# Testing the handedness of a heavy $W'$ at future hadron colliders

Mirjam Cvetič, Paul Langacker, and Jiang Liu

*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104*

(Received 12 August 1993)

We show that the associated production $pp \to W'W$ and the rare decay $pp \to W' \to \bar{l}lW$ are useful tests of $W'$ couplings to fermions at future hadron colliders. For $M_{W'} \sim (1-3)$ TeV they would allow a clean determination on whether the $W'$ couples to $V-A$ or $V+A$ currents. As an illustration a model in which the $W'^{\pm}$ couples only to $V-A$ currents is contrasted with the left-right-symmetric models which involve $V+A$ currents.

PACS number(s): 14.70.Pw, 12.10.Dm, 12.60.Cn, 13.38.$-$b

Many types of new physics, including some grand unified and superstring theories, predict the existence of additional charged and neutral gauge bosons ($W', Z'$). While their masses are *a priori* arbitrary, it is at least possible that they may be in the experimentally accessible range of a few TeV [1].

The present direct and indirect limits on additional gauge bosons are very model dependent. The bounds on the mass of a new $Z'$ are 160–400 GeV [2–5], although the limits are stronger, e.g., 500–1000 GeV, in some models in which the $Z'$ mass and the $Z$-$Z'$ mixing are related. In the version of left-right-symmetric models [6] with equal left- and right-handed gauge couplings and magnitudes of quark-mixing matrix elements, one has the stringent limit $M_{W'} > 1.4$ TeV from the $K_L - K_S$ mass difference [7]. In general left-right models, however, one has the weaker limit [8] $g_L M_{W'}/g_R > 300$ GeV. Stronger limits follow from $CP$ violation unless there is fine-tuning [9].

Heavy $Z'$ and $W'$ can be produced and detected by their leptonic decays at the CERN Large Hadron Collider (LHC) and Superconducting Super Collider (SSC) for masses up to $\sim 5$ TeV [1,10–17]. To identify the origin of such bosons, more detailed diagnostic probes of their couplings will be needed. Recent detailed studies [18–24] have demonstrated that the rare decay process [18,19] $Z' \to \bar{f}_1 f_2 V$ ($V = W, Z$), where $f_{1,2}$ are ordinary fermions, the associated production [23] $pp \to Z'V$ and the rapidity distribution in $pp \to Z' \to l^+ l^-$ [24] are useful diagnostics of the $Z'$ couplings to the ordinary fermions.

Another clean probe for the gauge couplings of $Z'$ and $W'$ is the forward-backward asymmetry [25]. For $pp \to Z' \to l^+ l^-$ ($l = e$ or $\mu$) and $pp \to W'^{\pm} \to l^{\pm} \nu_l$ the asymmetries can distinguish between different models for $M_{Z'(W')}$ up to a few TeV, and test some combinations of the couplings of $Z'$ and $W'$ to quarks and leptons. However, the forward-backward asymmetry for $W'^{\pm}$ does not distinguish $V+A$ couplings from $V-A$. Although the most likely extension of the standard model involving a $W'$ is the left-right-symmetric model [6] with $V+A$ couplings, it is possible to construct viable models with $V-A$ couplings as well [26]. It is therefore important to be able to distinguish $V+A$ from $V-A$.

Possibilities for distinguishing the handedness of $W'$

have been recently pointed out [19,22,23]. The basic idea is that the ordinary $W^{\pm}$ has only $V-A$ couplings, which acts as a filter for testing the handedness of $W'^{\pm}$. For example, if $W'$ has only $V+A$ couplings, the decay $W'^{\pm} \to W^{\pm} l^+ l^-$ will not occur at the lowest order except for small corrections from lepton masses. For the same reason the process $pp \to W'^{\pm} W^{\mp}$ would be strongly suppressed if $W'$ has the opposite handedness as $W$: in the left-right-symmetric model the suppression is proportional to the square of the $W'$-$W$ mixing angle or to the ratio $m_f^2/M_W^2$, where $m_f$ is a small fermion mass.

On the other hand, if the $W'$ couples to $V-A$ currents these processes would not be suppressed by the mismatch of the handedness. In this paper, we will examine this possibility in more detail. We will show that the number of events in the $V-A$ case can be sufficiently large to allow a clean determination of the handedness of a $W'$ with mass of the order of (1–3) TeV.

As an illustration we consider a theory [26] in which $W'$ couples to $V-A$ currents. This is an "ununified" theory of weak interaction with a gauge structure $SU(2)_q \times SU(2)_l \times U(1)_Y$, in which the left-handed quarks and leptons transform as doublets of their own SU(2). One set of linear combinations of the gauge bosons of $SU(2)_q$ and $SU(2)_l$ give the standard $W$ and $Z$, and the other become $W'$ and $Z'$. In this model both $W'$ and $Z'$ couple to $V-A$ currents. While this model was originally proposed as an alternative to the standard electroweak model with relatively light $W'$ and $Z'$, for our purpose we only consider situations in which the extra gauge bosons are heavy, i.e., $M_{W'}$, $M_{Z'} \geq 1$ TeV. Then, to leading order of $M_W^2/M_{W'}^2$, one finds $M_{W'} = M_{Z'}$. Neglecting fermion mixings the charged current interaction is given by

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}[(W_\mu^- + \cot\phi\, W_\mu'^-)\bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+ (W_\mu^- - \tan\phi\, W_\mu'^-)\bar{l}\gamma^\mu(1-\gamma_5)\nu_l]\,, \quad (1)$$

where $\tan\phi = g_l/g_q$ and $g_{l(q)}$ is the gauge coupling constant of $SU(2)_{l(q)}$. To have a meaningful perturbation calculation in what follows we consider that $\phi$ is not close to 0 or $\pi/2$. The neutral current interaction of $Z$ has the standard form, whereas that of $Z'$ is

$$\mathcal{L}_{\rm NC}(Z') = -\frac{g}{4} Z'_\mu \{ \cot\phi [ \bar{u}\gamma^\mu(1-\gamma_5)u - \bar{d}\gamma^\mu(1-\gamma_5)d ] - \tan\phi [ \bar{v}_l\gamma^\mu(1-\gamma_5)v_l - \bar{l}\gamma^\mu(1-\gamma_5)l ] \} \ . \tag{2}$$

The coupling constant for the trilinear $W'Z'W$ vertex is $g$, those involving a $W'ZW$ or $W'\gamma W$ vertex are further suppressed by the ratio $M_W^2/M_{W'}^2$. Gauge invariance relates the couplings in (2) and the trilinear gauge interactions, resulting in a destructive interference for the physical processes discussed below.

The heavy charged gauge boson $W'$, assuming its existence, can be produced at future hadron colliders (SSC and LHC) and can be detected via the resultant leptonic decays $pp \to W' \to \bar{l}v_l(\bar{v}_l l)$. For given $W'$ couplings the total cross section $\sigma(pp \to W')$ can be computed quite accurately. The cross sections are given in [15–17, 25]. For definiteness, we assume that the neutrinos to which the $W'$ couples are massless or light. This is the case for the ununified model [26], for which $v_l$ is the ordinary neutrino, and in some versions of the left-right-symmetric model. The same ideas would apply to models involving heavy (e.g., Majorona) neutrinos.

We first address the associated production. In the ununified model there are two tree-level graphs (Fig. 1). Contributions from these two graphs are equally important. In fact, gauge invariance requires that they interfere destructively to enforce unitarity. The squared amplitude for the quark process $q\bar{q} \to W'W$ averaged (summed) over initial (final) polarizations is

$$\frac{d\sigma_{W'W}}{dt} = \frac{g^4\cot^2\phi}{16\pi s^2}\mathcal{M} \ , \tag{3}$$

where

$$\mathcal{M} = -\frac{1}{4t^2}[3t^2 + t(s + M_{W'}^2 + M_W^2) + M_{W'}^2 M_W^2]$$

$$+ \frac{1}{s - M_{W'}^2}\left[ -\frac{M_{W'}^2}{2} + \frac{M_W^2}{8} + \frac{M_W^4}{8M_{W'}^2} - \frac{M_{W'}^4}{2t} - \frac{M_{W'}^2 M_W^2}{t} - \frac{tM_W^2}{16M_{W'}^2} - t \right]$$

$$+ \frac{1}{(s - M_{W'}^2)^2}\left[ -\frac{M_{W'}^2}{2} - \frac{7M_{W'}^2 M_W^2}{8} + \frac{M_W^4}{16} + \frac{tM_W^2}{2} + \frac{tM_W^4}{16M_{W'}^2} - \frac{t^2}{2} - \frac{t^2 M_W^2}{16M_{W'}^2} \right] \ , \tag{4}$$

and $s$ and $t$ are the Mandelstam variables.

The total cross section for $\sigma_{W'W}$ is obtained in a straightforward manner using the quark distribution functions of Ref. [27]. We define the cross section for $pp \to W'W$ as the sum over $W'^+W^-$ and $W'^-W^+$. For a 1 year ($10^7$ s) run at the LHC (SSC) with the projected luminosity of $10^{34}$ ($10^{33}$) cm$^{-2}$s$^{-1}$, the number of events along with typical statistical errors for the process $pp \to W'W$, with $W'$ subsequently decaying into $\bar{l}v_l$ and $\bar{v}_l l$ ($l = e$ and $\mu$) is presented in Table I. In obtaining these results we have assumed for simplicity that the $W'$ only decays to ordinary fermions, with the leading term of its total rate given by

$$\Gamma(W' \to \bar{f}f') = \frac{g^2 M_{W'}}{16\pi}(\tan^2\phi + 3\cot^2\phi) \ . \tag{5}$$

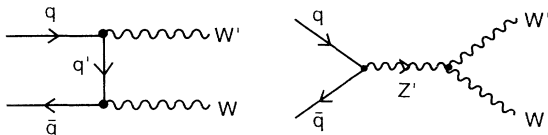These numbers are presented only for illustration. They should be contrasted with number zero, which would be the result if the $W'$ coupled to $V + A$ currents. On average, the numbers for the $W'W$ associated production are about two orders of magnitude larger than those from the $Z'W$ associated production [19]. One major reason is that in this model $W'$ has a larger coupling. Thus, the signal is still significant even for $M_{W'} = 3$ TeV.

The production of $W'W$, with $W'$ subsequently decaying into leptons and $W$ into hadrons are clean events without major background. The standard-model background from $pp \to WW$ with one $W$ decaying into leptons can be cleanly eliminated at a loss of only a few percent of the signal by requiring the transverse invariant mass of the lepton system to be larger than 90 GeV.

We now turn to the rare decay process $W' \to \bar{l}lW$. There are two tree-level graphs displayed in Fig. 2, and their contributions are equally important. Averaging



FIG. 1. Feynman diagrams for the associated production process $pp \to W'W$.

TABLE I. Number of events of the process $pp \to W'W$, with $W'$ subsequently decaying into leptons ($e$ and $\mu$), at the SSC and LHC. The errors are statistical.

| Collider | $W'$ mass (TeV) | $pp \to W'W$ $\phi = \pi/8$ | $\phi = \pi/4$ | $\phi = 3\pi/8$ |
|---|---|---|---|---|
| SSC | 1 | 1514±39 | 6681±82 | 4213±65 |
| | 2 | 131±11 | 579±24 | 365±19 |
| | 3 | 29±5 | 128±11 | 81±9 |
| LHC | 1 | 3200±57 | 14 120±119 | 8907±94 |
| | 2 | 146±12 | 644±25 | 406±20 |
| | 3 | 15±4 | 67±8 | 42±6 |

(summing) over the initial (final) polarizations of the squared amplitude we find

$$\frac{d\Gamma(W'\to\bar{l}lW)}{d\omega} = \frac{g^4\tan^2\phi}{24(2\pi)^5 M_{W'}^3 t^2(s-M_{W'}^2)^2}$$

$$\times \delta^4(P_{W'}-P_W-P_l-P_{\bar{l}})\mathcal{M}' , \qquad (6)$$

where

$$d\omega = (d^3\mathbf{P}_W/2P_W^0)(d^3\mathbf{P}_{\bar{l}}/2P_{\bar{l}}^0)(d^3\mathbf{P}_l/2P_l^0) ,$$

$t=(P_{W'}-P_l)^2$, $s=(P_{\bar{l}}+P_l)^2$, with $P_{W'}$, $P_W$, $P_{\bar{l}}$, and $P_l$ referring to the momenta of the corresponding particles, and

$$\mathcal{M}' = 16t^2 M_{W'}^2[M_{W'}^2(s-M_W^2)-t(s-M_{W'}^2)]+4tM_{W'}^2[3M_{W'}^4 M_W^2-3t(s+M_{W'}^4)-s(M_{W'}^4+sM_W^2+s^2)]$$

$$+4M_{W'}^2[M_{W'}^2(s^2+M_{W'}^4)(t-M_W^2)-2sM_{W'}^2 M_W^2(t-M_{W'}^2)-2t^4]$$

$$+t^2 M_W^2[2s(M_{W'}^2+M_W^2)-t(t+s-9M_{W'}^2)+M_W^2(t-M_{W'}^2)] . \qquad (7)$$

Because of the destructive interference of the two graphs in Fig. 2, there are no terms in (7) proportional to $1/M_W^2$. This preserves unitarity.

A simple analytic expression for $\Gamma(W'\to\bar{l}lW)$ can be obtained in the large $M_{W'}$ limit. The result is

$$\Gamma(W'\to\bar{l}lW) = \frac{2g^2\Gamma(W'\to\bar{f}f')}{192\pi^2(1+3\cot^4\phi)}\left[\left[\ln\frac{M_{W'}^2}{M_W^2}\right]^2 - 5\ln\frac{M_{W'}^2}{M_W^2} - \frac{\pi^2}{3} + \frac{37}{3} + O\left[\frac{M_W^2}{M_{W'}^2}\right]\right] . \qquad (8)$$

The double log term in (8) arises from the interference of the two graphs in Fig. 2 in the kinematic region in which $W$ is soft. For $M_{W'}\sim 1$ TeV numerical evaluation of $\Gamma(W'\to\bar{l}lW)$ using (6) and the analytic formula (8) is in excellent agreement with less than a few percent difference.

Although the rare decay $W'\to\bar{l}lW$ is suppressed by a factor of $\alpha/2\pi$ compared to $W'\to\bar{l}\nu_l$, the double log factor provides an enhancement. The observation of this logarithmic enhancement has led to a series of diagnostic studies [19–21] on the properties of $Z'$. The origin of these log factors is related to the infrared and collinear singularities of $S$-matrix elements, and is well known in QED and QCD.

To compare $W'\to\bar{l}lW$ with the basic process $W'\to\bar{l}\nu_l$ we define a ratio

$$R_{\text{lep}} = \frac{B(W'\to\bar{l}lW)}{B(W'\to\bar{l}\nu_l)} . \qquad (9)$$

We plot the distribution of $R_{\text{lep}}$ with respect to the invariant mass of the charged lepton pair for $M_{W'}=1$ TeV in Fig. 3. In accordance with the aforementioned logarithmic enhancement, the distribution is clearly dominated by configurations in which the dilepton invariant mass is large, implying that the $W$ is soft and/or collinear.

The number of events for the process $pp\to W'^\pm \to\bar{l}lW^\pm$ in the narrow width approximation of $W'$ is given by
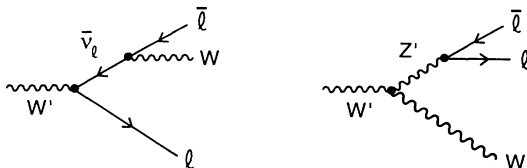
$$\mathcal{L}\sigma(pp\to W'^\pm)B(W'^\pm\to\bar{l}lW^\pm) .$$

The results along with their typical statistical errors are summarized in Table II. Again, they should be contrasted with number zero for a right-handed $W'$. Because of the large $W'$ gauge coupling the numbers for the $W'$ rare decay are about one order of magnitude larger than those of the corresponding $Z'$ decays [19–21].

The signal of the production of $W'$ followed by the rare decay $W'\to\bar{l}lW$ is very clean. The major background comes from the process $pp\to W'\to WZ$, with $Z$ decaying into a charged lepton pair. Although in the present model the coupling for the interaction $W'\to WZ$ is suppressed by $M_W^2/M_{W'}^2$, this background can be significant because of the enhancement of $W'$ decaying into longitudinally polarized $W$ and $Z$. However, the background events can
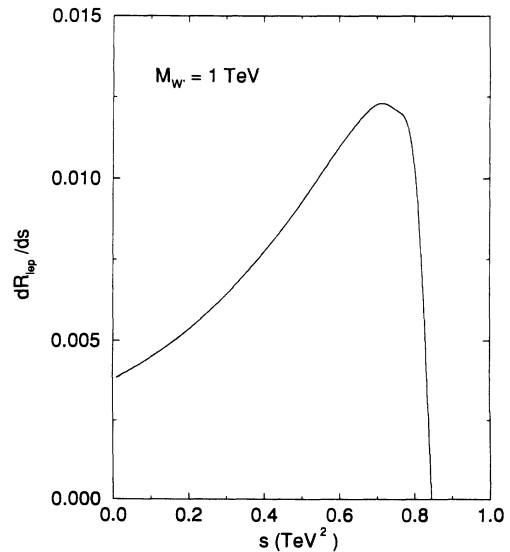
FIG. 2. Feynman diagrams for the rare decay process $W'\to\bar{l}lW$.

FIG. 3. Distribution of $R_{\text{lep}}$ defined in (9) with respect to the invariant mass of the charged lepton pair.

TABLE II. Number of events of the process $pp \to W'^{\pm} \to \bar{l}lW^{\pm}$ at the SSC and LHC, where $l = e$ and $\mu$. The errors are statistical.

| Collider | $W'$ mass (TeV) | $pp \to W'^{+} \to W^{+}\bar{l}l$ | | | $pp \to W'^{-} \to W^{-}\bar{l}l$ | | |
|---|---|---|---|---|---|---|---|
| | | $\phi = \pi/8$ | $\phi = \pi/4$ | $\phi = 3\pi/8$ | $\phi = \pi/8$ | $\phi = \pi/4$ | $\phi = 3\pi/8$ |
| SSC | 1 | 384±20 | 1694±41 | 1068±33 | 219±15 | 967±31 | 611±25 |
| | 2 | 79±9 | 348±19 | 220±15 | 40±6 | 175±13 | 111±11 |
| | 3 | 24±5 | 107±10 | 68±8 | 11±3 | 49±7 | 31±6 |
| LHC | 1 | 1065±33 | 4703±69 | 2965±54 | 513±23 | 2263±48 | 1427±38 |
| | 2 | 128±11 | 566±24 | 357±19 | 51±7 | 225±15 | 142±12 |
| | 3 | 21±5 | 95±10 | 60±8 | 7±3 | 33±6 | 21±5 |

cleanly be eliminated by requiring the invariant mass of the charged lepton system to be bigger than 100 GeV. This cut has been built into the numerical calculation. The loss of the signal associated with this cut is insignificant (a few percent), as expected from the kinematic distribution of $R_{lep}$ (Fig. 3). Another source of background comes from the standard model process $pp \to WZ \to Wl^{+}l^{-}$. However, requiring the $WZ$ invariant mass to be equal to $M_{W'} \pm 10$ GeV already puts the total cross section $\sigma(pp \to WZ)$ below $\sigma(pp \to W')$ for $M_{W'} \sim (1-3)$ TeV. The background from the $WZ$ production is thus eliminated by employing the dilepton invariant mass cut.

In this paper we have shown that the processes $pp \to W'W$ and $W' \to \bar{l}lW$ can be useful tests of whether a $W'$ has a $V - A$ or $V + A$ coupling at future hadron colliders. To illustrate the idea we have considered a specific example in which the $W'$ couples to $V - A$ currents. For $M_{W'} \sim (1-3)$ TeV, it is shown that the LHC and SSC can produce sufficient numbers of events from these processes for such a left-handed $W'$. On the other hand, the absence of such events would be a clean signal that the $W'$ is right handed. In addition, the rates for the above processes allow for a determination of the relative strength of the $V - A$ gauge coupling of $W'$ to quarks and lepton. It should be pointed out that an analysis on $\tau$ polarization in $W'$ and $Z'$ decays would also provide a useful probe on the heavy gauge boson couplings [28].

[1] M. Cvetič and P. Langacker, Phys. Rev. D **42**, 1797 (1990).

[2] P. Langacker and M. Luo, Phys. Rev. D **45**, 278 (1992); U. Amaldi et al., ibid. **36**, 1385 (1987); L. S. Durkin and P. Langacker, Phys. Lett. **166B**, 436 (1986). The sensitivity of future precision experiments is discussed by P. Langacker, M. Luo, and A. K. Mann, Rev. Mod. Phys. **64**, 87 (1992).

[3] G. Altarelli et al., Phys. Lett. B **263**, 459 (1991); **261**, 146 (1991); J. Layssac, F. M. Renard, and C. Verzegnassi, Z. Phys. C **53**, 97 (1992); F. M. Renard and C. Verzegnassi, Phys. Lett. B **260**, 225 (1991).

[4] K. T. Mahanthappa and P. K. Mohapatra, Phys. Rev. D **43**, 3093 (1991); P. Langacker, Phys. Lett. B **256**, 277 (1991).

[5] F. del Aguila, W. Hollik, J. M. Moreno, and M. Quiros, Nucl. Phys. **B372**, 3 (1992); F. del Aguila, J. M. Moreno, and M. Quiros, ibid. **B361**, 45 (1991); Phys. Lett. B **254**, 479 (1991); M. C. Gonzalez-Garcia and J. W. F. Valle, ibid. **259**, 365 (1991).

[6] J. C. Pati and A. Salam, Phys. Rev. Lett. **31**, 661 (1973); Phys. Rev. D **10**, 275 (1974); R. Mohapatra and J. C. Pati, ibid. **11**, 566 (1975).

[7] G. Beall, M. Bander, and A. Soni, Phys. Rev. Lett. **48**, 848 (1982).

[8] P. Langacker and U. Sankar, Phys. Rev. D **40**, 1569 (1989).

[9] D. London and D. Wyler, Phys. Lett. B **232**, 503 (1989).

[10] F. del Aguila, M. Quiros, and F. Zwirner, Nucl. Phys. **B284**, 530 (1987); P. Kalyniak and M. Sundaresan, Phys. Rev. D **35**, 75 (1987).

[11] N. Deshpande, J. Gunion, and F. Zwirner, in Experiments Detectors and Experimental Areas for the Supercollider, Proceedings of the Workshop, Berkeley, California, 1987, edited by R. Donaldson and M. G. D. Gilchriese (World Scientific, Singapore, 1988); N. Deshpande, J. Grifols, and A. Méndez, Phys. Lett. B **208**, 141 (1988).

[12] F. del Aguila, L. Ammetller, R. Field, and L. Garrido, Phys. Lett. B **201**, 375 (1988); **221**, 408 (1989).

[13] G. Kane and C. P. Yuan, Phys. Rev. D **40**, 2231 (1989).

[14] M. J. Duncan and P. Langacker, Nucl. Phys. **B277**, 285 (1986).

[15] V. Barger et al., Phys. Rev. D **35**, 2893 (1987).

[16] L. S. Durkin and P. Langacker, Phys. Lett. **166B**, 436 (1986); F. del Aguila, M. Quiros, and F. Zwirner, Nucl. Phys. **B287**, 419 (1987); **284**, 530 (1987); J. Hewett and T. Rizzo, in High Energy Physics in the 1990's, Proceedings of the Snowmass Summer Study, Snowmass, Colorado, 1988, edited by S. Jensen (World Scientific, Singapore, 1989); P. Chiappetta et al., in Proceedings of the ECFA Large Hadron Collider Workshop, Aachen, Germany, 1990, edited by G. Jarlskog and D. Rein (CERN Report No. 90-10, Geneva, Switzerland, 1990).

[17] J. Hewett and T. Rizzo, Phys. Rev. D **45**, 161 (1992).

[18] T. Rizzo, Phys. Lett. B **192**, 125 (1987).

[19] M. Cvetič and P. Langacker, Phys. Rev. D **46**, R14 (1992).

[20] F. del Aguila, B. Alles, L. Ametller, and A. Grau, Phys. Rev. D **48**, 425 (1993).

[21] J. Hewett and T. Rizzo, Phys. Rev. D **47**, 4981 (1993).

[22] M. Cvetič, B. Kayser, and P. Langacker, Phys. Rev. Lett. **68**, 2871 (1992).

[23] M. Cvetič and P. Langacker, Phys. Rev. D **46**, 4943 (1992).

[24] F. del Aguila, M. Cvetič, and P. Langacker, Phys. Rev. D **48**, 969 (1993).

[25] P. Langacker, R. Robinett, and J. Rosner, Phys. Rev. D **30**, 1470 (1984).

[26] H. Georgi, E. E. Jenkins, and E. H. Simmons, Phys. Rev.

Lett. **62**, 2789 (1989); **63**, 1540(E) (1989); Nucl. Phys. **B331**, 541 (1990).

[27] E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984).

[28] H. E. Haber, in *Design and Utilization of the Superconducting Super Collider,* Proceedings of the Summer Study, Snowmass, Colorado, 1984, edited by R. Donaldson and J. Morfin (Division of Particles and Fields of the APS, New York, 1985), p. 157.