Distinguishing Higgs models in $H^+ \to \tau^+ \nu/t\bar{b}$ at large $\tan \beta$ *)

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We present an experimental and theoretical analysis of the ratio of branching ratios
$R = \frac{BR(H^+ \to \tau^+ \nu/t\bar{b})}{BR(H^+ \to t\bar{b})}$ of charged Higgs boson decays as a discriminant quantity between supersymmetric and non-supersymmetric models.

PACS: 12.60.Fr; 12.60.Jv; 14.80.Cp

Key words: Higgs Physics, Supersymmetry Phenomenology, LHC

The detection of a charged Higgs boson $H^\pm$ would be a distinctive signal of physics beyond the Standard Model (SM), since such a particle does not exist in the SM. The associated production of a charged Higgs boson with a top quark ($pp \to H^+t + X$) [1] is mainly relevant at large values of $\tan \beta$, a regime where Higgs boson observables receive large Supersymmetric (SUSY) radiative corrections. Here we report on the investigation of the production of charged Higgs bosons in association with top quarks at the Large Hadron Collider (LHC), from the experimental and theoretical points of view, by studying hadronic ($H^+ \to t\bar{b}$) and leptonic ($H^+ \to \tau^+ \nu$) decay signatures. Details of the analysis have been presented in [2].

While SUSY radiative effects might be difficult to discern in the production cross-sections separately, they will appear neatly in the relation:

$$ R \equiv \frac{\sigma(pp \to H^+t + X \to \tau^+\nu t + X)}{\sigma(pp \to H^+t + X \to t\bar{b}t + X)} = \frac{BR(H^+ \to \tau^+\nu)}{BR(H^+ \to t\bar{b})} = \frac{\Gamma(H^+ \to \tau^+\nu)}{\Gamma(H^+ \to t\bar{b})}. \quad (1) $$

As eq. (1) shows, the dependence on the production mode (and on its large sources of uncertainty deriving from parton luminosity, unknown QCD radiative corrections, scale choices, etc.) cancels out.

On the other hand, the couplings of the Higgs particles to down-type fermions receive large quantum corrections in the Minimal Supersymmetric Standard Model (MSSM), enhanced by $\tan \beta = v_2/v_1$. These corrections have been resummed to all

*) Based on the poster presented by S. Peñaranda at Physics at LHC, 13-17 July 2004, Vienna, Austria. Preprint numbers: CERN-PH-TH/2004-170, SHEP-04-26.
orders in perturbation theory, with the help of the effective Lagrangian formalism for the $tbH^+$ vertex [3]. The relation between the fermion mass and the Yukawa coupling is modified by quantum corrections, encoded in a quantity $\Delta m_f$ ($f = b, \tau$), which is non-decoupling and contains all (potentially) large leading radiative effects. The ratio [4] receives large one-loop MSSM radiative corrections at large $\tan \beta$, due to $\Delta m_b$ and $\Delta m_{\tau}$, which we have considered in the present analysis.

We have performed a detailed phenomenological analysis of charged Higgs boson signatures for the LHC, by using the two-body production cross-section subprocess $gb \to H^+ \tilde{t}$, with the hadronic and leptonic decay channels of the charged Higgs boson. We have normalized our production cross-section to the LO result, for consistency with the tree-level treatment of the backgrounds. In our simulation, we have let the top quarks decay through the SM-like channel $t \to W^{\pm} b$. Further details of the studies presented here are available in [2, 4].

The Monte Carlo (MC) simulation has been performed using PYTHIA (v6.217) [5] for the signal and most of the background processes. We have cross-checked the signal cross-section with results presented in [6]. Discrepancies have been resolved by fixing a bug in PYTHIA (v6.217 or older). We have used HDECAY for the Higgs boson decay rates, TAUOLA for the $\tau$-lepton decays, TopReX for some background processes with a custom interface to PYTHIA, and ATLFAST for the detector simulation [7].

The leptonic decay channel (2) provides the best probe for the detection of such a state at the LHC. There is a good signal reconstruction and background-free environment for this channel. The main background processes in this channel are $gg \to t\bar{t} \to jj b\tau\nu\bar{b}$ and $gb \to W^+ \tilde{t} \to \tau^+\nu\tilde{t}$. We have used the following trigger conditions: one hadronic $\tau$-jet; a $b$-tagged jet and at least two light jets. Further, we have the cut $\Delta\phi(\hat{p}_T, \hat{p}_T) > 1$ for background suppression, $\Delta\phi$ being the azimuthal opening angle between the $\tau$-jet and the missing transverse momentum, $\hat{p}_T$. The missing transverse momentum is harder for the signal than for the background. These effects are well cumulated in the transverse mass, $m_T = \sqrt{2p_T^2 [1 - \cos(\Delta\phi)]}$, which provides good discrimination between the signal and the backgrounds, as shown in Fig. 4. A final cut $m_T > 200$ GeV was used for the calculations of the signal-to-background ratios and signal significances.

The production rates $\sigma \times BR(H^+ \to \tau^+\nu) \times BR(W \to jj)$ are shown in Table I. We can see that the cuts have a high efficiency. In fact, signal rates after cuts are large enough to indeed consider $H^+ \to \tau\nu$ a golden channel for the $H^+$ discovery at large $\tan \beta$. Despite the small branching ratio $BR(H^+ \to \tau^+\nu)$, the $\tau$-lepton affords an efficient trigger to observe this channel. Subsequently, we assume that the $H^+$ is discovered in this channel in order to reduce the combinatorial background in the hadronic channel.

The decay mode $H^\pm \to tb$ has large QCD backgrounds that come from $t\bar{t}q$ production with $t\bar{t} \to WbWb \to l\nu b jjb$. We search for an isolated lepton, three
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![Graphs showing transverse mass $m_T$ distributions for signal and total background in the leptonic channel, taking into account the polarization of the $\tau$-lepton, for an integrated luminosity of 30 fb$^{-1}$.](image)

Fig. 1. a) Transverse mass $m_T$ distribution for signal and total background in the leptonic channel, taking into account the polarization of the $\tau$-lepton, for an integrated luminosity of 30 fb$^{-1}$. b) The hadronic channel signal and the background distributions for the reconstructed invariant mass $m_{tb}$ of $m_{H^\pm} = 350$ GeV, $\tan \beta = 50$ and 30 fb$^{-1}$.

| $m_{H^\pm}$ | $\sigma \times BR$ | Events | Events after cuts | Efficiency | $S/B$ | $S/\sqrt{B}$ | Poisson |
|-------------|---------------------|--------|-------------------|------------|-------|-------------|---------|
| 350 GeV     | 99.9 fb             | 29958  | 174               | 0.6%       | 7.9   | 37.1        | 23.1    |
| 500 GeV     | 30.7 fb             | 9219   | 96                | 1%         | 4.4   | 20.5        | 14.6    |
| $tt$        | 79.1 pb             | 2.3 x 10$^6$ | 17               | 8 x 10$^{-5}$ | 6 x 10$^{-5}$ |
| $W^\pm t$   | 16.3 pb             | 4.89 x 10$^7$ | 3                | 6 x 10$^{-5}$ | 6 x 10$^{-5}$ |

Table 1. The signal and background cross-sections, the number of events before cuts, the number of events after all cuts, the total efficiency, the signal-to-background ratios ($S/B$), and the signal significances (Gaussian and Poisson) for the detection of the charged Higgs in the $\tau \nu$ channel at the LHC, for 300 fb$^{-1}$ integrated luminosity and $\tan \beta = 50$.

$\text{b}$-tagged jets and at least two non-$\text{b}$-jets. The jet-jet combinations whose invariant masses are consistent with the $W$-boson mass, $|m_W - m_{jj}| < 25$ GeV are retained, and then we use the $W$-boson mass constraint to find the longitudinal component of the neutrino momentum in $W^\pm \rightarrow l\nu$. We keep the best two top-quark candidate that minimize $\chi^2 \equiv (m_t - m_{l\nu b})^2 + (m_t - m_{jjb})^2$. The remaining $\text{b}$-jet can be paired with either top quark to give two charged Higgs candidates, one of which leads to a combinatorial background.

Assuming that the charged Higgs is discovered through the $H^\pm \rightarrow \tau \nu$ channel and its mass determined from the $\tau \nu$ transverse mass distribution, the correct $H^+$ candidate in the $tb$ channel can be selected by using the measured $m_{H^\pm}$ as a constraint. This is done by selecting the candidate whose invariant mass is closest to the measured charged Higgs mass: $\chi^2 = (m_{tb} - m_{H^\pm})^2$. Fig. 1(b) shows the signal
Table 2. The signal and background cross-sections, the number of events before and after cuts, the total efficiency, $S/B$, and the signal significances for the detection of the charged Higgs in the $tb$ channel at the LHC, for 300 fb$^{-1}$ integrated luminosity and $\tan \beta = 50$.

| $m_{H^\pm}$ = 350 GeV | $m_{H^\pm}$ = 500 GeV | $t\bar{t}q$ |
|------------------------|------------------------|-------------|
| $\sigma \times BR$ | 248.4 fb | 88 fb | 85 pb |
| Events | 74510 | 26389 | $2.55 \times 10^4$ |
| Events after cuts | 2100 | 784 | 59688 |
| Efficiency | 2.8% | 3% | 0.2% |
| $S/B$ | 0.035 | 0.013 |
| $S/\sqrt{B}$ | 8.6 | 3.2 |

The subtraction of the background can then be done by fitting the side bands and extrapolating in the signal region, which will be known from the $m_{H^\pm}$ determination in the $H^\pm \rightarrow \tau \nu$ channel. However, this would be possible only for Higgs masses above 300 GeV – see Fig. 1b. The signal and background results are summarized in Table 2. Even using the $m_{H^\pm}$ constraint, it is difficult to observe $H^\pm$ signals in this channel above $\sim 400$ GeV. For masses above $m_{H^\pm} \sim 400$ GeV the signal significance can be enhanced by using the kinematics of the three-body production process $gg \rightarrow H^\pm t\bar{b}$ [8].

Recent studies on the discovery prospects of a heavy charged MSSM Higgs boson in the $H^+ \rightarrow t\bar{b}$ channel using three $b$-quarks tagging shows that, taking into account influences of systematic background uncertainty, no discovery region is left in the MSSM parameter space [9]. The (relatively) small $S/B$ and significances in Table 2 also seem to suggest it. However, for the $gg \rightarrow H^+ t\bar{b}$ production process at the LHC, which together with the hadronic decay channel leads to four $b$-tagged jets, no significant improvement in the discovery potential with respect to the three $b$-quarks in the final states has been found [10]. Furthermore, in the 4-$b$ tag case the $H^+ \rightarrow \tau \nu$ channel becomes less visible. Our strategy consists in discovering (and measuring) the $H^\pm$ in the leptonic channel, and afterwards measuring it in the hadronic channel. In this case the background can be measured in the side bands with sufficient accuracy (see above) and the hadronic channel is visible. Therefore, 3-$b$ quarks in the final states is more successful in the analysis we are interested in.

The uncertainty in the ratio $R$ is dominated by the reduced knowledge of the background shape and rate in the $H^+ \rightarrow tb$ channel. We assume a theoretical uncertainty of 5% on the branching ratios, $BR$s. Previous ATLAS studies have...
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| $m_{H^\pm}$ | $m_{H^\pm}$ |
|------------|------------|
| 350 GeV    | 500 GeV    |

| Signals $\tau\nu/tb$ | 174 / 2100 = 0.08 | 96 / 784 = 0.12 |
|----------------------|-------------------|------------------|
| Signals (corrected) $\tau\nu/tb$ | 0.18 | 0.16 |
| Systematic uncertainty | $\sim$ 9% | $\sim$ 9% |
| Total uncertainty | 12% | 14% |
| Theory | 0.18 | 0.16 |

Table 3. Determination of the ratio $R$ for 300 fb$^{-1}$ and $\tan\beta = 50$. Shown are: signal after cuts; signal after correcting for efficiencies and branching ratios; systematic uncertainty; total combined uncertainty; and theoretical prediction without SUSY corrections.

![Graphs showing production rates and SUSY factors](image)

Fig. 2. a) Production rates enhancement/suppression factors for the $\tau$ and the $tb$ channels; b) the SUSY correction to the rate $R$. Plots as functions of $\tan\beta$ for $m_{H^\pm} = 350$ GeV and a SUSY spectrum as in SPS4, but for different choices of the signs of $\mu$ and $A_t$. Shown is also the experimental determination for each scenario.

shown that the residual $gg \rightarrow t\bar{t}$ shape and normalization can be determined to 5%, and the scale uncertainties on jet and lepton energies are expected to be of the order of 1% and 0.1% respectively [4]. As explained above, for $m_{H^\pm} > 300$ GeV, the side band procedure can be used to subtract the residual background under the $H^+ \rightarrow t\bar{b}$ signal: we assume also a 5% uncertainty in the background subtraction method. Thus, the statistical uncertainties can be estimated as $\sqrt{1/S}$. The cumulative results for the two channels are summarized in Table 3 at an integrated luminosity of 300 fb$^{-1}$. Here, the final result for the ratio $R$ is obtained by correcting the visible production rates after cuts for the total detection efficiency in Tables 1 and 2 and by the decay $BR$s of the $W$-bosons. The simulation shows that the above-mentioned ratio can be measured with an accuracy of $\sim 12$–14% for $\tan\beta = 50$, $m_{H^\pm} = 350$–500 GeV and at an integrated luminosity of 300 fb$^{-1}$.

The role of the SUSY radiative corrections is twofold. Firstly, by changing the value of the Yukawa coupling, they change the value of the observable $R$. Secondly, they change the value of the production cross-section $\sigma(pp \rightarrow H^+\ell^- + X)$. In Fig. 2b, we show the enhancement/suppression factors as a function of $\tan\beta$ for $m_{H^\pm} = 350$ GeV and a SUSY mass spectrum defined as SPS4 of the Snowmass.
Points and Slopes in [11], but choosing different scenarios for the signs of $\mu$ and $A_t$. The production rate in the $\tau$-channel is fairly independent of the SUSY radiative corrections. On the contrary, the hadronic $t\bar{b}$ production channel receives large radiative corrections. These corrections can be either positive (enhancing the significance in Table 2) or negative (reducing it). This might permit to overcome the low signal-to-background ratio of this channel in some SUSY scenarios.

Fig. 2b shows the prediction for the ratio $R$ as a function of $\tan\beta$ for $m_{H^\pm} = 350$ GeV. We also show the experimental determination carried out as before and repeated for each SUSY setup. From Fig. 2b it is clear that radiative SUSY effects are visible at the LHC at a large significance. In particular, the $\mu < 0$ scenarios can easily be discriminated, while the $\mu > 0$ ones will be more difficult to establish, since the signal rate of the hadronic channel is lower. This feature then also allows for a measurement of the sign of the $\mu$ parameter, which can be determined by a $\sim 14\%$ measurement of this ratio for $\tan\beta > 30$.

To summarize, we have quantitatively shown that an LHC measurement of $R$ can give clear evidence for or against the SUSY nature of charged Higgs bosons.

S.P. thanks the European Union for financial support (contract MEIF-CT-2003-500030).

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