Search for the charged Higgs boson in the decays of top quark pairs in the $e\tau$ and $\mu\tau$ channels at $\sqrt{s}$ =1.8 TeV

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Top quark production offers the unique opportunity to search for a charged Higgs boson ($H^{\pm}$), as the contribution from $t \to H^+ b \to \tau^+ \nu b$ can be large in extensions of the standard model. We use results from a search for top quark pair production by the Collider Detector at Fermilab (CDF) in the $e\tau + \not\!\!E_T +$jets and $\mu\tau + \not\!\!E_T +$jets signatures to set an upper limit on the branching ratio of $\mathcal{B}(t \to H^+ b)$ in 106 pb^{-1} of data. The upper limit is in the range 0.5 to 0.6 at 95% C.L. for H^+ masses in the range 60 to 160 GeV, assuming the branching ratio for $H^+ \to \tau\nu$ is 100%. The τ lepton is detected through its 1-prong and 3-prong hadronic decays.

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Many extensions of the standard model (SM) include a Higgs sector with two Higgs doublets, resulting in the existence of charged ($H^{\pm}$) as well as neutral (h, H^0, A) Higgs bosons. The simplest extensions are the two-Higgs doublet models (2HDMs) [1], in which the extension consists only of the extra doublet. In a type I 2HDM only one of the Higgs doublets couples to fermions, while in a type II model one Higgs doublet couples to the ''up'' fermions (e.g., u,c,t), while the other couples to the ''down'' fermions (e.g., d,s,b). The minimal supersymmetric model (MSSM) [2] is a further extension of the SM, and has a Higgs sector such as that of a type II 2HDM.

If the charged Higgs boson is lighter than the top quark [3–5], i.e. $m_{H^{\pm}} < (m_{top} - m_b)$, the decay mode $t \rightarrow H^+ b$ will compete with the SM decay $t \rightarrow W^+ b$. The consequence is that $t\bar{t}$ production and decay will provide a source of Higgs bosons in the channels $W^{\pm}H^{\mp}b\bar{b}$ and $H^+H^-b\bar{b}$ produced with a strong interaction rather than the weak-interaction cross section of direct H^+H^- pair production. In addition, the signature from top pair production and decay is much cleaner than that of the direct production with respect to QCD background.

In a 2HDM and in the MSSM the branching ratio for $t \rightarrow H^+ b$, $\mathcal{B}^{t}_{\rm Hb}$, depends on the charged Higgs boson mass and $\tan\beta$, the ratio of the vacuum expectation values for the two Higgs doublets. Figure 1 shows the expected branching ratio from a leading-log QCD calculation [6] in the MSSM for three different charged Higgs boson masses $m_{H^{\pm}} = 60,100,\ 140\ \mathrm{GeV}/c^2$ as a function of $\tan\beta$. For $\tan\beta \lesssim 1$ and $\tan\beta \gtrsim 70$ the MSSM predicts that the decay mode $t \rightarrow H^+ b$ dominates. Also shown in Fig. 1 is the predicted branching ratio in the MSSM at lowest order for the decay of the charged Higgs boson into a charged τ lepton and a τ neutrino ($\mathcal{B}^{\rm H}_{\tau\nu}$), which has little dependence on the charged Higgs boson mass. For $\tan\beta > 1$ the decay $H^+ \rightarrow \tau^+ \nu_\tau$ is predicted to dominate over the other main decay mode, $H^+ \rightarrow c\bar{s}$, and for $\tan\beta > 5$ the branching ratio $\mathcal{B}^{\rm H}_{\tau\nu}$ is expected to be nearly 100%. Thus, this model would predict an excess of top events with tau leptons over the number expected from SM events in which $t\bar{t} \rightarrow W^+W^-b\bar{b}$, followed by $W \rightarrow \tau\nu$.

Recent calculations, however, have shown that at large values of $\tan\beta$ the predicted branching ratio for $t \rightarrow H^+ b$ is highly sensitive to higher-order radiative corrections, which are model dependent [7]. Limits in the $\tan\beta - m_{H^{\pm}}$ parameter plane consequently depend critically on the parameters of the model. However the direct search for the signature of a τ lepton in top decays allows us to set an upper limit on the branching ratio of $t \rightarrow H^+ b$, assuming the branching ratio for $H^+ \rightarrow \tau\nu$ is 100%, for example.

Previous searches for the charged Higgs boson in top decay have been in the $\tau + \not{E}_t$ channel [8,9], $ll + \not{E}_T + X$ ($l = e$ or μ, $X =$ anything) channel [10], the $\not{E}_T + \tau +$ jets channel [11,12], the l +jets channel [13,14], and the $\not{E}_T + \tau b + O$ + jet ($O = e$, μ, τ or jet) channel [15]. Both Ref. [11] and Ref. [15] select events with a $\not{E}_T$ trigger, while Refs. [13,14] are indirect searches using a disappearance method. Searches for direct production at LEP set a lower limit on the mass of 69 GeV/c^2 [16]. Indirect limits have also been set from measurements of the rate for the decay $b \rightarrow s\gamma$ [17]. However higher-order calculations have shown that in both 2HDM models [18] and the MSSM [19] these limits are also highly model dependent.

The Collider Detector at Fermilab (CDF) Collaboration has published a search for τ leptons from decays of top quark pairs in the $l\tau + \not{E}_T + 2\mathrm{jets} + X$ ($l = e,\mu$) channel [20], where events were selected by requiring the presence of a high-p_T e or μ. We present here the constraints that this analysis (the ''$l\tau$'' analysis) imposes on the branching ratio of the top quark into a charged Higgs boson. This was suggested in Ref. [21], where the authors compare the CDF data with a generator-level Monte Carlo calculation for the number of expected events from charged Higgs decay.

In this paper we start with the number of top candidate events found in the $l\tau + \not{E}_T + 2\mathrm{jets} + X$ data in the analysis of Ref. [20]. We then apply the same selection criteria to Monte Carlo events that contain top quark pairs in which one or both top quarks decay to the charged Higgs bosons (i.e. $t\bar{t} \rightarrow W^{\pm}H^{\mp}b\bar{b}$ and $t\bar{t} \rightarrow H^+H^-b\bar{b}$), for different Higgs boson masses. We assume there are no top quark decays other than $t \rightarrow W^+ b$ and $t \rightarrow H^+ b$. We perform a full calculation of the acceptances including detector effects, and determine the expected number of events due to Higgs production and subsequent decay. From this we can set a limit on the branching ratio $t \rightarrow H^+ b$.

The selection used in this analysis requires high-p_T inclusive lepton events that contain an electron with $E_T > 20$ GeV or a muon with $p_T > 20\ \mathrm{GeV}/c$ in the central region ($|\eta| < 1.0$). The other lepton must be a tau lepton, also in the central region, with momentum $p_T > 15\ \mathrm{GeV}/c$ [25]. Dilepton events from $t\bar{t}$ decays are expected to contain two jets from b decays and large missing transverse energy from the neutrinos. Therefore, we select events with $\geqslant 2$ jets (with $E_T > 10$ GeV and $|\eta| < 2.0$), and with large $\not{E}_T$ significance ($S_{\not{E}_T} > 3$), as described in detail in Ref. [20].

Two complementary techniques, one which identified the τ lepton starting with clusters in the calorimeter, and another which started with a high p_T single track, were used for

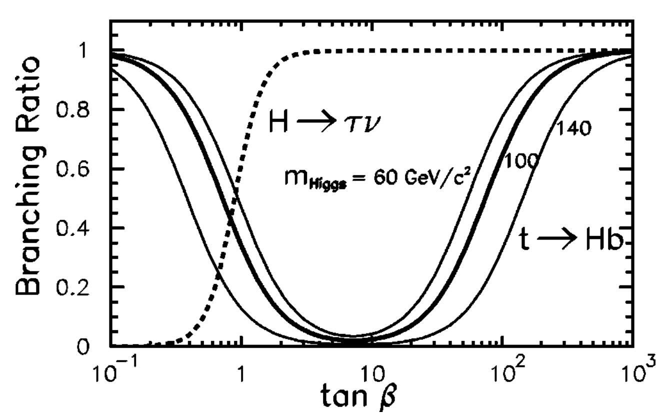

FIG. 1. Branching fraction of $H \rightarrow \tau\nu$ and $t \rightarrow Hb$ as a function of $\tan\beta$ at lowest order in the MSSM. The top quark mass is assumed to be 175 GeV/c^2.

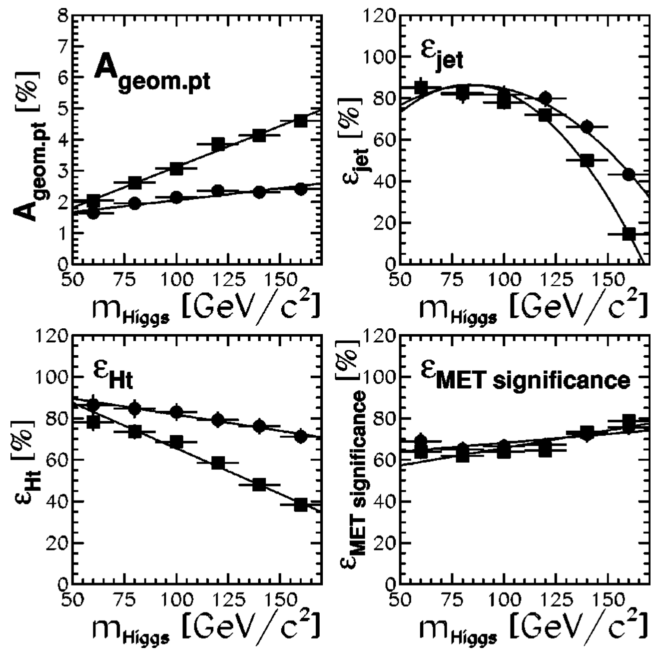

FIG. 2. Contributions to the total acceptance in the $l\tau+\not{E}_T+2\text{jets}+X$ channel versus the mass of the charged Higgs boson. The circles are for the $W^{\pm}H^{\mp}b\bar{b}$ decay of the $t\bar{t}$ pair; the squares for the $H^{+}H^{-}b\bar{b}$ decay.

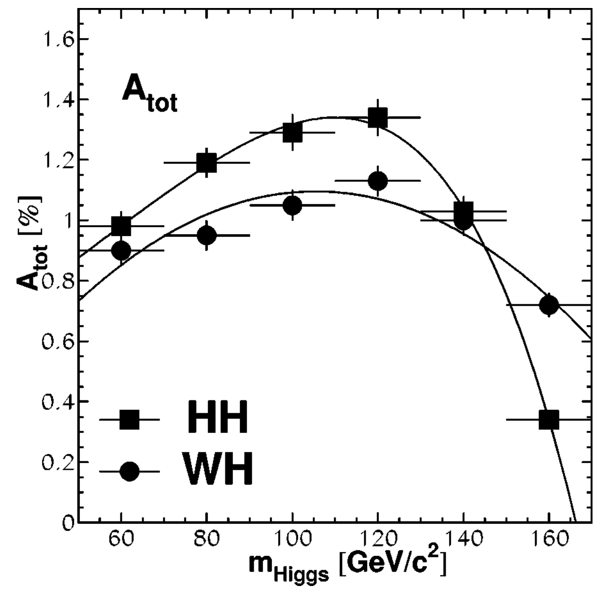

FIG. 3. Total acceptance in the ''tau dilepton'' channel, versus the mass of the Higgs boson. The circles are for the $W^{\pm}H^{\mp}b\bar{b}$ decay of the $t\bar{t}$ pair; the squares for the $H^{+}H^{-}b\bar{b}$ decay.

identifying hadronically decaying τ's [20]. Here, we combine the two tau selections by accepting events which pass either set of criteria. Both techniques find the same four top dilepton candidates in 106 pb^{-1} of data. The total acceptance of the combined selection for SM top quark pairs decays, i.e. the events that pass the final cuts divided by the number of generated $t\bar{t}$ events, is $(0.172\pm0.014)\%$. We expect a total of 3.1 ± 0.5 events from background sources. The dominant background is due to $Z/\gamma\rightarrow\tau^{+}\tau^{-}+\text{jets}$ events (1.8 ± 0.5 events), and to $W+\geqslant 3$ jets events where one jet is misidentified as a τ lepton (1.0 ± 0.1 events). We expect 0.3 ± 0.1 background events from WW and WZ production. We calculate the number of expected events in the $l\tau$ channel by combining the $t\bar{t}$ cross section, the luminosity and the total acceptance. For the $t\bar{t}$ cross section we use the CDF measurement in the ''lepton+jets'' channel, where one W decays leptonically and the other W decays hadronically. This yields the most precise determination of the $t\bar{t}$ cross section in a single channel, $\sigma_{t\bar{t}}=5.1\pm1.5$ pb [27]. Using this cross section we expect 0.9 ± 0.1 events from SM $t\bar{t}$ decay in the $e\tau$ and $\mu\tau$ channels.

Although the identification of b quarks was not part of the search criteria, three of the four candidate events contain at least one b-tagged jet [23], while we expect 0.2 tagged events from SM non-$t\bar{t}$ background [20]. In the following we will use the combined tau selection for our results.

If a charged Higgs boson is present all three of the final states $W^{+}W^{-}b\bar{b}$, $W^{\pm}H^{\mp}b\bar{b}$, and $H^{+}H^{-}b\bar{b}$ can contribute to the $l\tau$ channel. The total acceptance for top decay in the $l\tau$ channel is given by

$$A^{l\tau}_{tot}=(1-\mathcal{B}^{\text{t}}_{\text{Hb}})^2A^{l\tau}_{WW}+2(1-\mathcal{B}^{\text{t}}_{\text{Hb}})\mathcal{B}^{\text{t}}_{\text{Hb}}\mathcal{B}^{\text{H}}_{\tau\nu}A^{l\tau}_{WH}+(\mathcal{B}^{\text{t}}_{\text{Hb}})^2(\mathcal{B}^{\text{H}}_{\tau\nu})^2A^{l\tau}_{HH}. \qquad (1)$$

Here $A^{l\tau}_{WW}$ is the total acceptance of the event selection criteria for the case where the $t\bar{t}$ pair decays into $W^{+}W^{-}b\bar{b}$. It includes the geometric and kinematic acceptances, the efficiencies for the trigger, lepton identification, and cuts on the event topology, and all branching ratios of both the τ and the W boson [24]. Similarly, $A^{l\tau}_{WH}$ and $A^{l\tau}_{HH}$ are the respective total acceptances for the $t\bar{t}$ pair decays into $W^{\pm}H^{\mp}b\bar{b}$ and $H^{+}H^{-}b\bar{b}$, but where the branching ratio of the top to Higgs boson ($\mathcal{B}^{\text{t}}_{\text{Hb}}$) and of the Higgs boson to tau ($\mathcal{B}^{\text{H}}_{\tau\nu}$) have been factored out explicitly. We assume that $\mathcal{B}^{\text{H}}_{\tau\nu}$ is 100%, as it would be at large $\tan\beta$ in the MSSM, and set a limit on $\mathcal{B}^{\text{t}}_{\text{Hb}}$.

We use a top quark mass of 175 GeV/c^2. Monte Carlo simulations of $t\bar{t}$ production and decay in the three modes $W^{+}W^{-}b\bar{b}$, $W^{\pm}H^{\mp}b\bar{b}$, and $H^{+}H^{-}b\bar{b}$ provide estimates of the geometric and kinematic acceptance, $A_{geom\cdot P_T}$, and of the efficiency of the cuts on the event topology for different Higgs boson masses ($m_{H^{\pm}}=60,80,100,120,140,160$ GeV/c^2). We use the PYTHIA [22] Monte Carlo program to generate $t\bar{t}$ events, the TAUOLA package [26], which correctly treats the τ polarization, to decay the tau lepton, and a detector simulation. The selection of events is identical to that described in detail in Ref. [20]. The efficiencies for electron and muon identification are measured from $Z^{\circ}\rightarrow e^{+}e^{-}$ and $Z^{\circ}\rightarrow\mu^{+}\mu^{-}$ data.

Figure 2 shows $A_{geom\cdot P_T}$, the efficiency ϵ_{jet} of the 2-jet cut, the efficiency ϵ_{H_T} of the cut on the total transverse energy H_T [20], and the efficiency of the cut on the $\not{E}_T$ significance, as a function of Higgs boson mass. As $m_{H^{\pm}}$ increases the tau leptons become more energetic and $A_{geom\cdot P_T}$ in-

TABLE I. The total acceptance versus the mass of the charged Higgs boson for the $l\tau + \not{E}_T + 2$ jets $+X$ analysis. The uncertainties are statistical only. These numbers are to be compared to the acceptance for SM top quark pair decays of $A^{l\tau}_{WW} = (0.172 \pm 0.014)\%$. The larger acceptance with the charged Higgs is primarily due to the larger branching fractions into τ leptons.

M_{Higgs}	$A^{l\tau}_{WH}$ (%)	$A^{l\tau}_{HH}$ (%)
60	0.91 ± 0.06	1.00 ± 0.06
80	0.98 ± 0.06	1.17 ± 0.06
100	1.11 ± 0.06	1.32 ± 0.07
120	1.08 ± 0.06	1.32 ± 0.07
140	0.67 ± 0.05	0.98 ± 0.06
160	0.72 ± 0.05	0.32 ± 0.03

creases. When $m_{H^\pm}$ approaches m_{top} the b jets instead become less energetic and ϵ_{jet} drops rapidly. Figure 3 shows the resulting values for $A^{l\tau}_{WH}$ and $A^{l\tau}_{HH}$ versus $m_{H^\pm}$; the numerical values are listed in Table I. Note that relative to A_{HH}, A_{WH} has a factor of 2/9 in it due to the branching ratio for $W \to l\nu$, while the factor of two due to the two possible charge combinations W^+H^- and W^-H^+ is explicitly included in Eq. (1). Overall, the total acceptance ($A^{l\tau}_{tot}$) is rather insensitive to the value of the Higgs boson mass, ranging between 0.7% and 1.3% until $m_{H^\pm}$ approaches m_{top}. This is to be compared to the acceptance $A^{l\tau}_{WW}$ in the W^+W^- final state [20] of 0.17%.

The expected number of events in the $l\tau$ channel is given by

$$N^{l\tau}_{exp} = \sigma_{t\bar{t}} \cdot \mathcal{L} \cdot A^{l\tau}_{tot}(\mathcal{B}^{\mathrm{t}}_{\mathrm{Hb}}, m_{H^\pm}) \tag{2}$$

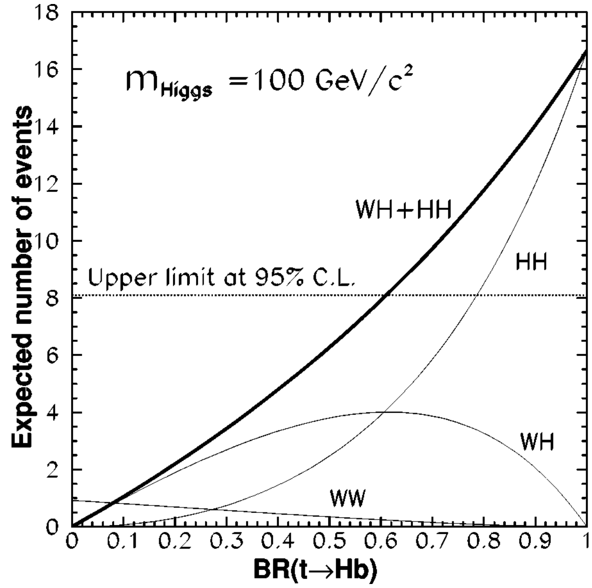

FIG. 5. The predicted number of events for 106 pb^{-1} of data versus the branching ratio for top decay into H^+b for $m_{Higgs} = 100$ GeV/c^2. The graph shows the contributions from the $W^+W^-b\bar{b}$, $W^\pm H^\mp b\bar{b}$, and $H^+H^-b\bar{b}$ channels separately.

and depends on $\mathcal{B}^{\mathrm{t}}_{\mathrm{Hb}}$, the Higgs boson mass, and $\sigma_{t\bar{t}}$, the total top pair production cross section. Rather than use the theoretical prediction for $\sigma_{t\bar{t}}$, for each value of $\mathcal{B}^{\mathrm{t}}_{\mathrm{Hb}}$ we normalize to the observed number of events in the ''lepton + jets'' channel with a secondary vertex tag, taking into account the contributions from the three separate decay final states of $W^+W^-b\bar{b}$, $W^\pm H^\mp b\bar{b}$, and $H^+H^-b\bar{b}$, calculated using the full Monte Carlo simulation and the updated tagging efficiency [27]. We have checked that the calculation

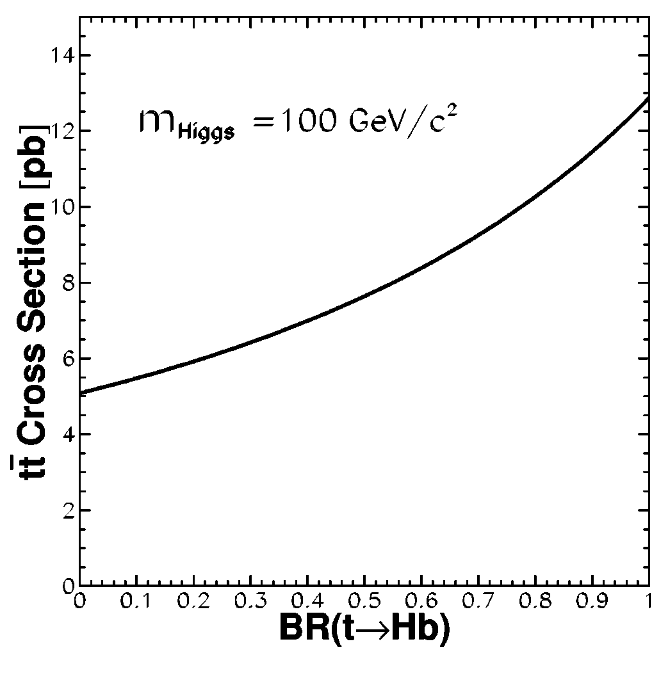

FIG. 4. The $t\bar{t}$ cross section is a function of the branching ratio $\mathcal{B}(t \to H^+b)$.

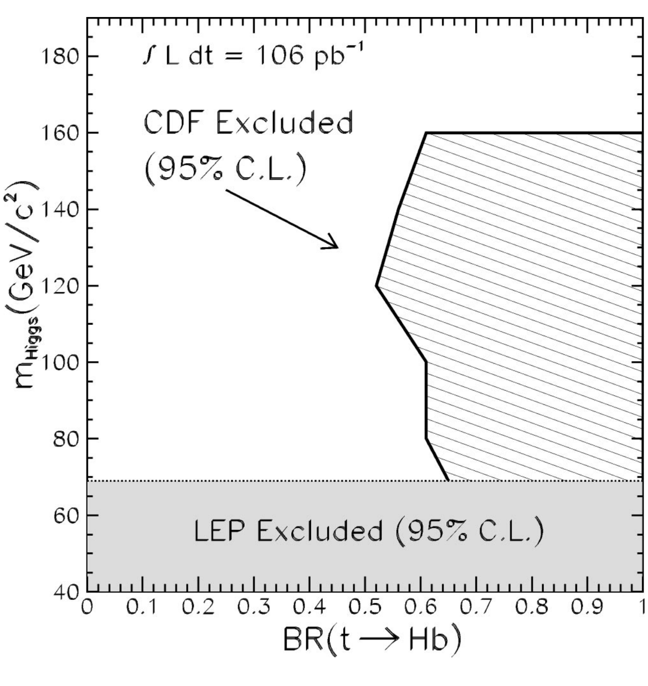

FIG. 6. The region excluded at 95% C.L. for charged Higgs production versus the branching ratio for top decay into H^+b.

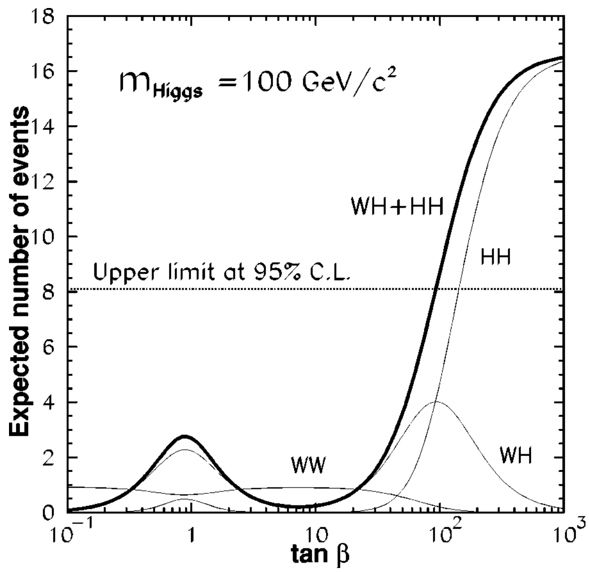

FIG. 7. The predicted number of events at lowest order in the MSSM for 106 pb^{-1} of data versus tanβ, for $m_{Higgs}=100$ GeV/c^2. The graph shows the different contributions from the $H^+H^-b\overline{b}$ and $W^{\pm}H^{\mp}b\overline{b}$ channels separately.

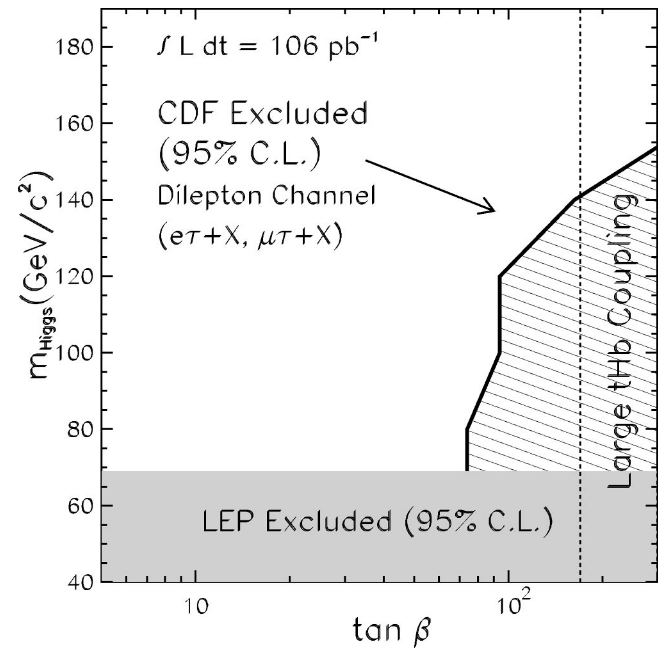

FIG. 8. Excluded regions (95% C.L.) at different values of tanβ for charged Higgs production, at lowest order in the MSSM. The coupling tbH^+ may become non-perturbative in the region at large values of tanβ, and the limit does not apply.

gives the value of $\sigma_{t\overline{t}}=5.1$ pb in the SM case of $\mathcal{B}^{\rm t}_{\rm Hb}=0$, in agreement with the CDF standard model analysis of the top cross section [27], as it must be. We thus calculate $\sigma_{t\overline{t}}$ from the number of observed events in the lepton plus jets channel with a secondary vertex tag, $N^{l+jets}=29$, the expected number of SM background events, $B^{l+jets}=8.0\pm1.0$, and a total acceptance $A^{l+jets}_{tot}(\mathcal{B}^{\rm t}_{\rm Hb},m_{H^{\pm}})$ that takes the $W^{\pm}H^{\mp}b\overline{b}$ and $H^+H^-b\overline{b}$ decay modes into account. This can be written as

$$\sigma_{t\overline{t}}=\frac{N^{l+jets}-B^{l+jets}}{\mathcal{L}\cdot A^{l+jets}_{tot}(\mathcal{B}^{\rm t}_{\rm Hb},m_{H^{\pm}})} \tag{3}$$

where A^{l+jets}_{tot} is given analogously to $A^{l\tau}_{tot}$ by

$$A^{l+jets}_{tot}=(1-\mathcal{B}^{\rm t}_{\rm Hb})^2A^{l+jets}_{WW}+2(1-\mathcal{B}^{\rm t}_{\rm Hb})\mathcal{B}^{\rm t}_{\rm Hb}A^{l+jets}_{WH} +(\mathcal{B}^{\rm t}_{\rm Hb})^2A^{l+jets}_{HH}. \tag{4}$$

Figure 4 shows how $\sigma_{t\overline{t}}$ increases as $\mathcal{B}^{\rm t}_{\rm Hb}$ becomes larger. The contribution from $H^+\to c\overline{s}$ decays is neglected, as we have assumed $\mathcal{B}^{\rm H}_{\tau\nu}=1$. For a large branching ratio into H^+b, the $H^+H^-b\overline{b}$ mode becomes dominant and the leptons (e or μ), which in this case originate from tau decays, have a softer p_T spectrum than leptons produced in W decays, and A^{l+jets}_{tot} decreases. Figure 5 shows the expected number of events versus $\mathcal{B}^{\rm t}_{\rm Hb}$ from each of the $W^+W^-b\overline{b}$, $W^{\pm}H^{\mp}b\overline{b}$, and $H^+H^-b\overline{b}$ decay modes for $m_{H^{\pm}}=100$ GeV/c^2.

Based on the observation of 4 events and the predicted background of 3.1 ± 0.5 events, we calculate a 95% C.L. upper limit on Higgs production of 8.1 events. When calculating the limit, we include the systematic uncertainties, which are dominated by uncertainties on N^{l+jets} (26%), tau identification (11%), b tagging efficiency (10%) and Monte Carlo statistics (8%). Then, to determine a limit on the branching ratio $\mathcal{B}^{\rm t}_{\rm Hb}$, we calculate the number of events expected versus $\mathcal{B}^{\rm t}_{\rm Hb}$ for different Higgs boson masses in steps of 20 GeV/c^2. Figure 6 shows the region excluded at 95% C.L. as a function of the branching ratio of $t\to H^+b$. The upper limit is in the range 0.5 to 0.6 at 95% C.L. for H^+ masses in the range 60 to 160 GeV.

For the special case of the MSSM, although the branching ratios have been shown to be strongly model dependent, for the Higgs boson mass parameter $\mu<0$ the SUSY QCD and QCD corrections come close to cancelling, and the next-to-leading order prediction is almost unchanged from the tree-level result [7]. Figure 7 shows the expected number of $l\tau$ events versus tanβ from each of the $W^+W^-b\overline{b}$, $W^{\pm}H^{\mp}b\overline{b}$, and $H^+H^-b\overline{b}$ decay modes for $m_{H^{\pm}}=100$ GeV/c^2, at lowest order in the MSSM. The shapes of the curves are mainly due to the variation of the branching ratio $\mathcal{B}^{\rm t}_{\rm Hb}$ as a function of tanβ. Figure 8 shows the excluded region in the plane of $m_{H^{\pm}}$ and tanβ, again at lowest order in the MSSM. In the region at large values of tanβ the tbH^+ Yukawa coupling may become non-perturbative (see Ref. [7]). In this case the limit is not valid.

We compare our results to those of Ref. [21]. We find that the acceptance is smaller by about a factor of two. The limits presented in this paper use the correct $W^+W^-b\overline{b}$, $W^{\pm}H^{\mp}b\overline{b}$, and $H^+H^-b\overline{b}$ acceptances, including the correlations among the different objects (e,μ,τ,b-quark) in the events. The insight of Ref. [21] that this will be a channel of much interest in Fermilab run II remains intact, however.

In conclusion, we have used the data from the CDF search [20] for top quark decays into final states containing a light

lepton (e or μ) and a τ lepton, detected through its 1-prong and 3-prong hadronic decays, to set a limit on the branching ratio of the top quark into the charged Higgs boson plus a b quark, $\mathcal{B}^{\rm t}_{\rm Hb}$. The limit ranges from 0.5 to 0.6 at 95% C.L. for H^+ masses in the range 60 to 160 GeV, assuming the branching ratio for $H^+ \rightarrow \tau\nu$ is 100%.

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[24] The reason the acceptance is quoted as containing the branching ratios is that $t\bar{t}$ events are complex, and can satisfy the event selection criteria via a number of different paths, such as the e or μ coming from the W and the τ from the H in the $WHb\bar{b}$ intermediate state, or, the τ coming from the W decay and the e or μ coming from the decay of a τ from the H, for example. We consequently perform the Monte Carlo calculations and include all decay modes except those involving the Higgs, for which the branching ratios are varied explicitly to find the acceptance for each value. The acceptance is then defined as the number of accepted events over the number of $t\bar{t}$ events generated.

[25] The selection criteria are that either a track exists with $p_T > 15$ GeV/c or the sum of the transverse momenta of the tracks and the transverse energies of π^0's be greater than 15 GeV/c. See Ref. [20] for details.

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