14

The Top Quark

Completing the Third Generation.

No one could doubt that there would be a sixth quark, the top or t, but it was equally certain that initially no one knew where it would be found. With the b quark near 5 GeV, 15 GeV or so seemed reasonable for the mass of the top quark. Every new accelerator that came on line had the potential to make the discovery and every one of them came up empty handed. Particularly disappointing were the cases of TRISTAN, an e^+e^- collider at KEK, which reached c.m. energy of 61.4 GeV and set a lower bound of 30.2 GeV and the S$p\overline{p}$S collider at CERN, which found the W and Z. Even SLC and LEP searched to no avail, setting limits at half the mass of the Z. This left the search to hadron colliders.

In 1984 and 1985 CERN's S$p\overline{p}$S collider reigned as the world's highest energy machine, with $\sqrt{s} = 630$ GeV. Having already discovered the W and Z, it was positioned to look for the top quark through the decay $W \to t\overline{b}$ and early results from UA-1 gave evidence for a top quark with a mass of 40 ± 10 GeV. However, additional running and further analysis did not confirm the result but instead produced a bound of 55 GeV.

With further running at the S$p\overline{p}$S in 1988/9 both UA-1 and UA-2 improved this limit. Using signals from muons and jets, UA-1 ruled out a top quark below 60 GeV, while UA-2, which looked in the electron plus jets channel excluded masses below 69 GeV.

At the same time, at CDF the lower limit on the top quark mass was raised to 77 GeV. Adding additional channels moved the limit higher, to 85 GeV, then to 91 GeV.

The Standard Model gave no direct information on the mass of the top quark, for all the quark masses are simply arbitrary parameters. However, using detailed electroweak measurements it was possible to make inferences about the mass of the top quark. Of all the particles in the Standard Model, only the t and the Higgs remained to be discovered. The prediction of the W mass in terms of the Z mass in lowest order is

$$m_W^2 = \frac{1}{2} m_Z^2 \left(1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_F m_Z^2}} \right). \tag{14.1}$$

The W and Z can undergo virtual transitions, the W to $t\overline{b}$ and the Z to $t\overline{t}$ or $b\overline{b}$. These result in small radiative corrections to the relation between their masses. It is also possible

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for the W and Z to make virtual transitions by emitting and reabsorbing a Higgs particle. It turns out that the mass of the Higgs boson enters these effects only as $\ln m_H^2$ while there are corrections to the W and Z masses squared proportional to m_t^2, as discussed in Chapter 13. A good measurement of the W mass together with a rough guess for the Higgs mass was enough to make a reasonable prediction of the mass of the top quark. By 1994, these estimates centered on values around 180 GeV.

Though the mass of the top was uncertain, its behavior was completely predicted by the Standard Model. Once the limits on the top mass exceeded the mass of the W it was clear that its decay would be $t \to W^+ b$, whose width is

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_t^2}\right). \tag{14.2}$$

If the t quark were well above the bW threshold, this width would be on the order of a GeV, meaning that any narrow bound states $t\overline{t}$ would be completely obscured. More picturesquely, the t would decay before it could bind.

The W^+ could decay leptonically to $e^+\nu_e$, $\mu^+\nu_\mu$, or $\tau^+\nu_\tau$, or nonleptonically, primarily to $u\overline{d}$ or $c\overline{s}$. Since the t was pair produced, there were four general forms for the events:

$$\begin{array}{lllll} t \to & b(\ell^+\nu) & \overline{t} & \to & \overline{b}(\ell^-\overline{\nu}) \\ t \to & b(q\overline{q}) & \overline{t} & \to & \overline{b}(\ell^-\overline{\nu}) \\ t \to & b(\ell^+\nu) & \overline{t} & \to & \overline{b}(q\overline{q}) \\ t \to & b(q\overline{q}) & \overline{t} & \to & \overline{b}(q\overline{q}) \end{array}$$

The last of these would be particularly hard to isolate since these events would be masked by much more common events in which jets were produced by ordinary QCD interactions. Leptons were thus the key signature for the t quark. The b and q and $\overline{q}$ quarks would appear as jets while the neutrinos would result in large missing "transverse energy," i.e. a transverse momentum imbalance.

The Tevatron Collider resumed running in 1992 and collected data during Run Ia (1992/3) and Run Ib (1994/5). Using Run Ia data, D0 raised the limit on the top quark mass to 131 GeV. By May 1994, CDF had enough events to declare that they had "evidence for the top quark," though they stopped short of announcing its discovery (Ref. 14.1). Two events were found that contained both an e and a μ, and which had both two additional jets (presumably from the b quarks) and missing transverse energy. Events in which a single lepton was found faced more severe backgrounds and additional requirements had to be imposed. Only events in which there were three or more jets were considered. In addition, there had to be evidence that at least one jet came from a b. This evidence was obtained in two ways. A lepton too "soft" (i.e. with not very high transverse momentum) to indicate a W was circumstantial evidence for the semileptonic decay of a b. Alternatively, the presence of the b could be demonstrated by finding a sign of the B decay itself.

The silicon vertex detector (SVX), the innermost part of CDF's tracking system, could measure tracks with a precision of tens of microns. This was good enough to identify B

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decays, for which a typical decay length would be $c\tau = 450$ μm times the boost due to the motion of the B. Six events with an apparent separated B vertex were found, with a background of 2.3 ± 0.3. The soft lepton tag found seven with a background of 3.1 ± 0.3. Three of the seven had SVX tags as well.

The mass of the t quark could be obtained from the events with a single lepton (and thus just one missing neutrino). Seven of the ten events had four or more jets and those with the highest transverse momentum were used to fit the hypothesis $(b\ell\nu)(bq\overline{q})$ where the b's and q's would appear as jets. This kinematical fit gave a mass determination (though no discovery was claimed!) of $m_t = 174 \pm 10^{+10}_{-12}$ GeV.

In February, 1995, both CDF (**Ref. 14.2**) and D0 (**Ref. 14.3**) were ready to declare the top quark found. CDF had 48 pb^{-1} of new data to add to their previous 19 pb^{-1}. Moreover, improvements in the silicon vertex detector increased its efficiency for finding b vertices in top events by a factor of two, to about 40%. There were 21 events in the data sample in which the SVX found vertices that were candidates for b decays. In six of the events, two jets were tagged. Additional candidates with soft lepton tags together with jets were identified. Six dilepton events were recorded. The refined mass measurement, $m_t = 176 \pm 8 \pm 10$ GeV, was quite close to that in the earlier CDF paper.

The D0 Collaboration had to overcome handicaps from the design of their detector, which was less suited for the task than was CDF, lacking both a magnetic field and a high precision silicon tracking device. See Figure 14.1. The basic strategy was the same as for CDF: identify leptons as candidates for decays of W's and jets as candidates for both the b quark-jets and products of nonleptonic W decays. To compensate for the limitations of the detector, D0 developed effective cuts that reduced background, in particular a cut on the total transverse energy. In the dilepton channels, two jets were required as well as missing transverse energy. In the single lepton channels, at least three jets were required. This was increased to four for events in which there was no lepton tag that would signal a b quark. Combining seven channels, D0 found 17 events with an anticipated background of 3.8. With their sample, D0 was not able to determine the mass with as much precision as CDF. Their result, $m_t = 199\ ^{+19}_{-21}$ GeV, was consistent, however, with the CDF result. Subsequent running at the Tevatron Collider enabled both experiments to observe additional top quark events and to reduce the uncertainty in the mass measurement. Their measurements in both dilepton and single lepton channels were in good agreement. The combined result from the two experiments for Run 1, $m_t = 174.3 \pm 5.1$ GeV, had the smallest fractional error of any quark mass determination.

The $t\overline{t}$ pairs are produced in two ways: $q\overline{q} \to t\overline{t}$ and $gg \to t\overline{t}$. Calculations show that at the Tevatron Collider, the former dominates. It is also possible to produce a single top quark through processes like $u\overline{d} \to W^+ \to t\overline{b}$, but these should not have passed the cuts imposed by the CDF and D0 experiments. The predicted cross section for $t\overline{t}$ was about 5–6 pb at the Tevatron Collider with $\sqrt{s} = 1.8$ GeV. The cross sections measured by CDF and D0 in Run 1 were near this, $6.5^{+1.7}_{-1.4}$ pb and 5.9 ± 1.7 pb.

The energy and luminosity of the Tevatron Collider were increased for Run 2, which began in 2001. By early 2008 more than 3 fb^{-1} had been collected and results were

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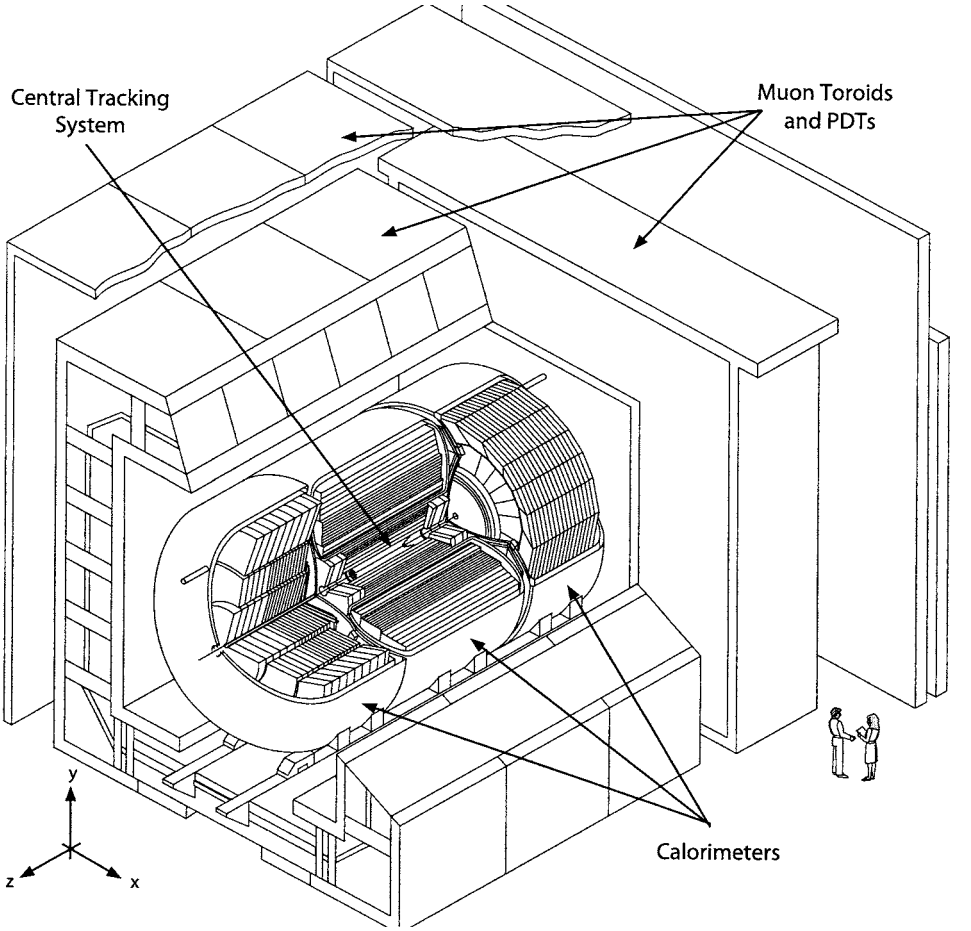


Figure 14.1. The D0 detector at the Fermilab Collider. Optimized for calorimetric measurements, D0 nonetheless was able to observe the t quark. [Courtesy D0 Collaboration.]

available for about 2 fb^{-1}, to be compared with 100 pb^{-1} in Run 1. The combined CDF and D0 result for m_t stood at 172.6 ± 1.4 GeV.

While the general agreement between the expected and measured cross sections and the conformity of the event structure to that anticipated from the Standard Model provides evidence that we do understand these processes, more exacting tests are needed to exclude exotic alternatives. The top quarks might, for example, be decay products of more massive particles rather than directly produced themselves. Absent such a surprise, the t may seem the most mundane of all quarks. Because of its rapid decay it doesn't produce stable hadrons as do all other quarks. In the t the quark concept is reduced to its most fundamental. Its interactions are for the most part described by perturbative QCD.

But this may be an illusion. Does the very large mass of the t quark point to a special role? Is it an indication of some new interactions not enjoyed by the lighter quarks?

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Exercises

14.1 A t quark decays into a b quark, whose momentum is measured, and W, which decays to $\mu\nu$. The momentum of the μ is measured and the momentum of the ν transverse to the beam direction, p_ν, is inferred from the missing transverse momentum in the event. If the transverse and longitudinal components of the muon momentum are $p_{\mu\perp}$ and $p_{\mu||}$, find the two possible values of the longitudinal momentum of the ν. When is there no solution for the longitudinal momentum of the ν? Do not assume that the mass of the t quark is known.

14.2 The coupling of the t, b, and W is described by

$$\frac{g}{\sqrt{2}}\overline{b}_L\gamma\cdot Wt$$

where $b_L = \frac{1}{2}(1-\gamma_5)b$. Here b and t stand for the corresponding spinor fields and W for its field. The square of the decay matrix element can be shown (perhaps by the reader) to be

$$\frac{g^2}{2}[2p_b\cdot\epsilon\; p_t\cdot\epsilon - p_b\cdot p_t\,\epsilon\cdot\epsilon].$$

The polarization of the W is ϵ, which obeys

$$\epsilon\cdot\epsilon = -1; \epsilon\cdot p_W = 0.$$

The three polarizations of the W are given by two choices of three-vectors perpendicular to the momentum of the W (transverse polarization) and one choice with both a time component and a space component parallel to the momentum of the W. (In writing the square of the matrix element the polarization vector was assumed real so the tranverse polarizations must be linear.) Using the two-body decay formula

$$d\Gamma = \frac{1}{32\pi^2}|\mathcal{M}|^2\frac{p_{cm}}{M^2}d\Omega$$

and ignoring the mass of the b quark, confirm the formula in the text for the decay rate of the t. Show that the ratio of longitudinal to transverse W's is $\frac{1}{2}(m_t^2/m_W^2)$.

Further Reading

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Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

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We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat}) \pm 10(\text{syst})$ GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

PACS numbers: 14.65.Ha, 13.85.Qk, 13.85.Ni

Recently the Collider Detector at Fermilab (CDF) Collaboration presented the first direct evidence for the top quark [1], the weak isodoublet partner of the b quark required in the standard model. We searched for $t\bar{t}$ pair production with the subsequent decay $t\bar{t} \rightarrow WbW\bar{b}$. The observed topology in such events is determined by the decay mode of the two W bosons. Dilepton events ($e\mu$, ee, and $\mu\mu$) are produced primarily when both W bosons decay into $e\nu$ or $\mu\nu$. Events in the lepton + jets channel (e, μ + jets) occur when one W boson decays into leptons and the other decays into quarks. To suppress background in the lepton + jets mode, we identify b quarks by reconstructing secondary vertices from b decay (SVX tag) and by finding additional leptons from b semileptonic decay (SLT tag). In Ref. [1] we found a 2.8σ excess of signal over the expectation from background. The interpretation of the excess as top quark production was supported by a peak in the mass distribution for fully reconstructed events. Additional evidence was found in the jet energy distributions

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in lepton + jets events [2]. An upper limit on the $t\bar{t}$ production cross section has been published by the D0 Collaboration [3].

We report here on a data sample containing 19 pb^{-1} used in Ref. [1] and 48 pb^{-1} from the current Fermilab Collider run, which began early in 1994 and is expected to continue until the end of 1995.

The CDF consists of a magnetic spectrometer surrounded by calorimeters and muon chambers [4]. A new low-noise, radiation-hard, four-layer silicon vertex detector, located immediately outside the beampipe, provides precise track reconstruction in the plane transverse to the beam and is used to identify secondary vertices from b and c quark decays [5]. The momenta of charged particles are measured in the central tracking chamber (CTC), which is in a 1.4 T superconducting solenoidal magnet. Outside the CTC, electromagnetic and hadronic calorimeters cover the pseudorapidity region $|\eta| < 4.2$ [6] and are used to identify jets and electron candidates. The calorimeters are also used to measure the missing transverse energy $\not\!\!E_T$, which can indicate the presence of undetected energetic neutrinos. Outside the calorimeters, drift chambers in the region $|\eta| < 1.0$ provide muon identification. A three-level trigger selects the inclusive electron and muon events used in this analysis. To improve the $t\bar{t}$ detection efficiency, triggers based on $\not\!\!E_T$ are added to the lepton triggers used in Ref. [1].

The data samples for both the dilepton and lepton + jets analyses are subsets of a sample of high-P_T inclusive lepton events that contain an isolated electron with $E_T > 20$ GeV or an isolated muon with $P_T > 20$ GeV/c in the central region ($|\eta| < 1.0$). Events which contain a second lepton candidate are removed as possible Z bosons if an ee or $\mu\mu$ invariant mass is between 75 and 105 GeV/c^2. For the lepton + jets analysis, an inclusive W boson sample is made by requiring $\not\!\!E_T > 20$ GeV. Table I classifies the W events by the number of jets with observed $E_T > 15$ GeV and $|\eta| < 2.0$. The dilepton sample consists of inclusive lepton events that also have a second lepton with $P_T > 20$ GeV/c, satisfying looser lepton identification requirements. The two leptons must have opposite electric charge.

The primary method for finding top quarks in the lepton + jets channel is to search for secondary vertices from b quark decay (SVX tagging). The vertex-finding efficiency is significantly larger now than previously due to an improved vertex-finding algorithm and the performance of the new vertex detector. The previous vertex-finding algorithm searched for a secondary vertex with two or more tracks. The new algorithm first searches for vertices with three or more tracks with looser track requirements, and if that fails, searches for two-track vertices using more stringent track and vertex quality criteria. The efficiency for tagging a b quark is measured in inclusive electron and muon samples which are enriched in b decays. The ratio of the measured efficiency to the prediction of a detailed Monte Carlo simulation is 0.96 ± 0.07, with good agreement ($\pm 2\%$) between the electron and muon samples. The efficiency for tagging at least one b quark in a $t\bar{t}$ event with ≥ 3 jets is determined from Monte Carlo simulation to be $(42 \pm 5)\%$ in the current run, compared to the $(22 \pm 6)\%$ reported in the previous publication [7]. In this Letter we apply the new vertex-finding algorithm to the data from the previous and the current runs.

In Ref. [1], we presented two methods for estimating the background to the top quark signal. In method 1, the observed tag rate in inclusive jet samples is used to calculate the background from mistags and QCD-produced heavy quark pairs ($b\bar{b}$ and $c\bar{c}$) recoiling against a W boson. This is an overestimate of the background because there are sources of heavy quarks in an inclusive jet sample that are not present in W + jet events. In method 2, the mistag rate is again measured with inclusive jets, while the fraction of W + jet events that are $Wb\bar{b}$ and $Wc\bar{c}$ is estimated from a Monte Carlo sample, using measured tagging efficiencies. In the present analysis, we use method 2 as the best estimate of the SVX-tag background. The improved performance of the new vertex detector, our ability to simulate its behavior accurately, and the agreement between the prediction and data in the W + 1-jet and W + 2-jet samples make this the natural choice. The calculated background, including the small contributions from non-W background, Wc production, and vector boson pair production, is given in Table I.

The numbers of SVX tags in the 1-jet and 2-jet samples are consistent with the expected background plus a small $t\bar{t}$ contribution (Table I and Fig. 1). However, for the $W+ \geq 3$-jet signal region, 27 tags are observed compared to a predicted background of 6.7 ± 2.1 tags [8]. The probability of the background fluctuating to ≥ 27 is calculated to be 2×10^{-5} (see Table II) using the procedure outlined in Ref. [1] (see [9]). The 27 tagged jets are in 21 events; the six events with two tagged jets can be compared with four expected for the top + background hypothesis and ≤ 1 for background alone. Figure 1 also shows the decay lifetime distribution for the SVX tags in $W+ \geq 3$-jet events. It is consistent with the distribution predicted for b decay from the $t\bar{t}$ Monte Carlo simulation. From the number of SVX-tagged events, the estimated background, the calculated

TABLE I. Number of lepton + jet events in the 67 pb^{-1} data sample along with the numbers of SVX tags observed and the estimated background. Based on the excess number of tags in events with ≥ 3 jets, we expect an additional 0.5 and 5 tags from $t\bar{t}$ decay in the 1- and 2-jet bins, respectively.

N_{jet}	Observed events	Observed SVX tags	Background tags expected
1	6578	40	50 ± 12
2	1026	34	21.2 ± 6.5
3	164	17	5.2 ± 1.7
≥ 4	39	10	1.5 ± 0.4

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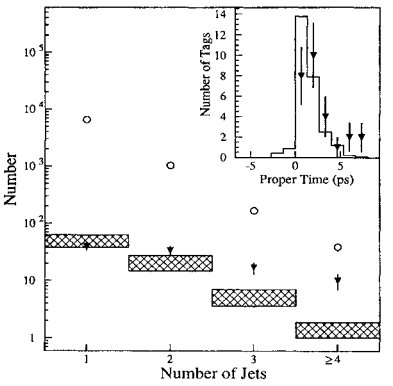


FIG. 1. Number of events before SVX tagging (circles), number of tags observed (triangles), and expected number of background tags (hatched) versus jet multiplicity. Based on the excess number of tags in events with ≥ 3 jets, we expect an additional 0.5 and 5 tags from $t\bar{t}$ decay in the 1- and 2-jet bins, respectively. The inset shows the secondary vertex proper time distribution for the 27 tagged jets in the $W+ \geq 3$-jet data (triangles) compared to the expectation for b quark jets from $t\bar{t}$ decay.

$t\bar{t}$ acceptance, and the integrated luminosity of the data sample, we calculate the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb, where the uncertainty includes both statistical and systematic effects. This differs from the cross section given in Ref. [1] by 6.9 ± 5.9 pb.

The second technique for tagging b quarks (SLT tagging) is to search for an additional lepton from semileptonic b decay. Electrons and muons are found by matching CTC tracks with electromagnetic energy clusters or tracks in the muon chambers. To maintain acceptance for leptons coming directly from b decay and from the daughter c quark, the P_T threshold is kept low (2 GeV/c). The only significant change to the selection algorithm compared to Ref. [1] is that the fiducial region for SLT muons has been increased from $|\eta| < 0.6$ to $|\eta| < 1.0$, resulting in an increase of the SLT total acceptance and background by a factor of 1.2.

The major backgrounds in the SLT analysis are hadrons that are misidentified as leptons, and electrons from unidentified photon conversions. These rates and the smaller $Wb\bar{b}$ and $Wc\bar{c}$ backgrounds are determined directly from inclusive jet data. The remaining backgrounds are much smaller and are calculated using the techniques discussed in Ref. [1]. The efficiency of the algorithm is measured with photon conversion and $J/\psi \rightarrow \mu\mu$ data. The probability of finding an additional e or μ in a $t\bar{t}$ event with ≥ 3 jets is $(20 \pm 2)\%$. Table II shows the background and number of observed tags for the signal region ($W+ \geq 3$ jets). There are 23 tags in 22 events, with 15.4 ± 2.0 tags expected from background. Six events contain both an SVX and SLT tag, compared to the expected four for top + background and one for background alone.

TABLE II. The number of tags or events observed in the three channels along with the expected background and the probability that the background would fluctuate to the observed number or more.

Channel	SVX	SLT	Dilepton
Observed	27 tags	23 tags	6 events
Expected background	6.7 ± 2.1	15.4 ± 2.0	1.3 ± 0.3
Background probability	2×10^{-5}	6×10^{-2}	3×10^{-3}

The dilepton analysis is very similar to that previously reported [1], with slight modifications to the lepton identification requirements to make them the same as those used in the single lepton analysis. The dilepton data sample, described above, is reduced by additional requirements on $\not\!\!E_T$ and the number of jets. In order to suppress background from Drell-Yan lepton pairs, which have little or no true $\not\!\!E_T$, the $\not\!\!E_T$ is corrected to account for jet energy mismeasurement [1]. The magnitude of the corrected $\not\!\!E_T$ is required to be at least 25 GeV and, if $\not\!\!E_T$ is less than 50 GeV, the azimuthal angle between the $\not\!\!E_T$ vector and the nearest lepton or jet must be greater than 20°. Finally, all events are required to have at least two jets with observed $E_T > 10$ GeV and $|\eta| < 2.0$.

The major backgrounds are Drell-Yan lepton pairs, $Z \rightarrow \tau\tau$, hadrons misidentified as leptons, WW, and $b\bar{b}$ production. We calculate the first three from data and the last two with Monte Carlo simulation [1]. As is shown in Table II, the total background expected is 1.3 ± 0.3 events. We observe a total of seven events, 5 $e\mu$ and 2 $\mu\mu$. The relative numbers are consistent with our dilepton acceptance, 60% of which is in the $e\mu$ channel. Although we estimated the expected background from radiative Z decay to be small (0.04 event), one of the $\mu\mu$ events contains an energetic photon with a $\mu\mu\gamma$ invariant mass of 86 GeV/c^2. To be conservative, we removed that event from the final sample, which thus contains six events. Three of these events contain a total of five b tags, compared with an expected 0.5 if the events are background. We would expect 3.6 tags if the events are from $t\bar{t}$ decay. When the requirement that the leptons have opposite charge is relaxed, we find one same-sign dilepton event ($e\mu$) that passes all the other event selection criteria. The expected number of same-sign events is 0.5, of which 0.3 is due to background and 0.2 to $t\bar{t}$ decay.

In summary, we find 37 b-tagged $W+ \geq 3$-jet events [10] that contain 27 SVX tags compared to 6.7 ± 2.1 expected from background and 23 SLT tags with an estimated background of 15.4 ± 2.0. There are six dilepton events compared to 1.3 ± 0.3 events expected from background. We have taken the product (P) of the three probabilities in Table II and calculated the likelihood that a fluctuation of the background alone would yield a value of P no larger than that which we observe. The result

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is 1×10^{-6}, which is equivalent to a 4.8σ deviation in a Gaussian distribution [11]. Based on the excess number of SVX-tagged events, we expect an excess of 7.8 SLT tags and 3.5 dilepton events from $t\bar{t}$ production, in good agreement with the observed numbers.

We performed a number of checks of this analysis. A good control sample for b tagging is Z + jet events, where no top contribution is expected. We observe 15, 3, and 2 tags (SVX and SLT) in the Z + 1-jet, 2-jet, and ≥3-jet samples, respectively, compared with the background predictions of 17.5, 4.2, and 1.5. The excess over background that was seen in Ref. [1] is no longer present. In addition, there is no discrepancy between the measured and predicted W + 4-jet background, in contrast to a small deficit described in Ref. [1] (see [12]).

Single-lepton events with four or more jets can be kinematically reconstructed to the $t\bar{t} \rightarrow WbW\bar{b}$ hypothesis, yielding for each event an estimate of the top quark mass [1]. The lepton, neutrino ($\not\!\!E_T$), and the four highest-E_T jets are assumed to be the $t\bar{t}$ daughters [13]. There are multiple solutions, due to both the quadratic ambiguity in determining the longitudinal momentum of the neutrino and the assignment of jets to the parent W's and b's. For each event, the solution with the lowest fit χ^2 is chosen. Starting with the 203 events with ≥3 jets, we require each event to have a fourth jet with $E_T > 8$ GeV and $|\eta| < 2.4$. This yields a sample of 99 events, of which 88 pass a loose χ^2 requirement on the fit. The mass distribution for these events is shown in Fig. 2. The distribution is consistent with the predicted mix of approximately 30% $t\bar{t}$ signal and 70% W + jets background. The Monte Carlo background shape agrees well with that meaured in a limited-statistics sample of Z + 4-jet events as well as in a QCD sample selected to approximate non-W background. After requiring an SVX or SLT b tag, 19 of the events remain, of which $6.9^{+2.5}_{-1.9}$ are expected to be background. For these events, only solutions in which the tagged jet is assigned to one of the b quarks are considered. Figure 3 shows the mass distribution for the tagged events. The mass distribution in the current run is very similar to that from the previous run. Furthermore, we employed several mass fitting techniques which give nearly identical results.

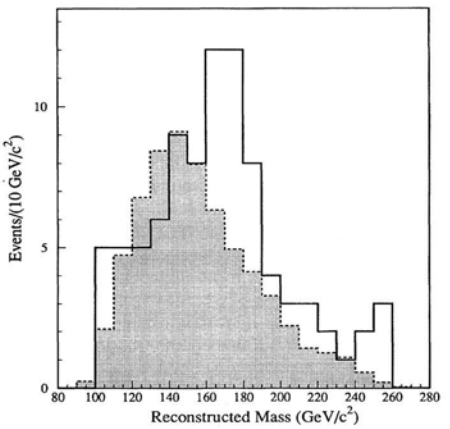


FIG. 2. Reconstructed mass distribution for the W+ ≥4-jet sample prior to b tagging (solid). Also shown is the background distribution (shaded) with the normalization constrained to the calculated value.

To find the most likely top mass, we fit the mass distribution to a sum of the expected distributions from the W + jets background and a top quark of mass M_{top} [1]. The −ln(liklihood) distribution from the fit is shown in the Fig. 3 inset. The best fit mass is 176 GeV/c^2 with a ±8 GeV/c^2 statistical uncertainty. We make a conservative extrapolation of the systematic uncertainty from our previous publication, giving $M_{top} = 176 \pm 8 \pm 10$ GeV/c^2. Further studies of systematic uncertainties are in progress.

The shape of the mass peak in Fig. 3 provides additional evidence for top quark production, since the number of observed b tags is independent of the observed mass distribution. After including systematic effects in the predicted background shape, we find a 2×10^{-2} probability that the observed mass distribution is consistent with the background (Kolmogorov-Smirnov test). This is a conservative measure because it does not explicitly take into account the observed narrow mass peak.

In conclusion, additional data confirm the top quark evidence presented in Ref. [1]. There is now a large

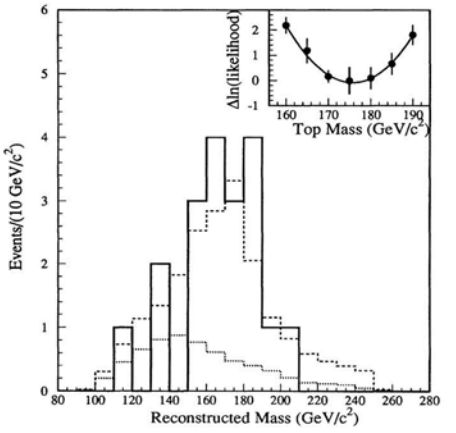


FIG. 3. Reconstructed mass distribution for the b-tagged W+ ≥4-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for $M_{top} = 175$ GeV/c^2 (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

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excess in the signal that is inconsistent with the background prediction by 4.8σ, and a mass distribution with a 2×10^{-2} probability of being consistent with the background shape. When combined, the signal size and mass distribution have a 3.7×10^{-7} probability of satisfying the background hypothesis (5.0σ). In addition, a substantial fraction of the jets in the dilepton events are b tagged. This establishes the existence of the top quark. The preliminary mass and cross section measurements yield $M_{\text{top}} = 176 \pm 8 \pm 10$ GeV/c^2 and $\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb.

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*Visitor.

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[6] 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 $P_T = P \sin\theta$. If the magnitude of this vector is obtained using the calorimeter energy rather than the spectrometer momentum, it becomes the transverse energy E_T. The difference between the vector sum of all the transverse energies in an event and zero is the missing transverse energy ($\not{E}_T$).

[7] A factor of 1.65 increase comes from the improvements noted. The remaining factor of 1.15 results from correcting an error in the b baryon lifetime used in the simulation of $t\bar{t}$ decay in Ref. [1].

[8] For comparison we note that if we had used both the tagging algorithm and background calculation (method 1) presented in Ref. [1], we would have 24 observed tags with a predicted background of 8.8 ± 0.6 tags.

[9] We get essentially the same probability if we use method 1 for the SVX-tag background because of its smaller systematic uncertainty.

[10] There are 21 events with SVX tags and 22 events with SLT tags. Six of these events have both SVX and SLT tags.

[11] This technique is chosen because we are combining channels with very different expected background rates. For comparison, if we apply the method used in Ref. [1] to the SVX and dilepton channels, the two low background modes, we obtain a probability of 1.5×10^{-6}.

[12] The improved agreement is due to the smaller $t\bar{t}$ production cross section obtained in this analysis as well as correcting an overestimate in Ref. [1] in the Monte Carlo background prediction.

[13] The jet energies used in the mass fitting have been corrected for instrumental and fragmentation effects.

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Observation of the Top Quark

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The D0 Collaboration reports on a search for the standard model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron with an integrated luminosity of approximately 50 pb^{-1}. We have searched for $t\bar{t}$ production in the dilepton and single-lepton decay channels with and without tagging of b-quark jets. We observed 17 events with an expected background of 3.8 ± 0.6 events. The probability for an upward fluctuation of the background to produce the observed signal is 2×10^{-6} (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measured its mass to be 199^{+19}_{-21} (stat) ± 22 (syst) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb.

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In the standard model (SM), the top quark is the weak isospin partner of the b quark. The D0 Collaboration published a lower limit on the mass of the top quark of 131 GeV/c^2, at a confidence level (C.L.) of 95%, based on an integrated luminosity of 13.5 pb^{-1} [1]. A subsequent publication [2] reported the top quark production cross section as a function of the assumed top quark mass. In that analysis, we found nine events with an expected background of 3.8 ± 0.9 events (statistical significance 1.9 standard deviations) corresponding to a production cross section of 8.2 ± 5.1 pb for an assumed top quark mass of 180 GeV/c^2. The Collider Detector at Fermilab (CDF) Collaboration published evidence for top quark production with a statistical significance of 2.8 standard deviations, a top quark of mass $174 \pm 10^{+13}_{-12}$ GeV/c^2, and a production cross section of $13.9^{+6.1}_{-4.8}$ pb [3]. Precision electroweak measurements predict a SM top quark mass of approximately 150−210 GeV/c^2, depending on the mass of the Higgs boson [4]. In the present Letter, we report new results from the D0 experiment that firmly establish the existence of the top quark.

We assume that the top quark is pair produced and decays according to the minimal SM (i.e., $t\bar{t} \rightarrow W^+W^-b\bar{b}$). We searched for the top quark in channels where both W bosons decayed leptonically ($e\mu$ + jets, ee + jets, and $\mu\mu$ + jets) and in channels where just one W boson decayed leptonically (e + jets and μ + jets). The single-lepton channels were subdivided into b-tagged and untagged channels according to whether or not a muon was observed consistent with $b \rightarrow \mu + X$. The muon-tagged channels are denoted e + jets/μ and μ + jets/μ.

Here we present an analysis based on data collected at the Fermilab Tevatron at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 44−56 pb^{-1}, depending on the channel. In the present analysis, the signal-to-background ratio for a high-mass top quark was substantially improved relative to Ref. [2]. An optimization of the selection criteria was carried out using Monte Carlo top quark events for signal and our standard background estimates. The result of this procedure was a factor of 3.7 better background rejection while retaining 70% of the acceptance for 180 GeV/c^2 top quarks. This corresponds to a signal-to-background ratio of 1:1 for a top quark mass of 200 GeV/c^2, assuming the expected SM top cross section [5]. The improved rejection arises primarily by requiring events to have a larger total transverse energy.

The D0 detector and data collection systems are described in Ref. [6]. The triggers and reconstruction algorithms for jets, electrons, muons, and neutrinos were the same as those used in our previous top quark searches [1,2].

The signature for the dilepton channels was defined as two isolated leptons, at least two jets, and large missing transverse energy $\not\!\!E_T$. The signature for the single-lepton channels was defined as one isolated lepton, large $\not\!\!E_T$, and a minimum of three jets (with muon tag) or four jets (without tag). The minimum transverse momentum p_T of tagging muons was 4 GeV/c. Requirements pertaining to the magnitude and direction of the $\not\!\!E_T$, the aplanarity of the jets $\mathcal{A}$, and the allowed ranges of pseudorapidity η were similar to Ref. [2]. Muons were restricted to $|\eta| < 1$ for the last 70% of the data because of forward muon chamber aging. Events in the $\mu\mu$ + jets and μ + jets/μ channels were required to be inconsistent with the Z + jets hypothesis, based on a global kinematic fit. The principal difference between the present analysis and the analysis of Ref. [2] was the imposition of a minimum requirement in all channels on a quantity H_T, which we defined as the scalar sum of the transverse energies E_T of the jets (for the single-lepton and $\mu\mu$ + jets channels) or the scalar sum of the E_T's of the leading electron and the jets (for the $e\mu$ + jets and ee + jets channels). The kinematic requirements for our standard event selection for all seven channels are summarized in Table I. In addition to the standard selection, we defined a set of loose event selection requirements, which differed from the standard set by the removal of the H_T requirement and by the relaxation of the aplanarity requirement for e + jets and μ + jets from $\mathcal{A} > 0.05$ to $\mathcal{A} > 0.03$.

For the dilepton channels, the main backgrounds were from Z and continuum Drell-Yan production ($Z, \gamma^* \rightarrow ee, \mu\mu$, and $\tau\tau$), vector boson pairs (WW, WZ), heavy flavor ($b\bar{b}$ and $c\bar{c}$) production, and backgrounds with jets misidentified as leptons. For the single-lepton channels, the main backgrounds were from W + jets, Z + jets, and multijet production with a jet misidentified as a lepton. The method for estimating these backgrounds was the same as in our previously published analyses [1,2].

H_T is a powerful discriminator between background and high-mass top quark production. Figure 1 shows a comparison of the shapes of the H_T distributions expected from background and 200 GeV/c^2 top quarks in the channels (a) $e\mu$ + jets and (b) untagged single-lepton + jets. We tested our understanding of background H_T distributions by comparing data and calculated background in background-dominated channels such as electron + two jets and electron + three jets (Fig. 2). The observed H_T distribution agrees with the background calculation, which includes contributions from both W + jets as calcu-

TABLE I. Minimum kinematic requirements for the standard event selection (energy in GeV).

	Leptons		Jets				
Channel	$E_T(e)$	$p_T(\mu)$	N_{jets}	E_T	$\not\!\!E_T$	H_T	$\mathcal{A}$
$e\mu$ + jets	15	12	2	15	20	120	···
ee + jets	20		2	15	25	120	···
$\mu\mu$ + jets		15	2	15	···	100	···
e + jets	20		4	15	25	200	0.05
μ + jets		15	4	15	20	200	0.05
e + jets/μ	20		3	20	20	140	···
μ + jets/μ		15	3	20	20	140	···

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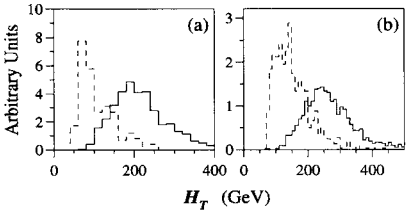


FIG. 1. Shape of H_T distributions expected for the principal backgrounds (dashed line) and 200 GeV/c^2 top quarks (solid line) for (a) $e\mu$ + jets and (b) untagged single-lepton + jets.

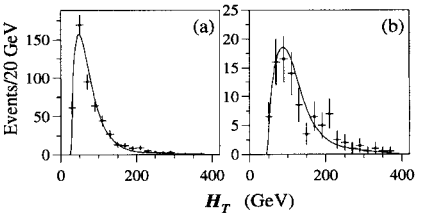


FIG. 2. Observed H_T distributions (points) compared to the distributions expected from background (line) for $\not\!\!E_T >$ 25 GeV/c and (a) $e+ \geq 2$ jets and (b) $e+ \geq 3$ jets.

lated by the VECBOS Monte Carlo program [7] and multijet events.

The acceptance for $t\bar{t}$ events was calculated using the ISAJET event generator [8] and a detector simulation based on the GEANT program [9]. As a check, the acceptance was also calculated using the HERWIG event generator [10]. The difference between ISAJET and HERWIG was included in the systematic error.

From all seven channels, we observed 17 events with an expected background of 3.8 ± 0.6 events (see Table II). The probability of an upward fluctuation of the background to 17 or more events is 2×10^{-6}, which corresponds to 4.6 standard deviations for a Gaussian probability distribution. Our measured cross section as a function of the top quark mass hypothesis is shown in Fig. 3. Assuming a top quark mass of 200 GeV/c^2, the production cross section is 6.3 ± 2.2 pb. The error in the cross section includes an overall 12% uncertainty in the luminosity. The cross section determined from the loose selection criteria is in good agreement with this value, demonstrating that the backgrounds are well understood. We calculated the probability for our observed distribution of excess events among the seven channels and find that our results are consistent with top quark branching fractions at the 53% C.L. Thus, we observe a statistically significant excess of events and the distribution of events among the seven channels is consistent with top quark production.

Additional confirmation that our observed excess contains a high-mass object comes from the invariant masses of jet combinations in single-lepton + jets events. For this analysis, we selected single-lepton + four-jet events using the loose event selection requirements (27 events). An invariant mass analysis was performed, based on the hypothesis $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu q\bar{q}b\bar{b}$. One jet was assigned to the semileptonically decaying top quark, and three jets were assigned to the hadronically decaying top quark. The jet assignment algorithm attempted to assign one of the two highest-E_T jets to the semileptonically decaying top quark and to minimize the difference between the masses of the two top quarks. The invariant mass of the three jets assigned to the hadronically decaying top quark is denoted by m_{3j}. Among the three possible jet pairs from the hadronically decaying top quark, the smallest invariant mass is denoted by m_{2j}. Figure 4 shows the distribution of m_{3j} vs m_{2j} for (a) background (W + jets and multijet) (b) 200 GeV/c^2 top Monte Carlo simulation, and (c) data. The data are peaked at higher invariant mass, in both dimensions, than the background. Based

TABLE II. Efficiency × branching fraction ($\varepsilon \times \mathcal{B}$) using standard event selection and the expected number of top quark events ($\langle N \rangle$) in the seven channels, based on the central theoretical $t\bar{t}$ production cross section of Ref. [5], for four top masses. Also given are the expected background, integrated luminosity, and the number of observed events in each channel.

m_t (GeV/c^2)	$e\mu$ + jets	ee + jets	$\mu\mu$ + jets	e + jets	μ + jets	e + jets/μ	μ + jets/μ	All
140 $\varepsilon \times \mathcal{B}$ (%)	0.17 ± 0.02	0.11 ± 0.02	0.06 ± 0.01	0.50 ± 0.10	0.33 ± 0.08	0.36 ± 0.07	0.20 ± 0.05	
$\langle N \rangle$	1.36 ± 0.21	1.04 ± 0.19	0.46 ± 0.08	4.05 ± 0.94	2.47 ± 0.68	2.93 ± 0.68	1.48 ± 0.42	13.80 ± 2.07
160 $\varepsilon \times \mathcal{B}$ (%)	0.24 ± 0.02	0.15 ± 0.02	0.09 ± 0.02	0.80 ± 0.10	0.57 ± 0.13	0.50 ± 0.08	0.25 ± 0.06	
$\langle N \rangle$	0.94 ± 0.13	0.69 ± 0.12	0.34 ± 0.07	3.13 ± 0.54	2.04 ± 0.53	1.95 ± 0.39	0.92 ± 0.24	10.01 ± 1.41
180 $\varepsilon \times \mathcal{B}$ (%)	0.28 ± 0.02	0.17 ± 0.02	0.10 ± 0.02	1.20 ± 0.30	0.76 ± 0.17	0.56 ± 0.09	0.35 ± 0.08	
$\langle N \rangle$	0.57 ± 0.07	0.40 ± 0.07	0.19 ± 0.04	2.42 ± 0.67	1.41 ± 0.36	1.14 ± 0.22	0.64 ± 0.16	6.77 ± 1.09
200 $\varepsilon \times \mathcal{B}$ (%)	0.31 ± 0.02	0.20 ± 0.03	0.11 ± 0.02	1.70 ± 0.20	0.96 ± 0.21	0.74 ± 0.11	0.41 ± 0.08	
$\langle N \rangle$	0.34 ± 0.04	0.25 ± 0.05	0.11 ± 0.02	1.84 ± 0.31	0.95 ± 0.24	0.81 ± 0.16	0.41 ± 0.10	4.71 ± 0.66
Background	0.12 ± 0.03	0.28 ± 0.14	0.25 ± 0.04	1.22 ± 0.42	0.71 ± 0.28	0.85 ± 0.14	0.36 ± 0.08	3.79 ± 0.55
$\int \mathcal{L}\, dt$ (pb^{-1})	47.9 ± 5.7	55.7 ± 6.7	44.2 ± 5.3	47.9 ± 5.7	44.2 ± 5.3	47.9 ± 5.7	44.2 ± 5.3	
Data	2	0	1	5	3	3	3	17

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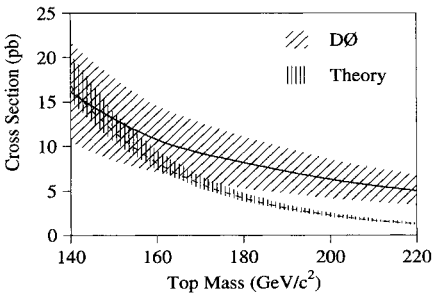


FIG. 3. D0 measured $t\bar{t}$ production cross section (solid line with one standard deviation error band) as a function of assumed top quark mass. Also shown is the theoretical cross section curve (dashed line) [5].

only on the shapes of the distributions, the hypothesis that the data are a combination of top quark and background events (60% C.L.) is favored over the pure background hypothesis (3% C.L.).

To measure the top quark mass, single-lepton + four-jet events were subjected to two-constraint kinematic fits to the hypothesis $t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu q\bar{q}b\bar{b}$. Kinematic fits were performed on all permutations of the jet assignments of the four highest-E_T jets, with the provision that muon-tagged jets were always assigned to a b quark in the fit. A maximum of three permutations with $\chi^2 < 7$ (two degrees of freedom) were retained, and a single χ^2-probability-weighted average mass ("fitted mass") was calculated for each event. Monte Carlo studies using the ISAJET and HERWIG event generators showed that the fitted mass was strongly correlated with the top quark mass. Gluon radiation, jet assignment combinatorics, and the event selection procedure introduced a shift in the fitted mass (approximately -20 GeV/c^2 for 200 GeV/c^2 top quarks), which was taken into account in the final mass determination.

Eleven of the 14 single-lepton + jets candidate events selected using the standard cuts were fitted successfully. Figure 5(a) shows the fitted mass distribution. An unbinned likelihood fit, incorporating top quark and background contributions, with the top quark mass allowed to vary, was performed on the fitted mass distribution. The top quark contribution was modeled using ISAJET. The background contributions were constrained to be consistent with our background estimates. The likelihood fit yielded a top quark mass of 199^{+31}_{-25} (stat) GeV/c^2 and described the data well.

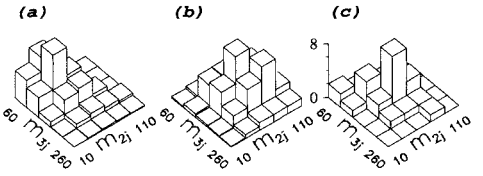


FIG. 4. Single-lepton + jets, two-jet vs three-jet invariant mass distribution for (a) background, (b) 200 GeV/c^2 top Monte Carlo simulation (ISAJET), and (c) data.

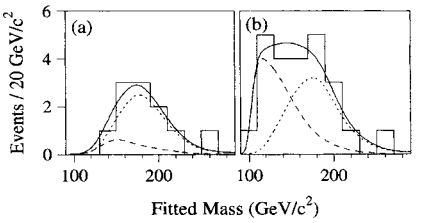


FIG. 5. Fitted mass distribution for candidate events (histogram) with the expected mass distribution for 199 GeV/c^2 top quark events (dotted curve), background (dashed curve), and the sum of top and background (solid curve) for (a) standard and (b) loose event selection.

To increase the statistics available for the mass fit, and to remove any bias from the standard H_T requirement, we repeated the mass analysis on events selected using the loose requirements. Of 27 single-lepton + four-jet events, 24 were fitted successfully. The removal of the H_T requirement introduced a substantial background contribution at lower mass in addition to the top signal, as shown in Fig. 5(b). A likelihood fit to the mass distribution resulted in a top quark mass of 199^{+19}_{-21} (stat) GeV/c^2, consistent with the result obtained from the standard event selection. The result of the likelihood fit did not depend significantly on whether the normalization of the background was constrained. Using HERWIG to model the top quark contribution resulted in a mass 4 GeV/c^2 below that found using ISAJET. This effect was included in the systematic error. The total systematic error in the top quark mass is 22 GeV/c^2, which is dominated by the uncertainty in the jet energy scale (10%).

In conclusion, we report the observation of the top quark. We measure the top quark mass to be 199^{+19}_{-21} (stat) ± 22 (syst) GeV/c^2 and measure a production cross section of 6.4 ± 2.2 pb at our central mass.

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