PARAMETER SPACE OF U(1) NEUTRAL GAUGE BOSONS*

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We introduce a novel way to represent the parameter space for U(1) extensions of the Standard Model. In our framework, the free parameters include the mass $M_{Z'}$ of the new neutral gauge boson Z', the associated gauge coupling (or, equivalently, the mixing angle between the Standard Model Z and the new Z' boson), and a suitably chosen ratio of the new U(1) gauge charges. Recent experimental data allow us to constrain these parameters over an approximate Z' mass range of $(10^{-2}, 10^{4})$ GeV/c^2. We also examine the role of the tree-level ρ parameter as an indirect constraint and discuss the prospects for Z' searches at future colliders.

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1. Introduction

In 2012, the Higgs boson — the final particle predicted by the Standard Model (SM) — was discovered at the Large Hadron Collider (LHC) [1]. The experiments at the LHC (and at the Large Electron Positron collider earlier) have since measured cross sections with extraordinary precision, reaching uncertainties at or below the per mille level, which demands equally precise theoretical predictions. Although extensive testing has confirmed the Standard Model's accuracy, unresolved issues such as the origin of neutrino masses and the nature of dark matter hint at the possibility of New Physics. Here, in the context of New Physics, we explore the parameter space of a possible extra neutral massive gauge bosons, called Z'. In the minimal scenario, this new particle emerges in U(1) extensions of the SM, and it might be too weakly coupled to the SM particles or too heavy to be produced at

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current experiments to be detectable. We argue that the properties of the Z' can be described by three free parameters and we can establish model-independent bounds both for light and heavy Z' bosons. This contribution is based on Ref. [2] where more details can be found.

2. Free parameters

The additional $\mathrm{U}(1)_z$ symmetry introduces a new gauge coupling g_z and a mixing coupling g_{yz} parametrized here with $\eta = \mathcal{O}(1)$ as $g_{yz} = -\eta g_z$. The fields become charged under the new gauge group and obtain z-charges, but only two of these charges are free parameters if we require gauge anomaly cancellation. The rotation of gauge eigenstates to mass eigenstates introduces a mixing angle θ_z, or rather $\sin\theta_z \equiv s_z$ as an additional parameter.

On top of the new gauge group, U(1)-extensions usually contain right-handed neutrinos (N) to explain the origin of neutrino masses, and a new scalar field to generate mass for the Z' and N via spontaneous symmetry breaking by the vacuum. In the minimal scenario, the new scalar χ is a complex scalar field able to provide a neutral Goldstone boson to be interpreted as the longitudinal component of the Z'. Nonetheless, χ obtains a vacuum expectation value (VEV) w.

We demonstrated that only three of these parameters are sufficient to describe minimal U(1)-extensions completely [2]: *(i)* the mass $M_{Z'}$ of the Z', *(ii)* the new gauge coupling g_z or equivalently s_z and finally, *(iii)* a special combination of the z-charges $\mathscr{Z} = (z_\phi - \eta/2)/z_N$, where z_ϕ and z_N are the free z-charges of the Brout–Englert–Higgs field and the sterile neutrinos.

We found that the ρ parameter in the U(1) extensions is [3]

$$\rho = \frac{M_W^2}{M_Z^2 c_W^2} = 1 - \left(1 - \frac{M_{Z'}^2}{M_Z^2}\right) s_Z^2, \quad \text{with} \quad \rho_{\text{exp}} = 1.00038 \pm 0.00020\,. \tag{1}$$

At the tree level in the SM $\rho = 1$ and global fits [4] yield the value ρ_{exp} for the purely beyond the Standard Model effects on ρ.

3. Exclusion limits and prospects of future Z' searches

A Z' boson with mass $M_{Z'} \approx M_Z$ would mix with the Z boson significantly, which is excluded by electroweak precision observables such as the ρ parameter. Thus, either $M_{Z'} \ll M_Z$ (light Z'), or $M_{Z'} \gg M_Z$ (heavy Z'). In the case of a light Z', Eq. (1) implies the limits

$$|s_Z| < 4.5 \times 10^{-3}\,, \qquad \text{or} \qquad |z_N g_z| < \frac{1.7 \times 10^{-3}}{|\mathscr{Z}|}\,. \tag{2}$$

As for the direct searches, we include the BaBar [5], NA64 [6], FASER [7], and the Belle II [8] experiments. We display our limits obtained for a specific model, called the superweak extension of the SM [9, 10], when $\mathscr{Z} = 2$ for $\eta = 0$, in Fig. 1.

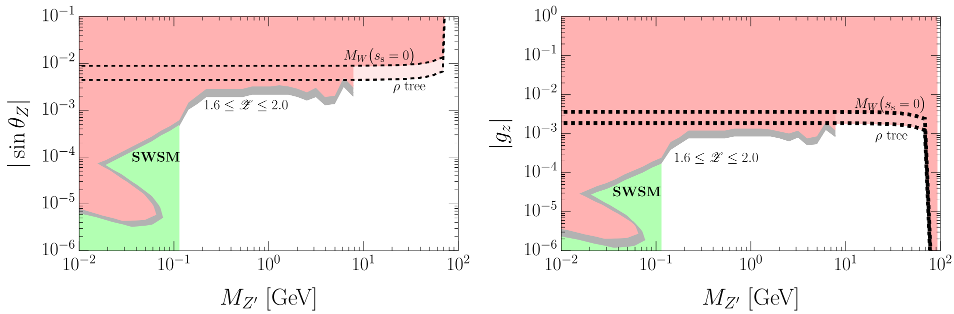


Fig. 1. Similar to Fig. 1 of Ref. [2], but with exclusion bounds cast for the superweak model with $z_N = 1/2$ and $z_\phi = 1$. The green region is the preferred parameter space. The dashed line with M_W is a limit obtained from the W-boson mass.

A Z' is considered heavy if $M_{Z'} \gg M_Z$. Here, we investigate the region of $M_{Z'} > 1$ TeV. The bounds from Eq. (1) are

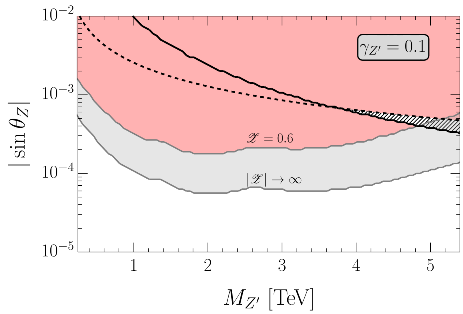
$$|s_Z| < 2.5 \times 10^{-3} \left[\frac{1\ \text{TeV}}{M_{Z'}}\right], \qquad \text{or} \qquad |z_N g_z| < \frac{0.11}{|\mathscr{Z}|}\left[\frac{M_{Z'}}{1\ \text{TeV}}\right]. \tag{3}$$

As for direct searches, we considered the recent ATLAS [11] and CMS [12] searches for a Z' boson in the Drell–Yan process $pp \to Z' \to \ell^+\ell^-$, where $\ell = e, \mu$. We find that there exists a specific value of $\mathscr{Z}^* = 0.60$ (0.54), which corresponds to an absolute bound on $|s_Z|$ ($|z_n g_z|$), independent of the specific z-charge assignment, as shown in the left panel of Fig. 2.

Using the special values $\mathscr{Z}^*$, we present projected exclusion bounds on Z' bosons for the High Energy LHC (HE-LHC) and the Future Circular Collider (FCC-hh) in the right panel of Fig. 2. The three-body decays of the Z' might have sizeable or even dominant branching ratios for $M_{Z'} \gtrsim 10$ TeV, with the exact value depending on $\mathscr{Z}$. Specifically, the process $pp \to Z' \to ZW^+W^-$ might dominate over the leptonic channel as

$$\frac{\sigma\left(pp \to Z' \to ZW^+W^-\right)}{\sigma\left(pp \to Z' \to \ell^+\ell^-\right)} \simeq 0.4 \frac{\mathscr{Z}^2}{2 - 6\mathscr{Z} + 5\mathscr{Z}^2}\left[\frac{M_{Z'}}{10\ \text{TeV}}\right]^2. \tag{4}$$

The centre-of-mass energies required for this scenario will be accessible at the FCC-hh.



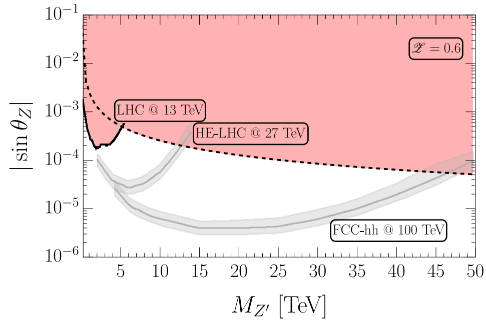


Fig. 2. Left: 95% C.L. exclusion bounds on s_Z for heavy Z' bosons obtained from the CMS and ATLAS experiments at the LHC for fixed ratios $\gamma_{Z'} = \Gamma_{Z'}/M_{Z'}$. The region in red is excluded, the solid black line corresponds to $\gamma_{Z'} = 0.1$ and the thick gray band incorporates the bounds for models with $0.6 < \mathscr{X} < \infty$. Right: Projected limits on s_Z from future colliders using detector simulations.

4. Summary

We presented an optimal choice of three free parameters to describe the properties of an extra neutral gauge boson in searches for such a particle. The Z' boson is introduced by extending the SM gauge group by an extra U(1) gauge symmetry. We showed that the ρ parameter given in Eq. (1) gives a stringent bound on the free parameters. We also presented exclusion bounds for light ($M_Z \gg M_{Z'}$) and heavy ($M_Z \ll M_{Z'}$) Z' bosons based on our choice of free parameters, and proposed direct searches for the final state $Z + W^+ + W^-$ at FCC-hh based on the three-body decays of the Z' boson.

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