Observation of Hadronic W Decays in $t\bar{t}$ Events with the Collider Detector at Fermilab

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We observe hadronic W decays in $t\bar{t} \to W(\to \ell\nu) + \geq 4$ jet events using a 109 pb^{-1} data sample of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab. A peak in the dijet invariant mass distribution is obtained that is consistent with W decay and inconsistent with the background prediction by 3.3σ. From this peak we measure the W mass to be $77.2 \pm 4.6(\text{stat} + \text{syst})\ \text{GeV}/c^2$. This result demonstrates the presence of a second W boson in $t\bar{t}$ candidates in the $W(\to \ell\nu) + \geq 4$ jet channel. [S0031-9007(98)06372-8]

PACS numbers: 14.65.Ha, 13.38.Be, 13.85.Qk

The Collider Detector at Fermilab (CDF) presented the first direct evidence for top quark production with 19.3 pb^{-1} of data collected in 1992–1993 [1] and also reported a detailed kinematic study of the presumed top decays with this data sample [2]. In 1995, the existence of the top quark was firmly established by CDF [3] and D0 [4]. CDF observed and studied $t\bar{t}$ production using a sample of 67 pb^{-1} employing techniques similar to those previously published [5,6].

These studies assume that a top quark decays predominantly into a bottom quark and a W boson, and that hadron jets may be used to reconstruct the original particles. To test these assumptions, we have searched for hadronic W decays in a $t\bar{t}$-enriched sample containing a high-P_T lepton, a high-P_T neutrino, and four or more jets, which is consistent with the process $p\bar{p} \to t\bar{t}X \to W^+bW^-\bar{b}X \to \ell\nu bjj\bar{b}X$ with $\ell = e$ or μ, and j representing a jet. Hereafter we call these events "$W+ \geq 4$ jet events." The observation of hadronic W decays in $W+ \geq 4$ jet events demonstrates the presence of two W bosons in the final state for $t\bar{t}$ candidates.

The studies reported here use a $109 \pm 7\ \mathrm{pb}^{-1}$ data sample. The CDF detector is described in detail elsewhere [7]. Three analysis techniques yield signal-to-background ratios ranging from 0.23 to 1.4 in the dijet invariant mass region 60–100 GeV/c^2.

Monte Carlo $t\bar{t}$ events are generated by the HERWIG program [8] with a top mass of 175 GeV/c^2 [9]. The expected background from direct W production recoiling against significant jet activity, hereafter referred to as W + multijet background, is modeled using the VECBOS Monte Carlo program [10]. Both programs use the world-average W mass of 80.4 GeV/c^2 [11]. A more detailed description of the Monte Carlo samples can be found elsewhere [1].

To select $t\bar{t} \to W+ \geq 4$ jet candidates, we require an isolated, high-P_T electron or muon ($P_T > 20\ \mathrm{GeV}/c$), high missing transverse energy [12] ($\not{E}_T > 20$ GeV) indicating the presence of a neutrino, three jets with $E_T >$ 15 GeV and $|\eta| < 2.0$, and a fourth jet with $E_T > 8$ GeV and $|\eta| < 2.4$. After these cuts 163 events remain. The expected fraction of $t\bar{t}$ events in this sample is estimated to be 33%, using the methods of the $t\bar{t}$ cross section measurement [13].

For the event selection, neither the jet E_T nor the $\not{E}_T$ are corrected for detector effects. However, when calculating a dijet invariant mass, jet energies are corrected by a pseudorapidity and energy-dependent factor which accounts for such effects as calorimeter nonlinearity, reduced response at detector boundaries, contributions from the underlying event, and multiple interactions and losses outside the clustering cone [14]. We apply an additional energy correction to the four highest-E_T jets in a $t\bar{t}$ candidate event. The correction depends on the type of parton they are assigned to: a light quark, a hadronically decaying b quark, or a b quark that decayed semileptonically [1]. This parton-specific correction was derived from a study of Monte Carlo $t\bar{t}$ events.

The lepton-$\not{E}_T$ transverse mass distribution is shown in Fig. 1. Also shown are the Monte Carlo expectations from $t\bar{t}$ as well as $t\bar{t}$ plus W + multijet background.

We use three methods to search for W decay to two jets: a top mass reconstruction technique, a total transverse energy cut, and the identification of both b jets.

In the first method, we search for a W decaying to two jets by kinematically reconstructing $t\bar{t} \to \ell\nu bjj\bar{b}$ with a constrained fitting technique similar to the one used for the determination of the top mass [1]. The constraints used in the top mass measurement include the requirement that the two jets hypothesized to come from the W decay have an invariant mass equal to the W mass. Here we eliminate the W mass constraint. There are multiple solutions due to the ambiguity in determining the neutrino longitudinal momentum and the assignment of jets to the parent partons. We choose the solution with the lowest χ^2. The resolution and signal-to-background ratio for $t\bar{t}$ events is improved by identifying b quark decays within jets and requiring that the "b tagged" jet correspond to a b quark in the fit. To tag b jets, we exploit either the long lifetime of b quarks by requiring a secondary vertex in the silicon vertex detector (SVX b tag), or the semileptonic decays of b quarks by searching for additional leptons (SLT b tag) [1]. The fraction of correct W jet assignments was found from Monte Carlo studies to be improved from 22% before b tagging to 37% after tagging.

Of the 163 events passing the $W+ \geq 4$ jet selection cuts, 37 have at least one b tag found by the SVX or SLT algorithms. The expected background is $8.9^{+2.0}_{-1.7}$ events, calculated using techniques described in [13]. The dijet

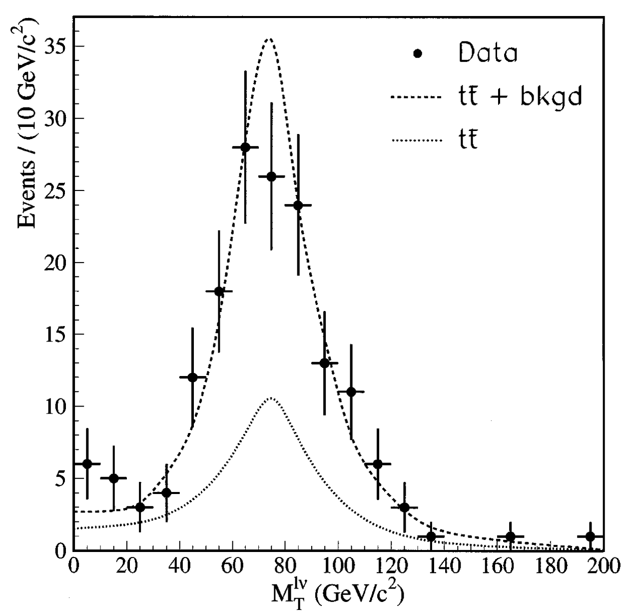

FIG. 1. The lepton-$\not{E}_T$ (neutrino) transverse mass distribution in the $W+ \geq 4$ jet data (points) along with the Monte Carlo expectations from $t\bar{t}$ (dotted line) and $t\bar{t}$ plus W + multijet background (dashed line).

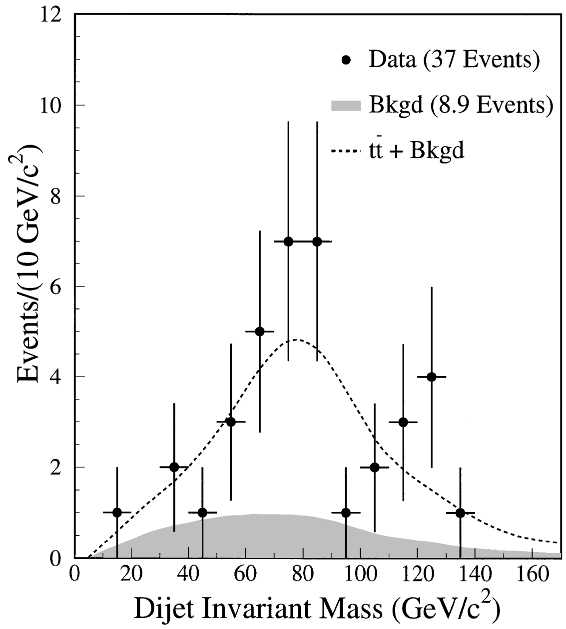

FIG. 2. Invariant mass distribution for the two jets that are associated with the W by the constrained kinematic fit. The shaded histogram shows the expected distribution from background events; $t\bar{t}$ plus background events are shown as a dashed line.

invariant mass distribution for these events is shown in Fig. 2. Also shown are the Monte Carlo distributions for $t\bar{t}$ and background, normalized to 28.1 and 8.9 events, respectively. We note a strong enhancement in the data distribution near the world-average W mass [11].

The second method employs a cut on the minimum total transverse energy H_T to enhance the $t\bar{t}$ contribution in the sample. H_T is defined as the scalar sum of the P_T of the lepton (E_T for an electron), the four highest-E_T jets, and the $\not{E}_T$ [6]. We optimize the H_T threshold (310 GeV) using $t\bar{t}$ and background simulations. This cut improves the fraction of $t\bar{t}$ events in the sample from 33% to 55%.

We calculate the invariant mass of each two-jet pair out of the four highest-E_T jets. Monte Carlo simulations predict that two jets from W decay are included in the four highest-E_T jets with an efficiency of 66%. There are six combinations of two jets in each event. To determine the contributions from non-$t\bar{t}$ backgrounds and combinatoric backgrounds in $t\bar{t}$ events, we fit the dijet mass distribution M_{jj} outside the W mass region to the following function: $N_{bg} f_{bg}(M_{jj}) + N_{\text{comb}} f_{\text{comb}}(M_{jj})$, where N_{bg} and N_{comb} are the number of non-$t\bar{t}$ and $t\bar{t}$ combinatoric background dijet pairs, respectively, and f_{bg} and f_{comb} are their dijet mass distributions, derived from Monte Carlo. Since non-$t\bar{t}$ backgrounds, such as WW, WZ, and $b\bar{b}$ are smaller and give dijet mass distributions similar to W + multijets, f_{bg} is obtained from VECBOS calculation of W + multijet backgrounds.

We extract the $W \rightarrow 2$ jets signal by subtracting the W + multijet backgrounds and the combinatoric background as shown in Fig. 3. We fit the resulting distribution to a Gaussian function with a fixed width of 11.7 GeV$/c^2$ (obtained from Monte Carlo) and find 29 ± 13 $W \rightarrow 2$ jet events in the mass region 70–90 GeV$/c^2$, which is consistent with the number of $W \rightarrow 2$ jet events (20 ± 6) expected from the CDF $t\bar{t}$ production cross section measurement [13]. This excess is inconsistent with the expected background by 2.8σ, corresponding to a probability of 2.6×10^{-3} of it being a background fluctuation. The signal-to-background ratio in the mass region 60–100 GeV$/c^2$ is 0.23, and the overall fraction of non-$t\bar{t}$ background is $(27 \pm 14)\%$. The dijet invariant mass peak has a mean of $77.1 \pm 3.8(\text{stat}) \pm 3.6(\text{syst})$ GeV$/c^2$. The systematic uncertainty comes mainly from the jet energy scale, which is the uncertainty on how well our measured jet energies correspond to the original parton energies. The systematics are listed in Table I, and are described in more detail in Ref. [9].

In the third method, we isolate the hadronic W decay by identifying two b jets in the four highest-E_T jets of $W+ \geq 4$ jet events. Such events are hereafter called "double-b tagged" $W+ \geq 4$ jet events. Double-b tagging eliminates ambiguity about which two jets are assigned to the W, and further suppresses non-$t\bar{t}$ background. Once we find at least one b jet with an SVX tag or an SLT tag in an event, we look for the second b jet. The second b tag can be an SVX tag, an SLT tag, or a looser jet probability tag [15]. The jet probability algorithm obtains the probability that a jet is consistent with the decay of a zero-lifetime particle by using the impact parameters of the tracks in the jet as measured in the silicon vertex detector. Jets with probabilities less than 5% are considered tagged. We form the invariant mass of the remaining two untagged jets.

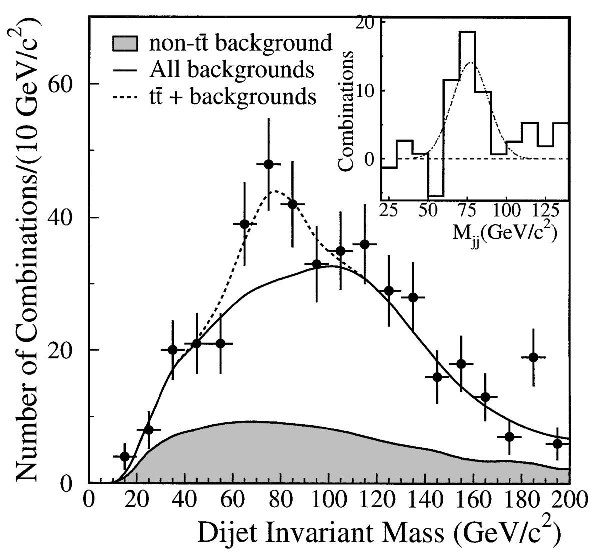

FIG. 3. Dijet mass distribution in $W+ \geq 4$ jet events after the $H_T > 310$ GeV cut. Also shown are a fitted curve of the sum (solid) of the W + multijet background (shaded) and the combinatoric background from $t\bar{t}$ events. A Gaussian distribution fitted to the W mass peak is shown by the dotted curve. The inset shows the W mass peak after subtracting the backgrounds.

TABLE I. The list of uncertainties (in GeV/c^2) in the $W \to 2$ jets mass for the H_T cut and double-b tag analyses. The columns "common" and "combined" correspond to the uncertainties common in the two analyses and the combined uncertainties of the two analyses, respectively.

Uncertainty (GeV/c^2)	H_T cut	Double-b tag	Common	Combined
Statistical	4.6	5.1	⋯	3.5
Jet energy scale				2.8
(a) Detector effects	1.9	1.9	1.9	
(b) Soft gluon effects	2.0	2.0	2.0	
Other systematics				0.6
(a) Backgrounds	0.5	0.2	⋯	
(b) Fitting	1.9	0.6	⋯	
(c) H_T cut	1.0	⋯	⋯	
Total uncertainty	5.8	5.9	2.8	4.6

In our $t\bar{t}$ Monte Carlo sample, 25% of the events are double-b tagged. The technique finds the two correct W jets in 43% of these events. However, this number is sensitive to the amount of initial and final state radiation in the simulation, since the largest contamination (38% of double-b tagged events) comes from events where the four highest-E_T jets do not correspond to two b jets and two jets from W decay. Other $t\bar{t}$ backgrounds include events where both W bosons decayed leptonically and only one lepton was identified (8%), events where a c quark from W decay was tagged (8%), and mistags in jets from W decay (3%), where a mistag means a tag of a jet originating from neither a b nor a c quark.

We expect 1.3 ± 0.3 double-tagged events from non-$t\bar{t}$ background, with the largest contributions being 0.6 ± 0.2 events from mistags and 0.4 ± 0.2 events from $Wb\bar{b}$ and $Wc\bar{c}$ process which are W + multijet events containing real heavy flavor.

In the data, we find eleven double-b tagged events. The dijet invariant mass of the two untagged jets in these eleven events is shown in Fig. 4. Eight of the eleven dijet combinations fall in the mass window of 60–100 GeV/c^2. In Monte Carlo simulations of both W + multijet and $t\bar{t}$ combinatoric backgrounds, only about a third of the dijet mass combinations fall in this window. The inset plot of Fig. 4 shows the mass of the hadronic W candidates against the transverse mass of the leptonic W candidates in the same events.

We fit this mass distribution to a sum of a Gaussian $W \to 2$ jets signal, $t\bar{t}$ backgrounds, and non-$t\bar{t}$ backgrounds, and obtain a W mass of $78.1 \pm 4.4(\text{stat}) \pm 2.9(\text{syst})$ GeV/c^2, with the systematic uncertainties listed in Table I. The fitted W signal has 8.7 events, and 0.7 events from $t\bar{t}$ backgrounds. Constraining the fit to the expected $W \to 2$ jets fraction in $t\bar{t}$ events yields 6.4 W events, and a W mass of $78.3 \pm 5.1(\text{stat}) \pm 2.9(\text{syst})$ GeV/c^2. We use this value for obtaining a final combined W mass.

We use likelihood fits to evaluate the significance of this peak. We first fit the data using a Gaussian W signal whose mean is the world-average W mass plus $t\bar{t}$ and non-$t\bar{t}$ backgrounds. Next we remove the signal term and note the change in likelihood. We then repeat this procedure on Monte Carlo pseudoexperiments using only $t\bar{t}$ and non-$t\bar{t}$ background events, and study how often the likelihood changes by at least the amount seen in the data. This change in likelihood was seen with a probability of 1.7×10^{-3}, corresponding to a Gaussian significance of 2.9σ. If we construct the pseudoexperiments with the expected W signal fraction, we find that a change in likelihood larger than the one seen in the data occurs 15% of the time.

An overall result is obtained by excluding the eleven double-b tagged events from the H_T cut analysis. We then combine the two analyses to obtain a W mass peak

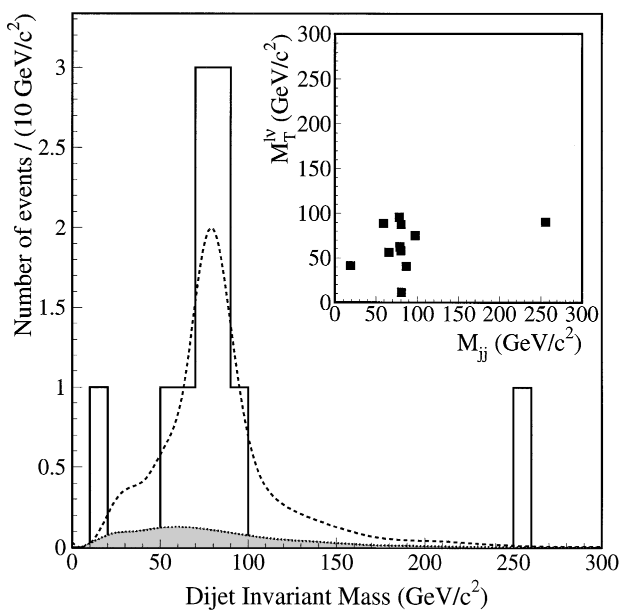

FIG. 4. Dijet mass spectrum of the two untagged jets in double-b tagged events. The shaded curve shows the expected distribution from W + multijet backgrounds and the dashed curve is from $t\bar{t}$ plus background. The inset compares the lepton-$\not{E}_T$ (neutrino) transverse mass to the dijet invariant mass in these eleven events showing evidence for events with both a leptonically decaying W and a hadronically decaying W.

significance of 3.3σ, corresponding to a probability of 5.4×10^{-4} of it being a background fluctuation and a W mass of $77.2 \pm 3.5(\text{stat}) \pm 2.9(\text{syst})\ \text{GeV}/c^2$ with the systematic uncertainties listed in Table I. This is consistent with the current world-average W mass of $80.375 \pm 0.120\ \text{GeV}/c^2$ [11].

In conclusion, we observe hadronic W decays as a dijet mass peak in $t\bar{t} \rightarrow W + \geq 4$ jet events. This demonstrates the presence of a second W boson in the $t\bar{t}$ candidates. In the future, these techniques can be used to set limits on nonstandard top decays.

We thank the Fermilab staff and the technical staffs of the participating institutions for their contributions. This work was supported by the U.S. Department of Energy and the National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Science, Culture, and Education of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China, and the A. P. Sloan Foundation.

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[12] In the CDF coordinate system, θ is the polar angle with respect to the proton beam direction. The pseudorapidity η is defined as $-\ln\tan(\theta/2)$. The transverse momentum of a particle is $P_T = P\sin\theta$. The analogous quantity using calorimeter energies, $E_T = E\sin\theta$, is called transverse energy. Missing transverse energy $\not{E}_T$ is defined as $-\Sigma E_T^i \cdot \hat{n}_i$, where $\hat{n}_i$ are the unit vectors, in the plane transverse to the beam line, pointing from the interaction point to the energy deposition in cell i of the calorimeter.
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