FERMILAB-CONF-07-520-E

arXiv:0710.0853v1 [hep-ex] 3 Oct 2007

# Search for supersymmetric charged Higgs bosons at the TeVatron.

Gérald Grenier[1 ab]

Institut de Physique Nucléaire de Lyon, CNRS/IN2P3, Université Lyon 1, Université de Lyon, F69622 Villeurbanne, France

**Abstract.** The data collected at the TeVatron RunIIa have been used to look for supersymmetric charged Higgs boson and Left-Right suspersymmetric doubly charged Higgs boson. No signal of such bosons has been found and this note reports on the current analyses and their observed excluded domains in models parameter space.

**PACS.** 14.80.Cp Non-standard-model Higgs bosons – 13.85.Rm Limits on production of particles

## 1 Introduction

The analyses reported in this note cover searches for charged and doubly charged Higgs bosons. The charged Higgs boson is a needed element of the Higgs sector of any supersymmetric model[1]. The doubly charged Higgs is here looked for in the context of Left-Right supersymmetric theories[2]. The data samples used for the analyses have been collected by either the DØ and CDF detectors during the RunIIa of the TeVatron which collides proton and antiproton with a center-of-mass energy of 1.96 TeV. Depending on the analysis, the integrated luminosity used ranges from 192 $pb^{-1}$ to 1.1 $fb^{-1}$. The acceptances in pseudo-rapidity for both the CDF and DØ detectors are shown in table 1. Those pseudo-rapidities are implicitely used in all the analyses described in this note.

## 2 MSSM charged Higgs

The Minimal Supersymmetric Standard Model[1] requires a Higgs mechanism with two Higgs doublet leading to the existence of a charged Higgs boson. At the TeVatron, the direct production of $p\bar{p} \to H^+H^-$ has a cross-section too low to provide sensitivity for the discovery of charged Higgs bosons [3]. Therefore, The charged Higgs is looked for in the decay of the top quark. Throughout this section, the signal searched for is
$p\bar{p} \to t\bar{t} + X$ with one top decaying into $H^+b$ and the other into $bl\nu$ where $l$ is either an electron or a muon.

[a] *Email:grenier@ipnl.in2p3.fr*
[b] on behalf of CDF and DØ collaborations

**Table 1.** Pseudo-rapidity acceptances for various reconstructed objects for the DØ and CDF detectors.

| | CDF | DØ |
|---|---|---|
| electron | $\|\eta\| < 2.0$ | $\|\eta\| < 3.0$ |
| muon | $\|\eta\| < 1.5$ | $\|\eta\| < 2.0$ |
| muon trigger | $\|\eta\| < 1.0$ | $\|\eta\| < 2.0$ |
| precision tracking | $\|\eta\| < 2.0$ | $\|\eta\| < 3.0$ |
| jets | $\|\eta\| < 3.6$ | $\|\eta\| < 4.2$ |

### 2.1 lepton+tau searches

The CDF collaboration reports a search for the signal of Sect. 2 in the case where the charged Higgs decays exclusively into a tau and a neutrino[4]. In this analysis, the tau is reconstructed only through its hadronic decays. The CDF tau identification uses a likelihood based on variables characterizing a tau [4]. Examples of such variables are isolation criteria in the tracking and the calorimeter or ratios of the transverse momentum of the tracks composing the reconstructed tau candidates. Four different likelihoods are used depending on the hadronic decay of the tau. The four likelihoods cover the following four kinds of tau decay topology : (1) one track and no $\pi^0$, (2) one track and one or more $\pi^0$, (3) three tracks with or without $\pi^0$ and (4) two tracks with or without $\pi^0$. The likelihoods aim at separating hadronically decaying taus from jets. A tau candidate is identified as a hadronically decaying tau if the likelihood is above 0.65.

The analysis requires at least one electron or muon with a transverse momentum greater than 20 GeV/c, at least two jets with a transverse momentum greater than 25 GeV/c for the most energetic one and greater than 15 GeV/c for the second most energetic one. At least one jet should be identified as a b-jet using a b-jet identification algorithm based on displaced vertices. The missing transverse energy should be greater than 20 GeV. $H_T$, the scalar sum of the transverse energy of

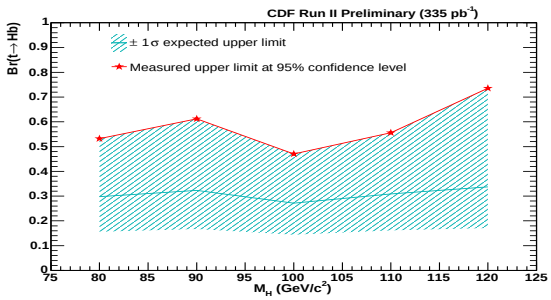


**Fig. 1.** 95 % confidence level upper limit on the branching fraction of $t \to bH^+$ as a function of the charged Higgs mass.

all calorimeter objects should be greater than 205 GeV and the event should contain exactly one recontructed tau lepton.

The observed numbers of events in a data sample of 335 pb$^{-1}$ are 4 for $1.90 \pm 0.26$ expected from the background in the electron+tau lepton channel and 2 for $1.97 \pm 0.27$ expected in the muon+tau lepton channel. Observed and expected numbers of events are in agreement. An upper limit on the branching fraction of $t \to bH^+$ ($Br(t \to bH^+)$) at the 95% confidence level is derived assuming a 100 % decay rate of $H^+ \to \bar{\tau}\nu$ and a Standard Model cross section of $p\bar{p} \to t\bar{t} + X$ of 7.0 pb. The limit is shown as a function of the charged Higgs mass on figure 1. The red (resp. blue) line is the limit obtained by (resp. without) taking into account the background estimation uncertainties.

### 2.2 Di-top analyses reinterpretation

If the decay $t \to H^+b$ is opened, then it will compete with the Standard Model decay $t \to W^+b$. $H^+$ and $W^+$ can decay into similar channel but with different branching ratios. The CDF collaboration reports a reuse of its previous analyses used in the measurement of the $t\bar{t}$ cross section to look for possible signs of decay of $H^+$ [5]. The reused analyses are :

- one muon or electron + one muon or electron, below referred to as the dilepton analysis [6].
- one muon or electron + jets with exactly one jet identified as a b-jet, below referred to as the lepton+ jets(1 tag) analysis [7].
- one muon or electron + jets with two or more jets identified as b-jets, below referred to as the lepton+ jets(2 tags) analysis [7].
- one muon or electron + one hadronically decaying tau, below referred to as the lepton+tau analysis [8].

The original analyses, done with a data sample corresponding to 192 pb$^{-1}$, are slightly modified to ensure that any selected event is selected exclusively by one of the four analyses. In the reinterpretation of the four analyses, the signal described at the beginning of section 2 is looked for assuming that the top quark decays only in $W^+b$ and $H^+b$ and that the $H^+$ can only decay

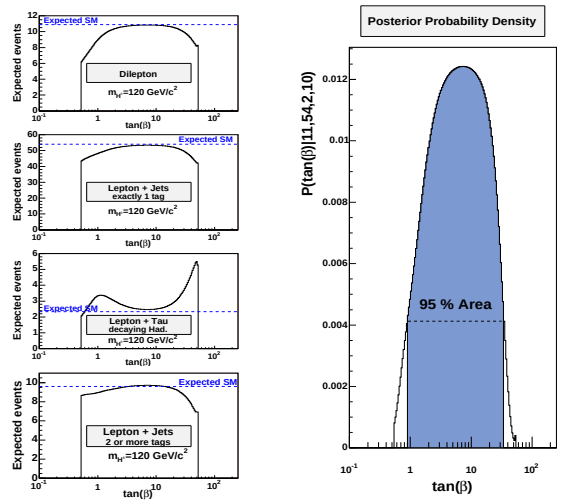


**Fig. 2.** Left: expected number of events to be seen by each of the four analyses for the Standard Model only and Standard Model+120 GeV/c$^2$ charged Higgs as a function of tan $\beta$. Right : posterior probability on tan $\beta$ (see text) assuming the number of observed events equals the Standard Model expectation shown on the left. The region outside the blue band would be excluded.

in the following four final states : $t^*\bar{b}$ , $c\bar{s}$ , $\bar{\tau}\nu_\tau$ , $W^+h^0$. Here the $h^0$ is reconstructed only through its decay in $b\bar{b}$. If the $H^+$ decays exclusively in $\bar{\tau}\nu_\tau$ then the lepton+tau analysis will have an excess of events with respect to the Standard Model expectations while the dilepton and lepton+jets analyses will have a deficit of event.

For the reinterpretation, one MSSM parameter is chosen, for example tan $\beta$. The number of events expected for each of the four analyses is computed for the Standard Model and for the Standard Model+MSSM as a function of the MSSM parameter. Such expectations are shown on the left of Figure 2 for a charged Higgs mass of 120 GeV/c$^2$ and a set of MSSM parameters described on figure 3. From these estimation, a likelihood based on Poisson probability to observe N events is derived for each analyses. The four likelihoods, the number of observed events and a prior probability on the MSSM parameter are combined to derived a posterior probability as a function of the MSSM parameter. This posterior probability is then used to exclude some values of the MSSM parameter as illustrated on the right side of figure 2 for tan $\beta$.

The observed and expected number of events are displayed in table 2. From there, excluded regions in the charged Higgs mass - tan $\beta$ plane are derived as shown on figure 3. On this figure, the red area is excluded by the present analysis, the dark line is the Standard Model expected excluded area with its one standard deviation shown as horizontal black lines. For high tan $\beta$, the charged Higgs decay mostly in $\bar{\tau}\nu_\tau$[5]. The same procedure using the parameter $Br(t \to H^+b)$ instead of tan $\beta$ leads to an upper limit on $Br(t \to H^+b)$ as a function of the charged Higgs mass shown on figure 4 which is comparable to the one shown on figure 1.

**Table 2.** Standard Model (SM) expected and observed number of events for the $t\bar{t}$ analyses. The $t\bar{t}$ cross section is assumed to be $6.7 \pm 0.9$ pb.

| analysis | SM non $t\bar{t}$ | $t\bar{t}$ | data |
|---|---|---|---|
| dilepton | $2.7 \pm 0.7$ | $10.9 \pm 1.4$ | 13 |
| lepton+jets(1 tag) | $21.8 \pm 3.0$ | $54.0 \pm 4.3$ | 49 |
| lepton+jets(2 tags) | $1.3 \pm 0.3$ | $10 \pm 1$ | 8 |
| lepton+tau | $1.3 \pm 0.2$ | $2.3 \pm 0.3$ | 2 |

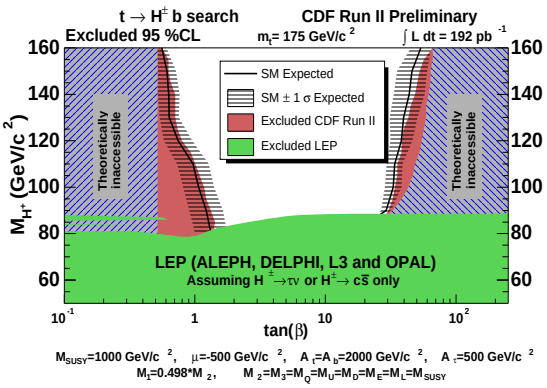


**Fig. 3.** Observed (red) and expected (black line) 95 % confidence level exclusion region in the charged Higgs mass-tan $\beta$ plane for MSSM parameters displayed on the figure.

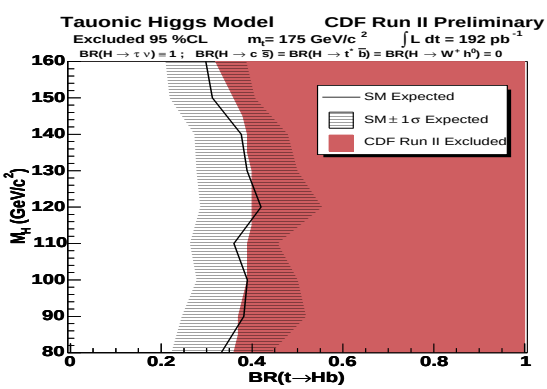


**Fig. 4.** 95 % confidence level excluded region in the charged Higgs mass - $\mathrm{Br}(t \to H^+ b)$ plane assuming $\mathrm{Br}(H^+ \to \bar{\tau}\nu_\tau) = 1$.

## 3 Doubly charged Higgs

The supersymmetric version of Left-Right symmetric models predicts the existence of two light doubly charged Higgs[2]. One, $H_L^{++}$, couples only to left-handed fermions and the other, $H_R^{++}$, only to right-handed fermions. At the TeVatron, the main production channel is the pair production of $H^{++}H^{--}$ through a $\gamma/Z^0$ s-channel exchange. The resulting cross section depends essentially on the $H^{++}$ mass and electroweak quantum numbers[9]. For all the results presented in this section, lower limits on the Higss mass are derived from upper limits on the $p\bar{p} \to H^{++}H^{--} + X$ cross section using the cross section computed in [9] as a function of the Higgs mass.

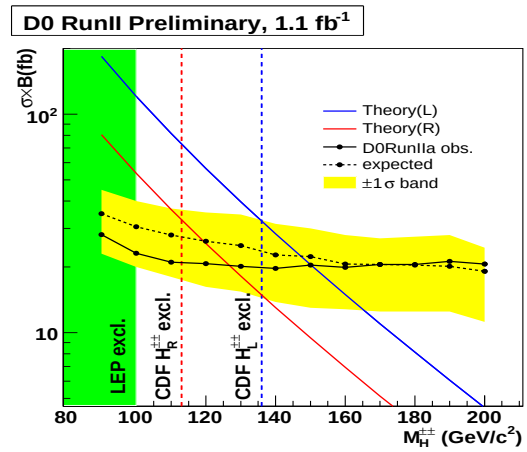


**Fig. 5.** Observed and expected 95 % confidence level upper limit on the cross section of the process $p\bar{p} \to H^{++}H^{--} + X$ as a function of the $H^{++}$ mass assuming a 100% decay rate for $H^{++} \to \mu^+\mu^+$.

### 3.1 $H^{++} \to \mu^+\mu^+$

#### 3.1.1 DØ analysis

The DØ collaboration reports a search for the process $p\bar{p} \to H^{++}H^{--} + X \to \mu^+\mu^+\mu^-\mu^- + X$ using a data sample of 1.1 $\mathrm{fb}^{-1}$ [10]. The analysis requests the events to be selected by a di-muon trigger. Each muon used in the event should be isolated in the tracker and in the calorimeter and have a transverse momentum of at least 15 GeV/c. Muon pairs compatible with being due to the passage of a cosmic muon are rejected. The events should contain at least one pair of like sign muons having a difference in azimuth less than 2.5 radians and an invariant mass greater than 30 $\mathrm{GeV/c^2}$. The event should contain at least three identified muons. The analysis leads to 3 events observed for an expected background of $3.1 \pm 0.5$. Assuming a 100% branching ratio of doubly charged Higgs into a muon pair, a 95% confidence level upper limit on the $p\bar{p} \to H^{++}H^{--} + X$ cross section is derived as shown on figure 5. This translates into lower mass limits of 126.5 $\mathrm{GeV/c^2}$ for the $H_R^{++}$ and 150 $\mathrm{GeV/c^2}$ for the $H_L^{++}$.

#### 3.1.2 CDF analysis

The CDF collaboration reports a similar analysis as the one described in section 3.1.1 but for a data sample of 242 $\mathrm{pb}^{-1}$[11]. In this analysis, events are selected if they fire a single muon trigger. The event should contain a pair of like sign isolated muons with an invariant mass greater than 80 $\mathrm{GeV/c^2}$. Pairs compatible with being due to a cosmic muon are rejected. In total, this analysis selects no event for an expectation of $0.8 \pm 0.5$. Assuming a 100% decay rate for $H^{++} \to \mu^+\mu^+$, 95% confidence level lower limits on mass are derived. Those limits, shown on figure 5 are 113 $\mathrm{GeV/c^2}$ for the $H_R^{++}$ and 136 $\mathrm{GeV/c^2}$ for the $H_L^{++}$.

### 3.2 other $H^{++}$ decays

Other decays looked for cover $H^{++} \to e^+e^+$, $H^{++} \to e^+\mu^+$, $H^{++} \to e^+\tau^+$ and $H^{++} \to \mu^+\tau^+$.

The like sign dielectron signal is searched for in 235 $pb^{-1}$ of CDF data where events are selected if they fire a di-electromagnetic trigger and if they contain a pair of like sign isolated electron with a tranverse momentum above 30 GeV/c. The invariant mass of the di-electron pair should be greater than 100 GeV/$c^2$. No event is found for an expectation of $1.1 \pm 0.4$ [11]. Corresponding lower mass limits for the doubly charged Higgs are displayed in table 3.

The like sign electron-muon signal is looked for in 240 $pb^{-1}$ of CDF data where events are selected if they fire a single electromagnetic trigger and contain a like sign pair made of an isolated electron and an isolated muon. The invariant mass of the pair should be greater than 80 GeV/$c^2$. No event is found for an expectation of $0.4 \pm 0.2$ [11]. Corresponding lower mass limits for the doubly charged Higgs are displayed in table 3.

Like sign electron+tau lepton and muon+tau lepton is searched for in the CDF data. For the electron+tau lepton (resp. muon+tau lepton) analysis, it is required to have one isolated electron (resp. muon) with a transverse momentum above 20 GeV/c, a hadronic decaying tau lepton or an electron with a transverse momentum above 15 GeV/c and a hadronic decaying tau lepton or an electron (resp. or an electron or a muon) with a transverse momentum above 10 GeV/c. The data samples are then divided according to the presence or absence of a fourth isolated high transverse momentum lepton. Extra selections based on di-lepton masses, missing transverse energy, the scalar sum of missing transverse momentum and transverse momenta of all leptons are performed as described in [12]. No event is observed in data for an expectation of $0.24 \pm 0.27$ (resp. $0.04 \pm 0.05$) for the three (resp. four) leptons eletron+tau lepton sample and of $0.27 \pm 0.125$ (resp. $0.14 \pm 0.05$) for the three (resp. four) leptons muon+tau lepton sample. Data sample luminosity and observed lower mass limits are shown in table 3.

Table 3 summarizes all the current TeVatron lower mass limits for the doubly charged Higgs boson for various decays and also for a search for Higgs as heavy charged particle decaying after the tracker[13].

**Table 3.** 95% confidence level lower mass limits on the doubly charged Higgs.

| hypothesis | exp | luminosity | mass limit (GeV/$c^2$) $H_L^{++}$ | $H_R^{++}$ |
|---|---|---|---|---|
| $Br(H^{++} \to e^+e^+) = 1$ [11] | CDF | 235 $pb^{-1}$ | 133 | |
| $Br(H^{++} \to \mu^+\mu^+) = 1$ [11] | CDF | 242 $pb^{-1}$ | 136 | 113 |
| $Br(H^{++} \to \mu^+\mu^+) = 1$ [10] | DØ | 1.1 $fb^{-1}$ | 150 | 126.5 |
| $Br(H^{++} \to e^+\mu^+) = 1$ [11] | CDF | 240 $pb^{-1}$ | 115 | |
| $Br(H^{++} \to e^+\tau^+) = 1$ [12] | CDF | 350 $pb^{-1}$ | 113.6 | |
| $Br(H^{++} \to \mu^+\tau^+) = 1$ [12] | CDF | 322 $pb^{-1}$ | 112.1 | |
| Long lived[13] | CDF | 292 $pb^{-1}$ | 133 | 109 |

### Acknowledgments

The CDF and DØ collaborations wish to thank the staffs at Fermilab and at their collaborating institutions.

## References

1. Hans Peter Nilles. Supersymmetry, supergravity and particle physics. *Phys. Rept.*, 110:1, 1984.
2. J. F. Gunion, J. Grifols, A. Mendez, B. Kayser, and Fredrick I. Olness. Higgs bosons in left-right symmetric models. *Phys. Rev.*, D40:1546, 1989.
3. Marcela S. Carena and Howard E. Haber. Higgs boson theory and phenomenology. ((v)). *Prog. Part. Nucl. Phys.*, 50:63–152, 2003.
4. The CdF Collaboration. Search for anomalous tau production in b-tagged top quark events. CdF preliminary results, CDF/ANA/EXOTIC/PUBLIC/8353, June 2006.
5. The CdF Collaboration. A search of charged higgs in the decay products of pair-produced top quarks. CdF preliminary results, http://www-cdf.fnal.gov/physics/new/top/2005/ljets/charged_higgs/higgs/V2/HiggsAnalysis_publicV2.html, 2005.
6. D. Acosta et al. Measurement of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ tev using dilepton events. *Phys. Rev. Lett.*, 93:142001, 2004.
7. D. Acosta et al. Measurement of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ tev using lepton + jets events with secondary vertex $b-$tagging. *Phys. Rev.*, D71:052003, 2005.
8. A. Abulencia et al. A search for $t \to \tau\nu q$ in $t\bar{t}$ production. *Phys. Lett.*, B639:172, 2006.
9. Margarete Muhlleitner and Michael Spira. A note on doubly-charged higgs pair production at hadron colliders. *Phys. Rev.*, D68:117701, 2003.
10. The DØ Collaboration. Search for pair production of doubly-charged higgs bosons in the $h^{++}h^{--} \to 4\mu$ final state at DØ. DØ preliminary results, conference note, DØ Note 5458-CONF, August 2007.
11. D. Acosta et al. Search for doubly-charged higgs bosons decaying to dileptons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ tev. *Phys. Rev. Lett.*, 93:221802, 2004.
12. The CdF Collaboration. Search for doubly charged higgs in lepton flavor violating decays involving taus. CdF preliminary results, http://www-cdf.fnal.gov/physics/exotic/r2a/20060406.HPlusPlus/, April 2006.
13. D. Acosta et al. Search for long-lived doubly-charged higgs bosons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ tev. *Phys. Rev. Lett.*, 95:071801, 2005.