

## 86. $W'$ -Boson Searches

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The  $W'$  boson is a massive hypothetical particle of spin 1 and electric charge  $\pm 1$ , 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

$$\frac{W'^+_\mu}{\sqrt{2}} \left[ \bar{u}_i (C_{qij}^R P_R + C_{qij}^L P_L) \gamma^\mu d_j + \bar{\nu}_i (C_{\ell ij}^R P_R + C_{\ell ij}^L P_L) \gamma^\mu e_j \right]. \quad (86.1)$$

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  $C_{qij}^L, C_{qij}^R, C_{\ell ij}^L$ , and  $C_{\ell ij}^R$  are complex dimensionless parameters. If  $C_{\ell ij}^R \neq 0$ , then the  $i$ th generation includes a right-handed neutrino. Using this notation, the SM  $W$  couplings are  $C_q^L = g V_{\text{CKM}}$ ,  $C_\ell^L = g \approx 0.63$  and  $C_q^R = C_\ell^R = 0$ .

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]; 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,  $\theta_+$ , 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  $\theta_+$  is given by [6]

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

where  $W^{\mu\nu} \equiv \partial^\mu W^\nu - \partial^\nu W^\mu$ , etc. The  $\theta_W$  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  $\xi_h$  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  $\theta_+$  mixing, so that  $C_q^L$  is proportional to the CKM matrix and its elements are much smaller than the diagonal elements of  $C_q^R$ . Generically,  $C_q^R$  does not need to be proportional to  $V_{\text{CKM}}$ .

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 “unified 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:  $C_{\ell_{ij}}^L \ll C_{q_{ij}}^L$  and  $C_{\ell_{ij}}^R = C_{q_{ij}}^R = 0$ . 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  $\theta_+$ . 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  $\pm 1$ . 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  $pp \rightarrow f\bar{f}'X$ , where  $X$  is any final state, may be approximated by the branching fraction  $B(W' \rightarrow f\bar{f}')$  times the production cross section [16], which may be written as

$$\sigma(pp \rightarrow W'X) \simeq \frac{\pi}{6s} \sum_{i,j} \left[ (C_{q_{ij}}^L)^2 + (C_{q_{ij}}^R)^2 \right] w_{ij} \left( M_{W'}^2/s, M_{W'} \right). \quad (86.4)$$

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

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

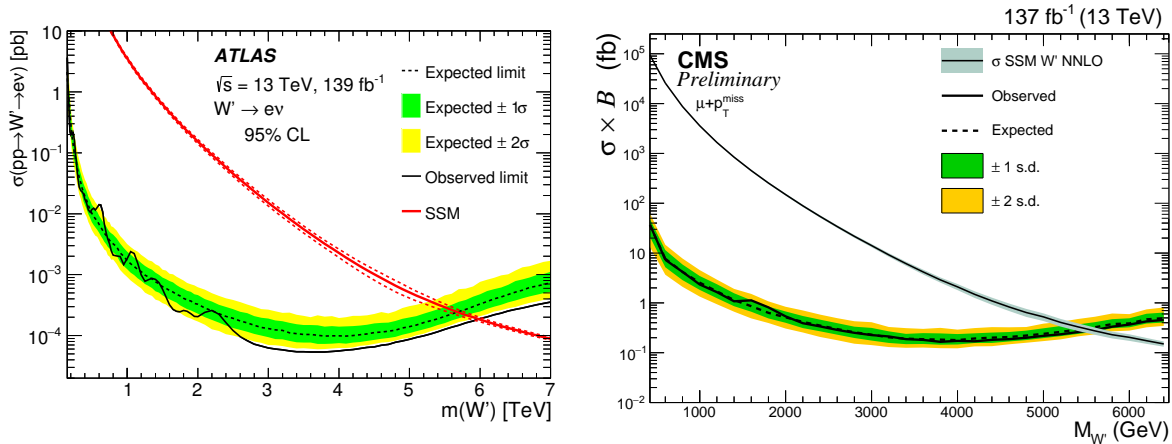
where  $u_i(x, \mu)$  and  $d_i(x, \mu)$  are the parton distributions inside the proton at the factorization scale  $\mu$  and parton momentum fraction  $x$  for the up- and down-type quarks of the  $i$ th generation, respectively. QCD corrections to  $W'$  production are sizable (they also include quark-gluon initial states), but preserve the above factorization of couplings at next-to-leading order [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  $W' \rightarrow e\nu$  and  $W' \rightarrow \mu\nu$  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  $C_q^R = gV_{\text{CKM}}$ ,  $C_\ell^R = g$ ,  $C_q^L = C_\ell^L = 0$ , 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  $137 \text{ fb}^{-1}$  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  $W' \rightarrow \mu\nu$  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  $\sigma(pp \rightarrow W'X) \times B(W' \rightarrow \ell\nu)$  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  $W' \rightarrow \tau\nu$  have been performed at 13 TeV by CMS with  $36 \text{ fb}^{-1}$  [24], and by ATLAS with  $139 \text{ fb}^{-1}$  [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,  $\nu_R$ , may also be followed by the  $\nu_R$  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  $\nu_R$  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  $\tau$  decays was also performed by CMS [28].

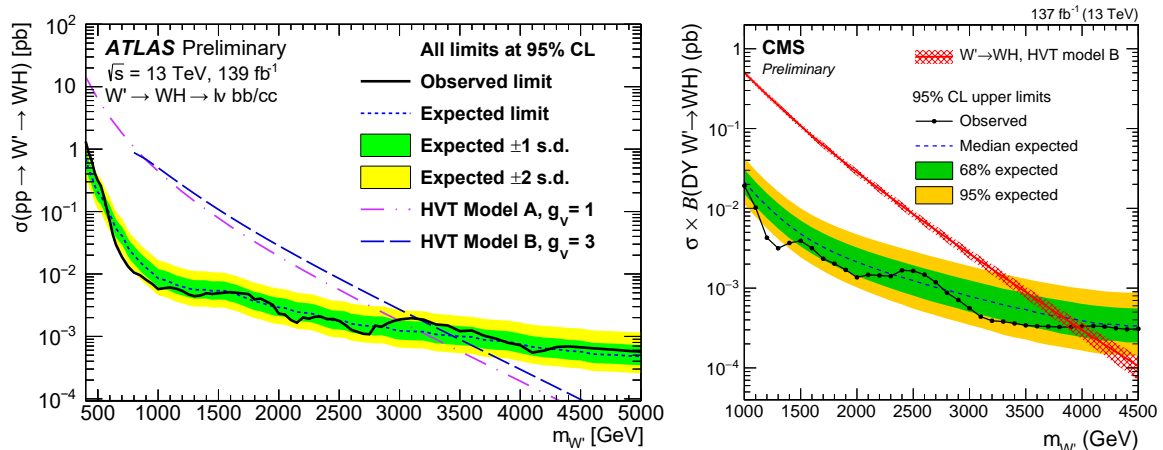
The  $t\bar{b}$  channel is particularly important because a  $W'$  boson that couples only to right-handed fermions cannot decay to leptons when the right-handed neutrinos are heavier than  $M_{W'}$ . Additional motivations are provided by a  $W'$  boson with enhanced couplings to the third generation [12], and by a leptophobic  $W'$  boson. The usual signature for  $W' \rightarrow t\bar{b}$  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  $W' \rightarrow q\bar{q}'$ . ATLAS [30] and CMS [31] provide similar coverage in the  $\sim 1.5$ –8 TeV mass range with  $139$  and  $137 \text{ fb}^{-1}$  of data, respectively, collected at  $\sqrt{s} = 13$  TeV. Interpretation in terms of  $W'$  decays with  $139 \text{ fb}^{-1}$  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  $\sim 0.5$  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  $\sim 1.5$  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  $pp \rightarrow W' \rightarrow WZ$  with the production mainly from  $u\bar{d} \rightarrow W'$ , 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  $\sim 36 \text{ fb}^{-1}$  at 13 TeV [39, 40] (see also Ref. [29]). More recent constraints with 77–139  $\text{fb}^{-1}$  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  $W \rightarrow \ell\nu$  or  $W \rightarrow q\bar{q}'$  and  $h^0 \rightarrow b\bar{b}$  by ATLAS [49, 50] and CMS [46, 51] with 36–139  $\text{fb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$ . Cross-section limits are set for  $W'$  masses between 0.4 and 5.0 TeV. The ATLAS and CMS 13 TeV analyses with  $W \rightarrow \ell\nu$  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  $e^+e^- \rightarrow \gamma^* \rightarrow W'^+W'^-$  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  $e^+e^- \rightarrow \gamma\nu\bar{\nu}$  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  $C_q^R = gV_{\text{CKM}}$  [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  $\nu_R$ . There are also  $W'$  contributions to the neutron electric dipole moment,  $\beta$  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  $\nu_R$  mass may be derived [56]. 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 [54]. For  $\nu_R$  masses below  $\sim 30$  MeV, the most stringent constraints on  $M_{W'}$  are due to the limits on  $\nu_R$  emission from supernovae.

### References

- [1] M. Bando, T. Kugo and K. Yamawaki, *Phys. Rept.* **164**, 217 (1988).
- [2] H.-C. Cheng *et al.*, *Phys. Rev.* **D64**, 065007 (2001), [[hep-th/0104179](#)].
- [3] See the Section on “ $Z'$ -boson searches” in this *Review*.
- [4] See the particle listings for  $W'$  in this *Review*.
- [5] H.-C. Cheng and I. Low, *JHEP* **09**, 051 (2003), [[hep-ph/0308199](#)].
- [6] B. A. Dobrescu and Z. Liu, *JHEP* **10**, 118 (2015), [[arXiv:1507.01923](#)].
- [7] G. Altarelli, B. Mele and M. Ruiz-Altaba, *Z. Phys.* **C45**, 109 (1989), [Erratum: *Z. Phys.* **C47**, 676 (1990)].
- [8] R. N. Mohapatra and J. C. Pati, *Phys. Rev.* **D11**, 566 (1975).
- [9] K. S. Babu, X.-G. He and E. Ma, *Phys. Rev.* **D36**, 878 (1987).
- [10] H. Georgi, E. E. Jenkins and E. H. Simmons, *Nucl. Phys.* **B331**, 541 (1990).
- [11] X.-y. Li and E. Ma, *J. Phys.* **G19**, 1265 (1993), [[hep-ph/9208210](#)].
- [12] D. J. Muller and S. Nandi, *Phys. Lett.* **B383**, 345 (1996), [[hep-ph/9602390](#)].
- [13] A. Donini *et al.*, *Nucl. Phys.* **B507**, 51 (1997), [[hep-ph/9705450](#)].
- [14] R. S. Chivukula *et al.*, *Phys. Rev.* **D74**, 075011 (2006), [[hep-ph/0607124](#)].
- [15] F. Pisano and V. Pleitez, *Phys. Rev.* **D46**, 410 (1992), [[hep-ph/9206242](#)].
- [16] V. D. Barger and R. J. N. Phillips, *Collider Physics* (1996), ISBN 978-0201149456.

- [17] Z. Sullivan, *Phys. Rev.* **D66**, 075011 (2002), [hep-ph/0207290].
- [18] G. Aad *et al.* (ATLAS), *Phys. Rev.* **D100**, 052013 (2019), [arXiv:1906.05609].
- [19] T. G. Rizzo, *JHEP* **05**, 037 (2007), [arXiv:0704.0235].
- [20] E. Accomando *et al.*, *Phys. Rev.* **D85**, 115017 (2012), [arXiv:1110.0713].
- [21] CMS Collab., CMS PAS EXO-19-017, Mar. 2021.
- [22] F. Abe *et al.* (CDF), *Phys. Rev. Lett.* **74**, 2900 (1995).
- [23] F. Abe *et al.* (CDF), *Phys. Rev. Lett.* **67**, 2609 (1991).
- [24] A. M. Sirunyan *et al.* (CMS), *Phys. Lett.* **B792**, 107 (2019), [arXiv:1807.11421].
- [25] ATLAS Collab., ATLAS-CONF-2021-025, Jun. 2021.
- [26] CMS Collab., CMS PAS EXO-20-002, Jul. 2021.
- [27] M. Aaboud *et al.* (ATLAS), *Phys. Lett. B* **798**, 134942 (2019), [arXiv:1904.12679].
- [28] A. M. Sirunyan *et al.* (CMS), *JHEP* **03**, 170 (2019), [arXiv:1811.00806].
- [29] K.M. Black *et al.*, “Dynamical electroweak symmetry breaking” in this *Review*.
- [30] G. Aad *et al.* (ATLAS), *JHEP* **03**, 145 (2020), [arXiv:1910.08447].
- [31] A. M. Sirunyan *et al.* (CMS), *JHEP* **05**, 033 (2020), [arXiv:1911.03947].
- [32] M. Aaboud *et al.* (ATLAS), *Phys. Rev. Lett.* **121**, 081801 (2018), [arXiv:1804.03496].
- [33] A. M. Sirunyan *et al.* (CMS), *JHEP* **08**, 130 (2018), [arXiv:1806.00843].
- [34] M. Aaboud *et al.* (ATLAS), *Phys. Lett.* **B788**, 316 (2019), [arXiv:1801.08769].
- [35] M. Aaboud *et al.* (ATLAS), *Phys. Lett.* **B795**, 56 (2019), [arXiv:1901.10917].
- [36] A. M. Sirunyan *et al.* (CMS), *Phys. Rev. D* **100**, 11, 112007 (2019), [arXiv:1909.04114].
- [37] A. M. Sirunyan *et al.* (CMS), *Phys. Rev. Lett.* **123**, 23, 231803 (2019), [arXiv:1905.10331].
- [38] CMS Collab., CMS PAS B2G-20-002, Mar. 2021.
- [39] M. Aaboud *et al.* (ATLAS), *Phys. Rev.* **D98**, 052008 (2018), [arXiv:1808.02380].
- [40] A. M. Sirunyan *et al.* (CMS), *Phys. Lett.* **B798**, 134952 (2019), [arXiv:1906.00057].
- [41] G. Aad *et al.* (ATLAS), *JHEP* **09**, 091 (2019), [arXiv:1906.08589].
- [42] G. Aad *et al.* (ATLAS), *Eur. Phys. J. C* **80**, 12, 1165 (2020), [arXiv:2004.14636].
- [43] A. M. Sirunyan *et al.* (CMS), *Eur. Phys. J. C* **80**, 3, 237 (2020), [arXiv:1906.05977].
- [44] CMS Collab., CMS PAS B2G-20-008, Mar. 2021.
- [45] CMS Collab., CMS PAS B2G-20-013, Jul. 2021.
- [46] A. Tumasyan *et al.* (CMS) (2021), [arXiv:2109.06055].
- [47] D. Pappadopulo *et al.*, *JHEP* **09**, 060 (2014), [arXiv:1402.4431].
- [48] H.-J. He *et al.*, *Phys. Rev.* **D78**, 031701 (2008), [arXiv:0708.2588].
- [49] ATLAS Collab., ATLAS-CONF-2021-026, Jun. 2021.
- [50] G. Aad *et al.* (ATLAS), *Phys. Rev. D* **102**, 11, 112008 (2020), [arXiv:2007.05293].
- [51] A. M. Sirunyan *et al.* (CMS), *JHEP* **11**, 172 (2018), [arXiv:1807.02826].
- [52] S. Godfrey *et al.*, *Phys. Rev. D* **61**, 113009 (2000), [hep-ph/0001074].
- [53] Y. Zhang *et al.*, *Phys. Rev.* **D76**, 091301 (2007), [arXiv:0704.1662].
- [54] P. Langacker and S. U. Sankar, *Phys. Rev.* **D40**, 1569 (1989).
- [55] J. F. Bueno *et al.* (TWIST), *Phys. Rev.* **D84**, 032005 (2011), [arXiv:1104.3632].
- [56] G. Prezeau, M. Ramsey-Musolf and P. Vogel, *Phys. Rev. D* **68**, 034016 (2003), [hep-ph/0303205].