THE W' SEARCHES

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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: $q_L(3, 1, -1/2, -1/2) + q_R(3, 1, 1/2, 1/2)$ for quarks and $\ell_L(1, 1, -1/2, 1/2) + \ell_R(1, 1, 1/2, -1/2)$ 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]

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

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 $u \to \nu$, $d \to e$ 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 $K \to 3\pi$ and $K \to 2\pi$ 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 $K \to 3\pi$ prediction will be spoiled unless $|\zeta| \leq 4 \times 10^{-3}$. (ii) $b \to s\gamma$: 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, $|\zeta| \leq 0.0333$ 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 $M_{W_2} \geq 549$ 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 $^4$He unless $M_{W_2}$ is greater than about 4 TeV [8]. Likewise the $\nu_{eR}$ produced via $e^+p \rightarrow n\nu_R$ inside a supernova must not drain too much of its energy, leading to limits $M_{W_2} > 23$ TeV [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 $^{76}$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 then 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 300 to 800 GeV [14], while CDF excludes the mass range of 225 to 566 GeV by searching for a $t\bar{b}$ final state [15].
If $\nu_R$ is lighter than $W_2$, the decay $W_2^+ \rightarrow e_R^+ \nu_R$ is allowed; if $m_{\nu_R} < M_{W_2}/2$ then a peak in the spectrum of hard electrons can be used as a signature for $W_2$ production. Using this technique, DØ has a limit of $M_{W_2} > 720$ GeV if $m_{\nu_R} \ll M_{W_2}$; the bound weakens to 650 GeV for $m_{\nu_R} = M_{W_2}/2$ [16]. One can also look for the decay of the $\nu_R$ into $e_R W_R^-$, leading to an $e e j \bar{j}$ signature. The DØ bound here is only slightly weaker than above. Finally one can search for a stable $\nu_R$ in leptons plus missing energy. CDF finds $M_{W_2} > 786$ GeV if $\nu_R$ is much lighter than $W_2$, using the $e$ and $\mu$ final states combined [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
a leptoquark gauge boson as well, with couplings of the type \((\bar{\nu}_L \gamma_\mu d_L + \bar{\nu}_L \gamma_\mu u_L) W'^\mu + (L \rightarrow R)\). The best limit on such a leptoquark \(W'\) comes from nonobservation of \(K_L \rightarrow ee\) and \(\mu e\), which require \(M_{W'} \geq 1400\) and 1200 TeV respectively; 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