# Progress in Top Quark Physics

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**Abstract.**
Experimental measurements of the properties of the top quark have improved and will continue to improve significantly, with the excellent operation of the CDF and D0 experiments and the Tevatron $p\bar{p}$ collider at the Fermi National Accelerator Laboratory. All of the final state experimental signatures from top quark production and decay are being analysed to test if this most massive quark is sensitive to new physics beyond the standard model. So far, observations are consistent with the standard model. New techniques have dramatically improved the precision of the top quark mass measurement to 1.7% and set the stage for a sub-1% measurement by 2008. This improved knowledge of the top quark mass sharpens the standard model prediction for the mass of the undiscovered Higgs boson, with implications for Higgs studies at the future LHC and ILC.

**Keywords:** top quark, Higgs boson
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## INTRODUCTION

The top quark [1, 2] was discovered in 1995 by CDF and D0 at the $\sqrt{s} = 1.8$ TeV $p\bar{p}$ Tevatron collider [3, 4]. The top quark is the most massive fundamental particle in the standard model of particle physics, with a mass approximately twice that of the $W$ and $Z$ bosons, the carriers of the electroweak force, and thirty-five times that of the next most massive fermion, the $b$ quark. The standard model neither predicts nor explains the observed mass hierarchy. The large mass of the top quark implies a unique large coupling to the elusive standard model Higgs boson. Precision studies of top quark properties have the potential to reveal effects from theories beyond the standard model. Until recently, this potential has been limited by low statistics, with only a few dozen candidates in the 100 $\text{pb}^{-1}$ collected through 1995.

This general review covers representative recent results on top quark physics from the CDF and D0 experiments with 350 $\text{pb}^{-1}$. Due to limited space, it cannot cover all of the many results [5].

## TOP QUARK PAIR PRODUCTION

Top quarks are produced in pairs via the strong interaction processes $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$. The prediction from QCD at next-to-leading order in $\alpha_s$ for the top quark pair production cross section [6, 7] is $6.7\pm^{0.7}_{0.9}$ pb for $m_{\text{top}} = 175$ GeV/$c^2$. Due to the increase in $\sqrt{s}$ to 1.96 TeV, this is 30% higher than at 1.8 TeV. The theoretical uncertainty includes scale and parton distribution function variations. Note that the production cross section depends strongly on the top quark mass, increasing to $7.8\pm^{0.9}_{1.0}$ pb for $m_{\mathrm{top}} = 170$ GeV/$c^2$.

In order to produce sufficient numbers of top quarks for precision studies, this tiny top quark pair production cross section necessitates the operation of the highest energy hadron collider in the world at the highest luminosity in the world. Current results from the CDF and D0 experiments at the Tevatron collider are based on detailed analysis of approximately 350 pb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV collected between 2002 and 2004. In 2005, the Tevatron reached peak instantaneous luminosities over $150\times10^{30}$cm$^{-2}$s$^{-1}$, and the CDF and D0 experiments each accumulated over 700 pb$^{-1}$. Instantaneous or integrated, the operation of the upgraded Tevatron is now over seven times better than for the 1994-1995 top quark discovery run! The future is even brighter: electron cooling [8] has begun to be used to reduce the size of the anti-proton beams prior to injection into the main Tevatron collider. This is the first application of electron cooling at relativistic beam energies, and also the first time the technique has been used concurrently with stochastic cooling. The ultimate potential of electron cooling is to increase the instantaneous luminosity by 50-100%, and to increase the expected integrated luminosity per experiment from 4 fb$^{-1}$ to as much as 8 fb$^{-1}$ by the end of 2009.

Having gone to all this effort to produce top quarks, their existence is truly fleeting. With a lifetime of the order of $10^{-25}$ s, there is not even enough time for the top quark to hadronise into mesons or baryons, unlike any other quark. Therefore, the spin of the top quark should be preserved in the angular distribution of the top quark decay products. In the standard model, the top quark decays via the electroweak interaction to a $W$ boson and a $b$ quark with a branching fraction of 99.8%. The total decay width is 1.5 GeV for $m_{\mathrm{top}}$=175 GeV/$c^2$. Note that the top quark is massive enough that it could also decay to new exotic particles, such as a charged Higgs boson, that have not been excluded yet by direct searches.

There are three experimental signatures from standard model top quark pair production and decay, $t\bar{t} \rightarrow W^+bW^-\bar{b}$, that are characterized by the number and type of charged leptons from the decay of the $W^+$ and $W^-$ bosons:

- **Dilepton (branching fraction 10.3%):** Both $W$ bosons decay to a lepton and a neutrino. The experimental signature is two isolated leptons with opposite electric charge, significant missing transverse energy from two undetected neutrinos, and at least two jets with large transverse energy originating from the two $b$ quarks.
- **Lepton + Jets (branching fraction 43.5%):** One $W$ boson decays to a lepton and a neutrino, the other $W$ boson decays to a quark and an anti-quark. The experimental signature is one isolated lepton, significant missing transverse energy from the undetected neutrino, and at least four jets with large transverse energy, with two of the jets originating from $b$ quarks.
- **All hadronic (Branching fraction 46.2%):** Both $W$ bosons decay to $q\bar{q}'$. The experimental signature is at least six jets with large transverse energy, with two of the jets originating from $b$ quarks.

In practice, the challenge of filtering off for later analysis less than 100 Hz of the 1.7 MHz $p\bar{p}$ bunch collision rate makes collecting a sample of top quarks a bit like trying to pan for gold under Niagara Falls! The huge $p\bar{p}$ cross section of 60 mb and the high instantaneous luminosity mean that on average there is at least one $p\bar{p}$ interaction per bunch collision that leaves measurable energy in the detectors. However, only one in ten billion $p\bar{p}$ interactions produces a brace of top quarks. Fortunately, an electron or muon with high transverse energy provides a highly efficient way to trigger on the dilepton and lepton+jets channels. Although the background from QCD multi-jet production is immense, the large number and high transverse energy of the jets in the all-hadronic channel also allows a trigger with high efficiency and low enough rate for the available bandwidth.

## Dilepton

D0's basic selection requires two isolated, identified leptons (electrons or muons) with $p_T$>15 GeV/$c$, and at least two jets with $p_T$>20 GeV/$c$ reconstructed by a cone algorithm with radius $\Delta\mathscr{R}$=0.5. The pseudo-rapidity ranges are $|\eta| < 2.5$ for jets, $|\eta| < 2.0$ for muons, and $|\eta| < 2.5$ excluding the range $1.1 < |\eta| < 1.5$ for electrons.

While the background process $Z/\gamma^\star \to \ell^+\ell^-$ with associated jets has a much larger production cross section than $t\bar{t}$, it can be reduced in the $e^+e^-$ and $\mu^+\mu^-$ channels by exploiting both the peak in dilepton invariant mass at the $Z$ boson mass, and the smaller missing transverse energy due only to the finite resolution on the measurement of jet energies. In the case of $Z/\gamma^\star \to \tau^+\tau^-$ with associated jets, with subsequent $\tau \to e\nu_e\nu_\tau$ or $\tau \to \mu\nu_\mu\nu_\tau$ decay, instead the lower $p_T$ of the charged leptons and the jets allows discrimination. Other sources of background include diboson production, and fakes, which are mainly from $W$ boson production with associated jets where a hadronic jet is mis-identified as a lepton.

After all selection requirements, the efficiency times branching fraction is about 0.7% for $t\bar{t}$. D0 observes 28 events in 370 pb$^{-1}$, with an estimated background of 6.8±2.2 events. Figure 1 compares the observed $p_T$ of the highest $p_T$ lepton with the expectation from the standard model. D0 measures $\sigma_{t\bar{t}} = 8.6 \pm^{2.3}_{2.0} \pm^{1.2}_{1.0} \pm 0.6$ pb [9], where the first uncertainty is statistical, the second due to systematic uncertainties on the signal efficiency and the background estimate, and the third from the uncertainty on the integrated luminosity. With 360 pb$^{-1}$, CDF measures $\sigma_{t\bar{t}} = 10.1 \pm 2.2 \pm 1.3 \pm 0.6$ pb [10].

CDF searches for the $e\tau$ and $\mu\tau$ final states, where the $\tau$ decays hadronically. Although the selection efficiency times branching fraction is only 0.08%, this final state could be enhanced by effects from new physics, *e.g.* if the top quark decays via a charged Higgs boson, $t \to H^+b$, with $H^+ \to \tau^+\nu_\tau$. In 195 pb$^{-1}$, CDF observes 2 events on a background of 1.3±0.1 events. CDF sets a 95% confidence level limit that the $t \to \tau\nu_\tau q$ branching fraction is no higher than 5.2 times the standard model branching fraction [11].

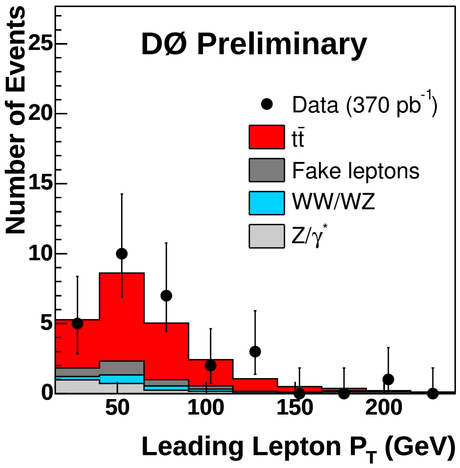

**FIGURE 1.** The $p_T$ distribution of the highest $p_T$ electron or muon in the D0 dilepton channel. The contribution from $t\bar{t}$ is normalized to 7 pb.

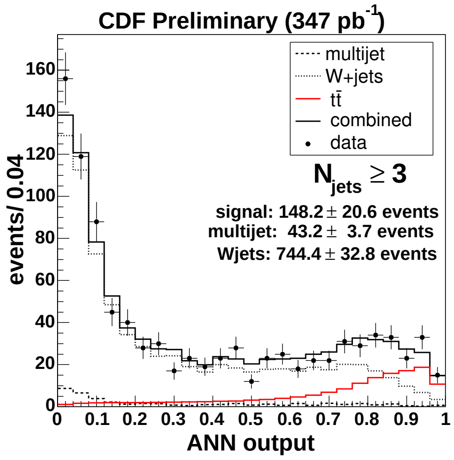

**FIGURE 2.** The artificial neural network output in the CDF lepton+jets channel. The best fit for the contribution from $t\bar{t}$ is shown.

## Lepton + Jets

CDF's basic selection requires exactly one isolated identified lepton (electron or muon) with $p_T$ >20 GeV/$c$, missing transverse energy above 20 GeV, and at least three jets with $E_T$ >15 GeV reconstructed by a cone algorithm with radius $\Delta\mathscr{R}$=0.4. The pseudo-rapidity ranges are $|\eta| < 2.0$ for jets and $|\eta| < 1.1$ for leptons. The efficiency times branching fraction is about 7% for $t\bar{t}$.

The decay products of the massive top quark are more energetic and central than those from the main background of $W$ boson production with associated jets. CDF combines the discriminating power of several kinematic and angular event observables in an artificial neural network. Figure 2 shows the neural network output for 936 observed data events in 347 pb$^{-1}$. The $t\bar{t}$ distribution is modeled by PYTHIA Monte Carlo, the $W$+jets distribution by ALPGEN $W+3$ parton matrix-element interfaced with HERWIG. Background from multi-jets, in which a hadronic jet is mis-identified as a lepton, is determined from data where the lepton is not isolated. The best fit to the data prefers 148.2±20.6 events from $t\bar{t}$, where the uncertainty is statistical only. CDF measures $\sigma_{t\bar{t}} = 6.3 \pm 0.8 \pm 0.9 \pm 0.4$ pb [12], where the dominant systematic uncertainty is from the dependence of the $W$+jets background shape on the Monte Carlo $Q^2$ scale. With 230 pb$^{-1}$, D0 measures $\sigma_{t\bar{t}} = 6.7 \pm^{1.4}_{1.3} \pm^{1.6}_{1.1} \pm 0.4$ pb [13].

Due to their long lifetime and large boost, the $B$ hadrons resulting from top quark decay travel several millimeters from the primary interaction point before decaying into several particles. While there are two jets originating from $b$ quarks in each $t\bar{t}$ event, only a few % of the $W$+jets background contains any jets from $b$ or $c$ quarks. Therefore the ability to identify (tag) a jet containing a $b$-quark provides a distinctive experimental signature that can be used to reduce the background from $W$+jets. The most powerful $b$-tag algorithm requires the direct reconstruction of a secondary vertex from the charged decay products of the $B$ hadron, where this secondary vertex is significantly displaced

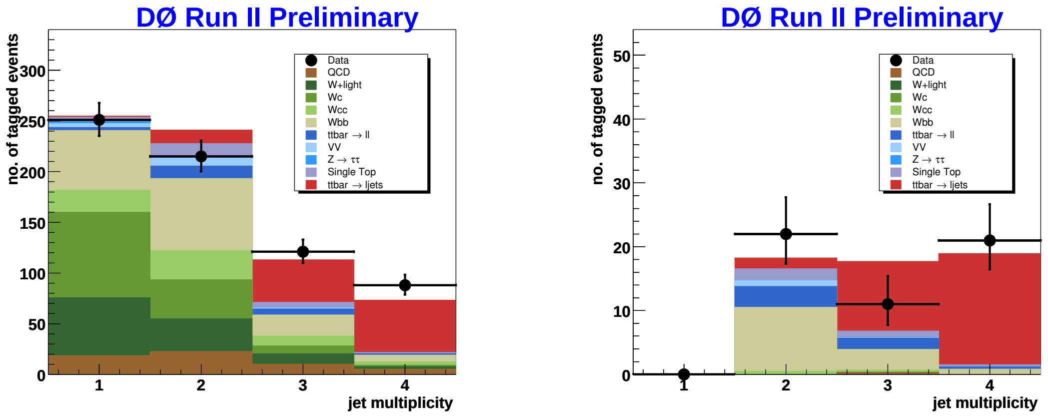

**FIGURE 3.** The number of predicted and observed events with a single $b$-tag (left) and two or more $b$-tags (right) as a function of jet multiplicity in the D0 lepton+jets channel. The contribution from $t\bar{t}$ is normalized to 7 pb.

along the direction of the parent jet from the primary $p\bar{p}$ interaction point. The typical efficiency of this algorithm is 45% for a $b$-jet with $E_T > 40$ GeV. The typical false positive (mistag) rate is 0.5%. Note that both the efficiency and the mistag rate depend on the jet $E_T$ and $\eta$.

With the requirement of at least one (two) $b$-tags, the efficiency times branching fraction for $t\bar{t}$ is about 4% (1%). In 365 pb$^{-1}$, D0 observes 209 events with exactly one $b$-tag for a background estimate of 93±10 events, and 32 events with at least two $b$-tags for a background estimate of 9±1 events. As is evident from Figure 3, which compares the observed number of events with exactly one $b$-tag and two or more $b$-tags with the expectation from the standard model, the background estimate contains contributions from many different processes. The dominant contributions from $Wb\bar{b}$, $Wc\bar{c}$, and $Wc$ production with associated jets are based on leading order in $\alpha_s$ Monte Carlo estimates of their rates relative to inclusive $W$+jets production. The absolute normalization is taken from the number of observed $W$+jets events before $b$-tagging. This procedure side-steps the large uncertainty (50%) on the leading order in $\alpha_s$ prediction of the absolute production rate of $W$+jets. Comparison of the number of observed and predicted events in the $W+1$ jet and $W+2$ jet regions, where little contribution from $t\bar{t}$ is expected, provides an important cross-check of the background estimate. D0 measures $\sigma_{t\bar{t}} = 8.1 \pm 0.9 \pm 0.9 \pm 0.5$ pb [14], where the dominant systematic uncertainties are on the $b$-tag efficiency and the background estimate. With 320 pb$^{-1}$, CDF measures $\sigma_{t\bar{t}} = 8.9 \pm 0.9 \pm^{1.1}_{0.8} \pm 0.5$ pb [15].

## All hadronic

Even after satisfying a CDF multi-jet trigger requiring at least four jets with $E_T$ >15 GeV and total transverse energy above 125 GeV, the expected signal-to-background ratio is only 1/3500. A kinematic selection exploits the higher transverse energy and more spherical distribution of jets from top quark decay to increase the S/B to 1/25. For events with between 6 and 8 jets in 311 $\text{pb}^{-1}$, CDF observes 816 $b$-tagged jets with an estimated background of 683±38 $b$-tagged jets. The kinematic selection efficiency times branching ratio for $t\bar{t}$ is about 7%, and on average there are 0.84 $b$-tags per $t\bar{t}$ event. The background $b$-tag rate is parameterized from data with exactly 4 jets before the kinematic selection. With the excess ascribed to $t\bar{t}$ production, CDF measures $\sigma_{t\bar{t}} = 8.0 \pm 1.7 \pm^{3.3}_{2.2} \pm 0.5$ pb [16]. The dominant systematic uncertainty is the dependence of the selection efficiency on the jet energy scale. With 350 $\text{pb}^{-1}$, D0 measures $\sigma_{t\bar{t}} = 5.2 \pm 2.6 \pm^{1.5}_{1.0} \pm 0.3$ pb [17].

## IS THERE SOMETHING NEW IN TOP QUARK DECAY?

The standard model predicts $t \rightarrow W^+ b$ with 99.8% branching fraction. CDF and D0 have performed several tests of non-standard model hypotheses.

**Is there always a $b$ quark?** From the relative rates and background estimate for 0, 1, and 2 $b$-tags in the lepton+jets and dilepton samples, one can extract the product of the $b$-tag efficiency and the branching ratio $R = \mathscr{BR}(t \rightarrow Wb)/\mathscr{BR}(t \rightarrow Wq)$, where $q$ is $d$, $s$, or $b$. With an independent estimate of the $b$-tag efficiency and 161 $\text{pb}^{-1}$, CDF sets a 95% C.L. limit that $R >$0.61 [18]. With 230 $\text{pb}^{-1}$, D0 sets a 95% C.L. limit that $R > 0.64$ [19].

**Is there always a $W^+$ boson?** In the minimal supersymmetric standard model, the branching fraction for $t \rightarrow H^+ b$ is significant (above 10%) for small and large values of $\tan\beta$. The $H^+$ decays differently than a $W^+$ boson. In particular, $H^+ \rightarrow \tau^+ \nu_\tau$ is enhanced at high $\tan\beta$, while $H^+ \rightarrow t^\star \bar{b} \rightarrow W^+ b\bar{b}$ is enhanced at low $\tan\beta$ for a large Higgs mass. CDF sets 95% C.L. limits in the plane of $\tan\beta$ and $H^+$ mass by comparison of the number of observed events in four final states (dilepton, dilepton with hadronic $\tau$ decay, lepton+jets with one $b$-tag, lepton+jets with two $b$-tags) with expectation from the minimal supersymmetric standard model [20].

**Is it $t \rightarrow W^+ b$ or $t \rightarrow W^- b$?** If the top quark electric charge is $-\frac{4}{3}$ instead of $+\frac{2}{3}$, then the charge of the $W$ boson from top quark decay would be reversed. D0 tests this hypothesis in 21 lepton+jets events with at least 4 jets and 2 $b$-tags in 365 $\text{pb}^{-1}$. This is a very pure sample with an estimated background of only 5%. The lepton and $b$-jet combination is chosen with an estimated 79% efficiency via a kinematic fit as the pairing most consistent with a top quark mass of 175 GeV/$c^2$. The magnitude of the top quark electric charge is estimated as sum of the lepton charge and the $b$-jet charge. D0 models jet charge from $b\bar{b}$ data. The information from the other top quark is not neglected, instead a second estimate of the top quark electric charge is obtained as the magnitude of the negative of the lepton charge and the second $b$-jet charge. Using a likelihood ratio test, D0 excludes the top quark electric charge $-\frac{4}{3}$ hypothesis at 94% C.L. [21].

**Is the $W^+$ helicity "right"?** 70% of the $W^+$ bosons from top quark decay are expected to have a helicity (the projection of particle's spin onto its momentum vector) of zero due to the large top quark mass. The standard model, a $V-A$ theory, predicts that the other 30% are left-handed with helicity of $-1$. However, if the top quark couples to new particles in the $t-W-b$ vertex, then some fraction of the other 30% could be right-handed with helicity $+1$. The emission angle of the charged lepton from the

$W$ boson decay with respect to the direction of the $W$ boson in the top quark rest frame, $\cos\theta^\star$, is directly related to the helicity of the $W$ boson. Left-handed $W^+$ bosons preferentially emit the lepton in the opposite direction to the $W$ boost, and vice versa for right-handed $W^+$ bosons. CDF and D0 have analysed distributions of lepton $p_T$ and estimators for the reconstructed $\cos\theta^\star$ in the lepton+jets and dilepton data samples. All results are consistent within large statistical uncertainties with the standard model prediction [22, 23].

## DOES SOMETHING NEW PRODUCE TOP QUARK PAIRS?

The tests in the previous section find that top quark decay is consistent with the standard model expectation. With this assurance that measurements in different final states are indeed related by the standard model branching fractions, CDF and D0 combine several measurements to obtain a more precise estimate of the top quark pair production cross section. CDF finds $\sigma_{t\bar{t}} = 7.1 \pm 0.6 \pm 0.7 \pm 0.4$ pb [24], and D0 finds $\sigma_{t\bar{t}} = 7.1 \pm 1.2 \pm^{1.4}_{1.1}$ $\pm 0.5$ pb [25] for a top quark mass of 175 GeV/$c^2$. These measurements are in good agreement with the prediction from NLO QCD.

Having checked the total production rate, CDF and D0 also search for indications of a resonance from a new massive particle, $X^0$, decaying into $t\bar{t}$. CDF and D0 reconstruct the invariant mass of the $t\bar{t}$ system in the lepton+jets channel. CDF uses all events with 4 or more jets, D0 requires in addition at least one $b$-tag. In 370 pb$^{-1}$, D0 sees a slight excess below $m_{t\bar{t}}$= 450 GeV/$c^2$ [27]. At the time of the conference with 320 pb$^{-1}$, CDF reported a 2-standard deviation excess around $m_{t\bar{t}}$ = 500 GeV/$c^2$. In a recent update with double the previous statistics, CDF now sees no excess in 680 pb$^{-1}$ [26]. The 95% C.L. limit for $\sigma_{X^0} \times \mathscr{BR}(X^0 \to t\bar{t})$ is about 2 pb for $m_{t\bar{t}}$= 500 GeV/$c^2$, and about 0.5 pb for $m_{t\bar{t}}$= 800 GeV/$c^2$.

## DOES SOMETHING NEW PRODUCE SINGLE TOP QUARKS?

Top quarks are also produced singly via the electroweak interaction. In the standard model, the single top quark production cross section, 0.88±0.11 pb in the s-channel and 1.98±0.25 pb in the t-channel from the theoretical prediction [28], is directly proportional to the CKM element $|V_{tb}|^2$, and is only 3 times smaller than the pair production cross section. The s-channel is sensitive to new resonances like a new massive $W'$ boson, while the t-channel is sensitive to changes in the $t-W-b$ vertex like flavor-changing-neutral-currents [29]. Furthermore, single top quark production is itself a background to the search for the standard model Higgs boson via $WH$ production [30, 31].

However, the experimental signature from single top quark production (isolated lepton, missing transverse energy, two or more jets, one [t-channel] or two [s-channel] $b$-tags) is swamped by background from $W$+jets and top quark pair production. D0 has developed several advanced multivariate techniques to discriminate single top quark production from backgrounds [32]. These require an excellent modeling of the background composition as well as the kinematics of both signal and background. In fact, for discovery of single top quark production, reduction of the systematic uncertainty from background modeling will be crucial. With a null hypothesis in 370 $\mathrm{pb}^{-1}$, D0 excludes at 95% C. L. an s-channel cross section above 5.0 pb and a t-channel cross section above 4.4 pb, with expected limits of 3.3 pb and 4.3 pb respectively. This is a factor of 2-3 away from the expected standard model cross sections, but is in the range of enhancements from physics beyond the standard model.

## PRECISION MEASUREMENT OF THE TOP QUARK MASS

Having proven that the observed top quark is consistent with the predictions of the standard model, CDF and D0 make a precision measurement of the top quark mass.

CDF performs a kinematic fit of lepton+jets events to the top quark pair production and decay hypothesis in order to obtain improved resolution on the reconstructed top quark mass. For each event with 0/1/2 *b*-tags, there are 12/6/2 permutations in the assignment of the four highest $E_T$ jets to the partons from the top quark decay. There are also two solutions for the neutrino $p_z$ from the quadratic ambiguity in the $W \to \ell\nu$ constraint. The estimator for the top quark mass is the reconstructed top quark mass for the combination most consistent with the observed final state and the top quark pair production and decay hypothesis. The top quark mass is extracted with a maximum likelihood fit of the observed reconstructed top quark mass distribution to simulated distributions with various assumed values for the top quark mass. CDF divides a 320 $\mathrm{pb}^{-1}$ lepton+jets sample into 4 subsets depending on *b*-tag and jet multiplicity, as shown in Figure 4, in order to optimize statistical sensitivity given the differences in signal-to-background and resolution. CDF measures a top quark mass of $173.5 \pm^{2.7}_{2.6} \pm 2.5 \pm 1.3$ GeV/$c^2$ [33], where the first uncertainty is statistical, the second is from the jet energy scale, and the third includes all other systematic uncertainties.

D0 uses the leading order matrix-element for $t\bar{t}$ production and decay to calculate the likelihood of the observed final state jets and lepton for each top quark mass hypothesis. As the matrix-element requires the parton momenta, the probability for a parton energy to yield an observed jet energy is parameterized from simulation. The current result does not use any *b*-tag information, instead the likelihoods from all 24 jet-parton and neutrino $p_z$ assignments are multiplied together. In 320 $\mathrm{pb}^{-1}$, D0 has 150 observed events with an estimated contribution from $t\bar{t}$ of 32±5%. D0 measures a top quark mass of $169.5 \pm 3.0 \pm 3.2 \pm 1.7$ GeV/$c^2$ [34].

CDF has developed the first application of a matrix-element technique to the dilepton channel. The presence of two undetected neutrinos makes reconstructing the top quark mass particularly challenging. With 33 events collected in 340 $\mathrm{pb}^{-1}$, CDF measures a top quark mass of $165.2 \pm 6.1 \pm 3.4$ GeV/$c^2$ [35], the most precise single measurement of the top quark mass in the dilepton channel.

The top quark mass measurement requires an excellent modeling of jet fragmentation and an excellent simulation of the calorimeter response to jets. The approximate 3% uncertainty on the CDF jet energy scale [36] translates into a 3 GeV/$c^2$ uncertainty on the top quark mass. At low jet $E_T$, the dominant systematic on the jet energy scale is from the modeling of energy outside the jet cone for these broader jets, while at high $E_T$, the dominant systematic is from the calibration of the calorimeter response. The balance of a well-measured photon, or $Z \to \ell\ell$, against a recoiling jet provides a cross

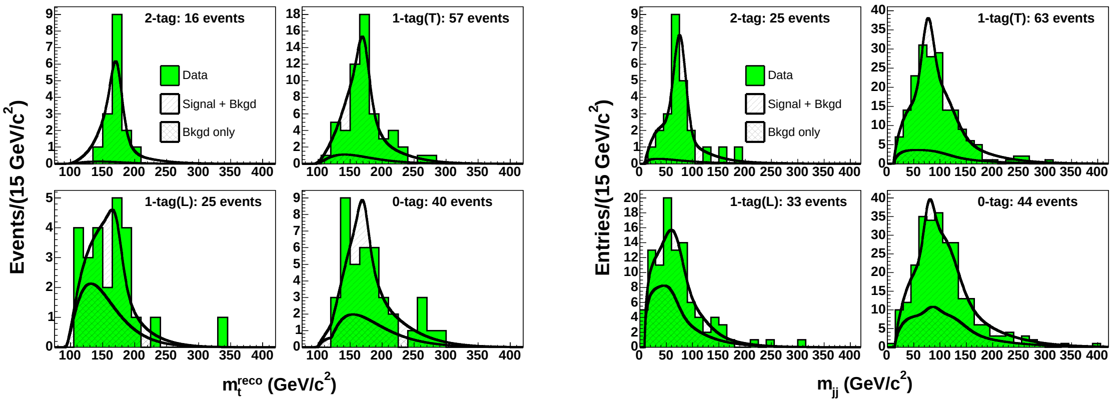

**FIGURE 4.** The reconstructed top quark mass (left) and reconstructed W boson mass (right) distributions from 320 $\mathrm{pb}^{-1}$ CDF lepton+jets data compared with the best fit.

check with limited statistics.

For the first time, with the higher statistics lepton+jets data samples, CDF and D0 are able to significantly constrain the jet energy scale from the invariant mass peak of the jets assigned to the $W \rightarrow qq'$ decay. This observable is sensitive to the jet energy scale but does not depend on the top quark mass. Figure 4 also shows the CDF observed di-jet mass distribution from all permutations not including the $b$-tagged jets. CDF extracts a correction of -0.10$\pm^{0.78}_{0.80}$ times the jet energy scale uncertainty, which is dependent on the jet $p_T$ and $\eta$. This is a correction of approximately -0.3% to the jet energy scale, and reduces the systematic uncertainty on the top quark mass from the jet energy scale by 20%. In the matrix-element technique of D0, the parton energies are divided by a single correction factor, which is determined by the constraint on the $W$ boson mass in the $t\bar{t}$ matrix-element. After calibration for limitations from the assumptions in the matrix-element technique, D0 extracts a correction of 1.034±0.034. This is a correction of approximately 3.4% to the jet energy scale. All of the above calibrations are for non-$b$ jets. Both CDF and D0 estimate a systematic of approximately 0.6 GeV/$c^2$ that accounts for relative differences between $b$-jets and light jets due to fragmentation models, semileptonic decay branching fractions, and color flow. With higher statistics, $\gamma b$ and $Zb$ production, and even $Z \rightarrow bb$ for which CDF has a secondary vertex trigger, may provide useful constraints.

The Summer 2005 combination of the best measurements from CDF and D0 in each channel from Run-I and Run-II yields a world average value for the top quark mass of 172.7±2.9 GeV/$c^2$ [37], a 40% improvement from 2004. Via quantum loops, the $W$ boson mass is sensitive to the square of the top quark mass, the logarithm of the Higgs boson mass, and to new massive particles from beyond the standard model [38]. With the full two-loop electroweak corrections [39], the experimental uncertainty on the top quark mass is by a factor of two the dominant uncertainty on the standard model prediction for the $W$ boson mass: the current 2.9 GeV/$c^2$ uncertainty on the top quark mass corresponds to about 18 MeV/$c^2$ on the $W$ boson mass prediction. In combination with other precision electroweak measurements, the improved measurement of the top quark mass sharpens the constraint on the undiscovered standard model Higgs boson mass to $91 \pm^{45}_{32}$ GeV/$c^2$ [40]. Including the direct search limit of 114.4 GeV/$c^2$ from LEP [41], the standard model Higgs boson mass is less than 219 GeV/$c^2$ at 95% C.L.

The future of the top quark mass measurement at the Tevatron is bright, as the dominant systematic uncertainty from the jet energy scale now scales with statistics thanks to the *in situ* constraint from $W \rightarrow qq'$. With an integrated luminosity of 2 fb$^{-1}$ per experiment and a conservative assumption of no reduction in other systematic uncertainties, the projected top quark mass uncertainty is 1.7 GeV/$c^2$. This is another 40% reduction in uncertainty, and it will sharpen the constraint on the Higgs boson mass even more at a very interesting time in particle physics, as the LHC turns on to search for the Higgs boson. With 4 fb$^{-1}$ and beyond, it is likely that the Tevatron precision measurement of the top quark mass will be comparable to the precision expected from the LHC [42].

## CONCLUSION

Thanks to the excellent performance of the Tevatron accelerator complex and the CDF and D0 experiments, the future of top quark physics at the Tevatron is bright. The precision of the top quark mass measurement, 172.7±2.9 GeV/$c^2$ has improved by 40% in the last year alone. Although the observed top quark is consistent with the standard model top quark so far, there is still lots of potential for surprises in the order of magnitude larger data samples currently under accumulation. Watch out for top results!

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