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Exclusive diffractive photoproduction of dileptons by timelike Compton scattering

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ABSTRACT

We derive the forward photoproduction amplitude for the diffractive $\gamma p \to l^+l^- p$ reaction in the momentum space, within the formalism of $k_\perp$-factorization. Predictions for the $\gamma p \to l^+l^- p$ reaction are given using unintegrated gluon distribution from the literature. We calculate the total cross section as a function of photon–proton center of mass energy and the invariant mass distribution of the lepton pair. We also discuss whether the production of timelike virtual photons can be approximated by continuing to the spacelike domain $q^2 < 0$. The present calculation provides an input for future predictions for exclusive hadroproduction in the $pp \to pl^+l^- p$ reaction.

1. Introduction

Measuring absolutely normalized cross sections at the LHC is of great importance for the high-energy physics community. This requires having a well understood luminosity monitor. Following the pioneering work [1], the QED process $pp \to pl^+l^- p$ via photon–photon fusion is often discussed as a process which can be used for measuring the luminosity at the LHC [2–4]. It is therefore very important to estimate other non-QED contributions to exclusive l^+l^- production. One possible source of dileptons is the exclusive production of vector mesons or Z-bosons (see e.g. [5–7]). The dilepton pairs originating from these processes however have invariant masses close to the mass of the decaying state. In Fig. 1 we show an exclusive diffractive mechanism which produces continuum dilepton pairs, and hence may compete with the standard QED process. In this reaction the coupling of the photon to the proton is known and can be expressed in terms of the nucleon electromagnetic form factors. At the small transferred momenta (t_1 or t_2) of relevance, it is sufficient, in the high energy limit, to include the Dirac electromagnetic form factor. Besides its role as a possible background to electromagnetic lepton pair production, the $\gamma p \to \gamma^* p$ amplitude may contain interesting information on the small-x gluon distribution in the nucleon.

In the present work we shall concentrate on the photon–pomeron subprocess. In Fig. 2 we show a QCD mechanism, where the photon splits into a quark–antiquark pair which interacts with the proton through the exchange of an off-diagonal QCD gluon ladder. In principle this process could have been studied at HERA. In Fig. 2 the incoming photon is spacelike (or quasireal), but the outgoing photon is timelike, i.e. its virtuality $q^2 > 0$. This process is often called timelike Compton scattering (TCS) in the literature, although the specific mechanism considered by us is maybe better termed a QCD version of (virtual) Delbrück scattering. A collinear factorisation treatment of timelike Compton scattering in terms of the nucleon's skewed (mainly quark-) distributions can be found in [8,9]. This approach is most relevant for lower center-of-mass energies. We will restrict ourselves to high energies, where the t-channel exchange is dominated by gluons, and choose a $k_\perp$-factorization formalism very similar to the one used in diffractive vector meson production [10,11].

The TCS cross section has also been evaluated in a color-dipole model with a saturation-idea inspired dipole-nucleon cross section [12]. However there both incoming and outgoing photons were assumed to be spacelike. A similar treatment had been also suggested for the case of Z^0-boson production in [15] within a color dipole approach. Subsequently, the correct timelike kinematics for the final state boson was incorporated within the color dipole approach in [13]. However, the numerical calculations in the impact parameter space involve strongly oscillating integrands. Here, similar as in our previous work on Z^0 production [7], we prefer the momentum space approach as it is better suited for correct kinematics and therefore for future applications in the hadronic process. A recent estimate of high energy cross sections in leading order collinear factorization, without explicit gluons, can be found in [14].

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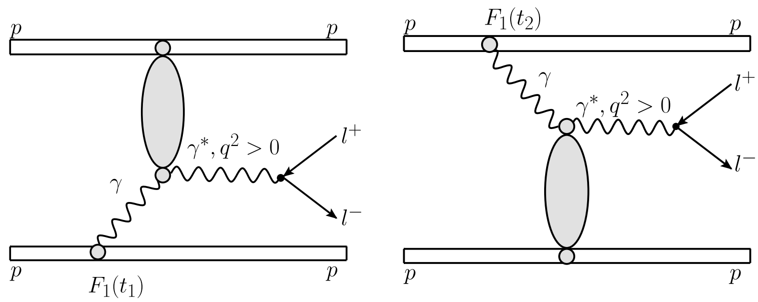

Fig. 1. An example of the non-QED mechanism for the production of opposite charge leptons in the $pp \to ppl^+l^-$ reaction.

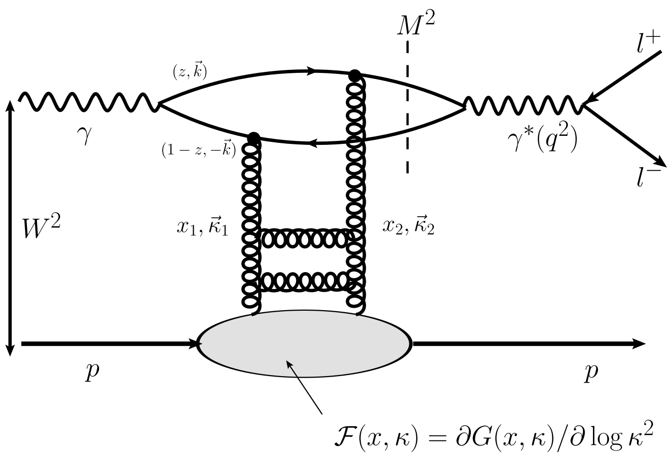

Fig. 2. The diagram for the production of virtual timelike photons.

In this work we present the momentum space formulation of timelike Compton scattering at small-x, taking due account of the timelike nature of the final state photon.

This Letter is organized as follows. In the next section, we present the formalism which is used in our calculations. In Section 3 we present the main results for the $\gamma p \to l^+l^- p$ reaction. Finally, in the last section we summarize our results and show further perspectives.

2. Formalism

The photoproduction amplitude will be the major building block for our prediction of exclusive dilepton pair production. The amplitude for the reaction is shown schematically in Fig. 2. In the diagram, we distinguish three stages of the process: first the incoming real photon fluctuates into a quark–antiquark pair, then a gluon ladder is exchanged between the $q\bar{q}$ pair and the proton and finally the $q\bar{q}$ pair recombines to form a virtual photon which subsequently decays into a lepton–antilepton pair.

The amplitude of the subprocess $\gamma p \to \gamma^*(q^2) p$ is a sum of the contributions for a given flavour f of quarks in the loop

$$\mathcal{M}\big(\gamma p \to \gamma^*(q^2) p\big) = \sum_f \mathcal{M}_f\big(\gamma p \to \gamma^*(q^2) p\big). \tag{2.1}$$

Here the initial state photon is real, and hence transversely polarized. We take only the dominant s-channel helicity conserving contribution into account, and suppress helicities of photons/protons in our notation. The calculation of the amplitude follows the same procedure as for the exclusive production of vector mesons, which is explained in great detail in Ivanov's thesis [10]. The main difference is that the final state light-cone wavefunction is replaced by a free quark propagator times the QED-spinor structure for the $q\bar{q} \to \gamma^*$ transition. The forward $\gamma p \to \gamma^* p$ amplitude for a given flavour contribution can then be written as:

$$\begin{aligned}\mathcal{M}_f\big(\gamma p \to \gamma^*(q^2) p\big) &= W^2 4\pi\alpha_{\mathrm{em}} e_f^2 2 \int_0^1 dz \int_0^\infty \pi\, dk_\perp^2 \frac{\mathcal{A}_f(z, k_\perp^2, W^2)}{[k_\perp^2 + m_f^2 - z(1-z)q^2 - i\varepsilon]} \\ &= W^2 4\pi\alpha_{\mathrm{em}} e_f^2 2 \cdot 2 \int_0^{1/2} \frac{dz}{z(1-z)} \int_0^\infty \pi\, dk_\perp^2 \frac{\mathcal{A}_f(z, k_\perp^2, W^2)}{[\frac{k_\perp^2 + m_f^2}{z(1-z)} - q^2 - i\varepsilon]},\end{aligned} \tag{2.2}$$

where the explicit form of $\mathcal{A}_f(z, k_\perp^2, W^2)$ will be discussed below, α_{em} is the QED fine-structure constant; $e_f = \frac{2}{3}$ for u, c, t and $e_f = -\frac{1}{3}$ for d, s, b is the quark charge. In the present Letter the quark masses (m_f) have been fixed for: $m_{u,d} = 0.22$ GeV, $m_s = 0.37$ GeV, $m_c = 1.5$ GeV, $m_b = 4.75$ GeV. The masses used here are consistent with the analysis of deep inelastic scattering data in Ref. [17]. This