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Generalized parton distributions of the photon with helicity flip

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ABSTRACT

We present a calculation of the generalized parton distributions (GPDs) of the photon when the helicity of the initial photon is different from the final photon. We calculate the GPDs using overlaps of photon light-front wave functions (LFWFs) at leading order in electromagnetic coupling α and zeroth order in the strong coupling α_s, when the momentum transfer is purely in the transverse direction. These involve a contribution of orbital angular momentum of two units in the LFWFs. We express these GPDs in the impact parameter space.

1. Introduction

Generalized parton distributions (GPDs) of the nucleon are unified objects giving a wide range of information on nuclear structure and spin [1]. These are non-perturbative objects appearing in the factorized amplitude of exclusive processes like deeply virtual Compton scattering (DVCS) and meson production; and can be expressed as an off-forward matrix element of light-cone bilocal operators. In [2] the amplitude of the DVCS process on a photon target $\gamma^*(Q)\gamma \to \gamma\gamma$ at high Q^2 is written in terms of photon GPDs. These photon GPDs were calculated at leading order in electromagnetic coupling α and zeroth order in the strong coupling α_s and upto leading logs; in the kinematical limit that there is no momentum transfer in the transverse direction. In fact the parton content of the photon is known to play an important role in high energy scattering processes. The parton distributions of the photon are now well understood both theoretically and experimentally [3]. On the other hand, the GPDs and generalized distribution amplitudes (GDAs) of the photon [4] are much less investigated objects. In a couple of recent works [5,6], we extended the calculation of photon GPDs in the more general kinematics when the momentum transfer has both transverse and longitudinal components. We have developed an overlap representation using the light-front wave function of the photon. We also showed that the impact parameter space interpretation of the photon GPDs give a 3D position space description of them. In another recent work [7], GPDs of the photon have been used to investigate analyticity properties of DVCS amplitudes and related sum rules for the GPDs.

As we know, in the DVCS process $eP \to e\gamma P$, the helicity of the proton may or may not flip due to the scattering. When the proton helicity is flipped, the DVCS amplitude is parametrized in terms of the GPD E [1]. This flip requires non-zero orbital angular momentum in the overlapping light-front wave functions (LFWFs) and is not possible unless there is non-zero momentum transfer in the transverse direction. For a transversely polarized nucleon, this gives a distortion of the parton distributions in the transverse position or impact parameter space [8]. In two previous articles, we calculated the impact parameter space representations of the photon GPDs when the helicity of the photon is not flipped. In this work, we calculate the GPDs that involve helicity flip of the photon and represent them in impact parameter space. Like the proton, these involve overlaps of LFWFs of the photon, with non-zero orbital angular momentum (OAM). The corresponding parton distributions in the impact parameter space show distortions related to the orbital angular momentum of the LFWFs.

2. GPDs of the photon with helicity flip

The GPDs of the photon can be expressed as the following off-forward matrix elements [5,6]

$$F^q = \int \frac{dy^-}{8\pi} e^{\frac{-iP^+y^-}{2}} \langle \gamma(P'), \lambda' | \bar{\psi}(0)\gamma^+\psi(y^-) | \gamma(P), \lambda \rangle, \qquad (1)$$

$$\tilde{F}^q = \int \frac{dy^-}{8\pi} e^{\frac{-iP^+y^-}{2}} \langle \gamma(P'), \lambda' | \bar{\psi}(0)\gamma^+\gamma_5\psi(y^-) | \gamma(P), \lambda \rangle \qquad (2)$$

here $|\gamma(P),\lambda\rangle$ is the (real) photon target state of momentum P and helicity λ. We work in the light-front gauge $A^+ = 0$. We use the standard LF coordinates $P^\pm = P^0 \pm P^3$, $y^\pm = y^0 \pm y^3$. Since the target photon is on-shell, $P^+P^- - P^{\perp 2} = 0$, the momenta of the initial and final photon in the most general case of momentum transfer are given by:

$$P = (P^+, 0^\perp, 0), \qquad (3)$$

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$$P' = \left((1-\zeta)P^+, -\Delta^\perp, \frac{\Delta^{\perp 2}}{(1-\zeta)P^+}\right). \tag{4}$$

The four-momentum transfer from the target is

$$\Delta = P - P' = \left(\zeta P^+, \Delta^\perp, \frac{t+\Delta^{\perp 2}}{\zeta P^+}\right), \tag{5}$$

where $t = \Delta^2$ and ζ is called the skewness variable. In addition, overall energy-momentum conservation requires $\Delta^- = P^- - P'^-$, which connects $\Delta^{\perp 2}$, ζ, and t according to

$$(1-\zeta)t = -\Delta^{\perp 2}. \tag{6}$$

In order to calculate the above matrix element, we use the Fock space expansion of the photon state, which can be written as [5]

$$\begin{aligned}\left|\gamma(P),\lambda\right\rangle = \sqrt{N}\bigg[&a^\dagger(P,\lambda)|0\rangle \\ &+ \sum_{\sigma_1,\sigma_2}\int\{dk_1\}\int\{dk_2\}\sqrt{2(2\pi)^3P^+}\delta^3(P-k_1-k_2) \\ &\times \phi_2(k_1,k_2,\sigma_1,\sigma_2)b^\dagger(k_1,\sigma_1)d^\dagger(k_2,\sigma_2)|0\rangle\bigg]\end{aligned} \tag{7}$$

where $\sqrt{N}$ is the normalization of the state; which in our calculation we can take as unity as any correction to it contributes at higher order in α. $\{dk\} = \int \frac{dk^+d^2k^\perp}{\sqrt{2(2\pi)^3k^+}}$, ϕ_2 is the two-particle ($q\bar{q}$) light-front wave function (LFWF) and σ_1 and σ_2 are the helicities of the quark and antiquark. The wave function can be expressed in terms of Jacobi momenta $x_i = \frac{k_i^+}{P^+}$ and $q_i^\perp = k_i^\perp - x_iP^\perp$. These obey the relations $\sum_i x_i = 1$, $\sum_i q_i^\perp = 0$. The Lorentz boost invariant two-particle LFWFs are given by $\psi_2(x_i,q_i^\perp) = \phi_2\sqrt{P^+}$. $\psi_2(x_i,q_i^\perp)$ can be calculated order by order in perturbation theory. The two-particle LFWFs for the photon are given by

$$\begin{aligned}\psi^\lambda_{2s_1,s_2}\left(x,q^\perp\right) = &\frac{1}{m^2 - \frac{m^2+(q^\perp)^2}{x(1-x)}}\frac{ee_q}{\sqrt{2(2\pi)^3}}\chi^\dagger_{s_1}\left[\frac{(\sigma^\perp\cdot q^\perp)}{x}\sigma^\perp\right. \\ &\left. - \sigma^\perp\frac{(\sigma^\perp\cdot q^\perp)}{1-x} - i\frac{m}{x(1-x)}\sigma^\perp\right]\chi_{-s_2}\epsilon^{\perp *}_\lambda\end{aligned} \tag{8}$$

where m is the mass of $q(\bar{q})$. λ is the helicity of the photon and s_1, s_2 are the helicities of the q and $\bar{q}$ respectively. We have used the two-component form of light-cone field theory [9], namely the component A^- of the photon field is constrained in the gauge $A^+ = 0$ and can be eliminated from the theory. So one has only the transverse components of the photon field $A^\perp$. Likewise, the 'bad' component of the fermion field $\psi^{(-)}$ is eliminated using constraint equation and $\psi^{(+)}$ is written in terms of two-component spinors, χ_s [9].

The GPDs can be written in terms of the overlaps of the LFWFs as follows:

$$\begin{aligned}F^q = &\int d^2q^\perp dx_1\,\delta(x-x_1)\psi_2^{*\lambda'}\left(x_1,q^\perp-(1-x_1)\Delta^\perp\right)\psi_2^\lambda\left(x_1,q^\perp\right) \\ &- \int d^2q^\perp dx_1\,\delta(1+x-x_1)\psi_2^{*\lambda'}\left(x_1,q^\perp+x_1\Delta^\perp\right) \\ &\times \psi_2^\lambda\left(x_1,q^\perp\right).\end{aligned} \tag{9}$$

We calculate the photon GPDs using overlaps of light-front wave functions. We take the momentum transfer to be purely in the transverse direction, unlike [2], where the momentum transfer was taken purely in the light-cone (plus) direction. GPDs in this case can be expressed in terms of diagonal (particle number conserving) overlaps of LFWFs. When there is non-zero momentum transfer in the longitudinal direction, there are off-diagonal particle number changing overlaps as well, similar to the proton GPDs [10].

The transverse polarization vector of the photon can be written as:

$$\epsilon^\perp_\pm = \frac{1}{\sqrt{2}}(\mp 1, -i). \tag{10}$$

We extract the GPD that involves a helicity flip of the target photon from the non-vanishing coefficient of the combination $(\epsilon^1_{+1}\epsilon^{1*}_{-1} + \epsilon^2_{+1}\epsilon^{2*}_{-1})$. The corresponding GPD without a helicity flip of the photon contains a leading logarithmic term at leading order in α and zeroth order in strong coupling constant and has been discussed in two previous articles [5,6]. The GPD with helicity flip is given by:

$$E_1 = \frac{\alpha e_q^2}{2\pi^2}x(1-x)\left[I_1 - (1-x)I_2\right]. \tag{11}$$

The integrals I_1 and I_2 are given by:

$$I_1 = \int d^2q^\perp\frac{((q^1)^2-(q^2)^2)}{D_1D_2}, \qquad I_2 = \int d^2q^\perp\frac{(q^1\Delta^1 - q^2\Delta^2)}{D_1D_2},$$

where q^1 and q^2 are the x and y components of $q^\perp$ and Δ^1 and Δ^2 are the x and y components of $\Delta^\perp$ respectively. The denominators are given by:

$$\begin{aligned}D_1 &= \left(q^\perp\right)^2 - m^2x(1-x) + m^2, \\ D_2 &= \left(q^\perp\right)^2 + (1-x)^2\left(\Delta^\perp\right)^2 - 2q^\perp\cdot\Delta^\perp(1-x) \\ &\quad - m^2x(1-x) + m^2.\end{aligned} \tag{12}$$

In order to simplify the above expression we use the formula [11]

$$\frac{1}{A^k} = \frac{1}{\Gamma(k)}\int_0^\infty \alpha^{k-1}e^{-\alpha A}\,d\alpha. \tag{13}$$

The integrals can be written in the form:

$$I_1 = \left(\left(\Delta^1\right)^2 - \left(\Delta^2\right)^2\right)\pi(1-x)^2\int_0^1 dq\,\frac{(1-q)^2}{B(q)},$$

$$I_2 = \left(\left(\Delta^1\right)^2 - \left(\Delta^2\right)^2\right)\pi(1-x)\int_0^1 dq\,\frac{(1-q)}{B(q)},$$

where

$$B(q) = m^2\left(1-x(1-x)\right) + q(1-q)(1-x)^2\left(\Delta^\perp\right)^2. \tag{14}$$

So we have

$$\begin{aligned}E_1 = &\frac{\alpha e_q^2}{2\pi}x(1-x)^3\left(\left(\Delta^1\right)^2 - \left(\Delta^2\right)^2\right) \\ &\times\left[\int_0^1\frac{dq}{B(q)}\left((1-q)^2-(1-q)\right)\right].\end{aligned} \tag{15}$$

The above has the expected quadrupole structure coming from $((\Delta^1)^2 - (\Delta^2)^2)$. As the photon is a spin one particle, in order to flip its helicity, the overlapping light-front wave functions should