Experimental Overview on DVCS Measurements (Past, Present and Future)

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Outline of this talk:
- Introduction
- Experiments
- Selected results:
  - Cross section
  - Beam charge & spin difference
  - Interference Term
  - Measurements for GPD E
Nucleon Tomography

Holy grail: Wigner Distributions
5 D picture of nucleon phase space $\rho(x,kT,bT)$

Experimentally from 3-D Pictures ...

... in momentum space ...

TMDs $F(x,kT)$

... in configuration space ...

GPDs
$H(x,b\perp) \leftrightarrow H(x,\xi,t)$

SIDIS

1D Parton Distribution Functions

Exclusive reactions
Accessing GPDs

- Deeply virtual Compton scattering
- Wide angle Compton scattering
- Form factors
- Timelike Compton scattering
- $\bar{p}p$ annihilation
- $\gamma\gamma \rightarrow \pi\pi, \ldots$
- Exclusive meson production
- Deep inelastic scattering
- PDFs

GPD filter by quantum numbers of final state:
- DVCS ($\gamma$): $H$, $E$, $\bar{H}$, $\bar{E}$
- VM ($\rho, \omega, \phi$): $H$, $E$
- Different quark flavours (p,e): $\bar{H}$, $\bar{E}$

GPDs and their Relation to Observables

The observables are some integrals of CFF integrated over $x$.

Dynamics of partons in nucleon models:
Parameterization

Elastic form factors

$\int H(x,\xi,t)dx = F(t)$

Ji's sum rule

$2J_q = \int x(H_q+E_q)(x,\xi,0)dx$

$1/2 = 1/2 \Delta \Sigma + Lq + \Delta G + Lg$

"Ordinary" parton density

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

Fit parameters to the data

Factorization
Exclusive reactions: DVCS and HEMP

Deeply Virtual Compton Scattering (DVCS):

\[ \gamma^* + Q^2 \rightarrow \gamma + p' \]

Hard Exclusive Meson Production (HEMP):

\[ \gamma^*_L + Q^2 \rightarrow \text{meson} + p' \]

Factorisation: Collins et al.

Q^2 large

\[ t \ll Q^2 \]

Meson w.f.

Large power & NLO

Very slow scaling
Deeply Virtual Compton Scattering (DVCS): 

\[ \gamma^* \rightarrow Q^2 \rightarrow \gamma \rightarrow x + \xi \rightarrow x - \xi \]

Definition of variables:

- \( x \): average long. momentum - NOT ACCESSIBLE
- \( \xi \): long. mom. difference \( \approx \frac{x_B}{2 - x_B} \)
- \( t \): four-momentum transfer related to \( b_\perp \) via Fourier transform

Golden channel
Cross Section & Angular Dependence

\[ d\sigma_{(\mu p \rightarrow \mu p')} = d\sigma^{BH} \]
\[ + d\sigma^{DVCS}_{unpol} + P_{\mu} d\sigma^{DVCS}_{pol} + e_{\mu} a^{BH}_{\Re} T^{DVCS} + e_{\mu} P_{\mu} a^{BH}_{\Im} T^{DVCS} \]

- \[ d\sigma^{BH} = \frac{\Gamma(x_B, Q^2, t)}{P_1(\phi)P_2(\phi)}(c^{BH}_0 + c^{BH}_1 \cos \phi + c^{BH}_2 \cos 2\phi) \]
- \[ d\sigma^{DVCS}_{unpol} = \frac{e^6}{y^2 Q^2}(c^{DVCS}_0 + c^{DVCS}_1 \cos \phi + c^{DVCS}_2 \cos 2\phi) \]
- \[ d\sigma^{DVCS}_{pol} = \frac{e^6}{y^2 Q^2}(s^{DVCS}_1 \sin \phi) \]
- \[ a^{BH}_{\Re} T^{DVCS} = \frac{e^6}{x y^3 t P_1(\phi) P_2(\phi)}(c^{Int}_0 + c^{Int}_1 \cos \phi + c^{Int}_2 \cos 2\phi + c^{Int}_3 \cos 3\phi) \]
- \[ a^{BH}_{\Im} T^{DVCS} = \frac{e^6}{x y^3 t P_1(\phi) P_2(\phi)}(s^{Int}_1 \sin \phi + s^{Int}_2 \sin 2\phi) \]

Known to 1%

Bilinear combination of GPDs

linear combination of GPDs

Twist 2

Twist 3

Twist 2 gluon
Example: Observables with unpolarized targets

$$d\sigma_{(\mu p \rightarrow \mu p\gamma)} = d\sigma^{BH}$$
$$+ d\sigma^{DVCS}_{\text{unpol}} + P_\mu d\sigma^{DVCS}_{\text{pol}}$$
$$+ e_\mu a^{BH} \text{Re} T^{DVCS} + e_\mu P_\mu a^{BH} \text{Im} T^{DVCS}$$

Beam Charge & Spin Sum:

$$S_{CS,U} = d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2(d\sigma^{BH} + d\sigma^{DVCS}_{\text{unpol}} + e_\mu P_\mu a^{BH} \text{Im} T^{DVCS})$$

Beam Charge & Spin Difference:

$$D_{CS,U} = d\sigma^{+\leftarrow} - d\sigma^{-\rightarrow} = 2(P_\mu d\sigma^{DVCS}_{\text{pol}} + e_\mu a^{BH} \text{Re} T^{DVCS})$$
Compton Form Factors are measured in DVCS

The amplitude DVCS at LT & LO in $\alpha_s$:

$$H = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} = \mathcal{P} \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i \pi H(x=\xi,\xi,t)$$

Real part measured in Beam Spin or Target Spin asymmetries

Im part measured in Beam Charge asymmetry or cross section
Bethe-Heitler & DVCS Cross Sections

Bethe-Heitler:

\[ d\sigma \propto |T_{BH}|^2 + \text{Interference Term} + |T_{DVCS}|^2 \]

DVCS:

Low \( x_B \): BH dominates

\[ 0.005 < x_B < 0.01 \]

Reference yield from almost pure BH

Large \( x_B \): Int dominates

\[ 0.01 < x_B < 0.03 \]

Study DVCS through interference term

\[ \Re T^{DVCS} & \Im T^{DVCS} \]

Transverse Imaging

Large \( x_B \): DVCS dominates

\[ x_B > 0.03 \]

Study \( d\sigma^{DVCS}/dt \)
Focus on DVCS$_2^2$ or Interference?

- Strong $x_{Bj} - E_{beam}$ correlation in fixed target experiments

**HERMES, J LAB, COMPASS**

- Only
  - H1, ZEUS, COMPASS

Low $x_B$: BH dominates

0.005 < $x_{Bj}$ < 0.01

Reference yield from almost pure BH

Large $x_B$: Int dominates

0.01 < $x_{Bj}$ < 0.03

Study DVCS through interference term

$\mathcal{R}e \, T^{DVCS}$ & $Im \, T^{DVCS}$

Large $x_B$: DVCS dominates

$x_{Bj}$ > 0.03

Study $d\sigma^{DVCS}/dt$

Transverse Imaging

$E_\mu = 160$GeV
**The ideal experiment**

**Beam:**
- High beam energy to ensure hard regime
- Longitudinally polarized beam
- Positive and negative lepton beam
- Variable energy for $\epsilon$ separation for DVCS² and interference term

**Target:**
- $H_2$ and $D_2$
- Unpolarized, longitudinal or transverse polarized target

**Detector:**
- Hermetic to ensure exclusivity
- Efficient calorimetry with good energy resolution

High luminosity to allow fully differential analysis in $x_B$, $Q^2$, $t$, $\phi$
Experiments in the past

Polarised 27 GeV $e^-/e^+$
Long, trans polarized p, d
Missing mass technique, 2006-07 recoil detector

Highly polarization 6 GeV $e^-$
Highest luminosity
Long, trans. polarized p, d
Missing mass technique
Present & Future Experiments (limited to this decade ... maybe ...)

Highly polarization 12 GeV $e^-$
Highest luminosity
Long, trans. polarized p, d
Missing mass technique

Highly polarised 160 GeV $\mu^+ / \mu^-$
Unpolarized p
(Long, trans. polarized p, d)
Recoil detection

Antiproton beam, fixed target p
time-like form factors

Highly polarization 12 GeV $e^-$
Highest luminosity
Long, trans. polarized p, d
Missing mass technique
Kinematic Coverage

Current DVCS data at colliders:
- ZEUS- total xsec
- ZEUS- dσ/dt
- H1- total xsec
- H1- dσ/dt
- H1- A_{CU}

Current DVCS data at fixed targets:
- HERMES- A_{LT}
- HERMES- A_{CU}
- HERMES- A_{LU}, A_{UL}, A_{LL}
- HERMES- A_{UT}
- Hall A- CFFs
- CLAS- A_{LU}
- CLAS- A_{UL}

Planned DVCS at fixed target:
- COMPASS- dσ/dt, A_{CSU}, A_{CST}
- JLAB12- dσ/dt, A_{LU}, A_{UL}, A_{LL}

EIC vs 45 GeV, 0.01 ≤ y ≤ 0.95
EIC vs 140 GeV, 0.01 ≤ y ≤ 0.95
Q^2 = 100 GeV^2
Q^2 = 50 GeV^2
y ≤ 0.6
y ≤ 0.6

COMPASS
JLAB 12 GeV
Some DVCS related measurements

- **H1 @ DESY**
  - X-sections

- **CLAS @ JLAB**
  - BSA

- **HERMES @ DESY**
  - BSA

- **HERMES**
  - BCA
  - TTSA

- **CLAS**
  - eg1b1-dvcs
  - LTSA

- **Hall A @ JLAB**
  - X-sections (p,n)

- **HERMES**
  - BCA & BSA (all data 96-07)
  - BCA & BSA (with recoil)

- **HERMES**
  - BSA & BSA (nuclear)

- **HERMES**
  - (Lpol p)

- **COMPASS @ CERN**
  - 2012 and >2014

- **JLAB 12**
  - >2020

- **PANDA**
  - >2020

- **EIC**
  - >2025
**Fixed target mode** slow recoil proton

\[ M_X^2 = (P_e + P_p - P_{e'} - P_{\gamma})^2 \]

**Exclusivity:** \( ep \rightarrow e + \gamma + p \)

- Without recoil detector

\[ \ell p \rightarrow \ell' + \gamma (+p') \]
\[ \ell p \rightarrow \ell' + \gamma (+\Delta^+) \]
\[ \ell p \rightarrow \ell' + \gamma (+\gamma + p' + ...) \]

(from \( \pi^0 \) decay...)

\( X = p \)
\( X = \Delta^+ \)
\( X = \pi^0 + .. \)
Fixed target mode slow recoil proton

\[ M_X^2 = (P_e + P_p - P_{e'} - P_\gamma)^2 \]

Exclusivity: \( ep \rightarrow e + \gamma + p \)

\( \ell p \rightarrow \ell' + \gamma (+p') \)

\( X = p \)

\( X = \Delta^+ \)

\( X = \pi^0 + \ldots \)

Kinematic fitting

from \( \pi^0 \) decay...

\( ep \rightarrow e + \gamma (+p + \ldots) \)

\( ep \rightarrow e + \gamma (+p \text{ in acceptance} + \ldots) \)

\( ep \rightarrow e + \gamma + p \)

without recoil detector

with recoil detector

\( ep \rightarrow e + \gamma + p \)
Exclusivity: $ep \rightarrow e + \gamma + p$

Fixed target mode slow recoil proton

$M_X^2 = (P_e + P_p - P_{e'} - P_\gamma)^2$

Background suppression ~ syst. error

without recoil detector

$l p \rightarrow l' + \gamma (+p')$

HallA
Exclusivity: $ep \rightarrow e + \gamma + p$

Collider mode $e-p$ forward fast proton

Outgoing proton escapes through the beam pipe
Tagged in forward proton spectrometer

Interference term integrated over $\phi$ $\rightarrow$ pure DVCS cross section
Cross sections measurements: DVCS and mesons

Study of the GPD H with DVCS on proton:
- Beam Spin Asymmetry: HallA – CLAS - HERMES
- Beam Charge Asymmetry: HERMES – H1 – COMPASS
- Cross section difference and sum: HallA – CLAS – COMPASS

Hunting GPD E:
- Beam Spin cross section on the neutron: HallA
- Transverse pol. Target Asymmetry on proton: HERMES

→ ‘Holy grail’ for OAM
Cross sections and W dependence

Are we in the hard regime?

$$\sigma(W) \propto W^{\delta}$$

$\delta$ increases from soft ($\sim 0.2$) to hard ($\sim 0.8$)
Almost no evolution as a function of $W$

$$B = 5.45 \pm 0.19 \pm 0.34 \text{ GeV}^2$$

at $<Q^2> = 8 \text{ GeV}^2$ and $<x> = 1.2 \times 10^{-3}$

$b$ decreases from soft ($\sim 10 \text{ GeV}^{-2}$) to hard ($\sim 5 \text{ GeV}^{-2}$)
Predictions for DVCS from KM model

one of the most general parameterization of GPDs based on their mathematic Properties fit to the DVCS data and DIS
**COMPASS: Beam Charge & Spin Difference $S_{CS,U}$ - Transverse imaging**

\[
S_{CS,U} = d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e\mu P_\mu a^{BH} I_m T^{DVCS}\right)
\]

- Using $S_{CS,U}$
- Integrating over $\phi$
- Subtracting BH

\[
\frac{d\sigma}{dt}\propto e^{-B|t|}
\]

\[
\langle r_{\perp}^2(x_B) \rangle \sim 2B(x_B)
\]

- Ansatz at small $x_B$:
  \[(x \sim x_B)\]
  \[B(x_B) = b_0 + 2\alpha' \ln x_0/x_B\]

- Measure $\alpha'$ with accuracy $>2.5\sigma$ for any $\alpha' > 0.125$

**Projection for 2012 run:**
- $\alpha' = 0.125$
- $\alpha' = 0.26$

**Projection for 2 years:**
- $L = 1222\ \text{pb}^{-1}$
- $\epsilon_{\text{global}} = 10\%$

**No Modell dependence**

- COMPASS $<Q^2> = 2\ \text{GeV}^2$
- 280 days at 160 GeV

- H1-HERA I $<Q^2> = 3.2\ \text{GeV}^2$
- H1-HERA II $<Q^2> = 8\ \text{GeV}^2$

- ZEUS $<Q^2> = 4\ \text{GeV}^2$

- with ECAL0+1+2
Beam Charge & Spin Difference $\mathcal{D}_{CS,U}$

$$\mathcal{D}_{CS,U} = d\sigma^{+\leftarrow} - d\sigma^{-\rightarrow} = 2(P_{\mu}d\sigma_{pol}^{DVCS} + e_{\mu}a^{BH}
\text{Re } T^{DVCS})$$

Need to control detector acceptance and beam flux with high precision

Error band includes a 3% systematic uncertainty between $\mu^+$ and $\mu^-$

Use inclusive events and BH for check
Beam Charge & Spin Asymmetry \( D_{CS,U} / S_{CS,U} \)

\[ BCSA = D_{CS,U} / S_{CS,U} = A_0 + A_{CS,U} \cos \phi + A_2 \cos 2\phi \]

\[ \Re(F_1H) > 0 \text{ @ H1} \]
\[ < 0 \text{ @ HERMES} \]

Node? Where in \( x_B \)?

\( \rightarrow \) COMPASS

**Predictions with VGG and D. Mueller**

- 0.005 < \( x_B \) < 0.01
- 0.01 < \( x_B \) < 0.02
- 0.02 < \( x_B \) < 0.03

Kumericki, Müller

Incl. HALL A

Without HALL A

arXiv:0904.0458
DVCS interference on the proton

\( \rightarrow Im \) DVCS with BSA or Beam Spin difference

\( \rightarrow Re \) DVCS with BCA or Beam Charge difference

\( \rightarrow \) mainly constrains on the GPD H
E00-110 pioneer experiment with magnetic spectrometer

3 measurements: \( x_B = 0.36 \), \( Q^2 = 1.5, 1.9, 2.3 \text{ GeV}^2 \)

\[ \vec{e}p \rightarrow e \gamma p \]

Data: Munoz et al. PRL97, 262002 (2006)
Model: Kroll, Moutarde, Sabatié, EPJC73 (2013) with GPDs from GK model

\[ x_B = 0.36 \quad Q^2 = 2.3 \text{ GeV}^2 \]

News:
- Re-analysis of the data (MC, RC, normalisation/DIS)
- 2010: run E07-007
  Rosenbluth-like DVCS\(^2\)/Int separation
- 2014: HallA with 11 GeV
- 2018: HallC with 11 GeV
Data: Munoz et al. PRL97, 262002 (2006)


GK12 model evaluated with KM and BMP prescription including kinematic corrections (finite-t, target mass corr.)

Beam Spin Sum = Total cross section

Beam Spin difference

Do we understand Hall A data?
JLAB Hall A & Hall C - future

with magnetic spectrometer + Calorimeter

E12-06-114: DVCS at 11 GeV in Hall A

- DVCS measurements in Hall A/JLab

- $Q^2$ (GeV$^2$)
- $x_{Bj}$

- Tentative running: ~ 2019-20

- Absolute cross-section measurements
- Test of scaling: $Q^2$ dependence of $d\sigma$ at fixed $x_{Bj}$
- Increased kinematical coverage

Start on Feb 2014, for 1 year of data taking

E12-13-010: DVCS at 11 GeV in Hall C

- Energy separation of the DVCS cross section
- Higher $Q^2$: measurement of higher twist contributions
- Low-$x_B$ extension (thanks to sweeping magnet)

Need a new challenging Calorimeter
CLAS: BSA in a large kinematic domain

Part 1 of the E01-113 or e1-DVCS exp

$\vec{e}p \rightarrow e \gamma p$

CLAS + Inner Calorimter
Solenoid magnet

No simple interpretation of $\alpha$

Data: Girod et al. PRL100, 162002 (2008)
Beam Spin Difference - CLAS

Data from: H.S. Jo

VGG
KM10a (without Hall A)
KM10b

PRELIMINARY

VGG (only H): Goeke, Polyakov, Vanderhaeghen, Prog.Part.Nucl.Phys. 47 401 (2001)
E12-06-119

Strong effort in Detector upgrades

Complete data set including 2006-07

High-purity event selection shows that there is only a small influence on the extracted BSA amplitude from events involving a $\Delta$ particle (associated DVCS)

The leading asymmetry has increased by $0.054 \pm 0.016$

Mainly dilution due to associated DVCS

Model: Kroll, Moutarde, Sabatié, EPJC73 (2013) with GPDs from GK model
Complete data set including 2006-07 without recoil detection

Goldstein, Hernandez, Liuti Phys. Rev. D84 (20101)
Large $A_{UT,DVCS} \sin(\phi - \phi_S)$
With strong $x_{Bj}$ dependence

Also large $A_{UT,I} \sin(\phi - \phi_S)$

Sensitive to GPD E $\rightarrow J_u, J_d$ (VGG model)
Model: Kroll, Moutarde, Sabatié, EPJC73 (2013) with GPDs from GK model

\[
A_{UT,DVCS}^{\sin(\phi - \phi_S)} \sim \text{Im}[\mathcal{E}^* \mathcal{H}]
\]

\[
A_{UT,DVCS}^{\sin(\phi - \phi_S)} \neq 0 \implies \mathcal{E} \neq 0
\]

cancellation between \(\mathcal{E}^s\) and \(\mathcal{E}^g\) does not occur as for \(\rho^0\) asymmetry, DVCS observables are very sensitive to \(E_{\text{sea}}\)

\[
\langle x_B \rangle \simeq 0.09
\]
\[
\langle Q^2 \rangle \simeq 2.5 \text{ GeV}^2
\]

\(E_{\text{sea}} < 0\) is favored by HERMES data
Hunting the GPD $E$ with CLAS12 at Jlab

$\vec{e} d \rightarrow e n \gamma (p)$  \hspace{1cm} E12-11-003

$\Delta\sigma_{LU} \sim Im (F_{1n} \mathcal{H} - F_{2n} \mathcal{E})$

With LD2 target + CLAS12
+ Forward Calorimeter
+ Neutron Detector ToF

$\vec{e} p \rightarrow e p \gamma$  \hspace{1cm} E12-12-010

$\Delta\sigma_{UT} \sin(\phi - \phi_s) \cos \phi = Im (F_2 \mathcal{H} - F_1 \mathcal{E})$

$\Delta\sigma_{LT} \sin(\phi - \phi_s) \cos \phi = Re (F_2 \mathcal{H} - F_1 \mathcal{E})$

With the HD ice target
(transv pol =60% H )
+ CLAS12

SELECTED IN THE «HIGH IMPACT» EXPERIMENTS
Dragon: among many others it is a symbol for fortune and glory … like the measurements of GPDs

The End

Thank you for your attention
Compton Form Factors are measured in DVCS

The amplitude DVCS at LT & LO in $\alpha_s$:

$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} = \mathcal{P} \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i \pi H(x=\xi,\xi,t)$$

$\xi \sim x_{Bj/2}$ fixed

$\text{Real part}$ measured in 
$\text{Beam Spin}$ or $\text{Target Spin}$ asymmetries

$\text{Im part}$ measured in 
$\text{Beam Charge}$ asymmetry or $\text{cross section}$

$D$ term related to the Energy-Momentum Tensor:

Polyakov, PLB 555 (2003) 57-62