PHYSICAL REVIEW D VOLUME 44, NUMBER 1 1 JULY 1991

Single-leptoquark production in Z decays

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(Received 4 March 1991)

The possibility of observing leptoquarks which manifest themselves as rare decay modes of the Z is examined in a wide variety of models. At a Z factory, with $\gtrsim 10^7$ Z's, a significant signal for the production and decay of such particles can be obtained for masses as large as $\simeq 80$ GeV in some models.

The existence of leptoquarks is a relatively common prediction of many scenarios which are based on extensions of the standard model (SM), e.g., E_6 [1] and technicolor [2] models. In general, such particles may be either spin 0 or spin 1 and can have generation-dependent couplings. In our discussion below we will limit ourselves to scalar (spin-0) leptoquarks coupling only to the first or second generation (but not both). These leptoquark couplings will be assumed to be chiral, thus avoiding a number of constraints [3] on the masses and coupling strengths of such particles.

Leptoquark production at $\overset{(-)}{p}p$ [4], e^+e^- [5], and ep [6] colliders has been considered by a number of authors, particularly within the context of E_6 models. Although a small mass window for these states may still exist such that pair production in Z decays is possible [7], recent data [8] from the CERN e^+e^- collider LEP strongly indicate that their mass is larger than $M_Z/2 \simeq 45.6$ GeV. For leptoquarks above this mass scale, both the Fermilab Tevatron [4] and particularly the DESY ep collider HERA [6] will be able to substantially extend this search range in the not too distant future. In this paper, we examine the possibilities that leptoquarks (h) may still be observable at LEP I through rare Z decays provided that they are lighter than $\simeq 80$ GeV or so. Instead of the usual pair-production mechanism, we consider the process $Z \to \bar{h}h^* + \overset{(-)}{h}{}^*h$ (where $\bar{h}$ is the antiparicle of h and the asterisk indicates an off-shell state) with the subsequent decay $\overset{(-)}{h}{}^* \to lq$ as shown in Fig. 1.

The most general $SU(3)_c \times SU(2)_L \times U(1)_Y$ dimensionless couplings for scalar leptoquarks have been given by Buchmüller *et al.* [9], assuming separate baryon- (B-) and lepton- (L-) number conservation; both $|\Delta F| = 0$ and 2 type couplings (where $F \equiv 3B + L$) are possible. In a modified version of their notation, these couplings are given by

$$\begin{aligned} \mathcal{L}_{|\Delta F|=2} &= g_{1L}\bar{q}_L^c i\tau_2 l_L S_1 + g_{1R}\bar{u}_R^c e_R S_1' \\ &\quad + \tilde{g}_{1R} d_R^c e_R \tilde{S}_1 + g_{3L}\bar{q}_L^c i\tau_2 \tau l_L \bar{S}_3 , \\ \mathcal{L}_{|\Delta F|=0} &= h_{2L}\bar{u}_R l_1 R_2 + h_{2R}\bar{q}_L i\tau_2 e_R R_2' \\ &\quad + \tilde{h}_{2L}\bar{d}_R l_1 \tilde{R}_2 , \end{aligned} \tag{1}$$

with q_L, l_L being the conventional left-handed quark and lepton doublets and $\psi^c = C\bar{\psi}^T$ as usual. In principle, both S_1 and S_1' and R_2 and R_2' can be the same state or related through some symmetry; e.g., in E_6 models [1] S_1 and S_1' are just $\tilde{h}$ and $\bar{\tilde{h}}^c$. Using (1) we can identify leptoquarks via their particular decay modes, weak isospin, electric charge, and the chirality of their couplings; these are listed in Table I for both the $|\Delta F| = 0$ and 2 possibilities. For each case shown in the table, there corresponds a Z decay into an lq pair (due to the off-shell decay of the leptoquark) plus an on-shell leptoquark with the given values of T_3 and Q. With the assumption of chiral couplings, the overall coupling strength and the leptoquark mass (M_h) remain the only unknowns. In what follows we will rescale all of our couplings to the electromagnetic strength (as is usually done), e.g., $g_{1L} \to eF_{iL}$, etc. The generic unknown scaling factor will then be denoted by F.

Summing over both $Z \to \bar{h}h^*$ and $Z \to \bar{h}^*h$ modes, the partial width (Γ) for a typical process of interest (shown in Fig. 1) is given by

$$\Gamma = \frac{G_F M_Z^3}{16\sqrt{2}\pi^2}\alpha(M_Z) F \int_0^{1-\delta^2} dx_1 \int_{x_2^{\min}}^{x_2^{\max}} dx_2 \tilde{\Gamma}(x_1, x_2) , \tag{2}$$

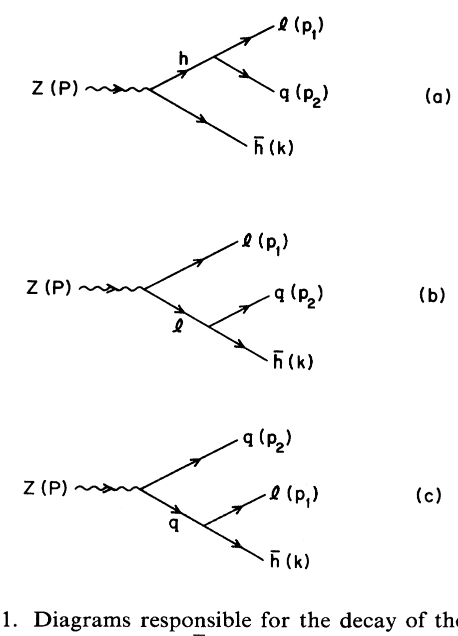

FIG. 1. Diagrams responsible for the decay of the Z into a single on-shell leptoquark ($\bar{h}$) accompanied by a lepton (l) and a quark (q).

TABLE I. Quantum numbers, couplings, and final-state decay modes for leptoquarks using the nomenclature in the text.

	Final state	$\|\Delta F\|$	Chirality	T_{3h}	Q_h	Origin
(1)	e^-u	2	LH	0	$-\frac{1}{3}$	S_1'
(2)	e^-u	2	RH	0	$-\frac{1}{3}$	$S_1,\mathbf{S}_3$
(3)	νd	2	RH	0	$-\frac{1}{3}$	$S_1,\mathbf{S}_3$
(4)	e^-d	2	LH	0	$-\frac{4}{3}$	$\tilde{S}_1$
(5)	νu	2	RH	1	$\frac{2}{3}$	$\mathbf{S}_3$
(6)	e^-d	2	RH	-1	$-\frac{4}{3}$	$\mathbf{S}_3$
(7)	$\nu\bar{u}$	0	RH	$\frac{1}{2}$	$-\frac{2}{3}$	R_2
(8)	$e^-\bar{u}$	0	RH	$-\frac{1}{2}$	$-\frac{5}{3}$	R_2
(9)	$e^-\bar{d}$	0	LH	$\frac{1}{2}$	$-\frac{2}{3}$	R_2'
(10)	$e^-\bar{u}$	0	LH	$-\frac{1}{2}$	$-\frac{5}{3}$	R_2'
(11)	$\nu\bar{d}$	0	RH	$\frac{1}{2}$	$\frac{1}{3}$	$\tilde{R}_2$
(12)	$e^-\bar{d}$	0	RH	$-\frac{1}{2}$	$-\frac{2}{3}$	$\tilde{R}_2$

where $x_2^{\min}=1-x_1-\delta^2$, $x_2^{\max}=1-\delta^2(1-x_1)^{-1}$ with $\delta \equiv M_h/M_Z$. We define, as usual,

$$P\cdot p_{1,2}=\tfrac{1}{2}M_Z^2x_{1,2},\quad P\cdot k=\tfrac{1}{2}M_Z^2x_3\ ,$$
$$p_{1,2}\cdot k=\tfrac{1}{2}M_Z^2(1-x_{2,1}-\delta^2)\ ,\quad p_1\cdot p_2=\tfrac{1}{2}M_Z^2(1-x_3+\delta^2)\ , \tag{3}$$

so that $x_1+x_2+x_3=2$. $\tilde{\Gamma}=|a+b+c|^2$, where

$$|a|^2=\frac{16C_h^2(1+\lambda^2)}{M_Z^4(1-x_3)^2}p_1\cdot p_2\left[\frac{(k\cdot P)^2}{M_Z^2}-M_h^2\right],$$
$$|b|^2=\frac{4(\alpha_1^2+\beta_1^2)}{M_Z^2(1-x_1)^2}\left[-M_h^2\left[p_1\cdot p_2+\frac{2P\cdot p_1\,P\cdot p_2}{M_Z^2}\right]+2p_2\cdot k\left[p_1\cdot k+\frac{2P\cdot p_1\,P\cdot k}{M_Z^2}\right]\right],$$
$$|c|^2=|b|^2(1\leftrightarrow 2)\ ,$$
$$2\,\mathrm{Re}(a^*c)=\frac{16C_h(\alpha_2+\lambda\beta_2)}{M_Z^4(1-x_2)(1-x_3)}\times\left[p_1\cdot p_2\left[-M_h^2+\frac{(P\cdot k)^2}{M_Z^2}\right]+\frac{P\cdot k}{M_Z^2}(P\cdot p_2\,p_1\cdot k-P\cdot p_1\,p_2\cdot k)\right],$$
$$2\,\mathrm{Re}(a^*b)=2\,\mathrm{Re}(a^*c)\quad(1\leftrightarrow 2,\ \text{and}\ \lambda\to-\lambda)\ ,$$
$$2\,\mathrm{Re}(b^*c)=\frac{8(\alpha_1\alpha_2-\beta_1\beta_2)}{M_Z^4(1-x_1)(1-x_2)}\times\left[p_1\cdot p_2(M_h^2+2p_1\cdot k)\frac{M_h^2+2p_2\cdot k}{M_Z^2}-4p_1\cdot k\,p_2\cdot k\right]. \tag{4}$$

In the above expressions we have defined $\alpha_1\equiv v_l-\lambda a_l$, $\alpha_2\equiv v_q+\lambda a_q$, $\beta_1\equiv a_l-\lambda v_l$, and $\beta_2\equiv a_q+\lambda v_q$ with $\lambda=+1$ $[-1]$ corresponding to left-handed (LH) [right-handed (RH)] leptoquark couplings and $v_{l,q}$ ($a_{l,q}$) are the usual vector (axial-vector) couplings of leptons and quarks to the Z boson in the SM (with $x_W\equiv\sin^2\theta_W$):

$$v_{l,q}=T_{3l,q}-2x_WQ_{l,q}\ ,\qquad a_{l,q}=T_{3l,q}\ . \tag{5}$$

The leptoquark coupling to the SM Z (C_h) has been normalized such that $C_h\equiv 2T_{3h}-2x_WQ_h$ with value of T_{3h} and Q_h which can be read off from Table I. In order to make specific numerical predictions we take the Z mass ($M_Z=91.177$ GeV) and the full Z width ($\Gamma_Z=2.496$ GeV) as given by the central values of the LEP data [8] and a value of x_W (the "effective" value of $\sin^2\theta_W$)$=0.2335$ corresponding to a common top-quark and Higgs-boson mass of 100 GeV [10]. In presenting our results we will display the corresponding branching fraction, $B=\Gamma/\Gamma_Z$, for the Z decay into a single-leptoquark final state as a function of the unknown leptoquark mass, M_h, for different values of F and the various choices for chirality, T_{3h} and Q_h.

Figures 2 and 3 show our results for B corresponding to the $|\Delta F|=2$ and $|\Delta F|=0$ cases, respectively. In addition to the obvious sensitivity to the overall coupling factor F and M_h, we see that B is remarkably sensitive to the leptoquark quantum numbers which is due to cancellation among the amplitudes shown in Fig. 1. For example, if $F=1$ and $M_h=60$ GeV, B can be as large as 1.0×10^{-5} or as small as 3×10^{-7}; the value of M_h for which B falls below 10^{-7} can range anywhere from 64 to 78 GeV. Typically, larger values of B are obtained when the leptoquark's charge and isospin assignments are somewhat exotic, e.g., if it is an isotriplet member or is contained in a doublet with a corresponding $Q=-\frac{5}{3}$ state.

Since the on-shell leptoquark subsequently decays, the actual parton level final state of the Z consists of two quarks and two leptons which may be observed in the 2 jet+missing energy, 2 jet+charged lepton+missing energy, or 2 jet$+l^+l^-$ modes depending on the leptoquark's quantum numbers. If, for example, the leptoquark is of the type S_1' or $\tilde{S}_1$ only the 2 jet$+l^+l^-$ mode is possible as a final state while leptoquarks of type S_1 or $\mathbf{S}_3$ (with $Q_h=-\frac{1}{3}$) can lead to all three possible final states. (The situation will be more difficult to analyze experimentally if the leptoquark is not an isosinglet and all the members of the multiplet have nearly degen-

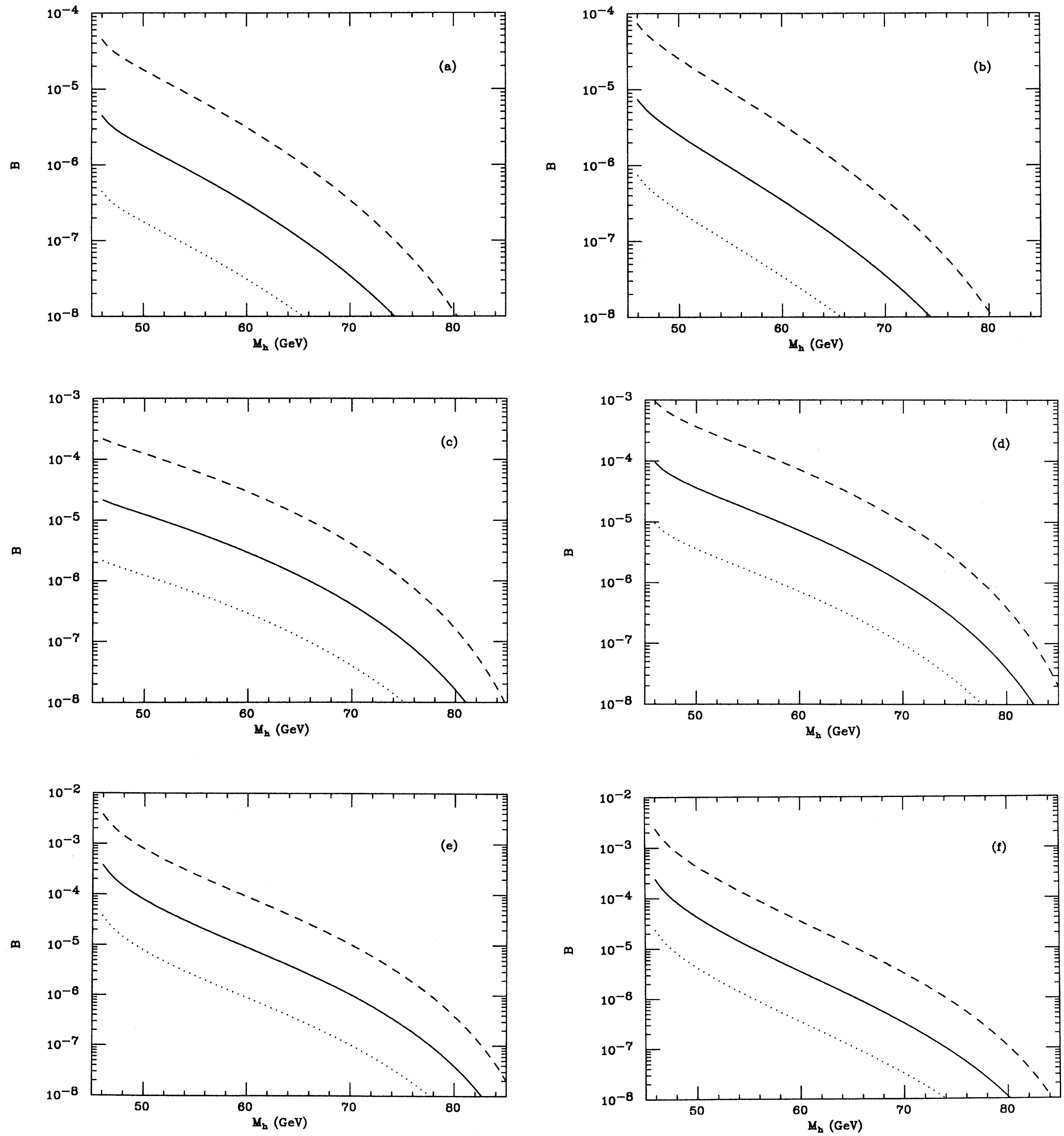

FIG. 2. Branching fraction for Z decay into a single leptoquark with $|\Delta F|=2$ type couplings for the following final states and coupling chiralities: (a) e^-u, LH; (b) e^-u, RH; (c) νd, RH; (d) e^-d, LH; (e) νu, RH; (f) e^-d, RH; corresponding to cases 1–6 in Table I. The various curves correspond to $F=10$ (dashed), 1 (solid), and 0.1 (dotted).

erate masses; this could happen, for example, in all of the $\Delta F=0$ type coupling cases.)

The SM backgrounds to these signatures are potentially large but they are quite dependent on which mode is being looked for experimentally. One potential background is $Z \to b\bar{b}$ with the b's decaying semileptonically; in this case the leptons and jets are nearby (leading to small invariant masses) and the events are accompanied by missing energy due to the associated neutrinos. Each jet+lepton pair would also be widely separated from the other since $b\bar{b}$ production is back to back. In the leptoquark 2 jet$+l^+l^-$ final-state case, the large value of M_h would tend to produce leptons and jets that are relatively isotropic in their distribution (with no accompanying

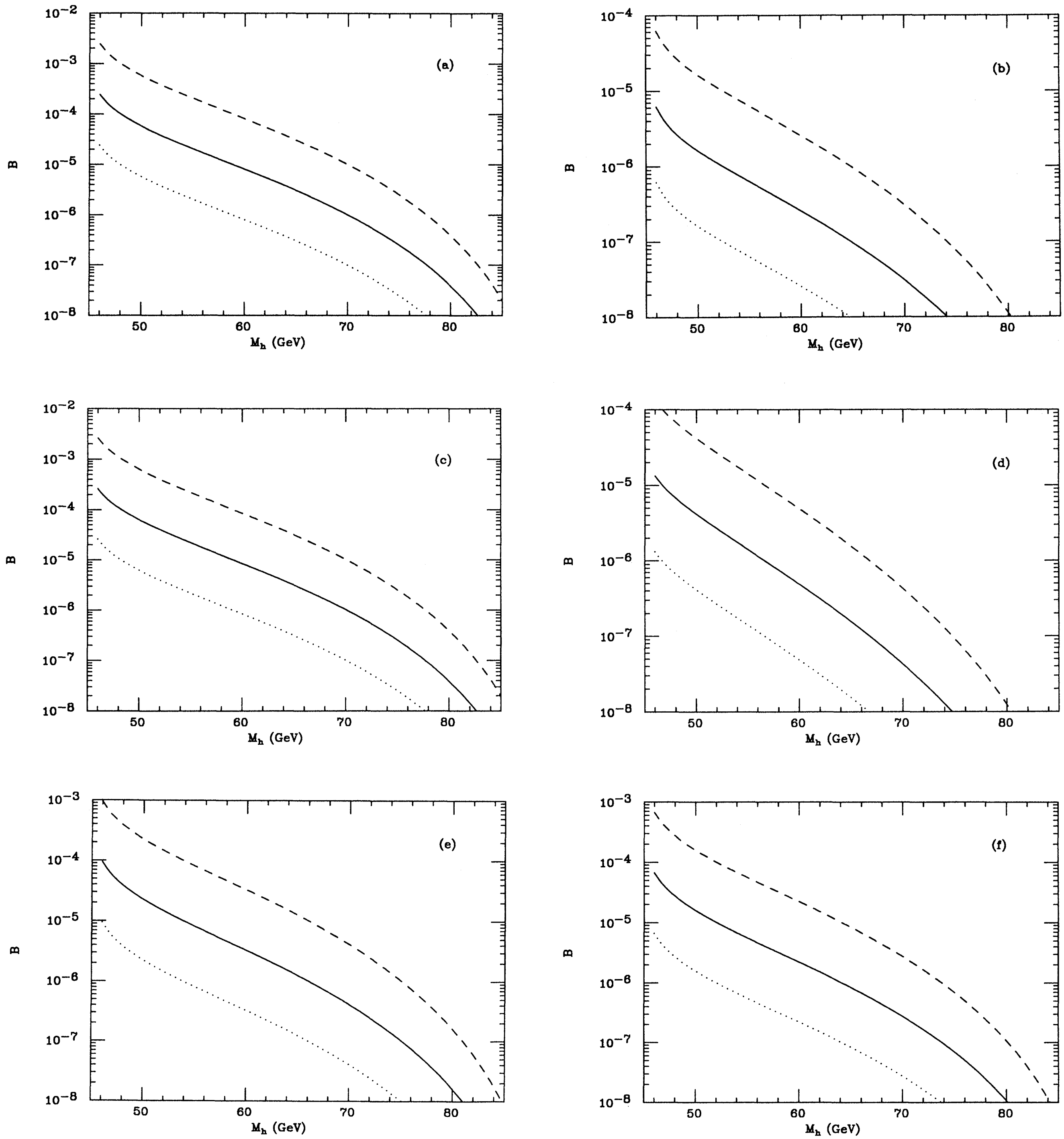

FIG. 3. Same as Fig. 2 but for $|\Delta F|=0$ type leptoquark couplings as given in Table I: (a) e^-u, RH; (b) $e^-\bar{u}$, RH; (c) $e^-\bar{d}$, LH; (d) $e^-\bar{u}$, LH; (e) $\nu\bar{d}$, RH; (f) $e^-\bar{d}$, RH.

missing energy) with the invariant mass of the l+jet from the on-shell leptoquark decay being large. Since $M_h \gtrsim 46$ GeV this l+jet pair will carry off at least 63% of the available energy with this fraction increasing to 72 (79) % for $M_h = 60$ (70) GeV. The lepton and associated jet from the off-shell decay will be much softer than their corresponding partners from the on-shell leptoquark decay, with the energy distribution for both these particles peaking at about $\frac{1}{3}$ of their maximum allowed values.

The second possible background in the 2 jet$+l^+l^-$ channel is from SM Higgs-boson production; we note that the branching fraction for $Z \to Z^* H \to H l^+ l^-$ in the SM is $\simeq 2\times 10^{-6}$ (4.5×10^{-7}) for a Higgs-boson mass (m_H) of 50 (60) GeV [11] and is comparable to the signal rate for our situation of interest. In the Higgs-boson case, however, the dilepton invariant-mass peaks as close to M_Z as possible and the dijets from the Higgs-boson decay will be predominantly b-quark jets which will have an invariant-mass peak at M_H with a width given by the detector resolution ($\simeq$ few GeV). These events will also have associated with them dijet and missing energy events (when $Z^* \to \nu\bar{\nu}$) at a rate $\simeq 6$ times more frequent than those with leptons. (Note that no *mixed* signatures are possible, *i.e.*, 2 jet$+l^\pm$+missing energy cannot arise from this background source.) Since the Higgs-boson events also do not show any l+jet peak they are easily separated from the leptoquark signal.

A third possibility is the decay of the Z directly into a two quark plus two lepton final state [12] through the emission of an additional virtual γ or Z off one of the fermion legs. The $q\bar{q}\nu\bar{\nu}$ final state is quite suppressed in this case since it can *only* proceed via emission of an additional Z; summing over three neutrino generations one finds a branching fraction $\lesssim 1.6\times 10^{-7}$ in this case [12] even without further cuts. The $l^+l^-q\bar{q}$ final state is potentially more dangerous since it is dominated by virtual-photon exchange; this background can be reduced significantly by requiring invariant masses of all fermion pairs to be $\gtrsim 10$ GeV since the l^+l^- or $q\bar{q}$ originating from the decay of the virtual photon will tend to have very small invariant masses. Such a cut has little effect on the signal since the leptons and jets are almost isotropic in the leptoquark case. With such a cut the background's branching fraction is reduced to $\simeq 1.8\times 10^{-6}$ which is still quite large. For this background, both leptons will have an identical energy distribution which is generally quite flat for lepton energies (E_l) in the range 8–40 GeV. The leptons from the leptoquark process will instead have quite different energy distributions and, as we noted above, the lepton from the virtual leptoquark decay will be quite soft. The jet pair mass from the background process will peak at the 10 GeV cut but no such peaking will be observable in the signal events; of course this background process does not show any lepton+jet mass peaking structure. it should be easily possible to reduce the background to the level of less than $B = 10^{-7}$ without too much difficulty and without a significant deficit in the leptoquark signal.

Given the broad range of possible couplings for leptoquarks in various models, they could be visible above SM backgrounds for masses $\gtrsim M_Z/2$ at LEP if their couplings are not too weak.

The author would like to thank the Phenomenology Institute at the University of Wisconsin—Madison for its hospitality and use of its facilities. This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the U.S. Department of Energy under Contract DE-AC02-76ER00881, and W-7405-ENG-82 (KA-01-01), Office of Basic Sciences.

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