Deep Virtual Compton Scattering at the Electron-Nucleon Collider HERA

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1 Physics Motivations

The relevance of Deep Virtual Compton Scattering (noted DVCS) has been recently emphasised by X. Ji [1], A. Radyushkin [2] and P.A.M. Guichon [3].

The reaction of interest is $ep \to e'p'\gamma'$ or $\gamma^* p \to p'\gamma'$ where γ^* is the virtual photon exchanged between electron and proton. The 4-momenta of the initial and final electrons, initial and final protons, initial (or virtual) and final photons are noted k, k', p, p', q, q' respectively. The reaction is defined by three kinematical invariants :

- $Q^2 = -q^2$ where q is the 4-momentum of the virtual photon which depends only on the electron kinematics,
- $s = (p+q)^2 = (p'+q')^2$ is the center of mass energy square of the system photon-proton (this system is noted in the following CM), (in the following we will prefer the x variable, $x = Q^2/(s - m_p^2 + Q^2)$)
- $t = (q-q')^2 = (p-p')^2$ is the transfer.

We have the relation $s + t + u = 2m_p^2 - Q^2$. The two other variables to describe completely the system are for example ϵ the polarisation of the virtual photon, and ϕ the angle between the leptonic plane and the hadronic plane.

The amplitude associated to the process $\gamma^* p \to \gamma' p'$ at t minimum, large Q^2 and large s is a generalization of the Deep Inelastic Scattering (noted DIS) amplitude $\gamma^* p \to \gamma^* p$ where the characteristics of the photon (essentially virtual) and proton are exactly the same in the initial and final states. In fact :

$$\sigma_{DIS} \sim \sum_X |\gamma^* p \to X|^2 \sim \mathcal{I}m(\gamma^* p \to \gamma^* p)_{t\,min}$$

The DVCS allows one to define in the light cone dynamics 4 new structure functions of the nucleon or Off Forward Parton Distributions (OFPD's) : H, E, $\tilde{H}$, $\tilde{E}$. They are function of the Bjorken variable x and the t variable. We have some relations between these new structure functions and the form factors or the structure functions of the nucleon. So the OFPD's satisfy a number of sum rules which either provides tests of the theoretical analysis or can shed a new light on the spin structure of the nucleon.

Kinematical conditions for DVCS

These new structure functions appear in the Bjorken limit : Q^2 large, s large and Q^2/s finite. It will be necessary to verify experimentally the scaling regime, which amounts to say that the structure functions are independent of Q^2. The goal of an experiment is to measure the differential cross section at small values of t in a large domain of x.

Problem of the Beithe-Heitler contribution

In the reaction $ep \to e'p'\gamma'$, the final state photon can be emitted either by the electron or by the proton. The last process is the process of interest, while the first one is described by the Bethe-Heitler (noted BH) amplitude which is completely calculable in QED. The BH amplitude goes like $1/t$ while the VCS goes like $1/Q^2$. Therefore the interesting region, large Q^2, small t favours the BH process. To overcome this problem the only way is to increase the virtual photon flux of the VCS process by increasing the energy of the initial system (electron-proton). The game is easy with a collider, while for a fixed target, we have to increase considerably the energy of the incident electron.

P.A.M. Guichon has made a preliminary evaluation of the cross sections. They are presented in Figure 1. The conditions are those of a Electron-Proton Collider with : $E_e = 27.5$ GeV and $E_p = 220$ GeV. The kinematical conditions are $Q^2 = 5$ or 10 GeV^2, $x = 0.1, 0.2, 0.3$. In these conditions, the Beite-Heitler contamination is never a problem. When Q^2 decreases, the photon flux for VCS is also increased, and then the VCS contribution is larger.

I can also recall that for the usual HERA conditions, $E_e = 27.5$ GeV and $E_p = 820$ GeV, the VCS cross sections are also larger.

2 Experimental Realisation

The experimental realisation of DVCS with fixed target is under study: at CEBAF (hall A Collaboration) with an electron energy of 6 GeV, and also very recently at CERN (COMPASS Collaboration) with the muon beam of 200 GeV.

2.1 Kinematics with a Collider

With a fixed target at small t, the momentum of the outgoing proton is small (only a few 100MeV/c), which may prevent the proton to escape the target. So while we can detect easily the electron and photon, the detection of the proton will be tricky.

The kinematics for two types of collider are given in the Table 1. They are indicated for the interesting case t minimum or $\theta\gamma\gamma'_{(\text{in CM})} = 0$.

So, all the three outgoing particles have large momentum, but the outgoing photon is focused in the incident proton direction. For the first case this angle is smaller than 4. deg if x is larger than 0.05. So the second case is really more favourable.

The outgoing proton is always focused in the direction of the incident proton, and we can use the dipoles of the proton beam transport to deflect the outgoing proton, and detect it in order to tag the DVCS event.

2.2 Principal source of background : π^0 production

The main source of background is the electroproduction of π^0 : $ep \to e'p'\pi^0$. The kinematics of the reaction is extremely close to the one of $ep \to e'p'\gamma'$. Even if the resolution of the tagging system is very good (of the order of a good spectrometer 10^{-4}), it will not be sufficient to separate the events at small values of x !

We can have an idea of the ratio between the π^0 and γ production with the experiments done with real photons. We can consider the results of M.Deutsch at al. [4] for photon production at Cornell and Cambridge, and the results of R.L.Anderson et al. [5] for π^0 production at SLAC. We get: $\sigma_{\pi^0}/\sigma_\gamma \simeq 4$ at Q^2=0, $E_\gamma \simeq 5$ GeV, $t = -0.2$ GeV^2.

The only way to get rid of this background is to measure it very carefully by a high resolution photon detector, in order to detect the two photons of π^0 decay and to subtract this background.

According to the paper of Collins [6] which develops the factorization for hard exclusive

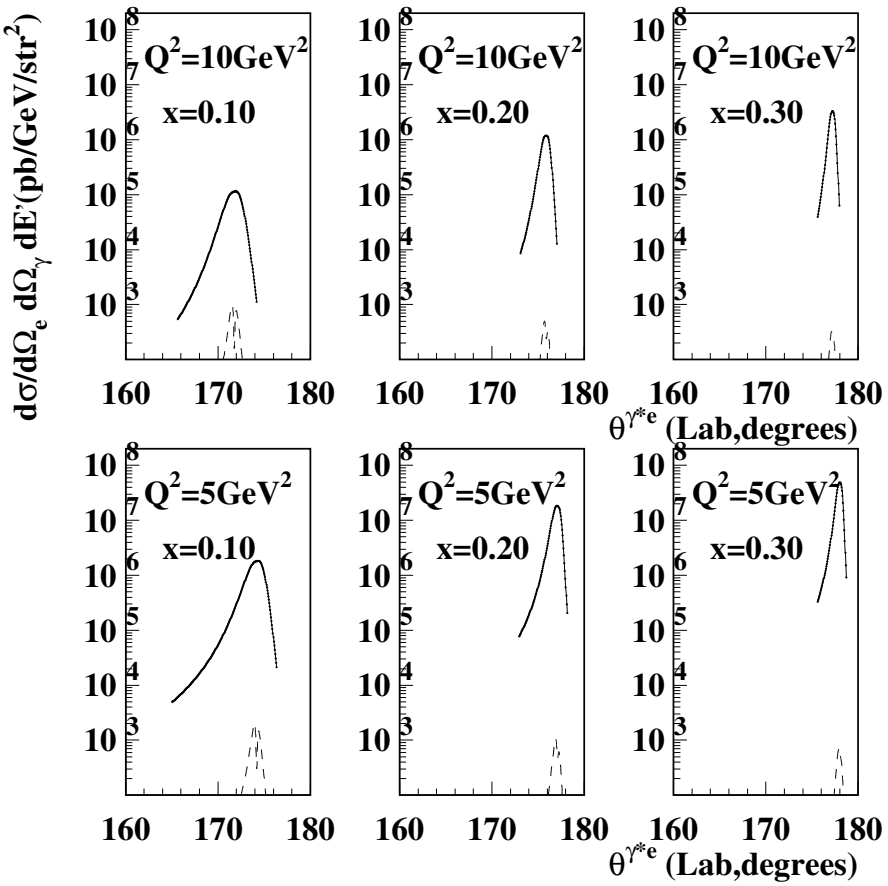

Figure 1: Cross sections calculated by P.A.M. Guichon for a collider with 27.5 GeV positrons and 220 GeV protons. In all the pictures, the BH contribution is indicated by the dashed line, the VCS contribution by the dotted line and the total contribution by the solid line. It is clear that in all these contributions the VCS and total contributions are almost the same, the BH contribution is always negligible.

$E_e = 27.5$ GeV and $E_p = 820.$ GeV $\rightarrow E'_e \simeq 27.5$ GeV and $\theta_e \simeq 6.6$ deg

Q^2	x	$p_{\gamma'}$	$\theta_{\gamma' p}$	$p_{p'p}$	$\theta_{p'p}$
10	0.05	41	4.4	779	1.10^{-4}
10	0.1	82	2.2	738	4.10^{-4}
10	0.2	162	1.1	657	2.10^{-3}
10	0.3	239	0.7	580	6.10^{-3}

$E_e = 27.5$ GeV and $E_p = 220.$ GeV $\rightarrow E'_e \simeq 27.5$ GeV and $\theta_e \simeq 6.6$ deg

Q^2	x	$p_{\gamma'}$	$\theta_{\gamma' p}$	$p_{p'p}$	$\theta_{p'p}$
10	0.05	11	16.4	209	$\sim$0
10	0.1	22	8.2	198	$\sim$0
10	0.2	43	4.1	176	$\sim$0
10	0.3	64	2.8	156	$\sim$0

Table 1: Kinematics for different collider options. The values of Q^2 and s are in GeV^2, of $p_{p'}$ and $p_{\gamma'}$ in GeV, of $\theta_{\gamma' p}$ and $\theta_{p'p}$ in degrees respectively to the incident proton direction.

electroproduction of mesons in QCD, it is also important to measure the production of π^0.

2.3 Expected Counting Rates

The differential cross sections $d^5\sigma/dk'd\Omega_{k'}d\Omega_{\gamma'\ lab}$ presented in Fig. 1 are always larger than 10^5 pb/GeV/sr^2 in the small t domain.

We would like to measure the differential cross section in bins in the CM of $\Delta\theta_{\gamma\gamma'(inCM)}$ =5 degrees, $\Delta\phi = 2\pi$, so in the laboratory $\Delta\theta_{\gamma\gamma'} = 1$ to 2 degrees, and $d\Omega_{\gamma'(inlab)}$ is larger than 4 msr.

The electron is detected with an energy resolution of 10% and a solid angle covering an angle of 1. degree around the outgoing electron direction (6.6 deg.) and $d\Omega_{e'\ (inlab)}$ is about 12 msr.

The number of events is :

$$\Delta N = \mathcal{L} \times \frac{d^5\sigma}{dk'd\Omega_{k'}d\Omega_{\gamma'}} \times \Delta k' \Delta\Omega_{k'} \Delta\Omega_{\gamma'}$$

$$\Delta N(h^{-1}) = \mathcal{L} \times 10^6.10^{-36} \times 3 \times .012 \times .004 \times 3600$$

For :

$$\Delta N(h^{-1}) \geq 10 \text{ events/h}$$

it is necessary to have

$$\mathcal{L} \geq 2.10^{31}\text{cm}^{-2}\text{s}^{-1}$$

This matches well the present and future luminosity of the HERA collider. All the kinematical points will be measured in a single experiment. Nevertheless to get comfortable statistics and to subtract the π^0 contribution, several months of data acquisition will be necessary.

3 Conclusions

A collider at HERA is a very suitable way to study Deep Virtual Compton Scattering far from the Bethe-Heitler dominance. The outgoing proton is always in the initial proton direction, and we can hope to detect it in the dipole of the HERA ring, in order to tag VCS events. Nevertheless the detection of the outgoing photon is easier outside the initial proton direction, and for that, it is better to have a collider with a not too high energy.

In the same time the experiment has to measure precisely the two reactions :

$$\begin{aligned} \gamma^* p &\rightarrow p\gamma \\ \gamma^* p &\rightarrow p\pi^0 \end{aligned}$$

with a photon detector of very high angular resolution.

References

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