88. Z'-Boson Searches

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The Z' boson is a massive, electrically-neutral and color-singlet hypothetical particle of spin 1. This particle is predicted in many extensions of the Standard Model (SM) and has been the object of extensive phenomenological studies [1].

88.1 Z' boson couplings

The couplings of a Z' boson to the first-generation fermions are given by

$$Z'_\mu \left(g_u^L \, \overline{u}_L \gamma^\mu u_L + g_d^L \, \overline{d}_L \gamma^\mu d_L + g_u^R \, \overline{u}_R \gamma^\mu u_R + g_d^R \, \overline{d}_R \gamma^\mu d_R + \; g_\nu^L \, \overline{\nu}_L \gamma^\mu \nu_L + g_e^L \, \overline{e}_L \gamma^\mu e_L + g_e^R \, \overline{e}_R \gamma^\mu e_R \right), \tag{88.1}$$

where u, d, ν, e are the quark and lepton fields in the mass eigenstate basis, and the coefficients g_u^L, g_d^L, g_u^R, g_d^R, g_ν^L, g_e^L, g_e^R are real dimensionless parameters. If the Z' couplings to quarks and leptons are generation-independent, then these seven parameters describe the couplings of the Z' boson to all SM fermions. More generally, however, the Z' couplings to fermions are generation-dependent, in which case Eq. (88.1) may be written with generation indices i, $j = 1$, 2, 3 labeling the quark and lepton fields, and with the seven coefficients promoted to 3×3 Hermitian matrices (*e.g.*, $g^L_{e\,ij} \, \overline{e}^i_L \gamma^\mu e^j_L$, where e^2_L is the left-handed muon, etc.).

The parameters describing the Z' boson interactions with quarks and leptons are subject to some theoretical constraints. Quantum field theories that include a heavy spin-1 particle are well behaved at high energies only if that particle is a gauge boson associated with a spontaneously broken gauge symmetry. Quantum effects preserve the gauge symmetry only if the couplings of the gauge boson to fermions satisfy the anomaly equations [2]. Furthermore, the fermion charges under the new gauge symmetry are constrained by the requirement that the quarks and leptons get masses from gauge-invariant interactions with the Higgs fields.

The relation between the couplings displayed in Eq. (88.1) and the gauge charges z^L_{fi} and z^R_{fi} of the fermions $f = u, d, \nu, e$ involves the unitary 3×3 matrices V^L_f and V^R_f that transform the gauge eigenstate fermions f^i_L and f^i_R, respectively, into the mass eigenstates. The Z' couplings also depend on the mixings of the new gauge boson in the gauge eigenstate basis ($\tilde{Z}'_\mu$). The main ones are a kinetic mixing $(-\chi/2) B^{\mu\nu} \tilde{Z}'_{\mu\nu}$ with the hypercharge gauge boson B^μ (χ is a dimensionless parameter), and a mass mixing $\delta M^2 \, \tilde{Z}^\mu \tilde{Z}'_\mu$ with the linear combination ($\tilde{Z}_\mu$) of neutral bosons that couples as the SM Z boson [3]. Since both the kinetic and mass mixings shift the mass and couplings of the Z boson, electroweak measurements impose upper limits on χ and $\delta M^2/(M^2_{Z'} - M^2_Z)$ of the order of 10^{-3} [4]. Keeping only linear terms in these two small quantities, the couplings of the mass-eigenstate Z' boson are given by

$$g^L_{f\,ij} = g_z V^L_{fii'} \, z^L_{f\,i'} \left(V^L_f \right)^\dagger_{i'j} + \frac{e}{c_W} \left(\frac{s_W \chi M^2_{Z'} + \delta M^2}{2 s_W \left(M^2_{Z'} - M^2_Z \right)} \sigma^3_f - \epsilon \, Q_f \right), \tag{88.2}$$

$$g^R_{f\,ij} = g_z V^R_{fii'} \, z^R_{fi'} \left(V^R_f \right)^\dagger_{i'j} - \frac{e}{c_W} \, \epsilon \, Q_f, \tag{88.3}$$

where g_z is the new gauge coupling, Q_f is the electric charge of f, e is the electromagnetic gauge coupling, s_W and c_W are the sine and cosine of the weak mixing angle, $\sigma^3_f = +1$ for $f = u, \nu$ and $\sigma^3_f = -1$ for $f = d, e$, and

$$\epsilon = \frac{\chi \left(M^2_{Z'} - c^2_W M^2_Z \right) + s_W \delta M^2}{M^2_{Z'} - M^2_Z}. \tag{88.4}$$

The interaction of the Z' boson with a pair of W bosons has the form

$$\left[i\left(W^-_\mu Z'_\nu - W^-_\nu Z'_\mu\right)\partial^\mu W^{+\nu} + \text{H.c.}\right] + i\left(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu\right)\partial^\mu Z'^\nu \tag{88.5}$$

with a coefficient of order $M_W^2/M_{Z'}^2$ [5]. The Z' also couples to one SM Higgs boson and one Z boson, $Z'_\mu Z^\mu h^0$, with a coefficient of order M_Z.

88.2 Z' models

A simple origin of a Z' boson is a new $U(1)'$ gauge symmetry. In that case, the matricial equalities $z_u^L = z_d^L$ and $z_\nu^L = z_e^L$ are required by the SM $SU(2)_W$ gauge symmetry. Given that the $U(1)'$ interaction is not asymptotically free, the theory may be well-behaved at high energies (*e.g.*, by embedding $U(1)'$ in a non-Abelian gauge group) only if the charges are commensurate numbers, *i.e.* any ratio of charges is a rational number. Satisfying the anomaly equations with rational numbers is highly nontrivial, and typically new fermions charged under $U(1)'$ are necessary.

If the couplings are generation-independent ($V_f^{L,R}$ are then unit matrices in Eq. (88.2)) and the mixings of $\tilde{Z}'$ are negligible, then there are five commensurate couplings: g_u^R, g_d^R, g_e^R, g_q^L ($q = u$ or d), g_l^L ($l = \nu$ or e). Four sets of charges are displayed in Table 88.1, each of them spanned by a free parameter x [6]. The first set, labelled $B-xL$, has charges proportional to the baryon number minus x times the lepton number. These charges allow all SM Yukawa couplings to a Higgs doublet which is neutral under $U(1)_{B-xL}$, so that there is no tree-level $\tilde{Z} - \tilde{Z}'$ mixing. For $x = 1$ one recovers the $U(1)_{B-L}$ group, which is non-anomalous in the presence of one "right-handed neutrino" (a chiral fermion that is a singlet under the SM gauge group) per generation. For $x \neq 1$, it is necessary to include some fermions that are vectorlike (*i.e.* their mass terms are gauge invariant) with respect to the electroweak gauge group and chiral with respect to $U(1)_{B-xL}$. In the particular cases $x = 0$ or $x \gg 1$, the Z' is leptophobic or quark-phobic, respectively.

The second set, $U(1)_{10+x\bar{5}}$, has charges that commute with the representations of the $SU(5)$ grand unified group. Here x is related to the mixing angle between the two $U(1)$ bosons encountered in the $E_6 \to SU(5) \times U(1) \times U(1)$ symmetry breaking patterns of grand unified theories [1,7]. With these charges, two Higgs doublets are typically required to generate masses for both up- and down-type fermions. This set leads to $\tilde{Z} - \tilde{Z}'$ mass mixing at tree level, such that for a Z' mass close to the electroweak scale, the measurements at the Z-pole require some fine tuning between the charges and VEVs of the two Higgs doublets. Vectorlike fermions charged under the electroweak gauge group and also carrying color are required (except for $x = -3$) to make this set anomaly free. The particular cases $x = -3, 1, -1/2$ are usually labelled $U(1)_\chi$, $U(1)_\psi$, and $U(1)_\eta$, respectively. Under the third set, $U(1)_{d-xu}$, the weak-doublet quarks are neutral, and the ratio of u_R and d_R charges is $-x$. For $x = 1$, this is the "right-handed" group $U(1)_R$. For $x = 0$, the charges are those of the E_6-inspired $U(1)_I$ group, which requires new quarks and leptons. Other generation-independent sets of $U(1)'$ charges are given in [8].

In the absence of new fermions charged under the SM group, the most general generation-independent charge assignment is $U(1)_{q+xu}$, which is a linear combination of hypercharge and $B - L$. Many other anomaly-free solutions exist if generation-dependent charges are allowed. An example is $B - xL_e - yL_\mu + (y - 3)L_\tau$, with x, y free parameters. This allows all fermion masses to be generated by Yukawa couplings to a single Higgs doublet, without inducing tree-level flavor-changing neutral current (FCNC) processes. There are also lepton-flavor dependent charges that allow neutrino masses to arise only from operators of high dimensionality [9].

If the $SU(2)_W$-doublet quarks have generation-dependent $U(1)'$ charges, then the mass eigen-state quarks have flavor off-diagonal couplings to the Z' boson (see Eq. (88.1), and note that

Table 88.1: Examples of generation-independent $U(1)'$ charges for quarks and leptons. The parameter x is an arbitrary rational number. Gauge anomaly cancellation requires certain new fermions [6].

fermion	$U(1)_{B-xL}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$	$U(1)_{q+xu}$
(u_L, d_L)	$1/3$	$1/3$	0	$1/3$
u_R	$1/3$	$-1/3$	$-x/3$	$x/3$
d_R	$1/3$	$-x/3$	$1/3$	$(2-x)/3$
(ν_L, e_L)	$-x$	$x/3$	$(-1+x)/3$	-1
e_R	$-x$	$-1/3$	$x/3$	$-(2+x)/3$

$V_u^L \left(V_d^L\right)^\dagger$ is the CKM matrix). These are severely constrained by measurements of FCNC processes, which in this case are mediated at tree-level by Z' boson exchange [10]. The constraints are relaxed if the first and second generation charges are the same, although they are increasingly tightened by the measurements of B meson properties [11]. If only the $SU(2)_W$-singlet quarks have generation-dependent $U(1)'$ charges, there is more freedom in adjusting the flavor off-diagonal couplings because the $V^R_{u,d}$ matrices are not observable in the SM.

The anomaly equations for $U(1)'$ could be circumvented only if there is an axion with certain dimension-5 couplings to the gauge bosons. However, such a scenario violates unitarity unless the quantum field theory description breaks down at a scale near $M_{Z'}$ [12].

Z' bosons may also arise from larger gauge groups. These may extend the electroweak group, as in $SU(2)\times SU(2)\times U(1)$, or may embed the electroweak group, as in $SU(3)_W \times U(1)$ [13]. If the larger group is spontaneously broken down to $SU(2)_W \times U(1)_Y \times U(1)'$ at a scale $v_\star \gg M_{Z'}/g_z$, then the above discussion applies up to corrections of order $M^2_{Z'}/(g_z v_\star)^2$. For $v_\star \sim M_{Z'}/g_z$, additional gauge bosons have masses comparable to $M_{Z'}$, including at least a W' boson [13]. If the larger gauge group breaks together with the electroweak symmetry directly to the electromagnetic $U(1)_{\rm em}$, then the left-handed fermion charges are no longer correlated ($z_u^L \neq z_d^L$, $z_\nu^L \neq z_e^L$) and a $Z'W^+W^-$ coupling is induced.

If the electroweak gauge bosons propagate in extra dimensions, then their Kaluza-Klein (KK) excitations include a series of Z' boson pairs. Each of these pairs can be associated with a different $SU(2)\times U(1)$ gauge group in four dimensions. The properties of the KK particles depend strongly on the extra-dimensional theory [14]. For example, in universal extra dimensions there is a parity that forces all couplings of Eq. (88.1) to vanish in the case of the lightest KK bosons, while allowing couplings to pairs of fermions involving a SM and a heavy vectorlike fermion. There are also 4-dimensional gauge theories (*e.g.* little Higgs with T parity) with Z' bosons exhibiting similar properties. By contrast, in a warped extra dimension, the couplings of Eq. (88.1) may be sizable even when SM fields propagate along the extra dimension.

Z' bosons may also be composite particles. For example, in confining gauge theories [15], the ρ-like bound state is a spin-1 boson that may be interpreted as arising from a spontaneously broken gauge symmetry [16].

88.3 Non-resonant Z' signatures at colliders

In the presence of the couplings shown in Eq. (88.1), the Z' boson may be produced in the s-channel at colliders, and would decay to pairs of fermions. The decay width into a pair of electrons is given by

$$\Gamma\left(Z' \to e^+e^-\right) \simeq \left[\left(g_e^L\right)^2 + \left(g_e^R\right)^2\right] \frac{M_{Z'}}{24\pi}, \tag{88.6}$$

where small corrections from electroweak loops are not included. The decay width into $q\bar{q}$ is similar, except for an additional color factor of 3, QCD radiative corrections, and fermion mass corrections. Thus, one may compute the Z' branching fractions in terms of the couplings of Eq. (88.1). However, other decay channels, such as WW or a pair of new particles, could have large widths and need to be added to the total decay width.

As mentioned above, there are theories in which the Z' couplings are controlled by a discrete symmetry that forbids decays into a pair of SM particles. Typically, such theories involve several new particles, which may be produced only in pairs and undergo cascade decays through Z' bosons, leading to signals involving missing (transverse) momentum. Given that the cascade decays depend on the properties of new particles other than the Z' boson, this case is not discussed further here.

The Z' contribution to the cross sections for $e^+e^- \to f\bar{f}$ proceeds through an s-channel Z' exchange (when $f = e$, there are also t- and u-channel exchanges). For $M_{Z'} < \sqrt{s}$, the Z' appears as an $f\bar{f}$ resonance in the radiative return process where photon emission tunes the effective center-of-mass energy to $M_{Z'}$. The agreement between the LEP-II measurements and the SM predictions implies that either the Z' couplings are smaller than or of order 10^{-2}, or else $M_{Z'}$ is above 209 GeV, the maximum energy of LEP-II. In the latter case, the Z' exchange may be approximated up to corrections of order $s/M_{Z'}^2$ by the contact interactions

$$\frac{g_z^2}{M_{Z'}^2 - s}\left[\bar{e}\gamma_\mu\left(z_e^L P_L + z_e^R P_R\right)e\right]\left[\bar{f}\gamma^\mu\left(z_f^L P_L + z_f^R P_R\right)f\right], \tag{88.7}$$

where $P_{L,R}$ are chirality projection operators, and the relation between Z' couplings and charges (see Eq. (88.2) in the limit where the mass and kinetic mixings are neglected) is used, assuming generation-independent charges. The four LEP collaborations have set limits on the coefficients of such operators for all possible chiral structures and for various combinations of fermions [17]. Thus, one may derive bounds on $(M_{Z'}/g_z)|z_e^L z_f^L|^{-1/2}$ and the analogous combinations of LR, RL and RR charges, which are typically on the order of a few TeV. LEP-II limits were derived [6] on the four sets of charges shown in Table 88.1.

Somewhat stronger bounds can be set on $M_{Z'}/g_z$ for specific sets of Z' couplings if the effects of several operators (88.7) are combined. Dedicated analyses by the LEP collaborations have set limits on Z' bosons for particular values of the gauge coupling (see section 3.5 of Ref. [17]). For example, $M_{Z_{\rm SSM}} > 1.76$ TeV for a "sequential" Z' of same couplings as the SM Z boson, while $M_{Z_\chi} > 0.785$ TeV for the Z' associated with $U(1)_\chi$ assuming a unification condition for the gauge coupling.

88.4 Searches at hadron colliders

Z' bosons with couplings to quarks (see Eq. (88.1)) may be produced at hadron colliders in the s-channel and would show up as resonances in the invariant mass distribution of the decay products. The cross section for producing a Z' boson at the LHC, which then decays to some $f\bar{f}$ final state, takes the form [18]

$$\sigma\left(pp \to Z'X \to f\bar{f}X\right) \simeq \frac{\pi}{6\,s}\sum_q c_q^f\, w_q\left(s, M_{Z'}^2\right) \tag{88.8}$$

for flavor-diagonal couplings to quarks. Here, we have neglected the interference with the SM contribution to $f\bar{f}$ production, which is a good approximation for a narrow Z' resonance (deviations from the narrow width approximation are discussed in Ref. [19]). The coefficients

$$c_q^f = \left[\left(g_q^L\right)^2 + \left(g_q^R\right)^2\right] B(Z' \to f\bar{f}) \tag{88.9}$$

contain all the dependence on the Z' couplings, while the functions w_q include all the information about parton distributions and QCD corrections [6, 8]. This factorization holds exactly to NLO and the deviations from it induced at NNLO are very small. Note that the w_u and w_d functions are substantially larger than the w_q functions for the other quarks. Eq. (88.8) also applies to the Tevatron, except for changing the pp initial state to $p\bar{p}$, which implies that the $w_q(s, M_{Z'}^2)$ functions are replaced by some other functions $\bar{w}_q((1.96\,\text{TeV})^2, M_{Z'}^2)$.

It is common to present results of Z' searches as limits on the cross section versus $M_{Z'}$ (see for example Fig. 88.1). An alternative is to plot exclusion curves for fixed $M_{Z'}$ values in the $c_u^f - c_d^f$ planes, allowing a simple derivation of the mass limit within any Z' model. CMS upper limits in the $c_u^\ell - c_d^\ell$ plane ($\ell = e$ or μ) for different $M_{Z'}$ are shown in Ref. [22] (for Tevatron limits, see Refs. [8, 23]).

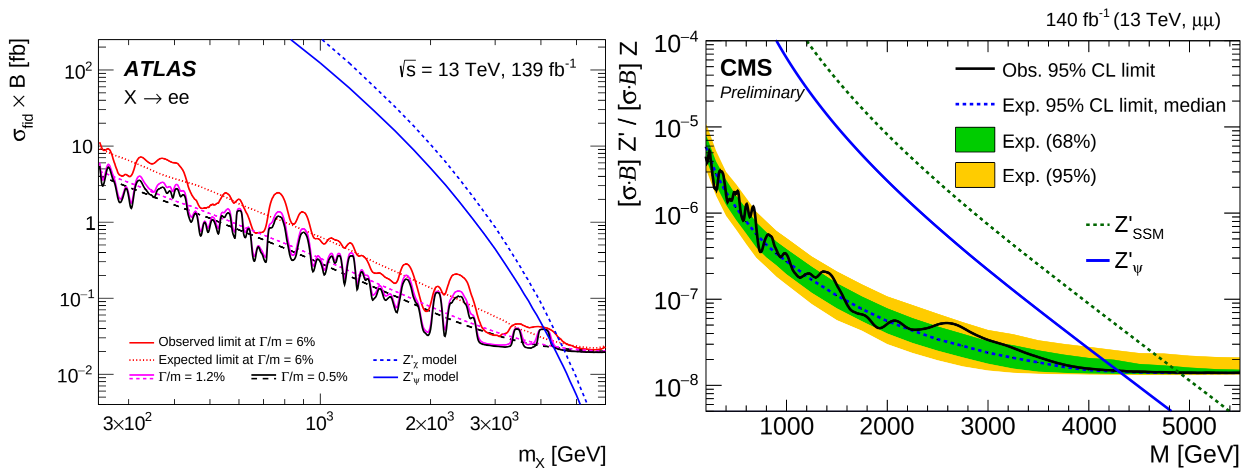

Figure 88.1: Upper limits on the cross section for Z' production times the branching fraction for $Z' \to e^+e^-$ (left panel, set by ATLAS [20]) or $Z' \to \mu^+\mu^-$ (right panel, set by CMS [21]) as a function of $M_{Z'}$. The lines labelled by Z'_ψ and Z'_χ are theoretical predictions for the $U(1)_{10+x\bar{5}}$ models in Table 88.1 with $x = -3$ and $x = +1$, respectivxoely, for g_z fixed by an E_6 unification condition. The $Z'_{\rm SSM}$ line corresponds to Z' couplings equal to those of the Z boson.

The discovery of a dilepton resonance at the LHC would determine the Z' mass and width. A measurement of the total cross section would define a band in the $c_u^\ell - c_d^\ell$ plane. Angular distributions can be used to measure several combinations of Z' parameters (angular distributions were used in Ref. [24] to improve the Tevatron sensitivity). Even though the original quark direction in a pp collider is unknown, the leptonic forward-backward asymmetry $A_{\rm FB}^\ell$ can be extracted from the kinematics of the dilepton system, and is sensitive to parity-violating couplings. A fit to the Z' rapidity distribution can distinguish between the couplings to up and down quarks. These measurements, combined with off-peak observables, have the potential to differentiate among various Z' models [25]. In some cases, $A_{\rm FB}^\ell$ may provide discovery sensitivity that is competitive with the mass distribution [26]. The spin of the Z' boson may be determined from angular distributions [27].

Searches for Z' decays into e^+e^- and $\mu^+\mu^-$ by the ATLAS and CMS collaborations [20, 21] have set 95% C.L. upper cross-section limits as low as 0.02 fb (see Fig. 88.1), with the mass lower

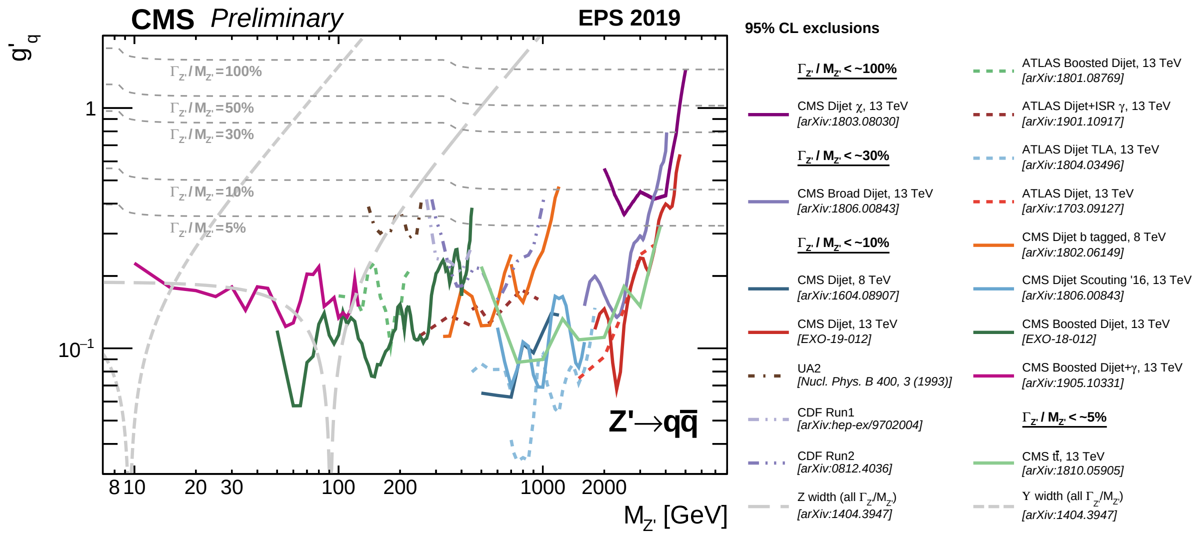

Figure 88.2: Upper limits on the Z' coupling to quarks as a function of $M_{Z'}$ based on various searches performed by the ATLAS, CMS, CDF, and UA2 experiments [28].

limits in specific models as high as 4.9 TeV in a single channel. Cross section limits in the dimuon channel for low mass regions, below 200 GeV but not near the Z mass, have been set at the LHC by CMS [29] and LHCb [30] (and also in e^+e^- collisions by BaBar [31], assuming a dark photon, *i.e.*, a Z' boson whose couplings arise only from the kinetic mixing with the hypercharge gauge boson).

In the case of final states with tau-leptons, the mass lower limits obtained at 13 TeV are as high as ~ 2.4 TeV for the $\tau^+\tau^-$ [32] decay in the case of a sequential Z'. Limits in the flavor-violating leptonic final states have also been reported by ATLAS [33] and CMS [34] at 13 TeV, for resonances in the $e^\pm\mu^\mp$, $e^\pm\tau^\mp$ and $\mu^\pm\tau^\mp$ channels.

Final states with higher background, $t\bar{t}$, $b\bar{b}$ and jj, are also important as they probe various combinations of Z' couplings to quarks, see Ref. [35] for further discussion. Besides the improved sensitivity at masses of several TeV, the LHC searches in the dijet channel have been also extended to masses as low as 10 GeV, through the use of new techniques involving boosted topologies and initial state radiation [36]. Limits from such Z' searches in hadronic final states are summarized in Fig. 88.2.

Z' decays to Zh^0 with $Z \to \ell^+\ell^-$, $\nu\bar{\nu}$ or $q\bar{q}$ and $h^0 \to b\bar{b}$ have been studied by ATLAS [37, 38] and CMS [39, 40] using 13 TeV data. The most stringent constraint is set in the fully hadronic channel, with a mass lower limit of 2.65 TeV in the context of the Heavy Vector Triplet (HVT) model weakly-coupled scenario A [41].

Searches for a Z' boson lighter than the SM Z and which couples to leptons have been performed in the 4-lepton final state. CMS [42] focused on the Z decays into a muon pair followed by the radiation of a Z' boson which decays itself into a muon pair. ATLAS [43] considered the $h^0 \to ZZ'$ and $h^0 \to Z'Z'$ processes followed by the leptonic decays of both Z and Z'.

The $pp \to Z'X \to W^+W^-X$ process has also been searched for at the LHC. The channel where the Z' boson is produced through its couplings to quarks, and the W bosons decay hadronically, has been explored using boosted techniques to analyze the 13 TeV data [44, 45] with a mass lower limit of 2.9 TeV in the HVT model A. The Z' boson may also be produced through its couplings to W bosons [46], which has been explored by ATLAS with the use of forward jets consistent with a vector boson fusion event topology.

At the Tevatron, the CDF and DØ collaborations have searched for Z' bosons in the e^+e^- [47], $\mu^+\mu^-$ [48], $e^\pm\mu^\mp$ [49], $\tau^+\tau^-$ [50], $t\bar{t}$ [51], jj [52] and W^+W^- [53] final states. These limits have been mostly superseded by the LHC results.

88.5 Low-energy constraints

Z' boson properties are also constrained by a variety of low-energy experiments [54]. Polarized electron-nucleon scattering and atomic parity violation are sensitive to electron-quark contact interactions, which get contributions from Z' exchange that can be expressed in terms of the couplings introduced in Eq. (88.1) and M'_Z. Further corrections to the electron-quark contact interactions are induced in the presence of $\tilde{Z}-\tilde{Z}'$ mixing because of the shifts in the Z couplings to quarks and leptons [3]. Deep-inelastic neutrino-nucleon scattering is similarly affected by Z' bosons. Other low-energy observables are discussed in [4]. Viable models with Z' bosons much lighter than the Z boson have been constructed, despite many additional experimental constraints [55].

In some models, the lower limits on $M_{Z'}$ set by low-energy data are above 1 TeV. For example, $M_{Z_\chi} > 1.1$ TeV and $M_{Z_\eta} > 0.43$ TeV assuming that the Higgs sectors consist of electroweak doublets and singlets only [4], while the gauge coupling is fixed by an $SO(10)$ unification condition for $U(1)_\chi$ and $U(1)_\eta$. For more general models, see [1,6,56]. The mass bounds from direct searches at the LHC [20,21] exceed the electroweak constraints by a factor of three or more for the models mentioned here. This conclusion could change if the collider bounds are weakened by exotic decay channels [57].

Although the LHC data are most constraining for many Z' models, one should be careful in assessing the relative reach of various experiments given the freedom in Z' couplings. For example, a Z' coupled to $B-yL_\mu+(y-3)L_\tau$ has implications for the muon $g-2$, neutrino oscillations or τ decays, and would be hard to see in processes involving first-generation fermions. Moreover, the combination of LHC searches and low-energy measurements could allow a precise determination of the Z' parameters [58].

References

[1] A. Leike, Phys. Rept. **317**, 143 (1999), [hep-ph/9805494].

[2] T. P. Cheng and L. F. Li, *Gauge Theory of Elementary Particle Physics* (1984), ISBN 9780198519614.

[3] K. S. Babu, C. F. Kolda and J. March-Russell, Phys. Rev. **D57**, 6788 (1998), [hep-ph/9710441].

[4] J. Erler *et al.*, JHEP **08**, 017 (2009), [arXiv:0906.2435].

[5] B. A. Dobrescu and P. J. Fox, JHEP **05**, 047 (2016), [arXiv:1511.02148].

[6] M. Carena *et al.*, Phys. Rev. **D70**, 093009 (2004), [hep-ph/0408098].

[7] F. Del Aguila, M. Cvetic and P. Langacker, Phys. Rev. **D52**, 37 (1995), [hep-ph/9501390].

[8] E. Accomando *et al.*, Phys. Rev. **D83**, 075012 (2011), [arXiv:1010.6058].

[9] M.-C. Chen, A. de Gouvea and B. A. Dobrescu, Phys. Rev. **D75**, 055009 (2007), [hep-ph/0612017].

[10] P. Langacker and M. Plumacher, Phys. Rev. **D62**, 013006 (2000), [hep-ph/0001204].

[11] A. J. Buras, F. De Fazio and J. Girrbach, JHEP **02**, 116 (2013), [arXiv:1211.1896].

[12] L. E. Ibanez and G. G. Ross, Phys. Lett. **B332**, 100 (1994), [hep-ph/9403338].

[13] See the Section on "W' searches" in this *Review.*

[14] J. Parsons and A. Pomarol, "Extra dimensions" in this *Review.*

[15] K.M. Black *et al.*, "Dynamical electroweak symmetry breaking" in this *Review.*

[16] M. Bando, T. Kugo and K. Yamawaki, Phys. Rept. **164**, 217 (1988).

[17] S. Schael *et al.* (ALEPH, DELPHI, L3, OPAL, LEP Electroweak), Phys. Rept. **532**, 119 (2013), [arXiv:1302.3415].

[18] G. Paz and J. Roy, Phys. Rev. **D97**, 075025 (2018), [arXiv:1711.02655].

[19] E. Accomando *et al.*, JHEP **10**, 153 (2013), [arXiv:1304.6700].

[20] G. Aad *et al.* (ATLAS), Phys. Lett. **B796**, 68 (2019), [arXiv:1903.06248].

[21] CMS Collab., PAS EXO-19-019, Aug. 2019.

[22] V. Khachatryan *et al.* (CMS), JHEP **04**, 025 (2015), [arXiv:1412.6302].

[23] A. Abulencia *et al.* (CDF), Phys. Rev. Lett. **95**, 252001 (2005), [hep-ex/0507104].

[24] A. Abulencia *et al.* (CDF), Phys. Rev. Lett. **96**, 211801 (2006), [hep-ex/0602045].

[25] F. Petriello and S. Quackenbush, Phys. Rev. **D77**, 115004 (2008), [arXiv:0801.4389].

[26] E. Accomando *et al.*, JHEP **01**, 127 (2016), [arXiv:1503.02672].

[27] P. Osland *et al.*, Phys. Rev. **D79**, 115021 (2009), [arXiv:0904.4857].

[28] CMS Collab., https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV.

[29] CMS Collab., PAS EXO-19-018, Aug. 2019.

[30] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **120**, 061801 (2018), [arXiv:1710.02867].

[31] J. P. Lees *et al.* (BaBar), Phys. Rev. Lett. **113**, 201801 (2014), [arXiv:1406.2980].

[32] M. Aaboud *et al.* (ATLAS), JHEP **01**, 055 (2018), [arXiv:1709.07242].

[33] M. Aaboud *et al.* (ATLAS), Phys. Rev. **D98**, 092008 (2018), [arXiv:1807.06573].

[34] A. M. Sirunyan *et al.* (CMS), JHEP **04**, 073 (2018), [arXiv:1802.01122].

[35] See the Section on “Dynamical Electroweak Symmetry Breaking” in this *Review*.

[36] A. M. Sirunyan *et al.* (CMS) (2019), [arXiv:1905.10331].

[37] M. Aaboud *et al.* (ATLAS), Phys. Lett. **B774**, 494 (2017), [arXiv:1707.06958].

[38] M. Aaboud *et al.* (ATLAS), JHEP **03**, 174 (2018), [Erratum: JHEP **11**, 051 (2018)], [arXiv:1712.06518].

[39] A. M. Sirunyan *et al.* (CMS), JHEP **11**, 172 (2018), [arXiv:1807.02826].

[40] A. M. Sirunyan *et al.* (CMS), Eur. Phys. J. **C77**, 636 (2017), [arXiv:1707.01303].

[41] D. Pappadopulo *et al.*, JHEP **09**, 060 (2014), [arXiv:1402.4431].

[42] A. M. Sirunyan *et al.* (CMS), Phys. Lett. **B792**, 345 (2019), [arXiv:1808.03684].

[43] M. Aaboud *et al.* (ATLAS), JHEP **06**, 166 (2018), [arXiv:1802.03388].

[44] G. Aad *et al.* (ATLAS), JHEP **09**, 091 (2019), [arXiv:1906.08589].

[45] A. M. Sirunyan *et al.* (CMS) (2019), [arXiv:1906.05977].

[46] H.-J. He *et al.*, Phys. Rev. **D78**, 031701 (2008), [arXiv:0708.2588].

[47] V. M. Abazov *et al.* (D0), Phys. Lett. **B695**, 88 (2011), [arXiv:1008.2023].

[48] T. Aaltonen *et al.* (CDF), Phys. Rev. Lett. **106**, 121801 (2011), [arXiv:1101.4578].

[49] A. Abulencia *et al.* (CDF), Phys. Rev. Lett. **96**, 211802 (2006), [hep-ex/0603006].

[50] D. Acosta *et al.* (CDF), Phys. Rev. Lett. **95**, 131801 (2005), [hep-ex/0506034].

[51] T. Aaltonen *et al.* (CDF), Phys. Rev. **D84**, 072004 (2011), [arXiv:1107.5063].

[52] T. Aaltonen *et al.* (CDF), Phys. Rev. **D79**, 112002 (2009), [arXiv:0812.4036].

[53] T. Aaltonen *et al.* (CDF), Phys. Rev. Lett. **104**, 241801 (2010), [arXiv:1004.4946].

[54] V. D. Barger *et al.*, Phys. Rev. **D57**, 391 (1998), [hep-ph/9707412].
[55] R. Harnik, J. Kopp and P. A. N. Machado, JCAP **1207**, 026 (2012), [arXiv:1202.6073].
[56] E. Rojas and J. Erler, JHEP **10**, 063 (2015), [arXiv:1505.03208].
[57] J. Kang and P. Langacker, Phys. Rev. **D71**, 035014 (2005), [hep-ph/0412190].
[58] Y. Li, F. Petriello and S. Quackenbush, Phys. Rev. **D80**, 055018 (2009), [arXiv:0906.4132].