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First Observation of the All Hadronic Decay of $t\bar{t}$ Pairs

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First observation of the all hadronic decay of $t\bar{t}$ pairs

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We present the first observation of the all hadronic decay of $t\bar{t}$ pairs. The analysis is performed using 109 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). We observe an excess of events with five or more jets, including one or two b jets, relative to background expectations. Based on this excess we evaluate the production cross section to be in agreement with previous results. We measure the top mass to be $186 \pm 10 \pm 12$ GeV/c^2.

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At the Tevatron the dominant mechanism for top quark production in $p\bar{p}$ collisions is $q\bar{q}$ annihilation to $t\bar{t}$. In the framework of the Standard Model, each top quark decays almost exclusively into a W boson and a b quark. The CDF and DØ collaborations have already reported the observation of the top quark in events where one or both of the W bosons decays leptonically [1–3]. In this analysis we search for events in which both W bosons decay into quark–antiquark pairs, leading to an all hadronic final state. The study of this channel, with a branching ratio of about 4/9, complements the leptonic modes and the mass measurement takes advantage of a fully reconstructed final state. Since the expected decay signature involves only hadronic jets, a very large background from standard QCD multijet production is present and dominates over $t\bar{t}$ production. To reduce this background, we search for b quark decays with a displaced secondary vertex.

The $t\bar{t}$ signal is obtained using two separate approaches. In the first, events with at least one identified b jet are required to pass strict kinematic criteria that favor $t\bar{t}$ production and decay. In the second, on events with two identified b jets, we impose a minimum energy requirement. In both cases we observe an excess of events with respect to the background prediction, from which we measure the production cross section. We observe a structure in the 3–jet mass distribution for fully reconstructed 6–jet events including at least one identified b jet, which provides additional support that the excess is coming from $t\bar{t}$ production. We use these events to measure the mass of the top quark.

The data sample used in this analysis was collected with the CDF detector from 1992 to 1995, corresponding to a total integrated luminosity of $\int\mathcal{L}dt = 109 \pm 7$ pb^{-1}. The CDF detector is described in detail elsewhere [4]. The vertex detector, a four–layer silicon strip device, located immediately outside the beampipe, provides precise track reconstruction in the plane transverse to the beams and is used to identify secondary vertices from b and c quark decays. The vertex detector [5] operating during the first period of data taking (1992–93, $\int\mathcal{L}dt = 19 \pm 1$ pb^{-1}) was replaced in 1994 by a new detector equipped with radiation hard electronics [6], collecting data through 1995 ($\int\mathcal{L}dt = 90 \pm 7$ pb^{-1}). The momenta of charged particles are measured in the central tracking chamber (CTC), which is inside a 1.4 T superconducting solenoidal magnet. Outside the CTC, electromagnetic and hadronic calorimeters, segmented in $\eta - \phi$ towers, cover the pseudorapidity region $|\eta| < 4.2$ [7], and are used to identify jets and electron candidates. Outside the calorimeters, drift chambers in the region $|\eta| < 1.0$ provide muon identification.

The trigger, developed specifically for this analysis, relies on calorimeter energy measurement and requires four or more clusters of contiguous towers [8], with transverse energy per cluster $E_T = E\sin\theta \geq 15$ GeV and a total transverse energy $\sum E_T \geq 125$ GeV. Jets are reconstructed [9] using a cone with a radius of 0.4 in η–ϕ space, and the data sample is defined by the requirement of four or more jets, each with $E_T > 15$ GeV and $|\eta| < 2.0$. This set consists of approximately 230 000 events, with an expected signal to background ratio $S/B \approx 1/500$ [10]. Jet energies are then corrected by a pseudorapidity and energy–dependent factor that accounts for calorimeter nonlinearity, reduced response at detector boundaries, energy radiated out of the jet reconstruction cone and for the energy inside the cone that comes from partons not associated with the hard scatter [9,11]. Since $t\bar{t}$ events are characterized by high jet multiplicity and have a harder E_T distribution than the QCD background, additional requirements can be imposed to increase S/B. We select events with ≥ 5 jets, and require the total transverse energy, evaluated as the sum of the corrected jet E_T's, to be $\sum E_T \geq 300$ GeV, yielding 21 890 events. The accuracy of background calculations is verified using events with 4 jets, where the expected $t\bar{t}$ signal is small. Events containing high P_T electrons or muons, defined as in [2], are removed. The resulting data sample is still dominated by multijet production from QCD processes ($S/B \approx 1/110$). To reject events with only light quark and gluon jets, we require at least one jet to be identified as a b candidate whose decay point is displaced from the primary vertex [2]. A tag is defined as positive (negative) if the projection of the secondary vertex displacement points along (opposite) the jet direction in the plane transverse to the beam line [1]. Due to tracking resolution effects, light quark or gluon jets can also be misidentified as b candidates (fake tags) and are equally likely to have positive or negative tags. We identify b quark jets by requiring a positive tag and this results in 1596 events with an expected $S/B \approx 1/20$.

In the first approach (Technique I) we require that $\sum E_T$ divided by the invariant mass of the multijet system, $\sqrt{\hat{s}}$, be greater than 0.75. In addition, we demand that A, the aplanarity [12] of the events calculated from the jet momenta, be $A > -0.0025 \sum E_T + 0.54$ (with $\sum E_T$ in GeV), where the sum does not include the contribution from the two highest E_T jets. The values chosen for both cuts are those that maximize the expected signal significance for $t\bar{t}$ events, while maintaining a high efficiency. The background to the $t\bar{t}$ signature, from QCD production of heavy quark pairs ($b\bar{b}$ and $c\bar{c}$) and fake tags, is estimated from the multijet sample by applying a parameterization of the positive tag probability event by event. This calculation assumes that the sample contains no $t\bar{t}$ events and needs an iterative correction to account for them [1]. The tag probability is parameterized as a function of E_T, η and track multiplicity of each jet, along with the event aplanarity. This parameterization is found to describe within 3% the number of observed tags in multijet data at different jet multiplicities, without the kinematic requirements mentioned above. Good agreement between data and predicted b tags is also found in an independent sample from a high-$\sum E_T$ trigger [13].

The sample selected with all the kinematic requirements of Technique I consists of 187 events containing a total of 222 b tags. The number of tagged b jets expected from the background is $164.8 \pm 1.2 \pm 10.7$. The first uncertainty comes from the uncertainties in the parameterization. The systematic uncertainty on this estimate comes from several sources: the dependence of the tag probability on the kinematic requirements (5.0%) and jet multiplicity (3.0%), its correlation with the instantaneous luminosity and run conditions (2.3%), the correlations among tags in the same event (1.3%) and W and Z production (1.0%), for a total uncertainty of 6.5%. Table I summarizes the number of tagged jets and events observed and the estimated background for each jet multiplicity.

The significance of the excess of observed tags is estimated from the probability that the background fluctuates up to the number of b tags found or more. For events with ≥ 5 jets, we calculate this probability to be $\mathcal{P} = 1.5 \times 10^{-3}$, corresponding to 3 standard deviations for a Gaussian distribution. From the number of tagged events and the background estimate corrected for the $t\bar{t}$ content, we extract the number of $t\bar{t}$ candidates to be 10.4 ± 6.0 and 34.7 ± 16.1 for the first and second period of data taking, respectively. The efficiency of the trigger, kinematic selections and b tagging are evaluated using the HERWIG Monte Carlo program [14] and a full simulation of the CDF detector. The CLEO Monte Carlo program

[15] is used to model the decays of b hadrons. The combined efficiency of the trigger and kinematic selection amounts to $9.9 \pm 1.6\%$ for a top mass of $m_t = 175$ GeV/c^2, where the uncertainty is mainly systematic and due to jet energy scale (9%), different fragmentation (9%) and gluon radiation modeling (11%). The b tagging efficiency has been calculated for the two periods of data taking separately and amounts to $38 \pm 11\%$ and $46 \pm 5\%$ respectively. The measured cross section, obtained for $m_t = 175$ GeV/c^2, is $\sigma_{t\bar{t}} = 9.6 \pm 2.9(stat)^{+3.3}_{-2.1}(syst)$ pb.

In the second approach (Technique II) we require the presence of additional b tags. A study of possible physics processes that result in ≥ 2 b tags in the final state indicates that the dominant sources are QCD heavy flavor pair production and fake double tags. Fake double tags have at least one negative tag from a light quark or a gluon. The number of fake double tags observed in the data is compared with the expected number from a calculation using the probability of having a negative tag which is parameterized in terms of the E_T of the jet, its track multiplicity and the total transverse energy of the event. The two numbers agree within 5%.

To determine the expected number of double tags due to QCD production of heavy flavors we use PYTHIA Monte Carlo [16] samples of QCD multijet production. First, we scale the jet multiplicity distribution of QCD Monte Carlo events so that it describes the data with at least one b tagged jet after subtracting fake double tags. Using this jet multiplicity distribution, the QCD heavy flavor background in all multiplicities for events with ≥ 2 b tags can be estimated as long as the absolute QCD cross section is known. To obtain this cross section we use events with four jets and ≥ 2 b tags, which are dominated by QCD heavy flavor production and fake double tags. We normalize the absolute prediction of the QCD Monte Carlo to the total number of such events after accounting for fake double tags and the small presence of $t\bar{t}$ in 4–jet events.

We observe 157 events with ≥ 5 jets containing ≥ 2 b tags with a predicted background of 122.7 ± 13.4 from QCD heavy flavor and fake double tags. To combine the excess in different jet multiplicity bins we employ a simultaneous likelihood fit of the events to a sum of fake double tags, QCD heavy flavors and $t\bar{t}$ production. The number of events from QCD heavy flavors is constrained to the expectation from the normalization procedure described above and allowed to vary within its total uncertainty. The likelihood function takes into account the correlations between different systematic effects. The number of $t\bar{t}$ candidate events returned by the fit is 5.9±3.9 and 31.6±16.4 for the first and second period of data taking respectively. The corresponding numbers of background events are 21.1±4.5 and 98.4±17.3 (see Table II). The efficiency for passing the trigger and the kinematic requirement is $26.3 \pm 4.5\%$ for a top mass of 175 GeV/c^2, where the sources of systematic uncertainty are the jet energy scale (8%), different fragmentation (13%), gluon radiation modeling (8%) and the determination of the QCD heavy flavor normalization (18%). The efficiency for tagging ≥ 2 heavy flavor jets is calculated to be $7 \pm 6\%$ and $12 \pm 2\%$ for the two data taking periods.

Using the results of the fit, the measured cross section is $11.5 \pm 5.0(stat)^{+5.9}_{-5.0}(syst)$ pb. The significance of the excess is estimated using the probability that the background fluctuates up to the number of observed tagged events or more. This probability is found to be $\mathcal{P} = 2.5 \times 10^{-2}$, corresponding to 2 standard deviations for a Gaussian distribution.

To combine the cross sections from the two approaches we take into account the correlations between the efficiencies for the two methods and the large overlap between the two data samples (34 events in common). The combined cross section is evaluated using a multivariate Gaussian function which takes into account these correlations (correlation coefficient $\rho = 0.34 \pm 0.13$). For $m_t = 175$ GeV/c^2, the combined cross section is measured to be $\sigma_{t\bar{t}} = 10.1 \pm 1.9(stat)^{+4.1}_{-3.1}(syst)$ pb. The cross section changes by -12% ($+20\%$) if the top mass is assumed to be 10 GeV/c^2 higher (lower). This value has to to be compared with the latest theoretical predictions which are in the range of 4.75–5.50 pb for $m_t = 175$ GeV/c^2 [17]. This measurement will be combined with those obtained from leptonic channels in a forthcoming paper.

To determine the top quark mass, full kinematic reconstruction is applied to the sample of events with 6 or more jets, one or more tags and the kinematic requirements of Technique I. Events are reconstructed to the $t\bar{t} \to W^+b\, W^-\bar{b}$ hypothesis, where both W bosons decay into a quark pair, with each quark associated to one of the six highest E_T jets. This corresponds to 16 four–momentum conservation equations with 13 unknown variables, the three–momenta of the two top quarks and the two W bosons, and the unknown top quark mass. Since all events contain at least one b tag, we require the tagged jet to be assigned to a b or $\bar{b}$ quark. A kinematic fit is applied and the combination with lowest χ^2 is chosen. In order to avoid threshold effects in the mass distributions the $\sum E_T$ cut is lowered from 300 to 200 GeV, while keeping the other requirements unchanged. The 3–jet mass distribution for the 136 tagged events is displayed in Figure 1 along with the expected background and $t\bar{t}$ contributions. The background is calculated by normalizing the spectrum of the untagged sample of 1121 events to 108 ± 9 events, estimated from the tag probability. A maximum likelihood method is applied to extract the top quark mass. The experimental data are compared to HERWIG Monte Carlo samples of $t\bar{t}$ events, in a top quark mass range from 160 to 210 GeV/c^2, and a background sample from the untagged events. The same method was applied in Ref. [1] and [2]. The difference in $-\ln(\text{likelihood})$ with respect to the minimum is shown in the inset to Fig. 1. The minimum is at 186 GeV/c^2, with a ± 10 GeV/c^2 statistical uncertainty. Systematic uncertainties in this fit arise from gluon radiation and fragmentation effects ($\pm 4.6\%$), the jet energy scale ($\pm 2.9\%$), the fitting procedure ($\pm 2.8\%$) and background estimation ($\pm 0.9\%$). Combining all these uncertainties in quadrature gives a value of $\pm 6.2\%$. We thus measure a top quark mass of $186 \pm 10(stat) \pm 12(syst)$ GeV/c^2. This value agrees well with that of Ref. [2], and correlations in the systematic uncertainties will be treated in a forthcoming paper.

In conclusion, with the aid of a dedicated multijet trigger, an optimized kinematic selection and a b jet identification technique, we isolate for the first time a signal in the all hadronic final state of $t\bar{t}$ decay. The $t\bar{t}$ production cross section is measured to be $10.1^{+4.5}_{-3.6}$ pb assuming $m_t = 175$ GeV/c^2. The top quark mass is measured to be $186 \pm 10 \pm 12$ GeV/c^2.

These results agree well with previous measurements from leptonic channels.

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TABLE I. Technique I: Number of events with at least one b tag and number of tagged jets in those events. The background is estimated using the positive tag parameterization. In events with 4 jets we observe 12 tagged jets over a predicted background of 11.7 ± 0.8.

Number of jets	5	6	≥ 7
Tagged evts	70	82	35
Background	58.3 ± 3.8	62.8 ± 4.1	30.3 ± 2.0
Tagged jets	80	99	43
Background	62.8 ± 4.1	68.6 ± 4.5	33.4 ± 2.2

TABLE II. Technique II: Number of events with at least two b tags. The numbers of events from QCD heavy flavor production and fake double tags are returned by the likelihood fit. In events with 4 jets we observe 95 tagged events over a predicted background of 90.9 ± 9.1.

Number of jets	5	6	≥ 7
Tagged events	102	42	13
QCD h. f.	60.3 ± 10.1	21.3 ± 5.6	4.6 ± 2.2
Fakes	22.5 ± 7.0	7.7 ± 2.2	3.1 ± 3.1

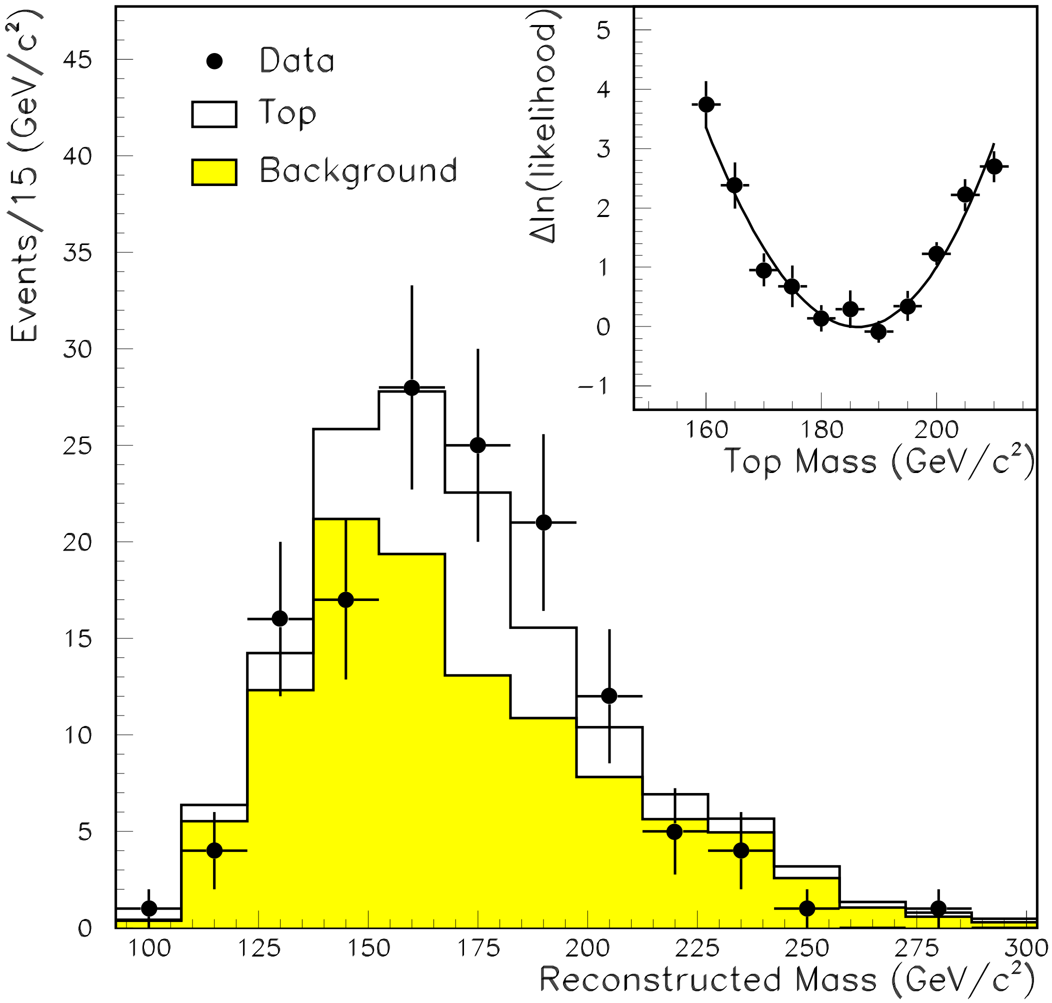

FIG. 1. Technique I: Reconstructed mass distribution for events with at least one tag (•). Also shown are the background distribution (shaded) and the contribution from $t\bar{t}$ Monte Carlo events with $m_t = 175$ GeV/c^2 (hollow). The inset shows the difference in $-\ln$(likelihood) and the fit used to determine the top mass.