Measurement of $t\bar{t}$ production in the $\tau +$ jets topology using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present a measurement of the $t\bar{t}$ production cross section multiplied by the branching ratio to tau lepton decaying semihadronically ($\tau_h$) plus jets, $\sigma(pp \to t\bar{t}+X) \cdot BR(t\bar{t} \to \tau_h+\text{jets})$, at a center of mass energy $\sqrt{s} = 1.96$ TeV using 1 fb$^{-1}$ of integrated luminosity collected with the D0 detector. Assuming a top quark mass of 170 GeV, we measure $\sigma_{t\bar{t}} \cdot BR_{t\bar{t}+j} = 0.60_{-0.22}^{+0.15}$ (stat) $^{+0.23}_{-0.14}$ (syst) $\pm 0.04$ (lumi) pb. In addition, we extract the $t\bar{t}$ production cross section using the $t\bar{t} \to \tau_h+\text{jets}$ topology, with the result $\sigma_{t\bar{t}} = 6.9^{+1.2}_{-1.1}$ (stat) $^{+0.7}_{-0.5}$ (syst) $\pm 0.4$ (lumi) pb. These findings are in good agreement with standard model predictions and measurements performed using other top quark decay channels.

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The decay $t \to Wb \to \tau\nu\bar{b}$ provides a unique laboratory to investigate the properties of the third generation fermions — the top ($t$) and bottom ($b$) quarks, the tau lepton ($\tau$), and the tau neutrino ($\nu_{\tau}$) — in a single process. In the standard model (SM), the $t$ quark branching ratio (BR) to a $W$ boson and a $b$ quark is $\approx 100\%$, and the final state is determined by the SM BR of the $W$ boson. Since the $t$ is the heaviest quark and the $\tau$ the heaviest lepton, any non-SM mass- or flavor-dependent couplings could change the $t$ quark decay rate into final states with $\tau$ leptons. Therefore, any deviation in the BR of $t \to \tau\nu\bar{b}$ from that predicted by the SM can be an indication of non-SM physics. For example, in the Type 2 two-Higgs doublet model [1], such as required by the minimal supersymmetric standard model [2], the $t$ quark can have a significant BR to a charged Higgs bo-

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son ($H^\pm$) and a $b$ quark if $m_{H^\pm} < m_t - m_b$. For large values of $\tan \beta$, the ratio of the vacuum expectation values of the two-Higgs doublets, the charged Higgs boson preferentially decays to $\tau \nu$, thereby increasing the BR of $t \rightarrow \tau \nu b$ relative to the SM expectation and leading to a larger measured $\sigma(p\bar{p} \rightarrow t\bar{t} + X) \cdot \text{BR}(t\bar{t} \rightarrow \tau \tau + \text{jets})$ compared to the value expected from SM assumptions for the BRs and the production cross section \cite{8}. Other possible non-SM processes that can enhance the $t$ quark to $\tau$ lepton BR are $R$-parity violating decays of the $t$ quark in supersymmetric models \cite{6} and new $Z'$ bosons with nonuniversal couplings \cite{3}.

In this article, we present the first measurement of $t\bar{t}$ production in the $\tau + \text{jets}$ final state using a data sample corresponding to an integrated luminosity of 1 fb$^{-1}$ collected with the D0 detector \cite{5} at the Fermilab Tevatron $p\bar{p}$ Collider operating at a center of mass energy $\sqrt{s} = 1.96$ TeV. This measurement uses semihadronic $\tau$ lepton decays, with BR $\approx 65\%$, as secondary electrons and muons from $\tau$ lepton decays are difficult to distinguish from primary electrons and muons resulting from $W$ decays. Previous measurements of $t\bar{t}$ production using $\tau$ leptons in the final state have been performed by the D0 \cite{3} and CDF \cite{10} collaborations in the $\tau_h + \ell$ channel, where $\tau_h$ represents semihadronic $\tau$ lepton decay modes and $\ell$ represents either an electron or a muon.

We apply the following preselection requirements: events must satisfy a multijet trigger requiring at least four jets; this is the same trigger used in the $t\bar{t}$ cross section measurement in the all-hadronic decay mode \cite{11}. Reconstructed events are required to have missing transverse energy $E_T \geq 15$ GeV and $E_T$ significance $>3$, where the $E_T$ significance is a measure of the likelihood that the $E_T$ arises from physical sources rather than fluctuations in the measurement of the energies of the physics objects (jets, muons, electrons and unclustered energy) \cite{12}. Each event must also have at least four reconstructed jets with pseudorapidity $|\eta| < 2.5$ and transverse momentum $p_T > 15$ GeV using an iterative jet cone algorithm \cite{13} with a cone size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$ \cite{14}. The jet energies are corrected for the energy response of the calorimeter, the cone size, multiple $p\bar{p}$ interactions, event pile-up, and calorimeter noise \cite{13}. At least one jet is required to have $p_T > 35$ GeV, and at least two jets are required to have $p_T > 25$ GeV. Each event is also required to have at least one $\tau_h$ candidate with $p_T > 10$ GeV, $|\eta| < 2.5$, and tau neural network output, $NN_\tau > 0.3$ \cite{16}. Finally, to ensure this analysis is statistically independent of other D0 $t\bar{t}$ cross section measurements so that it can be included in a combined cross section measurement, events satisfying the requirements of the $t\bar{t} \rightarrow e(\mu) + \text{jets}$ channel \cite{17}, which include an isolated electron (muon) with $p_T > 20$ GeV, are rejected, as are events satisfying the requirements of the $t\bar{t}$ cross section measurement in the all-hadronic channel \cite{13}.

A semihadronic $\tau$ lepton candidate is a calorimeter cluster of cone size $\Delta R = 0.5$ that includes any subclusters that might be present with $E > 800$ MeV constructed from cells in the electromagnetic (EM) section of the calorimeter and the associated tracks with $p_T > 1.5$ GeV in a cone $\Delta R = 0.3$ contained within the calorimeter cluster. These $\tau$ candidates are classified according to one of three types based on the number of tracks and activity in the EM calorimeter, motivated by the semihadronic $\tau$ lepton decays: (1) $\tau^\pm \rightarrow \pi^\pm \nu_\tau$, (2) $\tau^\pm \rightarrow \pi^\pm\pi^0\nu_\tau$, (3) $\tau^\pm \rightarrow \pi^\pm\pi^0\pi^0(\pi^0)\nu_\tau$. We define the three tau-types as follows: a single track with no EM subclusters (tau-type 1); a single track and $\geq 1$ EM subclusters (tau-type 2); and at least two tracks and $\geq 0$ EM subclusters (tau-type 3).

To further reduce the number of quark and gluon jets reconstructed as $\tau$ leptons, we train separate neural networks for each $\tau_h$ lepton decay type to improve the discrimination of $\tau$ lepton candidates from the jet background. The input variables to $NN_\tau$ are chosen to be minimally dependent on the $\tau$ lepton energy and to exploit the low track multiplicity and the narrow width of the calorimeter cluster produced by $\tau$ leptons decaying semihadronically, the low mass of the $\tau$ lepton, and the differences in longitudinal and transverse shower shapes between $\tau$ leptons and jets \cite{16}. A total of 12 $NN_\tau$ input variable are used to characterize the presence and properties of $\tau_h$ leptons, with seven of these variables in common for all three tau-types. The 12 variables are classified as follows: isolation variables, shower shape variables, and correlation variables between the calorimeter cluster and the associated charged particle tracks. Each $NN_\tau$ is trained on $Z \rightarrow \tau^+\tau^-$ Monte Carlo (MC) events for signal and jets from data, where a jet and a nonisolated muon are back-to-back in $\phi$, for background. These are the same training samples used in Ref \cite{18}.

To measure the number of $t\bar{t} \rightarrow \tau_h + \text{jets}$ signal events in data, the physics and instrumental backgrounds must be determined. The main physics backgrounds are $W + \text{jets}$ events, where the $W$ boson decays to a $\tau$ lepton, and to a smaller extent $Z + \text{jets}$ events, where the $Z$ boson decays to a pair of $\tau$ leptons with one misidentified as a jet and the $E_T$ is due to the neutrinos from the decays of the $\tau$ leptons. The main instrumental background is multijet production where a jet is misidentified as a $\tau$ lepton and the energy is mismeasured leading to a net $E_T$.

The preselection efficiencies and SM BRs for $t\bar{t}$ to final states with leptons \cite{16} are given in Table \ref{tab:signal}. These, as well as the final efficiencies, are calculated using a MC simulation of the experiment. The $t\bar{t}$ signal with leptons in the final state and $W(Z) + \text{jets}$ background are simulated using the ALPGEN 1.2 \cite{20} matrix element generator assuming a $t$ quark mass of 170 GeV and using the CTEQ6L1 \cite{21} parton distribution function set. These events are then processed through PYTHIA 6.2 \cite{22} to simulate parton showering, fragmentation, hadroniz-
TABLE I: A summary of the SM BRs of the various $t\bar{t}$ sub-processes and the preselection efficiencies, where the uncertainties are derived from MC statistics. The leptonic $\tau$ lepton decays are included in the $e$ and $\mu$ channels, and $l^\pm$ represents an $e$, $\mu$ or $\tau$ lepton.

| Process | BR (%) | $\epsilon_{\text{preselection}}$ (%) |
|---------|--------|-------------------------------------|
| $t\bar{t} \rightarrow \tau\_\ell + \text{jets}$ | 9.75 | 40.5±0.2 |
| $t\bar{t} \rightarrow e + \text{jets}$ | 17.7 | 17.0±0.2 |
| $t\bar{t} \rightarrow \mu + \text{jets}$ | 17.6 | 11.1±0.1 |
| $t\bar{t} \rightarrow l^+l^- + \text{jets}$ | 11.1 | 4.04±0.03 |

The numbers of signal and background events are extracted from the final selected sample using a neural network ($NN_{sb}$) event discriminant with the following input variables: (1) the scalar sum of the $p_T$ of all jets and the $\tau$ lepton candidate in the event; (2) the anaplarity [23]; (3) the $E_T$ significance; (4) the invariant mass of all jets and the $\tau$ lepton candidate in the event; and (5) a $\chi^2$ representing how well the 2 and 3 jet invariant masses agree with values expected for hadronic $t$ quark decays, $\chi^2 = (M_{3\text{jet}} - m_t)/\sigma_t^2 + (M_{2\text{jet}} - m_W)^2/\sigma_W^2$, with $M_{2\text{jet}}$ ($M_{3\text{jet}}$) being the 2 (3) jet invariant mass, $m_t = 170$ GeV, $\sigma_t = 45$ GeV and $m_W = 80$ GeV, $\sigma_W = 10$ GeV are the uncertainties on the $NN_{sb}$, uses nine input variables that characterize the presence and properties of secondary vertices and track impact parameters within the jet [27]. The efficiencies of these selections are shown in Table [II].

The expected fraction of $t\bar{t}$ events in the signal sample is $\approx 15\%$ for tau-type 1 and 2, and $\approx 3\%$ for tau-type 3 assuming $\sigma_{t\bar{t}} = 6.9$ pb as measured in this analysis. In addition, the signal sample contains $W(Z) + \text{jets}$ and multijet background events that must be subtracted. The $W(Z) + \text{jets}$ contamination is determined using MC events, while the multijet background is determined from data. We start with the preselected sample and apply a loose $\tau$ lepton veto, $NN_{\tau} < 0.9$. Using MC events, we expect that the resulting sample contains $< 2\%$ $t\bar{t} \rightarrow \tau\_\ell + \text{jets}$ events and $< 3\%$ $W(Z) + \text{jets}$ events, and therefore provides a good representation of the multijet background. To further improve the modeling, the $W(Z) + \text{jets}$ expectation is subtracted from the multijet background data sample.
The difference in the jet finding efficiency in data and 

The measured value of $\sigma_{tt} \cdot BR_{\tau \rightarrow l}$ is 

$0.60_{-0.22}^{+0.23}$ (stat) $+0.15_{-0.14}^{+0.10}$ (syst) $\pm 0.04$ (lumi) pb,

where we combine the tau-type 1 and 2 measurement with the tau-type 3 measurement. Using the theoretical cross section $\sigma_{tt} = 8.06_{-0.75}^{+0.52}$ pb for $m_t = 170$ GeV from Ref. [3], we measure $BR_{\tau \rightarrow l} = 0.074_{-0.029}^{+0.029}$ which is consistent with the SM value given in Table I.

Table IV summarizes the systematic uncertainties on $\sigma_{tt} \cdot BR_{\tau \rightarrow l}$. These are calculated by varying the source by plus and minus one standard deviation, and propagating the uncertainty to the final $\sigma_{tt} \cdot BR_{\tau \rightarrow l}$. The jet energy corrections account for the effect of the jet energy scale and resolution. Jet identification takes account of the difference in the jet finding efficiency in data and

MC. The $b$-tagging entry accounts for the systematic uncertainties on its efficiency. The $\tau$ lepton identification uncertainty is derived by fluctuating the value of each input variable within its statistical uncertainty and observing its effect on the $NN_\tau$ output. The trigger category accounts for the uncertainty in the multijet trigger turn-on and also takes into account the possibility that a multijet event with a $\tau$ lepton can have a different trigger turn-on. Multijet modeling accounts for the uncertainty of the multijet sample to model the $tt \rightarrow \tau_\tau$ + jets background and its limited statistics. The category MC modeling accounts for the $W$ + jets modeling, the uncertainty in the scale factor both for light flavor jets and heavy flavor jets, and the parton distribution function uncertainty. The $tt$ cross section systematic uncertainty represents the effect of the normalization of the non-tau lepton $tt$ background, which is normalized to the theoretical value of the cross section. In addition to the sources listed in Table IV there is a $\pm 6.1\%$ uncertainty in the luminosity measurement.

In addition, we present the combined measurement of the production cross section for $tt$ using all measured $tt$ channels with leptons in the final state listed in Table III that satisfy the selection criteria described above. We repeat the negative log-likelihood fit for the number of $tt$ signal and multijet background events fixing the $tt$ BRs to their SM values, but this time fit for all $tt$ channels arriving at 60.5 $\pm$ 11.8 (stat) events and 24.0 $\pm$ 11.4 (stat) events for channels with tau-types 1 and 2 and with tau-type 3 characteristics, respectively. The fitted multijet backgrounds in this case are 336.7 $\pm$ 11.8 (stat) events

TABLE II: The efficiencies for the tight $\tau$ lepton candidate ($NN_\tau > 0.95$) and $b$-tagging selections for tau-type 1 and 2, and tau-type 3 channels. The uncertainties are based on MC statistics.

| Channel | Trigger (%) | $NN_\tau > 0.95$ (%) | $b$-tag (%) |
|---------|-------------|----------------------|-------------|
| $tt \rightarrow \tau_\tau + jets$ | 74.8 $^{+0.7}_{-0.1}$ | 23.7 $^{+0.3}_{-0.2}$ | 60.1 $^{+2.7}_{-2.2}$ |
| $t\bar{t} \rightarrow e + jets$ | 69.9 $^{+1.5}_{-0.1}$ | 33.1 $^{+0.4}_{-0.2}$ | 58.7 $^{+2.8}_{-2.7}$ |
| $t\bar{t} \rightarrow \mu + jets$ | 63.9 $^{+1.5}_{-0.1}$ | 3.8 $^{+0.1}_{-0.1}$ | 60.3 $^{+2.8}_{-2.7}$ |
| $t\bar{t} \rightarrow l^+l^- + jets$ | 50.5 $^{+1.1}_{-0.2}$ | 43.7 $^{+0.4}_{-0.2}$ | 60.2 $^{+2.8}_{-2.7}$ |

TABLE III: Expected event yields in the two analysis channels assuming the measured $tt$ production cross section of 6.9 pb. The uncertainties are derived from MC statistics.

| Channels | Expected yield |
|----------|----------------|
| $tt \rightarrow \tau_\tau + jets$ | 27.6 $^{+0.4}_{-0.4}$ |
| $t\bar{t} \rightarrow e + jets$ | 26.3 $^{+0.4}_{-0.4}$ |
| $t\bar{t} \rightarrow \mu + jets$ | 2.0 $^{+0.1}_{-0.1}$ |
| $t\bar{t} \rightarrow l^+l^- + jets$ | 4.1 $^{+0.1}_{-0.1}$ |
| Total $tt \rightarrow$ leptons | 61.3 $^{+0.6}_{-0.6}$ |
| $W + jets$ | 13.5 $^{+0.3}_{-0.3}$ |
| $Z + jets$ | 3.4 $^{+0.4}_{-0.4}$ |

FIG. 1: The output of $NN_{lb}$ for a) the tau-type 1 and 2 channel, b) the tau-type 3 channel. The $\chi^2$ per degree of freedom between data and templates is 0.6 for a) and 0.5 for b).
and 1083.2 ± 11.4 (stat) events, for the two channels, respectively. The production cross section is calculated using the negative log-likelihood defined in Eq. 1 for tau-types 1 and 2 and tau-type 3 separately. The two cross sections are then combined to give

\[ \sigma_{\text{H}} = 6.9 \pm^{+1.2}_{-1.1} \text{(stat)} \pm^{+0.8}_{-0.7} \text{(syst)} \pm 0.4 \text{(lumi)} \text{ pb}. \]

To estimate the dependence on \( m_t \), we reevaluate the efficiencies and templates using \( m_t = 175 \text{ GeV} \) and find

\[ \sigma_{\text{H}} = 6.3 \pm^{+1.2}_{-1.1} \text{(stat)} \pm^{+0.7}_{-0.7} \text{(syst)} \pm 0.4 \text{(lumi)} \text{ pb}. \]

In summary, we have performed a measurement of \( \sigma_{\text{H}} \cdot \text{BR}_{\tau_h + j} \) = 0.60 ± 0.28 pb and, using the theoretical \( \bar{t} t \) production cross section, extracted \( \text{BR}_{\tau_h + j} = 0.074 \pm 0.029 \), which agrees with the SM expectation. In addition, we have performed a measurement of the \( p\bar{p} \rightarrow \bar{t} t \pm X \) production cross section, \( \sigma_{\text{H}} = 6.9 \pm^{+1.5}_{-1.4} \text{ pb} \), using the \( \bar{t} t \rightarrow \tau_h + \text{jets} \) topology. The measurement is in agreement with the SM \([3,4]\) and previous experimental measurements using other \( \bar{t} t \) channels \([19]\) at the Tevatron.

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### Table IV: Systematic uncertainties on \( \sigma_{\text{H}} \cdot \text{BR}_{\tau_h + j} \) (in pb) as measured for the \( \bar{t} t \rightarrow \tau_h + \text{jets} \) channel.

| Source                          | \( \tau_h + \text{jets (type 1 and 2)} \) | \( \tau_h + \text{jets (type 3)} \) | Combined |
|---------------------------------|-----------------------------------------|-----------------------------------|----------|
| Jet energy corrections          | -0.078                                  | +0.081                            | -0.047   |
| Jet identification              | -0.019                                  | +0.019                            | -0.012   |
| b tagging                       | -0.074                                  | +0.084                            | -0.035   |
| Tau identification              | -0.035                                  | +0.035                            | -0.020   |
| Trigger                         | -0.002                                  | +0.053                            | -0.000   |
| Multijet modeling               | -0.090                                  | +0.090                            | -0.169   |
| MC modeling                     | -0.028                                  | +0.028                            | -0.012   |
| \( \bar{t} t \) cross section   | -0.064                                  | +0.068                            | -0.020   |
| Total systematic uncertainty     | -0.16                                   | +0.15                             | -0.18    |

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