86. W'-Boson Searches

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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).

86.1 W' couplings to quarks and leptons

The Lagrangian terms describing the couplings of a W'^+ boson to fermions are given by

$$\frac{W'^+_\mu}{\sqrt{2}}\left[\overline{u}_i\Big(C^R_{q_{ij}}P_R+C^L_{q_{ij}}P_L\Big)\gamma^\mu d_j+\overline{\nu}_i\Big(C^R_{\ell_{ij}}P_R+C^L_{\ell_{ij}}P_L\Big)\gamma^\mu e_j\right]. \quad (86.1)$$

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]; the W'-to-Z' mass ratio is often a free parameter.

A tree-level mass mixing may be induced between the electrically-charged gauge bosons. Upon diagonalization of their mass matrix, the W-to-Z mass ratio and the couplings of the observed W boson are shifted from the SM values. Their measurements imply that the mixing angle, θ_+, between the gauge eigenstates must be smaller than about 10^{-2} [4]. In certain theories the mixing is negligible (*e.g.*, due to a new parity [5]), even when the W' mass is near the electroweak scale. Note that $SU(2)$ gauge invariance suppresses the kinetic mixing between the W and W' bosons (in contrast to the case of a Z' boson [3]).

The W' coupling to WZ is fixed by Lorentz and gauge invariances, and to leading order in θ_+ is given by [6]

$$\frac{g\,\theta_+ i}{\cos\theta_W}\left[W'^+_\mu\left(W^-_\nu Z^{\nu\mu}+Z_\nu W^{-\mu\nu}\right)+Z^\nu W^{-\mu}W'^+_{\nu\mu}\right]+\text{H.c.}, \quad (86.2)$$

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 Ref. [7], 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

$$-\,\xi_h\, g_{W'} M_W\, W'^+_\mu\, W^{\mu -} h^0 + \text{H.c.}, \quad (86.3)$$

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 [6].

In models based on the "left-right symmetric" gauge group [8], $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, 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 $V_{\rm CKM}$.

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 [9], all the couplings shown in Eq. (86.1) 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" [10], 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 [11]. In particular, the couplings to third generation quarks may be enhanced [12].

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

86.2 Collider searches

At hadron colliders, W' bosons can be detected through resonant pair production of fermions (f and f') or electroweak bosons with a net electric charge equal to ± 1. When W' has a width much smaller than its mass ($\Gamma_{W'}/M_{W'} \lesssim 7\%$), the contribution of the s-channel W' exchange to the total rate for $pp \to f\bar{f}'X$, where X is any final state, may be approximated by the branching fraction $B(W' \to f\bar{f}')$ times the production cross section [16], which may be written as

$$\sigma(pp \to W'X) \simeq \frac{\pi}{6s} \sum_{i,j} \left[(C^L_{q_{ij}})^2 + (C^R_{q_{ij}})^2\right] w_{ij}\left(M^2_{W'}/s, M_{W'}\right) . \tag{86.4}$$

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

$$w_{ij}(z,\mu) = \int_z^1 \frac{dx}{x}\left[u_i(x,\mu)\,\bar{d}_j\left(\frac{z}{x},\mu\right) + \bar{u}_i(x,\mu)\,d_j\left(\frac{z}{x},\mu\right)\right] , \tag{86.5}$$

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 quarks 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 [17].

The most commonly studied W' signal consists of a high-momentum electron or muon and large missing transverse momentum. The signal transverse mass distribution forms a Jacobian peak with its endpoint at $M_{W'}$ (see Fig. 1 (top) of Ref. [18]). Given that the branching fractions for $W' \to e\nu$ and $W' \to \mu\nu$ could be very different, the results in these channels should be presented separately. Searches in these channels often implicitly assume that the left-handed couplings vanish (no interference between W and W'), and that the right-handed neutrino is light compared to the W' boson and escapes the detector. An example of parameter values that satisfy these assumptions is $C^R_q = gV_{\rm CKM}$, $C^R_\ell = g$, $C^L_q = C^L_\ell = 0$, which define a model that preserves lepton universality and predicts the same total cross section as the Sequential SM used in many W' 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 [19], providing information about the W' couplings. The effects of the W' width on interference are discussed in Ref. [20].

In the $e\nu$ channel, the ATLAS and CMS collaborations set limits on the W' production cross section times branching fraction $\sigma \times B$ (and thus indirectly on the W' couplings). These limits are set for $M_{W'}$ in the $0.15 - 7$ TeV range and are based on 139 fb^{-1} at $\sqrt{s} = 13$ TeV [18,21], with the most stringent limits reproduced in Fig. 86.1. ATLAS sets the strongest mass limit $M_{W'} > 6.0$ TeV in the Sequential SM (all limits in this mini-review are at the 95% CL). The coupling limits are much weaker for $M_{W'} < 150$ GeV, a range last explored with the Tevatron at $\sqrt{s} = 1.8$ TeV [22].

In the $\mu\nu$ channel, ATLAS and CMS set rate limits for $M_{W'}$ in the $0.15 - 7$ TeV range [18, 21], with the strongest mass lower limit of 5.6 TeV in the Sequential SM set by CMS [21] using 137 fb^{-1} of $\sqrt{s} = 13$ TeV data, as shown in Fig. 86.1. When combined with the $e\nu$ channel assuming lepton universality, the upper limit on the $\sqrt{s} = 13$ TeV cross section times branching fraction to $\ell\nu$ varies between 0.05 and 2.1 fb for $M_{W'}$ values between 1 and 6 TeV [18]. Only weak limits on $W' \to \mu\nu$ exist for $M_{W'} < 150$ GeV [23]. Note that masses of the order of the electroweak scale are interesting from a theoretical point of view, while lepton universality does not necessarily apply to a W' boson.

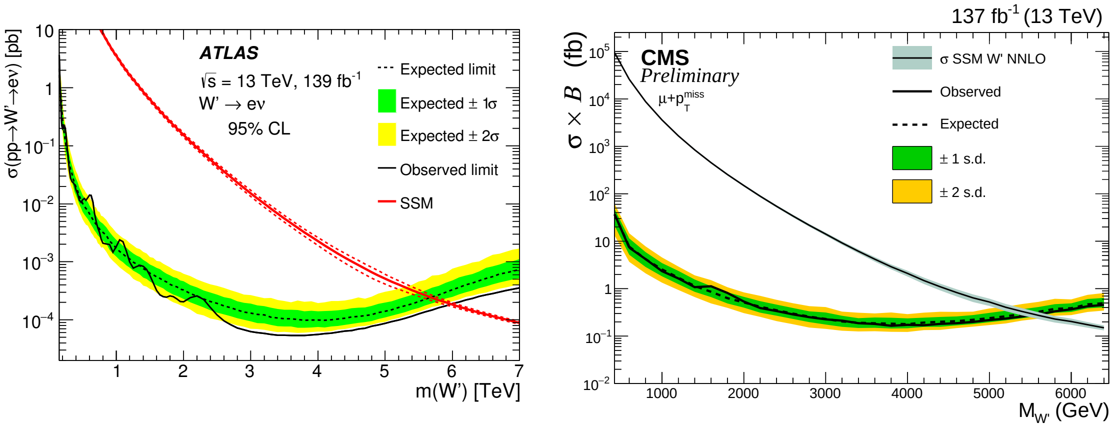

Figure 86.1: Upper limit on $\sigma(pp \to W'X) \times B(W' \to \ell\nu)$ in the $e\nu$ channel from ATLAS [18] (left) and the $\mu\nu$ channel from CMS [21] (right). The red (black) line shows the theoretical prediction in the Sequential SM in the $e\nu$ ($\mu\nu$) channel.

Searches for $W' \to \tau\nu$ have been performed at 13 TeV by CMS with 36 fb^{-1} [24], and by ATLAS with 139 fb^{-1} [25]. Limits are set on $\sigma \times B$ for $M_{W'}$ between 0.4 and 6 TeV. A mass lower limit of 5.0 TeV is set in the Sequential SM, and the upper limit on the cross section times branching fraction to $\tau\nu$ at 13 TeV varies between 0.4 and 9 fb for $M_{W'}$ values between 1 and 5 TeV [25].

The W' decay into a charged lepton and a right-handed neutrino, ν_R, may also be followed by the ν_R decay through a virtual W' boson into a charged lepton and two quark jets. The CMS [26] and ATLAS [27] searches in the $eejj$ and $\mu\mu jj$ channels have set limits at $\sqrt{s} = 13$ TeV on the cross section times branching fractions as a function of the ν_R mass and of $M_{W'}$. No requirement is placed on the charge of the lepton pair. A related W' search in the $\tau\tau jj$ channel with hadronic τ decays was also performed by CMS [28].

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 [12], and by a leptophobic W' boson. The usual signature for $W' \to t\bar{b}$ 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. For a detailed discussion of this channel, see Ref. [29].

Searches for dijet resonances may be used to set limits on $W' \to q\bar{q}'$. ATLAS [30] and CMS [31] provide similar coverage in the $\sim 1.5 - 8$ TeV mass range with 139 and 137 fb^{-1} of data, respectively, collected at $\sqrt{s} = 13$ TeV. Interpretation in terms of W' decays with 139 fb^{-1} of 13 TeV data yields a W' mass lower limit of 4.0 TeV in the Sequential SM [30]. For masses in the range $\sim 0.5 - 1.5$ TeV, analyses based on jets reconstructed online provide the best sensitivity because they circumvent trigger bandwidth limitations [32, 33]. For W' masses below ~ 0.5 TeV, the best limits are set in novel analyses exploiting boosted technologies and initial state radiation [34–37]. Cross-section limits for W' masses below ~ 1.5 TeV can be derived from the dijet limits on Z' bosons summarized in Ref. [3].

In some theories [5] 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 often include missing transverse momentum or boosted multi-jet topologies. An example is a search performed by CMS [38] for W' decays into a vector-like quark and a top or a bottom quark. The final state studied in this analysis involves a boosted SM Higgs boson or Z, as well as a $t\bar{t}$ or $b\bar{b}$ pair, with all heavy particles decaying into jets.

Searches for WZ resonances at the LHC have focused on the process $pp \to W' \to WZ$ with the production mainly from $u\bar{d} \to W'$, assuming SM-like couplings to quarks. ATLAS and CMS have set the upper limits on the $W'WZ$ coupling for $M_{W'}$ in the $0.2 - 5.0$ TeV range with a combination of fully leptonic, semi-leptonic and fully hadronic channels with ~ 36 fb^{-1} at 13 TeV [39, 40] (see also Ref. [29]). More recent constraints with 77–139 fb^{-1} at 13 TeV were also set in individual channels by ATLAS [41, 42] and CMS [43–46]. The strongest lower limit on the W' mass is set by ATLAS [42] in the semi-leptonic channel with a lower limit on $M_{W'}$ of 3.9 TeV [42] in the context of the Heavy Vector Triplet (HVT) weakly-coupled scenario A [47]. 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 [48]. Results of the search for the latter are reported in Refs. [39, 42, 44, 46].

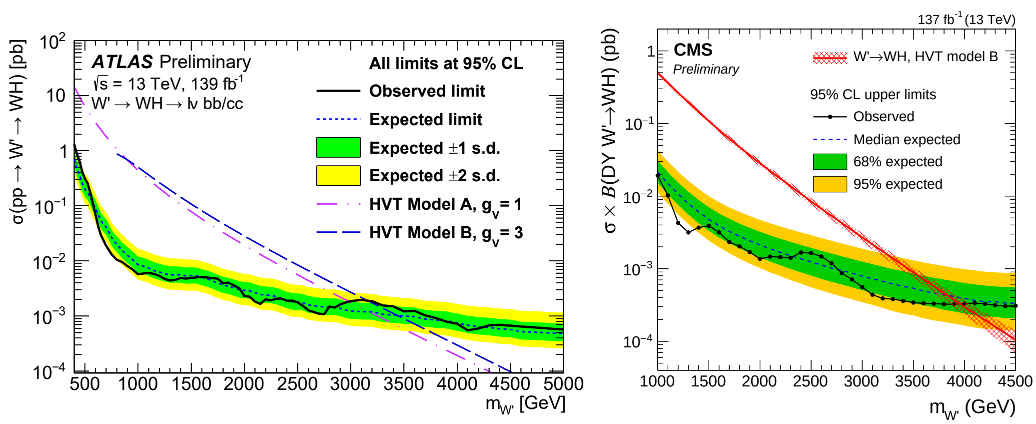

Figure 86.2: Upper limits on W' production cross section times branching fraction into a W and a SM Higgs boson decaying into heavy-flavor quarks, from ATLAS [49] (left) and CMS [46] (right).

W' bosons have also been searched for in final states with a W boson and a SM Higgs boson in the channels $W \to \ell\nu$ or $W \to q\bar{q}'$ and $h^0 \to b\bar{b}$ by ATLAS [49, 50] and CMS [46, 51] with 36–139 fb^{-1} at $\sqrt{s} = 13$ TeV. Cross-section limits are set for W' masses between 0.4 and 5.0 TeV. The ATLAS and CMS 13 TeV analyses with $W \to \ell\nu$ set the most stringent upper limits on the cross section at low and high $M_{W'}$, respectively, as shown in Fig. 86.2.

At lepton colliders, W' bosons may be produced in pairs via their photon coupling, which is model independent. At LEP-II, although dedicated searches for W' bosons have not been performed, the large cross section for $e^+e^- \to \gamma^* \to W'^+W'^-$ and small backgrounds suggest that any W' is ruled out up to the kinematic limit, $M_{W'} < \sqrt{s}/2 \approx 105$ GeV, for most decay modes.

Sensitivity to $M_{W'}$ above $\sqrt{s}$ could be achieved [52] using the $e^+e^- \to \gamma\nu\bar{\nu}$ process via a t-channel W' exchange, if the W' coupling to $e\nu$ is large enough.

86.3 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 [4] 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 [14].

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 $C_q^R = gV_{\rm CKM}$ [53]. However, if no correlation between the W' and W couplings is assumed, then the limit on $M_{W'}$ may be significantly relaxed [54].

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 [55] 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 [4].

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 [56]. 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 [54]. For ν_R masses below $\sim$30 MeV, the most stringent constraints on $M_{W'}$ are due to the limits on ν_R emission from supernovae.

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