Recent Results of Searches for New Particles at Fermilab [1]

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Abstract

I review recent results from particle searches at Fermilab, with particular emphasis on the searches for the top quark at the Collider by D0 and CDF.

1 Introduction.

In this talk I will start by reviewing searches at Fermilab for exotica: leptoquarks, new bosons W' and Z', excited quarks (compositeness), SUSY, and the charged Higgs. I will then discuss the D0 top search, and the CDF search that has presented evidence for the top quark.

The Tevatron Collider Run Ia extended from August 1992 to the end of May 1993. Run 1b started in January 1994. The integrated luminosities to tape in Run 1a for D0 and CDF were approximately 15 and 20 pb^{-1}, respectively. For Run 1b, as of the end of May 1994 the two experiments have each accumulated only about 6.5 pb^{-1} to tape , disappointingly low. The D0 experiment has done a very good job of commissioning, as shown by its accumulated luminosity.

2 Exotica

The Tevatron Collider is the world's highest energy machine, and with it we have observed collisions with visible total transverse momenta above 1 TeV. For new interactions comparable in strength with the strong interaction we should be able to see effects in this mass region. We can explore weaker interactions, such as those that might couple to new W-like gauge bosons, up to the many hundreds of GeV level.

2.1 Leptoquarks

Leptoquarks (LQ's) are hypothetical composite objects that would decay to a lepton and a quark in a two-body decay. They are fractionally-charged, colored, bosons, either spin 0 (scalar) or 1 (vector). The absence of flavor-changing neutral currents implies that a leptoquark couples to a single quark generation and a single lepton generation ('diagonal' in generations). The reader is referred to an excellent review by Leurer, in which strong

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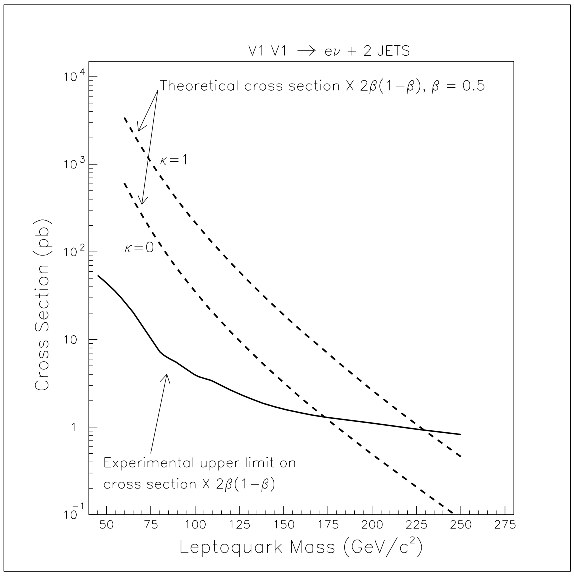
constraints from low-energy processes are derived [1]. In a hadron collider leptoquarks are assumed to be produced strongly in pairs the way quarks are; we also assume that there are no form factors. The decay of a LQ is to a quark + lepton, where the lepton is either charged or a neutrino; the parameter β is the branching ratio into the charged lepton. The signature is thus two same-generation charged leptons (e.g. e^+e^-) and two jets, or one lepton, missing $\not\!\!E_T$ and two jets. The production and detection of leptoquarks at a hadron collider such as



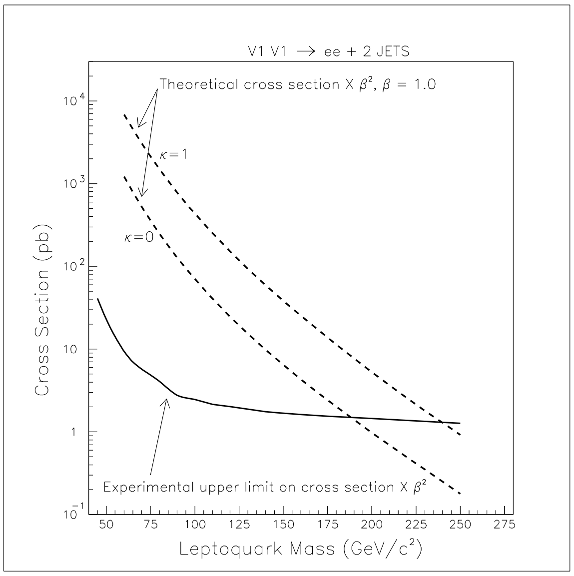


Figure 1: (Left): The D0 limit on vector leptoquark production from the mode $VV \rightarrow e\nu$ assuming $\beta = 1/2$. The theoretical predictions for are from Hewitt et al. for values of the anomalous magnetic moment $\kappa = 0$ and 1. Figure 2 (Right): The analogous D0 limit on vector leptoquark production from the mode $VV \rightarrow ee$.

D0 has new limits on a vector first-generation (decaying into u and d quarks and electrons or ν_e) leptoquarks. Figure 1 shows the D0 leptoquark limit on eν plus 2 jets as well as a theoretical prediction [3] Figure 2 shows the limit on ee plus 2 jets. For κ=1 they find mass limits of $M_{LQ} > 244$ GeV for β=1, and $M_{LQ} > 243$ GeV for β=0.5, where κ is the anomalous magnetic moment of the vector leptoquark. For κ=0 the respective limits are 193 GeV for β=1, and 189 GeV for β=0.5. Previous limits have been restricted to scalar leptoquarks, with limits of 133 and 120 GeV for β=1 and 0.5, respectively [2]

The CCFR neutrino collaboration also has new limits on leptoquarks coupling to muon neutrinos. These limits are at low-mass, but are sensitive to very small couplings. Figure 3 shows the limits versus the LQ mass for three possible cases.

2.2 Excited Quarks

CDF has searched [4] for resonances in the jet-photon and jet-W mass distributions (see Figures 4 and 5). Figure 6 shows a comparison of the limit on the production cross-section

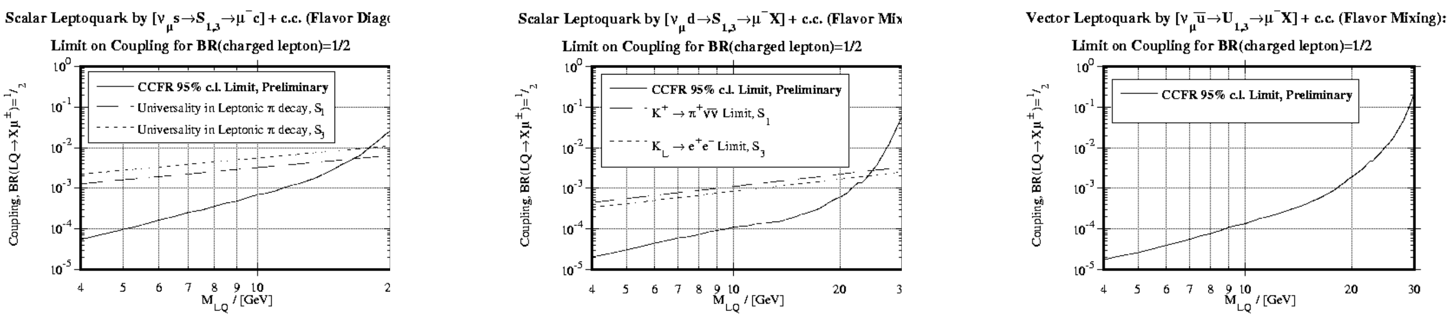


Figure 3: The preliminary limits on leptoquark production from CCFR.

of resonances compared to a simple model [5]. At 95% $C.L.$ an excited quark with a mass below 540 GeV is ruled out. The regions excluded by the excited quark search in the mass-coupling plane are shown in Figure 7.

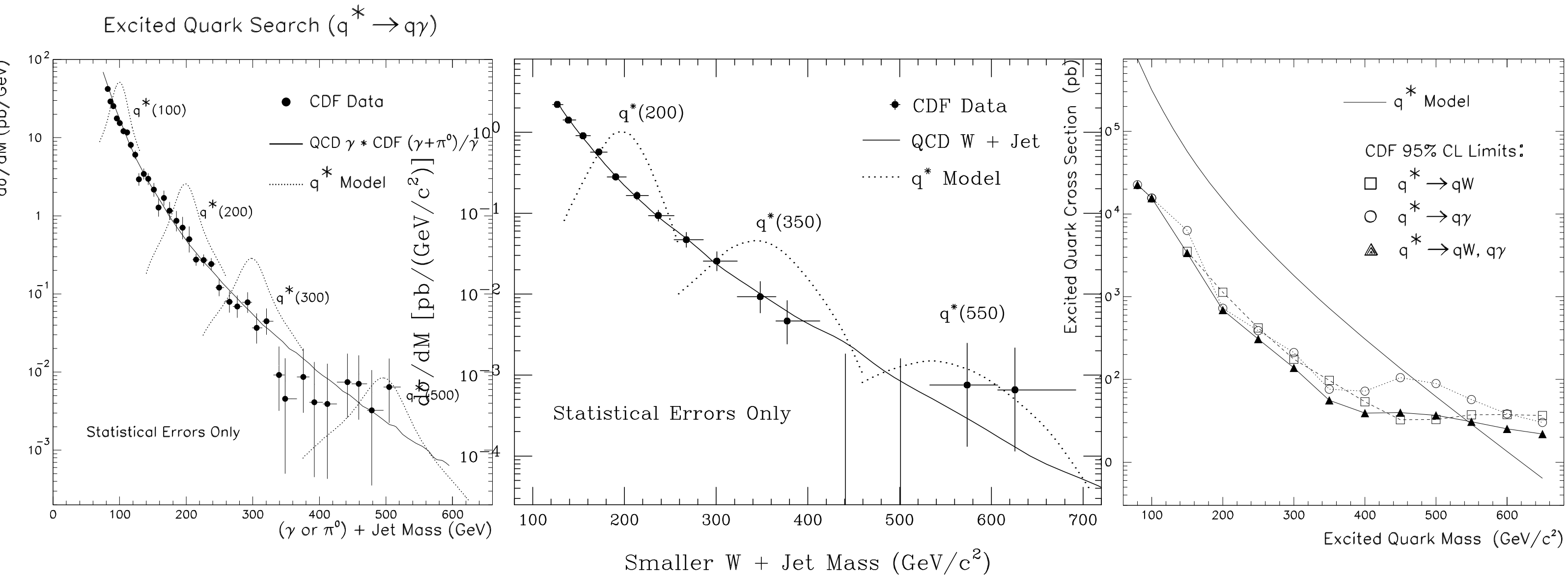
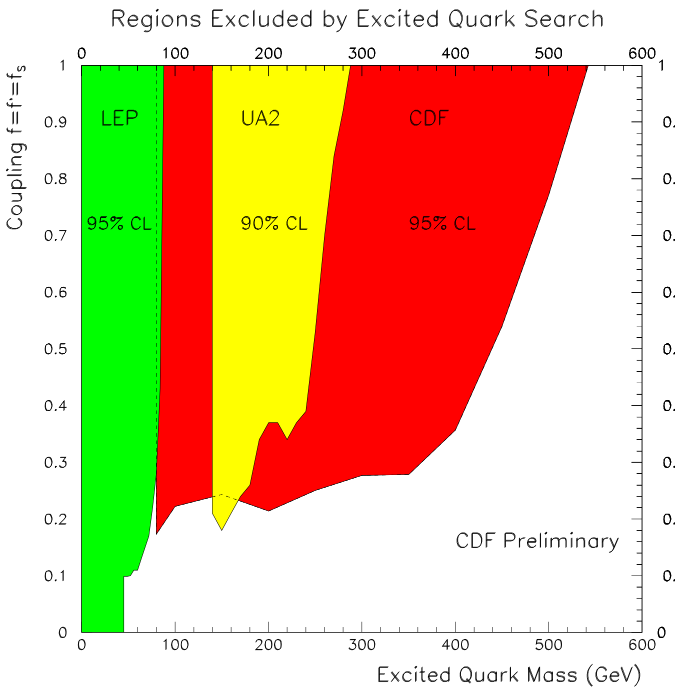


Figure 4: (Left): The CDF photon-jet mass spectrum. Figure 5 (Middle): The CDF W-jet mass spectrum Figure 6 (Right): The CDF limit on excited quarks.

2.3 Searches for Supersymmetry.

Both D0 and CDF have searched for wino-zino (chargino-neutralino) pair production by searching for trileptons (eee,eeμ,e$\mu\mu$,$\mu\mu\mu$) accompanied by missing Et. D0 finds 1 eeμ event, with a background of less than 0.5 events. They do not yet have a limit on model parameters. Similarly, CDF finds no events, but only excludes a tiny bit of parameter space beyond the



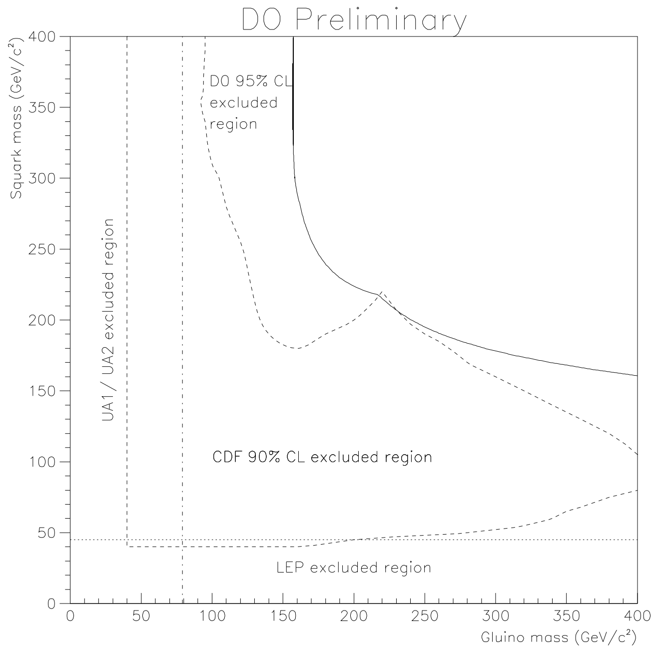


Figure 7: (Left): The world limits on excited quark production. Figure 8 (Right): The preliminary D0 limits in the squark-gluino mass plane.

LEP limits. I believe that these searches will do much better by using the signature of 2 of the 3 leptons: the acceptance will be appreciably higher, and the backgrounds may be manageable (see the section on the search for the charged Higgs below).

D0 has a new and substantial limit on the production of squarks and gluinos for a search requiring 3 jets with $E_T > 25$ GeV, and $\not{E}_t > 75$ GeV. The new limit in the plane of squark and gluino masses is shown in Figure 8, and is compared with the previously published [6] CDF limits.

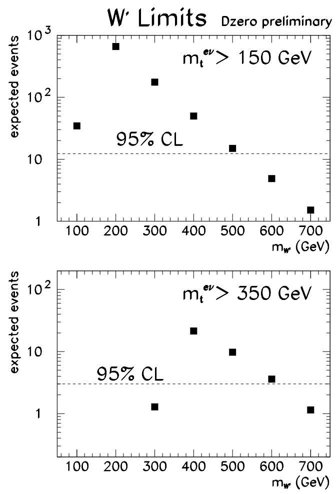
2.4 W' and Z': New Gauge Bosons?

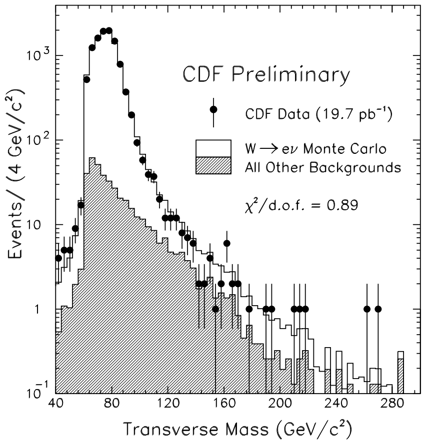
Both D0 and CDF have new limits on the production of charged and neutral vector gauge bosons heavier than the W and the Z, respectively. Figure 9 shows the D0 limits on the W' from 15 pb^{-1} of electron data. They see no events with transverse mass above 350 GeV, leading to a 95% $C.L.$ limit of $M_{W'} > 600$ GeV. Similarly Figure 10 shows the $e\nu$ transverse mass spectrum from CDF, with 19.7 pb^{-1} of data. The CDF 95% $C.L.$ preliminary limit is $M_{W'} > 634$ GeV [7].

The mass limit from the D0 search for $Z' \to ee$ is shown in Figure 11. There are no events with invariant mass above 250 GeV, leading to a mass limit of $M_{Z'} > 440$ GeV (95% $C.L.$) if one assumes standard- strength couplings. Figure 12 shows the dielectron mass spectrum from CDF; a fit to a mix of the Z, photon, and a possible Z' gives a 95% $C.L.$ limit of $M_{Z'} > 505$ GeV. Figure 13 shows an event accumulated on May 17th (two weeks ago) in Run 1b by CDF; it is the highest mass dilepton event yet seen, with a dielectron mass of 0.511 TeV.

Expt.	Int. Lum.	Wprime	Zprime
D0	15 pb^{-1}	600 GeV	440 GeV
CDF	20 pb^{-1}	634 GeV	505 GeV

Table 1: The preliminary limits on new W-like and Z-like gauge bosons, assuming Standard Model strength couplings.





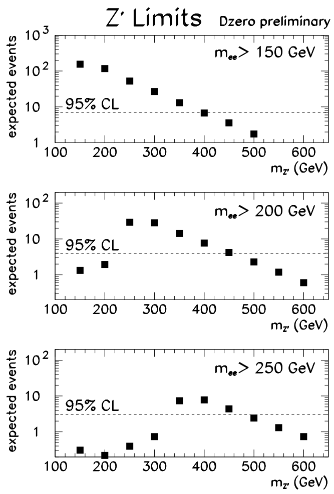
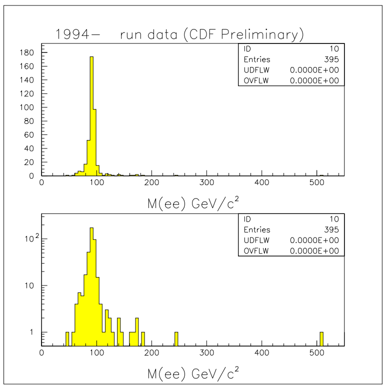
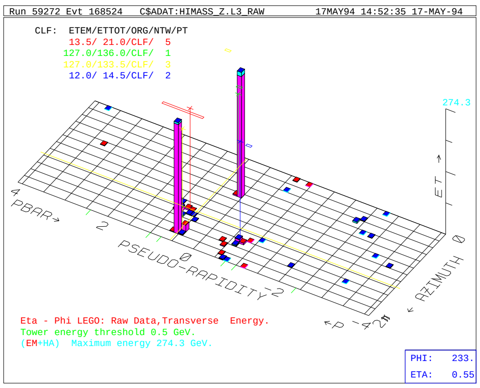


Figure 9: (Left): The D0 expected number of W' events versus mass. Figure 10 (Middle): The CDF W-prime mass spectrum. Figure 11 (Right): The D0 expected number of Z' events versus mass.





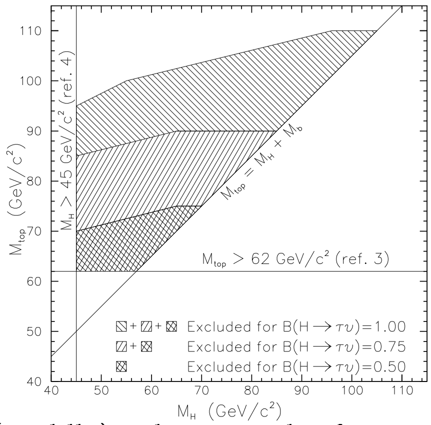


Figure 12: (Left): The CDF Z-prime mass spectrum. Figure 13 (Middle): The Lego plot for the new 511 GeV invariant mass di-electron event from CDF. Figure 14 (Right): The CDF limits in the $\mathrm{M_T} - M_{Higgs}$ plane on the top decaying to a charged Higgs.

2.5 The Charged Higgs

CDF has also pursued a search for the charged Higgs through a non-standard decay mode of the top quark, $t \rightarrow H^+ + b$. The decay of a $t\bar{t}$ pair would thus result in two b jets, and either a pair of charged Higgs, one charged Higgs and one W, or two W's (which is the Standard Model decay discussed below). The Higgs are expected to decay to τ's, which in turn decay with substantial branching ratios into leptons. The b's also have substantial leptonic branching ratios. The signature that is thus searched for is two leptons (of lower pt than in the standard model search discussed below, as they are daughters of the tau's or b's), and missing Et. Two e-μ events are observed: one is one of the top dilepton candidates discussed below. The rate is compared to expectations, leading to the exclusion of the area in the $\mathrm{M_T} - M_{Higgs}$ plane shown in Figure 14.

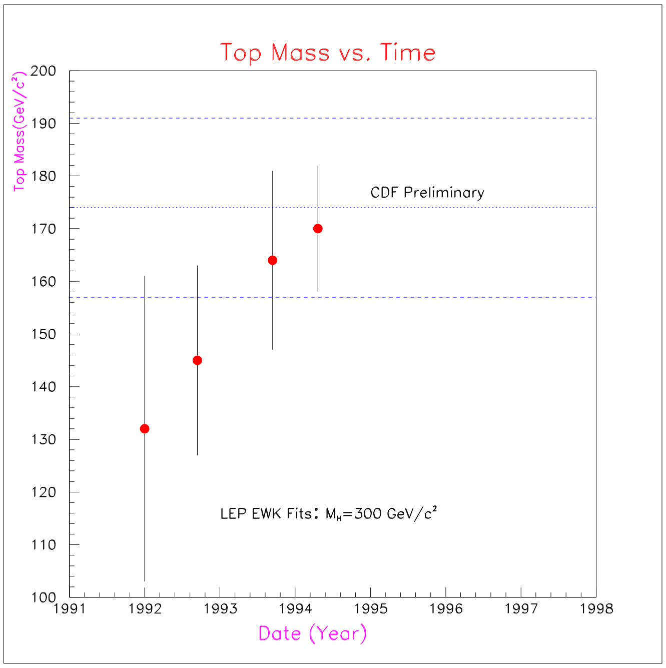
3 The Search for the Top Quark

Figure 15 shows the prediction of the top mass from precision electroweak fits versus calendar time [8]. We are somewhat concerned at CDF that the increase in mass with time may be faster than the increase in Tevatron luminosity, in which case we've seen evidence for the top for the last time. Figure 16 shows predictions from Ellis et al. [9] and Laenen et al. [10] of the top production cross-section versus top mass. One can get a quick idea of the experimental problem by noting that the theoretical cross-section for a 180 GeV top is 4.2 pb; in an exposure of 20 pb^{-1} one would thus produce 80 top pairs. Each dilepton mode (e.g. e^+e^-) has a branching ratio of 1/81, leading to the expectation of 1 event in Run 1a for 100% acceptance. The lepton + jets modes such as e^+ or e^- have each 12/81, leading to 12 events of each, again at 100% acceptance. Figure 17 summarizes the branching ratios and signatures in $t\bar{t}$ decays.

3.1 The D0 Top Search

D0 has published the initial analysis of the Run Ia data (about 15 pb^{-1}) [11]. They see 3 events on an estimated background of 6 ± 3 events. This leads to a mass limit of $M_{top} > 131$ GeV, at 95% $C.L.$ One $e - \mu$ event has a 'high signal-to-background ratio'[13]. In addition the reconstructed mass of this one event 'peaks near 145 GeV....but up to 200 GeV cannot be excluded'[13]. However the peaking is due to a cross-section bias in the method used- in general dilepton events have a fairly flat probability distribution for masses well above a lower threshold. Figure 18 shows the Lego plot for this event.

D0 has now presented a new analysis of the same data (the '1994 analysis'). A summary of these (preliminary) results is given in Table 2. A discussion of the comparison with the CDF results is given in Section 3.3.



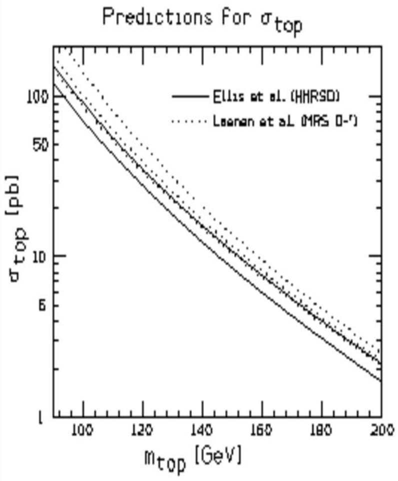


Figure 15: (Left): The best-fit value for the top mass from precision EWK fits versus time. Figure 16 (Right): The predicted cross-section for top quark production vs. M_{Top}.

Table 2. The D0 top search summary table, giving the results and expectations for each of the 6 modes used by D0. The notation $+\mu$ signifies the soft-muon tagging. Note that all numbers are preliminary [13].

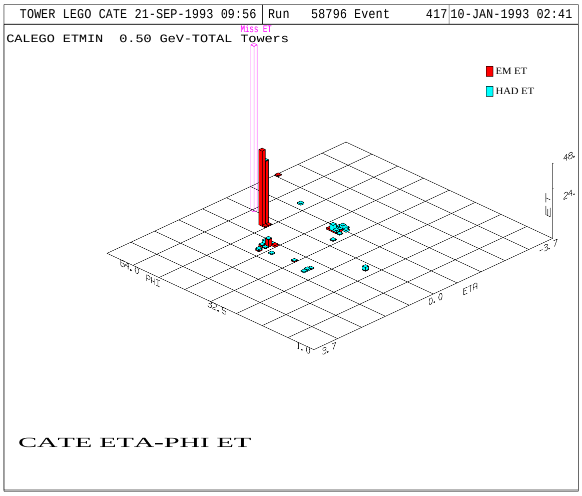


Figure 17: (Left): The matrix of branching ratios for the two W's from $t\bar{t}$ decay. Figure 18 (Right): The Lego plot of the D0 dilepton event.

3.2 The CDF Top Search

The CDF top search has now been published (since the talk was given) , and so for reasons of space I refer the reader to the two papers [12] for any details beyond the brief overview and the summary of the mass analysis given here.

3.2.1 Evidence for the Top

There were three 'analyses' defined *a priori*:

1. High-p_T Dileptons (ee, eμ, and $\mu\mu$)
2. Lepton + Jets + silicon-vertex b-tag (SVX)
3. Lepton + Jets + soft-lepton b-tag (SLT)

The dilepton analysis finds two events with two high Pt leptons, missing Et, and 2 jets, well separated from background, with an expected background of 0.6 events.

Both of the lepton plus jets analyses start with a sample of 52 events that have a high-p_T lepton, missing Et ($\not{E}_t$), and 3 or more jets. The analysis starts with the question: "Are there extra b's in these 52 events over expectation?"

CDF starts by assuming that **all 52 events are background**, and parameterizes the SVX tagging probability per jet and the SLT tagging probability per track from inclusive jet and other control samples. It is an important point that the background estimates are thus data driven, and do *not* come from Monte Carlo. These (parameterized) tag rates are applied to the 52-event sample to predict the number of tags expected assuming that these events are all W+jets background. The result is that 6 events are tagged by the SVX algorithm and 7 events are tagged by the SLT algorithm, with 2.3 and 3.1 events, being the respective backgrounds predicted by applying the control sample parameterizations to the 52 events. Three events are tagged by both algorithms so that there are 10 events total which contain the 13 tags.

Channel:	SVX	SLT	Dilepton
Expected # events $M_{top} = 120$ GeV/c^2	7.7 ± 2.5	6.3 ± 1.3	3.7 ± 0.6
Expected # events $M_{top} = 140$ GeV/c^2	4.8 ± 1.7	3.5 ± 0.7	2.2 ± 0.2
Expected # events $M_{top} = 160$ GeV/c^2	2.7 ± 0.9	1.9 ± 0.3	1.3 ± 0.1
Expected # events $M_{top} = 180$ GeV/c^2	1.4 ± 0.4	1.1 ± 0.2	0.68 ± 0.06
Expected Bkg.	2.3 ± 0.3	3.1 ± 0.3	$0.56^{+0.25}_{-0.13}$
Observed Events	6	7	2

Table 3: Numbers of $t\bar{t}$ events expected, the numbers of candidate events observed, and the expected backgrounds.

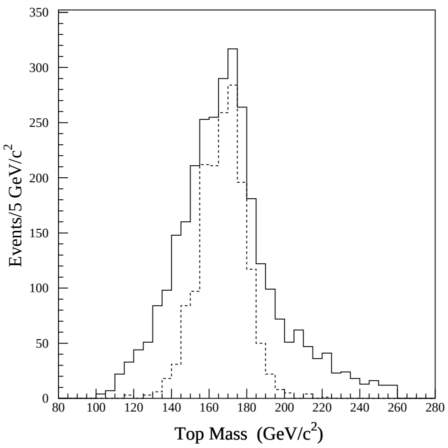
This method gives a conservative estimate of how many tags one would expect if the 52 events were all background: it assumes that the probability that a jet comes from a b in the jet control samples is the same as for the W+jets background. The jets in the control samples, however, are expected to have a larger contribution from b and c quark production than the jets in W+jets, which are expected to be mostly gluons, so that this method over-estimates the expected tag rate. In fact an alternative method using Monte Carlo gives a lower background estimate [12].

The probability of getting the number of dilepton events, SVX tags, and SLT tags from the background fluctuating up is 0.26%, which corresponds to a 2.8σ effect if the uncertainties were Gaussian. The significance is appreciably greater if Monte Carlo estimates of the background are used. The above is called 'the counting experiment' – i.e. asking if there is an excess above expectations assuming there is no top and all events are background.

3.2.2 The top Mass

For the mass analysis it is assumed that the excess of tags in the W+ 3-or-more-jets 52-event sample is due to $t\bar{t}$ events. The top mass is found in the W+4 jet events, where two of the jets are expected to be the b and the $\bar{b}$ quarks from the t and $\bar{t}$ decays and two are expected to be from the W that decayed hadronically, $W \rightarrow q\bar{q}$. Thus the invariant mass of one pair of jets should reconstruct to that of the W, and each of the Wb systems should be consistent with coming from a top (i.e. the invariant masses of the t and the $\bar{t}$ should be consistent with being equal.)

Of the 10 b-tagged events 4 have 4 or more jets. In order to get more 4-jet events to fit kinematically CDF takes the 52 events with 3 or more jets and relaxes the cuts on the 4th jet to lower p_T ($p_T > 8$ from 15 GeV) and to a larger rapidity interval ($|\eta| < 2.4$ from 2.0). Further requiring a b-tag gives 7 events (7 out of the 10 b-tagged events), listed in Table 4. There are 3 SVX tags, 3 SLT tags, and one double-tag (same jet). In this sample of 7 it is estimated from the tagging background rates that there are 1.4 events background.



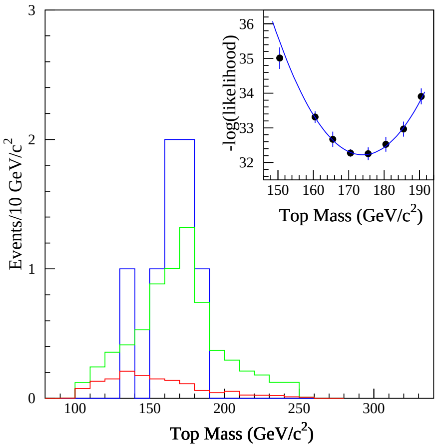


Figure 19: (Left): the fit with an input mass of 170 GeV. The dashed line is when the correct jet assignment is forced- the solid line is when one b is tagged and the 4 highest Et jets used. Figure 20 (Right): The distribution in fitted mass from the 7 events in the mass sample. Also shown are the shapes from W+jets background (dotted), and a mix of 5.6 events from top and 1.4 from background.

These 7 events are fit to the top hypothesis. The jets are first corrected with new jet corrections that account for energy sharing (e.g. from $W^{\pm} \to jj$) and for b-jets. The 4 highest Et jets are then used, with the constraint that the tagged jet has to be assigned to be one of the b jets. There are 20 equations and 18 unknowns, so it is a 2C fit. However there are 6 combinations of the 4 jets, times 2 solutions for the longitudinal component of the neutrino from the W leptonic decay, so there are 12 combinations per event. All 12 combinations are fitted, and the solution with the best χ^2 is used.

The combinatorics are a problem. Monte Carlo studies show that the correct jet assignment is chosen only 31% of the time; 22% of the time the solution has the right jets but the wrong assignment, and 47% there is a mismatch between the measured jet and the corresponding parton direction by $\Delta R > 0.5$. Figure 19 shows the effect on the mass resolution of the combinatorics. The mean of the distribution does not shift; the errors in jet assignment correspond to a poorer mass resolution.

Figure 20 shows the distribution in fit masses for the 7-event mass sample. Also shown are the shape of the expected background, normalized to 1.4 events, and the expected shape from a Monte Carlo mix corresponding to 5.6 $t\bar{t}$ and 1.4 background events. The inset shows the negative log likelihood versus top mass from the fit. The result is

$$M_{top} = 174 \pm 10(stat)^{+13}_{-12}(sys)\ GeV. \tag{1}$$

The systematic uncertainties in the top mass determination are itemized in Table 5.

The tagging rate observed in the 52 event sample implies that approximately half of the 52 events are from top [12]. With the looser cuts there are 26 4-jet events. The best-fit

Nev	Run-Event	ℓ	b-tag	top w. b-tag	mass (GeV/c^2)	χ^2
1	40758-44414	e^+	SVX	j j b	172 $\pm$ 11	0.0
2	43096-47223	e^-	SVX	e ν b	166 $\pm$ 11	2.0
3	43351-266423	μ^-	SLT(μ^-)	j j b	158 $\pm$ 18	6.1
4	45610-139604	μ^+	SVX	j j b	180 $\pm$ 9	5.0
5	45705-54765	e^-	SLT(e^+)	e ν b	188 $\pm$ 19	0.4
6	45879-123158	μ^+	SLT(μ^-),SVX	j j b	169 $\pm$ 10	2.2
7	45880-31838	e^-	SLT(e^-)	j j b	132 $\pm$ 8	1.7

Table 4: Characteristics of mass fits to the seven candidate events

mass for these events is 167$\pm$10(stat) GeV with no background constraint, and 172$\pm$11(stat) GeV with the background constrained to be 50% of the sample [12].

There is intense interest in how well the top mass can be determined in the future. Until the LHC turns on the determining factor will be the integrated luminosity accumulated by CDF and D0 at Fermilab. I believe that we can do as well as, if not better than, the $\sqrt{\mathcal{L}}$ scaling from the present 17 GeV (for approximately 20 pb^{-1}) down to below 1 GeV, given appropriate support for the detector upgrades and for the accelerator upgrades and operation.

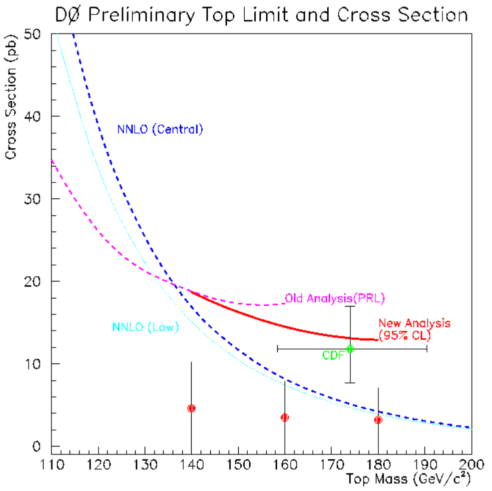
	Systematic uncertainties	(%)
a.	Jet Energy Scale (detector effects)	1.8
b.	Gluon radiation effects on parton energy	4.4
c.	Different backgrounds	$^{+5.3}_{-4.4}$
d.	Effects due to tagging algorithms	1.4
e.	Different likelihood fits	1.1

Table 5: Systematic uncertainties in the top mass measurement

3.3 A brief D0/CDF Comparison

The CDF and D0 results are statistically not in conflict. Figure 21 [13] shows the D0 cross-section limits compared to the CDF result as well as to theoretical predictions. The dependence of the CDF cross-section on mass is mild, so the error ellipse is close to horizontal. Given the size of the error bars there is not yet a problem.

It is interesting to compare the results of the two experiments at a deeper level. The number of W+ jet events for different numbers of jets is given in Table 7; the cuts for the



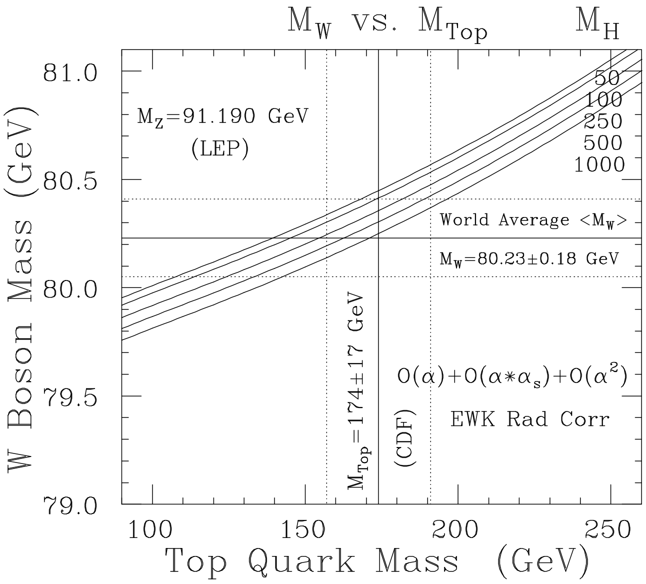


Figure 21: (Left): The D0 summary plot of the top cross section versus top mass. Figure 22 (Right): The M_W versus M_{top} plane.

event selections are given in Table 6. One sees that for electrons the two experiments see similar results on the number of W+ jet events; the difference in the muons is presumably due to thresholds.

Electrons		Muons	
CDF	D0	CDF	D0
$E_T^e > 20$	$E_T^e > 20$	$p_T^\mu > 20$	$p_T^\mu > 15$
$\not{E}_t > 20$	$\not{E}_t > 30$	$\not{E}_t > 20$	$\not{E}_t > 20$
$\lvert\eta^e\rvert < 1.0$	$\lvert\eta^e\rvert < 2.5$	$\lvert\eta^\mu\rvert < 1.0$	$\lvert\eta^\mu\rvert < 1.7$
Iso < 0.1	Iso < 0.1	Iso < 0.1	Iso < 0.1
Z removal: $70 < m_{ee} < 110$	$\lvert m_Z - m_{ee}\rvert < 12$, $\not{E}_t < 40$		
Jets: $E_T > 15$, $\lvert\eta\rvert < 2.0$, R=0.4	Jets: $E_T > 15$, $\lvert\eta\rvert < 2.0$, R=0.5	Jets: $E_T > 15$, $\lvert\eta\rvert < 2.0$, R=0.4	Jets: $E_T > 15$, $\lvert\eta\rvert < 2.0$, R=0.5

Table 6: A comparison of the selection cuts for the D0 [13] and CDF top searches. All energies are in GeV.

4 M_W vs M_{top}

We are now for the first time in a position to plot direct measurements of the top mass and W mass in the M_W vs M_{top} plane. Figure 22 shows a plot based on the calculations of Halzen and Kniehl [14]. The program calculates $O(\alpha) + O(\alpha\alpha_s) + O(\alpha^2)$ contributions to ΔR. The top mass value is from CDF.

	Electrons					Muons				
	CDF		D0		D0/CDF	CDF		D0		D0/CDF
	Events	σ(ev/pb)	Events	σ(ev/pb)	$\sigma^{D0/CDF}$	Events	σ(ev/pb)	Events	σ(ev/pb)	$\sigma^{D0/CDF}$
W+0 Jet	10,663	552	?	?	———-	6264	325	?	?	———-
W+1 Jet	1058	55	1240	82	1.49 $\pm$0.06	655	34	180	16.4	0.48 $\pm$.04
W+2 Jets	191	9.9	250	816	1.66 $\pm$0.16	90	4.7	56	5.1	1.09 $\pm$.19
W+3 Jets	30	1.6	47	3.1	1.99 $\pm$0.46	13	0.7	19	1.7	2.56 $\pm$.09
W+4 Jets	6	0.3	6	0.4	1.27 $\pm$0.73	1	0.05	4	0.36	7 $\pm$.8
W+5 Jets	1	0.05	1	0.07	1.27 $\pm$1.8	1	0.05	0	0.0	———-
W+6 Jets	0	0.0	2	0.13	———-	0	0.0	0	0.0	———-

Table 7: A comparison of the number of W + jet events for the D0 [13] and CDF top searches.

5 Acknowledgements

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