Experimental studies of generalised parton distributions

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– Physics motivation
– Deeply virtual Compton scattering
– Experimental results
– Future plans
Motivation

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space

Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Slide from V.D. Volker, LANL 2007
Access GPD through hard exclusive reactions

**DVCS**

- generalised parton distributions for quarks and gluons $H^f, E^f, \tilde{H}^f, \tilde{E}^f(x, \xi, t)$
- limits: $q(x) = H(x, 0, 0)$ normal PDF
  $F(t) = \int dx \ H(x, \xi, t)$ elastic FF
- Factorisation for $Q^2$ large, $t < 1 \text{ GeV}^2$
- $H, \tilde{H}$ conserve nucleon helicity
  $E, \tilde{E}$ flip nucleon helicity
- $H, E$ refer to unpolarised distributions
  $\tilde{H}, \tilde{E}$ refer to polarised distributions

**Ji’s sumrule**

$$J^f = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \ x \ [H^f(x, \xi, t) + E^f(x, \xi, t)]$$

$J^f$: total angular momentum contribution of quark $f$
Experimental challenge

- **interference** of DVCS and Bethe Heitler

\[ d\sigma = d\sigma^{BH} + d\sigma^{DVCS} + \text{interference term} \]

- \(d\sigma^{DVCS}\) and interference term related to **Compton form factor** \(\mathcal{H}(\xi, t)\)

- can be used to extract **GPDs**, mainly GPD \(H\) at high energies

\[
\text{Im} \mathcal{H}(\xi, t) \overset{\text{LO}}{=} H(\xi, \xi, t)
\]

\[
\text{Re} \mathcal{H}(\xi, t) \overset{\text{LO}}{=} \mathcal{P} \int_{-1}^{1} dx \, H(x, \xi, t) \frac{1}{x - \xi}
\]

- BH known, control of experiment; DVCS also \(d\sigma^{DVCS}/d|t|\)
Generalised parton distributions

Cross-section ($\sigma$) measurement and beam charge difference ($\text{Re} T$) integrate GPDs with $1/(x \pm \xi)$ weight.

Beam or target spin $\Delta \sigma$ contain only $\text{Im} T$, therefore GPDs at $x = \xi$ and $-\xi$.

Lattice Moments

$$= \int x^n H(x, \xi, t) dx$$
Azimuthal angular dependence

- separation of DVCS and BH via $\phi$ dependence
- e.g. $Q^2 = 2$ GeV$^2$, $|t| = 0.1$ GeV$^2$

BH dominates, excellent reference yield

BH and DVCS compatible, DVCS amplitude from interference

DVCS dominates, study of $d\sigma/d|t|$, difficult at low energies
Parametrisations of GPDs

• predictions with different models

with factorisation: $H(x, \xi, t) \propto q(x)F(t)$

with Regge motivated $t$ dependence: $x$-$t$ correlation

– idea: core of fast partons, meson cloud at larger distance
  $H(x, 0, t) \propto q(x) \exp(-B|t|)$

– Ansatz: $B = 1/2 \langle b_\perp^2 \rangle = B_0 + 2\alpha' \ln \frac{x_0}{x}$
  ($\alpha'$ slope of Regge trajectory)

– valence quarks: $\alpha' \sim 1 \text{ GeV}^{-2}$ from form factors, gluons: $\alpha'$ small

• analysis of data

  local fits to $\text{Im } H, \text{Re } H$ indep. (M.Guidal)

  global fits: all kinematic bins at the same time, parametrisation of CFF or GPD
  (G.Goldstein, K.Kumericki and D.Müller)

hybrids: local/global fits (H.Moutarde)

neural networks for PDF, work started for GPDs (K.Kumericki and D. Müller)
Nucleon tomography

- GPDs allow simultaneous measurement of longitudinal momentum and transverse spatial structure

\( \xi \to 0: \quad t = -\Delta_{\perp}^2 \) purely transverse and

\[
q^f(x, b_{\perp}) = \int \frac{d^2 \Delta_{\perp}}{(2\pi)^2} e^{-i \Delta_{\perp} \cdot b_{\perp}} H^f(x, 0, -\Delta_{\perp}^2)
\]

- \( b_{\perp} \) distance to center of momentum (\( b \) in figure is \( b_{\perp} \))

\( x \sim 0.003 \quad x \sim 0.03 \quad x \sim 0.3 \)
Experiments

- **JLAB:**
  - DVCS cross sections, asymmetries
  - Hall A:
    - high precision, limited kinematics
  - Hall B:
    - wide kinematics, “limited” precision
  - very different systematics

- **HERMES:**
  - beam charge (BCA) and spin (BSA) asymmetries
  - transverse asymmetries
  - ongoing analysis with recoil detector

- **H1/ZEUS**
  - DVCS cross section, $t$ dependence, beam charge asymmetries
JLAB: Hall A and Hall B

- E00-110: DVCS cross section with unpol. p target, check of factorisation
- E03-116: measurement with d target
- E07-007: “Rosenbluth” sep. of Compton amplitudes

CLAS (E01-113, E06-003): BSA in large kinematic range
- not well described by current modells
- E05-114: TSA with pol. NH$_3$ target

PRL97(2006)262002

PRL100(2008)162002
Results on BCA and BSA: combined 1996-2005 and new 2006-7 data using missing mass technique

- $\cos \phi$ term related to Re $H$, $\cos 0\phi$ kinematically suppressed
DVCS at H1

**DVCS cross section:** $Q^2$, $W$, $t$ dependence

**Nucleon tomography:** $t$ slope $b$ related to size of nucleon at low $x$
Future plans: JLAB12

several experiments planned

- **Hall A: E12-06-114**
  - follow up of E00-110
  - $e^+ p \rightarrow ep\gamma$ at fixed $x$, several $Q^2$, several beam energies
  - high precision cross section measurements for $t$-dependence, $\text{Im} \mathcal{H}$, $\text{Re} \mathcal{H}$

- **Hall B: E12-06-119**
  - follow up of E01-113, E06-003, E05-114
  - large kinematic coverage with CLAS at 11 GeV, high statistics
  - extension to low and high $x$ ($0.1 < x < 0.7$)
  - second phase: polarised NH$_3$ target
  - $\text{BSA}(x, t, Q^2)$, $\text{TSA}(x, t, Q^2)$

- **Hall B: E12-11-003**
  - using CLAS at 11 GeV plus new recoil neutron detector
  - $\text{BSA}(x, t, Q^2)$ in large kinematic range
  - flavour separation of GPD $H$
Future plans: COMPASS

Exclusive measurements: DVCS and HEMP

Phase 1:
2.5 m $\text{lH}_2$ target
4 m long recoil detector

Phase 2:
transversely pol. target with recoil detector

classified CERN $\mu^\pm$ beam

high precision
beam flux and acceptance determination

trigger in large kinematic range

upgrade ECAL1/2
new ECAL0 before SM1
Target and recoil detector

- 2.5 m $\text{IH}_2$, 40 mm diameter
- minimum thickness of cryostat and target cell
- density fluctuations < 3%
- **TOF detector** 2 layers of scintillators
- 300 ps time resolution

- high occupancy due to $\delta$ rays
- **Gandalf Project**: 1GHz digitisation of signals to cope with high rate
Electromagnetic calorimeter ECAL0

- **Shashlik modules** (length about 35 cm)
- scintillator lead sandwich with 15 radiation length
- light read-out with wave length shifting fibres
- **avalanche micropixel photo diodes** need temp. stability $\leq 0.2K$
- test at CERN T9 beam and at muon beam

$\Rightarrow$ ok for GPD measurements
- result confirms expectations
- shape in $\phi$ determined by current photon acceptance in ECAL1/2
- ECAL0 needed for more uniform acceptance in $\phi$

$\Rightarrow$ clear DVCS signal observed at $Q^2 > 1$ GeV$^2$, $x_{Bj} > 0.03$
Projected results

- Transverse imaging:
  \[ B(x) \sim \frac{1}{2} \langle r_{\perp}^2(x) \rangle \]
  no model dependence

- Azimuthal dependence:
  \[ \text{Re}\mathcal{H}, \text{Im}\mathcal{H} \]
  comparison to different models

projections with 2 years of data
\[ \varepsilon_{\text{global}} = 10\% \]
\[ L = 1222 \text{ pb}^{-1} \]
Summary

● **GPDs** are a new active field (exp. and theor.)

● **DVCS** is the golden channel for GPDs
  in addition hard exclusive meson production

● first round of high statistics experiments at JLAB and DESY

● compelling GPD programm at JLAB12 and CERN

● **COMPASS** will fill the gap between H1/ZEUS and JLAB/HERMES
  – **phase 1**: study of GPD $H$ with unpolarised proton target
  – **phase 2**: study of GPD $E$ with transversely polarised NH$_3$
  – dress rehearsal for phase 1: this autumn
Deeply virtual meson production

\[ H_{\rho^0} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} H^u + \frac{1}{3} H^d + \frac{3}{8} H^g \right) , \quad H_\omega = \frac{1}{\sqrt{2}} \left( \frac{2}{3} H^u - \frac{1}{3} H^d + \frac{1}{8} H^g \right) , \quad H_\phi = -\frac{1}{3} H^s - \frac{1}{8} H^g \]

- **cross section measurement:** \( \rho : \omega : \phi \approx 9 : 1 : 2 \) at large \( Q^2 \)

  Vector meson production \( (\rho, \omega, \Phi) \Rightarrow H, E \)
  Pseudo-scalar production \( (\pi, \eta, \ldots) \Rightarrow \tilde{H}, \tilde{E} \)

- **transversely pol. target asymmetries:** constraint of \( E/H \)

\[ A_{UT}(\rho^0) \propto \sqrt{|-t'|} \frac{\text{Im}(E^*H)}{|H|^2} \]

larger effects expected for \( \omega, \rho^+ \)
Towards GPD $E$

measurements with transversely polarised target

$$D_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) - d\sigma_T(\mu^{-\uparrow})$$

$$^{\text{LO}} \propto \sin(\phi - \phi_S)(c_{0T}^I + c_{1T}^I \cos \phi)$$

$$c_{1T}^I \propto \text{Im} \left( (2 - x) F_1 E - 4 \frac{1 - x}{2 - x} F_2 H \right)$$

projections with 2 years of data

$\varepsilon_{global} = 10\%$

1.2 m pol. NH$_3$ target ($f=0.26$)

160 GeV, 280 days with ECAL2+ECAL1

with $|t_{min}|=0.10 \ (0.14) \ \text{GeV}^2$