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Exclusion bounds for neutral gauge bosons

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We present a novel representation of the parameter space of $U(1)$ extensions of the standard model. The free parameters are the mass $M_{Z'}$ of the new neutral gauge boson Z', the new gauge coupling or equivalently the mixing angle between the standard model Z and the new Z' boson and finally an appropriately chosen ration of the new $U(1)$ gauge charges. We use recent experimental data to constrain these parameters in the approximate range $(10^{-2}, 10^{4})$ GeV/c^2 of Z' masses. The role of the tree-level ρ parameter as an indirect bound is investigated. Finally, we discuss the prospects of Z' searches at future colliders. This proceedings is based on Ref. [1].

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1. Introduction

The last elementary particle predicted by the standard model of particle physics (SM) – the famous Higgs boson — was found at the Large Hadron Collider (LHC) in 2012 [2]. The LHC and its predecessor, the Large Electron Positron Collider (LEP) measured the cross sections of elementary particle processes at staggering precisions [3, 4], with relative uncertainties as small as or even smaller than the per mille level. In order to compare the experimental results to the SM theoretical predictions, the latter needs to match this level of uncertainty with high precision calculations.

Despite decades of thorough scrutiny, no new elementary particles have been discovered, and no cross-section measurements have revealed any evidence that the SM fails to account for. However, there remain several compelling open questions that necessitate new physics at the fundamental level, such as the origin of neutrino masses, or could potentially be explained by physics beyond the Standard Model (BSM), such as the nature of dark matter.

It is also quite possible that new physics is too weakly coupled to the Standard Model (SM) for current experiments to detect, or that the new particles are too heavy to be produced in today's particle accelerators. In this context, we investigate neutral massive gauge bosons, a type of hypothetical elementary particle that could fall into either of these categories. On the one hand, the observation of such a particle would mean, that that there is a fifth fundamental interaction in nature. On the other hand, it would imply, that there are further elementary particles that exist but not yet observed.

In the minimal scenario, Z' bosons arise in $U(1)$ extensions of the SM. As part of this extension, the specific properties of the Z' boson are determined by free parameters that would need to be fixed through a potential experimental observation.

2. Free parameters

The extension of the SM gauge group by an additional $U(1)_z$ factor introduces a new gauge field B'_μ in addition to the hypercharge gauge field B_μ. Consequently, the covariant derivative is modified. The piece which contains the $U(1)$ fields is given as

$$D_\mu^{\mathrm{U}(1)} = -\mathrm{i}\begin{pmatrix} y & z \end{pmatrix}\begin{pmatrix} g_y & -g_z\eta \\ 0 & g_z \end{pmatrix}\begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} B_\mu \\ B'_\mu, \end{pmatrix} \tag{1}$$

where y is the hypercharge and g_y is the hypercharge gauge coupling. The new gauge field introduces its corresponding charges denoted with z and a new gauge coupling g_z. The offdiagonal parameter η corresponds to the kinetic mixing between the field strength tensors of the two $U(1)$ fields. Namely, if the kinetic mixing is defined as $\mathcal{L}_{\mathrm{kin.}} \supset -\varepsilon F'_{\mu\nu}F^{\mu\nu}/2$, then $\eta \simeq \varepsilon g_y/g_z$. Lastly, the rotation angle α in Eq. (1) is an unphysical one, as it can be absorbed into the redefinition of the gauge fields.

In order to compute predictions, one works in the so called mass eigenstates, where the mass matrices of the fields are diagonal. In order to rotate the original gauge fields to mass eigenstates in the SM one has to introduce the weak mixing angle θ_W. Here, with an additional neutral gauge field a new $Z - Z'$ mixing angle θ_Z is required to diagonalize the gauge boson mass matrix. In order to make it massive, the scalar sector is extended by a singlet scalar field, which obtains a vacuum expectation value (VEV) w and supplies mass to the Z' via spontaneous symmetry breaking. Finally, additional fermion fields are required to cancel the gauge triangle anomalies[1]. We choose the new fermions to be right handed neutrinos as it is phenomenoloically well motivated.

The vector-axial vector couplings and thus the branching ratios of the Z' boson can be expressed with a single combination

$$\mathscr{X} = \frac{z_\phi - \eta/2}{z_N} \tag{2}$$

of z_ϕ and z_N, the z charges of the Brough-Englert-Higgs doublet and that of the right handed neutrinos. For instance, one has $\mathscr{X} = 0$ for the vanilla $B - L$ model or $\mathscr{X} = 2$ for the superweak extension of the SM at the renormalization scale where η is chosen to vanish [7, 8].

The predictions can be expressed with three parameters: (i) the charge ratio $\mathscr{X}$, (ii) $M_{Z'}$ or rather the dimensionless ratio $\xi = M_{Z'}/M_Z$ and lastly (iii) the new mixing angle s_Z or equivalently $(z_N g_z)$ the new gauge coupling scaled to the z charge of the right handed neutrinos. The latter is possible due to the relation

$$-\mathrm{s}_Z \mathrm{c}_Z \frac{1-\xi^2}{\rho} = 2\mathscr{X} \frac{z_N g_z}{\sqrt{g_Y^2 + g_L^2}}, \tag{3}$$

where $\mathrm{s}_Z = \sin(\theta_Z)$ the ρ parameter in the $U(1)$ extensions (c.f. Ref. [9]) is given as

$$\rho = \frac{M_W^2}{M_Z^2 \mathrm{c}_W^2} = 1 - (1-\xi^2)\mathrm{s}_Z^2, \quad \text{with experimental value } \rho_{\text{fit}} = 1.00038 \pm 0.00020. \tag{4}$$

At the tree level in the SM $\rho = 1$ and global fits [5] yield the value ρ_{fit} for the beyond the standard model effects on ρ. Hence, the ρ parameter provides a stringent and easy-to-calculate estimate for the exclusion limits obtained from the electroweak precision observables.

3. Exclusion bounds

We consider the ρ parameter (4) as an indirect bound on thee free parameters alongside with direct experimental searches for new particles, as the latter ones with null results provide considerably more stringent limits on the free parameters on the models accommodating the given particle. The final exclusion limits are cast on the absolute values $|\mathrm{s}_Z|$ and $|z_N g_z|$ as the cross sections and the total decay width of the Z' depends on the squares s_Z^2 or $(z_N g_z)^2$.

3.1 Light Z' bosons

A Z' boson is considered light if $\xi \ll 1$, which implies the limits

$$|\mathrm{s}_Z| < 4.5 \cdot 10^{-3} \quad \text{or} \quad |z_N g_z| < \frac{1.7 \cdot 10^{-3}}{|\mathscr{X}|} \tag{5}$$

obtained from Eq. (4). As for the direct searches, we include the BaBar [10], NA64 [11], FASER [12] and the BelleII [13] experiments. The first three of these search for so-called dark photons A' described by its mass $m_{A'}$ and its coupling ϵe to fermions. These parameters are matched

[1] It is possible to cancel the anomalies without any new fermion field, for instance in the $L_\mu - L_\tau$ type models [6]. In this context it means that the leftover nonzero terms in the anomaly equations are to be canceled with a generation dependent choice for the z charges.

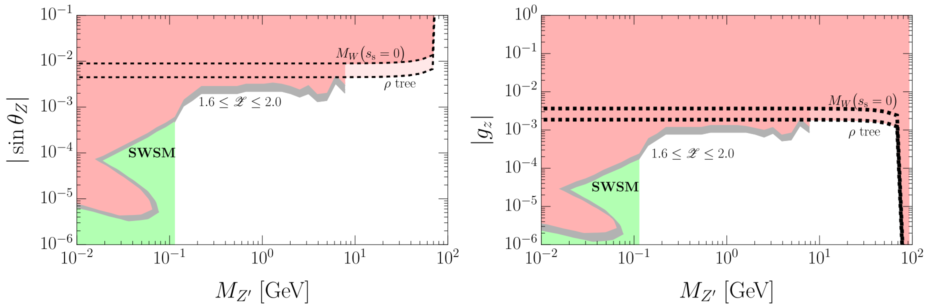

Figure 1: Similar to Fig. 1 of Ref. [1], but with exclusion bounds cast for the superweak model with $z_N = 1/2$ and $z_\phi = 1$. The green region is the preferred parameter space. The dashed line with M_W is a limit obtained from the W-boson mass.

to the free parameters of our choice by the procedure described in Refs. [1, 14]. The BelleII experiment searches for Z' bosons in the context of the $L_\mu - L_\tau$ model and the matching procedure is performed accordingly. However, the bounds obtained from BelleII are comparable to the bounds obtained from the ρ-parameter and thus less severe than the exclusion limits from the previous three experiments.

The exclusion limits may be cast for different benchmark values of $\mathscr{Z}$ as shown in Fig. 1. of Ref. [1], which shows one such benchmark plot for $\mathscr{Z} = 1$. The red regions are excluded and the gray band is the uncertainty in the location of the boundary of the exclusion limits.

One may also investigate a specific model. Then, the running of the η parameter can be taken into account as uncertainty in the value of $\mathscr{Z}$. As a specific model we chose to exhibit the bounds on the superweak model as shown in Fig. 1. In order to asses the reliability of the limits obtained from the ρ-parameter we also compute the limit obtained from the W-boson mass M_W. Here we consider the world average $M_W^{\text{exp.}} = 80.377$ given in Ref. [5] with combined theoretical and experimental uncertainty of 15 MeV.

3.2 Heavy Z' boson

A Z' is considered heavy if $\xi \gg 1$. Here we investigate the region $M_{Z'} > 1$ TeV. The bounds from Eq. (4) read as

$$|s_Z| < 2.5 \cdot 10^{-3} \left[\frac{1\ \text{TeV}}{M_{Z'}}\right] \quad \text{or} \quad |z_N g_z| < \frac{0.11}{|\mathscr{Z}|}\left[\frac{M_{Z'}}{1\ \text{TeV}}\right], \tag{6}$$

which shows that while the limit on $|s_Z|$ gets more stringent with increasing values of $M_{Z'}$, the limit on the new gauge coupling gets more relaxed. As for direct searches, we considered the recent ATLAS [15] and CMS [16] searches for a Z' boson in the Drell-Yan process $pp \to Z' \to \ell^+\ell^-$, where $\ell = e, \mu$. We find, that there exist a specific value of $\mathscr{Z}^* = 0.60$ (0.54) , which corresponds to a least severe bound on $|s_Z|$ ($|z_n g_z|$), as shown in Fig. 2.

4. Prospects of future Z' searches

Using the special values $\mathscr{Z}^*$ reported in Sect. 3.2 for the charge ratio Eq. (2) we present projected exclusion bounds on Z' bosons for the High Energy LHC (HE-LHC) and the Future

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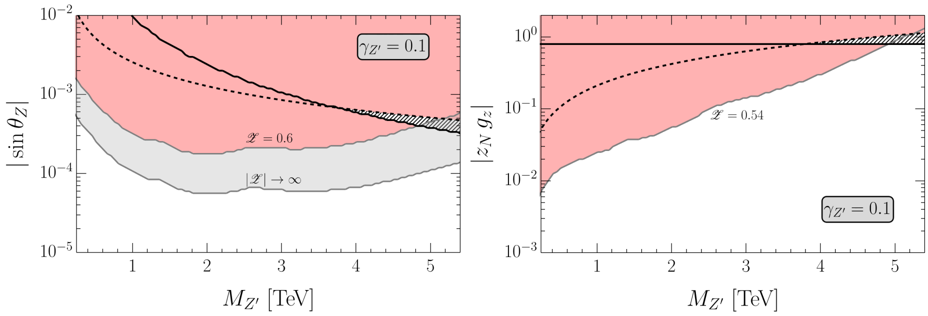

Figure 2: 95% CL exclusion bounds for heavy Z' bosons obtained from the CMS and ATLAS experiments at the LHC for fixed ratios $\gamma_{Z'} = \Gamma_{Z'}/M_{Z'}$. The region in red is excluded, the solid black line corresponds to $\gamma_{Z'} = 0.1$ and the thick gray band incorporates the bounds for models with $0.6 < \mathscr{Z} < \infty$. Only $s_Z = 0$ is allowed for $\mathscr{Z} = 0$ and lastly the exclusion limits tends to the lowest line in the plot for $\mathscr{Z} \to -\infty$.

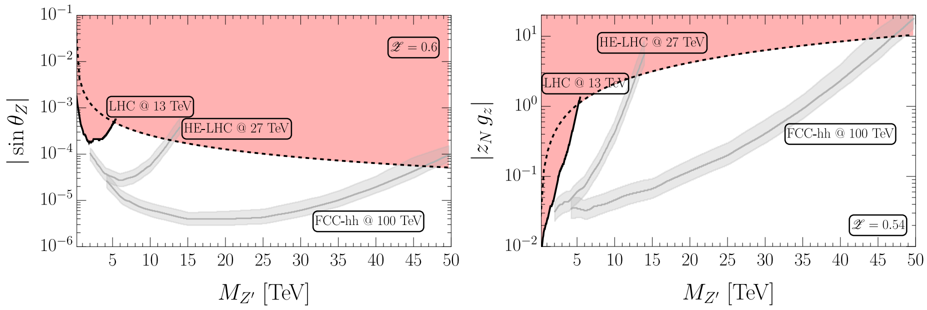

Figure 3: Projected exclusion bounds on $|s_Z|$ at $\mathscr{Z}^* = 0.6$ and on $|z_N\, g_z|$ at $\mathscr{Z}^* = 0.54$ for the HE-LHC and FCC-pp experiments using the simulated exclusion bands obtained in Refs. [17] and [18]. The dark gray line is the expected median exclusion limit and the width of the gray bands correspond to the 95% CL expected limit. The dashed line represents the exclusion by the ρ parameter and the red shaded area is already excluded at 95% CL.

Circular Collider (FCC-hh) in Fig. 3.

As the mass $M_{Z'}$ of the Z' boson becomes large enough, three-body decay channels become accessible. As compared to a two-body decay, the corresponding partial width scales with a higher power of $M_{Z'}$ but it is suppressed by a phase space factor. At $M_{Z'} \sim 10$ TeV, the partial width $\Gamma(Z' \to ZW^+W^-)$ becomes competitive with the partial width $\Gamma(Z' \to \ell^+\ell^-)$. Thus, at high center of mass energies – accessible at the FCC-hh – it is worthwhile to consider searching for the process $pp \to Z' \to ZW^+W^-$, as the ratio of the cross section compared to the dilepton channel is

$$\frac{\sigma\big(pp \to Z' \to ZW^+W^-\big)}{\sigma\big(pp \to Z' \to \ell^+\ell^-\big)} \simeq 0.4 \frac{\mathscr{Z}^2}{2 - 6\mathscr{Z} + 5\mathscr{Z}^2} \left[\frac{M_{Z'}}{10\ \text{TeV}}\right]^2 . \tag{7}$$

5. Summary

We presented an efficient choice of free parameters to describe the properties of an extra neutral gauge boson, called the Z' boson. The particle is introduced by extending the SM gauge group by an extra $U(1)$ gauge symmetry. We shown that choosing the new gauge coupling g_z introduced by additional gauge group is equivalent to choosing the mixing s_Z between the Z and

Z' bosons. In addition to this, we choose the mass $M_{Z'}$ of the particle and a specific combination $\mathscr{Z}$ of unconstrained z-charges and the kinetic mixing parameter η. We shown that the ρ parameter given in Eq. (4) gives a stringent bound on the free parameters. Lastly, we present 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. We also propose direct searches for the final state $Z + W^+ + W^-$ at the FCC based on the three-body decays of the Z' boson.

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