

Charged Higgs discovery potential in the single top mode in 2HDMs

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We discuss the discovery potential of a charged Higgs boson in the single top mode. The models discussed include a CP-conserving and a CP-violating version of the softly broken Z_2 symmetric 2HDM potential. We conclude that the single top mode could help to constrain the $(m_{H^\pm}, \tan\beta)$ plane in several versions of 2HDMs.

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1. Introduction

As the 8 TeV run at the CERN's Large Hadron Collider (LHC) is reaching the end, one may ask if a light charged Higgs will survive the confrontation with experimental data in extensions of the Standard Model (SM) that allow for the existence of at least one charged Higgs boson. In models where portions of the parameter space will still survive the 8 TeV data, is there any hope of excluding a light charged Higgs for all of the parameter space by the end of the 13-14 TeV run? As will be clear later on, the answer to that question is no for some versions of two-Higgs doublet models (2HDMs). However, we will show that a slight improvement can nevertheless be obtained by complementing the present search, based on the $t\bar{t}$ mode, with the search in the single top mode.

2. Two-Higgs doublet models

CP-conserving as well as CP-violating (either explicit or spontaneous) 2HDMs' potentials with a softly broken Z_2 symmetry, $\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow -\Phi_2$, can be written as

$$V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{1}{2} \lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}], \quad (2.1)$$

where Φ_i , $i = 1, 2$ are complex SU(2) doublets.

Hermiticity of the potential forces all parameters except m_{12}^2 and λ_5 to be real. The choice of m_{12}^2 and λ_5 , together with the nature of the vacuum expectation values (VEVs) will determine the CP nature of the model (see [1] for a review). This, in turn, dictates whether we end up with two CP-even Higgs states, usually denoted by h and H , and one CP-odd state, usually denoted by A (the CP-even case) or with three spinless states with undefined CP quantum number, usually denoted by h_1 , h_2 and h_3 (the CP-violating case). However, as long as the VEVs do not break the electric charge, which was shown to be possible in any 2HDM [2], there are in any case two (identical) charged Higgs boson states, one charged conjugated to the other.

In this work we will focus on two specific realisations, one CP-conserving and the other explicitly CP-violating [3, 4]. In the CP-violating version m_{12}^2 and λ_5 are complex and $Im(\lambda_5) = v_1 v_2 Im(m_{12}^2)$. In both models the VEVs are real. By defining $\tan \beta = v_2/v_1$, it is then possible to choose the angle β as the rotation angle from the group eigenstates to the mass eigenstates in the charged Higgs sector. By then extending the Z_2 symmetry to the Yukawa sector we end up with four independent 2HDMs, the well known [5, 6] Type I (only ϕ_2 couples to all fermions), Type II (ϕ_2 couples to up-type quarks and ϕ_1 couples to down-type quarks and leptons), Type Y or III (ϕ_2 couples to up-type quarks and to leptons and ϕ_1 couples to down-type quarks) and Type X or IV (ϕ_2 couples to all quarks and ϕ_1 couples to leptons) (details and couplings can be found in [7]).

We will now very briefly discuss the main experimental and theoretical constraints affecting the 2HDM parameter space. The signal in our analysis originates from single top production with the subsequent decay $t \rightarrow bH^\pm \rightarrow b\tau\nu$. Hence, only the charged Higgs Yukawa couplings are present and therefore the only parameters we need to be concerned with are $\tan \beta$ and the charged Higgs mass. Values of $\tan \beta$ smaller than $O(1)$ together with a charged Higgs with a mass below 100 GeV are disallowed both by the constraints [8] coming from R_b , from $B_q \bar{B}_q$ mixing and from

$B \rightarrow X_s \gamma$ for all models. Furthermore, data from $B \rightarrow X_s \gamma$ impose a lower limit of $m_{H^\pm} \gtrsim 340$ GeV, but only for models Type II and Type Y. The LEP experiments have set a lower limit on the mass of the charged Higgs boson of 79.3 GeV at 95% C.L., assuming only $BR(H^+ \rightarrow \tau^+ \nu) + BR(H^+ \rightarrow c\bar{s}) = 1$ [9]. These bounds led us to take $m_{H^\pm} > 90$ GeV and $\tan\beta > 1$ for type I and X. We will also present results for model type II, where the bounds on the charged Higgs mass can be evaded due to the presence of new particles as is the case of the MSSM.

3. Results and discussion

$pp \rightarrow t\bar{t}$ is the best process to search for a charged Higgs boson at the LHC. However, because the single top production cross section is about one third of $\sigma_{pp \rightarrow t\bar{t}}$, it certainly deserves a full investigation regarding its contribution to the production of charged Higgs bosons. The signal consists mainly of a light charged Higgs boson produced via t -channel graphs, $pp \rightarrow t j \rightarrow H^+ \bar{b} j$ and $H^+ \rightarrow \tau^+ \nu$, together with $pp \rightarrow \bar{t} j \rightarrow H^- b j$ and $H^- \rightarrow \tau^- \bar{\nu}$, where j represents a light-quark jet. In what follows we are considering proton-proton collisions at a center-of-mass (CM) energy of $\sqrt{s} = 14$ TeV and a top-quark mass $m_t = 173$ GeV. We consider a charged Higgs boson mass interval of 90 to 160 GeV and the analysis is performed in 10 GeV mass steps.

Maximising the signal-to-background significance (S/\sqrt{B}) makes both the s -channel and the tW single-top production modes negligible - only the t -channel process survives the set of cuts imposed. Signal events were generated with POWHEG [10] at NLO with the CTEQ6.6M [11] PDFs. The top was then decayed in PYTHIA [12]. We have considered only the leptonic decays of the tau-leptons, that is, the signal final state is $pp \rightarrow lb j \cancel{E}$, where $l = e, \mu$ (electrons and muons) while \cancel{E} means missing (transverse) energy.

The irreducible background, single-top production with the subsequent decay $t \rightarrow bW^+$, was also generated with POWHEG. The main contributions to the reducible background are: $t\bar{t}$ production, $W^\pm + \text{jets}$ (including not only light quarks and gluons, but also c - and b -quarks) and the pure QCD background (jjj , where j is any jet). The $t\bar{t}$ background was generated with POWHEG while $W^\pm + \text{jets}$ (1, 2 and 3 jets) was generated with AlpGen [13]. Finally, the QCD background was generated with CalcHEP [14] (with CTEQ6.6M PDFs). The hadronisation was performed with PYTHIA 6. After hadronisation DELPHES [15], was used to simulate the detector effects. For the detector and trigger configurations, we resorted to the ATLAS default definitions.

In order to maximise S/\sqrt{B} we apply the following selection cuts (see [7] for details)

1. We demand one electron with $p_T > 30$ GeV or a muon with $p_T > 20$ GeV, and $|\eta| < 2.5$ for both leptons.
2. We veto events with two or more leptons with $p_T > 10$ GeV. This cut eliminates the leptonic $t\bar{t}$ background almost completely.
3. We veto events with leptons having p_T above 55 GeV.
4. Events with missing energy below 50 GeV are excluded. This is a cut that dramatically reduces the QCD background.

5. We ask for one and only one b -tagged jet with $p_T < 75$ GeV. We assume a b -tagging efficiency of 0.4 (with $R = 0.7$), while the misidentification rates for the case of c -quark jets we take 0.1 and for lightquark/ gluon jets we adopt 0.01.
6. We reconstruct a "top quark invariant mass" as defined in [7] and demand all events to have this invariant mass above 280 GeV.
7. We define a leptonic transverse mass [7], M_T^{lv} , and we have accepted events with $30\text{ GeV} < M_T^{lv} < 60\text{ GeV}$ for charged Higgs masses between 90 and 130 GeV and $30\text{ GeV} < M_T^{lv} < 60\text{ GeV}$ or $M_T^{lv} > 85\text{ GeV}$ for higher values of the charged Higgs mass.
8. We have chosen events with one and one jet (non- b) only with $p_T > 30$ GeV and $|\eta| \leq 4.9$.
9. We veto all events with a jet multiplicity equal to two or above for jets with $p_T > 15$ GeV and $|\eta| \leq 4.9$.
10. We only accept events where jets have a pseudorapidity $|\eta| \geq 2.5$.

Putting all the numbers together we can find S/B and S/\sqrt{B} as a function of the charged Higgs mass as presented in table 1.

m_{H^\pm} (GeV)	Signal (S)	Background (B)	S/B (%)	S/\sqrt{B}
90	38.6	29.5	130.92	7.11
100	40.5	29.5	137.19	7.45
110	45.6	29.8	153.00	8.35
120	47.7	30.1	158.26	8.69
130	42.3	32.68	129.53	7.41
140	117.1	77.9	150.25	13.26
150	120.0	86.6	138.64	12.90
160	109.7	100.8	108.81	10.92

Table 1: Signal-to-Background ratio (S/B) and significance (S/\sqrt{B}) as a function of the charged Higgs mass for $\sqrt{s} = 14$ TeV and a luminosity of 1 fb^{-1} . The numbers presented for the signal we take $\text{BR}(t \rightarrow bH^\pm) = 100\%$ and $\text{BR}(H^- \rightarrow \tau^- \nu) = 100\%$ and all other BRs have the usual SM values.

The results can be presented in a model independent manner [7] and exclusion plots can be derived for the different 2HDMs. In figure 1 we present the exclusion plots for the MSSM (left) and Type X (right) in the $(\tan\beta, m_{H^\pm})$ plane at the 95% CL assuming the LHC at 14 TeV and for several luminosity sets. The results show similar trends to the ones obtained for $t\bar{t}$ production. We started with a cross section that is about three times smaller than the $t\bar{t}$ one and ended up with a result that is 2 to 3 times worse than the prediction presented by ATLAS [16]. It is expectable that both ATLAS and CMS will improve the results on the single top mode presented here, improving the constraints on the $(m_{H^\pm}, \tan\beta)$ plane. One may now ask what are the chances to probe the entire $(m_{H^\pm}, \tan\beta)$ plane by the end of the 14 TeV run. In view of the results for 7 TeV [17, 18], one expects a type II charged Higgs to be excluded by then. However, there are models where the Yukawa couplings always decrease with $\tan\beta$ as is the case of models I and X. For those models,

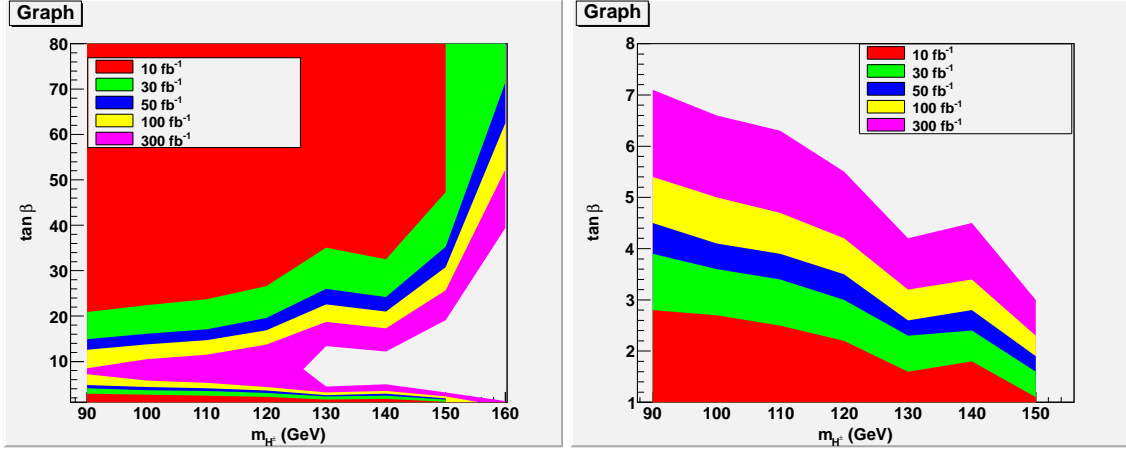


Figure 1: The MSSM (left) and Type X (right) exclusion limits over the $(\tan \beta, m_{H^\pm})$ plane at the 95% CL assuming the LHC at 14 TeV and for several luminosity sets.

we know that $pp \rightarrow t\bar{t}$ will provide the strongest constraint on the $(m_{H^\pm}, \tan \beta)$ plane, and that the single top mode is bound to contribute even if only with a slight improvement. Are there any other processes that could help to probe the large $\tan \beta$ region?

There is another Yukawa process, $cs \rightarrow H^\pm(+jet)$ [19, 20], that could in principle help to probe the above mentioned region. It was however shown to be negligible for large $\tan \beta$. The remaining possibility [20] is to look for processes that either do not depend on $\tan \beta$, or even better, that grow with $\tan \beta$. There are terms both in $gg \rightarrow H^+W^-$ and in Vector Boson Fusion ($pp \rightarrow jjH^+H^-$ where j is a light quark jet) that are independent of $\tan \beta$. Furthermore, for the CP-conserving potential, there is a term in $gg \rightarrow H^+H^-$ that has the form

$$\sigma_{pp \rightarrow H^+H^-} \propto \sin(2\alpha) \tan \beta (m_H^2 - M^2) \quad (3.1)$$

where α is the rotation angle in the CP-even sector, m_H is the heavier CP-even scalar mass and $M^2 = m_{1/2}^2 / (\sin \beta \cos \beta)$. Hence, there are regions of the 2HDM parameter space that can be probed for larger values of $\tan \beta$. However, the bounds will no longer be for a two parameter space but instead for a multi-dimension space with all 2HDM parameters playing a role. Further, values of the cross section that could lead to meaningful significances, are only obtained for resonant production. Therefore, only a small portion of the multidimensional space can be probed for large $\tan \beta$ (see [20] for details).

A final comment about theoretical bounds. Assuming that the Higgs boson was discovered with a mass of 125 GeV, it was recently shown in [21] that for the particular case of an exact CP-conserving Z_2 symmetric model $\tan \beta < 6$. Therefore, that particular model will probably see a light charged Higgs ruled out when all the 8 TeV data is analysed.

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