

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

Revised November 2013 by G. Brooijmans (Columbia University), M.-C. Chen (UC Irvine) and B.A. Dobrescu (Fermilab).

The  $W'$  boson is a massive hypothetical particle of charge  $\pm 1$  and spin 1, predicted in various extensions of the Standard Model (SM).

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

$$\frac{W'^+}{\sqrt{2}} \left[ \bar{u}_i \left( C_{qij}^R P_R + C_{qij}^L P_L \right) \gamma^\mu d_j + \bar{\nu}_i \left( C_{lij}^R P_R + C_{lij}^L P_L \right) \gamma^\mu e_j \right]. \quad (1)$$

Here  $u, d, \nu$  and  $e$  are the SM 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. Using this notation, the SM  $W$  couplings are  $C_q^L = g V_{CKM}$ ,  $C_l^L = g$  and  $C_q^R = C_l^R = 0$ .

Unitarity considerations imply that the  $W'$  boson is associated with a spontaneously-broken gauge symmetry. This is true even when it is a composite particle (*e.g.*,  $\rho^\pm$ -like bound states [1]) if its mass is much smaller than the compositeness scale, or a Kaluza-Klein mode in theories where the  $W$  boson propagates in extra dimensions [2]. The simplest extension of the electroweak gauge group that includes a  $W'$  boson is  $SU(2)_1 \times SU(2)_2 \times U(1)$ , but larger groups are encountered in some theories. A generic property of these gauge theories is that they also include a  $Z'$  boson [3]; whether the  $W'$  boson can be discovered first depends on theoretical and experimental details.

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

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  $W$  boson are shifted from the SM values. Their

measurements imply that the  $W - W'$  mixing angle 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 (*e.g.* due to a new parity [4]), even when the  $W'$  and  $Z'$  masses are below the electroweak scale.

A popular model [5] is based on the “left-right symmetric” gauge group,  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ , with the SM fermions that couple to the  $W$  boson transforming as doublets under  $SU(2)_L$ , and the other ones transforming as doublets under  $SU(2)_R$ . In this model the  $W'$  boson couples primarily to 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 [6], all the couplings shown in Eq. (1) vanish, but there are some new fermions such that the  $W'$  boson couples to pairs involving a SM fermion and a new fermion. In the “ununified SM” [7], 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  $W'$  boson:  $C_{l_{ij}}^L \ll C_{q_{ij}}^L$  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 [8]. In particular, the couplings to third generation quarks may be enhanced [9].

It is also possible that the  $W'$  couplings to SM fermions are highly suppressed. For example, if the quarks and leptons are singlets under one  $SU(2)$  [10], then the couplings are proportional to a mixing angle that could be very small. Similar suppressions may arise if some vectorlike fermions mix with the SM ones [11].

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 [12].

**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 to rule out  $M_{W'} \leq \sqrt{s}/2 \approx 105$  GeV for most patterns of decay modes.

At hadron colliders,  $W'$  bosons can be detected through resonant pair production of fermions or electroweak bosons. Assuming that the  $W'$  width is much smaller than its mass, the contribution of the  $s$ -channel  $W'$  boson exchange to the total rate for  $pp \rightarrow f\bar{f}'X$ , where  $f$  and  $f'$  are fermions whose electric charges differ by  $\pm 1$ , and  $X$  is any final state, may be approximated by the branching fraction  $B(W' \rightarrow f\bar{f}')$  times the production cross section

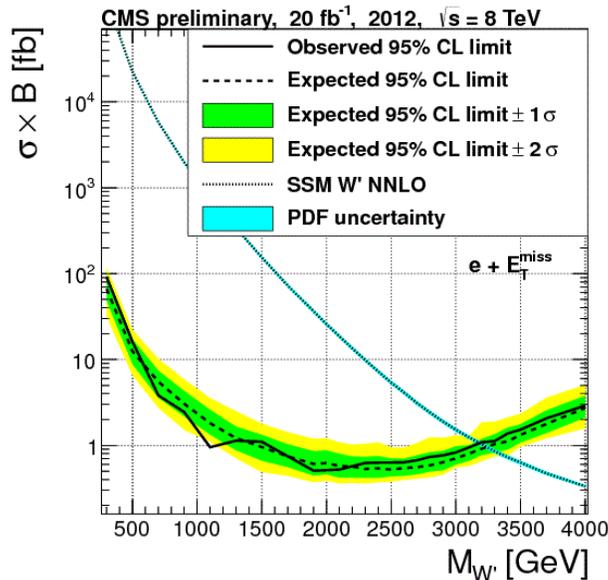
$$\sigma(pp \rightarrow W'X) \simeq \frac{\pi}{48s} \sum_{i,j} \left[ (C_{qij}^L)^2 + (C_{qij}^R)^2 \right] w_{ij}(M_{W'}^2/s, M_{W'}). \quad (2)$$

The functions  $w_{ij}$  include the information about proton structure, and are given to leading order in  $\alpha_s$  by

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

where  $u_i(x, \mu)$  and  $d_i(x, \mu)$  are the parton distributions inside the proton, at the factorization scale  $\mu$  and parton momentum fraction  $x$ , for the up- and down-type quark of the  $i$ th generation, respectively. QCD corrections to  $W'$  production are sizable (they also include quark-gluon initial states), but preserve the above factorization of couplings at next-to-leading order [13].

The most commonly studied  $W'$  signal consists of a high-energy electron or muon and large missing transverse energy, with the transverse mass distribution forming a Jacobian peak with its endpoint at  $M_{W'}$  (see Fig. 2 of Ref. 14) Given that the branching fractions for  $W' \rightarrow e\nu$  and  $W' \rightarrow \mu\nu$  could be very different, these channels should be analyzed separately. Searches in these channels often assume that the left-handed couplings vanish (no interference between  $W$  and  $W'$ ), and that the right-handed neutrino of the first generation is light compared to  $M_{W'}$  and escapes the detector. However, if a  $W'$

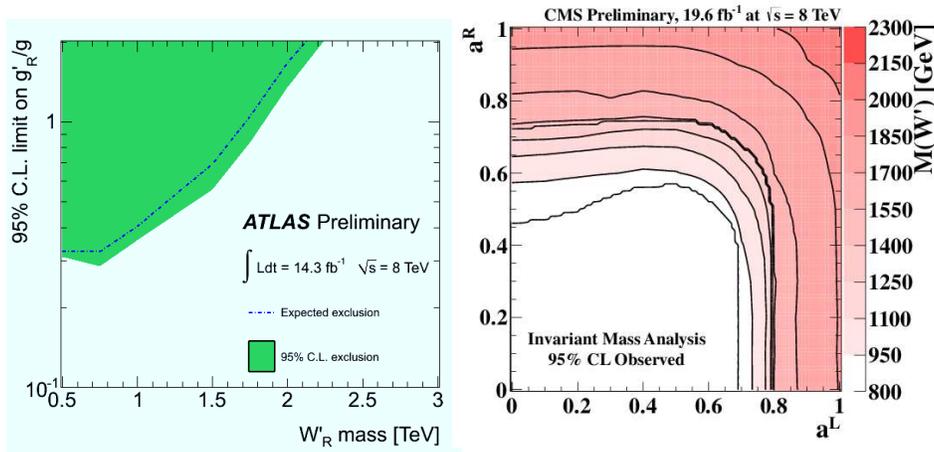


**Figure 1:** 95% CL limit on  $\sigma(pp \rightarrow W'X) \times B(W' \rightarrow e\nu)$  from CMS [16]. The theoretical prediction (dotted line) is for  $C_q^R = gV_{\text{CKM}}$ ,  $C_l^R = g$ ,  $C_q^L = C_l^L = 0$ .

boson were discovered and the final state fermions have left-handed helicity, then the effects of  $W - W'$  interference could be observed [15], providing useful information about the  $W'$  couplings.

In the  $e\nu$  channel, the CMS Collab. has set limits [16] for  $M_{W'}$  in the 0.3 – 4 TeV range, based on  $20 \text{ fb}^{-1}$  of LHC data at  $\sqrt{s} = 8 \text{ TeV}$ , as shown in Fig. 1. For  $M_{W'}$  in the 500 – 600 GeV range, the limits on  $W'$  couplings set by CDF [17] are also stringent (for a comparison, see Fig. 4 of Ref. 14). The limits are much weaker for  $M_{W'}$  in the 200 – 300 GeV range because these were obtained using only  $0.2 \text{ fb}^{-1}$  of Tevatron data [18], while the 105 – 200 GeV range has been even less explored (see the UA1 and UA2 references in Ref. 19).

In the  $\mu\nu$  channel, the most stringent limits in the 0.3 – 4 TeV range are set by CMS [16] using the  $\sqrt{s} = 8 \text{ TeV}$  data. When combined with the  $e\nu$  channel, the limit varies between 71 and 1.7 fb. The ATLAS  $\mu\nu$  limit [14] uses the 7 TeV data set. For  $M_{W'}$  in the 200 – 300 GeV range there are only weak limits on the  $W'$  couplings from Run I [20] of the Tevatron. There are no direct limits on  $W' \rightarrow \mu\nu$  for  $M_{W'}$  in the 105 – 200



**Figure 2:** 95% CL upper limits on  $W'$  couplings using the  $t\bar{b}$  and  $\bar{t}b$  final states, assuming that the diagonal couplings are generation independent. Left panel: ATLAS [23] limit on  $C_{q11}^R/g$ . Right panel: CMS [24] limit on  $M_{W'}$  as contours in the  $C_{q11}^R/g - C_{q11}^L/g$  plane.

GeV range. Note that masses of the order of the electroweak scale are interesting from a theory point of view, while lepton universality does not necessarily apply to a  $W'$  boson.

Dedicated searches for the  $W' \rightarrow \tau\nu$  decay have not yet been performed, but limits can be derived from some searches in the  $\ell + \cancel{E}_T$  channel as well as from charged-Higgs searches such as  $pp \rightarrow t\bar{b}\tau\nu X$ .

The  $W'$  decay into a lepton and a right-handed neutrino,  $\nu_R$ , may also be followed by the  $\nu_R$  decay through a virtual  $W'$  boson into a lepton and two quark jets. The CMS [21] and ATLAS [22] searches in the  $eejj$ ,  $\mu\mu jj$  and  $\tau\tau jj$  channels have set limits on various quantities for  $M_{W'}$  in the 0.6 – 3 TeV range.

The  $t\bar{b}$  channel is particularly important because a  $W'$  boson that couples only to right-handed fermions cannot decay to leptons when the right-handed neutrinos are heavier than  $M_{W'}$  (additional motivations are provided by a  $W'$  boson with enhanced couplings to the third generation [9], and by a leptophobic  $W'$  boson). The usual signal consists of a leptonically decaying  $W$  boson and two  $b$ -jets. Upper limits on the  $W'$  couplings to right- and left-handed quarks normalized to the SM  $W$  couplings, have been set by ATLAS [23] and CMS [24] as shown

in Fig. 2. The best limits on the couplings to right-handed quarks for  $M_{W'}$  in the 300–500 GeV range have been set by CDF with  $1.9 \text{ fb}^{-1}$  [25], while on couplings to left-handed quarks for  $M_{W'}$  in the 600–800 GeV range have been set by DØ with  $2.3 \text{ fb}^{-1}$  [26]. For  $M_{W'} \gg m_t$ , one could also use hadronic  $W$  boson decays to search for  $W' \rightarrow t\bar{b}$  with a boosted top quark. Finally, if  $W'$  couplings to left-handed quarks are large, then interference effects modify the SM  $s$ -channel single-top production [27].

Searches for dijet resonances may be used to set limits on  $W' \rightarrow q\bar{q}'$ . The best limits on  $W'$  couplings to quarks have been set by UA2 [28] in the 140 – 250 GeV mass range, by CDF [29] in the 250 – 900 GeV range, and by CMS [30] in the  $\sim 1 - 3$  TeV range.

In some theories [4], the  $W'$  couplings to SM fermions are suppressed by discrete symmetries.  $W'$  production then occurs in pairs, through a photon or  $Z$  boson. 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.

Searches for  $WZ$  resonances at the LHC have focused on the process  $pp \rightarrow W' \rightarrow WZ$  with the production mainly from  $u\bar{d} \rightarrow W'$  assuming SM-like couplings to quarks. CMS [32] and ATLAS [33] have set upper limits on the  $W'WZ$  coupling for  $M_{W'}$  in the 170 – 2000 GeV range. Similar searches have also been performed at the Tevatron [34].

A fermiophobic  $W'$  boson that couples to  $WZ$  may be produced at hadron colliders in association with a  $Z$  boson, or via  $WZ$  fusion. This would give rise to  $(WZ)Z$  and  $(WZ)jj$  final states, where the parentheses represent a resonance [31].

**Low-energy constraints.** The properties of  $W'$  bosons are also constrained by measurements of processes at energies much below  $M_{W'}$ . The bounds on  $W - W'$  mixing [19] are mostly due to the change in  $W$  properties compared to the SM. Limits on deviations in the  $ZWW$  couplings provide a leading constraint for fermiophobic  $W'$  bosons [11].

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  $W'$  boson 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 [35]. However, if no correlation between  $C_{qij}^R$  and  $C_{lij}^R$  is assumed, then the limit on  $M_{W'}$  may be significantly relaxed [36].

$W'$  exchange also contributes at tree level to various low-energy processes. In particular, it would impact the measurement of the Fermi constant  $G_F$  in muon decay, which in turn would change the predictions of many other electroweak processes. A recent test of parity violation in polarized muon decay [37] has set limits of about 600 GeV on  $M_{W'}$ , assuming  $W'$  couplings to right-handed leptons as in left-right symmetric models. There are also  $W'$  contributions to the neutron electric dipole moment,  $\beta$  decays, and other processes [19].

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 [38]. For  $\nu_R$  masses below a few GeV, the  $W'$  boson contributes to leptonic and semileptonic  $B$  meson decays, so that limits may be placed on various combinations of  $W'$  parameters [36]. For  $\nu_R$  masses below  $\sim 30$  MeV, most stringent constraints on  $M_{W'}$  are due to the limits on  $\nu_R$  emission from supernovae.

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