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Bremsstrahlung contributions to $W\gamma\gamma$ production in high-energy proton-proton collisions

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The production of photon pairs in association with W bosons is an important background to $WH(\to\gamma\gamma)$ production in high-energy proton-proton collisions. Previous estimates of this background have been calculated using the leading-order $2\to 3$ processes only. We calculate higher-order bremsstrahlung contributions where the photons are radiated off final-state quarks and gluons, using the leading-logarithm fragmentation function approach. We show that although these indirect contributions are generally dominant, they can be suppressed to a manageable level by imposing isolation cuts on the photons.

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It has now been established that with sufficient luminosity, the cleanest way to detect the intermediate mass standard model Higgs boson at high-energy proton-proton colliders such as the CERN Large Hadron Collider (LHC) and the Superconducting Super Collider (SSC) is via associated production with W bosons and $t\bar{t}$ pairs [1]. For example, the process $pp\to W(\to\ell\nu)+H(\to\gamma\gamma)+X$ provides a very clean signature. The important reducible and irreducible backgrounds have been estimated and shown to be largely under control. In particular, the dominant irreducible background from $q\bar{q}\to W\gamma\gamma$ does not appear to pose any serious problems provided diphoton mass resolution of order 3% or better can be achieved [2]. Various irreducible backgrounds, in particular from processes like $b\bar{b}\gamma\gamma$, have been considered in Ref. [3]. Provided that leptons from b decay can be efficiently identified by their nonisolation, these backgrounds are also not a serious problem. Similar remarks apply to production with $t\bar{t}$ pairs [4].

However, experience from similar studies [5] of direct Higgs production ($gg\to H\to\gamma\gamma$) and the corresponding direct backgrounds ($q\bar{q},gg\to\gamma\gamma$) has shown that there are also significant background contributions from quark and gluon production processes involving photon bremsstrahlung, e.g., $gg\to q(\to\gamma+X)+\bar{q}(\to\gamma+X)$. Since the presence of collinear singularities means that such photons are preferentially emitted in the direction of the parent quark or gluon, these contributions can be estimated using a fragmentation function approach, i.e., by introducing fragmentation functions $D_{\gamma/q}(z,Q^2)$ and $D_{\gamma/g}(z,Q^2)$. The fact that these functions grow with Q^2 as $\alpha/\alpha_s(Q^2)$ means that they are formally of the same order as the leading-order processes. Explicit calculations [5] do indeed confirm that these bremsstrahlung contributions are numerically important. They can, however, be reduced by requiring that the photons are "isolated," i.e., unaccompanied by collinear hadronic energy. In the fragmentation function approach, such isolation cuts can be modelled by imposing a lower limit on the fragmentation parameter z, the fraction of the parent's momentum carried by the photon.

In this paper we perform an analysis similar to Ref. [5] but for $WH(\to\gamma\gamma)$ rather than single $H(\to\gamma\gamma)$ production. That is, we compute the following indirect background processes

$$q+g\to W+\gamma+q(\to\gamma X)\,, \tag{1}$$
$$q+\bar{q}\to W+\gamma+g(\to\gamma X)\,, \tag{2}$$
$$q+\bar{q}\to W+g(\to\gamma X)+g(\to\gamma X)\,, \tag{3}$$
$$q+\bar{q}\to W+q(\to\gamma X)+\bar{q}(\to\gamma X)\,, \tag{4}$$
$$q+g\to W+q(\to\gamma X)+g(\to\gamma X)\,, \tag{5}$$
$$g+g\to W+q(\to\gamma X)+\bar{q}(\to\gamma X)\,. \tag{6}$$

The first two of these we call "single bremsstrahlung," the latter four "double bremsstrahlung." Other processes involving the replacement of q by $\bar{q}$ are of course implied. Representative Feynman diagrams for both types of processes are shown in Fig. 1, together with a "direct" contribution diagram for comparison. (Note that there is no analogue of the "box diagram" direct contribution $gg\to\gamma\gamma$ [6] in the present context.) The $2\to 3$ matrix elements for the single bremsstrahlung, double bremsstrahlung, and direct subprocesses were taken from Refs. [7], [8], and [2], respectively. The decay of the W bosons into $\ell\nu$ ($\ell=e,\mu$) final states is included and the contributions from W^+ and W^- have been summed. The corresponding cross sections are estimated by folding the appro-

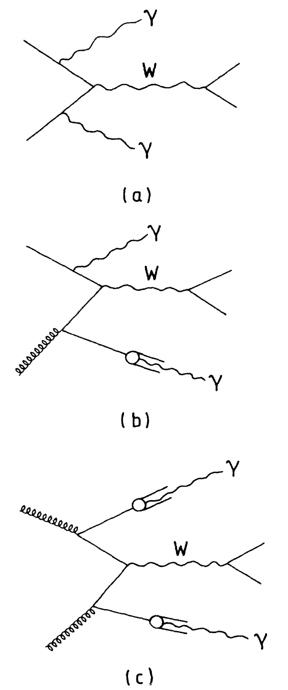

FIG. 1. Example Feynman diagrams for the three different $W\gamma\gamma$ production processes: (a) direct process, (b) single bremsstrahlung process, and (c) double bremsstrahlung process.

priate $2 \to 3$ matrix elements with photon fragmentation functions and initial-state parton distributions. For the latter we use the Harriman-Martin-Roberts-Stirling (HMRS) set B distributions with $\Lambda^{(4)}_{\rm NLO} = 190$ MeV [9]. The fragmentation functions are the leading-logarithm parametrizations of Ref. [10]:

$$zD^{LL}_{\gamma/q}(z,Q^2) = F\left[\frac{e_q^2(2.21 - 1.28z + 1.29z^2)z^{0.049}}{1 - 1.63\ln(1-z)} + 0.0020(1-z)^{2.0}z^{-1.54}\right], \qquad (7)$$

$$zD^{LL}_{\gamma/g}(z,Q^2) = \frac{0.194}{8}F(1-z)^{1.03}z^{-0.97}, \qquad (8)$$

where $F = (\alpha/2\pi)\ln(Q^2/\Lambda^2)$ and $\Lambda = \Lambda^{(4)}_{\rm LO} = 190$ MeV. The scale in α_s, the fragmentation functions, and the parton distribution functions is taken to be $Q^2 = \hat{s}$ and the one-loop expression has been used for α_s. Note that in this calculation we are mixing next-to-leading-order structure functions with leading-logarithm fragmentation functions and leading-order matrix elements. However, the ambiguity that this introduces is smaller than the overall level of precision of this type of analysis.

In order to mimic the experimental situation we must impose cuts on the final-state particles. Some of these cuts are also necessary to avoid the soft and collinear singularities implicit in the matrix elements. Our primary interest is in the LHC ($\sqrt{s} = 16$ TeV) and SSC ($\sqrt{s} = 40$ TeV) cross sections, and so we choose the following "representative" cuts:

$$\begin{array}{lll} p_T(\ell) > 20\ \text{GeV}, & p_T(\gamma) > 20\ \text{GeV}, & \not{p}_T > 20\ \text{GeV}, \\ |y_\ell| < 2.5\,, & |y_\gamma| < 2.5\,, & \\ \Delta R_{\ell\gamma} > 0.4\,, & \Delta R_{\gamma\gamma} > 0.4\,, & \end{array} \qquad (9)$$

where $(\Delta R)^2 = (\Delta\phi)^2 + (\Delta y)^2$ and $\not{p}_T$ is the missing transverse momentum. The ΔR separation cut between the photons deserves further discussion. We are primarily interested in photon pairs which have a large invariant mass (of order M_H) and are therefore naturally separated. The direct background process $q\bar{q} \to W\gamma\gamma$ has no matrix element singularity when the photons are collinear. In contrast, the single bremsstrahlung process $qg \to W\gamma q(\to \gamma)$ *does* have such a singularity, from diagrams where the outgoing quark emits one photon before fragmenting to another (collinear) photon. Some of the double bremsstrahlung processes are also singular when the photons become collinear, for example, $q\bar{q} \to Wg^* \to Wq(\to \gamma)\bar{q}(\to \gamma)$. If the cross sections of interest received contributions from these collinear configurations, then our simple fragmentation function approach would break down. For example, $q^* \to \gamma + q(\to \gamma X)$ would more accurately be represented by a *double* fragmentation function $q \to \gamma\gamma X$. In practice, however, the photon separations of interest are well away from the matrix element singularities and so there is no problem (see below).

Our results are summarized in Figs. 2–5. In Fig. 2 we show the inclusive photon transverse momentum distribution at $\sqrt{s} = 40$ TeV from the direct and indirect processes. We see immediately that the single bremsstrahlung contribution is an order of magnitude larger than either the direct or double bremsstrahlung contributions. The $qg \to W\gamma q(\to \gamma)$ subprocess is re-

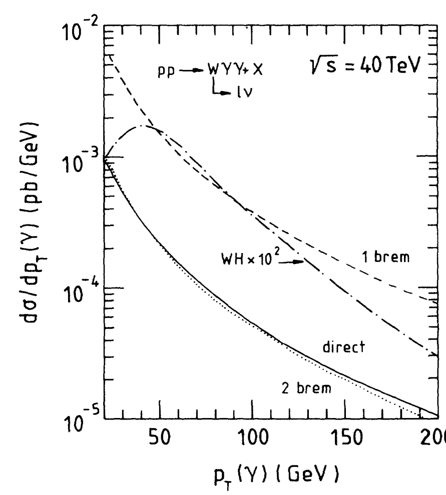

FIG. 2. Inclusive photon transverse momentum distribution for $pp \to W(\to \ell\nu)\gamma\gamma + X$ at $\sqrt{s} = 40$ TeV. The direct (solid line), single bremsstrahlung (dashed line), and double bremsstrahlung (dotted line) background processes are shown. The WH signal for $M_H = 100$ GeV (dash-dotted line) is shown scaled up by a factor of 10^2.

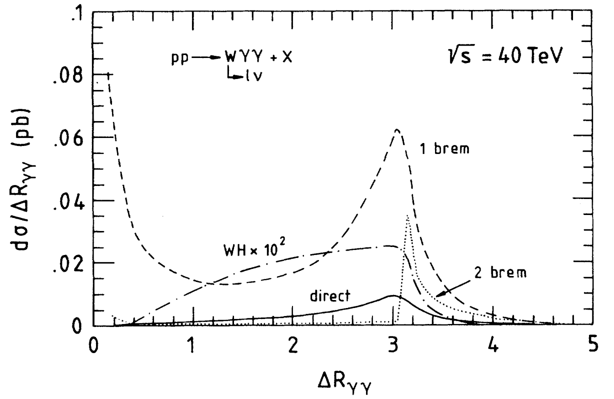

FIG. 3. Distribution of $\Delta R_{\gamma\gamma}$ for $pp \to W(\to \ell\nu)\gamma\gamma + X$ at $\sqrt{s} = 40$ TeV. The labeling conventions are the same as Fig. 2.

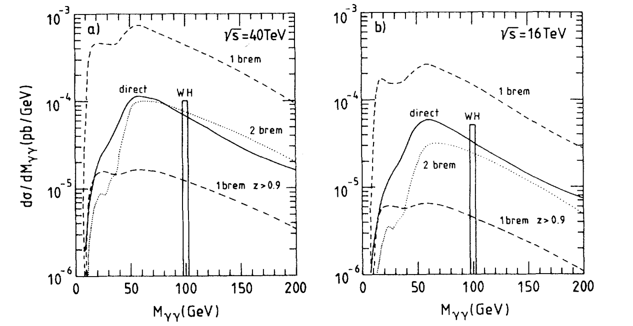

FIG. 5. Diphoton invariant mass for $pp \to W(\to \ell\nu)\gamma\gamma + X$; parts (a) and (b) are for the SSC and LHC center-of-mass energies, respectively. The labeling conventions are the same as Fig. 2. The single bremsstrahlung process is shown with and without the photon isolation cut $z > 0.9$. (The double bremsstrahlung process with photon isolation cut is too small to appear on this figure.) For comparison, the WH signal for $M_H = 100$ GeV has been put in a 5 GeV bin.

sponsible, since it is able to take advantage of both the large initial state gluon distribution and the hard quark $\to$ photon fragmentation function. Also shown, for comparison, is the p_T distribution of photons from WH production, scaled by 10^2. Unlike all the background processes, which are singular as $p_T \to 0$, this process has a maximum around $p_T = 40$ GeV and falls off faster at large p_T.

Of course we might expect that much of the single bremsstrahlung contribution comes from configurations where the photons are collinear, and therefore have low invariant mass. Thus Fig. 3 shows the distribution in the photon separation variable $\Delta R_{\gamma\gamma}$. We again see that the single bremsstrahlung contribution is dominant over the whole range. The singularity as $\Delta R_{\gamma\gamma} \to 0$, although clearly visible, is only partly responsible for the enhancement. There is an equally important contribution for $\Delta R_{\gamma\gamma} \sim \pi$, corresponding to photons which are back-to-back in azimuthal angle. The peaking of this contribution around π is explained by the fact that the rapidity distributions of both the photon and the jet are peaked at $y = 0$, and hence $\Delta R_{\gamma\gamma} \sim \Delta\phi_{\gamma\gamma} \sim \pi$. The WH signal is fairly uniformly distributed in the region $1 < \Delta R_{\gamma\gamma} < 3$.

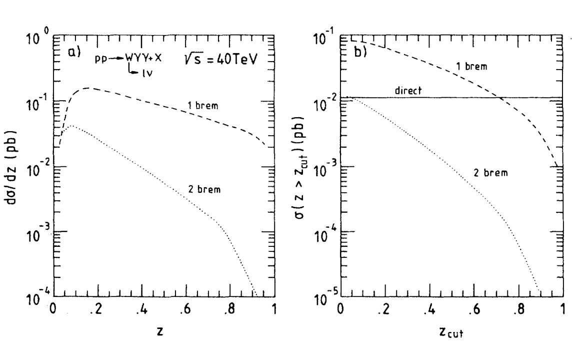

FIG. 4. (a) The differential cross section $d\sigma/dz$ vs z and (b) the integrated cross section $\sigma(z > z_{\rm cut})$ vs $z_{\rm cut}$. The single and double bremsstrahlung processes are shown in both parts; the direct process is also shown in part (b).

Figures 2 and 3 show clearly that there are no further photon p_T and separation cuts which will suppress the single bremsstrahlung contribution to or below the level of the direct contribution. This raises the question of whether claims that the $W\gamma\gamma$ background is under control have been too optimistic. However, the key factor that has not yet been exploited in our study is the fact that the bremsstrahlung photon is part of a *jet* and is therefore accompanied by hadronic energy. In practice, there will be an isolation requirement to suppress precisely this type of contribution. Without detailed fragmentation Monte Carlo and detector simulation studies we cannot readily perform a detailed analysis. We can, however, model the isolation process by cutting on the fraction of the energy carried by the photon in the jet. This procedure was adopted for direct photon studies at LHC and SSC in Ref. [11].

A photon isolation cut typically requires the sum of the hadronic energy $E_{\rm had}$ in a cone of size R_0 about the direction of the photon to be less than a fraction ϵ_h of the photon energy E_γ, i.e.,

$$\sum_{\Delta R < R_0} E_{\rm had} < \epsilon_h \, E_\gamma \, . \tag{10}$$

Since the fragmentation approach treats the photons as collinear with the parent partons, this reduces to a restriction on the fragmentation parameter z:

$$\frac{1}{1+\epsilon_h} < z < 1 \, . \tag{11}$$

To explore the effect of cutting on z we first consider the differential z distribution of the single and double bremsstrahlung processes, Fig. 4(a). (Recall that the direct process has $z = 1$.) As expected, both distributions fall off sharply as $z \to 1$, particularly the double bremsstrahlung contribution which involves two fragmentation functions. For the double bremsstrahlung process, $z = \min(z_1, z_2)$ where z_1 and z_2 are the fragmentation parameters of photons 1 and 2. Figure 4(b) shows the integrated cross sections with the cut $z > z_{\text{cut}}$ imposed, as a function of z_{cut}. Now we see clearly that the single bremsstrahlung contribution can be suppressed below the direct contribution by choosing $z_{\text{cut}} > 0.7$ which in turn corresponds to $\epsilon_h < 0.4$. Fortunately, this is not a particularly stringent cut, and so we may conclude that the background from bremsstrahlung photons can be controlled.

In practice, it should be possible to achieve isolation at the $\epsilon_h \simeq 15\%$ level, which corresponds to $z > 0.9$ [11]. At this level, the bremsstrahlung contributions are almost completely suppressed. We show in Fig. 5 the diphoton invariant mass distribution at (a) SSC and (b) LHC energies, for both signal and backgrounds. We have taken $M_H = 100$ GeV for illustration, and put the signal cross section in a 5 GeV bin, corresponding to modest $M_{\gamma\gamma}$ resolution. Similar figures comparing the signal and the direct background for other M_H values can be found, for example, in Ref. [2]. Notice that with a $z > 0.9$ cut, the bremsstrahlung contributions are far below the signal and direct background. (The double bremsstrahlung background becomes too small to appear on the graph.) The only exception is at very small $M_{\gamma\gamma}$, where the backgrounds are comparable. This is due to the effect of the collinear singularity in the bremsstrahlung contributions, already evident in Fig. 3.

In conclusion, we have shown that single and double bremsstrahlung contributions provide potentially overwhelming backgrounds to intermediate-mass Higgs boson searches in the $W\gamma\gamma$ channel. However, they can be almost completely removed by imposing reasonable photon isolation cuts, for example, by requiring that the accompanying hadronic energy is less than 15% of the photon's energy. This leaves the main background coming from direct $W\gamma\gamma$ production, and this in turn can be controlled with modest diphoton mass resolution.

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