Towards the Parton Densities of Polarized Photons at HERA

M. Stratmann
Department of Physics, University of Durham,
Durham DH1 3LE, England

and

W. Vogelsang
C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook,
NY-11794, USA

Abstract

Di-jet photoproduction in polarized \( ep \) collisions at HERA is studied as a possible tool to determine the parton content of circularly polarized photons. The concept of the ‘effective parton density’ approximation is extended to the spin-dependent case.

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Towards the Parton Densities of Polarized Photons at HERA

M. Stratmann\textsuperscript{a} and W. Vogelsang\textsuperscript{b}

\textsuperscript{a} Department of Physics, University of Durham, Durham DH1 3LE, England
\textsuperscript{b} C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, NY-11794, USA

Abstract: Di-jet photoproduction in polarized \textit{ep} collisions at HERA is studied as a possible tool to determine the parton content of circularly polarized photons. The concept of the ‘effective parton density’ approximation is extended to the spin-dependent case.

1 Introduction and General Framework

Previous studies \cite{1, 2} have exposed the photoproduction of (di-)jets in longitudinally polarized \textit{ep} collisions at HERA as a very promising and feasible tool to measure the parton densities of circularly polarized photons in ‘resolved’-photon processes. It should be stressed that these photonic parton distributions, defined as

\[ \Delta f^\gamma(x, Q^2) \equiv f_{+}^\gamma(x, Q^2) - f_{-}^\gamma(x, Q^2), \] (1)

where \( f_{+}^\gamma \) (\( f_{-}^\gamma \)) denotes the density of a parton \( f \) with helicity ‘+’ (‘−’) in a photon with helicity ‘+’, are completely unmeasured so far. The \( \Delta f^\gamma \) contain information different from that included in the unpolarized \( f^\gamma \) [defined by taking the sum in (1)], and their measurement is indispensable for a thorough understanding of the partonic structure of the photon. As in \cite{1, 2} we will exploit the predictions of two very different models for the \( \Delta f^\gamma \) \cite{3}, and study the sensitivity of di-jet production to these unknown quantities. In the first case (‘maximal scenario’) we saturate the positivity bound \( |\Delta f^\gamma(x, Q^2)| \leq f^\gamma(x, Q^2) \) at a low input scale \( \mu \simeq 0.6 \text{ GeV} \), using the unpolarized GRV densities \( f^\gamma \) \cite{4}. The other extreme input (‘minimal scenario’) is defined by a vanishing hadronic input at the same scale \( \mu \). We limit ourselves to leading order (LO) QCD, which is entirely sufficient for our purposes; however both scenarios can be straightforwardly extended to the next-to-leading order (NLO) of QCD \cite{5}.

The generic expression for polarized photoproduction of two jets with laboratory system rapidities \( \eta_1, \eta_2 \) reads in LO

\[ \frac{d^3\Delta\sigma}{dp_T d\eta_1 d\eta_2} = 2p_T \sum_{f, f'} x_e \Delta f^e(x_e, \mu_T^2) x_p \Delta f^p(x_p, \mu_T^2) \frac{d\Delta\hat{\sigma}}{dt}, \] (2)

where \( p_T \) is the transverse momentum of one of the two jets (which balance each other in LO), \( x_e \equiv p_T/(2E_e)(e^{-m} + e^{-m}) \), and \( x_p \equiv p_T/(2E_p)(e^m + e^m) \). The \( \Delta f^p \) in (2) denote the spin-dependent parton densities of the proton, and

\[ \Delta f^e(x_e, \mu_T^2) = \int_{x_e}^{1} \frac{dy}{y} \Delta P_{e/\gamma}^e(y) \Delta f^\gamma(x_{\gamma} = \frac{x_e}{y}, \mu_T^2), \] (3)

\[ 1 \]The direct (‘unresolved’) photon contribution to (2) is obtained by setting \( \Delta f^\gamma(x_{\gamma}, \mu_T^2) \equiv \delta(1 - x_{\gamma}) \) in (3).
where $\Delta P_{\gamma/e}$ is the polarized ‘equivalent-photon’ spectrum for which we will use

$$\Delta P_{\gamma/e}(y) = \frac{\alpha_{em}}{2\pi} \left[ \frac{1 - (1 - y)^2}{y} \right] \ln \frac{Q_{\text{max}}^2(1 - y)}{m_e^2 y^2}, \quad (4)$$

with the electron mass $m_e$ and $Q_{\text{max}}^2 = 4 \text{ GeV}^2$. Needless to say that the unpolarized LO jet cross section $d^3\sigma$ is obtained by using the corresponding unpolarized quantities in (2)-(4). The appropriate LO $2 \to 2$ partonic cross sections $d\hat{\sigma}$ in (2) for the direct ($\gamma b \to cd$) and resolved ($ab \to cd$) cases can be found, for instance, in [7].

The key feature of $d\gamma$-jet production is that a measurement of both jet rapidities allows for fully reconstructing the kinematics of the underlying hard subprocess and thus for determining the variable $x_{\gamma}^{\text{OBS}} = \sum_{\text{jets}} p_{T} e^{-\eta_{\text{jet}}} / (2yE_e)$, which to LO equals $x_{\gamma} = x_e / y$, with $y$ being the fraction of the electron’s energy taken by the photon. In this way it becomes possible to experimentally suppress the direct contribution by introducing some suitable cut $x_{\gamma}^{\text{OBS}} \leq 0.75$.\footnote{Very recently the non-logarithmic corrections to (4) have been calculated in [6]. They typically lead to an $O(10\%)$ correction which, however, cancels to a large extent in the experimentally relevant spin asymmetry $\Delta\sigma/\sigma$, and thus can be safely neglected here.}

In the unpolarized case a useful approximation procedure was developed in [11]. It was observed that the ratios of the dominant, properly symmetrized, LO subprocesses are roughly independent of the c.m.s partonic scattering angle $\Theta$ and, most importantly, that for $\cos \Theta = \pm 1$ all ratios tend to the same value determined by the color factors $C_A$ and $C_F$:

$$\left. \frac{\hat{\sigma}_{qq}}{\hat{\sigma}_{gg}} \right|_{\cos \Theta = \pm 1} = \left. \frac{\hat{\sigma}_{qq}}{\hat{\sigma}_{gg}} \right|_{\cos \Theta = \pm 1} = \left. \frac{\hat{\sigma}_{qq}}{\hat{\sigma}_{gg}} \right|_{\cos \Theta = \pm 1} = \frac{C_F}{C_A} = \frac{4}{9}. \quad (5)$$

Making use of (5) for all values of $\Theta$ and introducing the ‘effective’ parton density combinations

$$f_{\text{eff}}^{(p,\gamma)} \equiv \sum_q [q^{(p,\gamma)} + \bar{q}^{(p,\gamma)}] + \frac{9}{4} q^{(p,\gamma)}, \quad (6)$$

the jet cross section factorizes into these densities times a single subprocess cross section (cf. Eq. (9) below). The ratios of the parton cross sections are depicted in Fig. 1, and, although

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they considerably deviate from $4/9$ for $\cos \Theta \neq \pm 1$, the approximation works amazingly well at a level of about $\mathcal{O}(10\%)$ accuracy.

Unfortunately this approximation has no straightforward extension to the spin-dependent case as is obvious from Fig. 1. The ratios of the LO polarized subprocess cross sections obey

$$
\frac{\Delta \hat{\sigma}_{qq'}}{\Delta \hat{\sigma}_{qq}} \bigg|_{\cos \Theta = \pm 1} = \frac{4}{11}, \quad \frac{\Delta \hat{\sigma}_{qq'}}{\Delta \hat{\sigma}_{qg}} \bigg|_{\cos \Theta = \pm 1} = \frac{8}{33}, \quad \frac{\Delta \hat{\sigma}_{qg}}{\Delta \hat{\sigma}_{gg}} \bigg|_{\cos \Theta = \pm 1} = \frac{22}{81} \quad (7)
$$

rather than approaching a common value for $\cos \Theta = \pm 1$, and, consequently, the factorization as outlined above is bound to fail. However, one also notices that all spin-dependent ratios in Fig. 1 are more flattish w.r.t $\cos \Theta$ than in the unpolarized case, and $qq'/qg = 4/11$ is exact for all values of $\cos \Theta$. It turns out that by approximating all ratios by $4/11$ and introducing

$$
\Delta f^{(p,\gamma)}_{\text{eff}} \equiv \sum_q [\Delta q^{(p,\gamma)} + \Delta \bar{q}^{(p,\gamma)}] + \frac{11}{4} \Delta g^{(p,\gamma)}, \quad (8)
$$

the effective parton density approximation works remarkably well also in this case, and (2) factorizes, e.g., for the resolved contribution, schematically into

$$
d \Delta \sigma^{2-\text{jet}} \simeq \int \Delta f^{\gamma}_{\text{eff}} \Delta f^{p}_{\text{eff}} d \Delta \hat{\sigma}_{qq' \rightarrow qq'}. \quad (9)
$$

For all relevant purposes the approximated and the exact polarized LO di-jet cross sections agree within $\leq 5\%$, even better than what is achieved in the unpolarized case. Figure 2 shows the polarized effective photon density according to (8) for the two extreme scenarios specified above at a scale relevant for the production of jets with $p_T$ values of about $5 - 10 \text{ GeV}$.

### 3 Results and Conclusions

Figure 3 shows the experimentally relevant di-jet spin asymmetry $A^{2-\text{jet}} \equiv d \Delta \sigma / d \sigma$, for three different bins in $x_\gamma$, using similar cuts as in [12]: the difference of the jet pseudorapidities is required to be $|\Delta \eta^{\text{jets}}| < 1$, for the average rapidity we demand $0 < (\eta_1 + \eta_2)/2 < 1$,
and \( 0.2 < y < 0.83 \). The factorization scale \( \mu_F \) in (2) was chosen to be equal to \( p_T \), but the asymmetry is largely independent of that choice. Very recently, the complete NLO QCD corrections to polarized jet-(photo)production have become available \([14, 6]\). They lead to an improved scale dependence of the cross sections. Moderate NLO corrections for the asymmetry were found for the single-inclusive case \([6]\); similar results should be expected also for di-jet production.

As can be inferred from Fig. 3, the effective parton density approximation works very well. It is only for \( 0.4 \leq x_\gamma \leq 0.75 \) and large \( p_T \) that the deviations from the exact results become more pronounced. Also shown in Fig. 3 is the expected statistical accuracy for such measurements, assuming three bins in \( p_T \) for each \( x_\gamma \) bin, an integrated luminosity of \( 200 \text{ pb}^{-1} \), and 70% beam polarizations. Given these error bars the prospects for distinguishing between different scenarios for \( \Delta f_{\gamma}^{\text{eff}} \) are rather promising provided the proton densities \( \Delta f_{p}^{\text{eff}} \), also entering (9), are known fairly well, which is clearly not the case yet. However, our ignorance of the \( \Delta f_{p}^{\gamma} \) will be vastly reduced by the upcoming polarized \( pp \) collider RHIC and ongoing efforts in the fixed target sector by HERMES and (soon) by COMPASS. It should be kept in mind that so far nothing at all is known about the \( \Delta f_{\gamma}^{\gamma} \), and even to establish the very existence of a resolved component also in the spin-dependent case would be an important step forward.

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Figure 3: Predictions for $A^{2\text{-jet}}$ for three different bins in $x_\gamma$, using the two scenarios for $\Delta f^\gamma$ as described in the text and the LO GRSV ‘standard’ distributions [13] for $\Delta f^p$. Also shown are the results using the effective parton density approximation (dotted lines) as outlined in Sec. 2 and the expected statistical errors for such a measurement (see text).

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