

TIMELIKE COMPTON SCATTERING AT LHC*

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Exclusive photoproduction of dileptons, $\gamma N \rightarrow \ell^+ \ell^- N$, is and will be measured in ultraperipheral collisions at hadron colliders. We demonstrate that the timelike deeply virtual Compton scattering (TCS) mechanism $\gamma q \rightarrow \ell^+ \ell^- q$, where the lepton pair comes from the subprocess $\gamma q \rightarrow \gamma^* q$, dominates in some accessible kinematical regions, thus opening a new way to study generalized parton distributions in the nucleon at small skewedness.

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1. Introduction

General Parton Distributions (GPDs) [1] are subject to intense theoretical study and experimental effort. The best known process in which GPDs factorize from perturbatively calculable coefficient functions is Deeply Virtual Compton Scattering (DVCS). Even though the DVCS, being an exclusive process, is very different from Deep Inelastic Scattering (DIS) (see Fig. 1) the description of the former can be easily understood as the generalization of description of the latter. Due to the optical theorem the cross-section of DIS is proportional to the imaginary part of the Feynman diagram shown on the Fig. 2(a), which is a special case of the diagram describing the amplitude of DVCS (Fig. 2(b)).

GPDs are functions of three kinematical variables: longitudinal momentum fraction x , skewedness ξ and overall momentum transfer t . In the forward limit: $t, \xi \rightarrow 0$, GPDs reduce to PDFs. When integrated over x , GPDs reduce to elastic form factors. First moment of GPDs enter the Ji's sum

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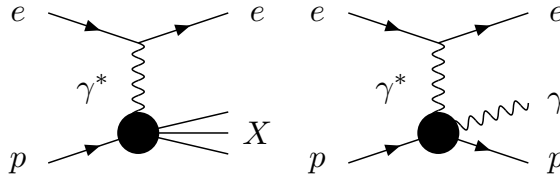


Fig. 1. Deep inelastic scattering (left) *versus* deeply virtual Compton scattering (right).

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 parton distribution in the transverse plane, for a given value of x .

In our work [2] we study the “inverse” process, $\gamma p \rightarrow \gamma^* p$ at small t and large timelike virtuality Q^2 of the final state photon, timelike Compton scattering (TCS) [3] which shares many features of DVCS. The possibility to use high energy hadron colliders as powerful sources of quasi real photons [4] leads to the hope of determining sea-quark and gluon GPDs in the small skewedness region, which is an essential program complementary to the determination of the quark GPDs at lower energy electron accelerators. Moreover, the crossing from a spacelike to a timelike probe is an important test of the understanding of QCD corrections, as shown by the history of the understanding of the Drell–Yan reaction in terms of QCD.

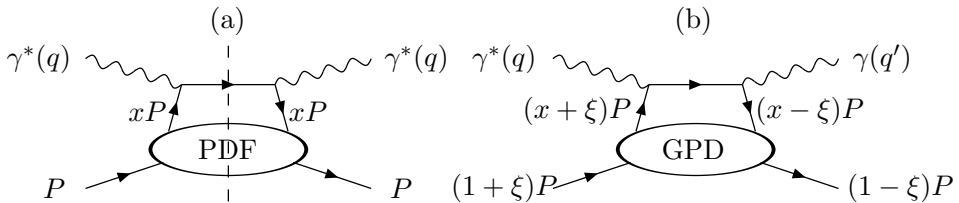


Fig. 2. Deep inelastic scattering cross-section is given by the imaginary part of diagram (a). Amplitude of deeply virtual Compton scattering is given by diagram (b).

2. Photoproduction of a lepton pair

The physical process where to observe TCS, is photoproduction of a heavy lepton pair, $\gamma N \rightarrow \mu^+ \mu^- N$ or $\gamma N \rightarrow e^+ e^- N$, shown in Fig. 3. As in the case of DVCS, the Bethe–Heitler (BH) mechanism contributes at the amplitude level. This process has a very peculiar angular dependence and over dominates the TCS process if one blindly integrates over the final phase

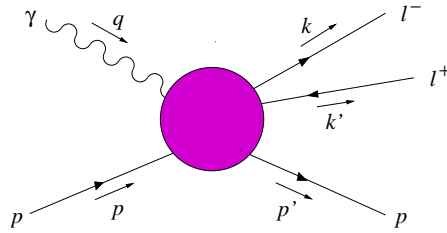


Fig. 3. Real photon–proton scattering into a lepton pair and a proton.

space. One may, however, choose kinematics where the amplitudes of the two processes are of the same order of magnitude, and either subtract the well-known Bethe–Heitler process or use specific observables sensitive to the interference of the two amplitudes. The Bethe–Heitler amplitude is calculated from the two Feynman diagrams in Fig. 4. Neglecting masses and t compared to terms going with s or Q'^2 , the Bethe–Heitler contribution to the unpolarized γp cross-section is (M is the proton mass)

$$\frac{d\sigma_{\text{BH}}}{dQ'^2 dt d\cos\theta} \approx 2\alpha^3 \frac{1}{-tQ'^4} \frac{1 + \cos^2\theta}{1 - \cos^2\theta} \left(F_1(t)^2 - \frac{t}{4M_p^2} F_2(t)^2 \right), \quad (1)$$

provided we stay away from the kinematical region where the product of lepton propagators goes to zero at very small θ ($F_1(t)$ and $F_2(t)$ are Dirac and Pauli nucleon form factors). The interesting physics program thus imposes a cut on θ to stay away from the region where the Bethe–Heitler cross-section becomes extremely large.

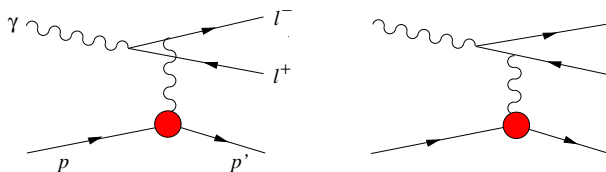


Fig. 4. The Feynman diagrams for the Bethe–Heitler amplitude.

In the region where the final photon virtuality is large, the Compton amplitude is given by the convolution of hard scattering coefficients, calculable in perturbation theory, and generalized parton distributions, which describe the nonperturbative physics of the process. To leading order in α_s one then has the dominance of the quark handbag diagrams of Fig. 5

$$\frac{d\sigma_{\text{TCS}}}{dQ'^2 d\Omega dt} \approx \frac{\alpha^3}{8\pi} \frac{1}{s^2} \frac{1}{Q'^2} \left(\frac{1 + \cos^2\theta}{4} \right) 2(1 - \eta^2) \left(|\mathcal{H}|^2 + |\tilde{\mathcal{H}}|^2 \right), \quad (2)$$

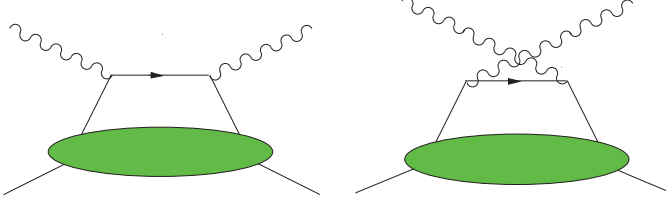


Fig. 5. Handbag diagrams for the Compton process in the scaling limit.

where \mathcal{H} and $\tilde{\mathcal{H}}$ are Compton formfactors, defined as in [3], and η is the skewedness parameter related to the Bjorken variable $\tau = Q'^2/s$ by $\eta = \tau/(2 - \tau)$. Full BH and TCS cross-section as a functions of c.m. energy squared s are shown in Fig. 6.

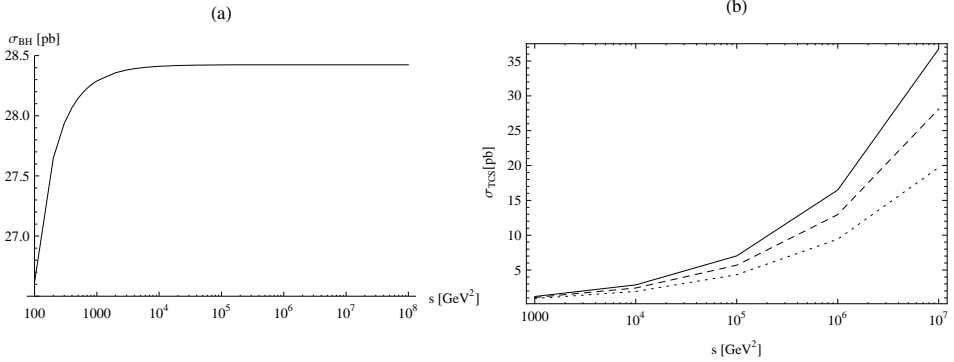


Fig. 6. (a) The BH cross-section integrated over $\theta \in [\pi/4, 3\pi/4]$, $\varphi \in [0, 2\pi]$, $Q'^2 \in [4.5, 5.5] \text{ GeV}^2$, $|t| \in [0.05, 0.25] \text{ GeV}^2$, as a function of γp c.m. energy squared s . (b) σ_{TCS} as a function of γp c.m. energy squared s , for GPD parametrization based on the GRVGJR2008 NLO PDF, for different factorization scales $\mu_F^2 = 4$ (dotted), 5 (dashed), 6 (solid) GeV^2 .

Since the amplitudes for the Compton and Bethe–Heitler processes transform with opposite signs under reversal of the lepton charge, it is possible to project out the interference term through a clever use of the angular distribution of the lepton pair. The interference part of the cross-section for $\gamma p \rightarrow \ell^+ \ell^- p$ with unpolarized protons and photons is given at leading order by

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

with $(-t_0 = 4\eta^2 M^2/(1 - \eta^2))$:

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

In Fig. 7 we show the interference contribution to the cross-section in comparison to the Bethe–Heitler and Compton processes, for various values of c.m. energy squared $s = 10^7 \text{ GeV}^2, 10^5 \text{ GeV}^2, 10^3 \text{ GeV}^2$. We observe that for large energies the Compton process dominates, whereas for $s = 10^5 \text{ GeV}^2$ all contributions are comparable.

3. Full cross-section

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

$$\sigma_{\text{pp}} = 2 \int \frac{dn(k)}{dk} \sigma_{\gamma p}(k) dk, \quad (5)$$

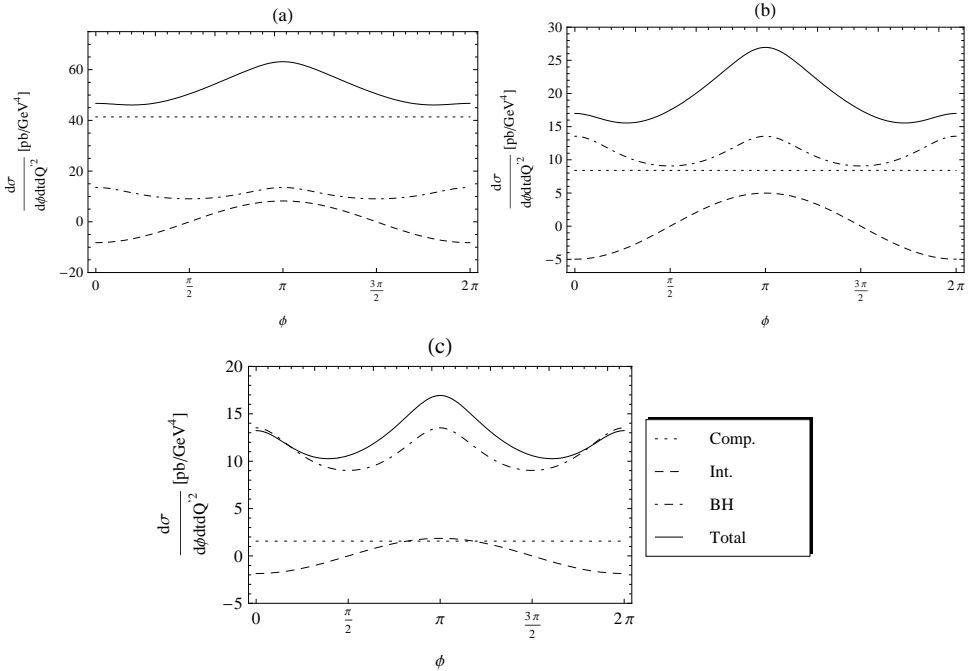


Fig. 7. The differential cross-sections (solid lines) for $t = -0.2 \text{ GeV}^2$, $Q'^2 = 5 \text{ GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of φ , for $s = 10^7 \text{ GeV}^2$ (a), $s = 10^5 \text{ GeV}^2$ (b), $s = 10^3 \text{ GeV}^2$ (c) with $\mu_F^2 = 5 \text{ GeV}^2$.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

where $\sigma_{\gamma p}(k)$ is the cross-section for the $\gamma p \rightarrow pl^+l^-$ process and k is the photon energy. $dn(k)/dk$ is an equivalent photon flux. The relationship between γp energy squared s and k is given by $s \approx 2\sqrt{s_{pp}}k$, where s_{pp} is the proton–proton energy squared ($\sqrt{s_{pp}} = 14$ TeV).

The Bethe–Heitler contribution to σ_{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:

$$\sigma_{pp}^{\text{BH}} = 2.9 \text{ pb}. \quad (6)$$

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

$$\sigma_{pp}^{\text{TCS}} = 1.9 \text{ pb}. \quad (7)$$

We have chosen the range of photon energies in accordance with expected capabilities to tag photon energies at the LHC. This amounts to a large rate of order of 10^5 events/year at the LHC with its nominal luminosity ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$).

4. Conclusions

Timelike Compton scattering in ultraperipheral collisions at hadron colliders opens a new way to measure generalized parton distributions. We have found sizeable rates of events at LHC, 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.

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