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## Recent CDF Results

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## Recent CDF Results

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Preliminary results from the CDF detector, based on analysis of data collected in Run Ia and Run Ib at the Tevatron, totalling  $110 \text{ pb}^{-1}$  integrated luminosity, place new limits on the masses and couplings of new particles including charged Higgs bosons, supersymmetric gauge particles and quarks, and new vector bosons. One of the observed events, having an  $e^+e^-$  pair, two photons, and large missing energy would not occur with significant rate in the Standard Model, leading to speculation regarding its origin and the possible existence of related events.

### 1. CDF in Run I

The CDF detector [1], comprising a charged particle tracking system in a 1.4-T magnetic field, electromagnetic and hadronic calorimeters, and muon chambers, collected data from  $\bar{p}-p$  annihilation in the years 1992-1995. The total accumulated integrated luminosity exceeded  $110 \text{ pb}^{-1}$  in this period, divided into Run Ia ( $20 \text{ pb}^{-1}$ ) and Run 1B ( $90 \text{ pb}^{-1}$ ).

This large sample of data provides a rich hunting ground for new phenomena, and led to the discovery of the top quark [2] in 1995. The most recent determination of the  $t\bar{t}$  production cross section and top quark mass appears in Fig. 1. The combined mass,  $176 \pm 9 \text{ GeV}/c^2$ , and cross section,  $7.5_{-1.6}^{+1.9} \text{ pb}$ , lie slightly higher than the predicted values shown on the plot [3].

Among the many new phenomena sought in CDF, this paper presents the preliminary results of searches for new vector bosons, charged Higgs bosons, and supersymmetric particles.

### 2. New Vector Bosons

The excellent lepton<sup>2</sup> triggering and identification efficiency in CDF allow measurement of invariant mass spectra such as those appearing in Fig. 2. The figure shows clearly the narrow peak

from the well-known Z resonance. From the absence of such peaks at higher masses one can infer that there exist no additional resonances arising from higher-mass Z-type bosons (denoted Z').

This inference depends on the assumptions regarding the coupling of the Z' to leptons. Fig. 3 shows the 95% CL limit for the product of the Z' production cross section and branching ratio to lepton pairs as a function of the mass of the Z', compared with a prediction assuming that its coupling to leptons and quarks is the same as that of the Z. As the plot depicts, one can infer that the mass of such a Z' does not exceed  $690 \text{ GeV}/c^2$ , combining the electron and muon data. Other assumptions regarding the couplings of the Z' to leptons, such as those from E6 models or supersymmetry, typically result in smaller values for the limit, ranging from  $555 \text{ GeV}/c^2$  to  $620 \text{ GeV}/c^2$ .

### 3. Charged Higgs from Top Decay

Many extensions to the Standard Model, and supersymmetry in particular, require the existence of two Higgs doublets. In the case most often considered, one Higgs couples to up-type quarks, whilst the other couples to down-type quarks and leptons [4]. In this scenario there arises a charged Higgs, denoted  $H^\pm$ , which can modify the decay behavior of the top quark.

Ordinarily, the top decays via a W to a b quark, but if the charged Higgs exists, has mass less than

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<sup>2</sup>In this context and elsewhere, the term "lepton" refers to electrons and muons, whose distinct signatures in the detector allow for easy identification.

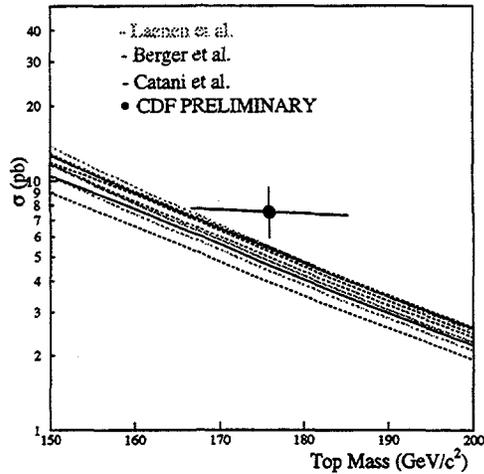


Figure 1. Measurement of the  $t\bar{t}$  production cross section and top quark mass (data point) compared with theoretical predictions.

that of the top quark, and couples strongly to the top quark, then the decay  $t \rightarrow H^+ b$  can compete and even dominate. Fig. 4 shows the branching ratio of  $t \rightarrow H^+ b$  as a function of  $\tan \beta$ , the ratio of the vacuum expectation values of the two Higgs doublets. This branching ratio also depends, to a lesser extent, on the masses of the top quark and charged Higgs. In the region of large  $\tan \beta$  this process dominates, and the charged Higgs in turn decays dominantly to  $\tau\nu_\tau$ .

The experimental signature for this process, therefore, differs from that of ordinary top decay in that one would observe an excess of final states with two taus and two  $b$  quarks and large missing transverse energy<sup>3</sup> To distinguish the taus from leptons (electrons and muons, that is) one exploits the roughly 65% branching ratio of the tau to hadronic final states.

Hadronic decays of the tau differ from hadronic jets from quarks and gluons in that they have

<sup>3</sup>The transverse energy is the magnitude of the two-dimensional vector sum of the final state energies projected onto the plane transverse to the beam direction.

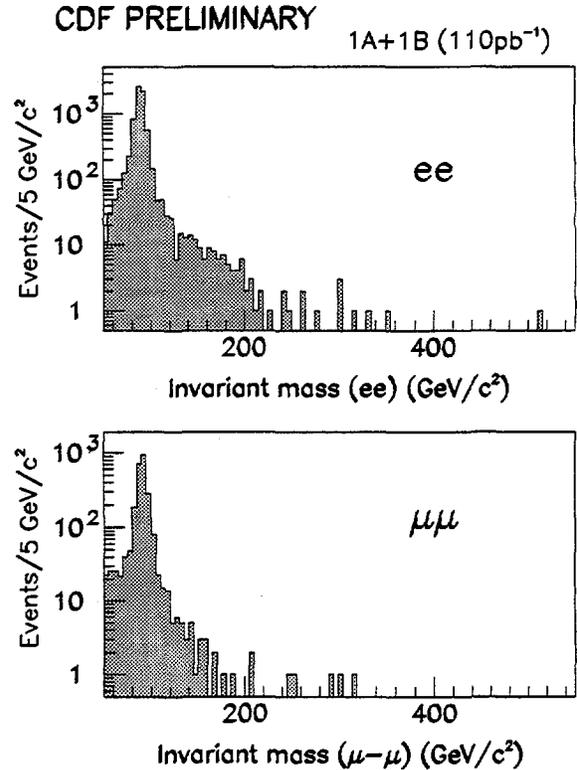


Figure 2. Invariant mass spectra for electron and muon pairs.

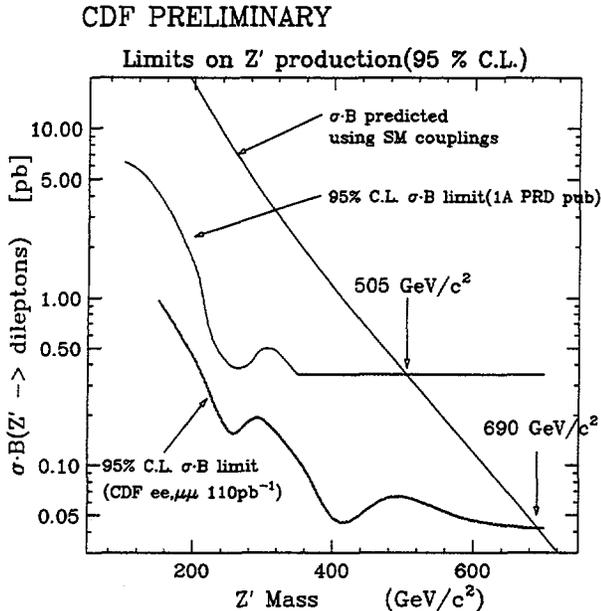


Figure 3. The 95% CL limit on new  $Z$  bosons.

a narrow, isolated energy deposit with one or three charged particles, and a total invariant mass of less than that of the tau mass,  $1.8 \text{ GeV}/c^2$ . Nevertheless the background from hadronic jets is large, and a signal-to-noise ratio of greater than unity in events with many jets is difficult to achieve; indeed this signal purity depends strongly on the final state sought.

To set a limit on this process, one selects from the Run Ib data those events which triggered due to missing energy in excess of  $35 \text{ GeV}$ , and had at least one hadronically decaying tau, one  $b$  quark jet (identified with the same algorithm as the standard top quark search), one other jet, and a fourth object which could be an electron, muon, another hadronically decaying tau, or another hadronic jet. Eight events satisfy all the search criteria, and 10.5 events are expected from background processes, dominantly those in which an ordinary hadronic jet "fakes" the tau signature. Of the 10.5 events, 2.0 are expected from  $\bar{t}t$  production, with  $t \rightarrow Wb$ . These events, however, are part of the signal for the purposes of setting

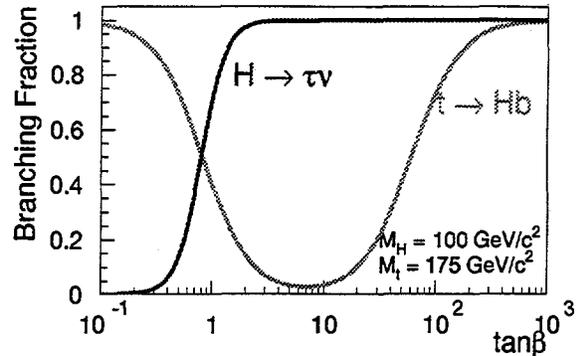


Figure 4. The branching ratios of  $t \rightarrow Hb$  and  $H \rightarrow \tau\nu$  as a function of  $\tan\beta$ , for a top mass of  $175 \text{ GeV}/c^2$  and a charged Higgs mass of  $100 \text{ GeV}/c^2$ .

a limit.

Given 8 observed events and  $8.5 \pm 1.6$  expected from background, and given a 30% systematic error on the overall acceptance, one can exclude with 95% confidence any contribution from the charged Higgs mode which would lead to more than 9.8 events. This allows the exclusion of the region shown in Fig. 5, at large  $\tan\beta$  and large charged Higgs mass.

#### 4. Chargino/Neutralino Pairs Production

The minimal supersymmetric extension to the standard model [5] predicts the existence of spin- $\frac{1}{2}$  partners of the neutral and charged gauge bosons called charginos (denoted  $\tilde{\chi}^\pm$ ) and neutralinos (denoted  $\tilde{\chi}^0$ ). In this model there exist two chargino mass states,  $\tilde{\chi}_{1,2}^\pm$  which are admixtures of the charged Higgs and  $W^\pm$  bosons, and four neutralino mass states,  $\tilde{\chi}_{1,2,3,4}^0$ , the partners of the photon,  $Z$  and neutral Higgses. The production and decay of charginos and neutralinos depends on parameters and assumptions in the model. In most searches for supersymmetric particles one assumes that they are pair-produced to conserve R-parity, and that the lightest supersymmetric particle (LSP) is neutral and (due

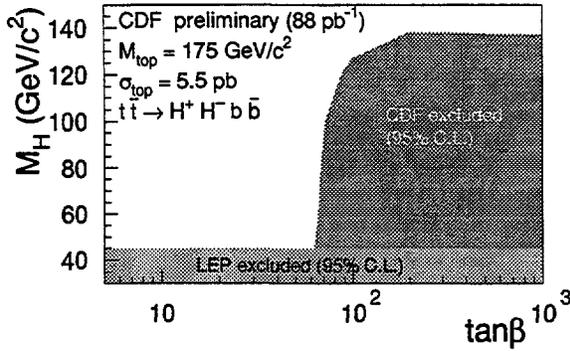


Figure 5. Excluded region in the plane of charged higgs mass and  $\tan\beta$ .

to R-parity conservation) stable. Further assuming unification along the lines of supergravity (SUGRA) [6] results in a great simplification of the many parameters of the general MSSM, providing relationships among the masses and couplings in the model.

In CDF,  $\bar{p}p$  collisions can produce chargino-neutralino pairs via an intermediate s-channel virtual W or via a t-channel sneutrino (the partner of the neutrino) exchange. These processes interfere destructively, and the overall production rate depends on the masses and couplings. Assuming SUGRA constraints, the chargino can decay to the final state  $\ell^\pm \tilde{\chi}^0 \nu$ , and the neutralino can decay to  $\ell^+ \ell^- \tilde{\chi}^0$ , giving rise to very distinct events having three leptons and missing transverse energy.

A search for such events results in no candidates, and 0.3 are expected from background processes such as Drell-Yan (plus a fake lepton),  $b\bar{b}$  and  $c\bar{c}$ , and diboson events. Thus a 95% CL limit on the product of the production cross section and branching ratio to the trilepton final state can be inferred. Fig. 6 shows this limit as a function of chargino mass, compared with the expected value for several model assumptions. One can thus rule out a chargino with mass less than 58 to 66  $\text{GeV}/c^2$ , depending on the value of  $\tan\beta$ , the ratio of the squark and gluino masses, and

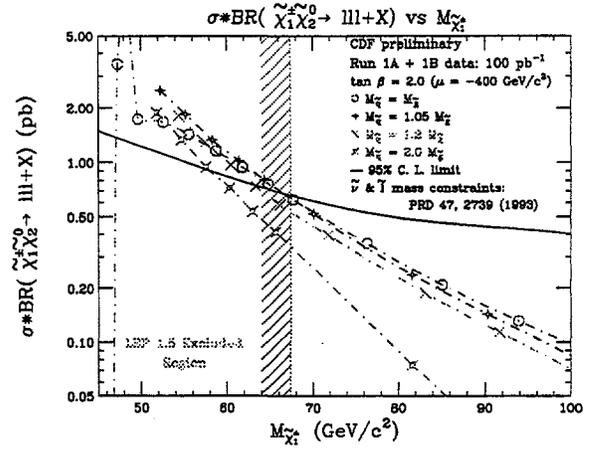


Figure 6. Limit in  $\sigma\mathcal{B}(\ell\ell)$  versus chargino mass for various models, compared with the LEP limit.

the parameter  $\mu$ . For comparison the limit from LEP [7] is shown, assuming a sneutrino mass of 100  $\text{GeV}/c^2$ ; they exclude a chargino with mass less than 68  $\text{GeV}/c^2$ . This limit reduces to near 60  $\text{GeV}/c^2$  for smaller sneutrino masses.

Fig. 7 shows the limit in the plane of chargino mass and  $\mu$ . The plot illustrates that the limit degrades for larger values of  $\mu$ .

## 5. Squark/Gluino Pair Production

The classic method for seeking evidence of supersymmetry at hadron colliders is the pair production of squarks and gluinos, the partners of quarks and gluons. In a wide range of parameter space these particles decay ultimately to jets and neutralinos. Since the lightest neutralino interacts only weakly, one would observe events with missing energy and jets in the final state.

A search for events with 3 or 4 or more jets plus large missing energy yields 18 and 6 events respectively. The presence of these events is accounted for by a combination of various backgrounds. The missing transverse energy distribution of these events appears in Fig. 8. The contribution from squark/gluino production would have been observed as a higher rate. Thus limits in the plane

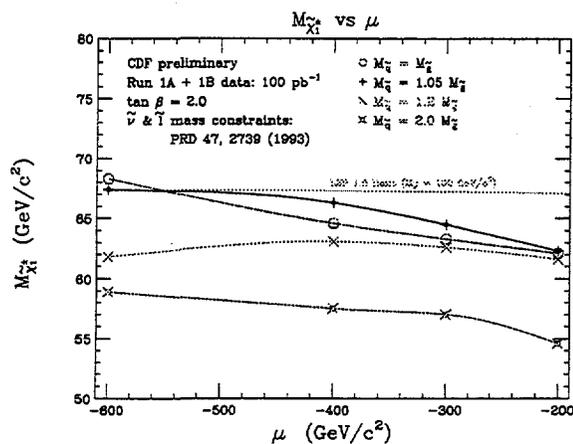


Figure 7. Limit in plane of chargino mass versus  $\mu$ .

of gluino mass and  $\mu$  obtain, as shown in Fig. 9. The mass of the gluino must exceed roughly  $165 \text{ GeV}/c^2$  if it decays to neutralinos.

The limit can be expressed in the plane of squark mass and gluino mass, as shown by the dashed line in Fig. 10. The limit in the upper left half region of the plot can be extended by searching in addition for events with lepton pairs with like charge, which would arise from "cascade" decays of the gluinos to quark pairs via charginos. Since there is no charge correlation between the charginos in the event, like-sign lepton pairs can result. This results in the shaded excluded region on the plot, increasing the gluino mass limit to around  $180 \text{ GeV}/c^2$ .

## 6. The $e\bar{e}\gamma\gamma$ Event

Fig. 11 shows a display of the energy deposited in the calorimeter for a single event in Run Ib at CDF. This event has four large, purely electromagnetic deposits of energy coming from an  $e^+$ , and  $e^-$ , and two photons. There are no other jets in the event, and the transverse energy imbalance is in excess of  $50 \text{ GeV}$ . The figure indicates the transverse energies, azimuth, and pseudorapidity of the electrons and photons.

Such an event eludes explanation in the context

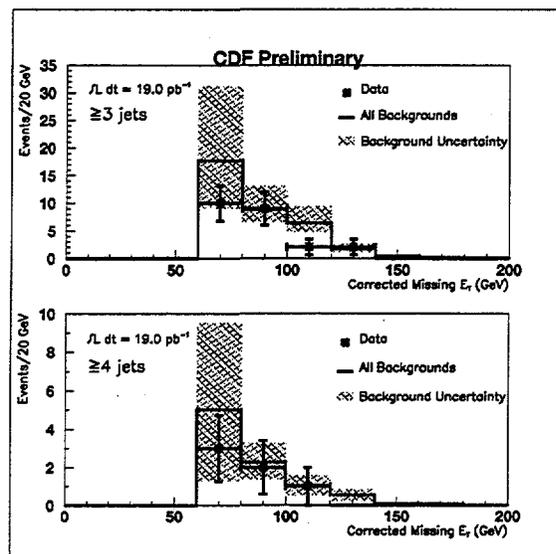


Figure 8. Transverse energy distribution of events with 3 or more jets (top plot) and 4 or more jets (bottom plot), compared with prediction from background.

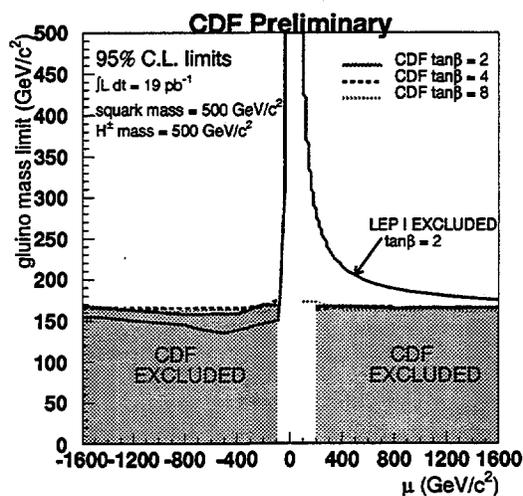


Figure 9. Excluded region in plane of gluino mass versus  $\mu$  mass from  $E_T$  search (solid area).

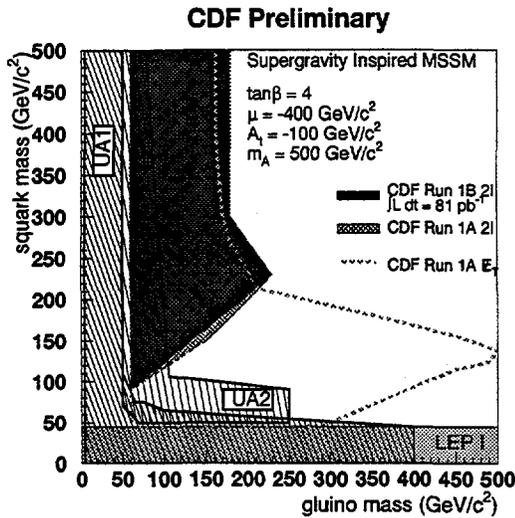


Figure 10. Excluded region in plane of squark mass versus gluino mass from  $E_T$  search (dashed curve) and like-sign dilepton search (solid area).

of the Standard Model. The only remote possibility,  $WW\gamma\gamma$  production, would contribute fewer than 0.001 expected events at most. Of course, such events can and do occur in the experiment, and one must take into consideration the fact that CDF has recorded nearly  $10^8$  events in total.

Nevertheless the event remains one of the most striking and unusual recorded, and has natural explanations in the MSSM in terms of selectron-pair production. [8]. In these scenarios, the selectron would decay to a neutralino which is not the LSP, and it in turn would decay to the LSP, either a lighter neutralino or a very light gravitino.

If such a scenario is correct, one expects other types of events to be produced with similar frequency, such as the charged-current final state  $e\bar{\nu}$ . The collaboration continues to search actively for events with photons, missing transverse energy, and leptons.

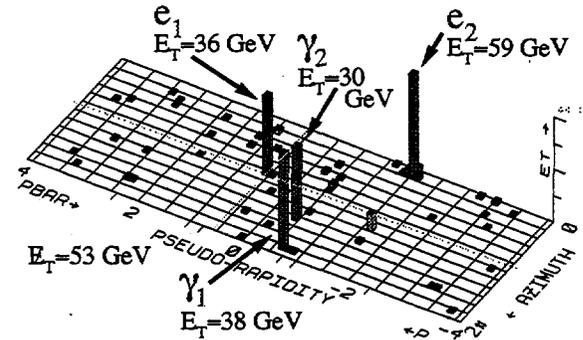


Figure 11. An event with an  $e^+$ , and  $e^-$ , two photons, and large missing  $E_T$ .

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