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Heavy Charged MSSM Higgs Bosons in the $H^{\pm} \to tb$ Decay in CMS

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Abstract

In this study the prospects are presented to discover a heavy charged MSSM Higgs boson with the CMS experiment at the LHC, in the $gb \to tH^{\pm} \to ttb$ channel, tagging three b–quarks. This analysis includes the correct signal cross section values, a dedicated simulation of the large $t\bar{t}+\mathrm{jets}$ background, a study of trigger acceptances, advanced reconstruction results, and influence on the visibility due to systematic uncertainties on the background cross section. The discovery reach is investigated, and it is concluded that no visibility is left in the MSSM parameter space for this channel.

1 The LHC and the CMS Experiment

The new accelerator currently under construction at CERN, the LHC (Large Hadron Collider), will collide protons onto protons every $25\,\mathrm{ns}$, at a center of mass energy of $14\,\mathrm{TeV}$. During the first three years it will operate at a 'low' luminosity of $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The Compact Muon Solenoid (CMS) detector, shown in Fig. 1, will be one of the four experiments at the LHC. It's main purpose is the search for the Higgs boson and supersymmetric particles. For this, a compact design was chosen, with a strong magnetic field of $4\,\mathrm{T}$.

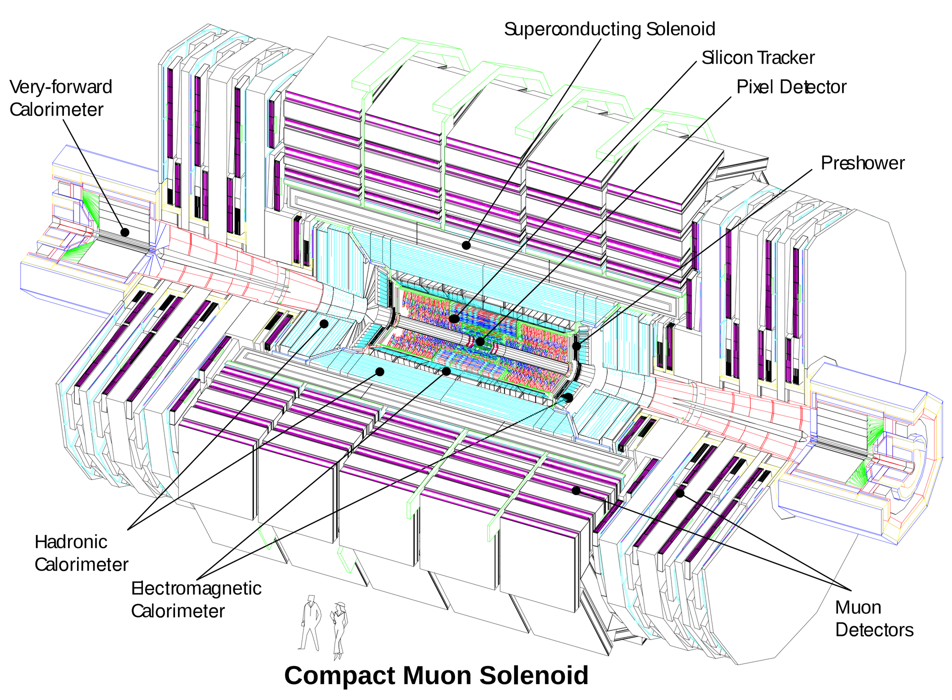

Fig. 1: The CMS detector.

2 The Charged Higgs Boson

The Minimal Supersymmetric Standard Model (MSSM) contains five Higgs bosons, two of which are the charged scalars $H^{\pm}$. The production of the charged Higgs boson is considered in the dominant inclusive channel $pp \to tH^{\pm}X$. The cross section for this process at large $m_H^{\pm}$ should be evaluated at leading order in the channel $gb \to tH^{\pm}$. In Fig. 2 the time evolution is shown of the PYTHIA cross section value of $gb \to tH^{\pm}$.

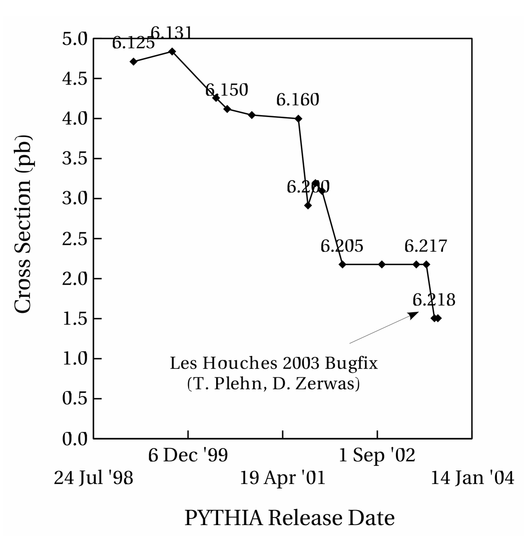

Fig. 2: Evolution through time of the PYTHIA cross section for $gb \to tH^{\pm}$. The PYTHIA version is shown in the labels on the curve. ($m_A = 300\,\mathrm{GeV}/c^2$, $\tan\beta = 50$)

The production cross section and decay modes of $H^{\pm}$ can be described in the MSSM by two parameters at tree level: the ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta = v_2/v_1$, and the mass of the pseudoscalar Higgs $m_A^2 = m_{H^{\pm}}^2 - m_{W^{\pm}}^2$. Its dependency on $\tan\beta$ and $m_{H^{\pm}}$ is shown in Figs. 3 and 4.

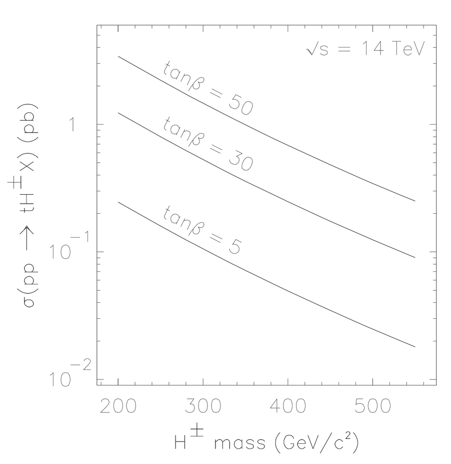

Fig. 3: $pp \to tH^{\pm}X$ cross section dependence on $m_{H^{\pm}}$.

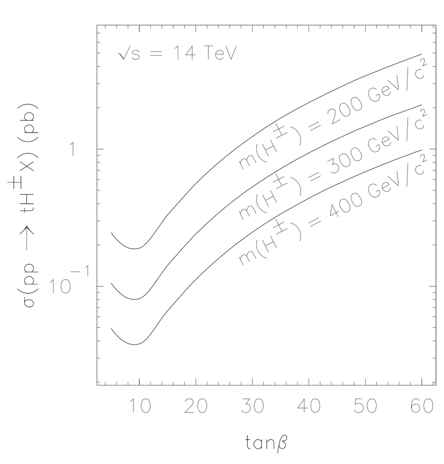

Fig. 4: $pp \to tH^{\pm}X$ cross section dependence on $\tan\beta$.

The branching fractions for the charged Higgs depend mainly on its mass. For masses above $m_t + m_b$, the channel $H^{\pm} \to tb$ dominates (Fig. 5). In the main production channel $gb \to tH^{\pm}$, it will result in complex final states, the most interesting being the semileptonic one (Fig. 6), because the Higgs boson mass can still be reconstructed, while an isolated lepton is present to trigger on.

3 Signal and Background Simulation

The signal was generated with PYTHIA, scaling to the correct cross section values, and forcing the $H^{\pm} \to tb$ decay. Six samples were generated for m_A ranging from $250\,\mathrm{GeV}$ to $500\,\mathrm{GeV}$.

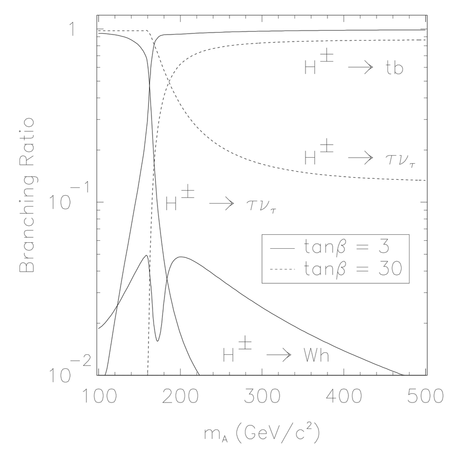

Fig. 5: $H^{\pm}$ branching fractions in function of m_A.

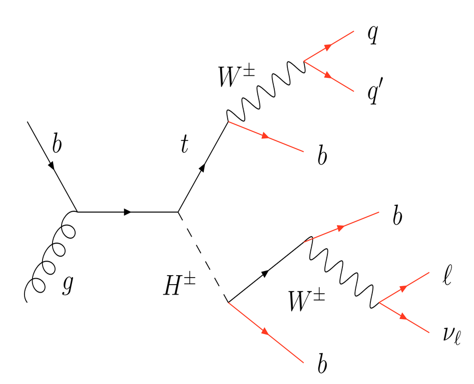

Fig. 6: Semileptonic $H^{\pm} \to tb$ decay in the $gb \to tH^{\pm}$ production channel.

At leading order, the dominant background comes from Standard Model $gb \to t\bar{t}b$ and $t\bar{t}+\mathrm{jet}$ production, where in the latter case a light quark or gluon jet is misidentified as being a b–jet. These processes cannot be generated with PYTHIA. Therefore the simulation of the background has been done with:

- $t\bar{t}$ events from PYTHIA, with extra jets from the parton shower ($560\,\mathrm{pb}$).
- by exact matrix element calculation with MadGraph/MadEvent of $pp \to t\bar{t}b$ and $pp \to t\bar{t}j$ ($678\,\mathrm{pb}$).

The total number of signal and background events before selection is shown in the second column of Table 1.

4 Event Selection and Triggering

The CMS detector performance was simulated with a fast detector response parametrization. Only events were accepted with at least

- 1 isolated lepton ($e^{\pm}$ or $\mu^{\pm}$) with $|\eta| < 2.4$, and $p_T > 19\,\mathrm{GeV}$ for muons and $p_T > 29\,\mathrm{GeV}$ for electrons.
- 5 jets (b or non b) with $p_T > 20$ GeV and $|\eta| < 2.4$. Jets are reconstructed using a cone algorithm with $\Delta R = 0.5$.
- 3 b–tagged jets. b–tagging is performed using the signed impact parameter significance of tracks.

The number of events after applying these cuts, is shown in the third column of Table 1.

Only the inclusive electron and muon triggers are considered. The low luminosity High Level Trigger (HLT) cuts are taken at $29\,\mathrm{GeV}$ for single electrons and $19\,\mathrm{GeV}$ for single muons, correcting for differences with full detector simulation studies. For background and signal, about 86% of the previously selected events pass these HLT cuts.

5 Solution Finding

To reconstruct the Higgs boson mass, all combinations of jets are made, satisfying $|m_{qq'} - m_{W^{\pm}}| < 30\,\mathrm{GeV}$, $|m_{qq'b} - m_t| < 50\,\mathrm{GeV}$ and $|m_{\ell\nu b} - m_t| < 50\,\mathrm{GeV}$. The z–component of the missing energy is fixed by the $W^{\pm}$ mass constraint. An additional cut $p_T(b_{H^{\pm}}) > 50\,\mathrm{GeV}$ on the fifth jet is imposed. If no solution is found, the event is discarded. The final number of events, passing all cuts and having at least one solution, is shown in the last column of Table 1.

$\tan\beta = 50,\, 30\,\mathrm{fb}^{-1}$	# events before cuts	# events after minimal selection criteria	# events after HLT and with ≥ 1 solution
$t\bar{t}$ background	16 800 000	15 736 (0.09%)	4 932 (31%)
$t\bar{t}b/t\bar{t}j$ background	20 340 000	23 593 (0.12%)	7 872 (33%)
$tH^{\pm}$ ($m_A = 250\,\mathrm{GeV}$)	54 644	769 (1.41%)	314 (41%)
$tH^{\pm}$ ($m_A = 300\,\mathrm{GeV}$)	36 681	659 (1.80%)	235 (36%)
$tH^{\pm}$ ($m_A = 350\,\mathrm{GeV}$)	23 988	492 (2.05%)	173 (35%)
$tH^{\pm}$ ($m_A = 400\,\mathrm{GeV}$)	16 176	381 (2.36%)	116 (30%)
$tH^{\pm}$ ($m_A = 450\,\mathrm{GeV}$)	10 888	270 (2.48%)	86 (32%)
$tH^{\pm}$ ($m_A = 500\,\mathrm{GeV}$)	7 472	198 (2.65%)	72 (36%)

Table 1: Selection and solution finding efficiencies.

For a given event, the best solution is chosen as the one maximizing the likelihood function

$$\mathcal{L} = \exp\left[-\frac{1}{2}\left(\frac{m_{qq'} - m^*_{qq'}}{\sigma^*_{m_{qq'}}}\right)^2 - \frac{1}{2}\left(\frac{m_{qq'b} - m^*_{qq'b}}{\sigma^*_{m_{qq'b}}}\right)^2 - \frac{1}{2}\left(\frac{m_{\ell\nu b} - m^*_{\ell\nu b}}{\sigma^*_{m_{\ell\nu b}}}\right)^2\right].$$

The values of the masses m^* and widths σ^*_m are obtained from those events where the jets and lepton are matched to the particles at generator level they come from.

6 Results

Each top quark candidate is combined with a remaining b–tagged jet, giving rise to two valid charged Higgs candidates. The distribution of their reconstructed Higgs boson masses is shown in Fig. 7, for the signal, the $t\bar{t}$ background, and the sum of both, for $m_A = 300\,\mathrm{GeV}$ and $\tan\beta = 50$.

Defining the statistical significance as $\sigma = S/\sqrt{B}$, with S and B the number of signal and background events respectively, discovery contours have been constructed in the MSSM parameter space for $\sigma = 5$. In Fig. 8 the comparison is shown of these contours for the PYTHIA $t\bar{t}$ background, and the MadGraph/MadEvent $t\bar{t}b/t\bar{t}j$ background.

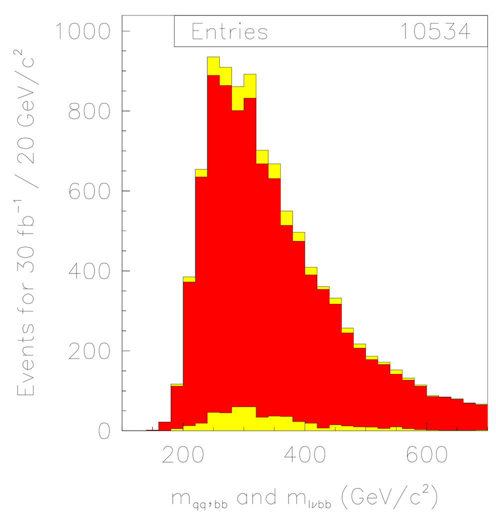

Fig. 7: $H^{\pm}$ mass distribution for the signal, the background and the sum of both. ($m_A = 300\,\mathrm{GeV}$, $\tan\beta = 50$, $30\,\mathrm{fb}^{-1}$)

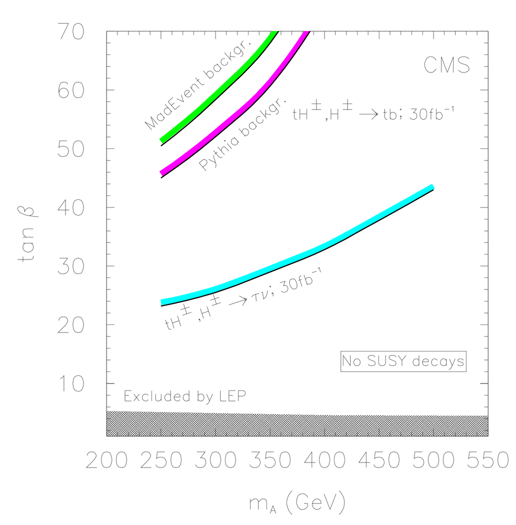

Fig. 8: Discovery contours with $30\,\mathrm{fb}^{-1}$, for the backgrounds $t\bar{t}$ from PYTHIA and $t\bar{t}b/t\bar{t}j$ from MadGraph/MadEvent.

7 Systematical Uncertainties

Previously, only statistical uncertainties were considered. Taking, however, a systematical uncertainty of ϵB background events after full analysis, the significance for S signal events now becomes $\sigma = S/\sqrt{B + \epsilon^2 B^2}$. In Fig. 9 the discovery contours are plotted, when supposing perfect knowledge of the $t\bar{t}$ cross section ($\epsilon = 0$), a 1% ($\epsilon = 0.01$) and a 3% uncertainty ($\epsilon = 0.03$).

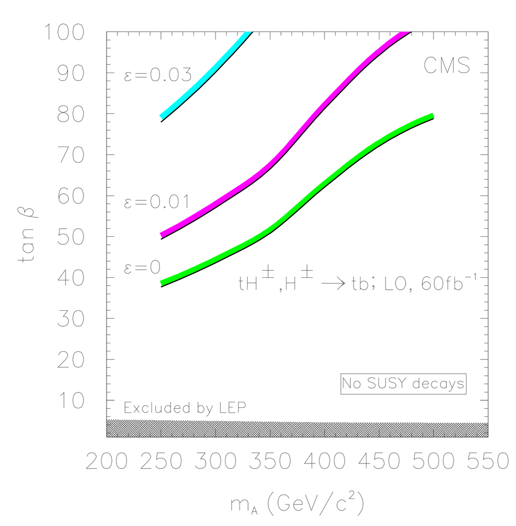

Fig. 9: Influence of systematical uncertainties ϵ (0%, 1% and 3%) on the $t\bar{t}$ background, for $60\,\mathrm{fb}^{-1}$.

In the references a detailed estimation of the expected systematical uncertainty is performed. At least 10% uncertainty is to be expected, leaving no visibility in the MSSM for this channel.

8 Fully Hadronic Channel

The fully hadronic $tH^{\pm} \to ttb$ channel, where both $W^{\pm}$'s decay hadronically, suffers from the absence of a lepton to trigger on. The HLT jet triggers alone already reduce the signal to 1 to 7% for $250\,\mathrm{GeV} < m_A < 500\,\mathrm{GeV}$. Without a dedicated HLT trigger, no hope is left for this channel.

9 Conclusion

The prospects were presented to discover in CMS at low luminosity, a heavy charged MSSM Higgs boson in the $H^{\pm} \to tb$ decay channel, asking for three b–tagged jets. Due to the effects of systematical uncertainties, one has to conclude that no visibility for this channel is left in the MSSM parameter space at low luminosity.

References

[1] S. Lowette and J. Heyninck, *Heavy Charged MSSM Higgs Bosons in the $H^{\pm} \to tb$ Decay in CMS*, CMS AN 2003/012 (Submitted as CMS NOTE), 2004, and references therein.

[2] S. Lowette, P. Vanlaer and J. Heyninck, *Heavy Charged MSSM Higgs Bosons in the $H^{\pm} \to tb$ Decay in CMS*, in *The Higgs working group: Summary report 2003*, hep-ph/0406152.