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CDF

CDF Searches for New Phenomena

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CDF SEARCHES FOR NEW PHENOMENA

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Abstract

We present results of recent searches for new physics using the CDF detector at the Fermilab Tevatron. Presented are searches for Higgs $\rightarrow \gamma\gamma$, as well as more general searches in $\gamma\gamma + X$ where X is \cancel{E}_T , jets, charged leptons, b -quarks or extra photons. The CDF $ee\gamma\gamma\cancel{E}_T$ candidate event is discussed along with estimates of the expected rates in the Standard Model. Other searches for SUSY, Higgs and Technicolor look for particles which decay to vector bosons and b -quarks.

1 Introduction

Many possible extensions to the Standard Model include final state signatures involving vector bosons. For example, events which can decay to final state photons have recently received a great deal of attention. We present recent results from data collected by the CDF detector [1] during the 1992-1995 collider run of the Fermilab Tevatron.

We begin with a search for new heavy particles which decay into two photons e.g. $Higgs \rightarrow \gamma\gamma$ [2]. Other searches in two photon events look for missing E_T , jets, charged leptons, b -quarks and/or extra photons and provide sensitivity to Supersymmetry and other theoretical models [3, 4, 5]. The CDF $ee\gamma\gamma\cancel{E}_T$ candidate event [6] turns up naturally in these searches and we present the results of a detailed study of the event. The expected number of events with the $ee\gamma\gamma\cancel{E}_T$ signature from Standard Model production are summarized. A number of models which predict $ee\gamma\gamma\cancel{E}_T$ events also predict events in the inclusive $\gamma\gamma + \cancel{E}_T$ and $\gamma\gamma$ +jets data and limits are presented on these models. We conclude with searches for Supersymmetry, associated Higgs production and Technicolor by looking for new particles which decay to final states which contain a vector boson (γ, W or Z^0) and a b -quark [2, 4, 7, 8].

2 High Mass $X \rightarrow \gamma\gamma$ Search

Many models of new physics predict events with two photons in the final state. We begin with a search for new heavy particles which decay via $X \rightarrow \gamma\gamma$. The invariant mass of isolated diphoton candidates with $E_T^\gamma > 22$ GeV and $|\eta| < 1.0$ in 100 ± 7 pb⁻¹ of data is shown in Figure 1 along with the Standard Model predictions. There is no evidence for an excess or resonance at high mass. Using a model of direct Higgs production in which the Higgs decays via $H \rightarrow \gamma\gamma$ [2], an experimental limit is set as a function of the Higgs mass and is shown in Figure 2. Limits on associated Higgs production from CDF are in progress; limits from DØ and OPAL are discussed in Refs. [9, 10].

3 $\gamma\gamma + X$

In the last couple of years, many models of new physics predict events with two high- P_T isolated photons produced in association with other particles in the final state. CDF has recently submitted a paper which describes a set of searches using a sample of two

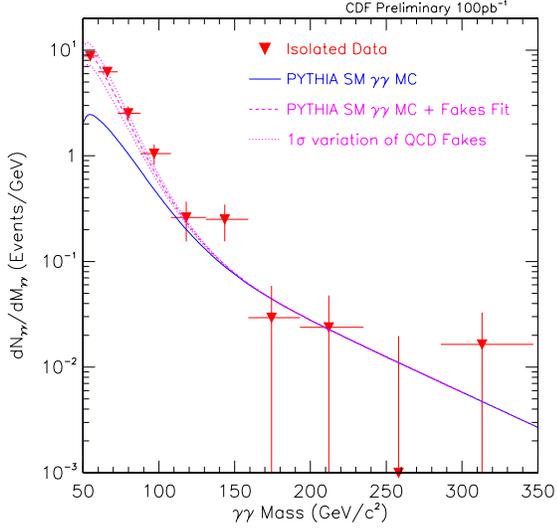


Figure 1: Diphoton mass distribution from CDF in the high mass $X \rightarrow \gamma\gamma$ search. The triangles are diphoton candidates, the solid line is the Standard Model prediction using PYTHIA. The dashed line is the sum of the PYTHIA diphotons and fakes. The dotted lines represent the 1σ uncertainties on the fakes estimate.

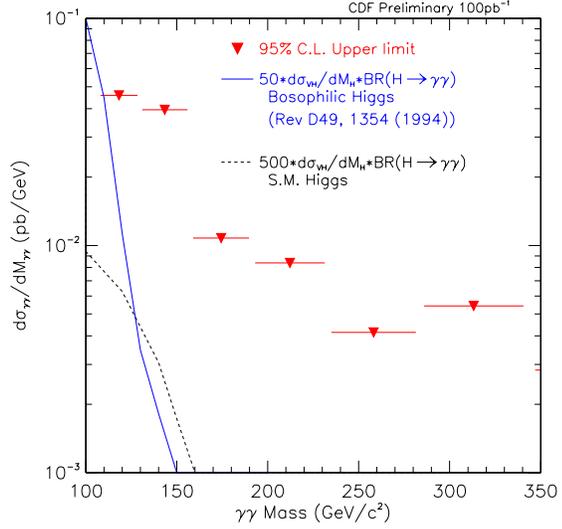


Figure 2: Cross section limit for high mass $X \rightarrow \gamma\gamma$ production.

isolated photons with $E_T^\gamma > 12$ GeV and $|\eta| < 1.0$ [6]. Each event is searched for anomalous production of $\gamma\gamma + X$ where X is \cancel{E}_T (from neutrinos or other particles such as Supersymmetric LSP's), jets, electrons, muons and taus, b -tagged jets, or extra photons.

3.1 $\gamma\gamma + \cancel{E}_T$

The $\gamma\gamma + \cancel{E}_T$ search is optimized to look for new heavy particles produced in Gauge-Mediated Supersymmetry with a light gravitino (\tilde{G}). In many of these models the sparticles decay into the lightest neutralino, N_1 , which in turn decays via $N_1 \rightarrow \gamma\tilde{G}$ producing two photons and \cancel{E}_T in every event. CDF has searched an integrated luminosity of 85 ± 7 pb^{-1} for $\gamma\gamma + \cancel{E}_T$ events using two different photon E_T thresholds: $E_T^\gamma > 12$ GeV and $E_T^\gamma > 25$ GeV. The results are shown in Figure 3. With a threshold of $E_T^\gamma > 12$ GeV, $\cancel{E}_T > 35$ GeV, 0.5 ± 0.1 events are expected with 1 event observed. For a threshold of

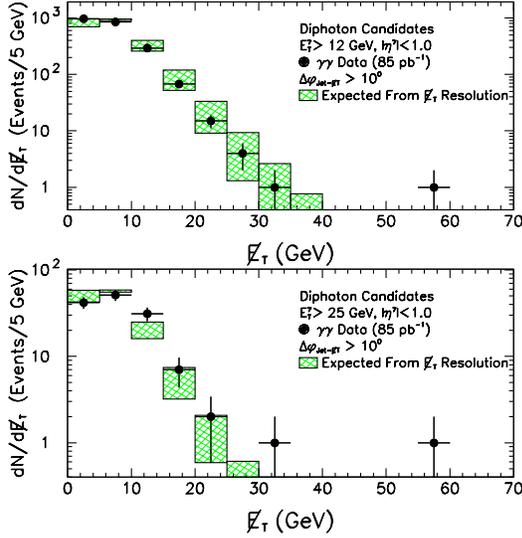


Figure 3: The E_T spectrum for diphoton events with $E_T^\gamma > 12$ GeV and $E_T^\gamma > 25$ GeV in the data from the CDF detector. The boxes indicate the range of the values of the E_T distribution predicted from detector resolution. The one event on the tail is the $ee\gamma\gamma E_T$ candidate event.

$E_T^\gamma > 25$ GeV and $E_T > 25$ GeV, 0.5 ± 0.1 events are expected with 2 events observed. The observations are consistent with background expectations with one possible exception on the tail of the distribution of Figure 3. This event is the $ee\gamma\gamma E_T$ candidate event (see Figure 6) and will be discussed later.

Limits have been set on a number of Supersymmetric models with a light gravitino by other collaborations [11, 12]. The CDF limit, interpreted in a Gauge-Mediated scenario in the MSSM with a light gravitino and using the full one-loop normalization group corrections (See Ref. [3]e) is shown in Figure 4. The lowest value of the lightest chargino mass, M_{C_1} , that is excluded at 95% C.L. is $M_{C_1} < 120$ GeV. Similarly, $M_{N_1} < 65$ GeV is excluded at the 95% C.L.

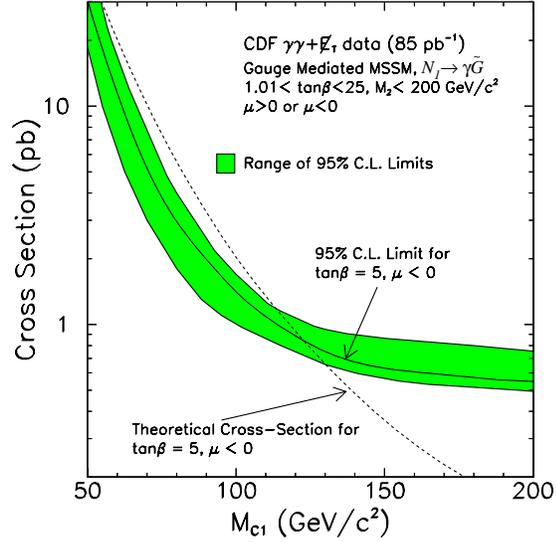


Figure 4: The cross-section upper limits versus the mass of the C_1 for a Gauge-Mediated model with a light gravitino in the MSSM and taking into account the one-loop renormalization group effects [3]e. The C_1 is excluded for all masses with $M_{C_1} < 120$ GeV.

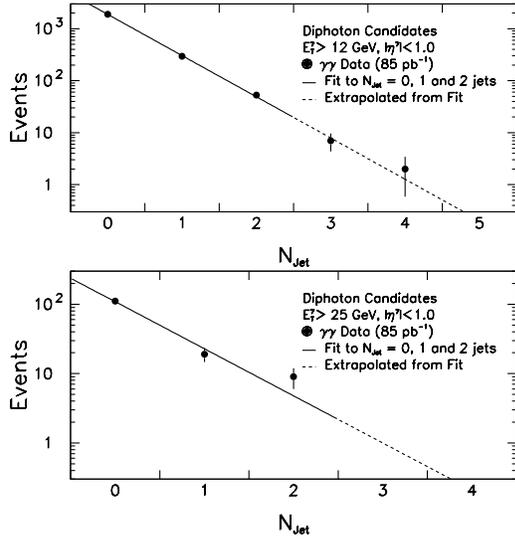


Figure 5: The number of jets, N_{Jet} , produced in association with diphoton pairs with $E_T^\gamma > 12$ GeV and $E_T^\gamma > 25$ GeV. The solid line is an exponential fit to the data, the dashed line represents the extrapolation for large values of N_{Jet} .

3.2 $\gamma\gamma + \text{Jets}$

The $\gamma\gamma$ data has also been searched for additional jet production. Jets which have $E_T > 10$ GeV and have $|\eta| < 2.0$ are counted and compared to expectations by using the low N_{Jet} results to estimate the production for large N_{Jet} . In the data with two photons with $E_T^\gamma > 12$ GeV, 2 events are observed with ≥ 4 jets with 1.6 ± 0.4 expected. Similarly, when both photons are required to have $E_T^\gamma > 25$ GeV, a total of 1.7 ± 1.5 are expected with ≥ 3 jets with 0 events observed. These results are shown in Figure 5 and are consistent with background expectations.

3.3 Other $\gamma\gamma + X$ Results

The $\gamma\gamma$ data is also searched for the presence of associated lepton, b -quark and/or additional photon production. The results are presented in Table 1. A total of 2 events with b -tags are found, consistent with background expectations. No events with a third

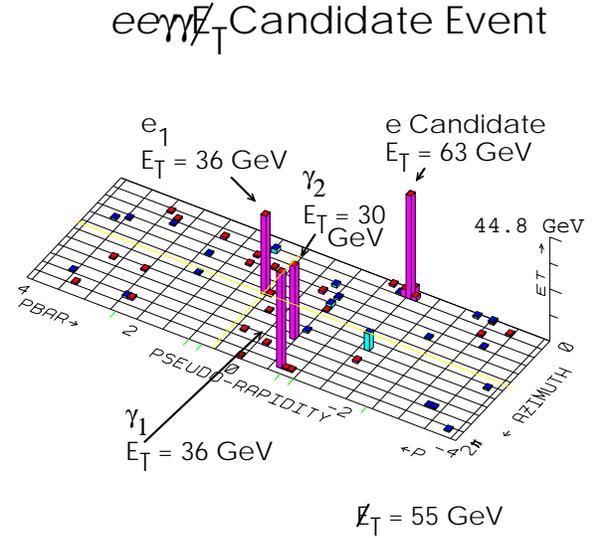


Figure 6: An event display for the CDF $ee\gamma\gamma E_T$ candidate event.

$E_T^\gamma > 12 \text{ GeV}$ Threshold		
Signature (Object)	Obs.	Expected
$\cancel{E}_T > 35 \text{ GeV}, \Delta\phi_{\cancel{E}_T\text{-jet}} > 10^\circ$	1	0.5 ± 0.1
$N_{\text{jet}} \geq 4, E_T^{\text{jet}} > 10 \text{ GeV}, \eta^{\text{jet}} < 2.0$	2	1.6 ± 0.4
Central e or μ , $E_T^e \text{ or } \mu > 25 \text{ GeV}$	3	0.3 ± 0.1
Central τ , $E_T^\tau > 25 \text{ GeV}$	1	0.2 ± 0.1
b -tag, $E_T^b > 25 \text{ GeV}$	2	1.3 ± 0.7
Central γ , $E_T^{\gamma 3} > 25 \text{ GeV}$	0	0.1 ± 0.1
$E_T^\gamma > 25 \text{ GeV}$ Threshold		
Object	Obs.	Exp.
$\cancel{E}_T > 25 \text{ GeV}, \Delta\phi_{\cancel{E}_T\text{-jet}} > 10^\circ$	2	0.5 ± 0.1
$N_{\text{Jet}} \geq 3, E_T^{\text{Jet}} > 10 \text{ GeV}, \eta^{\text{Jet}} < 2.0$	0	1.7 ± 1.5
Central e or μ , $E_T^e \text{ or } \mu > 25 \text{ GeV}$	1	0.1 ± 0.1
Central τ , $E_T^\tau > 25 \text{ GeV}$	0	0.03 ± 0.03
b -tag, $E_T^b > 25 \text{ GeV}$	0	0.1 ± 0.1
Central γ , $E_T^{\gamma 3} > 25 \text{ GeV}$	0	0.01 ± 0.01

Table 1: Number of observed and expected $\gamma\gamma$ events with additional objects in 85 pb^{-1} from CDF.

photon are found. There are 4 events with a central lepton: one event is consistent with a double-radiative Z^0 decay ($m_{\mu\mu\gamma\gamma} = 92 \pm 1 \text{ GeV}/c^2$), one is consistent with a radiative Z^0 decay with a lost track ($m_{ee\gamma} = 91 \pm 2 \text{ GeV}/c^2$), and one has a τ candidate, for which there is a fake background expectation of 0.2 ± 0.1 events. Other than the fourth event, the $ee\gamma\gamma\cancel{E}_T$ candidate event, there is agreement between the observations and the predictions.

4 The CDF $ee\gamma\gamma\cancel{E}_T$ Candidate Event

The CDF $ee\gamma\gamma\cancel{E}_T$ candidate event [6] (see Figure 6) is an unusual event. It has two photons which are very energetic ($E_T = 32$ and 36 GeV respectively), large \cancel{E}_T ($\cancel{E}_T = 55 \pm 7 \text{ GeV}$), a high- E_T central electron (36 GeV) and an electromagnetic cluster in the plug calorimeter (63 GeV) which easily passes the standard electron selection criteria used for Z^0 identification. The total P_T of the 4-cluster system is $48 \pm 2 \text{ GeV}/c$, opposite to the \cancel{E}_T and in good agreement with the measured magnitude, implying the imbalance is intrinsic to the 4-cluster system. The invariant mass of the electron and the

electromagnetic cluster in the plug calorimeter is $163 \pm 3 \text{ GeV}/c^2$, far from the Z^0 mass.

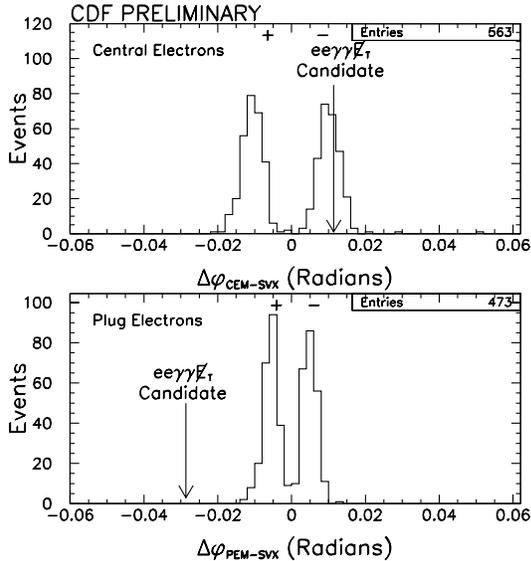


Figure 7: The $\Delta\phi$ between the measured electron position from the calorimeter and the ϕ from the SVX tracker for electrons from a $Z^0 \rightarrow e^+e^-$ control sample. The two peaks correspond to the bending of positively and negatively charged electrons in the magnetic field.

$Z^0 \rightarrow e^+e^-$ events. The probability of an electron to have a ϕ mismatch this large is estimated to be less than 0.3% at 95% C.L.

The interpretation of the cluster as coming from a photon, the 1-prong hadronic decay of a τ , or a jet, while possible, are unlikely in that this would be an unusual example of any of them [13]. The photon interpretation is unlikely as it requires the tracks in the SVX and VTX to be completely unrelated. The probabilities of this have been estimated to be at the few percent level. Another possibility is that this is the 1-prong hadronic decay of a τ , e.g, $\tau \rightarrow \pi^+\pi^0\nu_\tau$. However, more than 95% of τ 's leave a greater percentage of their energy in hadronic calorimeter than is observed. The probability that a generic jet would fake the electron signature in the plug calorimeter is estimated to be 2×10^{-3} / jet. The conclusion is that there is not enough information to establish the origin of the cluster.

Although the electromagnetic cluster in the plug calorimeter passes all of the standard electron selection criteria, there is reason to believe it is not an electron. CDF uses three tracking chambers to determine the charged particle trajectory. The trajectory only passes through the inner layers of the Central Tracking Chamber, so the efficiency to see a track is ≈ 0 . In addition, there is too much activity from the underlying event to see individual hits which might indicate a track. The results from the vertex finding chamber (VTX) are completely consistent with the single electron hypothesis. However, these results are not as precise as the silicon vertex detector (SVX) which shows no clear track pointing directly at the cluster. There is, however, a track 26 mrad away in ϕ . While this electron may have passed through a bad region of the detector, there are no other such events in a control sample of electrons (see Figure 7) from

4.1 How many $ee\gamma\gamma\cancel{E}_T$ events expected?

The Standard Model rates for producing a signature of two photons, two electromagnetic clusters (one central) passing the electron requirements and \cancel{E}_T , all with $E_T > 25$ GeV, and $M_{ee} > 110$ GeV/ c^2 (above the Z^0 boson) [13] has been estimated for $WW\gamma\gamma$ and $t\bar{t}$, as well as sources which include additional cosmic ray interactions, jets which fake electrons and/or photons, and overlapping events.

The primary estimate allows sources from both real electrons and fakes to contribute. The number of events is dominated by $WW\gamma\gamma$ production which should produce $(8 \pm 8) \times 10^{-7}$ events. The next highest producer is $t\bar{t}$ and yields $(3 \pm 3) \times 10^{-7}$ events. Fakes contribute $(3 \pm 3) \times 10^{-7}$ events. Two overlapping events (including cosmic ray contributions) contribute $(8 \pm 8) \times 10^{-9}$ events. Summing all sources yields $(1 \pm 1) \times 10^{-6}$ events. Since the plug cluster may not be due to an electron, a separate estimate is made by including only sources where the plug cluster is due to a jet faking an electron. The rate is reduced because the dominant sources are no longer allowed to contribute and the dominant source becomes $e\gamma\gamma\cancel{E}_T + j$ where the jet fakes the plug electron. In this case, the total rate is estimated to be $(6 \pm 6) \times 10^{-8}$ events.

5 Interpreting the Event

There has been a great deal of speculation about the $ee\gamma\gamma\cancel{E}_T$ candidate event. While *a priori* it's unlikely to be $WW\gamma\gamma$ production, it could be an example of 'anomalous' $WW\gamma\gamma$ production. This hypothesis allows for a quantitative estimate of anomalous $WW\gamma\gamma$ by looking for the hadronic decays of $WW\gamma\gamma$. Given 1 $ll\gamma\gamma\cancel{E}_T$ candidate event and using the ratio of acceptances and branching ratios, CDF predicts a total of 30 times as many $\gamma\gamma jjjj$ events to be seen in the data with two photons with $E_T > 25$ GeV. From Figure 5 no such $\gamma\gamma jjjj$ events are seen in the data. Anomalous $WW\gamma\gamma$ is excluded at the 95% C.L. as the source of the $ee\gamma\gamma\cancel{E}_T$ candidate event.

Most new models which predict $ee\gamma\gamma\cancel{E}_T$ events also predict $\gamma\gamma + \cancel{E}_T$. Currently a number of limits have already been for these models and there is no experimental evidence which furthers the understanding of the event.

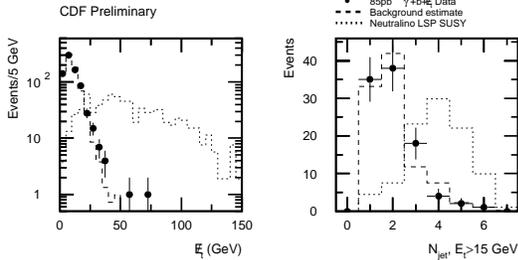


Figure 8: The missing E_T in $\gamma + b$ events, and the number of jets produced in $\gamma + b + \cancel{E}_T$ events from CDF. The dashed line is the background prediction, the points are the data, and the dotted line is the prediction from the light \tilde{t} model. The N_{Jet} spectrum is made by requiring $\cancel{E}_T > 20$ GeV. The SUSY model is normalized by a factor of 100 times the expected rate in the \cancel{E}_T plot and a factor of 10 in the N_{Jet} plot.

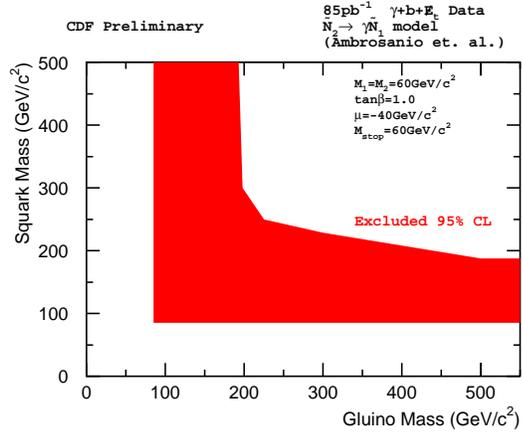


Figure 9: The area in the squark and gluino mass plane excluded in the $N_2 \rightarrow \gamma N_1$ model of Ambrosanio *et al.*, using the $\gamma + b + \cancel{E}_T$ analysis.

6 Searches in $\gamma b + X$

6.1 SUSY Models: light \tilde{t}

Motivated in part by the $e\bar{e}\gamma\gamma\cancel{E}_T$ candidate event, Ambrosanio *et al.* have predicted a neutralino LSP model, $N_2 \rightarrow \gamma N_1$ [4] with a light \tilde{t} . In this case, a chargino would decay via $C \rightarrow b\tilde{t} \rightarrow b(cN_1)$ and CN_2 production would have the final state signature $\gamma bc\cancel{E}_T$. At the Tevatron, the dominant production mechanism is from squark and gluino production which decay to CN_2 . CDF has studied $\gamma + b$ production in 85 ± 7 pb^{-1} of data with isolated photons with $E_T > 25$ GeV and $|\eta| < 1.0$, and a b -tagged jet with $E_T > 30$ GeV, and $|\eta| < 2.0$. A total of 1175 events are observed with 1000 ± 200 events expected, dominated by multijets with fake photons. The \cancel{E}_T distribution is shown in Figure 8 with two events passing a cut of $\cancel{E}_T > 40$ GeV. As a second search, the N_{Jet} distribution in the $\gamma + b + \cancel{E}_T$ events is studied. The N_{Jet} distribution for events with $\cancel{E}_T > 20$ GeV is shown in Figure 8. Since there is no excess, limits are set and shown in Figure 9.

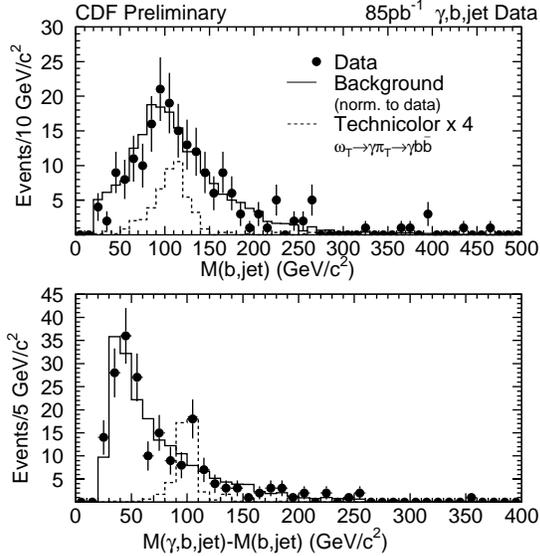


Figure 10: The $M(b_{\text{jet}})$ (top) and $M(\gamma, b_{\text{jet}}) - M(b_{\text{jet}})$ (bottom) for events with a photon, one b -tagged jet and second jet. The data are the points with error bars; the solid histogram is the background estimate (normalized to the data); the dashed histogram is a Monte Carlo simulation of a point in Technicolor parameter space, scaled up by a factor of 4

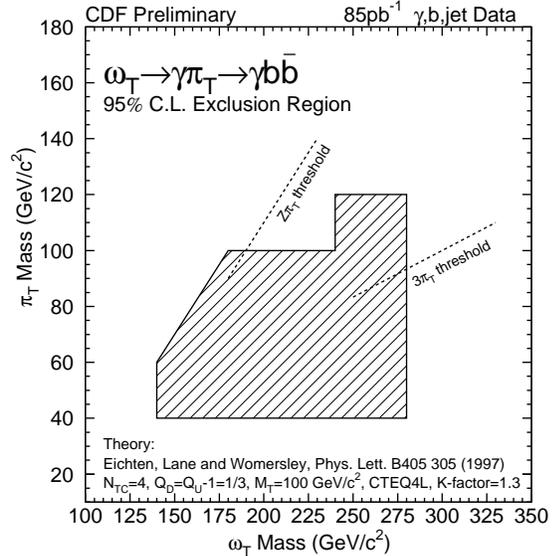


Figure 11: The 95% C.L. excluded region in the $\omega_T - \pi_T$ mass plane. The dashed lines indicate the thresholds for decay modes that are assumed to be zero in the model.

6.2 Technicolor: ω_T

In new models of Technicolor [7], there exists a new particle, ω_T , which for some region of parameter space decays predominantly via $\omega_T \rightarrow \gamma\pi_T \rightarrow \gamma b\bar{b}$. CDF has searched for such a decay using the same $\gamma + b$ datasets as before. In addition to the isolated photon with $E_T > 25$ GeV and $|\eta| < 1.0$, two jets are required with $E_T > 30$ GeV and $|\eta| < 2.0$, one of which is required to be b -tagged. There are 200 events in the data sample with 130 ± 40 events expected, dominated by fake photon backgrounds. Since the masses are fully reconstructed, peaks are expected in the $M(b_{\text{jet}})$ and $M(\gamma, b_{\text{jet}}) - M(b_{\text{jet}})$ distributions. The data as well as background expectations are shown in Figure 10. There is no evidence of new particle production. Limits are set on production assuming $\text{Br}(\omega_T \rightarrow \gamma b\bar{b}) = 100\%$ with the results shown in Figure 11.

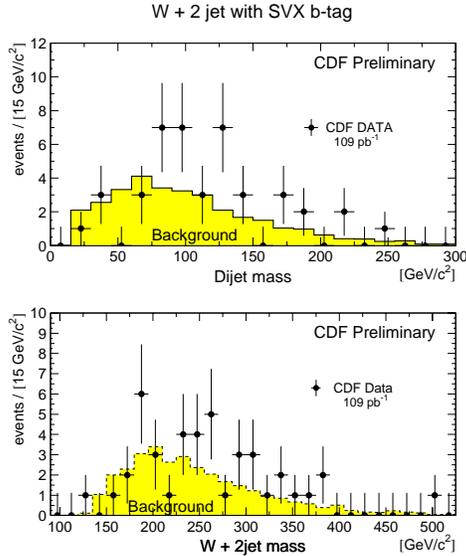


Figure 12: The invariant mass of the dijet and W +dijet mass systems for the W +2 jet sample with a b -tag.

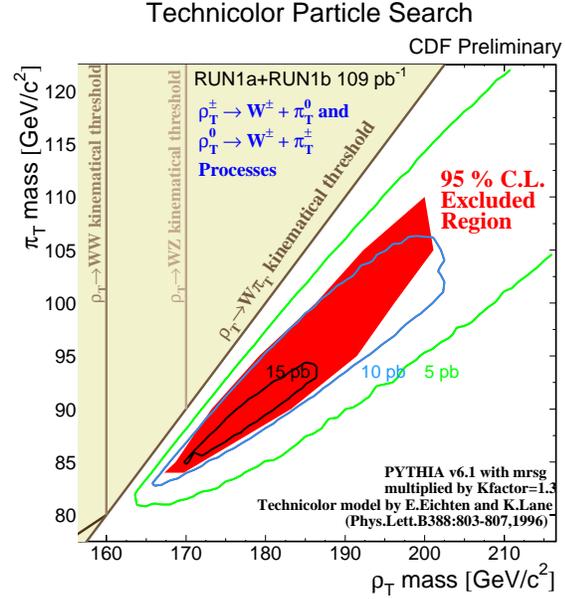


Figure 13: The 95% C.L. excluded region in the M_{π_T} vs. M_{ρ_T} mass plane (dark shaded region). The lines represent the contour of constant total production cross section.

7 WX and ZX production

7.1 Technicolor: ρ_T

The ω_T is not the only Technicolor particle recently searched for at the Tevatron. Recent results from a CDF search in $109 \pm 7 \text{ pb}^{-1}$ of data look for the production and decay of the ρ_T . The ρ_T can come in charged and neutral states and decay via $\rho_T^0 \rightarrow W \pi_T^\pm \rightarrow \nu b \bar{c}$ and $\rho_T^\pm \rightarrow W \pi_T^0 \rightarrow \nu b \bar{b}$ [8]. The search requires a high- P_T , charged lepton (e or μ), missing transverse energy, and two jets, one of which is required to pass b -tagging requirements. The e or μ is required to be isolated, have $P_T > 20 \text{ GeV}$ and have $|\eta| < 1.0$. The missing transverse energy is required to be $\cancel{E}_T > 20 \text{ GeV}$. The event is required to have two and only two jets with $E_T > 15 \text{ GeV}$ and $|\eta| < 2.0$. A total of 42 events are observed in the data with an expectation of 32 ± 4 events. The dijet and W +dijet masses¹ are shown in Figure 12. While a signal would show up as a bump in both distributions, there is no evidence for a bump in either. Limits on the production of the ρ_T are shown in Figure 13.

¹The W +Dijet mass is made by constraining the \cancel{E}_T system to have a mass consistent with that of a W boson.

7.2 Associated Higgs $\rightarrow b\bar{b}$

Both CDF and DØ have used the $\ell\nu b\bar{b}$ decay channel to search for and set limits on associated Higgs production (VH where V is a W or a Z^0) with $H \rightarrow b\bar{b}$ [2]. These results [14] are displayed along with results using the hadronic decays of the W boson from CDF and the $Z^0 \rightarrow \nu\bar{\nu}$ results from DØ [15] in Figure 14.

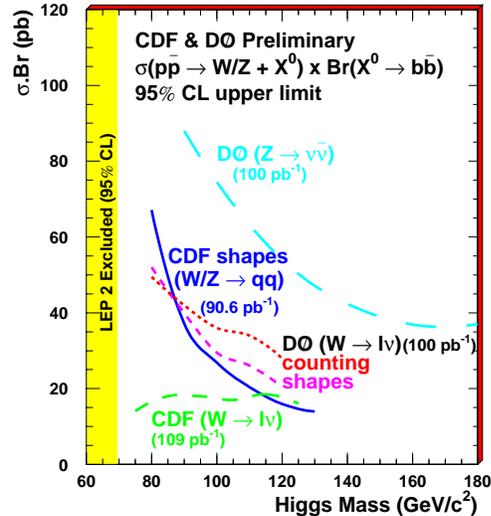


Figure 14: Summary of associated Higgs production limits with $H \rightarrow b\bar{b}$ from the CDF and DØ collaborations.

8 Conclusions

The CDF collaboration continues to search for new phenomena at the Fermilab Tevatron and has set limits on a number of Supersymmetric, Technicolor and Higgs models. The CDF $ee\gamma\gamma\cancel{E}_T$ candidate event has now been studied systematically. However, one of the electron candidates has an ambiguous interpretation and the origin of the event remains a mystery. While many searches for hints of its origin are complete (for some interpretations), many are still underway. With the Run II upgrades providing better acceptance and many times the data the future is very promising.

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