Minijets and Large Hadronic Backgrounds at e^+e^- Supercolliders

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We show that the hadronic structure of the photon, along with the beamstrahlung phenomenon, leads to a very large rate of $\gamma\gamma \rightarrow$ jets at e^+e^- supercolliders. At $\sqrt{s}=1$ TeV, for round, dense bunches, we expect $\sim$5–50 "minijet" events per bunch crossing, giving rise to an "underlying event." Thus e^+e^- supercolliders will be "messier" than expected, unless beamstrahlung can be kept under control.

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The main argument in favor of e^+e^- (super)colliders [1] as compared to pp supercolliders such as the Superconducting Super Collider or the CERN Large Hadron Collider is the supposed "cleanliness" of the electron machines, i.e., the absence of an "underlying event" produced by the spectator jets which are part of any hard interaction event at hadron colliders, spraying a multitude of usually soft hadrons over the detector, which cause many background problems. In this Letter, we point out that, due to the hadronic structure of (quasi)real photons [2], hadronic two-photon interaction rates at future e^+e^- colliders will be very large, making such machines much "messier" than usually anticipated. This problem is aggravated by the beamstrahlung phenomenon [3], which at center-of-mass energies $\sqrt{s}$ around 1 TeV can increase the effective single photon flux by an order of magnitude.

For the purpose of this Letter we need only discuss the inclusive production of two high-p_T jets in the collision of two (quasi)real photons. Three different classes of processes [4] contribute to this reaction. The "direct" process of Fig. 1(a), $\gamma\gamma \rightarrow q\bar{q}$ is already present in the naive quark-parton model. However, to first order in α the photon develops [2] a nonvanishing quark and gluon content. It is thus possible to "pull" quarks or gluons out of photons in much the same way they can be "pulled out" of nucleons. In Fig. 1(b) only one photon is resolved into its partonic components, which then interact with the other photon; we call these the "once-resolved" processes ("1-res" for short). Finally, in the "twice-resolved" ("2-res") processes of Fig. 1(c) both photons are resolved, so that the hard scattering is a pure QCD $2 \rightarrow 2$ process. It is very important to note that every resolved photon produces [5] a spectator jet of hadrons with small transverse momentum relative to the initial photon direction, which coincides with the beam direction.

Schematically, the cross section for the twice-resolved contributions can be written as [5]

$$d\sigma = f_{\gamma/e}(x_i)\mathbf{q}^{\gamma}(x_2,Q^2)f_{\gamma/e}(x_3)\mathbf{q}^{\gamma}(x_4,Q^2)d\hat{\sigma}, \tag{1}$$

where the $\hat{\sigma}$ are the cross sections for the hard $2 \rightarrow 2$ subprocesses [6,7]. At present only two parametrizations of the parton densities inside the photon $\mathbf{q}^{\gamma}=(u^{\gamma},d^{\gamma},G^{\gamma})$ exist. The DO parametrization [7] uses the "asymptotic" prediction of Witten [2]. For our choice $\Lambda_{\text{QCD}}=400$ MeV this has to be augmented [5] by a "hadronic" component, which can be estimated from the vector meson dominance (VMD) model, in order to describe data [8] on the electromagnetic structure function F_2^{γ} of the photon. However, this parametrization cannot (and was never intended to) be used at very small x, since it diverges even worse than the $x^{-1.6}$ behavior of the exact asymptotic prediction for $\mathbf{q}^{\gamma}(x,Q^2)$. We have therefore modified the original parametrization of [7] in the region $x<0.05$:

$$\mathbf{q}^{\gamma}(x,Q^2)=\mathbf{c}\ln(Q^2/\Lambda^2)x^{-1.6}, \tag{2}$$

where $\mathbf{c}$ is fixed to give smooth transitions at $x=0.05$. Note that the VMD contribution [5] is *not* affected by this modification, as it is well behaved for $x \rightarrow 0$. We call this the "modified DO + VMD" parametrization. The DG parametrization [9] avoids the problem of $x \rightarrow 0$ divergencies, since it parametrizes the well-behaved [10] Q^2 evolution of some input distributions at scale $Q_0^2=1$ GeV^2, which were chosen such that a preliminary version of the data of [8] were reproduced; it also fits the final

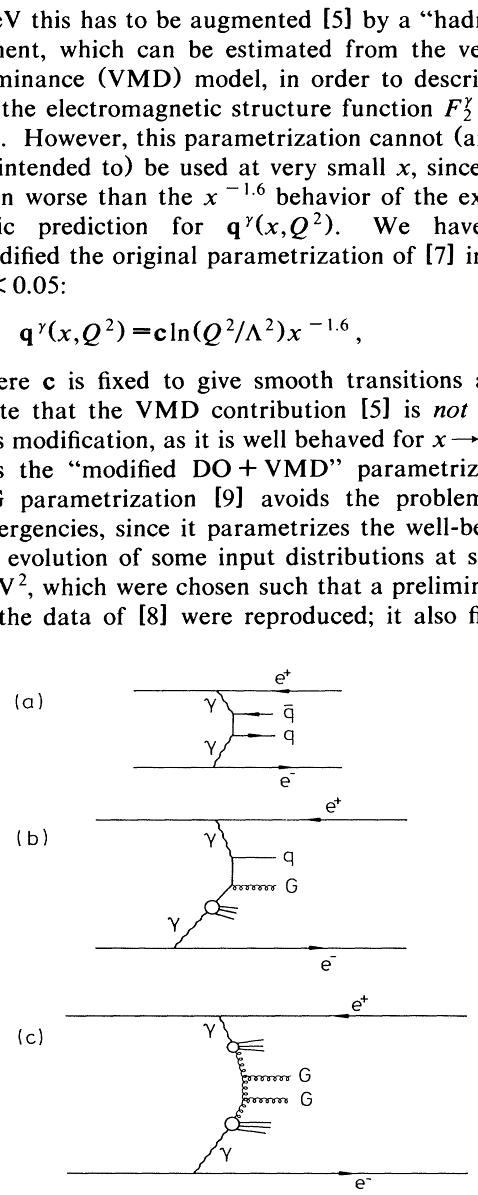

FIG. 1. Typical Feynman diagrams for the (a) direct, (b) once-resolved, and (c) twice-resolved contributions to the production of high-p_T jets in $\gamma\gamma$ collisions at e^+e^- colliders.

version of these data quite well [5]. The use of the DG parametrization probably leads to a conservative estimate of two-photon cross sections, since here it is assumed that gluons are only created radiatively inside the photon. In contrast, due to their very rapid increase at low x [see Eq. (2)] and the large VMD contribution in particular to G^γ, the modified DO + VMD parametrization might well overestimate two-photon cross sections. We have chosen the momentum scale $Q^2 = \hat{s}/4$ everywhere; $\hat{s}$ is the squared invariant mass of the two high-p_T jets. Furthermore, we have varied the number N_f of active flavors with Q^2, using $N_f = 3$ for $Q^2 < 50\ \text{GeV}^2$ and $N_f = 5$ for $Q^2 > 500\ \text{GeV}^2$. This should be a conservative treatment since we have, e.g., set the charm contribution to zero for $\hat{s} < 200\ \text{GeV}^2$.

For the flux $f_{\gamma/e}$ of photons which are *not* resolved into their partonic constituents we have included contributions beyond the leading logarithmic terms [11]. Here one integrates the virtuality P^2 of the exchanged photon over the full kinematic range. However, the parton content of the photon decreases [12] once $P^2 \gg \Lambda^2$. Indeed, if P^2 is larger than the scale Q^2 at which the photon is probed, the process can be described fully perturbatively, without having to resort to structure functions. We have conservatively ignored these contributions altogether. Furthermore, the reduction of virtual photon structure functions for $\Lambda^2 < P^2 < Q^2$ has been taken into account by introducing a suppression factor of 0.85, which has been estimated from numerical results of Rossi [12]. Altogether we thus have for the effective flux of resolved photons due to bremsstrahlung

$$f_{\gamma/e}^{\text{res}}(z) = 0.85 \frac{\alpha}{2\pi} \frac{1+(1-z)^2}{z} \ln\left(\frac{Q^2}{m_e^2}\right), \tag{3}$$

where m_e is the electron mass.

We are now in a position to present results on two-photon production of jets for negligible beamstrahlung. This is expected to be true for $\sqrt{s} < 500$ GeV. [However already at the planned Japan Linear Collider ($\sqrt{s} = 500$ GeV) beamstrahlung effects could be sizable [13].] In Fig. 2 we show the energy dependence of the cross section for the production of hard central jets with $p_T > 5$ GeV and rapidities $|y_{1,2}| < 2$. For these kinematical cuts, the direct contribution still dominates at energies of the CERN e^+e^- collider LEP, $\sqrt{s} \leq 200$ GeV. However, it increases only logarithmically with $\sqrt{s}$, while the resolved contributions increase much faster, almost linearly for the twice-resolved case. Even for our cuts, which are quite stringent for two-photon physics, the direct contribution alone underestimates the total rate by a factor of 5 to 10 already at $\sqrt{s} = 500$ GeV. Note that the cross sections of Fig. 2 are huge compared to typical annihilation cross sections. For instance, the QED cross section for $e^+e^- \to \mu^+\mu^-$ amounts to only 0.4 pb at $\sqrt{s} = 500$ GeV, less than 0.3% of our hard two-photon cross section; most cross sections for the production of new, heavy particles will be even smaller. Nevertheless, at this energy the two-photon background can still be brought under contol quite easily; it can be reduced to the level of the annihilation cross sections by increasing the p_T cut to about 20 GeV, with only mild effects on most "new physics" searches.

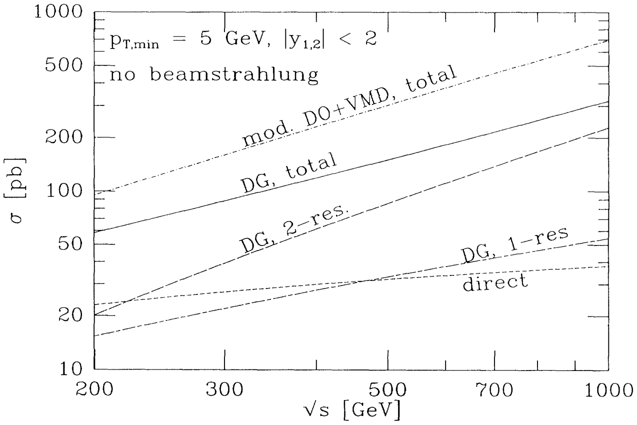

FIG. 2. The cross section for the production of hard central jets. The contributions of the three classes of processes shown in Fig. 1 are shown separately, for the parametrization of Ref. [9]. The total cross section as predicted by the modified DO + VMD parametrization is shown for comparison. Beamstrahlung is not included.

The situation could be quite different, however, for $\sqrt{s} \geq 1$ TeV. Figure 2 shows that the ratio of two-photon events from bremsstrahlung photons to annihilation events increases roughly like $s^{3/2}$. In addition, at these energies beamstrahlung [3] can become very important. It is produced when particles in one bunch undergo bremsstrahlung upon entering the electromagnetic field of the other bunch; these particles thus interact *coherently* with a sizable part of the opposite bunch. The intensity of the emitted beamstrahlung therefore increases with the strength of the fields produced by the bunches, which in turn grows with the particle density of the bunches, and hence with the luminosity per bunch crossing. Notice that beamstrahlung produces truly real photons, so that the hadronic structure of the photon plays an even greater role than for photons produced by bremsstrahlung. In order to estimate how big the effect of beamstrahlung could be at $\sqrt{s} = 1$ TeV we have parametrized the beamstrahlung contribution to $f_{\gamma/e}$, using the most extreme result of [14], which assumes round beams, a bunch length of 0.3 mm, and a luminosity of 2.8×10^{30} cm^{-2} per bunch crossing. Their result can be written as

$$f_{\gamma/e}^{\text{beam}} = \left[2.25 - \left(\frac{x}{0.166}\right)^{1/2}\right] \left(\frac{1-x}{x}\right)^{2/3}, \tag{4}$$
$$x < 0.84,$$

with $f_{\gamma/e}^{\text{beam}}(x \geq 0.84) = 0$. Of course, the bremsstrahlung contribution has to be added to this [15].

In Fig. 3 we show the resulting p_T spectrum as predicted by the DG parametrization. We see that beam-

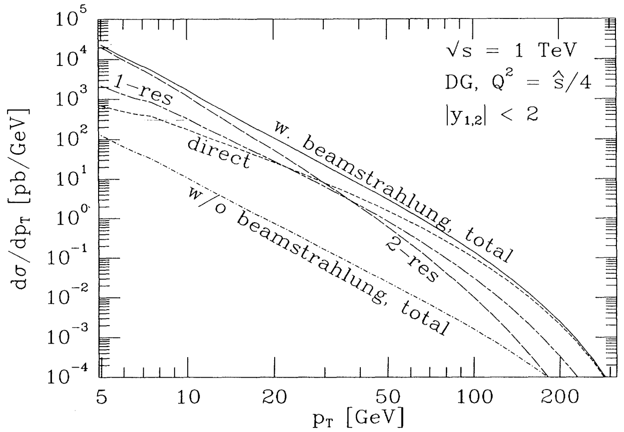

FIG. 3. The transverse momentum spectrum of central jets at $\sqrt{s} = 1$ TeV. The upper four curves include the beamstrahlung contribution according to Eq. (4), while the lowest curve shows the total result if beamstrahlung is neglected. All results are for the DG parametrization [9]. The kinks at $p_T \simeq 7$ GeV occur since we have conservatively switched off the charm contribution for $Q^2 < 50$ GeV^2, as described in the text.

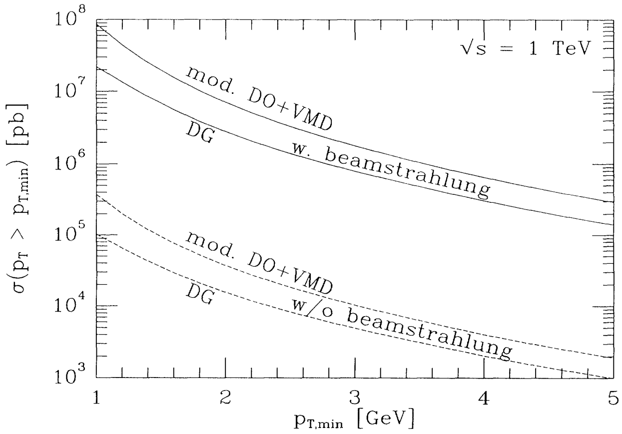

FIG. 4. The total cross section for the production of jets with $p_T > p_{T,\min}$ at $\sqrt{s} = 1$ TeV, with (solid) and without (dashed) the beamstrahlung contribution of Eq. (4). The upper (lower) curves of given pattern are for the modified DO + VMD (DG) parametrization. All curves sum direct and resolved photon contributions.

strahlung can increase the two-photon event rate by at least 2 orders of magnitude over the whole range of p_T values shown. One would then have to increase the p_T cut to around 120 GeV in order to reduce the two-photon cross section to the level of typical annihilation cross sections. Since in the presence of strong beamstrahlung many annihilation events contain considerably less energy than the nominal $\sqrt{s}$ of the machine, this is a significant cut, in particular if the signal cross section is also peaked at small angles, which is true, e.g., for the $e^+e^- \to VV$ ($V = W,Z$) cross sections.

Note that we get roughly one event containing central jets with $p_T > 5$ GeV every ten bunch crossings, if beamstrahlung is as strong as assumed in Eq. (4). This raises the question how large these event rates become if we relax our cuts to the limits of applicability of perturbative QCD. The result is shown in Fig. 4, where we give the cross section (1) integrated over the full kinematically allowed range of rapidities and have varied the lower limit $p_{T,\min}$ of the p_T integration, for $\sqrt{s} = 1$ TeV. $p_{T,\min}$ cannot be predicted from first principles, but analyses of pp and γp scattering might serve as indications. The idea that QCD jets with p_T in the GeV range could drive the observed rise in total hadronic cross sections dates back more than fifteen years [16]. More recent analyses [17] show that the rise of the total pp and $\bar{p}p$ cross sections can be reproduced by minijets with $p_{T,\min} \simeq 1.3$–2 GeV, for $\sqrt{s} \leq 1$ TeV. Similar values of $p_{T,\min}$ can describe [18] the energy dependence of the total γp cross section. In view of these results the choice of the DG parametrization with $p_{T,\min} \simeq 2$–2.5 GeV seems quite conservative. We see from Fig. 4 that for the case of maximal beamstrahlung, this translates into 4–8 minijet events *per bunch crossing.* Allowing for somewhat smaller values of $p_{T,\min}$ and/or a larger gluon content of the photon, we can at present not exclude the possibility that the true number is an order of magnitude higher than this.

Recall that the twice-resolved contribution, which is by far the dominant one, is characterized by two spectator jets. For the case of Fig. 4 these jets have typical energies around 100 GeV. Most of this energy will disappear in the beam hole, but, due to the nontrivial color flow between the spectator jets and the hard jets, the spectator jets will deposit about 1.5–2 GeV transverse energy per unit of rapidity. Adding 4 GeV transverse energy from the hard jets and integrating over the region $|y| < 2$ we thus estimate that each minijet event will deposit about 10 GeV transverse energy in the central part of the detector. For ten simultaneous events this yields an underlying event contributing as much as 100 GeV *transverse* energy, or 20% of the beam energy, which is considerably *worse* than at hadron colliders. We emphasize again that, except for the choice of maximal beamstrahlung, we consider our estimates to be quite conservative.

Beamstrahlung can be reduced [14] by using elliptical beams with large ratio r of semimajor and semiminor axes. However, if the bunch length and luminosity per bunch crossing are left unaltered, one has to choose r as large as 100 in order to reduce $f_{\gamma/e}^{\text{beam}}$ roughly to the level of $f_{\gamma/e}^{\text{brems}}$, leading to a minijet cross section roughly 4 times bigger than indicated by the dashed curves in Fig. 4. This could still take us dangerously close to the level of one event per bunch crossing. Moreover, making the beams very flat might make it even more difficult to achieve head-on collisions. Furthermore, the number of minijet events increases very rapidly with $\sqrt{s}$. The machine luminosity has to be increased like s in order to achieve a constant rate of annihilation events. If a larger luminosity necessitates denser bunches, raising the machine energy with a fixed rate of annihilation events increases both the flux and the average energy of beamstrahlung photons; recall that minijet cross sections increase with the center-of-mass energy of the parent particles. It thus seems quite possible that for $\sqrt{s} \gtrsim 2$ TeV the underlying event contains *more* transverse energy than a typical annihilation event. At these energies the traditional cleanliness of e^+e^- colliders can probably only be preserved if the number of bunches can somehow be increased considerably, which would allow for less dense bunches without reducing the integrated annihilation event rate. Most recent designs [19] for machines with $\sqrt{s} = 1$ TeV indeed use flat beams and a number of bunches that is larger than the "cycle rate" of the accelerator. At those machines the hadronic background due to beamstrahlung should therefore be smaller than in our worst-case scenario; however, it can still be very serious.

The validity of our conclusions crucially hinges on the existence of the resolved photon processes. In the traditional VDM picture [20] one also expects large two-photon cross sections, but it will be dominated by diffractive events with very little energy deposition in the central part of the detector. However, models based on the incoherent sum of these soft contributions and the direct process of Fig. 1(a) have consistently *failed* to describe data [21] on jet production in $\gamma\gamma$ collisions at SLAC and DESY storage rings PEP and PETRA. Very recently the AMY Collaboration has found [22] that they were able to fully describe their real $\gamma\gamma$ data only after resolved photon contributions were added. The DG parametrization reproduces the data well for $p_{T,\min} \simeq 1.6$ GeV. This is the first time that real $\gamma\gamma$ data were reproduced by full Monte Carlo program, and clearly strengthens our point.

In summary, we have pointed out that the combination of the beamstrahlung phenomenon with QCD predictions for the hadronic structure of the photon leads to very large two-photon event rates at e^+e^- supercolliders. At $\sqrt{s} = 1$ TeV the two-photon contribution can totally dominate two-jet production up to $p_T \simeq 100$–130 GeV if round, dense bunches are used in the accelerator. With such bunches one also has to expect ~ 5, or possibly even ~ 50, minijet events per bunch crossing, leading to an "underlying event." Data from KEK TRISTAN and DESY HERA should help to sharpen these predictions, which are obviously relevant for the planning of future e^+e^- accelerators and experiments.

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