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New Particle Searches at CDF

Kaori Maeshima
For the CDF Collaboration
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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NEW PARTICLE SEARCHES AT CDF

KAORI MAESHIMA

Fermilab, PO BOX 500, Batavia, IL 60510, USA

For the CDF Collaboration

We present recent results of searches for new particles beyond the Standard Model at the Collider Detector at Fermilab (CDF). These include searches for supersymmetric (SUSY) particles, charged Higgs, heavy gauge bosons (Z' and W'), and stable massive charged particles.

1 Introduction

The Tevatron, a $p\bar{p}$ collider with the currently highest center of mass energy in the world($\sqrt{s}$ =1.8TeV), is in a unique position to explore new phenomena beyond the Standard Model (SM). The broad-band nature of the production process via Drell-Yan or gluons is an advantage for searches.

The CDF experiment is actively searching for new phenomena and sets many of the best limits in direct searches available to date. In this paper we describe some of our ongoing searches for new phenomena. These include searches for supersymmetric (SUSY) particles, charged Higgs, heavy gauge bosons (Z' and W'), and stable massive charged particles. For leptoquark searches at CDF see reference [1].

The datasets were collected during three running periods 88-89, 92-93 (Run 1a), and 94-95 (Run 1b) yielding approximately 4, 20 and 90 pb^{-1} respectively. All limits quoted in this paper are at 95% confidence level.

2 Susy

Supersymmetric (SUSY) models add a new symmetry to the Standard Model (SM) wherein each fermion has a supersymmetric bosonic partner and vice versa. It contains many theoretical desirable features [2]. However the price is a large expansion in the number of free parameters in the model. A series of assumptions reduces the number of free parameter to a manageable number. We use the minimal supersymmetric extension to the Standard Model (MSSM) containing two Higgs doublets.[3] After electroweak symmetry breaking, there are five Higgs bosons—h, H, A, and $H^{\pm}$. Assuming absolute conservation of R-parity implies that all SUSY particles must be produced in pairs and that the lightest SUSY particle (LSP) is absolutely stable. The LSP is usually assumed to be the lightest neutral SUSY particle. Finally, we demand that the theory be consistent with grand unification and super gravity (SUGRA) constraints.[4,5] This leaves only five free parameters in the model—m_0, $m_{1/2}$, A_t, $\tan\beta$, and sgn(μ) where m_0 is the common boson mass, $m_{1/2}$ is the common fermion mass, A_t is the trilinear coupling term, $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets, and μ is the Higgs mass parameter. Instead of m_0 and $m_{1/2}$, we use $M_{\tilde{q}}$ and $M_{\tilde{g}}$ where $M_{\tilde{q}}$ is the common mass of squarks (except the third generation) and $M_{\tilde{g}}$ is the common mass of the gluinos. In this case, both the sign and value of μ are important.

Following four subsections summarize various SUSY particle searches based on experimental signatures; Multiple Jet Plus Missing E_T, dilepton, trilepton, and photonic SUSY signatures[6].

2.1 Multiple Jet Plus Missing E_T Search

Because of R-parity conservation all SUSY decay chains must contain at least two of the lightest supersymmetric particles. These LSPs are neutral and weakly-interacting; thus, they will not be directly detected by the CDF detector and will show up as missing transverse momentum ($\not\!E_T$). Conceptually, the simplest search is to look for an excess of events with a large missing transverse momentum. This *inclusive* measurement will have a large production cross-section (compared to any individual channel) but will also have a large background from Standard Model processes and from detector mismeasurement of $\not\!E_T$.

In particular, this search looks for squark and gluino production from $p\bar{p}$ collision at the Teva-

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tron using 19 pb^{-1} of data. The collisions produce

$$p\bar{p} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$$

where for $M_{\tilde{q}} > M_{\tilde{g}}$,

$$\tilde{q} \rightarrow q\tilde{g} \text{ and } \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$$

and for $M_{\tilde{q}} < M_{\tilde{g}}$,

$$\tilde{g} \rightarrow \bar{q}\tilde{q} \text{ and } \tilde{q} \rightarrow q\tilde{\chi}_1^0$$

where $\tilde{\chi}_1^0$ is the LSP. If any of the charginos is lighter than the squarks or gluinos then there are cascade decays which tend to produce more jets and less $\not{E}_T$ making this search less sensitive. However, the dilepton search described later specifically addresses these cascade decays.

The analysis identifies events with large $\not{E}_T$ ($\not{E}_T > 60$ GeV) and 3 or more jets with $E_T > 15$ GeV. A series of "topology" and "clean-up" cuts are applied to reduce the background events. After all cuts, 23 events remain in the 3 or more jets sample and 6 events remain in the 4 or more jets sample, while we expect 35^{+11}_{-9} (*stat*) $^{+17}_{-9}$ (*sys*) ($9^{+4}_{-3} \pm 3$) background events in the 3 or more (4 or more) jets sample. In the 3 or more jets sample, the largest background contributions are expected from $W \rightarrow \tau\nu + \text{jet(s)}$ production where the tau has decayed hadronically and from multijet QCD events in which one or more of the jets is mismeasured producing a large, spurious $\not{E}_T$. For the 4 or more jet sample, the primary components are $t\bar{t}$ production and multijet QCD events. In both samples the number of observed events is consistent with the background estimation.

Signal events were simulated using Isajet 7.06 at leading-order. A simple Monte Carlo was used to determine the number of expected signal events necessary to exclude a model at the 95% C.L. The excluded region in the $M_{\tilde{q}}$ vs. $M_{\tilde{g}}$ plane is shown in Fig. 1. Below the diagonal the 3 or more jet analysis is more sensitive; above and on the diagonal the 4 or more jet analysis is more sensitive. Note that below the diagonal, the SUGRA constraints are non-physical. In this region, the slepton masses have been set to 350 GeV/c^2. This analysis excludes $M_{\tilde{g}} < 169$ GeV/c^2 independent of $M_{\tilde{q}}$ and $M_{\tilde{q},\tilde{g}} < 213$ GeV/c^2 for $M_{\tilde{q}} = M_{\tilde{g}}$. The gluino mass limit is rather insensitive to both μ and $\tan\beta$.

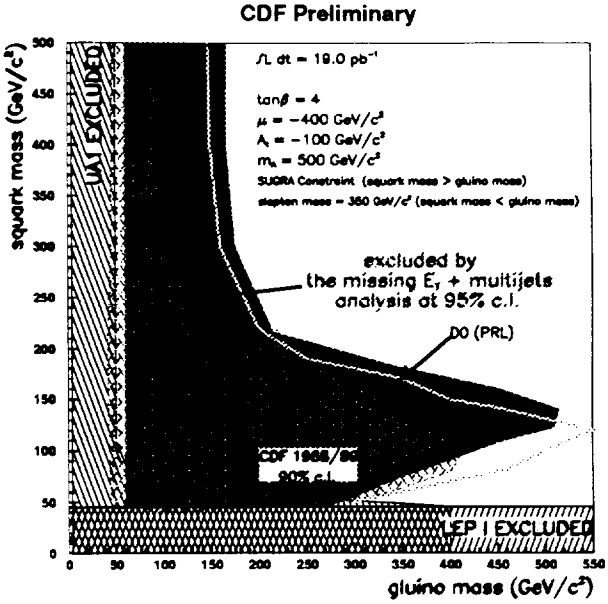

Figure 1: Excluded region from multiple jet plus $\not{E}_T$ analysis in $M_{\tilde{q}}$ and *mgluino* plane.

2.2 *Dilepton Search*

While the $\not{E}_T$ search benefits from large production cross-sections, it suffers from large backgrounds. To avoid backgrounds, we additionally search for leptonic SUSY channels with little background from Standard Model processes. Two, in particular, are a same-sign dilepton signature and a trilepton signature which is described in the next subsection. (Leptons for these analyses are electrons or muons.) Both analyses use the same lepton identification cuts. Both require that the primary lepton have an $E_T > 11$ GeV; the other lepton(s) must have $E_T > 5$ GeV. All of the leptons must be isolated in both the calorimeter and in the tracking chambers.

The dilepton search looks for cascade decays of gluinos. Specifically, a gluino pair is produced in the $p\bar{p}$ collision and each gluino decays $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_1^{\pm}$. The chargino subsequently decays into $\tilde{\chi}_1^{\pm} \rightarrow \ell^{\pm}\nu\tilde{\chi}_1^0$ resulting in a final state with two leptons with *uncorrelated* sign and four jets.[7]

The analysis cuts require two *same*-sign leptons and two or more jets in the event all originating from a common vertex. The jets must have a corrected $E_T > 15$ GeV and $|\eta| < 2$. A moderate missing transverse momentum cut of 25 GeV is also required. After all cuts, 2 events remain

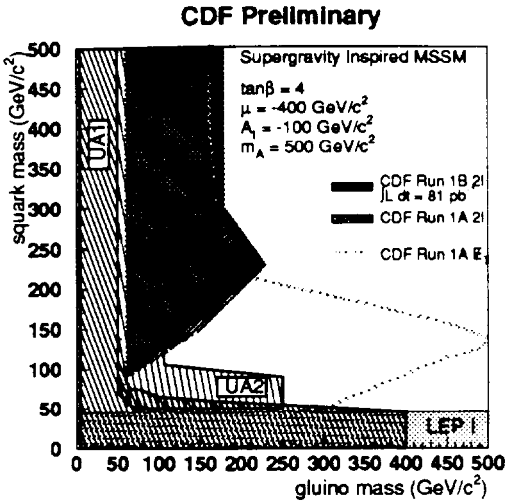

Figure 2: Excluded region from like-sign dilepton analysis.

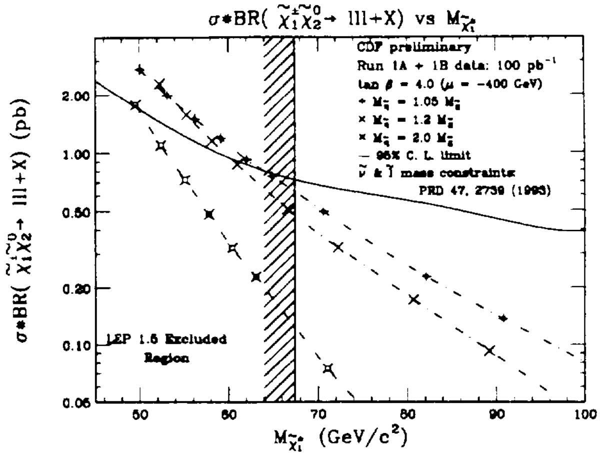

Figure 3: Limit on $\sigma \cdot B$ for chargino neutralino production into trileptons at the 95% C.L. for $\tan\beta = 2$ (left) and $\tan\beta = 4$ (right).

from a sample of 81 pb^{-1}. The dominant background contributions are $t\bar{t}$ and Drell-Yan production where the sign of one of the leptons has been mismeasured. Overall, the background contributes $1.3 \pm 0.6\,(stat) \pm 0.4\,(sys)$ events, consistent with the 2 observed events.

Using Poisson statistics and convoluting all of the statistical and systematic errors into the calculation, we exclude any model which produces more that 5.8 events. This calculation uses the next-to-leading production cross-sections. Fig. 2 shows the exclusion region in the $M_{\tilde{q}}$ vs. $M_{\tilde{g}}$ mass plane. This analysis excludes $M_{\tilde{g}} < 180$ GeV/c^2 independent of $M_{\tilde{q}}$ and $M_{\tilde{q},\tilde{g}} < 230$ GeV/c^2 for

2.3 Trilepton Search

The trilepton search looks for direct production of chargino neutralino pairs with subsequent decays of the chargino and neutralino into leptons. That is,

$$p\bar{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0} \rightarrow \ell^{\pm}\nu\tilde{\chi}_1^{0}\;\ell^{+}\ell^{-}\tilde{\chi}_1^{0}.$$

Notice that this requires the next-to-lightest neutralino to be produced.

The analysis requires three leptons ($e^+e^-e^{\pm}$, $e^+e^-\mu^{\pm}$, $\mu^+\mu^-e^{\pm}$, $\mu^+\mu^-\mu^{\pm}$) originating from a common vertex. Events with opposite sign leptons consistent with J/ψ (2.9–3.3 GeV/c^2), Υ (9-11 GeV/c^2), or Z (76–106 GeV/c^2) resonances are removed. Each event must also have $\not{E}_T >$ 15 GeV. After all of the cuts, no events remain in a data sample of 100 pb^{-1}.

Considering $t\bar{t}$, $b\bar{b}/c\bar{c}$, diboson, and Drell-Yan processes, only 0.3 ± 0.1 background events are expected. Figs. 3 show the $\sigma \cdot$ B limit at 95% C.L. for $\tan\beta = 4$. The actual limits are quite competitive with LEP 1.5[8] and probe a different region of μ. Note that the LEP limit shown assumes $m_{\tilde{\nu}} = 100$ GeV/c^2. If this mass is lowered, the LEP limit degrades because of destructive interference from a t-channel diagram.

2.4 Photonic signature SUSY Particle Search

On April 28, 1995, an $ee\gamma\gamma\not{E}_T$ candidate event was recorded at CDF. This event is shown in Figure 4. Since then, there have been numerous theoretical papers which explore possible new physics explanations for this event[9]. Many of these models postulate anomalous production of events with large $\not{E}_T$ and two photons in addition to this $ee\gamma\gamma\not{E}_T$ candidate event. To address this hypothesis, we performed a preliminary systematic study of the $\not{E}_T$ distribution in diphoton events using 85pb^{-1} of data[9]. Figure 5 shows the $\not{E}_T$ distribution for diphoton candidate events(points) with photon $E_T > 12$ GeV. In order to search for anomalous production we compare the shape

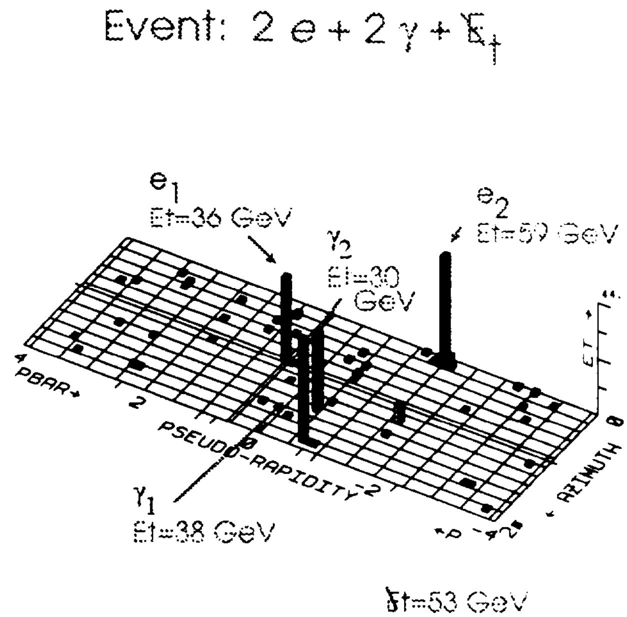

Figure 4: The $ee\gamma\gamma\not{E}_T$ candidate event from CDF.

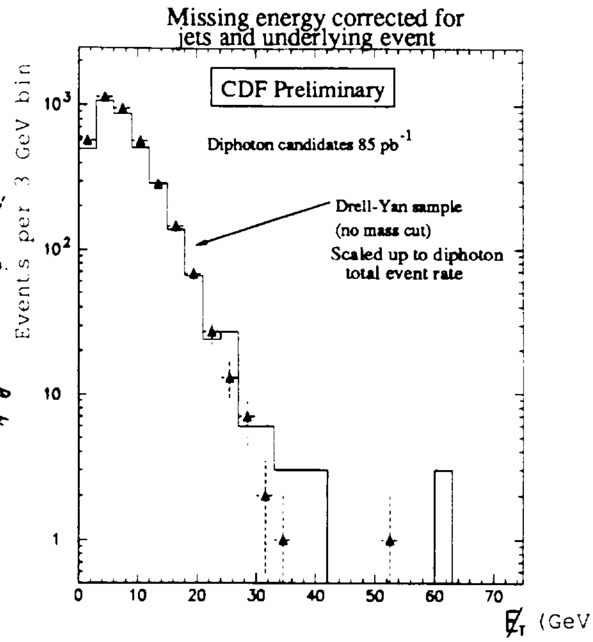

Figure 5: The $\not{E}_T$ distribution for diphoton candidate events (points) and e^+e^- events (solid line). $E_T >$ 12 GeVis required for both photons and electrons.

of the $\not{E}_T$ spectrum to e^+e^- events with electron $E_T > 12$ GeV(solid line) since the detector response for the electromagnetic clusters should be similar. Note that e^+e^- events contain small amounts of $WW, WZ, Z \to \tau\tau, b\bar{b}$ and $t\bar{t}$ events which produce events with large $\not{E}_T$. Figure 6 shows similar distributions for diphotons (points) and dielectrons (solid lines) with $E_T > 25$ GeV. Here, an e^+e^- invariant mass cut is applied to select $Z \to ee$ events. Since the diphoton sample contains more QCD background events than the dielectron ($Z \to ee$) sample, we expect the $\not{E}_T$ spectrum of the diphoton sample is somewhat harder than that of the dielectron sample due to the resolution of the calorimeter energy measurements. In both plots, the diphoton event with the largest $\not{E}_T$ is the $ee\gamma\gamma\not{E}_T$ event and there are no other significant deviations from the background estimate. We have investigated our sensitivity to one of the SUSY theories with light Gravitinos [10] which predict anomalous $\gamma\gamma\not{E}_T + X$ productions. The dashed line in Figure 6 shows the number of expected events in the data as predicted from the theoretical cross section after the detector simulation and analysis cuts are applied. More work is in progress to quantify the results and constrain these theories within certain regions of parameter space.

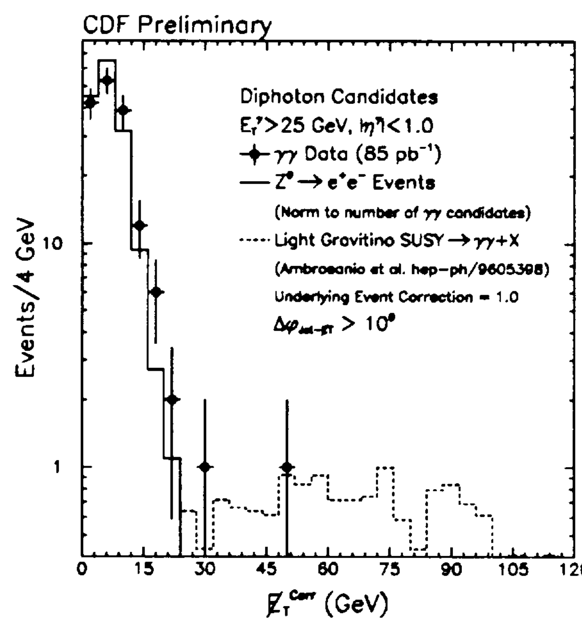

Figure 6: The $\not{E}_T$ distribution for diphoton candidate events (points) and e^+e^- events (solid line). $E_T >$ 25 GeVis required for both photons and electrons. Invariant mass cut of ± 10 GeVis applied for the background $Z \to e^+e^-$ sample. The dashed line shows the number of expected events in the data as predicted from the theoretical cross section after the detector simulation and analysis cuts are applied.

3 Charged Higgs Search

Many extensions to the Standard Model contain an expanded Higgs sector. SUSY and E_6 models, for instance, contain two Higgs doublets where one doublet gives mass to the up-type quarks and the other gives mass to the leptons and down-type quarks.[13] After electroweak symmetry breaking, there are five physical Higgs bosons three of which are neutral and two of which are charged.

The ratio $\tan\beta$ controls the dominant decay modes for the charged Higgs and top quark. For large $\tan\beta$, $t \rightarrow Hb$ and $H \rightarrow \tau\nu$ exclusively. This leads to distinctive events with two tau leptons, two b-jets, and large $\not{E}_T$.[?] For smaller values of $\tan\beta$, the top decays are a mixture of $t \rightarrow Wb$ and $t \rightarrow Hb$. This search requires the topology $\tau jjX + \not{E}_T$ where the tau decays hadronically and X can be either an electron, muon, tau, or additional jet. One of the jets in the event must be b-tagged with CDF's silicon vertex detector. The $\not{E}_T$ must exceed 60 GeV.

Identification of hadronically decaying taus starts with a jet having $E_T > 10$ GeV. There must be either one or three charged particles in a 10° cone about the jet axis and no other charged particles above 1 GeV between the 10° cone and a 30° cone. The cluster cannot be consistent with an electron.

After all analysis cuts, 8 events remain in a sample of 88 pb^{-1}. All of these events have a $\tau + 3$ jet topology. Jets which have fluctuated to low charged particle multiplicity and have faked a tau lepton comprise the dominant background. We expect 8.5 ± 1.7 background events including small contributions from electroweak processes and diboson production. Fig. 7 shows the limit in the M_H vs. $\tan\beta$ plane. For large values of $\tan\beta$ we exclude charged Higgs masses with $M_H < 150$ GeV/c^{2}assuming $\sigma_{top} = 5.0$ pb.

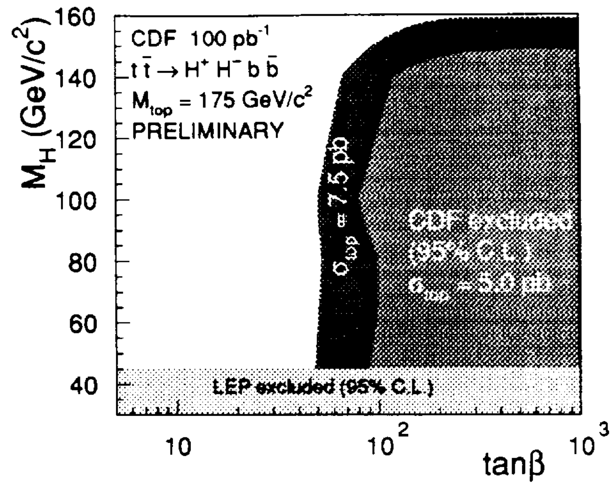

Figure 7: Excluded region in M_H vs. $\tan\beta$ plane.

4 New Gauge Bosons Z' and W'

Heavy neutral gauge bosons in addition to the Z^0, generically denoted as Z', occur in any extension of the Standard Model which contains an extra U(1) after symmetry breaking. The couplings of the Z' depend on the specific model. Examples are Z_{LR} which appears in Left-right symmetric models or one model based on E_6 as the grand unified gauge group [14] contains a Z_ψ from the symmetry breaking $E_6 \rightarrow SO(10) \times U(1)_\psi$ and a Z_χ from the symmetry breaking $SO(10) \rightarrow SU(5) \times U(1)_\chi$[a]. A Z_η defined as $Z_\eta = \sqrt{3/8}Z_\chi + \sqrt{5/8}Z_\psi$ appears in a Superstring motivated E_6 model. A convenient way [b] to gauge the limits is the introduction of a Z'_{SM} which is assumed to have the same couplings as the Z^0.

We have searched for Z' in both dimuon and dielectron decay modes with 110 pb^{-1} of Run Ia and Ib data. Figures 8 shows the invariant mass distributions of dimuons and dielectrons in the Z' search data sample. The 95% C.L. limit on the cross section times branching ratio to dileptons that we obtain is shown as a function of mass in Figure 9. We can use this experimental result to set limits on the Z'-mass for different models. Assuming Standard Model couplings we obtain $M_{Z'} > 690$ GeV/c^2 (see Figure 9). We also compared the experimental limit with specific models. We set the lower mass limits for Z_ψ, Z_η, Z_χ, Z_I, Z_{LR} and $Z_{\rm ALRM}$ to be 580, 610, 585, 555, 620, and 590 GeV/c^2, respectively assuming the Z' decays only into known SM fermions.

Heavy W bosons, W', occur in extended gauge models with an extra $SU(2)$, for example, the left-right symmetric model [15] of electroweak interactions $SU(2)_R \times SU(2)_L \times U(1)_Y$. CDF has searched for $W' \rightarrow l\nu$ in the electron and muon

[a]The SU(5) symmetry then breaks to recover the Standard Model: $SU(5) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$.

[b]not necessarily motivated theoretically.

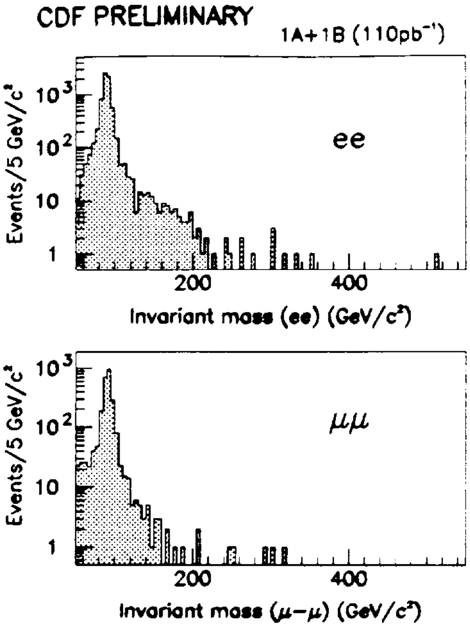

Figure 8: The dielectron and dimuon invariant mass distributions for the Z' search data sample.

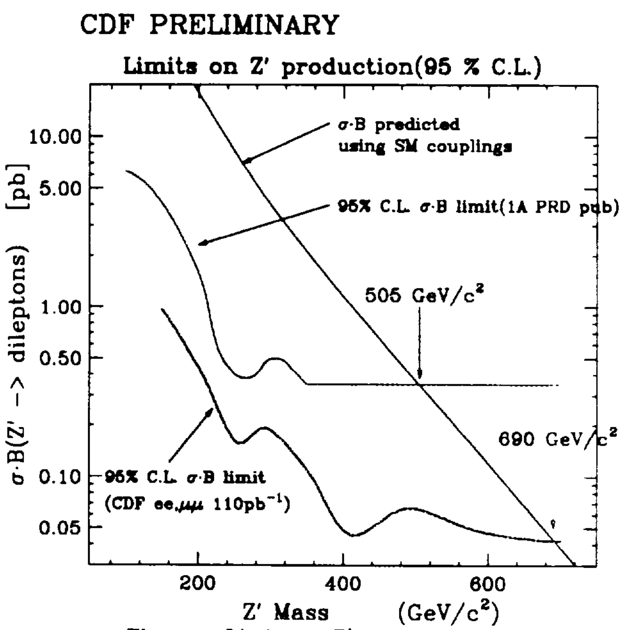

Figure 9: Limits on Z' production.

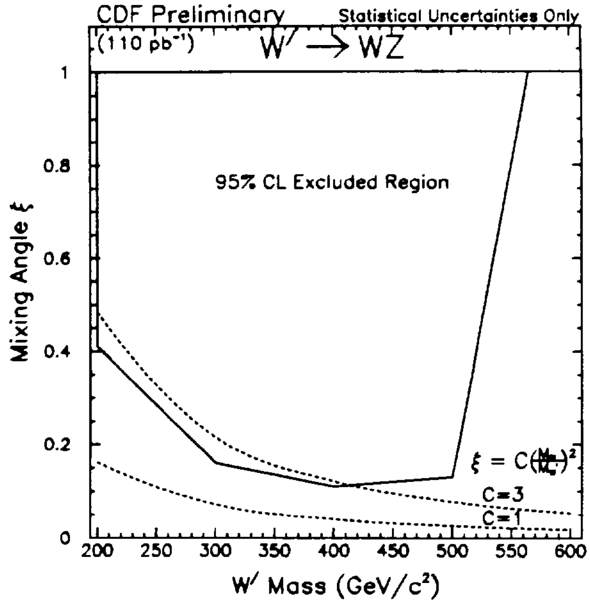

Figure 10: Limits are shown for $W' \to WZ$.

channels [16,17]. The analysis of Run Ia electron data yielded a limit of $M_{W'} > 652$ GeV/c^2, assuming Standard Model couplings and that the decay $W' \to WZ$ is not allowed. The search for $W' \to e\nu$ and $\mu\nu$ using Run Ib data is in progress.

We have also performed a search for W' decaying to WZ [18] where the Z is identified by requiring two jets with invariant mass close to the Z^0-mass. In extended gauge models W and W' are not mass eigenstates and so mixing must occur. We have excluded a region in the mass vs. mixing angle ($\xi \equiv c\left(\frac{M_W}{M_{W'}}\right)^2$) space. This region is shown in Figure 10.

5 Massive Stable Particles

Massive stable particles are possible features of several theories[19] for physics beyond the standard model including supersymmetry, mirror fermions, and higher color multiplets. If such particles were charged, they could be detected directly in CDF's tracking chambers. We have searched for heavy stable charged particles based upon their expected high transverse momenta, relatively low velocities, and muon-like penetration of matter. Low velocity particles are distinguished by their large ionization deposition, dE/dx. CDF measures dE/dx with both its central tracking chamber (a gaseous

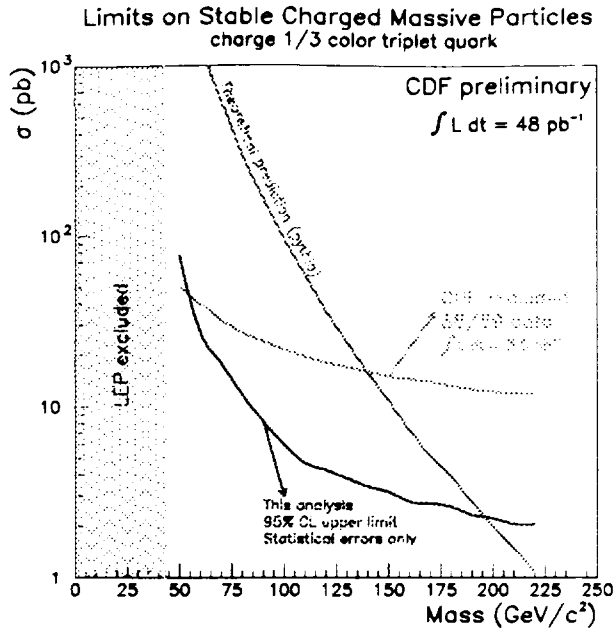

Figure 11: Limits on stable charge 1/3 color triplet quarks.

wire chamber) and its silicon vertex detector (a solid state detector). Combining the two measurements provides strong rejection of minimum ionizing particles (MIPS) while maintaining efficiency for tagging particles with low velocity, $\beta\gamma < 0.65$.

We have searched in 48 pb^{-1} of Run Ib data. Because of their properties this particles should fire our muon triggers and be part of our inclusive muon sample. Requiring the transverse momentum $p_T > 30$ GeV/c, the dE/dx to be at least 1.8 times bigger than expected for a MIP in the central tracker and at least 2.5 times bigger in the silicon tracker, we observe no candidates. This non-observation can be used to set limits on a variety of theories. We have thus far only addressed the simplest case; a stable color triplet quark. For that case, we have obtained a preliminary limit of $190 GeV/c^2$, as shown in Figure 11. The remaining data will be analysed soon, and the limit will be extended to other models.

6 Summary and future prospects

CDF has searched for new particles beyond the Standard Model. We have recorded some 'interesting' events (the $ee\gamma\gamma\not{E}_T$ candidate event, for example), however, our analysis results show no evidence for new physics beyond the Standard Model

Results of CDF New Particle Searches

Searches	Current CDF limit (GeV) (mostly Preliminary) Excluded reagion at 95% C.L.	data set(pb^{-1})
$W' \rightarrow e\nu$ (SM)	< 652	1a (20)
$W' \rightarrow WZ$	< 560 (ref. model excluded)	1a+1b (110)
$Z' \rightarrow \ell\ell$ (SM)	< 690	1a+1b (110)
$Z_\psi, Z_\eta, Z_\chi, Z_I$	< 580, 610, 585, 555	1a+1b (110)
Z_{LR}, Z_{ALRM}	< 620, 590	1a+1b (110)
Axigluon → dijet	200 < M < 930	1a+1b (103)
Technirho→ dijet	250 < M < 500	1a+1b (103)
topgluon $\Gamma = .1M$	200 < M < 550	1a (20)
topgluon $\Gamma = .5M$	200 < M < 370	1a (20)
Leptoquark(2nd gen.)	< 180(scalar, $\beta = 1$)	1a+1b(70)
Leptoquark(3rd gen.)	< 99(scalar)	1a+1b(110)
Leptoquark(3rd gen.)	< 170, 225(vector,$\kappa = 0, 1$)	1a+1b(110)
Pati-Salam LQ(B_s-eμ)	< 12100	1b (88)
Pati-Salam LQ(B_d-eμ)	< 18300	1b (88)
Composit, Scale (qqee)	< 3400(−), 2400(+)	1a+1b (110)
Composit, Scale (qq$\mu\mu$)	< 3500(−), 2900(+)	1a+1b (110)
q^*(W+jet, γ+jet)	< 540	1a (20)
$q^* \rightarrow$ dijet	200 < M < 750	1a+1b (103)
massive ch. stable ptl.	< 190(color tripl. q)	1b (48)
gluino(MSSM)	< 180(all $\tilde{q}$ mass)	1b (80)
gluino(MSSM)	< 230($M_{\tilde{q}} = M_{\tilde{g}}$)	1b (80)
gaugino(MSSM)	< 68 ($\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$)	1a+1b (110)
$H^\pm$	< 150*	1a+1b (100)
$H^0(\bar{p}p \rightarrow WH^0, H^0 \rightarrow b\bar{b})$	> 15pb#	1a+1b (110)

* $\tan\beta > 100, M_{top} = 175GeV, \sigma_{top} = 5$pb

\# for $90 < M_{H^0} < 130$ GeV, (in W→dijet channel)

Figure 12: Summary of CDF New Particle (phenomena) Search Limits.

so far. We set many of the currently best limits on these particles and they are summarised in Figure 12. Some of the analyses presented in this paper used only a subset of the current dataset and will clearly benefit from using the full 110 pb^{-1} of run I.

We are currently upgrading the CDF detector. The upgrades include new integrated tracking with better pattern recognition and improved coverage, improved calorimeter, muon, and b-tagging coverage, and the ability to trigger on b jets. We look forward to searching for new phenomena with the upgraded detector with more integrated luminosity in run II.

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