Paper I

Study of the $H^{\pm} \to W^{\pm}H^{0}$ decay in a large mass splitting MSSM scenario with ATLAS

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We investigate the possibility for detecting a heavy charged Higgs boson in a large mass splitting MSSM scenario. In this until now unexplored part of parameter space the $H^{\pm} \to W^{\pm}H^{0}$ decay channel is opened and in particular it yields a sizable branching ratio in the intermediate tanβ region. This is of particular interest since the intermediate tanβ region is uncovered in terms of charged Higgs discovery without turning to SUSY decay channels. However, despite a large branching ratio for $H^{\pm} \to W^{\pm}H^{0}$ the similarity of the signal distributions to those of the $t\bar{t}$ background makes the detection prospects of the charged Higgs challenging in this channel.

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I. INTRODUCTION

The Higgs sector of the the Minimal Supersymmetric Standard Model (MSSM) contains five particles: Three neutral (h^0,H^0,A^0) and two charged (H^+,H^-) ones. The dominant decay modes of the charged Higgs boson in most of the parameter space of the MSSM are fermionic, where the decay channels $H^{\pm} \to \tau\nu_{\tau}$ and $H^{\pm} \to tb$ are the most promising ones for the detection with the ATLAS detector at the LHC [1, 2, 3]. However, both search channels show a lack of sensitivity for the so called intermediate tanβ region around tan$\beta \approx 7$.

Recently it was found that the decay channel $H^{\pm} \to W^{\pm}H^{0}$, involving the heavier of the two neutral CP even Higgs bosons, could become dominant in a previously neglected region of the MSSM parameter space [4]. Here MSSM parameters are tuned in order to generate a large mass splitting between $m_{H^{\pm}}$ and m_{H^0}. It turns out that large branching ratios (BR) are obtainable for tanβ values around 7. Hence the $H^{\pm} \to W^{\pm}H^{0}$ decay mode could add sensitivity in the intermediated tanβ region, without turning to decay modes involving supersymmetric (SUSY) particles. The latter show good potential for the detection of a heavy charged Higgs boson for intermediate tanβ values [5, 6].

The bosonic decay mode $H^{\pm} \to W^{\pm}h^{0}$ has previously been studied in [7]. There it was concluded that this search channel is not a viable option when taking current LEP limits of $m_{h^0} \geq 92.9$ GeV [8] into account.

In this note we investigate the bosonic $H^{\pm} \to W^{\pm}H^{0}$ decay of the charged Higgs boson in the region of the MSSM parameter space where the branching ratio (BR) for $H^{\pm} \to W^{\pm}H^{0}$ is large. We use the fast ATLAS detector simulation to study the viability of detecting a charged Higgs boson in this decay channel at the LHC.

In the following section we describe the size $m_{H^{\pm}} - m_{H^0}$ mass splittings are in the MSSM. We describe the tools used to evaluate the MSSM spectrum and explain how the MSSM parameters for our simulation study are chosen. In section III the generation and detector simulation of events is explained and section IV describes the details of the analysis. Results are presented in section V and conclusions are given in section VI.

II. PARAMETER SPACE AND SUBSEQUENT DECAYS

The MSSM Higgs spectrum is at tree level completely determined by two parameters: The ratio of the vacuum expectation values of the two electroweak Higgs doublets, $\tan\beta$, and one of the masses of the Higgs bosons. In this paper we use the mass of the charged Higgs boson $m_{H^{\pm}}$ as the second parameter. When radiative

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corrections are taken into account, more MSSM parameters enter the calculations of the MSSM Higgs boson spectrum and rather large differences to the tree level predictions can be obtained.

Large mass splitting between the charged and the heavy neutral Higgs boson is achievable if the quartic couplings of the effective Lagrangian receive radiative corrections from trilinear Yukawa couplings of the Higgs field to the third generation of squarks. At the 1-loop level the quartic couplings may be written as (keeping dominant terms) [9]:

$$\begin{aligned}
\lambda_4 &\approx \frac{g_w^2}{2} - \frac{3}{96\pi^2}\left[h_t^4\left(\frac{3|\mu|^2}{M_{SUSY}^2} - \frac{3|\mu|^2|A_t|^2}{M_{SUSY}^4}\right) + h_b^4\left(\frac{3|\mu|^2}{M_{SUSY}^2} - \frac{3|\mu|^2|A_b|^2}{M_{SUSY}^4}\right)\right] + \frac{3}{8\pi^2}h_t^2h_b^2\left[\frac{1}{2}X_{tb}\right] \\
\lambda_5 &\approx \frac{3}{192\pi^2}\left[h_t^4\left(\frac{\mu^2A_t^2}{M_{SUSY}^4}\right) + h_b^4\left(\frac{\mu^2A_b^2}{M_{SUSY}^4}\right)\right] \\
\lambda_6 &\approx -\frac{3}{96\pi^2}\left[h_t^4\frac{|\mu|^2\mu A_t}{M_{SUSY}^4} - h_b^4\frac{\mu}{M_{SUSY}}\left(\frac{6A_b}{M_{SUSY}} - \frac{|A_b|^2A_b}{M_{SUSY}^3}\right)\right]
\end{aligned}$$

Here X_{tb} is a function of $A_{t,b}$, μ and M_{SUSY}. The mass difference between the charged Higgs and the heavy neutral Higgs boson is approximately given by [4]:

$$M_{H^\pm}^2 - M_{H^0}^2 \sim v^2\left(\frac{\lambda_4}{2} + \Re\lambda_5 + \frac{2\Re\lambda_6}{\tan\beta}\right). \tag{1}$$

If Eq. (1) should produce a large mass splitting, large quartic coupling terms are needed. Since these are suppressed by small coefficients, ($3/96\pi^2$ and $3/192\pi^2$), they are in general small. However, if we allow for $\mu, A_t > 4M_{SUSY}$ we see that the $|\mu|^2|A_t|^2/M_{SUSY}^4$ term in the expression for λ_4 becomes large and hence it would overcome the suppression from the small coefficients. Consequently quartic coupling terms of $\mathcal{O}(1)$ would lead to a large mass splitting $m_{\mathrm{H}^\pm} - m_{\mathrm{H}^0}$. The exact magnitude of the mass splitting is sensitive to the trilinear coupling constant A_t but also to higher order loop corrections.

In [4] a set of MSSM parameters is suggested which maximises BR($\mathrm{H}^\pm \to \mathrm{W}^\pm\mathrm{H}^0$) for $m_{\mathrm{H}^\pm} = 250\,\mathrm{GeV}$ and tan$\beta \approx 10$. We use the Feynhiggs program [10] for the calculation of the MSSM Higgs boson spectrum. This program includes higher order corrections and the results obtained are quite different from the ones presented in [4]. After scanning the MSSM parameter space with respect to tanβ and $m_{\mathrm{H}^\pm}$, with the remaining MSSM parameters are set as listed in Table I, results in BR($\mathrm{H}^\pm \to \mathrm{W}^\pm\mathrm{H}^0$) are shown in Figure 1. The white regions are either physically not allowed within the MSSM or violate the experimental limit on m_{h^0}, where the latter constraint has only a small effect. Figure 1 also shows the large sensitivity to the trilinear coupling constant contrary to the weaker sensitivity to μ.

The region of large BR($\mathrm{H}^\pm \to \mathrm{W}^\pm\mathrm{H}^0$) proposed in [4] turns out to be unphysical in the framework of the MSSM. According to the Feynhiggs calculation, the largest branching ratio for $\mathrm{H}^\pm \to \mathrm{W}^\pm\mathrm{H}^0$ is now obtained for charged Higgs masses of $\mathcal{O}$ 600 GeV and tan$\beta \approx 7 - 10$ in the case of a $A_t = 1900$ GeV.

TABLE I: MSSM parameters used in scan. $M_{\tilde{Q}_3}, M_{\tilde{t}}, M_{\tilde{b}}$ refer to third generation squark soft SUSY breaking masses [4].

$M_{\tilde{Q}_3}$	$M_{\tilde{t}}$	$M_{\tilde{b}}$	μ	A_t	A_b
500	550	550	3500	1300, 1600, 1900	0
500	550	550	4000	1300, 1600, 1900	0
500	550	550	4500	1300, 1600, 1900	0

In order to estimate the possible discovery potential at the ATLAS we perform the analysis for MSSM parameters which maximise the expected signal yield. Therefore not only the BR($\mathrm{H}^\pm \to \mathrm{W}^\pm\mathrm{H}^0$) is important but also the cross section for charged Higgs production and the branching ratio for the assumed $\mathrm{H}^0 \to b\bar{b}$ decay. The latter is also predicted using Feynhiggs and results of BR($\mathrm{H}^0 \to b\bar{b}$) are presented as a function of $m_{\mathrm{H}^\pm}$ and tanβ in Fig. 2.

The $\mathrm{H}^\pm \to \mathrm{W}^\pm\mathrm{H}^0$ decay is kinematically allowed only for $m_{\mathrm{H}^\pm} - m_{\mathrm{H}^0} > m_{\mathrm{W}^\pm}$. In order to avoid problems with the LEP constraints on m_{h^0} we restrict ourselves to the search for a heavy charged Higgs boson with $m_{\mathrm{H}^\pm} > 200\,\mathrm{GeV}$. The dominant production channel in this region is the $gb \to t\mathrm{H}^\pm$ production process. We use Pythia 6.221 [11] to estimate production cross sections corresponding to this production process in the (tanβ,$m_{\mathrm{H}^\pm}$) plane, see Fig. 2. Calculating the total cross section times branching ratio for the

$$gb \to t\mathrm{H}^\pm \to t\mathrm{H}^0\mathrm{W}^\pm \to \mathrm{W}^\pm b b\bar{b}\mathrm{W}^\mp \tag{2}$$

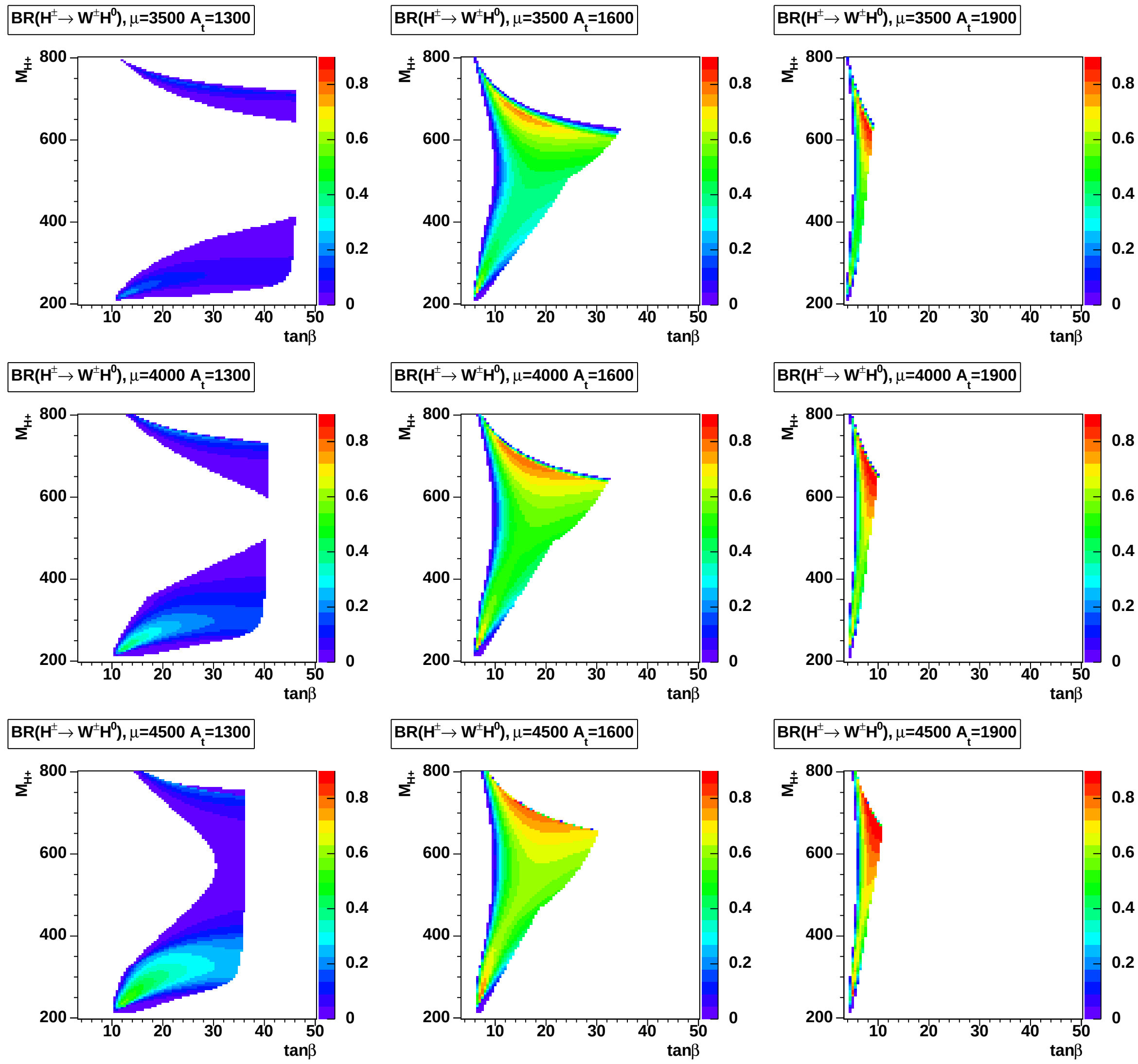

FIG. 1: Scan of the MSSM parameter space with respect to tanβ and $m_{\mathrm{H}^\pm}$for 9 combinations of μ and A_t as indicated in the plots (Units in GeV). The remaining MSSM parameters are set as shown in table I.

signal process (see Fig. 2), we see that the maximum yield is $\sim 110\,\mathrm{fb}$ for $m_{\mathrm{H}^\pm} = 250\,\mathrm{GeV}$ and tan$\beta = 4.6$. Consequently these two parameters together with the remaining MSSM parameters as set in Table II define the complete set of MSSM parameters used in this simulation study.

TABLE II: Parameters for Point A.

	$\tan\beta$	$m_{H^\pm}$ [GeV]	m_{H^0} [GeV]	$\sigma\times$ BR [fb]	$M_{\tilde{Q}_3}$	$M_{\tilde{t}}$	$M_{\tilde{b}}$	μ	A_t	A_b
Point A	4.6	250	129	110	500	550	550	4000	1900	0

III. EVENT GENERATION AND DETECTOR SIMULATION

The signal process Eq. (2) is generated using Pythia with the default settings within the Athena framework of the ATLAS Software Release 9.0.3. The Feynman diagram depicting the signal process is shown in Figure 3. We require one of the $\mathrm{W}^\pm$ in the event to decay hadronically ($q\bar{q}'$) and the other one to decay to an electron or muon ($l\nu$). The isolated, high p_T lepton from the latter $\mathrm{W}^\pm$ decay is used to trigger the experiment. The

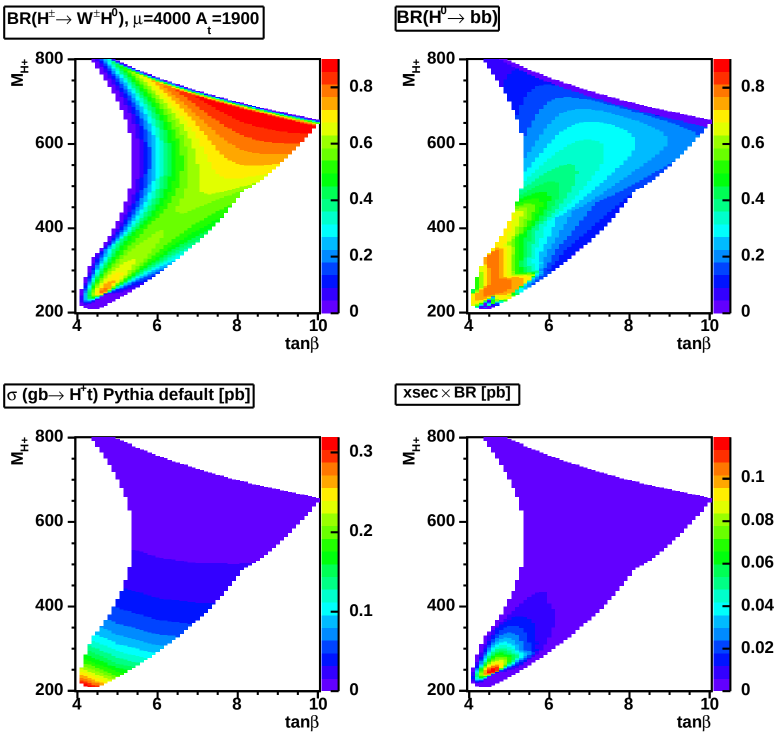

FIG. 2: Upper left: Mass splitting as obtained with Feynhiggs and SUSY parameters as given in table II. Here only mass splitting $M_{H^\pm} - M_{H^0} > M_W$ is shown. Upper right: Branching ratio $H^0 \to bb$ as obtained with Feynhiggs. Lower left: Charged Higgs production cross-section, default Pythia 6.221 [11]. Lower right: Resulting total cross-section when multiplying the three other histograms together.

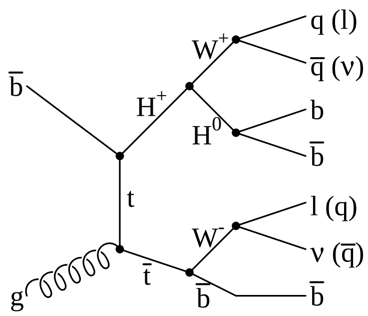

FIG. 3: Example for a Feynman diagram, depicting the signal process.

final state contains three b–jets, two light jets and a lepton and neutrino. The latter escapes detection and is the source for missing transverse momentum, $(p_T)_{miss}$.

The main background process to this signal is $t\bar{t} + jet$ production with one jet mistagged as a b–jet. We use the Pythia $t\bar{t}$ production process, i.e.

$$t\bar{t} \to W^+ bW^- \bar{b} \to q\bar{q}bl\nu\bar{b}, \tag{3}$$

and rely on the parton shower to model the additional jets. We assume a leading order $t\bar{t}$ production cross-section of 590 pb. In the analysis presented here we will only study this main contribution to the expected background and neglect all possible contributions from other processes. This assumption has no influence on the conclusions drawn from this analysis, see section VI.

When producing the Monte Carlo samples (500 000 signal and 1 000 000 background events), we require for the background, as for the signal, that one of the $W^\pm$ in the event decays hadronically $(q\bar{q}')$ whereas the other decays leptonically ($l\nu$). We take the fraction of W decays to $q\bar{q}'$ to be 2/3 and to $l\nu$ to be 2/9. Since either of the $W^\pm$ can decay hadronically or leptonically, the total BR for this forced W decay is 8/27.

The ATLAS detector response was simulated with ATLFAST as represented in ATLAS Software Release 9.0.3. Jets are reconstructed with a cone based algorithm using a cone size of $\Delta R = 0.4$. For this analysis jets were calibrated and b–tagged by the ATLFASTB routine. A b–tagging efficiency of 50 % is applied, foreseen for ATLAS data taking at high luminosity. The corresponding averaged rejection factors for c–jets and light jets are 1/10.9 and 1/231 respectively. An 90 % efficiency to identify isolated electrons or muons is also assumed.

Unless otherwise stated all plots and figures in this paper are given for an integrated luminosity of $300 fb^{-1}$, corresponding to three years of high luminosity running at the LHC.

IV. ANALYSIS

The analysis follows closely the one outlined in [7] and is divided into two parts: First a preselection is applied in order to reject most of the potential Standard Model (SM) background based on simple cuts on pseudorapidity and transverse momenta. The second part aims at reconstructing the decay products present in the decay of the charged Higgs boson. From these, charged Higgs candidates are formed in a subsequent step and their reconstructed mass is calculated.

A. Preselection

The preselection requires each event to have:

- Exactly one isolated lepton with transverse momentum $p_T > 25(20)$ GeV and pseudorapidity $|\eta| < 2.5$ if the lepton is identified as an electron (muon),
- exactly 3 b–tagged jets with $p_T > 30$ GeV GeV and $|\eta| < 2.5$,
- two or more light jets with $p_T > 30$ GeV and $|\eta| < 5$.

The requirements on the lepton are set to meet the requirements for efficient triggering.

B. Event Reconstruction

Events passing the preselection cuts are further treated by the event reconstruction routine, outlined in the following:

- The $W^\pm$ decaying to jets is reconstructed from two of the not b–tagged jets in the event. All jet–jet combinations giving a combined invariant mass consistent with the $W^\pm$ mass , i.e. $|m_{jj} - m_{W^\pm}| < 25$ GeV, are accepted and the jet momenta are rescaled to give $m_{jj} = m_{W^\pm}$ before the candidates are stored as W_{had} candidates.
- The leptonically decaying $W^\pm$ is reconstructed from the isolated lepton and measured missing transverse momentum $(p_T)_{miss}$. By assigning the missing transverse momentum to the neutrino we can use the $W^\pm$ mass as a constraint to find the neutrino's longitudinal component. Two or zero physical solutions can be found and the whole event is rejected in the latter case. The reconstructed $W^\pm$ are stored as W_{lep} candidates.
- The associated top–quark of the signal is reconstructed by minimising the chi-square

  $$\chi^2 = (m_{W_i b_k} - m_t)^2.$$

  Here $m_{W_i b_k}$ is the invariant mass of one of the $W^\pm$ candidates, $i = had \bigvee lep$, and one of the three b–tagged jets, $k = 1, 2, 3$. This procedure determines both the b–quark originating from the top–quark's decay and if one of the hadronic or leptonic $W^\pm$ candidates should be used for the charged Higgs reconstruction.
- The two remaining b–jets not used for the top–quark reconstruction in the previous step are assigned to the H^0 decay.

- Finally we reconstruct all charged Higgs candidates. The number of candidates depends on the W$^\pm$ decay mode in $H^\pm \to WH^0$. If it decays leptonically there are up to two solutions to the neutrino's longitudinal momentum and hence at maximum two charged Higgs candidates are formed. If the W$^\pm$ decays hadronically there will be one or more candidates depending on how many jet-jet combinations pass the cut on the reconstructed W_{had} mass. We find an average of 1.98 charged Higgs candidates per event.

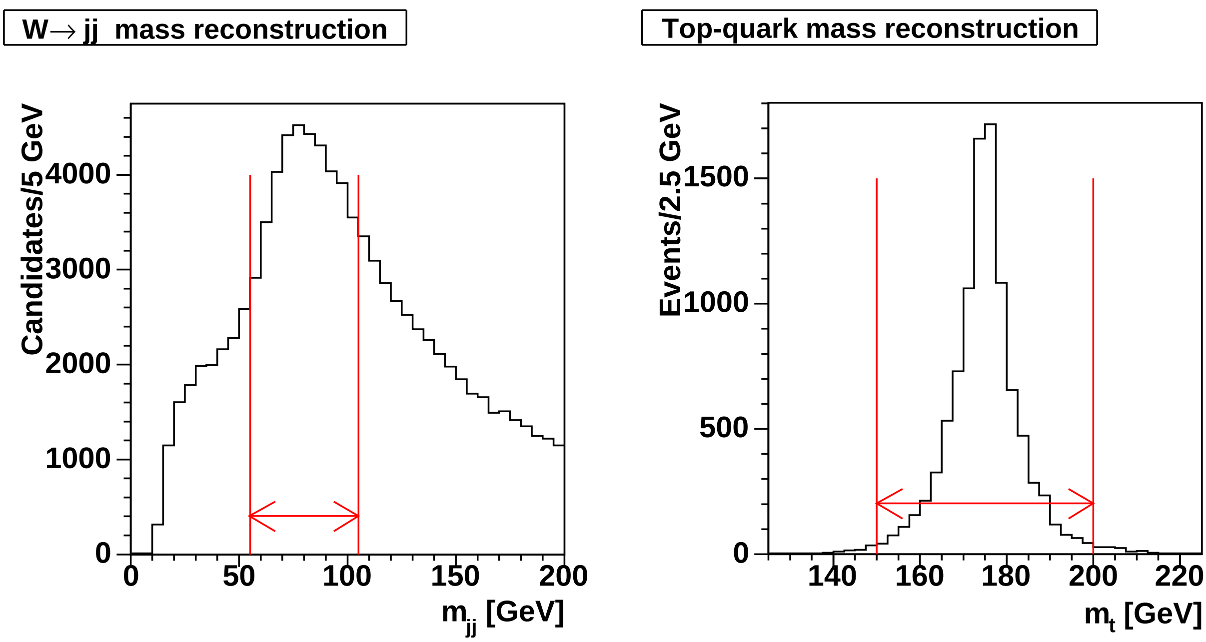

FIG. 4: The mass distributions for the hadronically decaying W candidates and the associated top–quark, both taken from the point A simulation results. The vertical lines indicate the reconstruction cuts.

Figure 4 shows invariant masses of the reconstructed $W \to jj$ candidates, and the associated top–quark.

So far, no cut has been applied to reject significantly the $t\bar{t}$ background Eq. (3). Several kinematic variables were studied for their power to discriminate between the signal and background processes. Unfortunately no variable with reasonable separation power was found. Some of the variables investigated are presented in Fig. 5.

One would expect that a veto on a second reconstructed top–quark candidate in the event should yield good separation power since only one top–quark is present in the signal, Eq. 2 whereas two top–quarks should be found in the background process, Eq. 3. However, these expectations are not met, due to the high jet multiplicity, making it almost always possible to find a combination of jets whose invariant mass resembles m_t even in the signal events. The lower right histogram of Figure 5 shows the mass distribution of the second top–quark candidates for signal and background. The reason for the dip in the distributions at 175 GeV is that the best top candidates are selected for the charged Higgs reconstruction.

Also the H^0 mass would be expected to be a possible cut parameter. Unfortunately the H^0 mass distribution for the signal is too broad for any cut to be applied. See top left histogram of Figure 5. Adding the H^0 mass to the χ^2–method only results in both signal and background peaking at the same central value.

If the difference between $m_{\mathrm{H}^\pm}$ and m_{H^0} is large, the H^0 obtains a large boost and consequently the b–quarks originating from its decay have a small opening angle ΔR_{bb} between them. For the background, ΔR_{bb} is the opening angle between a b–quark originating from a top–quark decay and the mistagged light jet. The resulting ΔR_{bb} distribution should be rather flat. However, even though mass splittings of $\mathcal{O}(200\,\mathrm{GeV})$ are obtainable, these appear for relatively large charged Higgs masses ($\sim$ 650 GeV) and intermediate values of $tan\beta$ where BR(H$^\pm \to$ W$^\pm$H^0) is small and also the production cross-section falls below 10 fb. For the MSSM parameter values under consideration in this analysis, H^0 receives only a small boost and hence ΔR_{bb} provides no good separation power, see Figure 5.

In [7] a number of other variables, in addition to the ones mentioned above, are suggested which could improve the signal separation from the backgrounds. Figure 5 shows the P_T distributions for the H^0 and H$^\pm$ and the opening angle between H^0 and $W^\pm$. However, since neither these nor the previously suggested cut variables provide any separation between the signal and the background process, no further cuts are applied.

V. RESULTS

As previously mentioned Point A was selected as a best possible simulation point in order to test the signal for any discovery potential. Table III shows the cumulative cut efficiencies at each analysis step for signal versus background. The cut with the largest single discrimination power is the requirement of tagging exactly 3 b-jets. In the $t\bar{t}$+jets background only two b-jets are expected at tree level and events surviving this cut are dominated by events where a c-quark in the decay of the hadronically decaying $W^{\pm}$ is mistagged as a b-jet.

From the bottom line of Table III it is clear that the signal is overwhelmed by the background. Quoted numbers of expected events are for an integrated luminosity of 300 fb^{-1} and figure 6 shows the mass distributions for signal and background. Using Monte Carlo truth it can be shown that among these 186 fully reconstructed signal events, a fraction of 80% will contain the true charged Higgs candidate among the reconstructed candidates.

This channel does not present any discovery potential for the charged Higgs, even though large branching ratios for the $H^{\pm} \to W^{\pm}H^{0}$ decay are obtainable. The production cross-section in the large mass region ($m_{H^{\pm}} \gtrsim 500$ GeV), where sizable branching ratios can be obtained, is too small ($\sim$ 10fb). For small $m_{H^{\pm}} \approx 250$ GeV (point A), and before any reconstruction cuts are applied, the signal to background ratio is S:B$\sim$1:5400. This, combined with the similarity between the signal and background distributions, renders this search channel non-viable at the LHC.

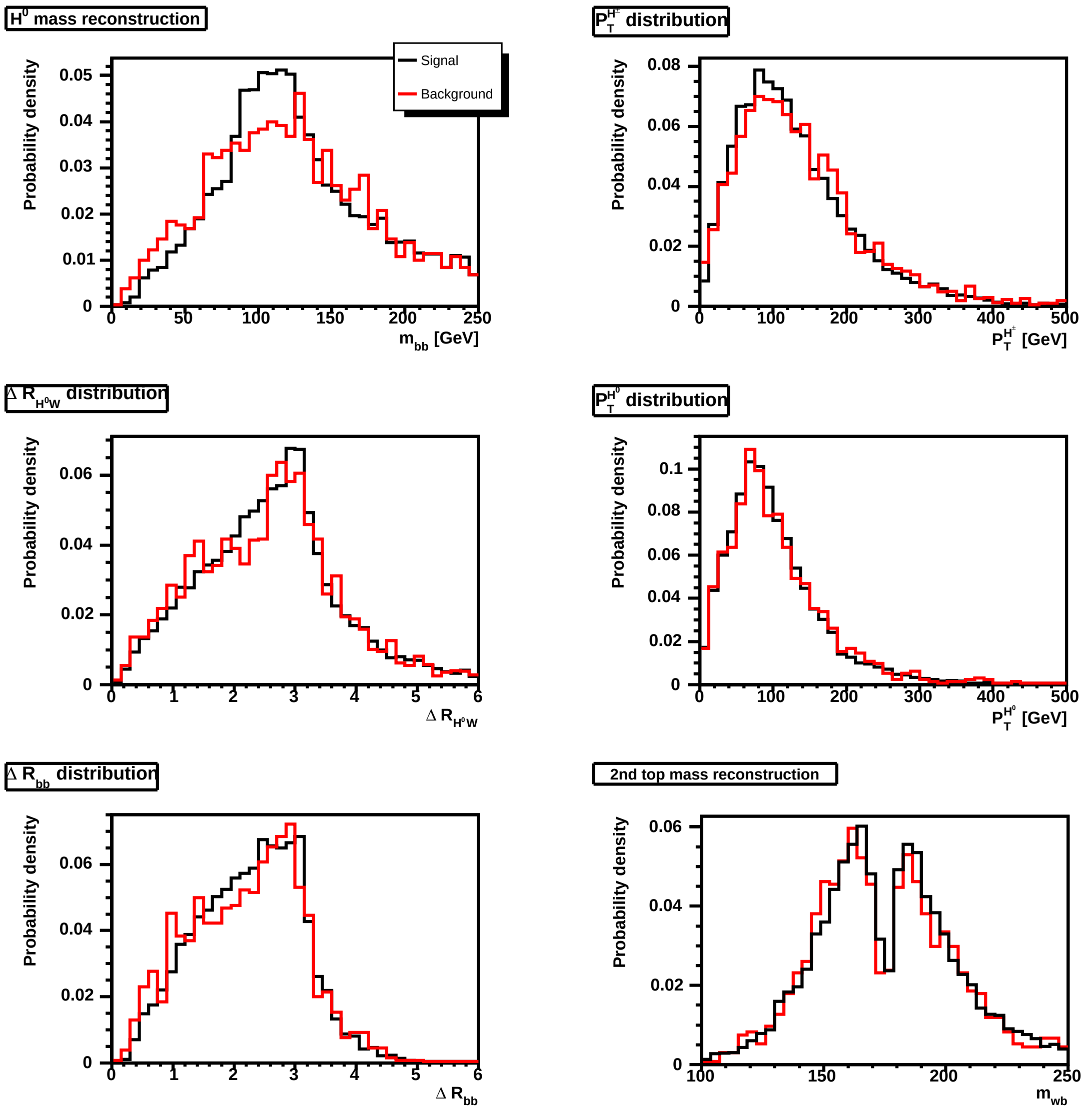

FIG. 5: Probability density functions for suggested cut variables.

TABLE III: Point A signal and background reconstruction efficiencies.

Step/Cut	Signal [%]	Background [%]
1 lepton ($p_T > 25(20)$ GeV, $\eta < 2.5$)	58.9	59.1
3 b–jets ($p_T > 30$ GeV, $\eta < 2.5$)	4.5	0.42
≥ 2 light jets ($p_T > 30$ GeV, $\eta < 5$)	4.1	0.31
W_{had} ($\lvert m_{W_{had}} - m_{\mathrm{W}^{\pm}} \rvert < 25\,\mathrm{GeV}$)	3.0	0.20
W_{lep} (Cut, unphysical solution)	2.0	0.13
Top–quark $\lvert m_{t_{rec}} - m_{\mathrm{t}} \rvert < 25\,\mathrm{GeV}$	1.9	0.13
Reconstructed events ($300\,\mathrm{fb}^{-1}$)	186.0	68177.8

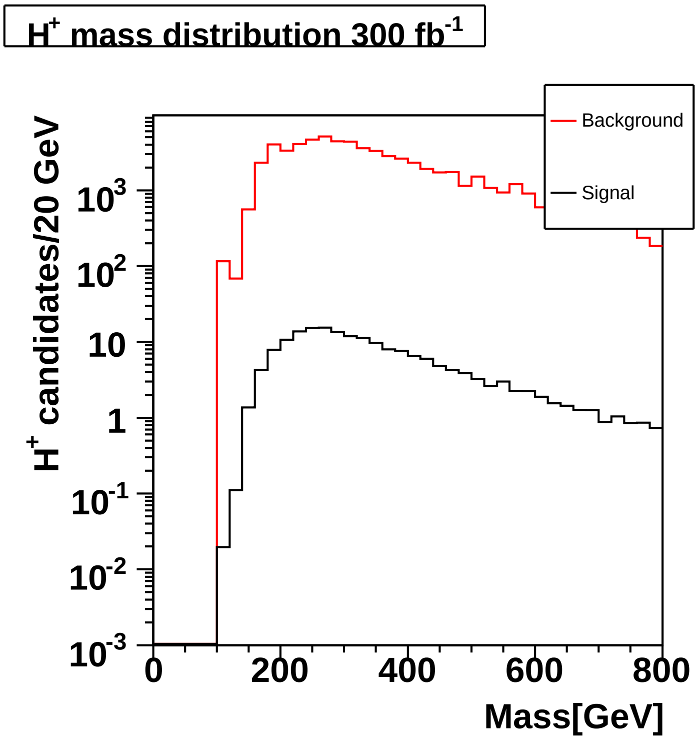

FIG. 6: The reconstructed $m_{\mathrm{H}^{\pm}}$ distributions for both signal and background. The histograms are normalised to the rate after dividing each entry by the number of charged Higgs candidates in the event.

VI. CONCLUSIONS

In this analysis we have investigated the possibility of detecting a heavy charged Higgs boson through the decay $H^{\pm} \rightarrow W^{\pm}H^0$ in a large mass splitting MSSM scenario at the LHC. Large mass splittings ($m_{H^{\pm}} > m_{H^0}$) occur in the region of the MSSM parameter space(μ, $A_t > 4M_{SUSY}$), where the quartic couplings no longer are suppressed by small coefficients. Once the splitting is larger than the W mass the decay of the charged Higgs to $W^{\pm}H^0$ is open and can receive a sizable branching ratio. In particular large branching ratios are possible in the intermediate $tan\beta$ region where no other channel gives any discovery potential for charged Higgs masses larger than m_{t}.

Above the top-quark mass the main contribution to the charged Higgs production cross-section is the $gb \rightarrow tH^+$ process. As for the subsequent decays we have used $H^0 \rightarrow b\bar{b}$, $t \rightarrow Wb$ and $W \rightarrow qq(l\nu)$, leading to a final state with 2 light jets, 3 b-jets, 1 lepton and a neutrino. The main background contribution is $t\bar{t}$ production with one extra jet mistagged as a b–jet.

The detector response was simulated with ATLFAST in the ATHENA framework, and presented here is a reconstruction technique which closely follows the one outlined in [7]. All results are normalised to an integrated luminosity of $300\,\text{fb}^{-1}$, and after reconstruction the background is found to be three orders of magnitude larger than the signal. This is related to the small production cross–section and that no good discriminating variable between signal and background could be found. Hence one will have to look for other decay channels to cover the intermediate $tan\beta$ region for a heavy charged Higgs Boson.

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