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Jet Production in Two Photon Collisions at Present and Future e^+e^- Colliders*

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Abstract

Some issues related to jet production in $\gamma\gamma$ collisions are discussed. In particular, the importance of the "resolved photon" contributions is emphasized. A comparison between $\gamma\gamma$ and $p\bar{p}$ scattering indicates that the total $\gamma\gamma$ cross section might grow considerably at high energies, due to semi-hard "minijet" contributions.

1. Introduction

The "hot topic" of this workshop has been the production of jets in (quasi–)real (no–tag) $\gamma\gamma$ collisions, both at present (TRISTAN, LEP) and future e^+e^- colliders; of particular interest has been the experimental observation of "resolved photon" contributions, and the theoretical prediction that these processes can lead to an "underlying event" at high–energy e^+e^- linacs. My talk at the workshop only concerned the second phenomenon; this talk was based on ref.[1], which contains a fairly comprehensive treatment of leading order $\gamma\gamma$ processes at future linear e^+e^- supercolliders. In this contribution to the proceedings I decided not to simply re–iterate the summary of that paper; instead, I will address a number of issues raised during the workshop itself.

I will start with some remarks on the terminology used to describe the various classes of two–photon reactions; not surprisingly, I will defend the notation introduced by Godbole and me [2]. I will emphasize that the different classes of contributions have quite different p_T spectra; *none* of them can be fully described by a simple power law. Next the question will be addressed why resolved photon contributions are "suddenly" being found to be sizeable; this is partly connected to the first two points. Then I will comment on the differences in event structure between $\gamma\gamma$ collisions at present energies and pp scattering at ISR energies. I will argue that the difference is at least partly due to an anomalously small soft contribution to the total $\gamma\gamma$ cross section. This might indicate a rapid increase of the total $\gamma\gamma$ (and γp!) cross section at high energies, where the cross section might be dominated by perturbative processes. This leads to the problems caused if the two–photon event rate becomes so large that several such events occur simultaneously with each annihilation events; the two–photon reactions then form an "underlying event". Finally a brief outlook will be presented.

2. Terminology

Three classes of processes contribute to jet production in real $\gamma\gamma$ collisions [3], as shown in fig.1. The first process, $\gamma\gamma \to q\bar{q}$, has always been included in experimental [4] as well as theoretical [5] analyses. To my knowledge, ref.[3] is the first paper to point out the existence of the other two classes of diagrams, where either one or both incident photons are resolved into their hadronic substructure; the hard scattering process necessary for perturbative QCD to be applicable then only involves the constituents, *not* the entire photon. In ref.[2] we proposed to label these processes as direct, single resolved (1–res) and double resolved (2–res), respectively. We chose this terminology because it is very descriptive; it also immediately leads to the prediction that every resolved photon must produce a "spectator" or "remnant" jet, since the process of extracting a coloured constituent out of the incident photon leaves

*To appear in the Proceedings of the *9th Interntaional Workshop on Photon-Photon Collisions*, San Diego, March 1992 a coloured remnant, which must hadronize into a jet.

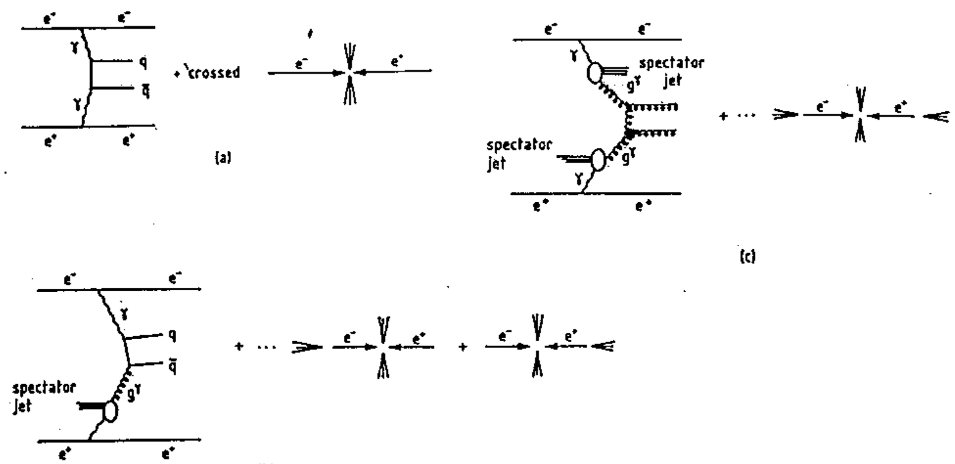

Fig.1: Examples of Feynman diagrams (left) as well as the final state topology (right) for the 3 classes of hard two–photon reactions.

I wish to emphasize here that the resolved photon contributions should *not* be regarded as higher order corrections to the direct process, even though on the face of it they seem to involve additional vertices. The reason is that these diagrams involve the parton content of the photon, described by the parton distribution functions $\vec{q}^{\gamma}(x,Q^2) \equiv (q_i^{\gamma}, G^{\gamma})(x,Q^2)$. These parton densities *grow* logarithmically [6] with Q^2, which has to be interpreted as a factor $1/\alpha_s(Q^2)$ in leading–log summed perturbation theory; this summation is *always* implied in perturbative QCD whenever one deals with hadronic initial states.† One thus has:

$$\sigma(1-\mathrm{res})/\sigma(\mathrm{dir}) \propto \alpha_s(Q^2)\vec{q}^{\gamma}(Q^2)/\alpha_{\mathrm{em}} \propto 1, \tag{1}$$

since $\vec{q}^{\gamma} \propto \alpha_{\mathrm{em}}/\alpha_s$; similarly, $\sigma(2-\mathrm{res})/\sigma(1-\mathrm{res}) \propto 1$, too. Note that here Q^2 is the scale of the hard scattering process, *not* the virtuality of the photon. The fact that the three classes of processes are formally of the same order has already been stressed in refs.[3, 7], but has not always been appreciated in the subsequent literature.

Very often, the resolved photon processes are called "multi–jet" processes; see e.g. ref.[3]. As mentioned above, resolving a photon into its constituents does indeed produce an additional (spectator) jet. Nevertheless, in my opinion this terminology is not as clear as that of ref.[2], since there are also multi–jet processes which *are* genuine higher order corrections, e.g. the process $\gamma\gamma \to q\bar{q}g$ where all three final state partons are well separated from each other as well as from the beam pipe. Indeed, "multi–jet" always smacks of higher orders, which is quite misleading.

† As an example, consider scaling violating parton densities in $p\bar{p}$ scattering. Formally, scaling violations are induced by diagrams involving additional gluon radiation. Nevertheless the step from scaling to non-scaling parton densities does *not* imply that one went to higher orders in QCD perturbation theory, since the new diagrams are of order $\alpha_s \log Q^2 \propto 1$ compared to the simplest diagrams. In QCD, "higher orders" means additional powers of α_s *without* additional powers of $\log Q^2$.

3. p_T spectrum

Another misconception about the processes of fig.1 is that they "basically" all lead to the same p_T^{-4} transverse momentum spectrum. This can be traced back to the first quantitative treatment of all three classes of contributions, given in ref.[7], where this supposed property was mostly used as a book–keeping device to distinguish between the leading twist diagrams of fig.1 and higher twist diagrams which are suppressed by additional powers of p_T^2. This claim is based on the simple argument that, for fixed–angle scattering, p_T is the only scale in the process, so that $d\sigma/dp_T^2 \propto p_T^{-4}$ by dimensional arguments. To see the fallacity of this argument, consider the general expression for the triple differential jet cross section:

$$\frac{d\sigma\left(e^+e^- \to e^+e^- j_1 j_2 X\right)}{dp_T^2 dy_1 dy_2} = x_1 f_{a|e}(x_1) x_2 f_{b|e}(x_2) \frac{d\hat{\sigma}(ab \to j_1 j_2)}{d\hat{t}}, \tag{2}$$

where a and b stands for a photon, quark or gluon, j_1 and j_2 are the two high–p_T (parton) jets with rapidities y_1 and y_2, and $\hat{t}$ is the Mandelstam variable for the hard scattering process. Dimensional arguments do indeed imply that $d\hat{\sigma}/d\hat{t} \propto p_T^{-4}$ for fixed rapidities; however, they tell us nothing about the behaviour of the flux factors $f_{a,b|e}(x)$. For fixed rapidities (i.e., fixed angles), $x_{1,2} \propto x_T \equiv 2p_T/\sqrt{s}$. One can thus write [8]

$$\frac{d\sigma}{dp_T^2 dy_1 dy_2} \propto p_T^{-4} F(x_T). \tag{3}$$

The differences between the p_T distributions of the contributions from the 3 classes of processes of fig.1 come from the different "residual" p_T dependence $F(x_T)$. Consider the simple example of jet production at 90°, i.e. $y_1 = y_2 = 0$. This implies $x_1 = x_2 = x_T$, so that

$$F(x_T) = x_T^2 f_{a|e}(x_T) f_{b|e}(x_T). \qquad (y_1 = y_2 = 0) \tag{4}$$

For the direct process, $F_{\mathrm{dir}}(x_T) = [1 + (1-x_T)^2]^2$ in this configuration, which falls from 4 at $x_T \simeq 0$ to 1.85 at $x_T = 0.4$. (The region $x_T \geq 0.4$ is not accessible to present $\gamma\gamma$ experiments.) We thus see that even for this simple case, the ansatz $d\sigma/dp_T^2 \propto p_T^{-4}$ describes the true spectrum only within a factor of two or so. The deviations are *much* more dramatic for the resolved photon processes, since the distribution of partons "in" the electron, computed from a convolution of $f_{\gamma|e}$ with the parton densities $\vec{q}^{\gamma}$, are obviously softer than $f_{\gamma|e}$ itself, especially if there is a gluon in the initial state. The differences in the p_T spectra were already pointed out in refs. [9, 8], where simple approximate expressions for the $\vec{q}^{\gamma}$ were used; they are also borne out by a calculation [2] using (hopefully) realistic parametrizations for $\tilde{q}^\gamma$; an example is shown in fig.2.

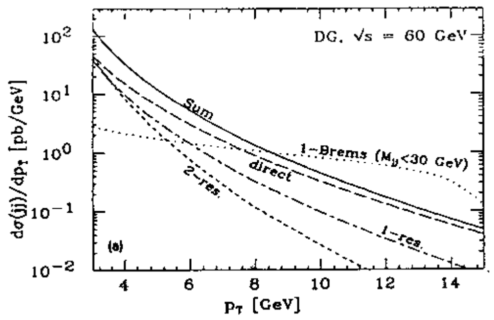

Fig.2: Example of jet transverse momentum distribution, taken from ref.[2]. The dotted curve shows the background from annihilation events with single hard photon radiation from the initial state.

4. The size of the resolved photon contributions

It has been known for quite some time that the direct ("QPM") process alone, even when augmented by a soft component estimated from the Vector Dominance Model (VDM), cannot explain data on jet production [10]. Recently the AMY collaboration has shown [11] that the agreement between data and Monte Carlo predictions improves dramatically once resolved photon contributions are included in the analysis. At this meeting we have seen a beautiful confirmation by the TOPAZ collaboration [12] of this pioneering work; there are also first indications from LEP data pointing in the same direction [13, 14]. The apparent ease with which the resolved photon contributions could explain the sizeable excess of data over QPM+VDM predictions seemed to surprise many participants of this workshop. There even was the claim that "the theorists" had "always" predicted resolved photon contributions to be "small".

This misperception is probably partly due to the incorrect description of these processes as higher order corrections, which already intimates that they are small. Also, the (correct) statement [9, 8] that resolved photon contributions are subdominant for $x_T > 0.2$ together with the (incorrect) claim that all three contributions show essentially the same p_T dependence may have led people to conclude that the contributions from these processes are indeed always small. In fact, the authors of refs. [9, 8] should perhaps have put more emphasis on the fact that these contributions are *not* small for $x_T < 0.2$. It is important to notice here that $x_T < 0.2$ is *not* a "small region"; after all, data from PEP and PETRA only extend to $p_T \simeq 5$ GeV, which corresponds to $x_T \leq 0.35$. The proper interpretation of the results of refs.[9, 8, 2] is therefore that *resolved photon contributions play an important or even dominant role over a substantial part of the x_T region which is experimentally accessible.* This result has (or should have) been known for 13 years [9].

Things are a bit more complicated when one looks at more differential cross sections; e.g. the different contributions have different rapidity distributions for the high p_T jets [7, 9, 8, 2, 1], as well as quite different thrust distributions [11-14]. One can therefore enhance or suppress the resolved photon contributions by certain combinations of cuts. Of course, the size of these contributions also depends on the parton density functions $\tilde{q}^\gamma(x, Q^2)$. At present, only the sum $\sum_i e_i^2 q_i^\gamma$ has been measured, where e_i is the charge of the i-th quark; even here the measurements only cover the region $x \geq 0.05$, and become very poor for $x > 0.5$. The quark densities at low x, the flavour structure, and the gluon density at any x still await experimental determination. By now several parametrizations of the $\tilde{q}^\gamma(x, Q^2)$ exist [15], but these are all based on theoretical guesswork. It thus seems prudent to *always* include resolved photon processes at least in the beginning of an analysis.

5. $\gamma\gamma$ vs hadron–hadron collisions

In the VDM, one expects $\gamma\gamma$ collisions to look more or less like collisions of real hadrons, the main difference being that the total cross section is smaller by a factor $\simeq 5 \cdot 10^{-6}$. However, when comparing $\gamma\gamma$ data from PEP or PETRA with pp data from the ISR, one finds substantial differences: In case of $\gamma\gamma$ collisions the raw p_T spectrum already reveals the existence of hard scattering contributions [10], while at the ISR sophisticated jet analyses are necessary to isolate evidence for (partonic) hard scattering [16]. How can this discrepancy be explained?

At least part of the explanation is fairly obvious. In case of $\gamma\gamma$ collisions the whole cms energy can go into the (direct) hard scattering reaction, while in pp collisions typically 1/3 or less of the total energy is available for the hard scattering. In contrast, in a soft event the total cms energy can be converted into particles with low but finite p_T; the total scalar E_T or p_T of soft pp events may therefore not be (much) smaller than that of hard pp events.

However, this argument does not fully explain the observed differences. After all, as shown in the previous section, in the region of low x_T the total hard contribution to $\gamma\gamma$ collisions is dominated by resolved photon processes, which are rather similar to hard pp scattering processes; this is also true for a range of p_T values where the soft contribution is already subdominant or even negligible, e.g. 1.5 GeV $\leq p_T \leq$ 3 GeV at PETRA energies. Of course, the quark densities inside the photon are much harder than those inside the proton; $x \cdot q_i^\gamma(x)$ peaks at $x \simeq 0.9$, while $x \cdot q_i^p(x)$ peaks around $x \simeq 0.2$ for valence quarks. This allows the hard subprocesses to become important at much smaller energies in $\gamma\gamma$ collisions than in pp collisions. On the other hand, the typical $\gamma\gamma$ energy at PEP/PETRA ($W_{\gamma\gamma} < 20$ GeV) *is* indeed at least three times smaller than the pp energy at the ISR ($\sqrt{s} =$ 50 to 60 GeV). Increasing the centre-of-mass energy increases the importance of the hard processes, because their cross section increases with a power of the energy, while the soft cross section grows at most logarithmically. The fact that hard processes are easy to see in $\gamma\gamma$ collisions at $W_{\gamma\gamma} < 20$ GeV but difficult to isolate in pp scattering at 60 GeV thus seems to indicate that *the soft contribution to the $\gamma\gamma$ cross section is anomalously small.* This hypothesis is supported by the fact that $\sigma_{\gamma\gamma}^{tot}/\sigma_{pp}^{tot} \simeq 0.1\alpha_{em}^2$ at low energies; in other words, there is an additional suppression factor $\propto 0.1$ in addition to the obvious factor α_{em}^2.

This additional suppression factor is *not* present in the (resolved) hard contributions. The momentum carried by partons in the photon is larger or approximately equal to α_{em} for existing parametrizations [15]; the square of that fraction, which is obviously equal to 1 for hadrons, can serve as a first estimate [17] of the ratio of (resolved) hard contributions in $\gamma\gamma$ and hadron–hadron collisions.

The observation that the total $\gamma\gamma$ cross section at small energies might be "anomalously" small has important phenomenological consequences, since it indicates that this cross section could rise rapidly at higher energies. Such a behaviour might be expected if total hadronic cross sections at high energies are dominated by (semi–)hard, perturbative reactions producing "minijets"[‡]. This has been proposed [18] almost 20 years ago, and has subsequently been shown [19] to describe the energy dependence of the total pp and $p\bar{p}$ cross sections quite well.

Recall that the perturbative contributions to $\gamma\gamma \rightarrow$ hadrons are not suppressed compared to the case of pp collisions, apart from the obvious factor of α_{em}^2. If this contribution does indeed dominate total cross sections at high energies, one would therefore expect

$$\frac{4}{9}\alpha_{em}^2\sigma_{pp}^{tot} \leq \sigma_{\gamma\gamma}^{tot} \leq (\alpha_{em}/\alpha_s)^2\,\sigma_{pp}^{tot}, \qquad (5)$$

where the factor 4/9 in the lower bound can be motivated from the observation that in some sense the photon only "contains" two (valence) quarks, while the factor $\alpha_s^{\;-2}$ in the upper bound is motivated by the fact that formally $\vec{q}^{\gamma}(x,Q^2) \propto 1/\alpha_s(Q^2)$; the relevant scale Q^2 for minijet processes is a few GeV^2.

At what energies might the "asymptotic" bounds (5) be expected to become valid? We have already seen that at low energies, where $\sigma_{\gamma\gamma}^{tot}$ has been measured so far, the lower bound is violated by approximately a factor of 5. In the minijet picture, σ_{tot} depends not only on the parton densities, but also on a cut–off parameter $p_{T,min}$. This parameter has to be introduced since all partonic cross sections diverge as $p_T \rightarrow 0$. Using the DG parametrization at scale $Q^2 = \hat{s}/4$, the leading order estimate for the perturbative contribution to $\sigma_{\gamma\gamma}^{tot}$ can be approximated by

$$\sigma_{\gamma\gamma}^{tot}(DG) \simeq 270 \text{ nb} \left(\frac{W_{\gamma\gamma}}{50 \text{ GeV}}\right)^{1.4} \left(\frac{1.6 \text{ GeV}}{p_{T,min}}\right)^{3.6}; \qquad (6)$$

if the scale Q^2 in $\vec{q}^{\gamma}$ and α_s is chosen as p_T^2 instead, the constant in front is increased to 310 nb, but the functional form is not changed. Eq.(6) describes the exact numerical result to better than 20% for 20 GeV $\leq W_{\gamma\gamma} \leq$ 250 GeV. Unfortunately, $p_{T,min}$ has to be taken from experiment; the AMY analysis indicates [11] that it lies in the range 1.4 to 1.6 GeV at least at low $W_{\gamma\gamma}$. Of course, $\sigma_{\gamma\gamma}^{tot}$ cannot indefinetely grow with a power of $W_{\gamma\gamma}$; at some point unitarization will have to set in. This can be achieved by eikonalizing the cross section [20]. From the comparison of eq.(6) with the bounds (5), I expect unitarization effects to become important at $W_{\gamma\gamma}$ somewhere in between 100 GeV and 1 TeV. In contrast, if one assumes

[‡]Minijets should *not* be confused with resolved photon contributions; this expression merely refers to jets with only one or two GeV transverse momentum. At a 500 GeV e^+e^- linac, resolved photon contributions can easily extend out to $p_T \geq 20$ GeV [1].

that eikonalization can be described by the VDM, the asymptotic $\gamma\gamma$ cross section will not be [20] very much above the cross section at low energies, in which case unitarization effects must be important already at $W_{\gamma\gamma} \simeq 50$ GeV. However, the whole point of the argument of this section is that, if the low–energy VDM cross section is indeed anomalously small, the use of the VDM in estimates of the high–energy cross section is dangerous, even if it is only used to determine the parameter [20] P_{had}.

6. The "underlying event"

The behaviour of $\sigma_{\gamma\gamma}^{tot}$ at high energies is certainly of great theoretical and phenomenological interest. However, as already stated in ref.[21], and emphasized at this meeting by Bjorken, it has little impact on the question whether or not an underlying event will occur at a given e^+e^- linear collider with $\sqrt{s} \leq 1$ TeV. The reason is simply that the photon flux integrated over the time resolution of a detector differs [1] by more than 3 orders of magnitude for different existing designs, due to different beamstrahlung spectra [22] and different e^+e^- luminosities per bunch crossing; the uncertainty of the total $\gamma\gamma$ cross section in the relevant region of $W_{\gamma\gamma}$ is much smaller than this. In particular, whenever the perturbative leading order cross section (6) predicts an underlying event to occur, so does the VDM with a constant cross section of 250 nb. However, the two models seem to make quite different predictions for the size (total particle multiplicity or total E_T) of the underlying event. Standard VDM generators predict [23] a rather small particle multiplicity even at high energies. On the other hand, we heard at this meeting [14] that these generators seem unable to describe ALEPH events with small p_T but large visible energy; if this result holds up, these generators will have to be modified at large $W_{\gamma\gamma}$, perhaps by increasing the particle multiplicity.

Notice also that an early unitarization of the total cross section need not even have much effect on the size of the underlying event; in this case early unitarization would not alleviate the problems [1] that may be caused by this phenomenon. This is because eikonalization, the most popular method of unitarizing the cross section, basically fuses N events with one pair of (mini)jets each into one event with N pairs of jets; in this picture, the expression (6) does not give the total cross section, but the cross section multiplied with the average number $\langle N \rangle$ of jet pairs.[§] It is easy to see that the latter quantity is more closely related to the average size of the underlying event than the total cross section itself is; it is largely irrelevant whether 4 minijets are produced in 2 independent, but simultaneous $\gamma\gamma$ collisions, or whether they emerge from one single collision. The precise value of $\sigma_{\gamma\gamma}^{tot}$, as opposed to $\langle N \rangle \cdot \sigma_{\gamma\gamma}^{tot}$, is only important for the underlying event problem if the average number $\langle n_{\gamma\gamma} \rangle$ of $\gamma\gamma$ events per bunch crossing is close to 1; in that case the fraction of bunch crossings (and hence, of annihilation events) that is entirely free of an underlying event depends sensitively on $\langle n_{\gamma\gamma} \rangle$. This fraction is given by $\exp(-\langle n_{\gamma\gamma} \rangle)$, which decreases from 61% to 14% as $\langle n_{\gamma\gamma} \rangle$

[§]Of course, if the perturbative cross section is "small", $\langle N \rangle$ will be very close to one, since the probability to make two pairs of jets simultaneously will be even smaller; in that case eq.(6) is indeed (approximately) equal to the total perturbative cross section. Unfortunately, in case of $\gamma\gamma$ collisions it is not clear what "small" means exactly, since there is no clear–cut geometrical cross section with with eq.(6) can be compared, in contrast to the case of pp or $p\bar{p}$ collisions.

is increased from 0.5 to 2. As it happens, however, most existing designs do not have [1] $\langle n_{\gamma\gamma}\rangle \simeq 1$.

In the minijet picture, the size of the underlying event is thus characterized by eq.(6), i.e. it grows *indefinetely* with a power of the $\gamma\gamma$ (or e^+e^-) energy. There is some support for this in data [24] from $p\bar{p}$ collisions: if one plots the product of the total, inelastic cross section, the average charged particle multiplicity $\langle n_{ch}\rangle$, and the average transverse momentum of charged particles $\langle p_{T,ch}\rangle$, one finds an almost linear increase with energy[¶], see fig. 3. This indicates that semi-hard processes are indeed playing an increasingly important role in $p\bar{p}$ collisions; one would then expect the same to be true for $\gamma\gamma$ collisions.

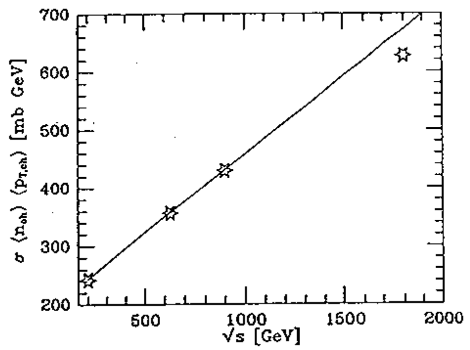

Fig.3: Data [24] for the product $\sigma_{p\bar{p}}^{\rm inel} \cdot \langle n_{ch}\rangle \cdot \langle p_{T,ch}\rangle$, where $\langle n_{ch}\rangle$ and $\langle p_{T,ch}\rangle$ are averaged over the rapidity window $|y| \leq 2.5$; the size of the points does not reflect the experimental errors, which are in the 10 to 15 % range. The straight line has been drawn to guide the eye.

7. Outlook

I think it is at present impossible to make reliable predictions for $\gamma\gamma$ scattering into hadronic final states at energies $W_{\gamma\gamma} \geq 50$ GeV; more experimental input is needed. Fortunately, new data are being collected even now. In order to extract a maximum amount of information from these data, it is desirable that all groups use the same analysis program(s). At present there are at least 4 different MC generators that include resolved photon processes (the original AMY code; PYTHIA 5.5; the TOPAZ generator; and the DELPHI/NOT generator). None of them is more than two years old, so there probably are bugs in some or all of them. A systematic comparison of these generators is urgently needed.

Once a standard (set of) generator(s) has been chosen, experimental results could be published as (parton–level) cross sections rather than as numbers of observed events. This obviously necessitates a fairly sophisticated unfolding technique, but here much experience has already been gained in analysing single–tag data in terms of the structure function F_2^γ. Once experimental measurements of cross sections are available, theorists can directly test their favorite parametrization for $\vec{q}^\gamma$; in particular, global fits of parton densities should then become much more constrained.

One should not forget that a large body of PEP and PETRA data already exists [10], which shows substantial excess over QPM+VDM predictions. It would be very interesting to re–analyze these data using the new Monte Carlo generators. Although I am personally already convinced that resolved photon contributions have indeed been seen, it would be desirable to demonstrate explicitly that QCD can describe *all* $\gamma\gamma$ data. It would also be interesting to check whether the parameter $p_{T,min}$ has to be varied with energy, which would have immediate consequences at large $W_{\gamma\gamma}$; see eq.(6).

Finally, it might soon become possible to try more detailed analyses of no–tag $\gamma\gamma$ events. In particular, it would be nice if the existence of the spectator jet(s) could be demonstrated more directly than via the inclusive thrust distribution. The analysis of more exclusive final states, e.g. $c\bar{c}$ or J/ψ production [2], might also prove rewarding, since it might allow more direct access to the gluon content of the photon.

It thus seems to me that the exploration of resolved photon processes offers both new challenges and new opportunities. Being from DESY, I cannot conclude this contribution without reference to the upcoming HERA collider. This machine, which should start collecting useful data within a few weeks, will study resolved photon reactions in photoproduction processes [25], at energies not accessible to $\gamma\gamma$ experiments at present e^+e^- colliders. With a wealth of new data coming up, and with older data awaiting (re–)analysis, I feel confident that a comprehensive understanding of resolved photon processes will soon be achieved.

¶Unfortunately, $\langle n_{ch}\rangle \cdot \langle p_{T,ch}\rangle$ is not directly proportional to the total p_T in the event. $\langle p_{T,ch}\rangle$ is affected by fragmentation effects, because part of the transverse momentum of a particle is due to its deviation from the direction of the original parton, or from the jet axis; this component of p_T cancels in the vector some over the particles in one hemisphere, but not in $\langle p_{T,ch}\rangle$. I thank Bob Fletcher for pointing this out to me. The total p_T per hemisphere has apparently not been published by the experiments.

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[24] UA1 data are collected in T. Sjöstrand and M. van Zijl, Phys. Rev. **D36** (1987) 2019. For CDF data, see F. Abe et al., Phys. Rev. Lett. **61** (1988) 1819, and Phys. Rev. **D41** (1990) 2330.

[25] A. Levy, these proceedings.