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## **New Particle Searches at $\bar{p}p$ Experiments \***

The CDF Collaboration

presented by

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## NEW PARTICLE SEARCHES AT $\bar{p}p$ EXPERIMENTS

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### Abstract

The search for new particles, such as the top quark, charged Higgs boson, heavy gauge bosons and supersymmetric particles, at the CERN and Fermilab proton-antiproton colliders is reviewed. A preliminary result by the CDF experiment of a reconstructed  $B$  meson mass peak from the decays  $B^\pm \rightarrow J/\psi K^\pm$  and  $B^0 \rightarrow J/\psi K^{*0}$  is also presented.

### 1 Introduction

Proton-antiproton collider experiments are a fruitful hunting ground for new particles. This was established in 1983 by the discovery of the  $W^1$  and  $Z^2$  intermediate vector bosons at the CERN collider. With the higher center-of-mass energy at the Fermilab Tevatron collider and the large data samples recently collected by the CDF, UA1, and UA2 experiments, new particle searches are beginning to constrain the flexibility and freedom enjoyed by the Standard Model and alternative supersymmetric models. In this paper, we first describe the search for the top quark at  $\bar{p}p$  experiments and present the most recent results of the UA1, UA2, and CDF experiments. We next present an analysis by the UA1 experiment of a search for  $t \rightarrow H^+ b$  and the resulting limit placed on the mass of a charged Higgs boson. This is followed by a search at the CDF experiment for additional heavy vector bosons  $W'$  and  $Z'$ . The latest mass limits on squarks and gluinos from the CDF experiment are given next and a search by the UA2 experiment for selectrons and winos is also presented. Finally, the observation by the CDF experiment of a reconstructed  $B$  meson mass peak from the decays  $B^\pm \rightarrow J/\psi K^\pm$  and  $B^0 \rightarrow J/\psi K^{*0}$  is reported.

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## 2 Search for the Top Quark

There is a large amount of evidence which supports the existence of the top quark in the Standard Model. This evidence includes the observation of a forward-backward asymmetry in  $e^+e^- \rightarrow b\bar{b}$ ,<sup>3, 4</sup> and the absence of flavor-changing neutral current interactions in  $B$  meson decay.<sup>5</sup> Both of these findings can be interpreted as a natural consequence of the  $b$  quark being in an SU(2) doublet with another quark (i.e. the top quark). In addition, a lower limit of 50 GeV/ $c^2$  has been placed on the top quark mass from the observed rate of  $B^0\bar{B}^0$  mixing<sup>6</sup> and an upper limit of  $\sim 200$  GeV/ $c^2$  from an analysis of weak neutral current and  $W$  and  $Z$  mass data.<sup>7</sup> Direct searches for the top quark at LEP have resulted in a lower limit of  $\sim 45$  GeV/ $c^2$  on its mass.<sup>8</sup> The most stringent limits on the top mass come from the Fermilab and CERN proton-antiproton colliders, as will be discussed below.

Figure 1 shows the two mechanisms for producing top quarks at  $\bar{p}p$  colliders. The first process is  $\bar{p}p \rightarrow t\bar{t}$ , which has been calculated to order  $\alpha_s^3$  with a theoretical uncertainty of 30%.<sup>9, 10</sup> The second process is  $W \rightarrow t\bar{b}$  (if kinematically allowed) and is known much more precisely from the expected branching ratio and measured  $W \rightarrow e\nu$  rate. As seen in Figure 1, the hadronic pair production of top quarks dominates over the decay  $W \rightarrow t\bar{b}$  at the Fermilab Tevatron collider energy of 1.8 TeV. The opposite is true at the CERN collider energy of 0.63 TeV where the main source of top quarks is from  $W \rightarrow t\bar{b}$ .

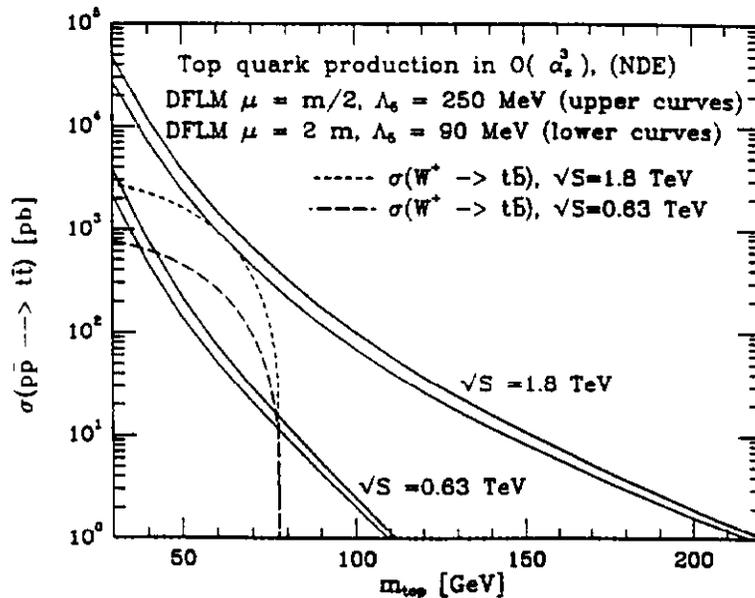


Figure 1: Cross section for top quark production at  $\bar{p}p$  colliders as a function of the top quark mass.

The Standard Model predicts that the top quark decays via the charged current interaction into a  $W$  boson and a  $b$  quark  $\sim 100\%$  of the time. The  $W$  boson,

which can be either real or virtual depending on the mass of the top quark, then decays into a quark pair ( $u\bar{d}$  or  $c\bar{s}$ ) or a lepton pair ( $e\nu$ ,  $\mu\nu$ , or  $\tau\nu$ ). The final state topology for a single top quark decay is then either three jets or a jet accompanied by a lepton plus a neutrino. For  $t\bar{t}$  pair production, the experimental signature is thus either six jets from the pure hadronic decay of both  $W$ s; four jets + lepton + neutrino from the hadronic decay of one  $W$  and the semileptonic decay of the other; or two jets + two leptons + two neutrinos from the double semileptonic decay of both  $W$ s. For  $W \rightarrow t\bar{b}$  production, there is either a four jet or a two jet + lepton + neutrino final state. Of course, not all of the produced jets are experimentally observable and at least one lepton is typically required in the final state in order to have some sensitivity to top quark production because of the large background from QCD multi-jet processes. Multi-lepton final states provide an even cleaner top signature but they suffer from low event rate.

### 2.1 Top Quark Search at UA1

The UA1 experiment first looked for evidence of top quark production and decay in the electron + jets channel (1983-1985 data).<sup>11</sup> Their most recent analysis<sup>12</sup> involved single muon + jets and dimuon data samples ( $4.7 \text{ pb}^{-1}$ ) in which they used a combination of cuts such as muon  $p_T$ ,  $\cancel{E}_T$ , and muon isolation to form a likelihood variable to discriminate a top signal from background. Figure 2 shows the top likelihood variable  $L_1$  for the single muon + jets sample.

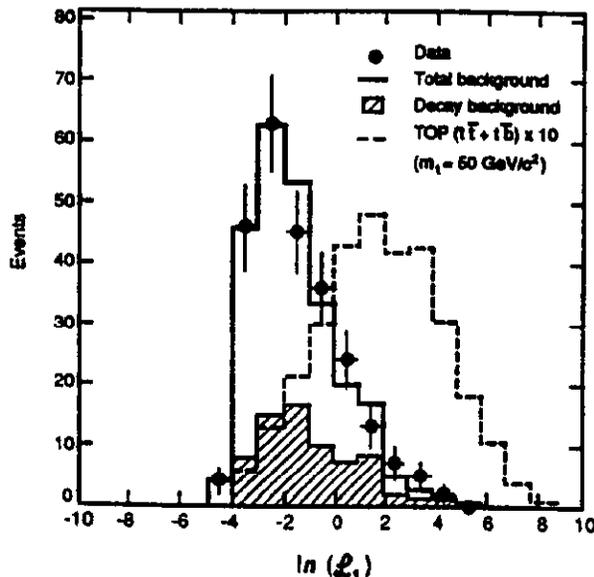


Figure 2: Distribution of the top quark likelihood variable in the UA1 single muon + jets sample.

The data points are consistent with the expected background. The distri-

bution expected from top events with  $M_{top} = 50 \text{ GeV}/c^2$  is shown and a search region was defined for  $\ln(L_1) > 4$ . Based on the number of events in the search region after background subtraction, an upper limit on the top quark production cross section was derived and this was translated into a limit on the top quark mass. For the single muon + jets sample,  $M_{top} > 52 \text{ GeV}/c^2$  at the 95% confidence level. A similar analysis was performed on the dimuon data sample with the result that  $M_{top} > 46 \text{ GeV}/c^2$  (95% C. L.). These results were combined with previous searches performed by the UA1 collaboration to reach their final result of  $M_{top} > 60 \text{ GeV}/c^2$  at the 95% confidence level.

## 2.2 Top Quark Search at UA2

The UA2 collaboration has recently searched for the existence of a top quark signal in their  $7.5 \text{ pb}^{-1}$  electron + jets data sample.<sup>13</sup> This was done by forming the transverse mass of the electron  $E_T$  and the  $\cancel{E}_T$  (corresponding to the neutrino from the  $W$  decay) in the event. Figure 3 shows the transverse mass distribution of the electron and neutrino compared to that expected from  $W$  boson decay and from a  $65 \text{ GeV}/c^2$  mass top quark.

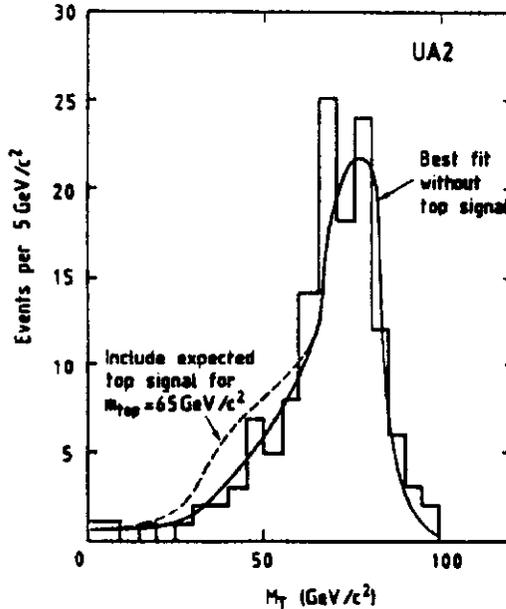


Figure 3: Transverse mass distribution of the electron +  $\cancel{E}_T$  in the UA2  $e + jets$  sample (histogram). The solid line is the expected distribution from  $W$  boson decays alone. The dashed line includes a contribution from top quark events for  $M_{top} = 65 \text{ GeV}/c^2$ .

The contribution from  $W$  boson decays appears to account for the data quite well. The transverse mass distribution was then fit to determine the exact contribution from  $W$  boson decay and from top quark decay for various top quark masses. An

upper limit on top quark production was extracted and this upper limit corresponds to a mass limit of  $M_{top} > 69 \text{ GeV}/c^2$  at the 95% confidence level.

### 2.3 Top Quark Search at CDF

The CDF collaboration has searched for the presence of the top quark through several decay modes in the  $4.4 \text{ pb}^{-1}$  data sample accumulated in 1988-89. The first analysis involved the electron + jets data sample and compared the transverse mass of the electron and neutrino to the expectations from  $W$  decay and top quark production.<sup>14</sup> This analysis, similar to the UA2 top search, found no significant top quark production and excluded a top quark with mass between 40 and 77  $\text{GeV}/c^2$  at the 95% confidence level. It is noted that this particular method is no longer useful when  $M_{top}$  approaches  $M_W$ , in which case the transverse mass distributions are very similar.

The next CDF top analysis required the presence of an electron and a muon with opposite electric charges in the final state and each with transverse momentum  $p_T > 15 \text{ GeV}/c$ .<sup>15</sup> This high transverse momentum requirement separates the  $t\bar{t}$  signal from  $b\bar{b}$  backgrounds which concentrate at low  $p_T$ . Figure 4 shows the 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.

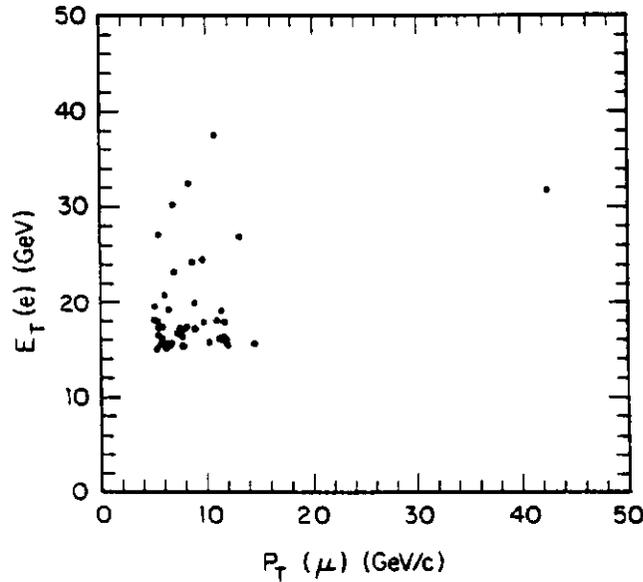


Figure 4: Electron transverse energy versus muon transverse momentum in the CDF electron + muon data sample ( $4.4 \text{ pb}^{-1}$ ).

There is one event in the top quark signal region. This event has an electron with  $E_T^e = 31.7 \text{ GeV}$  and a muon with  $p_T^\mu = 42.5 \text{ GeV}/c$ . The dilepton opening angle is  $137^\circ$ . There is also a second muon candidate in the event in the forward region, and a jet with  $E_T = 14 \text{ GeV}$ . Given this one candidate event, a 95% C. L. upper limit

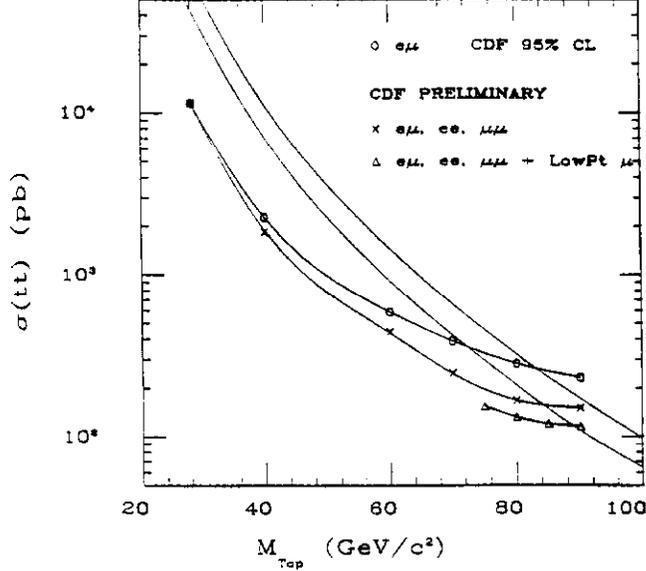


Figure 5: CDF 95% confidence level upper limit on the  $t\bar{t}$  production cross section as a function of top quark mass. Also shown are the upper and lower bounds from an  $O(\alpha_s^3)$  theoretical calculation.

on the number of  $t\bar{t} \rightarrow e\mu + X$  events expected was obtained and converted into an upper limit on the  $t\bar{t}$  production cross section. This result is shown in Figure 5 and is compared with the theoretical calculation of the  $t\bar{t}$  production cross section from Figure 1. The 95% C.L. upper limit cross section curve intersects the lower edge of the theoretical calculation band at  $M_{top} = 72 \text{ GeV}/c^2$  and this is the lower limit on the top quark mass from the  $e\mu$  channel analysis.

A straightforward extension of the  $e\mu$  analysis is to search for the top quark in the dielectron ( $ee$ ) and dimuon ( $\mu\mu$ ) channels. Dielectron and dimuon events were selected by requiring each lepton to have a  $p_T > 15 \text{ GeV}/c$ . In the  $ee$  and  $\mu\mu$  channels there are additional backgrounds, predominantly from  $Z$  decays but also from Drell-Yan,  $\Upsilon$ , and  $J/\psi$  production, which must be removed. A simple dilepton mass cut around the  $Z$  peak which rejects events if they fall in the region  $75 \text{ GeV}/c^2 < M_{l+l-} < 105 \text{ GeV}/c^2$  removes most of the background with little impact on the  $t\bar{t}$  signal. After the dilepton mass cut, the signal to background ratio is improved by requiring a missing transverse energy of  $\cancel{E}_T > 20 \text{ GeV}$  in the event. Additional events with back-to-back or collinear dileptons are also eliminated by requiring the dilepton azimuthal opening angle,  $\Delta\phi_{l+l-}$ , to be in the region  $20^\circ < \Delta\phi_{l+l-} < 180^\circ$ . After all of these 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  $\mu\mu$  events) are expected from  $t\bar{t}$  production for  $M_{top} = 80 \text{ GeV}/c^2$ . With only one  $e\mu$  event observed, the combined limit from the  $e\mu$ ,  $ee$ , and  $\mu\mu$  channels is  $M_{top} > 84 \text{ GeV}/c^2$  at the 95% confidence level. This result also holds for a fourth generation  $b'$  quark decaying via the charged current interaction.

Finally, the CDF experiment has looked for additional low  $p_T$  muons in the  $e + jets$  and  $\mu + jets$  samples. The low  $p_T$  muon in the event is used as a possible tag of the bottom quark in the decay chain  $t \rightarrow b \rightarrow \mu$ . Backgrounds to these soft muons from decay-in-flight of pions and kaons and hadronic punchthrough are reduced by rejecting events where the muon is within  $\Delta R = \sqrt{(\eta_{jet} - \eta_\mu)^2 + (\phi_{jet} - \phi_\mu)^2} < 0.6$  of either of the two leading jets. Figure 6 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  $M_{top} = 90 \text{ GeV}/c^2$   $t\bar{t}$  Monte Carlo. No candidate events were found. The result of the low  $p_T$  muon search combined with the previous dilepton result extends the CDF top quark mass limit to  $M_{top} > 89 \text{ GeV}/c^2$  at the 95% C. L.<sup>16</sup> (Figure 5).

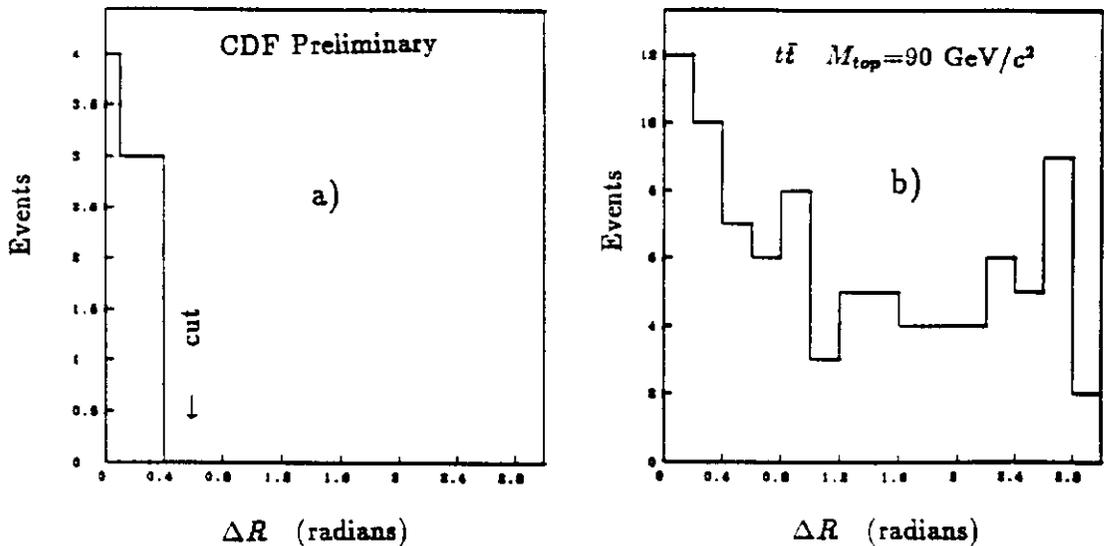


Figure 6: Distribution of  $\Delta R$ , the distance in  $\eta - \phi$  space between the low  $p_T$  muon and the nearest of the two leading jets. a) CDF data ( $4.4 \text{ pb}^{-1}$ ); b)  $M_{top} = 90 \text{ GeV}/c^2$   $t\bar{t}$  Monte Carlo ( $250 \text{ pb}^{-1}$ ).

### 3 Top Quark Decay into Charged Higgs at UA1

The UA1 experiment has recently searched for the presence of the top quark via the decay mode  $t \rightarrow H^+ b$ , which has a branching ratio of 100% for  $M_H + M_b < M_t < M_W + M_b$  in many two Higgs doublet models.<sup>17</sup> It is assumed that the ratio of the vacuum expectation values of the two Higgs doublets  $v_2/v_1 > 2$  so that the Higgs boson subsequently decays into a tau lepton and neutrino with a branching ratio of 93%. The signature for such an event is one or more muons + jets from the decay of the tau lepton and the  $b$  quark. UA1 uses both a single muon +  $\geq 2$  jets sample and a dimuon +  $\geq 1$  jet sample to search for  $t \rightarrow H^+ b$ . Similar to their previous top analysis, variables such as muon  $p_T$ ,  $\cancel{E}_T$ , and muon isolation are used to form a

likelihood variable to separate the top decay signal from background. Figure 7 shows the likelihood distribution for the single muon +  $\geq 2$  jets sample.

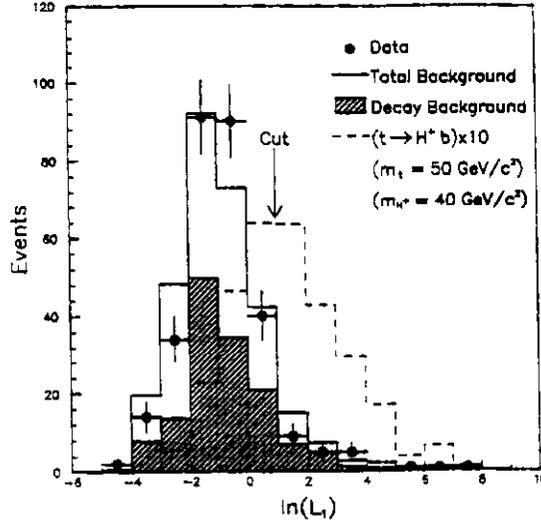


Figure 7: Likelihood distribution for single muon +  $\geq 2$  jets data from the UA1  $t \rightarrow H^+ b$  decay search.

A signal search region is defined for the  $\ln(L_1) > 1$ . It is found that the number of signal events is consistent with the expected background and no signal for the decay  $t \rightarrow H^+ b$  is present. The same is true for the dimuon +  $\geq 1$  jet sample and these results are combined to exclude allowed regions in the  $(m_t, m_{H^+})$  mass plane at the 90 and 95% confidence level limits (Figure 8).<sup>18</sup>

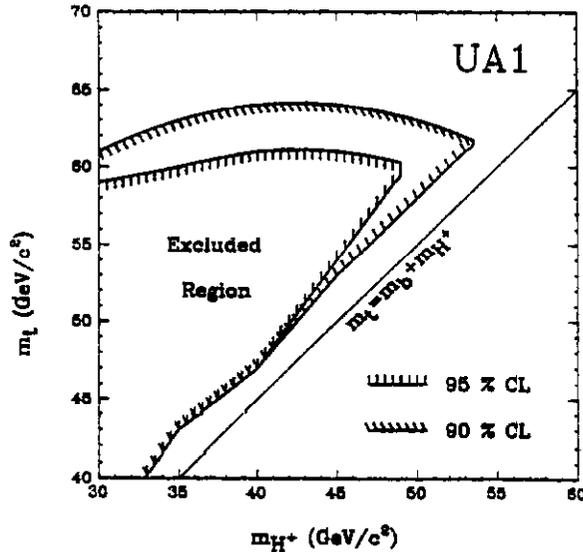


Figure 8: Excluded regions in the  $(m_t, m_{H^+})$  mass plane from the combined UA1 single muon and dimuon channel results.

## 4 Heavy Gauge Boson Search at CDF

In many extensions of the minimal Standard Model, additional charged and neutral vector bosons,  $W'$  and  $Z'$ , are expected to be observed. Experimentally, the presence of a heavy  $W'$  boson would appear ideally as a peak in the lepton-neutrino transverse mass distribution at high transverse mass values above the standard  $W$  boson peak. Similarly, a heavy  $Z'$  particle would be observed as a peak in dilepton invariant mass for masses above the standard  $Z$  boson mass peak.

The CDF experiment has searched for a  $W'$  production signal in a sample of events containing an electron with  $E_T > 30$  GeV and with missing transverse energy  $\cancel{E}_T > 30$  GeV. The  $e-\cancel{E}_T$  transverse mass distribution is shown in Figure 9, along with the expectations from  $W$  boson production.

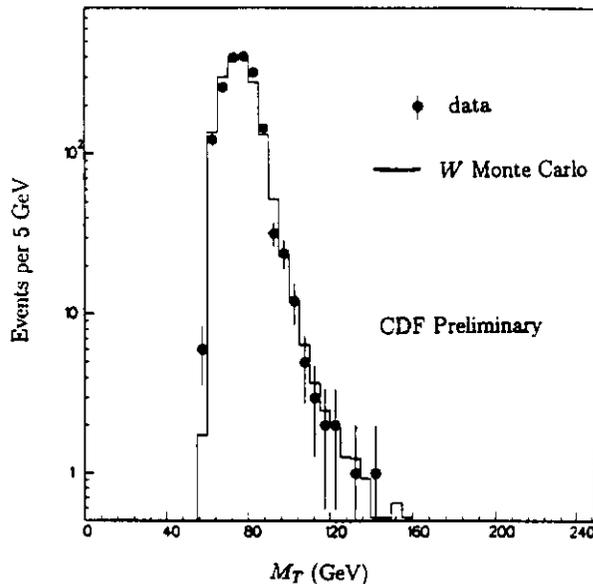


Figure 9: Comparison of the electron- $\cancel{E}_T$  transverse mass distribution for the CDF data and  $W \rightarrow e\nu$  Monte Carlo.

The data are well explained by  $W \rightarrow e\nu$  production alone and the absence of events at high transverse mass allows CDF to set limits on the production cross section times branching ratio for  $W' \rightarrow e\nu$ . Assuming Standard Model couplings and branching ratios, the resulting lower limit on the  $W'$  mass is  $M_{W'} > 478 \text{ GeV}/c^2$  at the 95% confidence level.<sup>19</sup>

A similar search was performed in the CDF dielectron data sample for the production and decay of a heavy  $Z'$  boson. Figure 10 shows that the data are consistent with  $Z$  boson and Drell-Yan production and decay into electron pairs. No events with dielectron mass above 200  $\text{GeV}/c^2$  were observed and a 95% C. L. lower limit on a  $Z'$  mass of  $M_{Z'} > 380 \text{ GeV}/c^2$  was obtained for Standard Model couplings and branching ratios.<sup>19</sup>

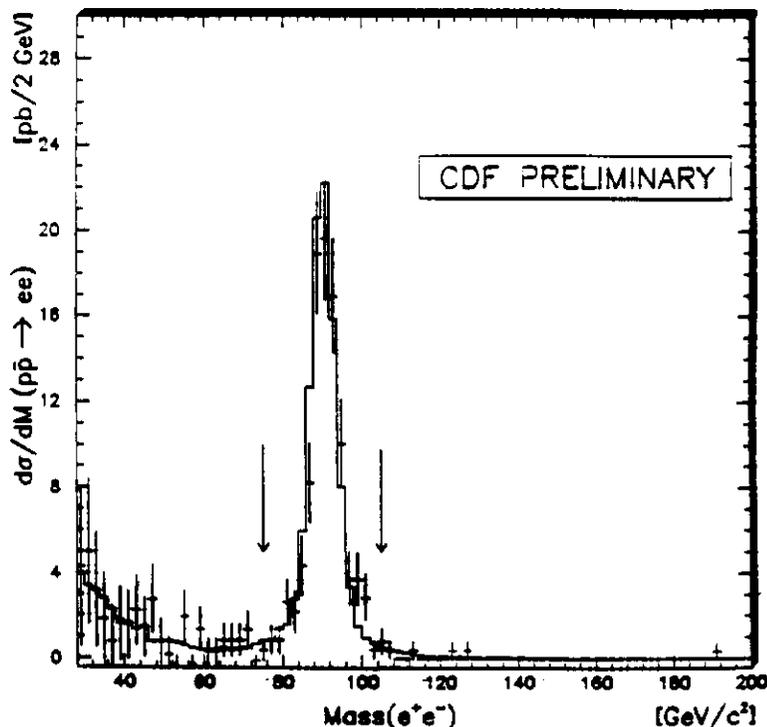


Figure 10: Comparison of the dielectron invariant mass spectrum for CDF data and combined  $Z^0, \gamma^* \rightarrow e^+e^-$  Monte Carlo.

## 5 Supersymmetric Particle Searches

Supersymmetry<sup>20</sup> (SUSY) is a proposed theory which eliminates quadratically divergent mass corrections to the fundamental scalar particles in the Standard Model. This is done by introducing additional fermions and bosons into the theory so that the quadratic divergences cancel. For each known fermion (boson) there is associated a supersymmetric boson (fermion) partner. For example, the quark, gluon, and photon have supersymmetric partners known as the squark ( $\tilde{q}$ ), gluino ( $\tilde{g}$ ), and photino ( $\tilde{\gamma}$ ). The masses of the supersymmetric partners are not predicted by the theory. In the minimal SUSY model, it is assumed that all six squarks have the same mass and that the photino is the lightest supersymmetric particle (LSP). Rigorous conservation of SUSY quantum number is assumed and this implies that the LSP is a stable particle and that supersymmetric particles are always produced in pairs. In  $\bar{p}p$  collisions, the dominant source of SUSY particles is the production of  $\tilde{q}\tilde{q}^*$ ,  $\tilde{q}\tilde{g}$ , and  $\tilde{g}\tilde{g}$  pairs. The gluino decay mode  $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$  and the squark decay modes  $\tilde{q} \rightarrow q\tilde{g}$  (for  $M_{\tilde{q}} > M_{\tilde{g}}$ ) and  $\tilde{q} \rightarrow q\tilde{\gamma}$  (for  $M_{\tilde{q}} < M_{\tilde{g}}$ ) are assumed to dominate. The final state particles then consist of normal quarks and gluons, and photinos. Since the photinos are assumed to be only weakly interacting and escape undetected, SUSY events will contain jets plus missing transverse momentum. For example, the experimental signature for  $\bar{p}p \rightarrow \tilde{q}\tilde{q}^* + X$  is  $\cancel{E}_T + 6$  jets for  $M_{\tilde{q}} > M_{\tilde{g}}$  and  $\cancel{E}_T + 2$  jets for  $M_{\tilde{q}} < M_{\tilde{g}}$ .

### 5.1 Squark and Gluino Search at CDF

The CDF experiment has searched for squarks and gluinos under the assumptions of the minimal supersymmetric model described above. The SUSY data sample consisted of events with  $\cancel{E}_T > 40$  GeV and at least two jets with  $E_T^{jet} > 15$  GeV. Events containing cleanly identified electrons and muons were removed from the sample. The resulting 98 events in this sample are consistent with background expectations of  $86 \pm 14 \pm 12$  events from  $W \rightarrow \tau\nu, \mu\nu, e\nu + jets$  and  $Z \rightarrow \nu\nu + jets$  and  $4 \pm 4$  events from QCD processes. Further cuts were then applied to enhance any SUSY signal over the background. Two mass regions were considered separately. For the case of  $M_{\tilde{q}} < M_{\tilde{g}}$ , the missing  $E_T$  cut was raised to  $\cancel{E}_T > 100$  GeV. Three events passed this cut with an expected background of  $1.3 \pm 1.3$  events. A SUSY signal for  $(M_{\tilde{q}}, M_{\tilde{g}}) = (150, 400)$  GeV/ $c^2$  would give 4.9 events. For  $M_{\tilde{q}} > M_{\tilde{g}}$ , four or more jets with  $E_T^{jet} > 15$  GeV were required in the event selection. There were two events which passed these cuts with an estimated background of  $1.3 \pm 1.3$  events. A SUSY signal for  $(M_{\tilde{q}}, M_{\tilde{g}}) = (500, 150)$  GeV/ $c^2$  would give 5.6 events.

Figure 11 shows the region excluded at the 90% confidence level by the CDF experiment based on the non-observation of a SUSY signal. The discontinuity along the line  $M_{\tilde{q}} = M_{\tilde{g}}$  is due to the different acceptances of the two cases considered. The asymptotic 90% C. L. mass limits are  $M_{\tilde{g}} > 150$  GeV/ $c^2$  (independent of  $M_{\tilde{q}}$ ) and  $M_{\tilde{q}} > 150$  GeV/ $c^2$  (for  $M_{\tilde{g}} < 400$  GeV/ $c^2$ ).<sup>19</sup>

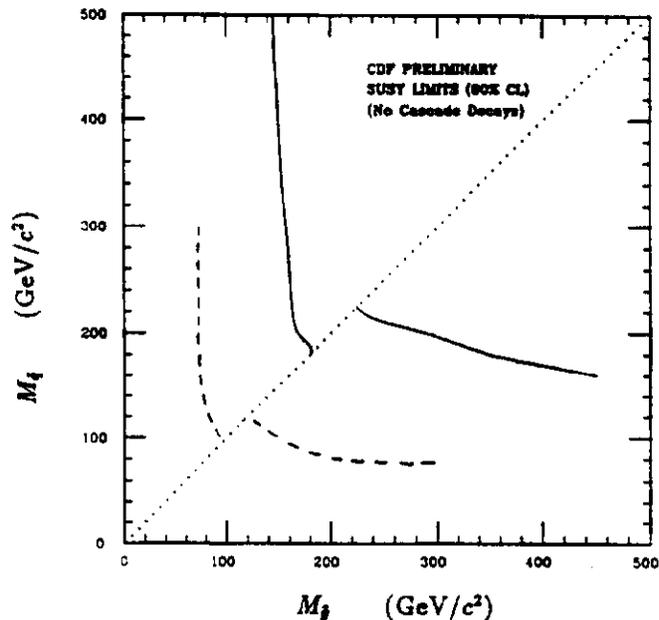


Figure 11: The region in the gluino-squark mass plane excluded by the CDF experiment at the 90% confidence level. The solid line is a preliminary result based on the 1988-1989 data. The dashed line is the result from the previous 1987 data.

It has been mentioned that if squarks and gluinos are heavy enough, they would first decay into other heavy supersymmetric particles (charginos and neutralinos) which would themselves decay into the lightest supersymmetric particle.<sup>21</sup> The effect of such cascade decays would be to reduce the missing  $E_T$  sensitivity of the SUSY signal and it is estimated that the squark and gluino mass limits given above would be reduced by  $\sim 30 \text{ GeV}/c^2$ .

## 5.2 Selectron and Wino Search at UA2

The UA2 experiment has searched for electron pairs produced in association with  $\cancel{E}_T$  as a possible signature for the production of selectron or wino pairs (the supersymmetric partners of the electron and  $W$  boson) through the decays  $Z \rightarrow \tilde{e}\tilde{e} \rightarrow ee\tilde{\gamma}\tilde{\gamma}$  or  $Z \rightarrow \tilde{W}\tilde{W} \rightarrow ee\tilde{\nu}\tilde{\nu}$ .<sup>22</sup> The variables used to separate the SUSY signal from background were the dielectron mass, the  $\cancel{p}_T$ , and the dielectron  $p_T$  projected along the pair bisector. The number of events after cuts was found to be consistent with the expected background and there was no evidence of a SUSY signal in the data. Using this result and a Monte Carlo estimation of the expected signal, regions in the  $(M_{\tilde{e}}, M_{\tilde{\gamma}})$  and the  $(M_{\tilde{W}}, M_{\tilde{\nu}})$  mass planes were excluded at the 90% confidence level. This is shown in Figure 12 along with the asymptotic result that  $M_{\tilde{e}} > 40 \text{ GeV}/c^2$  and  $M_{\tilde{W}} > 45 \text{ GeV}/c^2$  at the 90% confidence level.

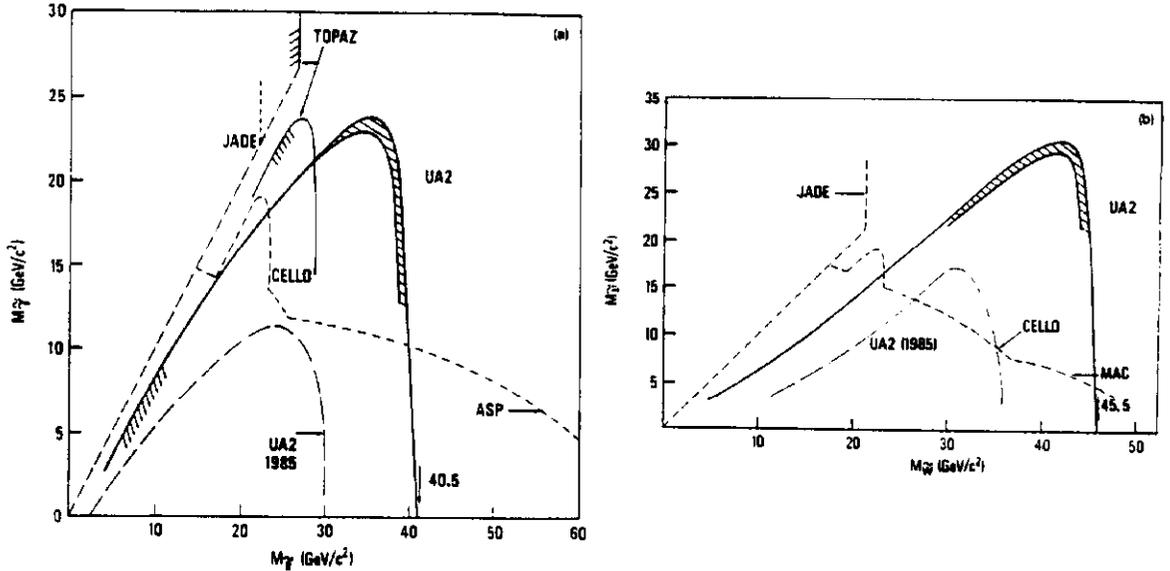


Figure 12: Excluded regions from the UA2 experiment at the 90% confidence level in (a) the  $(M_{\tilde{e}}, M_{\tilde{\gamma}})$ , and (b) the  $(M_{\tilde{W}}, M_{\tilde{\nu}})$  plane.

## 6 Conclusions

Experiments at  $\bar{p}p$  colliders have searched for the top quark, the Higgs boson, additional heavy gauge bosons and supersymmetric particles over a broad mass range. Unfortunately, the result of these searches have yielded no new particles. Prospects for the future are very good for either finding the top quark or setting a limit inconsistent with expectations of the Standard Model. The CDF experiment anticipates collecting at least  $25 \text{ pb}^{-1}$  in the next collider run at Fermilab. The data from this run should allow CDF to search for the top quark in the mass region of  $120\text{-}150 \text{ GeV}/c^2$ . Upgrades to the CDF detector such as improved muon coverage and the addition of a silicon vertex detector should begin a long and thorough program of  $B$  physics. As shown in Figure 13 this program has already started with the reconstruction of a  $B$  meson mass peak for the decays  $B^\pm \rightarrow J/\psi K^\pm$  and  $B^0 \rightarrow J/\psi K^{*0}$  in the current CDF data. Perhaps, in the near future, there will be new particles to report on!

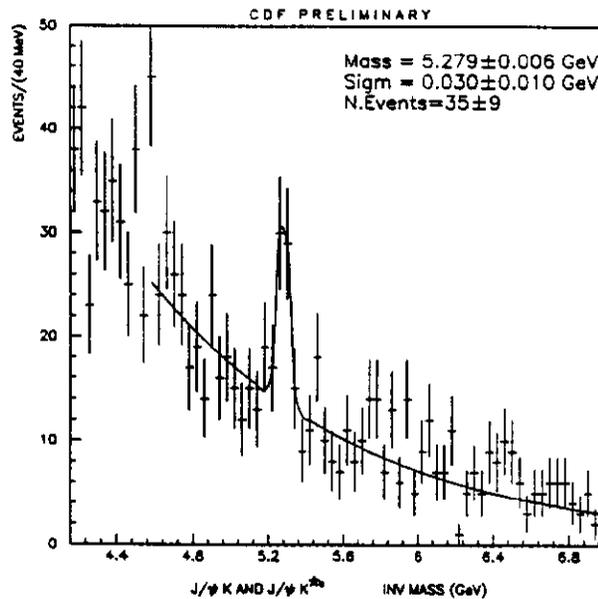


Figure 13: Reconstructed  $B$  meson mass peak from the decays  $B^\pm \rightarrow J/\psi K^\pm$  and  $B^0 \rightarrow J/\psi K^{*0}$  by the CDF experiment.

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