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Searches for New Phenomena at CDF

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Abstract

We present recent results of searches for new physics in 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1800$ GeV using the CDF detector. Presented are searches for third generation leptoquarks, charged and neutral Higgs bosons and the supersymmetric partner of the top quark ($\tilde{t}$). A search for new physics in diphoton events tests some models attempting to explain the CDF "$ee\gamma\gamma\,\not\!\!E_{\mathrm{T}}$" event. Finding no signal in any of these channels, production limits are presented.

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1 Introduction

Many possible extensions to the Standard Model include signatures involving third generation fermions: top quarks, bottom quarks or tau leptons. For example, since the Higgs couples to mass its most prolific decay channel is $H \to b\bar{b}$. In the case of the top quark it is massive enough to be a possible parent of new particles such as a charged Higgs or a supersymmetric top. Another signature which has received significant attention in the past year are events with two photons.

Data for results presented here were collected by the CDF experiment operating at the Tevatron $p\bar{p}$ collider at Fermilab during the 1992-95 collider run (known as Run 1). Unless otherwise noted, the dataset consists of an integrated luminosity of approximately 110 pb^{-1}. The CDF detector has been described in detail elsewhere[1].

Most of the analyses presented here use tools developed during the past few years to identify jets associated with b quarks and/or τ leptons. The algorithm for tagging b jets uses the precise track reconstruction of the silicon vertex detector to identify secondary vertices which have significant displacement from the primary vertex. Positive (negative) tags are defined as secondary vertices that are on the same (opposite) side of the primary vertex as the jet direction. This algorithm was developed for the top quark analyses[2].

Jets are identified as hadronic tau decays based on track multiplicity and isolation using the high quality tracks from the central drift chamber[3, 4]. The algorithm starts with central jets which contain at least one track with $P_t > 10$ GeV/c. The highest $\mathrm{P_T}$ track is used as a seed around which cones of $10°$ and $30°$ are defined. A τ is defined as having exactly 1 or 3 tracks with $\mathrm{P_T} > 1$ GeV/c within the $10°$ cone and no additional $\mathrm{P_T} > 1$ GeV/c tracks between the $10°$ and $30°$ cones.

2 Third Generation Leptoquarks

Extensions of the Standard Model which unify the quark and lepton sectors predict the existence of Leptoquarks (LQ). These are color triplet bosons (scalar or vector) which couple directly to ℓq or $\ell\bar{q}$. In $p\bar{p}$ collisions, leptoquarks would be produced strongly in pairs with a cross section which is independent of the quark-lepton coupling constant (λ). The primary free parameter affecting searches at the Tevatron are the branching ratios to $l^{\pm}j$ (β) and to νj ($1-\beta$). Theoretically, cross-generational leptoquarks carrying the lepton number from one generation and the quark flavor from another are allowed. However, limits on Flavor Changing Neutral Currents and lepton flavor violating decays set very stringent limits on the masses of such leptoquarks. For example, CDF has searched for the decays $B_d \to e\mu$ and $B_s \to e\mu$ setting upper limits on the branching fractions of 4.4×10^{-6} and 2.3×10^{-5} respectively. These limits in turn imply limits on Pati-Salam leptoquarks of $M_{LQ} > 18.3$ TeV/c^2 and $M_{LQ} > 12.1$ TeV/c^2 respectively. For all other CDF leptoquark searches it is assumed that the lepton and quark flavors are from the same generation.

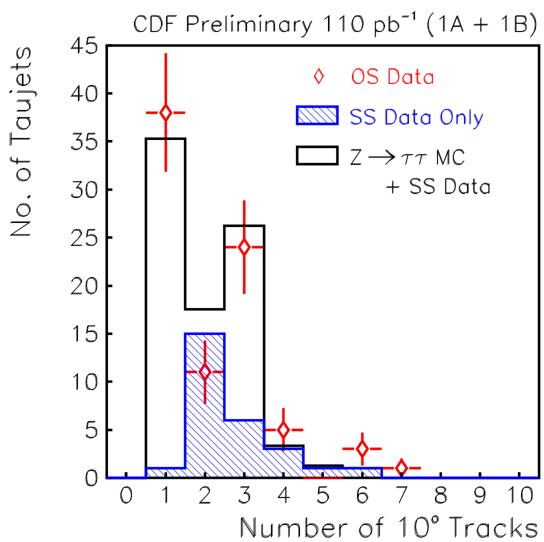
Previously, CDF published[5] a search for first generation leptoquark pairs where both leptoquarks decay to electron plus jet. No $eejj$ events were observed in 4 pb^{-1} of data from the 1988-89 run and leptoquark mass limits were set at 95% confidence level at $M_{LQ1} > 113(80)$ GeV/c^2 for $\beta = 1.0(0.5)$. A search for second generation leptoquarks in $\mu\mu jj$ was published in 1995[6] based on the first 70 pb^{-1} of Run 1. Mass limits of $M_{LQ2} >$ 180(141) GeV/c^2 at 95% confidence level were set for $\beta = 1(0.5)$. All of these limits are for a scalar leptoquark. Since "Les Rencontres de Physique de La Vallee d'Aoste" results from complete Run 1 analyses have extended these limits[7] to: $M_{LQ1} > 210$ GeV/c^2 for $\beta = 1$ and $M_{LQ2} > 195(147)$ GeV/c^2 for $\beta = 1(0.5)$.

CDF has recently published results of a search for third generation leptoquarks[3] looking for the decay $LQ3\overline{LQ3} \to \tau^+ b \tau^- b$. The signature of the analysis is two tau leptons, one decaying leptonically (electron or muon) and one hadronically, combined with 2 jets. The electron or muon must be central ($|\eta| < 1.0$) and isolated with $P_T > 20$ GeV/c. The hadronic tau is identified with the algorithm described above requiring $E_T(jet) > 15$ GeV. The tau candidates must be of opposite sign.

All events which have any track which combined with the lepton satisfy $75 < M(l, track) <$ 105 GeV/c^2 are removed to reject $Z \to ll$. To suppress the potentially significant W + jets background, the azimuthal angle between the lepton and the $\not{E}_T$ is required to be less than 50°. To suppress $Z \to \tau\tau$, 2 or more jets are required with $E_T > 10$ GeV and $|\eta| < 4.2$. No b-tag requirement is placed on the jets to maintain high efficiency.

Figure 1 shows the track multiplicity of the hadronic tau candidates with all cuts except the $N_{jet} \geq 2$ applied. There is a clear indication of an excess of τ-like opposite sign events with 1 or 3 tracks which is consistent with a combination of the same sign background and a Monte Carlo prediction of $Z \to \tau\tau$.

After applying the 2 jet cut, 1 event is observed in the data. The predicted background is $2.4^{+1.2}_{-0.6}$ events, which is dominated by 2.1 ± 0.6 events from $Z \to \tau\tau$. Seeing no excess of events, we set 95% C.L. upper limits on $\sigma(p\bar{p} \to LQ3\overline{LQ3}) \times \beta^2$ as a function of M_{LQ3} for vector and scalar leptoquarks. The limits are shown in Figure 2. Assuming $\beta = 1$, we set lower limits on the leptoquark mass of 99 GeV/c^2 for scalars, 225 GeV/c^2 for gauge vectors and 170 GeV/c^2 for non-gauge vectors.



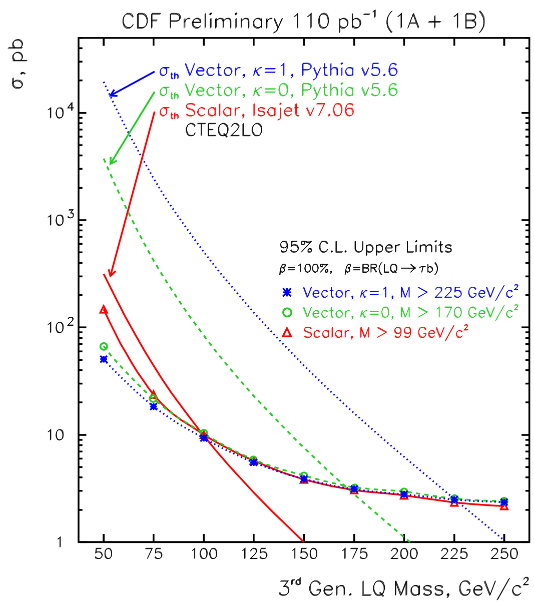


Figure 1: Track multiplicity of hadronic tau candidates in lepton + hadronic tau events. The points are opposite sign data; the hatched histogram are same sign data.

Figure 2: Upper limits at 95% C.L. on third generation leptoquark production as a function of leptoquark mass for $\beta = 1$.

3 Charged Higgs

Extensions to the Standard Model with a two-Higgs doublet include predictions for the existence of charged Higgs particles. Assuming only a two-Higgs doublet extension to the Standard Model, the measurement of the electromagnetic penguin decay $b \to s\gamma$ by CLEO[8] sets a lower limit on the charged Higgs mass of $M_{H^\pm} > 244 + 63/(\tan\beta)^{1.3}$ GeV/c^2. However, additional new particles (e.g. SUSY) could interfere in the penguin loop and significantly reduce this limit.

The couplings of the charged Higgs are paramterized by $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs. As shown in Figure 3 the branching fraction for $t \to H^+ b$ is significant for both small (< 2) and large (> 20) values of $\tan\beta$ while it is small for values in between. In these ranges, if the Higgs were lighter than the top by more than the mass of the b quark then the decay $t \to H^+ b$ will compete with the Standard Model decay $t \to W^+ b$. In addition, for $\tan\beta > 1$ the dominant decay is $H^\pm \to \tau\nu$ while below 1 it is $H^\pm \to cs$. CDF has carried out searches for charged Higgs in top decay at high and low $\tan\beta$.

3.1 High $\tan\beta$

For $\tan\beta > 100$, the signature is $t\bar{t} \to H^+bH^-\bar{b} \to \tau^+\tau^-b\bar{b}\nu_\tau\bar{\nu_\tau}$. To extend the reach of the search below $\tan\beta = 100$, the analysis was optimized to be sensitve to $WbH\bar{b}$ final states as well. The event selection requires one hadronic tau, an additional tau or W like object, 2 additional jets and significant $\not{E}_{\rm T}$. The tau is identified with the hadronic tau identification requiring a jet with $E_T > 20$ GeV and $|\eta| < 1.0$. The second tau or W object can be any one of the following with $E_T > 10$ GeV and $|\eta| < 1.0$: a hadronic tau, an electron, a muon or a jet. The jets are both required to have $E_T > 10$ GeV and at least one must have a b-vertex tag to reduce the backgrounds from $W + jets$. The missing $\rm E_T$ is formed using all the identified objects in the event (leptons, jets, photons) and must be greater than 30 GeV.

We predict a total background of 7.4 ± 2.0 events from fake τ's (5.4 ± 1.5), $W \to \tau\nu\ jet$ (1.3 ± 1.3), $Z \to \tau\tau\ \ jet$ (0.6 ± 0.3), and dibosons (0.08 ± 0.06). We observe 7 events in the data, one τejj and six τjjj, from which we set an upper limit of 8.9 signal events at 95% C.L. Figure 4 shows the lower limits on $M_{H^\pm}$ as a function of $\tan\beta$ assuming $M_t = 175$ GeV/c^2. Curves for two possible $t\bar{t}$ cross sections[2] (5.0 pb and 7.5 pb) are shown. For high $\tan\beta$, we set a lower limit of $M_{H^+} > 158(147)$ GeV/c^2 at 95% C.L. for $\sigma_{t\bar{t}} = 7.5(5.0)$ pb.

3.2 Low $\tan\beta$

At low $\tan\beta$, the strategy used is to explore the effect of the dominant $H^+ \to c\bar{s}$ decay channel on yields of the standard top dilepton and lepton + jets analyses[2]. The presence of a charged Higgs decaying to $c\bar{s}$ would be to reduce the number of high $\rm P_T$ leptons (from $W \to \ell\nu$) found relative to the number of all hadronic final states.

The yield of dilepton and lepton plus jets events as a function of $\tan\beta$ and M_{H^+} is predicted from Monte Carlo and compared to the yields in the data. In the dilepton channel we find 9.0 ± 3.0 events with an expected background of 2.2 ± 0.4 while in the lepton + jets channel there are 34.0 ± 5.8 events with a predicted background of 10.4 ± 1.6. These yields are consistent with the predicted number of events from $t\bar{t} \to W^+W^-b\bar{b}$ with no charged Higgs. Combining the two samples, we set 95% C.L. lower limits on the charged Higgs mass as a function of $\tan\beta$ for $\sigma_{t\bar{t}} = 7.5$ pb and 5.0 pb. The limit contours are shown on the lower end of the $\tan\beta$ scale of Figure 4.

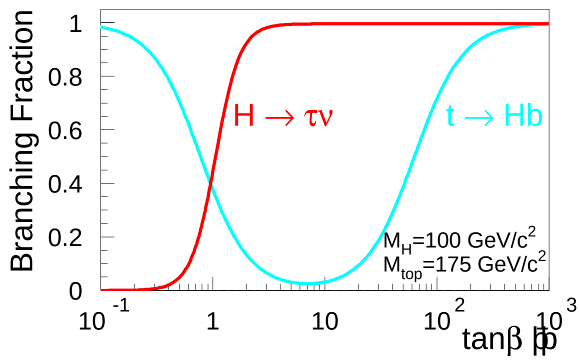


Figure 3: Branching ratios $H \to \tau\nu$ and $t \to Hb$ as a function of $\tan\beta$.

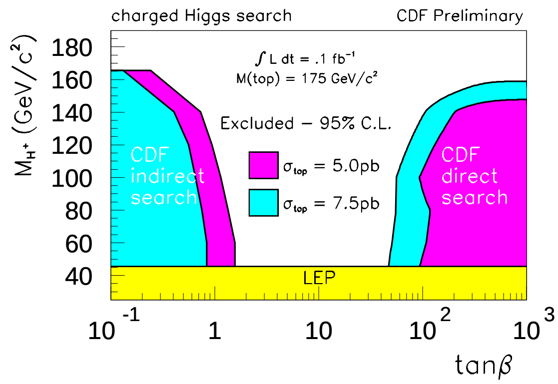


Figure 4: Upper limits at 95% C.L. on charged Higgs from top decay as a function of $\tan\beta$.

4 Heavy Neutral Scalar

We have searched for the associated production of a vector boson (W or Z) and a heavy neutral scalar (e.g. Higgs or Technipion) which decays to $b\bar{b}$. In the analysis presented here, the vector bosons decay to two quarks resulting in a final state of four jets of which two are b quarks. A separate analysis using the leptonic decays of the vector bosons is in progress.

The event selection requires at least four jets with $\mathrm{E_T} > 10$ and $|\eta| < 2.1$ two of which must have b vertex tags. To reduce the background from direct heavy flavor production the combined $b\bar{b}$ pair is required to have $\mathrm{P_T}(b\bar{b}) > 50$ GeV/c. No excess of events is seen when comparing the invariant mass spectrum of the tagged jets to predictions of heavy flavor production (Pythia) and fake tags. Figure 5 shows a likelihood fit to the M_{bb} spectrum with a combination of QCD, fakes, top and WH for four Higgs masses. From these fits we extract the 95% C.L. upper limit, including full systematic uncertainties (not available at the time of "Les Rencontres de Physique de La Vallee d'Aoste"), on the production cross section for $W/Z + X^0$ as a function of M_{X^0}. This limit is plotted in Figure 6 along with the latest D0 results[9].

There is insufficient sensitivity to set limits on the neutral Higgs mass since the predicted cross section is $\sigma_{VH} = 0.9 - 0.13$ pb in this mass range. Evaluation of the sensitivity for Technicolor is ongoing.

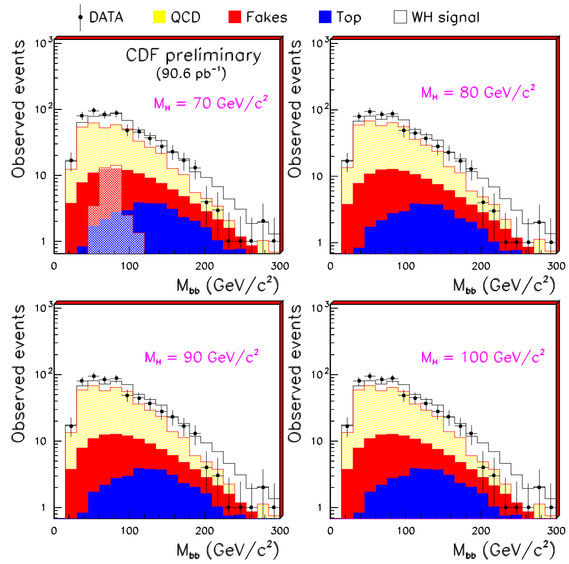


Figure 5: Likelihood fit of M_{bb} to a combination of QCD, fakes, top and WH signal for four different Higgs masses.

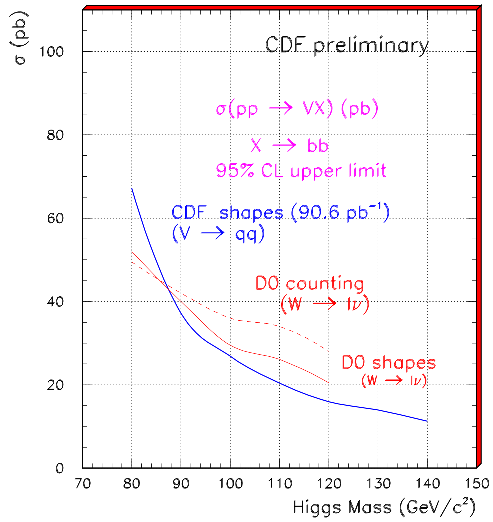


Figure 6: Upper limits at 95% C.L. on associated neutral scalar production. Includes full sytematic uncertainties.

5 Supersymmetric top ($\tilde{t}$)

Recent MSSM models show that the very high mass of the top quark results in a large splitting between its two supersymetric partners ($\tilde{t_1}$, $\tilde{t_2}$) with the $\tilde{t_1}$ potentially significantly lighter than the top. The stop could then be dectectable through the decay of the top: $t \rightarrow \tilde{t}\tilde{\chi}_1^0$ or via direct production ($\sigma_{\tilde{t}\tilde{\bar{t}}}/\sigma_{t\bar{t}} \sim 0.1$). Here the $\tilde{\chi}_1^0$ is assumed to be the lightest supersymmetric particle (LSP).

The dominant decay channel of the stop depends on the relative masses of the $\tilde{t}$, $\tilde{\chi}^+$, and $\tilde{\ell}$. For $M_{\tilde{t}} > M_{\tilde{\chi}^+}$, the dominant decay is $\tilde{t} \rightarrow \tilde{\chi}^+ b$. If $M_{\tilde{t}} < M_{\tilde{\ell}}$, $M_{\tilde{\chi}^+}$, the dominant decay is $\tilde{t} \rightarrow c\ LSP$. CDF has performed two searches for $\tilde{t} \rightarrow \ell b \not{E}_T$: one in top decays and the other in direct production.

In top decays, we search for events where one top has decayed via the Standard Model process $t \rightarrow Wb \rightarrow \ell b \nu$ and other via $t \rightarrow \tilde{t}\ LSP$. The stop decays to $\tilde{\chi}^+ b$ and the $\tilde{\chi}^+ \rightarrow jj\ LSP$. The result is a lepton + 3 jets signature like Standard Model $t\bar{t}$. However, the jet spectrum is softened and the $\not{E}_T$ spectrum stiffened by the two LSP's.

The event selection requirements are similar to the lepton plus jets top sample[10]: one central lepton (e or μ) with $P_T > 20$ GeV/c, two jets with $E_T > 20$ GeV ($|\eta| < 2$), a third jet with $E_T > 15$ GeV, at least one b-vertex tag, and $\not{E}_T > 25$ GeV. The requirement

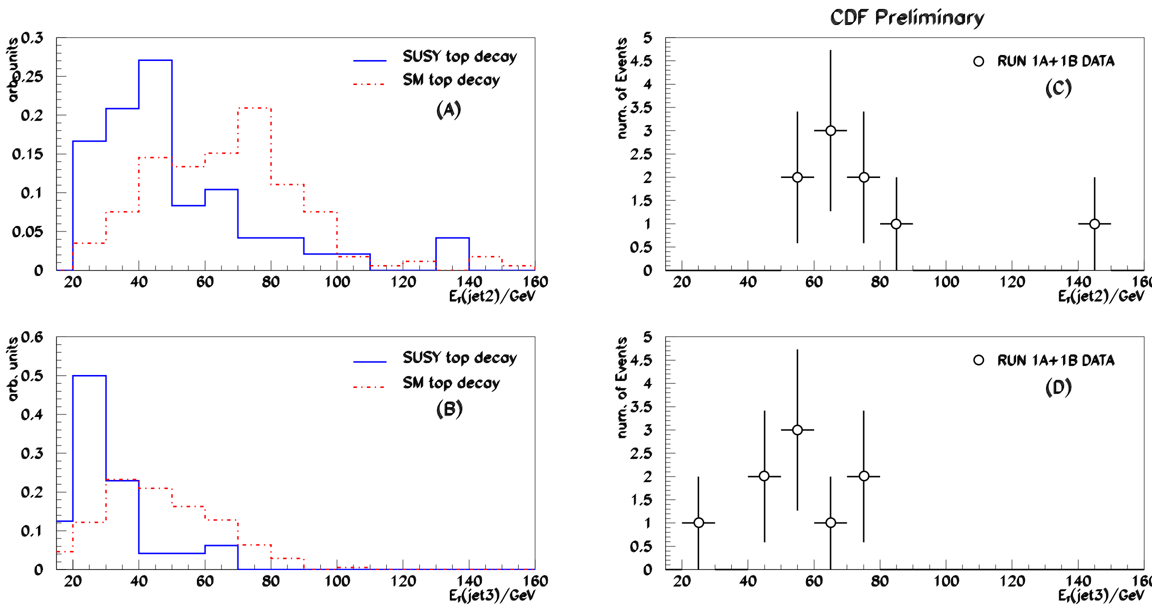


Figure 7: Jet E_T distributions for 2nd and 3rd jets from: SUSY and Standard Model Monte Carlo (Left), and data (right).

on the third jet is lowered to 15 GeV to increase the acceptance for the jets from $\tilde{t}$ decay. Since this allows in more background from QCD, additional requirements on the lepton and missing E_T are imposed: $\not{E}_T > 45$ GeV, $M_T(\ell, \not{E}_T) > 45$ GeV, and $P_T(\ell, \not{E}_T) > 50$ GeV/c.

Figure 7 shows the Monte Carlo predicted jet E_T distributions for the second and third jets for Standard Model and SUSY top decay. The SUSY decays are clearly softer. Also shown are the distributions for the 9 events in the data which are clearly harder than the predicted SUSY spectra.

A relative likelihood function is formed using the SUSY and Standard Model distributions. All 9 events are in the Standard Model region with $\ln(R_L) > -1$. Seeing no evidence for $\tilde{t}$ decays we set upper limits on $BR(t \to \tilde{t}\tilde{\chi}^0)$ of about 50% for much of the relevant mass ranges ($M_{\tilde{t}}$ and $M_{\tilde{\chi}_1^+}$) as shown in Figure 8.

A search has also been performed for direct stop pair production with both decaying via $\tilde{t} \to \tilde{\chi}^+ b$. One $\tilde{\chi}^+$ is required to decay to $\ell\nu$ LSP and the other to jj LSP. The dataset is the top lepton plus jets sample requiring $2 \leq N_{jet} \leq 4$, and at least one b vertex tag. A likelihood fit to $M_T(\ell, \not{E}_T)$ and $\Delta\phi(\ell, j_2)$ is used to separate stop from top and other backgrounds. Figure 9 shows the 95% C.L. upper limit on the $\tilde{t}$ pair production

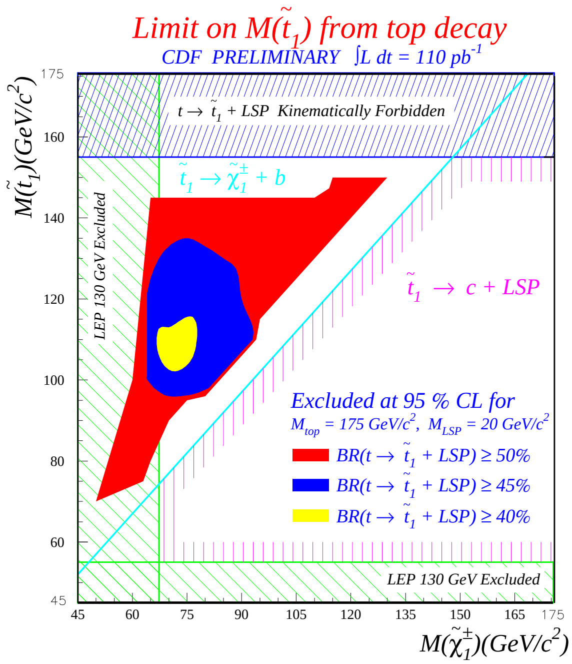


Figure 8: Upper limits on Br($t \to \tilde{t}\tilde{\chi}_1^0$) in the $M_{\tilde{t}} - M_{\tilde{\chi}_1^0}$ plain.

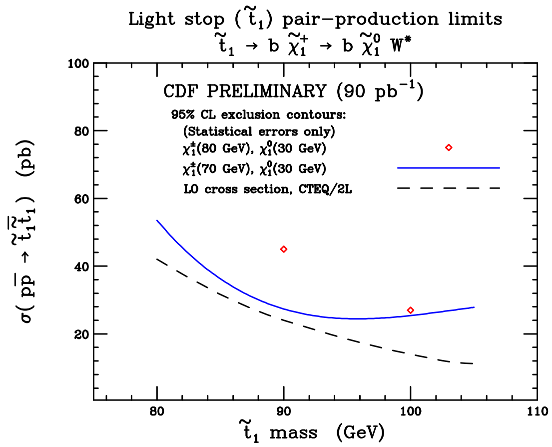


Figure 9: Upper limit on the direct stop pair production cross section.

cross section. Unfortunately, the requirements on lepton $\mathrm{P_T}$ and $\not{E}_\mathrm{T}$ in this preliminary analysis are too high for the search to be sensitive to the predicted $\tilde{t}\bar{\tilde{t}}$ production cross section.

6 Searches in Diphoton events

Finally, we report preliminary results of searches for an explaination of the CDF "$ee\gamma\gamma\not{E}_\mathrm{T}$" event: an unusual event containing 2 high $\mathrm{E_T}$ central photons, a high $\mathrm{P_T}$ central electron, an additional high $\mathrm{E_T}$ electromagnetic object in the plug region and very large $\not{E}_\mathrm{T}$. Over the past two years this event has generated significant activity both in theory and experiments. At CDF, this activity includes a detailed study of the event itself and more general searches for other events that could have come from the same underlying process. The strategy of the searches is to test hypotheses of the source of the event by looking in channels that would have larger yields. We search in samples of diphoton events and high $\mathrm{P_T}$ lepton events for additional distinguishing features (leptons, jets, b-tagged jets, photons, $\not{E}_\mathrm{T}$). We report here the qualitative results of diphoton searches motivated by

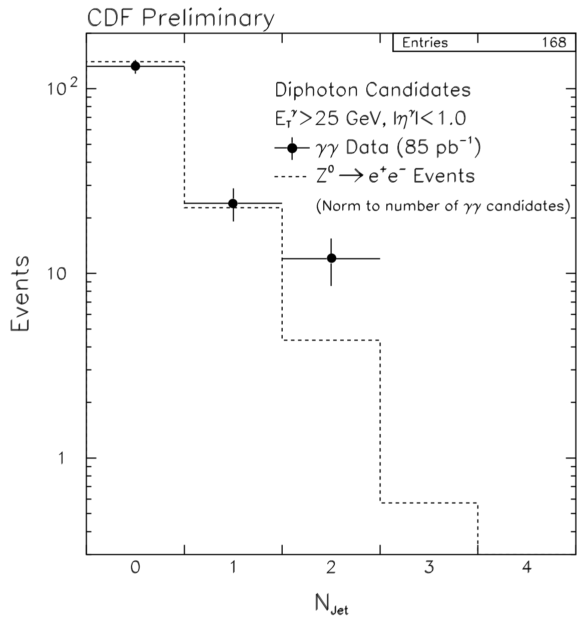


Figure 10: Jet multiplicity distribution in diphoton events. The dashed line shows the distribution in $Z \rightarrow ee$ events normalized to the same number of events.

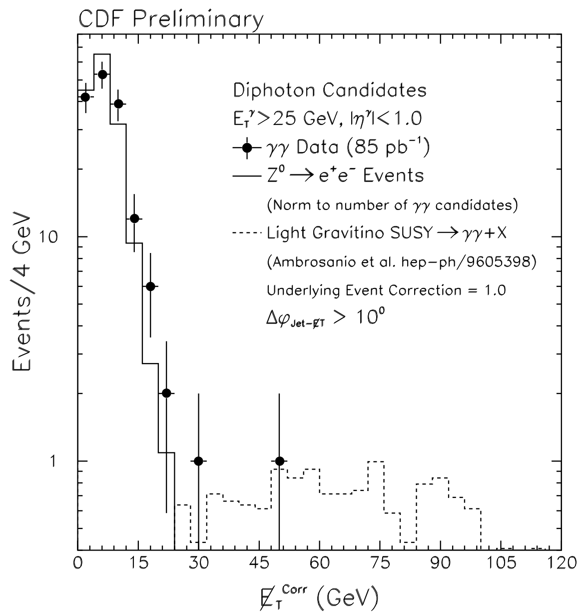


Figure 11: $\not{E}_{\rm T}$ distribution in diphoton events. The solid histogram shows the $\not{E}_{\rm T}$ distribution in $Z \rightarrow ee$ events and the dashed histogram the prediction from a light gravitino model.

two hypotheses for the event: anomalous $WW\gamma\gamma$ production and MSSM light gravitino models. These studies include approximately 85 pb^{-1} of data taken in the last running period (1994-95).

The diphoton sample consists of events with two isolated central ($|\eta| < 1.0$) photon candidates[11] with $E_T > 25$ GeV. Note that unlike the high P_T lepton samples, the high P_T photon samples at the Tevatron have significant backgrounds from jets.

If the "$ee\gamma\gamma\not{E}_{\rm T}$" event is representative of $WW\gamma\gamma$, then the cross section for this process would appear to be anomalously high since the predicted number of events is 7.9×10^{-5}[12]. Estimates of the fake backgrounds are at a similar level. Assuming the event is $WW\gamma\gamma$, the expected number of events with one or both W's decaying hadronicaly should be much larger. Figure 10 shows the jet multiplicity ($E_T(jet) > 10$ GeV, $|\eta(jet)| < 4.0$) in diphoton events with the shape of the jet distribution in $Z^0 \rightarrow ee$ events overlayed. There are no events with $N_{jet} \geq 3$ compared to 40 expected if the "$ee\gamma\gamma\not{E}_{\rm T}$" event were representative of the $WW\gamma\gamma$ cross section.

Many extensions to the Standard Model, most SUSY based, have been proposed to explain this event. We focus here on the MSSM light Gravitino ($M_{\tilde{G}} \approx 1$ KeV) scenarios where the gravitino is the LSP and the favored decay chains would always end in $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$. As a result, the decay of any pair of supersymmetric particles would result in the signature: $\gamma\gamma \not{E}_{\rm T} X$. Figure 11 shows the $\not{E}_{\rm T}$ distribution for diphoton events with the shape of the $\not{E}_{\rm T}$ distribution from $Z \rightarrow ee$ events overlayed (solid histogram). The Z sample provides a good model for the effect of mismeasurements in highly electromagnetic events which is the primary background source. There is only one diphoton event with significant $\not{E}_{\rm T}$ and that is the "$ee\gamma\gamma \not{E}_{\rm T}$" event. The dashed overlay is the expected distribution from a representative light gravitino model[13] which is clearly much stiffer than the observed distribution.

We see no evidence of new physics in cenral diphoton events; quantitative limits are in progress. There is no confirmed explaination of the "$ee\gamma\gamma \not{E}_{\rm T}$" event.

7 Conclusions

CDF has searched for new physics with many different signatures based on numerous extensions to the Standard Model. Unfortunately, we see no evidence for: leptoquarks, charged or neutral higgs, or supersymmetric top. We have set limits on production cross sections and in most cases masses of these objects. We find no evidence in diphoton events for the SUSY light gravitino scenarios and have no proven explaination of the "$ee\gamma\gamma \not{E}_{\rm T}$" event.

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