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Direct Measurement of the Top Quark Mass

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Abstract

We measure the top quark mass m_t using $t\bar{t}$ pairs produced in the DØ detector by $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions in a 125 pb^{-1} exposure at the Fermilab Tevatron. We make a two constraint fit to m_t in $t\bar{t} \to bW^+ \bar{b}W^-$ final states with one W decaying to $q\bar{q}$ and the other to $e\nu$ or $\mu\nu$. Events are binned in fit mass *versus* a measure of probability for events to be signal rather than background. Likelihood fits to the data yield $m_t = 173.3 \pm 5.6$ (stat) ± 6.2 (syst) GeV/c^2.

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The top quark has a large mass m_t that can be determined to greater fractional precision than is possible for the lighter quarks, which decay after they form hadrons. Since m_t is large, it controls the strength of quark-loop corrections to tree-level relations among electroweak parameters. If these parameters and m_t are measured precisely, the Standard Model Higgs boson mass can be constrained.

Direct measurements of m_t have been published as part of the initial observations [1] of $t\bar{t}$ production in $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions. At present, the best accuracy in m_t is achieved for lepton + jets (ℓ+jets) final states in which one W boson (from $t \to bW$) decays to $e\nu$ or $\mu\nu$ and the other W decays to a $q\bar{q}$ pair that forms jets. We report a measurement of m_t in the ℓ+jets channel using the $\approx$125 pb^{-1} exposure of the DØ detector during the 1992–96 Fermilab Tevatron runs. Since Ref. [1] appeared, our data sample has doubled, and for a fixed sample size our error on m_t has halved.

The DØ detector and our basic methods for triggering, reconstructing events, and identifying particles are described elsewhere [2]. Recent advances include enhanced triggering and reconstruction efficiency for μ+jets events, due in part to better use of calorimeter data. As a signature of $W \to \ell\nu$, we require missing energy transverse to the beam ($\not\!\!E_T$) > 20 GeV, and one isolated e or μ (ℓ) with $E_T^\ell > 20$ GeV and pseudorapidity $|\eta_e| < 2$ or $|\eta_\mu| < 1.7$. We also demand $\not\!\!E_T^{\rm cal} > 25$ (20) GeV for e+jets (μ+jets) events, where $\not\!\!E_T^{\rm cal}$ is $\not\!\!E_T$ measured only in the calorimeter. As signatures of the $q\bar{q}$ from W decay and the b and $\bar{b}$ from t and $\bar{t}$ decay, we require $\geq$4 jets reconstructed with cones of half-angle $\Delta\mathcal{R} \equiv (\Delta\phi^2 + \Delta\eta^2)^{1/2} = 0.5$, having $E_T > 15$ GeV and $|\eta| < 2$.

Within $\Delta\mathcal{R} = 0.5$ of a jet axis, additional muons (μ tags) satisfying $p_T^\mu > 4$ GeV/c and $|\eta_\mu| < 1.7$ arise mainly from b and c quark semileptonic decay. These occur in $\approx$20% of $t\bar{t}$ events but only $\approx$2% of background events [2]. In untagged events, to suppress background we require E_T^L ($\equiv |E_T^\ell| + |\not\!\!E_T|$) > 60 GeV and $|\eta_W| < 2$ for the $W \to \ell\nu$. The latter cut, exhibited in Fig. 1(a), reduces the difference in η_W distributions between data and Monte Carlo (MC) simulated background. We use the HERWIG MC [3] to simulate top signal, and the VECBOS MC [4] (with HERWIG fragmentation of partons into jets) to simulate (but not to normalize) the dominant W+multijet background. The $\approx$20% of background events from non-W sources are modeled by multijet data that barely fail the lepton identification criteria.

To each event passing the above cuts, we make a two constraint (2C) kinematic fit [5] to the $t\bar{t} \to \ell$+jets hypothesis by minimizing a $\chi^2 = (\mathbf{v} - \mathbf{v}^*)^T G (\mathbf{v} - \mathbf{v}^*)$, where $\mathbf{v}$ ($\mathbf{v}^*$) is the vector of measured (fit) variables and G^{-1} is its error matrix. Both reconstructed W masses are constrained to equal the W pole mass, and the same fit mass $m_{\rm fit}$ is assigned to both the t and $\bar{t}$ quarks. If the event contains $>$4 accepted jets, only the four jets with highest E_T are used. In $\approx$50% of MC top events, these jets correspond to the b, $\bar{b}$, q, and $\bar{q}$. With (without) a μ tag in the event, there are 6 (12) possible fit assignments of these jets to the quarks, each having two solutions to the ν longitudinal momentum p_z^ν. We use $m_{\rm fit}$ only from the permutation with lowest χ^2, the correct choice for $\approx$20% of MC top events. Because of the ambiguities, $m_{\rm fit}$ is not the same as m_t, though they are strongly correlated. Our best estimate of m_t is obtained from the best match between MC samples and the data.

From the 90-event distribution shown in Fig. 1(b) we select 77 events with a 2C fit satisfying $\chi^2 < 10$. Of these, 5 are μ tagged and $\approx$65% are background. Further separation of signal and background events is based on four kinematic variables $\mathbf{x} \equiv \{x_1, x_2, x_3, x_4\}$

chosen to have small correlation with m_{fit}. On average, all are larger for MC top events than for background events, selected to have the same $\langle m_{\text{fit}}\rangle$ as the top events [6]. The simpler variables are $x_1 \equiv \not\!\!E_T$ and $x_2 \equiv \mathcal{A}$, where aplanarity $\mathcal{A}$ is $\frac{3}{2}\times$ the least eigenvalue of the normalized laboratory momentum tensor of the jets and the W boson. The third variable $x_3 \equiv H_{T2}/H_z$ measures the event's centrality, where H_z is the sum of $|p_z|$ of ℓ, ν, and the

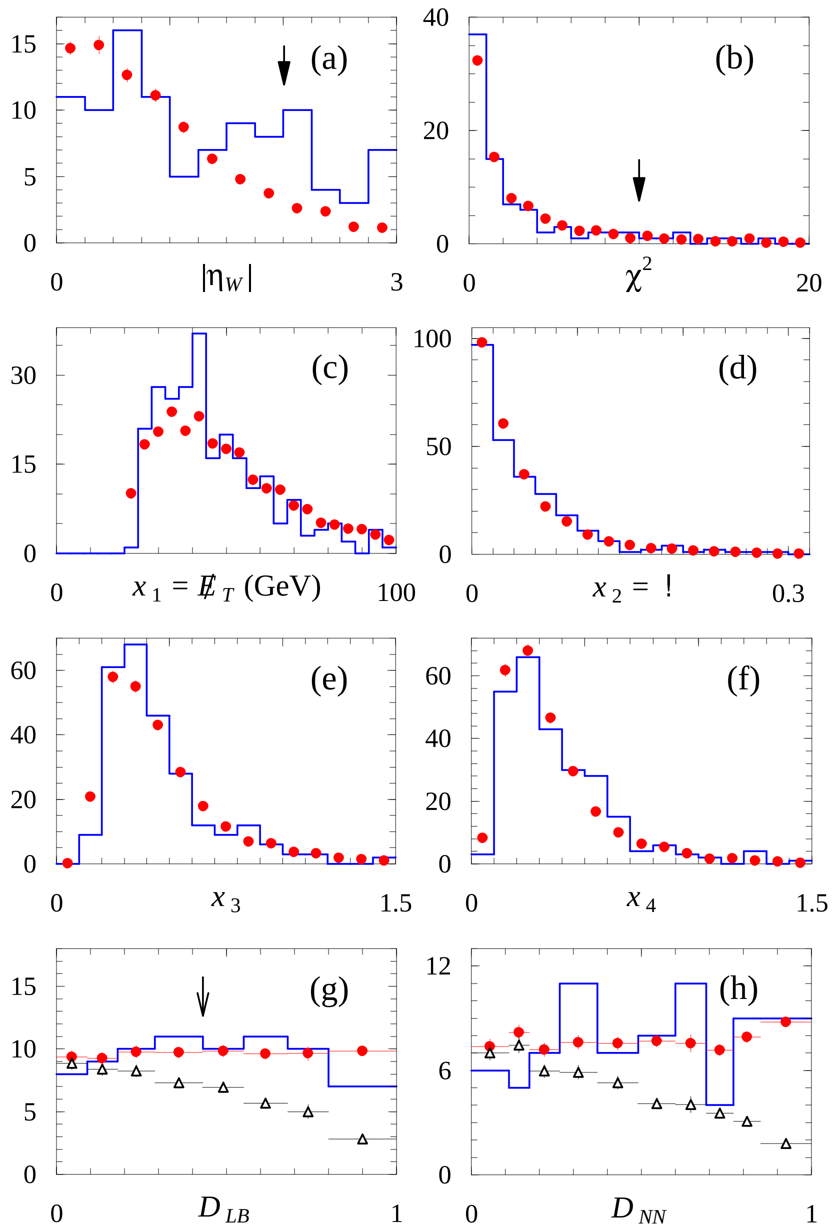

FIG. 1. Events per bin *vs.* event selection variables defined in the text, plotted for (a–b, g–h) top quark mass analysis samples, and (c–f) W+3 jet control samples. Histograms are data, filled circles are expected top + background mixture, and open triangles are expected background only. Solid arrows in (a–b) show cuts applied to all events; the open arrow in (g) illustrates the LB cut. The nonuniform bin widths in (g–h) are chosen to yield uniform bin populations.

jets, and H_{T2} is the sum of all jet $|E_T|$ except the highest. Finally, $x_4 \equiv \Delta\mathcal{R}_{jj}^{\min} E_T^{\min}/E_T^L$ measures the extent to which jets are clustered together, where $\Delta\mathcal{R}_{jj}^{\min}$ is the minimum $\Delta\mathcal{R}$ of the six pairs of four jets, and $E_T^{\min}$ is the smaller jet E_T from the minimum $\Delta\mathcal{R}$ pair. As shown for the background dominated W+3 jet sample in Fig. 1(c–f), x_1–x_4 are reasonably well modeled by MC; this is true also for the W+2 jet and top mass samples (not shown).

We bin events in a two-dimensional array with abscissa m_{fit} and ordinate $D(\mathbf{x})$, where D is a multivariate discriminant. To show that our results are robust, we use two methods for which the definition of D, the granularity with which it is binned, and the additional requirements are different. In our "low bias" (LB) method, we first parametrize $\mathcal{L}_i(x_i) \equiv s_i(x_i)/b_i(x_i)$, where s_i and b_i are the top signal and background densities in each variable, integrating over the others. We form the log likelihood $\ln\mathcal{L} \equiv \sum_i \omega_i \ln\mathcal{L}_i$, where the weights ω_i are adjusted slightly away from unity to nullify the average correlation ("bias") of $\mathcal{L}$ with m_{fit}, and for each event we set $D_{\text{LB}} = \mathcal{L}/(1+\mathcal{L})$. Finally, we divide the ordinate coarsely into signal- and background-rich bins according to whether the LB cut is passed. This cut is satisfied if a μ tag exists; otherwise it is not satisfied if $D_{\text{LB}} < 0.43$ (Fig. 1(g)) or if $H_{T2} < 90$ GeV.

Our neural network (NN) method is sensitive to the correlations among the x_i as well as to their individual densities. We use a three layer feed-forward NN with 4 input nodes fed by $\mathbf{x}$, 5 hidden nodes, and 1 output node, trained on samples of top signal (background) with

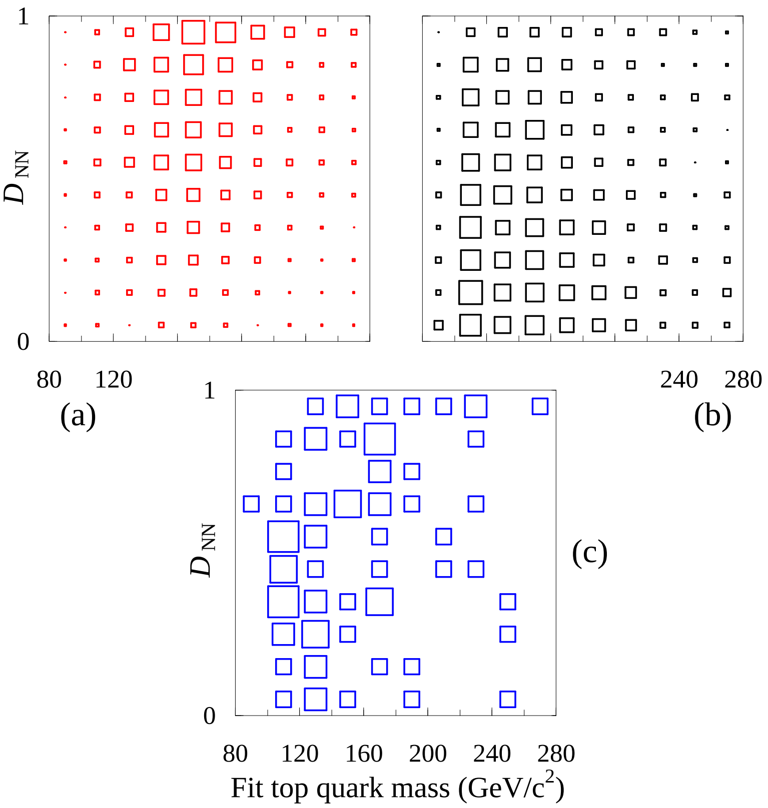

FIG. 2. Events per bin ($\propto$ areas of boxes) *vs.* D_{NN} (ordinate) and m_{fit} (abscissa) for (a) expected 172 GeV/c^2 top signal, (b) expected background, and (c) data. D_{NN} is binned as in Fig. 1(h).

density $s(\mathbf{x})$ ($b(\mathbf{x})$) [7]. For a given event, the network output $D_{\rm NN}$ approximates the ratio $s(\mathbf{x})/(s(\mathbf{x})+b(\mathbf{x}))$. We divide the ordinate finely into ten bins in $D_{\rm NN}$, independent of H_{T2} or μ tagging. Figure 1(g–h) shows that $D_{\rm LB}$ and $D_{\rm NN}$ are distributed as predicted and provide comparable discrimination, as we expect when the ω_i are close to unity and the $\mathcal{L}_i$ are not strongly correlated. Figure 2 exhibits the arrays for the NN method. Little correlation between $D_{\rm NN}$ and $m_{\rm fit}$ is evident in the expected signal or background distributions, which are distinct; the data clearly reveal contributions from both sources. Figure 3 shows the distributions of $m_{\rm fit}$ for data (a) passing and (b) failing the LB cut.

To each m_t for which we have generated MC, we assign a likelihood L which assumes

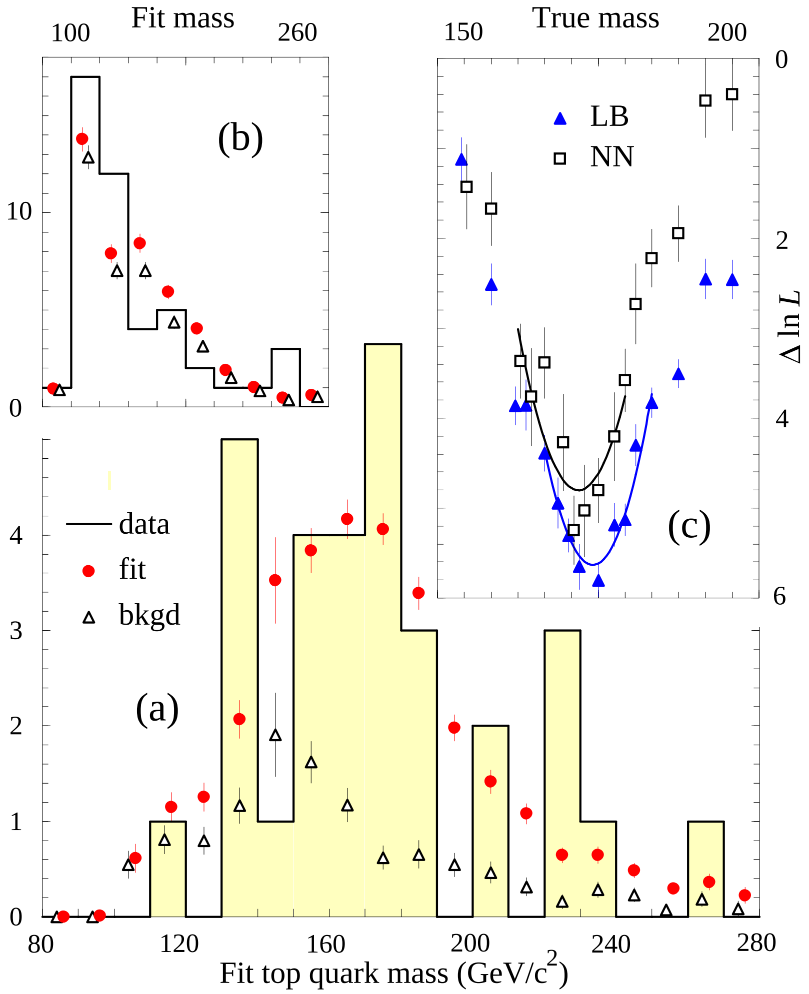

FIG. 3. (a–b) Events per bin *vs.* $m_{\rm fit}$ for events (a) passing or (b) failing the LB cut. Histograms are data, filled circles are the predicted mixture of top and background, and open triangles are predicted background only. The circles and triangles are the average of the LB and NN fit predictions, which differ by <10%. (c) Log of arbitrarily normalized likelihood L *vs.* true top quark mass m_t for the LB (filled triangles) and NN (open squares) fits, with errors due to finite top MC statistics. The curves are quadratic fits to the lowest point and its 8 nearest neighbors. In MC studies, 7% (27%) of simulated experiments yield a smaller LB (NN) maximum likelihood.

TABLE I. Results of fits to data and MC events. Fits to data yield values and errors σ(stat) for m_t, n_s, and n_b (described in the text). Systematic errors are combined in quadrature. The resulting m_t and its statistical error σ_m are the combined LB and NN values. Fits to MC use ensembles of 10,000 simulated experiments composed of top + background, with m_t, $\langle n_s \rangle$, and $\langle n_b \rangle$ as listed. They yield a mean result $\langle m_t \rangle$, a mean statistical error $\langle \sigma_m \rangle$, and a range $\pm\delta m$ within which 68% of the results fall. Using the LB (NN) method, 6% (25%) of the simulated experiments produce a σ_m which is smaller than we obtain. For an "accurate subset" of the MC ensembles with mean σ_m / m_t that matches our value, δm is smaller.

Fits to data	---LB fit---		---NN fit---	
Quantity fit	value	σ(stat)	value	σ(stat)
m_t (GeV/c^2)	174.0	± 5.6	171.3	± 6.0
n_s	23.8	$^{+8.3}_{-7.8}$	28.8	$^{+8.4}_{-9.1}$
n_b	53.2	$^{+10.7}_{-9.3}$	48.2	$^{+11.4}_{-8.7}$
Systematic error on m_t	energy scale	± 4.0		
	generator	± 4.1		
	other	± 2.2		
Resulting m_t (GeV/c^2)	**173.3 ± 5.6 (stat) ± 6.2 (syst)**			

Fits to MC	type	----input----				----output----	
(top + background)	of fit	m_t	$\langle n_s \rangle$	$\langle n_b \rangle$	$\langle \sigma_m \rangle$	$\langle m_t \rangle$	δm
full ensemble	LB	175	24	53	9.9	175.0	8.7
"	NN	172	29	48	8.5	171.6	8.0
accurate subset	LB	175	24	53	5.5	175.3	4.6
"	NN	172	29	48	5.8	172.0	6.0

that all samples obey Poisson statistics. Bayesian integration [8] over possible true signal and background populations in each bin yields

$$L(m_t, n_s, n_b) = \prod_{i=1}^{M} \sum_{j=0}^{n_i} \binom{n_{si}+j}{j} \binom{n_{bi}+k}{k} p_s^j (1+p_s)^{-n_{si}-j-1} \, p_b^k (1+p_b)^{-n_{bi}-k-1} \ ,$$

where n_s (n_b) is the expected number of signal (background) events in the data; n_i, n_{si}, and n_{bi} are the actual number of data, MC signal, and MC background events in bin i; $k \equiv n_i - j$; $p_{s,b} \equiv n_{s,b}/(M + \sum_i n_{si,bi})$; and $M = 40$ (200) bins for the LB (NN) methods. Maximizing L for each m_t gives the best estimates $n_s^*(m_t)$ and $n_b^*(m_t)$ for n_s and n_b. Figure 3(c) displays $\ln L(m_t, n_s^*(m_t), n_b^*(m_t))$ *vs.* m_t, where the curves determine the best fit m_t and its statistical error σ_m.

Table I presents the fit results, which are consistent with Ref. [1] and with recent reports [9]. The LB and NN results $m_t^{\rm LB}$ and $m_t^{\rm NN}$ are mutually consistent; in 21% of MC experiments they are further apart. Nevertheless we include half of $m_t^{\rm LB} - m_t^{\rm NN}$ in the systematic error. To obtain our result, shown in Table I, we combine $m_t^{\rm LB}$ and $m_t^{\rm NN}$ allowing for their $(88 \pm 4)\%$ correlation (determined by MC experiments). Figures 3(a–b) show that this result represents the data well. From the MC experiments summarized in Table I we measure the interval $\pm\delta m$ within which 68% of the MC estimates fall. For the full ensemble, δm is larger than σ_m from our data. However, for "accurate subsets" of the ensemble for which the average σ_m/m_t is the same as we observe, δm is close to σ_m [10].

A principal systematic error in m_t arises from uncertainty in the jet energy scale, which is calibrated in three steps. In step 1, applied before events are selected, the summed energy $E_{\rm jet}$ of particles emitted within the jet cone is related [11] to the measured energy $E_{\rm m}$ by $E_{\rm jet} = (E_{\rm m} - O)/R(1 - S)$. Here the calorimeter response R is calibrated using $Z \to ee$ decays and E_T balance in γ+jet events, the fractional shower leakage S out of the jet cone is set by test beam data, and the energy offset O due to noise and the underlying event is determined using events with multiple interactions. Steps 2 and 3 are applied only to jet energies used to find $m_{\rm fit}$. In step 2, top MC is used to correct $E_{\rm jet}$ to the parton energy in both data and MC. This sharpens the resolution in $m_{\rm fit}$. Step 3 is a final adjustment based on more detailed study of γ+jet events in data and MC, particularly focused on the dependence of the E_T balance upon η of the jet. We assign a jet-scale error of $\pm(2.5\% + 0.5$ GeV) based on the internal consistency of step 3, on variations of the γ+jet cuts and the model for the underlying event, and on an independent check of the E_T balance in Z+jet events. This leads to an error on m_t of ±4.0 GeV/c^2.

We estimate the uncertainties in modeling of QCD by substituting the ISAJET MC generator [12] for HERWIG, independently for top MC and for VECBOS fragmentation, and by changing the VECBOS QCD scale from jet $\langle p_T\rangle^2$ to M_W^2. The resulting systematic error due to the generator is ±4.1 GeV/c^2. Other effects including noise, multiple $p\bar{p}$ interactions, and differences in fits to $\ln L$ contribute ±2.2 GeV/c^2. All systematic errors (Table I) sum in quadrature to ±6.2 GeV/c^2. Therefore our direct measurement of the top quark mass is $m_t = 173.3 \pm 5.6$ (stat) $\pm$ 6.2 (syst) GeV/c^2.

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