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What HERA tells us about the photon

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Abstract. An account is given of photon physics at HERA. The basic physical processes are described, some theoretical models are outlined, and it is shown how measurements at HERA have already helped to confirm our basic understanding of the hadronic nature of the photon.

1. Introduction

One of the main aims of the electron-proton collider HERA is to explore the nature of the proton. As the electron passes the proton it may emit a virtual photon (fig. 1) and the latter is capable of probing the proton's partonic structure. In particular, photons with a large Q^2 value (the negative of the four-momentum squared) are capable of knocking quarks out of the proton to form jets. From this so-called deep inelastic scattering (DIS), the parton distributions in the proton may be measured.

But we may equally well regard the proton as a device for probing the nature of the photon! When the photon is highly virtual, its interactions with hadronic matter are relatively well-defined as far as the photon itself is concerned: it couples electromagnetically to a charged object, such as a quark in a proton. However, low Q^2 photons have in addition to their electromagnetic nature a hadronic nature, and the latter is not yet fully understood. The proton and its quarks and gluons can act as probes for investigating this aspect of the photon. Such studies form an important part of the HERA program. My purpose here is to introduce the reader to this subject.

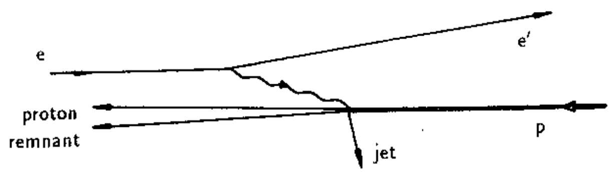

Figure 1. Electron-proton scattering at HERA via a virtual photon.

[1] Talk given at Institute of Physics Conference, Glasgow,1 April 1993

It must be appreciated that most HERA events (by far) have very low Q^2 photons. The collisions of these with the proton are governed by a cross section $\sigma_{\gamma p}$ which is essentially the same as for real γp collisions. The observed ep cross section can be written

$$\frac{\mathrm{d}^2\sigma(ep)}{\mathrm{d}y\,\mathrm{d}Q^2} = \frac{\alpha}{2\pi}\frac{1}{Q^2}\left[\frac{1+(1-y)^2}{y}\sigma_T(y,Q^2) + 2(1-y)\sigma_L(y,Q^2)\right], \qquad (1)$$

where $y = (E_e - E_e')/E_e = E_\gamma/E_e$ for small electron scattering angles. E_e and E_e' are the energies of the incoming and outgoing electron in the laboratory frame; σ_T and σ_L are the γp cross sections for transversely and longitudinally polarised virtual photons, respectively. Equation (1) is to be integrated over the Q^2 and y ranges of interest in the experiment. By neglecting σ_L (normally a very good approximation at low Q^2) we obtain the Weizsäcker-Williams approximation, and $\sigma_T(y,Q^2) \simeq \sigma_{\gamma p}(y)$. The minimum Q^2 value is $m_e^2 y^2 E_e/E_e'$ and is typically of the order of 10^{-6} GeV^2. The presence of the $1/Q^2$ term in (1) thus tells us that most of the virtual photons are almost real.

The two major experiments at HERA, H1 and ZEUS, each have a tagging device to flag low Q^2 events. This consists of an electron detector adjacent to the beam pipe, downstream of the apparatus in the electron beam direction. It allows many events to be identified in which the electron radiates an almost real photon, and is thus deflected by only a very small angle. However the acceptance of such a device is limited, and many low Q^2 events of interest are not tagged in this way. At high Q^2, of course, the large-angle scattered electron is detected in the main calorimeter of the apparatus.

2. Types of photon-proton interaction

2.1. *"Soft" processes*

It has long been known that the photon can behave as a hadron in its interaction with a proton. At energies of fixed target experiments, a good description of hadronic photon interactions is given by the hypothesis of *vector meson dominance* (VMD). It is supposed that the photon interacts with the proton by first turning into a hadronic intermediate state. This intermediate state is a vector meson V, where $V = \rho, \omega, \phi$ in the approximate ratios 9:1:2. The γV coupling constant contains a factor α. The VMD model can be extended by including small amounts of higher vector meson states.

These ideas may be expected to remain valid at HERA energies. Thus a large class of events will resemble high energy meson-proton collisions. Such processes are mainly "soft"; that is to say, the transverse momenta (p_T) involved are rarely more than a few hundred MeV.

Thus we may expect to detect multiparticle events in which the particles are produced over a large range of rapidity, but with a mean transverse momentum of around 300 MeV/c. Such events have been studied in fixed target experiments at the CERN SPS [2]. There are in addition "elastic" processes of the type $\gamma p \to Vp$. Here we are mainly investigating meson physics rather than photon physics as such; however our understanding of the photon as a hadron demands that the presence of such processes should be confirmed at the right level. It would also be good to check whether the coupling of the photon to the vector mesons is energy-independent. Further discussion of these points may be found in [3, 4].

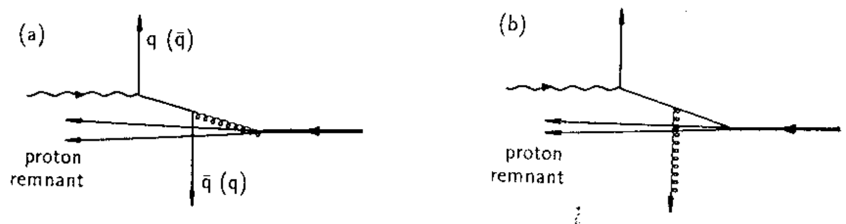

Figure 2. Direct photon-proton processes: (a) photon gluon fusion, (b) "QCD Compton".

2.2. "Hard" processes

Here we are talking about processes in which, somewhere in the Feynman diagram, there are outgoing partons with high p_T. This portion of the diagram is known as the "hard subprocess". Exactly what is meant by "high p_T" is not very well defined (as we shall see), but it should be at least 1 GeV and perhaps at least 2 GeV. We may then hope to use perturbative QCD to evaluate the hard subprocess to a good approximation, which is not possible with soft processes. Experimentally, the observation of low Q^2 events with high p_T jets is a sign that such processes are taking place. Jets of just a few GeV/c transverse momentum, emerging from hard subprocesses, are often referred to as "minijets".

Hard photoproduction processes can be classified into several types:

(i) *"Direct" processes.* In these processes, the virtual photon connects directly to a quark line in the Feynman diagram; the quark line effectively absorbs the photon. Examples are shown in fig. 2. Jets may be observed if there is a high p_T value between the parts of the quark line before and after the photon vertex. Photon-gluon fusion is the best way at HERA to study the gluonic structure of the proton, and is most easily identified in the case of heavy (e.g. charm) quark production.

(ii) *"Resolved" processes.* Here, the virtual photon behaves as a source of partons, and one of these takes part in the hard subprocess. It interacts with a parton from the proton, and a variety of qg, qq and gg processes can occur, each with a standard cross section in lowest order QCD. Fig. 3 shows some examples. The rest of the photon forms a low-p_T "remnant", analogous to the proton remnant in DIS processes. The hard subprocess is always characterised by a Q^2 value, for example that of an exchanged high p_T gluon. The photon parton distributions may be expected to be related to those in a vector meson.

It is important to note the presence of the photon remnant. This is the signature of the resolved process, and it must be adequately measured if we are to characterise these processes well.

(iii) *"Anomalous" processes.* In resolved processes, the transverse momentum of the partons inside the photon is largely ignored. However there may be, unlike the proton case, a tail to high p_T values. When the parton p_T is not ignorable, the process is called "anomalous" [4]; this implies something outside simple VMD. An example of an "anomalous" configuration is illustrated. Observable jets may be generated depending

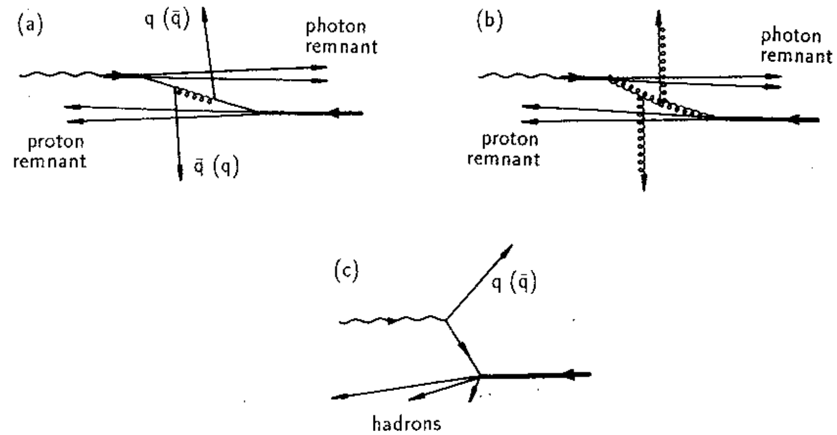

Figure 3. Some resolved photon-proton processes: (a) quark-quark scattering, (b) gluon-gluon scattering, (c) An "anomalous" process.

on the hardness of the different parts of the diagram. Care should be taken in using Monte-Carlo packages to ensure whether or not the anomalous contribution is included within the others.

2.3. The "soft-hard interface"

All the high p_T subprocesses can take place also at low p_T. But then the cross sections become large (even infinite in the case of massless partons) and non-perturbative effects usually set in. From a different viewpoint, one may say that the soft processes already contain all the diagrams of interest of the hard processes. These just "emerge" in different ways as we make different parts of the process hard. When higher order diagrams are introduced, moreover, the clean distinction between direct and resolved processes may become blurred.

All this is very difficult to model or calculate. The simplest approach is:

1. Get a model for the soft process (e.g. multiparticle photoproduction final states).
2. Add the hard process calculated to the desired order in QCD, with a low p_T cut-off, known as $p_{T min}$.

The value of $p_{T min}$ cannot be calculated *a priori*. The possibility cannot be excluded that it varies from one hard subprocess to another, or even with the centre of mass energy $\hat{s}$ of a given hard subprocess. It is thus an experimentally determined quantity at present. More sophisticated Monte Carlo approaches are being introduced, but always with some theoretical uncertainty in this area.

3. The structure of the photon

If the photon can behave as a hadron, then it must contain partons. Now, in resolved processes the partons in either colliding hadron (i.e. the proton or photon) may be thought of as undergoing deep inelastic scattering off the other hadron. This gives a way of measuring the parton densities in the photon, namely (a) the quark densities $q_i(x, Q^2_{probe})$ for different types of quark, and (b) the gluon densities $g(x, Q^2_{probe})$. Like those of the proton, such quantities of are basic physical interest. At this point, some comments need to be made:

(i) It is essential to distinguish between the Q^2 of the photon itself and the Q^2 parameter of the parton densities within it. These are now subscripted Q^2_γ and Q^2_{probe}. Effectively, photons with different Q^2_γ form a continuum of different states with different parton densities. Q^2_{probe} refers to the hard subprocess which probes the parton density. The Q^2_{probe} dependence is in part like a form factor for the parton within the photon.

(ii) It is normally assumed that the same Q^2_{probe} dependence applies to a given parton irrespective of the actual hard process used to measure it; for example, it does not matter whether a quark absorbs a virtual photon or a virtual gluon, at given Q^2_{probe}. If the partons really do physically exist, with definable properties, then such an assumption seems reasonable. Fixed distributions of pointlike partons would give no Q^2_{probe} dependence at fixed x; such behaviour in DIS-like processes is known as scaling. QCD effects modify the number of partons available for processes at different Q^2_{probe} values, however, so that scaling cannot be expected to hold perfectly.

(iii) As usual, x in the above can be interpreted as the fraction of the photon's total 4-momentum effectively carried by the given parton. (See standard texts on DIS for the mathematical definition.)

For two partons to contribute to a resolved cross section, they must have enough energy to generate final-state partons with sufficient p_T. Subject to this, the cross section can be written [5] as an integral of a given QCD cross section (e.g. $gg \to gg$), taken over the parton x values (x_γ, x_p) and weighted by the respective parton (e.g. gluon) densities in the photon and proton. Thus:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2} = \int\int \mathrm{d}x_p\, \mathrm{d}x_\gamma\, P_{i,p}(x_p, Q^2_{probe})\, P_{j,\gamma}(x_\gamma, Q^2_{probe})\, \frac{\mathrm{d}\sigma_{ij}(QCD)}{\mathrm{d}p_T^2},$$

where P_i is the density of parton type i. At given centre of mass energy, the p_T value determines the value of Q^2_{probe}. The total resolved cross section is the sum over all the possible parton processes. Resolved processes may be expected to give increasing "minijet" cross sections at very high energies, because as energy increases partons at lower x become able to scatter at high p_T.

Direct processes are evaluated similarly, but x_γ is now always 1 since the entire photon interacts (and there is no photon remnant). Thus the presence of direct processes is important for our understanding of physics, and is affected importantly by the structure of the proton, but tells us nothing about the structure of the photon. At low Q^2_γ the resolved processes dominate [5]; at higher Q^2_γ the direct processes dominate. A simple picture can be given for this: the photon remnant must have positive $(\mathrm{mass})^2$, and generating this becomes increasingly hard as $-Q^2_\gamma$ becomes increasingly negative. Also, a highly virtual photon will be very much off the mass shell of an intermediate VMD state.

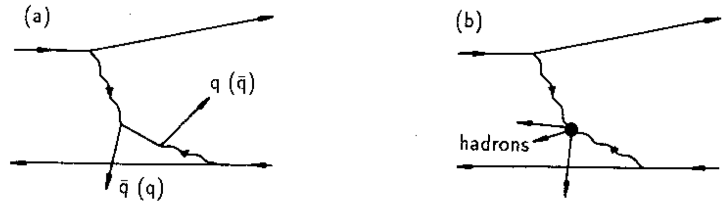

Figure 4. The photon-photon collision process: (a) pointlike diagram; (b) hadronic (direct-resolved). In each case illustrated, the upper beam lepton is radiating a high-Q^2 photon.

4. Connection with $\gamma\gamma$ physics

Two-photon processes have been measured at e^+e^- colliders for many years. They are processes in which the beam particles each radiates a virtual photon, which then interact. Thus, for example, there is a "deep inelastic" process in which a high Q^2 photon (the "probe" photon) is used to study the structure function F_2^γ of a second, almost-real photon (the "target" photon). When Q^2_{probe} is very high, this reaction is dominated by the process $\gamma\gamma \to q\bar{q}$ (fig. 4a), usually referred to as the "pointlike" process. It is very rare for both photons to be at high Q^2.

However as Q^2_{probe} decreases, $\gamma\gamma$ scattering becomes increasingly hadronic in nature. One or both of the photons behave in a resolved way, and we can draw "direct-resolved" (fig. 4b) and "resolved-resolved" diagrams as well as the "direct-direct" process of fig. 4a. Resolved-resolved collisions between two nearly-real photons involve the parton densities in each photon, and resemble resolved photon-proton collisions. Of course, there remains a major difference between $\gamma\gamma$ and γp interactions in that the proton can never interact in a "direct" manner.

The direct-resolved process forms a hadronic background to the pointlike which can never be completely neglected. It is sensitive to the quark structure within the target photon. $\gamma\gamma$ reactions have thus provided our first experimental information about photon parton densities (see section 6). It should be remembered, however, that in the direct-resolved process the probe photon — unlike a gluon — couples only to the quarks in the target photon and not to the gluons.

The resolved-resolved process has gluonic hard subprocesses, however. In general, for $\gamma\gamma$ masses above about 10 GeV, one may begin to observe minijets in the final state. LEP 200 should therefore be a good place to observe these effects, and may indeed provide excellent opportunities to measure the gluon densities in the photon.

5. Quantities that can be measured at HERA

5.1. Total γp cross section at low Q^2_γ

The total photoproduction cross section is dominated by soft processes, and varies with centre of mass energy $\sqrt{s_{\gamma p}}$ in largely the same way as any other hadron-hadron cross section. At HERA energies, the cross section is expected to show a definite rise with $s_{\gamma p}$, due mainly to resolved processes. The magnitude of the rise thus depends on the parton structure of the photon.

Partons in the photon and proton with $x > 4p_{Tmin}^2/s_{\gamma p}$ can contribute to the reaction. A parton at x_p in the proton can interact with partons with $x_\gamma \geq 4p_{Tmin}^2/x_p s_{\gamma p}$ in the photon. The cross section is therefore sensitive to p_{Tmin} as well as to the parton densities themselves. In addition, the choice of "eikonalisation" procedure begins to affect predictions for $\sigma_{\gamma p}$ at HERA. This is a unitarisation method which takes account of multiple parton interactions in a hadronic system. It lessens the rise in the cross section which might otherwise be expected. Further details can be found in [6].

In all the measurements considered here, the proton parton densities must be known well if we are to investigate those of the photon. Fixed-target DIS measurements have been performed already over a sufficiently wide x_p range, and various analyses of the large amounts of data have been presented [7]. However (c.f. fig. 5), the differences between these analyses can give rise to significant systematic effects in photon measurements. Care must therefore be taken to use the best proton information available.

As mentioned in section 2.1, processes such as $\gamma p \to \rho p$ may also provide useful information concerning the overall hadronic properties of the photon. Detailed or precision investigations may be difficult: a study of the elastic processes, and the related diffractive processes in which the vector meson is excited to a higher state, demands good particle tracking at low angles in the electron direction, and neither H1 nor ZEUS has initially placed major experimental resources in this area. However, upgrades to the apparatus may improve the situation, and the ZEUS Leading Proton Spectrometer should enable the t-distributions of elastic processes to be measured.

5.2. Jet cross sections.

A more direct measurement of the parton densities requires identification of the jets in the resolved scattering process. Single jet distributions give useful information, but it is better to measure the 4-momenta of both jets emerging from the hard parton scatter, together with the energy of the virtual photon. The latter can be obtained from the tagger or from a good measurement of the photon remnant. (It is of course not possible to label the final-state jets individually as coming from the photon or proton, nor at these p_T values can gluon and quark jets be distinguished from each other.)

The x values of the two interacting partons are then given by [8]:

$$x_\gamma = \hat{s}/s' \qquad \text{and} \qquad x_p = s'/s_{\gamma p} = s'/ys. \tag{2}$$

$\hat{s}$ is the effective mass squared of the two-jet system; s' is that of the system comprising the photon and the parton in the proton (or, equivalently, the two jets plus the photon remnant). $\sqrt{s}$ is the ep centre of mass energy, and y is as in equation (1). For untagged events, y is conveniently estimated by the Jacquet–Blondel method [9]. Provided no energy is lost down the electron beam pipe, x_γ is conveniently estimated by the quantity $\sum_{jets}(E-p_z)/\sum_{event}(E-p_z)$. The sums are over all tracks or calorimeter energy deposits in the two jets and in the whole apparatus, respectively. A detailed knowledge of the proton remnant is not needed.

If the masses of the jets can be neglected and the jets conserve transverse momentum, an alternative set of formulae is easily derived. If E_1, E_2 and θ_1, θ_2 are the energies

and polar angles of the jets, and p_T is the jet transverse momentum, then energy and momentum conservation give:

$$x_\gamma = (p_T/2E_\gamma)\,[\tan(\theta_1/2) + \tan(\theta_2/2)]\,; \quad x_p = (p_T/2E_p)\,[\cot(\theta_1/2) + \cot(\theta_2/2)]\,. \tag{3}$$

There are a number of experimental difficulties. Jets with $p_T \geq 3 - 4$ GeV/c seem to be actually identifiable in practice, but can extend over a wide area of the apparatus, and possibly overlap with the proton or photon remnant. Losses of photon remnant energy in the beampipe can increase the apparent value of x_γ. There may be traces of a soft "underlying event", due to multiple soft scattering accompanying the hard scatter. Initial-state gluon radiation and hadronisation effects can generate many unwanted "high-p_T jets". Correcting for these effects will require careful studies. A suitable choice of jet cone radius may reduce certain higher order QCD effects. At $p_T = 15$ GeV two estimates of the optimum value are 0.7 and 0.9 radians [17, 11].

For the photon as for the proton, it is of particular interest to measure the low-x distributions, particularly that of the gluon: for $x_\gamma < 0.1$, say. If we demand two detected jets, then the apparatus acceptance at HERA (using (3) and inserting typical numbers) extends to a lower limit of $x_\gamma \approx 0.02$ with $x_p \approx 0.04$. Such jets may be close to the proton remnant. Thus there is experimental acceptance for this physics, but a good understanding of proton remnant behaviour is needed, and very good rejection of backgrounds. Most of the energy in the resolved photon remnant must be detected. The lowest x_γ values are measured above the E_γ range which gives an electron in the tagging system. All this represents a substantial experimental challenge.

The single-jet cross section at given p_T and θ measures an average parton density over a range of x_γ. It is sensitive to x_γ values down to approximately $(p_T/2E_\gamma)\tan(\theta/2)$. This is half the limit from two-jet events, but the situation is much less clean, particularly since the parton densities vary rapidly at low x. A further possibility is to measure events with a directly emitted isolated high-p_T photon in the final state. This can come from hard quark-gluon or gluon-gluon scattering in which the more normal final-state gluon is replaced by a photon. Such photons are analogous to gluon jets, but might be cleaner to identify. This type of process is rarer than those with two final-state parton jets, but has an enhanced sensitivity to the initial-state gluon densities.

6. Theoretical models

I shall not attempt to review in detail here all the theoretical predictions for the partonic structure of the photon. Some of the more recent sets of parton densities are the following. In all cases the "Altarelli–Parisi" equations, which are perturbative in QCD, are used to evolve solutions from lower to higher Q^2 values.

- Drees and Grassie (DG) [12]. F_2^γ data at $Q^2 = 5.9$ GeV from the PLUTO experiment were fitted using a simple model with minimal gluon content.
- Abramowicz, Charchuła and Levy (LAC) [13]. All available F_2^γ data were fitted using a multi-parameter model which allowed the gluon content of the photon to vary. Since the data are insensitive to the latter quantity, the resulting gluon densities are unreliable.

- Glück, Reya and Vogt (GRV) [14]. At low Q^2 (0.25 – 0.30 GeV^2) the photon structure is modelled on that of a pion (or other $q\bar{q}$ meson) on the basis of our belief in VMD and existing ideas on the pion structure. Distributions at higher Q^2 are evolved. Because of the low Q^2 of the starting point, higher order QCD effects are likely to be significant; a second set of distributions is given which includes these, and indeed shows differences of up to 25 percent at Q^2=10 GeV^2. F_2^γ data were used to fit the one undetermined numerical parameter.
- Gordon and Storrow (GS) [15]. Putting constraints on the gluon distribution, these authors fit a variety of data at $Q^2 > 5.3$ GeV^2. They do not claim validity for their solutions below 3–4 GeV^2 value. A higher order solution is also presented.

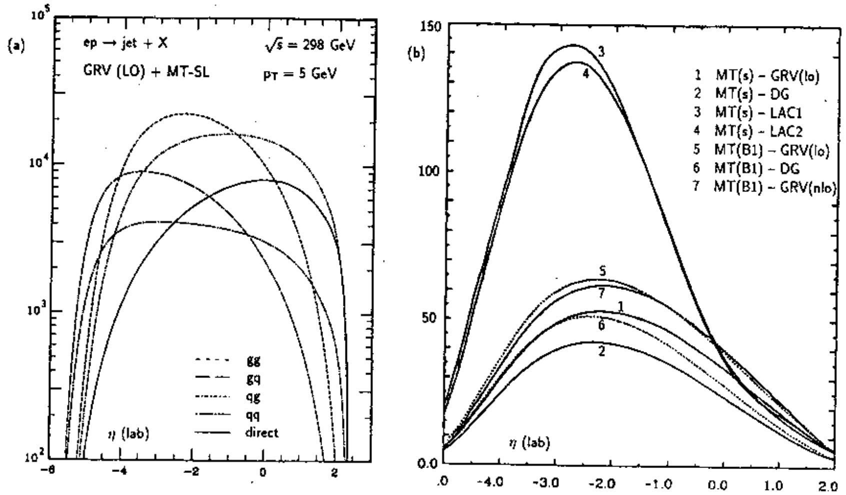

Figure 5. Cross sections in resolved γp scattering [17] (a) QCD parton-parton cross sections for a typical set of parton densities in the photon and proton; (b) single-jet cross sections, summing over (a), for various parton density sets. Positive rapidity is in the photon direction. Experimental acceptance at HERA is confined within the rapidity range $\simeq \pm 2.5$. Vertical scales are $d^2\sigma/d\eta\, dp_T$ in pb/GeV (a), nb/GeV (b).

One of HERA's tasks is therefore to distinguish between these and other models of the photon, to find which (if any) is correct. The uncertainty in what $p_{T min}$ value to take will inevitably reduce the accuracy of our conclusions when using "soft + hard" models. The task is made more complex by the presence of higher order QCD effects in the scattering process in addition to those present in calculating the sets of parton distributions. Thus, multi-jet processes, jet broadening and corrections to the one- and two-jet cross sections may be needed to be taken into account. None of the above models has Lipatov behaviour at low x [16].

Differences between various theoretical predictions for single-jet distributions are illustrated in fig. 5. The LAC predictions are seen to be very different from the others,

owing to their high gluon content. Two different models for the proton structure [7] are included to illustrate the sensitivity to this quantity, since single-jet distributions are sensitive to the structure of both incoming particles.

7. Results from HERA so far

Although the luminosity in HERA in 1992 was far from its design value, useful measurements were still obtainable. Total $\sigma_{\gamma p}$ results from ZEUS and H1 are shown in fig. 6. The two experiments are in good agreement. We may note the following despite the large errors.

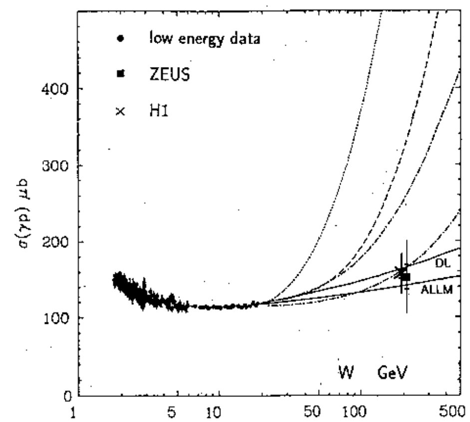

Figure 6. Total photoproduction cross section results. Dotted, dashed curves: LAC 1 with $p_{T min}$ = 1.4, 2.0 GeV/c; Dash-dotted (upper, lower): DG with $p_{T min}$ = 1.4, 2.0 GeV/c.

(i) The phenomenological formula of ALLM [20] (basically a parameterisation of low energy results) and the Regge-based prediction of Donnachie and Landshoff [21] agree well with the HERA data. In other words, no surprises have appeared.

(ii) The data are also seen to agree with one of the more "conservative" models of the photon parton structure, namely DG, but not with the LAC parton densities. These statements hold for a reasonable range of $p_{T min}$ values.

(iii) A fairly "high" value of $p_{T min}$ seems indicated even for the DG prediction.

Both H1 [22] and ZEUS [23] have presented studies on hard photoproduction. Some results are shown in fig. 7. The single-jet p_T spectra are in agreement with GRV (c) and also with DG. Two-jet events offer a more constrained final state, but with lower statistics. Jet pairs are seen, as expected, at an azimuthal separation peaking at 180 degrees (a). The observation of hard jets at $p_T \geq 3$ GeV/c would appear to mean that $p_{T min}$ must certainly be less than this. The energy flow around the jet axis (not shown) is also in agreement with expectations. It should be remembered that a jet extending over ±1 units of rapidity is a very broad object in the laboratory frame. Such a rapidity range corresponds to most of the length of the barrel calorimeter of H1 or ZEUS!

It is found that substantial energy is usually present in the photon direction even when the nearer hard jet is at a positive rapidity (b). This is interpreted as signs of the photon remnant, and confirms the dominance of resolved processes in hard photoproduction at low Q^2_γ. First measurements of x_γ (with some experimental smearing) have also been given (d). They indicate an important gluon component to the photon, particularly at low x_γ. This takes us beyond what can be found from F_2^γ measurements. Our portrait of the photon as a particle with a genuine hadronic identity is thus taking an increasingly firm shape.

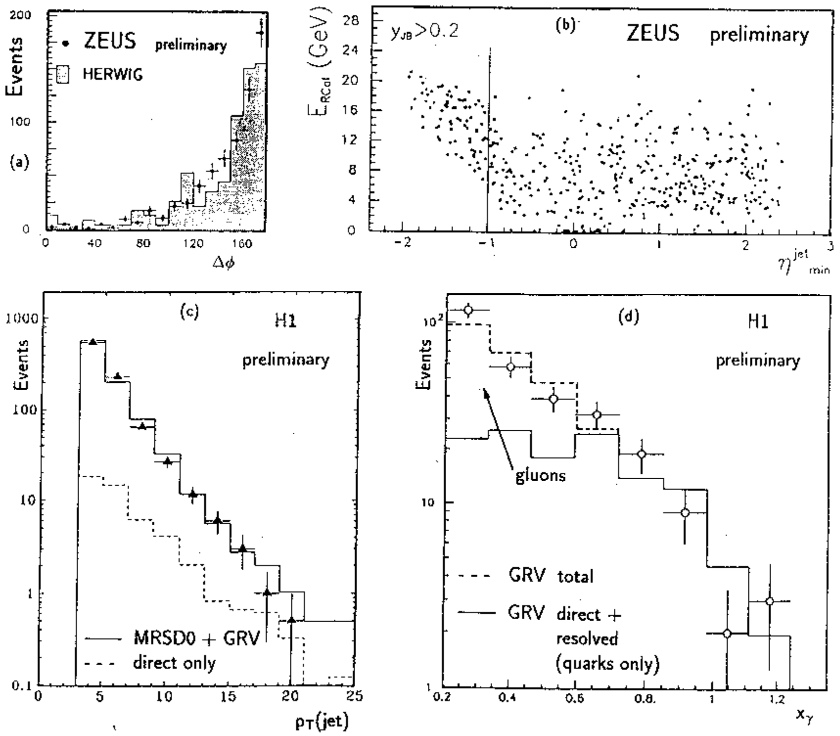

Figure 7. Some preliminary HERA results on hard photoproduction. (a) Azimuthal separation of jet pairs, showing the expected tendency to a back-to-back configuration. (b) Minimum rapidity η of a jet in a two-jet event, versus total energy in ZEUS rear calorimeter, whose acceptance covers $\eta \leq -1$. (Positive η is in proton direction.) (c) Single-jet distribution in p_T (all η): data points and histogrammed theoretical predictions. (d) x_γ distribution, confirming the need for a dominant gluon contribution at low x_γ.

8. Summary

At the present point in time we may say that HERA has already demonstrated its ability to perform investigations on the physical nature of the photon. The photoproduction total cross section has ruled out some models of the photon to be eliminated. This is despite the uncertainties involved in $p_{T min}$, in other words in the effective boundary below which higher order QCD processes dominate. These measurements will be improved with better statistics and fuller understanding of the apparatus. However it is not clear that measurements at the few percent level are achievable, which would be needed to explore the variation of $\sigma_{\gamma p}$ with energy at HERA. Vector meson studies will provide an extra handle on soft γp physics.

Jets signifying the presence of hard photoproduction have also been observed. The results so far are in agreement with expectations, and indicate the presence of resolved processes which had not been so clearly seen in fixed-target experiments. Two-jet events can tell us most about the partonic structure of the photon. They are a relatively direct indicator of the underlying physics, and with more statistics should allow different models to be distinguished.

Parton density measurements for $x_\gamma > 0.1$ will be easiest to perform, since they give more easily observable (i.e. harder) jets. For $x_\gamma < 0.1$, in many ways the most interesting range, the situation is more difficult. Raising the electron energy to the planned 30 GeV could be of some help. However in all these studies the presence of background processes makes the analysis less than straightforward.

With improved electron detection at fairly small angles, these measurements could also be carried out as a function of the virtuality of the photon. It is expected that the resolved photon effects should die out quickly with Q^2_γ.

In short, HERA has provided physicists with a unique tool for exploring the partonic constitution of photons as well as protons. This is, of course, in addition to its capabilities for studying electroweak effects and searching for new kinds of particle. With the expected increases in luminosity, large quantities of data should become available. The coming years promise to be very fruitful for all of us who are working at DESY.

Acknowledgments

It would be invidious to attempt to mention by name the many ZEUS colleagues who in a multiplicity of ways have enlarged my understanding of photon physics. I extend my gratitude to them, and also to G. Kramer, J. Storrow and P. Zerwas.

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