Two reactions, the photoproduction of a direct photon plus a jet and the photoproduction of a charged hadron plus a jet, are studied in view of their potential to constrain the gluon distribution in the proton. The results are based on a program of partonic event generator type which includes the full set of NLO corrections.

1 Introduction

The theoretical predictions for prominent processes like $gg \to H$ or the $t\bar{t}$ cross section still suffer from a rather large uncertainty stemming from the parton distributions functions (PDFs) in the proton, in particular from the gluon distribution. In view of the LHC with its large gluon luminosity, it is therefore important to analyse how present experiments can be used to constrain the gluon further. HERA has always played a major role in the task of PDF determinations, most importantly through DIS experiments. However, the large-$x$ range ($x > 0.2$) is still rather poorly constrained, being mainly probed only by fixed target experiments and recently by the high-$E_T$ Tevatron jet data.

In photoproduction reactions at HERA, a quasi-real photon, emitted at small angle from the electron, interacts with a parton from the proton. The photon can either participate directly in the hard interaction or be resolved into a partonic system, in which case a parton stemming from the photon takes part in the hard interaction. Therefore the interest in photoproduction experiments has rather been focused on measuring the parton distributions in the photon than in the proton. However, as will be argued in the following, photoproduction reactions can also serve to probe the gluon in the proton, complementary to other measurements. Here I will consider in particular the following two reactions: $\gamma p \to \gamma + \text{jet}$ and $\gamma p \to h^\pm + \text{jet}$, where $h^\pm$ is a charged hadron. As compared to dijet photoproduction, these reactions have the experimental advantage that photons as well as charged hadrons are straightforward to measure. However, large-$p_T$ photons can also stem from the fragmentation of a hard parton or from light meson decay, such that isolation cuts have to be imposed. While isolation may introduce a source of systematic errors, it also reduces the uncertainty stemming from the photon fragmentation functions. In the case of charged hadron production, the dependence on...
the hadron fragmentation functions is unavoidable; on the other hand, the $h^\pm + \text{jet}$ cross section has the advantage of being substantially larger than the $\gamma + \text{jet}$ cross section.

The photoproduction of prompt photons has been measured by ZEUS\textsuperscript{12} and compared to theoretical predictions some time ago\textsuperscript{13,14,15}. The case where a jet in addition to the prompt photon is also measured allows for a more detailed reconstruction of the underlying parton dynamics and has recently been analysed in the context of a determination of the effective transverse momentum $\langle k_T \rangle$ of the partons in the proton\textsuperscript{16,17}. The photoproduction of large-$p_T$ charged hadrons has been measured at HERA\textsuperscript{8} and compared to theoretical predictions\textsuperscript{9,10} only for the inclusive case so far.

2 Optimisation of the sensitivity to the gluon in the proton

As observables which serve to reconstruct the longitudinal momentum fraction of the parton stemming from the proton respectively photon, it is common to use

$$x_{\text{obs}}^p = \frac{p_T e^\eta + E_T\eta_{\text{jet}}}{2E_p}, \quad x_{\text{obs}}^\gamma = \frac{p_T e^{-\eta} + E_T e^{-\eta_{\text{jet}}}}{2E_{\gamma}},$$

(1)

where $p_T$ and $\eta$ are transverse momentum and pseudo-rapidity\textsuperscript{b} of the final state photon respectively hadron. However, as the determination of $E_{\text{jet}}$ introduces a source of systematic errors, we propose a slightly different variable which does not depend on $E_{\text{jet}}$,

$$x_{\text{LL}}^p = \frac{p_T (e^\eta + e^{\eta_{\text{jet}}})}{2E_p}, \quad x_{\text{LL}}^\gamma = \frac{p_T (e^{-\eta} + e^{-\eta_{\text{jet}}})}{2E_{\gamma}}.$$

(2)

In the case of direct photons in the initial state, the $x_{\text{obs,LL}}^\gamma$ distributions are peaked at values close to one, whereas resolved photons correspond to lower values of $x_{\text{obs,LL}}^\gamma$.

In order to constrain the gluon distribution function $g(x^p)$ in the proton, we need to find a kinematic region where the sensitivity of the cross section to $g(x^p)$ is large. Clearly, $g(x^p)$ is large at small $x^p$, which means, according to\textsuperscript{11} and\textsuperscript{12}, at small $\eta, \eta_{\text{jet}}$. On the other hand, small values of $\eta, \eta_{\text{jet}}$ imply that $x^\gamma$ is large and therefore processes initiated by direct photons dominate over resolved ones. Therefore, if appropriate rapidity cuts select the backward region, we expect that the contribution from the gluon in the proton is large, while the uncertainty stemming from the parton distributions in the photon is minimised, as the resolved photon component is small.

Let us now verify these considerations by numerical results obtained with the NLO partonic event generator EPHOX\textsuperscript{7,10,11}. We used $\sqrt{s} = 300$ GeV, the MRST01 set\textsuperscript{12} proton PDFs, the AFG photon PDFs\textsuperscript{13} and the fragmentation functions BFGW\textsuperscript{14} for the hadrons, BFG\textsuperscript{15} for the photons. Further, the cuts $E_{\text{jet}} > 5$ GeV, $p_T^\gamma > 6$ GeV and $p_T^h > 7$ GeV have been applied in order to be well within the perturbative region.

For the case of hadron+jet production, we can see from Fig. 1 that indeed the gluon (from the proton) initiated processes dominate for $-2 < \eta^{h,\text{jet}} < 0.5$. Unfortunately, the scale dependence of the $h^\pm + \text{jet}$ cross section is also large. Varying the renormalisation scale $\mu$ and the initial/final state factorisation scales $M/M_F$ diagonally between $p_T/2$ and $2p_T$ leads to a variation of the cross section of about $\pm 20\%$. On the other hand, a scale optimisation can be performed\textsuperscript{10} where a region of minimal sensitivity can be localised close to $\mu = M = M_F = p_T/2$.

\textsuperscript{b}We use the HERA convention that the proton is moving towards positive rapidities.
In the case of $\gamma +\text{jet}$ production, the situation is very different. As the photon is isolated, the fragmentation contribution to the cross section is suppressed, and the leftover candidates for dominant subprocesses at small $x^p$ are (a) $g^p + q\gamma \rightarrow \gamma + \text{jet}$ (resolved $\gamma$), (b) $g^p + \gamma \rightarrow \gamma + \text{jet}$. However, the process (b) only exists at next-to-leading order! This means that the $g^p + \gamma$ initiated subprocess cannot be dominant at small $x^p$ as in the case of $h^\pm$ production. Although this looks like an inconvenience, we can turn it into a virtue: If we can find a kinematic region where the process (a) dominates, the sensitivity to the gluon in the proton is not confined to the small $x^p$ range. The price to pay is of course a dependence on the photon PDFs, but as the quark distributions in the photon are rather well known, the task is to isolate a region where the subprocess $g^p + q\gamma \rightarrow \gamma + \text{jet}$ dominates.

In Fig. 2 it is shown that this can in fact be achieved by rapidity cuts only. Fig. 2(a) shows that the process $g^p + q\gamma \rightarrow \gamma + \text{jet}$ contributes about 30% to the cross section $d\sigma/dx^p_{LL}$ if the whole rapidity range $-2 < \eta^\gamma, \eta^{\text{jet}} < 2$ is considered. Selecting the forward region $0 < \eta^\gamma, \eta^{\text{jet}} < 2$ increases the contribution of the $g^p + q\gamma$ initiated processes to about 50% of the total, while the contribution from the gluon in the photon is still very small, as can be seen from Fig. 2(b). If we increase $\eta_{\text{min}}$ even further, the total cross section becomes rather small and the gluon from the photon starts to become important, as shown in Fig. 2(c). Therefore, the region $0 < \eta^\gamma, \eta^{\text{jet}} < 2$ is optimal in what concerns the sensitivity to $g^p$ while minimising the uncertainty from the photon PDFs.

An important feature of the $\gamma + \text{jet}$ cross section is that the scale dependence is very weak. From Figs. 3(a),(b) one can see that in the bins around 0.02, where the difference between the MRST01 and CTEQ6 parametrisations is significant, the uncertainty due to scale variations is

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It has to be stressed that selecting only particular subprocesses in an NLO calculation is unphysical, such that the precise magnitude of the subprocess contribution is quite sensitive to scale changes. However, it has been verified that the pattern shown in Fig. 2 remains valid for other scale choices, as it reflects the physical behaviour of the cross section due to the underlying parton dynamics.
smaller than the difference between these two parametrisations.

Nevertheless, the region $0 < \eta^\gamma, \eta^{jet} < 2$ does not select the high-$x$ range. In order to access $x$ values beyond $x_p > 0.1$, more stringent cuts have to be placed, selecting the very forward region, which has not been accessible by HERA 1, but will be accessible by future HERA experiments.

As an example, it is shown in Fig. 4 (a) that $x_{LL}^p > 0.1$ can be achieved by the cuts $\eta^\gamma, \eta^{jet} > 2$, $p_T^\gamma > 10 \text{ GeV}$. However, the contribution from the gluon in the proton is rather small in this region. On the other hand, the contribution from the gluon in the photon is substantial, such that this region is favourable to pin down the gluon distribution in the photon, as can be seen from Fig. 4 (b).

3 Conclusions and outlook

The $h^\pm + \text{jet}$ cross section shows a large sensitivity to the gluon distribution $g(x_p)$ in the proton around $x_p \sim 0.01$, but it suffers from a scale dependence of the order of 20%. In contrast, the scale dependence of the $\gamma + \text{jet}$ cross section is quite weak ($\lesssim 7\%$). In the $\gamma + \text{jet}$ case, maximising the sensitivity to $g(x_p)$ while at the same time minimising the uncertainty from the photon PDFs suggests the rapidity cuts $0 < \eta^\gamma, \eta^{jet} < 2$, probing the $x_p$-range $0.01 \lesssim x_p \lesssim 0.05$. Future HERA experiments with an improved forward tracking system and high statistics could allow to cut even more towards forward rapidities and thus access $x_p$ values of about $0.1 \lesssim x_p \lesssim 0.3$.

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