Searching for a very light Higgs boson at the Tevatron

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Abstract

Light Higgs bosons ($h^0$) with a mass below 60 GeV may have escaped detection at LEP due to a suppressed cross–section for $e^+e^- \rightarrow Zh^0$. Their discovery is also problematic in standard search channels at the Tevatron Run II and LHC. Such a $h^0$ can arise in the two Higgs doublet model (2HDM) and in the Minimal Supersymmetric Standard Model (MSSM) with explicit CP violating phases. We propose the mechanism $p\bar{p} \rightarrow H^\pm h^0$ which offers cross–sections of up to 500 fb in the 2HDM, or up to 100 fb in the MSSM. The possibility of a large branching ratio for $H^\pm \rightarrow h^0 W^\pm$ would give rise to the non–standard signature $h^0h^0W^\pm$ which might facilitate detection.

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1 Introduction

The quest for Higgs bosons is of utmost importance at high energy colliders [1]. The Standard Model (SM) predicts one neutral Higgs boson ($\phi^0$) for which a lower limit on its mass $m_{\phi^0} > 114$ GeV has been obtained by direct searches at LEP2 in the production channel $e^+e^- \to \phi^0Z$ [2]. For the lightest CP–even Higgs boson ($h^0$) of the Minimal Supersymmetric Standard Model (MSSM) the analogous mechanism $e^+e^- \to h^0Z$ has a mixing angle suppression of $\sin^2(\beta - \alpha)$ relative to the cross-section for $\phi^0$. However, this factor is close to 1 in most of the allowed supersymmetric (SUSY) parameter space, and even if $\sin^2(\beta - \alpha)$ is suppressed, the complementary channel $e^+e^- \to h^0A^0 \sim \cos^2(\beta - \alpha)$ can be used. Combining these two search mechanisms enabled LEP to obtain the bound $m_{h^0} > 90$ GeV in the MSSM [2].

Nevertheless, much weaker numerical bounds apply to the lightest neutral CP–even Higgs boson $h^0$ in a general (non–supersymmetric) two Higgs doublet model (2HDM) [3]. Here the factor $\sin^2(\beta - \alpha)$ is a free parameter and merely taking $\sin(\beta - \alpha) < 0.1$ reduces the direct search bound to $m_{h^0} > 20$ GeV [4]. Hence a very light $h^0$ ($m_{h^0} << 100$ GeV) is not excluded by direct searches and is also entirely consistent with electroweak precision fits [5]. In the MSSM case the above bound $m_{h^0} > 90$ GeV can be weakened in specific regions of parameter space if explicit CP violating phases are present in some SUSY parameters. In this scenario the CP–even and CP–odd scalar fields mix resulting in three mass eigenstates $h_1, h_2, h_3$ which are now not definite eigenstates of CP [6], [7]. The coupling $h_1ZZ$ can be very suppressed, thus debilitating the LEP searches in the channel $e^+e^- \to h_1Z$. In addition, the complementary search channel $e^+e^- \to h_2h_2$ can be rendered ineffective due to the dominance of the experimentally challenging decay $h_2 \to h_1h_1$. If the CP violating phases are large ($> \pi/3$), and other SUSY parameters are chosen to enhance the scalar–pseudoscalar mixing (called the “CPX scenario” in [8]), there remains a region $m_{h_1} < 60$ GeV, $3 < \tan \beta < 5$ and $120 < m_{H^\pm} < 130$ GeV which was not covered by LEP and will remain elusive in all standard search channels at both the Tevatron Run II and LHC [8]. A high energy $e^+e^-$ linear collider operating at $\sqrt{s} = 500$ GeV would provide much improved coverage of this region via $e^+e^- \to h_1Z$ and $e^+e^- \to h_1h_2$ [9].

In the meantime, it is of interest to seek alternative production mechanisms for a very light $h^0$ (of the 2HDM) and $h_1$ (of the MSSM) at existing colliders such as the Tevatron Run II.\(^1\) Recently, diffractive Higgs production, $p\overline{p} \to p\overline{p}h_1$, has been suggested [11] which can lead to sizeable cross–sections in the MSSM case of order $100$ fb for $m_{h_1} < 20$ GeV. This mechanism might offer a favourable signal/background ratio, but requires suitable proton tagging detectors to be installed. In this paper we suggest an additional production process, $p\overline{p} \to H^\pm h_1, H^\pm h_0$, which is unsuppressed in the above elusive parameter space. This mechanism was first proposed in [12] in the context of light fermiophobic Higgs bosons ($h_f$) with enhanced $h_f \to \gamma\gamma$ decays, and in this paper we consider its application to the above scenarios of a light $h^0$ and $h_1$. We will show that $\sigma(p\overline{p} \to H^\pm h_1, H^\pm h_0)$ can be comparable in size to the diffractive production mechanism, and that the branching ratio (BR) for $H^\pm \to h_1W^\pm, h^0W^\pm$ can be large in the parameter space of interest, which would lead to the non–standard signature of $h^0h^0W^\pm$. Given the importance of finding unsuppressed mechanisms for producing a very light $h^0$ or $h_1$, the process $p\overline{p} \to H^\pm h^0 \to h^0h^0W^\pm$ possibly merits a detailed experimental simulation.

\(^1\)We will not be concerned with a very light pseudoscalar $A^0$ which has zero tree–level coupling $A^0ZZ$ – see [10].
In section 2 we introduce the mechanism $p\overline{p} \rightarrow H^\pm h^0(h_1)$, section 3 presents our numerical results with conclusions in section 4.

## 2 The mechanism $p\overline{p} \rightarrow H^\pm h^0$

The cross-section for the process $p\overline{p} \rightarrow H^\pm h^0$ [12] depends on three input parameters: $m_{h^0}$, $m_{H^\pm}$ and the coupling $|W^\pm H^\pm h^0|^2$.

![Diagram](image)

This mechanism has been disregarded as an effective way of producing $h^0$ and/or $H^\pm$ at hadron colliders (e.g. Tevatron). This view is justified in the MSSM without explicit CP violating phases in the SUSY parameters. A small $\sigma(p\overline{p} \rightarrow H^\pm h^0)$ is ensured since the coupling $|W^\pm H^\pm h^0|^2 \sim \cos^2(\beta - \alpha)$ is suppressed in the MSSM parameter space for $m_{A^0} > m_Z$. In addition, the phase space suppression is substantial at Tevatron energies due to the current lower bounds of $m_{h^0} \geq 90$ GeV and $m_{H^\pm} \geq 120$ GeV. However, $\sigma(p\overline{p} \rightarrow H^\pm h^0)$ is much larger if the following conditions are fulfilled [12]:

(i) There is little or no mixing angle suppression in the coupling $|W^\pm H^\pm h^0|^2$

(ii) $h^0$ is very light

Both these conditions are satisfied in the MSSM elusive parameter space of a light $h_1$ with suppressed coupling $ZZh_1$. In a 2HDM the condition for a light, undetected $h^0$ is merely that the coupling $ZZh^0$ is small. This corresponds to taking small values of $\sin^2(\beta - \alpha)$ which maximizes the coupling $|W^\pm H^\pm h^0|^2 \sim \cos^2(\beta - \alpha)$. In both these scenarios the processes $p\overline{p} \rightarrow H^\pm h^0$ and $p\overline{p} \rightarrow H^\pm h_1$ are not so suppressed, and thus this mechanism may offer a chance of probing the problematic parameter space.

In [12] this mechanism was applied to a special case of the 2HDM with a light fermiophobic Higgs, $h_f$, which has a large BR($h_f \rightarrow \gamma\gamma$) and thus a relatively high experimental detection efficiency. It was shown that $p\overline{p} \rightarrow H^\pm h_f$ at Tevatron energies can offer cross-sections $> 100$ fb for $m_{H^\pm} < 100$ GeV and $m_{h_f} = 50$ GeV. In the two scenarios of interest in this paper the dominant decay of $h^0$ and $h_1$ is to $b$ quarks, ($h^0, h_1 \rightarrow b\overline{b}$), and assuming $H^\pm \rightarrow \tau^\pm \nu_\tau$ the experimental signature of $b\overline{b}\tau\nu_\tau$ would suffer from a much larger background than in the fermiophobic case. We are not aware of an experimental simulation although this may become available soon for the case of the related process $p\overline{p} \rightarrow H^\pm A^0$, where $m_A > 90$ GeV was assumed [13]. Hence it is not clear at this stage if $p\overline{p} \rightarrow H^\pm h^0$ would be observable above the background even if $\sigma(p\overline{p} \rightarrow H^\pm h^0)$ were sizeable ($> 100$ fb). Nevertheless, given the need to probe the problematic parameter space we believe it is beneficial to give a numerical estimation of $\sigma(p\overline{p} \rightarrow H^\pm h^0)$ in both the above scenarios. Interestingly, we will show that
BR($H^\pm \to h^0W^\pm$) can be large, which would give rise to the non–standard signature of $h^0h^0W^\pm$ and might ameliorate the signal–background situation.

In order for $p\bar{p} \to H^\pm h^0$ to be maximized, $H^\pm$ should not be too heavy. It is known that the rare decay $b \to s\gamma$ imposes strong lower bounds on $m_{H^\pm}$ in the 2HDM (Model II), but these are easily avoided in Model I for $\tan\beta > 1$ [14]. For Model II type fermionic couplings one has $m_{H^\pm} > 200$ GeV [14], which would render $\sigma(p\bar{p} \to H^\pm h^0)$ small at Tevatron energies. A caveat here is that this bound can be weakened to the current direct search limits ($m_{H^\pm} > 80$ GeV) if CP violating phases are added in the 2HDM [15], or in a model with more than 2 Higgs doublets [16],[17]. Given these possibilities, in our analysis for the 2HDM we will consider $m_{H^\pm}$ as light as 90 GeV. In the MSSM it is known that $b \to s\gamma$ constraints depend strongly on the flavour sector and 120 GeV < $m_{H^\pm}$ < 130 GeV (corresponding to the elusive region) is permissible parameter space.

3 Numerical Results

We will show results for $\sigma(p\bar{p} \to H^\pm h^0)$ for a light $h^0$ in the 2HDM. The angular factor $\cos^2(\beta - \alpha)$ arising from the squared coupling $|W^\pm H^\pm h^0|^2$ is close to 1 in the parameter space of interest of $\sin^2(\beta - \alpha) << 1$, and for definiteness we take 0.97. The cross–section for $h_1$ in the problematic parameter space in the MSSM can be obtained from the 2HDM cross–section by taking $m_{h_1}$ and $m_{H^\pm}$ to lie in the elusive region $m_{h_1} \leq 60$ GeV, 120 GeV < $m_{H^\pm}$ < 130 GeV. We calculate the coupling $|W^\pm H^\pm h_1|^2$ in this region by using the public code cph.f [18] (which was used in [8]) and find $|W^\pm H^\pm h_1|^2 \geq 0.95$, which is consistent with our choice of 0.97 used above. We sum over the rates for $\sigma(p\bar{p} \to H^\pm h^0)$ and $\sigma(p\bar{p} \to H^- h^0)$, and use the Martin-Roberts-Stirling-Thorne parton distribution functions (MRST2002) from [19]. In Fig.1 we plot $\sigma(p\bar{p} \to H^\pm h^0)$ as a function of $m_{h^0}$, for 10 GeV < $m_{h^0}$ < 90 GeV. Note that we are considering smaller $m_{h^0}$ than in [12], which took $m_{h^0} > 50$ GeV. We plot several curves corresponding to different values of $m_{H^\pm}$. For the lightest values of the Higgs masses ($m_{h^0} = 10$ GeV and $m_{H^\pm} = 90$ GeV) we obtain cross–sections as large as 450 fb. The MSSM result can be read off from the curve for $m_{H^\pm} = 127$ GeV and 10 GeV < $m_{h_1}$ < 60 GeV, which gives cross–sections of 100 fb → 60 fb. We note that a further enhancement of $\sigma(p\bar{p} \to H^\pm h^0)$ comes from the the QCD correction factor of 1.3 [20] which we have not included in Fig.1. The cross–sections for the MSSM case are smaller than those for the diffractive production mechanism [11] if $m_{h_1} < 20$ GeV, but are larger if $m_{h_1} > 20$ GeV.

BR($H^\pm \to h^0W^\pm$) can be very large when $h^0$ is light. Previous analyses of this decay mode have been performed in the (CP conserving) MSSM [21], 2HDM (Model II) [16], and 2HDM (Model I) [22]. For $m_{H^\pm} < m_t + m_b$ of interest to us, the dominant competing decay is $H^\pm \to \tau^\pm \nu_\tau$ whose rate is proportional to $\tan^2\beta$ for Model II type fermionic couplings on which we will focus. In Fig.2 we take $\tan\beta = 4.2$ for all curves, which is inside the problematic interval of $3 < \tan\beta < 5$ in the MSSM case. We find BR($H^\pm \to h^0W^\pm$) > 80% for the MSSM curve of $m_{H^\pm} = 127$ GeV if $m_{h_1} < 40$ GeV. Thus $H^\pm$ decays dominantly in this non–standard way in most of the elusive parameter space. In the 2HDM case, the lighter values of $m_{H^\pm}$ (which have the largest cross–sections) correspond to smaller, but still sizeable BR($H^\pm \to h^0W^\pm$). This decay would lead to a signature of $h^0h^0W^\pm$, followed by $h^0 \to b\bar{b}$. A detailed signal to
Figure 1: Production cross-section $\sigma(p\bar{p} \rightarrow H^\pm h^0)$ at the Tevatron as a function of $m_{h^0}$ for various values of $m_{H^\pm}$, without including QCD enhancement factor of 1.3.

Figure 2: $BR(H^\pm \rightarrow h^0W^\pm)$ as a function of $m_{h^0}$ for various values of $m_{H^\pm}$.
background simulation would be needed to evaluate the detection prospects in this channel. Given the reasonable cross-sections we encourage experimental simulations. We note that some studies of the detection prospects of $H^\pm \to h^0W^\pm$ decays have been performed for LHC energies in the context of the Next to Minimal Supersymmetric Standard Model (NMSSM), which may also have a large BR($H^\pm \to h^0W^\pm$) [23]. Here the production mechanism $pp \to H^\pm tb$ was used, and promising signal/background ratios were obtained when BR($H^\pm \to h^0W^\pm$) is large. We are not aware of any such simulations at Tevatron energies. We note that the analogous mechanism at the Tevatron $p\bar{p} \to H^\pm tb$, followed by $H^\pm \to h^0W^\pm$ decay could also be used for the scenario of a light $h^0$ and $h_1$. Here $\sigma(p\bar{p} \to H^\pm tb)$ is around $50 \to 100$ fb [24] for the MSSM elusive region of 120 GeV < $m_{H^\pm}$ < 130 GeV and $3 < \tan\beta < 5$. These cross-sections are comparable to those of our proposed channel $p\bar{p} \to H^\pm h_1$.

4 Conclusions

A very light ($< 60$ GeV) Higgs boson $h^0$ would have escaped detection at LEP if the coupling $h^0ZZ$ were suppressed. Searching for such a Higgs boson at the Tevatron Run II and the LHC in standard channels is also problematic. We considered two models which may provide such a $h^0$; the 2HDM and the MSSM with SUSY sources of CP violation (the latter for a very specific parameter choice). We showed that the mechanism $p\bar{p} \to H^\pm h^0$ at the Tevatron Run II offers sizeable cross-sections of up to 500 fb in the 2HDM and 100 fb in the MSSM. The possibility of a large branching ratio for $H^\pm \to h^0W^\pm$ would lead to the non-standard $h^0h^0W^\pm$ signature. Given the reasonable cross-sections we encourage experimental simulations of this production mechanism for a light $h^0$.

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