Deeply Virtual Compton Scattering off $^{4}$He:

New results and future perspectives

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(On behalf of the CLAS collaboration)

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**EMC effect**

- Precise measurements at CERN, SLAC and JLab
  → Links with the nuclear properties, i.e. mass & density

- The **origin** of the EMC effect is still not fully understood, but possible explanations:
  → Modifications of the nucleons themselves
  → Effect of non-nucleonic degrees of freedom, e.g. pions exchange
  → Modifications from multi-nucleon effects (binding, N-N correlations, etc...)

- Clear explanations may arise from measuring the nuclear modifications via measuring the **Generalized Parton Distributions**.

**EMC effect**: the modification of the PDF $f_2$ as a function of $x$ [0.3, 0.75] carried by the parton.


Generalized Parton Distributions (GPDs)

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

- **Can be accessed via hard exclusive processes, such as DVCS.**

At leading twist (twist-2) and leading order $\alpha_s$, the DVCS is:

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

**GPD($x, \xi, t$):** the probability amplitude of picking up a parton with a longitudinal momentum $x + \xi$ and putting it back with a longitudinal momentum $x - \xi$ without breaking the nucleon with a momentum transfer squared $t$.
DVCS off nuclei

Two DVCS channels are accessible with nuclear targets:

◊ **Coherent DVCS:** $e^- A \rightarrow e^- A \gamma$
  → Study the partonic structure of the nucleus.
  → **One chiral-even GPD** $(H_A(x, \xi, t))$ is needed to parametrize the structure of the spinless nuclei ($^4$He, $^{12}$C, $^{16}$O, ...).

◊ **Incoherent DVCS:** $e^- A \rightarrow e^- N \gamma X$
  → The nucleus breaks and the DVCS takes place on a nucleon.
  → Study the partonic structure of the bound nucleons (4 chiral-even GPDs are needed to parametrize their structure).

\[
\begin{align*}
\text{conserve nucleon spin} & \quad \{ H(x, \xi, t), \tilde{H}(x, \xi, t) \} \\
\text{unpolarized} & \quad \{ E(x, \xi, t), \tilde{E}(x, \xi, t) \} \\
\text{flip nucleon spin} & \quad \{ H(x, \xi, t), \tilde{H}(x, \xi, t) \}
\end{align*}
\]
Nuclear spin-zero DVCS observables

The GPD $H_A$ parametrizes the structure of the spinless nuclei ($^4$He, $^{12}$C …)

$$H_A(\xi, t) = Re(H_A(\xi, t)) - i\pi Im(H_A(\xi, t))$$

$$Im(H_A(\xi, t)) = H_A(\xi, \xi, t) - H_A(-\xi, \xi, t)$$

$$Re(H_A(\xi, t)) = \mathcal{P} \int_0^1 dx [H_A(x, \xi, t) - H_A(-x, \xi, t)] C^+(x, \xi)$$

→ Beam-spin asymmetry ($A_{LU}(\phi)$) : (+/- beam helicity)

$$A_{LU}(\phi) = \frac{1}{P_B N^+ + N^-}$$

$$= \frac{x_A(1 + \epsilon^2)^2}{y} s^{INT}_1 \sin(\phi) \left[ \sum_{n=0}^{n=2} c_n^{BH} \cos(n\phi) + \frac{x_A^2 t(1 + \epsilon^2)^2}{Q^2} P_1(\phi) P_2(\phi) C_0^{DVCS} + \frac{x_A(1 + \epsilon^2)^2}{y} \sum_{n=0}^{n=1} c_n^{INT} \cos(n\phi) \right]$$
Theoretical predictions of the EMC in 4He

On-shell calculations:

1. Impulse approximation
   \[ \text{GPD}^{4\text{He}}(x, \xi, t) = \sum (\text{free p and n GPDs}) \ast F^{4\text{He}}(t) \]

2. Medium modifications:
   \[ H^{q/p*}(x, \xi, t, Q^2) = \frac{F^{p*}_{1}(t)}{F^{p}_{1}(t)} H^{q}(x, \xi, t, Q^2) \]

\[ H^{A}(x, \xi, t) = \sum_{N} \int \frac{d^2 P_{\perp} dY}{2(2\pi)^3} \frac{1}{A - Y} A^{P^{2}}(P_{2}, P_{2}) t \times \sqrt{\frac{Y - \xi}{Y}} \left[ H^{N}_{\text{OFF}}(\frac{x}{Y}, \frac{\xi}{Y}, P_{2}, t) - \frac{1}{41 - \xi/Y} E^{N}_{\text{OFF}}(\frac{x}{Y}, \frac{\xi}{Y}, P_{2}, t) \right] \]

Off-shell calculations:

Nucleus = bound nucleons + nuclear binding effects

Nuclear spectral function

\[ e(4\text{He}, e' B p X) \]

[S. Liuti, K. Taneja, PRC 72 (2005) 034902]

Nuclear DVCS measurements: HERMES

- The exclusivity is ensured via cut on the missing mass of $e\gamma X$ final state configuration.

- Coherent and incoherent separation depending on -t, i.e. coherent rich at small -t.

- Conclusions from HERMES:
  No nuclear-mass dependence has been observed.

\[
A_{LU}^{\sin} = \frac{1}{\pi} \int_{0}^{2\pi} d\phi \sin \phi A_{LU}(\phi)
\]

In CLAS - E08-024, we measure EXCLUSIVE coherent and incoherent DVCS channels off $^4$He

**CLAS - E08-024 experimental Setup**

\[ e^- \, ^4\text{He} \rightarrow e^- \, (^4\text{He}/pX) \, \gamma \]

- **Beam polarization (P_B) = 83%**

### CLAS:
- Superconducting Torus magnet.
- 6 independent sectors:
  - DCs track charged particles.
  - CCs separate $e^/\pi$.
  - TOF Counters identify hadrons.
  - ECs detect $\gamma$, $e^-$ and n [$8^\circ,45^\circ$].

### IC:
- Improves $\gamma$ detection acceptance [$4^\circ,14^\circ$].

### RTPC:
- Detects low energy nuclear recoils.

### Solenoid:
- Shields the detectors from Møller electrons.
  - Enables tracking in the RTPC.

### Target:
- $^4\text{He}$ gas @ 6 atm, 293 K
DVCS events selection (1/2)

We select **COHERENT** events which have:
◊ Only one good electron, at least one photon and only one good $^4$He.
◊ $E\gamma > 2$ GeV and $Q^2 > 1$ GeV$^2$.
◊ Exclusivity cuts (3 sigmas).

- In **BLUE**, coherent events before all exclusivity cuts.
- In shaded **BROWN**, coherent DVCS events which pass all the other exclusivity cuts except the one on the quantity itself.
We select **INCOHERENT** events which have:

- Only one good electron, at least one photon and only one good \( p \).
- \( E_{\gamma} > 2 \, \text{GeV} \), \( W > 2 \, \text{GeV}/c^2 \) and \( Q^2 > 1 \, \text{GeV}^2 \).
- Exclusivity cuts (3 sigmas).

- In **BLUE**, incoherent events before all exclusivity cuts.
- In shaded **BROWN**, incoherent DVCS events which pass all the other exclusivity cuts except the one on the quantity itself.
Coherent beam-spin asymmetries

- Due to statistical constraints, we construct 2D bins -t or x_B or Q^2 versus $\phi$

He-4 CFF extraction

\[ A_{LU}(\phi) = \frac{\alpha_0(\phi) \, \Im m(H_A)}{\alpha_1(\phi) + \alpha_2(\phi) \, \Re e(H_A) + \alpha_3(\phi) \left( (\Re e(H_A))^2 + (\Im m(H_A))^2 \right)} \]

\[
\begin{align*}
\alpha_0(\phi) &= \frac{x_A(1+\varepsilon^2)^2}{y} S_{++}(1) \sin(\phi) \\
\alpha_1(\phi) &= \alpha_0^{BH} + c_1^{BH} \cos(\phi) + c_2^{BH} \cos(2\phi) \\
\alpha_2(\phi) &= \frac{x_A(1+\varepsilon^2)^2}{y} (C_{++}(0) + C_{++}(1) \cos(\phi)) \\
\alpha_3(\phi) &= \frac{x_A^2 t (1+\varepsilon^2)^2}{y} P_1(\phi) \frac{P_2(\phi)}{1+\varepsilon^2} \cdot 2 - 2y + y^2 + \frac{\varepsilon^2 y^2}{2} 
\end{align*}
\]

→ The first ever experimental extraction of the real and the imaginary parts of the He-4 CFF:

→ Difference between the precision of the extracted real and imaginary parts; \( A_{LU} \) is mostly sensitive to the imaginary part of the CFF HA.
Incoherent beam-spin asymmetries

- 2D bins -t or x_B or Q^2 versus \( \phi \).

- Fit ALU signals: \( \alpha \sin(\phi)/(1 + \beta \cos(\phi)) \)

EMC ratio (1/2)

◊ Comparing our measured incoherent asymmetries with the asymmetries measured in CLAS DVCS experiment on the proton.

◊ The bound proton shows a lower asymmetry relative to the free one in the different bins in $x_B$.

◊ At small $-t$, the bound proton shows lower asymmetry than the free one.

◊ At high $-t$, the two asymmetries are compatible.
EMC ratio (2/2)

◊ Comparing the coherent asymmetries to the free proton ones:

→ Consistent with the enhancement predicted by the Impulse approximation model
  [V. Guezy et al., PRC 78 (2008) 025211]

→ Does not match the inclusive measurement of HERMES.

→ Additional nuclear effects have to be taken into account in the nuclear spectral function calculations. [S. Liuti and K. Taneja. PRC 72 (2005) 032201]
Future perspectives and proposals using “CLAS12 + ALERT” experimental setup


◊ CLAS–E08-024 experiment:
  → 2D binning due to limited statistics and limited phase-space.

◊ We propose to measure:
  - Partonic Structure of Light Nuclei.
  - Tagged DVCS Off Light Nuclei
  - Tagged EMC on Light Nuclei

→ CLAS12-ALERT setup will allow higher statistics and wider kinematical coverage
  → 3D binning
  → More precise CFF extractions.
Proposed experimental setup:

**CLAS12 detector**

- High luminosity & large acceptance.
- Measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes

**ALERT detector**

- Can be included in the trigger.
- Separate protons, deuterium, tritium, alpha, helium-3.
- Can be used for BoNuS12, tagged EMC and DVCS on He4 ...
The statistical error bars are calculated for:
- 20 days at a luminosity of $3.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.
- 10 days at a luminosity of $6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.
φ production off He-4: Gluon profiles

\[ e + ^4He \rightarrow e' + ^4He + \phi(K^+ + K^-) \]

\[ \frac{d\sigma_L}{dt} = \frac{1}{(\varepsilon + 1/R)\Gamma(Q^2, x_B, E)} \frac{d^3\sigma}{dQ^2 dx_B dt} \]

R can be extracted from the angular distribution of the kaon decay
In the phi helicity frame, assuming s-channel helicity conservation:

\[ W(\cos \theta_H) = \frac{3}{4} \left[ (1 - r_{00}^{04}) + (3r_{00}^{04} - 1) \cos^2 \theta_H \right] \]

Angular distribution amplitude
Spin-density matrix coefficient: \( r_{00}^{04} = \frac{\epsilon R}{1 + \epsilon R} \)
Angle of kaon decay
In phi helicity frame

Gluon density calculation:

\[ \rho_g(x, 0, b_\perp) \rightarrow \int_0^\infty J_0(b\sqrt{t}) \sqrt{\frac{d\sigma_L}{dt}} \frac{\sqrt{t}}{2\pi} dt \]

\[ 0.18 < x_{vp} < 0.25 \]
\[ 2.0 < Q^2 < 3.0 \text{ GeV}^2 \]
Conclusions

◊ CLAS – E08-024 experiment:
  → The first exclusive measurement of DVCS off $^4$He.
  → The coherent DVCS shows a stronger asymmetry than the free proton as was expected from theory.
  → We performed the first ever experimental extraction of the real and imaginary parts of the He-4 CFF.
  → We extracted EMC ratios and compared them with theoretical predictions.
  → The bound proton has shown a different trend compared to the free one indicating the medium modifications of the GPDs.

◊ We proposed new generation nuclear physics experiments to extract quarks' and gluons' GPDs of He-4 using CLAS12 detector that will be upgraded with a low energy recoil tracker.
  >> Wider kinematical coverage and better statistics that will allow 3D binnings for both the DVCS and DVMP channels  
  >> Will allow model independent extractions of the charge and the gluon densities of He-4.
Monte Carlo simulation

◊ We use Monte Carlo for two goals:
- Understanding the behavior of each particle type in our detectors
- Calculate the acceptance ratio for the purpose of the $\pi^0$ background subtraction

◊ Simulation stages:
- Event generator: $e^4{^4}\text{He} \gamma$, $e^4{^4}\text{He}\pi^0$, $e\gamma$ and $e\pi^0$ events are generated in their measured phase space ($Q^2$, $x_B$, $-t$, $\phi_h$) following this parametrization of the cross section.
- Simulation (GSIM): GEANT3, describes the detectors' response to the different particles.
- Smearing (GPP): Makes the simulation more realistic by smearing the positions, energies and times.
- Reconstruction (RECSIS): (ADCs, TDCs) $\rightarrow$ physical quantities.

Coherent DVCS

Incoherent DVCS

Adequate agreement between data and simulation
Background Subtraction

◊ With our kinematics, the main background comes from the exclusive $\pi^0$ channel,

\[ e^4He \rightarrow e^4He\pi^0 \rightarrow e^4He\gamma\gamma \quad \quad ep \rightarrow ep\pi^0 \rightarrow ep\gamma\gamma \]

in which one photon from $\pi^0$ decay is detected and passes the DVCS selection.

◊ We combine real data with simulation to compute the contamination of $\pi^0$ to DVCS.

\[
\frac{N_{DVCS/BH}}{N_{e^4He\gamma}} = \frac{N_{e^4He\gamma}^{Exp} - N_{e^4He\gamma\pi^0(1\gamma)}^{Exp}}{N_{e^4He\gamma}\pi^0(2\gamma)^{MC}} \times \frac{N_{e^4He\gamma\pi^0(1\gamma)}^{Exp}}{N_{e^4He\gamma\pi^0(2\gamma)^{MC}}} 
\]

→ In -t bins (integrated over $\phi_h$, $Q^2$, $x_B$):

◊ Background yield ($\frac{N_{e^4He\gamma\pi^0(1\gamma)}^{Exp}}{N_{e^4He\gamma}^{Exp}}$) ratio ~ 2-4% (8-11%) in $e^4He\gamma$ (ep$\gamma$) channel.
# Design parameters of CLAS12

<table>
<thead>
<tr>
<th></th>
<th>Forward detector</th>
<th>Central detector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Angular range</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracks</td>
<td>$5 - 40^\circ$</td>
<td>$35 - 125^\circ$</td>
</tr>
<tr>
<td>Photons</td>
<td>$2.5 - 40^\circ$</td>
<td>n.a.</td>
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<tr>
<td><strong>Resolution</strong></td>
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<tr>
<td>$\delta p/p$</td>
<td>$&lt; 1% @ 5$ GeV/c</td>
<td>$5% @ 1.5$ GeV/c</td>
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<tr>
<td>$\delta \theta$</td>
<td>$&lt; 1$ mr</td>
<td>$&lt; 10-20$ mr</td>
</tr>
<tr>
<td>$\delta \phi$</td>
<td>$&lt; 3$ mr</td>
<td>$&lt; 5$ mr</td>
</tr>
<tr>
<td><strong>Photon detection</strong></td>
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<tr>
<td>Energy</td>
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<tr>
<td>$\delta \theta$</td>
<td>$4$ mr @ 1 GeV</td>
<td>n.a.</td>
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<tr>
<td><strong>Neutron detection</strong></td>
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<tr>
<td>Efficiency</td>
<td>$&lt; 0.7$</td>
<td>under dev.</td>
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<tr>
<td><strong>Particle ID</strong></td>
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<tr>
<td>$e/\pi$</td>
<td>Full range</td>
<td>n.a.</td>
</tr>
<tr>
<td>$\pi/p$</td>
<td>Full range</td>
<td>$&lt; 1.25$ GeV/c</td>
</tr>
<tr>
<td>$\pi/K$</td>
<td>Full range</td>
<td>$&lt; 0.65$ GeV/c</td>
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<tr>
<td>$K/p$</td>
<td>$&lt; 4$ GeV/c</td>
<td>$&lt; 1$ GeV/c</td>
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<tr>
<td>$\pi \to \gamma \gamma$</td>
<td>Full range</td>
<td>n.a.</td>
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<tr>
<td>$\eta \to \gamma \gamma$</td>
<td>Full range</td>
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</table>
**DVCS worldwide effort**

### JLAB

<table>
<thead>
<tr>
<th>Hall A</th>
<th>Hall B</th>
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</thead>
<tbody>
<tr>
<td>p,n,d -DVCS: X-sec</td>
<td>p-DVCS: BSA,LTSA, DSA, X-sec, Helium-4: BSA</td>
</tr>
</tbody>
</table>

### CERN

**COMPASS**

- p-DVCS: X-sec, BSA, BCA, tTSA, LTSA, DSA

### DESY

<table>
<thead>
<tr>
<th>HERMES</th>
<th>H1/ZEUS</th>
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<tr>
<td>p-DVCS</td>
<td>p-DVCS</td>
</tr>
<tr>
<td>BSA, BCA, TTSA, LTSA, DSA</td>
<td>X-sec, BCA</td>
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</table>

Promising future experiments with JLab upgrade and COMPASSII