Search for charged Higgs bosons in decays of top quarks
in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We report on the first direct search for charged Higgs bosons decaying into $c\bar{s}$ in $t\bar{t}$ events produced by $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The search uses a data sample corresponding to an integrated luminosity of 2.2 fb^{-1} collected by the CDF II detector at Fermilab and looks for a resonance in the invariant mass distribution of two jets in the lepton+jets sample of $t\bar{t}$ candidates. We observe no evidence of charged Higgs bosons in top quark decays. Hence, 95% upper limits on the top quark decay branching ratio are placed at $\mathcal{B}(t \to H^+b) < 0.1$ to 0.3 for charged Higgs boson masses of 60 to 150 GeV/c^2 assuming $\mathcal{B}(H^+ \to c\bar{s}) = 1.0$. The upper limits on $\mathcal{B}(t \to H^+b)$ are also used as model-independent limits on the decay branching ratio of top quarks to generic scalar charged bosons beyond the standard model.

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The standard model (SM) is remarkably successful in describing the fundamental particles and their interactions. Nevertheless, it is an incomplete theory. An important unresolved question is the mechanism of electroweak symmetry breaking (EWSB). In the SM, a single complex scalar doublet field breaks the symmetry, resulting in massive electroweak gauge bosons and a single observable Higgs boson [1]. To date, the Higgs boson has not been discovered, and consequently the mechanism of EWSB remains in question.

Beyond the SM, many diverse hypotheses with extended Higgs sectors have been proposed to explain EWSB. The simplest extension is a two Higgs-doublet model (2HDM). The minimal supersymmetric standard model (MSSM) employs the type-II 2HDM, where at leading order one doublet couples to the up-type fermions and the other couples to the down-type fermions [2]. The two Higgs doublet fields manifest themselves as two charged Higgs bosons ($H^{\pm}$) and three neutral Higgs bosons (h, H, A).

In 2HDM and MSSM, the top quark is allowed to decay into a charged Higgs boson (H^+) [3] and a bottom quark. The tree level branching ratio of top quarks to H^+, $\mathcal{B}(t \to H^+b)$, is a function of the H^+ mass (m_{H^+}) and $\tan\beta$. The parameter $\tan\beta$ is the ratio of vacuum expectation values of the two Higgs doublets. In MSSM, $\mathcal{B}(t \to H^+b)$ also depends on extra parameters related to the masses and couplings of the other supersymmetric particles. The $\mathcal{B}(t \to H^+b)$ is relatively large if $\tan\beta$ is small ($\lesssim 1$) or large ($\gtrsim 15$) [4]. At low $\tan\beta$, H^+ predominantly decays into $c\bar{s}$ for low m_{H^+} ($\lesssim 130$ GeV/c^2) and $t^*\bar{b}$ ($\to Wb\bar{b}$) [5] for higher m_{H^+}. In the high $\tan\beta$ region, the H^+ decays into $\tau^+\nu$ almost 100% of the time.

At Tevatron collider experiments, H^+ searches have been performed for the $H^+ \to \tau\bar{\nu}$ in $t\bar{t}$ decays. Some searches placed direct upper limits on $\mathcal{B}(t \to H^+b)$ by

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taking advantage of the expectation that $\mathcal{B}(H^+ \to \tau\bar{\nu})$ = 1.0 at high $\tan\beta$ [6]. Other searches set limits on the MSSM parameter plane (m_{H^+}, $\tan\beta$) using inclusive H^+ decay branching ratios in the MSSM [7]. The various H^+ final states supplement the SM $t\bar{t}$ decay channels. The previous searches focused on measuring deviations from the SM prediction for the $t\bar{t}$ production and decay, rather than reconstructing H^+ bosons.

In this Letter, we report on the first direct search for $H^+ \to c\bar{s}$ produced in top quark decays by fully reconstructing the $c\bar{s}$ mass. The final state of $H^+ \to c\bar{s}$ is mostly two jets, as is the hadronic decay of the W boson [8] in SM top quark decays. The search is performed by looking for a second peak in the dijet mass spectrum (in addition to that from the W boson) in top quark decays.

In the SM, each top quark decays into a W boson and a b-quark exclusively. In this analysis we use the lepton+jets $t\bar{t}$ sample [9], where in the SM one W decays to quarks ($q\bar{q}'$) and the other W decays to $e\bar{\nu}$ or $\mu\bar{\nu}$. Each final-state quark is assumed to form a hadronic jet; the jets are clustered using a cone algorithm with a cone radius ΔR ($= \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$) of 0.4 [10]. This lepton+jets sample has a good signal-to-background ratio for $t\bar{t}$ and is ideal for dijet mass analysis.

The CDF II experiment at the Fermilab Tevatron measures the products of proton-antiproton collisions at $\sqrt{s}$ = 1.96 TeV. The lepton momentum is measured using an eight-layer silicon microstrip detector and a cylindrical drift chamber immersed in a 1.4 T magnetic field. The energies of electrons and jets are measured using calorimeters with acceptance up to pseudorapidity as of $|\eta| = 3.6$ [11]. Charged particle detectors outside the calorimeter identify muon candidates up to $|\eta| = 1.0$. Details of CDF II can be found elsewhere [12].

Lepton+jets $t\bar{t}$ events are selected by requiring an electron or a muon with $p_T > 20$ GeV within $|\eta|=1$ and by requiring missing transverse energy larger than 20 GeV to account for the neutrino [13]. Then, the four most energetic jets (called leading jets) within $|\eta| < 2.0$ are required to have $E_T > 20$ GeV after jet energy corrections [10]. In addition, at least two of the leading jets are required to contain a long-lived hadron containing a b-quark [14] by demanding that these jets contain tracks forming a displaced secondary vertex (called a b-tag).

The SM processes are regarded as backgrounds for the H^+ search. The largest background is W bosons in SM $t\bar{t}$ events (92% of the total background). The rest of the SM processes are referred to as non-$t\bar{t}$ backgrounds. These include W+jets, multijets, Z+jets, diboson (WW, WZ, ZZ), and single top events. Details of the non-$t\bar{t}$ background estimation method are given in [14]. Assuming a $t\bar{t}$ cross section of 6.7 pb [15] and a top quark mass of 175 GeV/c^2, we expect 152.6 ± 25.0 events from SM $t\bar{t}$ production and 13.9 ± 7.5 events from non-$t\bar{t}$ backgrounds in the 2.2 fb^{-1} CDF II data sample.

The mass of the H^+ candidate is directly reconstructed

using the two jets. The mass resolution is improved by reconstructing the $t\bar{t}$ event as a whole with a kinematic fitter used for the precision top quark mass measurement described in Ref. [12]. The original kinematic fitter is modified for the H^+ search. In the fitter, the lepton, the missing E_T (from a neutrino), and the four leading jets are assigned to the decay particles from the $t\bar{t}$ event, and the quality of the assignment is evaluated using this χ^2:

$$\chi^2 = \sum_{k=jjb,l\nu b} \frac{(M_k - M_t)^2}{\Gamma_t{}^2} + \sum_{i=l,4\text{jets}} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i{}^2}$$
$$+ \frac{(M_{l\nu} - M_W)^2}{\Gamma_W{}^2} + \sum_{j=x,y} \frac{(p_j^{UE,\text{fit}} - p_j^{UE,\text{meas}})^2}{\sigma_{UE}{}^2}. \quad (1)$$

The χ^2 is minimized by constraining leptonic W final state ($l\nu$) to have the W invariant mass (80.4 GeV/c^2) [16] and both top quark final states ($bl\nu$ and bjj) to have the same top quark mass of 175 GeV/c^2. No constraint is imposed on the dijet mass of the hadronic boson (jj). In the mass constraints, the transverse energies of the final-state objects ($p_T^{i,\text{meas}}$) are allowed to vary within measurement uncertainties (σ_i). The unclustered energy ($p_j^{UE,\text{meas}}$) is the sum of measured transverse energies not included in the leading jets E_T and is used to correct the missing E_T. In the jet assignment, b-tagged jets are assigned to the b-quarks. The jets assigned to the b-quarks are called b-jets, and the other two jets are called h-jets. If the $t\bar{t}$ event has more than two b-tagged jets, the jets with the best χ^2 are assigned to b-quarks. Then, we reconstruct the mass of hadronic boson using two h-jets with fit energies ($p_T^{i,\text{fit}}$). In this kinematic event reconstruction, only 55% of the SM $t\bar{t}$ events have correctly matching jets. The wrong jet-parton assignments dominantly come from hard radiation jets which are selected as leading jets and from the falsely b-tagged jets originating from the hadronic decays of W bosons.

The expected dijet mass distributions of H^+ and W in top quark decays are produced using the PYTHIA generator [17] and the full CDF II detector simulation. The ALPGEN generator [18] with the PYTHIA parton shower simulation is used for non-$t\bar{t}$ backgrounds. In the simulation sample, the H^+ is forced to decay solely into $c\bar{s}$ with zero width and with masses ranging from 60 to 150 GeV/c^2.

The simulation shows that the reconstructed H^+ has a significant low-mass tail, which is predominantly caused by final-state gluon radiation (FSR) from the hadronic decays of the Higgs boson. The hard FSR results in more than four final-state jets in a lepton+jets $t\bar{t}$ event. To recover the energy loss due to the FSR, the fifth most energetic jet is merged with the closest jet among the four leading ones if the pair has a ΔR distance smaller than 1.0, provided that the fifth most energetic jet has $E_T > 12$ GeV and $|\eta| < 2.4$. Merging the fifth jet results in better jet energy resolution and improves the m_{H^+}

resolution by approximately 5% in more than four final jets events for 120 GeV/c^2 Higgs sample.

In the CDF II data sample of 2.2 fb^{-1}, we observe 200 $t\bar{t}$ candidates in the lepton+jets decay channel. No significant excess is observed in the dijet invariant mass of top quark decays. Figure 1 shows that the observed dijet mass distribution agrees with the SM expectations. Hence, we extract upper limits on $\mathcal{B}(t \rightarrow H^+b)$ using a binned likelihood fit on the dijet mass distribution.
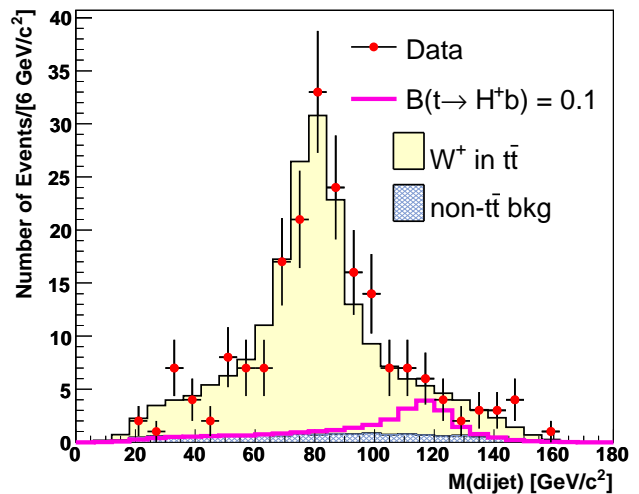

FIG. 1: Observed dijet mass distribution (crosses) compared with background distributions of W bosons (filled) and non-$t\bar{t}$ processes (cross hatched) in CDF II data sample of 2.2 fb^{-1}; the background distributions are added on top of each other. An example of the dijet mass distribution from 120 GeV/c^2 H^+ bosons (bold line) is overlaid assuming $\mathcal{B}(t \rightarrow H^+b) = 0.1$, which is about the 95% C.L. upper limit on $\mathcal{B}(t \rightarrow H^+b)$.

The binned likelihood (LH) function is constructed employing Poisson probabilities:

$$\mathcal{L} = \prod_i \frac{\nu_i^{n_i} \times e^{-\nu_i}}{n_i!} \times G(N_{\text{bkg}}, \sigma_{N_{\text{bkg}}}). \quad (2)$$

The probability of finding events in the mass bin i comes from a set of simulated dijet mass distributions of H^+, W, and non-$t\bar{t}$ backgrounds. These distributions are called templates. The Poisson probability (P^i) in each bin is computed from the number of observed events, n_i, and from the number of expected events, $\nu_i = P_{H^+}^i \times N_{H^+} + P_W^i \times N_W + P_{\text{bkg}}^i \times N_{\text{bkg}}$, where N_{H^+}, N_W, and N_{bkg} are parameters representing the total number of events in each template category. The minimization of $-\ln \mathcal{L}$ gives the most probable values for N_{H^+}, N_W, and N_{bkg}. In the LH fit, N_{H^+} and N_W are free to vary, however, the non-$t\bar{t}$ background (N_{bkg}) is estimated independently and is allowed to vary within its Gaussian uncertainty ($\sigma_{N_{\text{bkg}}}$). Based on the number of events from the LH fit, a $\mathcal{B}(t \rightarrow H^+b)$ is extracted

assuming $\mathcal{B}(H^+ \to c\bar{s}) = 1$. In Figure 1, dijet mass distributions of the SM events are normalized by the likelihood fit to the observed dijet mass distribution with $\mathcal{B}(t \to H^+b)$ fixed to 0.

The sources of systematic uncertainty in the extracted $\mathcal{B}(t \to H^+b)$ include uncertainties in the jet energy scale corrections [10], initial state and final-state radiation, modeling of the non-$t\bar{t}$ background, choice of event generators in simulation. These systematic sources perturb the shape of the dijet mass and cause a shift in the result of the LH fit. The shift in the resulting $\mathcal{B}(t \to H^+b)$ is estimated using "pseudoexperiments" of the perturbed and unperturbed dijet mass distributions for each systematic source; the pseudoexperiments are generated by the bin-to-bin Poisson fluctuations of the simulated dijet mass distributions. The dominant systematic uncertainty originates from the choice of event generators in the simulation, unless m_{H^+} is close to m_W, in which case the jet energy scale uncertainty dominates. The other systematic uncertainties from data/Monte Carlo differences in b-tagging rates and top quark mass constraints in $t\bar{t}$ reconstruction are negligible compared to the uncertainties from the perturbed dijet mass shape.

The individual systematic uncertainties are combined in quadrature. The total systematic uncertainty $(\Delta\mathcal{B}(t \to H^+b))$ is represented by a nuisance parameter which adds to the branching ratio and has a Gaussian prior PDF with width $\Delta\mathcal{B}(t \to H^+b)$. We eliminate this nuisance parameter by Bayesian marginalization [19] and obtain a posterior PDF in $\mathcal{B}(t \to H^+b)$ assuming a uniform prior PDF in $0 \leq \mathcal{B}(t \to H^+b) \leq 1$. The expected upper limits on $\mathcal{B}(t \to H^+b)$ with 95% C.L. are derived from a thousand pseudoexperiments using the SM backgrounds events for each m_{H^+}.

The upper limits on $\mathcal{B}(t \to H^+b)$ at 95% C.L. show a good agreement between the observation and the SM expectation. The upper limits in Figure 2 includes the systematic uncertainty in $\mathcal{B}(t \to H^+b)$. Since the LH fit has very little sensitivity for $m_{H^+} \approx m_W$, the upper limits around 80 GeV/c^2 H^+ are omitted in the Figure. The exact values of the upper limits in the Figure 2 are listed in Table I.

m_{H^+}(GeV/c^2)	60	70	90	100	110	120	130	140	150
Expected	0.13	0.19	0.22	0.15	0.13	0.12	0.10	0.10	0.09
Observed	0.09	0.12	0.32	0.21	0.15	0.12	0.08	0.10	0.13

TABLE I: Expected and Observed 95% C.L. upper limits on $\mathcal{B}(t \to H^+b)$ for H^+ masses of 60 to 150 GeV/c^2.

This analysis can set model-independent limits for anomalous scalar charged bosons production in top quark decays. Besides the assumption that a scalar boson decays only to $c\bar{s}$ with zero width, no model-specific parameter is used in this analysis. Therefore any generic
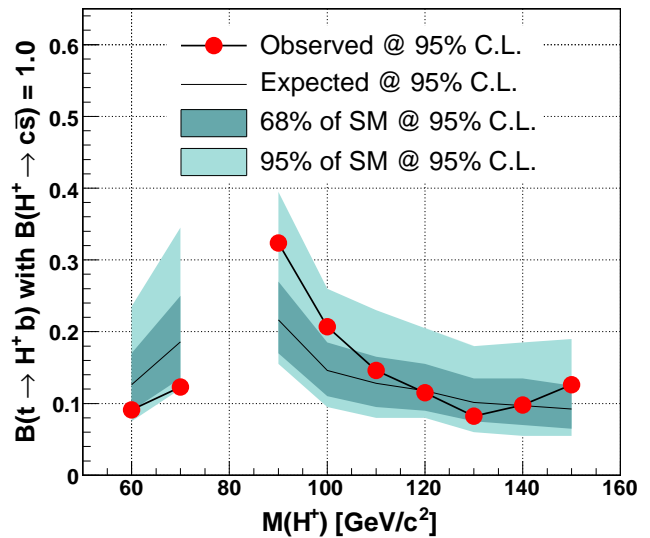

FIG. 2: The upper limits on $\mathcal{B}(t \to H^+b)$ at 95% C.L for charged Higgs masses of 60 to 150 GeV/c^2 except a region for $m_{H^+} \approx m_W$. The observed limits (points) in 2.2 fb^{-1} CDF II data are compared to the expected limits (solid line) with 68% and 95% uncertainty band.

charged boson would make a secondary peak in the dijet mass spectrum if it decays into a dijet final state like the $H^+ \to c\bar{s}$ in top quark decays. Here, we extend the search below the W boson mass [20] down to 60 GeV/c^2 for any non-SM scalar charged boson produced in top quark decays, $t \to X^+(\to u\bar{d})b$. This process is simulated for the CDF II detector and is similar to $H^+ \to c\bar{s}$. In the simulation, we obtain a better dijet mass resolution for $u\bar{d}$ decays than for the $c\bar{s}$ decays. The difference in the mass resolution comes from the smaller chance of false b-tagging from light quark final states of X^+ than the $c\bar{s}$ decays, thus resulting in a smaller ambiguity of jet-parton assignments in the $t\bar{t}$ reconstruction. Consequently, the upper limits on $\mathcal{B}(t \to X^+(\to u\bar{d})b)$ are lower than the limits on $\mathcal{B}(t \to H^+(\to c\bar{s})b)$ regardless of the charged boson mass.

In summary, we have searched for a non-SM scalar charged boson, primarily the charged Higgs boson predicted in the MSSM, in top quark decays using lepton+jets $t\bar{t}$ candidates. This is the first attempt to search for $H^+ \to c\bar{s}$ using fully reconstructed charged Higgs bosons. In the CDF II data sample of 2.2 fb^{-1}, we find no evidence of charged Higgs bosons in the dijet mass spectrum of the top quark decays. Hence, upper limits on $\mathcal{B}(t \to H^+b)$ with 95% C.L. are placed at 0.1 to 0.3 assuming of $\mathcal{B}(H^+ \to c\bar{s}) = 1.0$ for charged Higgs masses of 60 to 150 GeV/c^2. This analysis also yields conservative upper limits on any non-SM scalar charged boson X^+ production from top quarks. Based on simulation, we find that the upper limits on the branching ratio

$\mathcal{B}(X^+ \to u\bar{d})$ are always better than the upper limits on $\mathcal{B}(H^+ \to c\bar{s})$.

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