• From Rutherford Scattering to Deeply Virtual Compton Scattering (DVCS)

• Generalised Parton Distributions and the 3D Structure of the Proton

• Recent DVCS Results from HERMES

• Future Experiments in DVCS
Imagine you have a sand filled sack, and a cannon ball hidden somewhere inside. One way of figuring out where the cannon ball is, is shooting at it with a shotgun. You get a kind of picture and some of the bullets scatter back.

One (important) difference: Electron scattering off a proton, or alpha particles off a nucleus, is more like shooting individual bullets at lots of different (albeit supposedly identical) sacks. A combination of imaging and destructive testing....
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Rutherford Scattering Experiment

Rutherford Experiment:
Nuclear Atom
Rutherford Cross Section

Classical as well as quantum mechanical result under the assumption that

- target recoil can be neglected
- spin effects can be neglected
- the target is point-like

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{Rutherford}} = \frac{(Ze^2)^2}{(4\pi\varepsilon_0) \cdot 4E^2 \sin^4 \frac{\theta}{2}}
\]
Taking target recoil and spin effects into account leads to the Mott cross section. Any further deviation is therefore an indication that the target is not point-like. This is the basic method to show that something has a substructure.

R.Hofstadter et al., Phys.Rev.92, 978 (1953)
Nuclear Form Factor: Ratio of measured elastic electron scattering cross section and theoretical cross section for a point-like particle.

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{exp}} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \cdot |F(q^2)|^2
\]

Radial charge distribution from Fourier transformation.
Elastic Scattering off a Nucleus

Deviation from Rutherford Scattering (point-like)

Nuclear Form Factor

Thursday, 11 August 2011
Elastic Scattering off a Nucleus

Elastic Scattering off a Nucleon

Deviation from Rutherford Scattering (point-like)

Nuclear Form Factor

\[ G_E = \frac{G_p}{2.79} \]

\[ M = \frac{G_n}{-1.91} \]

Nucleon Form Factors

\[ G^p_E \]
\[ G^n_E = \frac{G^p_E}{2.79} \]
\[ G^n_E = \frac{G^p_E}{1.91} \]
Elastic Scattering off a Nucleus

Elastic Scattering off a Nucleon

Elastic Scattering off a Quark/Parton i.e. DIS

Deviations from Rutherford Scattering (point-like)

Nuclear Form Factor

Nucleon Form Factors

Parameterisation of the Experimental Results

Parton Distribution Functions

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Structure and Rutherford Scattering

Elastic Scattering off a Nucleus

Deviation from Rutherford Scattering (point-like)

Nuclear Form Factor

Elastic Scattering off a Nucleon

Deviation from Rutherford Scattering (point-like)

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Parameterisation of the Experimental Results

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Deeply Virtual Compton Scattering i.e. DVCS

Parameterisation of the Experimental Results

Generalised Parton Distributions

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Structure and Rutherford Scattering

Elastic Scattering off a Nucleus

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Deviation from Rutherford Scattering (point-like)

Nuclear Form Factor

Nucleon Form Factors

Parameterisation of the Experimental Results

Generalised Parton Distributions

Parameterisation of the Experimental Results

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Proton and Neutron - The Basic Idea

**Proton**

3 quarks (uud)
Q = \( \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1 \)
quarks in 3 colors

**Neutron**

3 quarks (udd)
Q = \( \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0 \)
quarks in 3 colors
Spin 1/2
Quarks also Spin 1/2
Spin 1/2
Quarks also Spin 1/2
Spin 1/2
Quarks also Spin 1/2

Gluons & Sea Quarks
Spin 1/2
Quarks also Spin 1/2

Gluons & Sea Quarks
Spin 1/2
Quarks also Spin 1/2

Gluons &
Sea Quarks

Orbital
Angular
Momentum
Generalised Parton Distributions

Form Factors (FFs)

Parton Distribution Functions (PDFs)

Generalised Parton Distributions (GPDs)
Often the so-called handbag diagram is used to illustrate GPDs. The simplest process to access GPDs is Deeply Virtual Compton Scattering (DVCS), shown in the diagram.

- GPDs are functions of 3 variables: $H_q(x, \xi, t)$ as well as of $Q^2$.
- They include PDFs as limiting case: $q(x)=H_q(x,0,0)$
- Form factors are first moments of GPDs
- 4 quark GPDs: $H, \tilde{H}, E, \tilde{E}$
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• 4 quark GPDs: $H, \tilde{H}, E, \tilde{E}$
Rudolph

GPDs

\[ e' \]

\[ \gamma^* \]

\[ \gamma' \]

\[ \gamma \]

\[ t \]

\[ p \]

\[ p' \]
‘Reindeer Diagram’

Rudolph

(c) Max Kaiser, 7 (now 9)
PDF measured in DIS

$H(x=\xi)$ measured in DVCS

$q(-x) = -\bar{q}(x)$
Fourier transformation of GPDs at $\xi=0$ yields 2+1 dimensional picture of the nucleons, i.e. longitudinal in momentum fraction and transversal in 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. GPD model fit based on existing form factor data.

Distribution Graph

GTMD
\[ X(x, \xi, \Delta_\perp, k_T, k_T \cdot t) \]

Integrate over \( k_T \)

Integrate over Impact Parameter Space

Integrate over \( \Delta_\perp \)

Take limit \( \xi = 0 \)

WD
\[ X(x, \xi, b_\perp, k_T, k_T \cdot b_\perp) \]

Integrate over \( k_T \)

Integrate over \( \xi = 0 \)

TMD
\[ h_\perp(x, k_T) \]

Integrate over \( k_T \)

Take limit \( \xi = 0 \)

Integrate over \( x \)

GPD
\[ H(x, \xi, t) \]

Integrate over \( \xi \)

Integrate over \( \Delta_\perp \)

\[ FT \Delta_\perp / b_\perp \]

Spin Densities

Charge Densities

PDF

Integrate over \( k_T \)

Take limit \( \xi = x = 0 \)

FF

Integrate over \( x \)

Integrate over \( \xi = 0 \)

FT \[ \Delta_\perp / b_\perp \]

Courtesy M. Murray, Glasgow

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DVCS measurements with Recoil Detector in 2006/7 yielded about as much data as 1995-2005.
DVCS Asymmetries
\[ A_C(\phi) \equiv \frac{d\sigma^+(\phi) - d\sigma^-(\phi)}{d\sigma^+(\phi) + d\sigma^-(\phi)} \]

\[ A_{LU}(\phi) \equiv \frac{[\sigma^{\rightarrow \leftarrow}(\phi) + \sigma^{\rightarrow \Rightarrow}(\phi)] - [\sigma^{\leftarrow \leftarrow}(\phi) + \sigma^{\leftarrow \Rightarrow}(\phi)]}{[\sigma^{\rightarrow \leftarrow}(\phi) + \sigma^{\rightarrow \Rightarrow}(\phi)] + [\sigma^{\leftarrow \leftarrow}(\phi) + \sigma^{\leftarrow \Rightarrow}(\phi)]} \]

\[ A_{UL}(\phi) \equiv \frac{[\sigma^{\leftarrow \rightarrow}(\phi) + \sigma^{\rightarrow \Rightarrow}(\phi)] - [\sigma^{\leftarrow \leftarrow}(\phi) + \sigma^{\rightarrow \leftarrow}(\phi)]}{[\sigma^{\leftarrow \rightarrow}(\phi) + \sigma^{\rightarrow \Rightarrow}(\phi)] + [\sigma^{\leftarrow \leftarrow}(\phi) + \sigma^{\rightarrow \leftarrow}(\phi)]} \]

\[ A_{LL}(\phi) \equiv \frac{[\sigma^{\rightarrow \Rightarrow}(\phi) + \sigma^{\leftarrow \leftarrow}(\phi)] - [\sigma^{\leftarrow \rightarrow}(\phi) + \sigma^{\rightarrow \leftarrow}(\phi)]}{[\sigma^{\rightarrow \Rightarrow}(\phi) + \sigma^{\leftarrow \leftarrow}(\phi)] + [\sigma^{\leftarrow \rightarrow}(\phi) + \sigma^{\rightarrow \leftarrow}(\phi)]} \]
\[ \mathcal{A}_C(\phi) \equiv \frac{d\sigma^+(\phi) - d\sigma^-(\phi)}{d\sigma^+(\phi) + d\sigma^-(\phi)} \]

\[ \mathcal{A}_{LU}(\phi) \equiv \frac{[\sigma^{\rightarrow\rightarrow}(\phi) + \sigma^{\rightarrow\leftarrow}(\phi)] - [\sigma^{\leftarrow\rightarrow}(\phi) + \sigma^{\rightarrow\leftarrow}(\phi)]}{[\sigma^{\rightarrow\rightarrow}(\phi) + \sigma^{\rightarrow\leftarrow}(\phi)] + [\sigma^{\leftarrow\rightarrow}(\phi) + \sigma^{\rightarrow\leftarrow}(\phi)]} \]

\[ \mathcal{A}_{UL}(\phi) \equiv \frac{[\sigma^{\leftarrow\rightarrow}(\phi) + \sigma^{\rightarrow\rightarrow}(\phi)] - [\sigma^{\rightarrow\leftarrow}(\phi) + \sigma^{\rightarrow\leftarrow}(\phi)]}{[\sigma^{\rightarrow\rightarrow}(\phi) + \sigma^{\rightarrow\leftarrow}(\phi)] + [\sigma^{\leftarrow\rightarrow}(\phi) + \sigma^{\rightarrow\leftarrow}(\phi)]} \]

\[ \mathcal{A}_{LL}(\phi) \equiv \frac{[\sigma^{\rightarrow\rightarrow}(\phi) + \sigma^{\leftarrow\leftarrow}(\phi)] - [\sigma^{\rightarrow\leftarrow}(\phi) + \sigma^{\leftarrow\leftarrow}(\phi)]}{[\sigma^{\rightarrow\rightarrow}(\phi) + \sigma^{\rightarrow\leftarrow}(\phi)] + [\sigma^{\leftarrow\leftarrow}(\phi) + \sigma^{\leftarrow\leftarrow}(\phi)]} \]

Statistics: Only 1 DVCS event for 1000 DIS events at HERMES kinematics!
HERMES DVCS

- Amplitude Value

- Hydrogen
- Deuterium
- Hydrogen Preliminary
Beam Charge Asymmetry

\[ \phi \cos (C) \, A \]

\[ \phi \cos (2C) \, A \]

\[ \phi \cos (3C) \, A \]

Overall fraction: 

Beam Charge Asymmetries access Re(\mathcal{H})

\[ \Delta \text{-resonance} \]

Thursday, 11 August 2011
Beam Spin Asymmetry

**Beam Spin Asymmetries access \( \text{Im}(\mathcal{H}) \)**

Larger values for the BSA than BCA
Wanted

BH/DVCS from $\Delta$, e.g.

$e \Delta \rightarrow e \Delta \gamma \rightarrow e p \pi^0$

$e p \rightarrow e X$

$e p \rightarrow e p$
Kinematic event fitting technique
- All 3 particles in final state detected $\rightarrow$ 4 constraints from energy-momentum conservation
- Selection of elastic DVCS with high efficiency ($\sim 84\%$)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level ($\sim 0.1\%$)

Missing mass distribution
- No requirement for Recoil
- Positively charged Recoil track
- Kinematic fit probability $> 1\%$
- Kinematic fit probability $< 1\%$
Without Recoil Detector

In Recoil Detector acceptance

With Recoil Detector

Similar background

Background-free

Similar kinematics

Process fractions

Elastic Assoc.

with Recoil Det.
in Recoil Det. accept.
without Recoil Det.

overall -t [GeV^2] x_B Q^2 [GeV^2]
**HERMES DVCS BSA with Recoil Detector**

**HERMES PRELIMINARY 2006/07 data**

3.4% scale uncertainty

- **without Recoil Det.**
- **with Recoil Det.**
- **in Recoil Det. accept.**

\[ \text{e}^+ p \rightarrow \text{e}^+ p \gamma \]

Overall

\[ -t \ [\text{GeV}^2] \]

\[ 10^{-1} \]

\[ 10^1 \]

\[ x_B \]

\[ 1 \]

\[ Q^2 \ [\text{GeV}^2] \]

\[ 10 \]

**PhD Thesis Jennifer Bowles, Glasgow, in preparation**
DVCS Measurements over the Years

H1 @ DESY
cross-section

2001

ZEUS @ DESY
cross-section

2003

HERMES @ DESY
BSA

CLAS @ JLab
BSA

List does not claim
to be exhaustive.

Courtesy C. Riedl, DESY
DVCS Measurements over the Years

- **H1 @ DESY**: cross-section (2001)
- **ZEUS @ DESY**: cross-section (2003)
- **HERMES @ DESY**: BSA (2006)
- **CLAS @ JLab**: BSA (2007)
- **HERMES BCA**: pol-H, -D; nuclear (2008)
- **HERMES pol-H, -D; nuclear**: (2010)
- **Hall A @ JLab**: cross-section (p,n) (2011)

List does not claim to be exhaustive.

Courtesy C. Riedl, DESY
DVCS Measurements over the Years

**H1 @ DESY**
2001

cross-section

**ZEUS @ DESY**
2003

cross-section

**HERMES @ DESY**
2006

BSA

**CLAS @ JLab**
2007

BSA

**Hall A @ JLab**
2009

cross-section (p,n)

**HERMES pol-H, -D; nuclear**
2010

**COMPASS @ CERN: program with Recoil**
> 2011

**CLAS Tpol target**

**JLab 12**

**HERMES results with Recoil**

**EIC**

List does not claim to be exhaustive.

Courtesy C. Riedl, DESY
JLab Experiments: CLAS12 Detector
CLAS

Projection for CLAS12
2000 hrs at L=10^{35} \text{cm}^{-2}\text{s}^{-1}
COMPASS Setup for DVCS Measurements

Tests in 2008-09
40cm LH2 target + 1m RPD

Phase 1 (COMPASS-II)
2.5 m LH2 target + 4m RPD

Phase 2 (in future)
Polarised Transverse Target integrating RPD

4.6 \times 10^8 \mu^+
for 2.7 \times 10^{13} protons per SPS spill
(9.6s each 48 s)

\Rightarrow Lumi= 10^{32} \text{ cm}^{-2} \text{ s}^{-1} with 2.5m LH2 target

\gamma
\rightarrow ECALs upgraded

ECAL0 before SM1

Courtesy N.D’Hose
COMPASS Recoil Proton Detector

3.6 m long scintillator slabs
~ 300 ps timing resolution

Tests made with
• 2006: 4m sector prototype
• 2008-9: 1m long RPD

Observation of BH and DVCS events in 2009 data taken with 1 m RPD.

Courtesy N.D’Hose, Saclay
Projection for combined beam spin and charge asymmetry

for 2 years of data taking at 160 GeV with 2.5 m LH2 target

2013-15
Present and Future ep-Facilities

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

$10^{38}$

$10^{37}$

$10^{36}$

$10^{35}$

$10^{34}$

$10^{33}$

$10^{32}$

$10^{31}$

$E_{CM} [GeV]$ 1000

100

10

1

Luminosity

HALL A

CLAS 12

CLAS

ELIC

ENC @ FAIR

eRHIC

HERMES

COMPASS

H1 ZEUS

LHeC
• Generalised Parton Distributions are promising to revolutionise our knowledge about nucleon structure and will eventually deliver a 3D picture of the proton.

• Recent and present experiments at HERMES and JLab are playing a pioneering role in this field.

• Future experiments especially at JLab after the upgrade and at COMPASS 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. This could be EIC and/or ENC.

• All of this will only be successful in the combination of experiments, lattice calculations and GPD model fits to the data.
Thank you very much for your attention!
Additional Slides
Postulate GPDs from first principle models

http://arxiv.org/abs/0904.0458
Kumerički and Müller
To appear in Nucl. Phys. B

http://arxiv.org/abs/1005.4922
M. Guidal
New CFF Fit Result incorporating $A_{UL}$ moments

http://arxiv.org/abs/0904.0458
Kumerički and Müller
To appear in Nucl. Phys. B