W'-BOSON SEARCHES

Revised March 2016 by M.-C. Chen (UC Irvine), B.A. Dobrescu (Fermilab) and S. Willocq (U Massachusetts).

The W' boson is a massive hypothetical particle of spin 1 and electric charge ±1, which is a color singlet and is 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

$$\frac{W'^+_\mu}{\sqrt{2}}\left[\overline{u}_i\Big(C^R_{q_{ij}}P_R+C^L_{q_{ij}}P_L\Big)\gamma^\mu d_j+\overline{\nu}_i\Big(C^R_{\ell_{ij}}P_R+C^L_{\ell_{ij}}P_L\Big)\gamma^\mu e_j\right] . \tag{1}$$

Here u, d, ν 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 $C^L_{q_{ij}}$, $C^R_{q_{ij}}$, $C^L_{\ell_{ij}}$, and $C^R_{\ell_{ij}}$ are complex dimensionless parameters. If $C^R_{\ell_{ij}} \neq 0$, then the ith generation includes a right-handed neutrino. Using this notation, the SM W couplings are $C^L_q = gV_{\rm CKM}$, $C^L_\ell = g \approx 0.63$ and $C^R_q = C^R_\ell = 0$.

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.

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 mixing angle between the gauge eigenstates, θ_+, must be smaller than about 10^{-2}. In certain theories the mixing is negligible (*e.g.* due to a new parity [4]), even when the W' mass is near the electroweak scale.

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The W' coupling to WZ is fixed by Lorentz and gauge invariances, and to leading order in θ_+ is given by [5]

$$\frac{g\,\theta_+ i}{\cos\theta_W}\left[W'^+_\mu\left(W^-_\nu Z^{\nu\mu} + Z_\nu W^{-\mu\nu}\right) + Z^\nu W^{-\mu} W'^+_{\nu\mu}\right] + \text{H.c.}, \quad (2)$$

where $W^{\mu\nu} \equiv \partial^\mu W^\nu - \partial^\nu W^\mu$, etc. The θ_W dependence shown here corrects the one given in [6], which has been referred to as the Extended Gauge Model by the experimental collaborations. The W' coupling to Wh^0, where h^0 is the SM Higgs boson, is

$$-\xi_h\, g_{W'} M_W\; W'^+_\mu\, W^{\mu-} h^0 + \text{H.c.}, \quad (3)$$

where $g_{W'}$ is the gauge coupling of the W' boson, and the coefficient ξ_h satisfies $\xi_h \leq 1$ in simple Higgs sectors [5].

In models based on the "left-right symmetric" gauge group [7], $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, the SM fermions that couple to the W boson transform as doublets under $SU(2)_L$ while the other fermions transform as doublets under $SU(2)_R$. Consequently, the W' boson couples primarily to right-handed fermions; its coupling to left-handed fermions arises due to the θ_+ mixing, so that C^L_q is proportional to the CKM matrix and its elements are much smaller than the diagonal elements of C^R_q. Generically, C^R_q does not need to be proportional to V_{CKM}.

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' boson couples to pairs involving a SM fermion and a new fermion. In the "ununified SM" [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' boson: $C^L_{\ell_{ij}} \ll C^L_{q_{ij}}$ and $C^R_{\ell_{ij}} = C^R_{q_{ij}} = 0$. 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].

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 $SU(2)$ [12], then the couplings are proportional to the tiny mixing angle θ_+. Similar suppressions may arise if some vectorlike fermions mix with the SM fermions [13].

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 [14].

Collider searches. At LEP-II, W' bosons could have been produced in pairs via their photon and Z couplings. The production cross section is large enough to rule out $M_{W'} < \sqrt{s}/2 \approx$ 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 $pp \to f\bar{f}'X$, where f and f' are fermions with an $f\bar{f}'$ electric charge of ± 1, and X is any final state, may be approximated by the branching fraction $B(W' \to f\bar{f}')$ times the production cross section

$$\sigma\big(pp \to W'X\big) \simeq \frac{\pi}{48\,s} \sum_{i,j} \Big[(C^L_{q_{ij}})^2 + (C^R_{q_{ij}})^2 \Big] \, w_{ij}\left(M^2_{W'}/s, M_{W'}\right) . \tag{4}$$

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

$$w_{ij}(z,\mu) = \int_z^1 \frac{dx}{x} \left[u_i(x,\mu)\, \overline{d}_j\left(\frac{z}{x},\mu\right) + \overline{u}_i(x,\mu)\, d_j\left(\frac{z}{x},\mu\right) \right] , \tag{5}$$

where $u_i(x,\mu)$ and $d_i(x,\mu)$ are the parton distributions inside the proton, at the factorization scale μ and parton momentum fraction x, for the up- and down-type quark of the ith 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 [15].

The most commonly studied W' signal consists of a high-momentum electron or muon and large missing transverse momentum, with the transverse mass distribution forming a Jacobian peak with its endpoint at $M_{W'}$ (see Fig. 1e of [16]). Given that the branching fractions for $W' \to e\nu$ and $W' \to \mu\nu$ could be very different, these channels should be analyzed separately. Searches in these channels often implicitly assume that the left-handed couplings vanish (no interference between W

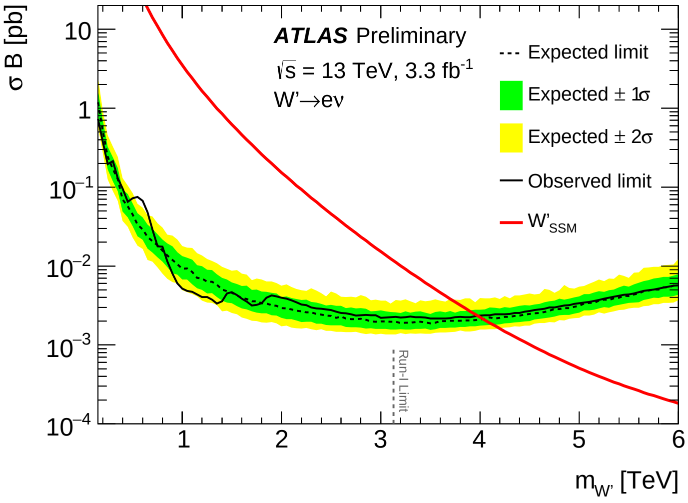

Figure 1: Upper limit on $\sigma(pp \rightarrow W'X)\, B(W' \rightarrow e\nu)$ from ATLAS [20], at 95% CL. The red line shows the theoretical prediction in the Sequential SM.

and W'), and that the right-handed neutrino is light compared to the W' boson and escapes the detector. These assumptions correspond to the following choice of parameters: $C_q^R = gV_{\rm CKM}$, $C_\ell^R = g$, $C_q^L = C_\ell^L = 0$, which define a model that is essentially equivalent to the Sequential SM used in many searches. However, if a W' boson were discovered and the final state fermions have left-handed helicity, then the effects of $W - W'$ interference could be observed [17], providing useful information about the W' couplings.

In the $e\nu$ channel, the ATLAS and CMS Collaborations set limits on the W' production cross section times branching fraction (and thus indirectly on the W' couplings) when $M_{W'}$ is in the $0.2 - 6$ TeV range, based on 20 fb^{-1} of LHC data at $\sqrt{s} = 8$ TeV [16,18] and 2–3 fb^{-1} at $\sqrt{s} = 13$ TeV [19,20], as shown in Fig. 1. ATLAS sets the strongest mass lower limit $M_{W'} > 4.0$ TeV in the Sequential SM (all limits in this mini-review are at the 95% CL). The coupling limits are much weaker for $M_{W'} < 200$ GeV, a range last explored with the Tevatron at $\sqrt{s} = 1.8$ TeV [21].

In the $\mu\nu$ channel, ATLAS and CMS set rate limits for $M_{W'}$ in the $0.2 - 6$ TeV range from the same analyses as mentioned above, with the strongest lower mass limit of 4.0 TeV set by CMS [19] using the $\sqrt{s} = 13$ TeV data. When combined with the $e\nu$ channel, the upper limit on the $\sqrt{s} = 13$ TeV cross section times branching fraction to $\ell\nu$ varies between 1 and 2 fb for $M_{W'}$ between 1 and 5 TeV [19]. Only weak limits on $W' \to \mu\nu$ exist for $M_{W'} < 200$ GeV [22]. 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.

A dedicated search for $W' \to \tau\nu$ has been performed by the CMS Collaboration at 8 TeV [23]. Limits are set on $\sigma \cdot B$ for $M_{W'}$ between 0.3 and 4.0 TeV. A lower mass limit of 2.7 TeV is set in the Sequential SM.

The W' decay into a lepton and a right-handed neutrino, ν_R, may also be followed by the ν_R decay through a virtual W' boson into a lepton and two quark jets. The ATLAS [24] and CMS [25] searches in the $eejj$ and $\mu\mu jj$ channels have set limits on the cross section times branching fraction as a function of the ν_R mass or of $M_{W'}$. These searches are typically performed with same-charge lepton pairs that provide strong background reduction and are motivated by models with a left-right symmetry. However, it is also interesting to search in final states with opposite-charge lepton pairs, as done in the CMS analysis.

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 the W' boson (additional motivations are provided by a W' boson with enhanced couplings to the third generation [11], and by a leptophobic W' boson). The usual signature consists of a leptonically-decaying W boson and two b-jets. Recent studies have also incorporated the fully hadronic decay channel for $M_{W'} \gg m_t$ with the use of jet substructure techniques to tag highly boosted top-jets. Upper limits on the W' couplings to right- and left-handed quarks normalized to the SM W couplings have been set by ATLAS [26] and CMS [27] at $\sqrt{s} = 8$ TeV, as shown in Fig. 2. Using about 2 fb^{-1} of data at $\sqrt{s} = 13$ TeV in the $\ell +$ jets channel, CMS [28] sets an upper limit on the W' production cross section times branching fraction to the $\ell\nu b\bar{b}$ final state decreasing from 1.6 pb at $M_{W'} = 1$ TeV to 35 fb

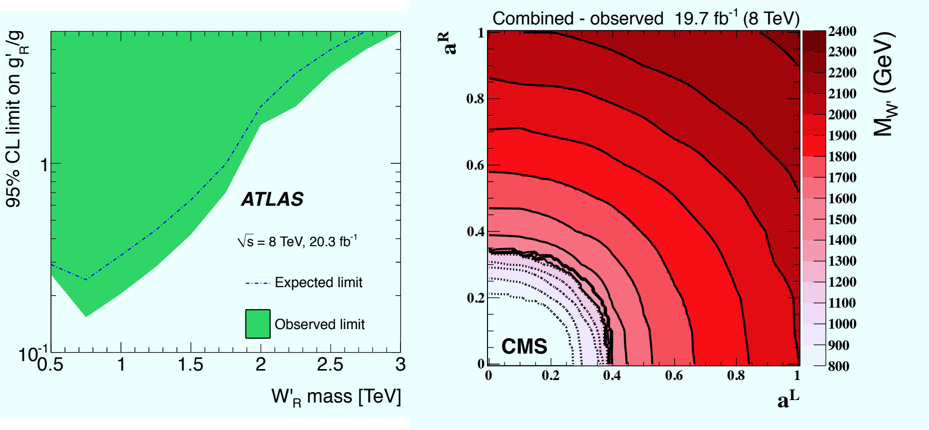

Figure 2: Upper limits on W' couplings (at 95% CL) using the $t\bar{b}$ and $\bar{t}b$ final states, assuming that the diagonal couplings are generation independent. Left panel: ATLAS [26] limit on C^R_{q11}/g. Right panel: CMS [27] limit on $M_{W'}$ as contours in the C^R_{q11}/g – C^L_{q11}/g plane.

at $M_{W'} = 3$ TeV The limit $M_{W'} > 2.38$ TeV obtained in the Sequential SM with a light ν_R increases with the ν_R mass. The best limits on the couplings to right-handed quarks for $M_{W'}$ in the 300–600 GeV range have been set by CDF with 9.5 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [29]. Finally, if W' couplings to left-handed quarks are large, then interference effects modify the SM s-channel single-top production [30].

Searches for dijet resonances may be used to set limits on $W' \to q\bar{q}'$. The best limits on W' couplings to quarks have been set by UA2 [31] in the $140 - 250$ GeV mass range, by CDF [32] in the $250 - 500$ GeV range and by CMS [33] in the $500 - 750$ GeV range. ATLAS and CMS provide similar coverage in the $\sim 0.75 - 7$ TeV range with data collected at $\sqrt{s} = 8$ and 13 TeV [34] with the most stringent lower W' mass limit in the Sequential SM set to 2.6 TeV using 13 TeV data.

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 momentum.

Searches for WZ resonances at the LHC have focused on the process $pp \to W' \to WZ$ with the production mainly from

$u\bar{d} \rightarrow W'$ assuming SM-like couplings to quarks. ATLAS and CMS have set the strongest upper limits on the $W'WZ$ coupling for $M_{W'}$ in the $0.2 - 4$ TeV range with a combination of fully leptonic, semi-leptonic and fully hadronic channels at both 8 and 13 TeV [35,36,37,38]. ATLAS has also combined the results from all channels at 8 TeV and obtains $M_{W'} > 1.81$ TeV in the Sequential SM [39].

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 [40].

W' bosons have also been searched for recently in final states with a W boson and a SM Higgs boson in the channels $W \rightarrow \ell\nu$ and $h^0 \rightarrow b\bar{b}$ or $h^0 \rightarrow WW$ by ATLAS [41,42] and CMS [43] at $\sqrt{s} = 8$ and 13 TeV. Cross section limits are set for W' masses in the range between 0.4 and 3.0 TeV. The strongest lower limit on the mass is set by the ATLAS 13 TeV analysis: $M_{W'} > 1.49$ TeV in the context of the Heavy Vector Triplet weakly-coupled scenario A [44].

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 [45] 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 [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' 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: $M_{W'} > 2.9$ TeV for $C_q^L = C_q^R$ [46]. However, if no correlation between the W' and W couplings is assumed, then the limit on $M_{W'}$ may be significantly relaxed [47].

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 [48] has set limits of about 600 GeV on $M_{W'}$, assuming W' couplings to right-handed leptons as in left-right symmetric models and a light ν_R. There are also W' contributions to the neutron electric dipole moment, β decays, and other processes [45].

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 [49]. For ν_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 [47]. For ν_R masses below ~ 30 MeV, the most stringent constraints on $M_{W'}$ are due to the limits on ν_R emission from supernovae.

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