Timelike Compton Scattering in Ultraperipheral Collisions.

Jakub Wagner, Institute for Nuclear Studies, Warsaw, Poland

DIS2009, 26-30 April 2009, Madrid

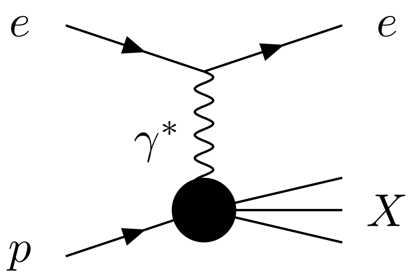
Phys.Rev.D79:014010,2009
arXiv:0811.0321 [hep-ph]
in colaboration with:
B.Pire, CPHT, Ecole Polytechnique
L.Szymanowski, Institute for Nuclear Studies

Outline of the talk.

1. Deeply virtual Compton scattering (DVCS) and Generalized Parton Distributions (GPDs)
   - Big theoretical and experimental effort in the DVCS ($\gamma^* p \to \gamma p$), an exclusive reaction where GPDs factorize from perturbative coefficient functions, when the virtuality of the incoming photon is high.
2. Properties of Timelike Compton Scattering (TCS)
   - Exclusive process ($\gamma p \to \gamma^* p$), for large timelike virtuality shares many features of DVCS.
   - Crossing from spacelike to timelike probe - important test of QCD corrections.
3. Timelike Compton Scattering at LHC.
   - Hadron Colliders as powerful sources of quasi real photons in UPC.
   - First study of the feasibility of extraction of the TCS signal.

DIS vs. DVCS

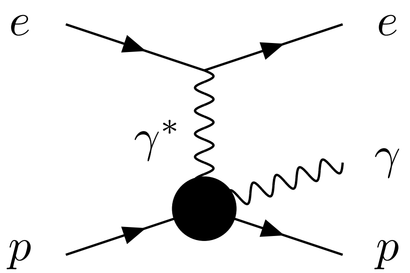
- Deep Inelastic Scattering:



$$ep \longrightarrow eX$$

$$\gamma^* p \longrightarrow X$$

- Deeply Virtual Scattering (DVCS):

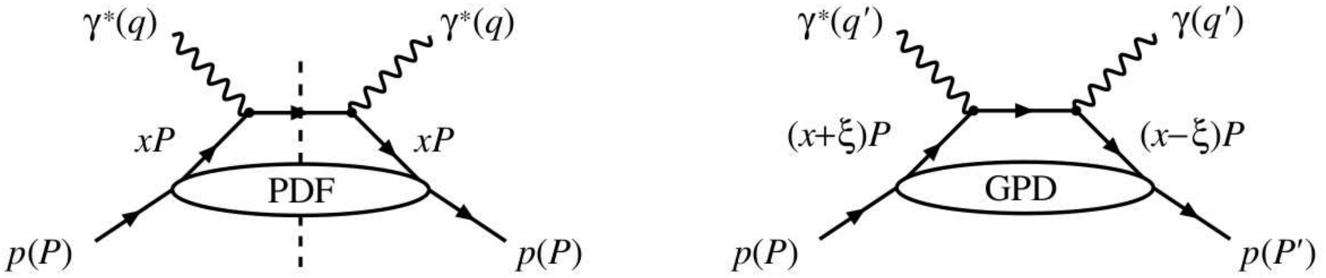


$$ep \longrightarrow ep\gamma$$

$$\gamma^* p \longrightarrow p\gamma$$

DIS vs. DVCS

- DIS vs. DVCS



- factorization:

$$
\begin{array}{lcccc}
\text{DIS} & : & \sigma & = & [\text{PDF}] \otimes [\text{partonic cross section}] \\
\text{DVCS} & : & \mathcal{M} & = & [\text{GPD}] \otimes [\text{partonic amplitude}]
\end{array}
$$

Definition of GPDs

- Definition of PDFs:

$$\frac{1}{2}\sum_{spin}\int\frac{d\lambda}{2\pi}e^{-i\lambda x}\langle p(P)|\bar{\psi}_q(z)\not{n}\,\psi_q(0)|p(P)\rangle \equiv q(x)$$

where: $z^\mu = \lambda n^\mu$, $n^2 = 0$, $n \cdot P = 1$.

- Definition of GPDs:

$$\begin{aligned}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle p(P')|\bar{\psi}_q(-z/2)\not{n}\,\psi_q(z/2)|p(P)\rangle \quad &\equiv \quad H^q(x,\xi,t)\bar{u}(P')\not{n}\,u(P) \\ &+ \quad E^q(x,\xi,t)\bar{u}(P')\frac{i\sigma^{\beta\alpha}\Delta_\alpha n_\beta}{2M}u(P)\end{aligned}$$

where: $z^\mu = \lambda n^\mu$, $n^2 = 0$, $n \cdot \frac{P+P'}{2} = 1$, $\Delta^\mu = (P' - P)^\mu$, $t = \Delta^2$.

Generalized Parton Distributions

- GDPs enters factorization theorems for hard exlusive reactions (DVCS, deeply virtual meson production etc.), in a similar manner as PDFs enter factorization theorem for DIS.
- GPDs are functions of **three** kinematical variables: longitudal momentum fraction x, longitudinal momentum transfer ξ and overall momentum transfer t.

Generalized Parton Distributions (2)

- In the forward limit: $t, \xi \to 0$, GPDs reduce to PDFs.

$$H^q(x, \xi = 0, t = 0) = \begin{cases} q(x) & \text{for} \quad x > 0 \\ -\bar{q}(-x) & \text{for} \quad x < 0 \end{cases}$$

- When integrated over x, GPDs reduce to elastic form factors.

$$F_1(t) = \sum_q \int_{-1}^{1} dx H^q(x, \xi, t)$$

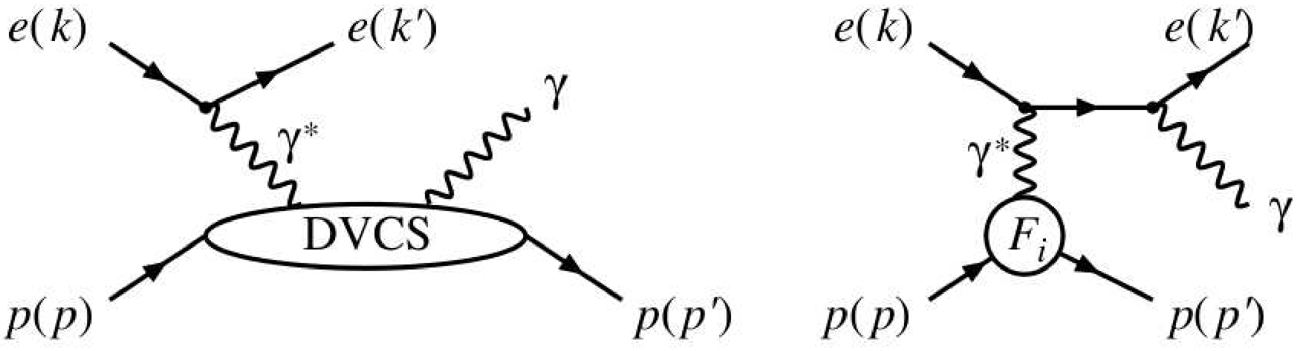
$$F_2(t) = \sum_q \int_{-1}^{1} dx E^q(x, \xi, t)$$

ξ dependence vanishes after integration over x (also factorization scale dependence).

Generalized Parton Distributions

- First moment of GPDs, enter the Jis sum rule for the angular momentum carried by partons in the nucleon.
- Fourier transform of GPDs to impact parameter space can be interpreted as ,,tomographic 3D pictures of nucleon, describing charge distribution in the transverse plane, for a given value of x.

DVCS and Bethe-Heitler contribution.



$$\sigma \sim |\mathcal{A}_{DVCS} + \mathcal{A}_{BH}|^2 = |\mathcal{A}_{DVCS}|^2 + |\mathcal{A}_{BH}|^2 + \mathcal{A}^*_{DVCS}\mathcal{A}_{BH} + \mathcal{A}_{DVCS}\mathcal{A}^*_{BH}$$

Different beam charges allow to filter the interference term (linear in lepton charge), and extract information about GPDs.

Exclusive photoproduction of dileptons, $\gamma N \to \ell^+ \ell^- N$

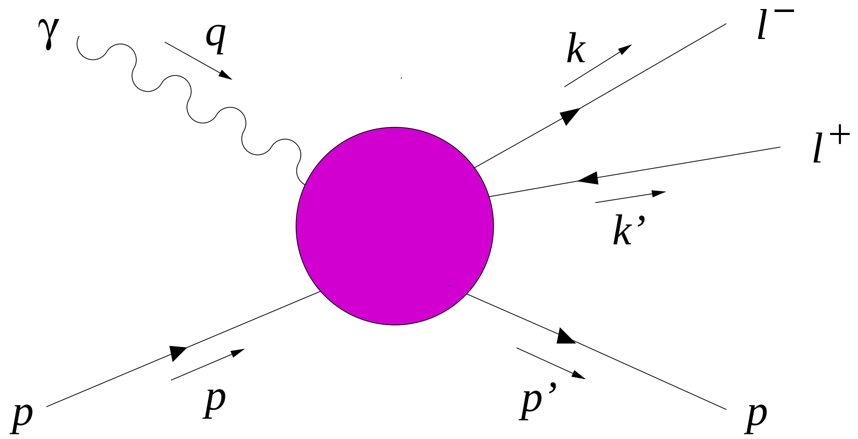


Figure 1: Real photon-proton scattering into a lepton pair and a proton.

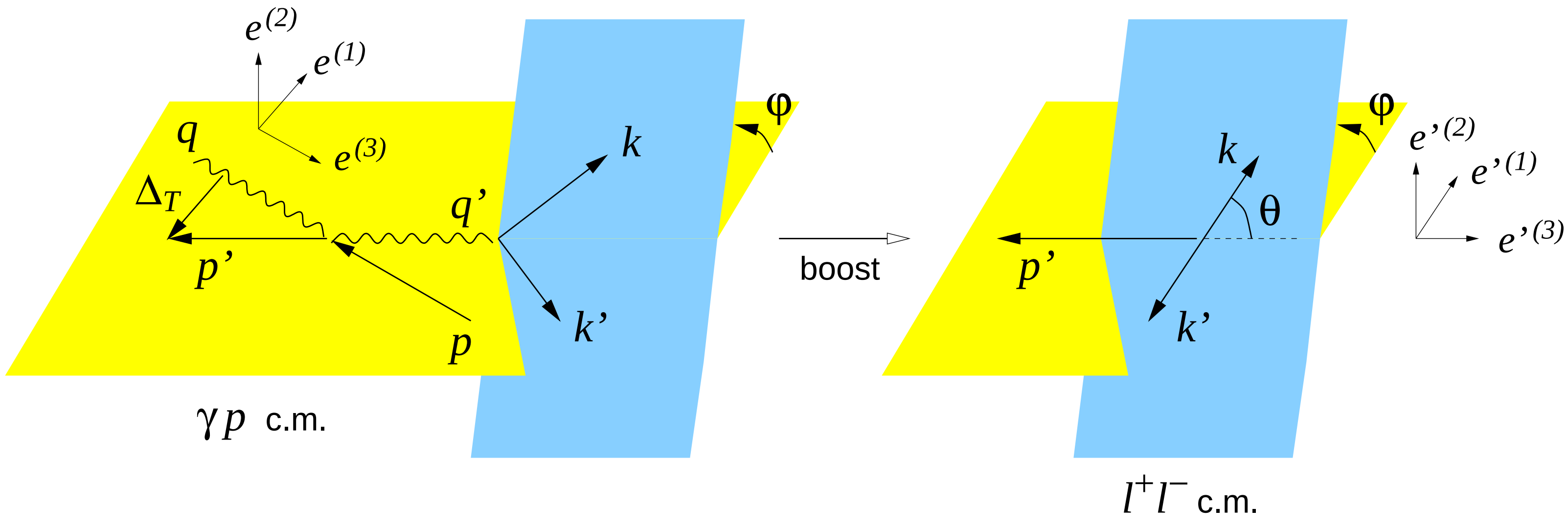


Figure 2: Kinematical variables and coordinate axes in the γp and $\ell^+\ell^-$ c.m. frames.

Bethe-Heitler process

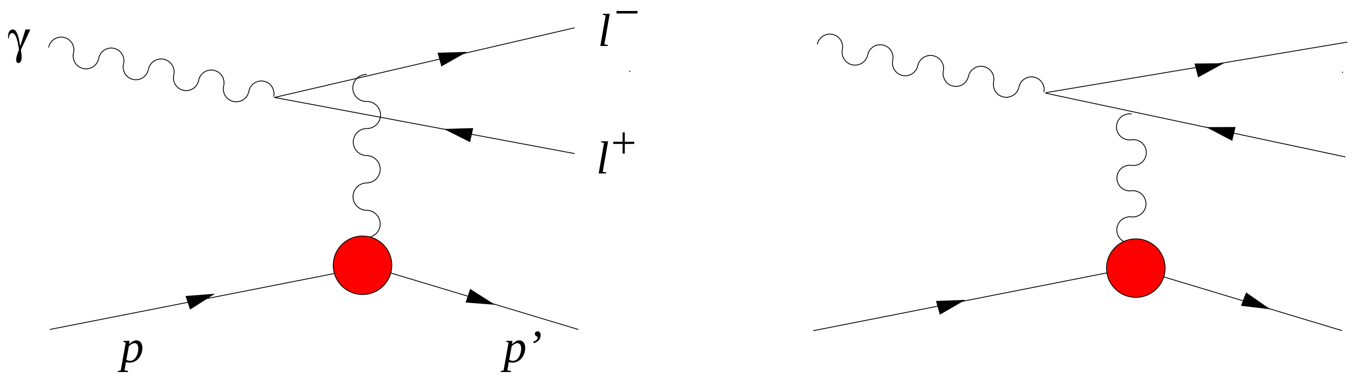


Figure 3: The Feynman diagrams for the Bethe-Heitler amplitude.

$$\frac{\mathrm{d}\sigma_{BH}}{\mathrm{d}Q'^2\mathrm{d}\Omega\mathrm{d}t} \longrightarrow \frac{\alpha^3}{4\pi}\frac{1}{-tL}(1+\cos^2\theta)\left(F_1^2 - \frac{t}{4M_p^2}F_2^2\right)$$

For small θ BH contribution becomes extremely large.

Timelike Compton Scattering

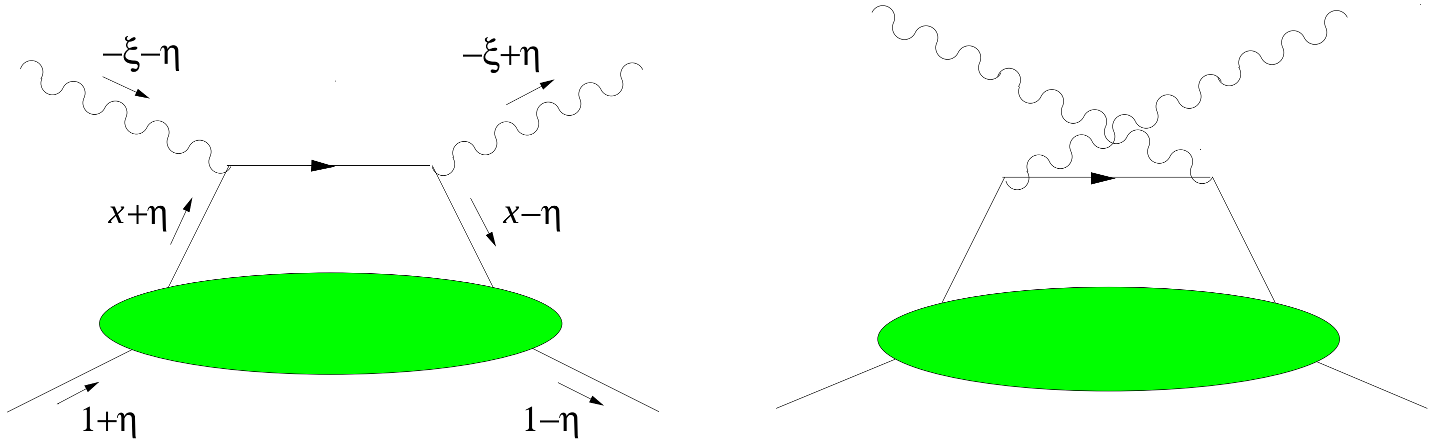


Figure 4: Handbag diagrams for the Compton process in the scaling limit. The plus-momentum fractions x, ξ, η refer to the average proton momentum $\frac{1}{2}(p+p')$.

$$T^{\alpha\beta} = -\frac{1}{(p+p')^+}\bar{u}(p')\left[g_T^{\alpha\beta}\left(\mathcal{H}\gamma^+ + \mathcal{E}\frac{i\sigma^{+\rho}\Delta_\rho}{2M}\right) + i\epsilon_T^{\alpha\beta}\left(\tilde{\mathcal{H}}\gamma^+\gamma_5 + \tilde{\mathcal{E}}\frac{\Delta^+\gamma_5}{2M}\right)\right]u(p)$$

Factorization

$$\begin{aligned}
\mathcal{H}(\xi,\eta,t) &= \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) H^q(x,\eta,t) \\
\mathcal{E}(\xi,\eta,t) &= \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) E^q(x,\eta,t) \\
\tilde{\mathcal{H}}(\xi,\eta,t) &= \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{\xi - x - i\epsilon} + \frac{1}{\xi + x - i\epsilon} \right) \tilde{H}^q(x,\eta,t) \\
\tilde{\mathcal{E}}(\xi,\eta,t) &= \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{\xi - x - i\epsilon} + \frac{1}{\xi + x - i\epsilon} \right) \tilde{H}^q(x,\eta,t)
\end{aligned}$$

$$\frac{\mathrm{d}\sigma_{TCS}}{\mathrm{d}Q'^2 \mathrm{d}\Omega \mathrm{d}t} \approx \frac{\alpha^3}{8\pi} \frac{1}{s^2} \frac{1}{Q'^2} \left(\frac{1+\cos^2\theta}{4} \right) 2(1-\eta^2) \left(|\mathcal{H}|^2 + |\tilde{\mathcal{H}}|^2 \right)$$

Modelizing GPDs

In this first study of the feasibility of the extraction of the TCS signal, we simplify our calculations by using a factorization ansatz for the t dependence of GPDs:

$$
\begin{aligned}
H^u(x,\eta,t) &= h^u(x,\eta)\frac{1}{2}F_1^u(t) \\
H^d(x,\eta,t) &= h^d(x,\eta)F_1^d(t) \\
H^s(x,\eta,t) &= h^s(x,\eta)F_D(t)
\end{aligned}
$$

and a double distribution ansatz for h^q without any D-term:

$$
\begin{aligned}
h^q(x,\eta) &= \int_0^1 dx' \int_{-1+x'}^{1-x'} dy' \Big[\delta(x-x'-\eta y')q(x') - \delta(x+x'-\eta y')\bar{q}(x')\Big]\pi(x',y') \\
\pi(x',y') &= \frac{3}{4}\frac{(1-x')^2-y'^2}{(1-x')^3}
\end{aligned}
$$

Factorization scale dependence.

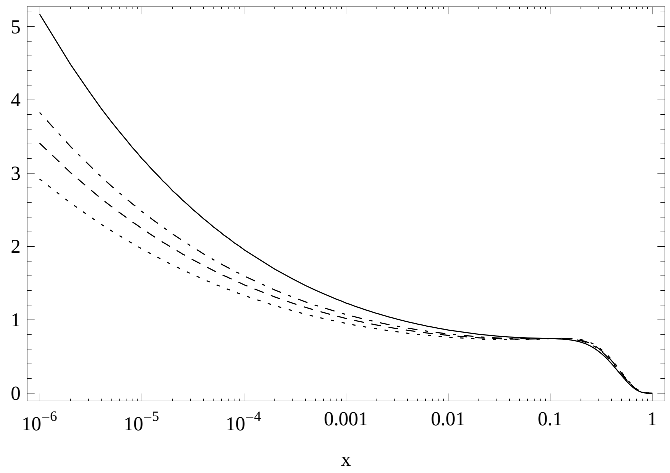


Figure 5: The NLO($\overline{MS}$) GRVGJR 2008 parametrization of $u(x) + \bar{u}(x)$ for different factorization scales $\mu_F^2 = 4$ (dotted) , 5 (dashed) , 6 (dash-dotted) , 10 (solid) GeV^2.

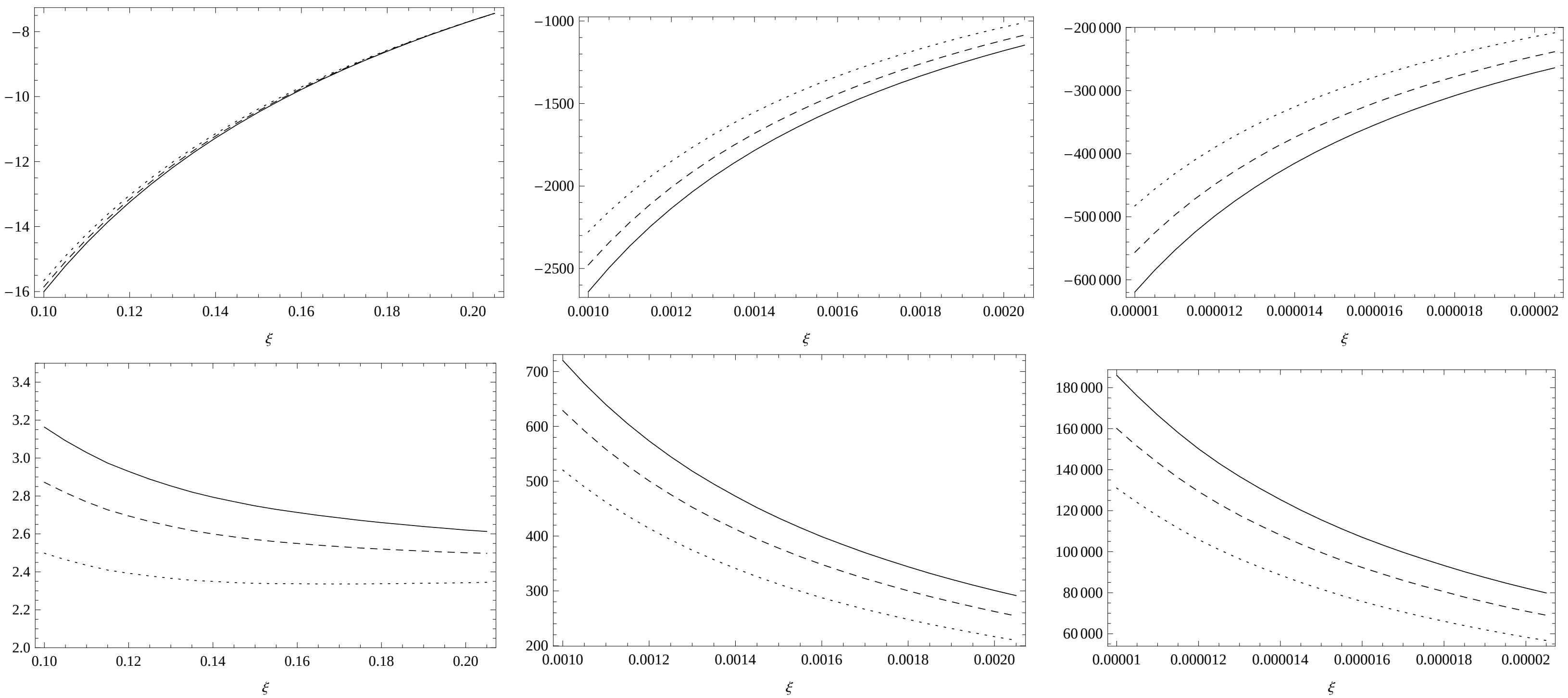


Figure 6: Im$\mathcal{H}^u$ (up) and Re$\mathcal{H}^u$ (down) divided by $\frac{1}{2}F^u$ for various factorization scales $\mu_F^2 = 4$ (dotted), 5 (dashed), 6 (solid) GeV^2 and various ranges of ξ : $[1 \cdot 10^{-1}, 2 \cdot 10^{-1}]$,$[1 \cdot 10^{-3}, 2 \cdot 10^{-3}]$,$[1 \cdot 10^{-5}, 2 \cdot 10^{-5}]$.

Interference

The interference part of the cross-section for $\gamma p \to \ell^+ \ell^- p$ with unpolarized protons and photons is given at leading order by

$$\frac{d\sigma_{INT}}{dQ'^2\, dt\, d\cos\theta\, d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\cos\varphi\frac{1+\cos^2\theta}{\sin\theta}\mathrm{Re}\mathcal{M}$$

with

$$\mathcal{M} = \frac{2\sqrt{t_0 - t}}{M}\frac{1-\eta}{1+\eta}\left[F_1\mathcal{H}_1 - \frac{t}{4M^2}F_2\,\mathcal{E}_1\right]$$

Since the amplitudes for the Compton and Bethe-Heitler processes transform with opposite signs under reversal of the lepton charge, the interference term between TCS and BH is odd under exchange of the ℓ^+ and ℓ^- momenta. It is thus possible to project out the interference term through a clever use of the angular distribution of the lepton pair.

Cross sections

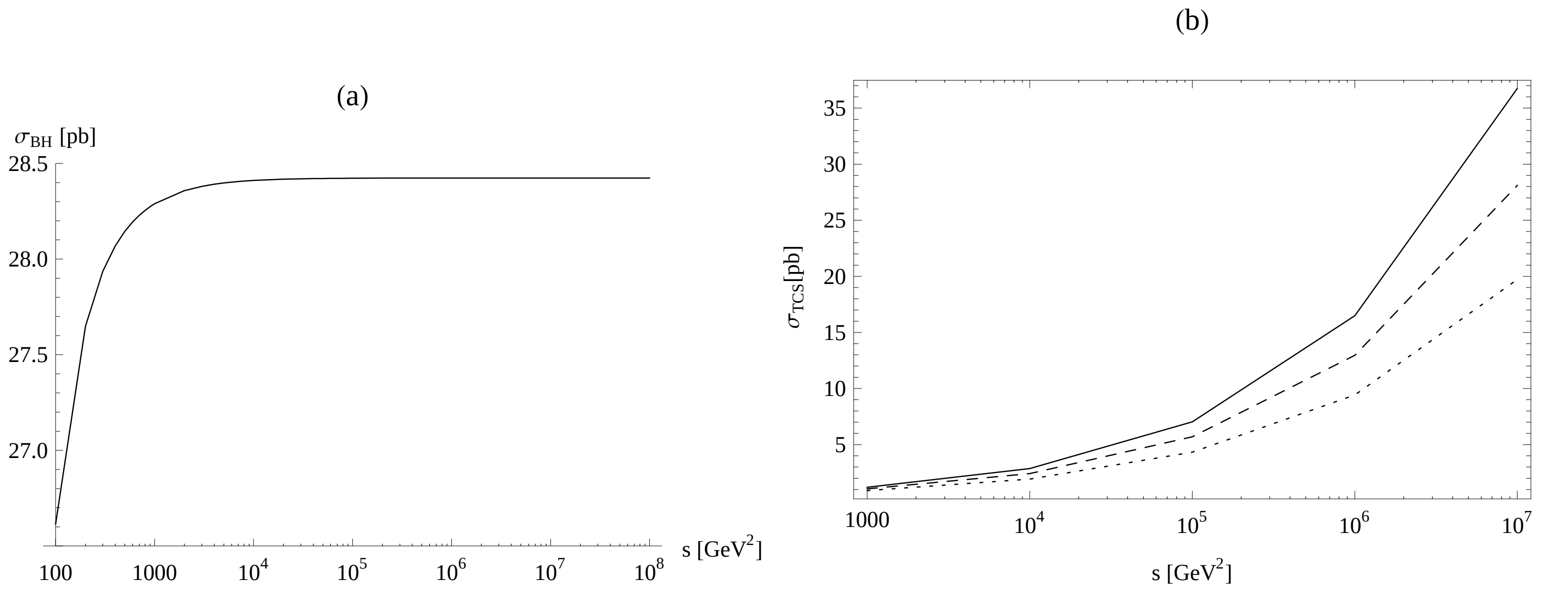
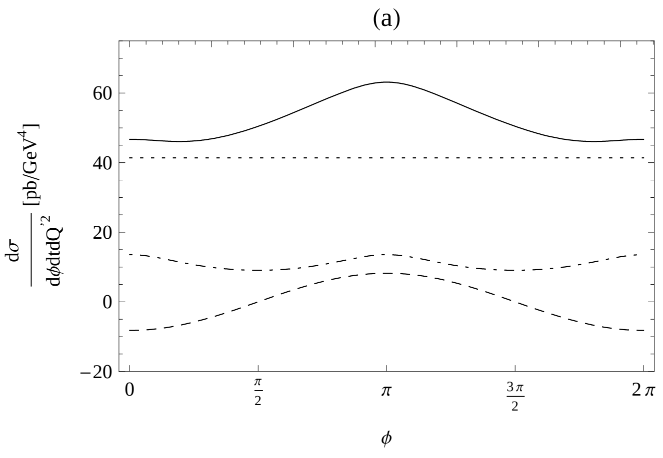
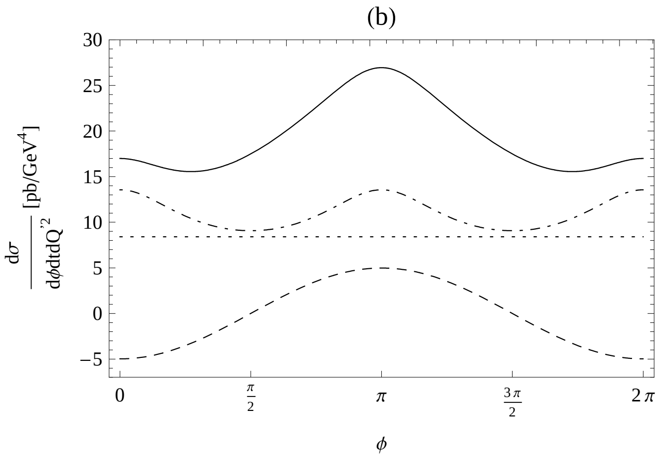
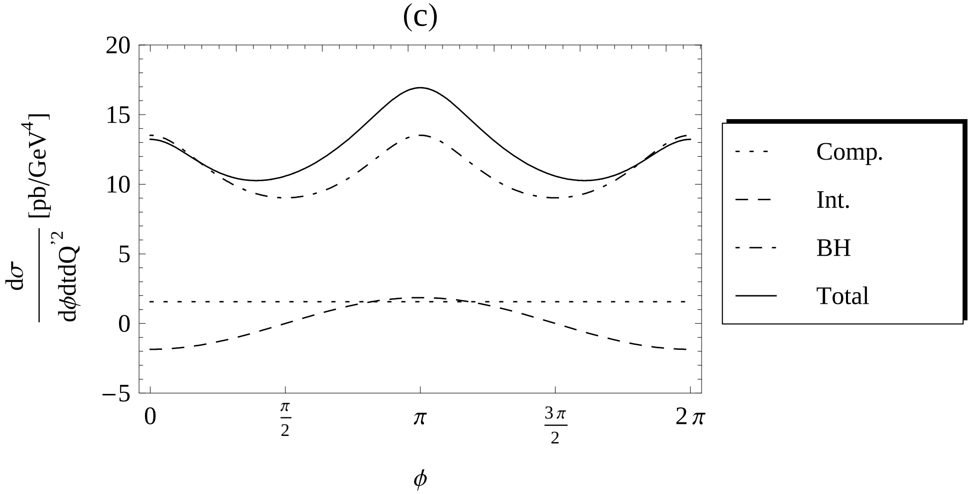


Figure 7: (a) The BH cross section integrated over $\theta \in [\pi/4, 3\pi/4]$, $\varphi \in [0, 2\pi]$, $Q'^2 \in [4.5, 5.5]\,\mathrm{GeV}^2$, $|t| \in [0.05, 0.25]\,\mathrm{GeV}^2$, as a function of γp c.m. energy squared s. (b)σ_{TCS} as a function of γp c.m. energy squared s, for GRVGJR2008 NLO parametrizations, for vorious factorization scales $\mu_F^2 = 4$ (dotted), 5 (dashed), 6 (solid) GeV^2.

Angular distributions

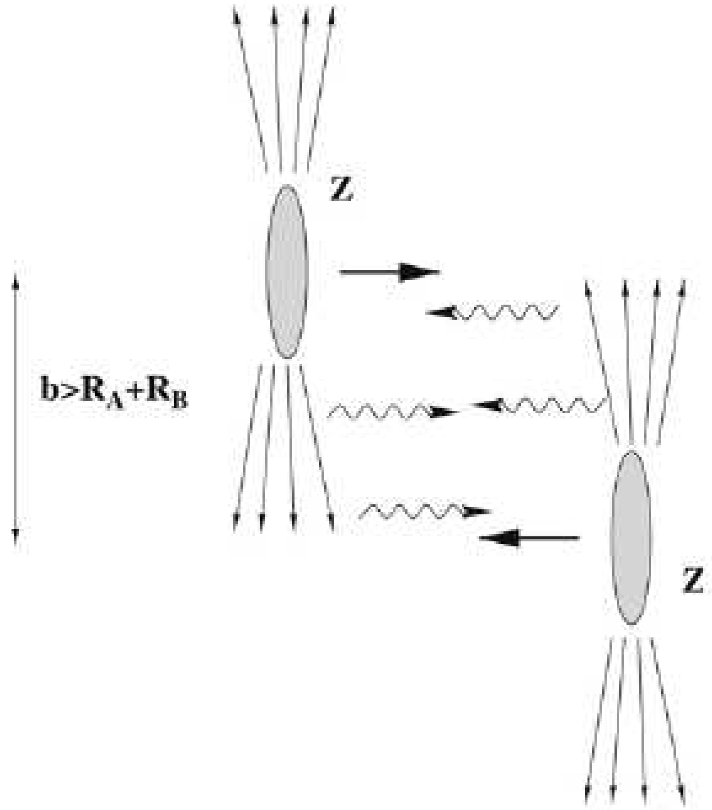






Hadron colliders as photon colliders.

Ultraperipherical collisions:



Effective photon approximation

The cross section for photoproduction in hadron collisions is given by:

$$\sigma_{pp} = 2\int \frac{dn(k)}{dk}\sigma_{\gamma p}(k)dk \tag{1}$$

where $\sigma_{\gamma p}(k)$ is the cross section for the $\gamma p \to p l^+ l^-$ process and k is the photon energy. $\frac{dn(k)}{dk}$ is an equivalent photon flux (the number of photons with energy k), and is given by:

$$\frac{dn(k)}{dk} = \frac{\alpha}{2\pi k}\left[1 + (1 - \frac{2k}{\sqrt{s_{pp}}})^2\right]\left(\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right) \tag{2}$$

where: $A = 1 + \frac{0.71\,\mathrm{GeV}^2}{Q^2_{min}}$, $Q^2_{min} \approx \frac{4M_p^2 k^2}{s_{pp}}$ is the minimal squared fourmomentum transfer for the reaction, and s_{pp} is the proton-proton energy squared ($\sqrt{s_{pp}} = 14\,\mathrm{TeV}$). The relationship between γp energy squared s and k is given by:

$$s \approx 2\sqrt{s_{pp}}k$$

Full cross sections

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

$$\sigma_{pp}^{BH} = 2.9\,\mathrm{pb}\ . \tag{3}$$

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

$$\sigma_{pp}^{TCS} = 1.9\,\mathrm{pb}\ . \tag{4}$$

- The range of photon energies - expected capabilities to tag photon energies at the LHC.
- 10^5 events/year at the LHC with its nominal luminosity ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

Summary

- Compton scattering in ultraperipheral collisions at hadron colliders opens a new way to measure generalized parton distributions.
- Sizeble rates even for the lower luminosity which can be achieved in the first months of run.
- Our work has to be supplemented by studies of higher order contributions which will involve the gluon GPDs; they will hopefully lead to a weaker factorization scale dependence of the amplitudes.