DISCOVERY POTENTIAL FOR $H^\pm$ AT LHC IN $H^\pm \to \tau^\pm \nu$ DECAYS

A. TRICOMI

Dipartimento di Fisica e Astronomia and INFN Catania
Catania, Italy

The discovery potential of charged Higgs from $pp \to tH^\pm$ in the $H^\pm \to \tau \nu$ decay channel is investigated in CMS and ATLAS. For $m_{H^\pm} > m_t$, the most relevant channels are $H^\pm \to tb$ and $H^\pm \to \tau \nu$. Whereas the former has the largest branching ratio it suffers of large irreducible backgrounds, while the latter offers a very clean environment when appropriate cuts are used. Making use of the $\tau$ polarization effects, in the purely hadronic final states an almost background-free signal is selected. The expected discovery range is evaluated for CMS and ATLAS with 30 fb$^{-1}$ each in the low luminosity running conditions and the combined results are presented.

1 Introduction

In the Minimal Supersymmetric Standard Model (MSSM), the Higgs sector consists of five physical states, two of which are charged ($H^\pm$), while the other are neutral ($h^0$, $H^0$ and $A^0$). At tree level all Higgs masses and couplings are expressed in terms of two parameters, generally taken as $m_{A_1}$, the mass of the CP-odd neutral Higgs $A^0$, and $\tan \beta$, the ratio of the vacuum expectation values of the Higgs doublets. While any of the neutral Higgs bosons may be difficult to distinguish from the Standard Model one, the $H^\pm$ carries a distinctive signature of the SUSY Higgs sector. Moreover the coupling of $H^\pm$ are uniquely related to $\tan \beta$, therefore the detection of $H^\pm$ and the measurement of its mass and couplings should play a very important role in probing the MSSM Higgs sector.

In a model independent way, LEP experiments have set lower limits on the mass of the charged Higgs boson, $m_{H^\pm} > 78.5 \text{ GeV}/c^2$ for any $\tan \beta$. CDF and DØ have performed several searches for $H^\pm$: a direct search through the decay $H^\pm \to \tau \nu$ was performed at high $\tan \beta$ ($> 10$), while at low $\tan \beta$ ($< 1$) an indirect search for the decay channel $H^\pm \to c\bar{s}$ was carried out. DØ performed a disappearance search considering all the fermionic decay modes of the
charged Higgs. The searches at TEVATRON excluded the low (< 1) and high (> 40) tan β region up to 120 GeV/c² and 160 GeV/c², respectively.

In the study described herein, the charged Higgs discovery potential in \( H^{\pm} \to \tau \nu \) decay mode for \( m_{H^{\pm}} > m_{\tau} \), at LHC is investigated. The \( t \to bH^{+} \) decay is known to provide promising signatures for charged Higgs boson search at TEVATRON upgrade and LHC for \( m_{H^{\pm}} < m_{\tau} \). But it is hard to extend the \( H^{\pm} \) search beyond \( m_{\tau} \), because in this case the combination of dominant production and decay channels, \( tH^{-} \to t\bar{b}H^{+} \), suffers from a large QCD background. Moreover the subdominant production channels of \( H^{\pm}W^{\pm} \) and \( H^{\pm}H^{\pm} \) have been found to give no viable signature at LHC. In view of this both ATLAS and CMS have performed several studies of the most promising decays channels of a heavy charged Higgs signature at LHC. Above the top quark mass the dominant decay mode is the \( tb \) channel. However, it suffers of large irreducible background, while the \( \tau \nu \) decay channel, which is the sub-dominant decay mode, can offer a free of background environment, taking advantage of the distinctive \( \tau \) polarization effect. In the following, some details of the current analysis performed by CMS and ATLAS are discussed in the framework of the discovery potential achievable at LHC.

### 2 Analyses

Both CMS and ATLAS analyses are looking for \( H^{\pm} \to \tau \nu \to h + E_T^{\text{miss}} + X \) decays in which the \( H^{\pm} \) is produced in association with a top quark through the processes \( gb \to tH^{\pm} \) and \( gg \to tbH^{\pm} \). The production cross section at LHC is evaluated in ref. eliminating the double counting for the two processes. The associated top quark is required to decay hadronically, \( t \to jbjb \), in order that the missing energy gets contribution mainly due to the neutrino from \( H^{\pm} \to \tau \nu \) and the transverse mass distribution reconstructed from the \( \tau \) jet and the missing transverse energy, has a jacobian type structure with an endpoint at \( m_{H^{\pm}} \). It is also shown that effect of the \( \tau \) polarization can be used to enhance the signal over background with appropriate \( \tau \) selection cuts. The main background, in fact, are due to the \( t\bar{t} \) events with \( W_{1} \to \tau \nu, W_{2} \to qq', W + \text{jet events with } W \to \tau \nu \) and \( Wt \) events with \( W_{1} \to \tau \nu, W_{2} \to qq' \). Since all these backgrounds contain the \( W \to \tau \nu \) decay they can be efficiently reduced thanks to the \( \tau \) polarization effect: indeed due to the scalar nature of the decaying \( H^{+} \) the \( \tau^{+} \) from its decay is produced in a left-handed polarization state. In the simplest scenario of \( \tau^{+} \to \pi^{+} \tilde{\nu} \) decay the right-handed \( \tilde{\nu} \) is preferentially emitted in the direction opposite to the \( \tau^{+} \) in the \( \tau \) rest frame to preserve the polarization. On the contrary, in the dominant \( t\bar{t} \) background the \( \tau^{+} \) from \( W^{+} \to \tau^{+} \nu \) decay is produced right-handed due to the vector nature of the \( W^{+} \) forcing the \( \tilde{\nu} \) from \( \tau^{+} \to \pi^{+} \tilde{\nu} \) to be emitted in the same direction as the \( \tau^{+} \) in the \( \tau \) rest frame. Therefore harder pions are expected from the signal than from the background.

The \( \tau^{\pm} \to \pi^{\pm} \tilde{\nu} \) contributes as 12.5% to the charged one prong decays. Significant contributions to the one prong decay come also from vector meson production, \( \tau^{\pm} \to \rho^{\pm} \tilde{\nu} \) and \( \tau^{\pm} \to a_{1}^{\tau} \tilde{\nu} \) with branching ratios of 26% and 7.5%, respectively. In this case harder pions are produced from the longitudinal vector meson components relative to the background while the opposite is true for the transverse components, which contribute to smear the polarization effect. This difference in the pion spectra can be exploited by requiring a large fraction of the \( \tau \) jet energy to be carried by a single charged hadron in the jet. The signal selection relies heavily on the these two future for both the two analyses. To further reduce the large background coming from \( W + \text{jet events with } W \to \tau \nu \), \( W \) and top mass reconstruction is performed. Other cuts characteristic of each analysis is described in the following sections.
2.1 CMS analysis

As mentioned in the previous section, the hadronic \( \tau \) signature of a heavy charged Higgs boson from \( pp \to t\bar{t}H^\pm \) at the LHC is useful. To select signal over background we exploit the \( \tau \) polarization effects and large missing energy. Several other cuts are used to further reduce the background. Details of this analysis can be found in ref. [10].

The real \( \tau \) jet is chosen as the \( \tau \) jet candidate requiring \( E_t > 100 \) GeV and \( |\eta| < 2.5 \). To benefit of the \( \tau \) polarization effect the variable \( r = p^\pi / E_{\tau jet} \) > 0.8 is used, where \( p^\pi \) is the momentum of a hard pion from \( \tau \) decay in a cone of \( \Delta R < 0.1 \) around the calorimeter jet axis and \( E_{\tau jet} \) is the hadronic energy of the \( \tau \) jet (\( E_t > 100 \) GeV) reconstructed in the calorimeters (electromagnetic and hadronic) in a cone of \( \Delta R < 0.4 \). Figure 1 shows the variable \( r \) for all the hadronic \( \tau \) decays for \( m_{H^\pm} = 200 \) and 400 GeV (Fig.1a) while in Fig 1b the \( H^\pm \to \tau \nu \), \( \tau^\pm \to \pi^\pm \bar{\nu} \) decays are compared with \( W^\pm \to \tau \nu \), \( \tau^\pm \to \pi^\pm \bar{\nu} \) from \( t\bar{t} \) decays. The efficiency of this \( \tau \) selection for the signal events is about 18% while for the \( t\bar{t} \) events the efficiency is only 0.4% (including the \( E_t \) threshold for jet). A reconstruction efficiency of 95% is assumed for the hard isolated track from \( \tau \).

Figure 1: Distribution of \( r = p^\pi / E_{\tau jet} \) for \( H^\pm \to \tau \nu \), \( m_{H^\pm} = 200 \) GeV and \( m_{H^\pm} = 400 \) GeV; (a) all hadronic \( \tau \) decays; (b) \( H^\pm \), \( \tau^\pm \to \pi^\pm \bar{\nu} \) decays are compared with \( W^\pm \to \tau \nu \), \( \tau^\pm \to \pi^\pm \bar{\nu} \) from \( t\bar{t} \) decays.

In Table 1 a complete list of all the selection performed is reported together with the efficiency for signal and background. As expected a large impact is due to the overall \( \tau \) selection, the missing transverse energy cut and \( W \) and top mass reconstruction.

A large missing transverse energy is expected in the signal events due to the neutrino from \( H^\pm \) decay. Efficiency of the cut \( E^{\text{miss}}_t > 100 \) GeV is about 75% for the signal events and about 38% for the \( t\bar{t} \) background.

For the reconstruction of the \( W \) and top masses the events with at least three jets with \( E_t > 20 \) GeV, in addition to the \( \tau \) jet, are selected. The \( W \) and top masses are reconstructed minimizing the variable \( \chi^2 = (m_{jj} - m_W)^2 + (m_{jjj} - m_t)^2 \), where \( m_W \) and \( m_t \) are the nominal \( W \) and top masses.

To further reduce the background, after the \( W \) and top mass reconstruction and the mass window cuts, b-tagging is applied on the jet not assigned to the \( W \). This jet is required to be harder with \( E^{\text{jet}}_t > 30 \) GeV. The tagging efficiencies based on the impact parameter method obtained from a full simulation and track reconstruction in the CMS tracker are used [11]. For b-jets with \( E_t = 50 \) GeV the efficiency is found to be \(~50\%\) averaged over the full \( \eta \) range (\(|\eta| < 2.5\)). The mis-tagging rate for the corresponding light quark and gluon jets is 1.3%.

The reconstructed transverse mass \( m_{\tau\nu}^{T} \) over the total background is shown in Fig. 2a for
Table 1: Efficiency for selection cuts for two different signal, \((m_{H^\pm} = 200\text{ GeV}, \tan \beta = 15)\) and \((m_{H^\pm} = 400\text{ GeV}, \tan \beta = 23)\) and main background decay channels.

|                    | \((m_{H^\pm} = 200, \tan \beta = 15)\) | \((m_{H^\pm} = 400, \tan \beta = 23)\) | \(t\bar{t}\) | \(Wtb\) | \(W + jet\) |
|--------------------|----------------------------------------|----------------------------------------|-------------|---------|-------------|
| \(E_l > 100\text{ GeV}\) | 28.1%                                  | 65.4%                                  | 8.2%        | 3.9%    | 3.7%        |
| \(r > 0.8\)       | 26.4%                                  | 27.4%                                  | 5.2%        | 5.9%    | 9.6%        |
| total \(\tau\) selection | 7.4%                                  | 17.9%                                  | 0.4%        | 0.2%    | 0.36%       |
| \(E_{miss}^\tau > 100\text{ GeV}\) | 28.7%                                  | 74.7%                                  | 37.6%       | 28.4%   | 42.1%       |
| \(W\) and top mass reconstruction | 42.7%                                  | 38.9%                                  | 46.1%       | 30.9%   | 6.5%        |
| \(b\)-tagging       | 50.0%                                  | 50.0%                                  | 50.0%       | 50.0%   | 1.3%        |
| Second top veto     | 87.7%                                  | 95.6%                                  | 47.0%       | 77.5%   | 75.3%       |
| \(\Delta \phi(\tau_{\text{jet}}, E_{miss}) > 60^\circ\) | 53.2%                                  | 90.3%                                  |             |         |             |

\(m_{H^\pm} = 400\text{ GeV}\) and \(\tan \beta = 40\) for 30 \(\text{fb}^{-1}\). For \(m_{\tau^\nu} > 100\text{ GeV}\) about 40 signal events are expected. About 5 background events from \(t\bar{t}\) and \(W + jet\) are expected for \(m_{\tau^\nu} > 100\text{ GeV}\).

Further reduction of the \(t\bar{t}\) background is still possible using a jet veto cut and a veto on a second top in the event. The central jet veto and the second top veto, being closely correlated cuts, reduce \(t\bar{t}\) background by a factor of \(\sim 7\). The transverse mass \(m_{\tau^\nu}\) distribution over the total background including the jet and second top veto is shown in Fig. 2b for \(m_{H^\pm} = 400\text{ GeV}\) and \(\tan \beta = 40\).

\(m_{H^\pm} = 400\text{ GeV}\) and \(\tan \beta = 40\) for 30 \(\text{fb}^{-1}\). For \(m_{\tau^\nu} > 100\text{ GeV}\) about 40 signal events are expected. About 5 background events from \(t\bar{t}\) and \(W + jet\) are expected for \(m_{\tau^\nu} > 100\text{ GeV}\).

Further reduction of the \(t\bar{t}\) background is still possible using a jet veto cut and a veto on a second top in the event. The central jet veto and the second top veto, being closely correlated cuts, reduce \(t\bar{t}\) background by a factor of \(\sim 7\). The transverse mass \(m_{\tau^\nu}\) distribution over the total background including the jet and second top veto is shown in Fig. 2b for \(m_{H^\pm} = 400\text{ GeV}\) and \(\tan \beta = 40\).

The visibility of the signal can be significantly improved, especially at \(m_{H^\pm} = 200\text{ GeV}\), with a cut on the \(\Delta \phi\) angle between the \(\tau\) jet and the \(E_{miss}\). Although \(\Delta \phi\) is directly proportional to \(m_{\tau^\nu}\), a cut in \(\Delta \phi\) suppresses the background efficiently at the lower end of the expected signal region.

After all the cuts a significant signal is expected for \(\tan \beta > 15\) between 180 \text{GeV} \leq m_A \leq 200 \text{ GeV}\) for an integrated luminosity of 30 \(\text{pb}^{-1}\). For \(m_A < 200\text{ GeV}\) the branching ratio for \(H^\pm \rightarrow \tau \nu\) increases rapidly however the selection efficiency, especially the one of the \(\Delta \phi\) cut, decreases significantly. The sensitivity for a heavy Higgs is for \(\tan \beta > 25\) at \(m_A \sim 400\text{ GeV}\) and for \(\tan \beta > 42\) at \(m_A = 600\text{ GeV}\). Study of the observability of \(H^\pm \rightarrow \tau \nu\) decay in the high luminosity running conditions are in progress, as well as the effect of stop mixing and lighter SUSY scale on the cross sections and branching ratios.
2.2 ATLAS analysis

The strategy used by ATLAS is similar to the one of CMS. Details can be found in ref. [12]. Several different cuts are used to separate signal from background exploiting the $\tau$ polarization effect and the large missing energy due to the neutrino from $H^\pm \to \tau \nu$. Advantage is taken of the different kinematical properties of the signal and background: imposing a large cut on the $p_T$ of $\tau$ jet, the background events need a large boost from $W$ boson to satisfy this cut. This results in a small azimuthal opening angle between the $\tau$ jet and the missing momentum while, on the contrary, the signal events not require such a boost, leading to a backward peak in the azimuthal opening angle. The difference in azimuthal angle between signal and background and in the missing momentum, which increases with $m_{H^\pm}$, can be taken into account looking at the transverse mass distribution. For the signal the transverse mass is bound from above to $m_{H^\pm}$, while for the background the transverse mass is constrained to be lower than $m_W$. $W$ and top quark mass reconstruction is performed to further reduce $W + \text{jet}$ background and $b$ tagging and second $b$-jet veto are also used to improve the signal selection. The final transverse mass reconstruction for signal and background is shown in Fig. [3]. An almost background free signal is selected; significances upwards of $5\sigma$ can be achieved for $m_{H^\pm} > m_t$ and $\tan \beta > 10$, for an integrated luminosity of 30 fb$^{-1}$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{mT_reconstruction.png}
\caption{The final transverse mass $m_T$ reconstruction for signal and background, for an integrated luminosity of 30 pb$^{-1}$.}
\end{figure}

3 Conclusions

The preliminary studies made by ATLAS and CMS leads to the conclusion that $H^\pm \to \tau \nu$ from $pp \to tH^\pm$ is a very promising discovery channel for charged Higgs bosons at the LHC. For $m_{H^\pm} > m_t$, the $tb$ and the $\tau \nu$ decay channels constitute the main decay modes of the charged Higgs. While the first suffers of a large irreducible QCD background, the latter could be free of such background, thereby extending the discovery potential beyond that achievable in the $tb$ channel, especially at large $\tan \beta$. It has been demonstrated that in the purely hadronic final states an almost background free signal is selected benefitting of the $\tau$ polarization effect and the large missing energy due to the neutrino from $H^\pm \to \tau \nu$ decay. As it is shown in Fig. [4], a combined significance upwards of $5\sigma$ can be achieved in a large part of the parameter space ($\tan \beta > 10$ for $m_{H^\pm} > m_t$), for an integrated luminosity of 30 fb$^{-1}$ for each experiment. Indeed, the range of discovery potential is limited by the signal size itself.
Figure 4: Expected $5\sigma$ discovery limits for $pp \rightarrow tH^\pm$, $H^\pm \rightarrow \tau \nu$ and $t \rightarrow j j b$, for an integrated luminosity of 30 fb$^{-1}$ for each experiment. Limits for other $H^\pm$ decay channels and the parameter space excluded by LEP experiments in the no-mixing scenario are also shown in the figure.

Acknowledgments

I would like to thank R. Kinnunen and D. Denegri for very helpful discussions and K. Assamagan for provide me useful material. I also thank the conference organizers for their kind and friendly hospitality.

References

1. P. H. Nilles, Phys. Rev. 110, 1 (1984); H. Haber and G. Kane, Phys. Rev. 115, 75 (1985); J.F. Gunion, H.E. Haber, G.L. Kane and S. Dawson in The Higgs Hunters’ Guide (Addison-Wesley, reading, MA, 1990).
2. A. Holzner, Search for Charged Higgs Bosons at LEP, XXXVI Rencontres de Moriond, Electroweak Interactions and Unified Theories, Les Arcs, France, March 2001.
3. L. Groer for CDF and DØ Collaborations, hep-ex/9707034.
4. CDF Collaboration, Phys. Rev. Lett. 79, 357 (1997).
5. DØ Collaboration, hep-ex/9902028.
6. S. Raychaudhuri and D.P. Roy, Phys. Rev. D 52, 1556 (1995) and Phys. Rev. D 53, 4902 (1996); E. Ma et al, Phys. Rev. Lett. 80, 1162 (1998).
7. V. Barger et al, Phys. Lett. B 324, 236 (1994); J.F. Gunion, Phys. Lett. B 322, 125 (1994).
8. A.A. Barrientos Bendezú and B.A. Kniehl, Phys. Rev. D 59, 015009 (1999) and hep-ph/9908385; S. Moretti and K. Odagiri, Phys. Rev. D 59, 055008 (1999).
9. D.P. Roy, Phys. Lett. B 459, 607 (1999); S. Moretti and D.P. Roy, Phys. Lett. B 470, 209 (1999); M. Dress et al, Phys. Lett. B 471, 39 (1999); D.P. Roy, hep-ph/0102091; K.A. Assamagan, ATLAS Internal Note ATL-PHYS-99-013, ATL-PHYS-99-025 (1999).
10. R. Kinnunen, CMS Internal Note CMS NOTE 2000/045 (2000).
11. CMS Collaboration, The tracker project, Technical Design Report, CERN/LHCC 98-6, CMS TDR 5, 26 February 1998.
12. K.A. Assamagan, ATLAS Internal Note ATL-PHYS-2000-031 (2000).