Jet Photoproduction at THERA

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Abstract

We demonstrate that a future high-energy electron-proton collider like THERA could largely extend the current HERA program in jet photoproduction of testing QCD and determining the partonic structure of the proton and the photon. Depending on the electron beam energy (250–500 GeV) and the collider mode (ep or γp), the range in the hard transverse energy scale of the jets could be increased by a factor of 2–3 and the reach in the momentum fraction $x$ of the partons in the proton or photon by at least one order of magnitude. It would thus become possible to check the determinations of the gluon density in the proton obtained in deep-inelastic scattering experiments, to measure the gluon density in the photon down to low values of $x$, and to study the QCD dynamics in multi-jet events.

1 Motivation

In electron-proton collisions at the DESY HERA collider, the exchange of almost real photons is responsible for the largest fraction of the scattering events. In a subclass of these photoproduction events, hard jets are produced with large transverse energies. The presence of a hard scale then allows for a comparison of the data with predictions based on perturbative QCD.

Measurements of inclusive jets, dijets, and three jets have been performed by the H1 and ZEUS collaborations at HERA over the last nine years and were found to be in qualitatively good agreement with these predictions. They can also be used to extract the free parameters of the theory like the strong coupling constant or the parton densities in the colliding proton and photon. In the proton case, this information is complementary to determinations in deep-inelastic electron- or neutrino scattering or lepton pair production in hadronic collisions. The HERA deep-inelastic scattering data have been particularly useful to pin down the previously unknown gluon density at low values of the partonic
momentum fraction $x$. However, it is important to test this determination in a second independent process like photoproduction. Information on the photonic parton densities is still very limited: Only the quark distributions have been constrained in deep-inelastic electron-photon scattering, and only at large $x$. Little is known about the gluon density in the photon.

The determination of the parton densities in the proton and photon is thus an important research goal in the jet photoproduction experiments at HERA and also in photon-photon scattering at LEP2. Unfortunately, the experiments have so far been limited to transverse jet energies which may be too low to suppress the soft underlying event coming from the proton or photon remnants or the non-perturbative effects affiliated with hadronization. Furthermore, they are kinematically limited to relatively large values of $x$.

It is the aim of this paper to demonstrate that both of these restrictions can be overcome if the electron energy is raised and/or the exchanged photons are produced by laser backscattering. This may be possible at a facility where a high-energy electron beam from a future linear electron accelerator like TESLA is collided with a high-energetic proton beam like the one available at HERA. At such a ‘THERA’ collider it will thus be possible to reach smaller values of $x$ and larger hard scales at the same time.

## 2 Dijet Cross Section

For the proton beam we choose an energy of $E_p = 920$ GeV, at which HERA is currently operating. For the electron beam, we start with the current HERA energy of $E_e = 27.5$ GeV. If only one arm of the future electron accelerator is used, 250 and 400 GeV can be reached in the first and second stages of TESLA, respectively. If both arms are used, the electron energy can be raised to as much as 500 GeV already in the first stage. Photoproduction events are selected by requiring that the electron scattering angle is less than $1^\circ$ and that the photon momentum fraction lies within the range $0.2 < y < 0.85$. For the different electron beam energies, this maximum scattering angle corresponds to maximum photon virtualities of 0.18, 15, 39, and 61 GeV$^2$ at low $y$. The alternative approach of choosing a constant maximum virtuality of 1 GeV$^2$ leads to unrealistically small values of $\sim 0.1^\circ$ at TESLA energies. Finally, we investigate the potential of a THERA $\gamma p$ collider where highly energetic real photons are produced by backscattering laser light off a 250 GeV electron beam.

In leading order of perturbative QCD, two partons with equal transverse energies are produced, corresponding to two hard jets. The dijet cross section is then given by

$$\frac{d^3 \sigma}{dE_T^2 d\eta_1 d\eta_2} = \sum_{a,b} x_\gamma y f_{a/e}(\gamma, y, \mu_F^2) x_p f_{b/p}(x_p, \mu_F^2) \frac{d\sigma}{dt}(ab \rightarrow p_1 p_2).$$  \hspace{1cm} (1)
In next-to-leading order there may also be a third, softer jet. We can then use the average transverse energy $E_T$ and the average rapidity $\eta$ of the dijet system as observables and allow the two jets to differ in transverse energy by as much as $\Delta E_T < E_T/2$. This choice, which allows for a full cancellation of infrared singularities and avoids the sensitive region of two equal minimal $E_T$ [1], has also been made in a recent H1 analysis [2]. The rapidity difference of the two jets $\Delta \eta$ is related to the center-of-mass scattering angle $\cos(\theta^{*}) = \tanh(\Delta \eta)/2$. While inclusive jet measurements yield higher statistics, only dijet analyses allow for a reconstruction of

$$x_p^{\text{obs}} = \frac{E_{T,1}e^{+\eta_1} + E_{T,2}e^{+\eta_2}}{2E_p}, \quad x_\gamma^{\text{obs}} = \frac{E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}}{2yE_e}$$

which, in leading order, match exactly the momentum fractions of the partons in the proton $x_p$ and photon $x_\gamma$, but neglect the contribution of a possible third jet. Jet photoproduction has been calculated in next-to-leading order QCD using three different phase space slicing methods [3, 4, 5, 6, 7] and the subtraction method [8]. The results were found to agree with each other within a few percent [7, 9]. In our next-to-leading order calculation [4, 8], jets are defined according to the $k_T$ cluster algorithm with the parameter $R = 1$ [10, 11]. For the parton densities in the photon and proton, we choose the next-to-leading order set of GRV [12] and the latest CTEQ parameterization 5M [13] with the corresponding value of $\Lambda_{\overline{MS}}^{10,5} = 226$ GeV. The strong coupling constant $\alpha_s$ is evaluated at two loops and at the scale $\mu = \mu_f = \max(E_{T,1}, E_{T,2})$. The sensitivity of a THERA collider to different photon parton densities has been analyzed in detail elsewhere [14].

With higher electron beam energies, the HERA center-of-mass energy $\sqrt{S}$ of 318 GeV can be increased to 959, 1213, or even 1357 GeV, approaching the 2 TeV regime of the Fermilab Tevatron in Run 2. At the Tevatron, jets with transverse energies in excess of 50 GeV are selected. Since THERA would operate at roughly half the Tevatron center-of-mass energy, we cut on $E_T > 25$ GeV.

3 Results

Like hadronic jet cross sections, photoproduction jet cross sections drop steeply in transverse energy. It is therefore interesting to study the size of the dijet photoproduction cross section as a function of $E_T$ as shown in Figure [1]. At $E_T = 40$ GeV, THERA with electron beam energies of 250 to 500 GeV produces cross sections which are larger than the HERA cross section by about a factor of 20-40. At a THERA photon collider, the cross section is even larger by a factor of 500. The larger cross sections result, of course, in a much extended range in $E_T$. With an expected luminosity of 100 pb$^{-1}$/year, the range can be extended from 75 GeV at HERA to 150 GeV at THERA $ep$ or 225 GeV at THERA $\gamma p$, i.e. by a factor of 2-3.
Figure 1: Differential dijet photoproduction cross section as a function of the average transverse energy of the two jets $E_T$. The thin lines show the separate contributions from the resolved (direct) processes for HERA and THERA with $E_e=250$ GeV, which dominate at small (large) $E_T$.

Of course, these jets need not only be produced but also be measured in a detector. An important question in this context is the required coverage in rapidity. In Figure 2 we therefore show the average rapidity distribution of the produced dijet system with $E_T > 25$ GeV. Jets at HERA are produced mostly in the proton (forward) direction $0 < \eta < 3$, which has lead to the characteristic asymmetric designs of the H1 and ZEUS detectors. In contrast, jets at THERA will be produced centrally in the range $-3 < \eta < 3$, requiring a more symmetric detector design, closer to the design used at hadron colliders. Therefore, if the H1 and ZEUS detectors are to be used, some modifications will be necessary. However, an upgrade of the electron beam energy from 250 to 500 GeV will probably not necessitate additional changes, since the rapidity range is then only slightly extended.

The rapidity difference of the two jets or, equivalently, the cosine of the center-of-mass scattering angle $\cos(\theta^*)$ is related to the $2 \rightarrow 2$ Mandelstam variables of the underlying
Figure 2: Differential dijet photoproduction cross section as a function of the average rapidity of the two jets $\bar{\eta}$. For THERA ep we show results with three different electron beam energies $E_e =$250, 400, and 500 GeV.

partonic subprocesses by

$$t = -\frac{1}{2}s(1 - \cos \theta^*) , \quad u = -\frac{1}{2}s(1 + \cos \theta^*) , \quad (3)$$

where $s = (p_a + p_b)^2 = x_\gamma y x_p S$ is the partonic center-of-mass energy squared. Most of the resolved (parton-parton) scattering processes are characterized by the exchange of a massless vector boson in the $t$-channel

$$|M|^2 \propto t^{-2} = \left[-\frac{1}{2}s(1 - \cos \theta^*)\right]^{-2} , \quad (4)$$

whereas the direct processes proceed through a massless fermion exchange in the $t$-channel with less singular behavior,

$$|M|^2 \propto t^{-1} = \left[-\frac{1}{2}s(1 - \cos \theta^*)\right]^{-1} \quad (5)$$

or through $s$-channel contributions without any singular behavior. In Figure 3 we show
the normalized dijet cross section as a function of $|\cos(\theta^*)|$. At HERA, the rather high cut on $E_T > 25$ GeV results in a $|\cos(\theta^*)|$ distribution which is mostly dominated by phase space. At THERA, the center-of-mass energies are larger: Phase space restrictions are unimportant, and the normalized distribution no longer depends on the electron beam energy or the collider mode ($ep$ or $\gamma p$), if the $E_T$ cut is kept fixed. Therefore the expected singular behavior can now clearly be seen. The same distribution is valid if the HERA cut is scaled down to $E_T > 318$ GeV/959 GeV × 25 GeV ≃ 8 GeV, which is similar to the cut $E_T > 6$ GeV used in a recent ZEUS analysis [15]. The ZEUS data were found to agree with next-to-leading order QCD predictions [5, 16]. In Figure 3, we also show results for direct and resolved photoproduction separately (thin curves). The resolved curve clearly shows the singular behavior in contrast to the direct contribution, which contributes only a small fraction to the total result (see also Figure 1).

For determinations of the partonic structure of protons and photons, distributions in the observed partonic momentum fractions are of great value. Figure 4 demonstrates that the range in $x_p^{obs}$, in which the proton structure can be analyzed, is extended by at least
Figure 4: Differential dijet photoproduction cross section as a function of the observed parton momentum fraction in the proton $x_p^{obs}$. For THERA $ep$ we show results with three different electron beam energies $E_e = 250, 400, \text{and } 500$ GeV.

one order of magnitude from 0.03 at HERA to 0.003–0.001 at THERA. Since the gluon dominates at values below 0.2, the low-$x$ gluon determinations in deep-inelastic scattering could thus be tested in photoproduction for the first time.

Similarly, the range in $x_\gamma^{obs}$ would be extended by at least one order of magnitude from 0.04 at HERA to 0.004–0.0025 at THERA. This can be seen in Figure 5. In the photon case, the gluon dominates below 0.25, so that HERA should already have the potential to constrain the gluon in the photon with photoproduced high-$E_T$ jets in the region 0.04–0.25. THERA could, however, constrain the gluon down to much lower values of $x_\gamma^{obs}$.

THERA $ep$ cross sections with an electron beam energy of 250 GeV and different next-to-leading order parameterizations for the gluon density in the photon differ by 30–50\% for $E_T > 29$ and 14 GeV [14].
Figure 5: Differential dijet photoproduction cross section as a function of the observed parton momentum fraction in the photon $x_{\gamma}^{\text{obs}}$. For THERA ep we show results with three different electron beam energies $E_e=250, 400, \text{and } 500 \text{ GeV}$.

4 Conclusion

Collisions of high-energy electrons from a future linear accelerator like TESLA with an existing proton beam in a ‘THERA’ $ep$ machine offer great opportunities for jet photoproduction: They would naturally build on the current HERA program of testing QCD and determining the partonic structure of the proton and the photon. The range in the hard scale $E_T$ could be extended by a factor of 2–3, which would reduce complications from the soft underlying event and hadronization. At the same time the range in the partonic momentum fractions $x_p$ and $x_\gamma$ could be extended by at least one order of magnitude. Determinations of the gluon in the proton at low $x_p$ in deep inelastic scattering could then be tested, and the gluonic structure of the photon could be determined for the first time. Furthermore, event rates with three or more observed jets in the final state are expected to be larger at higher energies and could be compared to then-available higher order predictions to study the multi-particle QCD dynamics. The physics program of any future linear collider would thus greatly benefit from these additional opportunities.
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