Limits on t -Quark Decay into Charged Higgs from a Direct Search at the CERN $p\bar{p}$ Collider

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Abstract

A search for t-quark decay into charged Higgs, $t \rightarrow H^+ b$, with the charged Higgs decaying via the $H^+ \rightarrow \tau^+ \nu_\tau$ mode, has been done in proton-antiproton collisions at $\sqrt{s} = 0.63 \text{ TeV}$ with the UA1 experiment. No evidence for this decay has been observed. Mass limits at 95 % and 90% CL for the t-quark and the charged Higgs are presented. The results have also been interpreted in terms of the $\tan \beta$ parameter of a two-doublet Higgs sector.

1 Introduction

All searches for the t-quark performed so far at $p\bar{p}$ colliders [1, 2, 3] lead to the conclusion that, within the context of the Minimal Standard Model, the t-quark must be very heavy: a new bound on the t-quark mass has recently been reported by the CDF experiment [4], which has excluded $m_t < 89 \text{ GeV}/c^2$ at 95 % CL. A search for the t-quark was performed in the isolated $e(\mu)$ -plus-jets and dilepton channels and the t-quark mass limits were derived under the assumption of the Standard Model that the t-quark semileptonic branching ratio is 1/9 (for each lepton species).

It has been suggested [5] that the failure to observe the expected t-quark signature at $p\bar{p}$ colliders might be attributed to an alternative mechanism in which standard semileptonic decay modes are suppressed by competition with additional non-standard decays. Such a mechanism can occur in two-doublet Higgs models which imply the existence of charged Higgs bosons [6] (for a general review see also [7] and references therein). If the mass of the charged Higgs $m_{H^\pm}$ does not exceed the mass difference $m_t - m_b$, the on-shell $t \rightarrow H^+ b$ decay mode would compete with the standard $t \rightarrow W^+ b$ mode and would be totally dominant if the on-shell W decay of the t-quark were kinematically excluded, *i.e.* if m_t were smaller than M_W : in the latter scenario, since the dominant H^+ decays are expected to be $H^+ \rightarrow \tau^+ \nu_\tau$ and $H^+ \rightarrow c\bar{s}$, the $t \rightarrow e(\mu)\nu_{e(\mu)}b$ mode would be completely suppressed and t-quark mass limits derived at hadron colliders under the assumption of 1/9 semileptonic branching ratio would no longer be valid.

The t-quark production, via the strong process $p\bar{p} \rightarrow t\bar{t}X$ and the electroweak process $p\bar{p} \rightarrow WX \rightarrow t\bar{b}X$, should not be affected by the charged Higgs. At the CERN $p\bar{p}$ collider, with $\sqrt{s} = 630 \text{ GeV}$, the electroweak production is dominant for $40 \lesssim m_t \lesssim 75 \text{ GeV}/c^2$. For an integrated luminosity of 5 pb^{-1} about 100 events would be produced assuming a t-quark of $80 \text{ GeV}/c^2$: the sensitivity to the t-quark with 4.7 pb^{-1} of data collected with single muon and dimuon triggers by the UA1 experiment during the CERN Collider runs in 1988-89 is therefore limited to the mass region $m_t < M_W$, where the on-shell $t \rightarrow H^+ b$ decay would have a branching ratio $\simeq 100 \%$.

The signature for this non-standard decay of the t-quark depends upon the H^+ decays. The branching ratios of the dominant H^+ decays, $H^+ \rightarrow \tau^+ \nu_\tau$ and $H^+ \rightarrow c\bar{s}$, are determined by the parameter $\tan \beta \equiv v_2/v_1$, where v_1 and v_2 are the vacuum expectation values of the doublets giving masses to charge 2/3 and $-1/3$ quarks, respectively. For $\tan \beta \simeq 1$ the

¹ Hereafter, whenever a particle or physical state with non-zero charge is mentioned, the charged conjugate is also assumed to have the same physical characteristics.

$H^+ \rightarrow \tau^+ \nu_\tau$ branching ratio is $\simeq 30\%$ while for $\tan \beta \gtrsim 3$ this branching ratio gets its maximum value of $\gtrsim 95\%$ ².

The mass m_{H^+} and $\tan \beta$ are *a priori* unknown in a general two-doublet model. In minimal supersymmetry (SUSY) models, m_{H^+} is constrained to be greater than M_W [9], thus not accessible to investigation with our present data sample. In the following we will assume the most general two-doublet Higgs model.

A possibility of detecting $t \rightarrow H^+ b$ decay at hadron colliders is offered by a large $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau)$: the signature of $t \rightarrow H^+ b$ decay, with $H^+ \rightarrow \tau^+ \nu_\tau$, would be an isolated ‘ τ -jet’ or lepton (μ or e from τ leptonic decay), accompanied by jets and missing energy. This signature is similar to that from the standard semileptonic decay of the t -quark; however the spectrum of the isolated lepton is generally softer.

We have searched for t -quark decay into charged Higgs in single muon-plus-jets events and dimuon events.

2 Search for t -Quark Decay into Charged Higgs

The UA1 experiment has recorded 4.7 pb^{-1} of data during the CERN $p\bar{p}$ Collider runs in 1988 and 1989, at $\sqrt{s} = 0.63 \text{ TeV}$, with single muon and dimuon triggers. These data have been analyzed to search for the standard semileptonic t -quark decay in the single muon and dimuon channels, resulting in a lower limit for the t -quark mass of $60 \text{ GeV}/c^2$ ($63 \text{ GeV}/c^2$) at 95 % CL (90 % CL) [3].

The first step in our search for the decay of the t -quark into a charged Higgs was to understand the signature of this process in our detector. We generated $t\bar{b}$ and $t\bar{t}$ events using the ISAJET Monte Carlo program [10], modified to impose 100% branching ratios for the t -quark decay to a charged Higgs plus a b -quark and for the Higgs decay to a tau plus a neutrino. These events were then passed through a Monte Carlo program involving a full simulation of the UA1 detector response, acceptance and trigger efficiency. We found that the UA1 standard t -quark analysis, applied to the $t \rightarrow H^+ b$ simulated events, would yield a t -quark mass lower limit of $48 \text{ GeV}/c^2$, for $m_{H^+} \leq 39 \text{ GeV}/c^2$ and 95 % branching ratio of the $H^+ \rightarrow \tau^+ \nu_\tau$ mode. The loss of sensitivity of the UA1 standard t -quark analysis (hereafter referred to as “standard analysis”; see ref.[3] for details) is mainly due to the hard cuts on the muon transverse momentum, *i.e.* $p_\mu^T > 12 \text{ GeV}/c$, in the single muon channel, and $p_{\mu_1}^T > 8 \text{ GeV}/c$, for the leading muon, in the dimuon channel. These cuts are suitable for standard

²The values of $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau)$ and $\text{BR}(H^+ \rightarrow c\bar{s})$ as function of $\tan \beta$, used in this paper, are calculated from the formulae given in ref.[8].

semileptonic t -quark decay, where the highest p^T muon comes directly from the t -quark, but inefficient in searching for $t \rightarrow H^+b$, where the highest p^T muon comes from the leptonic decay of the τ from the charged Higgs.

The signature of the $t \rightarrow H^+b$ decay in the single muon channel is an isolated muon accompanied by at least two hard hadronic jets, from the fragmentation of the two b -quarks in the event, and missing energy from the decay of the charged Higgs. A similar signature occurs in the dimuon channel, with one of the two jets replaced by a second, softer muon surrounded by hadronic fragments from the semileptonic decay of one of the two b -quarks. Due to the large masses of the t -quark and the charged Higgs, the decay products are generally well separated in direction and the muon and the neutrino are centrally produced. A difference in event topology between standard t -quark and $t \rightarrow H^+b$ decays is expected when the mass of the charged Higgs is close to the kinematic limit $m_{H^+} \lesssim m_t - m_b$: in this case the b -quark jet, from $t \rightarrow H^+b$ decay, is typically very soft and would not be reconstructed in the detector. The effect of this possibility will be evident in the results discussed in Section 3.

As in the standard t -quark search, the main background comes from heavy-flavour pair production, $p\bar{p} \rightarrow b\bar{b}(c\bar{c})X$, and from decay-in-flight of pions and kaons.

In this analysis we have modified the cuts used in the standard t -quark search in order to optimize sensitivity to $t \rightarrow H^+b$ decay [11].

2.1 Search in the single muon channel

The initial data sample was selected by requiring a single muon with $p_\mu^T > 8 \text{ GeV}/c$ and at least two jets with transverse energy $E_J^T > 7 \text{ GeV}/c$. In addition, the two highest E^T jets were required to be in a central pseudo-rapidity interval $|\eta_J| < 2$, with at least one of the two in $|\eta_J| < 1.5$, and well-separated from the muon, by a cut, $\Delta R_{\mu-J} > 1$, where $\Delta R_{\mu-J}$ is the distance in pseudorapidity-azimuthal angle space between the muon direction and the jet axis. This selection kept 1272 events.

This sample was reduced to 878 events by standard cuts, namely: $E_{J1}^T > 13 \text{ GeV}$, $E_{J2}^T > 7 \text{ GeV}$ and transverse mass of the muon-neutrino system $m_{\mu\nu}^T < 60 \text{ GeV}/c^2$. Requiring in addition an isolated muon³, with $I_\mu < 2$, left 298 events. For a signal from $t \rightarrow H^+b$ decay, for example with $m_t = 50 \text{ GeV}/c^2$, $m_{H^+} = 40 \text{ GeV}/c^2$, and 95 % branching ratio of the $H^+ \rightarrow \tau^+\nu_\tau$ decay, we predict 31.3 events. The expected contributions from the different

³The isolation variable is defined as $I_\mu \equiv [(\sum (E^T/3)^2 + \sum (p^T/2)^2)]^{1/2}$, with the sums including the calorimeter cells, ($\sum E^T$), and Central Detector tracks, ($\sum p^T$) in a cone of $\Delta R = 0.7$ around the muon direction.

backgrounds and the data, after the selection described above, are given in Table 1.

To improve sensitivity to a possible $t \rightarrow H^+ b$ signal, a likelihood function was defined using variables that better differentiate between signal and background. The likelihood was defined as follows:

$$L_1 = \prod_i \frac{P^t(x_i)}{P^b(x_i)},$$

where $P^t(x_i)$ is the probability density function of the variable x_i for t -quark events and $P^b(x_i)$ the corresponding distribution for $b\bar{b}$ and $c\bar{c}$ events; $\prod$ indicates a product over all values of the index i . The variables used in the analysis of the single muon sample are : the muon transverse momentum, p_μ^T , the missing transverse energy, E_{miss}^T , and the $|\cos\theta_{J2}^*|$ (cosine of the second highest E^T jet, in the rest frame of the 4-body system μ -jet₁-jet₂- $\vec{E}_{miss}^T$). The distributions of these three variables are shown in Fig.1 for the data, compared to the sum of standard processes and to $t \rightarrow H^+ b$ decay with $m_t = 50 \text{ GeV}/c^2$, $m_{H^+} = 40 \text{ GeV}/c^2$ and $BR(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$. The resulting distributions in $\ln(L_1)$ are shown in Fig.2. We define our search region by $\ln(L_1) > 1$. In Table 1 the expected contributions from the backgrounds and the data in the signal region are reported: the $b\bar{b}$ and $c\bar{c}$ contribution was normalized to the difference between data and the sum of the contributions from decay background and from Drell-Yan processes, Υ and W and Z decays, in the $\ln(L_1) \leq 0$ region where the t -quark contribution is expected to be negligible. In Table 2, we give the expected rate of $t \rightarrow H^+ b$ events in the region $\ln(L_1) > 1$ for different (m_t, m_{H^+}) combinations, assuming $BR(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$.

2.2 Search in the dimuon channel

In the dimuon channel, the initial sample of data was selected by requiring two muons, one with $p_{\mu 1}^T > 6 \text{ GeV}/c$ in the rapidity interval $|\eta_{\mu 1}| < 1.6$, accompanied by at least one central jet in the region $|\eta_J| < 1.5$. Additional cuts were : second muon $p^T > 3 \text{ GeV}/c$, transverse energy of the central jet $> 10 \text{ GeV}$; dimuon invariant mass between $6 \text{ GeV}/c^2$ and $50 \text{ GeV}/c^2$, loose isolation requirement for the first muon ($I_{\mu 1} < 6$) and non-isolation requirement for the second muon ($I_{\mu 2} > 2$). This selection left 263 events.

As in the single muon analysis, additional cuts were applied to reduce the background. Exploiting the sphericity properties of events with $t \rightarrow H^+ b$ decay, we applied a cut on the azimuthal angle difference between the jet and the first muon, $30^\circ < \Delta\phi_{\mu 1-J} < 160^\circ$ and a $|\cos\theta_J^*| < 0.8$ cut ($\cos\theta_J^*$ being the cosine of the jet, in the rest frame of the 4-body system μ_1 - μ_2 -jet- $\vec{E}_{miss}^T$). This selection left 74 events in the data and 5.0 events expected from $t \rightarrow H^+ b$ decay for $m_t = 50 \text{ GeV}/c^2$, $m_{H^+} = 40 \text{ GeV}/c^2$ and $BR(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$. The

data and the expected background contributions from known physics processes are listed in Table 3.

To improve sensitivity, a likelihood function for dimuon events was defined (analogous to that for single muon events) using the two most discriminating variables: $p_{\mu 1}^T$ and $I_{\mu 1}$. In Fig. 3 the distributions of these two variables for the data are compared to the sum of standard processes and to $t \rightarrow H^+ b$ decay, with $m_t = 50 \text{ GeV}/c^2$, $m_{H^+} = 40 \text{ GeV}/c^2$ and $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$. In Fig. 4 we compare the distribution in $\ln(L_2)$ for dimuon events and predicted backgrounds from known processes: the $b\bar{b}$ and $c\bar{c}$ contribution was normalized to the difference between data and the sum of the other backgrounds in the $\ln(L_2) \leq 1$ region. We defined the search region as $\ln(L_2) > 2$, in which we found no events in the data. Table 3 gives the expected contributions from the backgrounds and the data events in the signal region and in Table 4 we report the expected $t \rightarrow H^+ b$ events in the signal region for different (m_t, m_{H^+}) combinations, assuming $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$.

The systematic errors affecting the background estimate and the predicted numbers of t-quark events were evaluated as in Ref.[3]: systematic and statistical errors for single muon and dimuon channels are listed in Table 5 and Table 6, respectively.

3 Results

The agreement between the measured distributions and those of known physics processes shows that there is no evidence in our data for $t \rightarrow H^+ b$ decay, with the charged Higgs decaying via the $H^+ \rightarrow \tau^+ \nu_\tau$ mode. To obtain a limit on m_t as function of m_{H^+} , the results from the single muon and dimuon channel analysis were combined. From the comparison between the data and the predictions for background and for $t \rightarrow H^+ b$ decay events, we can exclude, at 95 and 90 % CL, the regions of the (m_t, m_{H^+}) plane shown in Fig.5 where, again, $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$ is assumed. The region close to the kinematical bound $m_t = m_{H^+} + m_b$ cannot be excluded by this analysis, as discussed in Section 2. We can also interpret our result in terms of the $\tan \beta$ parameter of a general two-doublet Higgs model: in Fig. 6, we show the 95 % CL and 90 % CL limits on $\tan \beta$ as function of the charged Higgs mass, for $m_t = 60 \text{ GeV}/c^2$. For this m_t value, we exclude $\tan \beta \geq 2.3$ for $m_{H^+} \leq 47 \text{ GeV}/c^2$ and $\tan \beta \geq 1.6$ for $m_{H^+} \leq 51 \text{ GeV}/c^2$ at 95 % and 90 % CL respectively; the region on the left-hand side of the dashed line is excluded by LEP experiments at 95 % CL [16, 17, 18]. In Fig. 7, the limits on $\tan \beta$ as function of m_t , for $m_{H^+} = 44 \text{ GeV}/c^2$, are shown; the dashed line indicates the 95 % CL lower limit on m_t , independent on the t-quark decay, from direct searches for $Z^0 \rightarrow t\bar{t}$ at e^+e^- colliders [12, 13, 14, 15]; the dotted line

shows the 90 % CL lower limit on m_t , also model independent, from the measurement of the W total width Γ_W^{tot} at $p\bar{p}$ colliders [19].

4 Conclusions

Direct searches for $t \rightarrow H^+ b$ decay have previously been performed only at e^+e^- colliders: experiments at LEP [12, 13, 14] and SLAC [15] have excluded at 95 % CL $m_t \leq 45.2 \text{ GeV}/c^2$, almost independently of the assumed H^+ decay mode. Negative searches for pair-produced charged Higgs in Z^0 decays at LEP [16, 17, 18] imply $m_{H^+} > 43 \text{ GeV}/c^2$ for $\tan \beta \gtrsim 3$, *i.e.* maximum branching ratio of the $H^+ \rightarrow \tau^+ \nu_\tau$ decay, and $> 38 \text{ GeV}/c^2$ for $\tan \beta \lesssim 0.4$, *i.e.* maximum branching ratio of the $H^+ \rightarrow c\bar{s}$ decay.

Indirect effects of the charged Higgs on a variety of weak-interaction processes, among others, $B^0 - \bar{B}^0$ mixing and $K^0 - \bar{K}^0$ mixing, can also be used to constrain the parameter of a two-doublet Higgs model. It is generally possible to explain the experimental measurements, in the context of a general two-doublet extension of the Standard Model, only if the t -quark mass, the charged Higgs mass and the value of $\tan \beta$ are properly correlated. Analyses [20, 21] of experimentally determined values of parameters involved in several weak interaction processes indicate that, for a given t -quark mass, larger $\tan \beta$ values favor smaller m_{H^+} values. As an example, for a 60-70 GeV/c^2 t -quark mass, and relatively small charged Higgs masses ($m_{H^+} \lesssim 50\text{-}60 \text{ GeV}/c^2$), large values of $\tan \beta$ ($\gtrsim 1\text{-}2$) are preferred by experimental data [20].

We have searched for the decay $t \rightarrow H^+ b$, in the $H^+ \rightarrow \tau^+ \nu_\tau$ channel, above the kinematic limit $m_t = m_{H^+} + m_b$ plus $\lesssim 3 \text{ GeV}/c^2$, using single muon and dimuon triggers. For large $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau)$, *i.e.* $\tan \beta \gtrsim 2$, we exclude this decay at 95 % (90 %) CL in the range: $m_t \leq 61$ (64) GeV/c^2 and $m_{H^+} \leq 47$ (51) GeV/c^2 .

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Tables

	K and π decays	W and Z , J/Ψ , Υ and Drell-Yan	b-quark and c-quark decays	Total background $\pm$ total error	Data
Selection	142	10.5	153	305 ± 55	298
$\ln(L_1) > 1$ cut	15.8	3.8	11.8	31.4 ± 5.6	24

Table 1: Comparison between data and expected contributions from known physics processes after selection cuts in the single muon channel.

$m_{H^+}(GeV/c^2)$	$m_t(GeV/c^2)$						
	40	45	50	55	60	65	70
30	20.1	21.8	15.7	11.9	7.9	4.8	2.1
35	0	10.9	19.1	17.7	9.7	6.3	3.1
40	0	0	17.6	17.6	10.6	7.1	3.6
45	0	0	0	11.8	10.6	7.0	3.6
50	0	0	0	0	9.8	6.2	3.2
55	0	0	0	0	0	4.5	2.5
60	0	0	0	0	0	0	1.4

Table 2: Number of predicted events with $t \rightarrow H^+ b$ decay, for $BR(H^+ \rightarrow \tau^+ \nu_\tau) = 95\%$, in the single muon channel, after applying the selection criteria described in Section 2.1 and with the cut $\ln(L_1) > 1$. The estimated error is 23 %.

	K and π decays	W and Z , J/Ψ , Υ and Drell-Yan	b-quark and c-quark decays	Total background $\pm$ total error	Data
Selection	19	1.1	62	82 ± 23	74
$\ln(L_2) > 2$ cut	0.4	0.6	2.4	3.4 ± 1.0	0

Table 3: Comparison between data and expected contributions from known physics processes after selection cuts in the dimuon channels.

$m_{H^+}(GeV/c^2)$	$m_t(GeV/c^2)$						
	40	45	50	55	60	65	70
30	4.9	5.0	3.2	2.3	1.5	0.9	0.4
35	0	2.5	3.2	2.9	1.6	1.0	0.5
40	0	0	2.7	2.7	1.6	1.1	0.5
45	0	0	0	1.7	1.4	0.9	0.4
50	0	0	0	0	1.0	0.6	0.3
55	0	0	0	0	0	0.2	0.2
60	0	0	0	0	0	0	0.1

Table 4: Number of predicted events with $t \rightarrow H^+ b$ decay, for $BR(H^+ \rightarrow \tau^+ \nu_\tau)=95\%$, in the dimuon channel, after applying the selection criteria described in Section 2.2 and with the cut of $\ln(L_2) > 2$. The estimated error is 22 %.

	Errors (in %) on background estimate	
	Single Muon Channel	Dimuon Channel
Jet energy scale (12 % energy scale uncertainty)	2	10
Normalization of decay-in-flight background	11	18
Normalization of W , Z , Drell-Yan, J/Ψ , Υ	6	6
Background model uncertainty	8	7
Statistical error on Monte Carlo	9	11
Statistical error on number of events in normalization region	6	12
Total error on background estimate in search region	18	28

Table 5: Errors affecting the background estimates after $\ln(L)$ cut.

	Errors (in %) on predictions for $t \rightarrow H^+b$ events	
	Single Muon Channel	Dimuon Channel
Integrated luminosity and cross section	11	12
Monte Carlo model uncertainty	7	7
Jet energy scale	14	9
Selection efficiency	10	10
Monte Carlo statistical error	7	11
Total error	23	22

Table 6: Errors affecting the predictions for $t \rightarrow H^+b$ decay events in single muon and dimuon channels after $\ln(L)$ cut.

Figure Captions

- Fig.1 Distributions of the three variables used to define the likelihood function for single muon events: (a) p_μ^T , (b) $|\cos \theta_{J2}^*|$, (c) E_{miss}^T for the data compared to the sum of the contributions from known physics processes and (d) p_μ^T , (e) $|\cos \theta_{J2}^*|$, (f) E_{miss}^T for $t \rightarrow H^+ b$ simulated events for $m_t = 50 \text{ GeV}/c^2$, $m_{H^+} = 40 \text{ GeV}/c^2$ and $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$.
- Fig.2 Distribution in $\ln(L_1)$ for single muon events. The data are compared with the simulation of the background from known physics processes and the simulation of events with $t \rightarrow H^+ b$ decay, for $m_t = 50 \text{ GeV}/c^2$, $m_{H^+} = 40 \text{ GeV}/c^2$ and $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$.
- Fig.3 Distributions of the two variables used to define the likelihood function for dimuon events: (a) $p_{\mu 1}^T$, (b) $I_{\mu 1}$ for the data compared to the sum of the contributions from known physics processes and (c) $p_{\mu 1}^T$, (d) $I_{\mu 1}$, for $t \rightarrow H^+ b$ simulated events for $m_t = 50 \text{ GeV}/c^2$, $m_{H^+} = 40 \text{ GeV}/c^2$ and $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$.
- Fig.4 Distribution in $\ln(L_2)$ for dimuon events. The data are compared with the simulation of the background from known physics processes and the simulation of events with $t \rightarrow H^+ b$ decay, for $m_t = 50 \text{ GeV}/c^2$, $m_{H^+} = 40 \text{ GeV}/c^2$ and $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$.
- Fig.5 The regions of the (m_t, m_{H^+}) plane excluded at 95 % and 90 % CL by the analysis described in section 2, assuming $\text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) = 95 \%$. Also shown is the line delimiting the kinematical region accessible to on-shell $t \rightarrow H^+ b$ decay. The regions below and on the left-hand side of the dashed lines are excluded at 95 % CL by $e^+ e^-$ experiments [12, 13, 14, 15], [16, 17, 18] and the region below the dotted line is excluded at 90 % CL by the measurement of the W total width Γ_W^{tot} at $p\bar{p}$ colliders [19].
- Fig.6 The regions of the $(\tan \beta, m_{H^+})$ plane excluded at 95 % and 90 % CL by the analysis described in section 2, for $m_t = 60 \text{ GeV}/c^2$. Also shown, on the left-hand side of the dashed line, is the region excluded by LEP experiments [16, 17, 18].
- Fig.7 The regions of the $(\tan \beta, m_t)$ plane excluded at 95 % and 90 % CL by the analysis described in section 2, for $m_{H^+} = 44 \text{ GeV}/c^2$. The dashed line indicates the 95 % CL lower limit on m_t , independent of the t -quark decay, from direct searches for $Z^0 \rightarrow t\bar{t}$.

at e^+e^- colliders [12, 13, 14, 15]; the dotted line shows the 90 % CL lower limit on m_t , also model independent, from the combined results of the measurement of the W total width Γ_W^{tot} at $p\bar{p}$ colliders [19].

FIG.1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7