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Recent results on resolved photon processes

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Abstract. During the last 18 months, experiments at both e^+e^- and ep colliders have begun to test earlier predictions for processes that probe the hadronic structure of the photon. All the main qualitative predictions have already been verified; more detailed analyses are now starting to improve our quantitative understanding of photon structure functions. Some comments on minijets and total cross sections are also included.

1. What are "resolved photon processes"?

The hard scattering between a real (on–shell) photon and a hadron can proceed in two quite different ways: The photon can either couple directly to the partons (quarks and gluons) inside the hadron; in these "direct processes" the entire photon energy is available for the hard partonic scattering. Alternatively, the photon can itself undergo a transition into a (virtual) hadronic state, so that the partons "in" the photon [1] interact with the partons in the hadron; in these "resolved photon" processes only some fraction of the photon energy is available for the hard scattering, the rest being carried away by a "remnant" or "spectator" jet that results whenever a coloured parton is "pulled out" of a colour–singlet object (hadron or photon).

Since resolved photon events contain an additional spectator jet, their cross–section depends more sensitively on the size of the available phase space than the cross–section for direct contributions does. Mathematically this results from a factor of the parton density in the photon $\vec{q}^{\gamma}(x, Q^2) \equiv (q_i^{\gamma}, G^{\gamma})(x, Q^2)$ in the cross–section formula, which in case of direct processes has to be replaced by $\delta(1-x)$. Consider e.g. the simple case of di–jet production in γp collisions:

$$\frac{d\sigma^{\rm res}(\gamma p \to \text{jets})}{dp_T} = \int_{x_{min}}^{1} dx_1 q_a^p(x_1, Q^2) \int_{x_{min}/x_1}^{1} dx_2 q_b^{\gamma}(x_2, Q^2) \frac{d\hat{\sigma}(ab \to \text{jets})}{dp_T}(\hat{s}, p_T), \tag{1}$$

where $\hat{s} = x_1 x_2 s$ with $\sqrt{s}$ the γp cms energy, $x_{min} = 2p_T/\sqrt{s}$, and $\hat{\sigma}$ is the hard partonic $2 \to 2$ cross–section [2]. In case of the direct contribution the second integral is not necessary; therefore the cross–section is less sensitive to changes of x_{min}. As a result, the size of resolved photon contributions will always drop faster with increasing p_T than that of the direct contribution, and will increase more rapidly with increasing energy.

It should be emphasized that resolved photon contributions are *not* higher order corrections to direct contributions. The reason is that the parton densities in the photon grow logarithmically [1] with the momentum scale Q^2 of the process under consideration; in a leading–log summed perturbation theory this has to be counted as a factor of $1/\alpha_s(Q^2)$, since here one considers $\alpha_s(Q^2)\ln Q^2 \sim \mathcal{O}(1)$. Therefore $\vec{q}^{\gamma} \sim \mathcal{O}\left(\alpha/\alpha_s(Q^2)\right)$, so that direct and resolved photon processes occur at the same order in perturbation theory.

I will now briefly describe theoretical predictions for and recent experimental results on resolved photon processes in $\gamma\gamma$ scattering at e^+e^- colliders as well as γp scattering at ep colliders. For reasons of space I cannot discuss many of the interesting recent developments in the theory and phenomenology of resolved photon processes; the interested reader may find some more information in ref.[3].

2. Jet production in real $\gamma\gamma$ scattering

Since we now have two photons in the initial state, we actually have to consider 3 classes of hard (perturbatively calculable) contributions [4], see Fig. 1: In the direct process both photons couple directly to the quark line, giving rise to a $q\bar{q}$ final state, while in the single (double) resolved contribution, one (both) photon(s) is (are) resolved, giving rise to one (two) spectator jet(s). The corresponding cross–

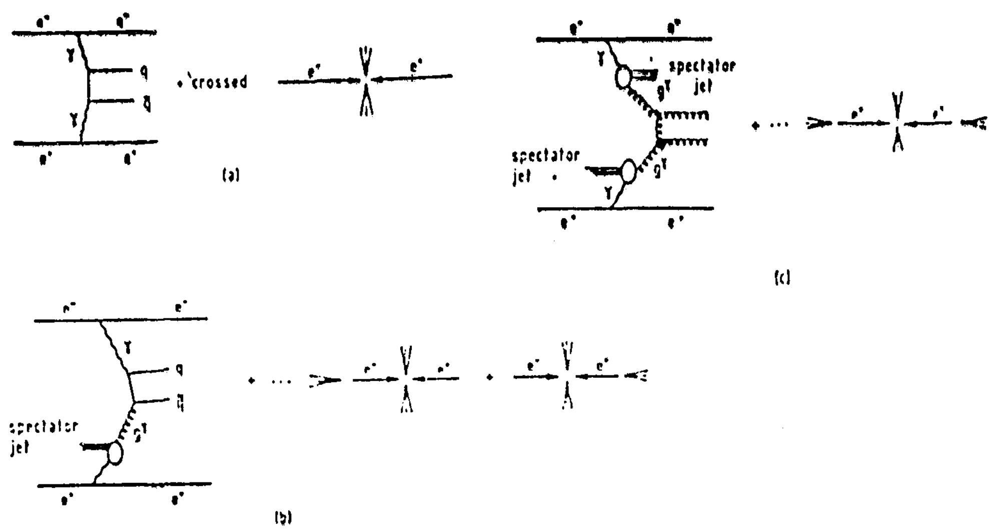

Figure 1. Different contributions to the production of high p_T jets in e^+e^- collisions with the associated topologies.

sections were for the first time estimated in refs.[5], using simple analytical approximations for $\vec{q}^{\gamma}(x,Q^2)$. The first calculation using an at least potentially realistic parametrization [6] for $\vec{q}^{\gamma}$ was presented in ref.[7]. A sample result is shown in Fig. 2, where the p_T spectrum of the produced jets is plotted for $\sqrt{s}\ (e^+e^-) = 60$ GeV, the operating energy of the TRISTAN collider at KEK in Tsukuba, Japan.

As expected from the discussion in the previous section, the resolved photon con-

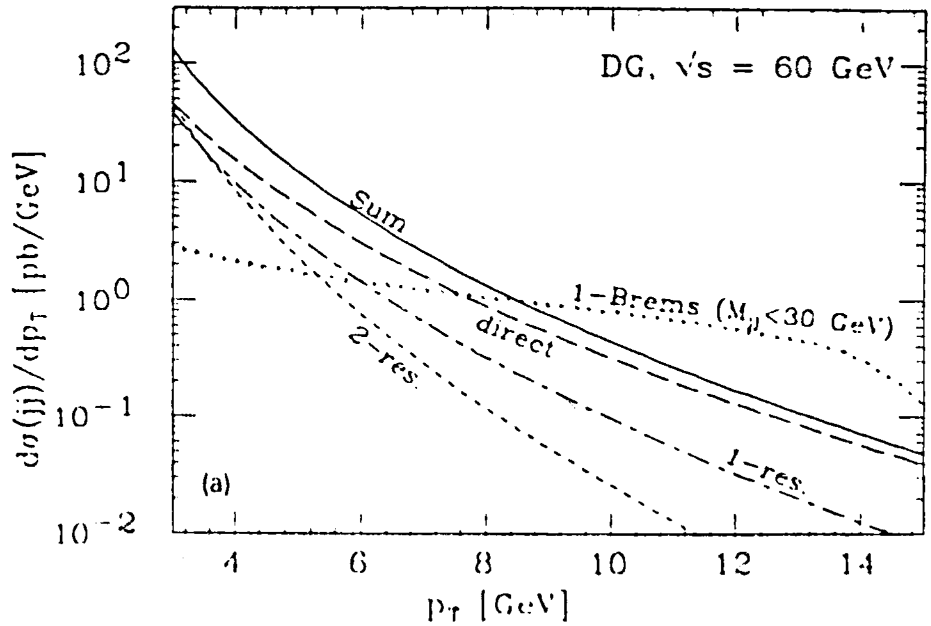

Figure 2. The transverse momentum spectrum of jets produced in real $\gamma\gamma$ scattering at $\sqrt{s}$ = 60 GeV, for the DG parametrization.

tributions have a steeper p_T spectrum. Moreover, the additional spectator jet(s) should make these events more spherical, i.e. they should tend to have smaller thrust. Of course, much of the spectator jet(s) will be lost in the beam pipes and the surrounding dead zones. However, the colour flow between the spectator jet(s) and the hard jets, as well as the boost of the $\gamma\gamma$ cms system with respect to the lab frame, usually ensure that at least parts of these jets are visible in the detector.

Fig. 2 shows that the sum of the resolved photon contributions actually exceeds the direct contribution for $p_T \leq 4.5$ GeV, at least according to the "DG" parametrization of ref.[6] that has been used in this calculation; this is a quite respectable transverse momentum for two photon physics. As expected from the previous section, resolved photon contributions are relatively less important at lower (PEP and PETRA) energies. Nevertheless, it was speculated in ref.[7] that they might provide the "third component" found in previous analyses of $\gamma\gamma$ scattering data [8]. These analyses had consistently shown that the sum of the direct ("QPM") contribution and a "soft" contribution (with exponential p_T spectrum, estimated from VMD ideas) could *not* describe the data; the excess was concentrated at small thrust, and had a steeper p_T spectrum than the direct contribution, but harder than the VMD contribution.

Stimulated by the results of ref.[7], the AMY collaboration at the TRISTAN collider decided to prepare an MC program for $\gamma\gamma$ collisions that includes the resolved photon contributions. They found [9] that this MC simulation reproduces their data quite well. For this analysis a cut–off parameter $p_{T,min}$ had to be introduced, which determines the minimal partonic transverse momentum allowed for the hard contributions; such a cut-off is necessary since the partonic cross-sections diverge badly as $p_T \to 0$. $p_{T,min}$ describes the limit of applicability of perturbative QCD; one thus expects it to lie between 1 and 2 GeV. Indeed, AMY finds $p_{T,min}$ = 1.6 GeV if the data are to be described by the DG parametrization. It should be mentioned that AMY does not use a jet finding algorithm; rather, the whole event is split into two thrust hemispheres. The measured transverse momentum is simply the sum of the p_T's of all the particles in one hemisphere; its relation to the partonic p_T is rather indirect. Nevertheless the region $p_T(\text{thrust}) \geq 3$ GeV is quite insensitive to the choice of $p_{T,min}$. In Fig. 3 we therefore show the thrust distribution of events in this region. The agreement between the QCD MC prediction and the data is satisfactory, if and only if resolved photon contributions are included. The figure can even be interpreted as first experimental evidence that the photon

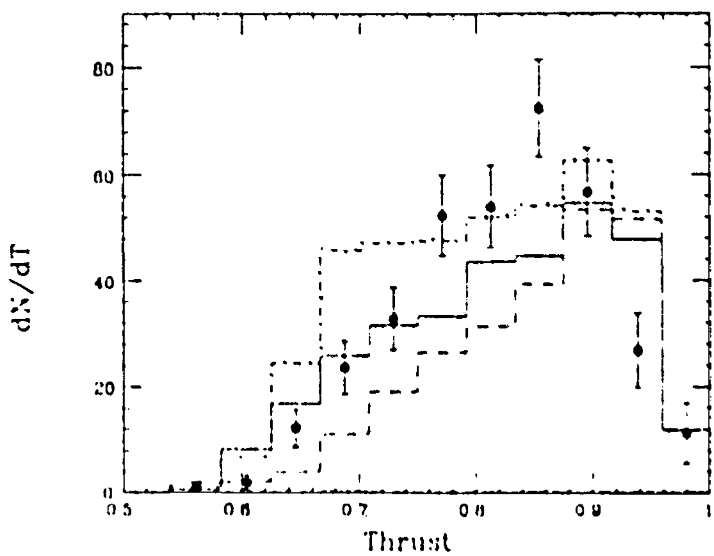

Figure 3. Data on the thrust distribution of $\gamma\gamma$ events with $p_T \geq 3$ GeV compared with various Monte Carlo predictions: The dotted histogram shows the prediction of the "QPM+VMD" model, while the solid, dashed and dot-dashed histograms show the predictions using the full DG parametrization, DG with $G^\gamma = 0$, and the DO+VMD parametrization [10], respectively. From ref.[9].

has a nonzero gluon content. Finally, it should be emphasized that inclusion of the spectator jets is crucial to obtain agreement between MC predictions and data [11].

More recently, the TOPAZ group from TRISTAN as well as the LEP experiments ALEPH and DELPHI have confirmed the AMY result [12], using independent MC codes. The AMY group continues to collect more data and to refine their analysis. In particular, they have compared their data with the more recent "LAC" parametrizations for $\vec{q}^\gamma(x, Q^2)$ [13]. They find [14] that the LAC1 parametrization describes the data slightly better than the DG parametrization does, while the LAC3 parametrization, which assumes a very hard and large gluon component of the photon, is clearly excluded. Finally, very recently the TOPAZ collaboration announced [15] that they succeeded in extracting a partonic cross–section from their data. For the first time in two photon physics they actually used a jet finding algorithm; nevertheless some "unfolding" of the data using Monte Carlo techniques was necessary to extract the QCD cross–sections. The preliminary results are in good agreement with predictions from the DG and LAC1,2 parametrizations, while LAC3 predicts a cross–section that exceeds the measured one by more than a factor of three. This measured partonic cross–section also allows theorists to directly test their favorite model for $\vec{q}^{\gamma}(x, Q^2)$.

3. Jet production in γp scattering

Compared to $\gamma\gamma$ scattering at existing e^+e^- colliders, γp scattering at the ep collider HERA operating at DESY in Hamburg, Germany, offers much larger cross–sections and higher energies. The cross–section is now of order $\alpha^2 \ln s/m_e^2$, compared to $\alpha^4 \ln^2 s/m_e^2$ for $\gamma\gamma$ scattering; at HERA ($\sqrt{s}$ (ep) = 314 GeV), γp cms energies up to 250 GeV can be probed, while even LEP is only sensitive to $\gamma\gamma$ energies up to 40 GeV or so.

The importance of resolved photon contributions to real γp scattering (photoproduction) was first pointed out by Owens [16]. The first calculations of jet production rates at HERA appeared in refs. [17] and [18]. In the former paper resolved photon contributions were still treated as higher order corrections, which is inconsistent from the point of view of leading log summed perturbation theory; it also makes it difficult to appreciate the importance of these contributions at HERA. This point is brought home by Fig.4, where we show the ratio of resolved and direct contributions to the production of two high p_T jets at HERA. We see that even the conservative DG parametrization predicts this ratio to exceed 10 for $p_T \leq 5$ GeV; it remains larger than 1 all the way up to $p_T \simeq 35$ GeV. The absolute size of the cross–section amounts to about 3 μb/GeV (9 nb/GeV) at $p_T = 3$ (10) GeV.

Recently the two HERA experiments H1 [19] and ZEUS [20] have published analyses of the first 1 nb^{-1} worth of photoproduction data. Both groups find the cross–section for the production of events with sizable transverse energy E_T to be too large to be described by direct processes alone. On the other hand, once resolved photon contributions are included, the measured cross–section can be reproduced nicely. This is illustrated in Fig. 5, which shows the cross–section for events with $E_T > E_{T,0}$ vs. $E_{T,0}$ as measured by the ZEUS collaboration [20]. The curve shows MC predictions using the DG parametrization with $p_{T,min} = 1.5$ GeV; obviously it describes the data well.

As already emphasized in the first section, the kinematics is different for direct and resolved photon contributions. Due to the asymmetric initial state this manifests itself also in the rapidity (or angular) distribution of high p_T jets produced in γp collisions: Since a parton "in" a photon carries less energy than the photon itself, the parton in the proton has to contribute more energy–momentum if the total invariant mass of the partonic system is to remain constant. This means that the partonic system will be boosted in the direction of the proton beam. This boost will be stronger for softer partons in the photon; we therefore expect the contributions from gluons in the photon to be peaked at larger rapidities. This is demonstrated in Fig. 6. Notice that the direct contribution actually peaks at negative rapidity,

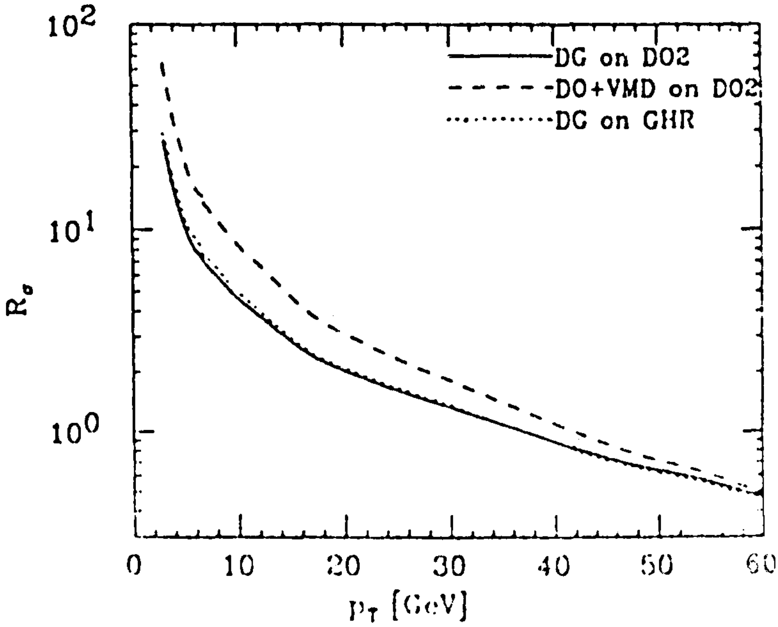

Figure 4. Ratio of resolved and direct contributions for $d\sigma(ep \to \text{jets})/dp_T$ as a function of p_T [18].

because the (bremsstrahlung) photon spectrum is harder than the parton spectrum in the proton; configurations with a soft parton (gluon) in the proton and a hard photon are more likely to occur than those with a soft photon and a hard parton.

At present the number of HERA events with reconstructed jets is still quite small. However, already the sample of 51 events seen by H1 in the first run [19] indicates that the angular distribution more closely follows the pattern expected from resolved photon contributions: The region close to the proton beam is populated, while only few events are found at negative rapidities.

Of course, the most direct signature of resolved photon events remains the spectator jet from the photon. The presence of such jets has already been inferred from the thrust distribution of $\gamma\gamma$ events, as described in the previous section. The good angular coverage of HERA detectors, as well as the strong boost from the γp system to the lab frame which increases the opening angle of the spectator jet, allows for a more direct observation of this jet. This is illustrated in Fig. 7, which shows the energy flow in the H1 calorimeter [19]; only events where both high p_T jets are more than 80° away from the electron beam direction are included. As a result, in direct events one expects almost no energy flow at $\theta \geq 150°$ (the proton beam direction corresponds to $\theta = 0$ here); in contrast, the data show a constant or even slowly increasing energy flow in that region, in good agreement with MC simulations of resolved photon contributions.

4. Minijets and total cross sections

We have already seen in sec. 2 that partonic processes with transverse momentum as

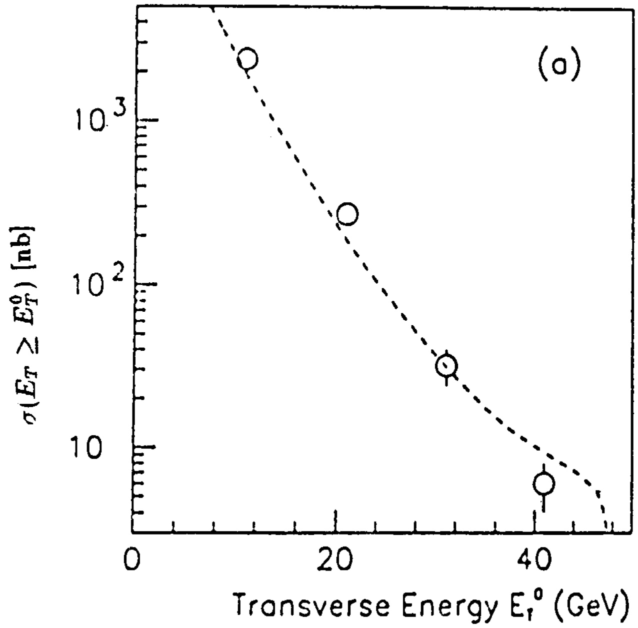

Figure 5. The total *ep* cross-section for transverse energies larger than E_T^0 measured by ZEUS [20]. The curve is the HERWIG prediction, using the DG parametrization with $p_{T,min} = 1.5$ GeV.

small as 1.5 GeV have to be included in order to reproduce existing $\gamma\gamma$ data. The production cross-section for "minijets" with $p_T \simeq p_{T,min}$ will grow very rapidly with increasing energy; this has been suggested as a possible explanation of the growth of the total pp and $p\bar{p}$ cross-sections [21]. It should be noted that the inclusive minijet cross-section will be larger than the total inelastic cross-section at high energies; this implies that the average number of minijet pairs per interaction will be larger than 1. Mathematically the relation between the hard inclusive (QCD) cross-section and the total cross-section is given by an eikonal formalism [21]. For the case of γp collisions one writes [22]

$$\sigma_{\text{tot}}^{\gamma p} = \int d^2 b P_{\text{had}} \left\{1 - \exp\left[-\left(\sigma_{\gamma p}^{\text{hard}}(s) + \chi_{\gamma p}^{\text{soft}}\right) A(b)/P_{\text{had}}\right]\right\}. \tag{2}$$

Here, $A(b)$ describes the transverse distribution of the partons, $\sigma_{\gamma p}^{\text{hard}}$ is the hard QCD cross-section (defined as an integral over the region $p_T \geq p_{T,min}$), $\chi_{\gamma p}^{\text{soft}}$ is a soft (nonperturbative) contribution to the eikonal which can be fitted from low energy data, and P_{had} describes the probability for the photon to go into a (virtual) hadronic state. Clearly the prediction for the total cross-section depends on several parameters that cannot be computed perturbatively: P_{had}, $A(b)$, $p_{T,min}$ and the parton densities at low x. It is therefore not surprising that predictions [22,23] for the total γp cross-section varied widely prior to the recent measurements [24,25] of this quantity at HERA. An example is shown in Fig. 8, where low energy data and the recent ZEUS measurement are compared to some model predictions. Both Pomeron-based fits of low energy data and a minijet calculation using the DG

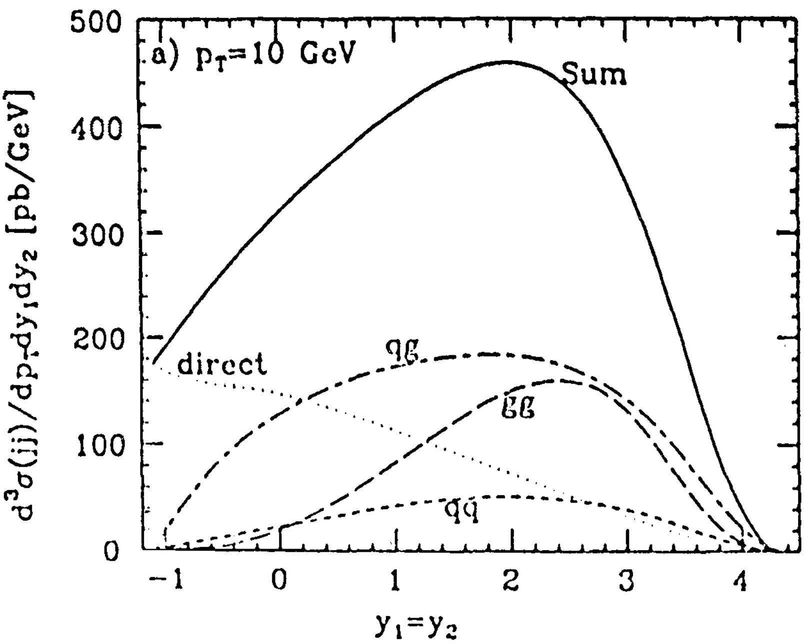

Figure 6. The rapidity distribution of jets produced at HERA. The resolved photon contributions with different final states are shown separately. From ref.[18].

parametrization with $p_{T,min} = 2$ GeV and a VMD–inspired choice of P_{had} and $A(b)$ describe all existing data; the LAC1 parametrization seems disfavoured, but might be rescued by using a different choice of P_{had} and/or $A(b)$. As long as we cannot compute these parameters, or at least fit them unambiguously from existing data, we cannot make firm predictions for the behaviour of the total γp or $\gamma\gamma$ cross–section at high energies.

Nevertheless we *can* predict already now that some existing designs for future linear e^+e^- supercolliders (linacs) will have [26] more than one 2–photon event per bunch crossing, i.e. suffer from an "underlying event", which might make it difficult to perform precision experiments. The culprit here is not so much the $\gamma\gamma$ cross–section, which may or may not rise with energy, but the $\gamma\gamma$ flux, which is expected to be very large at these colliders. This is due to beamstrahlung [27]. In linear high energy colliders, a very large luminosity per bunch crossing has to be achieved in order to maintain a useful rate of annihilation events. That forces one to use very dense bunches, which give rise to strong electromagnetic fields. When the particles in the opposite bunch enter these fields, they are accelerated and therefore radiate real photons. The amount of beamstrahlung produced depends on the size and shape of the bunches. Since the luminosity per bunch crossing can be smaller if many bunch collisions occur in a given unit of time, beamstrahlung intimately linked with the design of the accelerating structures.

The increased photon flux due to beamstrahlung obviously increases the rates for all 2–photon reactions. However, not only the normalization but also the shape

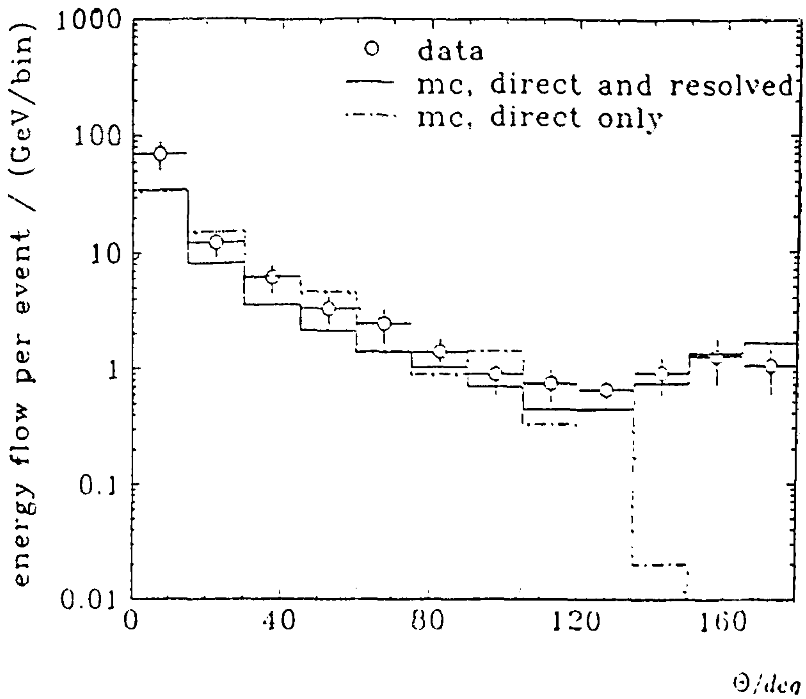

Figure 7. Histogram of energy flow per event versus polar angle. The open points represent the data, while the full and dotted lines give the MC prediction with and without resolved photon contributions. From ref.[19].

of the beamstrahlung spectrum differs between different designs; this also means that some cross-sections are more sensitive to beamstrahlung. A detailed discussion of these effects can be found in ref.[28]. In particular, it was found that existing designs of e^+e^- linacs operating at $\sqrt{s} = 500$ GeV produce between 0.004 and ~ 25 minijet pairs in a time slice of 10 nanoseconds. Since a clean experimental environment, without underlying event, greatly facilitates the detailed study of annihilation (and hard $\gamma\gamma$) events, keeping the number of soft and semi-hard $\gamma\gamma$ reactions per bunch crossing small should be an important consideration in the design of future e^+e^- colliders.

5. Summary and conclusions

The existence of resolved photon processes has been established in at least 6 independent experiments: AMY and TOPAZ at TRISTAN; ALEPH and DELPHI at LEP; and H1 and ZEUS at HERA. All theoretical predictions have been borne out at least qualitatively. Quantitative predictions depend on the parton densities in the photon; different parametrizations vary widely for the quark content at small x and the gluon content at all x. The old DG parametrization seems still viable, while the more recent LAC3 parametrization is clearly excluded by AMY and TOPAZ data, and the LAC1 and LAC2 parametrizations seem to be disfavoured by the

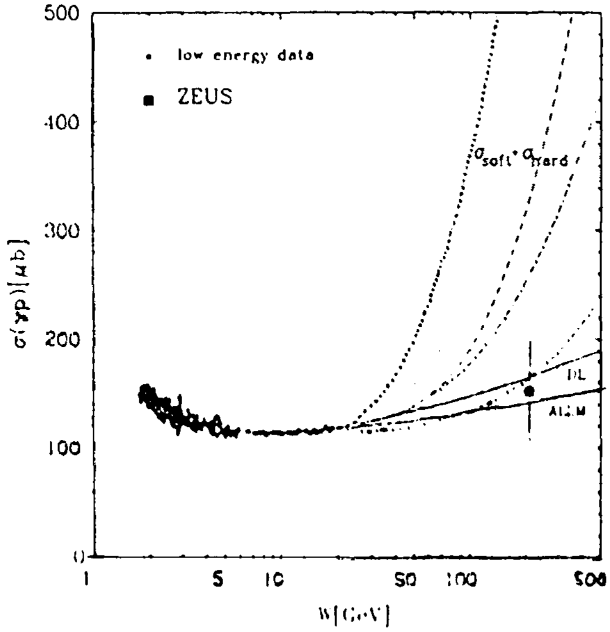

Figure 8. Comparison of low energy data and the recent ZEUS measurement of the total γp cross-section with theoretical models. The two solid curves are Pomeron-based fits of the low energy data. The other curves are predictions of minijet models; the dot-dashed curves are for the DG parametrization, while the dotted and dashed curves are for LAC1. In both cases the upper (lower) curve is for $p_{T,min} = 1.4$ (2.0) GeV. From ref.[24].

recent measurements of the total γp cross-section at HERA. It should be stressed, however, that total cross-sections cannot be predicted unambiguously from perturbative QCD; especially where photons are involved, there is no general agreement yet on the proper way to unitarize the jet cross-section.

In the near future more detailed information about the parton content of the photon and on the transition from the soft to the hard region should become available. I would not be surprised if then all existing parametrizations of the hadronic structure of the photon will be found wanting in some respect. In spite of our present lack of knowledge, we can predict with some confidence that designs of e^+e^- supercolliders that produce a large beamstrahlung flux will suffer from an underlying event, i.e. will not be as clean as traditional e^+e^- storage rings. Even if beamstrahlung can be kept under control, the importance of resolved photon contributons will continue to grow with energy; the study of these interactions will thus be of increasing importance at future high energy colliders.

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Discussion

X. Tata : Why did the $p_{T,min}$ in the last figure you showed change from 1,5 GeV to 2 GeV [1.5 GeV was its value in earlier figures, I think]?

M. Dres : The last figure was from the ZEUS paper on $\sigma_{\rm tot}(\gamma {\rm p})$; it shows "typical" minijet predicitions. However, I should emphasise that "minijet" calculations contain additional free parameters besides $p_{T,min}$ and $\vec{q}^\gamma$ (x,Q^2). One is the transverse distributon of partons in the photon, the other is the probabilitity P_{had} of the photon to go into a hadronic state. ZEUS estimates these from VMD, but this is not particularly compelling. Hence the interpretation of the $\sigma_{\rm tot}(\gamma {\rm p})$ measurement is not straight forward in QCD.

H.S. Mani : What is the difference between LAC distribution and the DG ditribution function?

M. Drees : The LAC1 and LAC2 parametrizations assume a very large gluon content of the photon at small x. These small x values are now being probed in photoproduction experiments at HERA.

R.V. Gavai : The resolved photon processes crucially needed the (α/α_s) factor. Can you please explain its origin and specify its region of validity?

M. Drees : Peterbative calculations of the (evolution of) $\vec{q}^\gamma$ always include diagrams with potentially on-shell partons, leading to logarithmic singularities. These lead to a behaviour $\vec{q}^\gamma$ $(\mathrm{Q}^2) \sim \ln \mathrm{Q}^2$. In leading log summed QCD, which is standard leading order QCD, one always has to treat $\alpha_s(\mathrm{Q}^2) \cdot \ln \mathrm{Q}^2$ $\sim \mathcal{O}(1)$; hence formally $\vec{q}^\gamma \sim \ln \mathrm{Q}^2 \sim 1/\alpha_s$. This is true whenever parton language is used.