Probing GPDs in Ultraperipheral Collisions

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timelike-DVCS: B.Pire, L.Szymanowski
$J/\Psi$ photoproduction: D.Ivanov, L.Szymanowski
Deep Inelastic Scattering $e p \rightarrow e X$

In the Björken limit i.e. when the photon virtuality $Q^2 = -q^2$ and the squared hadronic c.m. energy $(p + q)^2$ become large, with the ratio $x_B = \frac{Q^2}{2p \cdot q}$ fixed, the cross section factorizes into a hard partonic subprocess calculable in the perturbation theory, and a parton distributions.
Parton distributions encode the distribution of \textit{longitudinal} momentum and polarization carried by quarks, antiquarks and gluons within fast moving hadron.

PDFs don’t provide information about how partons are distributed in the \textit{transverse} plane and ...

about how important is the \textit{orbital angular momentum} in making up the total spin of the nucleon.

Recently - growing interest in the \textit{exclusive} scattering processes, which may shed some light on these issues through the \textit{generalized parton distributions (GPDs)}.
The simplest and best known process is **Deeply Virtual Compton Scattering**: 
\[ e p \rightarrow e p \gamma \]

Factorization into GPDs and perturbative coefficient function - on the level of amplitude.

**DIS**: \[ \sigma = \text{PDF} \otimes \text{partonic cross section} \]

**DVCS**: \[ M = \text{GPD} \otimes \text{partonic amplitude} \]
GPDs

- **GPDs** enter factorization theorems for hard *exclusive* reactions (DVCS, deeply virtual meson production, TCS etc.), in a similar manner as **PDFs** enter factorization theorems for *inclusive* (DIS, etc.)

- **GPDs** are functions of $x, t, \xi, \mu_F^2$

- First moment of GPDs enters the Ji’s sum rule for the *angular momentum* carried by partons in the nucleon,

- 2+1 *imaging* of nucleon,

- Deeply Virtual Compton Scattering (DVCS) is a golden channel for GPDs extraction,
DVCS - what else, and why

- Difficult: exclusivity, 3 variables, GPD enter through convolutions, only GPD(ξ, ξ, t) accessible through DVCS at LO!
- universality,
- flavour separation,

- Meson production - additional information (and difficulties),
So, in addition to spacelike DVCS …

**Figure:** Deeply Virtual Compton Scattering (DVCS) : $lN \rightarrow l'N'\gamma$
we can also study timelike DVCS

Figure: Timelike Compton Scattering (TCS): $\gamma N \rightarrow l^+ l^- N'$

Why TCS:

- universality of the GPDs
- another source for GPDs (special sensitivity on real part of GPD $H$),
- spacelike-timelike crossing,
- first step towards DDCVS,
General Compton Scattering:

\[ \gamma^*(q_{in})N(p) \rightarrow \gamma^*(q_{out})N'(p') \]

variables, describing the processes of interest in this generalized Bjorken limit, are the scaling variable \( \xi \) and skewness \( \eta > 0 \):

\[ \xi = -\frac{q_{out}^2 + q_{in}^2}{q_{out}^2 - q_{in}^2} \eta, \quad \eta = \frac{q_{out}^2 - q_{in}^2}{(p + p') \cdot (q_{in} + q_{out})}. \]

- **DDVCS:** \( q_{in}^2 < 0, \quad q_{out}^2 > 0, \quad \eta \neq \xi \)
- **DVCS:** \( q_{in}^2 < 0, \quad q_{out}^2 = 0, \quad \eta = \xi > 0 \)
- **TCS:** \( q_{in}^2 = 0, \quad q_{out}^2 > 0, \quad \eta = -\xi > 0 \)
Coefficient functions and Compton Form Factors

CFFs are the GPD dependent quantities which enter the amplitudes. They are defined through relations:

\[
A^{\mu\nu}(\xi, \eta, t) = -e^2 \frac{1}{(P + P')^+} \bar{u}(P') \left[ g^{\mu\nu} \left( \mathcal{H}(\xi, \eta, t) \gamma^+ + \mathcal{E}(\xi, \eta, t) \frac{i\sigma^{+\rho} \Delta_\rho}{2M} \right) ight.
\]

\[
+ i\epsilon^{\mu\nu}_T \left( \tilde{\mathcal{H}}(\xi, \eta, t) \gamma^+ \gamma_5 + \tilde{\mathcal{E}}(\xi, \eta, t) \frac{\Delta^+ \gamma_5}{2M} \right) \bigg] u(P),
\]

where:

\[
\mathcal{H}(\xi, \eta, t) = + \int_{-1}^{1} dx \left( \sum_q T^q(x, \xi, \eta) H^q(x, \eta, t) + T^g(x, \xi, \eta) H^g(x, \eta, t) \right)
\]

\[
\tilde{\mathcal{H}}(\xi, \eta, t) = - \int_{-1}^{1} dx \left( \sum_q \tilde{T}^q(x, \xi, \eta) \tilde{H}^q(x, \eta, t) + \tilde{T}^g(x, \xi, \eta) \tilde{H}^g(x, \eta, t) \right).
\]
LO and NLO Coefficient functions

▶ DVCS vs TCS at LO

\[
\begin{align*}
DVCS T^q &= -e^2 q \frac{1}{x + \eta - i\epsilon} - (x \to -x) = (TCS T^q)^* \\
DVCS \tilde{T}^q &= -e^2 q \frac{1}{x + \eta - i\epsilon} + (x \to -x) = -(TCS \tilde{T}^q)^*
\end{align*}
\]

\[DVCS Re(\mathcal{H}) \sim P \int \frac{1}{x \pm \eta} H^q(x, \eta, t), \quad DVCS Im(\mathcal{H}) \sim i\pi H^q(\pm \eta, \eta, t)\]

▶ DDVCS at LO

\[
DDVCS T^q = -e^2 q \frac{1}{x + \xi - i\epsilon} - (x \to -x)
\]

\[DDVCS Re(\mathcal{H}) \sim P \int \frac{1}{x \pm \xi} H^q(x, \eta, t), \quad DDVCS Im(\mathcal{H}) \sim i\pi H^q(\pm \xi, \eta, t)\]

But this is only true at LO. At NLO all GPDs hidden in the convolutions.

▶ DVCS vs TCS at LO

The results for DVCS and TCS cases are simply related:

\[
TCS T(x, \eta) = \pm \left(DVCS T(x, \xi = \eta) + i\pi \cdot C_{coll}(x, \xi = \eta)\right)^*,
\]

TCS and Bethe-Heitler contribution to exclusive lepton pair photoproduction.

Figure: The Feynman diagram for the Bethe-Heitler amplitude.

Figure: The Feynman diagram for the Compton amplitude.
Figure: Kinematical variables and coordinate axes in the $\gamma p$ and $\ell^+\ell^-$ c.m. frames.
Interference

B–H dominant for not very high energies:

\[
\text{Figure: } \text{LO (dotted) and NLO (solid) TCS and Bethe-Heitler (dash-dotted) contributions to the cross section as a function of } t \text{ for } Q^2 = \mu^2 = 4 \text{ GeV}^2 \text{ integrated over } \theta \in (\pi/4; 3\pi/4) \text{ and over } \phi \in (0; 2\pi) \text{ for } E_\gamma = 10 \text{ GeV}(\eta \approx 0.11).\]

The interference part of the cross-section for \( \gamma p \rightarrow \ell^+ \ell^- p \) with unpolarized protons and photons is given by:

\[
\frac{d\sigma_{INT}}{dQ^2 \, dt \, d\cos \theta \, d\phi} \sim \cos \varphi \cdot \text{Re} \mathcal{H}(\eta, t)
\]

Linear in GPD’s, odd under exchange of the \( l^+ \) and \( l^- \) momenta \( \Rightarrow \) angular distribution of lepton pairs is a good tool to study interference term.
Figure: $e^+e^-$ invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1 \text{ GeV}$ and $s_{\gamma p} > 4.6 \text{ GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.
Theory vs experiment
R.Paremuzyan and V.Guzey:

\[ R = \frac{\int d\phi \cos \phi \int d\theta \, d\sigma}{\int d\phi \int d\theta \, d\sigma} \]

\( Q^2 = 1.3 \text{ GeV}^2 \quad E_\gamma = 3.536 \text{ GeV} \)

Figure: Thoeretical prediction of the ratio \( R \) for various GPDs models. Data points after combining both e1-6 and e1f data sets.
Jefferson Lab PAC 39 Proposal
Timelike Compton Scattering and $J/\psi$ photoproduction on the proton
in $e^+e^-$ pair production with CLAS12 at 11 GeV

I. Albayrak, V. Burkert, E. Chudakov, N. Dashyan, C. Desnault, N. Gevorgyan,
Y. Ghandilyan, B. Guegan, M. Guidal, V. Guzey, K. Hicks, T. Horn, C. Hyde,
Y. Ilieva, H. Jo, P. Khetarpal, F.J. Klein, V. Kubarovsky, A. Marti, C. Munoz Camacho,
P. Nadel-Turonski, S. Niccolai, R. Paremuzyan, B. Pire, F. Sabatié, C. Salgado,
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Approved experiment at Hall B, and LOI for Hall A.
Ultraperipheral collisions

\[
\sigma^{AB} = \int dk_A \frac{dn^A}{dk_A} \sigma^B(W_A(k_A)) + \int dk_B \frac{dn^B}{dk_B} \sigma^A(W_B(k_B))
\]

where \( k_{A,B} = \frac{1}{2} x_{A,B} \sqrt{s} \).
BH cross section at UPC

![Graph](image)

**Figure:** (a) The BH cross section integrated over $\theta \in [\pi/4, 3\pi/4]$, $\varphi \in [0, 2\pi]$, $Q'^2 \in [4.5, 5.5] \text{GeV}^2$, $|t| \in [0.05, 0.25] \text{GeV}^2$, as a function of $\gamma p$ c.m. energy squared $s$. (b) $\sigma_{TCS}$ as a function of $\gamma p$ c.m. energy squared $s$, for GRV GJR2008 NLO parametrizations, for different factorization scales $\mu_F^2 = 4$ (dotted), 5 (dashed), 6 (solid) $\text{GeV}^2$.

For very high energies $\sigma_{TCS}$ calculated with $\mu_F^2 = 6 \text{GeV}^2$ is much bigger then with $\mu_F^2 = 4 \text{GeV}^2$. Also predictions obtained using LO and NLO GRV GJR2008 PDFs differ significantly.
The interference cross section at UPC

Figure: The differential cross sections (solid lines) for \( t = -0.2 \text{ GeV}^2 \), \( Q'^2 = 5 \text{ GeV}^2 \) and integrated over \( \theta = [\pi/4, 3\pi/4] \), as a function of \( \varphi \), for \( s = 10^7 \text{ GeV}^2 \) (a), \( s = 10^5 \text{ GeV}^2 \) (b), \( s = 10^3 \text{ GeV}^2 \) (c) with \( \mu_F^2 = 5 \text{ GeV}^2 \). We also display the Compton (dotted), Bethe-Heitler (dash-dotted) and Interference (dashed) contributions.
UPC Rate estimates

The pure Bethe - Heitler contribution to $\sigma_{pp}$, integrated over $\theta = [\pi/4, 3\pi/4]$, $\phi = [0, 2\pi]$, $t = [-0.05 \text{ GeV}^2, -0.25 \text{ GeV}^2]$, $Q'^2 = [4.5 \text{ GeV}^2, 5.5 \text{ GeV}^2]$, and photon energies $k = [20, 900] \text{ GeV}$ gives:

$$\sigma_{pp}^{BH} = 2.9 \text{ pb}.$$ 

The Compton contribution (calculated with NLO GRVGJR2008 PDFs, and $\mu_F^2 = 5 \text{ GeV}^2$) gives:

$$\sigma_{pp}^{TCS} = 1.9 \text{ pb}.$$ 

LHC: rate $\sim 10^5$ events/year with nominal luminosity ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$)
The amplitude $\mathcal{M}$ is given by factorization formula:

$$\mathcal{M} \sim \left( \frac{\langle O_1 \rangle_V}{m^3} \right)^{1/2} \int_{-1}^{1} dx \left[ T_g(x, \xi) F^g(x, \xi, t) + T_q(x, \xi) F^{q,S}(x, \xi, t) \right],$$

$$F^{q,S}(x, \xi, t) = \sum_{q=u,d,s} F^q(x, \xi, t).$$

where $m$ is a pole mass of heavy quark, $\langle O_1 \rangle_V$ is given by NRQCD through leptonic meson decay rate.
Hard scattering kernels

\[
T_g(x, \xi) = \frac{\xi}{(x - \xi + i\epsilon)(x + \xi - i\epsilon)} A_g \left( \frac{x - \xi + i\epsilon}{2\xi} \right),
\]

\[
T_q(x, \xi) = A_q \left( \frac{x - \xi + i\epsilon}{2\xi} \right).
\]

- **LO**

\[
A_g^{(0)}(y) = \alpha_S, \quad \text{In the first paper it was : } \alpha_S(1 + \epsilon)
\]

\[
A_q^{(0)}(y) = 0.
\]

- **NLO**

$T_g(x, \xi)$ - unchanged, and in $T_q(x, \xi)$ one has to correct:

\[
\left( \log \frac{4m^2}{\mu_F^2} - 1 \right) \rightarrow \left( \log \frac{4m^2}{\mu_F^2} \right)
\]

Erratum is being written, but phenomenological consequences unchanged.
Photoproduction amplitude and cross section - LO

**Figure:** (left) Imaginary part of the amplitude $\mathcal{M}$ and (right) photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$. 
Photoproduction amplitude and cross section - LO and NLO.

**Figure:** Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO
Photoproduction cross section

NLO/LO for large $W$:

$$\sim \frac{\alpha_S(\mu_R) N_c}{\pi} \ln \left( \frac{1}{\xi} \right) \ln \left( \frac{\frac{1}{4} M_{V}^2}{\mu_F^2} \right)$$

What to do ??? (PMS??, BLM??, resummation?,...?)

Figure: Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO. Thick lines for LO and NLO for $\mu_F^2 = 1/4 M_{J/\psi}^2$. 
Cross section for Ultraperipheral p-Pb collision in the EPA, $\sqrt{s} = 5$ TeV as a function of $y$.

(left) LO and NLO $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$.
(right) LO and NLO for $\mu_F^2 = 1/4 M_{J/\psi}^2$. 
Summary

- GDPs enter factorization theorems for hard exclusive reactions (DVCS, deeply virtual meson production etc.), in a similar manner as PDFs enter factorization theorem for DIS - Ji’s sum rule, „tomographic” 3D images
- DVCS is a golden channel, a lot of new experiments planned to measure DVCS - JLAB 12, COMPASS, EIC(?)
- but we want to describe other exclusive processes - TCS, double DVCS, DVMP, photoproduction of heavy mesons...
- TCS already measured at JLAB 6 GeV, but much richer and more interesting kinematical region available after upgrade to 12 GeV, maybe possible at COMPASS.
- Ultraperipheral collisions at hadron colliders opens a new way to measure GPDs,
- NLO corrections very important, also important for GPD extraction at $\xi \neq x$.
- Situation for $\Upsilon$ should be better - higher factorization scale, and $\xi$ not that small (comparing to $J/\Psi$).