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Top Quark Mass Measurements from the Tevatron

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Abstract

We review the measurements of the top quark mass by the CDF and DØ collaborations using Run I data in excess of 100 pb^{-1}. The DØ collaboration [1] has recently updated its measurement of the top quark mass in the lepton + jets channel. The world average of the top quark mass from the CDF [2] and DØ measurements in the lepton + jets channel now stands at 175.6 ± 5.5 GeV/c^2.

1 Introduction

The top quark is of fundamental importance in understanding the standard model of particle interactions. The measurement of the top quark mass and the mass of the W boson can be used together to constrain the mass of the Higgs particle, an as yet unobserved particle which is responsible for the generation of masses in the standard model. Failure to obtain Higgs mass constraints within reasonable limits can become the first indication of the incompleteness of the standard model. This paper reports on the latest measurements of the top quark mass from the Tevatron experiments, CDF and DØ. Combining the measurements of the mass from the lepton + jets channel from the two experiments yields a value for the top quark mass which has the least error obtained to date. In what follows, we will report on mass measurements in three different decay modes of the $t\bar{t}$ system. The standard model top quark decays into a b quark and a W. The final states of the $t\bar{t}$ system are distinguished by the decay modes of the two W's in the event. These are,

- the dilepton channel, where both the W's decay into a lepton and a neutrino. Due to the presence of the two neutrinos, this channel is underconstrained. Both CDF and DØ have differing methods to extract the mass from this channel.
- the all jets channel, where both the W's decay into $q\bar{q}$ pairs. There are no neutrinos in this channel that can lead to missing transverse energy. CDF has reported a measurement in this channel.
- the lepton + jets channel, where one W decays into a lepton and neutrino and the other decays into $q\bar{q}$. Both CDF and DØ have similar methods to extract the mass information. The DØ analysis, using multivariate techniques, is new and is being reported for the first time at this conference. We will describe this channel from both experiments more completely than the others, since the global average mass is being determined using this channel only and also because the other results have been reported at previous conferences.

In all that follows, jet energies have been corrected down to the parton level, using Monte Carlo models of fragmentation. In making event selection cuts, however, CDF uses uncorrected jet energies whereas DØ uses corrected energies.

2 Kinematic fitting

In the absence of initial or final state gluon radiation, the 6 decay particles of the $t\bar{t}$ system can be described by 18 variables. Each particle is described by a three momentum, its energy being determined given its rest mass. The hadronic system that recoils against the $t\bar{t}$ system is described by its p_t, which adds another two variables. There are five constraints on the model to fit the event, namely that the effective mass of the two W decay particles has to equal the W mass, that the effective masses of the top and anti-top decay products have to be equal to each other and that the transverse momentum components of the recoiling hadronic system have to equal the transverse momentum components of the $t\bar{t}$ system. This implies that the theoretical fitting model has 15 free parameters. In the all jets case, all the final state particles and the transverse momentum components of the recoiling system are observed, yielding 20 measurements. The system is thus overconstrained by 5, yielding a 5C fit. In the lepton + jets case, the neutrino three momentum is unknown, yielding 17 measured variables leading to a 2C fit. In the dilepton channel, two neutrinos are missing, yielding 14 measured variables. This leads to an underconstrained situation (-1C fit). If the top quark mass is specified, one gets a

0C case, and the neutrino solutions can be determined for each given top quark mass, leading to a likelihood distribution for the top quark mass for each event. Since in general, one does not know if a particular jet is the result of a b quark decay, there exist several permutations of final state particles that must be fitted for the hypothesis in question. In the all jets case, when both the b quarks are tagged, there exist 6 ways of combining the remaining 4 jets into two W decay groups. With only one b quark tagged, there exist 10 ways of combining the remaining 5 jets into the two jets associated with the tagged b jet and another three permutations among the remaining three jets to assign the untagged b jet, yielding 30 combinations in all. For the lepton + jets channel, there are 12 combinations in the untagged case and 6 combinations in the tagged case. For the dilepton channel, there are two combinations for the tagged and untagged case. The fitting procedure is applied to each combination independently and only combinations that meet a goodness of fit χ^2 criterion are kept in the constrained case. In the unconstrained case, the likelihood distributions from the combinations are added up and renormalized to obtain the likelihood distribution for the event. When extra jets are present, the number of combinations increases rapidly. For this reason, unless otherwise stated, only the highest E_T jets are used in the fit, the number of jets being the minimum required to fulfill the kinematic hypothesis.

3 The Dilepton channels

The CDF collaboration [2] employs two different techniques in extracting the mass from the dilepton channels. Using event selection cuts described in the previous talk [3], and a cut $H_T >$ 170 GeV, where H_T is the scalar sum of the E_T of the various objects, CDF obtains 1 candidate in the ee channel, 1 in the $\mu\mu$ channel and 6 in the $e\mu$ channels. The first method compares E_T of the found jets with Monte Carlo from different masses. This relies on the fact the average E_T of the two b quark jets from top quark decay is directly related to the top quark mass. The heavier the top quark, the more energetic are the b quarks on average. This method yields a mass of 159 $^{+24}_{-22}(stat)\pm 17$(sys) GeV/c^2 .

The second method uses the approximate expression

$$M_{top}^2 = M_W^2 + 2 < M_{lb}^2 > /(1- < \cos(\theta_{lb}) >)$$

where M_{lb} is the lepton b quark effective mass and θ_{lb} is the angle between the lepton and the b quark. The quantity $< \cos(\theta_{lb}) >$ is obtained from Monte Carlo and a correspondence function between Monte Carlo and data is used to calibrate the result yielding a mass of $162 \pm 21.0(stat)^{+7.1}_{-7.6}(sys)$ GeV/c^2.

The DØ collaboration uses a variant of the method proposed by Dalitz, Goldstein [4] and Kondo [5] where for each top mass hypothesis, one tries to obtain solutions for the neutrinos. This results in 0,2 or 4 solutions. The event four vectors are smeared many times in order to estimate the probability of neighbouring events fluctuating to give the observed event. If one introduces additional information on the QCD production of the $t\bar{t}$ system, one can weight each solution by a weight proportional to the product of the structure functions and a decay probability[4]. The DØ analysis yields a mass [6] of $158 \pm 24.0(stat) \pm 10(sys)$ GeV/c^2.

4 The All jets channel

Only the CDF collaboration has reported a mass measurement in this channel. CDF performs a three constraint fit in this channel, (instead of a possible five constraint fit) by not demanding

p_t balance between the recoiling system and the $t\bar{t}$ system. By demanding $5 < N_{jets} < 10$ per event and the jet $\Sigma E_T > 200$ GeV, CDF observes 142 events with a b quark tag in the silicon vertex detector, with a calculated background of 113. This agrees with the rate expected from top quark production. Performing a kinematical 3C fit yields a mass [2] of $187 \pm 8(stat)^{+13}_{-12}(sys)$ GeV/c^2 in this channel. Figure 1 shows the likelihood function for the CDF mass fit in this channel.

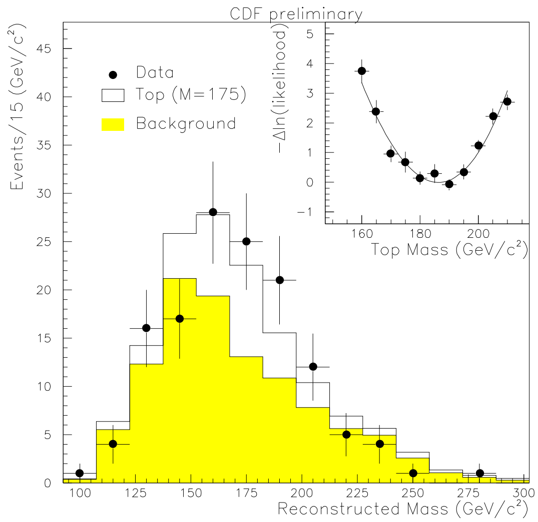

Figure 1: Likelihood function versus mass for the CDF all jets mass determination

5 The lepton + jets channels

5.1 CDF results

The CDF collaboration uses three different techniques to determine the mass from the lepton + jets channels. The first is largely unchanged from the time of the top quark discovery [7]. They require 3 jets with E_T >15 GeV and pseudo-rapidity $|\eta| < 2.0$ and a fourth jet with E_T >8 GeV and $|\eta| < 2.4$. They require at least one jet to be b-tagged with the silicon vertex detector or using a secondary lepton. Thirty four events pass the selection criteria. All events are treated as a single sample . The estimated non-top background in this sample is $6.4^{+2.0}_{-1.5}$ events. This yields a top quark mass of $175.6 \pm 5.7(stat) \pm 5.9(sys)$GeV/c^2.

The second method is called the L** method, where they use in addition the jet charge and jet tagging probability to enhance the χ^2 discriminant. The silicon vertex detector tagging probability is used to assign a jet to be of primary (b quark) or secondary (W decay) origin. This information is used to weight each combination. An algorithm is used to estimate the leading quark charge to discriminate between b and $\bar{b}$ jets. This method yields a top quark mass of $174.2 \pm 5.5(stat) \pm 5.3(sys)$GeV/c^2.

The third method used is termed the optimized method, where they divide the data into 4 mutually exclusive sub-samples.

- Events in which a single jet is tagged as a b quark jet using the silicon vertex detector (SVX). This yields a mass of $176.3 \pm 8.2(stat)$GeV/c^2.

- Events in which two jets are tagged as b quark jets using the silicon vertex detector (SVX). This yields a mass of $174.3 \pm 7.9(stat)$GeV/c^2.

- Events in which one or more jets are tagged as a b quark using an associated lepton and no SVX tag is present. This yields a mass of $140.0 \pm 24.1(stat)$GeV/c^2.

- Untagged events. This yields a mass of $180.9 \pm 6.4(stat)$GeV/c^2.

The signal to background in the untagged events is increased by demanding all jets to have $E_T > 15$ GeV. Background analysis is performed for each individual subsample and separate fits are performed for each subsample. The results of the optimized fitting method are shown in figure 2. The optimized method results form the main CDF measurement in this channel, the other two methods serving as cross checks. The systematic errors for the optimized method

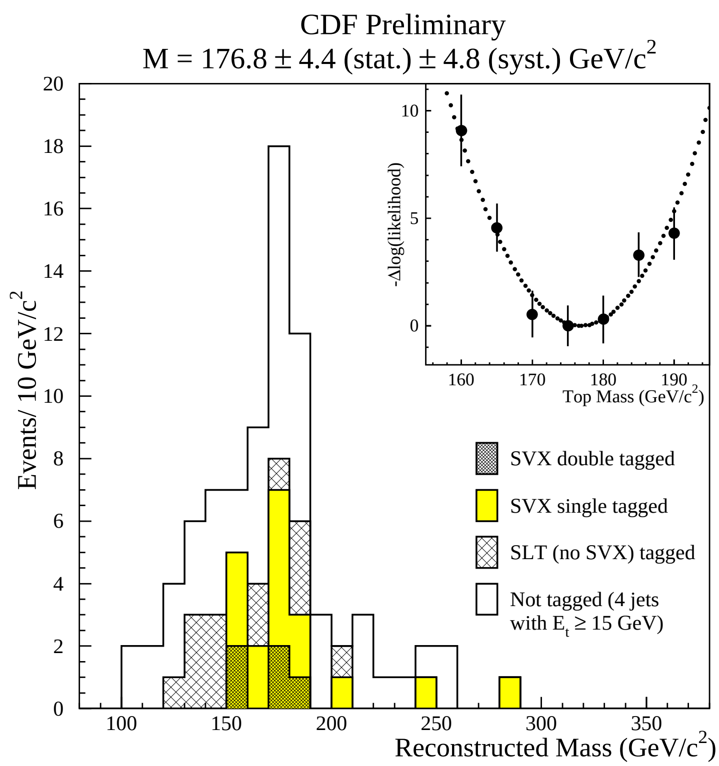

Figure 2: Reconstructed mass for various sub-samples of the CDF optimized lepton + jets fitting. Inset shows the global negative log likelihood function as a function of the top quark mass

have been worked out in detail and are shown in table 1. The sub-sample likelihoods are combined into one global likelihood yielding a mass of $176.8 \pm 4.4(stat) \pm 4.8(sys)$ GeV/c^2 for the optimized method.

5.2 DØ results

DØ uses two independent multivariate techniques to extract the signal. Multivariate techniques permit the separation of signal from background by using an appropriate discriminant that is a function of more than one variable. These techniques are superior to the conventional cuts method prevalent in high energy physics where signal is separated from background by cutting on single variables sequentially. When many variables are needed to separate signal from

CDF Systematic	Error GeV/c^2	DØ systematic	Error GeV/c^2
Soft Gluon + Jet E_T scale	3.6	Jet energy scale	4.0
Monte Carlo event Generators	1.4	Generator ISAJET/HERWIG	3.3
		Generator VECBOS	2.6
Hard Gluon Effects	2.2	Multiple interactions	1.2
Kinematic and Likelihood fitting methods	1.5	LB/NN difference	1.4
b-tagging bias	0.4	Likelihood fit	1.0
Monte Carlo statistics	0.8	Monte Carlo statistics	0.8
Background spectrum	0.7		
CDF Total	4.8	DØ total	6.2

Table 1: Systematic uncertainties for the CDF optimized method and the DØ multivariate methods

background, the cuts method results in serious losses of signal, especially in cases when the amount of signal is small and the signal to background ratio is small in any given variable.

5.2.1 Event selection

DØ selects events with electrons(muons) with $E_T > 20$ GeV, with $|\eta| < 2.0(1.7)$ and missing transverse momentum $\not\!\!E_T > 20(25)$ GeV. DØ further demands ≥ 4 jets with $E_T > 15$ GeV and $|\eta_{jet}| < 2.0$. There is also a cut on the scalar E_T sum of the W leptonic decay products, $E_T^L \equiv (E_T^{lepton} + \not\!\!E_T) > 60$ GeV, with $|\eta_W| < 2.0$, for events without a b quark muon tag. Events which have a b tag are selected with $p_T^\mu > 4$ GeV, with the muon within $\Delta R \equiv \sqrt{(\Delta\eta^2 + \Delta\phi^2)} <$ 0.5 of a jet. These cuts yield 91 events of which 7 are b tagged. A 2C top mass fit is performed to these events which yields 77 events with $\chi^2 < 10$, of which 5 are b tagged and $\approx 65\%$ are background. HERWIG Monte Carlo [8] is used to simulate the signal, VECBOS MC [9] is used to simulate the dominant W + multijet background. The $\approx 20\%$ of background events from non-W sources are modeled by multijet data, where one of the jets fluctuates to a lepton that almost passes the lepton selection.

5.2.2 Multivariate methods

DØ defines 4 variables to be used in the multivariate analysis, which are so chosen to enable us to obtain good signal to background differentiation. These are

- $x_1 \equiv \not\!\!E_T$ (Missing E_T)
- $x_2 \equiv \mathcal{A}$, the aplanarity, being defined as 3/2 the least eigenvalue of the normalized momentum tensor of the jets and the W boson.
- $x_3 \equiv \frac{H_T - E_T^{jet1}}{H_z}$ where $H_T = \Sigma E_T$ of jets and $H_z \equiv \Sigma|E_z|$ of the lepton, neutrino and the jets, E_z being the momentum component of the object along the beam direction. x_3 measures the centrality of the event.
- $x_4 \equiv \frac{(\Delta R_{jj}^{min}) E_T^{min}}{E_T^L}$, where ΔR_{jj}^{min} is the minimum ΔR of the six pairs of four jets and E_T^{min} is the smaller jet E_T from the minimum ΔR pair. This variable measures the extent to which the jets are clustered together.

Signal events have larger values of the variables $x_1 \ldots x_4$ on average than the background events that fit with the same value of the top quark mass as the signal. DØ forms two multivariate discriminants $D_{\rm LB}$ and $D_{\rm NN}$ using these four variables, where LB stands for the "low bias method" and NN denotes a three layer feed-forward neural network with 4 input nodes fed by 5 hidden nodes and 1 output node. In the LB method, they first parametrize $L_i(x_i) \equiv s_i(x_i)/b_i(x_i)$ where s_i and b_i are the signal and background densities in each variable, integrating over the others. A log likelihood $\ln \mathcal{L} \equiv \Sigma_i w_i \ln L_i$ is computed where the weights w_i are adjusted slightly away from unity to compensate for any correlation of $\mathcal{L}$ with the fitted top quark mass. $D_{\rm LB}$ is then defined as $\mathcal{L}/(1+\mathcal{L})$. An event is accepted as a signal event if there exists a b quark tag. It is taken as a background event if $D_{\rm LB}$ <0.43 or if $H_T - E_T^{jet1} < 90$ GeV. In the neural network approach, the network output $D_{\rm NN}$ approximates the ratio $s(x)/(s(x)+b(x))$. Figure 3 displays the correlation between $D_{\rm NN}$ and the fitted top quark mass $m_{\rm fit}$ for signal events, background events and data. Signal peaks at high values of $D_{\rm NN}$ at the generated top quark mass of 172 GeV/c^2 whereas the background peaks at lower values of $m_{\rm fit}$ and $D_{\rm NN}$.

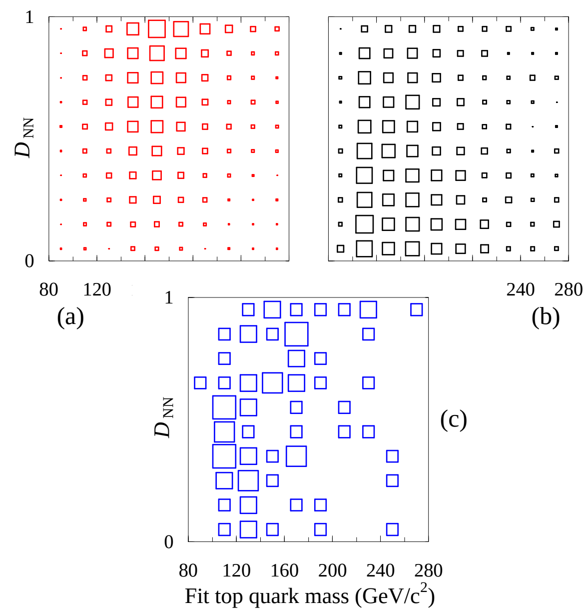

Figure 3: Events per bin ($\propto$ areas of boxes) *vs.* $D_{\rm NN}$ (ordinate) and $m_{\rm fit}$ (abscissa) for (a) expected 172 GeV/c^2 top signal, (b) expected background, and (c) data.

Figure 4 shows the distributions of $m_{\rm fit}$ for data (a) passing and (b) failing the LB cut. The likelihood analysis proceeds by binning the LB(NN) methods in 40(200) bins in $D_{\rm LB/NN}$ $m_{\rm fit}$ space and for each bin maximizing the likelihood L(m_t, n_s, n_b) assuming Poissonian statistics and Bayes' theorem[10]; n_s, n_b are the signal and background events expected in the data. Figure 4(c) shows the negative log likelihood thus obtained as a function of the top quark mass. This yields a top quark mass of $174.0 \pm 5.6(stat)$ GeV/c^2 for the LB method and $171.3 \pm 6.0(stat)$ GeV/c^2 for the NN method. Table 1 shows the breakdown of the systematic errors for DØ. The LB and NN methods are correlated $88 \pm 4\%$ with each other. The two results are combined taking into account these correlations yielding a top quark mass of $173.3 \pm 5.6(stat) \pm 6.2(sys)$ GeV/c^2 .

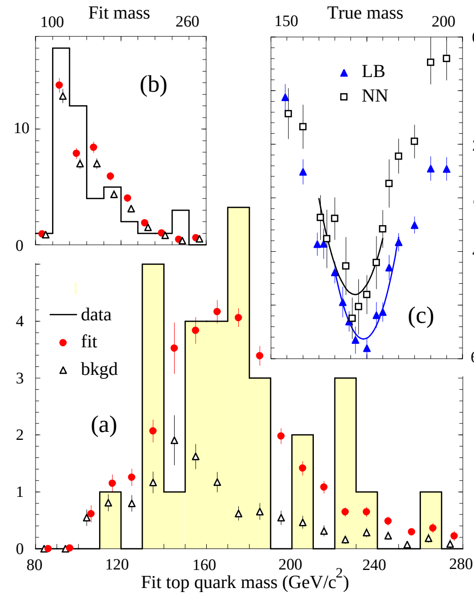

Figure 4: (a–b) Events per bin *vs.* m_{fit} for events (a) passing or (b) failing the LB cut. Histograms are data, filled circles are the predicted mixture of top and background, and open triangles are predicted background only.(c) Log likelihood L *vs.* true top quark mass m_t for the LB (filled triangles) and NN (open squares) fits, with errors due to finite top MC statistics.

5.3 Combining CDF and DØ results

In order to combine the two results, it is necessary to estimate the common systematic between the two experiments. These occur in the areas of Monte Carlo generators for signal and background, parton fragmentation and luminosity related systematics. While it is certainly not a very well defined process, reasonable people can agree, by examining the breakdown of systematic errors shown in table 1, that the common systematic error between CDF and DØ is conservatively in the neighborhood of 3.0 GeV/c^2. With this assumption, the CDF optimized method result and the DØ multivariate method result can be combined to yield a world average top quark mass of 175.6 ± 5.5 (stat and sys) GeV/c^2. Figure 5 shows the mass measurements from the various channels and their errors from the two experiments.

6 M_W vs M_{top}

Using a world average W boson mass of 80.410 ± 0.090 GeV/c^2[11], and the currently obtained top quark mass, we obtain the comparison shown in figure 6. Within the currently prevalent errors, the standard model is in good agreement, the data perhaps favoring lower Higgs masses.

7 Conclusion

We present the measurements of the top quark mass and its world average using lepton + jets channels from the CDF and DØ experiments at the Fermilab Tevatron. The top quark mass measurements using other decay channels are in agreement with the world average within errors. A comparison of the top quark mass and W mass world average with the predictions of the standard model radiative corrections show no disagreement from what is expected in the standard model. Further large improvements in the top quark mass measurement error must await data from the upgraded Tevatron and detectors.

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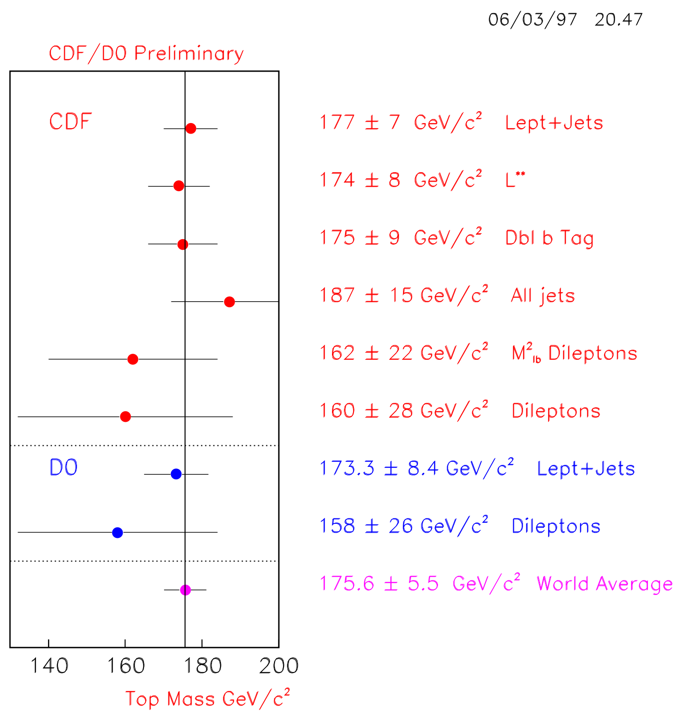

Figure 5: Summary of mass measurements and errors from the two experiments using various methods. The world average, indicated by the vertical line is obtained using the lepton + jets channel measurements from CDF and DØ

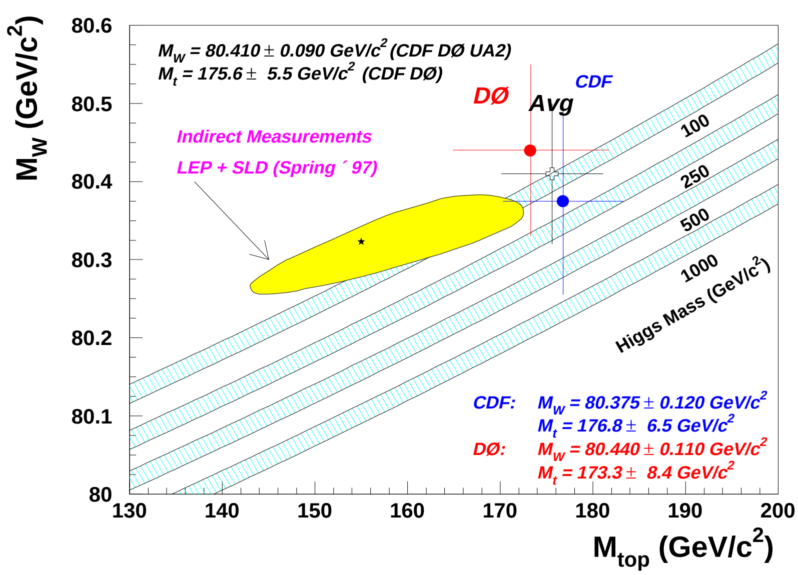

Figure 6: Comparison of M_W vs M_{top}. Contour shows regions allowed by LEP and SLD data