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CDF

CDF Top Physics

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Abstract

We present the latest results about top physics obtained by the CDF experiment at the Fermilab Tevatron collider. The data sample used for these analysis (about 110 pb^{-1}) represents almost the entire statistics collected by CDF during four years (1992–95) of data taking. This large data size has allowed detailed studies of top production and decay properties. The results discussed here include the determination of the top quark mass, the measurement of the production cross section, the study of the kinematics of the top events and a look at top decays.

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1 Introduction

The top quark was discovered in early 1995 by the CDF[1)] and D0[2)] Collaborations. The announcement followed and confirmed a first direct evidence of top quark production obtained by CDF[3)] in 1994. At the time of the discovery, CDF had collected around 67 pb^{-1} of data and observed an excess of events in two independent top channels (see next section), inconsistent with background at the 4.8–5.0σ level. Using these samples, CDF could measure the top mass to be $M_{\rm top}$= 176 ± 8(stat) ± 10(syst) GeV/c^2 and the production cross section as $\sigma_{t\bar{t}}$= $6.8^{+3.6}_{-2.4}$ pb (at the measured top mass).

Now that the Tevatron collider run is over, CDF has updated its results using almost the entire statistics (109.4 ± 7.2 pb^{-1} out of about 115 pb^{-1} collected). Having the existence of the top quark already been established, CDF top studies have naturally moved from a search oriented direction to a point in which it is important to measure all the top properties with the best possible accuracy. This new look at the problem has been partly possible thanks to the large statistics now available. The structure of this paper reflects this change. The top sample selection is only briefly summarized in section 2 while all the rest of the paper is devoted to the dicussion of the top physics under investigation at CDF. The measurement of the production cross section and of the mass are covered in section 3 and 4, respectively. Studies on the kinematics of the top production and of the $t\bar{t}$ system are presented in section 5 and some results on top decay physics in section 6. We conclude with a brief mention to some aspect of top physics connected to the Higgs search (section 7).

2 Top samples

In $p\bar{p}$ collisions at $\sqrt{s}$=1.8 TeV top quarks are produced mainly in pairs via quark-antiquark annihilation. Within the framework of the Standard Model (SM) the top quark decays almost exclusively into a W boson and a b quark (see section 6). The two W bosons subsequently decay either to a lepton and a neutrino or to a quark-antiquark couple, while the b quarks hadronize to jets. We classify our top samples according to the decay of the W bosons. In the dilepton sample (DIL) both W's decay into $e\nu$ or $\mu\nu$. Events in the e,μ+jets channel occur when one W decays semileptonically and the other one decays into quarks. We require three or more jets in the event and to further reduce background in this channel we identify b quarks either by reconstructing secondary vertices from b decays (SVX) or by finding additional leptons from b semileptonic decays (SLT). The analysis in these three samples led to the announcement of the top discovery.

Since then we have been able to isolate a top signal in two more sample. In the so-called *full hadronic* sample (HAD) both W's decay to $q\bar{q}$. After a series of topological and kinematical cuts a top signal is identified by requiring the presence of a b jet as in the SVX sample. The TAU sample is similar to the DIL sample but one of the two leptons is a τ which has been identified in its decay to one or three hadrons by using tracking and calorimeter informations. To enhance the S/N in this sample a b tag (as for SVX and SLT) can also be required. The number of events in each of these samples are summarized in table 1. Also shown is the expected number of background events. To complete the full $t\bar{t}$ decay picture only the τ+jets and the $\tau\tau$ channels are still missing: while the former is under investigation the latter seems hardly achievable.

channel		events	background
SVX		34	7.96 ± 1.69
SLT		40	24.3 ± 3.5
DIL		10	2.1 ± 0.4
HAD		192	137.1 ± 11.3
TAU	no tag	4	1.96 ± 0.35
	tag	3	0.225 ± 0.011

Table 1: Summary of available top samples.

We conclude this section by recalling that CDF also identified top enriched samples by cutting on specific kinematical parameters of the event such as the E_t of the second and third leading jet in the event[4)] or the total transverse energy.[5)] The former sample (ES) will be used in section 6.

3 Cross Section

The $t\bar{t}$ production cross section can be calculated in each of the samples described above. The cross section in the TAU sample will not be discussed here because the limited statistics available strongly reduces the significance of the measurement.

channel	A (%)	ε_{trg} (%)	ε_{tag} (%)
SVX	9.94 ± 0.95	92.0 ± 9.0	40.5 ± 4.0
SLT			20.0 ± 2.0
DIL	0.78 ± 0.08		–
HAD	$9.9^{+3.0}_{-3.6}$		47.2 ± 4.7

Table 2: Acceptance and efficiency (calculated for M_{top}= 175 GeV/c^2) summary .

The number of signal and background events in each sample has been already reported in table 1. So the only quantity still missing is the acceptance of each analysis; we can write this as the product of the selection acceptance (A), the trigger efficiency (ε_{trg}) and the tagging efficiency (ε_{tag}) where applicable. While the former is a function of the top mass, the other two quantities are almost indipendent of it. All these quantities have been calculated using the PYTHIA Monte Carlo (MC) and are reported in table 2.

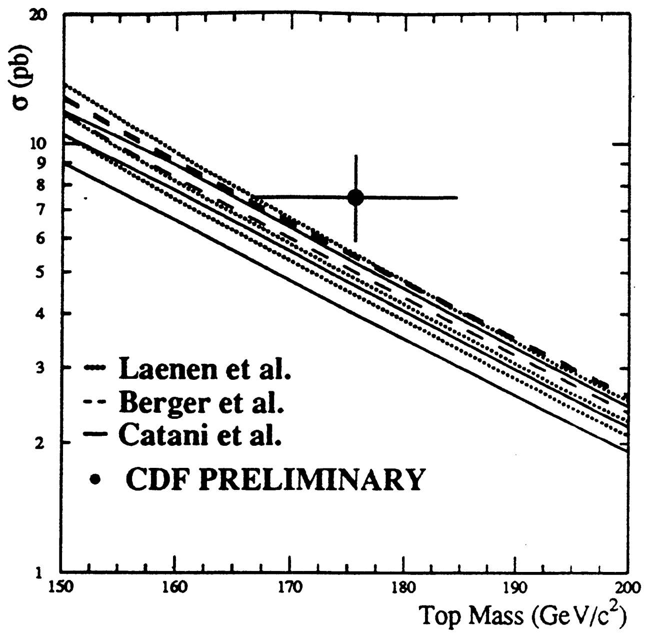

Figure 1: Combined $t\bar{t}$ cross section vs. $M_{\rm top}$ from data (point) and three different theory (bands).

The cross section for the DIL ($9.3^{+4.4}_{-3.4}$ pb), HAD ($10.7^{+7.6}_{-4.0}$ pb), SVX ($6.8^{+2.3}_{-1.8}$ pb) and SLT ($8.0^{+4.4}_{-3.6}$ pb) samples are all consistent within the indicated uncertainties.

A better statistical result can be obtained by combining the results together (taking into account correlations). For the time being we have done this only for the DIL, SVX and SLT samples. Work is still in progress to include also the HAD sample which is correlated both in acceptance and tagging efficiency with the SVX sample. Our combined result is $\sigma_{t\bar{t}}= 7.5^{+1.9}_{-1.6}$ pb at the top mass value measured by CDF (see next section). The error (about 30%) splits almost equally between statistical and systematical uncertainties. In fig. 1 we show our result compared to three different theoretical predictions for the top cross section as a function of the top mass.6)–8) For each theory curve, the central value and the upper and lower bounds have been drawn.

4 Mass

As in previous publications, CDF measures the top mass in a subset of the lepton plus three or more jets sample (325 events in 110 pb^{-1}). We start by selecting a smaller sample (*pretag* sample) by requiring the presence of a fourth jet in the event (this leaves us with 153 events) to allow a one-to-one matching with the partons from t and $\bar{t}$ (two b's and two quarks from the decay of one of the W's). Finally we require one of the four highest E_t jets to be tagged by either the SVX or SLT algorithms. In the end we are left with 34 events (14 tagged by SLT, 13 by SVX and 7 by both algorithms); the expected background in this sample amounts to $6.4^{+2.1}_{-1.4}$ events. Each event is kinematically fitted to the top hypothesis. The tagged jet is assumed to be one of the b's and all the other jet assignements are tried. There are also two solutions for the longitudinal components of the ν momentum (which is not measured). In the end the arbitration is done using the χ^2 of the fit. The distribution of the reconstructed masses is shown in fig. 2 together with the distribution of the background and a combination of background and top MC. Also shown is the behaviour of the fit likelihood; the curve has a minimum at 175.6 GeV/c^2 and the statistical uncertainty is equal to 5.7 GeV/c^2. We can also apply our fitting procedure to the pretag mass sample: the reconstructed mass sample (fig. 2) shows a clear peak standing over the background . A determination of the top mass in this sample is in progress and the result is consistent with our previous determination.

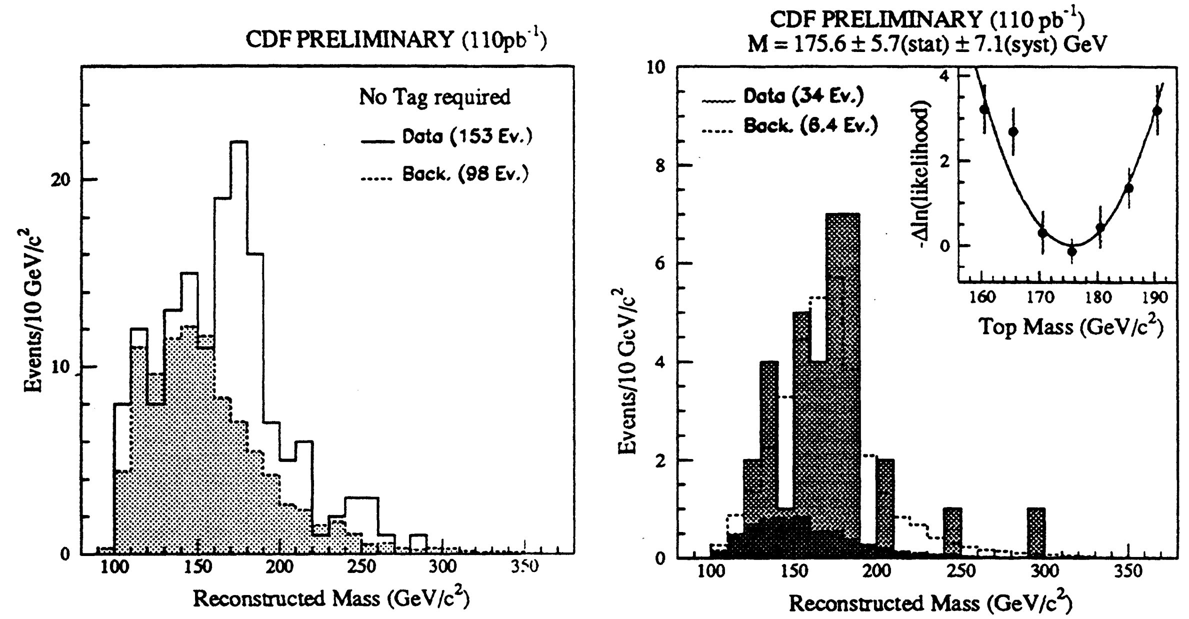

Figure 2: Top mass distribution in the pretag sample (left) and in the tagged mass sample (right).

Main top mass systematical uncertainties come from jet energy measurement uncertainties which propagate to the top mass through the fit. CDF reconstruct jets using a 0.4 fixed cone clustering algorithm. The raw E_t determined in this way needs to be corrected for a series of effects which include non-linear response of the calorimeter to low-p_t tracks (*absolute corrections*), non-uniform calorimeter response as a function of rapidity (*relative corrections*), the contribution of the underlying event and the loss of the energy which is not clustered in our cone (mainly due to soft gluon radiations). There could also be a misassociation between the four highest E_t jets and the partons from top decays due to the presence of hard gluons in the event.

For what the effect of soft gluons is concerned, at the time of the discovery CDF attributed a conservative 10% uncertainty to this correction. This translated into a 4.4% error on the top mass (7.7 GeV/c^2). With the higher statistics now available we have performed a detailed study of the energy flow in an annulus around a jet using samples of γ+1 jet, Z+1 jet and W+1 jet events. By comparing these data to MC samples obtained using the HERWIG generator, we estimate an uncertainty due to this effect that ranges from 5.6% at 8 GeV to 1.4% at 150 GeV.

effect	GeV/c^2	%
Jet E_t scale (detector effects)	3.1	1.8
Soft gluon effects	1.9	1.1
Different generators	0.9	0.6
Hard gluons effects	3.6	2.1
b-tagging bias	2.3	1.3
Background spectrum	1.6	0.9
Fit configuration	2.5	1.4
Likelihood method	2.0	1.1
Monte Carlo statistics	2.3	1.3
Total	7.1	4.0

Table 3: Systematic uncertainties in the top mass measurement.

We have also recalculated most of the other uncertainties associated to the jet energy determination. We now estimate an uncertainty due to the absolute energy corrections that ranges from 2.9% (at 8 GeV) to 2.4% (at 200 GeV), a 2% error due to relative energy corrections and an additional 2% uncertainty due to calorimeter instability with time. A $\pm$0.1 GeV uncertainty is finally associated to the correction for the underlying event contribution.

A direct measurement on the data of the hard gluons effects has not been possible. The HERWIG MC estimates that 55% of the time we have a gluon jet among the four highest E_t jets. Our uncertainty due to this effect is obtained by adding in quadrature the change in mass mean (1 GeV/c^2) and on its error (3.5 GeV/c^2) when we conservatively change HERWIG hard gluon percentage from 25% to 85% ($\pm 1\sigma$ on a flat distribution with mean of 55%) and we sum in quadrature the results.

All the uncertainties on the top mass are summarized in table 3. Our final top mass measurement using this method is $M_{\rm top}$= 175.6 $\pm$ 5.7(stat) $\pm$ 7.1(syst) GeV/c^2.

CDF has also measured the top mass in the HAD and DIL samples. The procedure used in the HAD sample is similar to the one just described but it is affected by an higher combinatorics. We obtain $M_{\rm top}$= 187 $\pm$ 8 $\pm$ 12 GeV/c^2. For the DIL sample we choose a different technique because the presence of two ν's makes it hard to close the kinematics. We determine the top mass by comparing the energy of the two highest E_t jets in the event with MC templates obtained at different top masses. With this method we obtain $M_{\rm top}$= 159^{+24}_{-22} $\pm$ 17 GeV/c^2, where the jet energy scale is still conservatively kept at 10%. All the three mass measurements are consistent within their errors: work is in progress to combine the three results together.

5 Kinematics

First of all in this section we want to discuss an interesting consistency check of our analysis. In the mass sample we assume that together with the $W \to l\bar{\nu}$ boson on which we trigger, another W decaying hadronically is also present in the event.

We want to see if we can reconstruct this last decay. To reduce the combinatorics we select only double tagged events so that we can assume that the other two jets in the event are from the W decay. The final sample consists of 10 events if we use also a loose jet probability b tagging algorithm,[3] together with SVX and SLT, to increase our double tagging efficiency. We then calculate the invariant mass of the two untagged jets. The mass spectrum (see fig. 3) show a clear peak that can be fitted to give a mass of 79.8 ± 4.7 GeV/c^2, well consistent with the world avarage W mass. To further check the internal consistency of our analysis we can ask ourselves how well these events fit to the top hypothesis. A preliminary determination of the top mass using the standard likelihood technique for the 8 events in the W peak gives a result in excellent agreement with the top mass measurement using single tagged events (as we have done in section 4).

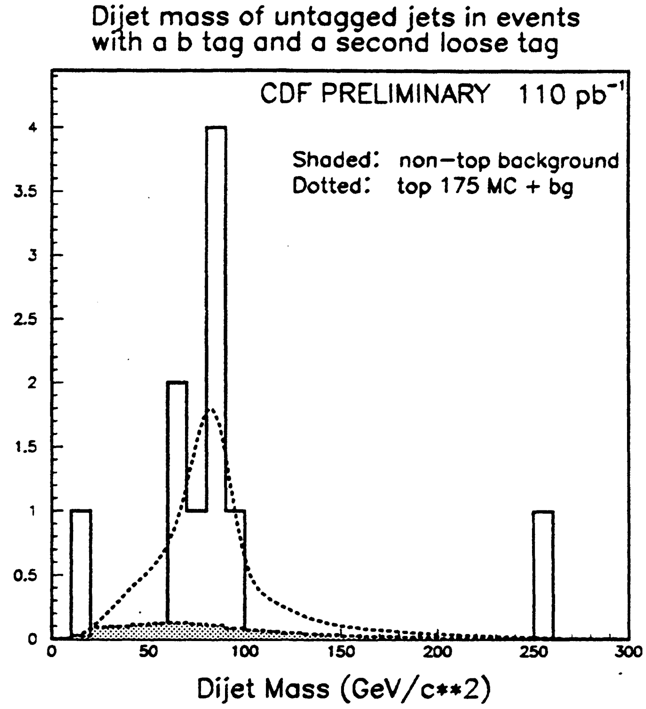

Figure 3: Invariant mass of untagged dijets in double tagged events

We now move to a comparison which has been performed between data and MC for a series of kinematical variables which include the invariant mass of the $t\bar{t}$ system, the p_t of the top, the $\Delta\phi$ between t and $\bar{t}$, the rapidity (y) of the top, the rapidity of the $t\bar{t}$ system and the Δy between t and $\bar{t}$. For the time being we compare just the *observed* quantities, which are biased by the trigger and by all the selection cuts, with the corresponding MC predictions. This is a consistency check of our analysis and also a check of the SM predictions for top production and kinematics. Work is in progress to go back to the *true* quantities and so obtain also differential cross sections. The comparison is done in three samples: the pretagged mass sample, the mass sample and the double tagged mass sample (similar to the one used in the W to dijets reconstruction analysis just described). As an example we show two of these variables, measured in the mass sample, in fig 4. In this plots, as in all the other similar plots that can be produced for all the other variables, no discrepancy with the SM predictions is observed.

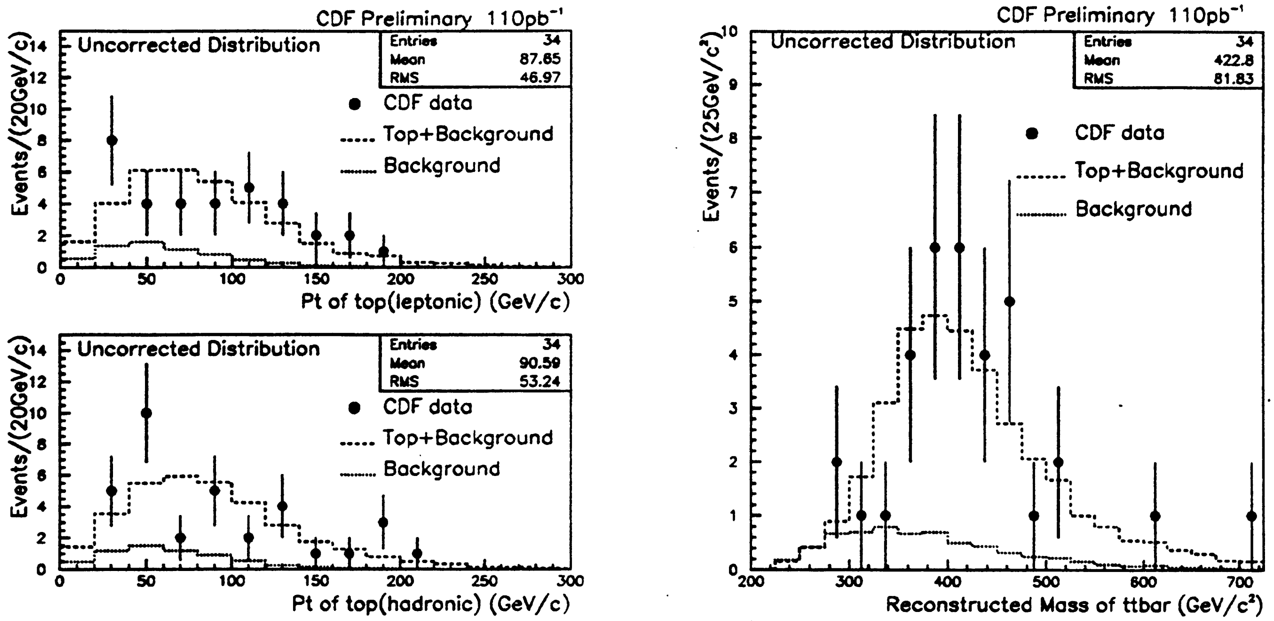

Figure 4: The p_t of the top quark associated to the leptonic (upper left) and hadronic (lower left) W and the invariant mass of the $t\bar{t}$ system (right) in the tagged mass sample.

6 Decays

We have measured B, branching fraction of top decaying to bottom. The measurement is performed using the DIL sample combined with either the mass sample or the ES sample (a W plus jets sample enhanced in top content by kinematical cuts). Due to the fact that the mass sample requires by construction the presence of a b jet, the advantage of the second method is clear: we can estimate B not only from the ratio of double to single tagged event but also from the ratio of tagged to untagged events. The results of the first method have been presented in previous conferences.9) Here we present the results obtained with the second one. Work is in progress to combine both results into a single measurement. The technique we use consists in describing the number of observed untagged, single and double tagged events with a model in which B is a free parameter and the acceptances and the tagging efficiency are determined with MC. Using a likelihood fit we obtain $B = 1.23^{+0.37}_{-0.31}$ where the error is dominated by statistics. From this measurement we can deduce a lower limit on B which favors $B > 0.61$ at the 95% CL. Once we have determined B we can calculate

$|V_{tb}|$. Assuming a three generation SM and neglecting small phase-space effects B and $|V_{tb}|$ are connected by the relation $B = |V_{tb}|^2/(|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2)$. Assuming unitarity ($|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2 = 1$) and using the previous result for B we obtain $|V_{tb}| = 1.12 \pm 0.16$ or $|V_{tb}| > 0.78$ (95% CL). Relaxing the unitarity constraint and using the best estimate available for V_{ts} and V_{td} we can only put the limit $|V_{tb}| > 0.0502$ (95% CL).

We have also searched for the flavor changing neutral current (FCNC) top decay $t \rightarrow Zq$ that in some theoretical models can have a branching ratio as high as 0.01. Our search includes events in which either one or both top quarks decay to Zq. In either case we search for a Z (decaying to ee or $\mu\mu$) and four jets. In our data sample we expect $0.604 \pm 0.140(\text{stat}) \pm 0.117(\text{syst})$ background events coming from $WZ, ZZ+$ jets productions. One $Z \rightarrow \mu\mu$ event survives our cuts. Assuming it is signal we can set the limit $BF(t \rightarrow Zq) < 0.44$ at the 90% CL.

Another FCNC top decay that we have investigated is the $t \rightarrow \gamma q$ process where q is either a u or a c quark. The SM predicts this process to have a branching ratio in the range $10^{-7} \div 10^{-12}$. In our search one top decays according to this mode and the other one decays to Wb. If the W decays semileptonically the signature is represented by a photon, a lepton, two or more jets and missing E_t in the final state. After some kinematical cuts the background is expected to be about 0.06 events. We observe one event. On the other hand, if the W decays hadronically the signature is represented by a photon and four or more jets. To reduce the background due to QCD production we require one of the four jets to be tagged as a b. The background after all cuts is estimated to be 0.5 events. We do not observe any candidate. Combining the two channels we can set the limit $BF(t \rightarrow \gamma q) < 0.029$ (90% CL).

7 A look at the Higgs sector

CDF has also conducted a search for the decay $t \rightarrow H^+ b$, where $H \rightarrow \tau\bar{\nu}$.$^{10)}$ This has allowed to exclude some regions in the $(M_{\text{top}}, M_{H^-})$ plane as a function of the theory parameter $\tan\beta$ (see fig. 5). This analysis has not yet been updated to the full statistics. Moreover, CDF top mass and W mass$^{11)}$ measurements can be used to try to set some constraints on the mass of the neutral Higgs, H^0. This is done by comparing the measured values with SM fit predictions at various H^0 masse (see fig. 5).

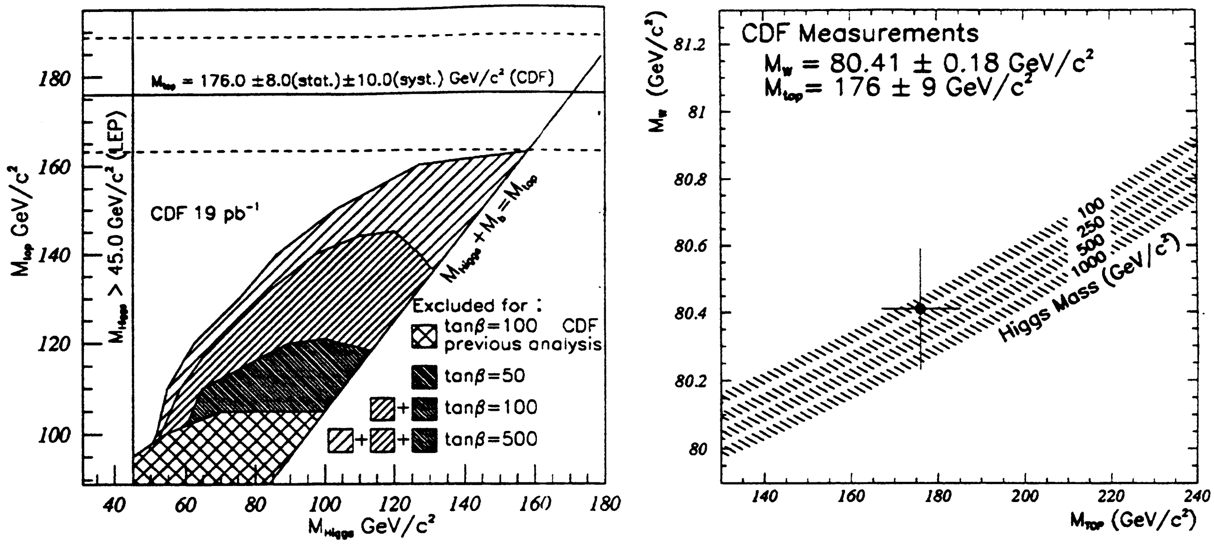

Figure 5: Regions of the $(M_{\rm top}, M_{H^+})$ plane excluded at the 95% CL at different tanβ values (left) and M_W vs. $M_{\rm top}$ compared to SM predictions for various H^0 masses (right).

8 Conclusions

At the end of the Tevatron Run I, CDF has updated most of its top physics results using almost the entire statistics available. A partial list of results has been presented here and shows the extreme power of the CDF detector in this field. While these analysis are still in progress, it is already clear that some of these studies are limited only by statistics. This makes the future Run II program, with both significant luminosity increase and detector upgrade, extremely promising and exciting.

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