W'-BOSON SEARCHES

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

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

Here u, d, ν and e are the 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 $C^L_{q_{ij}}$, $C^R_{q_{ij}}$, $C^L_{l_{ij}}$, $C^R_{l_{ij}}$ are complex dimensionless parameters. If $C^R_{l_{ij}} \neq 0$, then the ith generation includes a right-handed neutrino. Using this notation, the Standard Model 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' is a gauge boson associated with a spontaneously-broken gauge symmetry. This is true even when it is a composite particle (*e.g.*, techni-$\rho^\pm$ in technicolor theories [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; whether the W' boson can be discovered first depends on theoretical 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 Standard Model values.

Given that these are well measured, 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 [3]), even when the W' and Z' masses are below the electroweak scale.

A popular model [4] 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 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 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 [5], all the couplings shown in Eq. (1) vanish, but there are some new fermions such that the W' boson couples to pairs involving a Standard Model fermion and a new fermion. In the "ununified Standard Model" [6], 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: $C^L_{l_{ij}} \ll C^L_{q_{ij}}$ and $C^R_{q_{ij}} = C^R_{l_{ij}} = 0$. Fermions of different generations may also transform as doublets under different $SU(2)$ gauge groups [7]. In particular, the couplings to third generation quarks may be enhanced [8].

The W' couplings to Standard Model fermions may be highly suppressed if the quarks and leptons are singlets under one $SU(2)$ [9], or if there are some vectorlike fermions that mix with the Standard Model ones [10]. 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 [11].

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

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

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 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 [12].

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. 1 of Ref. [13]). 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' boson were discovered and the final state fermions have left-handed helicity, then the effects of $W - W'$ interference could be observed [14], providing useful information about the W' couplings.

In the $e\nu$ channel, the 95% CL limit set by the ATLAS Collaboration [13] with 1 fb^{-1} of data on the cross section (at

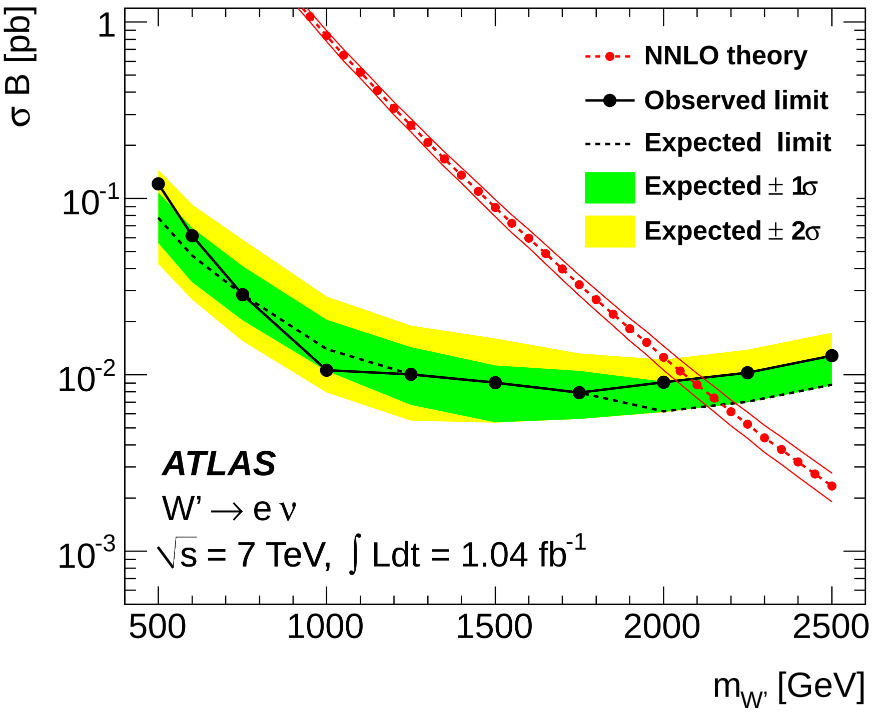

Figure 1: 95% CL limit on $\sigma(pp \to W'X) \times B(W' \to e\nu)$ from ATLAS [13] . The theoretical prediction (dash-dotted line) is for $C_q^R = gV_{\rm CKM}$, $C_l^R = g$, $C_q^L = C_l^L = 0$. Color version at end of book.

$\sqrt{s} = 7$ TeV) times branching fraction is shown in Fig. 1. The CMS limit based on 1.1 fb^{-1} of data in this channel [15], for $M_{W'}$ in the 1.4 – 2.5 TeV range, is also around 10 fb. For $M_{W'}$ in the 500 – 600 GeV range, the strongest limits on W' couplings are set by CDF [16] with 5.3 fb^{-1} (for a comparison, see Fig. 3 of Ref. [13]). The limits are much weaker for $M_{W'}$ in the 200 – 500 GeV range because these were obtained using only 0.2 fb^{-1} of Tevatron data [17], while the 105 – 200 GeV range has been even less explored (see the UA1 and UA2 references in Ref. [18]).

In the $\mu\nu$ channel, the ATLAS limit [13] is higher by about 50% compared to that shown in Fig. 1, while the CMS limit [15] is 6 – 7 fb for $M_{W'}$ in the 1.4 – 2.5 TeV range. For $M_{W'}$ in the 200 – 500 GeV range there are only weak limits on the W'

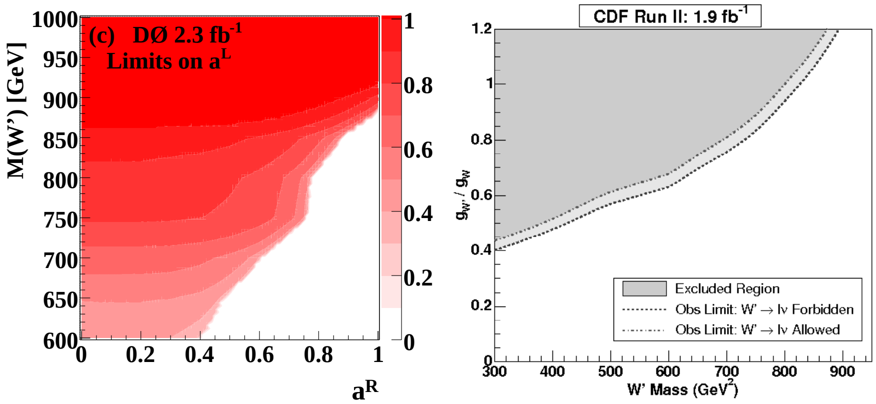

Figure 2: 95% CL upper limits on W' couplings using the $t\bar{b}$ and $\bar{t}b$ final states, assuming that the diagonal couplings are generation independent. Left panel: DØ [21] limit on C^L_{q11}/g as contours in the C^R_{q11}/g – $M_{W'}$ plane. Right panel: CDF [22] limit on C^R_{q11}/g. Color version at end of book.

couplings from the Tevatron Run I [19]. There are no direct limits on $W' \to \mu\nu$ for $M_{W'}$ in the $105 - 200$ GeV range.

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 search [20] with 0.24 fb^{-1} sets cross-section limits of roughly 50 fb in the e^+e^-jj and $\mu^+\mu^-jj$ channels.

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 [8], and by a leptophobic W' boson). The usual signal consists of a leptonically decaying W boson and two b-jets. The upper limits on the W' couplings to left- and right-handed quarks normalized to the Standard Model W boson couplings, set by DØ with 2.3 fb^{-1} [21] and by CDF with 1.9 fb^{-1} [22], respectively, are shown in Fig. 2. 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. If W' couplings to left-handed quarks are large, then interference effects modify the Standard Model s-channel single-top production [23].

Searches for dijet resonances may be used to set limits on $W' \to q\bar{q}'$ [18]. In the $105 - 200$ GeV mass range the limits are rather weak, as they have been set so far only by the UA2 Collaboration; even in the $200 - 700$ GeV range only small data sets from the Tevatron and the LHC have been used so far.

In some theories [3], the W' couplings to Standard Model 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.

A fermiophobic W' boson which 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 [24]. The study of these processes is important for understanding the origin of electroweak symmetry-breaking. The DØ [25] and CDF [26] Collaborations have set limits on $\sigma(p\bar{p} \to W'X) \times B(W' \to WZ)$ for $M_{W'}$ in the $180 - 1000$ GeV range, while the CMS Collaboration [27] has set cross-section limits for $M_{W'}$ in the $300 - 900$ GeV range using 7 TeV pp collissions.

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 [18] are mostly due to the change in the properties of the W boson compared to the Standard Model. Limits on the deviation in the ZWW coupling provide a leading constraint for fermiophobic W' bosons [10].

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 [28]. 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 [29].

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 [30] 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 [18].

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 [31]. 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 [29]. For ν_R masses below $\sim$30 MeV, most stringent constraints on $M_{W'}$ are due to the limits on ν_R emission from supernova.

References

1. M. Bando, T. Kugo, and K. Yamawaki, Phys. Rept. **164**, 217 (1988).
2. H.C. Cheng *et al*, Phys. Rev. D**64**, 065007 (2001).
3. H.C. Cheng and I. Low, JHEP **0309**, 051 (2003).
4. R.N. Mohapatra and J.C. Pati, Phys. Rev. D**11**, 566 (1975). G. Senjanovic and R.N. Mohapatra, Phys. Rev. D**12**, 1502 (1975).
5. K.S. Babu, X.G. He, and E. Ma, Phys. Rev. D**36**, 878 (1987).
6. H. Georgi, E.E. Jenkins, and E.H. Simmons, Nucl. Phys. B**331**, 541 (1990).
7. See, *e.g.*, X.y. Li and E. Ma, J. Phys. G**19**, 1265 (1993).
8. D.J. Muller and S. Nandi, Phys. Lett. B**383**, 345 (1996). E. Malkawi, T. Tait, and C.P. Yuan, Phys. Lett. B**385**, 304 (1996).
9. A. Donini *et al*, Nucl. Phys. B**507**, 51 (1997).
10. R.S. Chivukula *et al*, Phys. Rev. D**74**, 075011 (2006). H.J. He, T. Tait, and C.P. Yuan, Phys. Rev. D**62**, 011702 (2000).

11. F. Pisano and V. Pleitez, Phys. Rev. D**46**, 410 (1992); **51**, 3865 (1995).
12. Z. Sullivan, Phys. Rev. D**66**, 075011 (2002).
13. G. Aad *et al.* [ATLAS Collaboration], `arXiv:1108.1316`.
14. T.G. Rizzo, JHEP **0705**, 037 (2007). E. Boos *et al*, Phys. Lett. B**655**, 245 (2007).
15. CMS Collaboration, note CMS-PAS-EXO-11-024, July 2011.
16. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **83**, 031102 (2011).
17. A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. **D75**, 091101 (2007).
18. See the particle listings for W' in this *Review*.
19. F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **84**, 5716 (2000).
20. CMS Collaboration, note CMS-PAS-EXO-11-002, July 2011.
21. V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. **B699**, 145 (2011).
22. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 041801 (2009).
23. T.M.P. Tait, C.-P. Yuan, Phys. Rev. **D63**, 014018 (2000).
24. H.J. He *et al.*, Phys. Rev. D**78**, 031701 (2008).
25. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **107**, 011801 (2011).
26. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **104** (2010) 241801.
27. CMS Collaboration, note CMS-PAS-EXO-11-041, Aug. 2011.
28. Y. Zhang *et al*, Phys. Rev. D**76**, 091301 (2007).
29. P. Langacker and S.U. Sankar, Phys. Rev. D**40**, 1569 (1989).
30. J. F. Bueno *et al.* [TWIST Collaboration], Phys. Rev. D **84**, 032005 (2011).
31. See Fig. 5 of G. Prezeau, M. Ramsey-Musolf, and P. Vogel, Phys. Rev. D**68**, 034016 (2003).