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 $B^0_s$ and $B^0_d$.

1 Introduction

The Standard Model which is based on the strong and electroweak interactions with the $SU(3) \otimes SU(2) \otimes U(1)$ 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 fermion generations 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 in order to avoid large flavour-changing neutral current processes. One therefore speaks of leptoquarks of first, second, or third generation, which we generically denote by $\Phi_i$, $i = 1, 2, 3$. 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. 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 $B^0_s \rightarrow e\mu$ and $B^0_d \rightarrow e\mu$. 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 $B^0_s \rightarrow e\mu$ and $B^0_d \rightarrow e\mu$ 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. The contribution to the production rate from the direct $\Phi ql$ coupling is suppressed relative to the dominant QCD mechanisms. The cross section can therefore be calcu-
lated independently of the value of the leptoquark coupling $\lambda$, and is currently evaluated up to next-to-leading order (NLO) accuracy.

In this study we concentrate on leptoquarks which can decay to a quark and a charged lepton, with a non-zero branching ratio $\beta$. The search is therefore based on events with two charged leptons plus $\geq 2$ 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 has searched for third generation leptoquarks decaying into two $\tau$'s and two jets ($\Phi_3 \Phi_3 \rightarrow \tau^+\tau^-jj$). The results of this search have been published in ref.\cite{ref}, to which we refer the reader for full details. We present here a brief summary of the analysis. We require one $\tau$ to decay leptonically, the other hadronically. In the first case we consider $e$ or $\mu$ decays, with the following selection criteria: $p_T(e,\mu) > 20 \text{ GeV}/c$, the $E_T$ should point within $50^\circ$ of the lepton direction and the leptons should be isolated. For the hadronic $\tau$ decay we require 1 or 3 charged tracks within a $10^\circ$ cone about the jet axis and no other tracks above 1 GeV/c between the $10^\circ$ and $30^\circ$ cones. Having selected $\tau\tau$ events we then require two additional jets with $E_T > 20$ GeV. The jet algorithm with a 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 a $\Phi_3$ candidate, with an expected background of $2.4^{+1.6}_{-0.8}$. coming mainly 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 $\kappa$, 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 2.

2.2 2$^{nd}$ generation search

The search for $\Phi_2$ production looks for events where the $\Phi_2$ pair decays into dimuon + dijets ($\Phi_2\Phi_2 \rightarrow \mu^+\mu^-jj$). A previous CDF study\cite{ref} excluded $M_{\Phi_2} < 131(96)$ GeV/c$^2$ for $\beta = 1(0.5)$ using 19 pb$^{-1}$ CDF data from Run IA. Results have also been published by D0\cite{ref}. Here we present the new CDF limit using 110 pb$^{-1}$ of data.

We require events with two muons, satisfying $p_T > 30$ GeV/c($\mu_1$) and $> 20$ GeV/c($\mu_2$). Muon quality cuts, such as isolation, a fiducial requirement and vertex matching, are also applied. Then we ask for $\geq 2$ 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 a dimuon invariant mass in the region $M_{\mu\mu} < 10$ GeV/c$^2$ and $76 < M_{\mu\mu} < 106$ GeV/c$^2$. A total of 11 events pass the above selection cuts and are shown in Figure 2, plotted in the muon-jet invariant-mass plane ($M_{\mu_j}$ v.s. $M_{\mu_j}$). 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 $\sigma$. We therefore search for leptoquark candidates by selecting events in a $3\sigma$ region of the $M_{\mu_j}$ v.s. $M_{\mu_j}$ plane around any given mass, as shown in Figure 2.
requirement reduces the background substantially, since in the background events, the reconstructed muon-jet invariant masses 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 $M_{\Phi^2}$ 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 a 20% systematic uncertainty.

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

### 2.3 1st generation search

The previous search for $\Phi_1$ 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. Interest in extending this search to the mass region around 200 GeV/$c^2$ is stimulated by the recent results from the HERA experiments, reporting an excess of high-$Q^2$ deep inelastic scattering events.

The event selection for $\Phi_1$ is similar to the $\Phi_2$ selection, requiring high-$E_T$ dielectrons in an event with at least two jets. We first select two electrons by requiring $E_T(e_1) > 25$ GeV. We then ask for two or more jets in the whole rapidity range with $E_T(j_1) > 30$ GeV and $E_T(j_2) > 15$ 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 is efficient in removing major backgrounds such as Drell-Yan. The events passing this cut are displayed on the $M_{ej}$ vs. $E_{T\text{jet}}$ plane in Figure 4. The $e$-jet pairings are chosen in the same way as in the $\Phi_2$ search.

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

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

3 Indirect Search for Leptoquarks (Search for the decays $B^0_s \to e\mu$ and $B^0_d \to e\mu$)

CDF has searched for the decays $B^0_s \to e\mu$ and $B^0_d \to e\mu$ using $\approx 85$ 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 $B^0_d$ candidates in a mass window of $5.174 - 5.384$ GeV/$c^2$ ($\pm 3\sigma$ of our mass resolution) and one $B^0_s$ candidate in a mass window of $5.270 - 5.480$ GeV/$c^2$.

We extract 95% CL limits at $\text{Br}(B^0_s \to e\mu) < 2.3 \times 10^{-5}$ and $\text{Br}(B^0_d \to e\mu) < 4.4 \times 10^{-6}$, including the systematic uncertainties. From this we derive the following 95% C.L. limits on the mass of Pati-Salam leptoquarks as discussed in ref.\textsuperscript{1}. $M > 12.1$ TeV/$c^2$ for the $B_s$ (as shown in Fig. 4) and $M > 18.3$ TeV/$c^2$ for the $B_d$. This last limit improves the CLEO bound of 16 TeV/$c^2$\textsuperscript{13}.

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 $\Phi_3$ 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 $B^0_s \to e\mu$ and $B^0_d \to e\mu$, setting preliminary mass limits for Pati-Salam type leptoquarks at 12.1 TeV/$c^2$ from $B^0_s$ decays, and 18.3 TeV/$c^2$ from $B^0_d$ decays.

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Figure 6: Pati-Salam leptoquark mass limit.

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