

## THE $W'$ SEARCHES

Written October 1997 by K.S. Babu, C. Kolda, and J. March-Russell (IAS/Princeton).

Any electrically charged gauge boson outside of the Standard Model is generically denoted  $W'$ . A  $W'$  always couples to two different flavors of fermions, similar to the  $W$  boson. In particular, if a  $W'$  couples quarks to leptons it is a leptoquark gauge boson.

The most attractive candidate for  $W'$  is the  $W_R$  gauge boson associated with the left-right symmetric models [1]. These models seek to provide a spontaneous origin for parity violation in weak interactions. Here the gauge group is extended to  $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  with the Standard Model hypercharge identified as  $Y = T_{3R} + (B-L)/2$ ,  $T_{3R}$  being the third component of  $SU(2)_R$ . The fermions transform under the gauge group in a left-right symmetric fashion:  $q_L(3, 2, 1, 1/3) + q_R(3, 1, 2, 1/3)$  for quarks and  $\ell_L(1, 2, 1, -1) + \ell_R(1, 1, 2, -1)$  for leptons. Note that the model requires the introduction of right-handed neutrinos, which can facilitate the see-saw mechanism for explaining the smallness of the ordinary neutrino masses. A Higgs bidoublet  $\Phi(1, 2, 2, 0)$  is usually employed to generate quark and lepton masses and to participate in the electroweak symmetry breaking. Under left-right (or parity) symmetry,  $q_L \leftrightarrow q_R$ ,  $\ell_L \leftrightarrow \ell_R$ ,  $W_L \leftrightarrow W_R$  and  $\Phi \leftrightarrow \Phi^\dagger$ .

After spontaneous symmetry breaking, the two  $W$  bosons of the model,  $W_L$  and  $W_R$ , will mix. The physical mass eigenstates are denoted as

$$W_1 = \cos \zeta W_L + \sin \zeta W_R, \quad W_2 = -\sin \zeta W_L + \cos \zeta W_R \quad (1)$$

with  $W_1$  identified as the observed  $W$  boson. The most general Lagrangian that describes the interactions of the  $W_{1,2}$  with the quarks can be written as [2]

$$\begin{aligned} \mathcal{L} = & -\frac{1}{\sqrt{2}} \bar{u} \gamma_\mu \left[ \left( g_L \cos \zeta V^L P_L - g_R e^{i\omega} \sin \zeta V^R P_R \right) W_1^\mu \right. \\ & \left. + \left( g_L \sin \zeta V^L P_L + g_R e^{i\omega} \cos \zeta V^R P_R \right) W_2^\mu \right] d + h.c. \quad (2) \end{aligned}$$

where  $g_{L,R}$  are the  $SU(2)_{L,R}$  gauge couplings,  $P_{L,R} = (1 \mp \gamma_5)/2$  and  $V^{L,R}$  are the left- and right-handed CKM matrices in the

quark sector. The phase  $\omega$  reflects a possible complex mixing parameter in the  $W_L$ - $W_R$  mass-squared matrix. Note that there is  $CP$  violation in the model arising from the right-handed currents even with only two generations. The Lagrangian for leptons is identical to that for quarks, with the replacements  $u \rightarrow \nu$ ,  $d \rightarrow e$  and the identification of  $V^{L,R}$  with the CKM matrices in the leptonic sector.

If parity invariance is imposed on the Lagrangian, then  $g_L = g_R$ . Furthermore, the Yukawa coupling matrices that arise from coupling to the Higgs bidoublet  $\Phi$  will be Hermitian. If in addition the vacuum expectation values of  $\Phi$  are assumed to be real, the quark and lepton mass matrices will also be Hermitian, leading to the relation  $V^L = V^R$ . Such models are called *manifest* left-right symmetric models and are approximately realized with a minimal Higgs sector [3]. If instead parity and  $CP$  are both imposed on the Lagrangian, then the Yukawa coupling matrices will be real symmetric and, after spontaneous  $CP$  violation, the mass matrices will be complex symmetric. In this case, which is known in the literature as *pseudo-manifest* left-right symmetry,  $V^L = (V^R)^*$ .

***Indirect constraints:*** In minimal version of manifest or pseudo-manifest left-right symmetric models with  $\omega = 0$  or  $\pi$ , there are only two free parameters,  $\zeta$  and  $M_{W_2}$ , and they can be constrained from low energy processes. In the large  $M_{W_2}$  limit, stringent bounds on the angle  $\zeta$  arise from three processes. (i) Nonleptonic  $K$  decays: The decays  $K \rightarrow 3\pi$  and  $K \rightarrow 2\pi$  are sensitive to small admixtures of right-handed currents. Assuming the validity of PCAC relations in the Standard Model it has been argued in Ref. 4 that the success in the  $K \rightarrow 3\pi$  prediction will be spoiled unless  $|\zeta| \leq 4 \times 10^{-3}$ . (ii)  $b \rightarrow s\gamma$ : The amplitude for this process has an enhancement factor  $m_t/m_b$  relative to the Standard Model and thus can be used to constrain  $\zeta$  yielding the limit  $-0.01 \leq \zeta \leq 0.003$  [5]. (iii) Universality in weak decays: If the right-handed neutrinos are heavy, the right-handed admixture in the charged current will contribute to  $\beta$  decay and  $K$  decay, but not to the  $\mu$  decay. This will modify the extracted values of  $V_{ud}^L$  and  $V_{us}^L$ . Demanding that the difference not upset the three generation

unitarity of the CKM matrix, a bound  $|\zeta| \leq 10^{-3}$  has been derived [6].

If the  $\nu_R$  are heavy, leptonic and semileptonic processes do not constrain  $\zeta$  since the emission of  $\nu_R$  will not be kinematically allowed. However, if the  $\nu_R$  is light enough to be emitted in  $\mu$  decay and  $\beta$  decay, stringent limits on  $\zeta$  do arise. For example,  $|\zeta| \leq 0.039$  can be obtained from polarized  $\mu$  decay [7] in the large  $M_{W_2}$  limit of the manifest left-right model. Alternatively, in the  $\zeta = 0$  limit, there is a constraint  $M_{W_2} \geq 484$  GeV from direct  $W_2$  exchange. For the constraint on the case in which  $M_{W_2}$  is not taken to be heavy, see Ref. 2. There are also cosmological and astrophysical constraints on  $M_{W_2}$  and  $\zeta$  in scenarios with a light  $\nu_R$ . During nucleosynthesis the process  $e^+e^- \rightarrow \nu_R\bar{\nu}_R$ , proceeding via  $W_2$  exchange, will keep the  $\nu_R$  in equilibrium leading to an overproduction of  ${}^4\text{He}$  unless  $M_{W_2}$  is greater than about 1 TeV [8]. Likewise the  $\nu_{eR}$  produced via  $e_R^-p \rightarrow n\nu_R$  inside a supernova must not drain too much of its energy, leading to limits  $M_{W_2} > 16$  TeV and  $|\zeta| \leq 3 \times 10^{-5}$  [9]. Note that models with light  $\nu_R$  do not have a see-saw mechanism for explaining the smallness of the neutrino masses, though other mechanisms may arise in variant models [10].

The mass of  $W_2$  is severely constrained (independent of the value of  $\zeta$ ) from  $K_L$ – $K_S$  mass-splitting. The box diagram with exchange of one  $W_L$  and one  $W_R$  has an anomalous enhancement and yields the bound  $M_{W_2} \geq 1.6$  TeV [11] for the case of manifest or pseudo-manifest left-right symmetry. If the  $\nu_R$  have Majorana masses, another constraint arises from neutrinoless double  $\beta$  decay. Combining the experimental limit from  ${}^{76}\text{Ge}$  decay with arguments of vacuum stability, a limit of  $M_{W_2} \geq 1.1$  TeV has been obtained [12].

**Direct search limits:** Limits on  $M_{W_2}$  from direct searches depend on the available decay channels of  $W_2$ . If  $\nu_R$  is heavier than  $W_2$ , the decay  $W_2^+ \rightarrow \ell_R^+\nu_R$  will be forbidden kinematically. Assuming that  $\zeta$  is small, the dominant decay of  $W_2$  will be into dijets. UA2 [13] has excluded a  $W_2$  in the mass range of 100 to 251 GeV in this channel. DØ excludes the mass range of 340 to 680 GeV [14], while CDF excludes the

mass range of 300 to 420 GeV for such a  $W_2$  [15]. If  $\nu_R$  is lighter than  $W_2$ , the decay  $W_2^+ \rightarrow e_R^+ \nu_R$  is allowed. The  $\nu_R$  can then decay into  $e_R W_R^*$ , leading to an  $eejj$  signature.  $D\bar{O}$  has a limit of  $M_{W_2} > 720$  GeV if  $m_{\nu_R} \ll M_{W_2}$ ; the bound weakens, for example, to 650 GeV for  $m_{\nu_R} = M_{W_2}/2$  [16]. CDF finds  $M_{W_2} > 652$  GeV if  $\nu_R$  is stable and much lighter than  $W_2$  [17]. All of these limits assume manifest or pseudo-manifest left-right symmetry. See [16] for some variations in the limits if the assumption of left-right symmetry is relaxed.

**Alternative models:**  $W'$  gauge bosons can also arise in other models. We shall briefly mention some such popular models, but for details we refer the reader to the original literature. The *alternate* left-right model [18] is based on the same gauge group as the left-right model, but arises in the following way: In  $E_6$  unification, there is an option to identify the right-handed down quarks as  $SU(2)_R$  singlets or doublets. If they are  $SU(2)_R$  doublets, one recovers the conventional left-right model; if they are singlets it leads to the alternate left-right model. A similar ambiguity exists in the assignment of left-handed leptons; the alternate left-right model assigns them to a  $(1, 2, 2, 0)$  multiplet. As a consequence, the ordinary neutrino remains exactly massless in the model. One important difference from the usual left-right model is that the limit from the  $K_L$ – $K_S$  mass difference is no longer applicable, since the  $d_R$  do not couple to the  $W_R$ . There is also no limit from polarized  $\mu$  decay, since the  $SU(2)_R$  partner of  $e_R$  can receive a large Majorana mass. Other  $W'$  models include the un-unified Standard Model of Ref. 19 where there are two different  $SU(2)$  gauge groups, one each for the quarks and leptons; models with separate  $SU(2)$  gauge factors for each generation [20]; and the  $SU(3)_C \times SU(3)_L \times U(1)$  model of Ref. 21.

**Leptoquark gauge bosons:** The  $SU(3)_C \times U(1)_{B-L}$  part of the gauge symmetry discussed above can be embedded into a simple  $SU(4)_C$  gauge group [22]. The model then will contain leptoquark gauge boson as well, with couplings of the type  $\{(\bar{e}_L \gamma_\mu d_L + \bar{\nu}_L \gamma_\mu u_L) W'^\mu + (L \rightarrow R)\}$ . The best limit on such leptoquark  $W'$  comes from nonobservation of  $K_L \rightarrow \mu e$ , which requires  $M_{W'} \geq 1400$  TeV; for the corresponding limits on

less conventional leptoquark flavor structures, see Ref. 23. Thus such a  $W'$  is inaccessible to direct searches with present machines which are sensitive to vector leptoquark masses of order 300 GeV only.

## References

1. J.C. Pati and A. Salam, Phys. Rev. **D10**, 275 (1974);  
R.N. Mohapatra and J.C. Pati, Phys. Rev. **D11**, 566 (1975); *ibid.* Phys. Rev. **D11**, 2558 (1975);  
G. Senjanovic and R.N. Mohapatra, Phys. Rev. **D12**, 1502 (1975).
2. P. Langacker and S. Uma Sankar, Phys. Rev. **D40**, 1569 (1989).
3. A. Masiero, R.N. Mohapatra, and R. Peccei, Nucl. Phys. **B192**, 66 (1981);  
J. Basecq, *et al.*, Nucl. Phys. **B272**, 145 (1986).
4. J. Donoghue and B. Holstein, Phys. Lett. **113B**, 383 (1982).
5. K.S. Babu, K. Fujikawa, and A. Yamada, Phys. Lett. **B333**, 196 (1994);  
P. Cho and M. Misiak, Phys. Rev. **D49**, 5894 (1994);  
T.G. Rizzo, Phys. Rev. **D50**, 3303 (1994).
6. L. Wolfenstein, Phys. Rev. **D29**, 2130 (1984).
7. P. Herczeg, Phys. Rev. **D34**, 3449 (1986).
8. G. Steigman, K.A. Olive, and D. Schramm, Nucl. Phys. **B180**, 497 (1981).
9. R. Barbieri and R.N. Mohapatra, Phys. Rev. **D39**, 1229 (1989);  
G. Raffelt and D. Seckel, Phys. Rev. Lett. **60**, 1793 (1988).
10. D. Chang and R.N. Mohapatra, Phys. Rev. Lett. **58**, 1600 (1987);  
K.S. Babu and X.G. He, Mod. Phys. Lett. **A4**, 61 (1989).
11. G. Beall, M. Bender, and A. Soni, Phys. Rev. Lett. **48**, 848 (1982).
12. R.N. Mohapatra, Phys. Rev. **D34**, 909 (1986).
13. J. Alitti, *et al.* (UA2 Collaboration), Nucl. Phys. **B400**, 3 (1993).
14. B. Abbott, *et al.* (DØ Collaboration), International Europhysics Conference on High Energy Physics, August 19-26, 1997, Jerusalem, Israel.
15. F. Abe, *et al.* (CDF Collaboration), Phys. Rev. **D55**, R5263 (1997).

16. S. Abachi, *et al.* (DØ Collaboration), Phys. Rev. Lett. **76**, 3271 (1996).
17. F. Abe, *et al.* (CDF Collaboration), Phys. Rev. Lett. **74**, 2900 (1995).
18. E. Ma, Phys. Rev. **D36**, 274 (1987);  
K.S. Babu, X-G. He and E. Ma, Phys. Rev. **D36**, 878 (1987).
19. H. Georgi and E. Jenkins, Phys. Rev. Lett. **62**, 2789 (1989);  
Nucl. Phys. **B331**, 541 (1990).
20. X. Li and E. Ma, Phys. Rev. Lett. **47**, 1788 (1981);  
R.S. Chivukula, E.H. Simmons, and J. Terning, Phys. Lett. **B331**, 383 (1994);  
D.J. Muller and S. Nandi, Phys. Lett. **B383**, 345 (1996).
21. F. Pisano, V. Pleitez, Phys. Rev. **D46**, 410 (1992);  
P. Frampton, Phys. Rev. Lett. **69**, 2889 (1992).
22. J.C. Pati and A. Salam, Phys. Rev. **D10**, 275 (1974).
23. A. Kuznetsov and N. Mikheev, Phys. Lett. **B329**, 295 (1994);  
G. Valencia and S. Willenbrock, Phys. Rev. **D50**, 6843 (1994).