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$\gamma\gamma$ processes at high energy $p-p$ colliders

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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 [2], or in extended Higgs sectors (with or without supersymmetry). In general, the different charged scalars will have different interactions at tree level. 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:

$$\gamma\gamma \rightarrow H^+H^-, \ \tilde{l}^+\tilde{l}^-, \ ... \tag{1}$$

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

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

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 [3]. This would be an interesting possibility of producing charged heavy scalars at hadronic colliders or for that matter 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 like E_6 [4]. 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 $b \rightarrow s\gamma$ decay. The calculation for $\gamma\gamma \rightarrow L^+L^-$ at pp colliders has been done recently [5]. The result in [5] 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 LHC energies the $\gamma\gamma$ cross section in the same mass range was found to be [5] one order of magnitude smaller 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 [6]. 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 [7] for the inelastic case (γpX vertex) and a modified version of this approximation [8, 9] for the elastic case (γpp vertex). In the latter case the proton remains intact. The inelastic (inel.) total pp cross section for H^+H^- as well as L^+L^- production reads

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

where m is the mass of either $H^\pm$ or $L^\pm$, $e_u = 2/3$, $e_d = -1/3$ 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, $f_{\gamma/q}$ is the photon spectrum inside a quark. We use the the MRSD$'_-$ parameterization for the partonic densities inside the proton [10]. The scale Q^2 has been chosen throughout the paper to be $\hat{s}/4$. We use

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

There is a certain ambiguity about the choice of the scales Q_i^2 in the argument of the log 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 semi-elastic (semi-el.) cross section for $pp \to H^+H^-(L^+L^-)pX$ is given by

$$\sigma_{pp}^{semi-el.}(s) = 2 \int_{4m^2/s}^{1} dx_1 \int_{4m^2/sx_1}^{1} dz_1 \int_{sm^2/sx_1z_1}^{1} dz_2 \frac{1}{x_1} \; F_2^p(x_1,\,Q^2) \cdot f_\gamma(z_1)\, f_{\gamma/p}^{el.}(z_2)\, \hat{\sigma}_{\gamma\gamma}(x_1z_1z_2s) \quad (5)$$

The subprocess energy now is given by $\sqrt{\hat{s}} = \sqrt{sx_1z_1z_2}$. The elastic photon spectrum $f_{\gamma/p}^{el.}(z)$ has been obtained in the form of an integral in [8]. However, we use an approximate analytic expression given in [9] which is known to reproduce exact results to about 10%. The form we use is given by

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

where

$$A = 1 + \frac{0.71(\mathrm{GeV})^2}{Q^2_{min}} \quad (7)$$

with

$$Q^2_{min} = -2m_p^2 + \frac{1}{2s}\Big[(s+m_p^2)(s-zs+m_p^2) - (s-m_p^2)\sqrt{(s-zs-m_p^2)^2 - 4m_p^2zs}\Big] \quad (8)$$

At high energies Q^2_{min} 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. (8),(7) and (6) 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

$$\sigma_{pp}^{el.}(s) = \int_{4m^2/s}^{1} dz_1 \int_{4m^2/z_1 s}^{1} dz_2 \; f_{\gamma/p}^{el.}(z_1)\, f_{\gamma/p}^{el.}(z_2)\, \hat{\sigma}_{\gamma\gamma}(\hat{s} = z_1 z_2 s) \tag{9}$$

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

$$\hat{\sigma}(\gamma\gamma \to H^+H^-) = \frac{2\pi\alpha^2_{em}(M_W^2)}{\hat{s}}\hat{\beta}_H \left[2 - \hat{\beta}_H^2 - \frac{1-\hat{\beta}_H^4}{2\hat{\beta}_H}\ln\frac{1+\hat{\beta}_H}{1-\hat{\beta}_H}\right] \tag{10}$$

and for lepton production

$$\hat{\sigma}(\gamma\gamma \to L^+L^-) = \frac{4\pi\alpha^2_{em}(M_W^2)}{\hat{s}}\hat{\beta}_L \left[\frac{3-\hat{\beta}_L^4}{2\hat{\beta}_L}\ln\frac{1+\hat{\beta}_L}{1-\hat{\beta}_L} - (2-\hat{\beta}_L^2)\right] \tag{11}$$

Note that we have used $\alpha_{em} = 1/137$ in (4) and (6) and $\alpha_{em}(M_W^2) = 1/128$ in the subcross sections (10) and (11).

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:

$$\begin{aligned}\hat{\sigma}(q\bar{q} \to H^+H^-) = \frac{4\pi\alpha^2_{em}(M_W^2)}{3\hat{s}}\,\frac{(\hat{\beta}_H)^{3/2}}{4}\Bigg[&e_q^2 + 2e_q g_{V_q}\frac{\cot 2\theta_W}{\sin 2\theta_W}\,\frac{\hat{s}(\hat{s}-m_Z^2)}{(\hat{s}-m_Z^2)^2+\Gamma_Z^2 m_Z^2} \\ &+ (g_{V_q}^2 + g_{A_q}^2)\frac{\cot^2 2\theta_W}{\sin^2 2\theta_W}\,\frac{\hat{s}^2}{(\hat{s}-m_Z^2)^2+\Gamma_Z^2 m_Z^2}\Bigg]\end{aligned} \tag{12}$$

In the above g_{V_q} , 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 [3] 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^2_{em} in the $\gamma\gamma$ process. Even if the Higgs is doubly charged (such a Higgs appears in triplet models [11]) the ratio of DY to $\gamma\gamma$ cross section changes only by a factor 1/4 as compared to the singly charged Higgs production. We also find that contributions from elastic, semi-elastic 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

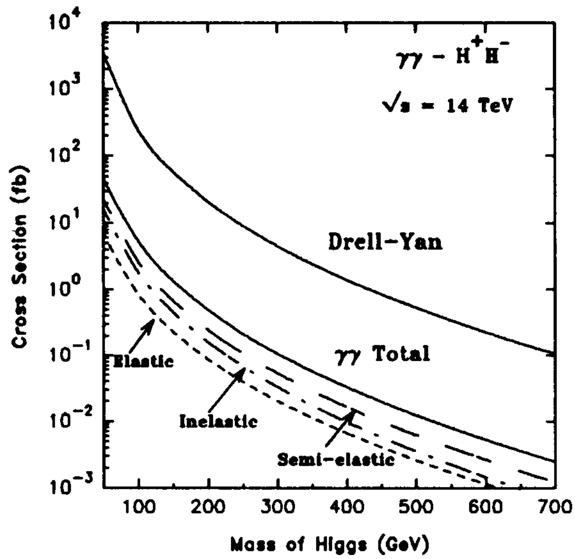

Figure 1. Cross section in fb for DY and $\gamma\gamma$ production of the charged Higgs at LHC energies, as a function of the Higgs mass. The dashed, dash-dotted and long-dashed lines show the el., inel. and semi-el. contributions (as defined in the text) to the $\gamma\gamma$ cross sections. The total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

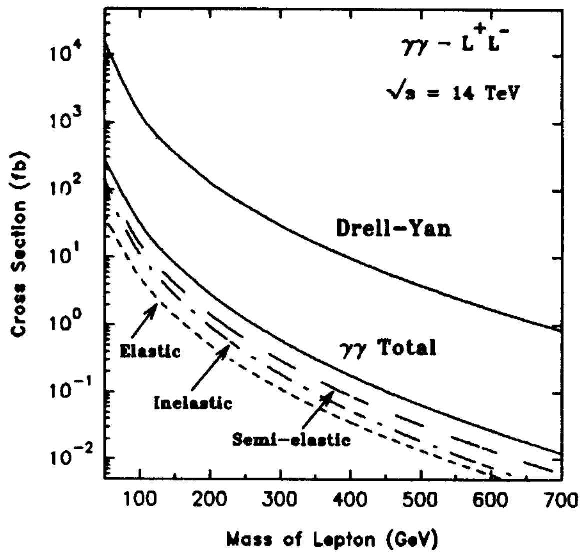

Figure 2. Cross section in fb for DY and $\gamma\gamma$ production of the charged Leptons at LHC energies, as a function of the Lepton mass. The convention is the same as in Fig. 1

masses in the range of 50 − 100 GeV[6]. 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.

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

$$\begin{aligned} gg &\rightarrow H^+H^- \\ gg &\rightarrow L^+L^- \end{aligned} \tag{13}$$

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 [12] 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 (1–loop) ggH^{0*} and ggZ^{0*} couplings dominate the production of both charged [13] and neutral [14] 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 % 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 LEP200. We do therefore not expect $\gamma\gamma$ fusion processes at the LHC to be competitive with more traditional mechanisms for the production of new particles.

While writing this note we have received a preprint [15] 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.

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