W'-BOSON SEARCHES

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The W' boson is a hypothetical massive particle of electric charge ± 1 and spin 1, which is predicted in various extensions of the standard model.

W' couplings to quarks and leptons. The Lagrangian terms describing couplings of a W' boson to fermions are given by

$$W'_\mu \left[\overline{u}_i \left(C^R_{q_{ij}} P_R + C^L_{q_{ij}} P_L \right) \gamma^\mu d_j + \overline{\nu}_i \left(C^R_{l_{ij}} P_R + C^L_{l_{ij}} P_L \right) \gamma^\mu e_j \right] + \text{h.c.} \tag{1}$$

Here u, d, ν and e are the standard model fermions in the mass eigenstate basis, $i, j = 1, 2, 3$ label the fermion generation, and $P_{R,L} = (1 \pm \gamma_5)/2$. The coefficients $C^L_{q_{ij}}$, $C^R_{q_{ij}}$, $C^L_{l_{ij}}$, $C^R_{l_{ij}}$ are complex dimensionless parameters. If $C^R_{l_{ij}} \neq 0$, then the ith generation includes a right-handed neutrino. It is often assumed that there are correlations between the left- and right-handed couplings [1]. Although this is true in some of the original models that include a W' [2], there exist theories where all the left- and right-handed couplings are free parameters.

Unitarity considerations imply that the W' is a gauge boson associated with a spontaneously broken gauge symmetry. This is true even when it is a composite particle (*e.g.*, the charged techni-ρ in technicolor theories [3]) or a Kaluza-Klein mode in theories where the W boson propagates in extra dimensions [4]. The simplest extension of the electroweak gauge group that includes a W' is $SU(2)_1 \times SU(2)_2 \times U(1)$, but larger groups are also encountered in some theories. A generic property of all these gauge theories is that besides a W' they contain at least a Z' boson, whose mass is typically comparable or smaller than $M_{W'}$. Despite the severe limits on Z' bosons [5], theories where the properties of the new gauge bosons would allow the W' to be discovered before the Z' are quite common (for example, a leptophobic W' decaying to $t\bar{b}$ may be observed easier than a Z' in the $t\bar{t}$ final state which has higher backgrounds).

The renormalizable photon-W' coupling is completely fixed by electromagnetic gauge invariance. By contrast, the renormalizable $W'WZ$ and $W'W'Z$ couplings are model dependent, and the same is true for the W' couplings to Z' or Higgs bosons.

Depending on the symmetry breaking sector, a tree-level mass mixing may be induced between the electrically-charged gauge bosons. Upon diagonalization of their mass matrix, the $W - Z$ mass ratio and the couplings of the observed W are shifted from the standard model values. Given that these are well measured, the mixing angle between the two gauge bosons must be smaller than about 10^{-2}. Similarly, a $Z - Z'$ mixing is induced in generic theories, leading to even tighter constraints. There are, however, theories in which these mixings are negligible even when the W' and Z' masses are below the electroweak scale (for example, this is a consequence of a new parity, as in [7]) .

A popular model [2] is based on the "left-right symmetric" gauge group, $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, with the standard model fermions that couple to W transforming as doublets under $SU(2)_L$ and the other ones transforming as doublets under $SU(2)_R$. In this model the W' couples primarily to the right-handed fermions, and its coupling to left-handed fermions arises solely due to W-W' mixing. As a result, C_q^L is proportional to the CKM matrix, and its elements are much smaller than the diagonal elements of C_q^R.

There are many other models based on the $SU(2)_1 \times SU(2)_2 \times U(1)$ gauge symmetry. In the "alternate left-right" model [8], all the couplings shown in Eq. (1) vanish, but there are some new fermions such that the W' couples to pairs involving a standard model fermion and a new fermion. In the "ununified standard model" [9], the left-handed quarks are doublets under one $SU(2)$ and the left-handed leptons are doublets under a different $SU(2)$, leading to a mostly leptophobic W': $C_{l_{ij}}^L \ll C_{q_{ij}}^L$ and $C_{q_{ij}}^R = C_{l_{ij}}^R = 0$. Fermions of different generations may also transform as doublets under different $SU(2)$ gauge groups [10]. In particular, the couplings to third generation quarks may be enhanced [11].

The W' couplings to standard model fermions may be highly suppressed if the quarks and leptons are singlets under one $SU(2)$ [12], or if there are some vectorlike fermions that mix with the standard model ones [13,14]. Gauge groups that embed the electroweak symmetry, such as $SU(3)_W \times U(1)$ or $SU(4)_W \times U(1)$, also include one or more W' bosons [15].

Collider searches. At LEP-II, W' bosons could have been produced in pairs via their photon and Z couplings. The production cross section depends only on the W' mass, and is large enough for $M_{W'} \leq \sqrt{s}/2 \approx 105$ GeV so that W' bosons are ruled out for essentially any pattern of decay modes.

Searches for W' bosons in the Run II at the Tevatron have been performed so far by the DØ and CDF Collaborations for W' decays into $e\nu$ [16,17] or $t\bar{b}$ [18,19]. Assuming that the W' boson has a narrow width, the contribution of the s-channel W' exchange to the total rate for $p\bar{p} \to f\bar{f}'X$, where f and f' are fermions and X is any final state of charge ± 1, may be approximated by the branching fraction $B(W' \to f\bar{f}')$ times the production cross section

$$\sigma\left(p\bar{p} \to W'X\right) \approx \frac{\pi}{48\,s} \sum_{i,j} \left[(C^L_{q_{ij}})^2 + \left(C^R_{q_{ij}}\right)^2 \right] w_{ij}\left(s, M^2_{W'}\right) \;, \tag{2}$$

where the i, j indices label the fermion generations. The functions w_{ij} include the information about proton structure, and are given to leading order in α_s by

$$w_{ij}(z) = \int_z^1 \frac{dx}{x} \left[u_i(x)\, d_j\left(z/x\right) + \overline{u}_i(x)\, \overline{d}_j\left(z/x\right) \right] \;, \tag{3}$$

where $u_i(x)$ and $d_i(x)$ are the parton distributions inside the proton for the up- and down-type quark of the ith generation, respectively. QCD corrections to W' production are sizable, but preserve the above factorization of couplings at next-to-leading order [20].

Similar considerations apply at the LHC, except that the $q\bar{q}$ initial state involves a sea parton in pp collisions. Nevertheless, the energy and luminosity will be substantially higher than at the Tevatron, so that W' bosons with masses in the several TeV range will be probed [21]. If a W' boson will be discovered and the final state fermions have left-handed helicity, then the effects of $W - W'$ interference could be observed at the LHC [22] (and perhaps at the Tevatron [23]), providing useful information about the W' couplings.

In the $e\nu$ channel, the signal consists of a high-energy electron and a large missing transverse energy, with the invariant mass distribution forming a peak at $M_{W'}$. The best upper limit to date on the production cross-section $\sigma(p\bar{p} \to W'X)$ times the branching fraction $B(W' \to e\nu)$ has been set by DØ at around 200 fb for $M_{W'}$ in the $0.5 - 1$ TeV range [17]. This preliminary limit at 95% CL, based on 900 pb^{-1} of data, applies only if the right-handed neutrino of the first generation is light compared to $M_{W'}/2$ and escapes the detector. In the particular case $C_q^R = gV_{\rm CKM}$, $C_l^R = g$, $C_q^L = C_l^L = 0$, the limit corresponds to $M_{W'} > 965$ GeV.

In the $t\bar{b}$ channel, the signal consists of a W decaying leptonically and two b-jets. The current best upper limit on the

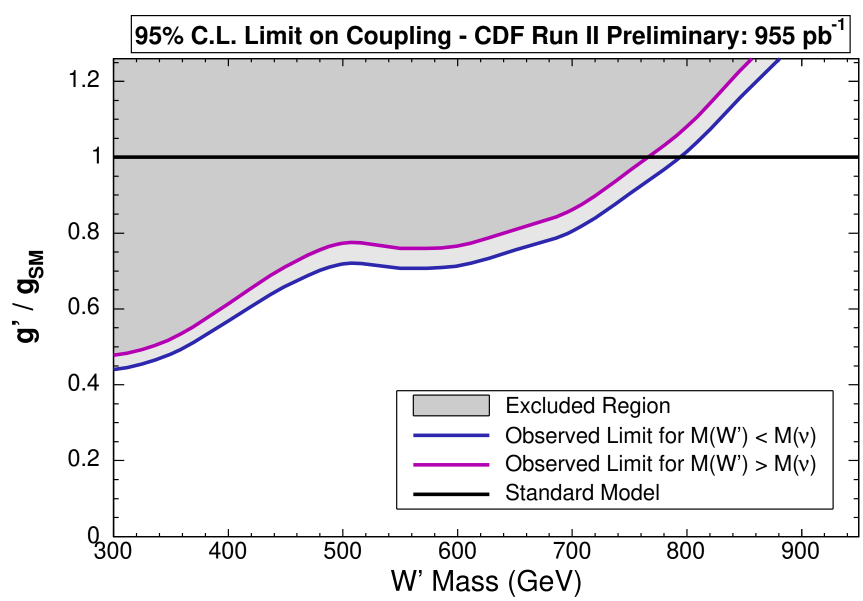

Figure 1: 95% CL exclusion limit from CDF [19] in the gauge coupling versus $M_{W'}$ plane, using the $t\bar{b}$ and $\bar{t}b$ final states.

W' coupling to quarks ($C^R_{q_{11}}$ normalized to the standard model W coupling) set by CDF with 955 pb^{-1} [19], is shown in Fig. 1.

In some theories (*e.g.*, [7]) the W' couplings to standard model fermions are suppressed due to a discrete symmetry. The W' bosons may then be produced in pairs via their couplings to the photon and Z. The decay modes are model dependent and often involve other particles beyond the standard model. The ensuing collider signals arise from cascade decays and typically include missing transverse energy.

Low-energy constraints. The properties of the W' are also constrained by measurements of processes at energies much below $M_{W'}$. The bounds on the tree-level $W - W'$ mixing [6] are mostly due to the change in the properties of the W boson compared to the standard model. Limits on the deviation in the ZWW coupling provide a leading constraint for fermiophobic W' bosons [13].

Constraints arising from low-energy effects of W' exchange are strongly model dependent. If the W' couplings to quarks are not suppressed, then box diagrams involving a W and a W' contribute to neutral meson mixing. In the case of W' couplings to right-handed quarks as in the left-right symmetric model, the limit from $K_L - K_s$ mixing is severe: $M_{W'} > 2.5$ TeV [24]. However, if no correlation between $C^R_{q_{ij}}$ and $C^R_{l_{ij}}$ is assumed, then the limit on $M_{W'}$ may be significantly relaxed [1]. There are also contributions of W' to the neutron electric dipole moment, muon decays and other processes.

If right-handed neutrinos have Majorana masses, then there are tree-level contributions to neutrinoless double-beta decay, and a limit on $M_{W'}$ versus the ν_R mass may be derived [25]. For ν_R masses below a few GeV, W' contributes to leptonic and semileptonic B meson decays, so that limits may be placed on various combinations of W' parameters [1]. For right-handed neutrino masses below ~ 30 MeV, most stringent constraints on $M_{W'}$ are due to the limits on ν_R emission from supernova.

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