DVCS} . T^{BH}) + |T^{DVCS}|^2 + |T^{BH}|^2$$

The polarized cross-section difference accesses the imaginary part of the interference and therefore GPDs at $x=\pm\xi$

$$d^4\sigma - d^4\bar{\sigma} = 2\mathfrak{Im}(T^{DVCS} . T^{BH})$$
Deeply Virtual Compton Scattering

At leading order (LO) and leading twist (LT) (twist-2):

\[ d^4\overline{\sigma} - d^4\overline{\sigma} = 2\Im m(T^{DVCS}T^{BH}) \]

\[ d^4\overline{\sigma} + d^4\overline{\sigma} = 2\Re e(T^{DVCS}T^{BH}) + |T^{DVCS}|^2 + |T^{BH}|^2 \]

Bilinear combination of Compton Form Factors CFFs

\[ C^{DVCS}(F, F^*) \propto 4(1-x_B)\mathcal{H}\mathcal{H}^* - f(x_B,Q^2,t)(\mathcal{H}\mathcal{E}^* + \mathcal{E}\mathcal{H}^*) + \ldots \]

Linear combination of CFFs

\[ C^I(F) = F_1(t)\mathcal{H} + \frac{x_B}{2-x_B} (F_1(t) + F_2(t))\tilde{\mathcal{H}} - \frac{t}{4M^2} F_2(t)\mathcal{E} \]

\[ \Re(\mathcal{H}^q) = \sum_q P \int dx \left( \frac{1}{x-\xi^+} \pm \frac{1}{x+\xi^+} \right) \mathcal{H}^q(x,\tilde{\xi},t) \]

\[ \Im m(\mathcal{H}^q) = -\pi \sum_q e_q^2 \left( \mathcal{H}^q(x = \xi, \xi, t) - \mathcal{H}^q(x = -\xi, \xi, t) \right) \]

We can extract 8 GPDs observables at LO/LT: \( \Re e \) and \( \Im m \left( F \in \{ \mathcal{H}, \tilde{\mathcal{H}}, \mathcal{E}, \tilde{\mathcal{E}} \} \right) \)

Known term

(fully calculable with nucleon FFs)

BMK : Belitsky et al.
BMP : Braun et al.
Deeply Virtual Compton Scattering

Access to GPDs via the **unpolarized cross section**:

- Subtract the known contribution of BH

\[
d^4\sigma + d^4\sigma = 2\Re( T^{DVCS} \cdot T^{BH} ) + |T^{DVCS}|^2 + |T^{BH}|^2
\]

**Known** (fully calculable with nucleon FFs)
Deeply Virtual Compton Scattering

Access to GPDs via the unpolarized cross section:

- Studying the $\phi$ and $E_{\text{beam}}$ dependence of $I$ and $|T^{\text{DVCS}}|^2$ at fixed $x_B$, $Q^2$ and $t$ allows to deduce some observables

$$d^4\sigma + d^4\sigma = 2\Re e(T^{\text{DVCS}} \cdot T^{\text{BH}}) + |T^{\text{DVCS}}|^2 + |T^{\text{BH}}|^2$$

$$|T^{\text{DVCS}}|^2 \propto \Gamma^{\text{DVCS}} E_{\text{beam}}^2 \left[ c_0^{\text{DVCS}}(\mathcal{F}) + c_1^{\text{DVCS}}(\mathcal{F}) \cos \phi + \ldots \right]$$

$$2\Re e(T^{\text{DVCS}} \cdot T^{\text{BH}}) \propto \Gamma^1 E_{\text{beam}}^3 \left[ c_0^1(\mathcal{F}) + c_1^1(\mathcal{F}) \cos \phi + c_2^1(\mathcal{F}) \cos 2\phi + c_3^1(\mathcal{F}) \cos 3\phi + \ldots \right]$$

$\mathcal{F} \in \{\mathcal{H}, \mathcal{H}, \mathcal{E}, \mathcal{E} \}$ : Compton Form Factors CFFs
Motivation (DVCS off the neutron)

- DVCS off the **neutron**: $F_1(t) \ll F_2(t)$

\[
C^I(\mathcal{F}) = F_1(t) \mathcal{H} + \frac{x_B}{2 - x_B}(F_1(t) + F_2(t))\tilde{\mathcal{H}} - \frac{t}{4M^2} F_2(t) E
\]

- **Sensitive to GPD** $E$ (least constrained GPD) and which is important to access quarks orbital momentum via Ji’s sum rule:

\[
\frac{1}{2} \int_{-1}^{+1} dx \ x \ [H_q(x, \xi, t = 0) + E_q(x, \xi, t = 0)] = J^q = \frac{1}{2} \Delta \Sigma_q + L_q
\]

- Neutron has different flavors from the proton => GPDs flavor separation:

\[
H^p(\xi, \bar{\xi}, t) = \frac{4}{9} H^u(\xi, \bar{\xi}, t) + \frac{1}{9} H^d(\xi, \bar{\xi}, t) \quad H^n(\xi, \bar{\xi}, t) = \frac{4}{9} H^d(\xi, \bar{\xi}, t) + \frac{1}{9} H^u(\xi, \bar{\xi}, t)
\]
E03-106: pioneer experiment of the DVCS off the neutron (2004):
Polarized cross section difference was determined at: $Q^2 = 1.91$ GeV$^2$; $x_B = 0.36$, $E_{\text{beam}} = 5.75$ GeV


Unpolarized cross section could not be extracted (huge systematic uncertainties)

Next experiment
Experimental setup

The **E08-025** (n-DVCS) experiment was performed at JLab Hall A in 2010

- **Goal:** Measure the n-DVCS total cross-section

**Beam Energy** = 4.45 GeV & 5.54 GeV

**I_{beam} ≈ 2-3 μA (80% polar.)**

\[
ep \rightarrow e\gamma p
\]

\[
ed \rightarrow e\gamma n (p)
\]

- The data were taken at two kinematics (**Kin2high** and **Kin2low**):
  - \( Q^2 = 1.75 \text{ GeV}^2 \)
  - \( x_{Bj} = 0.36 \)
  - \( t \sim [-0.5 , -0.1] \text{ GeV}^2 \)
  - Maximal luminosity = 3. \( 10^{37} \text{cm}^{-2}\text{s}^{-1} \)

- **Electromagnetic Calorimeter**
  - 13 X 16 PbF2 blocs (density 7.77 g/cm³)
  - block size : 3x3 cm² x 20 \( X_0 \)
  - Each blok is connected to (PM + base)
  - The detection Based on Čerenkov light detection
Selection of the n-DVCS events
Accidentals &\& \pi^0 contamination subtraction

The raw data: detect $e'$ and $\gamma$ in coincidence ( $eN \rightarrow e' \gamma X$)

• 1 track in the HRS and 1 cluster in the calorimeter (energy $> 1$ GeV)

→ The detected photon may be in fortuitous coincidence with the scattered electron

→ The photon detected in the calorimeter may come from the decay of $\pi^0$ and resembles kinematically to a DVCS photon: $eN \rightarrow e'\pi^0 X \rightarrow e' \gamma_1 \gamma_2 X$

$Spectrum : M_X^2 = (e + N - e' - \gamma)^2$

![Graphs showing the spectra for different processes](image)
Selection of the n-DVCS events

After:
- subtracting the accidentals,
- subtracting single photons coming from π⁰ decay (π⁰ contamination),
- adding Fermi momentum to H2 data,
- normalizing H2 and D2 data to the same luminosity,

\[ D(e,e'γ)pn = p(e,e'γ)p + n(e,e'γ)n + d(e,e'γ)d \]

We obtain the difference

\[ D(e,e'γ)X - H(e,e'γ)X = n(e,e'γ)n + d(e,e'γ)d + \ldots \]
Adjusting the simulation to the experimental data

Experimental data

+  

simulated data:

1- have the same cuts applied to the experimental data
2- have the same resolution and the same calibration as experimental data
3- takes into account the radiative corrections

Adjustment : \[ \chi^2 = \sum_{e=0}^{N_{\text{bin}}} \left( \frac{N_{e}^{\text{sim}} - N_{e}^{\text{exp}}}{\Delta \sigma_{e}^{\text{exp}}} \right)^2 \]

Cross Section \( \sigma^{\text{exp}} \)
Adjusting the simulation to the experimental data

**Experimental data**

\[ \text{Experimental data} \]

**simulated data:**
1. have the same cuts applied to the experimental data
2. have the same resolution and the same calibration as experimental data
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Adjustment: \[ \chi^2 = \sum_{e=0}^{N_{\text{bin}}} \left( \frac{N_{e}^{\text{sim}} - N_{e}^{\text{exp}}}{\Delta \sigma_{e}^{\text{exp}}} \right)^2 \]

Cross Section \[ \sigma^{\text{exp}} \]

**Diagram:**
- Experimental data
- Simulated data
- After smearing
- Simulation after smearing

**Graph:**
- X-axis: \( M_{X}^{2} \) (GeV^2)
- Y-axis: Number of entries
n-DVCS cross section (+d-DVCS)

Binning: \(12 \times 2 \times 5 \times 30\) bins in \(\varphi\), \(E\), \(t\) and \(M_X^2\)

- Dependence in \(\varphi\) ➔ Separate the different neutron LO/LT CFFs
  observables \(X_{in}\) (neutron) (or \(X_{id}\) (coherent deuton))

- Binning in \(M_X^2\) ➔ Separate \(n(e,e'\gamma)n\) and \(d(e,e'\gamma)d\) contributions
  \(M_X^2 d \approx M_X^2 n + t/2\)

The unpolarized \((nDVCS + dDVCS)\) total cross section (simplified expression):

\[
\frac{d^4 \sigma_{(nDVCS + dDVCS)}}{dQ^2 dx_B dt d\varphi} = BH_n + BH_d + \sum_i \Gamma_{in}(Q^2, x_B, t, \varphi) X_{in} + \sum_i \Gamma_{id}(Q^2, x_B, t, \varphi) X_{id}
\]

\(BH\_neutron\) contribution \(\rightarrow\) BH\_coherent deuteron contribution

Kinematical factor \(\rightarrow\) \((DVCS^2+i)\) neutron Contribution \(\rightarrow\) \((DVCS^2+i)\) Coherent deuteron Contribution

The observables we want to extract: the linear combinations of CFFS which contain GPDs
n-DVCS cross section (+d-DVCS)

Unpolarized cross section as a function of $\phi$, $E$ and $t$ bins:

- $E_{\text{beam}} = 4.45$ GeV
- $E_{\text{beam}} = 5.55$ GeV

- Neutron and coherent deuteron cross sections
- Neutron contribution (inclu syst. and stat. errors)
- Neutron BH
- Deutron contribution (inclu syst. and stat. errors)
- Deutron BH
- VGG prediction
- Cano and Pire
n-DVCS cross section (+d-DVCS)

Unpolarized cross section as a function of $\phi$, $E$ and $t$ bins:

- $E_{\text{beam}} = 4.45$ GeV
- $E_{\text{beam}} = 5.55$ GeV

- First experimental determination of the unpolarized cross section
- The first experimental evidence of a positive n-DVCS signal
n-DVCS cross section (+d-DVCS)

Simultaneous fit of two $E_{\text{beam}}$

- $E_{\text{beam}} = 4.45$ GeV
- $E_{\text{beam}} = 5.55$ GeV

Separate $|DVCS|^2$ and $|DVCS.BH|$ contributions

- $|DVCS|^2$ neutron contribution:
  - VGG prediction

- $|DVCS.BH|$ neutron contribution:

The DVCS² has a significant contribution to the cross section (in agreement with proton results at the same kinematics: M. Defurne et al., Nature Commun. 8, 1408, 2017)
Conclusion

- **First measurements** of the unpolarized cross section of the photon electroproduction off a deuterium target

- **Rosenbluth separation** of the DVCS and the interference terms for the neutron and the coherent deuteron

- **Neutron results**: significant deviation of the cross section from the n-BH:
  - a non-zero n-DVCS signal

- **Deuteron results**: compatible with d-BH and theoretical expectations

- A flavor decomposition of the CFFs can be performed by combining proton and neutron data

- The neutron results are sensitive to GPD E and can be exploited to constraint the quark angular momentum
Thank you for your attention
BACK-UP
Extraction of the cross section

According to the formalism of Muller Belitsky and the differential cross section is:

\[ d^4 \sigma = |T^{DVCS}|^2 + 2 T^{BH} \Re(T^{DVCS}) + |T^{BH}|^2 \]

\[ |T^{DVCS}|^2 \sim \Gamma_{DVCS} C_{0}^{DVCS} + \Gamma_{1}^{DVCS} C_{1}^{DVCS} \cos(\varphi) \]

\[ C_{DVCS} \sim \Gamma_{DVCS} C_{DVCS} (\mathcal{F}, \mathcal{F}^*) + \Gamma^{DVCS} C^{DVCS} (\mathcal{F}_{eff}, \mathcal{F}_{eff}^*) \]

\[ I \propto \Gamma_{0}^{1} C_{0}^{1} + \Gamma_{1}^{1} C_{1}^{1} \cos(\varphi) + \Gamma_{2}^{1} C_{2}^{1} \cos(2\varphi) + \Gamma_{3}^{1} C_{3}^{1} \cos(3\varphi) \]

\[ C_{n}^{I} = \Gamma_{n}^{I} \Re C_{++}^{I} (n|\mathcal{F}) + \Gamma_{n}^{I} \Re C_{0+}^{I} (n|\mathcal{F}_{eff}) + \Gamma_{n}^{I} \Re C_{-+}^{I} (n|\mathcal{F}_{eff}) \]

\[ \Re C_{++}^{I} (n|\mathcal{F}) = \Re C_{++}^{I}(\mathcal{F}) + \Re C_{++}^{I}(\mathcal{F}) + \ldots \]

\[ \Re C_{0+}^{I} (n|\mathcal{F}_{eff}) = \ldots \Re C_{0+}^{I}(\mathcal{F}_{eff}) + \Re C_{0+}^{I}(\mathcal{F}_{eff}) + \ldots \]

Electromagnetic Calorimeter

- 13x16 PbF₂ blocks (Čerenkov light detection)
  - Block size: 3x3 cm² x 20 X₀
  - Short radiation length:
    -> X₀ = (1/20) crystal length
  - Molière radius = 2.2 cm
- Electromagnetic shower is contained in 9 adjacent blocks
- Each block is connected to (PMT + base + ARS)

 ✓ Recording the input signal on 128 ns (ARS) as in a digital oscilloscope in order to solve the pile up signals.
 ✓ Digitization and recording of all calorimeter channels for each electron detected in HRS (trigger)
 ✓ The energy deposit determination is based on a waveform analysis of the ARS signals.

Blackening blocks under the effects of radiation:
  → The gains of the blocks decrease
  → Calibrate the response of the electromagnetic calorimeter

Arrival times signal

Amplitude

128 ns
Calorimeter energy calibration

Calibration method

\[ eN \rightarrow e' \pi^0 N \quad \gamma_1 \gamma_2 \quad \text{(Detected)} \]

The calibration method is based on the comparison between the measured energy of a detected \( \pi^0 \) from \( H(e,e' \pi^0)p \) events and its expected energy calculated with its scattering angle:

\[
\cos(\theta_{\gamma^*\pi^0}) = \frac{\vec{q}_{\gamma^*} \cdot \vec{q}_{\pi^0}}{||\vec{q}_{\gamma^*}|| \cdot ||\vec{q}_{\pi^0}||}
\]

\[
\chi^2 = \sum_{j=1}^{N} \left( \frac{E_j}{\pi} - \sum_{i=0}^{207} C_i E_i \right)^2
\]

Sum over all events

Calculated energy of pion

Sum over all blocks

Calibration coefficients

Calculated energy of \( \pi^0 \) (elastically calibrated)

The momentum of \( \pi^0 \) reconstructed using \( \vec{q}_{\gamma_1} \) et \( \vec{q}_{\gamma_2} \) several iterations to get the final coefficients for each block \( i \)

\[
C_i^\text{final} = C_i^{\text{iter} 1} \times C_i^{\text{iter} 2} \times \ldots C_i^{\text{iter} 7}
\]
The photon detected in the calorimeter may come from the decay of $\pi^0$ and resembles kinematically to a DVCS photon: $eN \rightarrow e'\pi^0 X \rightarrow e' \gamma_1 \gamma_2 X$

We applied a cut on the blocks of the edges and on the corner of the calorimeter to better estimate the $\pi^0$ contamination (Efficiency = 100% +/- 1)
Smearing of the simulation data

Smearing Result

For 5 in t and 20 in φ

- Good agreement between the resolution of the data and the simulation for each bin (t and φ)
- Good agreement between the calibration of the data and the simulation for each bin (t and φ)
- The first 20 bins are rejected (blocks on board of the calorimeter)
- The coefficients of the smearing determined with LH2_data and the p_DVCS simulation are then applied to d_DVCS and n_DVCS simulation.
Smearing of the simulation data

**Smearing Result**  
For 5 in $t$ and 20 in $\phi$

- Good agreement between the resolution of the data and the simulation for each bin ($t$ and $\phi$)
- Good agreement between the calibration of the data and the simulation for each bin ($t$ and $\phi$)
- The first 20 bins are rejected (blocks on board of the calorimeter)
- The coefficients of the smearing determined with LH2_data and the p_DVCS simulation are then applied to d_DVCS and n_DVCS simulation.

Calibration (position du pic)

The first 20 bins are rejected