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Search for Hidden Dimensions in Run I Tevatron Data

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We describe the results of four new searches based on data samples from the 1992−1996 $p\bar{p}$ Collider run at Fermilab at $\sqrt{s} = 1.8$ TeV. DØ has searched for resonant slepton production in the two muon plus two jet channel. Using the R-parity violating ($\not{R}$) mSUGRA model, $\tilde{\nu}$ and $\tilde{\mu}$ masses up to 280 GeV/c^2 are excluded. CDF has searched for $\not{R}$ scalar top quark decays in two tau plus two jet events and set a limit of $m_{\tilde{t}_1} > 119$ GeV/c^2. DØ has searched for evidence of large extra dimensions in monojet production. Limits are set on M_D, the fundamental mass scale, of 0.68 and 0.63 TeV for $n = 4$ and 6 dimensions. CDF has interpreted a search for new physics in photon + missing energy events as a search for a gravitino and alternatively as a search for effects of graviton production. A gravitino mass limit $m_{3/2} > 1.17 \times 10^{-5}$ eV is set. Limits on M_D of 0.55, 0.58, and 0.60 TeV for $n = 4$, 6, and 8 are also determined.

1 Introduction

The Standard Model (SM) of particles and forces provides a solid framework for interpreting all the experimental data obtained so far. But it gives no explanation for the great difference between the Planck scale of 10^{19} GeV or the unification scale of 10^{16} GeV where all forces except gravity have equal strength, and the electroweak scale of 1 TeV where only the weak and electromagnetic forces are unified. This is refered to as the "hierarchy problem." Supersymmetry (SUSY), which is a symmetry between fermions and bosons, has been proposed as a solution to this problem. It predicts superpartners for all known particles. The cancellation of terms between superparticles solves the Higgs mass radiative correction problem. R-parity, a quantum number is defined which is +1 for SM particles and −1 for SUSY particles [1]. $R = (-1)^{3B+L+2S}$ where B, L and S are the baryon, lepton and spin quantum numbers. If R-parity is conserved then SUSY particles are produced in pairs and decay to the lightest supersymmetric particle (LSP). But R-parity is not required by SUSY to be conserved.

In supersymmetry, R-parity violation ($\not{R}$) can occur through the following additional terms in the superpotential, which are trilinear in the quark and lepton superfields [1]:

$$\lambda_{ijk} L_i L_j \bar{E}^c_k + \lambda'_{ijk} L_i Q_j \bar{D}^c_k + \lambda''_{ijk} \bar{U}^c_i \bar{D}^c_j \bar{D}^c_k, \tag{1}$$

where i, j, and k are family indices; L and Q are the SU(2)-doublet lepton and quark superfields; E, U, and D are the singlet lepton, up and down quark superfields respectively.

R-parity is approximately conserved. Experimental limits have been placed on the λ, λ', and λ'' coefficients [2,3]. To conform to these limits, usually only one coefficient is assumed to be non-zero. R-parity violation can occur in the production of only one SUSY particle, in the decay of the LSP to standard particles or in both production and decay.

Theories with large extra dimensions eliminate the hierarchy problem by bringing quantum gravity down to the electroweak scale. In a model developed by Arkani-Hamed, Dimopoulos, and Dvali [4], n extra spatial dimensions are assumed to be compactified. Standard Model gauge forces are confined to a 3+1 dimensional brane, while gravitons can propagate in the whole space. The compactification of these dimensions gives rise to Kaluza-Klein towers of states which appear as massive gravitons in the 3+1 brane. If such gravitons are directly produced and leave the 3 spatial dimensions, the experimental signature is the apparent non-conservation of energy and momentum, such as in events with a single photon or a single jet. The studies below use the phenomenological convention of Guidice, Rattazzi and Wells [5]. The compactified space is assumed to be a torus with radius R and fundamental mass scale M_D. Newton's constant $G_N^{-1} = M_{Pl}^2$ is replaced by $G_N^{-1} = 8\pi R^n M_D^{2+n}$, making the effective Planck scale the same as the electroweak scale for distances less that R. Constraints from astrophysical and cosmological considerations [6] are stronger than limits from gravitational measurements [7] and rule out models of with $n < 4$ large extra dimensions.

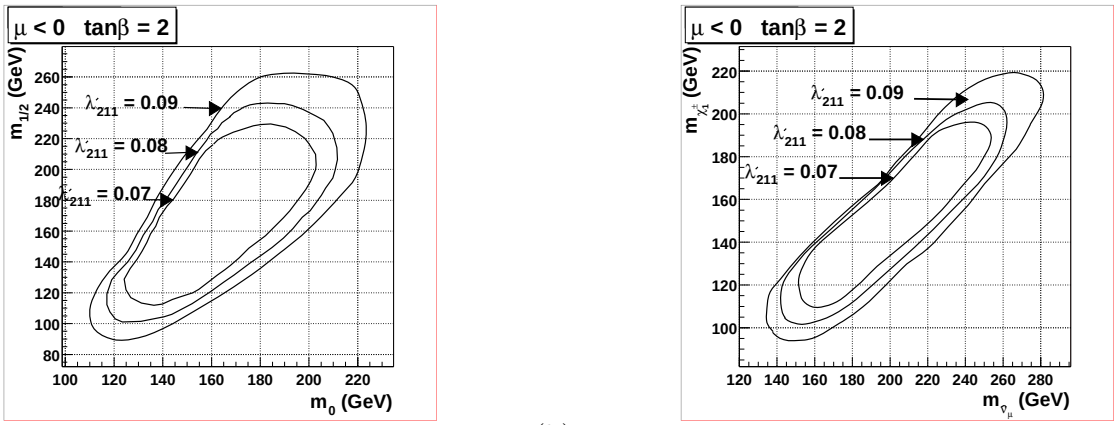
The DØ and CDF experiments took data from 1992−1996 at the Tevatron $p\overline{p}$ Collider at Fermilab at $\sqrt{s} = 1.8$ TeV. This data has been extensively studied to look for hints of SUSY and its hidden sectors, and more recently to look for effects predicted by theories with large extra dimensions. The results of four new searches are presented below.

2 DØ Search for Resonant Slepton Production

The two muon plus two jet final state has been studied by DØ using 94 pb^{-1}of data. The DØ detector is described in detail elsewhere [8]. The results of this study have been interpreted in terms of the R-parity violating mSUGRA model with single smuon and smuon neutrino s-channel production, assuming dominant λ'_{211} coupling ($L_2 Q_1 \bar{D}^c_1$). The production of a slepton (smuon or smuon neutrino) results in either a chargino or a neutralino together with either a charged lepton or a neutrino. It is assumed that the chargino decays into a neutralino, which decays into two jets and a muon, if λ'_{211} is dominant. The muon sneutrino decay into a muon and a chargino and the smuon into a muon and a neutralino lead to at least two muons and two jets in the final state. The results of the analysis are expressed in terms of the 5 mSUGRA parameters: m_0, the universal scalar mass at the unification scale M_{GUT}; $m_{1/2}$, the universal gaugino mass at M_{GUT}; $A = A_t = A_b = A_\tau$, the trilinear Yukawa coupling at M_{GUT},which is assumed to be zero, sign(μ), the sign of the Higgsino mixing parameter and $\tan\beta$, the ratio of the vacuum expectation values of the Higgs fields.

The initial data selection consists of two central jets, with $|\eta| < 1.0$ and $E_T > 20.0$ GeV and two central muons using 94 pb^{-1} of data. The sum of the E_T of the jets is also required to be greater than 50 GeV.

The signal topologies were generated with the SUSYGEN Monte Carlo program [9] using the cross sections computed in two papers by F. Déliot *et al.* [10,11] for a wide range of (m_0, $m_{1/2}$) masses. The analysis is further refined using a 7–5–3–1 neural network with the input variables:



(a) (b)

Figure 1: (a) DØ exclusion contours at the 95% C.L. in the (m_0, $m_{1/2}$) plane for $\tan\beta = 2$ and λ'_{211} =0.09, 0.08 and 0.07. (b) Exclusion contours at the 95% C.L. in the ($m_{\tilde{\mu}}/m_{\tilde{\nu}}$, m_{χ^+}) plane for $\tan\beta = 2$ and three values of λ'_{211}. Note that all contour plots are given as a function of the sneutrino mass. Due to the fact that the sneutrino mass is very close to the smuon mass for a given set of parameters, these contours are very close to the sneutrino contour plot and thus are not plotted.

the sum of the transverse energies of the two leading jets, the sum of the transverse momenta of the two leading muons, the distance in (η, ϕ) space between the two muons, the leading dimuon mass, the (η, ϕ) distance between the most energetic muon and its nearest jet, the sphericity in the laboratory frame, and the aplanarity. The neural network parameters are trained for desired results of -1 for background and +1 for signal events. Applying the best signal-over-background ratio to the neural network output gives optimized cuts at 0.0 for the $\tilde{\nu}$ and -0.10 for the $\tilde{\mu}$, respectively. The overall efficiency is 8% for $\tilde{\nu}$ and 4% for $\tilde{\mu}$. The estimated background is 1.01 ± 0.02, mostly from Z+2 jets and $t\bar{t}$, with a small contribution from WW + jets and is consistent with the 2 events observed. A Bayesian method is used to calculate the exclusion confidence levels (C.L.). To set exclusion contours, the (m_0, $m_{1/2}$) plane is scanned for three values of the coupling constant $\lambda'_{211} = 0.09,\ 0.08,\ 0.07$, with $\tan\beta = 2$, and sign(μ) $= -1$. The resulting exclusion contours at the 95% C.L. are shown in the (m_0, $m_{1/2}$) plan in Figure 1 (a) and in the ($m_{\tilde{\mu}}/m_{\tilde{\nu}}$, m_{χ^+}) plane in Figure 1 (b). Values of $m_{1/2}$ up to 260 GeV/c^2 for $\tan\beta$=2 and $\lambda'_{211} = 0.09$ are excluded. Equivalently masses up to 280 GeV/c^2 of $\tilde{\nu}$ and $\tilde{\mu}$ are excluded.

For low values of m_0 and $m_{1/2}$, the smuon mass is close to the chargino or neutralino mass, the p_T spectrum of the muons is soft, and the search is inefficient. For μ >0 and higher values of $\tan\beta$, the sensitivity decreases because the photino component of the LSP becomes small, resulting in the decrease of the branching fraction of the LSP into muons. In addition, charginos and neutralinos become light, resulting in events with softer muons and jets that fail the kinematic requirements.

3 CDF Search for R-parity Violating Scalar Top Quark Decays in Two Tau and Two Jet Events

A search for the lightest scalar top quark ($\widetilde{t}_1$), a supersymmetric partner of the top quark, has been performed using the 105.3 pb^{-1} data collected by the CDF detector, which is described elsewhere [12]. It is assumed that the scalar top quarks are produced in pairs and each decays through the $\lambda'_{333}\,\not{R}$ coupling: $\widetilde{t}_1 \to \tau + \mathrm{b}$. This implies that R-parity violation happens only in the third generation ($L_3 Q_3 \bar{D}^c_3$ superpotential term).

The experimental signature is two tau leptons and two b jets, where one tau decays into either an electron or a muon and the other tau decays into hadrons. The electron is required

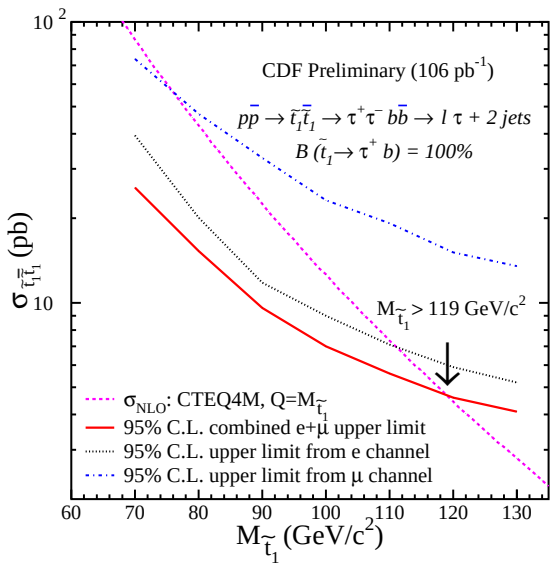


Figure 2: CDF 95% C.L. upper limit $\tilde{t}_1\overline{\tilde{t}_1}$ cross section from the e channel, 95% C.L. upper limit $\tilde{t}_1\overline{\tilde{t}_1}$ cross section from the μ channel, and 95% C.L. combined e+μ upper limit cross section for $\tilde{t}_1\overline{\tilde{t}_1} \to \tau\tau\ b\bar{b}$ and a NLO QCD cross section calculation using PROSPINO and CTEQ4M.

to have $E_T > 10$ GeV, $p_T{}^{trk} > 8$ GeV/c, and $|\eta| < 1.0$. The muon is required to have $p_T > 10$ GeV/c and $|\eta| < 0.6$. The second tau, decaying into hadrons (τ_h), is required to have $p_T > 15$ GeV/c and $|\eta| < 1.0$. The τ_h must have 1 or 3 tracks in a narrow cone and meet the CDF tau identification cuts [13]. Accepted events must also have two or more jets with $E_T > 15$ GeV. Additional selection criteria were imposed on transverse mass and scalar E_T: $M_T(l, \not{E}_T) < 35$ GeV/c^2 and $H_T(l, \tau_h, \not{E}_T) > 75$ GeV, where $l =$ e or μ. After applying these cuts no event is observed in either the electron or muon channels. The expected background is 1.92 ± 0.18 for the electron channel and 1.13 ± 0.14 for the muon channel from $Z(\to \tau\tau)$+jets, W+jets, diboson, Drell-Yan, top, and multijet events. The acceptance for $m_{\tilde{t}_1} = 120$ GeV/c^2 is 3.18% for electron data and 1.79% for muon data. The cross section of $\tilde{t}_1\overline{\tilde{t}_1}$ events is calculated by normalizing to Z $\to \tau\tau$ events, which cancels some systematic uncertainties. A 95% C.L. upper limit $\tilde{t}_1\overline{\tilde{t}_1}$ cross section from the e channel, a 95% C.L. upper limit $\tilde{t}_1\overline{\tilde{t}_1}$ cross section from the μ channel, and a 95% C.L. combined $e + \mu$ upper limit cross section are shown in Fig. 2 along with the next-to-leading order (NLO) QCD calculation using PROSPINO [14] and CTEQ4M. This gives a limit of $m_{\tilde{t}_1} > 119$ GeV/c^2.

4 DØ Search for Evidence of Large Extra Dimensions in Monojet Production

A search has been made for evidence of real graviton emission by DØ using 78.8 pb^{-1} of data. Events are required to have one jet with $E_T > 150.0$ GeV and $\not{E}_T > 150.0$ GeV. Events are rejected if there is a second jet with $E_T > 50.0$ GeV or if the event has an isolated muon. The background is estimated to be 38.0 ± 9.6, with 30.2 ± 6.4 from WZ production and the remaining contributions from QCD and cosmics. This is consistant with 38 events remaining in the data. Graviton Monte Carlo signal events were generated using a subroutine provided by J. Lykken and K. Matchev [15] as the external processs in PYTHIA [16]. 1000 events were generated for a range of n dimensions from 2 to 7, with the fundamental mass scale, M_D, ranging from 600 GeV to 1200 GeV, in 200 GeV intervals. The signal and background monte carlo samples were processed through the D0 Fast Monte Carlo Simulation Program. The acceptance for the signal varies between 5% and 8% depending on the values of n and M_D. Upper limits on the cross

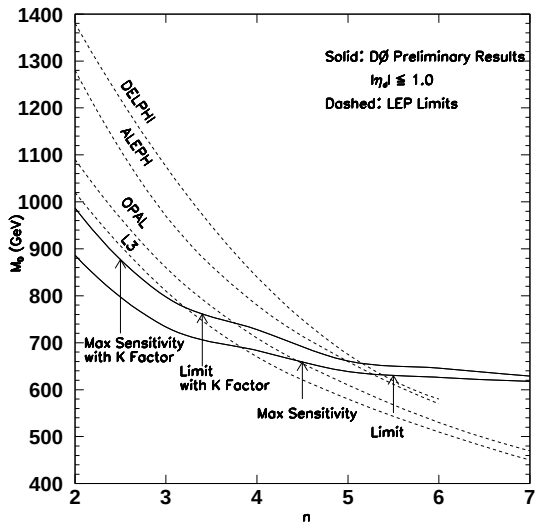


Figure 3: DØ 95 % C.L. exclusion contour for large extra dimensions with leading jet $E_T > 150.0$ GeV, $\not\!\!E_T > 150.0$ GeV, and $|\eta| \leq 1.0$. Dashed curves are the LEP limits .

section for the production of gravitons are calculated using Bayesian statistics and assuming no signal contribution in the data. Limits assuming a K factor [17] of 1.34 are also calculated. From these cross sections, lower limits on M_D are determined for different interger values of n. These are shown in Fig. 3 and listed in Table 1. The DØ limit is less than the best LEP limit from DELPHI [18] of $M_D >$ 0.84 TeV for $n = 4$. But the higher center-of-mass energy of the Tevatron leads to a better DØ limit of 0.63 TeV for n =6, compared to the DELPHI limit of 0.58 TeV.

Table 1: Lower limits at 95% C.L. on the fundamental mass scale, M_D, in TeV.

no. of extra dimensions	n=2	n=3	n=4	n=5	n=6	n=7
M_D(TeV)	0.89	0.73	0.68	0.64	0.63	0.62

5 CDF Limits on Extra Dimensions and New Particle Production in Photon + Missing Energy Events

Single photon production can indicate the production of invisible particles such as the gravitino in SUSY models and the graviton in models with large extra dimensions. CDF has studied the photon + $\not\!\!E_T$ channel using 87 pb^{-1} of data. The main selection criteria are one electromagnetic (EM) jet with $E_T{}^{\gamma} > 55.0$ GeV and $|\eta^{\gamma}| < 1.0$. The EM jet must pass CDF photon identification cuts [19,20]. Additional requirements include $\not\!\!E_T >$ 45 GeV, no jets with $E_T >$ 15 GeV and no tracks with $P_T >$ 5 GeV. Special timing cuts were also made to reduce cosmic ray events. The overall efficiency for all cuts varies from 45% at E_T= 55 GeV to 56% for $E_T >$ 100 GeV.

The SM background is small for this signature. The largest background, 6.2 ± 2.0 events, is due to remaining cosmic ray muons that bremsstrahlung a γ in the EM calorimeter, but no corresponding track is found. The second largest background from $q\overline{q} \rightarrow Z\gamma \rightarrow \nu\overline{\nu}\gamma$ is 3.2 ± 1.0 events. Small background contributions also come from W $\rightarrow e\nu$, prompt diphoton production, and $W\gamma$ production. The QCD background is estimated to be less that 1.0 events, but is not used since the uncertainty is very large. This gives a more conservative limit. The total background of 11.0 ± 2.2 is consistant with the 11 events which remain after the cuts.

Both background and signal events were generated using a modified version of PYTHIA with CTEQ5L and then processed through the CDF detector simulation program. The lack of excess events can be interpreted as a limit on superlight gravitino production in the process $q\overline{q} \rightarrow \widetilde{G}\widetilde{G}\gamma$, using the model of Brignole *et al.* [21], which assumes that the gravitino is the LSP and

that the other supersymmetric particles are too massive to be produced at Tevatron energies. This sets an absolute lower limit on the gravitino mass, $m_{3/2}$ and supersymmetry breaking scale $|F|^{1/2}$, where $|F| = \sqrt{3}m_{3/2}M_{Pl}$. From the lack of excess events in $\gamma + \not\!\!E_T$, a 95% C.L. limit of $|F|^{1/2} > 221$ GeV is set. The is equivalent to a gravitino mass limit $m_{3/2} > 1.17 \times 10^{-5}$ eV, which is similar to previous limits set by DELPHI in a $\gamma + \not\!\!E_T$ study and by CDF in a monojet $+ \not\!\!E_T$ analysis [18,19].

The same channel can also be interpreted as a search for direct graviton production from quark-antiquark annihilation. The limits obtained are listed in Table 2.

Table 2: Lower limits at 95% C.L. on the fundamental mass scale, M_D, in TeV.

no. of extra dimensions	n=4	n=6	n=8
M_D(TeV)	0.55	0.58	0.60

6 Conclusions

The new searches of Tevatron data show no evidence of the effects of supersymmetry or large extra dimensions. Other Tevatron analyses are now in progress. There is more good physics results to come from Run I data, while we look forward to Run II results!

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