I. Introduction

Recently a lot of attention has been paid to deeply virtual Compton scattering (DVCS) [1, 2]. It was realized that there exists a close relation with the problem of a proton spin carried by gluons and quarks. Indeed the decomposition of the nonforward Compton scattering amplitude for the case when one of photons on-mass shell and another one is off-mass shell contains fifteen structure functions and four out of them could be put to the test [1, 3]. Their first moments determine the Dirac, Pauli, axial-vector and pseudoscalar formfactors of a proton while their second moments are related with the structure functions mentioned above. The contribution derived here is sensitive only to the gluon density $zg(z, Q^2)$ inside a proton. For small values of energy fraction $z$ carried by sea gluons, one has $zg(z, Q) \approx 6Q^2 [GeV^2], Q^2 \sim 1 GeV^2$ [4].

In what follows we study the case in which an initial proton is unpolarized and the final states are a scattered lepton, a recoil photon and a hard photon from the fragmentation region of initial lepton. Furthermore the lowest order contribution ($\sim \alpha_s^2$) to the asymmetry is dealt with. The higher PT effects were considered in the paper [3] and took into account the BFKL ladder.

II. Bethe–Heitler Amplitude

Let’s consider the radiative electron-proton scattering,

$$e(p_1, \xi) + P(p) \rightarrow e(p_2) + P(p') + \gamma(k_1),$$

where we indicate in parenthesis the 4-momenta of particles, $\xi$ is the degree of the longitudinal polarization of electron. We will restrict ourselves to the kinematics where the absolute magnitude of a square of momentum transfer between initial and final state electrons is small with respect to the cms energy squared,

$$s = (p_1 + p)^2 \gg Q_1^2 = -(p_1 - p_2)^2, \quad (1)$$

$$Q^2 = -q^2 \gg p_1^2 = p_2^2 = m_e^2,$n^2 = m_e^2,$

$$p^2 = p'^2 = M^2, \quad q = p' - p.$$The main contribution non-vanishing in the limit of large $s$ arises from the two Feynman amplitudes. One of them, describing the hard photon emission by the electron blob,
the so called Bethe-Heitler amplitude, has the following form,

\[ M_{BH}^{\lambda} = \frac{(4\pi\alpha)^{3/2}}{q^2} \tilde{u}(p_2)O_{\mu\alpha}u(p_1,\xi)\bar{u}^\lambda(p')V_\nu u^\lambda(p)g^{\mu\nu}e^\sigma(k_1) \]

\[ = \frac{(4\pi\alpha)^{3/2}}{q^2} \left( \frac{-2x_1}{sdd_1} \right) \bar{u}(p_2)v_\sigma u(p_1,\xi)e^\sigma(k_1)sN^\lambda, \]

with

\[ V_\nu = \gamma_\nu F_1(q^2) + \frac{[\gamma_\nu, q]}{2M} F_2(q^2), \]

\[ N^\lambda = \frac{1}{s} \bar{u}^\lambda(p') \left( \frac{\hat{q}p_1}{M} F_2 \right) u^\lambda(p), \]

\[ \sum_\lambda |N^\lambda|^2 = 2F(Q^2), \quad F(Q^2) = F_1^2(q^2) + \frac{Q^2}{M^2} F_2^2(q^2). \]

Here \( \lambda = \pm 1 \) describes a proton chiral state, \( F_{1,2} \) are the Dirac and Pauli form factors, \( M \) is a proton mass, \( e(k_1) \) is the photon polarization vector and

\[ v_\sigma = sx(d - d_1)\gamma_\sigma + xd_1\gamma_\alpha \hat{q}\bar{p} + dp\bar{q}\gamma_\sigma, \]

the effective vertex describing the Compton scattering \([\text{F}]\). The quantities

\[ d = xx_1[(p_1 - q)^2 - m_e^2], \quad d_1 = -x_1[(p_1 - k_1)^2 - m_e^2], \quad q^2, \]

can be re-expressed using the Sudakov decomposition of the 4-vectors,

\[ d = x_1^2m_e^2 + (k_1 + x_1q)^2, \quad d_1 = x_1^2m_e^2 + k_1^2, \quad Q^2 = -q^2 = q^2, \]

where \( k_1, p_2, q \) are the two-dimensional transverse to the beam axis components of photon, scattered electron and recoil proton momenta which obey the conservation law \( k_1 + p_2 + q = 0 \), and \( x, x_1 \) are the energy fractions of the scattered electron and real photon satisfying \( x + x_1 = 1 \). The corresponding modulus of the matrix element squared and summed over polarization states and the cross section can be brought to the form \([\text{F}]\),

\[ \sum |M_{BH}^{\lambda}|^2 = 2^{11}\pi^3\alpha^3 \frac{x_1^2(1 + x_2^2)}{q^2} F(Q^2) \frac{d\sigma^{P\to(\gamma\gamma)P}}{d^2q dx} = \frac{2\alpha^2 x_1(1 + x_2^2)}{\pi^2 q^2} F(Q^2) d^2k_1 d^2q dx. \]

It is important to note that the amplitude \( M_{BH}^{\lambda} \) is real.

### III. ASYMMETRY EVALUATION

Consider now the 2-loop level correction to the amplitude studied above, describing emission of a hard photon from the intermediate state of a pair of charged quarks created by the virtual photon and converted to the real one through the two gluons exchange. The corresponding amplitude differs from the QED one only by the factor \( C = \sum Q_q^2 / Q_\gamma^2 \) (\( Q_q \) is a quark charge in units of \( e \)) and the gluon density factor \( G(z,k,Q) = zdg(z,k,Q)/d\ln Q^2, k^2 \sim Q^2 \ll s \) (see Ref. [3]).

The amplitude of IF mechanism is pure imaginary and may be expressed in terms of the photon IF,

\[ M_{IF}^{\lambda} = 4\alpha^2\alpha \frac{\Delta k^2}{q_1^2} \tilde{u}(p_2)\gamma_\nu u(p_1,\xi)N^\lambda \]

\[ \times \int \frac{d^2k G(z,k,Q)^2 d^2q \cdot dq_+}{\pi k^2(q - k)^2} \frac{1}{\pi x + x_1} I_{\mu\sigma}e^\sigma(k_1), \quad q_1^2 = \frac{p_2^2}{x}. \]

where the tensor \( I_{\mu\sigma} \) is given through the tensor of elastic gluon-photon scattering,

\[ I_{\mu\sigma} = \frac{p^\alpha p^\beta}{s^2} T_{\alpha\beta\mu\sigma}. \]

Its explicit form is given in Appendices A and C. In the last appendix we infer the heavy photon IF with both photons off-mass shell.

The relevant expression for the contribution to the cross section reads,

\[ \Delta |M|^2 = \sum 2M_{IF}^{\lambda}(M_{BH}^*)^* \]

\[ = s^2 \xi^{21} C \frac{x_1^2 \pi^2}{q^2 p_2^2 d_1} \alpha^3 \alpha^2 \int \frac{d^2k G(k,Q,z)}{\pi k^2(q - k)^2} \]

\[ \times \int \frac{d^2q_+ dq_+}{x + x_1} J \cdot F(Q^2), \]

\[ J = \frac{i}{8} I_{\mu\nu} L_{\mu\nu}, \quad L_{\mu\nu} = \frac{1}{4} \text{Tr}[\hat{p}_2 \gamma_\nu \gamma_\mu \gamma_\sigma], \]

Using the gauge invariance conditions \( T_{\alpha\beta}.k_\alpha = T_{\alpha\beta}.(q-k)_\beta = 0 \) we can perform the following replacement in the expression for \( I_{\mu\sigma} \),

\[ \frac{p_\alpha p_\beta}{s^2} \rightarrow k_\alpha^+(q - k)_\beta^+, \]

\[ \tilde{s} = \frac{1}{x_1} [(q_+ + q_-)^2 + (q_1 + k_1)^2], \]

\[ s_1^2 = \frac{1}{x_1} [(q_+ + q_-)^2 + (k_1 + k - q)^2]. \]

The next step is to perform the \( d^2k \) integration. We suppose that small values of \( |k| \) dominate as this region is enhanced by the factor \( zg(z,|k|) \). Then the integration could be carried out as follows,

\[ \int \frac{d^2k}{\pi k^2 k^2} k^i k^j G(z,k,k') \]

\[ = \frac{1}{\pi} \int_0^1 dx \int \frac{d^2k k^i (q - k)^j G(z,k,q - k)}{[(k - xq)^2 + Q^2 x(1 - x)]^2} \]

\[ \approx \frac{1}{2} \delta^{ij} \int_0^1 dx z g(z, xQ, (1 - x)Q) \approx \frac{1}{2} \delta^{ij} z g(z, Q/2). \]
Thus to the accuracy of approximately 10% (with $Q^2$ of a few $\text{GeV}^2$) we may put $|k| = |k'| = Q/2$ in the nonsingular part of the integrand.

It should be noted that only the structure

$$E = (p, p_1, p_2, q) = \varepsilon_{\alpha\beta\gamma\delta} p^\alpha p_1^\beta p_2^\gamma q^\delta = \frac{s}{2} [p_2 \times q]_z$$

survives integrations over $d^2 q_+ \, dz_+$ (for details see appendices A,B). Then the asymmetry is found to be,

$$A = \xi \frac{Q(z/Q^2)_{|z \to 0}}{F(Q^2)} \frac{q}{p_2} \Phi(x) \sin \phi, \quad (10)$$

$$\Phi(x) = -\frac{1 + x}{3[1 + x^2]} \left(2 \ln \frac{p_2^2}{m^2} - 1\right),$$

Here $Q = |q|$ is the momentum transfer to a proton which bears to a some extent a latent dependence on an energy fraction of the scattered lepton, $|p_2|$ is the transverse component of the scattered electron momentum, $m = 0.3 \text{ GeV}$ is a quark constituent mass. Besides it has been assumed that $p_2^2 \gg Q^2 \gg m^2$ and the terms of order $(m^2/p_2^2) \ln(p_2^2/m^2)$ have been dropped for their subleading nature (which gives an accuracy of the derivation to be $\sim 10\%$)\(^1\)

IV. CONCLUSION

Above we gave a rather rough estimate for the azimuthal asymmetry of a real photon emission induced by longitudinally polarized electron in its fragmentation region. It turns out that the asymmetry is enhanced by a sea gluon density $zg(z,Q)$ which for $z \to 0$ appears to be $\sim 5/7 \, (Q(\text{GeV})^2)$\(^2\). Evidently the asymmetry results from the interference between the Born-level Bethe-Heitler amplitude and that of two-loop level containing a photon-gluon fusion block. The first amplitude is real and the last one is completely imaginary. Aiming at obtaining a definite analytical result for the asymmetry we study the problem restricted by the requirement $p_2^2 \gg Q^2 \gg m^2$. Using this approximation we extract the gluon density factor $zg(z,Q)$. The non-enhanced terms are estimated to give a contribution of order unity thereby claiming the accuracy of the calculation to be of order $15 \pm 20\%$. Just to illustrate what the asymmetry looks like we give a plot of the beam-spin analyzing power values (which is merely a multiplicative factor in front of $\sin \phi$ in Eq. (10)) for the momentum transfer $Q_1^2 = 1 \div 50 \, \text{GeV}^2$. The ratio of $|q/p_2|$ is kept to be 0.1 for all curves in the plot. The fall of the asymmetry for high values of $z$ and $Q_1^2$ is caused by relatively large values of $|q|$ and, as a result, by the little bit less $\alpha_s$ values.

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APPENDIX A: EXPLICIT FORM OF $I_{\mu\nu}$

To calculate the contribution of FD containing the impact factor of a heavy photon we need the trace,

$$I_{\mu\nu} = \frac{1}{s^2} \text{Tr}[(\hat{q}_+ + m) B_\mu (\hat{q}_- - m) R_\nu], \quad (A.1)$$

$$B_\mu = \frac{1}{d_+} \gamma_\mu (\hat{k} - \hat{q}_+ + m) \hat{p}_2 + \frac{1}{d_-} \hat{p}_2 (\hat{q}_- - \hat{k} + m) \gamma_\mu,$$

$$R_\nu = \frac{1}{d_-} \gamma_\nu (\hat{q}_- - \hat{k} + m) \hat{p}_2 + \frac{1}{d_+} \hat{p}_2 (\hat{k}' - \hat{q}_+ + m) \gamma_\nu,$$

where $m$ is a quark mass and \(d_\pm = k^2 - 2kq_\pm, \quad d'_\pm = k'^2 - 2k'q_\pm\).

It’s easy to show that the gauge conditions for the on-mass shell quarks are satisfied,

$$\bar{u}(q_-) B_\nu v(q_+) q_1^\nu = 0, \quad \bar{v}(q_+) R_\mu u(q_-) k_1^\mu = 0. \quad (A.2)$$

\(^{1}\)Note that we use the notation typical for calculations based on Sudakov parameterization of four-vectors. The invariants do not always coincide with those used by experimentalists. Thus our $x, Q_1^2 = p_1^2/x$ and $Q^2$ correspond to $1 - y, Q^2$ and $-t$, in order, adopted by experimental collaborations; $y$ is the scaling variable.

\(^{2}\)See, for instance, W. Beenakker and R. Kleiss, Phys. Lett. 101B, 307 (1981).
Taking into account an enhancement due to large gluon density factor $x g(z, Q) \gg 1$ one can restrict further consideration to the kinematics $p_2^2 \gg k^2 \sim q^2$ which is thus preferable. Then it could be verified that

$$d = d' = -x s, \quad s = \frac{1}{s} [s_1 + s_2], \quad \sigma = \frac{1}{y + y'}, \quad \sigma = m^2 + q^2,$$

$$s_1 = (q_+ + q_-)^2 = \frac{1}{y + y'} [m^2 + q^2], \quad (A.3)$$

$$\sigma = m^2 + q^2, \quad m^2 = m^2 + y + y - p_2^2,$$

$$q_i = q_+ + y + p_2 = -q_+ - y - p_2, \quad y \pm = \frac{x}{x_1}.$$

Here $x_{\pm}$ are the energy fractions of the pair, $q_{\pm}$ — their components of momentum transverse to the beam axis. They obey the conservation laws,

$$y_+ + y_- = 1, \quad \text{and} \quad q_+ + q_- + p_2 = 0.$$

With the substitution $p_{2\mu} \rightarrow -s k_{1\mu} / \hat{s}$ in the quantity $B$ and, respectively, $p_{2\mu} \rightarrow -s k_{1\mu} / \hat{s}$ in $R$ the tensor $I_{\mu\nu}$ can be transformed to take the following form,

$$I_{\mu\nu} = \frac{1}{4 s^4} \text{Tr}[(\hat{q}_- + m) B_{1\nu}(\hat{q}_+ - m) R_{1\nu}], \quad (A.4)$$

$$B_{1\nu} = \frac{s}{s} \left( \frac{1}{x_+} \gamma_\mu \hat{p} k - \frac{1}{x_-} \hat{k} \gamma_\mu \right) + \gamma_\mu Z,$$

$$R_{1\nu} = \frac{s}{s} \left( -\frac{1}{x_+} \gamma_\nu \hat{p} k' - \frac{1}{x_-} \hat{k} \gamma_\nu \right) + \gamma_\nu Z',$$

$$Z = 2 x + x - r k, \quad Z' = 2 x + x - r k', \quad r = x_1 q_i.$$

Here the vectors $k, k' = k - q$ are pure 2-dimensional ones transverse to the beam axis.

Once again one can check that the gauge conditions,

$$u(q_-) B_{1\nu} v(q_+) q^\nu_i = 0, \quad (A.5)$$

$$\bar{u}(q_+) R_{1\mu} u(q_-) k^\mu_i = 0,$$

are satisfied up to the terms of order $k^2 / p_2^2$.

**APPENDIX B: INTEGRATION OVER QUARK PAIR MOMENTA**

Using the Sudakov parametrization of 4-vectors,

$$p_1 \approx \tilde{p}_1, \quad p_2 = x \tilde{p}_1 + \frac{p_2^2}{x s} \hat{s} + p_2^\perp,$$

$$q_{\pm} = \pm \tilde{p}_1 + \frac{q^2 + m^2}{s x_\perp} \hat{s} + q_{\pm}^\perp,$$

$$k_1 = x_1 \tilde{p}_1 + \frac{k^2}{s x_1} \hat{s} + k_1^\perp, \quad \hat{s} = \hat{s}^2 = 0,$$

$$\hat{s} = p - \frac{M^2}{s} p_1, \quad 2 \tilde{p} \tilde{p}_1 = s, \quad a_\perp \tilde{p}_1 = a_\perp \hat{s} = 0,$$

and the conservation law $x_+ + x_- = x_1$, the scalar products used can be written as follows,

$$2 p_1 q_{\pm} = \frac{1}{x_{\pm}} [q^2_{\pm} + m^2] \equiv a_{\pm},$$

$$2 p_2 q_{\pm} = \frac{1}{x_{\pm}} [m^2 q^2 + (x q_{\pm} - p_2 x_{\pm})^2] \equiv a_{\pm}' \quad (B.2)$$

Upon averaging over the azimuthal angle of gluon momenta and using the permutation symmetry

$$x_- \leftrightarrow x_+, \quad q_- \leftrightarrow q_+,$$

the quantity $J$ could be symbolically written in the following manner,

$$J \frac{s^4}{p_2^2} = \frac{1}{2} (1 + P_\perp) [x B + C],$$

$$C = E \left[ \frac{4 m^2 r^2}{x z^2} + 2 (p, p_2, q_{\perp}, q) \left( \frac{2 s_1}{x_1 x z} q_+ r + \frac{s_1^2}{x_1 z} - \frac{s_2^2}{x_1 z} \right) \right] - 2 (p, p_2, q, r) s_2 a_+, \quad (B.3)$$

$$B = 2 (p, p_1, q_{\perp}, q) \left( \frac{s_1}{x_1 z} + \frac{s_1}{x z} r q_+ - \frac{s_1}{x_1 z} r^2 \right)$$

$$- \left( \frac{s_2}{x_1 z} + \frac{s_2}{x z} \right) + (p, p_1, q, r) s_2 a_+ + (p, p_1, p_2, r)$$

$$\times \left( \frac{s_2}{x_1 z} + \frac{s_2}{x z} \right) \left( \frac{s_1}{x_1 z} r q_+ - \frac{2}{z^2} r^2 \right) q_+ q$$

$$+ E \left[ \frac{2 s_1 (x_1 + x_-)}{x_1 x z} r q_+ - \frac{s_2^2}{2 z^2} - \frac{2}{z^2} r^2 \left( s_1 - p_2^2 \right) \right]$$

$$+ 2 (p_2, q_{\perp}, q) \left( \frac{s_2}{x_1 z} + \frac{s_2}{x z} \right) + (p, p_2, r, q) s_2 a_+ + s \left( 2 (p_1, p_2, q_{\perp}, q) \right.$$

$$\times \frac{s_2^2}{2 z^2} + (p_1, p_2, q, r) \frac{x}{x_1 z} - s_1 \right).$$

where $s_1 = x_1 s$ and $z = x_1 + x_-$ and $P_\perp$ is the permutation operator. In deriving these formulæ it has been assumed that $k^2 \gg q^2$. The structures $\ldots$ entering Eq. (B.3) can be rewritten as follows.

$$(p, p_2, q_{\perp}, q) = x (p, p_1, q_{\perp}, q) - x E,$$

$$s (p_1, p_2, q_{\perp}, q) = - \frac{P_2^2}{x} (p, p_1, q_{\perp}, q) + a_+ E,$$

$$s (p_1, p_2, q, r) = \frac{P_2^2}{x} (p_1, p_1, r, q),$$

$$(p, p_2, q, r) = - x (p, p_1, r, q).$$

2At this point one should be aware that only the transverse components of the 4-vector have to be taken into account.
Having all the above at hand we turn to the $d^2 q_\perp$ integration. A set of relevant integrals reads,

$$
\int \frac{d^2 q_\perp}{\pi} \left\{ \frac{1}{\sigma^2} \frac{r^2}{\sigma^2} \frac{q_i^i}{\sigma^2} \frac{r^j}{\sigma^2} \frac{r^2 q_i^r}{\sigma^2} \frac{(r q_r^i q_i^r)}{\sigma^2} \right\},
$$

and the quantity $N_3$ given in the Eq. (B.3). The tensor $I_{\mu\nu}$ has the form (see Eq. (A.1)),

$$
\frac{1}{x_{+} x_{-}} I_{\mu\nu} = (1 + P_{\pm}) \left\{ \frac{x_{+}}{a_{+} a_{+}}(2q_{\mu} q_{\nu} + (2 - 4x_{+})q_{\mu} q_{\nu} - 8x_{-}q_{\mu} q_{\nu} + \frac{1}{a_{-} a_{+}}(2x_{+} q_{\mu} q_{-\nu} + (2 - 8x_{+})q_{\nu} q_{-\mu} + 4x_{+} x_{-} q_{\mu} q_{-\nu} + (2 - 8x_{+} x_{-}) q_{\mu} q_{-\nu} + (2 - 8x_{+} x_{-}) q_{\mu} q_{-\nu} + (2 - 8x_{+} x_{-}) q_{\mu} q_{-\nu}) + x_{+} x_{-}(q^2 - Q^2 + (Q^2)) + \frac{x_{+} x_{-}(Q^2)}{x_{+} x_{-}(Q^2)} \right\},
$$

with

$$
a_{\pm} = a + q_{\pm}, \quad a_{\pm} = b + (q_{\pm} - x_{+} q_{-\pm})^2, \quad a = m^2 + x_{+} x_{-} Q^2, \quad b = m^2 + x_{+} x_{-} Q^2.
$$

One can argue that the gauge condition $I_{\mu\nu} = 0$ for $k = 0, k' = 0$ is satisfied. Joining the denominators with the use of the Feynman trick and performing an integration over the transverse to the beam axis components of the quark pair momenta we get,

$$
\int \frac{d^2 q_+}{\pi a_{+} a_{+} a_{+}} = \int \frac{dy_{L}}{D_{++}}, \quad \int \frac{d^2 q_+}{\pi a_{-} a_{-} a_{-}} = \int \frac{dy_{L}}{D_{--}},
$$

where $L = \ln(p_2^2/m^2)$.

**APPENDIX C: HEAVY PHOTON IMPACT FACTOR**

To obtain the heavy photon IF one has to consider the s-channel discontinuity of the heavy photon amplitude in an external field,

$$
\gamma_{\mu}(P_1) + A(p) \rightarrow q(q_+ + \bar{q}(q_-) + A(p'))
\rightarrow \gamma_{\mu}(P_2) + A(p')
\quad \text{(C.1)}
$$

$$
P_2^2 = -Q^2, \quad P_2^2 = -Q^2,
$$

which is described by the tensor

$$
\Delta A_{\mu\nu}(s, t) = \frac{(4\pi \alpha)^2}{k^2 k^2} \left( \frac{2}{s} \right)^2 N_3 s^4 I_{\mu\nu} d\Gamma_3
$$

with

$$
d\Gamma_3 = \frac{1}{(2\pi)^3} \frac{d^3 q_+ d^3 q_- d^3 p''}{2\varepsilon \varepsilon} \delta^4(P_1 + p - q + q - p'')
\quad \text{(C.3)}
$$

$$
\tau_{ij} = 2\alpha^2 \int dx_+ dx_- \delta(x_+ + x_- - 1) \int \frac{dy_{L}}{D_{++}}
\quad \text{with}
$$

$$
\tau_{k=0} = \tau_{k=q} = 0.
$$

5
It is important to note that even for the on-mass shell photons $Q^2 = Q'^2 = 0$ this expression differs from the one derived by Cheng and Wu [8]. The difference is found to be

\[ \Delta \tau_{ij} = \tau - \tau_{CW} \]

\[ = 4\alpha^2 \int dx_+ dy \left( x_+ x_+ (1-2x_+) q_j \left( \frac{x_+ q_i}{D^0_{++}} + \frac{b_i}{D^0_{-+}} \right), \right) \]

\[ D^0_{++} = m^2 + x_+^2 y (1-y) q^2, \]
\[ D^0_{-+} = m^2 + y (1-y) b^2. \]

The reason for this discrepancy is in the different definition of initial and final photons' 4-momenta. The similar results were obtained in Ref. [9].

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