Fermilab FERMILAB-Conf-00-294-E D0 February 2001

SEARCH FOR CHARGED HIGGS BOSONS IN DECAYS OF PAIR-PRODUCED TOP QUARKS AT DØ

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We present a search for $t \to bH^+$ in $t\bar{t}$ candidate events at DØ based on two methods. The first seeks a deficit in signal relative to expectations from the standard model (SM). Such a deficit would imply the presence of a non-SM decay of the top quark. This search involves the full data sample of ≈ 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, collected with the DØ detector. The second method looks for charged Higgs decays to τ leptons (and associated neutrinos), and is based on a 62 pb^{-1} subset of the aforementioned data sample.

1. Introduction

The standard model (SM) relies on the Higgs mechanism for gauge invariant generation of particle masses. It contains a single complex scalar doublet field, whose only observable particle is the neutral Higgs boson, H^0. At present there are no experimental results that limit the Higgs sector to a single doublet. We search for evidence of a minimal extension to the Higgs sector, through the addition of a second scalar doublet. We examine predictions of a model that couples one doublet to up-type quarks and neutrinos, and the other to down-type quarks and charged leptons, as is the case for the minimal supersymmetric model. The additional degrees of freedom provide a total of five observable Higgs fields: two neutral CP-even scalars h^0 and H^0, a neutral CP-odd scalar A^0, and two charged scalars $H^{\pm}$. The model has two free parameters that can be taken to be the mass of the charged scalars, $M_{H^{\pm}}$, and the ratio of the vacuum expectation values of the doublets, $\tan\beta$.

In the SM, the primary t quark decay is $t \to W^+b$. The addition of the second Higgs doublet allows for $t \to H^+b$ if this is kinematically possible. If $\tan\beta$ is larger or smaller by about an order of magnitude than $\sqrt{m_t/m_b}$, then $B(t \to H^+b)$ can be large, but it decreases as $M_{H^{\pm}}$ increases. In this analysis, we assume $B(t \to W^+b) + B(t \to H^+b) = 1$, and that the masses of the three neutral scalars are large enough to be suppressed in $H^{\pm}$ decays. At tree level, there are no $H^{\pm}$ direct couplings to SM vector bosons or flavor changing neutral currents. The only available decays of $H^{\pm}$ are fermionic, with the coupling proportional to the fermion mass. For $\tan\beta \geq 3$, $B(H^+ \to \tau^+\nu_\tau) \approx 1$, while for $\tan\beta < 0.4$, $B(H^+ \to c\bar{s}) \approx 1$, provided that $M_{H^{\pm}} < 110$ GeV; at larger values of $M_{H^{\pm}}$, $B(H^+ \to t^*\bar{b} \to W^+b\bar{b})$ becomes dominant for $\tan\beta < \sqrt{m_t/m_b}$ owing to the large mass and coupling of

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the top quark.[1]

DØ has carried out two independent searches for evidence of a minimal extension of the Higgs sector, by looking for evidence of $t \to H^+b$ and $\bar{t} \to H^-\bar{b}$. The indirect search looks for evidence of a decrease in the signal expected on the basis of the SM. The direct search looks for evidence of the $H^\pm$ through its characteristic decay modes.

2. Indirect Search

This analysis searches for evidence that the expected number of top events in the data is less than expected from theory.[2] Those regions of $(M_{H^\pm}, \tan\beta)$ parameter space that simultaneously have a large $B(t \to H^+b)$ and a low detection efficiency relative to $t \to W^+b$ can be excluded, because they would correspond to a significant diminution in the number of events.

The data for this search are identical to those from our previous study of $t\bar{t}$ production, and use the same event selection criteria as our $\sigma(t\bar{t})$ measurement in the lepton + jets final state.[3] A total of 30 events were observed in this channel. To calculate the number of events expected from theory, we cannot use either our measured values for $\sigma(t\bar{t})$ or m_t, since these are based on the assumption that $B(t \to Wb) = 1$. Since $t\bar{t}$ is produced primarily via the strong interaction, we use a QCD calculation giving $\sigma(t\bar{t}) = 5.5$ pb.[4] The DØ mass measurement would remain correct to within 5% for $M_{H^\pm} < 140$ GeV, and hence we use the value $m_t = 175$ GeV.[5] Given these parameters, a total of 30.9 ± 4.0 events are expected, with 11.2 ± 2.0 of these being from background. The main sources of background are $W+$ jets events and QCD multijet events with a misidentified lepton and a large imbalance in transverse momentum ($\not{E}_T$).

Since the number of observed events is approximately the same as the number expected, we therefore proceed to set limits on the two parameters. We use a modified version of ISAJET to generate $H^\pm$ events for different values of $M_{H^\pm}$ and $\tan\beta$.[6] Because the theory is a perturbative leading-order calculation, it is required that $\alpha_{H^\pm} < 1$. This limits our search to $0.3 < \tan\beta < 150$. In addition, the calculation is unreliable for small $|m_t - M_{H^\pm}|$ and large decay widths for t and $H^\pm$. This limits our search to regions where $M_{H^\pm} < 160$ GeV and $B(t \to H^+b) < 0.9$. We also impose a limit of > 77.4 GeV on $M_{H^\pm}$, this being the current upper mass limit from the LEP experiments.[7]

We then apply the same selection criteria as used in our lepton + jets analysis in order to calculate the efficiency for all possible t quark decay modes. For example, the efficiency for the SM $t\bar{t}$ decay is $(3.42 \pm 0.56)\%$; while for $M_{H^\pm} = 125$ GeV, for $t \to H^+b \to W^+\bar{b}b$ it is $(3.71 \pm 0.67)\%$, and for $t \to H^+b \to c\bar{s}b$ it is $(0.04 \pm 0.01)\%$. Clearly, the region of $\tan\beta$ associated with the $H^+ \to Wb\bar{b}$ cannot be excluded, while that associated with $H \to c\bar{s}$ can be. Once the efficiencies for allowed combinations of t and $H^\pm$ decays are calculated, a series of MC experiments is carried out to determine the probability of finding the observed number of events as a function of $M_{H^\pm}$ and $\tan\beta$. This is used to set Bayesian and frequentist limits.

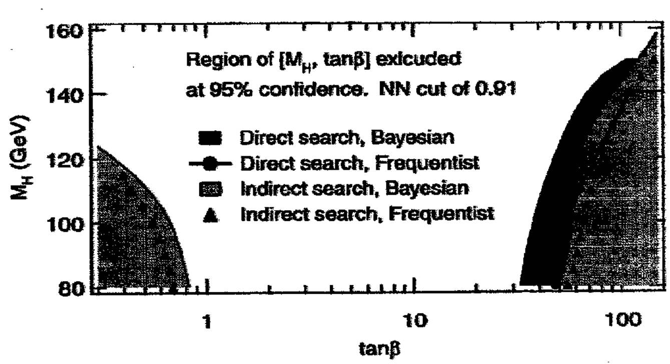

Fig. 1. The Bayesian and frequentist 95% CL exclusion region in $M_{H^\pm}$ and $\tan\beta$.

Using Bayes theorem, we calculate the posterior probability density assuming a uniform prior over the allowed regions of $M_{H^\pm}$ and $\log\tan\beta$. The 95% CL Bayesian limit in Fig. 1, is set by integrating $P(M_{H^\pm}, \tan\beta | n_{\rm obs})$ along a contour of constant probability. To set frequentist limits, we exclude any point in $(M_{H^\pm}, \tan\beta)$ when more than 95% of the trials in our MC experiment give $n_{\rm obs} < 30$.

3. Direct Search

The selection criteria for the direct search are optimized specifically for the charged Higgs final states.[8] This is to be contrasted with the indirect search, where the selection is optimized to the SM decay modes of the top quark. The direct search for H^+ can be divided into two regions of $\tan\beta$: (1) $\tan\beta \leq 1$, where final states are dominated by jets and there is no apparent imbalance in transverse momentum, and (2) $\tan\beta > 10$, where the dominant final state contains up to two τ leptons and large $\not{E}_T$. Since the charged Higgs signal for small $\tan\beta$ is indistinguishable from the large QCD multijet background, we concentrate on the $t\bar{t} \to \tau\bar{\tau}\nu_\tau\bar{\nu}_\tau +$ jets final states. Here we can use the difference in yield of τ leptons to differentiate the signal from that expected for the SM.

The data sample for this analysis corresponds to 62.2 ± 3.1 pb^{-1}, obtained using a QCD multijet trigger. To reduce background, we start with a set of loose selection criteria and then use a neural network (NN) to make more restrictive cuts. The loose criteria require that the event have $\not{E}_T > 25$ GeV, at least 4 jets each with $E_T > 20$ GeV, but no more than 8 jets each with $E_T > 8$ GeV.

We use a feed-forward NN based on JETNET with 3 input nodes, 7 hidden nodes, and 1 output node.[9] The 3 input variables are the $\not{E}_T$, and two of the three eigenvalues of the normalized momentum tensor. The NN is trained on both signal ($t \to H^+b$), and background. The sample used for training the NN on signal, $t\bar{t} \to H^+H^-b\bar{b}$, is generated using ISAJET with $m_t = 175$ GeV, and with both Higgs bosons decaying to $\tau\nu_\tau$, and the τ leptons decay to hadrons and ν_τ. The response of the NN is relatively insensitive to the Higgs mass, we therefore use only a single value, $M_{H^\pm} = 95$ GeV. The same NN is also used for classifying $t\bar{t} \to H^\pm W^\mp b\bar{b}$ channels, since the efficiency for this channel is comparable to that of the training sample.

The primary sources of background are from mismeasured multijet events, and $W+ \geq 3$ jet events. We therefore train the NN on multijet background events from data; even if a H^+ signal exists, it is expected to be very small, so this sample is effectively pure background. The $W+$ jets background is modeled using VECBOS for parton production, and ISAJET for hadronization.[10] The NN cutoff of 0.91, is based on a series of MC experiments that determined the maximum excluded area in $(M_{H^\pm},\ \tan\beta)$ space.

After applying the NN selection, we require that the event have at least one τ lepton that decays hadronically. The selection used in this analysis, follows that in our $W \to \tau\nu_\tau$ published results.[11] The principal requirement is that the jet be narrow ($\sqrt{\sigma_\eta^2 + \sigma_\phi^2} \leq 0.25$, where the σ correspond to the jet widths in η and ϕ). In addition to the previous requirements, we require that the discriminant $\chi_b^2 - \chi_s^2 > 0$, where the χ^2 are calculated using covariance matrices trained on background (χ_b^2) and on τ leptons from W boson decays (χ_s^2).

After applying all our selection criteria, 3 events remain where 5.2 ± 1.6 are expected from SM sources. Given that there is no excess of events, we proceed to set a limit in $(M_{H^\pm},\ \tan\beta)$ space, as was done in the indirect search. The limits are shown in Fig. 1.

4. Conclusion

In conclusion, we find no evidence for a charged-Higgs boson in our data. We exclude at the 95% CL large regions of parameter space for $\tan\beta < 1$ and for $\tan\beta > 30$.

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