PHYSICAL REVIEW D VOLUME 50, NUMBER 3 1 AUGUST 1994

$\gamma\gamma$ processes at high energy pp colliders

Manuel Drees
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

Rohini M. Godbole
Physics Department, University of Bombay, Vidyanagari, Bombay 400098, India

Marek Nowakowski and Saurabh D. Rindani
Theory Group, Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India

(Received 24 March 1994)

In this Brief Report we investigate the production of charged heavy particles via $\gamma\gamma$ fusion at high energy pp colliders. We revise previous claims that the $\gamma\gamma$ cross section is comparable to or larger than that for the corresponding Drell-Yan process at high energies. Indeed we find that the $\gamma\gamma$ contribution to the total production cross section at pp is far below the Drell-Yan cross section. As far as the individual elastic, semielastic, and inelastic contributions to the $\gamma\gamma$ process are concerned we find that they are all of the same order of magnitude.

PACS number(s): 13.85.Qk, 14.60.Hi, 14.80.Cp, 14.80.Ly

The detection of a fundamental charged scalar particle would certainly lead beyond the realm of the standard model (SM). These particles can arise either in the context of supersymmetric models, as superpartners of quarks and leptons [1], or in extended Higgs sectors, e.g., in two-Higgs-doublet models [2] (with or without supersymmetry) or in models with Higgs triplets [3]. In general, the different charged scalars will have different interactions at the tree level. For instance, sleptons do not couple to quarks in contrast with $H^\pm$ in the two-Higgs-doublet model, while one charged Higgs boson in triplet models does not couple to matter at all but has an unconventional $H^+W^-Z^0$ vertex. Hence a model-independent production mechanism is welcome. Such a model-independent interaction is clearly given by the scalar QED part of the underlying theory. For example, the $\gamma\gamma$ fusion processes

$$\gamma\gamma \to H^+H^-, \tilde{l}^+\tilde{l}^-, \ldots, \tag{1}$$

are uniquely calculable for given mass of the produced particles. At pp colliders we also have, however, the possibility of $q\bar{q}$ annihilation Drell-Yan processes:

$$q\bar{q} \to H^+H^-, \tilde{l}^+\tilde{l}^-, \ldots . \tag{2}$$

There has been a claim in the literature that the $\gamma\gamma$ fusion exceeds the Drell-Yan (DY) cross sections at pp by orders of magnitude [4]. This would create the interesting possibility of producing charged heavy scalars at hadronic colliders or, for that mater, any charged particle which does not have strong interactions.

Apart from the charged scalars mentioned above there exist various candidates for charged fermions. These fermions can be either fourth generation leptons, charginos, or exotic leptons in extended gauge theories such as E_6 [5]. Current limits on the masses of all exotic charged particles which couple to the Z with full strength are $\sim M_Z/2$. In the case of $H^\pm$ there exist additional constraints (clearly model dependent) from the experimental studies of the $b \to s\gamma$ decay. In one variation of the model, $m_{H^\pm} < 110$ GeV is ruled out for large values of $\tan\beta$ and for $m_t = 150$ GeV [6]. However, in the two-Higgs-doublet models with supersymmetry (SUSY) these constraints are much weaker [7]. (The same analysis also shows that there are no limits on the chargino masses from the $b \to s\gamma$ rate.) The calculation for $\gamma\gamma \to L^+L^-$ at pp colliders has been done recently [8]. The result in [8] is that the $\gamma\gamma$ cross section is comparable to the corresponding Drell-Yan process at high energies, e.g., at $\sqrt{s} = 40$ TeV for $m_L \sim 100$ GeV. At energies reached at the CERN Large Hadron Collider (LHC) the $\gamma\gamma$ cross section in the same mass range was found to be one order of magnitude smaller [8] than the DY cross section.

We have repeated the calculations for scalar and fermion pair production, and find that in both cases the $\gamma\gamma$ cross sections are well below the Drell-Yan contribution [9]. In what follows we outline briefly the basic tools and approximations in the calculation.

In order to calculate the pp cross section we have used the Weizsäcker-Williams approximation [10] for the inelastic case (γpX vertex) and a modified version of this approximation [11,12] for the elastic case (γpp vertex). In the latter case the proton remains intact. The inelastic total pp cross section for H^+H^- as well as L^+L^- production reads

$$\sigma_{pp}^{\rm inel}(s) = \sum_{q,q'} \int_{4m^2/s}^1 dx_1 \int_{4m^2/sx_1}^1 dx_2 \int_{4m^2/sx_1x_2}^1 dz_1 \int_{4m^2/sx_1x_2z_1}^1 dz_2 e_q^2 e_{q'}^2 \times f_{q/p}(x_1,Q^2) f_{q'/p}(x_2,Q^2) f_{\gamma/q}(z_1) f_{\gamma/q'}(z_2) \hat{\sigma}_{\gamma\gamma}(x_1x_2z_1z_2s) , \tag{3}$$

where m is the mass of either $H^\pm$ or $L^\pm$, $e_u = \frac{2}{3}$, $e_d = -\frac{1}{3}$, and $\hat{\sigma}_{\gamma\gamma}$ is the production subprocess cross section with the center of mass energy $\sqrt{\hat{s}} = \sqrt{x_1x_2z_1z_2s}$. The structure functions have the usual meaning: $f_{q/p}$ is the quark density inside the proton and $f_{\gamma/q}$ is the photon spectrum inside a quark. We use the Martin-Roberts-Stirling set D'_-

(MRSD$'_-$) parametrization for the partonic densities inside the proton [13]. The scale Q^2 has been chosen throughout the paper to be $\hat{s}/4$. With

$$f_\gamma(z) \equiv f_{\gamma/q}(z) = f_{\gamma/q'}(z) = \frac{\alpha_{\rm em}}{2\pi}\frac{1+(1-z)^2}{z}\ln(Q_1^2/Q_2^2)\ , \tag{4}$$

we can write (3) in a more compact form as

$$\sigma_{pp}^{\rm inel}(s) = \int_{4m^2/s}^{1} dx_1 \int_{4m^2/sx_1}^{1} dx_2 \int_{4m^2/sx_1x_2}^{1} dz_1 \int_{4m^2/sx_1x_2z_1}^{1} dz_2 \frac{1}{x_1}F_2^p(x_1,Q^2)\frac{1}{x_2}F_2^p(x_2,Q^2) f_\gamma(z_1) f_\gamma(z_2)\hat{\sigma}_{\gamma\gamma}(x_1x_2z_1z_2s)\ , \tag{5}$$

where F_2^p is the deep inelastic proton structure function. There is a certain ambiguity about the choice of the scales Q_i^2 in the argument of the logarithm in Eq. (4). We choose Q_1^2 to be the maximum value of the momentum transfer given by $\hat{s}/4 - m^2$ and the choice of $Q_2^2 = 1$ GeV^2 is made such that the photons are sufficiently off shell for the quark-parton model to be applicable.

The semielastic cross section for $pp \to H^+H^-(L^+L^-)pX$ is given by

$$\sigma_{pp}^{\rm semiel}(s) = 2\int_{4m^2/s}^{1} dx_1 \int_{4m^2/sx_1}^{1} dz_1 \int_{4m^2/sx_1z_1}^{1} dz_2 \frac{1}{x_1}F_2^p(x_1,Q^2) f_\gamma(z_1) f_{\gamma/p}^{\rm el}(z_2)\hat{\sigma}_{\gamma\gamma}(x_1z_1z_2s)\ . \tag{6}$$

The subprocess energy now is given by $\sqrt{\hat{s}} = \sqrt{sx_1z_1z_2}$. The elastic photon spectrum $f_{\gamma/p}^{\rm el}(z)$ has been obtained in the form of an integral in [11]. However, we use an approximate analytic expression given in [12] which is known to reproduce exact results to about 10%. The form we use is given by

$$f_{\gamma/p}^{\rm el}(z) = \frac{\alpha_{\rm em}}{2\pi z}[1+(1-z)^2] \times \left[\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right]\ , \tag{7}$$

where

$$A = 1 + \frac{0.71\ {\rm GeV}^2}{Q_{\rm min}^2} \tag{8}$$

with

$$Q_{\rm min}^2 = -2m_p^2 + \frac{1}{2s}[(s+m_p^2)(s-zs+m_p^2) - (s-m_p^2)\sqrt{(s-zs-m_p^2)^2 - 4m_p^2 zs}\ ]\ . \tag{9}$$

At high energies $Q_{\rm min}^2$ is given to a very good approximation by $m_p^2 z^2/(1-z)$. Since the relevant values of the scaled photon energy z_i can in general take smaller values in the elastic case as compared to the inelastic case, Eqs. (9), (8), and (7) imply that even in the elastic case there is a logarithmic enhancement of the photon densities.

Finally, the pure elastic contribution, wherein both the photons remain intact and hence can in principle give rise to clean events, can be written as

$$\sigma_{pp}^{\rm el}(s) = \int_{4m^2/s}^{1} dz_1 \int_{4m^2/z_1 s}^{1} dz_2 f_{\gamma/p}^{\rm el}(z_1) f_{\gamma/p}^{\rm el}(z_2)\hat{\sigma}_{\gamma\gamma}(\hat{s} = z_1z_2s)\ . \tag{10}$$

Defining $\hat{\beta}_{L,H} = (1 - 4m_{L,H}^2/\hat{s})^{1/2}$ the $\gamma\gamma$ subcross sections take the simple form

$$\hat{\sigma}(\gamma\gamma \to H^+H^-) = \frac{2\pi\alpha_{\rm em}^2(M_W^2)}{\hat{s}}\hat{\beta}_H\left[2 - \hat{\beta}_H^2 - \frac{1-\hat{\beta}_H^4}{2\hat{\beta}_H}\ln\frac{1+\hat{\beta}_H}{1-\hat{\beta}_H}\right]\ , \tag{11}$$

and, for lepton production,

$$\hat{\sigma}(\gamma\gamma \to L^+L^-) = \frac{4\pi\alpha_{\rm em}^2(M_W^2)}{\hat{s}}\hat{\beta}_L\left[\frac{3-\hat{\beta}_L^4}{2\hat{\beta}_L}\ln\frac{1+\hat{\beta}_L}{1-\hat{\beta}_L} - (2-\hat{\beta}_L^2)\right]\ . \tag{12}$$

Note that we have used $\alpha_{\rm em} = \frac{1}{137}$ in (4) and (7) and $\alpha_{\rm em}(M_W^2) = \frac{1}{128}$ in the subcross sections (11) and (12).

For completeness we also give here the Drell-Yan $q\bar{q}$ annihilation cross section to H^+H^- including Z^0 exchange, for the case that $H^\pm$ resides in an SU(2) doublet:

$$\hat{\sigma}(q\bar{q} \to H^+H^-) = \frac{4\pi\alpha_{\rm em}^2(M_W^2)}{3\hat{s}}\frac{(\hat{\beta}_H)^{3/2}}{4}\left[e_q^2 + 2e_q g_{V_q}\frac{\cot 2\theta_W}{\sin 2\theta_W}\frac{\hat{s}(\hat{s}-m_Z^2)}{(\hat{s}-m_Z^2)^2 + \Gamma_Z^2 m_Z^2} + (g_{V_q}^2 + g_{A_q}^2)\frac{\cot^2 2\theta_W}{\sin^2 2\theta_W}\frac{\hat{s}^2}{(\hat{s}-m_Z^2)^2 + \Gamma_Z^2 m_Z^2}\right]\ . \tag{13}$$

In the above, g_{V_q} and g_{A_q} are the standard vector and axial vector coupling for the quark.

The results of our calculations are presented in Fig. 1 for H^+H^- production and in Fig. 2 for the lepton case. As far as the H^+H^- production in $\gamma\gamma$ fusion is concerned, we differ from the results given in [4] by roughly three orders of magnitude: our $\gamma\gamma$ cross section is far below their results and also approximately two orders of magnitude smaller than the DY cross section. The logarithmic enhancement of the photon densities is simply not enough to overcome completely the extra factor α_{em}^2 in the $\gamma\gamma$ process. Even if the Higgs boson is doubly charged (such a Higgs boson appears in triplet models [3]), the ratio of DY to $\gamma\gamma$ cross section changes only by a factor $\frac{1}{4}$ as compared to the singly charged Higgs boson production. We also find that contributions from elastic, semielastic, and inelastic processes to the total $\gamma\gamma$ cross section are of the same order of magnitude. The elastic process contributes $\sim 20\%$ of the total $\gamma\gamma$ cross section at smaller values of m_H going up to 30% at the high end. This can be traced to the logarithmic enhancement of the photon density even in the elastic case mentioned earlier. Assuming the $\tilde{l}_L, \tilde{l}_R$ to be degenerate in mass, the cross section for $\gamma\gamma$ production of sleptons (for one generation) will be twice the corresponding H^+H^- cross sections.

Our results for leptons are given in Fig. 2. Here again we find that at LHC energies DY exceeds $\gamma\gamma$ by two orders of magnitude even for relatively small m_L masses in the range of 50–100 GeV [9]. In general, the L^+L^- cross sections are higher than the corresponding H^+H^- cross sections (both for $\gamma\gamma$ and DY) by about a factor of 5–7. This can be traced to the different spin factors and the different $\hat{\beta}$ dependence of the subprocess cross section for the fermions and scalars. The cross section for the $\gamma\gamma$ production of charginos will again be the same as that of the charged leptons.

One might think that by sacrificing rate for "cleanliness" the purely elastic processes might prove useful. Moreover, even inelastic or semielastic $\gamma\gamma$ events might be characterized by "rapidity gaps," where the only hadrons at central rapidities are due to the decay of the heavy particles produced. However, at the LHC one expects about 16 minimum bias events per bunch crossing at luminosity $\mathcal{L}=10^{34}$ cm^{-2} sec^{-1}; even the elastic $\gamma\gamma$ events will therefore not be free of hadronic debris. These "overlapping events" will fill the entire rapidity space with (mostly soft) hadrons, thereby obscuring any rapidity gap. Notice also that in the purely elastic events the participating protons only lose about 0.1% of their energy, making it very difficult to detect them in a forward spectrometer of the type now being installed at the DESY *ep* collider HERA. We are therefore forced to conclude that most likely one will not be able to distinguish experimentally between DY and $\gamma\gamma$ events if the LHC is operated anywhere near its design luminosity. The clean elastic events might be detectable at luminosities well below 10^{33} cm^{-2} sec^{-1}, where event overlap is not expected to occur. However, our results show that at such a low luminosity one is running out of event rate at masses not much above the limit that can be probed at the CERN e^+e^- collider LEP 200; moreover, there might be sizable backgrounds, e.g., due to the process $\gamma\gamma \to W^+W^-$.

At this point it might be instructive to compare the $\gamma\gamma$ cross sections with other (model-dependent) possible production mechanisms for various weakly interacting charged particles. Studies [14] have shown that a search for charginos in hadronically quiet multilepton events due to associated production of a chargino with a neutralino (via DY) at LHC might be feasible up to $m_{\chi^\pm} \simeq 250$ GeV. The detection of sleptons with mass up to ~ 250 GeV also seems possible [15]. Hence the DY process still seems to be the dominant mode for production for sleptons and charginos as well as heavy leptons. For larger masses the DY cross section falls off and in some cases the gluon induced production (which we discuss below) will take over.

For the charged Higgs bosons the situation is somewhat different. The question of DY, $\gamma\gamma$, or *gg* production becomes relevant in this case only for $m_t < m_{H^\pm}$. If

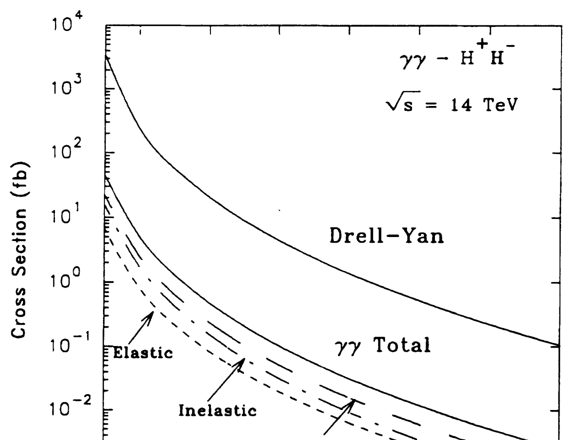

FIG. 1. Cross section in fb for DY and $\gamma\gamma$ production of the charged Higgs at bosons LHC energies, as a function of the Higgs boson mass. The dashed, dash-dotted, and long-dashed lines show the elastic, inelastic, and semielastic contributions (as defined in the text) to the $\gamma\gamma$ cross sections. The total $\gamma\gamma$ cross section and the DY contributions are shown by the labeled solid lines.

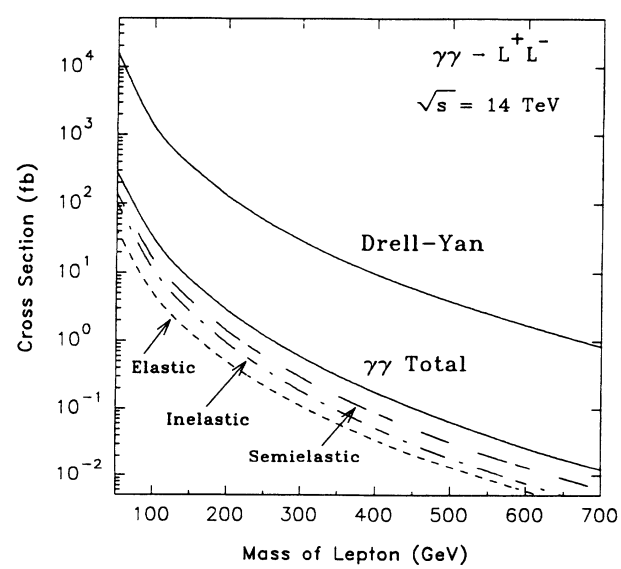

FIG. 2. Cross section in fb for DY and $\gamma\gamma$ production of the charged leptons at LHC energies, as a function of the lepton mass. The convention is the same as in Fig. 1.

$m_t > m_{H^\pm}$, the charged Higgs boson can be produced in the decay of the top quark and the strong production of top quarks gives large rates, allowing one to probe at LHC up to $m_{H^\pm} \sim m_t - 20$ GeV [16]. Even when $m_t < m_{H^\pm}$, production of a single charged Higgs boson in association with a t quark via the process

$$gb \to tH^- \tag{14}$$

might provide a measurable signal in the decay channel

$$tH^+ \to ttb \to b(bq\bar{q}')(bl\nu) \ . \tag{15}$$

The cross section is ~ 15 pb for $m_{H^\pm} \sim 150$ GeV and could provide a feasible signal up to $m_{H^\pm} \sim 200$ GeV over a wide range of parameter space, if b quarks can be tagged with high purity and not too low efficiency [17]. Figure 1 shows that even for the DY process the charged Higgs cross section is only a few tens of fb or less if $m_{H^+} > m_t$.

Another process that contributes to the pair production of Higgs bosons and charged leptons is one-loop gluon fusion:

$$\begin{aligned} &gg \to H^+H^- \ , \\ &gg \to L^+L^- \ . \end{aligned} \tag{16}$$

These contributions will only be competitive with ordinary DY production if some couplings of the produced particles grow with their mass. Accordingly, the first process will be large [18] if $m_t > m_{H^+}$ (in which case H^+ production from t decays will have even larger rates) but is expected to decrease for $m_{H^+} > m_t$. Since the coupling of chiral leptons to Higgs bosons and longitudinal Z bosons grows with the lepton mass, graphs containing the (one-loop) ggH^{0*} and ggZ^{0*} couplings dominate the production of both charged [19] and neutral [20] chiral leptons of sufficiently large mass.

In summary, we have shown that the cross section for the pair production of heavy charged scalars or fermions via $\gamma\gamma$ fusion amounts to at best a few percent of the corresponding Drell-Yan cross section; in many cases there are additional production mechanisms with even larger cross sections. Moreover, at the LHC overlapping events prevent one from isolating $\gamma\gamma$ events experimentally unless the machine is run at a very low luminosity, in which case the accessible mass window is not much larger than at LEP 200. We do not expect, therefore, $\gamma\gamma$ fusion processes at the LHC to be competitive with more traditional mechanisms for the production of new particles.

While writing this Brief Report, we have received a paper [21] which treats the same subject of $\gamma\gamma$ processes in pp colliders and gets similar results. However, we differ somewhat in the details, which is most probably due to the different treatment of the photon luminosity functions.

We thank the Department of Science and Technology (India) and the organizers of the WHEPP-III workshop held in Madras (India) where this work was partially done. The work of M.D. was supported by a grant from the Deutsche Forschungsgemeinschaft under the Heisenberg program, as well as in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881, by the Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and by the Texas National Research Laboratory Commission under Grant No. RGFY93-221. R.M.G. wishes to thank the Theory Group at PRL for hospitality. M.N. wishes to thank the Alexander von Humboldt Foundation for financial support under the Feodor-Lynen program.

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