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SEARCH FOR LEPTOQUARKS AT CDF

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We present the result of direct leptoquark searches based on 110 pb^{-1} of integrated luminosity collected by the Collider Detector at Fermilab during the 1992-93 and 1994-95 Tevatron runs at $\sqrt{s} = 1.8$ TeV. We present upper limits on the production cross sections as a function of the leptoquark mass. Using the NLO calculation of the leptoquark-pair production cross sections we extract lower-mass limits for 1^{st}, 2^{nd}, and 3^{rd} generation leptoquarks. We also present the result of an indirect search for Pati-Salam leptoquarks via exclusive $e\mu$ decay modes of B_s^0 and B_d^0.

1 Introduction

The Standard Model which is based on the strong and electroweak interactions with $SU(3) \otimes SU(2) \otimes U(1)$ gauge group has been successful in describing the phenomenology of high energy particle physics. Features of the Standard Model such as the mass spectrum of the three generations of fermions or the quark-lepton symmetry are not yet understood.

Leptoquarks appear in several extensions to the Standard Model. They are color-triplet bosons which mediate interactions between quarks and leptons. Leptoquarks with a mass accessible through direct production at the current accelerators are usually assumed to couple to quarks and leptons of the same generation [1], in order to avoid large flavour-changing neutral current processes. One therefore speaks of leptoquarks of first, second, or third generation, which we will generically denote by Φ_i, $i = 1, 2, 3$. Quantum numbers such as the charge Q and weak isospin are model dependent.

For very heavy leptoquarks, well above the TeV scale, FCNC constraints can allow couplings to quarks and leptons in different generations. This is the case, for example, of the so-called Pati-Salam leptoquarks [2]. They appear as gauge vector bosons in a grand-unified extension of the Standard Model based on an enlarged color group $SU(4)_c$, which contains the lepton number as fourth color. A color-triplet set of $SU(4)$ gauge bosons acquires a mass when the $SU(4)$ group is broken, at a large mass scale, to $SU(3) \times U(1)$. The gauge nature of these leptoquarks dictates that they should couple to all generations, thereby inducing, among other processes, decays such as $B_s^0 \to e\mu$ and $B_d^0 \to e\mu$ [3]. Setting limits on the branching ratio of these otherwise forbidden processes can probe masses in the multi-TeV range.

We present in this work the preliminary results of leptoquark searches performed by CDF using the full 110 pb^{-1} of integrated luminosity from the Run IA+B data samples collected at $\sqrt{s} = 1.8$ TeV during the 1992-1995 Tevatron run. The direct searches are discussed in section 2, and the indirect search using $B_s^0 \to e\mu$ and $B_d^0 \to e\mu$ is presented in section 3.

2 Direct Search for Pair Produced Leptoquarks

Leptoquarks can be produced in pairs in $p\bar{p}$ collisions via strong interactions, through gluon-gluon fusion and $q\bar{q}$ annihilation [4]. The contribution to the production rate from the direct $\Phi\bar{q}l$ coupling is suppressed relative to the dominant QCD mechanisms. The cross section can therefore be calculated independently of the value of the leptoquark coupling λ, and is known today up to next-to-leading order (NLO) accuracy [5].

In this study we concentrate on leptoquarks which can decay to a quark and a charged lepton, with a non-zero branching ratio β. The search is therefore based on events with two charged leptons plus ≥ 2 jets. The jets are defined by the standard cone algorithm using the cone of 0.7 on $\eta-\phi$ space, and, unless otherwise stated, are required to be within $|\eta| < 2.4$.

2.1 3^{rd} generation search

CDF searched for the third generation leptoquarks decaying into two τ's and two jets ($\Phi_3\bar{\Phi}_3 \rightarrow \tau^+\tau^- jj$). The results of this search have been published in ref. [6], to which we refer the reader for full details. We present here a brief summary of the analysis. We require one τ to decay leptonically, the other hadronically. In the first case we consider e or μ decays, with the following selection criteria: $p_T\ (e,\mu) > 20$ GeV$/c$, the $\not{E}_T$ should point within 50^0 of the lepton direction and the leptons should be isolated. For the hadronic τ decay we require 1 or 3 charged tracks within a 10^0 cone about the jet axis and no other tracks above 1 GeV$/c$ between the 10^0 and 30^0 cones. Having selected $\tau\tau$ events we then require two additional jets with $E_T > 20$ GeV. The jets algorithm with 0.4 cone in $\phi - \eta$ space is used, and b-tagging is not required.

The final candidate events are selected by rejecting the events with the $\tau\tau$ invariant mass consistent with the Z^0 mass. Events where the primary lepton and the leading tau-jet track have an invariant mass in the range 70 to 110 GeV$/c^2$are therefore removed. After the event selection, we observe one event as Φ_3 candidate, with an expected background of $2.4^{+1.2}_{-0.6}$, which mainly comes from $(Z^0 \rightarrow \tau^+\tau^-) + jets$. Accounting for the selection efficiency, we can then exclude $M_{\Phi_3} <$ 99 GeV$/c^2$at 95% C.L. For vector leptoquarks with anomalous chromomagnetic moments parameterised by κ [7], assuming $\beta = 1$, our new limits exclude $M_{\Phi_3} < 170$ GeV$/c^2$ and $M_{\Phi_3} < 225$ GeV$/c^2$ for $\kappa = 0$ and $\kappa = 1$ respectively. The results are summarised in Figure 1.

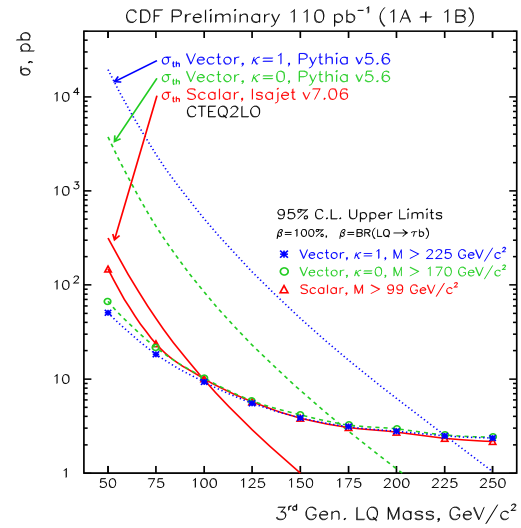

Figure 1: 95 % C.L. CDF cross section limit for Φ_3.

2.2 2^{nd} generation search

The search for Φ_2 production looks for events where the Φ_2 pair decays into dimuon + dijets ($\Phi_2\Phi_2 \rightarrow \mu^+\mu^- jj$). A previous CDF study [8] excluded $M_{\Phi_2} < 131(96)$ GeV$/c^2$ for $\beta = 1.0(0.5)$ using 19 pb^{-1} CDF data from Run IA. Results have also been published by D$\emptyset$ [9]. Here we present the new CDF limit using 110 pb^{-1} of data.

We require events with two muons, with $p_T > 30$ (μ_1) and > 20 (μ_2) GeV$/c$. Muon quality cuts, such as isolation, fiducial requirement and vertex matching, are also applied. Then we ask for ≥ 2 jets with $E_T{}^{(1)} > 30$ GeV and $E_T{}^{(2)} > 15$ GeV. The Z^0 and other resonances are removed by rejecting events with dimuon invariant mass ion the regions $M_{\mu\mu} < 10$ GeV$/c^2$and $76 < M_{\mu\mu} < 106$ GeV$/c^2$). 11 events pass the above selection cuts and are shown in Figure 2, plotted in the muon-jet invariant-mass plane ($M^1_{\mu j}$ v.s. $M^2_{\mu j}$). Of the two possible muon-jet pairings we choose the one with the smallest invariant mass difference.

In the case of leptoquark-pair decays the two muon-jet systems have approximately the same mass, within the mass resolution σ. We therefore search for leptoquark candidates by selecting events in a 3σ region of the $M^1_{\mu j}$ vs. $M^2_{\mu j}$ plane around any given mass, as shown in Fig. 2. This requirement reduces the background substan-

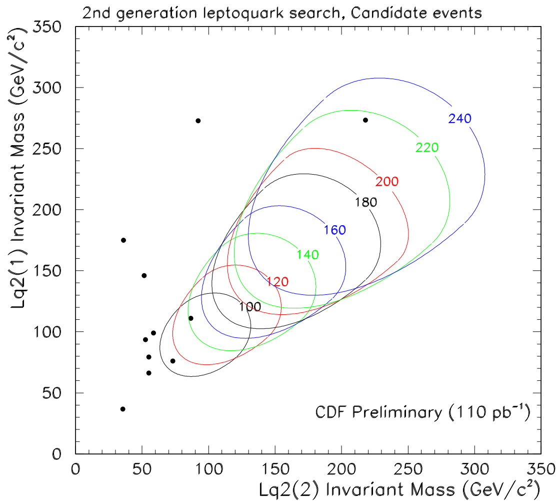

Figure 2: $M_{\mu j}$ distribution for events before the mass balancing cut.

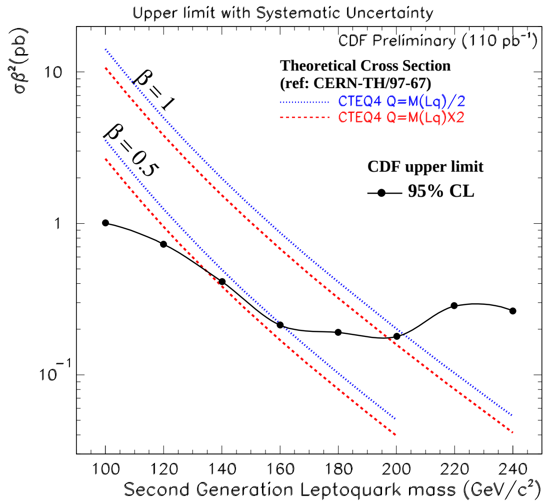

Figure 3: 95% C.L. CDF cross section limit for Φ_2.

tially, since the muon-jet invariant masses in background events are not correlated. Possible background sources are mainly from Drell-Yan and heavy flavour production and decay. The total signal detection efficiency for the signal depends on the Φ_2 mass, and it is calculated to be 15% at $M_{\Phi_2} = 200$ GeV$/c^2$. The major source of systematic uncertainty on the efficiency comes from the effects of gluon radiation. We compute the experimental cross section limit with 20 % systematic uncertainty.

Figure 3 shows the CDF 95% C.L. cross-section limit on the $\sigma(p\bar{p} \to \Phi_2\bar{\Phi}_2)\beta^2$. Comparing to the NLO cross-section calculation [5] a limit of $M_{\Phi_2} > 195$ GeV$/c^2$ ($\beta = 1.0$) is derived.

2.3 1^{st} generation search

The previous search for Φ_1 at CDF set a mass limit of 113(80) GeV$/c^2$ for $\beta = 1.0(0.5)$, using 4.05 pb^{-1} CDF data [10]. Interest in extending this search to the mass region around 200 GeV$/c^2$is stimulated by the recent results of the HERA experiments, which reported an excess of high-Q^2 deep inelastic scattering events [11].

The event selection for Φ_1 is similar to the Φ_2 selection, requiring high-E$_\mathrm{T}$ dielectrons in an event with at least two jets. We first select two electrons by requiring E$_\mathrm{T}$ > 25 GeV. We then ask for two or more jets in the whole rapidity range with E$_\mathrm{T}$ $(j_1) > 30$ GeV and E$_\mathrm{T}$ $(j_2) > 15$ GeV. A Z^0 veto is applied to the dielectron mass (76 GeV$/c^2 <$ M_{ee} 106 GeV$/c^2$). An additional cut is applied by requiring minimum values for the transverse-energy sum of the dielectron and dijet systems: $E_T(e_1) + E_T(e_2) > 70$ GeV and $E_T(j_1) + E_T(j_2) > 70$ GeV. This cut (ΣE_T cut) is efficient in removing major backgrounds such as Drell-Yan. The events passing this cut are displayed on the M^1_{ej} vs. M^2_{ej} plane in Figure 4. The e-jet pairings are chosen in the same way as in the Φ_2 search.

We select the Φ_1 candidates by requiring the two M_{ej}'s in the event to be within $< 0.2 \cdot M_{\Phi_1}$. The final Φ_1 candidates for a given mass M are selected by choosing events with the mean M_{ej} of the pair to be within 3σ of M.

The signal acceptance is evaluated using the PYTHIA Monte Carlo. It varies from 21% (M_{Φ_1} =140 GeV$/c^2$) to 28% (M_{Φ_1} =240 GeV$/c^2$). A 15% systematic uncertainty is used to compute the 95% C.L. CDF Φ_1 cross section limit, which is shown in Figure 5, compared with the theoretical calculations [5]. From this, we derive a limit of $M_{\Phi_1} > 210$ GeV$/c^2$ for $\beta = 1.0$.

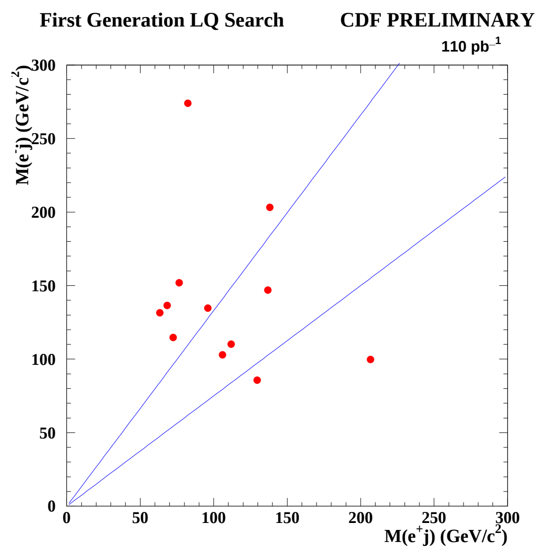

Figure 4: M_{ej} distribution of the events before leptoquark mass constraint.

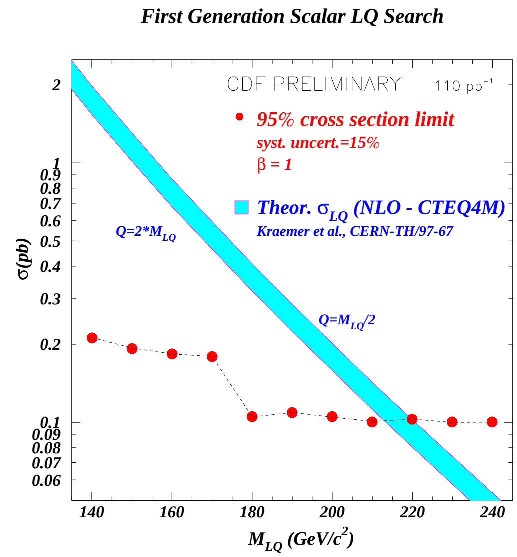

Figure 5: 95 % C.L. CDF cross section limit for Φ_1.

3 Indirect Search for Leptoquarks (Search for the decays $B_s^0 \to e\mu$ and $B_d^0 \to e\mu$)

CDF has searched for the decays $B_s^0 \to e\mu$ and $B_d^0 \to e\mu$ using $\approx$ 90 pb^{-1} of Run IB data. We select events with an oppositely charged $e\mu$-pair, the electron with E_T > 5.0 GeV and the muon with P_T >2.5 Gev/c. In addition we require the proper decay length $c\tau$ of the $e\mu$ system to be larger than $200\mu m$ and that the reconstructed momentum vector of the $e\mu$ pair point back to the primary vertex. We find no B_d^0 candidates in a mass window of $5.174 - 5.384$ GeV$/c^2$($\pm 3\sigma$ of our mass resolution) and one B_s^0 candidate in a mass window of $5.270 - 5.480$ GeV$/c^2$. We extract 95% CL limits at Br$(B_s^0 \to e\mu) < 2.3 \times 10^{-5}$ and Br$(B_d^0 \to e\mu) < 4.4 \times 10^{-6}$, including the systematic uncertainties. From this we derive the following limits on the mass of Pati-Salam leptoquarks discussed in ref. [3]: M > 12.1 TeV$/c^2$ for the B_s (as shown in Fig. 6) and $M >$ 18.3 TeV$/c^2$ for the B_d. This last limit improves the CLEO bound of 16 TeV$/c^2$ [12].

4 Summary

Using the full Run IA+B CDF data at the Tevatron, we have searched for direct production of leptoquark pairs in all three generations. For pair-produced scalar leptoquarks, the searches exclude $M_{\Phi_1} <$ 210 GeV$/c^2$ $(\beta = 1)$, $M_{\Phi_2} <$ 195 GeV$/c^2$ for $\beta = 1.0$, and $M_{\Phi_3} <$ 99 GeV$/c^2$ for $\beta = 1.0$. For the Φ_3 search, we also set limits for vector leptoquarks, excluding $M_{\Phi_3} <$ 225(170) GeV$/c^2$ for $\kappa = 1(0)$. CDF also performed an indirect leptoquark search via $B_s^0 \to e\mu$ and $B_d^0 \to e\mu$, setting preliminary mass limits for Pati-Salam type leptoquarks at 12.1 TeV$/c^2$ from B_s^0 decays, and 18.3 TeV$/c^2$ from B_d^0 decays.

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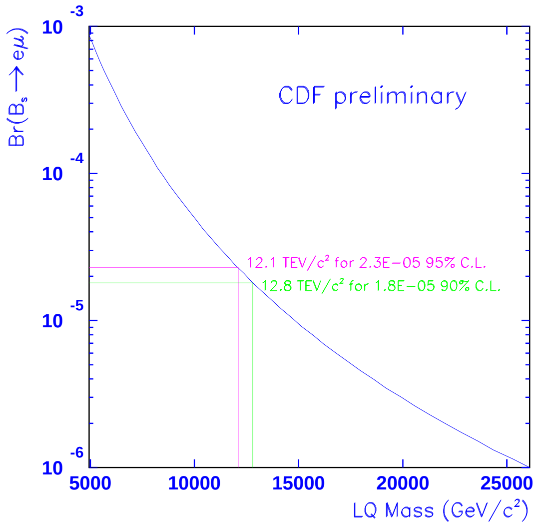

Figure 6: Pati-Salam leptoquark mass limit.

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