W'-BOSON SEARCHES

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The W' boson is a massive hypothetical particle of charge ± 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

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

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 $C^L_{q_{ij}}$, $C^R_{q_{ij}}$, $C^L_{l_{ij}}$, $C^R_{l_{ij}}$ are complex dimensionless parameters. If $C^R_{l_{ij}} \neq 0$, then the ith generation includes a right-handed neutrino. Using this notation, the SM W couplings are $C^L_q = gV_{\rm CKM}$, $C^L_l = g$ and $C^R_q = C^R_l = 0$.

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 $pp \to f\bar{f}'X$, where f and f' are fermions whose electric charges differ by ± 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

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

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

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

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 [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 $W' \to e\nu$ and $W' \to \mu\nu$ 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'

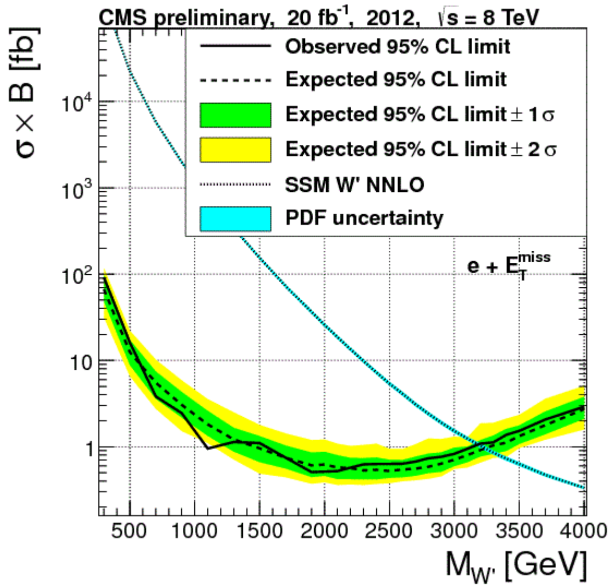

Figure 1: 95% CL limit on $\sigma(pp \to W'X) \times B(W' \to e\nu)$ from CMS [16]. The theoretical prediction (dotted line) is for $C_q^R = gV_{\rm CKM}$, $C_l^R = g$, $C_q^L = C_l^L = 0$.

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 fb^{-1} of LHC data at $\sqrt{s} = 8$ 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 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 $\sqrt{s} = 8$ 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 $W' \to \mu\nu$ for $M_{W'}$ in the $105 - 200$

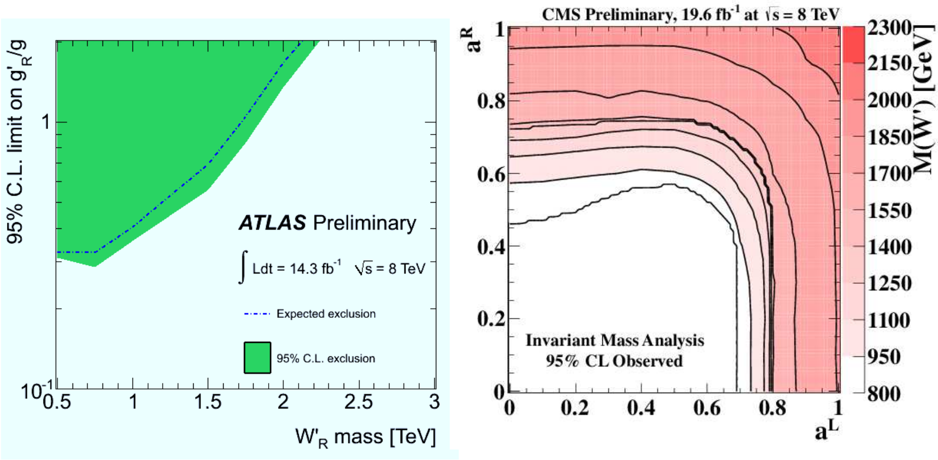

Figure 2: 95% CL upper limits on W' couplings using the $t\bar{b}$ and $\bar{t}b$ final states, assuming that the diagonal couplings are generation independent. Left panel: ATLAS [23] limit on C^R_{q11}/g. Right panel: CMS [24] limit on $M_{W'}$ as contours in the C^R_{q11}/g – C^L_{q11}/g plane.

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

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 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 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 fb^{-1} [26]. For $M_{W'} \gg m_t$, one could also use hadronic W boson decays to search for $W' \to t\bar{b}$ 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 $W' \to q\bar{q}'$. 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 $pp \to W' \to WZ$ with the production mainly from $u\bar{d} \to W'$ 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 $C^R_{q_{ij}}$ and $C^R_{l_{ij}}$ 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, β 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 ν_R mass may be derived [38]. 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 [36]. For ν_R masses below ∼30 MeV, most stringent constraints on $M_{W'}$ are due to the limits on ν_R emission from supernovae.

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