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HARD SCATTERING PROCESSES IN HIGH ENERGY γ-INDUCED REACTIONS

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Abstract

Recent results from photoproduction and $\gamma\gamma$ collisions are reviewed, with special focus on hard interactions, featuring the jets as the best evidence, as manifestation of parton-parton and photon-parton scattering. The experimental results are in good agreement with perturbative QCD expectations and the data are going to have the appropriate accuracy to discriminate between the available parametrizations of the photon structure functions. In particular, the combination of F_2^γ measured in $\gamma\gamma$ and the jet cross sections measured in $\gamma\gamma$ and γp will probably constrain in the near future the gluon content of the photon.

Invited talk given at the XIV International Conference on Physics in Collisions, Tallahassee, Florida, June 15-17, 1994.

1 Introduction

There has recently been a renewed interest in γp and $\gamma\gamma$ physics, triggered by the start of operation of HERA and by the new results from LEP and TRISTAN experiments.

At HERA measurements of the total hadronic γp cross section have been performed at $\approx 200\,GeV$ c.m. energy[1, 2, 3]; the results were awaited with curiosity since a steeply rising cross section, based on the *minijet* idea[4], was proposed to explain the μ abundance in very high energy cosmic rays showers[5]. Other important HERA results on photoproduction have been the observation of hard scattering and jets[6, 7], and the spectacular manifestation of event topologies related to the *direct* and *resolved* photon processes[6, 7, 8].

Also TRISTAN[9, 10, 11] and LEP[12, 13] experiments have observed clear jet structures in untagged $\gamma\gamma$ events[14] and they have performed new measurements of the photon structure functions[15, 16, 17].

Very recently the first evidence of jet production in photoproduction by real photons[18] and from deep inelastic $e\gamma$ scattering[16] has also been reported.

The comparison of the jet differential cross sections in $\gamma\gamma$ and γp offers interesting opportunities to test the QCD predictions[19], complementary to the extensive studies already performed at the hadron colliders[20]. From the present results it is clear that the factorization scheme of the inclusive jet cross section into parton density functions (PDF) and hard scattering, well tested in hadron collider, gives a good description of the $\gamma\gamma$ and γp data. Since in the calculations the main uncertainty is presently on the photon side, these new data are important to discriminate the different parametrizations[21, 22, 23, 24, 25, 26] of the photon structure function. Moreover, it is likely that the combination of inclusive jet cross sections with the global event topology and other inclusive reactions will result not only in a more accurate parametrization of the photon PDF but also in a better overall description of the complicated behaviour of the photon in hadronic collisions[27].

The next section will be devoted to summarize briefly the phenomenology of the photon hadronic interactions and to set the terminology used to present the results. The following section is dedicated to describe the reasons why one expects from HERA, just entering into the game, an interesting program on photoproduction. Then the experimental results will be discussed: first the measurements of the total cross section; then the evidence for hard processes and jets; finally the studies about the parton content of the photon.

2 The many faces of the photon

The photon, as the gauge boson of the electromagnetic field, couples with the particle charge and magnetic moment. Beside this fundamental aspect, it is also known since decades to behave like a vector meson in hadronic interactions. The experimental observation of this *second component* of the photon has originated the *vector meson dominance model* (VDM, [28]), which describes very successfully the low energy photoproduction data [29]. In this model the *physical photon* is imagined to be already in a virtual hadronic bound state before entering the interaction.

The *bare photon* can, because of the uncertainty principle, fluctuate into fermion pairs. The only ones relevant for the hadronic cross sections are, in first order, the $q\bar{q}$ pairs. If the lifetime of the virtual state is long enough, a cloud of soft gluons surrounds the quark-antiquark pair and the overall non-perturbative system can be described as a hadronic bound state having the quantum numbers of the photon, $J^{PC} = 1^{--}$, $Q = B = S = 0$. In the original formulation of the VDM only the lightest vector mesons $\rho°$, ω and ϕ were considered, and

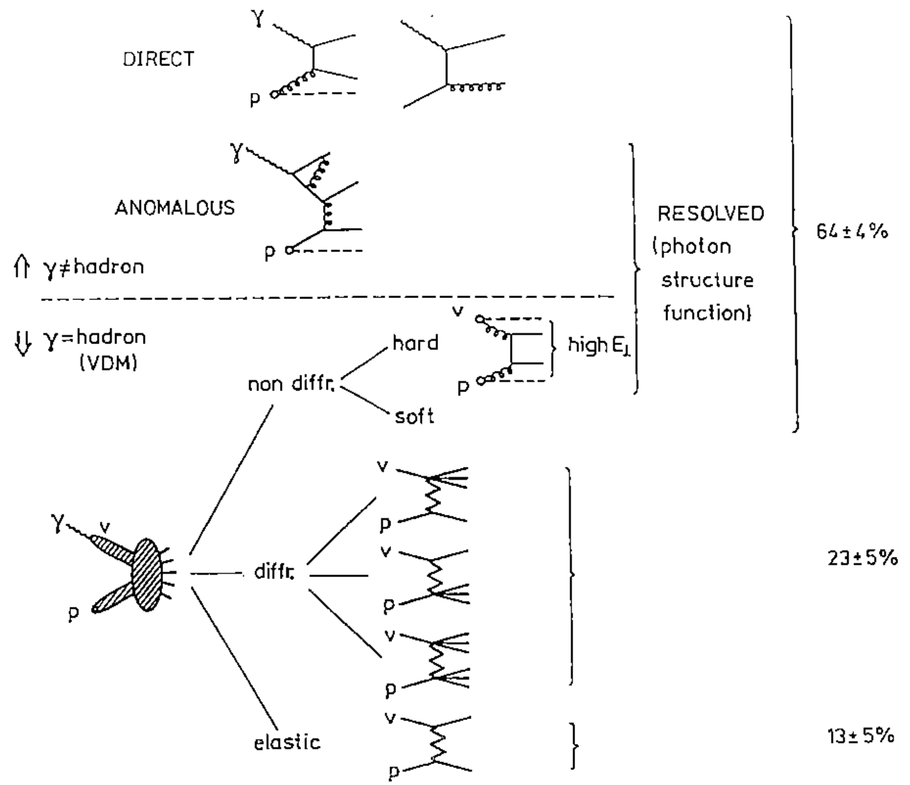


Figure 1: Classification of the γp processes. Referring to the notation of the text, the classes of processes are, starting from the top: A, B, E_2, E_1, D_1, D_2, D_3 and C. The percentages on the right end side are the contributions to the total cross section as measured by ZEUS[3].

their probabilities to couple to the photon were determined experimentally. The lifetime of the virtual state depends on the relative transverse momentum of the $q\bar{q}$ pair at the $\gamma q\bar{q}$ vertex. If the transverse momentum is larger than $O(1\,GeV/c)$, the reaction induced by this highly virtual and short living state cannot be described in the frame of the VDM model. Some extensions of the model to include the high virtuality states turned out to be inadequate to describe high energy e^+e^- annihilation and deep inelastic scattering (DIS) data. The *open* $q\bar{q}$ state and the subsequent gluon radiation can be better described in terms of perturbative QCD[30].

The physical photon state in hadronic interactions can be thought as a superposition of the bare photon, of vector mesons (V) and of quark-antiquark states:

$$|\gamma_{phys}>= \alpha_B|\gamma_B> + \sum_{V=\rho^0,\omega,\phi} \alpha_V|V> + \sum_{q=u,d,s,...} \alpha_{q\bar{q}}|q\bar{q}> \,. \qquad (1)$$

The coefficients α_i are the amplitudes of the components. The probability for the photon to remain in the bare state, equal to α_B^2, is approximately 99.5%[27], but nevertheless the event rate at high energy is dominated by the other two components, due to their higher cross sections.

Combining the above decomposition of the physical photon with the behaviour of each component in hadronic collisions, we can classify the processes contributing to the hadronic photoproduction cross section in the following way (see also Fig. 1):

point-like γ:

(A) direct photon: the photon interacts directly, via the exchange of a virtual quark, with a quark ($\gamma q \to \gamma q$, $\gamma q \to qg$) or a gluon ($\gamma g \to q\bar{q}$) of the proton. The processes are respectively called *DIS QED Compton*, *QCD Compton* and *photon-gluon fusion*. Since the photon side of the interaction as well as the dynamics of the hard scattering is under control, these reactions provide information about the proton structure complementary to standard DIS experiments.

(B) (resolved-)anomalous: one of the partons resulting from the QCD cascade developed from the primary splitting $\gamma \to q\bar{q}$ and having a limited transverse momentum k_T interacts with a parton of the proton and produces two high p_T partons in the final state, observed as jets. The other partons, spectators of the hard scattering, form the so-called *photon remnant* system.

γ = vector meson:

(C) elastic $\gamma p \to Vp$;

(D) diffractive: three possibilities have to be considered, depending upon whether the diffraction happens to the vector meson on the proton, the other way around, or both hadrons diffract on each other:

(D_1) $\gamma p \to X_1 p$

(D_2) $\gamma p \to V X_2$

(D_3) $\gamma p \to X_1 X_2$

(E_1) non-diffractive soft: these are peripheral interactions in the non-perturbative QCD regime, phenomenologically described by longitudinal phase space models.

(E_2) non-diffractive hard: this process is described by the QCD factorization of the hard parton-parton collisions, where the probability of finding a parton in the vector meson is empirically parametrized by PDF's in analogy to the nucleon ones. Like for the class B, the events are characterized by photon remnants.

It is clear that this sharp subdivision is unnatural, and at the edges of the kinematic regions there is always the risk of double counting. For example the QCD radiative corrections to A lead smoothly to B, and the region of separation between E_1 and E_2 is not uniquely defined.

Events with two partons in the final state are produced by the classes A, B and E_2. Since the jet total cross sections are divergent for small transverse momentum of the outgoing partons (with the exception of the heavy flavour production, where the mass acts as a cutoff) an artificial cutoff - p_T^{min}, usually of the order of $2\,GeV/c$ - is needed. The jets produced with transverse momenta not much higher that p_T^{min} are refered to as *minijets*[31].

The classes of events in which the hard scattering is initiated by a parton, either coming perturbatively from the photon (class B) or via the QCD evolution of the (initially non-perturbative) vector meson structure functions (class E_2), are named *resolved photon* reactions. Traditionally they are combined together in the definition of the photon structure function. The evolution equations differ then, with respect to normal hadrons, because of the *anomalous* point-like coupling of the beam particle with the quarks. This is the reason for the class B name.

A separation of the treatment of the two classes has been recently proposed[27]. Clearly this approach would offer the advantage, if thoroughly implemented in Monte Carlo simulations, to provide a detailed description of the final states, in particular of the photon remnants, both in terms of inclusive distributions and of flavour content.

Going from γp to $\gamma\gamma$ the same decomposition of the photon holds. Having now two physical photons in the initial state and focusing on the hard interactions, one may have *direct-direct*, *direct-resolved* and *double resolved* reactions.

3 The γp collider HERA

In fixed target experiments the photon beam is obtained from the bremsstrahlung of electrons on a radiator. The final state electron is tagged and the kinematics of the photon can be known on an event-by-event basis. The limited beam energy allows photoproduction studies up to c.m. energies of the order of $20\,GeV$.

The successful operation of the ep collider HERA at DESY has recalled new attention on the subject of photoproduction because of the new energy regime and the particular kinematics, well suited for this kind of study. At HERA $26.7\,GeV$ electrons collide with $820\,GeV$ protons, with a resulting center of mass energy of $296\,GeV$. The ep differential cross section, dominated by photon exchange at low transverse momentum, has a $1/Q^4$ dependence. The bulk of events is produced at very small Q^2, i.e. the photon is not far off its mass shell. One talks then about *quasi-real* photons. The electron beam can be seen as accompanied by a photon flux and the ep cross section can be expressed in terms of the γp cross section through the equivalent photon approximation (EPA)[32]. In fact, neglecting the Z° contribution at small Q^2, the differential cross section for ep scattering can be expressed in terms of the cross sections for transversely and longitudinally polarized virtual photons:

$$\frac{d\sigma_{ep}(y,Q^2)}{dydQ^2} = \frac{\alpha}{2\pi Q^2}\left[\left(\frac{1+(1-y)^2}{y} - 2\frac{(1-y)}{y}\frac{Q^2_{min}}{Q^2}\right)\sigma_T^{\gamma p}(y,Q^2) + 2\frac{(1-y)}{y}\sigma_L^{\gamma p}(y,Q^2)\right], \quad (2)$$

where y and Q^2 are the usual DIS variables. Q^2_{min} is related to the *inelasticity* y by $Q^2_{min} = m_e^2 y^2/(1-y)$, y being

$$y = 1 - (E'_e/E_e)\cos\theta\,, \quad (3)$$

where E_e and E'_e are the incoming and scattered electron energies, and θ their relative angle. Since the quasi-real photons are collinear to the incoming and outgoing electrons, y, like in fixed target DIS, has the simple meaning of fractional energy of the electron carried by the exchanged photon: $y \approx E_\gamma/E_e$. The γp invariant mass energy is then $W_{\gamma p} = \sqrt{y}\cdot W_{ep}$.

As Q^2 becomes very small the exchanced photon behaves as a real one: $\sigma_L^{\gamma p}$ goes to zero while $\sigma_T^{\gamma p}$, for a given ep beam configuration, becomes only a function of y, i.e. of the γp center of mass energy $W_{\gamma p}$.

Integrating (2) over Q^2 the relation between the ep cross-section per unit of y and the γp cross section at a given y is obtained:

$$\begin{aligned}\frac{d\sigma_{ep}(y)}{dy} &= \frac{\alpha}{2\pi}\left[\frac{1+(1-y)^2}{y}\ln\frac{Q^2_{max}}{Q^2_{min.}} - \frac{2(1-y)}{y}\left(1-\frac{Q^2_{min}}{Q^2_{max}}\right)\right]\sigma_{tot}^{\gamma p}(y)\,, &(4)\\ &\equiv f_{\gamma/e}(y)\times\sigma_{tot}^{\gamma p}(y). &(5)\end{aligned}$$

The coefficient $f_{\gamma/e}(y)$ has the meaning of the equivalent photon flux, i.e. it gives the number of photons in the electron with energy between yE_e and $(y+dy)E_e$.

Q^2_{min} and Q^2_{max} appearing in (4) are related to the angular and energy coverage of the detectors in tagging the photoproduction events. The HERA experiments detect the $\approx 0^\circ$ outgoing electrons in the *luminosity monitors* typically in the energy range $\approx 5-21\,GeV$, equivalent to $0.2 < y < 0.8$, and a γp c.m. energy $130 < W_{\gamma p} < 260\,GeV$. The geometric acceptance is reflected in a Q^2_{max} of $\approx 10^{-2}GeV^2$.

Since most of the events are produced at very low Q^2 it is possible, with a good approximation, to study *untagged* photoproduction events, i.e. with no electron detected either in the luminosity monitor or in the main detector. The use of untagged photoproduction events makes it possible to gain a factor 5-6 in statistics. The minimum angle reached by the detectors close to the beam pipe gives for multihadron untagged events $Q^2_{max} \approx 4\,GeV^2$, with a useful range of y above ≈ 0.2 ($W_{\gamma p} > 130GeV$), required in order to reduce the beam-gas background. The $W_{\gamma p}$ range can be extended down to $\approx 40GeV$ in the case of inclusive final state analysis, like ρ° and J/ψ, as then the background conditions are less severe.

It is interesting to remark that, in the familiar picture of the DIS, high Q^2 virtual photons are seen to probe deeply the proton, with a resolution power of the order of $1/\sqrt{Q^2}$, while low Q^2 photons are imagined to have just peripheral interactions. This would give a first impression that the quasi-real photon interactions are uninteresting as far as the partons inside the proton are concerned. One has to notice, on the other hand, that in the proton rest frame the photons can have energies up to $44\,TeV$, and hence they have a wavelength much smaller than the proton size. Interactions with the proton constituents are then possible and the typical scale of the hard interaction becomes of the order of the transverse momentum of the final state partons.

The promising potentiality of HERA to perform a rich photoproduction program, coming from several peculiarities of the machine and the detectors, can be summarized as follow:

- in the proton rest frame the photon reaches $44\,TeV$ at the present ep energies of 27+820 GeV, with a γp invariant mass up to $300\,GeV$, one order of magnitude higher than fixed target experiments;
- the equivalent luminosity for γp is roughly one tenth of the ep one;
- in the laboratory frame the γp system is moving with an average rapidity[1] of approximately 2 units, i.e. a particle emitted at 90° in the γp rest frame is observed at 15° in the direction of the incoming proton. Since the detectors cover, in the laboratory frame, typically $|\eta| < 4$, there is good acceptance for the particles produced in the photon direction up to ≈ 6 units of rapidity;
- the *transparency* of the target (compared to fixed target experiments) allows a good measurement of final states.
- both experiments can tag electrons scattered at 0°, thus allowing the measurement of the quasi-real photon energy.

The other sources of information for the hadronic behaviour of the photon are the $\gamma\gamma$ collisions[33] at the e^+e^- storage rings. Depending on the virtuality of either photons one can speak about a collision between two quasi-real photons or about the DIS on a quasi-real photon (Fig. 2). As the e^+e^- detectors tag the scattered electron only above a certain polar angle - and hence above a minimum Q^2 - the two classes of events are usually called *no-tag* and *single tag*[2].

[1] In reality one deals with "pseudorapidity", calculated from the polar angle θ as $-\ln\tan\frac{\theta}{2}$.

[2] It is interesting to notice the different use between HERA and the e^+e^- machines of the term *tagged* and

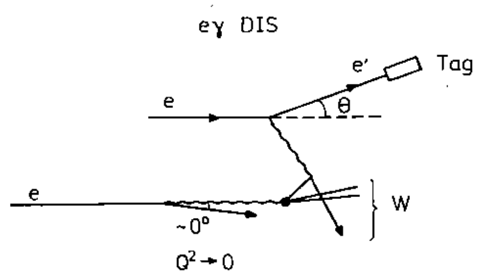


Figure 2: Diagram showing the $e\gamma$ DIS on a of a single tag $\gamma\gamma$ event.

4 Total and partial hadronic γp cross section at HERA

Among the first results of ZEUS[1] and H1[2] in 1992 has been the measurement of the total *hadronic* photoproduction cross section[3] $\sigma^{\gamma p}_{h\,tot}$ at $< W_{\gamma p} >\approx 200\,GeV$. Although the first measurements were obtained from a handful of events, the accuracy was enough to strongly favor a moderate increase of the cross section with respect to low energy data, instead of a steep rise. Hence extreme predictions of the total cross section based on minijets[5, 34] with too small p_T^{min} have not been confirmed. There is instead good agreement with simple parametrizations based on Regge phenomenology[35, 36]. Nevertheless, as has been recently pointed out[27, 37], these results are still consistent with a large minijet contribution (see also the comments in [38]).

ZEUS has recently published a new measurement of the total hadronic cross section, obtained from the 1992 fall data[3]. The value of

$$\sigma^{\gamma p}_{h\,tot}(< W_{\gamma p} >= 180GeV) = 143 \pm 7 \pm 17\,\mu b \qquad (6)$$

confirms the first results (see Fig. 3). The main sources of systematics are, apart from 4.3% due to the luminosity, the uncertainties in the electron tagger and in the main detector acceptance. The former has been reduced by restricting the fiducial energy range of the scattered electron. The latter, which depends on the different processes, has been deduced by fitting the photon component mixture that best describes the observed energy spectrum in the calorimeter. As the outcome of the fit the partial cross sections are obtained. The VDM-elastic cross section ($\gamma p \to Vp$) accounts for $13 \pm 5\,\%$ of the cross section, while $23 \pm 5\,\%$ is diffractive. The results on the partial cross sections are sketched in Fig. 1.

5 Hard scattering in γp and $\gamma\gamma$

The ZEUS result on partial cross sections indicate that almost 2/3 of the hadronic γp cross section comes from processes where the proton breaks up in the interaction and colour is exchanged between the proton and the physical photon. Of particular interest are the hard processes which can be described by perturbative QCD, for the reasons discussed in the introduction. Their

untagged. In $\gamma\gamma$ *untagged* simply means low Q^2 quasi-real photon and *tagged* high Q^2 virtual photon. At HERA both indicate quasi-real photons, with some possible DIS event contamination in the untagged sample.

[3] Although this cross section is often called simply "total" and indicated by $\sigma^{\gamma p}_{tot}$, it is important to remember that it differs from the "true total" cross section by the absence of the pure electromagnetic processes, like $\gamma p \to \gamma p$ and $\gamma p \to e^+e^-p$, whose contibutions are far from being negligible.

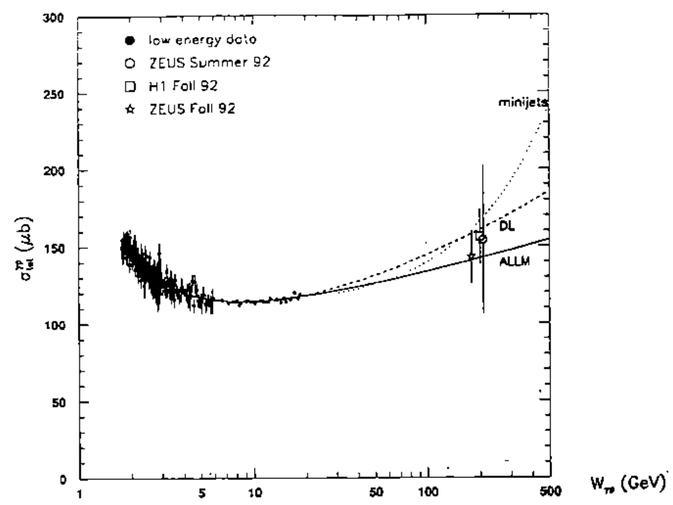


Figure 3: Total photoproduction cross section as a function of the γp center of mass energy.

global effect on the data have been easily observed in the event topology already with the first few nb^{-1} of luminosity[6, 7]: the distribution of the event transverse energy, as well as that of particle transverse energy, is far too hard with respect to what the elastic, diffractive and soft processes would allow, and jets structures have also been observed. Fig. 4 shows how the particles tend to cluster, in the transverse plane, around the particle with the highest p_t as the total transverse energy of the event increases. This is contrary to any simple phase space model. The jet observations at HERA have been the first in photoproduction. In fact it is interesting to notice that although there has been evidence of hard p_T tails in γp at fixed target, the first evidence of jet production in real photon beam collisions has shown up only this year by E683[18] at Fermilab.

Recently, clear jets have been observed also in $\gamma\gamma$[9, 10, 11, 12, 13, 16]. Fig. 5 shows, as an example, a nice two jet event recorded by TOPAZ[10].

Beside their spectacular aspects, the jet events are precious to understand the details of the hard processes and the properties of the photon. Looking at the diagrams of Fig. 1 (and thinking of the analogous ones in $\gamma\gamma$) one can easily imagine the questions which these events answer. In the following sections some of the questions to which an answer has been (often partially) given are outlined. Some other open questions will be discussed in the conclusions.

6 Evidence of the resolved photon interactions

The hard scattering of a resolved photon can be treated perturbatively independently of whether the photon is regarded as a vector meson or as an open $q\bar{q}$ with a relative transverse momentum much smaller than the scale of the hard interaction. A parton of the photon interacts with an external probe in a very short time interval and it is scattered at a large angle. The probe can be a lepton, a quark of another hadron, or a bare photon. The other partons do not participate in the interaction and continue moving along the photon direction, apart from long range colour interactions in the final state. Hence a clear signature[39] of the resolved photon is the event

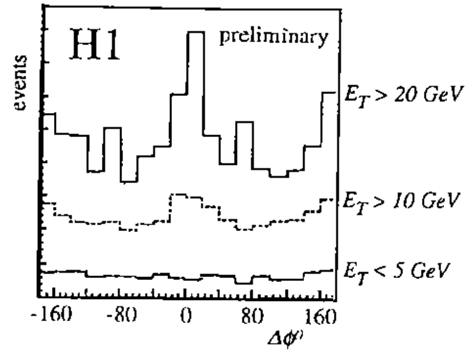


Figure 4: Azimuthal energy flow of charged particles with respect to the leading p_T charged particle as a function of the total transverse energy (H1[39]).

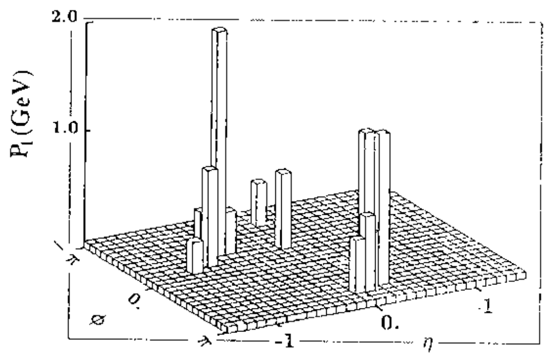


Figure 5: Example of two jet event observed in double tag $\gamma\gamma$ by TOPAZ [10]. The transverse momentum is shown as a function of the pseudorapidity (η) and the azimuthal angle (ϕ).

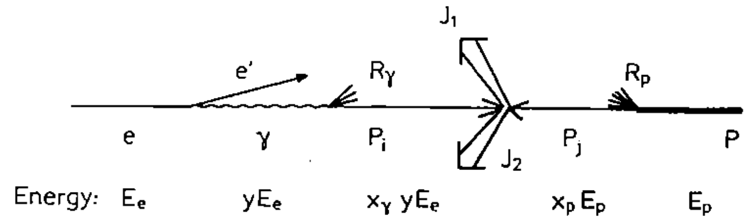


Figure 6: Diagram of a resolved photon event showing the meaning, in collinear approximation, the incoming parton fractional energies x_γ and x_p.

topology with two jets and some hadronic activity in the incoming electron direction.

Alternatively, using the 2-jet events one can calculate, from energy and momentum conservation, the fractional energy of the photon (x_γ) carried by the interacting parton, as can be easily seen from Fig. 6. In order to calculate x_γ one needs to know the photon energy from the measurement of y. This can be achieved either by tagging the electron or by making use of the Jacquet-Blondel method[41]:

$$y_{JB} = \frac{1}{2E_e} \sum_h \left(E^h - p_z^h\right) , \tag{7}$$

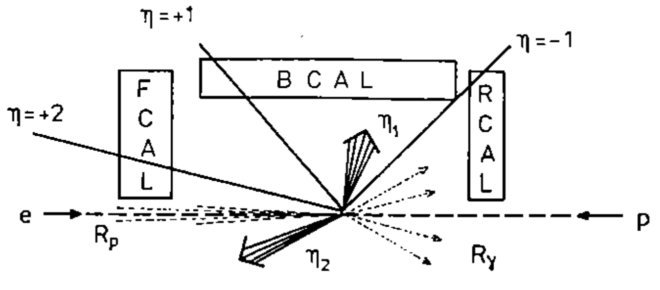
where the sum runs over all measured particles with the exception of the scattered electron. One has to notice that, although this method has been shown to work well at low Q^2 in photon-gluon fusion events[42], in the case of resolved photon processes the loss of some small angle particles in the direction of the photon could make the y measurement systematically underestimated. Several formulae can be used for x_γ depending upon whether the momentum or the transverse energy and rapidity of the jets are used.

In $\gamma\gamma$ only the first method can be used, as there is no way to know in no-tag events the individual energy of the photons event by event. A different, indirect, method is to compare the event topologies or jet differential cross sections with theoretical predictions using different hypotheses.

Presently all high energy γp and $\gamma\gamma$ agree on the evidence of resolved photon interactions. We show here the ZEUS result[6], because of its straightforward interpretation. Fig. 7 shows, for the 2-jet sample, the energy collected in the part of the calorimeter called RCAL (covering roughly 50° around the beam pipe along the electron direction) as a function of the minimum rapidity of the two jets η_{min}. One can notice that, even for η_{min} larger than 0, there is still up to 15 GeV collected in RCAL due to the photon remnant, with little dependence on η_{min}.

7 Evidence of direct interactions of photons with hadrons

Most of the global features of photoproduction up to the maximum energies reached at fixed target experiments can be explained in terms of a hadronic photon, although even the early cross section measurements[43] suggested an additional bare photon contribution. Also the hard p_T spectrum, very similar to the one of hadron-hadron collisions at the same energy, indicates that even parton-parton collisions are mostly due to the partonic structure of the vector mesons. Several studies were made in order to find evidence of the point like component of the photon, in particular at CERN by NA14[44, 45] and WA69 (Omega-Photon Collaboration)[46, 47]. Comparing photo- and hadro-production they found that, generally speaking, a *non*-VDM component was needed to describe a harder component absent in hadroproduction. This conclusion



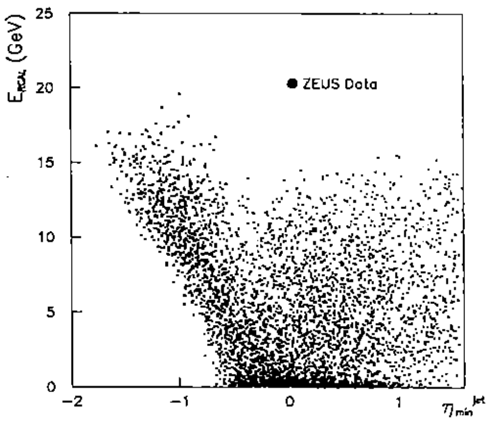


Figure 7: Energy detected in the rear part of the calorimeter (RCAL) as a function of the minimum jet rapidity (see also the text and the sketch above the scatter plot).

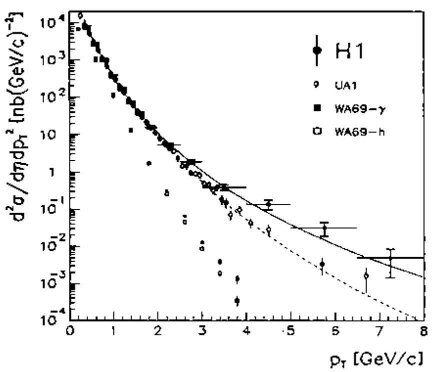


Figure 8: Comparison of inclusive transverse energy distribution of charged particles in hadro- and photoproduction (H1 [48]).

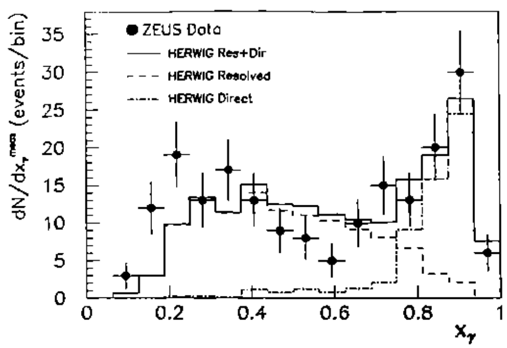


Figure 9: Distribution of x_γ, the momentum fraction of the parton of the photon which enters the hard scattering. The peak close to one is due to the direct photon contribution.

relies on the assumption that the (not measurable) vector meson parton densities are simply related, via the quark model, to those of π and K[46]. A similar analysis has recently been done by H1[48], which has compared the p_T spectrum of charged particles produced at an average $W_{\gamma p}$ of $197\,GeV$ with UA1 $p\bar{p}$ data at $200\,GeV$[49]. As in the WA69 analysis, the γp data show a shape similar to the $p\bar{p}$ ones up to $\approx 2\,GeV/c$, then the γp spectrum becomes harder (see Fig. 8). Although in this case the validity of the replacement of a vector meson by a proton is even more doubtful than in the WA69 analysis, it is interesting that the comparison shows the same trend. Apart from these uncertainties, these kinds of comparisons are not able to disentangle the direct and the anomalous components.

More convincing indications of the point-like direct coupling of the photon come from reactions which are particularly sensitive to the photon-parton collision. Evidence of γq scattering comes from the NA14 analysis[44] of DIS QED Compton ($\gamma q \to \gamma q$), while charm photoproduction with E691[50], NA14/2[51] and E687[52] has been shown to be sensitive to the photon-gluon fusion ($\gamma g \to c\bar{c}$) and in good agreement with the theoretical predictions[53].

At HERA ZEUS[8], using the x_γ measurement previously described, has shown a nice two component feature of the 2-jet events (see Fig. 9), indicating for the first time the presence of direct photon interactions in hard scattering. The same can be seen topologically in Fig. 7. One can notice an accumulation of points between[4] $-0.5 < \eta < +0.5$ with no energy in RCAL. They are attributed to the 2-jets events without remnants, and the calculation of their x_γ provides a consistent result.

8 Jet differential cross section

Using the collinear approximation shown in Fig. 6 it easy to show that the mass invariant squared and the rapidity of the hard scattering system is related to the beam energies and the fractional momenta x_γ and x_p by the following relations:

$$\hat{s} = 4x_\gamma x_p y E_e E_p = x_\gamma x_p y s\,, \qquad (8)$$

$$\hat{\eta} = \frac{1}{2}\ln\frac{x_p E_p}{x_\gamma y E_e}, \qquad (9)$$

[4]The upper limit in η is just an artifact of the event selection, as it is impossible to take untagged γp events with all particles going in the forward proton direction, due to the high proton-gas background.

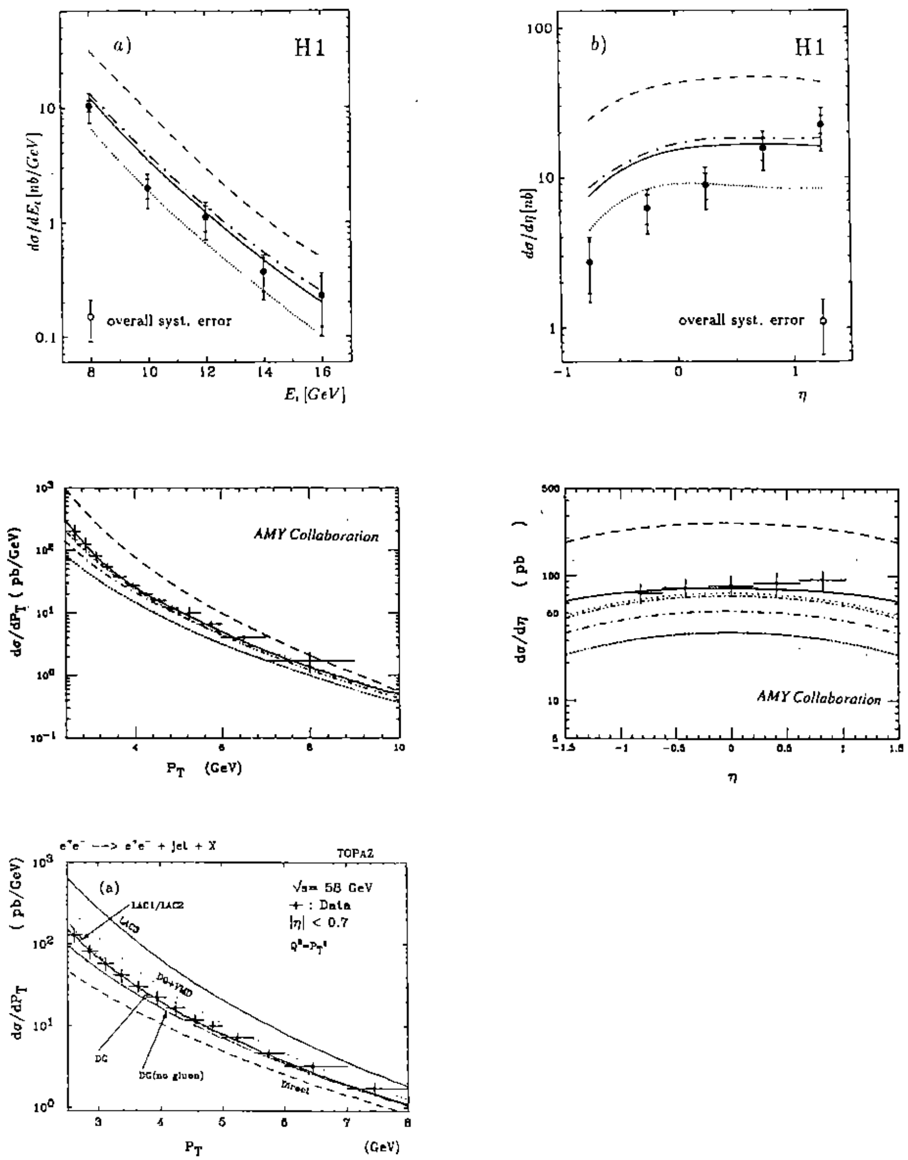


Figure 10: Inclusive jet differential cross sections measured in γp and in $\gamma\gamma$: $d\sigma/dE_T$ (left) and $d\sigma/d\eta$ (right). H1[54]: dashed, dashed-dotted, full and dotted lines stay for LAC3[23], LAC2, GRV-LO[24] and GRV-LO without gluon. AMY[11]: dot-dashed line represents LAC1[23] without gluon; for the other curves see Fig. 11. TOPAZ[10]: as indicated in the figure; DO and DG stay for the parametrizations of refs. [21] and [22].

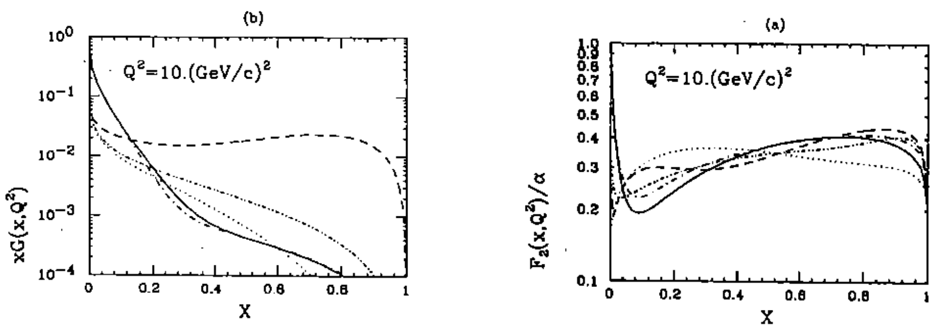


Figure 11. Comparison of $xg^\gamma(x)$ and $F_2^\gamma(x)$ parametrizations at $Q^2 = 10GeV^2$. Solid, dot-dashed, dashed, dotted and double-dot-dashed lines represents the LAC1[23], LAC2, LAC3, DG[22] and GRV[24] predictions.

where s is the ep invariant mass squared. Similar formulae hold for $\gamma\gamma$ if E_p is replaced by the energy of the second photon $(y_2 E_e)$ and x_p by x_{γ_2}.

In the case of two jet production, they have, in their center of mass frame, opposite rapidity, the module of which is indicated by η^*, related to the production angle by $\cos\theta^* = \tanh\eta^*$. Since the rapidities are additive under a Lorentz boost, the jet rapidities in the laboratory are $\eta_{1,2} = \hat{\eta} \pm \eta^*$. Moreover, the jet-jet invariant mass can be written in terms of η^* and the transverse momentum p_T as $\hat{s} = 4p_T^2\cosh^2\eta^*$.

Even if the simple picture offered by these formulae is modified by QCD corrections[54], one can see that the jet inclusive distributions are sensitive to the parton content in the proton and in the photon and to the dynamics of the hard scattering (the EPA is assumed to be correct). It is interesting to notice that the 2-jet events offer the possibility to somehow disentangle the contribution due to the structure function from those due to the hard process dynamics, as the center of mass scattering angle is related to the measured jet rapidities by $\cos\theta^* = \tanh[(\eta_1 - \eta_2)/2]$.

Several measurements of the jet differential cross sections, with comparisons to the theoretical expectations, as functions of transverse momentum and rapidities have been presented. In Fig. 10 are reported the results of H1[55], AMY[10] and ALEPH[12]. The results are compared with QCD predictions and several parametrizations of the photon structure functions. Apart from the H1 result, which disagrees with the shape of the rapidity distribution, all other results are in good agreement with the QCD expectations. Since the parametrizations mainly differ because of the gluon density (see Fig. 11) the comparisons show the discrimation power of the data within the present uncertainties. For example, LAC3[23], which has a very hard gluon, is ruled out. Similarly, the data cannot be explained by only direct photon interactions. Apart from some extreme cases of this kind, the present accuracy of the measurements is not yet adequate to make a clear discrimination between the models.

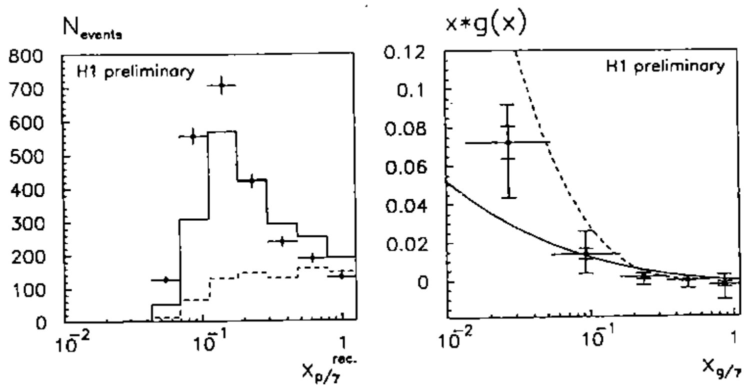


Figure 12: a) x_γ distribution (H1[56]) compared with the MC predictions using the GRV parametrization with (solid line) and without (dashed line) the gluon; b) $xg^\gamma(x)$ compared with the GRV (solid line) and the LAC1 (dashed line) predictions.

9 Direct measurement of the photon PDF

Instead of just comparing the model expectations with the differential cross section it may be desirable to infer directly the parton distribution from the experimental data. This is particularly true for the gluon density, as all present parametrizations come from fits to the photon structure function F_2^γ at high x, directly related to the quark densities. In fact F_2^γ is sensitive to the gluon density only through the evolution equations. Moreover, unlike the proton structure functions, there is no sum rule to constrain the gluon density.

One can make use, for example, of the measurement of the x_γ previously described to get the parton distribution inside the photon. To go from the generic parton to the gluon, one needs to subtract the quark contribution, or to go into kinematic regions where the gluon is supposed to dominate. The first preliminary analysis of this kind has been presented to conferences by H1[56]. Fig. 12 shows the x_γ distribution before and after the quark substraction performed with the expectations of the GRV parametrization[24]. Even if a caveat on the validity of the results is mandatory, due to the use of the quark distribution in a region below the range where the fit was performed, and to the fact that the x_γ distribution has to reflect somehow the disagreement of the η distribution of Fig. 10, this method should be exploited at HERA when higher statistics are available.

10 Conclusions

The last few years have brought quite a lot of nice results from photoproduction and $\gamma\gamma$ physics: $\sigma_{tot}^{\gamma p}$ has been measured at the c.m. energy one order of magnitude higher than the previous ones; hard scattering and jets have been seen in $\gamma\gamma$ and γp; the direct and resolved components of the quasi-real photon have been observed in an impressive way. Presently, the differential cross section measurements start to have an accuracy such as to allow precision QCD tests and a detailed study of the photon parton density. It is an easy prediction that in the near future the combination of old and recent F_2^γ measurements, together with the jet differential cross sections from γp and $\gamma\gamma$, will finally pin down the photon gluon density.

Some other questions which are left open are:

- is there a way to prove the anomalous component of the photon structure functions?
- what is the flavour composition of the photon?
- is it possible to prove the presence of the gluon component of the photon from some dynamical behaviour instead of from just inclusive measurements?

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