Detecting an Intermediate Mass Charged Higgs at $\gamma\gamma$ Colliders

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Abstract

The detection of an intermediate mass charged Higgs boson at $\gamma\gamma$ colliders via the modes $\gamma\gamma \to H^+H^- \to \nu\tau^+\bar{\nu}\tau^-$, $c\bar{s}$, and $\nu\tau^+\bar{c}s + c\bar{s}\nu\tau^-$ is considered. $W^+W^-$ boson pair production is the dominant background for these modes. The three modes may be used in a complementary fashion to detect a charged Higgs boson. The mixed leptonic-hadronic mode may be used to determine the charged Higgs mass by reconstructing the invariant hadronic mass. The sensitivity of $\text{Br}(H^+ \to c\bar{s}, \nu\tau^+)$ on the discovery limit of the charged Higgs boson is also discussed.

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1 Introduction

The symmetry breaking sector of the standard model will be a prime target of future colliders. Any enlargement of the sector beyond the single $SU(2)_L$ Higgs doublet of the minimal standard model necessarily involves new physical particles. With two or more doublets, as required in supersymmetric theories, the physical spectrum includes charged Higgs bosons. Technicolor theories can also lead to fairly light charged technipions. In this letter the production and detection of such charged scalars (subsequently referred to as charged Higgs bosons) in the intermediate mass range $m_W \lesssim m_{H^\pm} \lesssim 2m_W$ at proposed high energy $\gamma\gamma$ colliders [1] will be considered.

Assuming the Higgs-matter coupling is proportional to mass, the most promising means of production in hadronic colliders is by model-dependent associated production with, or decay of, the top quark; e.g., $t \to bH^+$ for $m_{H^+} < m_t - m_b$ [2]. At $e^+e^-$ colliders charged Higgs bosons are pair produced via $s$-channel $\gamma$ and $Z$ exchange [3]. At $\gamma\gamma$ colliders pair production proceeds through the model-independent $H^+H^-\gamma$ gauge coupling, as shown in Fig. 1. The primary advantage of $e^+e^-$ and $\gamma\gamma$ colliders with respect to hadronic colliders is of course the relative paucity of backgrounds for hadronic $H^\pm$ detection modes.

The dominant decay modes depend on the charged Higgs mass, $m_{H^\pm}$. For an intermediate mass charged Higgs boson, the decay mode $H^+ \to ZW^+$ is not available. With the current limit on the lightest neutral higgs mass, $m_{h^0} > 48$ GeV [3], the mode $H^+ \to h^0W^+$ is closed for $m_{H^\pm} \lesssim 130$ GeV. If LEP II pushes the bound on $m_{h^0}$ to its range of detectability (about $m_W$), this channel is also closed for $m_{H^\pm} < 2m_W$. The mode $H^+ \to \gamma W^+$ is absent at tree level and should be correspondingly suppressed. For $m_{H^\pm} < m_t + m_b$, where the top quark mass is assumed to be $m_t \approx 150$ GeV,
the mode $H^+ \rightarrow t \bar{b}$ will also be closed. With these assumptions, the dominant decay modes are $H^+ \rightarrow \nu \tau^+, c \bar{s}$. The decay $H^+ \rightarrow \bar{c} b$ is suppressed by the small mixing between second and third quark generations. Decays to other quarks and leptons are suppressed by small masses. To this extent, $\text{Br}(H^+ \rightarrow \nu \tau^+) + \text{Br}(H^+ \rightarrow c \bar{s}) \simeq 1$ over the mass range considered here.

The three decay modes of the charged Higgs pair, $H^+H^- \rightarrow \nu \tau^+\bar{\nu}\tau^-, c \bar{s}\bar{c}s$, and $\nu \tau^+ \bar{c}s + c \bar{s}\bar{c}\nu$ may be used in a complementary fashion to cover the whole intermediate mass range. The last decay mode, where detectable, may be used to determine $m_{H^\pm}$ by reconstructing the invariant mass of the $cs$ system.

2 Production of Charged Higgs Bosons

The initial state photons of the $\gamma\gamma$ collider can be produced by the laser back-scattering method [1] at a next-generation linear $e^+e^-$ or $e^-e^-$ collider. Compton scattering of laser photons (with an energy $\omega_0$ of a few eV) head-on with electron or positron beams of energy $E_0$ produces back-scattered photons with energy $\omega = xE_0$. The $e\gamma \rightarrow e\gamma$ conversion efficiency is taken to be 100%, multiple scattering is ignored, and the incoming photons are taken to be unpolarized. Under these assumptions, the back-scattered photon luminosity function is given by [1]

$$F_{\gamma/e}(x) = \frac{1}{D(\xi)} \left[ 1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2} \right],$$

where $D(\xi)$ is a normalization factor,

$$D(\xi) = (1 - \frac{4}{\xi} - \frac{8}{\xi^2}) \ln(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2},$$

and $\xi = 4E_0\omega_0/m_e^2$. The incoming photon energy, $\omega_0$, is chosen such that $\xi = 2(1 + \sqrt{2})$ to maximize the back-scattered photon energy while avoiding $e^+e^-$ pair
creation. The photon luminosity function vanishes for $x > x_{\text{max}} = \xi/(1 + \xi) \simeq 0.83$.

For definiteness the design parameters of the Next Linear Collider (NLC), with center of mass (CM) energy $\sqrt{s_{ee}} = 500$ GeV and luminosity $L_{ee} = 10$ fb$^{-1}$ yr$^{-1}$ will be employed. The mass range of a charged Higgs search in the $\gamma\gamma$ mode at the NLC is limited to $m_{H^{\pm}} < x_{\text{max}}\sqrt{s_{ee}}/2 \simeq 207$ GeV, well above the intermediate mass range considered here.

The cross section $\sigma$ for any process is the convolution of the hard-scattering cross section $\hat{\sigma}$ with the photon luminosity functions,

$$\sigma(s_{ee}) = \int_{\tau_{\text{min}}}^{x_{\text{max}}^2} d\tau \int_{\tau/x_{\text{max}}}^{x_{\text{max}}} \frac{dx_1}{x_1} F_{\gamma/e}(x_1) F_{\gamma/e}(\tau/x_1) \hat{\sigma}(\hat{s}_{\gamma\gamma} = \tau s_{ee}) ,$$  \hspace{1cm} (3)

where

$$\tau_{\text{min}} = \left(\frac{M_{\text{final}}}{s_{ee}}\right)^2 ,$$

and $M_{\text{final}}$ is the sum of final state particle masses.

The differential cross section for the process $\gamma\gamma \rightarrow H^+H^-$ (shown in Fig. 1) is given by

$$\frac{d\hat{\sigma}}{d |\cos \theta|} = \frac{\pi \alpha^2 \beta}{\hat{s}_{\gamma\gamma}} \left(1 - \frac{2 \beta^2 (1 - \beta^2) \sin^2 \theta}{(1 - \beta^2 \cos^2 \theta)^2}\right)$$  \hspace{1cm} (4)

where $\hat{s}_{\gamma\gamma}$ is the photon pair CM mass energy, $\theta$ is the $\gamma - H^+$ CM polar angle, and $\beta \equiv \sqrt{1 - 4m_{H^{\pm}}^2/s_{\gamma\gamma}}$. For $\sqrt{s_{\gamma\gamma}} \gg m_{H^{\pm}}$, $\hat{\sigma}$ falls as $s_{\gamma\gamma}^{-1}$ (as expected), and becomes isotropic in the CM frame. This is helpful, as the principal backgrounds from pair production of fermions and spin-one gauge bosons, while larger in magnitude, are sharply peaked in the forward direction for large $\hat{s}_{\gamma\gamma}$. The $\gamma\gamma \rightarrow H^+H^-$ total cross section for $\sqrt{s_{ee}} = 0.5$ TeV and 1 TeV, including the convolution (3), are shown in Fig. 2. For small Higgs mass the cross section is actually larger for 0.5 TeV than for 1 TeV. This is because the $\hat{s}_{\gamma\gamma}$ dependence convoluted with the soft
portion of the photon luminosity function increases the $H^+H^-$ production rate for $m_{H^\pm} << x_{\text{max}}\sqrt{s}/2$, compared with the monochromatic case.

Before considering detection of the charged Higgs via the three modes, it is necessary to comment on the assumptions made for detection of decay products, and on the acceptance cuts employed. For $\tau^\pm$ identification, the leptonic decay modes suffer irreducible backgrounds from $W^\pm$ decay discussed below. Only the hadronic modes $\tau^- \to \pi^-\nu_\tau$, $\rho^-\nu_\tau$, $a_1^-\nu_\tau$, with a total branching ratio 0.45, will be considered. Requiring visible decay product energy $E_{\tau}^{\text{vis}} > 10$ GeV ensures that the decay products travel essentially along the original $\tau^\pm$ direction. The $\tau^\pm$ decay product distributions depend on the $\tau^\pm$ charge, helicity, and decay mode. Summing over the hadronic modes given above, the decay product laboratory energy distribution may be approximated by

$$\frac{1}{\Gamma} \frac{d\Gamma}{dz} = 0.45 - 2SC(0.43z - 0.215)$$ \hspace{1cm} (5)

where $C$ and $S$ are the $\tau^\pm$ charge and helicity, $z = E_{\tau}^{\text{vis}}/E_\tau$, $E_\tau$ and $E_{\tau}^{\text{vis}}$ are the $\tau^\pm$ and decay product laboratory energies. The decay products of $\tau^\pm$ coming from $H^\pm$ decay have a somewhat harder distribution than from $W^\pm$ decay \cite{8} (the main background discussed below). The $E_{\tau}^{\text{vis}} > 10$ GeV cut therefore enhances the signal to background ratio. This ratio could be further enhanced by using correlations among the multi-pion final states \cite{8}.

In the absence of definite detector designs, representative parameters will be employed \cite{6}. The hadronic calorimeter is taken to have gaussian resolution with standard deviation

$$\frac{\delta E}{E} (%) = \sqrt{\frac{a^2}{E} + b^2}$$ \hspace{1cm} (6)
with $a = 60 \text{ GeV}^{1/2}$ and $b = 2$. Calorimeter and tracking coverage are assumed to extend to $|\cos \theta| < 0.95$. Photon identification is assumed to extend to $|\cos \theta| < 0.985$. Aside from the $\tau^+\tau^-\gamma$ background discussed in the next section, all visible decay products in the laboratory frame are required to have $|\cos \theta| < 0.95$, be separated by at least $15^\circ$, and have an energy $E^\text{vis} > 10 \text{ GeV}$. In addition to allowing for realistic detector acceptances, these cuts help suppress the backgrounds discussed below. Quark jet identification is taken to be 100%, but explicit dependence on $\tau^\pm$ identification efficiency, $\epsilon_{\tau}$, is retained below.

3 $H^+H^- \rightarrow \nu\tau^+\bar{\nu}\tau^-$

The first decay mode,

$$\gamma\gamma \rightarrow H^+H^- \rightarrow \nu\tau^+\bar{\nu}\tau^-$$

has background from the following processes:

$$\gamma\gamma \rightarrow \tau^+\tau^-$$

$$\gamma\gamma \rightarrow W^+W^- \rightarrow \nu\tau^+\bar{\nu}\tau^-$$

$$\gamma\gamma \rightarrow \tau^+\tau^-Z \rightarrow \tau^+\tau^-\nu\bar{\nu}$$

$$\gamma\gamma \rightarrow \tau^+\tau^-\gamma$$

The total cross section from process (8) is daunting at 49 pb (including the $\tau$ branching ratios). Because of $t$-channel enhancement though, the $\tau$’s are sharply peaked in the forward direction. The $|\cos \theta_\tau| < 0.95$ cut reduces the cross section to 9.2 pb. Since this is a two-body final state, however, the azimuthal angle $|\Delta \phi|$ between the $\tau$’s will be $180^\circ$. The requirement $E^\text{vis}_\tau > 10 \text{ GeV}$ sufficiently collimates the decay products along the original $\tau^\pm$ directions so that a cut of $|\Delta \phi| < 170^\circ$ should eliminate this
background. To the extent that the $H^+H^-$ pair is not extremely relativistic, the $\tau$'s from (7) have a relatively uniform distribution in $\Delta \phi$. An even stronger acoplanarity cut, if required, would therefore not significantly reduce the signal.

Process (9) involves the small branching ratio $[\text{Br}(W^+ \to \nu\tau^+)]^2 \approx (1/9)^2$. The $W^+W^-$ pair is largely transversely polarized and peaked strongly in the forward-backward direction. The $\tau$'s therefore tend to be softer or boosted along the beam. As discussed above, the decay products of a $\tau^\pm$ coming from $W^\pm$ decay have a softer distribution than those from $H^\pm$ decay, thus aiding the efficiency of the $E^\text{vis}_\tau$ cut. The acoplanarity cut does not greatly affect this background. After all cuts this background is 40 fb.

Although processes (10, 11) are higher order, the extra particle(s) in the final state potentially reduce the effectiveness of the acoplanarity cut. Both have a $t$-channel enhancement though, that is suppressed by the $|\cos \theta_\tau| < 0.95$ cut. This effectively eliminates the background (10), which after all cuts is only 0.26 fb. The background (11) is greatly reduced by vetoing on the presence of a “visible” photon, defined as being within the detector ($|\cos \theta_\gamma| < 0.985$), having energy greater than 10 GeV, and being farther than 5° from either $\tau$. What is left of this process requires that the photon be along one of the $\tau$’s, go down the beam, or be fairly soft in the central region. In any of these cases, the azimuthal angle between the $\tau$’s should not be very different from 180°, so that the acoplanarity cut effectively reduces this background. After all cuts this background is 5.6 fb.

The cross section for the signal (9) as a function of $m_{H^\pm}$, after all cuts, is shown in Fig. 3. It ranges from 79 fb (for $m_{H^\pm} = 50$ GeV) to 10.6 fb (for $m_{H^\pm} = 150$ GeV), assuming $\text{Br}(H^+ \to \nu\tau^+) = 1$. The backgrounds from processes (9) and (11) are also
shown. In this figure, the \( \tau \) detection efficiency, \( \epsilon_\tau \), is taken to be 100%. The actual cross sections of course scale like \( \epsilon_\tau^2 \).

4 \( H^+ H^- \rightarrow c\bar{s}\bar{c}s \)

The second decay mode

\[
\gamma\gamma \rightarrow H^+H^- \rightarrow c\bar{s}\bar{c}s, \tag{12}
\]

has the principal background

\[
\gamma\gamma \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}. \tag{13}
\]

In contrast to the analogous process of the previous section, this background is not greatly reduced by the branching ratio \([\text{Br}(W^\pm \rightarrow q\bar{q})]^2 \simeq (2/3)^2\). With all the cuts discussed in section 2, this background amounts to 12 pb. This may be reduced by vetoing events for which the dijet invariant mass, \( m_{qq} \simeq \sqrt{2p_\text{q}\cdot p_\text{q}} \), of any pair of jets, roughly reconstructs the \( W^\pm \) mass. Including the hadronic calorimeter resolution (6) and the cut \( |m_{qq} - m_W| > 8 \text{ GeV} \) on all jet pairs results in a reduction of a factor of approximately 80, to 0.1517 pb. Thus about 10% of all on-shell \( W^\pm \) decays remain after this cut. The entire background is now due to the hadronic calorimeter smearing of the two on-shell \( W^\pm \) decays. It is therefore worth considering whether the next order tree level electroweak processes (see Fig. 4) contained in

\[
\gamma\gamma \rightarrow qqW \rightarrow q\bar{q}q\bar{q}, \tag{14}
\]

contribute substantially since only one of the \( qq \) pair invariant masses necessarily reconstructs \( m_W \) (before including hadronic calorimeter resolution). The cross section for (14) with all cuts (including that on \( m_{qq} \)) is 0.1533 pb, almost identical to the
cross section from on-shell $W^+W^-$ decay. This result is not surprising since the full gauge invariant set of Feynman diagrams for (14) is dominated by a subset of diagrams, identical to the ones contributing to (13), in which one of the $W^\pm$ is nearly on-shell. With the energy resolution considered here the corrections from higher order the processes contained in (14) are therefore unimportant. Higher order electroweak processes contained in $\gamma\gamma \rightarrow q\bar{q}q\bar{q}$ would give an even smaller correction. The QCD processes $\gamma\gamma \rightarrow q\bar{q}qg, q\bar{q}gg$ would also contribute at roughly the same order as the correction from (14), and are therefore unimportant. If the background from (13) were reduced with significantly better hadronic resolution, the higher order processes might become important. Also for $m_{H^\pm}$ significantly different than $m_W$ the cut on $|m_{qq} - m_W|$ could be increased, thereby reducing the background without greatly affecting the signal. The choice of 8 GeV represents a compromise for the range of $m_{H^\pm}$ considered here.

Fig. 5 shows the cross sections for the signal with acceptance cuts as a function of $m_{H^\pm}$, with and without the requirement $|m_{qq} - m_W| > 8$ GeV. The cross sections for the background (13), with and without the $m_{qq}$ cut are also shown.

$5 \quad H^+H^- \rightarrow \nu\tau^+\bar{c}s, \; c\bar{s}\bar{\nu}\tau^-$

The third decay mode

$$\gamma\gamma \rightarrow H^+H^- \rightarrow \nu\tau^+\bar{c}s, \; c\bar{s}\bar{\nu}\tau^-,$$

has the principal background

$$\gamma\gamma \rightarrow W^+W^- \rightarrow \nu\tau^+q\bar{q}, \; q\bar{q}\bar{\nu}\tau^-.$$

5
This mode offers the possibility of reconstructing $m_{H^\pm}$ through $m_{qq}$. For $m_{qq}$ significantly different than $m_W$, the background (16) contributes only through the hadronic calorimeter smearing of on-shell $W^\pm$ decays. As in the previous section, it is therefore worth considering the next order tree level electroweak processes contained in

$$\gamma\gamma \rightarrow q\bar{q}W^\pm \rightarrow q\bar{q}\nu\tau^+, q\bar{q}\bar{\nu}\tau^-.$$ (17)

The differential cross section, $d\sigma/dm_{qq}$, with acceptance cuts, is shown in Fig. 6 as a function of $m_{qq}$ for the signal (15) and background (17). This figure assumes $\epsilon_\tau = 1$, $\text{Br}(H^+ \rightarrow \nu\tau^+) = \text{Br}(H^+ \rightarrow c\bar{s}) = 1/2$, and the hadronic calorimeter resolution (6). Again, the total cross section for (17) is dominated by diagrams identical to the ones contributing to (16) in which one of the $W^\pm$ is nearly on-shell. But with the hadronic calorimeter resolution assumed, the higher-order corrections contained in (17) do become important for $m_{qq} \lesssim 60$ GeV and $m_{qq} \gtrsim 100$ GeV.

As evident in Fig. 6, for $m_{H^\pm}$ sufficiently different from $m_W$, the background can be reduced by rejecting events outside a window centered on $m_{H^\pm}$. Implementing this requires an $m_{H^\pm}$ dependent analysis. In order to ensure that most of the signal is retained, a window of $\pm 8$ GeV will be used. The cross section for the signal (15) and background (17) as a function of the presumed charged Higgs mass is shown in Fig. 7. This figure includes the same cuts and assumptions as Fig. 6, and the requirement $|m_{qq} - m_{H^\pm}| < 8$ GeV.

6  Sensitivity to $\text{Br}(H^+ \rightarrow \nu\tau^+)$ and $\text{Br}(H^+ \rightarrow c\bar{s})$

In this section, the sensitivity of each mode to $\text{Br}(H^+ \rightarrow \nu\tau^+)$, $\text{Br}(H^+ \rightarrow c\bar{s})$, $m_{H^\pm}$, and the $\tau^\pm$ identification efficiency, $\epsilon_\tau$, is analyzed. For a 5 standard deviation
measurement, the requirement $N_s/\sqrt{N_b} > 5$ is imposed, where $N_s$ and $N_b$ are the number of signal and background events, respectively, including branching ratios and efficiencies.

Detection of the mode $H^+H^- \to \nu\tau^+\nu\tau^-$ over the $W^+W^-$ and $\tau^+\tau^-\gamma$ backgrounds requires

$$\text{Br}(H^+ \to \nu\tau^+) > \sqrt{\frac{\sqrt{\frac{5}{\epsilon^2}L\sigma_b}}{\epsilon^2 L\sigma_s}}$$

(18)

where $L = \int L \, dt$ is the integrated luminosity. The signal and background cross sections, $\sigma_s$ and $\sigma_b$, are from Fig. 3. The upper curve in Fig. 8 gives the minimum value of $\text{Br}(H^+ \to \nu\tau^+)$ accessible in this mode, for $L = 10 \, \text{fb}^{-1}$, and optimistically assuming $\epsilon_\tau = 1$ after all cuts. A smaller value of $\epsilon_\tau$ could be offset by an increase in $L$. In addition, increasing the cut $E_{\text{vis}}^\tau > 10 \, \text{GeV}$ to $E_{\text{vis}}^\tau > 20 \, \text{GeV}$ leaves the ratio $\sqrt{\sigma_b/\sigma_s}$ approximately constant over the range of $m_{H^\pm}$ considered. This would increase $\epsilon_\tau$ by improving tracking efficiency for hadronic $\tau^\pm$ decays.

The analogous analysis for the mode $H^+H^- \to c\bar{s}c\bar{s}$ requires

$$\text{Br}(H^+ \to c\bar{s}) > \sqrt{\frac{\sqrt{\frac{5}{\epsilon'^2}L\sigma_b}}{\epsilon'^2 L\sigma_s}}$$

(19)

where $\sigma_s$ and $\sigma_b$ are from Fig. 3. For $|m_{H^\pm} - m_W| \gtrsim 8 \, \text{GeV}$ the $m_{qq}$ cut discussed in Section 3 is imposed, while for $|m_{H^\pm} - m_W| \lesssim 8 \, \text{GeV}$ better significance is obtained without the $m_{qq}$ cut. The minimum value of $\text{Br}(H^+ \to c\bar{s})$ accessible in this mode for $L = 10 \, \text{fb}^{-1}$ is shown in Fig. 8.

Detection of the mixed mode $H^+H^- \to \nu\tau^+\bar{c}s$, $c\bar{s}\nu\tau^-$ requires

$$\min (\text{Br}(H^+ \to \nu\tau^+), \text{Br}(H^+ \to c\bar{s})) > \frac{1}{2} - \frac{1}{2} \sqrt{1 - \frac{5\sqrt{\epsilon_\tau L\sigma_b}}{\epsilon_\tau L\sigma_s}}$$

(20)
where $\sigma_s$ and $\sigma_b$ are from Fig. 7 and $\text{Br}(H^+ \rightarrow \nu \tau^+) + \text{Br}(H^+ \rightarrow c\bar{s}) = 1$ is assumed. The lower curve in Fig. 8 gives the minimum branching ratio accessible in this mode for $L = 10 \text{ fb}^{-1}$ and $\epsilon_\tau = 1$. This minimum branching ratio grows as $1/\sqrt{\epsilon_\tau}$ for $m_{H^\pm} \gtrsim 100 \text{ GeV}$.

As expected, the three modes considered here are complementary in the search for an intermediate mass charged Higgs. The mixed mode $H^+H^- \rightarrow \nu \tau^+\bar{c}s$, $c\bar{s}\bar{\nu}\tau^-$ offers the most complete coverage for discovery, assuming a reasonable $\tau$ identification efficiency and that neither branching ratio is very small. The other two modes may be used for confirmation over a somewhat more limited region of parameter space. If one of the branching ratios is too small for the mixed mode, a charged Higgs could be detected in the remaining mode. The entire intermediate mass range for the charged Higgs boson can therefore be covered by the NLC in the $\gamma\gamma$ mode.

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the Second Topical Conference on $e^+e^-$ Physics, November 1991, KEK, LBL preprint LBL-31697 (to be published).
Figure 1: Feynman diagram for $\gamma\gamma \rightarrow H^+H^-$. The crossed and seagull diagrams are not shown.

Figure 2: Cross section (pb) for $\gamma\gamma \rightarrow H^+H^-$ versus $m_{H^\pm}$ for $\sqrt{s_{ee}} = 0.5$ TeV and 1 TeV.

Figure 3: Cross section (pb) for $\gamma\gamma \rightarrow H^+H^- \rightarrow \nu\tau^+\bar{\nu}\tau^-$ versus $m_{H^\pm}$ for $\sqrt{s_{ee}} = 0.5$ TeV, including the acceptance cuts. The branching ratio $\text{Br}(H^+ \rightarrow \nu\tau^+) = 1$, $\epsilon_\tau = 1$, and $\text{Br}(\tau \rightarrow \nu_\tau + \pi, \rho, a_1)= 0.45$ are included. The horizontal lines are the $W^+W^- \rightarrow \nu\tau^+\bar{\nu}\tau^-$ and $\tau^+\tau^-\gamma$ backgrounds.

Figure 4: Feynman diagram for $\gamma\gamma \rightarrow q\bar{q}W$ in which only one on-shell $W$ is produced. Other diagrams related by gauge invariance, and including other quark flavors are not shown.

Figure 5: Cross sections (pb) for $\gamma\gamma \rightarrow H^+H^- \rightarrow c\bar{s}\bar{s}$ versus $m_{H^\pm}$ for $\sqrt{s_{ee}} = 0.5$ TeV, including different sets of cuts. The lower (upper) solid curve does (not) include the requirement $|m_{qq} - m_W| > 8$ GeV; the branching ratio $\text{Br}(H^+ \rightarrow c\bar{s}) = 1$. The lower (upper) dashed curve represents the $W^+W^- \rightarrow q\bar{q}q\bar{q}$ background with (without) the $m_{qq}$ cut. Both include the acceptance cuts.

Figure 6: Differential cross section $d\sigma/dm(q\bar{q})$ (pb/GeV) for $\gamma\gamma \rightarrow H^+H^- \rightarrow \nu\tau^+\bar{c}\bar{s}$, $c\bar{s}\bar{\nu}\tau^-$ (in solid curves) versus $m_{qq}$ with $m_{H^\pm} = 60, 80, 100, 120, \text{and } 140$ GeV, and the background $W^+W^- \rightarrow \nu\tau^+q\bar{q}$, $q\bar{q}\bar{\nu}\tau^-$ (dashed curve) for $\sqrt{s_{ee}} = 0.5$ TeV; $\epsilon_\tau = 1$, $\text{Br}(H^+ \rightarrow \nu\tau^+) = \text{Br}(H^+ \rightarrow c\bar{s}) = 0.5$, $\text{Br}(\tau \rightarrow \nu_\tau + \pi, \rho, a_1)= 0.45$, and acceptance cuts included.

Figure 7: The total cross section (pb) for $\gamma\gamma \rightarrow H^+H^- \rightarrow \nu\tau^+\bar{c}\bar{s}$, $c\bar{s}\bar{\nu}\tau^-$ (solid curve) and the background $W^+W^- \rightarrow \nu\tau^+q\bar{q}$, $q\bar{q}\bar{\nu}\tau^-$ (dashed curve) versus the presumed Higgs mass for $\sqrt{s_{ee}} = 0.5$ TeV; $\epsilon_\tau = 1$, $\text{Br}(H^+ \rightarrow \nu\tau^+) = \text{Br}(H^+ \rightarrow c\bar{s}) = 0.5$, $\text{Br}(\tau \rightarrow \nu_\tau + \pi, \rho, a_1)= 0.45$, $|m_{qq} - m_{H^\pm}| < 8$ GeV, and acceptance cuts included.

Figure 8: Minimum values of $\text{Br}(H^+ \rightarrow \nu\tau^+)$ and $\text{Br}(H^+ \rightarrow c\bar{s})$ for the given decay mode to have significance of at least 5, assuming an integrated luminosity of $10 \text{ fb}^{-1}$ and $\epsilon_\tau = 1$. 

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