Search for Higgs Bosons Decaying into $b\bar{b}$ and Produced in Association with a Vector Boson in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We present a new search for $H^0V$ production, where $H^0$ is a scalar Higgs boson decaying into $b\bar{b}$ with branching ratio $\beta$, and $V$ is a $Z^0$ boson decaying into $e^+e^-$, $\mu^+\mu^-, \tau^+\tau^-$, or $\nu\bar{\nu}$. This search is then combined with previous searches for $H^0V$ where $V$ is a $W^\pm$ boson or a hadronically decaying $Z^0$. The data sample consists of $106 \pm 4 \text{ pb}^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV accumulated by the Collider Detector at Fermilab. Observing no evidence of a signal, we set 95% Bayesian credibility level upper limits on $\sigma(p\bar{p} \rightarrow H^0V) \times \beta$. For $H^0$ masses of 90, 110 and 130 GeV/$c^2$, the limits are 7.8, 7.2, and 6.6 pb respectively.

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Although the dominant production mechanism is $gg \rightarrow H^0$, production in association with vector bosons ($q\bar{q} \rightarrow H^0W^\pm$, $q\bar{q} \rightarrow H^0Z^0$) provides the most sensitive channels for Higgs boson searches at the Tevatron if $M_H < 140$ GeV/$c^2$, because one can obtain significant background rejection from the additional high-energy objects in the event coming from the vector boson decays. The predicted cross section, $\sigma_{VH^0}$, for $VH^0$ production from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV varies between 0.50 and 0.15 pb for $H^0$ masses between 90 and 130 GeV/$c^2$, with the ratio $\sigma_{W} \approx \sigma_{Z} \approx 1.6$.

We have previously reported the results of searches in the $WH^0 \rightarrow \ell\nu\ell\nu$ ($\ell = e$ or $\mu$) and $VH^0 \rightarrow q\bar{q}b\bar{b}$ channels. Here we add the searches for $Z^0H^0$ production using the decay channels $\ell^+\ell^-b\bar{b}$ and $\nu\bar{\nu}b\bar{b}$. Finding no evidence for Higgs boson production using these decay modes, we set limits on the production cross section as a function of mass, and combine our results with the previous $VH^0$ cross section limits. These limits represent the final CDF cross section limits for Higgs boson production in association with a vector boson from the Run I data.

The CDF detector is described in Ref. and, and the coordinate system and various quantities used throughout this paper are defined in Ref. The momenta of the charged leptons are measured with the central tracking chamber in a 1.4 T superconducting solenoidal magnet. Electromagnetic and hadronic calorimeters surrounding the tracking chambers are used to identify electrons and jets and measure their energies. Muons are identified with drift chambers located outside the calorimeters. The silicon vertex detector (SVX) is the innermost detector used for precise tracking in the plane transverse to the beam.

In the analyses reported here, two algorithms using tracks measured with the SVX are applied to identify jets originating from heavy flavor quarks ($b$ and $c$). The first reconstructs a secondary vertex (a vertex displaced from the primary interaction vertex) produced by the heavy flavor decays and measures the transverse decay length (SVX tag). The resolution of the transverse decay length of the secondary vertex is typically of order 150 $\mu$m. The second algorithm uses the impact parameter of the tracks in the jet (the closest distance of the track to the primary vertex in the transverse plane) to calculate a probability that the jet is not from heavy flavor (JPB tag). The details of these tagging algorithms are given in Ref. For the details of the analyses previously published we refer to those publications, and list the results here when appropriate, as they are used in the combined cross section limits. We now describe the two new channels, $\ell^+\ell^-b\bar{b}$ and $\nu\bar{\nu}b\bar{b}$. Events for the $\ell^+\ell^-b\bar{b}$ channel analysis are required to pass a high-$P_T$ lepton trigger and must contain two high-$P_T$ oppositely charged leptons ($e$ or $\mu$) that are isolated from nearby tracks and calorimeter activity. At least one lepton is required to have $P_T > 20$ GeV$/c$ and be in the central detector ($|\eta| < 1.0$). For the second lepton the $P_T$ requirement is relaxed to 10 GeV$/c$ and the pseudorapidity range is extended into the plug calorimeter, up to $|\eta| \sim 2.4$. The dilepton invariant mass must be in the range $76 < M_{\ell\ell} < 106$ GeV/$c^2$ to be consistent with the decay of a $Z^0$ boson. This requirement essentially removes any sensitivity of this analysis to $Z^0 \rightarrow \tau^+\tau^-$. The event is additionally required to
contain two or three high-$E_T$ jets ($E_T > 15$ GeV), at least one of which is SVX tagged. A cut on the missing transverse energy ($E_T < 50$ GeV) is also applied, with the effect of reducing the $t\bar{t}$ background by approximately a factor of two, while preserving about 95% of the signal.

The $\nu \bar{\nu} b \bar{b}$ channel is characterized by two heavy flavor jets and large $E_T$ from the neutrinos. The data sample for this channel is derived from an event trigger requiring $E_T > 35$ GeV in addition to event quality cuts. To reject $W^\pm$ and $Z^0$ decays to leptons, events containing an isolated track with $P_T > 10$ GeV/c are removed from the sample. To ensure less susceptibility to the uncertainty in the trigger efficiency at threshold, the analysis requires $E_T > 40$ GeV. The trigger efficiency is approximately 60% at this value of $E_T$. Additionally the event must contain two or three jets with $E_T > 15$ GeV (about 20% of the $ZH^0$ signal contains a third jet). To reject QCD multi-jet events where the $E_T$ results from a mis-measured jet, the azimuthal angle between the $E_T$ and the direction of any jet with $E_T > 8$ GeV is required to be at least 1.0 radians. In addition, the jets from inclusive di-jet production tend to be back-to-back, while jets from $H^0 \rightarrow b \bar{b}$ in $ZH^0$ events tend to have a smaller opening angle, leading to the requirement that the azimuthal angle between the leading two jets be less than 2.6 radians. Approximately 10% of the efficiency from the $\nu \bar{\nu} b \bar{b}$ selection is contributed by $W^\pm H^0$ events where the lepton is undetected.

Events in the $\nu \bar{\nu} b \bar{b}$ sample are classified as “single-tagged” (exactly one SVX tagged jet) or “double-tagged” (one SVX tagged jet and a second jet tagged by either the SVX or JPB tagging algorithms). The backgrounds and efficiencies are calculated separately for these orthogonal sets, which are then treated as separate but correlated channels when combined with the other channels. This is analogous to what was done in the $WH^0 \rightarrow \ell \nu b \bar{b}$ search 6.

### TABLE I: Total selection efficiencies for $VH^0$ events in each analysis channel used in the combined result, as a function of the $H^0$ mass, $M_H$ (GeV/$c^2$). Numbers are percentages and include the branching ratios of the vector boson ($W^\pm$ or $Z^0$) in a given channel. ST refers to single-tagged events and DT to double-tagged events. Uncertainties include systematic effects.

| Channel | $VH^0$ event efficiencies (%) |
|---------|-------------------------------|
|         | $M_H = 90$ | $M_H = 110$ | $M_H = 130$ |
| $\ell^+ \ell^- b \bar{b}$ | 0.14 ± 0.03 | 0.20 ± 0.04 | 0.19 ± 0.04 |
| $\nu \bar{\nu} b \bar{b}$ (ST) | 0.51 ± 0.10 | 0.63 ± 0.13 | 0.76 ± 0.15 |
| $\nu \bar{\nu} b \bar{b}$ (DT) | 0.37 ± 0.08 | 0.43 ± 0.09 | 0.51 ± 0.10 |
| $\ell \nu b \bar{b}$ (ST) | 0.59 ± 0.15 | 0.72 ± 0.18 | 0.80 ± 0.20 |
| $\ell \nu b \bar{b}$ (DT) | 0.22 ± 0.06 | 0.29 ± 0.07 | 0.30 ± 0.08 |
| $q\bar{q} b \bar{b}$ | 1.3 ± 0.7 | 2.2 ± 1.1 | 3.1 ± 1.6 |

The efficiencies for identifying $VH^0$ events with our selection criteria are summarized in Table I and are determined from a PYTHIA Monte Carlo simulation of Higgs boson production via $V^* \rightarrow VH^0 \rightarrow Vb\bar{b}$ followed by a detector simulation. The Higgs boson is forced to decay to $b\bar{b}$ with a 100% branching ratio. The identification efficiencies for single lepton are measured from $\nu \bar{\nu} b \bar{b}$ with additional jets, hereafter abbreviated as “QCD”. Its normalization is difficult to predict and therefore left unconstrained in the analysis. Further details of the background calculations are given elsewhere 6.10.
TABLE II: Predicted numbers of events in each channel from all backgrounds (see text), expected number of signal events for $M_H = 110\text{ GeV}/c^2$, and number of events observed. Uncertainties include systematic effects. There is no reliable prediction for the background in the $qar{q}'b\bar{b}$ channel.

| Channel        | Background | Signal   | Data  |
|----------------|------------|----------|-------|
| $\ell^+\ell^-b\bar{b}$ | 3.2 ± 0.7  | 0.06 ± 0.01 | 5     |
| $\nu\bar{\nu}b\bar{b}$ (ST) | 39 ± 4     | 0.20 ± 0.04 | 40    |
| $\nu\bar{\nu}b\bar{b}$ (DT) | 3.9 ± 0.6  | 0.14 ± 0.03 | 4     |
| $\ell\nu b\bar{b}$ (ST) | 30 ± 5     | 0.23 ± 0.06 | 36    |
| $\ell\nu b\bar{b}$ (DT) | 3.0 ± 0.6  | 0.09 ± 0.02 | 6     |
| $q\bar{q}'b\bar{b}$       | 0.73 ± 0.29 | 589     |       |

A binned likelihood is used to compare the dijet mass spectrum (of the two tagged jets, or the one tagged jet and highest-$E_T$ untagged jet) in the data to a combination of expected distributions from the background processes and the $VH^0$ signal, as a function of $H^0$ mass. The observed dijet mass spectra for the $\nu\bar{\nu}b\bar{b}$ and $\ell^+\ell^-b\bar{b}$ channels are shown together with the expected background shapes in Figs. 1 and 2 respectively.

FIG. 1: Dijet invariant mass in $\nu\bar{\nu}b\bar{b}$ candidate events, for events with exactly one $b$-tagged jet and separately for events with two $b$-tagged jets. The single $b$-tag data includes one overflow event. The background shapes shown differ only in the inclusion of the predominant background of QCD $b\bar{b}$ production. The signal shape shown (dashed line) is for a SM Higgs mass of 110 GeV/c$^2$ and a normalization of 50 times the expected rate.

FIG. 2: Dijet invariant mass in $\ell^+\ell^-b\bar{b}$ candidate events. At least one jet is required to be $b$-tagged by the SVX algorithm. The background shapes shown differ only in the inclusion of the predominant background of $Z^0$+heavy flavor. The signal shape shown (dashed line) is for a SM Higgs mass of 110 GeV/c$^2$ and a normalization of 50 times the expected rate.

Since no signal is observed, we calculate upper limits on $VH^0$ production using a Bayesian procedure. For each channel, a posterior density is obtained by multiplying the likelihood function for that channel with prior densities for all the parameters in the likelihood: integrated luminosity, background normalizations, signal efficiency, and the product $\sigma'_{VH^0} \equiv \sigma_{VH^0} \times \beta$ of the signal cross section $\sigma_{VH^0}$ by the branching ratio $\beta$ for $H^0 \to b\bar{b}$. With two exceptions, these priors are truncated Gaussian densities constraining a given parameter to its expected value within its uncertainty. The exceptions are $\sigma'_{VH^0}$ and the QCD background normalization in the $q\bar{q}'b\bar{b}$ channel. Since nothing is presumed known a priori about these parameters, they are assigned uniform priors. The posterior density is then integrated over all parameters except $\sigma'_{VH^0}$, and a 95% credibility level (C.L.) upper limit on $\sigma'_{VH^0}$ is obtained by calculating the 95th percentile of the resulting distribution. When combining channels, the same procedure is applied to the product of their likelihoods. Correlations in the total efficiencies are taken into account by identifying common parameters such as the $b$-tagging efficiency and some kinematical efficiencies. Each of these common parameters is then assigned a single prior.

Upper limits on $\sigma_{VH^0} \times \beta$ in each channel and in all channels combined are summarized in Table III as a function of $H^0$ mass.

These results are also plotted in Figure 3. The standard model prediction is about 30 times smaller than the measured 95% C.L. upper limits. For the $\ell\nu b\bar{b}$ and $q\bar{q}'b\bar{b}$ channels, the limits reported here are slightly different from those previously published [10]; this is mainly due to our improved understanding of the $b$-tagging efficiency [10]. Table III also shows expected upper limits under the assumption of zero signal. These expectations are calculated over an ensemble of experiments similar to this one, but where the background normalizations are fluctuated around their expected values by their uncertainties. We note that the observed combined limits are driven by the
TABLE III: The 95% credibility level upper limits on \( \sigma(p\bar{p} \to VH^0) \times \beta \) where \( \beta = \text{BR}(H^0 \to b\bar{b}) \), for each of the search channels and their combination, as a function of \( H^0 \) mass, \( M_H \) (GeV/c²). Also shown are the expected limits under the assumption of no \( H^0 \) signal. ST designates the single \( b \)-tagged subsample and DT the double \( b \)-tagged subsample.

| Channel | Measured (expected) upper limits (pb) |
|---------|--------------------------------------|
| \( \ell^+\ell^- bb \) | 55.6 (36) 31.8 (24) 23.8 (25) |
| \( \nu\bar{\nu} bb \) (ST) | 20.8 (30) 20.8 (21) 18.4 (17) |
| \( \nu\bar{\nu} bb \) (DT) | 10.4 (17) 9.2 (14) 8.0 (12) |
| \( \nu\bar{\nu} bb \) (ST+DT) | 7.6 (13) 7.8 (11) 7.4 (8.8) |
| \( \ell\nu b \) (ST) | 30.0 (18) 29.4 (15) 27.6 (12) |
| \( \ell\nu b \) (DT) | 31.0 (24) 26.6 (19) 24.2 (18) |
| \( \ell\nu b \) (ST+DT) | 23.2 (13) 22.6 (11) 21.6 (9.0) |
| \( q\bar{q} bb \) | 38.2 (77) 21.2 (43) 17.8 (29) |
| All combined | 7.8 (7.1) 7.2 (5.7) 6.6 (4.7) |

In conclusion, we have searched for \( Z^0 H^0 \) production using the \( \ell^+\ell^- \) and \( \nu\bar{\nu} \) decay channels of the \( Z^0 \) and \( H^0 \) double and triple production using these channels. We combined these limits with those previously published using other decay channels of the vector bosons to obtain final CDF Run I 95% C.L. limits on \( \sigma_{VH^0} \times \beta \) ranging from 7.8 pb to 6.6 pb for \( H^0 \) masses of 90 GeV/c² to 130 GeV/c². These limits additionally apply to any scalar particle decaying to \( b\bar{b} \) that is produced in association with a vector boson. These results and the combination methodology establish the foundation for our searches in the Tevatron Run II data at \( \sqrt{s} = 1.96 \text{TeV} \) which are exploiting more search channels, an improved detector, and more advanced analysis techniques [13].

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