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Charged Higgs in Extended Higgs models (non-type II model)

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The phenomenology of charged Higgs bosons in various non-supersymmetric extensions of the Standard Model is discussed. Firstly, I discuss the phenomenology of singly charged Higgs bosons in the various versions of the Two Higgs Doublet Model without the Type II structure. Secondly, I summarise the phenomenology of doubly charged Higgs bosons in the Higgs Triplet Model. Finally, I highlight important search channels for the charged scalars of the above models for which there are no simulations.

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1. Introduction

Singly charged Higgs bosons ($H^{\pm}$) in non-supersymmetric Two Higgs Doublet Models (2HDM) have received considerable attention since the last meeting in this series (Charged2008). There has also been continued interest in the phenomenology of the Higgs Triplet Model, which has both singly and doubly charged ($H^{\pm\pm}$) Higgs bosons. In this talk I shall briefly discuss some topics in the phenomenology of the charged Higgs bosons in these models.

2. Non-supersymmetric Two Higgs Doublet Models

There are four distinct versions of the 2HDM [1, 2] in which the scalars do not induce flavour changing neutral currents (FCNCs) at the tree level. All four models have the same scalar potential, but differ in how the two Higgs doublets are coupled to the fermions (i.e. the Yukawa couplings). The first detailed comparison of the phenomenology of $H^{\pm}$ in all four models was performed in [3], and the models were referred to as Models I, II, III and IV. However, in the literature the term "Model III" is also used to denote a 2HDM in which there are FCNCs induced by scalars at tree level. In [4] an alternative notation, I′ and II′, was introduced for models IV and III respectively. I will use the notation of [4], which was also adopted in early studies [5, 6] of these two models. Other notations have been introduced in recent papers [7, 8, 9].

The structure Type II is required for the Minimal Supersymmetric Standard Model, and consequently much attention has been given to the phenomenology of $H^{\pm}$ with Type II Yukawa couplings. In this talk I will discuss some distinctive phenomenology of $H^{\pm}$ in Models I, I′ and II′. A public computer code for phenomenological studies of all four models is described in [10].

	X	Y	Z
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type I′	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type II′	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Table 1: The couplings X,Y and Z in the Yukawa interactions of $H^{\pm}$ in the four versions of the 2HDM.

The interaction of $H^{\pm}$ with fermions is described by the following Lagrangian:

$$\mathscr{L}_{H^{\pm}} = -\left\{ \frac{\sqrt{2}V_{ud}}{v}\overline{u}\left(m_u X P_L + m_d Y P_R\right) d H^{+} + \frac{\sqrt{2}m_{\ell}}{v} Z\overline{\nu_L}\ell_R H^{+} + H.c. \right\}$$

Here u and d denote up-type quarks and down-type quarks respectively (for all three generations); V_{ud} is a CKM matrix element; m_u, m_d and m_ℓ are the masses of the quarks and charged leptons; P_L and P_R are chirality projection operators, and $v = 246$ GeV. The couplings X, Y and Z are given in Table 1, where $\tan\beta = v_2/v_1$, and v_1 and v_2 are the vacuum expectation values of the two Higgs doublets. The Yukawa couplings of $H^{\pm}$ in the four versions of the 2HDM are different if $\tan\beta \neq 1$, which will result in a distinct phenomenology for each of the four models.

2.1 2HDM (Model I)

The phenomenology of $H^{\pm}$ of Model I has been studied quite thoroughly in the literature. The branching ratios for the fermionic decays $H^{\pm} \to f'\overline{f}$ are independent of $\tan\beta$, and hence are predictive: $\mathrm{BR}(H^{\pm} \to \tau^{\pm}\nu) \sim 66\%$ and $\mathrm{BR}(H^{\pm} \to cs) \sim 33\%$. As can be seen from Table 1, the coupling $H^{\pm}f'\overline{f}$ is proportional to $1/\tan\beta$ and thus $H^{\pm}$ decouples from the fermions ("fermiophobia") for $\tan\beta >> 1$. In contrast, fermiophobia is not possible in the other three models, as there is always one fermionic coupling which is proportional to $\tan\beta$. In Model I with $\tan\beta >> 1$, the constraints on $m_{H^{\pm}}$ from flavour physics (e.g. from the decay $b \to s\gamma$ which constrains $m_{H^{\pm}} > 300$ GeV in Model II) are significantly weakened and $H^{\pm}$ can be as light as the current bounds from the direct searches ($m_{H^{\pm}} > 80$ GeV). The fermiophobic nature of $H^{\pm}$ for $\tan\beta >> 1$ permits other decays to be dominant (if open kinematically), such as $H^{\pm} \to A^0 W^*$ [12] (where A^0 is the CP-odd neutral scalar). Searches for $H^{\pm} \to A^0 W^*$ have been carried out by the LEP collaborations DELPHI [13] and OPAL [14].

2.2 2HDM (Model I′)

This model has received substantial attention since the year 2008 [7] (see also [11] for a study in the context of LEP data for the leptonic decays of W). Since the coupling of $H^{\pm}$ to quarks is very suppressed for $\tan\beta >> 1$ (as in Model I), $H^{\pm}$ can avoid constraints from flavour physics and be as light as 80 GeV. Consequently, production processes for $H^{\pm}$ that rely on its couplings to quarks will not be very effective (in contrast to $H^{\pm}$ of Model II). A distinctive feature of $H^{\pm}$ of Model I′ would be a very large branching ratio for $H^{\pm} \to \tau^{\pm}\nu$ for $m_{H^{\pm}} > 175$ GeV (i.e. even when the decay $H^{\pm} \to tb$ is open) [3, 4, 5, 7, 8, 11]. For example, for $\tan\beta = 20$, the branching ratio of $H^{\pm} \to \tau^{\pm}\nu$ is $\sim 90\%$ for $m_{H^{\pm}} = 300$ GeV. The production mechanism $pp \to W \to H^{\pm}A^0$, which is independent of $\tan\beta$, could be used to produce $H^{\pm}$. The signature for the case of $\tan\beta >> 1$ would be three τ leptons, for which there is no simulation by LHC collaborations.

2.3 2HDM (Model II′)

This model also received very little attention until 2009. Like Model II, the $H^{\pm}$ of Model II′ would contribute sizeably to low-energy processes like $b \to s\gamma$ and thus the stringent bound $m_{H^{\pm}} >$ 300 GeV applies. For such masses the branching ratios of $H^{\pm}$ of Model II′ and Model II would be very similar, because the decay channel $H^{\pm} \to tb$ would dominate in both models. However, a difference is that in Model II′ the branching ratio of $H^{\pm} \to \tau^{\pm}\nu$ is negligible for $\tan\beta >> 1$, while in Model II its branching ratio is $\geq 10\%$, even for a very heavy $H^{\pm}$.

If one considers the case $m_{H^{\pm}} < m_t + m_b$ (which would require additional New Physics in order to partially cancel the contribution of $H^{\pm}$ to $b \to s\gamma$) then a distinctive signature of Model II′ would be a sizeable branching ratio for $H^{\pm} \to cb$ [3, 4, 5, 8, 9]. Such a $H^{\pm}$ could be searched for in the decays of the top quark, $t \to H^{\pm}b$. Present simulations of $t \to H^{\pm}b$ by the LHC collaborations only assume the decays $H^{\pm} \to cs$ and $H^{\pm} \to \tau^{\pm}\nu$. Efficient b-tagging would presumably allow the possibility of distinguishing the decays $H^{\pm} \to cs$ and $H^{\pm} \to cb$.

3. Higgs Triplet Model

In the Higgs Triplet Model (HTM) the scalar sector of the Standard Model is augmented by an $SU(2)$ triplet of scalar particles with hypercharge $Y = 2$ [15]. Therefore the HTM has seven scalars: a doubly charged Higgs boson ($H^{\pm\pm}$), a singly charged Higgs boson ($H^{\pm}$) and three neutral Higgs bosons. In the HTM, neutrinos acquire Majorana masses at tree level given by the product of a triplet Yukawa coupling (h_{ij}) and the vacuum expectation value of a neutral Higgs boson in the isospin triplet. Consequently, there is a direct connection between h_{ij} and the neutrino mass matrix, which gives rise to phenomenological predictions for processes which depend on h_{ij}, such as the branching ratios of $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ ($\ell = e, \mu, \tau$) [16, 17, 18, 19, 20, 21]. A distinctive signal of the HTM would be the observation of $H^{\pm\pm}$, whose mass ($m_{H^{\pm\pm}}$) may be of the order of the electroweak scale. Such particles can be produced with sizeable rates at hadron colliders in the processes $q\bar{q} \to H^{++}H^{--}$ [22, 23] and $q\overline{q'} \to H^{\pm\pm}H^{\mp}$ [22, 24, 25]. Direct searches for $H^{\pm\pm}$ have been carried out at the Fermilab Tevatron, assuming the production channel $q\bar{q} \to H^{++}H^{--}$ and *the leptonic* decays $H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$, and mass limits in the range $m_{H^{\pm\pm}} > 110 - 150$ GeV have been obtained [26, 27, 28, 29].

All the above searches at the Tevatron assume *only* the production mechanism $q\bar{q} \to \gamma^*, Z^* \to H^{++}H^{--}$. However, for $m_{H^{\pm}} \sim m_{H^{\pm\pm}}$ the partonic process $q\overline{q'} \to W^* \to H^{\pm\pm}H^{\mp}$ [22, 24, 25] has a cross section at hadron colliders comparable to that of $q\bar{q} \to H^{++}H^{--}$, and thus the former will also contribute to the search for $H^{\pm\pm}$. In Ref. [25], it is suggested that the search potential at hadron colliders can be improved by considering the following inclusive single $H^{\pm\pm}$ cross section ($\sigma_{H^{\pm\pm}}$):

$$\sigma_{H^{\pm\pm}} = \sigma(p\bar{p}, pp \to H^{++}H^{--}) + \sigma(p\bar{p}, pp \to H^{++}H^{-}) + \sigma(p\bar{p}, pp \to H^{--}H^{+}) \qquad (3.1)$$

At the Tevatron $\sigma(p\bar{p} \to H^{++}H^{-}) = \sigma(p\bar{p} \to H^{--}H^{+})$ while at the LHC $\sigma(pp \to H^{++}H^{-}) > \sigma(pp \to H^{--}H^{+})$. At present, the process $q\overline{q'} \to W^* \to H^{\pm\pm}H^{\mp}$ has not been considered in the searches for $H^{\pm\pm}$ at the Tevatron. Since the current search strategy [28] seeks three leptons ($\ell^{\pm}\ell^{\pm}\ell^{\mp}$), the inclusion of $q\overline{q'} \to W^* \to H^{\pm\pm}H^{\mp}$ (which also gives the signature of $\ell^{\pm}\ell^{\pm}\ell^{\mp}$) would naively extend the limit of $m_{H^{\pm\pm}} > 150$ GeV derived in [28] to around $m_{H^{\pm\pm}} > 180$ GeV. We note that $q\overline{q'} \to W^* \to H^{\pm\pm}H^{\mp}$ is currently not included in the event generator Pythia [30].

The LHC, using the above production mechanisms, will offer improved sensitivity to $m_{H^{\pm\pm}}$ [19, 20, 31, 32, 33]. As discussed earlier, the production mechanism $pp \to W^{\pm *} \to H^{\pm\pm}H^{\mp}$ will contribute to the signal for $H^{\pm\pm}$ if three (or more) leptons are required. The simulation in Ref. [20] is the first study of the mechanism $pp \to H^{\pm\pm}H^{\mp}$ together with $pp \to H^{++}H^{--}$, with the aim of optimising the sensitivity to $m_{H^{\pm\pm}}$ at the LHC. In Ref. [20] e and μ are not distinguished, and thus such an approach is sensitive to the sum of the branching ratios of $H^{\pm\pm} \to e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$ (and $H^{\pm} \to e^{\pm}\nu, \mu^{\pm}\nu$). Both a four-lepton signature and a three-lepton signature are studied, and the sensitivity to $m_{H^{\pm\pm}}$ for the two signatures is compared, assuming $m_{H^{\pm\pm}} = m_{H^{\pm}} = 300$ GeV. The three-lepton signature is defined as being *exactly* three leptons (3ℓ), *i.e.* a fourth lepton is vetoed. Note that this three-lepton signature differs from that defined in the latest search for $H^{\pm\pm}$ at the Tevatron [28] in which a fourth lepton is not vetoed ($\geq 3\ell$). In Ref. [20] it is concluded that the three-lepton signature offers considerably greater discovery potential for $H^{\pm\pm}$ in the HTM than the signature of four leptons.

The main reason for the superior sensitivity of the three-lepton signature in [20] is the extra contribution from $pp \to H^{\pm\pm}H^{\mp}$, which does not contribute to the four-lepton signature. Although the background from the Standard Model for the three-lepton signature is larger than that for the four-lepton signature, in the region of high invariant mass of $\ell^{\pm}\ell^{\pm}$ (relevant for $m_{H^{\pm\pm}} > 200$ GeV) the backgrounds are still sufficiently small, which gives rise to superior sensitivity to $m_{H^{\pm\pm}}$ for the three-lepton signature. A recent study [34] considered the signature of three or more leptons ($\geq 3\ell$, with $\ell = e, \mu$) for which one expects optimal sensitivity to $pp \to H^{++}H^{--}$ and $pp \to H^{\pm\pm}H^{\mp}$, because a fourth lepton (which can arise from $pp \to H^{++}H^{--}$) has not been vetoed. Various values of $m_{H^{\pm\pm}} (= m_{H^{\pm}})$ were considered, as well the effect of alternative cuts which were not used in [20] e.g. a cut on the total transverse energy of the event, which is very effective at reducing the backgrounds. Signatures from the combined signal of $pp \to H^{++}H^{--}$ and $pp \to H^{\pm\pm}H^{\mp}$ which involve τ leptons (such as those arising from the decays $H^{\pm\pm} \to e^{\pm}\tau^{\pm}$ and $H^{\pm\pm} \to \mu^{\pm}\tau^{\pm}$) have not yet been simulated.

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