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Searches for Exotic Particles at the Tevatron

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Searches for Exotic Particles at the Tevatron[1]

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This paper reports on recent searches for exotic particles by the CDF and DØ Collaborations. The results are derived from the data collected during the 1992-95 Run I at the Fermilab Tevatron. Limits are presented on new heavy gauge bosons, leptoquarks, monopoles and technicolor particles.

1 Introduction

The standard model has proved remarkably successful at describing the experimental observations at presently available energies. However, unsatisfactory explanations of some basic questions, notably the particle masses, have led to the development of extensions of the standard model. Many of these models predict the existence of new particles, some of which could be observed at the Tevatron. Both the CDF and DØ collaborations have searched for a number of these particles in the data collected during the 1992-95 Run I at a center of mass energy of 1.8 TeV, corresponding to an integrated luminosity of the order of 100 pb^{-1}. No evidence has been observed, therefore limits have been set on the production cross section times the branching ratio to a given channel as function the candidate particle mass.

New limits in a number of channels have been presented at this conference. This paper summarizes the present mass limits for new gauge bosons, leptoquarks, technicolor states, and monopoles, as well as for compositness scales.

2 Heavy Gauge Boson Searches

Heavy gauge bosons, in addition to the standard model W and Z, are predicted by many extensions of the standard model and Grand Unified Theories[2]. These particles may have decay modes analogous to the ones of the standrad model of W and Z. The models specify the coupling strengths, but make no predictions on the masses of the new bosons. In the absence of an observed signal, experiments set limits on the production cross section times branching ratio as a function of the new boson mass, from which mass limits are obtained in the context of a given model. Present searches via leptonic or quark decays have produced no observation of such particles. A recent search for $W' \to \mu\nu$ by the CDF collaboration that set a mass limit of 663 GeV/c^2 based on the Run I data set has been presented at this conference. The $\mu\nu$ transverse mass spectrum shown in Fig. 1 is consistent

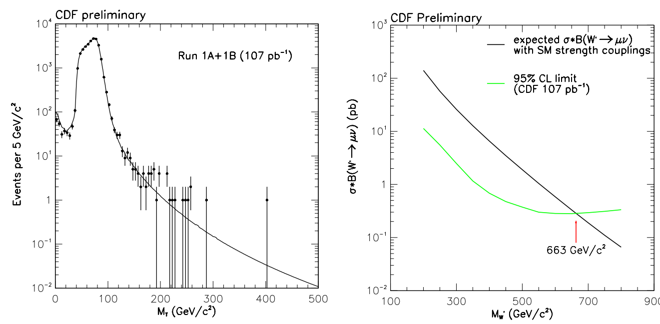

Figure 1: Left: Transverse mass distribution of the $\mu\nu$ system (dots) and the standard model expectation (line). Right: CDF upper limit on $\sigma \cdot B(W' \to \mu\nu)$ and the theoretical expectation for SM couplings.

with the expectation from W decay plus background, indicated by the line. The experimental limit on the cross section, with the theoretical expectation assuming standard model coupling strengths, is also shown in Fig. 1.

Table 1: New Gauge Bosons Mass Limits

	95% C.L. Limit (GeV/c^2)	$\int \mathcal{L}dt$ (pb^{-1})
$Z' \to e^+e^-$	> 655	CDF (110)
$Z' \to \mu^+\mu^-$	> 590	CDF (107)
$Z' \to l^+l^-(e^+e^-, \mu^+\mu^-)$	> 690	CDF (107)
$Z_\phi, Z_\eta, Z_\chi, Z_I \to l^+l^-$	>580,610,585,555	CDF (110)
$Z_{LR}, Z_{ALRM} \to l^+l^-$	$> 620{,}590$	CDF (110)
$W' \to e\nu$	>720	DØ (1a,1b)
$W'_R \to eN_R$ (heavy N_R)	> 650	DØ (1a,1b)
$W'_R \to eN_R$ (light N_R)	> 549	DØ (1a,1b)
$W' \to \mu\nu$	> 663	CDF (107)
$W' \to WZ$	> 560	CDF (90)
$W' \to jj$	$300 < M_{W'} < 420$	CDF (90)

Current mass limits for $Z' \to ee/\mu\mu$ in the contest of specific models[3] and for $W' \to (e/\mu)\nu/WZ/jj$[4] are

Table 2: Compositness Scale Limits (DØ)

Model	Λ^+ (GeV)	Λ^- (GeV)
LL	3300	4200
RR	3300	4000
LR	3400	3600
RL	3300	3700
VV	4900	6100
AA	4700	5500

summarized in Table 1.

3 Quark-Lepton Compositness

If quarks and leptons have a substructure, the constituent's contact interaction can contribute an additional amplitude to the standard cross section for the Drell-Yan process $q\bar{q} \to l^+l^-$. A deviation of the dilepton invariant mass distribution, M_{ll}, from the one predicted by Drell-Yan could indicated a compositness of the scattering partons. Previous searches performed with ee and $\mu\mu$ final states have set limits on the value of the compositness scale Λ in the range of 2.5 to 4.2 TeV[5], depending on the model. DØ has presented a new analysis of the dielectrons mass spectrum collected during Run I (120 pb^{-1}) to obtain the limits for the $e-q$ contact interaction scale shown in Table 2, where the +/- signs correspond to constructive or destructive interference, respectively.

4 Leptoquarks Searches

The apparent symmetry between leptons and quarks has suggested, in many extentions of the standard model, the existence of particles that carry both lepton and quark quantum numbers and couple directly to both leptons and quarks[6]. Theoretical models give no predictions on the values of the masses, but limits on these leptoquark states can be obtained from direct searches at the colliders, or indirectly from four-fermion interactions that could be induced by these particles. The absence of flavor-changing neutral currents and lepton family-violations, in particular, suggest leptoquarks that couple only within a single generation[7]. Leptoquarks may be directly pair produced at the Tevatron via the strong interactions, by $q\bar{q}$ annihilation or gluon fusion. The production cross section is therefore independent of the unknown $LQ-lq$ coupling.

Searches for all three generations of leptoquarks have been performed by the CDF and DØ collaborations. They have now combined their results for the search in a first generation scalar leptoquark[8,9], with the resulting mass limit of 242 GeV/c^2 for the branching ratio to

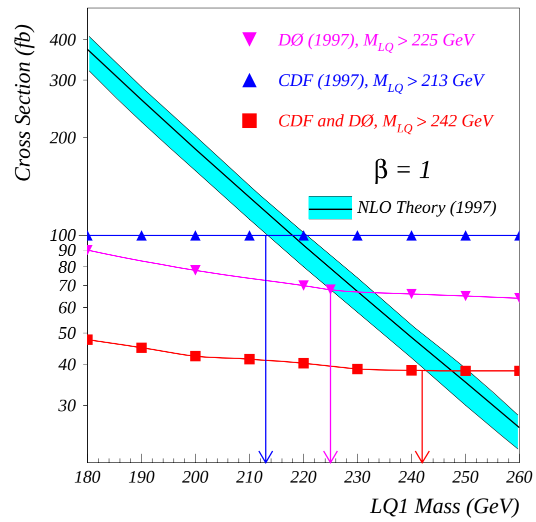

Figure 2: 95% CL upper cross section limits from CDF (triangles), D∅ (inverted triangles), and combined (squares) leptoquark analyses. The band shows the NLO theoretical cross section; arrows correspond to the respective 95% CL lower mass limits.

the ej channel $\beta = 1$. The combined cross section limit, with the theoretical calculation[10], is shown in Fig. 2. The DØ Collaboration has also extended the search for first generation leptoquarks to the vector case, using all final states corresponding to combinations of the decay mode into ej or νj. In this case the LQ cross section depends on the model and the mass limit is presented for typical choices of the couplings. The limits in M_{LQ} vs β space for different couplings are shown in Fig. 3. A summary of leptoquark mass limits, as a function of the unknown branching ratio β to the $(e/\mu/\tau)jet$ channel is shown in Table 3[11]. Although generational crossing is disfavoured by experimental constraints, it is not theoretically motivated. Bound states of leptons and quarks of different generations are allowed in some models, like the Pati-Salam model[12]. If such states exist, they could mediate decays of the type $B^o \to e\mu$, which are strictly forbidden in the standard model. This decay mode has been used by CDF to search for these leptoquarks in mass ranges well above those allowed by direct production at the Tevatron energies. The invariant mass distribution for oppositely-charged $e\mu$ pairs, originating from a vertex displaced from the primary interaction, has been searched for events consistent with the B_s (0 events) and B_d (1 event) masses. From the 95% limit on the branching ratios in 102 pb^{-1}, mass limits on the Pati-Salam leptoquarks of 19.3 TeV/c^2 and 20.4 TeV/c^2 have been obtained for the B_s and B_d cases, respectively.

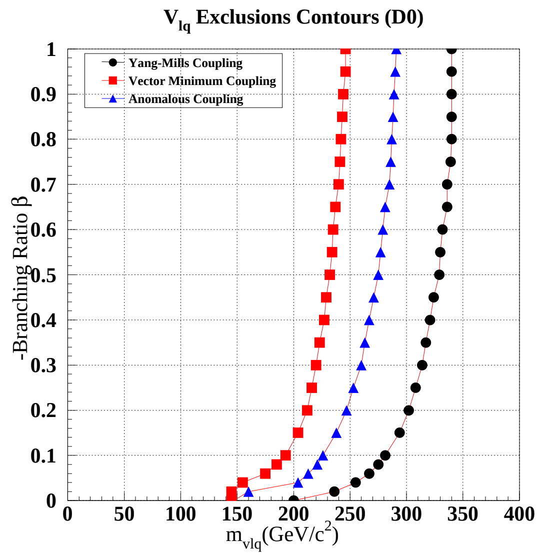

Figure 3: First generation vector LQ mass limits as function of the branching ratio β into the ej channel for Yang-Mills, anomalous, and minimal vector coupling.

Table 3: Leptoquarks Mass Limits

channel	β	$M_{LQ}(\text{GeV}/c^2)$	$(\int \mathcal{L}dt(pb^{-1}))$
first generation scalar			
$eejj$	1	213	CDF (110)
$eejj$	1	225	DØ (123)
$e(e/\nu)jj$	0.5	204	DØ (115)
$\nu\nu jj$	1	79	DØ (7.4)
$eejj$	1	242	CDF/DØ
first generation vector (Yang-Mills couplings)			
$eejj$	1	340	DØ (123)
$e(e/\nu)jj$	0.5	329	DØ (115)
$\nu\nu jj$	0	200	DØ (7.4)
second generation scalar			
$\mu\mu jj$	1	202	CDF (110)
$\mu\mu jj$	0.5	160	CDF (110)
$\mu\mu jj$	1	185	DØ
$\mu\mu jj$	0.5	140	DØ
third generation scalar			
$\tau\tau jj$	1	99	CDF (110)
$\nu\nu b\bar{b}$	0	94	DØ (1a,1b)
third generation vector (Yang-Mills couplings)			
$\tau\tau jj$	1	225	CDF (110)
$\nu\nu b\bar{b}$	0	216	DØ (1a,11b)

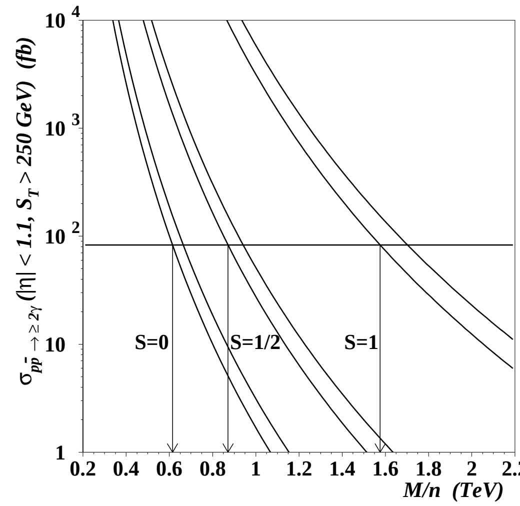

Figure 4: Theoretical cross section times acceptance for production of monopoles of spin 0, 1/2 and 1 as a function of M/n, where M is the monopole mass and n is an integer. The bands represent the uncertainty on the cross section. The horizontal line represents the DØ experimental cross section limit.

5 Monopole Search

DØ has searched for evidence of magnetic monopoles[13] in 70 pb^{-1} of diphoton data. Magnetic monopoles would allow rescattering of two photons via a box diagram, producing a distinct signature of two central, high energy photons. No events are observed with $S_T = \sum_i E_T^{\gamma_i} >$ 250 GeV, from which a 95% limit on the cross section, $\sigma(p\bar{p} \to \geq 2\gamma)|_{S_T>250GeV,|\eta^\gamma|<1.1} < 83fb$, is derived. Figure 4 shows the theoretical cross section for three values of the monopole spin times the experimental acceptances, compared to the observed $\sigma_{lim}^{95\%}$. The 95% C.L. mass limits are 610 GeV/c^2 (S=0), 870 GeV/c^2 (S=1/2) and 1580 GeV/c^2 (S=1).

6 Technicolor Searches

Technicolor models offer an alternative explanation for the mechanism of electroweak symmetry breaking. While in many extensions of the standard model the symmetry is spontaneously broken by fundamental scalar fields, the Higgs bosons, that give masses to the standard model W's and Z's, in technicolor models the symmetry is dynamically broken[14]. These models predict the existence of a number of new, heavy fermions interacting via the strong technicolor gauge interaction to form new boson bound states. Technicolor models have evolved to extended technicolor and topcolor-assisted technicolor to account for the fermion masses and the large value of the top quark mass. Recent models[15] predict techniparticles light enough to be produced at Tevatron en-

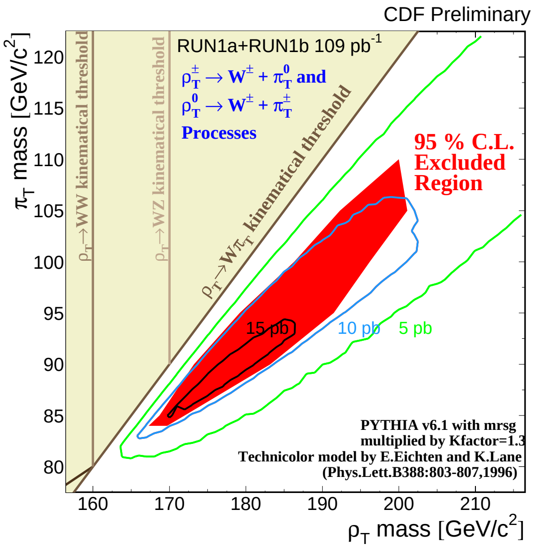

Figure 5: The 95% C.L. excluded region in the M_{ρ_T}, M_{π_T} plane. The lines represent production cross section contours.

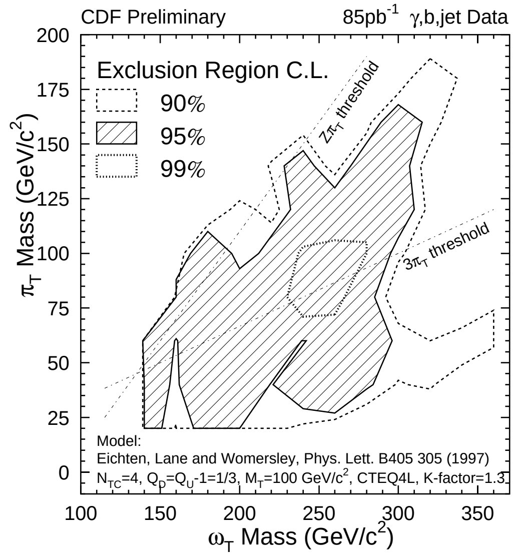

Figure 6: The 95% excluded region in the M_{ω_T}, M_{π_T} plane.

ergies. CDF has searched for technirho, ρ_T, and techniomega, ω_T, via their decay to technipions, π_T, and standard model bosons. The decays $\rho_T^\pm \to W^\pm \pi_T^o$ and $\rho_T^o \to W^\pm \pi_T^\mp$ would have the largest cross section for $M_W + M_{\pi_T} \leq M_{\rho_T} \leq 2M_{\pi_T}$. The π_T is expected to mostly decay to $b\bar{b}$ or $b\bar{c}$ states, therefore the final state will be characterized by the presence of two heavy quarks, identified by a vertex displaced from the primary interaction, while the W is identified by its leptonic decay into $(e/\mu)\nu$. The search requires an high transverse momentum, isolated lepton, large missing transverse energy, $\not{E}_T$, and two tagged jets. The presence of technicolor would be characterized by peaks in the $b\bar{b}$ ($\to \pi_T$) and the Wjj ($\to \rho_T$) mass distributions. A W mass constraint on the lepton and $\not{E}_T$ has been imposed for the M_{Wjj} calculation. The data are consistent with the expected background. Cross section limits for each M_{ρ_T}, M_{π_T} mass combination are obtained by counting events in a $\pm 3\sigma$ window around the given masses. Figure 5 shows the 95% C.L. excluded region.

Similarly, CDF has searched for ω_T via the $\gamma\pi_T$ decay channel, requiring an isolated photon and two jets, with at least one jet tagged as a b-jet. The distributions of the b-jet invariant mass and of $M_{\gamma,b,jet} - M_{b,jet}$ show no evidence of resonance production. The 95% C.L. excluded region in the M_{π_T}, M_{ω_T} plane is shown in Fig. 6.

7 Search for Resonances in $b\bar{b}$ States

New resonant states with widths narrower than the experimental resolution would manifest themselves in dijets mass spectra as peaks on top of a smooth distribution from the dominant QCD production of light quarks. Restricting the search to production of b quark pairs would reduce this background while increasing the sensitivity to production of new particles that couple preferentially to the third generation. Such exotic states would include a color-octect technirho ρ_{T8}[16], topgluon, topcolor Z'[17], and new gauge bosons. CDF has presented preliminary results from a study of the $M_{b\bar{b}}$ distribution from 87 pb^{-1} of data, shown in Fig. 7. The spectrum has been fitted to a smooth background plus a resonance shape, for a range of values of the resonance mass and width. The 95% C.L. upper limit on the cross section times branching ratio into $b\bar{b}$ pairs is shown in Fig. 8 as a function of the resonance mass for narrow states, and as an excluded region in the mass and width parameters for topgluons. The present data are not sensitive enough to exclude the models considered in this analysis, but the cross section limit can be applied to any state narrower than the exprimental resolution. This procedure appears promising for similar searches in the coming run of the Tevatron.

8 Conclusions

Searches for exotic particles with the data available from the Tevatron run I have not found any signals. New limits on the mass of a number of new particles have been presented at this conference:

- $M_{Z'}, M_{W'} > \approx 700$ GeV$/c^2$
- Compositness scale $\Lambda >$ (3.3 - 6.1) TeV
- Leptoquarks:
  - $M_{LQ1}^{scalar} > 242$ GeV$/c^2$ ($\beta = 1$)
  - $M_{LQ1}^{vector} > 340$ GeV$/c^2$ (Yang-Mills couplings)
  - Pati-Salam: $M_{LQ} > 20$ TeV$/c^2$

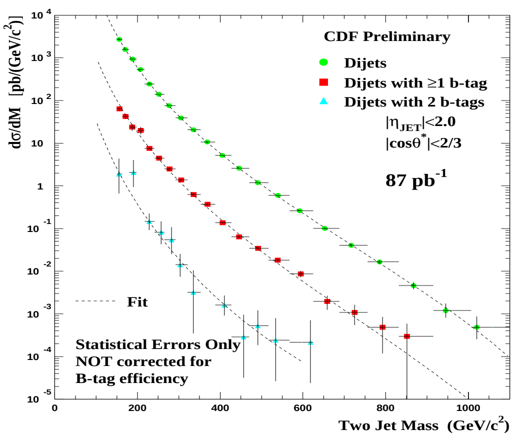

Figure 7: Mass spectra for inclusive dijet (dots), events with one b-jet (squares), and events with 2 b-jets (triangles).

- Dirac Monopole: $M/n > 610$ - 1580 GeV/c^2
- Walking Technicolor: limits on $\rho_T - \pi_T$, $\omega_T - \pi_T$
- Limits on topgluon, ρ_{T8} from $b\bar{b}$ mass spectrum

Run II, with an expected increase of luminosity of a factor of 20 and a center of mass energy of 2 TeV, will allow for either a discovery or significant increase of the present limits.

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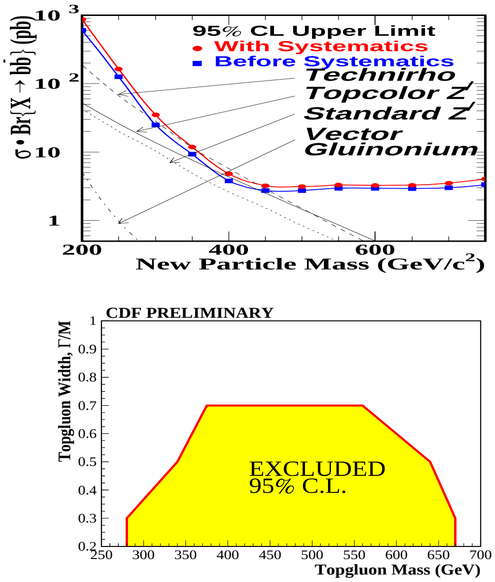

Figure 8: Top: 95% C.L. limit on $\sigma \times BR(X \to b\bar{b})$ as function of M_X, compared to the expected cross sections from typical models. Bottom: Togluon excluded region as a function of mass and width.