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 $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ with the Standard Model hypercharge identified as $Y = T_{3R} + (B\text{–}L)/2$, T_{3R} being the third component of $\mathrm{SU}(2)_R$. 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

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

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]

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

where $g_{L,R}$ are the $\mathrm{SU}(2)_{L,R}$ 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 ω 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 Φ will be Hermitian. If in addition the vacuum expectation values of Φ 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 π, there are only two free parameters, ζ 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 ζ 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 $|\zeta| \le 4 \times 10^{-3}$. (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 ζ yielding the limit $-0.01 \le \zeta \le 0.003$ [5]. (iii) Universality in weak decays: If the right-handed neutrinos are heavy, the right-handed admixture in the charged current will contribute to β decay and K decay, but not to the μ decay. This will modify the extracted values of V^L_{ud} and V^L_{us}. Demanding that the difference not upset the three generation unitarity of the CKM matrix, a bound $|\zeta| \le 10^{-3}$ has been derived [6].

If the ν_R are heavy, leptonic and semileptonic processes do not constrain ζ since the emission of ν_R will not be kinematically allowed. However, if the ν_R is light enough to be emitted in μ decay and β decay, stringent limits on ζ do arise. For example, $|\zeta| \le 0.039$ can be obtained from polarized μ 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 $M_{W_2} \ge 484$ 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 ζ in scenarios with a light ν_R. During nucleosynthesis the process $e^+e^- \to \nu_R\overline{\nu}_R$, proceeding via W_2 exchange, will keep the ν_R in equilibrium leading to an overproduction of ^{4}He unless M_{W_2} is greater than about 1 TeV [8]. Likewise the ν_{eR} produced via $e^-_R p \to n\nu_R$ inside a supernova must not drain too much of its energy, leading to limits $M_{W_2} > 16$ TeV and $|\zeta| \le 3 \times 10^{-5}$ [9]. Note that models with light ν_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 ζ) 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 $M_{W_2} \ge 1.6$ TeV [11] for the case of manifest or pseudo-manifest left-right symmetry. If the ν_R have Majorana masses, another constraint arises from neutrinoless double β decay. Combining the experimental limit from ^{76}Ge decay with arguments of vacuum stability, a limit of $M_{W_2} \ge 1.1$ 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 ν_R is heavier than W_2, the decay $W_2^+ \to \ell_R^+ \nu_R$ will be forbidden kinematically. Assuming that ζ 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 ν_R is lighter than W_2, the decay $W_2^+ \to e_R^+ \nu_R$ is allowed. The ν_R can then decay into $e_R W_R^*$, leading to an $eejj$ signature. DØ 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 ν_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 $\mathrm{SU}(2)_R$ singlets or doublets. If they are $\mathrm{SU}(2)_R$ 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 μ decay, since the $\mathrm{SU}(2)_R$ 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 $\mathrm{SU}(3)_C \times \mathrm{SU}(3)_L \times \mathrm{U}(1)$ model of Ref. 21.

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

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