Top Quark Physics

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Abstract. While the top quark was discovered in 1995 at the Fermilab Tevatron, a decade later we still have very little information about the top. As the heaviest particle yet discovered, the top quark is interesting in and of itself, but some speculate that it may play a special role in physics beyond the Standard Model. With Run 2 of the Tevatron well underway, we have the opportunity to study top quark properties with much better sensitivity, and to test whether top quarks behave as predicted by current theories. This article will focus on the basics of top quark physics at the Tevatron, highlighting only a sample of the many recent measurements, as new results are being released monthly, and constantly changing the landscape of our knowledge of top.

Keywords: top quark, heavy flavor, Tevatron
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INTRODUCTION

After almost two decades of searching, the top quark was finally discovered in 1995 by the CDF and DØ [1] experiments at the Fermilab Tevatron. The quest for the top quark had lasted so many years mainly due to its unexpectedly heavy mass. Indeed, at ~175 GeV [2], the top quark is about five orders of magnitude heavier than the electron.

Such a heavyweight decays very quickly, with lifetime $\tau_{top} \sim 10^{-24}$s, and width $\Gamma^{-1}_{QCD} \sim (1.5\ \mathrm{GeV})^{-1}$, much smaller than the scale for perturbative QCD ($\Lambda^{-1}_{QCD} \sim (200\ \mathrm{MeV})^{-1}$). The top quark thus decays before hadronizing, freeing it from the spectroscopy typical of heavy flavor [3]. In addition, its momentum and spin are transferred directly to the decay products, allowing us to learn a great deal about $t\bar{t}$ kinematics, and to test our theoretical models.

The large mass of the top also makes it interesting in searches for new phenomena: the top quark can probe physics at higher energy scales than other known fermions. Since the top mass is remarkably close to the electroweak scale, the coupling to a Higgs boson would be close to unity. The mass of the top quark is thus a key electroweak parameter. In fits to existing precision electroweak data, the top quark mass, together with the mass of the W boson, are key to constraining the mass at which we expect a Higgs boson to appear, as illustrated in Figure 1.

Yet some speculate that top may itself play a unique role in electroweak symmetry-breaking. Several such theories utilize top rather than a Standard Model Higgs, as in Top Color [4], which describes the Higgs as a bound state of top quarks. Other models, such as SUSY mirror models [5] and Little Higgs [6], predict an additional, heavier, top-like quark having similar signatures to the Standard Model top. Whether top behaves like a regular up-type quark, or is special in some way, it is clear that this interesting and relatively new particle deserves careful study as we explore the energy frontier further.

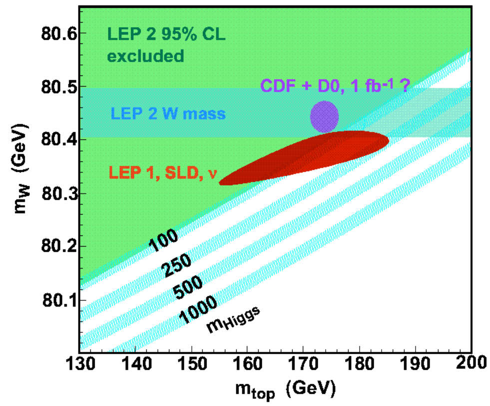


FIGURE 1. Projected measurement sensitivity (circle) of the top quark mass and the mass of the W boson for the Tevatron in Run 2 with only 1 fb^{-1}. The error ellipse from these important electroweak parameters, shown here for scale only, can be used to constrain the mass of the Higgs boson in the Standard Model. Shown also are the constraints from Lep1/SLD and LEP 2.

STUDYING TOP AT THE TEVATRON RUN 2

The top quark was discovered [1] only fairly recently: during Run 1 of the Tevatron, which lasted from 1991-1996. During this time, approximately 100 pb^{-1} of data were collected in each of the two experiments, allowing solid initial measurements of the mass of the top quark, top quark properties, and the $t\bar{t}$ production cross section at $\sqrt{s}$ =1.8 TeV. Yet finding top quark events is difficult. Each experiment likely produced close to 500 top quark pairs, but for example, CDF had only $\sim$34 $t\bar{t}$ pairs in the main mass sample. Statistics were quite limited.

As Run 2 of the Tevatron progresses, we are now able to make interesting measurements, and in some cases, first measurements, of a plethora of top quark properties, many of which are shown in Figure 2. Measurements of production properties, such as the production cross-section, possible production by high-mass resonances, and searches for electroweak production of “single top” [3] are well underway. Studies of top quark decay kinematics will give us $t\bar{t}$ spin correlations, and allows us to test the V-A nature of the tWb vertex via W helicity. Other decay properties, such as branching ratios, width and lifetime measurements, and rare decays are increasingly accessible as well. This rich territory will be explored in Run 2 of the Tevatron, and any one of these measurements may provide us a window onto new physics.

Improvements for Top Physics

In the next several years, the Tevatron experiments are well-poised to exploit the numerous opportunities in top physics. Run 2 of the Fermilab Tevatron began proton anti-proton collisions in 2001 at a center-of-mass energy of $\sqrt{s}$ = 1.96 TeV, higher than the 1.8 TeV collisions of Run 1. This may seem small, but this results in an expected increase of $\sim$30% in cross section for $t\bar{t}$ events. In addition, during the period between

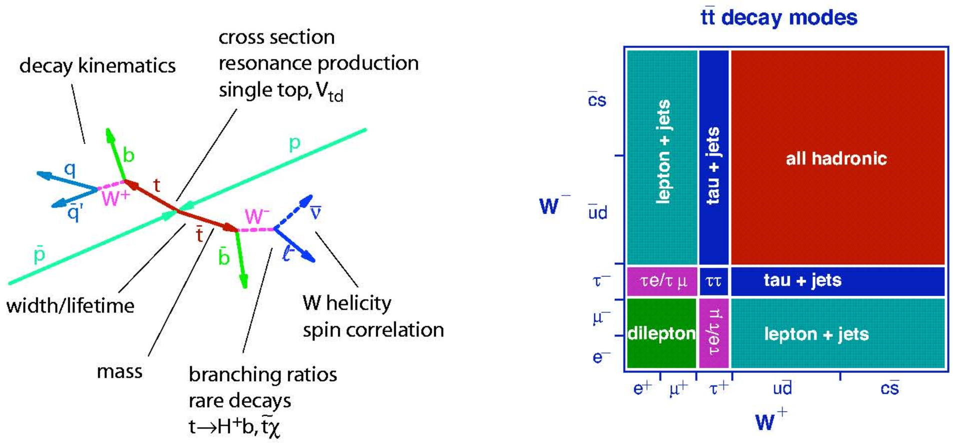


FIGURE 2. **Left:** Elucidating Top in Run 2: Most properties of the top quark remain to be measured with significant sensitivity. Thus the top sector provides both a rich environment to test Standard Model hypotheses, and possibly a window onto new physics. **Right:** Diagram showing the final state decays of $t\bar{t}$ events. Since top decays to a W boson and a b quark, events are characterized by the decay modes of the two Ws: so-called top di-lepton events, lepton+jets events, and all hadronic events.

Run 1 and Run 2, both CDF and DØ [7] detectors underwent extensive upgrades, increasing their acceptances for detecting top quark events. CDF improvements include brand new silicon detectors and a new wire drift chamber for tracking, upgrades to the calorimeter and muon systems, and all new trigger and DAQ systems. Improvements to DØ center on the addition of a tracking system, including a 2-Tesla solenoid, along with silicon detectors and a fiber tracker. In addition, DØ upgraded the muon system and the entire trigger and DAQ as well.

One of the largest improvements for Run 2, however, will be the increased datasets. Upgrades to the Tevatron accelerator complex, such as the new Main Injector, and the Recycler, have improved instantaneous luminosities in Run 2 tenfold. As of September 2005, the Tevatron has achieved record peak luminosities of over 1.3×10^{32} cm^{-2}s^{-1}, and hopes to reach three times that during Run 2. If current performance projections are achieved, Tevatron experimenters can hope to receive between 4 and 8 fb^{-1} of integrated luminosity, which means 40 to 80 times more data than in Run 1.

Because top quarks are currently only being produced at the Tevatron, and with such strong prospects for studying top at the Tevatron, top quark physics is one of the most important and interesting subjects at the CDF and DØ while on the energy frontier.

TOP QUARK PRODUCTION AND DECAY

The first thing one might ask in discussing top quark physics is how top is produced. Since the Tevatron is a proton anti-proton collider, pairs of top quarks are produced through the strong interaction by $q\bar{q}$ scattering ($\sim$85%) or by gluon-gluon fusion ($\sim$15%). But they are also produced quite rarely. At $\sqrt{s}$ = 1.96 TeV, the predicted $t\bar{t}$ cross section is 6.7 pb [8] (M_{top}=175 GeV), so that one top pair is produced in about every 10^{10} inelastic collisions, placing even greater importance on detecting top quark events as efficiently as possible.

How else is top produced? In the Standard Model top quarks can be produced singly via the electroweak interaction [3]. This process has a predicted cross section of $\sim$3 pb [9] at the Tevatron, but has yet to be observed. If we move beyond the Standard Model, some speculate that $t\bar{t}$ can also be produced via an unknown heavy resonant state (usually called generically "X"), or through some other process such as Topcolor-Assisted Technicolor [4].

To detect top, one needs first to understand how it decays. In the Standard Model, top decays to a W boson and a b quark basically 100% of the time. We thus discuss top measurements in terms of final states based on the decay channel of the W boson, since every top decay contains a b quark. Figure 2 shows the breakdown of each type of final state. Top di-lepton events, in which both W's decay to a lepton and a ν, are characterized by two high-p$_T$ leptons, $\not{E}_T$ from the ν decay, and two jets from the b quarks. Typically the leptons in di-lepton measurements are electrons and muons, though measurements with the messier tau leptons are becoming more common. The e/μ dilepton final state is very clean, and easy to trigger on due to the isolated leptons, but suffers from its branching ratio. It represents only 5% of $t\bar{t}$ decays.

In the case of the lepton+jets final state, one W decays leptonically (again mainly e/μ) and one decays to two quarks. The signature is thus a single, high-p$_T$ lepton, $\not{E}_T$, and four jets. This final state is also easy to trigger on, again due to the isolated lepton, but has more backgrounds than the di-lepton channel, the main one being a W boson produced in conjuntion with parton jets. Yet since the lepton+jets channel (e/μ) represents 30% of $t\bar{t}$ event decays, it has much larger statistics than di-lepton events, and is typically the most sensitive channel for top quark measurements. The all-hadronic final state, where both W bosons decay to $q\bar{q}$, is the most difficult: 40% of $t\bar{t}$ decays into this channel, but the six-jet signal is swamped by QCD backgrounds. Measurements in this channel are not as sensitive, as they require hard cuts, and hence statistics remain an issue.

Finding Top Quarks

With improved detectors, higher cross sections, and increased datasets, our top samples are larger than ever. Yet there remains the difficulty of separating $t\bar{t}$ from the main backgrounds, which for the di-lepton are di-boson, Drell-Yan and fakes, and for lepton+jets are largely W+jets. The initial requirement is to identify a high-p$_T$ e or μ. Further requiring $\not{E}_T$ and multiple jets gives us a predominantly W-like sample. To separate out $t\bar{t}$ events, traditionally one exploits the fact that top events always decay to a b quark. One then uses algorithms to "tag" b-quark jets in an event, taking advantage of the fact that the b quark has a lifetime $c\tau \sim 450\mu$m, and so can travel $\sim$3mm before decaying. This means that b-quark jets contain tracks that point back to a displaced vertex. There are several methods of tagging such jets. The most common and efficient is to take advantage of the track resolution of the silicon vertex detectors. Figure 3 shows a sketch of a displaced vertex from a b jet, alongside the CDF efficiency to tag a b-quark jet in top events as a function of jet E$_T$ for the silicon vertex-tagging algorithms.

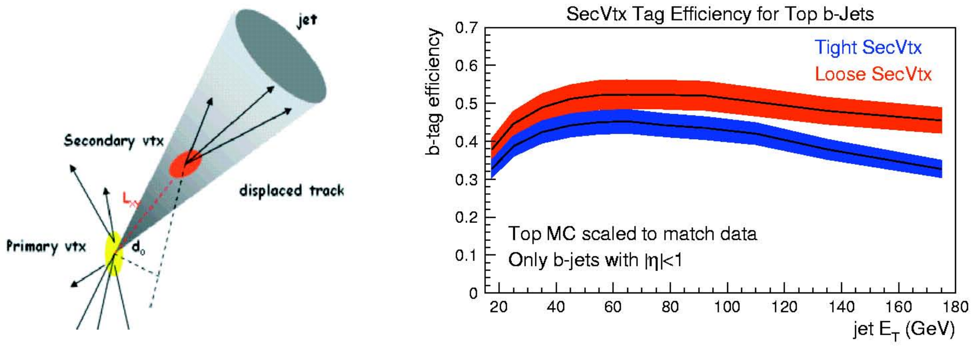


FIGURE 3. Left: Cartoon of a *b*-quark jet, showing tracks that point back to the jet's secondary vertex, caused by the long lifetime of the *b* quark. **Right:** CDF's measured efficiency for tagging a *b* jet inside top events as a function of jet E_T, using the silicon vertex tagger.

Other methods of tagging *b* jets are used to find top, as well. The "soft lepton taggers" take advantage of semi-leptonic b quark decays, which create jets containing relatively low energy muons and electrons. The "jet probability" tagger algorithms define a probability that tracks in a jet point back to the primary vertex of the event. One can then look for low probability jets, which will be a *b*-jet-enriched subsample. Once a *b* jet is selected, much of the W+light quark events are removed, and the dominant background is the much smaller W+heavy flavor processes, such as $W+b\bar{b}$.

Some top quark analyses do not require a *b*-tag in selecting top events, however. In this case, W+jets backgrounds are higher, but techniques are being refined to distinguish top events from background. These are so-called "kinematic" or "topological" methods, in which kinematic and event shape variables are used to discriminate $t\bar{t}$ events from background. Such methods include forming likelihood fits to event shapes, training neural networks, and forming other similar discriminants. These topological measurements are increasingly common and are achieving very good sensitivities.

Top Pair Production Cross Section

In discovering the top quark, one of the first things measured was the cross section: the rate of production of $t\bar{t}$ pairs. Run 1 measurements at $\sqrt{s}$=1.8 TeV were statistics limited. In Run 2, DØ and CDF have now *rediscovered* top by measuring the cross section again, now with three times the data, and at the higher center-of-mass energy. Measuring the production rate well is important in achieving full understanding of the top sector. If higher cross sections than predicted are seen, this could be a sign of non-standard model production mechanisms, such as resonant state production ($X \rightarrow t\bar{t}$), or perhaps anomalous couplings in QCD. Yet it might also mean that top is as expected, but that there is new physics lurking in our top quark samples, mimicking $t\bar{t}$.

***b*-Tagged Cross Section.** After requiring at least one tagged *b* jet in the selected W+jets samples, the sample is greatly reduced. To measure the rate of production, one

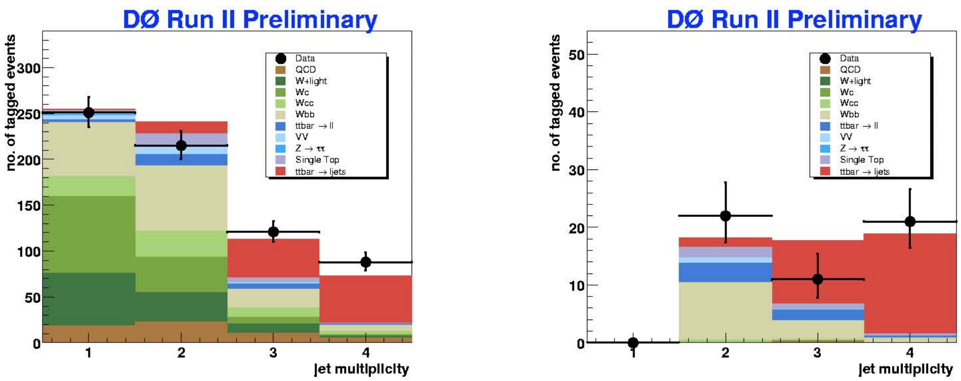


FIGURE 4. Measurement of the $t\bar{t}$ production cross section in the lepton+jets final state using 365 pb^{-1} of DØ data. Left: Jet multiplicity distribution of data (points) compared to Standard Model backgrounds and top for events having a single b-tagged jet (left) and those having both b quark jets tagged (right).

then basically counts the excess of events over other backgrounds, including mistags, with high jet multiplicity (traditionally 3 or more jets) as modeled in Monte Carlo and data. A recent preliminary measurement from DØ, shown in Figure 4, separates the samples into events with exactly three reconstructed jets, and those with at least four jets. These are further separated by lepton type (e or μ), and then into events containing a single tagged b jet, and those where both b jets from $t\bar{t}$ decay have been tagged. Exploiting the different signal-to-background (S/B) of these eight samples, they are placed in a joint likelihood and fit for the best cross section. In 365 pb^{-1}, DØ measure a cross section of $8.1^{+1.3}_{-1.2}(stat+sys)\pm 0.6(lumi)$ pb, in agreement with the Standard Model prediction of 6.7 ± 0.42 pb at M_{top} = 175 GeV.

Kinematic Cross Section. By not requiring a b-tagged jet to select top events, the full statistics of the W+jets sample may be used, but at the expense of higher backgrounds. Yet recent multivariate methods exploiting kinematic and topological variables, as mentioned above, have shown very good sensitivity, close to that achieved using b-tags. In addition, such methods provide a way to measure top quark properties independently of the number of b tags (or heavy flavor content). If results don't agree between the two samples, it may indicate a problem with the b tagger or the kinematics, or it may mean there are unexpected processes contributing to one of the samples, such as a new source of physics enhancing the heavy flavor content in W+jets.

A recent measurement by CDF, also in the lepton+jets final state, uses seven discriminating variables, including energetic variables such as H_T, the total scalar transverse energy in the event, and topological variables, such as jet pseudorapidity (maximum $|\eta|$), to separate top from background. These distributions are used to train a neural network to distinguish top from the dominant W+jets background, as shown in Figure 5. The neural network output variable (where a high value represents $t\bar{t}$-like events, a low value represents W+jets-like events) can be used to form templates with which to fit the data. In 350 pb^{-1} of data, CDF measure a $t\bar{t}$ production cross section of $6.0 \pm 0.9 \pm 1.0$ pb, in very good agreement with theory.

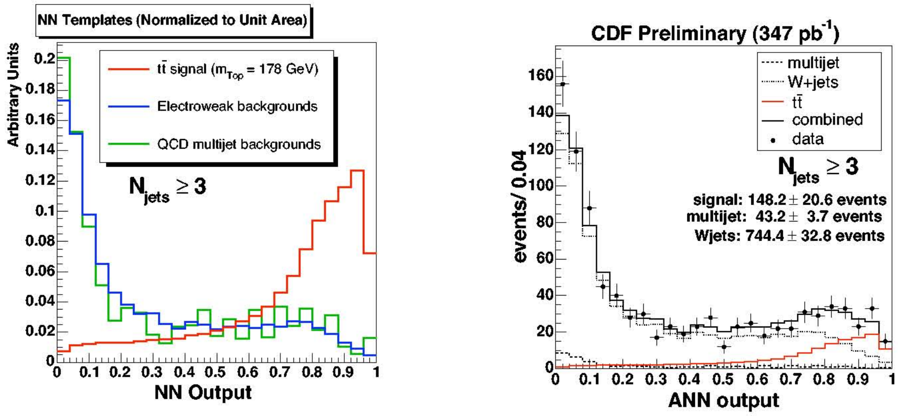
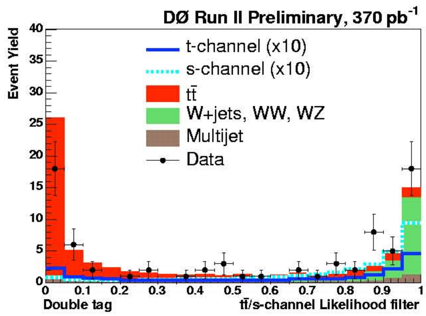


FIGURE 5. Left: Output distributions, normalized to equal area, from a 7-input neural network trained to separate top events from background for $t\bar{t}$ MC, W+jets MC, and QCD multi-jet backgrounds, taken from data. **Right:** 350 pb^{-1} of CDF data fit to the neural network templates, indicating that $t\bar{t}$ constitutes about 15% of the 3 or more jets sample.

Search for Single Top Production. Although measurements of pair production are increasingly refined, electroweak production of the top quark remains unseen. This mode is called "single top", as only one top quark is produced with another b quark through the Wtb vertex. Measurement of single top quark production could be used to constrain the CKM matrix element $|V_{tb}|$, to study the properties of the Wtb coupling, and to probe the PDF of the b quark directly. Single top production can also be used to constrain many models of new physics [10], such as the existence of a fourth generation, FCNC (t→Z/γ^* c), a new charged gauge boson W' (Top Flavor), and more. Yet finding single top is much more challenging than finding $t\bar{t}$ pairs due to the smaller cross section (s-channel: 0.88 $\pm$ 0.11 pb, t-channel: 1.98 $\pm$ 0.25 pb) [9], as well as the increased backgrounds in the two-jet final state.

The best limits on single top production to date come from a recent DØ analysis of 370 pb^{-1} of data. The signature requires a high-p$_T$ e or μ and $\not{E}_T$ from the W boson decay, along with two or three jets, at least one of which is tagged as a b jet. A likelihood discriminant method is used, in which uncorrelated topological variables are used to form a single discriminating variable. Since the s-channel and t-channel processes have different topologies, separate likelihood discriminants are used. In addition, separate discriminants are formed for the main $t\bar{t}$ and W+jets backgrounds, again due to differing topologies. The samples are separated further into e+jets, μ+jets channels, and single- and double-tagged events, due to the different signal-to-background ratios. This leads to 16 separate likelihood discriminants. Figure 6 shows the distributions for $t\bar{t}$ and W+jets discriminants for the s-channel only. As the number of data events in each sample is consistent with background only (within errors), the resulting expected/observed 95% CL upper limits on the single top quark production cross sections are 3.3/5.0 pb (s-channel) and 4.3/4.4 pb (t-channel). Using this method, it is estimated that several fb^{-1} of data are needed to finally observe single top production.



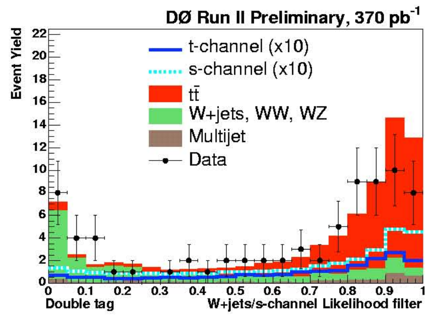


FIGURE 6. Data to Monte Carlo comparison of the discriminant distributions for combined e+jets and μ+jets channels in the double-tagged sample in the s-channel single top search. Comparison for the $tb/t\bar{t}$ filter (left) and for the tb/W+jets filter (right).

Top Quark Mass

As previously discussed, the mass of the top quark is an important electroweak parameter, and is one of the most anticipated measurements from the Tevatron. Yet precision top mass measurements are difficult. Background contamination can introduce biases in the mass sample. Statistical precision is affected by poor jet energy resolution, and by combinatorics. In the lepton+jets final state, for example, we have 24 combinations of assignments of jets to partons when reconstructing the top mass, including a two-fold uncertainty on the neutrino momentum z-component. The combinations are reduced by requiring one or two b-tagged jets, but this also reduces our statistical sample. Systematic uncertainties on the mass are dominated by knowledge of the jet energy scale. Predictions of how well we can measure the top mass at the Tevatron, then, necessarily depend on how we can improve our knowledge of the jet energies as we increase statistics.

Methodology. The technology for measuring the top mass has improved since the initial Run 1 measurements. The traditional “template” methods involve requiring at least one b tag, then associating the jets and leptons with each other in a manner that approximates the W mass, and such that the top and anti-top quarks have similar mass. A chisquare is formed taking into account these constraints, and the combination with the lowest chisquare is chosen to be the correct one. Using this reconstruction, Monte Carlo templates with different mass assumptions are fit to the data to find the best mass.

A late DØ re-analysis [11] of the Run 1 top mass data utilized a new category of methods, known as “matrix element” methods. On an event-by-event basis, a probability is formed by building the matrix element using properties of the measured event, then convoluting the PDFs as well as a detector response function. The probability varies as a function of assumed top mass, allowing the best value to be determined. These techniques utilize each combination of every event, so no events are thrown away, but those that are poorly reconstructed have lower weight.

Current Best Top Mass. Both CDF and DØ have several Run 2 mass results in the dilepton and lepton+jets channels using template methods, matrix element methods, and other similar techniques. While the matrix element reconstruction methods

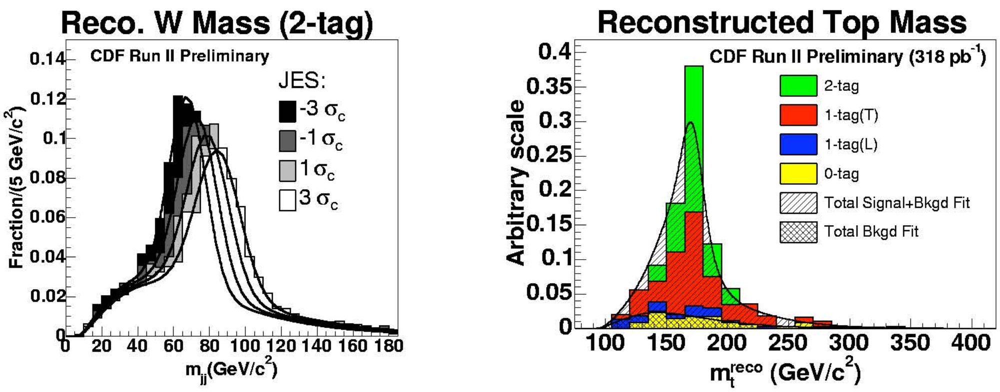


FIGURE 7. Left: $W \rightarrow$jet jet invariant mass templates for different assumed jet energy scales. Here the σ value indicates the difference from the nominal jet energy scale. **Right:** Distribution of reconstructed top mass for the four different b-tagged samples, weighted by their individual contribution to the likelihood fit, shown with the results of the fit overlaid.

show promise to be the most sensitive, the most precise mass result for summer 2005 is with 320 pb^{-1} of CDF data, using a unique template method. The silicon b-tagged lepton+jets sample was divided into four subsamples by the number of b jets found: zero tags, one loose tag, one tight tag, and two tags. This takes advantage of the different S/B in each sample. In addition, the invariant mass of the two jets from the W boson was reconstructed for the four b-tagged samples as well, where any two-jet combination having no b tags enter the di-jet mass distributions. Monte Carlo templates were formed for both the reconstructed top mass with differing mass hypotheses, and for the W di-jet mass with varying jet energy scale hypotheses. The four mass samples, along with the four W di-jet samples, were placed into a joint likelihood and fit simultaneously (Figure 7). This provided a best fit to the top mass as well as a best value for the jet energy scale, thus reducing the systematic error due to the jet energy scale significantly. It is currently (2005) the world's single most precise top mass measurement: M_{top} = 173.5 $\pm$ 3.7 (stat+JES) $\pm$ 1.7 (syst) GeV/c^2. With only 320 pb^{-1} CDF reports an uncertainty of 4 GeV, compared to the Run 2 projections of a $\sim$3 GeV uncertainty with 2 fb^{-1}. Both CDF and DØ can thus expect to do quite a bit better than originally expected as the Run 2 data become available.

For summer 2005 conferences, CDF and DØ made two consecutive top mass combinations of best measurements as they were released. The final combination, and subsequent to PIC '05, is available on archives [12]. This new world average gives M_{top} = 172.7 $\pm$ 2.9 GeV/c^2. Figure 8 shows the resulting constraint on the Standard Model Higgs mass using the new world average, along with predictions of the future precision for the top and W masses for the Tevatron, the LHC, and eventually, the ILC [13].

CONCLUSIONS

With datasets more than triple those of Run 1, Run 2 top quark measurements are well underway. Results for $t\bar{t}$ production cross sections are becoming quite precise, and top

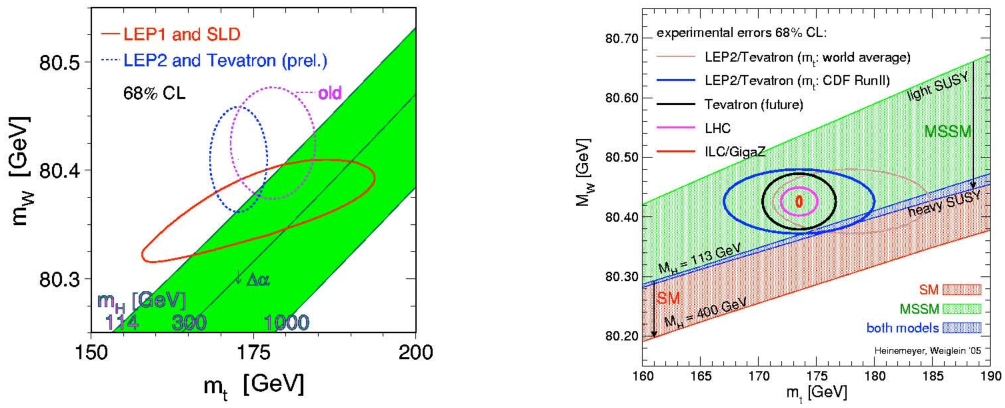


FIGURE 8. Left: Latest errors on M_{top} and M_W combining the 2005 top mass average with the W mass average from LEP2 and the Tevatron. The 1σ error ellipses are overlaid onto projections for the Higgs mass at 114, 300, and 1000 GeV/c^2, and have moved to further favor a light Standard Model Higgs. **Right:** Error ellipse projections for the top and W masses from current LEP2 and Tevatron data (CDF best top mass used here), and for future Tevatron, LHC, and ILC sensitivities. These are overlaid onto bands of predicted Higgs masses for the Standard Model, as well as for different SUSY model assumptions.

mass measurements have succeeded beyond prediction thus far. Single top production, however, has yet to be observed, and looks to be more difficult than originally projected. Yet many other measurements [14] of top production and decay properties are beginning to achieve interesting sensitivities. New results for resonance production of $t\bar{t}$ are available, for example, as well as for W helicity in top decays. Some measurements that have never been made, such as top lifetime, are also in progress. The landscape for top quark physics is extremely exciting in the next few years, and will continue to be well into the LHC era, where top will be produced in large quantities. We have much to learn about this very interesting quark, so stay tuned: top quark results are streaming out again.

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