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Search for the Standard Model Higgs Boson in Tau Final States

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We present a search for the standard model Higgs boson using hadronically decaying tau leptons, in 1 fb$^{-1}$ of data collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ collider. We select two final states: $\tau^+\tau^-$ plus missing transverse energy and $b$ jets, and $\tau^+\tau^-$ plus jets. These final states are sensitive to a combination of associated $W/Z$ boson plus Higgs boson, vector boson fusion, and gluon-gluon fusion production processes. The observed ratio of the combined limit on the Higgs production cross section at the 95% C.L. to the standard model expectation is 29 for a Higgs boson mass of 115 GeV.

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We present a search for the standard model Higgs boson using hadronically decaying tau leptons, in 1 fb$^{-1}$ of data collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ collider. We select two final states: $\tau^+\tau^-$ plus missing transverse energy and $b$ jets, and $\tau^+\tau^-$ plus jets. These final states are sensitive to a combination of associated $W/Z$ boson plus Higgs boson, vector boson fusion, and gluon-gluon fusion production processes. The observed ratio of the combined limit on the Higgs production cross section at the 95% C.L. to the standard model expectation is 29 for a Higgs boson mass of 115 GeV.

A standard model (SM) Higgs boson with a mass in the range 105–145 GeV is expected to be produced in $p\bar{p}$ collisions at a center-of-mass energy of 2 TeV with cross sections of $\mathcal{O}(100$ fb) for associated $VH$ production ($V = W$ or $Z$) and vector boson fusion (VBF), $q\bar{q} \rightarrow VVq'q'' \rightarrow q'q''H$, and of $\mathcal{O}(1$ pb) for gluon-gluon fusion (GGF) [1]. Previous searches for the SM Higgs boson at the Fermilab Tevatron collider [2] have sought the $VH$ processes with
W/Z decays to leptons other than taus and $H \rightarrow b\bar{b}$, and the gluon fusion process with $H \rightarrow VV^*$ with $V(V^*) \rightarrow ee$ or $\mu \mu$. Thus far, there have been no published searches in the case that either the $V$ or $H$ decays to $\tau$ leptons. Given the small Higgs boson production cross sections, it is advantageous to use all possible decay modes to increase the search sensitivity. Here, we present a search designed for either of the two final states: for type 1, a single track with $p_T > 15$ GeV, and associated EM cluster, and for type 3, at least one track decaying to leptons other than taus and $H$ boson decays to leptons with an isolation and the transverse and longitudinal shower profiles of the calorimeter energy depositions associated with the tau candidate. Tau preselection is based on the requirement that the output $\mathcal{N}N$ value, $\mathcal{N}_T$, exceeds 0.3 thus favoring the tau hypothesis. The tau transverse momentum $p_T^\tau$ is constructed from the transverse energy observed in the calorimeter, $E_T^\tau$, with type-dependent corrections based on the tracking information. For the three types we require $p_T^\tau$ to be greater than 12 (15), 10 (15), or (20) GeV for the $\tau\nu$ ($\tau\tau$) analyses. The $\tau\nu$ analysis subdivides the type 2 taus according to whether the energy deposit is electronlike or hadronlike and the two subsamples are treated separately in assessing the multijet background. For type 2 candidates in the $\tau\tau$ analysis, we require $0.7 < p_T^\tau / E_T^\tau < 2$ to remove backgrounds in regions with poor EM calorimetry or due to cosmic rays.

Jets are reconstructed with a cone of radius 0.5 in rapidity-azimuth space. Their energies are corrected to the particle level to account for detector effects and missing energy due to semileptonic decays of jet fragmentation products. We preselect jets with $p_T > 15$ GeV, $|\eta| < 2.5$, and separated by $\mathcal{R} > 0.5$ from $\tau$ and $\mu$ candidates.

Backgrounds other than those from multijet (MJ) production are simulated using Monte Carlo (MC) programs. We use ALPGEN [7] for $t\bar{t}$ and $V + j$ jets production; PYTHIA [8] for $WW$, $WZ$ and $ZZ$ (diboson) production; and COMPHEP [9] for single top quark production. The ALPGEN events are passed through PYTHIA for parton showering and hadronization. The Higgs boson signal processes are generated using PYTHIA and the CT10L [10] leading order parton distribution functions (PDF) for $M_H = 105-145$ GeV in 10 GeV steps. We normalize the cross sections to the highest available order calculations for the signal [11] and background [12]. Higgs decays are simulated using HDECAY [13] and for tau decays using TAUOLA [14]. All MC events are passed through the standard D0 detector simulation, digitization, and reconstruction programs.

Backgrounds due to MJ production, with spurious $E_T$ or misidentified taus are estimated from data samples. For the $\tau\nu$ analysis, an enriched multijet sample is formed by selecting taus with $0.3 < \mathcal{N}_N < 0.7$. The contributions from those background processes generated by MC simulations are then subtracted to give the $\mathcal{B}_{\tau\nu}$ multijet background sample which has negligible Higgs boson signal and provides the shapes of the multijet distributions in the kinematic variables. The normalization is given by the ratio of the number of events in the signal region, $\mathcal{N}_S$, to the number of events in the $\mathcal{B}_{\tau\nu}$ sample.
For the MJ background in the $\tau\tau$ analysis, we prepare a multijet background data sample (BG$_{\tau\tau}$), orthogonal to the signal sample (SG$_{\tau\tau}$) defined by the $\mu$, $\tau$, and jet preselection cuts above, by reversing both track and calorimeter isolation requirements for the muon and by requiring $N_{\tau} < 0.8$. For both BG$_{\tau\tau}$ and SG$_{\tau\tau}$ samples, the MC backgrounds are subtracted, and the same sign (SS) or opposite sign (OS) $\mu - \tau$ charge combinations subsets are formed. The BG$_{\tau\tau}$ sample provides the shape of the multijet background, with the normalization obtained by multiplying the number of SS SG$_{\tau\tau}$ events by the ratio of OS to SS events in the BG$_{\tau\tau}$ sample. These ratios are determined separately for each tau type, and are observed to be close to 1 and independent of $p_T$ and $p_T^\tau$.

The event sample for the $\tau\nu$ analysis is obtained with additional requirements after the object selections described above: (a) at least two jets with $p_T > 20$ GeV and $\leq 3$ jets with $p_T > 15$ GeV; (b) the angle $\Delta \phi (\vec{E}_T, \vec{T}_T) < \pi/2$, where $\vec{T}_T$ is the negative of the transverse component of the net momentum of all tracks in the event [15]; (c) $H_T < 200$ GeV, where $H_T$ is the scalar sum of the $p_T$ of all jets; (d) for hadronlike type 2 taus, the transverse mass, formed from the $\tau$ and $\vec{E}_T$, less than 80 GeV; (e) dijet invariant mass in the range $50 < M_{jj} < 200$ GeV; and (f) the requirement $\Delta \phi (\tau, \vec{E}_T) < 0.02(\pi - 2)(\vec{E}_T - 30) + 2$ ($\vec{E}_T$ in GeV) to reduce contamination due to poorly reconstructed multijet events in which a jet misidentified as a tau is nearly collinear with $\vec{E}_T$. To further improve the signal (S) over background (B) separation, we require two jets to be tagged with a $NN$ that discriminates $b$ quark jets and jets from light partons [16]. Figure 1(a) and 1(b) shows the $M_{jj}$ distribution before and after $b$ tagging and the event yields are summarized in Table 1.

Most of the signal processes sought in the $\tau\tau$ analysis contain light quark jets, so we do not employ $b$ tagging. We require 2 jets with $p_T > 20$ GeV. To further separate signals from backgrounds, we train a dedicated $NN$ for the signal processes (HZ, WH, ZH, VBF) and for each of the main background types ($W +$ jets, $Z +$ jets, $t\bar{t}$ and MJ). After requiring two jets, the MC GGF samples are small, making $NN$ training unreliable. Since the GGF and VBF processes both involve nonresonant dijet systems, we incorporate the GGF events with the VBF sample when constructing the final limit analysis. The $NN$s are separately trained for low mass (105, 115 and 125 GeV) and high mass (135, 145 GeV) Higgs bosons, giving 32 $NN$s in all. Twenty well-modeled input variables are considered for each of the $NN$s. They include transverse or invariant masses of combinations of jets and leptons, $\vec{E}_T$, angular correlations, and overall event distributions such as $H_T$ and aplanarity [17]. For each signal-background pair, a choice of six or seven variables is made using the criterion that each added variable must give significant improvement in $S/\sqrt{B}$. The same variable choices are made for all Higgs boson masses. All $NN$ input and output variables show good agreement between data and background prediction, and typically provide good discrimination between the signal and background under consideration. The $t\bar{t}$, $W +$ jets and MJ $NN$s give good separation of signal and background, whereas the $Z +$ jets $NN$ signal and background distributions are not so well differentiated. Thus we define the variables $NN_{bg}$ as the largest $NN$ output variable among the various signals, for each background source, $bg = t\bar{t}$, $W +$ jets, and MJ. We require $NN_{bg} > 0.4$, based on an optimization of the expected Higgs boson cross section limits. After this selection, the $NN$ outputs trained against the $Z +$ jets background for all signals are combined by taking their weighted average, $NN_{Zjets}$, over the four signal processes (HZ, WH, ZH, VBF), with weights equal to the relative expected yield for each signal. The $NN_{Zjets}$ distribution for the final sample is shown in Fig. 1(c), now including the GGF signal events. The signal and background event yields are given in Table 1.
Table I. Numbers of events at the preselection level and after the final selection (b tagging for \( \tau \nu \) and \( NN_{bg} \) cut for \( \tau \tau \)) for all \( \tau \) types combined, for data, estimated backgrounds and signal at \( M_H = 115 \) GeV. The V + jets background is given for light parton (u, d, s, g = lp) and heavy flavor (b, c = hf) jets separately. The uncertainties shown are statistical only. For the \( \tau \nu \) (\( \tau \tau \)) analysis the combined statistical and systematic uncertainties on the sum of backgrounds in the final selections are 5.5 (14.8) events.

<table>
<thead>
<tr>
<th>Source</th>
<th>( \tau \nu ) analysis</th>
<th>( \tau \tau ) analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preselection</td>
<td>Final</td>
</tr>
<tr>
<td>( W + lp )</td>
<td>1124 ± 18</td>
<td>0.5 ± 0.0</td>
</tr>
<tr>
<td>( W + hf )</td>
<td>308.2 ± 4.8</td>
<td>10.9 ± 0.3</td>
</tr>
<tr>
<td>( Z + lp )</td>
<td>49.1 ± 1.5</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>( Z + hf )</td>
<td>7.8 ± 0.5</td>
<td>0.4 ± 0.0</td>
</tr>
<tr>
<td>( \tilde{\tau} )</td>
<td>46.7 ± 0.4</td>
<td>9.5 ± 0.1</td>
</tr>
<tr>
<td>Diboson</td>
<td>54.9 ± 1.1</td>
<td>0.7 ± 0.0</td>
</tr>
<tr>
<td>Multijet</td>
<td>122.6 ± 11.2</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>Sum</td>
<td>1714 ± 22</td>
<td>23.3 ± 0.4</td>
</tr>
</tbody>
</table>

| Data | 1666 | 13 | 220 | 58 |
| \( HZ \) | | | 0.038 | 0.029 |
| \( WH \) | 0.543 | 0.201 | 0.145 | 0.106 |
| \( ZH \) | 0.023 | 0.015 | 0.094 | 0.069 |
| \( VBF \) | | | 0.071 | 0.059 |
| \( GGF \) | | | 0.041 | 0.030 |
| Sum | 0.566 | 0.216 | 0.389 | 0.293 |

Some systematic uncertainties induce a shape dependence on the final limit setting variable. For the \( \tau \nu \) analysis, such shape dependence is found for the jet energy scale, jet energy resolution, and the b-tagging efficiencies. Alternate shapes are determined by changing the relevant parameter by ±1 standard deviation from the nominal value and are provided to the limit setting program. For the \( \tau \tau \) analysis, only the multijet background is found to give an appreciable shape change. It is determined by varying the method for selecting MJ events, reversing either the muon or the tau requirements, but not both, relative to the standard choice. The remaining “flat” systematic uncertainties do not affect the final variable distribution shape. Such flat uncertainties for the \( \tau \nu \) (\( \tau \tau \)) analysis are, unless otherwise noted, fully correlated for different backgrounds and analysis channels, and include (a) integrated luminosity, 6.1% (6.1%) [18]; (b) trigger efficiency, 5.5% (3%) (uncorrelated \( \tau \nu \) and \( \tau \tau \)); (c) muon identification, (4.5%); (d) tau identification, 5.0%–6.0% (5.0%); (e) tau track efficiency, 3.0% (3.0%); (f) tau energy scale, 2.3%–2.7% (3.5%); (g) jet identification and reconstruction, 1.7%–4.9% (2%); (h) jet energy resolution, (4.5%); (i) jet energy scale (7.5%) [19]; (j) MC background cross sections, 6%–18% (6%–18%) (these are taken to be uncorrelated among the backgrounds); (k) higher order correction for the V + jets cross section, 20% (20%); (l) V+ heavy flavor jet cross section correction, 30% (30%); and (m) multijet background, 82%–100% (uncorrelated \( \tau \nu \) and \( \tau \tau \)).

The upper limits on the Higgs boson cross section are obtained using the modified frequentist method [20]. For the \( \tau \nu \) analysis, the test statistic is the negative log likelihood ratio (LLR) derived from the \( M_{jj} \) distribution. For the \( \tau \tau \) analysis, the LLR is formed from the \( NN_{jets} \) final neural network variable. The confidence levels \( CL_{b+} \) (\( CL_{b} \)) give the probability that the LLR value from a set of simulated pseudoexperiments under the signal plus background (background-only) hypothesis is less likely than that observed, at the quoted C.L. The hypothesized signal cross sections are scaled up from their SM values until the value of \( CL_s = CL_{b+}/CL_b \) reaches 0.05 to obtain the limit cross sections at the 95% C.L., both for expected and observed limits. In the calculation, all contributions to the systematic uncertainty are varied, subject to the constraints given by their estimated values, to give the best fit [21]. The correlations of each systematic uncertainty among signal and/or background processes are accounted for in the minimization.

The ratios of the expected and observed upper limits to the SM expectations are shown in Table II for the two channels separately and combined. For all Higgs boson masses, the observed limits are within 1σ of the expected limits. At \( M_H = 115 \) GeV, the observed (expected) 95% C.L. limit is 29 (28) times that predicted in the SM for the seven signal processes considered in the combined \( \tau \nu \) and \( \tau \tau \) analyses. This is the first limit on SM Higgs production using final states involving hadronically decaying tau leptons. These results contribute to the sensitivity of the combined Tevatron search for low mass Higgs bosons [2].

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[2] For references to the full set of Higgs searches by the CDF and D0 collaborations, see arXiv:0903.4001.
[15] In events with true $E_T^F$ due to noninteracting particles, $E_T^F$ and $T_6^F$ tend to be aligned, whereas for events with mis-measured jets in the calorimeter they do not.