

## REVIEW OF RECENT TOP QUARK MEASUREMENTS

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At the Tevatron Collider at Fermilab, a large number of top quarks have been produced in the ongoing run. The CDF and DØ collaborations have made first measurements of the  $t\bar{t}$  cross section in several decay channels, and have measured the top quark mass. In addition, they have set new limits on the cross sections for single top quark production, and have started to measure some of the properties of the top quark via studies of its decays. This paper summarizes the status of these measurements and discusses where they are heading in the next few years. The paper is based on a talk I gave at the Rencontres du Vietnam in Hanoi, August 2004; the results have been updated to show the latest values and new measurements.

### 1 Top in a Nutshell

The top quark is a spin  $+1/2$  fermion, with charge  $+2/3$ ; it is the weak-isospin partner of the bottom quark, and together the top and bottom quarks form the third generation of quark families. The top quark is approximately forty times heavy than its partner, with a mass of  $178.0 \pm 4.3$  GeV measured from the Tevatron Run I data.<sup>1</sup> Figure 1 shows the tree-level Feynman diagrams for top quark pair production at the Tevatron. About 85% of the rate comes from the  $q\bar{q}$  initial state and the remaining 15% comes from the  $gg$  initial state. The Standard Model cross section at next-to-next-to-leading order is  $6.8 \pm 0.4$  pb.<sup>2</sup>

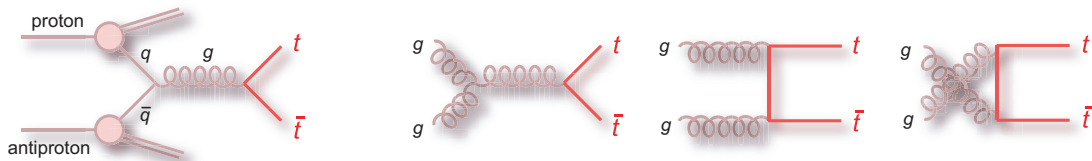


Figure 1: Tree-level Feynman diagrams for top quark pair production at the Tevatron Collider.

### 1.1 Properties, Production, and Decay

The top quark decays before it can hadronize, since its lifetime  $\Gamma_{\text{top}}^{-1} = (1.5 \text{ GeV})^{-1}$  is much less than the QCD scale  $\Lambda_{\text{QCD}}^{-1} = (200 \text{ MeV})^{-1}$ . Therefore, there are no top mesons or baryons. It decays 99.9% of the time into  $W^+b$ , as shown in Fig. 2(a). Top pair events are classified by the decays of the two  $W$  bosons: “dileptons” ( $ee, e\mu, \mu\mu$ ); “lepton+jets” ( $e$ +jets,  $\mu$ +jets); and “alljets.” The branching fractions for these decays are illustrated in Fig. 2(b). The  $\tau$  decays are included in the other channels experimentally, depending on the  $\tau$  decay mode.

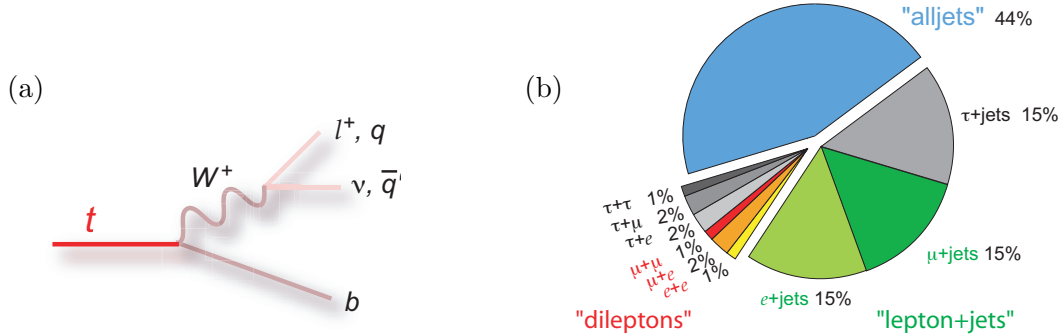


Figure 2: (a) Tree-level diagram of a top quark decay. (b) Pie chart of the branching fractions for  $t\bar{t}$  decays.

### 1.2 Detection and Reconstruction

Top quarks are produced at the Fermilab Tevatron Collider. This machine accelerates protons and antiprotons at a center-of-mass energy of 1.96 TeV, with two collision regions, one at the CDF detector, and the other at the DØ detector. The collider has been upgraded in energy and instantaneous luminosity and the detectors have had significant upgrades to match, including new tracking systems, and major improvements to the calorimeters and muon systems.

From the first part of Run II, April 2002 – August 2004, CDF collected  $370 \text{ pb}^{-1}$  of data ( $330 \text{ pb}^{-1}$  with the SVXII silicon tracker in operation), and DØ collected  $470 \text{ pb}^{-1}$  of data (all with the SMT silicon tracker operating). The results shown here are for the first 100–200  $\text{pb}^{-1}$  of data from each collaboration, several million triggered events. The collaborations select final samples of events from this data to maximize the measurement sensitivity, leading to about 100 top quark events above backgrounds identified so far.

### 1.3 Backgrounds

Processes that mimic top quark decays and thus form the backgrounds to the searches and measurements are dominated for most channels by events with real  $W$  or  $Z$  bosons in them ( $W$ +jets,  $Z$ +jets,  $WW$ ,  $WZ$ ,  $ZZ$ ). A simple  $Wb\bar{b}g$  three jet event is shown in Fig. 3(a). The next most common source of background is from events with misidentified leptons: multijet events with a jet misidentified as an electron; and  $b\bar{b}$ +jets events with a misidentified electron or muon from a  $b$  decay. One example is shown in Fig. 3(b). There are several additional sources that can contribute to the backgrounds at a lower level: these include cosmic rays, multiple  $p\bar{p}$  interactions in one bunch crossing, and pattern recognition mistakes when reconstructing final state objects. For most  $t\bar{t}$  decay channels, processes with a real  $W$  boson and non- $b$  jets with a fake tag are the most difficult to remove.



Figure 3: (a) A tree-level diagram for the  $Wb\bar{b}g$  process. (b) A tree-level diagram for the  $b\bar{b}g$  process.

#### 1.4 Bottom Quark Identification

In order to reject background processes while keeping signal, many top quark searches and measurements require that at least one jet is identified as originating from a  $b$  quark. CDF and DØ each do this by using high resolution three-dimensional position information for the charged tracks near the primary vertex. Fitted tracks are separated into those from the primary vertex and those from secondary vertices from the decays of the long-lived  $b$  quarks. Several algorithms are in use, including ones that measure the decay lifetime significance, and ones that measure the impact parameter significance. For each experiment, the probability to tag at least one jet in a  $t\bar{t}$  events is about 55%, with an associated probability for a fake tag of about 0.4%.

## 2 Top Pair Cross Section

The CDF and DØ collaborations have made a number of measurements of the  $t\bar{t}$  production cross section using the new Run II data. These may be compared with the theory value of 6.8 pb, which is only 0.03% of the  $W$  boson cross section at the Tevatron. All the main decay modes have been used for these measurements, and the selected events form the baseline samples for measurements of the top quark properties. The measurements cannot be combined in a simple manner to get an improved overall result, since many of them use the same input data and apply different selection methods to get the final results.

### 2.1 CDF's Measurements

The CDF collaboration has made 12 measurements of the  $t\bar{t}$  cross section: three using dilepton data; eight with the lepton+jets data; and one in the alljets channel.

#### Dilepton Measurements

CDF's first dilepton measurement is a traditional search where both leptons are identified, no  $b$  tagging is used, and the total transverse energy ( $H_T$ ) of the events is required to be  $> 200$  GeV. This yields a measurement with an uncertainty of 44%. (The values of the measurements will be given together at the end of this section.) The second measurement relaxes the identification on one of the two leptons by just requiring an opposite sign isolated track for it. This measurement gets a 43% uncertainty. These two measurements have been published.<sup>3</sup> A third measurement comes from a simultaneous fit of the cross sections to the data in the missing-transverse-energy/number-of-jets plane for  $t\bar{t}$ ,  $WW$ , and  $Z \rightarrow \tau\tau$ , plus other processes in a fixed background component. The resulting cross section has a 32% uncertainty. Fitting to one or more variables results in a better quality measurement than just counting events.

## Lepton+Jets Measurements

CDF have two measurements using lepton+jets data that require no  $b$  identification. The first makes a likelihood fit to the total transverse energy distribution and get a result with a 51% uncertainty. The second measurement combines seven variables in a neural network and performs a likelihood fit to the network output. This results in a measurement with a 28% uncertainty.

CDF have one result where a  $b$  jet is identified by the presence of a muon in the jet. Since the branching fraction for  $b$  to  $\mu$  is small, this method has a small acceptance; however, it uses an independent data sample from the other measurements and can thus readily be combined with them to get a better overall result. This measurement has an uncertainty of 77%.

CDF have several measurements that use jet and track properties to identify  $b$  jets. The first uses a jet-probability  $b$ -tagging method that results in a cross section measurement with a 32% uncertainty. The second uses a secondary-vertex  $b$ -tagging method with an  $H_T > 200$  GeV cut to make a 27% measurement,<sup>4</sup> which is the best result so far in any channel. They also use this  $b$  tagging method with a likelihood fit to the leading jet transverse energy instead of the  $H_T$  cut for a 33% measurement.<sup>5</sup> They have two double-tagged measurements: the first applies their standard secondary-vertex algorithm and obtains a 53% result;<sup>4</sup> the second uses a looser algorithm with higher efficiency and higher fake rate to make a 37% measurement. The secondary-vertex result with the  $H_T$  cut is shown in Fig. 4

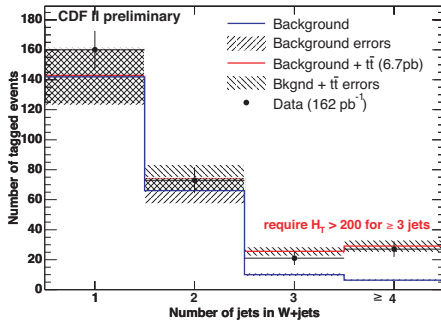


Figure 4: Number of jets after  $b$  tagging and the  $H_T$  cut, showing the  $t\bar{t}$  excess in the 3- and 4-jet bins.

## Top Pair Production Cross Section

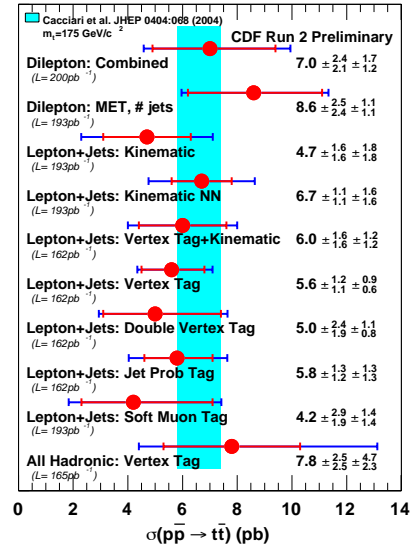


Figure 5: Measurements of the  $t\bar{t}$  production cross section by the CDF collaboration.

## Alljets Measurement

CDF have measured the  $t\bar{t}$  cross section in the all-hadronic decay channel. They cut on four kinematic variables chosen to reject the multijet background, and require a secondary vertex  $b$  tag. This results in a measurement with a 68% uncertainty. Again, although this measurement does not have much sensitivity on its own, it is independent of those in other decay channels, and so can be easily combined with them to improve the overall result. Such combination has not yet been done.

## CDF $t\bar{t}$ Cross Section Summary

Figure 5 shows almost all the results described above. (Only the loose double  $b$  tag is not shown: that measurement used 162  $\text{pb}^{-1}$  of data and found  $\sigma(p\bar{p} \rightarrow t\bar{t}) = 8.2^{+2.4}_{-2.1}(\text{stat})^{+1.8}_{-1.0}(\text{sys})$ .) The measurements are all consistent with the NNLO theory band, shown in cyan on the plot.

## 2.2 $D\bar{O}$ 's Measurements

The  $D\bar{O}$  collaboration has made 13 measurements of the  $t\bar{t}$  cross section: four in the dilepton channels; eight with the lepton+jets data; and one in the alljets channel.

### Dilepton Measurements

$D\bar{O}$ 's first three dilepton measurements are in the  $ee$ ,  $e\mu$ , and  $\mu\mu$  channels. Two opposite-sign leptons are reconstructed, and cuts made on the invariant mass of the dilepton pair and on the total transverse energy of the event. The uncertainty on the combined measurement is 41%.

A novel measurement has been made in the  $e\mu$  channel where a reconstructed secondary vertex in a jet has been used to identify the presence of a  $b$  jet. This method yields a very high purity sample, and a cross section uncertainty of 54%, which is statistics dominated and will improve with a looser tagging definition and more data.

### Lepton+Jets Measurements

$D\bar{O}$  have measured the  $t\bar{t}$  cross section in the single-electron and single-muon decay channels with an untagged analysis and by using three different  $b$ -identification methods. The untagged measurement performs a binned likelihood fit to a likelihood discriminant variable, and obtains an uncertainty of 42% for the combined electron and muon measurements. The first  $b$ -tagging result uses the muon-in-jet method, with cuts on aplanarity and  $H_T$ ; this gives a 41% uncertainty. The second method identifies  $b$  jets with a secondary vertex, and the third finds  $b$  jets with an impact-parameter significance check. These two methods both make a likelihood fit for events with exactly three jets, or four or more jets, and for exactly one tagged jets, or two or more tags. The resulting cross-section measurements have uncertainties of 29% for the secondary-vertex algorithm and 33% for the impact-parameter algorithm. The secondary-vertex tagged data are shown in Fig. 6.

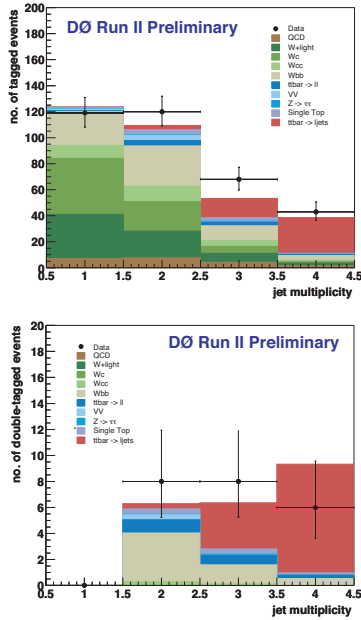


Figure 6: Jet multiplicity for lepton+jets events with exactly one tagged jet, and with at least two tagged jets.

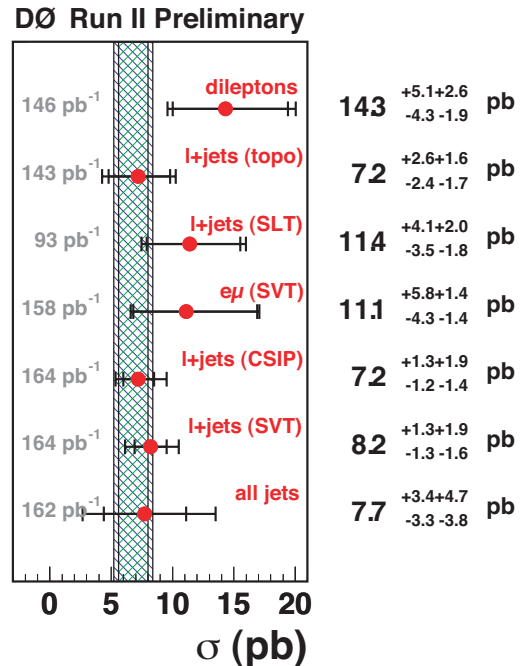


Figure 7: Measurements of the  $t\bar{t}$  production cross section by the  $D\bar{O}$  collaboration.

## Alljets Measurements

DØ have used events with at least six jets, including one with a secondary vertex  $b$ -identifying tag, to measure the  $t\bar{t}$  cross section in the all-hadronic decay mode. Nine different kinematic quantities are combined using three sequential neural networks, and events are counted after cutting on the outputs. The resulting measurement has a 76% uncertainty.

## DØ $t\bar{t}$ Cross Section Summary

Figure 7 shows the results described above. The measurements were made with between  $92 \text{ pb}^{-1}$  and  $162 \text{ pb}^{-1}$  of data, and are consistent with the NNLO theory band, shown in the cyan striped band on the plot.

### 2.3 Cross Section Summary

The cross section results are still statistics limited and are expected to improve significantly in precision as the datasets are enlarged. The uncertainty on Run I results was 26–30%; the best measurements so far have the same precision already, 27% (CDF) and 29% (DØ). With  $2 \text{ fb}^{-1}$  of data, the uncertainty is expected to improve to about 10%, when it will be dominated by the uncertainty on the integrated luminosity.

## 3 Single Top Quarks

In addition to the pair production of top quarks described above, they are also expected to be produced at the Tevatron singly. There are three modes,  $p\bar{p} \rightarrow t\bar{b}$ ,  $\rightarrow tq\bar{b}$ , and  $\rightarrow tW$ . The third one has a tiny cross section and will be very difficult to separate from  $t\bar{t}$  production. The CDF and DØ collaborations have both produced results from searches for the first two modes, known as  $s$ -channel and  $t$ -channel production. Figure 8 shows the main tree-level diagrams for these processes. The  $s$ -channel cross section is calculated to be  $0.88 \pm 0.11 \text{ pb}$  at next-to-leading order,<sup>6</sup> and the  $t$ -channel cross section is  $1.98 \pm 0.25 \text{ pb}$  at the same order.<sup>6</sup>

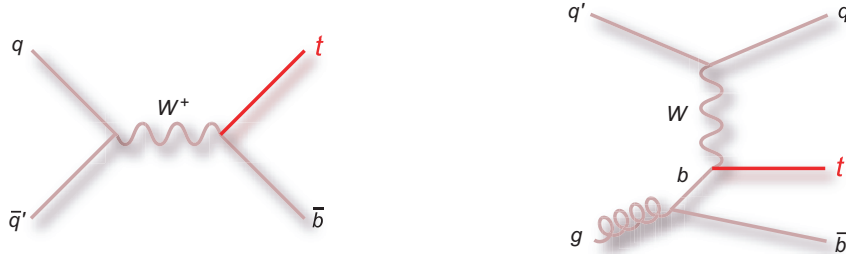


Figure 8: The main tree-level Feynman diagrams for single top quark production at the Tevatron Collider.

Since there are fewer jets in single top quark events than in most  $t\bar{t}$  ones, the  $W$ +jets backgrounds are at least ten times higher, and this is compounded by the lower signal cross sections. Consequently, it is much more difficult to separate single top events from background than  $t\bar{t}$  ones. Once single top quark production is observed, the collaborations expect to be able to use it to measure the CKM matrix element  $|V_{tb}|$  without assuming that there are only three quark generations or CKM unitarity, and hence will be able to determine the top quark width. Observation is hoped for with  $1\text{--}2 \text{ fb}^{-1}$  of data.

### 3.1 CDF's Measurements

CDF have recently submitted for publication the results of searches for  $s$ -channel single top, for the  $t$ -channel, and for a combined search.<sup>7</sup> The searches start with events with a  $W$  boson

reconstructed from an isolated lepton and missing transverse energy, and exactly two jets. Only events with  $140 \text{ GeV} \leq M_{l\nu b} \leq 210 \text{ GeV}$  are used in the search. A likelihood fit is made to the distribution of lepton charge times pseudorapidity of the untagged jet, which yields 95% confidence level (CL) upper limits of 14 pb on the  $s$ -channel cross section and 10 pb for the  $t$ -channel. A separate likelihood fit to the total transverse energy of the events gives a 95% CL upper limit on the cross section for  $s$ - and  $t$ -channel combined of 18 pb.

### 3.2 $D\bar{O}$ 's Measurements

$D\bar{O}$  have released preliminary results on single top quark searches. They allow between two and four jets, and do not make an invariant mass cut. Selecting events with high transverse energy of the lepton, neutrino, and the first two jets yields a 95% upper limit of 19 pb on  $s$ -channel top quark production, 25 pb on  $t$ -channel production, and 23 pb on the combined production.

### 3.3 Single Top Summary

Both collaborations are extending their searches by adding more data, improving the signal acceptances, background models,  $b$ -identification tools, uncertainties, and final selection methods. More sensitive results are expected soon.

## 4 Top Quark Mass and Other Properties

Many interesting measurements of top quark properties will be possible in the future; however, all require high statistics and are not very significant yet. The properties that will be studied include  $gtt$  and  $Wtb$  couplings in production, spin correlations between the top and antitop, and the production of top from or with new particles. In the decay, the charge and width will be measurable, together with the rare CKM branching fractions,  $W$  helicities, gluon radiation, transverse momentum spectra, and other rare decays. Several preliminary measurements have been made by CDF and  $D\bar{O}$ : interested readers are encouraged to read them on the web pages of the Top Groups of the two collaborations. Here, we will discuss the status of the top quark mass measurement, a flagship measurement of the Tevatron collider program.

The CDF and  $D\bar{O}$  collaborations have been measuring the top quark mass for the past ten years. The methods have developed significantly over this time. Early ones used kinematic fitting and compared the results to templates for many values of the top quark mass. Later methods added more variables and used likelihoods. The best methods now use all the available information in the events, but are extremely time-consuming to implement and to run the calculations. As the methods have improved, so have the uncertainties on the measurements. The first results in 1995 had at least a 7% error. Current results using Run II data have a 5% uncertainty. The best Run I result combining all decay channels from both experiments and using the best method for one of them has a 2.4% uncertainty. The goal for Run II data is to measure the top quark mass to 1%, which translates into a  $\pm 1.5$ –2 GeV error.

The world average measurement<sup>1</sup> of the top quark mass is:

$$m_{\text{top}} = 178.0 \pm 4.3 \text{ GeV},$$

which is dominated by  $D\bar{O}$ 's measurement in the lepton+jets channel using the matrix element method:<sup>8,9</sup>  $180.1 \pm 5.3 \text{ GeV}$ .

### 4.1 CDF's Measurements

CDF have made three measurements using dilepton events, and three using lepton+jets events. The first dilepton measurement finds the best fit mass mass after trying all possible solutions for

the  $\phi$  angles of the two neutrinos in each event, and compares these masses to template models. It uses 13 data events where both leptons are fully identified. The uncertainty on the result is 10.7%. The second dilepton measurement uses a similar method on almost the same data events, but instead of the  $\phi$  angles as test variable, it uses the longitudinal momentum of the  $t\bar{t}$  system. The uncertainty on the result is very similar to the first method, 10.5%. The third method uses a neutrino weighting algorithm on 19 events where one lepton has been identified and the other is assumed from an isolated track. This method yields a measurement with uncertainty 8.3%. The uncertainties on the dilepton mass measurements have a systematic component of 7–9 GeV, about the same size as in the lepton+jets measurements. However, owing to the small numbers of events, the statistical component of the uncertainties is much larger.

The first CDF measurement with lepton+jets events utilizes kinematic fitting and mass templates. The method has been applied to events with no  $b$  tag, exactly one tag, and two or more tags, and then the three measurements have been combined. Separately, the uncertainties on the three results are not as good as the following ones with more sophisticated techniques, but optimizing on the datasets independently improves the sensitivity, and the resulting measurement uncertainty is 4.6%. The second method is similar to the first, but uses the scalar sum of the first four jets as a variable, together with the standard reconstructed top quark mass one, for two-dimensional templates. It is applied to 33 events that have at least one tagged jet, and the uncertainty in the result is 5.2%.

The third method applied to tagged lepton+jets data is called the dynamical likelihood method. It is similar in concept to  $D\emptyset$ 's matrix element method, in that it uses all the information in each event, not just one or two variables, and each event is weighted by its probability to be signal or background, so signal-like events contribute more to the final result than background-like ones. There are some differences between the two methods, principally in how the backgrounds are handled. CDF's top mass measurement using the dynamical likelihood method has a 4.5% uncertainty, which is the most precise result from Run II so far. It is not as good as the best Run I result, which had a 2.9% uncertainty, because the jet energy scale is not as well calibrated yet.

CDF's top quark mass measurements are shown in Fig. 9. The yellow band shows the world average measurement from published Run I results.

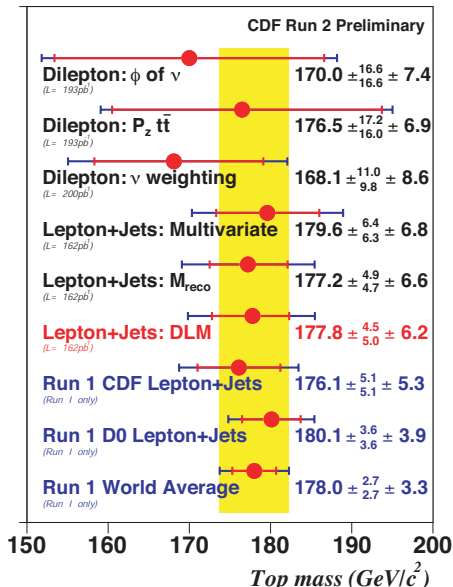


Figure 9: CDF's top quark mass measurements.

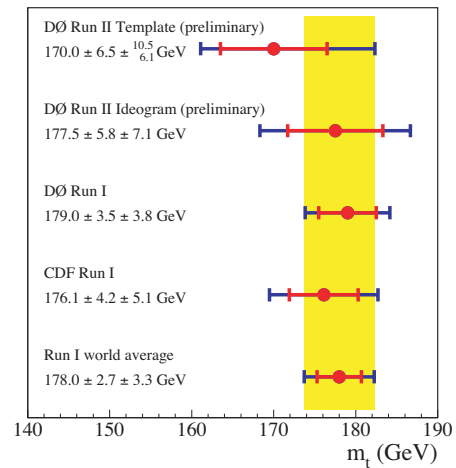


Figure 10:  $D\emptyset$ 's top quark mass measurements.



## 4.2 $D\bar{O}$ 's Measurements

$D\bar{O}$  have made two measurements of the top quark mass using Run II data, both in the lepton+jets decay channel. The first method uses templates for signal and background, and fitting to 86 data events yields a measurements with an uncertainty of 7.1%. The second method, called “ideogram,” uses an analytical likelihood for each event to see whether it is signal or background. The resulting mass measurement has an uncertainty of 5.2%. As with CDF’s measurements, this better result is from the method that uses more information about each event.  $D\bar{O}$ ’s top quark mass measurements are shown in Fig. 10. The yellow band shows the same world average measurement as in the neighboring CDF plot.

## 4.3 Top Mass Summary

New measurements using Tevatron data from Run II are now appearing, and in the future the precision will be better than 2 GeV. Since the top quark couples strongly to the Higgs boson, and plays a critical role in loop corrections, one can combine the mass information with other precision measurements to determine the most favored mass region for the Higgs boson. The Run II top quark mass results have not yet been published or combined with previous measurements; using the published values instead, the latest best fit Higgs boson mass is  $114^{+69}_{-45}$  GeV, and the 95% confidence level upper limit on the Higgs boson mass is 260 GeV.<sup>10</sup>

## 5 Future Top Quark Physics

The future of top quark physics is very bright. Whereas the Tevatron produces about  $10^4$  top quark pairs per year, the Large Hadron Collider (LHC) will produce  $10^7$  pairs per year for the first three years, and  $10^8$  per year after that. This is because both the energy, at 14 TeV, and the luminosity will be much higher, boosting both the cross section and the interaction rate. Because the LHC is a proton-proton machine, and not proton-antiproton, about 90% of the rate will come from the  $gg$  initial state and the remaining 10% from  $q\bar{q}$ , almost exactly opposite to the situation at the Tevatron.

At the International Linear Collider (ILC), if the electron-positron collisions are at the  $t\bar{t}$  threshold, about 360 GeV, then  $10^6$  pairs will be produced per year. The  $e^+e^- \rightarrow t\bar{t}$  cross section is much lower than at the Tevatron, but the ILC luminosity will be much higher. In addition, the backgrounds will be much lower than at the Tevatron, and many precision measurements will be possible.

At the LHC and ILC, all top quark properties, including SM and non-SM couplings, and rare production and decay modes, will be studied in detail. To give one example of the expected precision, let us consider the top quark mass. Similar precision is expected from both the Tevatron and the LHC, about 1–2 GeV. These measurements will be limited by our understanding of the final state radiation. At the ILC, one can scan the  $t\bar{t}$  threshold and fit  $m_{\text{top}}(1S)$ ,  $\alpha_s(M_Z)$ ,  $\Gamma_{\text{top}}$ , and  $g_{tH}$  to measurements of  $\sigma_{t\bar{t}}$ ,  $p_{\text{top}}$ , and  $A_{\text{FB}}^{\text{top}}$ , to yield a measurement of  $m_{\text{top}}(1S)$  to 20 MeV precision.<sup>11</sup> Converting  $m_{\text{top}}(1S)$  to  $m_{\text{top}}(\overline{\text{MS}})$  limits the  $m_{\text{top}}(\overline{\text{MS}})$  uncertainty to about 100 MeV.<sup>12</sup> The future precision on the Higgs boson from measurements of the  $W$  boson mass and top quark mass are shown in Fig. 11.

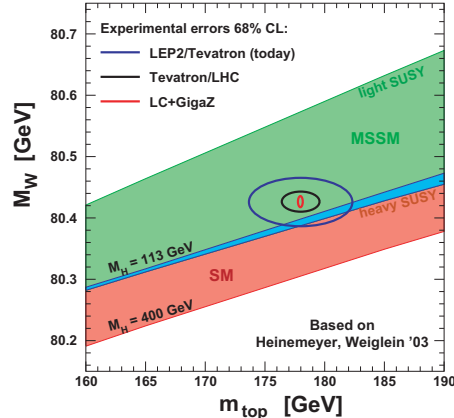


Figure 11: Predicted sensitivity to SM and MSSM Higgs boson mass from measurements of the top quark mass and  $W$  boson mass at future colliders.<sup>13</sup>

## 6 Summary

The Tevatron  $p\bar{p}$  Collider is the only top quark factory until the Large Hadron Collider turns on at the end of 2007. The Tevatron is meeting performance expectations and the CDF and DØ collaborations are collecting data at high efficiency. About 80 times more data in Run II is expected than was collected in Run I ( $100 \text{ pb}^{-1} \rightarrow 8 \text{ fb}^{-1}$ ). Many first measurements with the Run II data are now available; all are consistent with the Standard Model predictions. More data is needed to reduce both the statistical and systematic uncertainties on these measurements. In addition, more time is required to apply more sophisticated analysis methods to the measurements. As this begins to happen, a precision top quark physics program will emerge. The top quark will provide a unique window into hidden parts of the Standard Model and hopefully many regions beyond.

## Acknowledgments

I would like to thank the organizers and hosts of the Rencontres du Vietnam in Hanoi for their gracious and thoughtful hospitality. To travel to Vietnam and meet the generous people and see the beautiful countryside and fascinating city life was a great opportunity, one I shall never forget. The meeting itself was first class and extremely interesting.

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