

## **$W'$ -BOSON SEARCHES**

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The  $W'$  boson is a hypothetical massive particle of electric charge  $\pm 1$  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

$$W'_\mu \left[ \bar{u}_i \left( C_{qij}^R P_R + C_{qij}^L P_L \right) \gamma^\mu d_j + \bar{\nu}_i \left( C_{lij}^R P_R + C_{lij}^L P_L \right) \gamma^\mu e_j \right] + \text{h.c.} \quad (1)$$

Here  $u, d, \nu$  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  $C_{qij}^L, C_{qij}^R, C_{lij}^L, C_{lij}^R$  are complex dimensionless parameters. If  $C_{lij}^R \neq 0$ , then the  $i$ th 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- $\rho$  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 Ref. 6).

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 [7], 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 “unified Standard Model” [8], 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 [9]. In particular, the couplings to third generation quarks may be enhanced [10].

The  $W'$  couplings to Standard Model fermions may be highly suppressed if the quarks and leptons are singlets under one  $SU(2)$  [11], or if there are some vectorlike fermions that mix with the Standard Model ones [12]. 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 [13].

**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 most patterns 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  $e\nu$  [14,15] or  $t\bar{b}$  [16,17]. Assuming that the  $W'$  boson has a narrow width, the contribution of the  $s$ -channel  $W'$  exchange to the total rate for  $p\bar{p} \rightarrow f\bar{f}'X$ , where  $f$  and  $f'$  are fermions and  $X$  is any final state of charge  $\pm 1$ , may be approximated by the branching fraction  $B(W' \rightarrow f\bar{f}')$  times the production cross section

$$\sigma(p\bar{p} \rightarrow W'X) \approx \frac{\pi}{48s} \sum_{i,j} \left[ (C_{qij}^L)^2 + (C_{qij}^R)^2 \right] w_{ij}(s, M_{W'}^2) , \quad (2)$$

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  $\alpha_s$  by

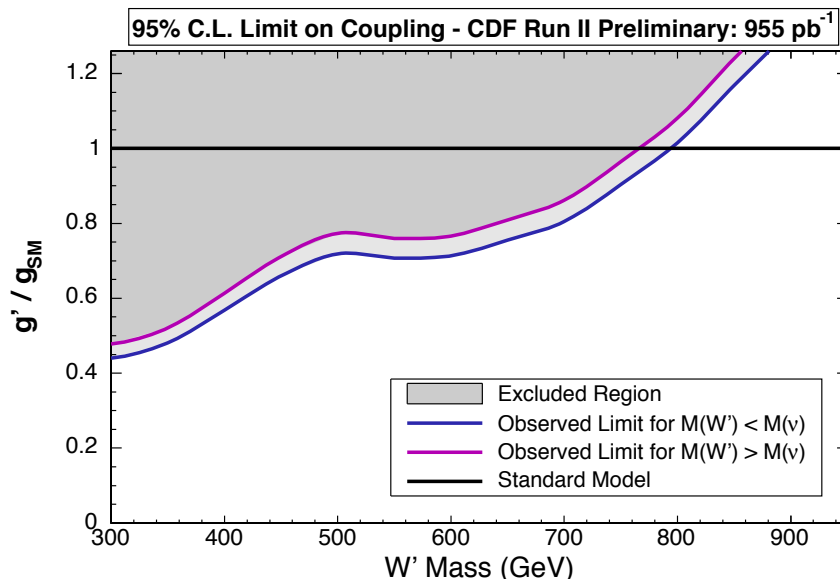
$$w_{ij}(z) = \int_z^1 \frac{dx}{x} \left[ u_i(x) d_j(z/x) + \bar{u}_i(x) \bar{d}_j(z/x) \right] , \quad (3)$$

where  $u_i(x)$  and  $d_i(x)$  are the parton distributions inside the proton for the up- and down-type quark of the  $i$ th generation, respectively. QCD corrections to  $W'$  production are sizable, but preserve the above factorization of couplings at next-to-leading order [18].

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 higher than at the Tevatron, so that  $W'$  bosons with masses in the several TeV range will be

probed. Preliminary studies of the discovery potential in the  $e\nu$  and  $\mu\nu$  channels have been presented by the CMS and ATLAS Collaborations in Ref. 19. 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 [20] (and perhaps at the Tevatron [21]), 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  $\sigma(p\bar{p} \rightarrow W'X)$  times the branching fraction  $B(W' \rightarrow e\nu)$  has been set by DØ at around 10 – 40 fb for  $M_{W'}$  in the 0.5 – 1.2 TeV range [15]. This limit at 95% CL, based on  $1 \text{ fb}^{-1}$  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 where the  $W'$  couplings to right-handed fermions are equal to the Standard-Model  $W$  couplings to left-handed fermions ( $C_q^R = gV_{\text{CKM}}, C_l^R = g, C_q^L = C_l^L = 0$ ), the limit corresponds to  $M_{W'} > 1.0 \text{ TeV}$ .



**Figure 1:** 95% CL exclusion limit from CDF [17] in the gauge coupling versus  $M_{W'}$  plane, using the  $t\bar{b}$  and  $\bar{t}b$  final states.

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  $W'$  coupling to quarks ( $C_{q11}^R$  normalized to the Standard Model  $W$  coupling) set by CDF with  $1.9 \text{ fb}^{-1}$  [17], is shown in Fig. 1.

In some theories (*e.g.*, [6]), the  $W'$  couplings to Standard Model fermions are suppressed by discrete symmetries.  $W'$  production then occurs in pairs, through a photon or  $Z$ . The decay modes are model-dependent and often involve other new particles. The ensuing collider signals arise from cascade decays and typically include missing transverse energy.

A fermiophobic  $W'$  which couples to  $WZ$  may be produced at hadron colliders in association with a  $Z$ , or via  $WW$  fusion. This would give rise to  $(WZ)Z$  and  $(WZ)jj$  final states (the parantheses represent a resonance) at the LHC [22]. The study of these processes would be important for understanding the origin of electroweak symmetry-breaking.

**Low-energy constraints.** The properties of  $W'$  bosons are also constrained by measurements of processes at energies much below  $M_{W'}$ . The bounds on the tree-level  $W - W'$  mixing [23] are mostly due to the change in the properties of the  $W$  compared to the Standard Model. Limits on the deviation in the  $ZWW$  coupling provide a leading constraint for fermiophobic  $W'$  bosons [12].

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:  $M_{W'} > 2.5 \text{ TeV}$  [24]. However, if no correlation between  $C_{qij}^R$  and  $C_{lij}^R$  is assumed, then the limit on  $M_{W'}$  may be significantly relaxed [1]. There are also  $W'$  contributions 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  $\nu_R$  mass may be derived [25]. For  $\nu_R$  masses below a few GeV, the  $W'$  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  $\sim 30$  MeV, most stringent constraints on  $M_{W'}$  are due to the limits on  $\nu_R$  emission from supernova.

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