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Study of the effective transverse momentum of partons in the proton using prompt photons in photoproduction at HERA

ZEUS Collaboration

Abstract

The photoproduction of prompt photons, together with an accompanying jet, has been measured with the ZEUS detector at HERA using an integrated luminosity of 38.6 pb^{-1}. A study of the effective transverse momentum, $<k_T>$, of partons in the proton, as modelled within the framework of the PYTHIA Monte Carlo, gives a value of $<k_T> = 1.69 \pm 0.18 \, ^{+0.18}_{-0.20}$ GeV for the γp centre-of-mass energy range $134 < W < 251$ GeV. This result is in agreement with the previously observed trend in hadron-hadron scattering for $<k_T>$ to rise with interaction energy.

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1 Introduction

The study of hard final-state photons in high-energy collisions is a powerful tool for the investigation of parton dynamics and hadron structure. Photons of this kind ('prompt photons') can emerge as a primary product of hard parton-scattering processes without the hadronisation by which outgoing quarks and gluons form observed jets. In this way, they provide information about the underlying parton processes that is relatively free from hadronisation uncertainties.

In a recent analysis [1], ZEUS presented inclusive measurements of prompt photon cross sections in photoproduction at HERA. The present paper describes a further study of such processes in which a hadron jet is also measured. The presence of the jet allows the underlying QCD process in the γp interaction to be identified more clearly, thus assisting the study of its dynamics. This work is motivated by the observation in a number of previous experiments [2–5], summarised in recent reviews [6, 7], that the inclusive production of prompt photons with low transverse energy in hadron-proton and hadron-nucleus reactions is unexpectedly large. One possible explanation is that the partons in the proton may effectively have a considerably higher mean intrinsic transverse momentum, $<k_T>$, than the traditionally assumed value of a few hundred MeV. Measurements by CDF [2] are consistent with a $<k_T>$ of 3.5 GeV, while in measurements at lower energies by E706 [4], a value of 1.2 GeV is suggested. Recently published results from D0 [5] are consistent with those of CDF.

The quantity $<k_T>$ has been measured directly from the kinematics of lepton or photon pairs that emerge from a hard interaction, but may also be measured indirectly by making use of a theoretical framework given by a next-to-leading-order (NLO) QCD calculation or a leading-order Monte Carlo generator such as PYTHIA. The magnitude of $<k_T>$ has been taken to reflect the confinement of quarks and the known size of the proton, with the assumption that these non-perturbative effects may be combined in a straightforward way with a perturbative calculation of the parton scattering. However, it has more recently been argued that when partons undergo hard scattering, the presence of additional initial-state gluon radiation beyond NLO in QCD can increase their effective $<k_T>$ value and that this may be a major contribution to the effects observed [8–13]. Within PYTHIA, both of these contributions are allowed for: there is an 'intrinsic' component together with a parton-shower component, and their combination is referred to here as the effective value of $<k_T>$.

In part of the measured pseudorapidity range, the ZEUS inclusive prompt photon cross sections [1] were found to be higher than predicted. However, Monte Carlo studies have indicated that increasing $<k_T>$ in the proton or photon is unable to account for this discrepancy. At the same time, the shape of the distribution in transverse energy, E_T, can be well described by NLO theory, and the overall normalisation, although slightly higher than predicted, is insensitive to variations of $<k_T>$ given the current experimental statistical accuracy. The aim of the present measurement is, therefore, to determine by a more direct kinematic method whether the partons in the proton possess high values of $<k_T>$ in interactions with a high-energy photon. This is facilitated by the use of event samples in which the 'direct photoproduction' process dominates [14], i.e. in which the entire incoming photon interacts with a quark in the proton, thereby avoiding any additional contributions to $<k_T>$ from the resolved photon. At leading order in photoproduction, the Compton process $\gamma q \to \gamma q$ is the only direct prompt photon process.

2 Apparatus and Method

The data were taken with the ZEUS detector at HERA, using an integrated e^+p luminosity of 38.6±0.6 pb^{-1}. The energies of the incoming positron and proton were, respectively, $E_e = 27.5$ GeV and $E_p = 820$ GeV. The apparatus and the details of the analysis method are described in detail elsewhere [1, 14]. Of particular relevance here are the compensating uranium-scintillator calorimeter [15] and the central tracking detector (CTD) [16]. The calorimeter provides almost hermetic coverage and has a relative energy resolution, as measured in test beams, of $0.35/\sqrt{E}$ for hadronic deposits and $0.18/\sqrt{E}$ for electromagnetic deposits, where E is in GeV. The CTD operates in a magnetic field of 1.43 T provided by a thin superconducting solenoid. The transverse momentum resolution in the central rapidity region is $\sigma(p_T)/p_T = 0.0058\,p_T \oplus 0.0065 \oplus 0.0014/p_T$ (p_T in GeV).

Photons used in the present analysis were measured in the electromagnetic section of the barrel region of the calorimeter, which covers the polar angular range[1] $36.7° < \theta < 129.1°$. The electromagnetic cells have a projective geometry as viewed from the interaction point. Each is 23.3 cm long in the azimuthal direction, representing 1/32 of the full 360°, and has a width of 4.9 cm along the beam direction at its inner face, at a radius 123.2 cm from the beam line. The hadronic section consists of non-projective cells, each of which covers four electromagnetic cells. The azimuthal position of a single-particle impact point within a cell is measured from the ratio of the signals read out by photomultiplier tubes at each end, giving a measurement with a resolution of ±2.5 cm. The photons were distinguished from neutral mesons (π^0, η^0) by means of variables derived from the clusters of calorimeter cells identified as electromagnetic signals, using the same method as employed in previous ZEUS analyses [1, 14]. The most important variable is the fraction of the cluster energy found in the cell with most energy, f_{max}, which peaks near unity for signals from single photons. After applying a cut to remove candidates with a large cluster width, the events in any given bin of a plotted physical quantity were divided into two classes with,

[1] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the 'forward direction', and the X axis pointing left towards the centre of HERA. The coordinate origin is at the nominal interaction point. The laboratory pseudorapidity, η, is defined as $-\ln\tan(\theta/2)$, where the polar angle, θ, is measured with respect to the proton beam direction. All kinematical calculations take into account the position of the event vertex.

respectively, high and low values of f_{max}. Information from simulated single high-energy photons, π^0 mesons and η^0 mesons was then used to perform a statistical subtraction of the background from the photon signal.

To reduce the backgrounds and the contribution from high-energy photons radiated from outgoing quarks, an isolation criterion was applied. Within a cone of unit radius in pseudorapidity and azimuth (η, ϕ) surrounding an outgoing photon candidate, the integrated transverse energy in the detector, excluding that of the photon candidate, was required not to exceed 10% of that of the photon candidate itself. Both calorimeter cells and tracks were taken into account in evaluating this condition. In addition, no photon candidate was permitted to have a track pointing within 0.3 radians of it. Given the excellent performance of the ZEUS CTD, this effectively assured that no electrons were misidentified as photons.

The trigger for the prompt photon events required an electromagnetic energy cluster in the barrel section of the calorimeter, together with further calorimeter requirements on the total energy of the event. The offline cuts were at an adequate margin above the trigger level. In the offline analysis, use was made of energy-flow objects which combine information from calorimeter cells and measured tracks [17]. For each event, the energy of the incoming virtual photon was estimated using the quantity $y_{\rm JB} = \sum(E - p_Z)/2E_e$, where the sum is over all energy-flow objects in the event, each of which is treated as if due to a massless particle with energy E and longitudinal momentum component p_Z. After correcting for the effects of energy losses, limits of $0.20 < y_{\rm JB} < 0.70$ were applied, approximately corresponding to a centre-of-mass γp energy range $134 < W < 251$ GeV. The lower limit removed proton beam-gas events, and the upper limit removed deep inelastic scattering events.

Events with a scattered beam positron identified in the calorimeter were rejected. The virtuality of the incoming photon was in this way limited to values below ≈ 1 GeV^2 with a median of 10^{-3} GeV^2. Jets were reconstructed, using energy-flow objects, by means of the Lorentz-invariant k_T-clustering algorithm KTCLUS [18] in the inclusive mode [19]. The standard settings were used. Corrections to the measured photon and jet energies were evaluated through the use of Monte Carlo event samples and were typically +5% to +10 % for both the photon and the jet. After correction, photons were required to have $E_T^\gamma > 5$ GeV and $-0.7 < \eta^\gamma < 0.9$, while jets were required to have transverse energy $E_T^{\rm jet} > 5$ GeV, with pseudorapidity in the range $-1.5 < \eta^{\rm jet} < 1.8$. These kinematic cuts confined both photons and jets to well-measured regions. The momentum components of the objects comprising the jet were summed to obtain the total jet-momentum vector. If more than one jet was found within the above kinematic limits, the jet with highest E_T was taken. After the above cuts and the cut on cluster width, the number of events with a prompt photon candidate and a jet was 1507, of which approximately half were background.

The fraction of the incoming photon energy that takes part in the QCD subprocess was estimated by evaluating $x_\gamma^{\rm meas}$, defined as [14]

$$x_\gamma^{\rm meas} = \frac{1}{2E_e\, y_{\rm JB}} \sum_{\gamma,\,\rm jet} (E - p_Z),$$

where the sum is over the high-energy photon and the contents of the jet. The $x_\gamma^{\rm meas}$ distribution peaks at values close to unity for direct photoproduction events, in which the whole photon takes part in the hard subprocess. It takes smaller values for resolved events, where the photon acts as a source of partons, one of which takes part in the hard subprocess.

3 Results

Figure 1(a) shows the distribution of $x_\gamma^{\rm meas}$ after the subtraction of background due to π^0 and η^0 mesons. The errors shown are statistical only; systematic errors are dominated by uncertainties on the parameters of the background subtraction and on the calorimeter energy scale, and are typically $\pm 7\%$. It is evident that both direct and resolved processes are present. The histograms show predictions from the PYTHIA 6.129 Monte Carlo [20], after the events have been passed through a full GEANT-based simulation [21] of the ZEUS detector. Default settings of PYTHIA 6.129 were used, together with the parton density functions MRSA [22] for the proton and GRV [23] for the photon. Approximately four times as many Monte Carlo events as data were generated. The PYTHIA distribution includes events from direct and resolved prompt photon photoproduction at lowest order in QCD, together with radiative dijet events in which an outgoing quark from a hard QCD scatter radiates a high-energy photon that satisfies the present experimental selections. Figure 1(b) shows the pseudorapidity distribution of the photons, the presence of a jet being required. The agreement with PYTHIA in both distributions is qualitatively satisfactory, although the predictions lie below the data, particularly at negative η^γ values. This was also observed in the ZEUS inclusive prompt photon measurements [1].

Figure 2 shows distributions of kinematic quantities of the prompt photon + jet system, for events selected with $x_\gamma^{\rm meas} > 0.9$. These events are predominantly from direct photoproduction processes; the restriction to high $x_\gamma^{\rm meas}$ also suppresses events with additional jets. Since the value of $<k_T>$ affects primarily the shapes of the distributions, these are area-normalised. As illustrated in Fig. 2(a), the plotted quantities describe the momentum imbalance of the photon-jet system projected on to the transverse plane. These quantities are the momentum component of the photon perpendicular to the jet direction, $p_\perp$; the momentum imbalance along the direction opposite to that of the jet, $p_\parallel$; and the azimuthal acollinearity between the photon and the jet, $\Delta\phi$. In plotting $p_\parallel$, the condition $(p_T^{\rm jet} + p_T^\gamma) > 12.5$ GeV was applied to remove an enhancement around zero due to the many events where the photon and jet transverse energies both lie just above their respective lower cuts. The quantity $p_T^{\rm jet}$ is not the Snowmass $E_T^{\rm jet}$, defined as the scalar sum of the E_T values of the individual particles in the jet, but is the transverse component of the vector sum of the momenta of the particles in the jet. The quantity $\Delta\phi$ is strongly correlated with $p_\perp$ but has less sensitivity to the measured photon and jet energies.

To evaluate the systematic effects, the parameters of the background subtraction and the calorimeter energy scale were varied within their uncertainties. For $p_\perp < 1$ GeV and $\Delta\phi > 170°$, the effects were typically 1-2% after normalisation of the distributions. Since there is some disagreement with theory at low η^γ, the photon rapidity range was also reduced at each end by 0.2. To observe the effects of including a greater proportion of resolved events, the cut on $x_\gamma^{\rm meas}$ was reduced to 0.85. As further checks, the mode of jet reconstruction was varied by (a) changing the jet-recombination scheme between the p_T and E modes [18], (b) using a cone jet algorithm [24], and (c) increasing the jet-radius parameter in the KTCLUS algorithm by a factor 1.25. The latter has sensitivity to the possible jet-broadening effects of hard final-state gluon radiation. The results in each case were consistent with the main method at the level of the statistical uncertainties. The largest systematic uncertainties come from the variations on the $x_\gamma^{\rm meas}$ and η^γ cuts. The effects of the incoming photon virtuality can be neglected in the present analysis. A relaxation of the lower cut on $y_{\rm JB}$ did not significantly affect the result.

The data are compared to different predictions from PYTHIA, which include the small contributions from radiative and resolved events with $x_\gamma^{\rm meas} > 0.9$. All the Monte Carlo results used here are based on samples selected with the same detector-level cuts as the data. Within PYTHIA it is possible to vary the 'intrinsic' smearing on the transverse momentum of the partons in an incoming hadron; this smearing is imposed in addition to the effects of parton showering, and results are shown for three values of its two-dimensional Gaussian width, k_0, as applied within the proton. The corresponding mean absolute value of the intrinsic transverse parton momentum in the proton, $<k_T^{\rm intr}>$, is then given by $<k_T^{\rm intr}> = \sqrt{\pi/4}\, k_0$ [6]. In PYTHIA 6.129, the default value[2] of k_0 for partons in the proton and in the resolved photon is 0.44 GeV. The photon k_0 was fixed at this value. The sensitivity of the present measurement to the photon k_0 is small since the selected events are predominantly from direct processes. From the figures it is seen that the $p_\parallel$ distribution lacks discriminating power, which prevents the use of the overall transverse momentum, Q_T, of the photon - jet system to measure $<k_T>$, since this depends substantially on $p_\parallel$. It is evident that proton k_0 values of ≥ 3 GeV or ≤ 0.44 GeV are disfavoured by the distributions in $p_\perp$ and $\Delta\phi$.

Normalised cross sections for $p_\perp$ and $\Delta\phi$ are presented in Fig. 3. The data have been corrected to the hadron level, applying the same kinematic cuts as for the corrected detector-level quantities, namely: $E_T^\gamma > 5$ GeV, $-0.7 < \eta^\gamma < 0.9$, $E_T^{\rm jet} > 5$ GeV, $-1.5 < \eta^{\rm jet} < 1.8$, $134 < W < 251$ GeV, and $x_\gamma^{\rm meas} > 0.9$. The PYTHIA prediction corresponding to a fitted value of k_0 (see below) describes the data well. The systematic uncertainties are

[2] In later versions of PYTHIA, this default value has been increased to approximately 1 GeV.

similar to those on the corresponding distributions of Fig. 2 and are small compared to the statistical uncertainties. Uncertainties in the calorimeter energy scale largely cancel in the normalised distributions. Within PYTHIA, the r.m.s. width in ϕ between the directions of the outgoing parton and the reconstructed jet was found to be $\pm 6.4^\circ$, considerably less than the corresponding value of $\pm 12.9^\circ$ between the jet and the reverse of the photon direction.

Further PYTHIA Monte Carlo samples were generated using proton k_0 values of 1.0 GeV and 2.0 GeV, in addition to those shown in Fig. 2. A χ^2 minimisation was performed to determine the optimal value of k_0 using the $p_\perp$ data and the five PYTHIA simulations at the detector level. The resulting fitted $<k_T^{\rm intr}>$ value is $1.25 \pm 0.41\ ^{+0.15}_{-0.28}$ GeV, where the first error is statistical and the second systematic. A fit to the $\Delta\phi$ data, which is highly correlated with $p_\perp$, gave a similar result with a larger statistical uncertainty. The value of $<k_T^{\rm intr}>$ does not include the parton-shower contribution to $<k_T>$, which was found to be approximately 1.4 GeV from a PYTHIA sample with $k_0 = 0$. Within the framework of direct photoproduction in PYTHIA, the contributions to $p_\perp$ at the parton level from the intrinsic component and from the parton shower may be combined to allow a total value of $<k_T>$ to be evaluated assuming that the overall distribution is Gaussian[3]. The total $<k_T>$ value corresponding to the fitted value of $<k_T^{\rm intr}>$ was evaluated in this way to be

$$<k_T> = 1.69 \pm 0.18\ ^{+0.18}_{-0.20}\ \text{GeV}.$$

The systematic error includes a contribution from the model-dependence of the result, as estimated from a calculation using HERWIG 6.1 [25]. HERWIG uses a parton-showering model which differs from that used in PYTHIA; in particular, it does not have the sharp lower cut-off in the shower evolution below which PYTHIA relies upon a suitable value of its phenomenological k_0 parameter [26]. It was found that the data were already well described by HERWIG with its k_0 at the default value of zero, so that the fitting method used above could not be repeated. The use of the default version of HERWIG gave a $<k_T>$ value 10% higher than the PYTHIA result; this was added to the systematic error as a contribution of ± 10%.

Both PYTHIA and HERWIG model the effects of final-state gluon radiation. As a further check, a sample of PYTHIA events was prepared with the final-state radiation turned off. The results were not significantly different from those using the standard version.

The value of $<k_T>$ determined here represents the mean absolute value of the parton transverse momentum in the proton, taking into account all the partonic effects modelled in direct photoproduction within PYTHIA. It may be compared with values of $<k_T>$

[3] Assuming Gaussian distributions, the relationship $<k_T> = \sqrt{\pi/2}<p_\perp^{\rm rms}>$ holds. By varying k_0 in PYTHIA and noting the resulting distributions of $<p_\perp^{\rm rms}>$, $<k_T>$ and $<k_T^{\rm intr}>$ at the parton level, for events passing the experimental cuts at the detector level, the relationship $<k_T>^2 = 1.92\ \text{GeV}^2 + 0.61<k_T^{\rm intr}>^2$ was obtained.

obtained previously by other methods, such as by the direct measurement of outgoing lepton or photon pairs.

Figure 4 shows the ZEUS result in comparison with mean $<k_T>$ values from other experiments [6, 27], plotted as a function of the hadronic centre-of-mass energy, W, of the incoming particles, namely the photon and proton in the present case. At low W, the data come mainly from the production of muon pairs by the Drell-Yan mechanism in fixed-target interactions, while the production of photon pairs has been studied at high W using the ISR [28] and Tevatron colliders. The ZEUS result bridges a gap between the low- and high-energy measurements. For a uniform presentation, the mean transverse momentum, $<Q_T>$, frequently quoted in the production of photon and muon pairs by pairs of incoming hadrons has, where necessary, been converted to a $<k_T>$ value for a single hadron by dividing by $\sqrt{2}$. It should be noted that while the measurement of final-state dimuon and photon pairs provides a direct determination of parton $<k_T>$, the other measurements require a physical model. Although different experimental methods have been employed, a clear trend for $<k_T>$ to rise with increasing W is evident, as discussed most recently by Laenen et al. [9]. The ZEUS result is fully consistent with this trend.

4 Conclusions

Photoproduction events containing a prompt photon balanced by a recoil jet have been studied using the ZEUS detector at HERA. Events in the γp centre-of-mass energy range $134 < W < 251$ GeV were selected containing a photon with $E_T^\gamma > 5$ GeV and $-0.7 < \eta^\gamma < 0.9$ and a jet with $E_T^{\rm jet} > 5$ GeV and $-1.5 < \eta^{\rm jet} < 1.8$. The kinematic properties of the photon-jet system were used to investigate the effective transverse momentum of the quarks in the proton, within the framework of the PYTHIA 6.129 Monte Carlo. A fit to the data gave a $<k_T>$ value of $1.69 \pm 0.18\ ^{+0.18}_{-0.20}$ GeV. This result is consistent with the trend, observed in a number of experiments at different energies, that the effective parton $<k_T>$ rises with the energy of the interacting hadronic system.

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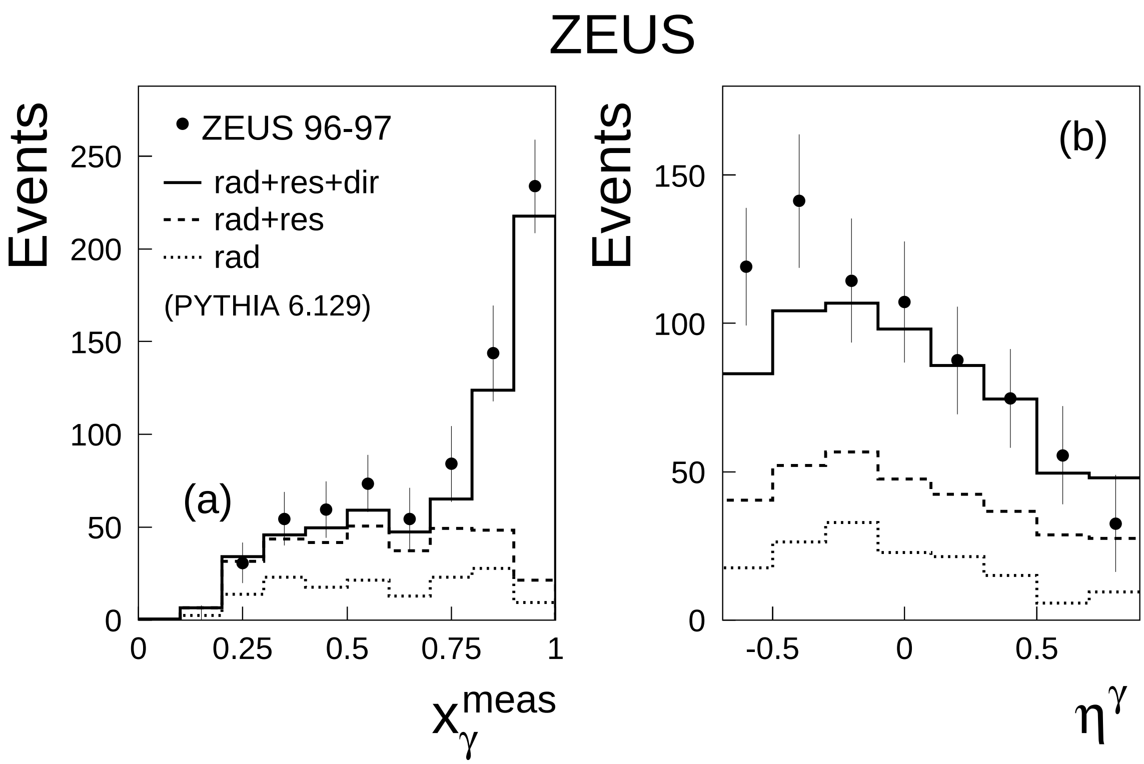

Figure 1: Distributions of (a) $x_\gamma^{\rm meas}$, (b) photon pseudorapidity, η^γ, for prompt photon events in which a jet is also observed. The plotted errors are statistical only. The data are compared with predictions from PYTHIA 6.129. The PYTHIA histograms indicate contributions from dijet events where a final-state quark radiates a photon (dotted line), summed with resolved prompt photon events (dashed line), and also with direct prompt photon events (full line). The PYTHIA 6.129 default $<k_T>$ values in the proton and photon have been used. The Monte Carlo predictions are normalised to the integrated luminosity of the data.

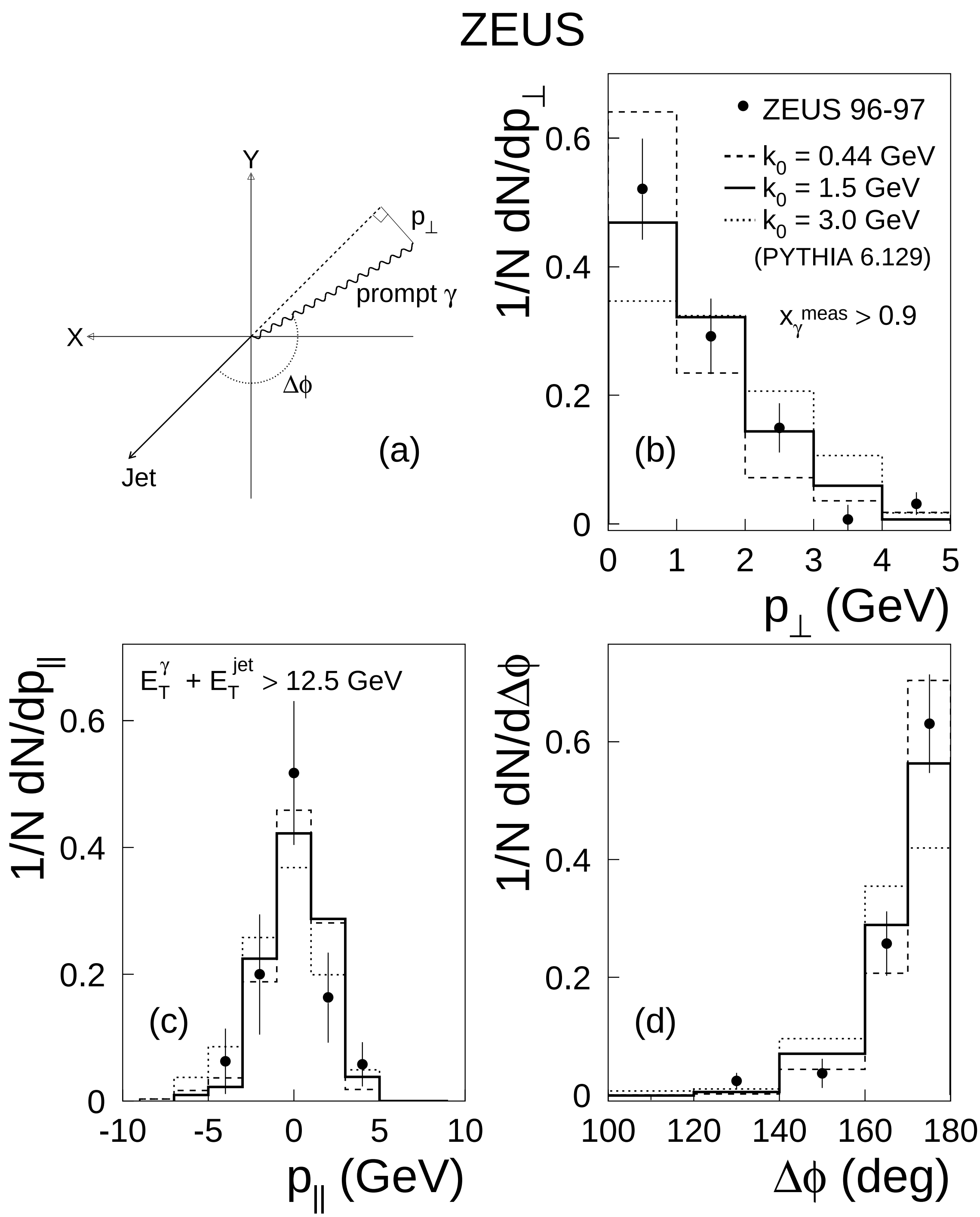

Figure 2: Normalised detector-level distributions of kinematic quantities observed in the production of a prompt photon with a jet, compared with predictions from PYTHIA 6.129 generated with different values of the 'intrinsic' transverse momentum, k_0, of the partons in the proton. Only events with $x_\gamma^{\rm meas} > 0.9$ are used. In (a) the configuration of the photon and jet in the plane transverse to the beam direction is illustrated. The plotted quantities, calculated in this plane, are: (b) perpendicular momentum component of the photon relative to the jet direction; (c) longitudinal momentum imbalance (photon − jet) along the jet direction; (d) difference in azimuthal angle between the photon and jet directions. Statistical errors only are shown.

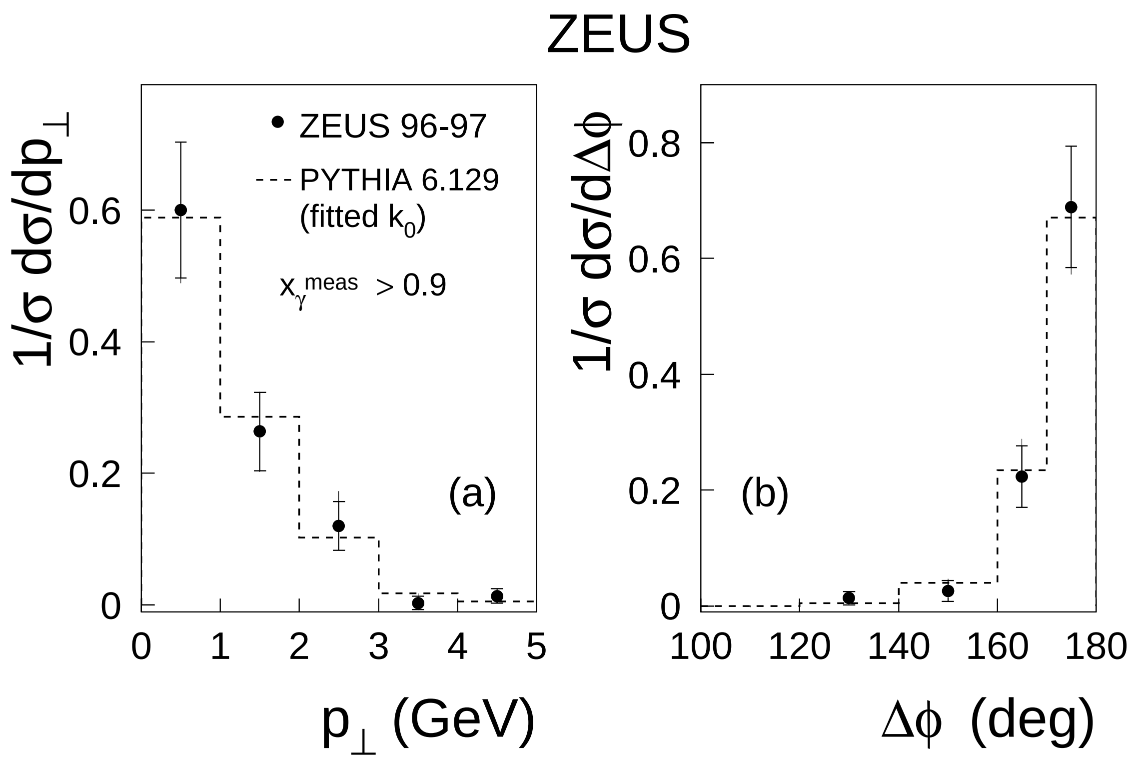

Figure 3: Normalised cross sections of kinematic quantities observed in the production of a prompt photon with a jet, compared with predictions from PYTHIA 6.129 corresponding to a fitted value of $k_0 = 1.42$ GeV. The inner and outer error bars represent statistical and total uncertainties, respectively. Only events with $x_\gamma^{\text{meas}} > 0.9$ are used. The plotted quantities, calculated as in Fig. 2 but at the hadron level, are: (a) perpendicular momentum component of the photon relative to the jet direction; (b) difference in azimuthal angle between the photon and jet directions.

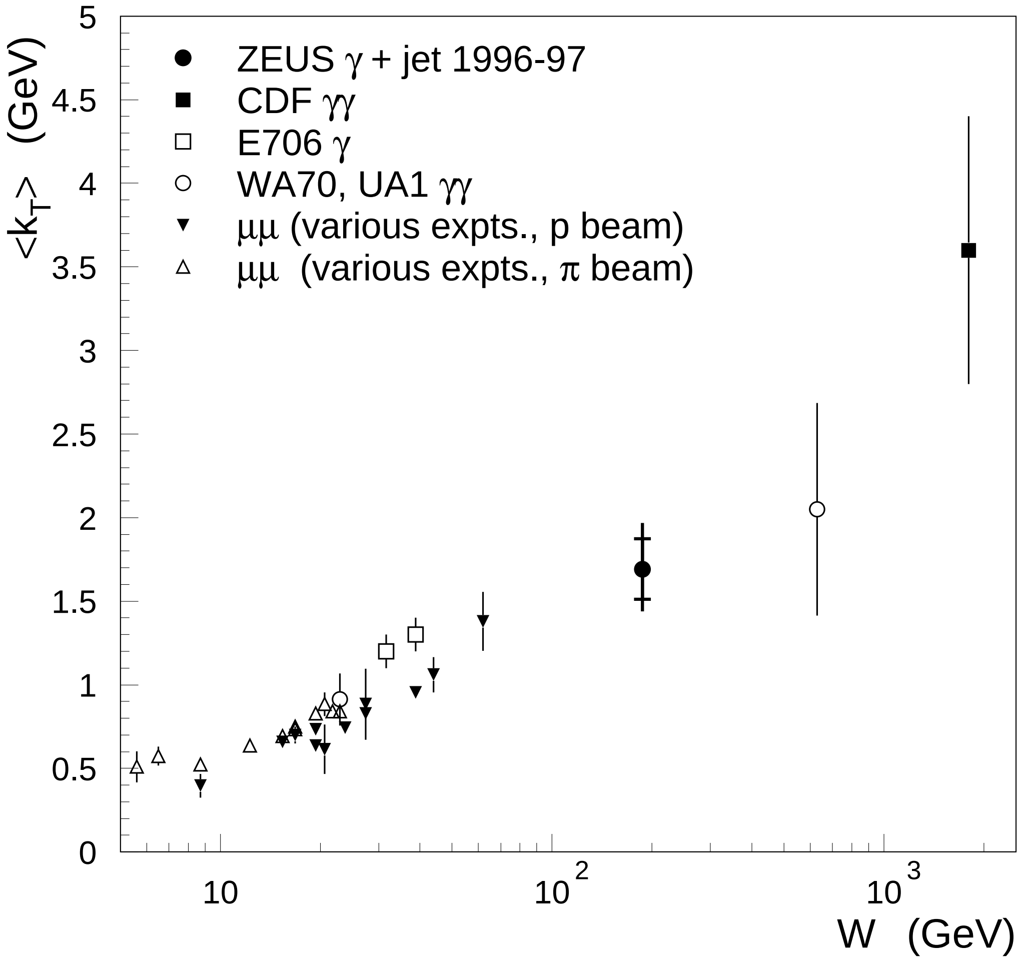

Figure 4: The ZEUS measurement for $<k_T>$ compared with results from other experiments. The inner and outer error bars on the ZEUS point represent statistical and total uncertainties, respectively. Other published results have been scaled by $\sqrt{2}$ as appropriate (see text). The single prompt photon results from CDF and D0 are in agreement with the double prompt photon CDF data-point [6]. Full references [27] may be found in a recent FNAL report [7]. The horizontal axis denotes the centre-of-mass energy of the colliding particles, which in the case of ZEUS are the photon and proton.