Exploring the Structure of the Nucleon

with Generalised Parton Distributions

Ralf Kaiser, University of Glasgow
• Generalised Parton Distributions
• GPD Experiments - with a Glaswegian Flavour
• Future Perspectives for GPD Measurements
Generalised Parton Distributions

Form Factor

Parton Distribution Function

Generalised Parton Distribution
parton distribution functions

\[ q(x) = H_q(x, 0, 0) \]
\[ \Delta q(x) = \tilde{H}_q(x, 0, 0) \]
\[ q(-x) = -\bar{q}(x) \]
\[ \Delta q(-x) = \Delta \bar{q}(x) \]

form factors

\[ F_1^q(t) = \int_{-1}^1 dx H^q(x, \xi, t) \]
\[ F_2^q(t) = \int_{-1}^1 dx E^q(x, \xi, t) \]
\[ g_a^q(t) = \int_{-1}^1 dx \tilde{H}^q(x, \xi, t) \]
\[ h_a^q(t) = \int_{-1}^1 dx \tilde{E}^q(x, \xi, t) \]

quark orbital angular momentum

\[ J_q = \frac{1}{2} \int_{-1}^1 x \, dx [H_q + E_q] \]
\[ = \frac{1}{2} \Delta \Sigma + L_q \]  [X.Ji 1997]
The Fourier transform of GPDs at $\xi = 0$ leads to a 3-dimensional picture of the nucleon - longitudinal momentum fraction and transverse impact parameter space.

$$q(x, b_\perp) = \int \frac{d^2 \Delta_\perp^2}{(2\pi)^2} H(x, 0, -\Delta_\perp^2) e^{-i\Delta_\perp \cdot b_\perp}$$
u-quark (left) and d-quark (right) density in impact parameter plane. Proton polarised in x-direction.

GPDs and the Spin Puzzle

\[ S_z = \frac{1}{2} = J_q + J_g = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

Ji Sum Rule:

\[ J_q = \frac{1}{2} \int_{-1}^{1} x dx [H_q + E_q] = \frac{1}{2} \Delta \Sigma + L_q \]

\[ \Delta \Sigma = \Sigma \Delta q \sim 0.3 \]

Measure GPDs to determine \( L_q \)!
GPDs and the DVCS Process

- Same final state in DVCS and Bethe-Heitler
  \[ d\sigma(eN \rightarrow eN\gamma) \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH}T^*_{DVCS} + T^*_{BH}T_{DVCS} \]
  
  \( T_{BH} \) is exactly calculable in QED

- \( T_{DVCS} \) is parameterized in terms of Compton form factors \( \mathcal{H}_q, \tilde{\mathcal{H}}_q, \mathcal{E}_q, \tilde{\mathcal{E}}_q \) (convolutions of GPDs \( H_q, \tilde{H}_q, E_q, \tilde{E}_q \))

- At HERMES kinematics: \( |T_{DVCS}|^2 \ll |T_{BH}|^2 \)

GPDs accessible through cross-section differences and azimuthal asymmetries via interference term
Beam Charge Asymmetry (BCA) $A_C(\phi)$
$$d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto Re[F_1H] \cdot \cos \phi$$

Beam Spin Asymmetry (BSA) $A_{LU}(\phi)$
$$d\sigma(\overrightarrow{e}, \phi) - d\sigma(\overleftarrow{e}, \phi) \propto Im[F_1H] \cdot \sin \phi$$

Transverse Target Spin Asymmetry (TTSA) $A_{UT}(\phi, \phi_S)$
$$d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi) \propto Im[F_2H - F_1E] \cdot \sin(\phi - \phi_S) \cdot \cos \phi$$

BCA: Especially sensitive to the D-term in GPD models
BSA: Best chance to directly extract the GPD $H^u$


TTSA: Only asymmetry in which GPD $E$ is not suppressed. Sensitive to $J_q$. 
Major GPD Experiments - Timeline

- HERMES (2008)
- COMPASS
- PANDA
- JLAB
- JLAB 12 GeV
- EIC (2025)

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Present and Future ep-Facilities

- **HALL A**
- **CLAS 12**
- **CLAS**
- **HERMES**
- **COMPASS**
- **H1**
- **ZEUS**

Luminosity [cm⁻² s⁻¹]

- $10^{38}$
- $10^{37}$
- $10^{36}$
- $10^{35}$
- $10^{34}$
- $10^{33}$
- $10^{32}$
- $10^{31}$

$E_{CM}$ [GeV]

- 1
- 10
- 100
- 1000

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Present and Future ep-Facilities

Luminosity [cm^{-2} s^{-1}]

10^{38}  
10^{37}  
10^{36}  
10^{35}  
10^{34}  
10^{33}  
10^{32}  
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E_{CM} [GeV]

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DVCS measurements with Recoil Detector in 2006/7 yielded about as much data as 1995-2005; data are being analysed.
HERMES Recoil Detector

Project Leader RK (Glasgow)
Limits on $J_u/J_d$

![Diagram showing limits on $J_u/J_d$.](image)

**HERMES DD**

**HERMES Dual**

**JLab DD**

**DFJK**

**QCDSF**

**LHPC**

*JHEP 0806:066, 2008*
Glasgow NP Group Member in Hall A and CLAS Collaborations
CLAS12 Detector

Central Detector

Forward Detector

CTOF

Glasgow involved in CTOF

arXiv:0711.0755 (submitted to PRL)
2000 hrs at $L=10^{35}$ cm$^{-2}$s$^{-1}$

Co-Spokesperson E12-06-119 D.Ireland (Glasgow)
2000 hrs at $L=10^{35}$ cm$^{-2}$s$^{-1}$

Co-Spokesperson E12-06-119 D.Ireland (Glasgow)
2000 hrs at L=10^{35} \text{ cm}^{-2}\text{s}^{-1}

Projection for GPD H

Co-Spokesperson E12-06-119 D.Ireland (Glasgow)
Transverse Asymmetry is large and has strong sensitivity to GPD $E$

CLAS 6 experiment scheduled for 25 days in 2011

RK co-spokesperson

Co-Spokesperson E08-021 RK

$$A_{UT} \sim \sin(\phi - \phi_s) \cos(\phi) \Im\{ F_2^H - F_1^E + \ldots \} + \ldots$$
Chair Collaboration Board G.Rosner (Glasgow)
Project Leader Disc Dirc Design B.Seitz (Glasgow)

STFC Grant for Dipole Magnet
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STFC Grant for Dipole Magnet
• PANDA can measure the ‘cross channel’ or ‘time-like’ version of the same process, that depends on the same GPDs
• More precisely on Generalised Distribution Amplitutes, introduced by M. Diehl et.al. to describe the inverse process [PRL.81:1782 (1998)].
The same factorisation proof as for DVCS does not hold for the crossed channel.

Alternative approach: Transition Distribution Amplitudes

TDAs extend the GPD concept to transitions


Impact parameter space interpretation as for GPDs

Fourier transform gives a transverse picture of the pion cloud in the proton
• Current models of TDA predict small cross section (~100 fb)

• Need excellent detector system to remove background

• Measurement feasible with PANDA

• Several concepts for future ep-facility: eRHIC at BNL, ELIC at JLab (together referred to as EIC), LHeC at CERN and ep@FAIR

• All designs use an existing machine and combine it with a second, new machine to a collider

• High luminosity, high energy, energy range

• GPDs are only part of the physics reach of such a facility

Glasgow NP Group Member in EIC Collaboration
DATA

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The Way Forward
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Combined Efforts by Experimentalists and Theorists required!!!
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EU FP7 JRA ‘Hard Exclusive Reactions Spokesperson RK
• Generalised Parton Distributions are promising to revolutionize our picture of the nucleon and to solve the spin puzzle.

• Present experiments at HERMES and JLab are playing a pioneering role, future experiments after the JLab upgrade, at COMPASS and FAIR will further complete the picture.

• Ultimately a future ep-facility with high luminosity and an energy range up to higher energies will be required to finalise the picture.

• All of this will only be successful in the combination of experiments, lattice calculations and GPD model fits to the data.
Expected sinφ-dependence in exclusive region.

First HERMES BSA paper was based on 3.3 Mio DIS events. 2006/7 data: 50 Mio DIS, 40 Mio on hydrogen (plus 10 Mio on deuterium), of which 29 Mio DIS (7 Mio) were taken with fully functional Recoil Detector.
GPD H in VGG Model
Symmetrized BCA in exclusive bin

\( \phi \rightarrow |\phi| \Rightarrow \) Cancel \( \sin(\phi) \) dependence

- Solid curve – 4 Parameter Fit
- \( P_1 + P_2 \cos \phi + P_3 \cos 2\phi + P_4 \cos 3\phi \)

\[ A_{C,Proton}^{\cos \phi} = 0.063 \pm 0.029 \text{(stat.)} \pm 0.026 \text{(sys.)} \]

Expected \( \cos(\phi) \) dependence \( \Rightarrow ReH \)

A. Airapetian et al, Phys. Rev. D 75 (2007) 011103(R)
GPDs - The Way Forward
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Combined Efforts by Experimentalists and Theorists required !!!
Present and Future ep-Facilities

Luminosity [cm$^{-2}$ s$^{-1}$]

- HALL A
- CLAS
- CLAS 12
- HERMES
- COMPASS
- FAIR
- ELIC
- eRHIC
- H1
- ZEUS
- LHeC

$E_{CM}$ [GeV]
Major GPD Experiments - Timeline

- HERMES
- COMPASS
- PANDA
- JLAB
- JLAB 12 GeV
- EIC

Timeline:
- 2008
- 2010
- 2015
- 2020
- 2025

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