Contributions due to the longitudinal virtual photon in the semi-inclusive ep collision at HERA

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Abstract

The importance of contributions due to the longitudinally polarised virtual photon, dσ_L, and the interference term dσ_{LT}, in the unpolarised ep collisions is discussed [1]. The numerical calculations for the Compton process ep → eγX at the HERA collider were performed in the Born approximation. The various distributions in the CM_{ep} and Breit frames are presented. These cross sections are dominated by the transversely polarised intermediate photon, even for large Q^2.

1 Introduction

In cross sections for semi-inclusive ep processes and collisions with two intermediate photon, the terms coming from the interference between γ_L^* and γ_T^* or between two different transverse states of γ^* can appear [2]. The detailed studies of various contributions for the process e^+e^- → e^+e^-μ^+μ^- performed for the kinematical range of the PLUTO and LEP experiments [3] show the importance of interference terms.

Here we study the longitudinal-transverse interference term (dσ_{LT}) and contributions due to exchange of γ_L^* (dσ_L) and γ_T^* (dσ_T) in the unpolarised semi-inclusive ep collisions [4]. Assuming one-photon exchange we factorise the cross-section onto the photon emission by the electron and the γ^*p collision in a way independent on the reference frame. For this purpose we use the propagator decomposition method and explicit forms of all polarisation vectors of the virtual photon (q^2 < 0).

2 Factorisation formulae for unpolarised ep collisions

The cross section for an unpolarised lN → lX process, for example DIS ep → eX, can be factorised onto the leptonic and hadronic tensors, dσ ∼ L^{μν}W_{μν}. Further on the differential cross section can be decomposed on the parts related to the subprocesses γ_T^*N → X and γ_L^*N → X, respectively:

\[ dσ^{ep→eX} = Γ_Tγ_T^{p→X} + Γ_Lγ_L^{p→X}. \]

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The above factorisation and separation formula can be obtained in various ways. One of them uses the known hadronic tensor and explicit form of the scalar polarisation vector\[4\]. Another way is the propagator decomposition method\[5\] in which the cross section is written as follows

\[
\frac{d\sigma^{ep\rightarrow eX}}{d\sigma^{ep\rightarrow eX}} \sim L_e^{\alpha \beta} \frac{g_{\alpha \mu}}{q^2} \frac{g_{\nu \beta}}{q^2} W_{\mu \nu}.
\]  

(2)

Afterwards one decomposes the propagator of the exchanged photon using the completeness relation, what leads directly to Eq. (3). This method is especially useful in analysing of the semi-inclusive processes.

In case of the semi-inclusive process one additional particle in the final state is produced. For example for the Compton process \( ep \rightarrow e\gamma X \) (Fig. 1) the differential cross section can be decomposed as follows:

\[
d\sigma^{ep\rightarrow e\gamma X} = d\sigma_T^{ep\rightarrow e\gamma X} + d\sigma_L^{ep\rightarrow e\gamma X} + d\sigma_{TT}^{ep\rightarrow e\gamma X} + d\sigma_{LT}^{ep\rightarrow e\gamma X}.
\]  

(3)

In the above formula two additional contributions, \( d\sigma_{LT} \) and \( d\sigma_{TT} \), appear. They are related to the interference between \( \gamma_L^* \) and \( \gamma_T^* \), and between two different transverse polarisation states of the \( \gamma^* \) respectively.
In studies of the interference terms in the semi-inclusive processes $ep \rightarrow e\gamma X$ the azimuthal angle $\phi$ distribution is especially useful. The angle $\phi$ is defined as the difference of the azimuthal angle of the final electron and of the final photon: $\phi = \phi_e - \phi_\gamma$.

In the Breit frame $\phi$ is the angle between the electron scattering plane and plane fixed by the momenta of the exchanged $\gamma^*$ and final photon $\gamma$. In this reference frame $d\sigma/d\phi$ is linear in $\cos \phi$, $\cos 2\phi$, $\sin \phi$ and $\sin 2\phi$. For calculations in the Born approximation the terms containing $\sin \phi$ and $\sin 2\phi$ vanish as a consequence of time-reversal invariance, so the azimuthal distribution for the Compton process reduces to the following form:

$$\frac{d\sigma_{ep \rightarrow e\gamma X}}{d\phi} = \sigma_0 + \sigma_1 \cos \phi + \sigma_2 \cos 2\phi.$$ (4)

The coefficients $\sigma_0$, $\sigma_1$ and $\sigma_2$ are related to $d\sigma_T/d\phi$, $d\sigma_L/d\phi$, $d\tau_{LT}/d\phi$ and $d\tau_{TT}/d\phi$. The third term arises from the interference between two different transverse polarisation states of the exchanged photon ($\sigma_2 \cos 2\phi = d\tau_{TT}/d\phi$). The longitudinal-transverse interference gives rise to the second term ($\sigma_1 \cos \phi = d\tau_{LT}/d\phi$). The $\sigma_0$ consists of the sum of the cross sections with the intermediate $\gamma^*_L$ and $\gamma^*_T$ ($\sigma_0 = d\sigma_L/d\phi + d\sigma_T/d\phi$). Therefore the $\phi$ distribution in the Breit frame is an excellent tool to identify and study interference terms.

### 3 Numerical results for Compton process $ep \rightarrow e\gamma X$

![Graph]

Figure 3: Contributions to $d\sigma/dQ^2$ (at the top) and to $d\sigma/(dpTdY)$ (below) as a functions of $p_T$ with $Y = 0$ (on left) or $Y$ with $p_T = 5$ GeV (on right), in $CM_{ep}$.

We calculate various contributions to the cross sections for the unpolarised Compton process $ep \rightarrow e\gamma X$ in both the $CM_{ep}$ and Breit frames for the HERA energy $\sqrt{S_{ep}} = 300$ GeV. We consider the emission of the $\gamma$ from the hadronic vertex at the Born level.
(i.e. the $\gamma^* q \rightarrow \gamma q$ subprocess only) For the proton we have used the CTEQ5L parton parametrization with $N_f = 4$ and the hard scale equals to $p_T$.

The cross section $d\sigma/dQ^2$, (Fig. 3, top) is strongly dominated by contribution due to the transversely polarised $\gamma^*$, even for large values of virtuality $Q^2$. Also the cross sections $d\sigma/(dp_T dY)$ (Fig. 3, bottom), as a function of $p_T$ or rapidity $Y$, are very well described by the $\gamma_T^*$ cross section only. Both contributions coming from the $\gamma_T^*$, $d\sigma_L$ and $d\tau_{LT}$, are below 10%, moreover due to opposite signs they almost cancel each other.

Figure 4: The ratio $[d\sigma_L/dQ^2]/[d\sigma_T/dQ^2]$ as a function of $Q^2$, in the $CM_{ep}$ frame (solid line) and in the Breit frame (dashed line).

The ratio $[d\sigma_L/dQ^2]/[d\sigma_T/dQ^2]$ (Fig. 4) shows interesting $Q^2$ dependence in two reference frames ($CM_{ep}$ and Breit frame). We see that domination of the cross sections by $\gamma_T^*$ is stronger in the $CM_{ep}$ frame in which $d\sigma_L$ and $d\tau_{LT}$ almost cancel each other.

For the azimuthal angle distribution in Breit frame the relatively large sensitivity to the interference term $d\tau_{LT}$ is found (Fig. 5), while the interference between two different transverse polarisation states of $\gamma$ is invisible.

Figure 5: The $d\sigma/d\phi$ in the Breit frame.

\footnote{The cross section for the Bethe-Heitler process, i.e. production of the $\gamma$ from the electron line, can be neglected for the photon’s rapidity range $Y(\text{CM}_{ep}) < 0$.}
4 Conclusions

Our analysis show that the cross section for the Compton process (the Born level) in $CM_{ep}$ is strongly dominated by $\gamma_7^\ast$. If the contributions due to $\gamma_L^\ast$ are included then interference terms need to be included in a consistent analysis because they both are similar in size but opposite in sign.

The studies of the azimuthal angle dependence, $d\sigma^{ep \rightarrow e\gamma X} / d\phi$, in the Breit frame give access to the longitudinal-transverse interference term.

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