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TIMELIKE COMPTON SCATTERING

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We investigate exclusive photoproduction of a lepton pair with a large invariant mass. Like deeply virtual Compton scattering, this process presents a valuable and versatile tool to study generalized parton distributions in the nucleon.

1 Introduction

A considerable amount of theoretical and experimental work is currently being devoted to the study of generalized parton distributions, whose measurement could make important contributions to our understanding of how quarks and gluons assemble themselves to hadrons [1,2,3,4]. The theoretically simplest and cleanest of the exclusive processes where these distributions occur is deeply virtual Compton scattering (DVCS), i.e., $\gamma^* p \to \gamma p$ at large spacelike virtuality Q^2 of the γ^* and small invariant momentum transfer t to the proton. In the present contribution, we investigate the "inverse" process, $\gamma p \to \gamma^* p$ at small t and large *timelike* virtuality Q' of the final state photon. We call this timelike Compton scattering (TCS). The combination of data on DVCS and TCS would offer a powerful tool to make sure we understand the reaction mechanism, and eventually to obtain stronger constraints on the generalized parton distributions than DVCS alone can provide. We present in the following the main results of [5], to which we refer for more details.

The physical process where to observe TCS is photoproduction of a heavy lepton pair, $\gamma p \to \ell^+ \ell^- \, p$ with $\ell = e$, μ. Despite the close analogy to real photon production $\ell p \to \ell \gamma p$, where DVCS can be accessed, there are important differences in the phenomenology of these reactions. In both cases, a Bethe-Heitler (BH) mechanism contributes at the amplitude level. Contrary to the case of DVCS, this contribution always dominates over the one from TCS in the kinematical regime where we want to study it. On the other hand, the interference between the TCS and BH processes can readily be accessed through the angular distribution of the lepton pair, whereas the corresponding observable for DVCS is the lepton charge asymmetry and requires beams of both positive and negative charge.

Another difference comes from the timelike nature of the virtual pho-

ton. Although analogies between TCS and other processes involving timelike photons have to be taken with care [5], we estimate from the data of hadron production in e^+e^- collisions that ranges of Q' where the leading twist description of TCS can work may be between about 2 GeV and the J/Ψ mass, and beyond the masses of the charmonium resonances.

2 The Compton amplitude

Both DVCS and TCS are limiting cases of the general Compton amplitude

$$\gamma^*(q) + p(p) \to \gamma^*(q') + p(p'), \tag{1}$$

where the photons with four-momenta q and q' can have any virtuality. In the region where at least one of the virtualities is large, the 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 quark handbag diagrams of Fig. 1. We note that the arguments for factorization [3,6] hold both for large spacelike and for large timelike virtualities.

In addition to the four-momenta indicated in (1) we will use the invariants

$$Q^2 = -q^2, \qquad Q'^2 = q'^2, \qquad s = (p+q)^2, \qquad t = (p-p')^2, \tag{2}$$

and write M for the proton mass. In the following we will consider the limit of large s, large $|q^2| + |q'^2|$, and small $|t|$.

The calculation of the handbag diagrams for the general Compton amplitude leads to the convolution

$$\mathcal{H}_1(\xi,\eta,t) = \sum_q e_q^2 \int_{-1}^{1} dx \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) H_q(x,\eta,t), \tag{3}$$

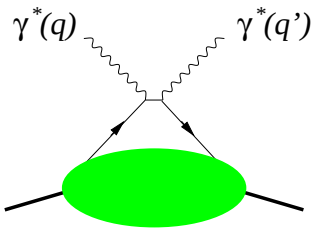

Figure 1. Handbag diagram for the Compton amplitude in the regime where it factorizes into a hard partonic subprocess and a generalized parton distribution. A second diagram is obtained by interchanging the photon vertices.

and analogous ones for the distributions E_q, $\tilde{H}_q$, and $\tilde{E}_q$, where we use Ji's notation [2] for the generalized quark distributions in the proton. The scaling variables ξ and η are given by

$$\xi \approx \frac{Q^2 - Q'^2}{2s + Q^2 - Q'^2}, \qquad \eta \approx \frac{Q^2 + Q'^2}{2s + Q^2 - Q'^2}, \tag{4}$$

where the approximations hold in the kinematical limit we are working in. x, ξ, and η represent plus-momentum fractions

$$x = \frac{(k + k')^+}{(p + p')^+}, \qquad \xi \approx -\frac{(q + q')^+}{(p + p')^+}, \qquad \eta \approx \frac{(p - p')^+}{(p + p')^+} \tag{5}$$

in frames where both protons are moving in the positive z direction, with plus-components defined as $v^+ = v^0 + v^3$ for any vector v.

The DVCS and TCS processes are limiting cases of (1) where one of the photons is on shell. The handbag diagrams only contribute to transitions that conserve the photon helicity, and lead to the simple relations

$$M^{\lambda' +, \lambda +}\Big|_{TCS} = \Big[M^{\lambda' -, \lambda -}\Big]^*_{DVCS}, \qquad M^{\lambda' -, \lambda -}\Big|_{TCS} = \Big[M^{\lambda' +, \lambda +}\Big]^*_{DVCS} \tag{6}$$

between the respective two-photon helicity amplitudes, where λ and λ' refer to the incoming and outgoing proton helicities, and $+$, $-$ to the helicities of the initial and final state photons. The amplitudes in (6) are to be evaluated at equal values of η and t, and also at corresponding values of Q'^2 and Q^2 since the photon virtualities play analogous roles in providing the hard scale of the respective processes and thus enter in the scale dependence of the parton distributions. The relations (6) tell us that at Born level and to leading power in $1/Q'$ or $1/Q$ one obtains the amplitudes for TCS from those of DVCS by changing the sign of the imaginary part and reversing the photon helicities. To this accuracy, the two processes thus carry exactly the same information on the generalized quark distributions. We remark that the relations (6) no longer hold at $O(\alpha_s)$, neither for the one-loop corrections to the quark handbag diagrams in Fig. 1 nor for the diagrams involving gluon distributions.

It is useful to define the variable $\tau = Q'^2/(2p \cdot q) \approx Q'^2/s$ for the TCS process as the analog of the Bjorken variable $x_B = Q^2/(2p \cdot q)$ in DVCS. The similar role played by these quantities reveals itself in their relations with η, which to leading twist accuracy reads $\eta = \tau/(2 - \tau)$ for TCS and $\eta = x_B/(2 - x_B)$ for DVCS.

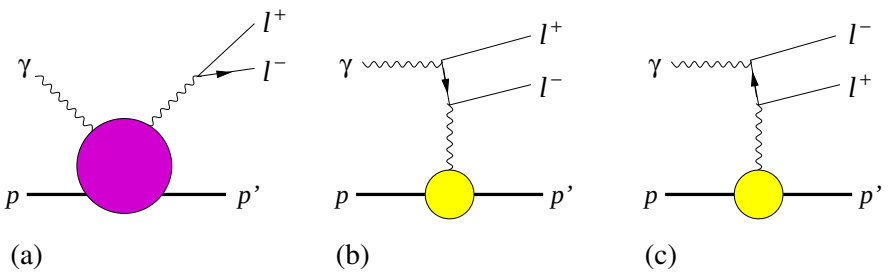

Figure 2. Diagrams for the (a) Compton and (b), (c) Bethe-Heitler contribution to lepton pair production.

3 Phenomenology

The contribution of Compton scattering to the processes

$$\begin{aligned} \ell(k) + p(p) &\to \ell(k') + \gamma(q') + p(p'), \\ \gamma(q) + p(p) &\to \ell^+(k) + \ell^-(k') + p(p'), \end{aligned} \tag{7}$$

competes in both cases with a Bethe-Heitler process, where the real photon is directly coupling to the leptons. For lepton pair production this is shown in Fig. 2. The Compton contributions to the amplitudes behave like $1/Q$ or $1/Q'$, whereas the corresponding factor in the Bethe-Heitler amplitudes is of order $1/\sqrt{-t}$. In general, the BH process thus dominates in the kinematics $Q^2, Q'^2 \gg -t$ we are interested in. In the case of DVCS this suppression can however be counteracted by the factor $1/y$ in the Compton contribution, where y is the usual inelasticity variable in electroproduction processes. This corresponds, e.g., to the kinematical regime of the H1 and ZEUS data. By crossing we obtain the corresponding factor in the TCS contribution to $\ell^+\ell^-$ production:

$$\frac{1}{y} = \left[\frac{k\cdot p}{(k-k')\cdot p}\right]_{\rm DVCS} \to \left[\frac{k\cdot p'}{(k+k')\cdot p'}\right]_{\rm TCS} \approx \frac{1+\cos\vartheta}{2}, \tag{8}$$

where ϑ is the lepton decay angle defined in Fig. 3. As this factor is never larger than 1, no enhancement of TCS is possible, and the BH process is always dominant.

Let us therefore explore how information on the Compton process can be obtained from the interference between the TCS and BH amplitudes. The general strategy is the same as described in [7] for the case of DVCS. We concentrate here on the following interesting feature of TCS: the amplitudes for

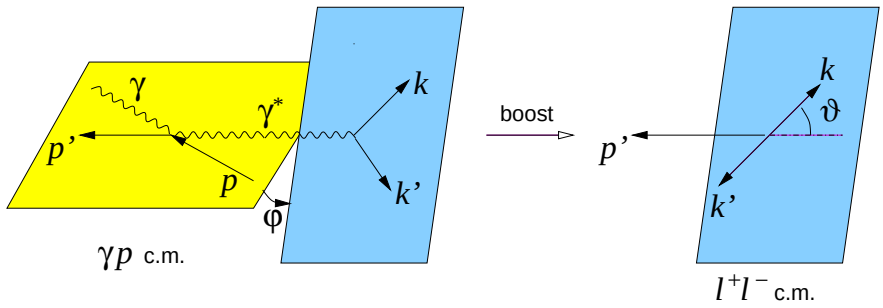

Figure 3. Definition of the angles ϑ and φ.

the Compton and Bethe-Heitler processes transform with opposite signs under reversal of the lepton charge. As a consequence the interference term between TCS and BH is odd under the exchange of the ℓ^+ and ℓ^- momenta, whereas the individual contributions of the two processes are even. Any observable that changes sign under $k \leftrightarrow k'$ will therefore project out the interference term, and thus eliminate in particular the large BH contribution. Clean information on the interference term is therefore contained in the angular distribution of the lepton pair. This is in contrast to the electroproduction process $\ell p \to \ell \gamma p$, where the corresponding observable is the lepton beam charge asymmetry, whose measurement presents important experimental challenges.

The crucial variable to access the interference term turns out to be the azimuthal angle φ defined in Fig. 3. Up to a global factor due to the lepton propagators in the diagrams of Fig. 2b and c, the φ-dependence of the interference contribution to the unpolarized cross section becomes a linear superposition of $\cos\varphi$, $\cos(2\varphi)$, and $\cos(3\varphi)$. At large Q'^2 the $\cos\varphi$ term dominates. Its coefficient is a weighted sum over the different proton helicities of the *real* parts of the Compton amplitudes $M^{\lambda'-,\lambda-}$.

We have estimated the corresponding angular distributions, calculating the handbag diagrams of Fig. 1 with simple models for the relevant generalized parton distributions, for details cf. [5]. To be in a region where the quark handbag can be expected to dominate the Compton amplitude, we chose HERMES-like kinematics, with a γp collision energy of $\sqrt{s} = 5$ GeV, and Q'^2 between 4 and 8 GeV^2, corresponding to τ between 0.16 and 0.32. In order to have $Q'^2 \gg -t$ we restricted ourselves to $-t$ below 0.4 GeV^2. The resulting $\cos\varphi$ asymmetries turn out to be very sensitive to details of the modeling, ranging from very small values up to around 10%. These values should be

taken with care, because the main impact on the size of the asymmetries is due to the behavior of H_q in the region $-\eta < x < \eta$. Here present-day modeling has its greatest uncertainties, since this is the region describing the emission of small-size $q\bar{q}$ pairs from the initial state proton, about whose physics we have no information from the usual parton densities.

We mention that for the kinematics and models we have explored, the real parts of the amplitudes $M^{\lambda'-,\lambda-}$ are significantly smaller than their imaginary parts. The latter can be accessed through a $\sin\varphi$ asymmetry if the initial photon has a circular polarization, as is the case for bremsstrahlung beams emitted by longitudinally polarized leptons.

4 Conclusions

Next to DVCS, timelike Compton scattering is the theoretically cleanest process where generalized parton distributions can be explored. The phenomenology of the two reactions is similar but has important differences, with the most salient feature of TCS being the relatively simple access to the real part of the Compton amplitude via the angular distribution of the produced lepton pair. We cannot reliably predict the size of the relevant angular asymmetries, but our estimates for HERMES kinematics ranged from about 1% to 10% for some of the models we explored. Whether the real part of TCS is observably large or not will thus already provide important information about the dynamics of the Compton process.

Acknowledgments

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References

1. D. Müller *et al.*, *Fortsch. Phys.* **42**, 101 (1994) [hep-ph/9812448].
2. X. Ji, *Phys. Rev. Lett.* **78**, 610 (1997) [hep-ph/9603249].
3. A. V. Radyushkin, *Phys. Rev.* D **56**, 5524 (1997) [hep-ph/9704207].
4. J. Blümlein *et al.*, *Phys. Lett.* B **406**, 161 (1997) [hep-ph/9705264].
5. E. R. Berger, M. Diehl, B. Pire, in preparation.
6. X. Ji, J. Osborne, *Phys. Rev.* D **58**, 094018 (1998) [hep-ph/9801260]; J. Collins, A. Freund, *Phys. Rev.* D **59**, 074009 (1999) [hep-ph/9801262].
7. M. Diehl *et al.*, *Phys. Lett.* B **411**, 193 (1997) [hep-ph/9706344].