Radiative corrections to semi-inclusive deep inelastic scattering induced by lepton and photon pair electroproduction

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Abstract

The contribution of lepton and photon pair production in $ep$-scattering to the cross section of semi-inclusive deep inelastic scattering $ep \rightarrow e'p'X$ has been calculated. The numerical results showed a large contribution of this process at $\phi_h = 180^\circ$, in a good agreement with preliminary experimental data.

1 Introduction

Semi-inclusive deep inelastic scattering (SIDIS) allows to investigate not only parton distributions but also shed light on parton hadronization process. During the data analysis of this reaction it is necessary to account for the QED radiative corrections spoiling experimental observables.

The lowest order radiative corrections to SIDIS were first calculated for the scattering of the polarized particles and three-fold cross section in [1]. These calculations allowed to develop the code SIRAD, which represented a modification of DIS program POLRAD [2]. Then in [3] the

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calculation of radiative corrections was generalized for unpolarized fivefold cross section and code HAPRAD was developed. In all these calculations Bardin-Shumeiko covariant approach [4] was used for cancellation of infrared divergences. At last in [5] the contribution of exclusive radiative tail was studied and a new version of HAPRAD (named 2.0) was written [7].

In the present work we consider another background process for a specific semi-inclusive reaction, in which the detected hadron is identical to the initial one. Preliminary experimental data from JLab [6] showed that in the kinematic region near $\phi_h = 180^\circ$ the measured cross section exceeded the calculated one-photon exchange (Born) contribution and the excess could not be described by the radiative corrections calculated before. It was noticed that the main contribution in this region came from the exclusive lepton pair electroproduction. In spite of its higher QED order (suppressed by $\alpha^2$) this process is enhanced by the square of proton electromagnetic form-factors at low $Q^2$. Therefore, in some specific kinematics the contribution of this process compete with SIDIS reaction cross section.

The matrix elements of the lepton pair electroproduction and the phase space of this process are considered in the next section. The contribution from two photon emission are also considered there as the process of the same order. Numerical result and conclusion presented in the next sections.

2 Method of calculation

Semi-inclusive reaction (see Fig. 1)

$$e^- (k_1) + p(p) \rightarrow e^- (k_2) + p(p_h) + X$$  \hspace{1cm} (1)
Figure 2: The four pairs of gauge invariant graphs for the lowest order of the lepton pair electroproduction in $ep$-scattering.

can be described by five variables:

$$Q^2 = -q^2 = -(k_1 - k_2)^2, \quad x = \frac{Q^2}{2pq}, \quad x_p = 1 - \frac{p_h q}{pq}, \quad t = (p - p_h)^2, \quad \phi_h,$$

(2)

where $\phi_h$ is the angle between $(k_1, k_2)$ and $(k_1 - k_2, p_h)$ planes.

The cross-section of electroproduction of the lepton pair in the $ep$-scattering

$$e^-(k_1) + p(p) \to e^-(k_2) + p(p_h) + e^-(l_-) + e^-(l_+)$$

(3)

at the lowest order reads:

$$d\sigma = \frac{1}{2S} \mathcal{M}^\dagger \mathcal{M} d\Gamma,$$

(4)

with $S = 2pk_1$.

We consider now the semi-inclusive process in which detected hadron is identical to the initial one. In order to use SIDIS variables the phase space of this process can be transformed in the following way:

$$d\Gamma = \frac{1}{(2\pi)^8} \frac{d^3k_2}{2k_{20}} \frac{d^3p_h}{2p_{h0}} d\Gamma_{2l} = \frac{S^2_2 dQ^2 dx d\phi_h dtd\phi_h}{2^9 \pi^7 Q^2 \sqrt{S_x^2 + 4M^2 Q^2}} d\Gamma_{2l},$$

(5)
$S_x = 2pq$ and the phase space of the lepton pair has a form:

$$d\Gamma_{2l} = \frac{d^3l_+ d^3l_-}{2l_+ 2l_-} \delta^4(k_1 + p - k_2 - p_h - l_- - l_+) = \frac{1}{8} d\Omega_R,$$

with $d\Omega_R$ being the solid angle of lepton pair defined in its center mass system ($l_+ + l_- = 0$).

The matrix element can be written as a sum of the four pairs of gauge invariant diagrams $\mathcal{M} = \mathcal{M}_a + \mathcal{M}_b + \mathcal{M}_c + \mathcal{M}_d$ presented in Fig. 2. The explicit expressions for each term read:

$$\mathcal{M}_a = \frac{4\pi\alpha}{k^2 q_h^2} \bar{u}(k_2) \left[ \frac{2k_{1\alpha} - \gamma_\alpha}{k^2 - 2k_1 k^-} + \frac{2k_{2\alpha} + \gamma_\alpha}{k^2 + 2k_2 k^-} \gamma_\mu \right] u(k_1) \times \bar{u}(l_-) \gamma_\alpha u(-l_+) J^h_{\mu},$$

$$\mathcal{M}_c = \frac{4\pi\alpha}{q_h^2} \bar{u}(l_-) \left[ \frac{\gamma_\mu - \gamma_\alpha - 2l_+ \alpha}{q^2 - 2l_+ q} + \frac{2l_- + \gamma_\alpha}{q^2 - 2l_- q} \gamma_\mu \right] u(-l_+),$$

$$\mathcal{M}_{b,d} = -\mathcal{M}_{a,c}(k_2 \leftrightarrow l_-).$$

where $k = l_+ + l_-, \quad q_h = q - k,$

$$J^h_{\mu} = \bar{u}(p_h) \left[ \gamma_\mu F_1 + i\sigma_{\mu\nu} \frac{p_{h}^\nu - p^\nu}{2M} F_2 \right] u(p)$$

and $F_{1,2}$ are the proton form factors.

Additional contribution of the same order comes from two photon emission which is shown in Fig. 3:

$$e^- (k_1) + p(p) \rightarrow e^- (k_2) + p(p_h) + \gamma(\kappa_1, \varepsilon_1) + \gamma(\kappa_2, \varepsilon_2),$$

where $\varepsilon_{1,2}$ are photon polarization vectors.
Figure 4: $\phi_h$-dependence of the different contributions to the semi-inclusive process $ep \to e'p'X$.

The matrix element of this process reads:

$$M_{2\gamma} = \frac{4\pi\alpha}{q_h^2} \bar{u}(k_2) \left[ - \frac{(2k_{2\mu} + \gamma_\mu \hat{q}_h) \hat{\varepsilon}_2 (2k_1 \varepsilon_1 - \hat{k}_1 \hat{\varepsilon}_1)}{2k_1 \kappa_1 (k^2 - 2k\kappa_1)} ight. $$

$$ \left. - \frac{(2k_2 \varepsilon_2 + \hat{\varepsilon}_2 \hat{k}_2) \gamma_\mu (2k_1 \varepsilon_1 - \hat{k}_1 \hat{\varepsilon}_1)}{4k_1 \kappa_1 k_2 \kappa_2} ight. $$

$$ \left. + \frac{(2k_2 \varepsilon_2 + \hat{\varepsilon}_2 \hat{k}_2) \hat{\varepsilon}_1 \gamma_\mu (2k_1 \mu - \hat{q}_h \gamma_\mu)}{2(k^2 + 2k_2 \kappa_2)} + (\kappa_1, \varepsilon_1 \leftrightarrow \kappa_1, \varepsilon_1) \right] u(k_1), \quad (10)$$

with $k = \kappa_1 + \kappa_2$, while the cross section and phase space looks like (5) and (4), respectively.

3 Numerical results

The $\phi_h$-dependence of the different contributions to the semi-inclusive reaction $e + p \to e' + p' + X$ is shown in Fig. 4. In the region near $\phi_h = 180^\circ$ a narrow peak is observed. Such behavior cannot be described by the Born contribution far as it has $\phi_h$-dependence inconsistent with the usual unpolarized SIDIS distribution $A + B \cos \phi_h + C \cos 2\phi_h$. Radiative corrections calculated in [3] as well as exclusive radiative tail [5] (rad and ex. tail lines
respectively) cannot improve this situation. The dominant contribution in this region comes from the exclusive electroproduction of lepton pairs in $ep$-scattering discussed above. Instead the two photon emission, shown in Fig. 3, is almost negligible despite being of the same $\alpha$-order. Moreover, detailed numerical estimates showed that most of correction strength came from the square of matrix element $M_b$ (see Fig. 2 (b) and equation (7)). These calculations are in good agreement with preliminary experimental data from [6].

4 Conclusion

Radiative corrections to semi-inclusive electroproduction of proton induced by the exclusive production of lepton and photon pairs have been calculated for the first time. Numerical results showed important contribution (mainly from diagrams Fig. 2 (b)) in the region of $\phi_b = 180^\circ$, in good agreement with preliminary experimental data. The presented approach is rather general and can be extended on analysis of $A'$-production [7].

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