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 in decays of top quarks in $p\bar{p}$ 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 $\mathcal{B}(t \rightarrow H^+b) < 0.1$ to 0.3 for charged Higgs boson masses of 60 to 150 GeV/c^2, assuming $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 1.0$. The upper limits on $\mathcal{B}(t \rightarrow H^+b)$ can also be 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 doublets result in two charged Higgs bosons ($H^{\pm}$) and three neutral Higgs bosons (h^0, H^0, A^0).

In 2HDM, as well as in MSSM, the top quark is allowed to decay into a charged Higgs boson (H^+) [3] and a bottom quark. The branching ratio of top quarks to H^+, $\mathcal{B}(t \to H^+ b)$, is determined by the H^+ mass (m_{H^+}) and $\tan\beta$, the ratio of vacuum expectation values of the two Higgs doublets. In the case of the MSSM, $\mathcal{B}(t \to H^+ b)$ also depends on extra parameters related to the masses and couplings of the other supersymmetric particles. In general, $\mathcal{B}(t \to H^+ b)$ becomes 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.

Previous H^+ searches have been performed using the $\tau\bar{\nu}$ final state in $t\bar{t}$ decays. Taking advantage of the exclusive decay branching ratio of $H^+ \to \tau^+\nu$ in the high $\tan\beta$ region, some searches set direct limits on $\mathcal{B}(t \to H^+ b)$ [6]. Other searches set limits on the MSSM parameter plane (m_{H^+}, $\tan\beta$), in consideration of inclusive H^+ decay branching ratios, resulting in various specific $t\bar{t}$ decay channels [7]. These searches focused on measuring deviations from the prediction for the production rates in the SM, rather than reconstructing H^+ bosons.

In this Letter, we report on the first direct search for $H^+ \to c\bar{s}$ in top quark decays with fully reconstructed mass, m_{H^+}. The final state of $H^+ \to c\bar{s}$ contains mostly two jets, as does the hadronic decay of 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.

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

The CDF II experiment on the Fermilab Tevatron detects the products of proton-antiproton collisions at $\sqrt{s}$ = 1.96 TeV. Nearly all subdetector systems provide information on the characteristics of $t\bar{t}$ decay events. 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 $|\eta| = 1.0$ and $|\eta| = 3.6$, respectively [11]. Charged particle detectors outside the calorimeter are used to identify muon candidates up to $|\eta| = 1.0$. Details of CDF II detector 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 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 tracks that form a secondary vertex, which is called a b-tag implying production of a long-lived hadron containing a b-quark [14]. The other two jets without a secondary vertex are called h-jets.

In the search for H^+, SM processes are regarded as backgrounds. 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 $t\bar{t}$ prediction and 13.9 ± 7.5 events from non-$t\bar{t}$ backgrounds in the 2.2 fb^{-1} CDF II data sample. We observe 200 $t\bar{t}$ candidates in the lepton+jets decay channel.

The mass of the H^+ is directly reconstructed using the two h-jets, and the mass resolution is improved by reconstructing the $t\bar{t}$ event as a whole. For the $t\bar{t}$ event reconstruction, we employ kinematic fitter used for the preci-

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sion top quark mass measurement described in Ref. [12]. In the fitter, the four leading jets, the lepton, and the missing E_T (from a neutrino) are assigned to particles from $t\bar{t}$ decays. The b-tagged jets are assigned to b-quarks. Then, the assignment of the jets to the four quarks is determined by selecting the combination with the lowest χ^2. In this analysis the original kinematic mass fitter is modified for the H^+ search. The kinematic fitter calculates χ^2 by constraining the leptonic W final state ($l\nu$) to have the W invariant mass (80.4 GeV/c^2) [16]. No constraint is imposed on the mass of the two h-jets (jj). Both top quark final states ($bl\nu$ and bjj) are constrained to have the same top quark mass of 175 GeV/c^2. In the mass constraints, the energies of the final state objects are allowed to vary within measurement uncertainties for the χ^2 minimization. Then we reconstruct the mass of hadronic boson using two h-jets from the χ^2 fit. In the dijet mass reconstruction, only 55% of the SM $t\bar{t}$ events are correctly matched to two jets from W decays and two b-jets from top quark decays. 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 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. And ALPGEN generator [18] 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 helps the final state objects to have a better energy fit in the $t\bar{t}$ reconstruction using the recovered energy. It improves the m_{H^+} resolution by approximately 5% in more than four final jets events of 120 GeV/c^2 Higgs sample.

In the CDF II data sample of 2.2 fb^{-1}, we observe no significant excess beyond the SM expectation 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. The distributions of SM backgrounds in the figure 1 are normalized by the likelihood fit to observed dijet mass distribution assuming $\mathcal{B}(t \rightarrow H^+b) =$ 0.

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

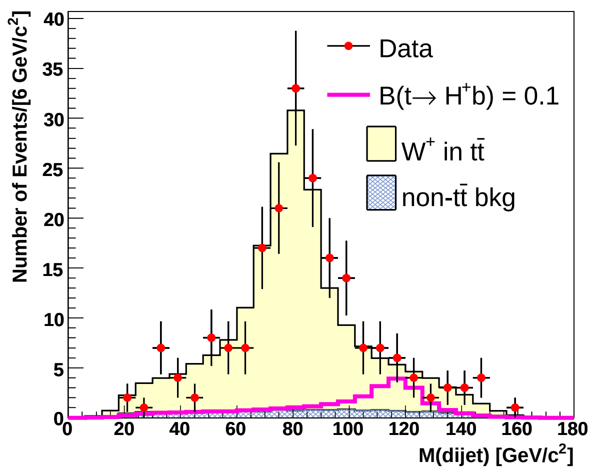

FIG. 1: Observed dijet mass distribution (crosses) compared with background distributions of W bosons (filled) and non-$t\bar{t}$ processes (cross hatched) in CDF II data sample of 2.2 fb^{-1}; the background distributions are added on top of each other. An example of the dijet mass distribution from 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 $\mathcal{B}(t \rightarrow H^+b)$.

$$\mathcal{L} = \prod_i \frac{\nu_i^{n_i} \times e^{-\nu_i}}{n_i!} \times G(N_{\rm bkg}, \sigma_{N_{\rm bkg}}). \quad (1)$$

The probability (P^i) 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 in each bin is computed from the number of observed events, n_i, and from the number of expected events, $\nu_i = P^i_{H^+} \times N_{H^+} + P^i_W \times N_W + P^i_{\rm bkg} \times N_{\rm bkg}$, where N_{H^+}, N_W, and $N_{\rm bkg}$ 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 $N_{\rm bkg}$. In the LH fit, N_{H^+} and N_W are free to vary, however, the non-$t\bar{t}$ background ($N_{\rm bkg}$) is estimated independently and is allowed to vary within its Gaussian uncertainty ($\sigma_{\rm N_{bkg}}$). Based on the number of events from the LH fit, a $\mathcal{B}(t \rightarrow H^+b)$ is extracted assuming $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 1$.

The sources of systematic uncertainty in the extracted $\mathcal{B}(t \rightarrow H^+b)$ 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 $\mathcal{B}(t \rightarrow H^+b)$ 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. Other systematic uncertainties from data/MC 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, and 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 probability density function (pdf) with width $\Delta\mathcal{B}(t \to H^+b)$. We eliminate this nuisance parameter by Bayesian marginalization and obtain a posterior pdf in $\mathcal{B}(t \to H^+b)$, assuming a uniform prior pdf in $0 \le \mathcal{B}(t \to H^+b) \le 1$. 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 observed upper limits on $\mathcal{B}(t \to H^+b)$ at 95% C.L. show a good agreement with the expected limits including systematic uncertainties in figure 2; the LH fit has very little sensitivity for the case of $m_{H^+} \approx m_W$, thus the upper limits around 80 GeV/c^2 H^+ are omitted in the figure. The exact values of observed and expected upper limits are listed in Table I.

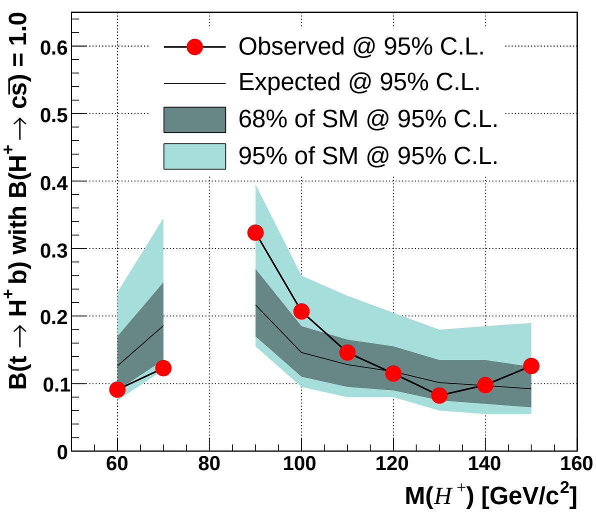

FIG. 2: The upper limits on $\mathcal{B}(t \to H^+b)$ at 95% C.L for charged Higgs masses of 60 to 150 GeV/c^2 except a region for $m_{H^+} \approx m_W$. The observed limits (points) in 2.2 fb^{-1} CDF II data are compared to the expected limits (solid line) with 68% and 95% uncertainty band.

This analysis is also able to yield 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 considered in this analysis. Therefore any generic charged boson, decaying to a dijet final state like a $c\bar{s}$ decay in top quark decays, would make a secondary peak in the dijet mass spectrum. Here, we extend the search below the W boson mass [19] 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.

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.

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 the 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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