RESULTS AND ACHIEVEMENTS AT CLAS

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OVERVIEW

- Generalized Parton Distributions (GPDs)
  - Introduction
  - Accessing GPDs: Deeply Virtual Compton Scattering (DVCS) & Deeply Virtual Meson Production (DVMP)
  - Asymmetries

- GPDs with the CLAS experiment
  - The Cebaf Large Acceptance Spectrometer
  - Selected results
    - e1-dvcs: polarized beam, unpolarized target
    - eg1-dvcs: polarized beam, polarized target
    - DVMP

- CLAS12
Beyond Form Factors and quark distributions - Generalized Parton Distributions

Proton form factors, transverse charge & current densities

Structure functions, quark longitudinal momentum & helicity distributions

Correlated quark momentum and helicity distributions in transverse space - GPDs

Electromagnetic vertices

\[ H(x, \xi, t) \approx \int dx <N'| \bar{Q}(x) \gamma^+ q(0) |N> \]

In a scattering process, they describe the hadronic bound state dynamics

GPDs are matrix elements of quark and gluons operators at a light-like separation. They depend on 3 variables:

- \( x \)
- \( t \)
- \( \xi \)

There are 4 GPD for each quark flavour: \( H, E, \tilde{H}, \tilde{E} \)

Link to known quantities:

DIS quantities\( @\xi=t=0 \):

- \( H(x,0,0) = q(x), -q(-x) \)
- \( \tilde{H}(x,0,0) = \Delta q(x), \Delta q(-x) \)

GPDs are also related to the quark angular momentum via the Ji’s sum rule:

\[ J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_0^1 dx \sum_q [H^q(x, \xi, 0) + E^q(x, \xi, 0)] \]

By using electromagnetic probes...

...one can test the relevant degrees of freedom inside the hadron, with a resolution depending on the exchanged four-momentum $Q^2$.

Two main processes can be used to access GPDs experimentally: **Deeply Virtual Compton Scattering** and **Deeply Virtual Meson Production**.

**DVCS**

$e \, p \rightarrow e' \, p' \, \gamma$

**DVMP**

$e \, p \rightarrow e'p'\pi, \rho, \omega...$

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**Diagram:**

- **DVCS:**
  - $\gamma_T^*(Q^2)$
  - $x+\xi$ to $x-\xi$
  - $H, \tilde{H}, E, \tilde{E} (x,\xi,t)$

- **DVMP:**
  - $\gamma_L^*(Q^2)$
  - $x+\xi$ to $x-\xi$
  - $H, \tilde{H}, E, \tilde{E} (x,\xi,t)$
  - Final meson
The most suitable process to extract GPDs is DVCS: it is described by the “Handbag” mechanism.

- \( Q^2 = - (e-e')^2 \)
- \( x_B = Q^2/2Mv, \nu = E_e - E_{e'} \)
- \( x + \xi, x - \xi \) longitudinal momentum fractions
- \( t = (p-p')^2 \)
- \( \xi \approx x_B/(2-x_B) \)

4 GPD:
- **Nucleon spin conserving**: Vector \( H(x,\xi,t) \) and Axial-Vector \( \tilde{H}(x,\xi,t) \)
- **Nucleon spin non-conserving**: Tensor: \( \tilde{E}(x,\xi,t) \) and Pseudoscalar \( E(x,\xi,t) \)
**Extraction of GPDs through DVMP**

Depending on the nature of the meson produced, different GPDs will be accessed:

- $E$, $H$ with vector mesons
- $\tilde{E}$, $\tilde{H}$ with pseudoscalar mesons

Quark flavour decomposition accessible via meson production

It is important to analyze the various channels $e \ p \rightarrow e' \ p' \ \rho, \ \omega, \ \phi ...$ in order to operate the decomposition!

<table>
<thead>
<tr>
<th>Meson Type</th>
<th>Corresponding GPD Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>$2\Delta u + \Delta d$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$2\Delta u - \Delta d$</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>$2u + d$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$2u - d$</td>
</tr>
<tr>
<td>$\rho^+$</td>
<td>$u - d$</td>
</tr>
</tbody>
</table>
Physical observables: Asymmetries

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

Depending on the polarization degrees of freedom acting in the process different combinations of GPDs can be accessed.

- Polarized beam, unpolarized target
  \[
  \Delta \sigma_{LU} \sim \sin \phi \text{Im}\{F_1 \hat{H} + \xi (F_1 + F_2) \hat{\bar{H}} - kF_2 E\} d\phi
  \]

- Unpolarized beam, longitudinally polarized target
  \[
  \Delta \sigma_{UL} \sim \sin \phi \text{Im}\{F_1 \hat{H} + \xi (F_1 + F_2) H - kF_2 E\} d\phi
  \]

- Polarized beam, polarized target
  \[
  \Delta \sigma_{LL} \sim \cos \phi \text{Re}\{F_1 \hat{H} + \xi (F_1 + F_2) (H + \ldots)\} d\phi
  \]

- ...and other combinations are available.

\( H, \bar{H}, E: \text{Compton Form Factors} \)
CEBAF LARGE ACCEPTANCE SPECTROMETER @JLAB

- Duty Factor ~ 100%
- $\sigma_E/E \sim 2.5 \times 10^{-5}$
- Beam Pol ~ 85%
THE CLAS DETECTOR

- Toroidal magnetic field (6 superconducting coils)
- Drift chambers (argon/CO2 Gas, 35000 cells)
- Time-of-flight scintillators
- Electromagnetic calorimeters
- Cherenkov counters (e/π separation)

- Performances:
  - Nearly 4π acceptance
  - Large kinematical coverage
  - Detection of charged and neutral particles
CLAS selected results on GPDs

DVCS:
- **e1-dvcs** experiment: polarized beam, unpolarized target
  - Beam Spin Asymmetry
- **eg1-dvcs** experiment: polarized beam, polarized target
  - Target Spin Asymmetry
  - Double Spin Asymmetry

DVMP:
- **e1-6** experiment: $e \ p \rightarrow e \ p \ \rho^0$
  - cross section
  - interpretations
- Other DVMP channels
**E1-dvcs: First CLAS dvcs-dedicated Experiment**

The final state to be detected is

\[ e \, p \rightarrow e' \, p' \, \gamma \]

An exclusive reconstruction of the final state is essential: in order not to lose high energetic (forward) dvcs photons, a new, forward electromagnetic calorimeter (IC) has been added.

- Experiment: March - May 2005
- \( E_e = 5.75 \) GeV
- Beam polarization: 76% - 82%
- Current: 20-25 nA
- Integrated luminosity: 33.3 fb\(^{-1}\)

New acceptance with IC:
\[ \theta \, [4^\circ, 43^\circ] \]
(old: \( \theta \, [17^\circ, 43^\circ] \))
E1-dVCS: Kinematics and Beam-Spin Asymmetry


\[ a = A(90^\circ) \text{ as a function of } -t. \]

\[ x_B = 0.249, \quad Q^2 = 1.95 \text{ GeV}^2 \]

\[ A \sim a \sin \phi/(1+c \cos \phi). \]

Black dashed curves: Regge calculation [\*].

Blue curves: GPD calculation[\**] at twist-2 (solid) and twist-3 (dot-dashed) levels, with H contribution only.


In the period **February - September 2009** a new DVCS-dedicated experiment run.

- NH3 and ND3 polarized targets
- Thanks to the polarized target, two new asymmetries are accessible: a **Target Spin Asymmetry** (TSA) and a **Double Spin Asymmetry** (DSA)
- As in the e1-dvcs case, the inner calorimeter is added to detect the dvcs photons

See Andrey Kim’s talk for more details on dvcs with the eg1-dvcs experiment!
**DVCS Target Spin Asymmetry**

\[ A_{UL} = \frac{1}{fP_T} \frac{(N^+ - N^-)}{(N^+ + N^-)} \]

Fitting function:

\[ A_{UL} \sim \alpha \sin \Phi + \beta \sin 2\Phi \]

- \(N^+(-)^+\): number of DVCS events with a positive (negative) target polarization
- \(P^+(-)^-\): target polarization
- \(f\): dilution factor

\[ x_B \sim 0.21 \]
\[ Q^2 \sim 2.15 \text{ GeV}^2 \]

\[ x_B \sim 0.46 \]
\[ Q^2 \sim 3.00 \text{ GeV}^2 \]

*Plots and analysis done by Erin Seder*
DVCS Double Spin Asymmetry

\[ A_{LL} = \frac{1}{f P_{beam} P_T} \frac{(N^{++} + N^{--}) - (N^{+-} + N^{-+})}{(N^{++} + N^{--}) + (N^{+-} + N^{-+})} \]

Fitting function:

\[ A_{LL} \sim \alpha + \beta \cos \varphi + \gamma (\cos \varphi)^2 + \delta (\sin \varphi)^2 \]

- \( N^{++(+/-)} \): number of DVCS events with a positive (negative) target polarization & a positive (negative) beam helicity
- \( P_{beam/T} \): beam/target polarization
- \( f \): dilution factor
EG1-DVCS: NEXT IMPROVEMENTS

Eg1-dvcs analyses are still on-going. Further improvements are expected, as:

- Nitrogen background evaluation
- Improvements in the calibration
- Subtraction of the $\pi^0$ contribution to the DVCS channel
- MC studies for a better background subtraction

Furthermore, other analyses are ongoing with eg1-dvcs data, as $e^+p \rightarrow e^+p\pi^0$ and nDVCS
Since the factorization theorems for the meson electroproduction have been proven only for the longitudinal component of the cross-section, a transverse-longitudinal separation is needed for $\sigma_{(\gamma p \rightarrow pp\rho^0)}$. Such a separation is realized by analyzing the decay-pion angular distribution in the $\rho^0$ center of-mass frame and relying on the $s$-channel helicity conservation.

- $E_e = 5.754$ GeV
- 5-cm-long liquid H target
- $1.8 < W$ (GeV) $< 2.8$
- $L = 28.5$ fb$^{-1}$
Two different behaviors:
• low $W$: $\sigma_L$ drops
• high $W$: $\sigma_L$ slowly rises

GPD approaches based on Double-Distributions

- thin blue VGG [*]
- thick blue VGG + strong D-term [*]
- dash-dotted JLM calculation à la Regge [*]

Hadronic approach

partonic descriptions are expected to be valid at large $Q^2$, while hadronic descriptions dominate in low-$Q^2$ electroproduction.
DVMP: OTHER CHANNELS

- C. Hadjidakis et al., Phys.Lett.B605:256-264, 2005: $e^+p \rightarrow e^+p\rho^0$ @4.2 GeV
- L. Morand et al., Eur.Phys.J.A24:445-458, 2005: $e^+p \rightarrow e^+p\omega$ @5.75 GeV
- K. Lukashin, Phys.Rev.C63:065205, 2001: $\phi$ @4.2 GeV): $e^+p \rightarrow e^+p\phi$ @4.2 GeV
- J. Santoro et al., Phys.Rev.C78:025210, 2008: $e^+p \rightarrow e^+p\phi$ @5.75 GeV

Ongoing analyses:
- $e^+p \rightarrow e^+p\pi^0$
- $e^+p \rightarrow e^+p\rho^+$

\[
\frac{d\sigma}{dt} \sim \sqrt{-t}e^{bt}
\]
GPDs@Clas12

GPD is one of the main subjects of the 12 GeV Hall-B physics program.

- **Broadened kinematic coverage**
- **Energy upgrade and higher luminosity:** *beam energy up to 11 GeV for Hall-B*
Deeply virtual exclusive processes

kinematics@CLAS12

GPDs@CLAS12: KINEMATICS

High precision DVCS data for:
- $Q^2 = 1.0 \div 7.5 \text{ GeV}^2$
- $X_B = 0.1 \div 0.65$
- $-(t-t_{\text{min}}) < 1.5 \text{ GeV}^2$
Various DVCS related measurements will be available in the wider kinematic range of CLAS12:

- Beam Spin Asymmetry
- Target Spin Asymmetry with a \textit{longitudinally} polarized target @11 GeV
- nDVCS: DVCS on the neutron will be studied with CLAS12
  - access to the GPD E
- Target Spin Asymmetry with a \textit{transversely} polarized target @11 GeV. It gives access to the GPD E&H
- $e^+ p \rightarrow e^+ p \pi^0$
- Furthermore, CLAS12 will allow us to measure DVCS polarized and unpolarized cross sections, vector and pseudo-scalar meson electroproduction...

\textbf{R&D underway}
$Q^2 = 5.5 \text{ GeV}^2$

$x_B = 0.35$

$-t = 0.25 \text{ GeV}^2$

$\xi_{independent}$

$\xi_{val} = 1.0, \xi_{sea} = 1.0$

$L = 1 \times 10^{35}$

$T = 2000 \text{ hrs}$
nDVCS is a strategic process to complete the information of the nucleon structure in terms of GPDs. It plays a role complementary to the proton DVCS, giving access at the less known and constrained GPD, $E$.

It allows, e.g., flavour decomposition:

$$H^p(\xi,\xi,t) = \frac{4}{9} H^u(\xi,\xi,t) + \frac{1}{9} H^d(\xi,\xi,t)$$

$$H^n(\xi,\xi,t) = \frac{1}{9} H^u(\xi,\xi,t) + \frac{4}{9} H^d(\xi,\xi,t)$$

$J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^{1} x dx \left[H^q(x, \xi,0) + E^q(x, \xi,0)\right]$ 

more than 80% of them will have a $\theta > 40^\circ$, that is it will be on the region covered by Central Detector.
SUMMARY & CONCLUSIONS

- DVCS is the cleanest reaction giving access to GPDs
- $e_1$-dvcs@CLAS $\rightarrow$ first extraction of BSA and polarized and unpolarized cross sections (analysis in progress) $\rightarrow$ strong constraint for GPD models $\rightarrow$ evidence for handbag dominance at modest $Q^2$
- $e^p \rightarrow e'p'\rho^0$: at low $W$ a hadronic approach seems to describe better the data, while at higher $W$ the GPD approach starts to be effective
- DVMP cross-sections analysis are underway using $e_1$-dvcs data $\rightarrow$ the aim is the flavour decomposition of GPD through the different channels: $ep\pi^0, ep\eta, ep\rho^+$
- TSA&DSA analyses in progress with polarized target data (e.g. $e_1$-dvcs)
- The JLab 12 GeV upgrade is essential for the study of 3-D nucleon structure in the valence region with high precision, allowing the measurement of deeply virtual exclusive processes with polarized beam and polarized targets
- CLAS12 will be worldwide the only full acceptance, general purpose detector for high luminosity electron scattering experiments
- The experimental program of CLAS12 will provide new insight into 3D structure of the nucleon’s interior and correlations
- The first 11 GeV electron beam is expected to hit the CLAS12 target at the end of 2014
BACKUP
Various experiments have been performed with the CLAS detector, that produced/are going to produce GPD-related results.

Unpolarized target
- e1-6
  - Data taking in 2001
  - Unpolarized H2 target
  - Measurement of the DVMP process $e p \rightarrow e p \rho^0$
  

- e1-dvcs
  - Data taking in 2005
  - Unpolarized H2 target
  - Measurements of the DVCS Beam Spin Asymmetry
  
  *F.X. Girod et al; Phys. Rev. Lett.100:162002,2008*

Polarized target
- eg1
  - Data taking in 2001
  - $^3$NH & $^3$ND target
  - First measurements of the DVCS Target Spin Asymmetry
  
  *S. Chen et al., Phys. Rev. Lett. 97, 072002 (2006).*

- eg1-dvcs
  - Data taking in 2009
  - $^{14}$NH$_3$ & $^{14}$ND target
  - Measurements of the DVCS Target Spin Asymmetry
Two main mechanisms contribute to the process $e p \rightarrow e' p' \gamma$: DVCS and Bethe-Heitler.
DVCS@CLAS: FIRST ASYMMETRIES

\[ e p \rightarrow e p \, X \]

S. Stepanyan et al., PRL 87 (2001)

\[ e p \rightarrow e p \, \gamma \]

S. Chen et al., PRL 97 (2006)

\[ Q^2 = 1.25 \text{ GeV}^2 \]
\[ \langle x_B \rangle = 0.19 \]
\[ \langle -t \rangle = 0.19 \text{ GeV}^2 \]

\[ E_e = 4.3 \text{ GeV} \]

\[ A = \alpha \sin \phi + \beta \sin 2\phi \quad \Rightarrow \beta \sim 0 \text{ confirms twist-2 dominance} \]
E1-6 BACKUP
“Hadron” Interpretation

GPD INTERPRETATION

E1-dvcs backup
EG1-DVCS BACKUP
DVMP@EG1-DVCS: $e\, p \rightarrow e\, p\, \pi^0$

Target spin asymmetry for the channel $e\, p \rightarrow e\, p\, \pi^0$

The superimposed fitting function is
\[ A = a \sin \phi + b \sin 2\phi \]

Plots and analysis done by Andrey Kim
CLAS12 BACKUP
CLAS12 TIME SCHEDULE
$E_p_{TR} \rightarrow E_p Rho_0$

$-t = 0.5 \text{ GeV}^2$

$J^u = 0.1$

$J^d = 0$

**HERMES (preliminary)**

**CLAS12**