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# **Search for the Top Quark and Other New Particles at $p\bar{p}$ Colliders \***

The CDF Collaboration

presented by

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# Search for the Top Quark and other New Particles at $p\bar{p}$ Colliders

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## Abstract

Results from searches for the top quark, supersymmetric particles, and new gauge bosons at the CERN and Fermilab proton-antiproton colliders are reviewed.

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# 1 Introduction

The performance of proton-antiproton ( $p\bar{p}$ ) colliders has increased significantly over the last few years, and it has been possible to search for new particles over a large mass range. Consider, for example, the search for the top quark. In the period 1983-1985, the CERN  $p\bar{p}$  collider operated at center-of-mass energies  $\sqrt{s} = 546$  and 630 GeV, and the UA1 experiment was able to collect a data sample with integrated luminosity of 0.7 pb<sup>-1</sup>. No evidence for the top quark was found in this sample and a lower limit on its mass,  $M_{top} > 41$  GeV/ $c^2$ , was determined [1]. More recently, in the period 1988-1989, new runs at CERN at  $\sqrt{s} = 630$  GeV permitted the collection of 4.7 pb<sup>-1</sup> by UA1 and of 6.4 pb<sup>-1</sup> by UA2. With the new data, the lower limits were pushed up to  $M_{top} > 60$  GeV/ $c^2$  and  $M_{top} > 69$  GeV/ $c^2$  by UA1 [2] and UA2 [3], respectively. During the same period the CDF experiment at Fermilab had its second run and recorded 4.4 pb<sup>-1</sup> of  $p\bar{p}$  collisions at  $\sqrt{s} = 1800$  GeV. Again, no top signal was observed, and CDF has placed a lower limit of  $M_{top} > 89$  GeV/ $c^2$  [6]. The preceding example illustrates the advances which have been possible with increased accelerator luminosities and energies.

The paper is organized as follows. In section 2, top quark searches carried out by UA1, UA2, and CDF are reviewed. In sections 3 and 4 we review  $p\bar{p}$  searches for supersymmetric particles and for new gauge bosons, respectively.

## 2 Search for the Top Quark

In the Standard Model the constituents of all matter are arranged in three generations of quarks and leptons. The forward-backward asymmetry measured in  $e^+e^- \rightarrow b\bar{b}$  [9] and the absence of flavor-changing neutral-currents in bottom quark ( $b$ ) decays [10], imply the existence of an iso-doublet partner of the  $b$  quark to complete the third generation. The postulated sixth quark ( $t$ , or top) has not yet been observed. Direct searches for the top quark in  $e^+e^-$  experiments at TRISTAN, SLAC and LEP have placed lower limits of about 45 GeV/ $c^2$  on  $M_{top}$  [11]. Phenomenologically, lower bounds of about 50 GeV/ $c^2$  on  $M_{top}$  have been obtained from fits to SM parameters to account for the observed degree of  $B^0\bar{B}^0$  mixing [12], and upper limits of about 200 GeV/ $c^2$  have been placed by requiring consistency of SM parameters with the measured  $W$  and  $Z$  boson masses,  $Z$  partial decay widths and weak neutral-current data [13]. The most stringent lower limits on  $M_{top}$  result from searches in  $p\bar{p}$  collisions. These results will be reviewed in what follows, and are summarized in table 1.

### 2.1 Production and Signatures

There are two ways of producing top quarks at a  $p\bar{p}$  collider : (i)  $p\bar{p} \rightarrow t\bar{t}$  and (ii)  $p\bar{p} \rightarrow W \rightarrow t\bar{b}$  (if kinematically allowed). The cross section for the first process has been calculated to order  $\alpha_s^2$  [7] and is known with a theoretical uncertainty of  $\sim 30\%$ . For the second process the production rate is predicted more precisely from branching

ratios and the measured rates for  $W \rightarrow e\nu$ . The production cross sections for the two processes are shown in figure 1 as a function of  $M_{top}$ . At the Fermilab collider, hadronic pair production of top quarks ( $t\bar{t}$ ) dominates over the decay  $W \rightarrow t\bar{b}$  except in the neighborhood of  $M_t = 60 \text{ GeV}/c^2$  where they are comparable. On the contrary, at the CERN collider the main contributing process is  $W \rightarrow t\bar{b}$ .

The top quark decays into a  $W$  boson and a bottom quark :  $t \rightarrow Wb$  (charged current decay). The  $W$ , which can be real or virtual depending on the mass of the top quark, then decays into a pair of quarks ( $u\bar{d}$  or  $c\bar{s}$ ) or into leptons ( $e\nu$ ,  $\mu\nu$ , or  $\tau\nu$ ). The final states of the top quark decay are either three jets or a jet accompanied by a charged lepton and a neutrino. Assuming a semileptonic branching ratio of  $\frac{1}{3}$  per lepton, purely hadronic final states are the most abundant. However, the resulting multijet events are difficult to distinguish from QCD multijet backgrounds. An enhancement in the signal to noise ratio is obtained by requiring at least one electron or muon in the final state. Figure 2 shows a list of final states and their branching ratios. All top quark results from  $p\bar{p}$  colliders come from searches employing the presence of at least one lepton ( $e$  or  $\mu$ ) as part of the signature.

## 2.2 Search for the Top at UA1

The UA1 detector triggers on single muons in the rapidity region  $|\eta| < 1.5$  and can detect muons out to  $|\eta| < 2.3$ . The central EM and forward calorimeters were removed for 1988-1989 in preparation for a new Uranium-TMP calorimeter. Recent top searches by UA1 have been in the  $\mu + \text{jets}$  and  $\mu\mu$  channels.

The  $\mu + \text{jets}$  selection applied on the 1988-1989 data required an isolated muon with transverse momentum  $P_T^\mu > 12 \text{ GeV}/c^2$  accompanied by at least two jets with transverse energies  $E_T^{jet1} > 13 \text{ GeV}$  and  $E_T^{jet2} > 7 \text{ GeV}$ . A transverse mass <sup>1</sup> cut of  $M_T^{\mu\nu} < 60 \text{ GeV}/c^2$  is used to reject backgrounds from  $W \rightarrow \mu\nu$  produced in association with jets. After selection, the main backgrounds for top are muons from the semileptonic decays of heavy flavors in  $b\bar{b}$  and  $c\bar{c}$  events, and from the decay in flight of kaons and pions. Four variables are used to distinguish the top signal from from backgrounds. (i) An isolation variable,  $I \equiv \sqrt{(\sum E_T/3)^2 + (\sum P_T/2)^2}$ , where the sum runs over all calorimeter cells and tracks in a cone of radius  $R=0.7$  <sup>2</sup> surrounding the muon. (ii) The muon transverse momentum,  $P_T^\mu$ . (iii) The missing transverse energy,  $\cancel{E}_T$ . (iv) The azimuthal separation between the muon and the leading jet,  $\Delta\phi(\mu - jet1)$ .

The distribution of the isolation variable is shown in figure 3 for the UA1 data, and for the expected backgrounds and top signal. Muons from  $b\bar{b}$  and  $c\bar{c}$  are produced inside or near jets and are not isolated while muons from very heavy quark decay are

<sup>1</sup>The transverse mass variable is defined as  $M_T^{\mu\nu} = \sqrt{2P_T^\mu \cancel{E}_T (1 - \cos \Delta\phi_{\mu\nu})}$ , with  $\cancel{E}_T$  the missing transverse energy in the event, and  $\Delta\phi_{\mu\nu}$  the azimuthal separation between the muon and missing transverse energy vectors.

<sup>2</sup>R is a distance measured in pseudorapidity-azimuth space (radians).  $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .  $\eta = -\ln(\tan(\theta/2))$ .  $\theta$  is the angle to the proton direction.

usually well separated from the jets and therefore isolated. No excess of isolated muons is observed in the UA1 data.

For improved sensitivity, all four variables are combined in a ‘likelihood’ variable :

$$L = \prod_{i=1}^4 P_{top}(X_i)/P_{bot}(X_i),$$

where  $P_{top}(X_i)$  and  $P_{bot}(X_i)$  are the probability density functions of the variable  $X_i$  for top signal events and for  $b\bar{b}$  and  $c\bar{c}$  background events, respectively. Figure 4 shows the distribution of this variable for the UA1 data, for the expected backgrounds, and for the top signal. After a final cut of  $\ln(L) > 4$ , only 2 events remain in the data while  $2.8 \pm 0.8$  events are expected from  $b\bar{b}$ ,  $c\bar{c}$  and decays in flight. A total of 6.2 top events (4.1 from  $t\bar{b}$  and 2.1 from  $t\bar{t}$ ) are expected for  $M_{top} = 50 \text{ GeV}/c^2$ . From the  $\mu + \text{jets}$  analysis, a 95 % CL lower limit of  $M_{top} > 52 \text{ GeV}/c^2$  is obtained.

The UA1 search in the  $\mu\mu$  channel required one isolated muon with  $P_T^\mu > 8 \text{ GeV}/c$ , a second non-isolated muon with  $P_T^\mu > 3 \text{ GeV}/c$  and at least one jet with  $E_T^{jet} > 10 \text{ GeV}$  to search for  $W \rightarrow t\bar{b}$ . Again, no top signal was found and the data were consistent with expected backgrounds, predominantly from b-quark and c-quark production and decays in flight. The  $\mu\mu$  channel alone excludes  $M_{top} > 46 \text{ GeV}/c^2$  at the 95 % CL.

UA1 has combined the 1988-1989 searches in the  $\mu + \text{jets}$  and  $\mu\mu$  channels with previous searches from 1983-1985 in the  $e + \text{jets}$ ,  $\mu + \text{jets}$ , and  $\mu\mu$  channels. The combined UA1 limit is  $M_{top} > 60 \text{ GeV}/c^2$  at the 90% CL.

### 2.3 Search for the Top at UA2

UA2 is a non magnetic detector with good electron identification capabilities. The UA2 collaboration has looked for semileptonic decays of the top quark in the  $e + \text{jets}$  channel [3]. Electrons are recognized in the region  $|\eta| < 1.0$  as electromagnetic clusters with small lateral size and small hadronic energy depositions. A scintillating fiber detector with tracking and a preshower section is used to match the tracks with the position of electromagnetic showers. A silicon detector outside the beam pipe is used to reduce backgrounds from photon conversions and Dalitz decays, by requiring a charge deposition consistent with one minimum ionizing particle.

The UA2  $e + \text{jets}$  selection required an electron candidate with  $E_T^e > 12 \text{ GeV}$ , missing transverse energy  $\cancel{E}_T > 15 \text{ GeV}$ , and at least one jet with  $E_T^{jet} > 10 \text{ GeV}$ . To reduce misidentification backgrounds, events with the electron back-to-back to the leading jet were rejected. The major background after these cuts is from high  $P_T$   $W$  events produced in association with jets. The transverse mass of the electron-neutrino system

$$M_T^{e\nu} = \sqrt{2E_T^e \cancel{E}_T (1 - \cos \Delta\phi_{e\nu})},$$

is used to distinguish a possible top signal from the  $W + \text{jets}$  background. Figure 5 shows the transverse mass distribution for the UA2 data, which is seen to be consistent with expectations from  $W$  boson decay alone. The top quark would manifest itself as

an excess of events in the low transverse mass region. The absence of such an excess in the UA2 data implies that  $M_{top} > 69 \text{ GeV}/c^2$  at the 95% CL.

## 2.4 Search for the Top at CDF

CDF is a solenoidal detector with good electron and muon identification capabilities. Electron candidates in the region  $|\eta| < 1.0$  have calorimeter clusters with mostly electromagnetic energy and with lateral shower profiles consistent with test beam electrons. They must be associated to a track in the central drift chamber extrapolating to the calorimeter shower position, and with momentum in good agreement with the calorimeter energy. Electron pairs from photon conversions and Dalitz decays can be rejected when a second nearby track forming a low mass pair is found in the drift chamber. Photon conversions can also be rejected if no track is found in the vertex time projection chamber located between the beam pipe and the central drift chamber. Muons are identified in the region  $|\eta| < 1.2$  by requiring that the tower to which the candidate track extrapolates has energy deposition consistent with that of a minimum ionizing particle. The region  $|\eta| < 0.6$  is instrumented with muon chambers, outside of the calorimeters, for triggering and improved muon identification.

The first CDF top results came from searches in the  $e + \text{jets}$ [5] channel and in the  $e\mu$ [4] channel. The search in  $e + \text{jets}$ , similar to the UA2 analysis already described, employed the transverse mass variable to discriminate between top events and the dominant  $W + \text{jets}$  background. A limit of  $M_{top} > 77 \text{ GeV}/c^2$  was obtained. This method is no longer useful when  $M_{top}$  approaches  $M_W$ , in which case the transverse mass distributions are very similar.

The  $e\mu$  signature requires the presence of an electron and a muon with opposite electric charges, each with transverse momentum above the threshold  $P_T^{min} = 15 \text{ GeV}/c^2$  (signal region). The high transverse momentum threshold separates the  $t\bar{t}$  signal from  $b\bar{b}$  backgrounds, which concentrate at low  $P_T$ . Figure 6 shows CDF electron-muon data selected with  $E_T^e > 15 \text{ GeV}$  and  $P_T^\mu > 5 \text{ GeV}/c$  in the  $E_T^e - P_T^\mu$  plane. There is one event in the top quark signal region. This event (see figure 7) has an electron with  $E_T^e = 31.7 \text{ GeV}$  and muon with  $P_T^\mu = 42.5 \text{ GeV}/c$ . The dilepton azimuthal opening angle is 137 degrees. There is also a second muon candidate in the event in the forward region, and a jet with  $E_T = 14 \text{ GeV}$ . Given one candidate event, a 95% CL upper limit on the number of  $t\bar{t} \rightarrow e\mu + X$  events expected is obtained and then converted into an upper limit on the  $t\bar{t}$  production cross section. The result is shown in figure 8, together with a theoretical calculation of the  $t\bar{t}$  production cross section [7,8]. The 95% CL upper limit cross section curve intersects the lower edge of the theoretical calculation band at  $M_{top} = 72 \text{ GeV}/c^2$ , which is the lower limit on the top quark mass from the  $e\mu$  channel.

A straightforward extension of the  $e\mu$  analysis is to also search for top in  $ee$  and  $\mu\mu$  events. In the  $ee$  and  $\mu\mu$  channels, additional backgrounds predominantly from  $Z$  decays and also from Drell-Yan,  $\Upsilon$  and  $J/\psi$  production must be removed. Dielectron

and dimuon events were selected by requiring  $P_T > 15 \text{ GeV}/c^2$  for each lepton. A simple mass cut around the  $Z$  peak removes most of the background with a moderate impact on the  $t\bar{t}$  signal. Namely, events are rejected if they fall in the region  $75 \text{ GeV}/c^2 < M_{l+l-} < 105 \text{ GeV}/c^2$ . After the mass cut, the signal to background ratio is improved by requiring missing transverse energy  $\cancel{E}_T > 20 \text{ GeV}$ . Also, events with back-to-back or collinear dileptons are eliminated by requiring the azimuthal opening between the leptons to be in the region  $20^\circ < \Delta_{l+l-} < 180^\circ$ . Figure 9 shows the scatter plots in the  $\Delta_{l+l-}$  vs  $\cancel{E}_T$  plane after the invariant mass cut, for the CDF dielectron data, dimuon data, and for  $t\bar{t} \rightarrow \mu\mu$  Monte Carlo. After all cuts, there are no  $ee$  or  $\mu\mu$  events remaining in the data. A total of 7.5 events (4.6  $e\mu$ , 1.4  $ee$  and 1.5  $\mu\mu$ ) are expected for  $80 \text{ GeV}/c^2$   $t\bar{t}$ . With only one  $e\mu$  event observed, the limit from the  $e\mu$ ,  $ee$ , and  $\mu\mu$  channels together is  $M_{top} > 84 \text{ GeV}/c^2$ .

Finally, CDF has looked for additional low  $P_T$  muons in the  $e + \text{jets}$  and  $\mu + \text{jets}$  samples. The low  $P_T$  muon in the event is employed as a possible tag of the bottom quark in the chain  $t \rightarrow b \rightarrow \mu$ . Backgrounds to these soft muons from decays in flight and hadronic punch through are reduced by rejecting events where the muon is within  $\Delta R < 0.6$  (see footnote 2) of either of the two leading jets. Figure 10 shows the distribution of the distance  $\Delta R$  between the soft muon and the nearest of the two leading jets for the CDF data and for  $t\bar{t}$  Monte Carlo. No candidates were found. The result of the low  $P_T$  muon search combined with the previous dilepton searches extends the CDF top quark mass limit to  $M_{top} > 89 \text{ GeV}$  at the 95% CL (see figure 8).

## 2.5 Prospects for the Top Quark

The Fermilab collider will have its next run in 1991-1992 and it is expected to deliver a factor of five more integrated luminosity than in the previous 1988-1989 run. There will be two collider experiments running, D0 and CDF. With the present acceptance to dileptons, the new data sample will give CDF sensitivity to  $M_{top} \sim 120 \text{ GeV}/c^2$ . A new silicon vertex detector (SVX) will be installed in CDF for the next run. A major goal is to tag bottom quarks by their displaced vertices. It has been shown that it is possible to separate b-enriched samples from  $p\bar{p}$  collisions [14]. Such samples will be crucial to debug, align and calibrate the SVX. In addition to the inclusive lepton samples, the  $J/\psi \rightarrow \mu\mu$  sample is also believed to have large b-content. Notably, the decay  $B^\pm \rightarrow J/\psi K^\pm$  has been recently reconstructed by CDF for the first time in a hadron collider (see figure 11). A very promising signature for top is to use the SVX to tag one of the two bottom quarks in a  $t\bar{t}$  event. This may give CDF enough sensitivity for  $M_{top} \sim 140 \text{ GeV}/c^2$  for the next run.

## 3 Supersymmetry

Supersymmetry[15] (SUSY) is a proposed symmetry that links fermions and bosons. A complete new spectroscopy is predicted, in which to each standard fermion (boson)

there corresponds a supersymmetric boson (fermion) partner. In particular, the quark, gluon, and photon have as SUSY partners the squark ( $\tilde{q}$ ), gluino ( $\tilde{g}$ ), and photino ( $\tilde{\gamma}$ ). The masses of the supersymmetric partners are not predicted by the theory. For concreteness, it is common to assume that all six squarks are degenerate in mass and that the photino is the lightest SUSY particle. Rigorous conservation of a SUSY quantum number is assumed, which implies that the lightest SUSY particle is stable, and that SUSY particles are always pair produced. In  $p\bar{p}$  collisions the dominant source of SUSY particles is the production of  $\tilde{q}\tilde{q}^*$ ,  $\tilde{q}\tilde{g}$  and  $\tilde{g}\tilde{g}$ . The assumed decay mode for the gluino is  $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ . For squarks, the assumed decay mode is  $\tilde{q} \rightarrow q\tilde{g}$  if  $M_{\tilde{q}} > M_{\tilde{g}}$  and  $\tilde{q} \rightarrow q\tilde{\gamma}$  if  $M_{\tilde{q}} < M_{\tilde{g}}$ . The final states will contain normal quarks and gluons, and photinos. Since the photinos escape undetected, SUSY events will have jets and imbalanced transverse momentum. For example, the signature for  $p\bar{p} \rightarrow \tilde{q}\tilde{q}^*X$  is  $\cancel{E}_T + 6$  jets, for the case  $M_{\tilde{q}} > M_{\tilde{g}}$ , or  $\cancel{E}_T + 2$  jets if  $M_{\tilde{q}} < M_{\tilde{g}}$ .

CDF has searched for squarks and gluinos in the context of the minimal SUSY model described above. The data sample consisted of events with  $\cancel{E}_T > 40$  GeV and at least two jets with  $E_T^{jet} > 15$  GeV. Events with identified electrons or muons were rejected. The  $\cancel{E}_T$  spectrum for this sample (98 events) is shown in figure 12. The number of events in the sample is consistent with background expectations:  $86 \pm 14 \pm 12$  events from  $W \rightarrow \tau\nu, \mu\nu, e\nu$  and  $Z \rightarrow \nu\nu$  (produced in association with jets), and  $4 \pm 4$  events from QCD. More stringent cuts are applied to further separate backgrounds from a possible SUSY signal. Two cases are considered. (i)  $M_{\tilde{q}} > M_{\tilde{g}}$ . Four or more jets with  $E_T^{jet} > 15$  GeV are required in this case. The CDF data contains 2 events passing these cuts, and the expected background is  $1.3 \pm 1.3$  events. A SUSY signal for  $(M_{\tilde{q}}, M_{\tilde{g}}) = (500, 150)$  GeV/ $c^2$  would give 5.6 events. (ii)  $M_{\tilde{q}} < M_{\tilde{g}}$ . In this case the missing  $E_T$  threshold is raised to  $\cancel{E}_T > 40$  GeV (still only two jets are required). Three events pass these cuts, and the expected background is  $1.3 \pm 1.3$  events. A SUSY signal for  $(M_{\tilde{q}}, M_{\tilde{g}}) = (400, 150)$  GeV/ $c^2$  would give 4.9 events.

Figure 13 shows the region in the  $M_{\tilde{g}} - M_{\tilde{q}}$  plane excluded at the 90% CL by CDF based on the non-observation of a SUSY signal. The discontinuity along the line  $M_{\tilde{g}} = M_{\tilde{q}}$  is due to the different acceptances of the cases considered. The asymptotic 90% CL mass limits are  $M_{\tilde{g}} > 150$  GeV/ $c^2$  (independent of  $M_{\tilde{q}}$ ), and  $M_{\tilde{q}} > 150$  GeV/ $c^2$  (for  $M_{\tilde{g}} \lesssim 400$  GeV/ $c^2$ ).

It has been noted[17] that if squarks and gluinos are heavy enough, they could decay into heavy supersymmetric particles (charginos and neutralinos) which would themselves decay into the lightest SUSY particle. It is expected that the effect of such cascade decays would lower the squark and gluino mass limits by  $\sim 30$  GeV/ $c^2$ .

The UA1 and UA2 collaborations have carried out similar  $\cancel{E}_T +$  jets analyses to search for squarks and gluinos [18,19]. The UA1, UA2, and CDF results for squarks and gluinos are summarized in table 2.

UA2 has also searched for electron pairs in association with  $\cancel{E}_T$  as a possible signal for selectrons or winos (partners of the electron and  $W$  boson) from the decays  $Z \rightarrow \tilde{e}\tilde{e} \rightarrow ee\tilde{\gamma}\tilde{\gamma}$  or  $Z \rightarrow \tilde{W}\tilde{W} \rightarrow ee\nu\bar{\nu}$ . No evidence for such exotic decays was found,

and assuming massless photinos and neutralinos, the lower mass limits are  $M_{\tilde{e}} > 40$  GeV/ $c^2$  and  $M_{\tilde{W}} > 45$  GeV/ $c^2$  at the 90 % CL [20].

## 4 New Gauge Bosons : $W'$ , $Z'$

New charged and neutral vector bosons, denoted generically by  $W'$  and  $Z'$ , respectively, may arise in theories in which the gauge group of the standard model is enlarged. Such is the case in some left-right symmetric models, composite models or superstring models [21]. Experimentally, heavy  $W$ -like particles would show up as a peak in the lepton-neutrino transverse mass distribution, above the standard  $W$  peak. Similarly, a heavy  $Z$ -like particle would peak in the dilepton invariant mass distribution, above the standard  $Z$  resonance.

The  $e - \nu$  transverse mass distribution for CDF events having an electron with  $E_T^e > 30$  GeV, and missing transverse energy  $\cancel{E}_T > 30$  GeV, is shown in figure 14. The data are well explained by  $W \rightarrow e\nu$  alone. The absence of events at high transverse mass (there are no events with  $M_T^{e\nu} > 140$  GeV/ $c^2$ ) allows CDF to set limits on the production times leptonic branching ratio for  $W' \rightarrow e\nu$ . Assuming standard couplings to quarks and standard branching ratio to electrons, the resulting 95% CL lower limit on the  $W'$  mass is  $M_{W'} > 478$  GeV/ $c^2$ .

The dielectron invariant mass for the CDF data is shown in figure 15. The data are consistent with  $Z$  and Drell Yan production and decay into electron pairs. No events with  $M_{ee}$  above 200 GeV/ $c^2$  are observed, and from this a 95% CL lower limit on the  $Z'$  mass of  $M_{Z'} > 380$  GeV/ $c^2$  is obtained assuming standard model couplings to quarks and standard branching ratio to electrons.

Results from similar searches by UA2[22] are summarized together with the CDF results in table 3.

## 5 Summary and Conclusions

Experiments at  $p\bar{p}$  colliders have carefully examined events with large missing transverse energy, large  $P_T$  leptons and dileptons. The distributions studied include missing  $E_T$ , lepton-neutrino transverse mass and dilepton invariant mass. The data are very well explained by standard processes alone, and no evidence has been found for new particles. The mass limits derived for the top quark, supersymmetric quarks and gluons, and new gauge bosons are the most stringent in the world today. A summary of these limits can be found in tables 1, 2, & 3. There is hope of finding the top quark in the next 1991-1992 Fermilab collider run if its mass is not heavier than  $\sim 120$ -140 GeV/ $c^2$ .

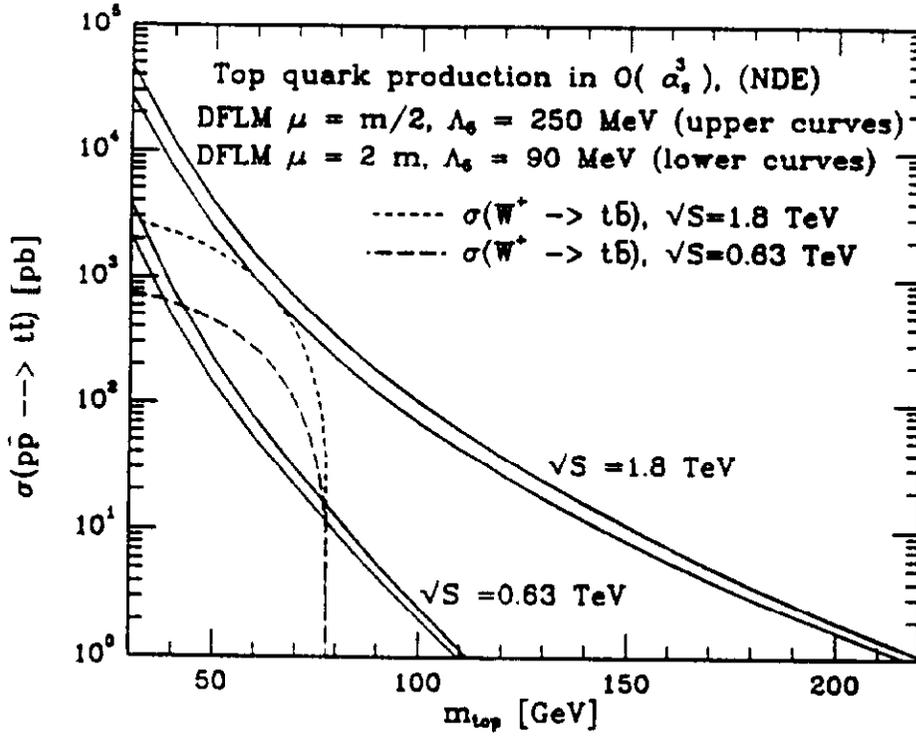


Figure 1: The predicted  $W \rightarrow t\bar{b}$  and  $t\bar{t}$  cross sections as a function of  $M_{top}$  [7,8].

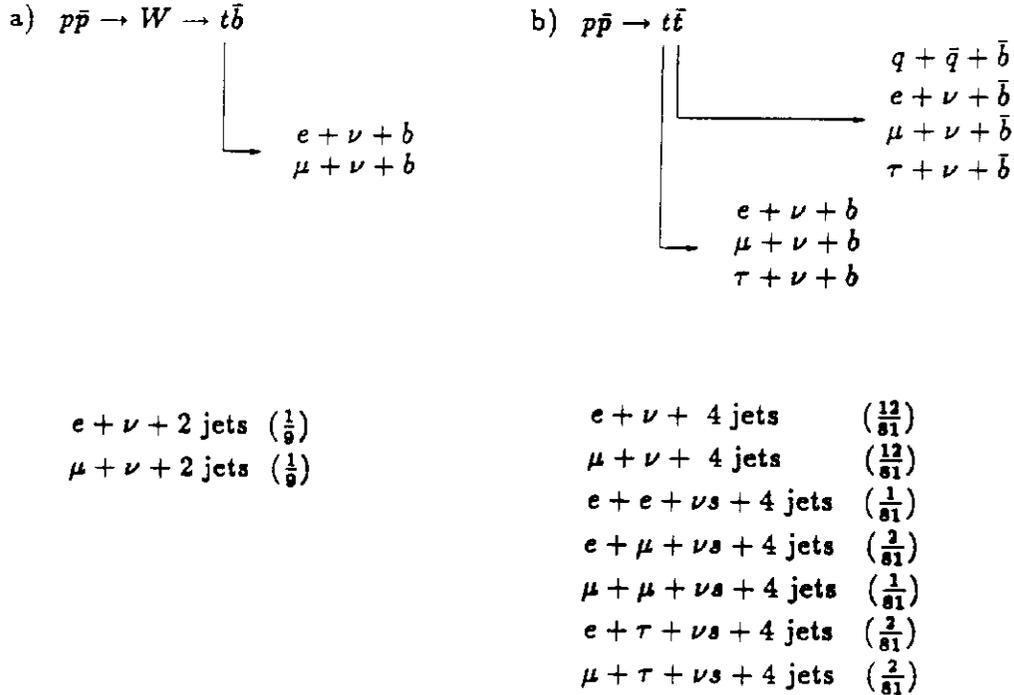


Figure 2: Parton final states and event topologies for a)  $W$  decay and b) top pair production. Only final states containing at least one electron or muon from the top decay are shown. The branching ratios are indicated in parentheses.

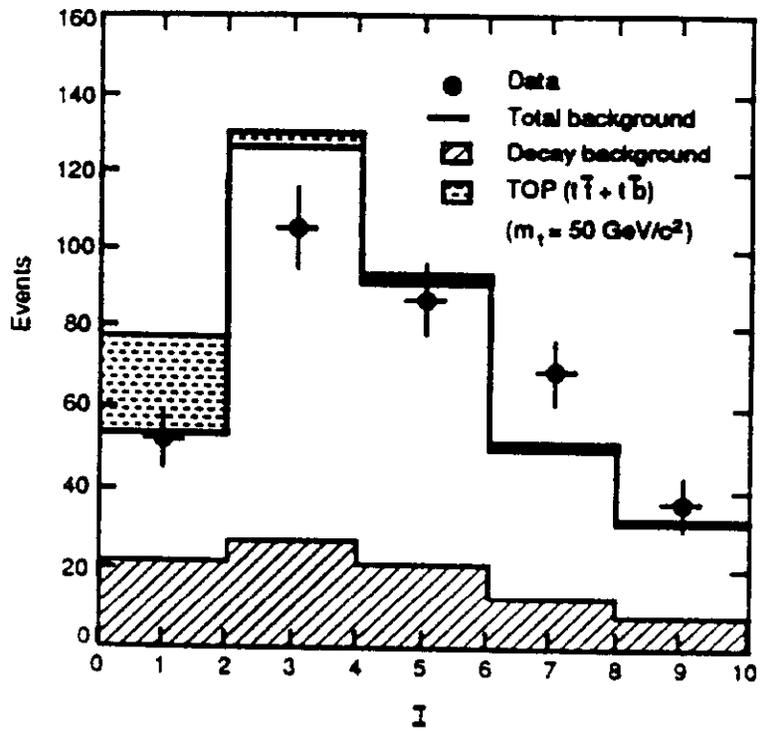


Figure 3: Distribution of the UA1 isolation variable.

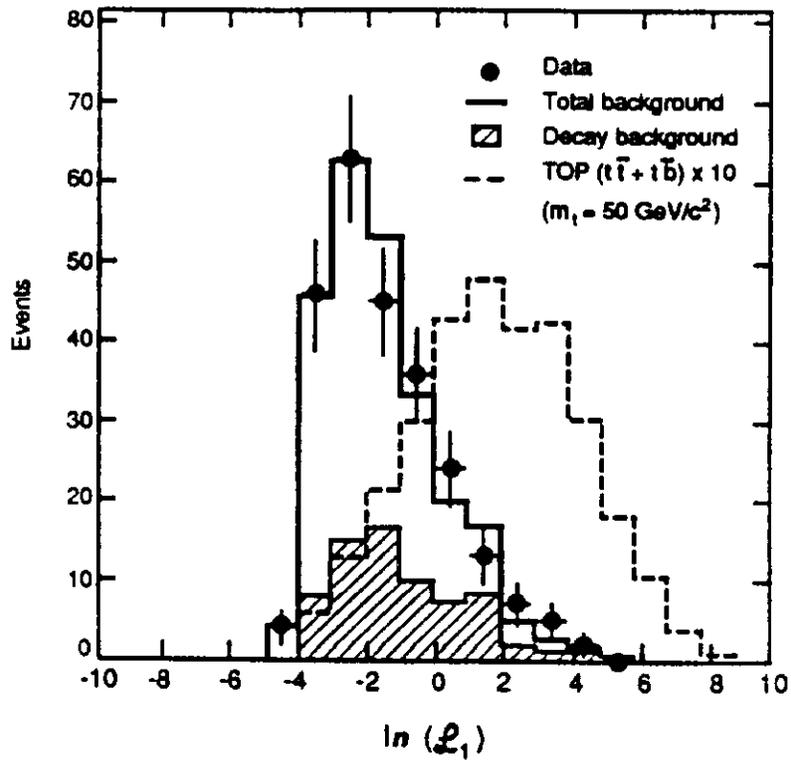


Figure 4: Distribution of the UA1 single muon 'top likelihood' variable.

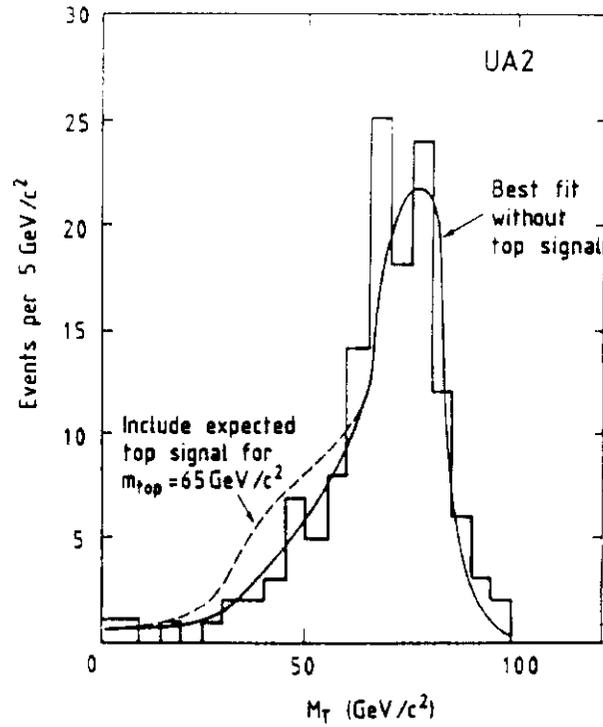


Figure 5: Transverse mass distribution for the UA2  $e + \text{jets}$  sample (histogram). The full line corresponds to expectations from  $W$  boson decays alone. The dashed line includes a contribution from top events for  $M_{top} = 65 \text{ GeV}/c^2$ .

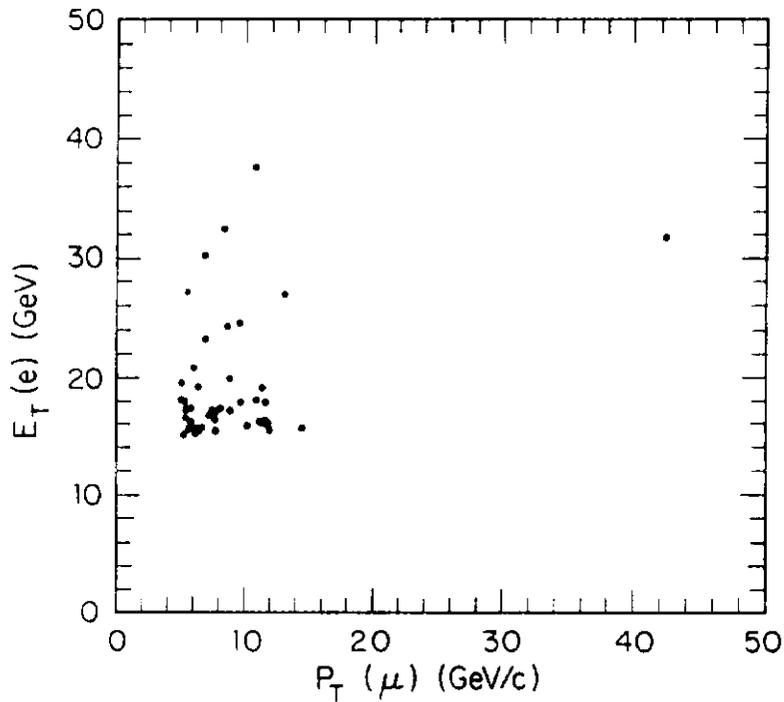


Figure 6: Electron transverse energy vs muon transverse momentum for the CDF data with an integrated luminosity of  $4.4 \text{ pb}^{-1}$ .

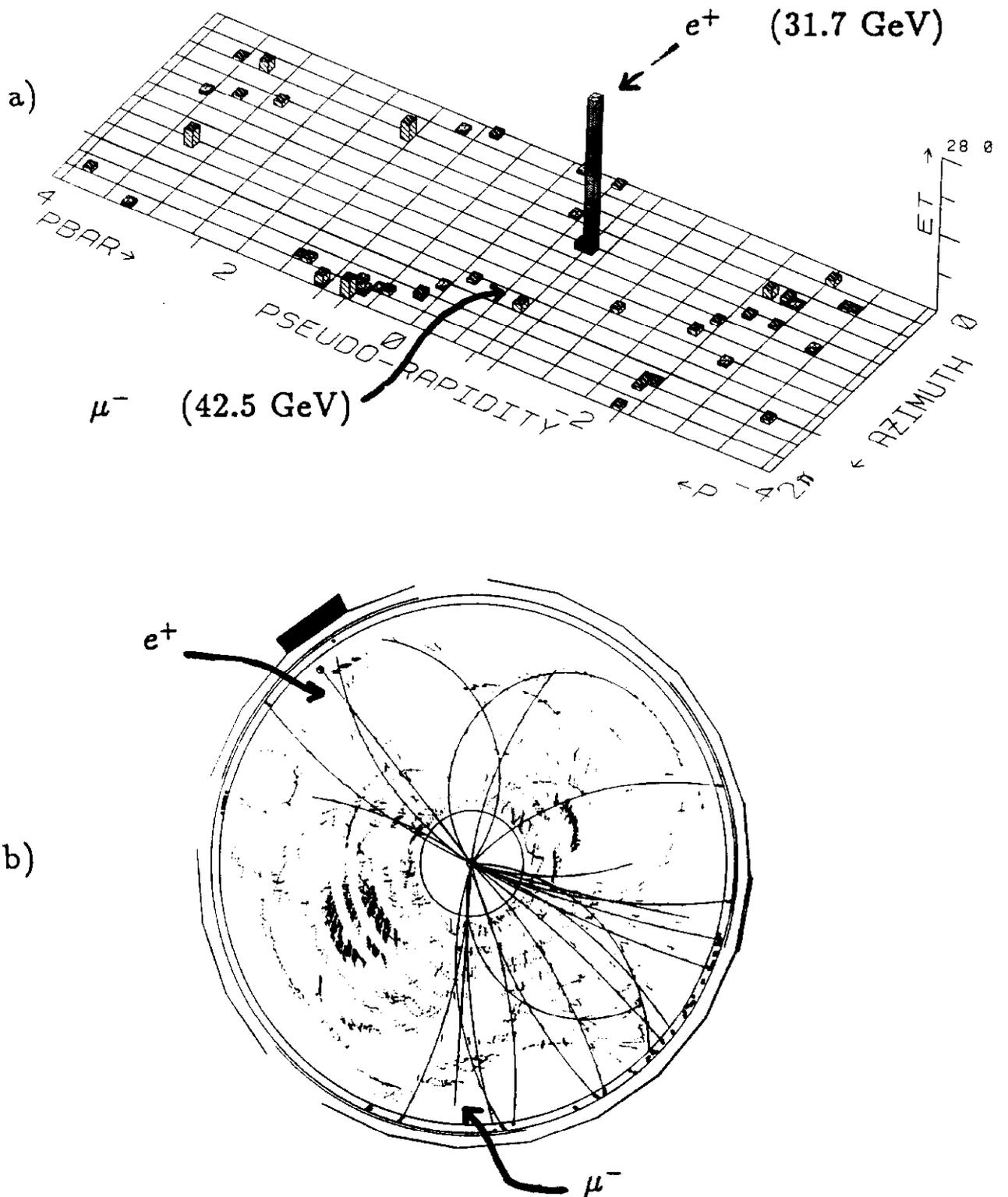


Figure 7: Displays of the CDF  $t\bar{t} \rightarrow e\mu + X$  candidate event. a) Calorimeter lego plot. b) Central tracking chamber view.

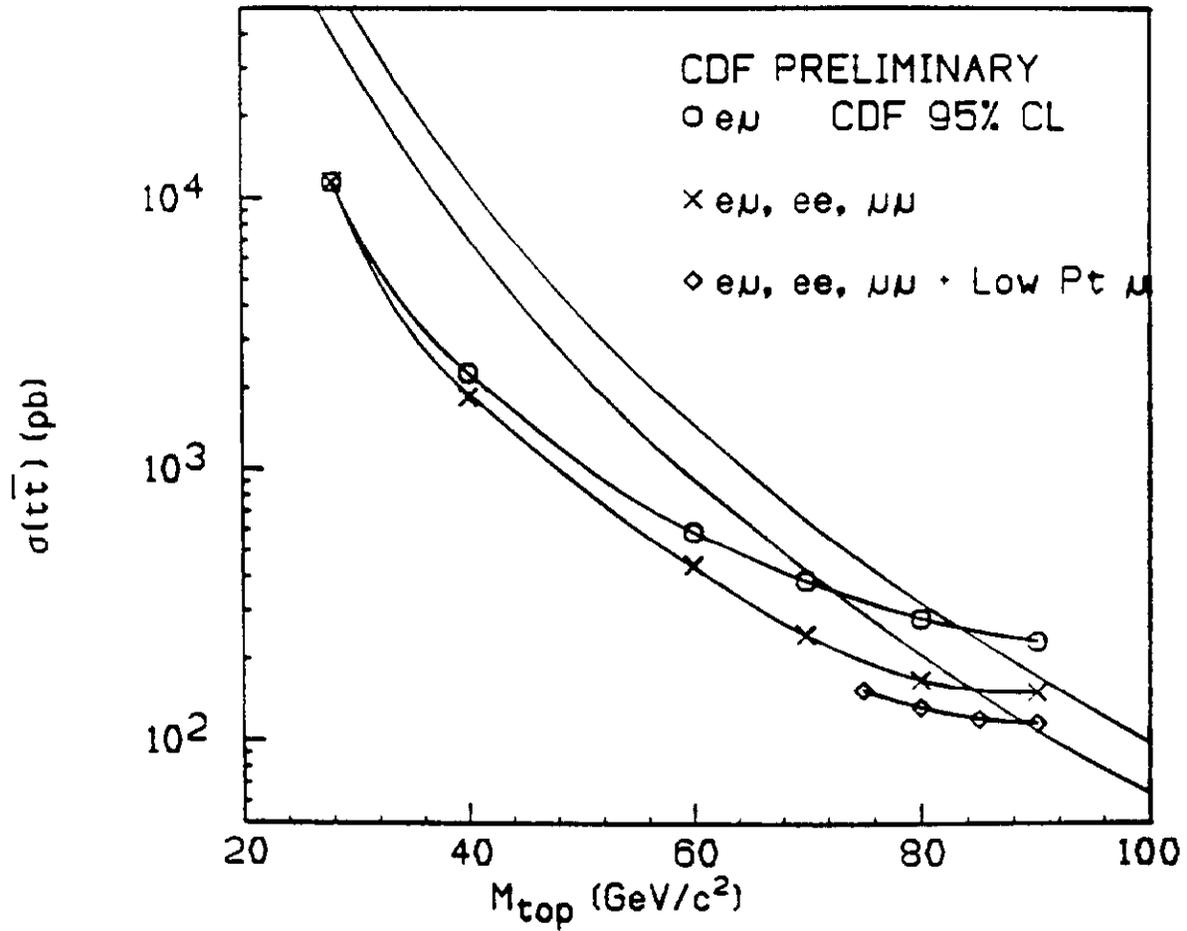


Figure 8: Experimental 95% upper limit on the  $t\bar{t}$  production cross section as a function of top-quark mass. Also shown are the upper and lower bounds from a theoretical calculation [7,8]. The top quark mass limits are derived by finding the intersection between the experimental cross section upper limit and the theoretical lower bound.

CDF Preliminary

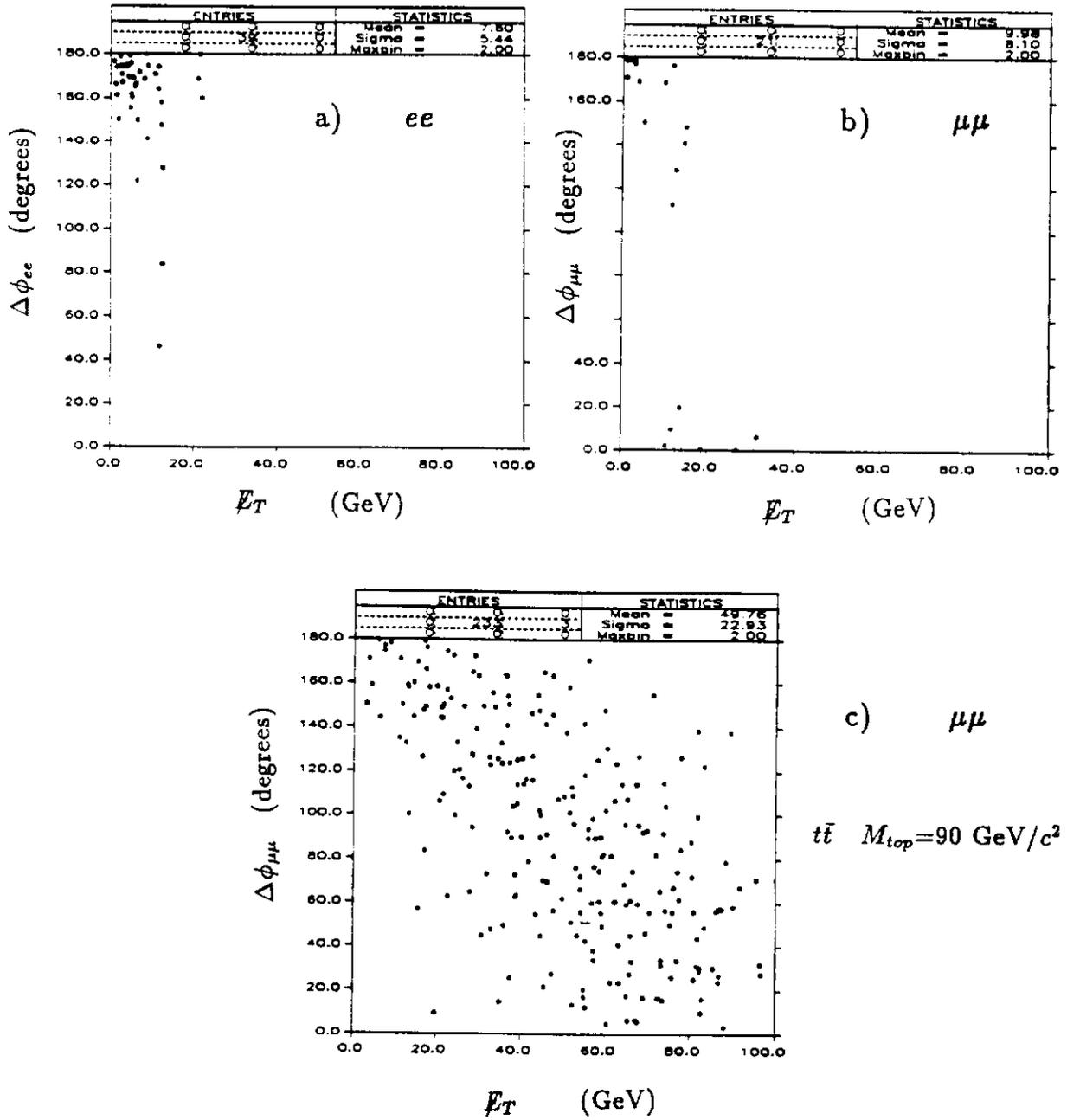


Figure 9: Dilepton azimuthal separation vs missing transverse energy after the  $Z$ -mass window cut. a) CDF  $ee$  data. b) CDF  $\mu\mu$  data. c)  $t\bar{t} \rightarrow \mu\mu$  Monte Carlo ( $M_{top} = 90 \text{ GeV}/c^2$ , unnormalized).

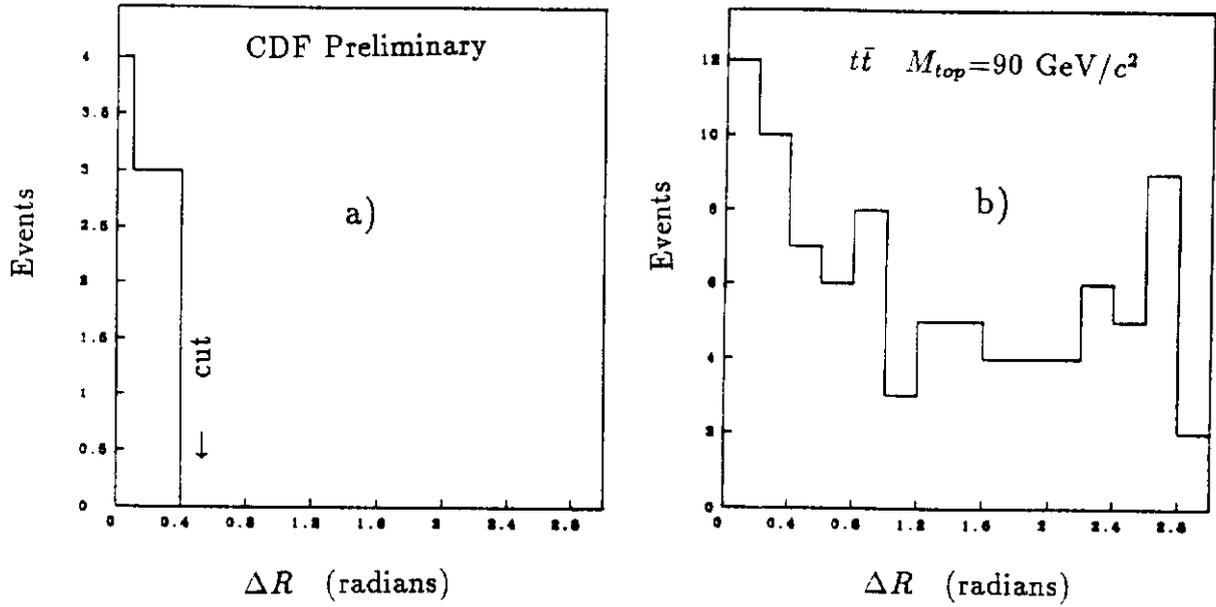


Figure 10: Distribution of  $\Delta R$ , the distance in  $\eta - \phi$  space between the low  $P_T$  muon and the nearest of the two leading jets. a) CDF data with integrated luminosity of  $4.4 \text{ pb}^{-1}$ . b)  $t\bar{t}$  Monte Carlo with integrated luminosity of  $250 \text{ pb}^{-1}$ .

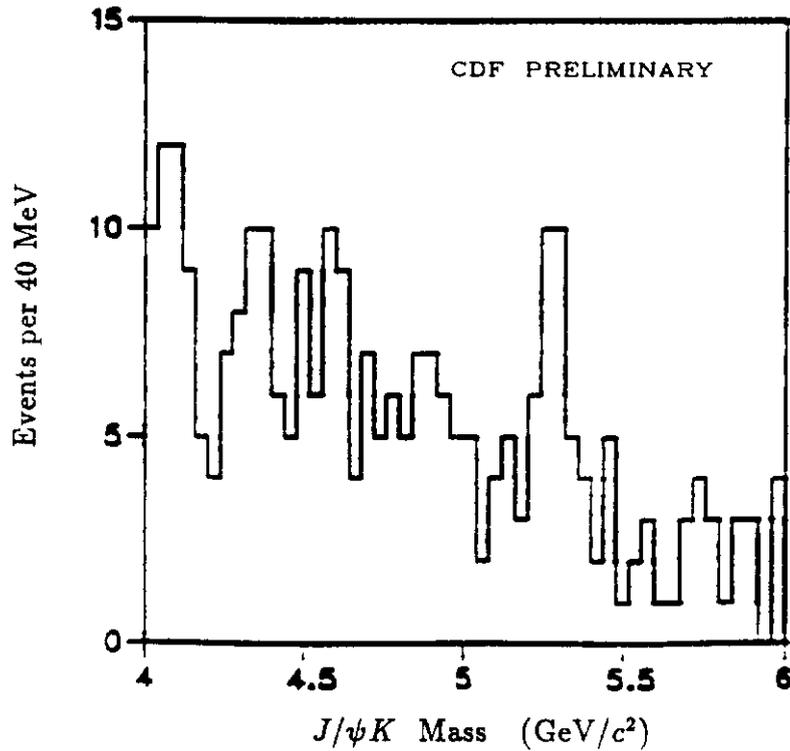


Figure 11: Invariant mass of the  $J/\psi K$  system from the CDF  $J/\psi \rightarrow \mu\mu$  sample. The observed peak is evidence for the decay  $B^\pm \rightarrow J/\psi K^\pm$ .

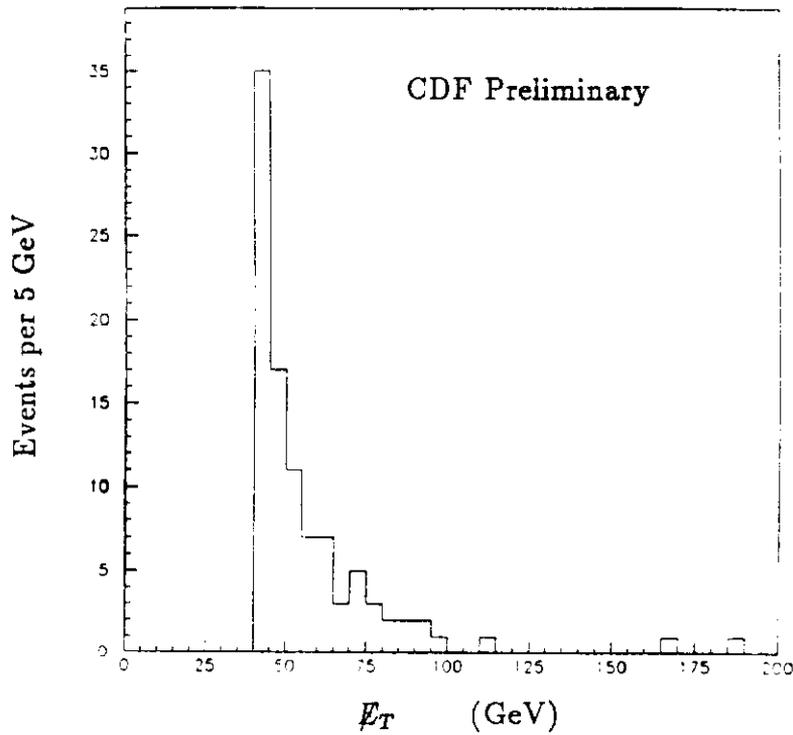


Figure 12: The missing transverse energy ( $E_T$ ) distribution for CDF events selected having  $E_T > 40$  GeV and at least two jets.

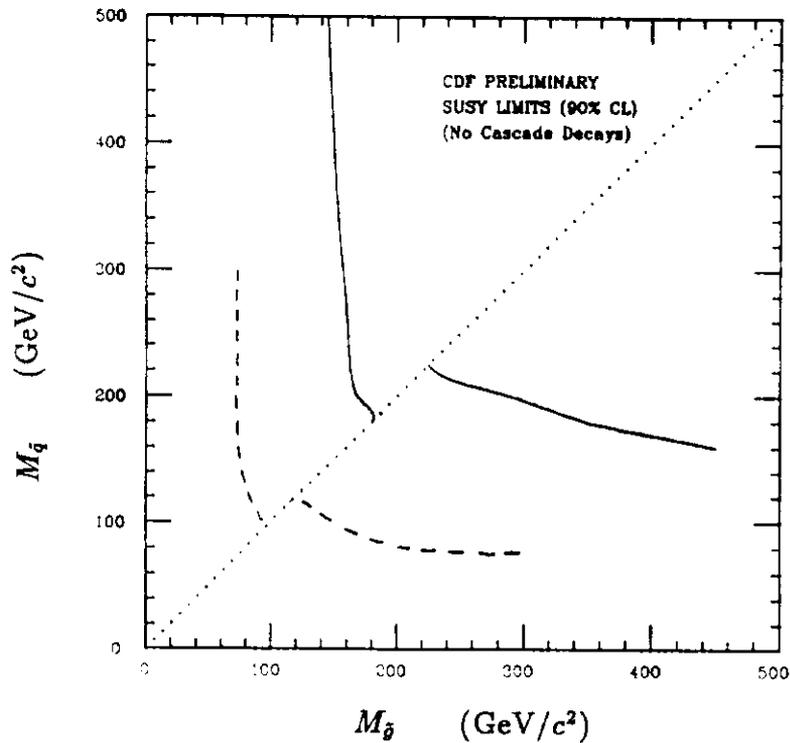


Figure 13: The region in the gluino-squark mass plane excluded by CDF (90% CL). The solid line is a preliminary result based on 1988-1989 data. The dashed line is the result from the previous 1987 data [16].

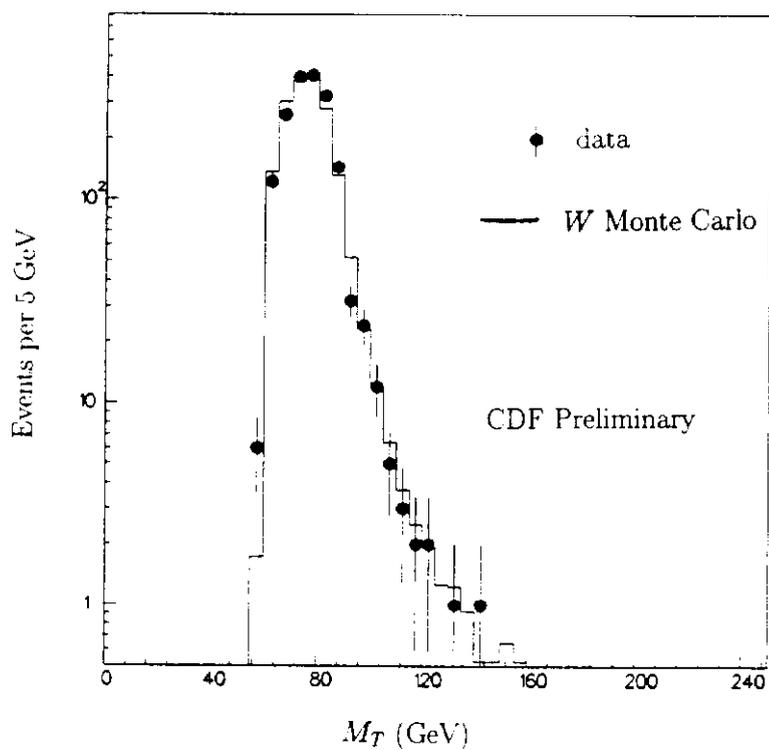


Figure 14: Comparison of the electron-neutrino transverse mass distribution for CDF data and  $W \rightarrow e\nu$  Monte Carlo.

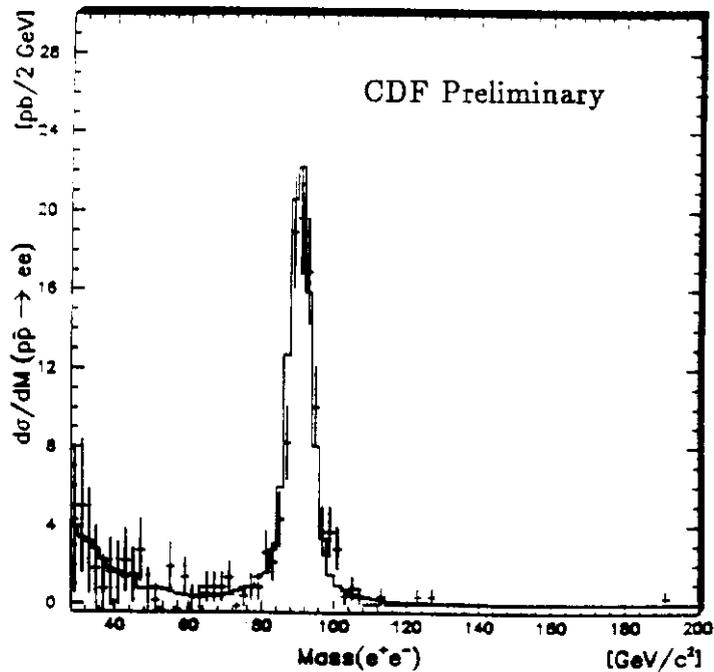


Figure 15: Comparison of the dielectron invariant mass distribution for CDF data and  $Z/\text{Drell-Yan} \rightarrow ee$  Monte Carlo.

Top Quark Mass Lower Limits (95% CL)		
UA1	$e + \text{jets}$ [1]	$M_{top} > 41 \text{ GeV}/c^2$
	$\mu + \text{jets}$ [2]	$M_{top} > 52 \text{ GeV}/c^2$
	$\mu\mu$ [2]	$M_{top} > 46 \text{ GeV}/c^2$
	Combined [2]	$M_{top} > 60 \text{ GeV}/c^2$
UA2	$e + \text{jets}$ [3]	$M_{top} > 69 \text{ GeV}/c^2$
CDF	$e + \text{jets}$ [5]	$M_{top} > 77 \text{ GeV}/c^2$
	$e\mu$ [4]	$M_{top} > 72 \text{ GeV}/c^2$
	$e\mu, ee$ and $\mu\mu$	$M_{top} > 84 \text{ GeV}/c^2$ (preliminary)
	$e\mu, ee, \mu\mu$ and Low $P_T \mu$	$M_{top} > 89 \text{ GeV}/c^2$ (preliminary)

Table 1: Top quark mass lower bounds from UA1, UA2, and CDF.

	Squarks 90% CL	Gluginos 90% CL
UA1 [18]	$M_{\tilde{q}} > 45 \text{ GeV}/c^2$	$M_{\tilde{g}} > 53 \text{ GeV}/c^2$
UA2 [19]	$M_{\tilde{q}} > 79 \text{ GeV}/c^2$	$M_{\tilde{g}} > 74 \text{ GeV}/c^2$
CDF (prelim.)	$M_{\tilde{q}} > 150 \text{ GeV}/c^2$	$M_{\tilde{g}} > 150 \text{ GeV}/c^2$

Table 2: Lower mass limits on squarks and gluginos.

	$W'$ 95% CL	$Z'$ 95% CL
UA2 [22]	$M_{W'} > 209 \text{ GeV}/c^2$	$M_{Z'} > 180 \text{ GeV}/c^2$
CDF (prelim.)	$M_{W'} > 478 \text{ GeV}/c^2$	$M_{Z'} > 380 \text{ GeV}/c^2$

Table 3: Lower mass limits on new gauge bosons.

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