Strategies for charged Higgs searches at the LHC

Merlin Kole

September 9, 2009

Abstract

Finding a charged Higgs particle at the LHC would be a great step towards the discovery of the minimal supersymmteric model. In the case of an H^+ with a mass below that of the top quark its main production mechanism is by top quark decay. The biggest SM background for this process will be top decay into W^+. For masses around the top quark mass and above it the production channel of interest is $bg \rightarrow H^+t$ with again the top quark pair production as the main background. This report contains the results of a Monte Carlo study on the search for a charged Higgs which makes use of the difference in spin between the W^+ and the H^+. It will be shown that the polarization effect is visible in both the rest frame of the top quark and the labframe, however the effect is too small to be used in a search method in most of the researched parameter space.

Contents

1 Introduction

Finding the mechanism behind the electroweak symmetry breaking is one of the goals of current particle physicists. With the upcoming start of the LHC at CERN one hopes to find both the mechanism behind EWSB and the possible existence of supersymmetry. Where the SM only has one Higgs the minimal super symmetric model (MSSM) needs two doublets for EWSB. One of these doublets contains the so called charged Higgs or H^+ (H^-). The mass of H^+ has been experimentally bound from below to be heavier than the W^+ by LEP and Tevatron data. However there are no tight upper constraint on the mass or its couplings the SM particles. Therefor different mass regions need to be considered, all of which need a different search strategy. In this report the strategy for finding a charged Higgs with a mass below that of the top quark will be discussed first. In this region the branching ratio of the H^+ into τ is almost a 100% and the dominant production process is by top decay. The process of interest is top pair production via either quark anti-quark fusion or by gluon gluon fusion with a subsequent decay channel $t \rightarrow H^+b \rightarrow \tau\nu_\tau b$. The other top quark will then be used for triggering when it decays via $W^+b \rightarrow \mu\nu_\mu b$. The main background for this is the process where both partners of the top quark pair decay via the W^+ channel. Especially for $m_{H^+} \approx m_{W^+}$ these processes are difficult to distinguish. Discovery is however possible using the excess of τ decay events which originates from the 100% BR of the H^+ whereas it is only 10.8% for the W^+.

The strategy discussed in this report will make use of the opposite polarization states of the τ coming from H^+ and W^+ [1], [2]. Because of the scalar nature of the charged Higgs the τ produced from its decay will subsequently decay with a different kinematical distribution than when it is produced by W decay. The channels of interest for this difference are the one-prong decay channels of the τ, meaning the three decay channels $\tau^+ \rightarrow \pi^+\pi^0$, $\tau^+ \rightarrow \rho^+\pi^0 \rightarrow \pi^+\pi^0\pi^0$, $\tau^+ \rightarrow a^+\pi^0 \rightarrow \pi^+\pi^0\pi^0$. The result of prior studies [1], [2] show that the π^+ coming from the charged Higgs on average gets a higher portion of the energy than in the case of a W decay. Using this characteristic of the H^+ decay channel it might be possible to increase the signal to background ratio by applying a lower cutoff in the charged pion energy spectrum. In the case of a charged Higgs with a mass above that of the W boson the effect of interest will be increased by the extra momentum boost the τ gets resulting from the extra available energy in the decay process.

The polarization strategy will also be extended to masses above m_t depending on the value of $\tan\beta$, the is the ratio between the vacuum expectation values of the two doublets. This parameter is important since it influences the branching ratios of H^+ as can be seen from (1) in which V_{ij} are the CKM matrix elements. As shown in (1) the branching ratio of H^+ to τ increases with $\tan\beta$ while that to the quarks decreases. For low values of $\tan\beta$ ($\tan\beta < 10$) the BR to $\tau\bar{\nu}$ will be very small when $m_{H^+} > m_t$. Therefore this mass region is only interesting for large $\tan\beta$. To compare both the high and the low mass region and the discovery potential 4 different values of $\tan\beta$ ($\tan\beta = 10, 20, 40, 60$) were investigated in this project.

$$\mathcal{L} = \frac{g}{\sqrt{2}m_W} H^+[\cot\beta V_{ij} m_{u_i} \bar{u}_i d_{jL} + \tan\beta V_{ij} m_{d_j} \bar{u}_{ii} d_{jR} + \tan\beta m_{l_j} \bar{\nu}_{j_i} l_{jR}] + H.c. \quad (1)$$

In the first part of this report the polarization strategy will be applied on a charged Higgs search in the low mass region ($m_{H^+} < m_{W^+}$) where the main background comes from $W^+ \to \tau$ with the W coming from top quark decay. The relevant process simulated by PYTHIA is therefor top quark pair production. Since both signal and background are produced by the same hard interaction process the relevant parameter for the signal to background ratio is the BR of the top quark. This BR is not implemented in PYTHIA but has been a subject of research in [3]. The BR presented in this paper were used as an input parameter for the simulations.

For the the mass region where $m_{H^+} > m_t$ production by top decay becomes impossible and therefor a different production method has to be investigated for this region. The production process with the highest cross section in this area is $bg \to H^+t$ [4] with the main background process being again the top quark pair production with one top quark decaying into τ via a W. This process is not only interesting for H^+ masses above the top quark mass but we will show that it is already of interest for $m_{H^+} > 140GeV$. One very important parameter for this process is the bottom density in the proton which is highly dependent on the beam energy, therefore several of the simulations were done not only at the LHC design $\sqrt{s}$ of 14 TeV. They were also performed at the now planned start up energy of 7 TeV and the planned beam energy after one year of running of 10 TeV.

2 Light Charged Higgs

2.1 $m_{H^+} = m_{W^+}$

Even though the situation where $m_{H^+} = m_{W^+}$ is already excluded by LEP data this simulation was done to investigate the difference in τ polarization. With these parameters the only difference in the production mechanism of the τ is the spin of its mother particle. The simulations were done using PYTHIA 8.125 using both of the relevant processes for top quark pair production and the the branching ratio of the top quark from figure 1 which is taken from [3].

To check the effect of the polarization on the measurable charged pion coming from the decaying τ a high statistics run was done for $m_{H^+} = m_{W^+}$ with a $\tan\beta$ of 20. Only events in which one of the top quarks decay channels results into a τ decaying into a one-prong hadronic shower were kept. This results in a reduction factor of 0.1 for the number of events with an intermediate W and no reduction factor for the H^+ events since it's branching ratio to τ is ≈ 100. The only cut applied in the simulation itself was a pseudorapidity cut of $\eta < |3|$ for the τ lepton. The detector efficiency for this process was later applied in the analysis by multiplying the number of events by a factor of 0.5 accounting for the b-tagging efficiency and a factor of ≈ 0.10 for the requirement that the partner of the top quark decays via a W into a muon on which one can trigger the event. The result of this first polarization check can be seen in figure 2 which shows the relative cross section as a function of $\frac{2E_\pi}{m_t}$ where E_{pion} is measured in the reference frame of the intermediate boson. The plot shows an increase in the relative cross section with increasing values of E_π as predicted by [1], [2]. To show that the effect is also visible in a detector the same relative cross section is plotted in 3 but this time against the energy of the π^+ in the lab frame.

2.2 $m_{H^+} > m_{W^+}$

When the mass of the charged Higgs is taken to be higher than that of the W-boson an extra boost of the pion is expected. This should then increase the rise of the relative cross section which was seen in the previous section. When this increase in relative cross section is big enough it could be advantageous to apply a cut in the pion energy spectrum to increase the signal to background ratio.

For these simulations the same settings were used as for the $m_{H^+} = m_{W^+}$ case. Simulations were performed for the charged Higgs masses of $100, 120, 140, 150$ and $160 GeV$. For all of these masses 4 different simulations were done with different values of $\tan\beta$ $10, 20, 40$ and 60. The amount of $t\bar{t}$ events needed to claim a 5σ discovery for any of these combinations can be found in 1.

As can be seen in figure 4 the effect of the mass difference increases the effect of the relative cross section as expected. To check if the combined effect from a mass boost and the polarization effect can be used to improve the signal to background ratio its value was plotted against the lower cutoff value for the pion energy. One of these plots can be seen in figure 5 for the case of $m_{H^+} = 100$ and $\tan\beta = 10$. As can be seen from this figure the preferred cutoff energy is 0 showing that the combined effect is too small. The reason for this is that even though the relative cross section of H^+ increases with increasing charged pion energy the overall cross section for producing these high energy pions is very small compared to the production cross section for low energy charged pions. Therefor a lower cutoff in this energy spectrum results in cutting the large majority of events. The same results were found for all the H^+ masses up till the top mass showing that in the lower mass region the polarization effect can not be used to improve the signal to background ratio.

3 Heavy charged Higgs

For the case in which the charged Higgs has a mass in the region of the top mass or above it the dominant production process for H^+ is $bg \to H^+t$. The background for this process is again from top quark pair production with subsequent decay into $W \to \tau$ by one of the top partners. Since top decay into H^+ is impossible for values of m_{H^+} above the top mass and negligible for values slightly below it the branching ratio of the top quark is set to 100% for the decay into Wb. The branching ratio of the H^+ into τ can no longer be considered to be a 100% in this region. These branching ratios were calculated by PYTHIA itself for these simulations for all the different charged higgs masses and values of $\tan\beta$. The same pseudorapidity cut was used in these simulations and again the factor of 0.5 was applied in the data analysis accounting for the b-tagging efficiency. The other reduction factor of 0.1 for the muon tagging used in the light charged Higgs scenario is no longer needed for these processes and will therefor not be used.

3.1 $m_{H^+} \approx m_t$

When m_{H^+} gets above about $140GeV$ the branching ratio of the top into H^+ becomes very small and the $bg \to H^+t$ process becomes interesting as can be seen in table 2 when comparing it to table 1. Here one can see that in this area the amount of data needed for a 5σ discovery gets similar for both processes around the mass of 140 GeV and becomes smaller when the mass becomes even higher. When checking again for the polarization effect we see the same results as in the light mass scenario. The relative cross section rises with increasing pion energy but the cross section at this point is so small compared to the cross section for low energy pions that applying a lower cutoff would simply remove too many events. This can be seen in figure 6. The figure shows the amount of generated events as a function of the charged pion energy. As can be seen the vast majority of the events results in pions with an energy below $100GeV$. Values larger than 0 do start to appear for the ideal cutoff energy at around 170 GeV but these are still below 10 GeV meaning that these events will probably be cut in the experiments already. Significant values of the ideal lower cutoff energy only appear for charged Higgs masses relatively far above the top mass as will be seen in the next section.

3.2 High mass charged Higgs

Increasing the mass of the charged Higgs far above the top quark results in a decrease of the production cross section. However in this region the simulations show that here a lower cutoff on the charged pion energy does become favourable. One example of this is the simulation for $m_{H^+} = 250GeV$ and $\tan\beta = 60$. In this case the $\tan\beta$ results in a relatively high amount of H^+ events compared to the lower values of $\tan\beta$. Looking again at the signal to background ratio as a function of the lower cutoff value in the charged pion energy we get figure 7. Here one can see that the ideal cutoff value is around 30 GeV. Simulations with even higher charged Higgs masses show that this cutoff value increases with increasing mass however the production cross section of the charged Higgs becomes very small even for high values $tan\beta$ and therefor other mechanisms for charged Higgs search should be applied.

4 Beam energy dependance

Since the originally planned centre of mass energy of 14TeV will not be achieved in the near future at the LHC it is important to also do these simulations at the now proposed start-up energy of 7TeV and the energy of 10TeV which will be used after the first year of running.

For the low mass region the relevant cross section which needs to be checked is that of the $t\bar{t}$ production since this is the only relevant parameter which changes with decreasing energy. At 10 TeV this cross section is reduced by a factor of 2 and at 7 TeV by a factor of 5. Since this results in a decrease of both the signal and the background the result on the signal to background ratio which is defined as $\sigma = \frac{signal}{\sqrt{background}}$ will be a reduction factor of $\sqrt{2}$ and $\sqrt{5}$ respectively. Even though this is of course not favourable it is still makes a search for the H^+ possible in most of the parameter space.

For a high mass charged Higgs the results will be more problematic since the production process for the signal differs from that for the background. The background process will change as mentioned for the light Higgs scenario. The signal process will decrease by a factor of ≈ 3 for 10 TeV and a factor of ≈ 11 at 7 TeV. Resulting in a decrease of σ by a factor of ≈ 5 at 7TeV compared to σ at 14 TeV. This makes a search at these energies even more difficult than it was before. In both the light and the heavy mass charged Higgs case the difference in energy does not have an effect on the importance of the polarization, the kinematics stay approximately the same.

5 Results

The results of all the simulations can be found in tables 1 and 2. These tables show the amount of data needed (in fb^{-1}) for a 5σ discovery. The values were calculated by taking all the events left after applying the earlier discussed cuts. So no lower cutoff was applied to the charged pion energy spectrum since this is the most favourable although experimentally impossible, setup for almost all of the chosen parameter combinations. The only parameter choices where the amount of needed data can be reduced are the ones with a charged Higgs mass above $200GeV$, so for the $250GeV$ and $300GeV$ cases. In the $250GeV$ case applying a cutoff at $30GeV$ would reduce the amount of data needed to $35.4fb^{-1}$ for $\tan\beta = 60$ and to $312fb^{-1}$ for $\tan\beta = 40$. For the $300GeV$ case the ideal cutoff value is around $60GeV$ in which case the amount of data needed would be reduced to $212fb^{-1}$ which is a big improvement. In all other cases cutoff application is not desirable and the favoured discovery method is by looking at the excess of charged pion from top quark events without the use of the polarization effect.

$\tan\beta$	$m_{H^+} = 100$	$m_{H^+} = 120$	$m_{H^+} = 140$	$m_{H^+} = 150$	$m_{H^+} = 160$
10	1.36	5.50	11.3	65.7	587
20	0.21	1.36	5.51	16.4	136
40	—-	—	0.61	1.45	21.7
60	—-	—	—	0.31	6.66

Table 1: Needed data (in fb^{-1}) without cutoff in charged pion energy spectrum for H^+ coming from top decay.

$\tan\beta$	$m_{H^+} = 140$	$m_{H^+} = 170$	$m_{H^+} = 250$	$m_{H^+} = 300$
10	198	347	—	—
20	18.9	37.0	—	—
40	1.15	2.30	359	—
60	—	0.45	44.2	331

Table 2: Needed data (in fb^{-1}) without cutoff in charged pion energy spectrum for H^+ coming from $bg \to H^+t$, severall parameter settings have been left empty since the amount of data would be too high or unreliably small.

6 Conclusion

For the light charged Higgs scenario it can be safely concluded that using the polarization effect for a charged Higgs search is not favourable. Since the branching ratio of the top quark in H^+ is relatively high in the mass region where top quark decay is interesting the excess of τ events can be used here to discover the H^+ within the LHC running time. The polarization effect is not needed here. For m_{H^+} above $140GeV$ the other production method becomes interesting but also in this region the combined polarization and mass boost effect can not be used to improve the signal to background ratio. This only becomes interesting for values of m_{H^+} larger than $250GeV$. For masses larger than this cutting out low energy charged pion events improves the signal to background ratio and the amount of data needed can be reduced by about 25% to 30% by using these cuts. For even higher masses simulations become difficult since the production cross section becomes very small and different search methods for the charged Higgs have to be applied for finding the charged Higgs within the LHC running time.

Operating the LHC at energies of 7 or 10 TeV has, as expected, a negative effect on the search especially in the case of the high mass charged Higgs where the signal process involves a b-quark coming from the proton. Since lower beam energies result in a lower b-quark density in the proton the signal process gets reduced more than the process responsible for the background. Where in the light charged Higgs scenario the signal to background ratio does not really suffer from the beam energy reduction it does in the case of the heavy charged Higgs, where the search was already difficult, in most of the parameter space.

7 Acknowledements

First of all I would like to thank Ahmed Ali for giving me the chance to work at DESY and for providing me with this interesting project and of course for all his help. Secondly I would like to thank Torbjőrn Sjőstrand for his quick responses to all my questions regarding PYTHIA. And lastly I would like to thank the organisers of the DESY summer student program for making all of this possible.

References

[1] B.K. Bullock, H. Hgiwara, A.D. Martin, Nucl. Phys. B 395 (1993) 499.

[2] S. Raychaudhuri, D.P. Roy, Phys. Rev. D 52 (1995) 1556; D 53 (1996) 4902.

[3] A. Sopczak, *Cross-sections and branching ratios for charged Higgs searches*, arXiv:0907.1498v1

[4] D.P. Roy, *The hadronic tau decay signature of the heavy charged Higgs boson at the LHC*, Phys B. 459 (1999) 607-614.

8 Figures

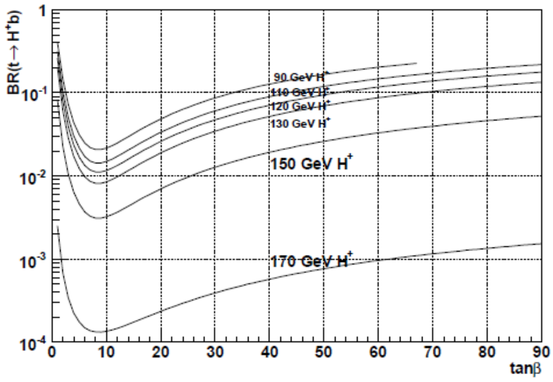

Figure 1: Expected top quark branching ratios as a function of $\tan\beta$ [3]

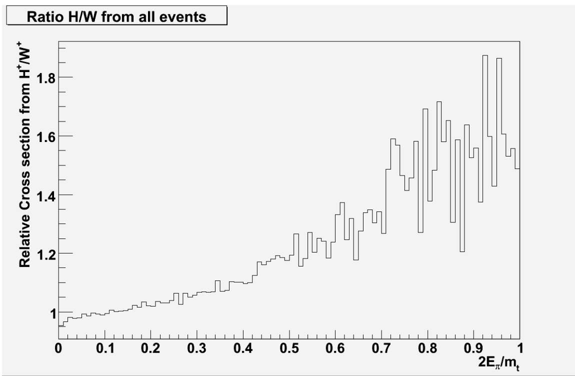

Figure 2: Ratio between the number of pions coming from H^+ decay over the number coming from W^+ decay as a function of $\frac{2*E_\pi}{m_t}$ with E_{pi} measured in the top reference frame. The ratio increases by 40% when going to $\frac{2*E_\pi}{m_t} = 1$. The bad statistics at high energies illustrate the small cross section in this region.

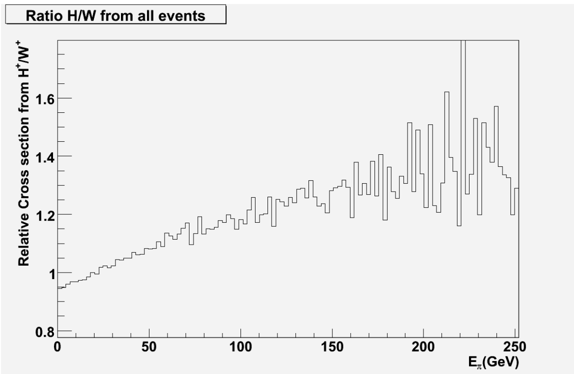

Figure 3: Similar to 2 but now plotted against E_{pi} as measured in the labframe.

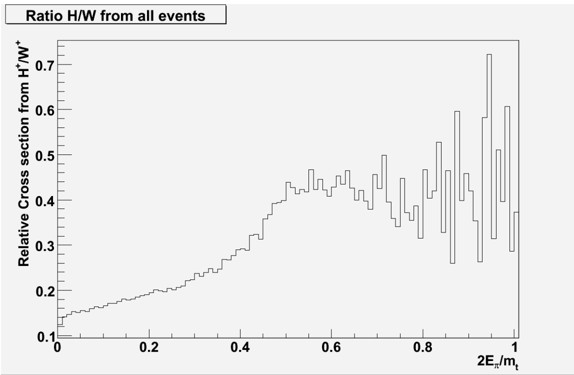

Figure 4: Similar to 2 but now for $H^+ = 100GeV$ and $\tan\beta = 10$.

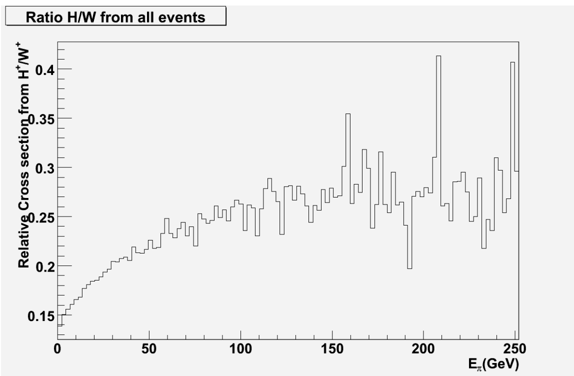

Figure 5: Similar to 3 but now for $H^+ = 100GeV$ and $\tan\beta = 10$.

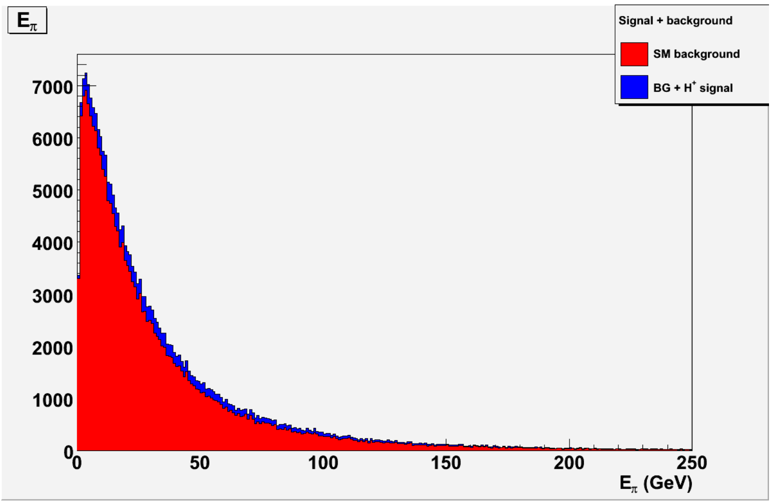

Figure 6: Histogram of the amount of charged pion events against the pion energy for $H^+ = 170GeV$ and $\tan\beta = 60$.

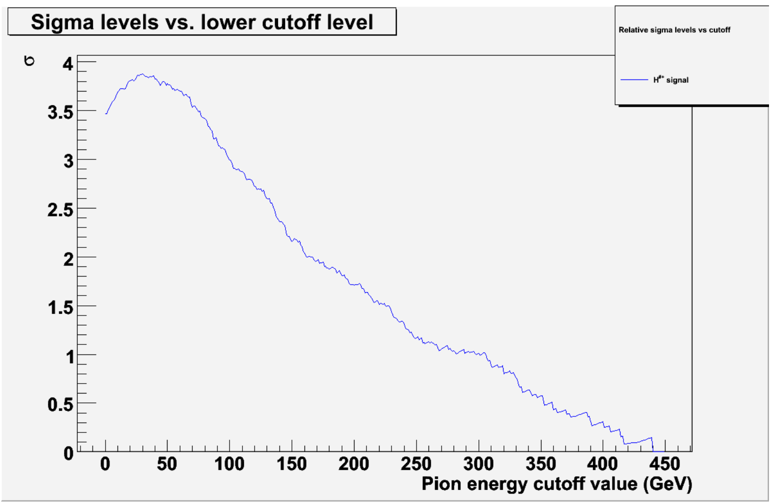

Figure 7: $\sigma = \frac{signal}{\sqrt{background}}$ versus the lower energy cutoff of the charged pion for $H^+ = 250GeV$ and $\tan\beta = 60$.