Prospects of Detecting Massive Charged Higgs from Hadronic Decay $H^\pm \rightarrow tb$ in CMS

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Abstract

The possibility to detect the massive charged Higgs boson $H^\pm$ using the hadronic decay channel $H^\pm \rightarrow tb$ in the associated production $pp \rightarrow tH^\pm + X$ in the CMS experiment at LHC is studied. There is a large background from $t\bar{t}bb$ events which makes the observation difficult. Detection of a Higgs signal in this channel requires an excellent b-tagging performance. Good calorimeter mass resolution is also necessary for the full event reconstruction.

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1 Introduction

The Minimal Supersymmetric Standard Model (MSSM) predicts five physical states in the Higgs sector: three neutral scalars \(h^0, H^0, A^0\) and a charge conjugated pair \(H^\pm\) \[1\]. At the tree-level just two free parameters are enough to fix masses of all these states \[2\]. The conventional choice is to use the mass of CP-odd neutral Higgs, \(m_A\), and the ratio of the vacuum expectations values of Higgs doublets, \(\tan \beta\). For the values of \(\tan \beta\) considered here, the mass of \(H^\pm\) does not differ considerably from that of \(A^0\).

Only few decay channels seem to be useful for the search of the charged Higgs boson at LHC. The most promising one is the \(H^\pm \to \tau \nu\) decay mode, in particular in the \(tbH^\pm\) associated production with a top quark decaying to a fully hadronic final state \[3\]. The \(H^\pm \to tb\) decay channel has also been proposed as a possible discovery channel for charged Higgs at LHC in phenomenological studies \[4\]. A further motivation for using the channel \(H^\pm \to tb\) in the search of the charged Higgs boson is shown in Figures \[123\] and \[4\]. The \(tb\) decay becomes abruptly the dominant mode when the mass of the \(H^\pm\) exceeds the sum of masses of top and bottom quarks, and is still not so heavy that the supersymmetric decay channels become significant. It represents more than 60\% to the branching ratio for 200 GeV \(\lesssim m_A \lesssim 400\) GeV, independently of the value of \(\tan \beta\) as shown in Figures \[1\] and \[2\]. In the present study the SUSY parameters are taken to be \(\lambda_1 = 0\) (no-mixing), \(M_2 = 200\) GeV, \(\mu = -200\) GeV and \(M_3 = 800\) GeV, \(M_{q, \tilde{t}} = 1\) TeV \[5\]. This \(H^\pm \to tb\) decay mode is not sensitive to the soft supersymmetry breaking parameters, at least to the sign of the higgsino mass parameter \(\mu\) neither to stop mixing seem as is visible from Figures \[3\] and \[4\].

2 Signal and Background Processes

The charged Higgs boson in association of a top quark is produced through the reactions \(gb \to tH^\pm\) and \(gg \to tbH^\pm\). The cross section for the production with 3 tagged b-jets is the sum of the cross sections for these two processes subtracting the common terms to avoid double counting \[4\]. Here the \(H^\pm\) is required to decay to top and bottom quarks. The top quarks decay further to a bottom quark and a \(W\) boson. In order to trigger the event one of \(W\)'s has to decay to a lepton and its antineutrino whilst the other one is assumed to decay hadronically to light quarks.

The main backgrounds are from \(t\bar{t}+\) jets with two real b-jets and a mistagged non-b-jet, and the irreducible background due to \(ttbb\). Potentially, there are also backgrounds from other processes, but these are much smaller. For example the process \(gg \to qW\) may cause some background events, but is unlikely to generate five jets which would fulfil the selection criteria. These other backgrounds are assumed to be negligible and are not included in this study.

We assume an integrated luminosity of 30 fb\(^{-1}\) and superimpose a pile-up of 3 minimum bias events on the physics events. For the signal this leads to the production (including branching ratios, without any selection cuts) of approximately 43 000 events for \(m_A = 250\) GeV and \(\tan \beta = 30\), but only slightly over 11 000 events for \(m_A = 400\) GeV and \(\tan \beta = 30\). The expected number of background events with this luminosity is about \(7 \times 10^6\).

3 Event Reconstruction

The event generation is carried out with sPythia \[6\] for both signal events using the process \(gb \to tH^\pm\) (Pythia subprocess 161) and the \(t\bar{t}\) background (processes 81 and 82) where additional jets come from parton showering. Detector performance is simulated using CMSJET \[8\] with parametrized track reconstruction performance based on GEANT simulations \[9\] for b-tagging.

As a first selection criterion for an event, we require an isolated lepton with transverse momentum \(p_t > 15\) GeV and at least five jets with \(E_t > 20\) GeV and \(| \eta | < 2.4\). Furthermore three of those jets have to be identified as b-jets (b-tagging is discussed in more detail in the following). If these conditions are not fulfilled, the event is rejected.

Then the event reconstruction is performed as follows. A combination of two non-b-jets with the mass closest to the nominal \(W\) mass is chosen to be assigned to the hadronically decayed \(W\) boson. If the reconstructed mass differs more than 20 GeV from the nominal value, the event is rejected. Then a b-jets is chosen to reconstruct the mass of the top quark together with the hadronically decayed \(W\), selecting the combination with the invariant mass closest to the nominal top mass. The reconstructed hadronic top mass distribution is shown in Figure \[5\]. The other
top is reconstructed from the leptonically decayed $W$ and a b-jet. The longitudinal component of the neutrino momentum is fixed using $W$ mass constraint. That procedure leads to two possible solutions, the smaller of which is taken. The missing transverse momentum is assumed to be due to the neutrino. The reconstructed $W$ is paired with another potential b-jet chosen to give the mass closest to the nominal top mass to reconstruct the leptonic top. The mass distribution for the leptonic top is shown in Figure 6. If the mass of either of the reconstructed top quarks deviates more than 45 GeV from 175 GeV, the event is rejected. Finally the most probable b-jet among the remaining b-jet candidates is chosen to be paired with either the hadronic or leptonic top to reconstruct the $H^\pm$. The hadronically and leptonically reconstructed Higgs mass distributions are shown in Figures 7 and 8 respectively. As it is not possible to know which of the two top quarks originates from the Higgs decay this procedure leads to a large combinatorial background from signal events. The following results shown are for $m_A = 300$ GeV and $\tan \beta = 30$ with b-likeness $> 3$, unless otherwise stated. The background events are found to be kinematically very similar to the signal events. One might expect that extra jets accompanying $t\bar{t}$ would be considerably softer compared to signal events, and hard kinematical cuts on transverse momenta of jets would improve considerably the background rejection. We argue that this is not the case, as the events fulfilling the selection criteria for at least five jets are in the rather energetic tail. They seem to be even harder on the average when compared to signal events in case of the relatively light Higgs ($m_A \lesssim 250$ GeV). For heavier Higgs ($m_A \approx 400$ GeV) the jets from signal events are more energetic than those coming from the background, but not significantly. Since the total number of events in this case is rather small (the cross-section diminishes with increasing $m_A$), kinematical cuts, which inevitable reduce the signal as well, do not lead to any higher value of the formal significance. For these reasons we do not introduce any kinematical cuts in addition to those mentioned earlier and coming from the basic detector performance. In conclusion, the severe complication in background rejection is due to the fact that the background very much mimics the shape of the signal. A possible improvement in the background rejection could be expected from from the application of neural network methods, but this approach is not justified at this stage.

4 Procedure for b-tagging and Results

The kinematical difference between the signal and the background being marginal, the fact that signal events contain one b-jet more than the background is of crucial importance. Actually, there is also an associated fourth b-jet in the signal event from the $tbH^\pm$ final state and a requirement for four tagged b-jets would reduce the number of background events drastically. Unfortunately, this fourth b-jet is on the average rather soft and its detection is not possible to know which of the two top quarks originates from the Higgs decay this procedure leads to a large combinatorial background from signal events. The following results shown are for $m_A = 300$ GeV and $\tan \beta = 30$ with b-likeness $> 3$, unless otherwise stated. The background events are found to be kinematically very similar to the signal events. One might expect that extra jets accompanying $t\bar{t}$ would be considerably softer compared to signal events, and hard kinematical cuts on transverse momenta of jets would improve considerably the background rejection. We argue that this is not the case, as the events fulfilling the selection criteria for at least five jets are in the rather energetic tail. They seem to be even harder on the average when compared to signal events in case of the relatively light Higgs ($m_A \lesssim 250$ GeV). For heavier Higgs ($m_A \approx 400$ GeV) the jets from signal events are more energetic than those coming from the background, but not significantly. Since the total number of events in this case is rather small (the cross-section diminishes with increasing $m_A$), kinematical cuts, which inevitable reduce the signal as well, do not lead to any higher value of the formal significance. For these reasons we do not introduce any kinematical cuts in addition to those mentioned earlier and coming from the basic detector performance. In conclusion, the severe complication in background rejection is due to the fact that the background very much mimics the shape of the signal. A possible improvement in the background rejection could be expected from from the application of neural network methods, but this approach is not justified at this stage.

The b-tagging procedure that we have used in this study has been proposed in [10]. At least two tracks in a jet of signal events is too low. The b-tagging procedure that we have used in this study has been proposed in [10]. At least two tracks in a jet of signal events is too low.
space almost independent on $\tan\beta$.

We have tried to compare our results to the corresponding predictions of the Atlas collaboration [13]. The final results for the discovery reach are similar. $5\sigma$-contour curves share the same peculiar shape, having a minimum at $m_A \approx 250$ GeV when the mass of Higgs is already significantly larger than that of top quark so that the jets coming from the decay process are energetic enough to be efficiently detected and the cross-section is still relatively large, guaranteeing plenty of events. However, the background invariant mass distribution in [13] is very different, with a monotonically decreasing behaviour, in contrast to our result with background peaking in the signal region. The monotonically decreasing background shape greatly favours the visibility of the signal peak and makes the determination of the background contribution under the signal peak easier. The kinematical cuts used in [13] are similar to ours, thus the only possible explanation may come from the b-tagging procedure. We tried to repeat the analysis using the idealised procedure for b-tagging. Namely, we accept a b-jet with a fixed probability independent of its momentum and ”mistag” a non-b-jet as a b-jet also with fixed probability. An example of the Standard Model (SM) background obtained this way is shown in Figure 18 where, naturally after necessary kinematical cuts, all the b-jets are identified correctly (b-tagging efficiency = 1) and no other jets are mistagged as a b-jet (impurity = 0). Despite this, we were not able to reproduce the desirable monotonically decreasing background shape.

5 Conclusions

In summary, we have studied the possibility to detect a massive charged Higgs boson in the CMS experiment at LHC when the $H^\pm$ decays to top and bottom quarks in the process $pp \to tH^\pm + X$. This channel is found to be a potential Higgs discovery channel at LHC for a significant part of the MSSM parameter space, although the large background from $t\bar{t}jj$ and $t\bar{t}b\bar{b}$ events and from signal combinatorics makes the extraction of the signal difficult. Because the decay $H^\pm \rightarrow tb$ does not lead to a well visible peak superimposed on the background, a precise theoretical estimate of the number of the SM background events is needed for the observation. Extraction of Higgs signal in this channel requires excellent b-tagging; both true b-jets have to be identified with high efficiency and the probability to mistag a non-b-jet must be very low; the $E_t$ threshold for b-jets must be low ($\sim 20$ GeV) to be able to improve the separation of the signal from the expected number of events. A significant improvement can be expected at high Higgs masses ($m_{H^\pm} \gtrsim 400$ GeV) from the optimization of the kinematical cuts to take into account the much harder spectrum of b-jets from $H^\pm$ decay in this domain. A further improvement could be expected eventually with the implementation of neural network techniques.
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Figure 1: The branching ratios of $H^\pm$ decay for $\tan \beta = 30$.

Figure 2: The branching ratios of $H^\pm$ decay for $\tan \beta = 5$. 

Figure 3: The branching ratios of $H^\pm$ decay for positive higgsino mass parameter $\mu$.

Figure 4: The branching ratios of $H^\pm$ decay assuming maximal stop mixing, $A_t = \sqrt{6}$ GeV.
Figure 5: The invariant mass distribution of the hadronically decayed top quark.

Figure 6: The invariant mass distribution of the leptonically decayed top quark.
Figure 7: The invariant mass distribution for $H^\pm$ ($m_{H^\pm}=300$ GeV, $\tan\beta=30$) reconstructed from the hadronically decaying top and a b-jet.

Figure 8: The invariant mass distribution for $H^\pm$ ($m_{H^\pm}=300$ GeV, $\tan\beta=30$) reconstructed from the leptonically decaying top and a b-jet.
Figure 9: The invariant mass distribution for $H^\pm$ ($m_{H^\pm}$=300 GeV, $\tan\beta$=30) reconstructed from the hadronically decaying top and a b-jet superimposed on the corresponding background for 30 fb$^{-1}$.

Figure 10: The invariant mass distribution for $H^\pm$ ($m_{H^\pm}$=300 GeV, $\tan\beta$=30) reconstructed from the leptonically decaying top and a b-jet superimposed on the corresponding background for 30 fb$^{-1}$.
Figure 11: The invariant mass distribution for $H^\pm$ ($m_{H^\pm}=300$ GeV, $\tan\beta=30$) including all signal events (reconstructed either from hadronically or leptonically decaying top) superimposed on the total background for 30 fb$^{-1}$.

Figure 12: The entire signal superimposed on the total background for $m_A = 250$ GeV and $\tan \beta = 30$. 
Figure 13: The entire signal superimposed on the total background for $m_A = 400$ GeV and $\tan \beta = 30$.

Figure 14: The entire signal for $m_A = 250$ GeV and $\tan \beta = 40$ superimposed on the total background with b-likeness $> 3$ (significance $\sigma \approx 21$)
Figure 15: The entire signal for $m_A = 250$ GeV and $\tan \beta = 40$ superimposed on the total background with b-likeness > 4 (significance $\sigma \simeq 19$).

Figure 16: The entire signal for $m_A = 250$ GeV and $\tan \beta = 40$ superimposed on the total background with b-likeness > 5 (significance $\sigma \simeq 18$).
Figure 17: \(5\sigma\)-discovery contour curves for charged Higgs in CMS for 30 fb\(^{-1}\).

Figure 18: The invariant mass distribution for the background assuming ideal b-tagging.