PROCEEDINGS OF SCIENCE

A reappraisal of constraints on Z' models from unitarity and direct searches at the LHC

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We reexamine the ubiquitous $U(1)$ extension of the Standard Model (SM), with a new neutral gauge boson (Z'), in a truly model-independent approach. No new fermions, except for three right-handed neutrinos, are added. We use the current LHC Drell-Yan data to put model-independent constraints on the Z' parameter space, defined by $M_{Z'}$, the Z-Z' mixing angle (α_z) and the extra $U(1)$ effective gauge coupling (g'_x), which absorb all model dependence. Additional constraints are imposed from unitarity and ν_μ-e scattering. However, limits extracted from direct searches turn out to be the most stringent.

The 20th International Workshop on Neutrinos (NuFact2018)
12-18 August 2018
Blacksburg, Virginia

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We concentrate on models where the standard model (SM) gauge group, $\mathscr{G}_{\rm SM}$, is extended by a $U(1)_X$ symmetry. The spontaneous symmetry breaking $\mathscr{G}_{\rm SM}\times U(1)_X\to\mathscr{G}_{\rm SM}$ by the vev, v_Φ, of the scalar $S\equiv(1,1,0,1/2)$ (under $(SU(3),SU(2),U(1)_Y,U(1)_X)$) results in the massive gauge boson Z'. The SM is broken by the vev v of $\Phi\equiv(1,2,1/2,x_\Phi/2)$. The gauge kinetic lagrangian is:

$$\mathscr{L}\supset-(1/4)Y^{\mu\nu}Y_{\mu\nu}-(1/4)X^{\mu\nu}X_{\mu\nu}-(\sin\chi/2)Y^{\mu\nu}X_{\mu\nu}, \tag{1}$$

Performing the transformation, $\left(Y'_\mu,X'_\mu\right)=\left(Y_\mu,X_\mu\right)\cdot M$, where $M_{11}=1, M_{12}=0$, $M_{21}=\sin\chi$, $M_{22}=\cos\chi$, to go to diagonal gauge kinetic lagrangian, the scalar covariant derivatives become:

$$D_\mu\Phi=\partial_\mu\Phi-i(g/2)\left(\tau_aW^a_\mu+\tan\theta_wY'_\mu+\tan\theta_x x'_\Phi X'_\mu\right)\Phi;\ \ D_\mu S=\left(\partial_\mu-i(g'_x/2)X'_\mu\right)S \tag{2}$$

$$\text{with,}\ \tan\theta_w=\frac{g_Y}{g};\ \tan\theta_x=\frac{g'_x}{g};\ g'_x=g_x\sec\chi;\ x'_\Phi=x_\Phi-\frac{g_Y}{g_x}\sin\chi;\ r=v_\Phi/v. \tag{3}$$

Diagonalising the neutral gauge boson mass matrix, we get the following consistency relations:

$$M_Z^2\cos^2\alpha_z+M_{Z'}^2\sin^2\alpha_z=M_W^2/\cos^2\theta_w; \tag{4}$$

$$M_{Z'}^2\cos^2\alpha_z+M_Z^2\sin^2\alpha_z=M_W^2\tan^2\theta_x\left(r^2+x'^2_\Phi\right); \tag{5}$$

$$\left(M_{Z'}^2-M_Z^2\right)\sin2\alpha_z=2x'_\Phi\tan\theta_xM_W^2/\cos\theta_w\,. \tag{6}$$

$M_W=gv/2$, θ_w and α_z are the angles of the rotation matrix. Taking ($M_{Z'}$, α_z, $\tan\theta_x$) as the independent variables, we replace (x'_Φ, θ_w, r), the dependent ones. Making the charge x'_Φ a dependent variable is interesting as from anomaly cancellation we can express all the particles' $U(1)_X$ charges in terms of x'_Φ (table 1). Model dependence of amplitudes, and hence bounds, is encoded in this charge and replacing it with model independent parameters makes the results model independent.

Multiplet	Q_L	u_R	d_R	ℓ_L	e_R	N_R	Φ	S
$U(1)_X$ charge	$\frac{x'_\Phi}{3}+\frac{1}{12}$	$\frac{4x'_\Phi}{3}+\frac{1}{12}$	$-\frac{2x'_\Phi}{3}+\frac{1}{12}$	$-x'_\Phi-\frac{1}{4}$	$-2x'_\Phi-\frac{1}{4}$	$\frac{1}{4}$	x'_Φ	$\frac{1}{2}$

Table 1: *$U(1)_X$-charge assignments of the multiplets, as functions of x'_Φ, satisfying the anomaly constraints. The symbols have the usual meanings. In addition to the the SM fermions, there is one RH neutrino, N_R, per generation for neutrino masses. The charge of N_R is fixed from the requirement that the masses be Majorana type. The $U(1)_X$ charges have been taken to preserve the generational structure of the fermions.*

Preserving unitarity of the scattering amplitude $W^+_LW^-_L\to W^+_LW^-_L$ (L denoting longitudinal) leads to the following constraint (G_F is the Fermi constant):

$$(M_{Z'}^4\sin^2\alpha_z)/\left(M_Z^2\cos^2\alpha_z+M_{Z'}^2\sin^2\alpha_z\right)<8\pi\times3/(32\sqrt{2}G_F)\,. \tag{7}$$

The tree unitarity constraint leads to an upper bound on $M_{Z'}$ (fig 1, right panel). We can bound $M_{Z'}$ even in the case of no Z-Z' mixing. The additional Z' will contribute to the $\nu_\mu e\to\nu_\mu e$ amplitude, modifying the vector and axial interactions. Using the measured values of these, $g_V^{\nu e}=-0.040\pm0.015, g_A^{\nu e}=-0.507\pm0.014$ [1], we can set bounds on the Z' parameter space (fig 1, right). Finally, we find bounds on the Z' parameter space from latest limits on the Drell Yan cross section by ATLAS [2], and cast them in a model-independent manner. The cross section

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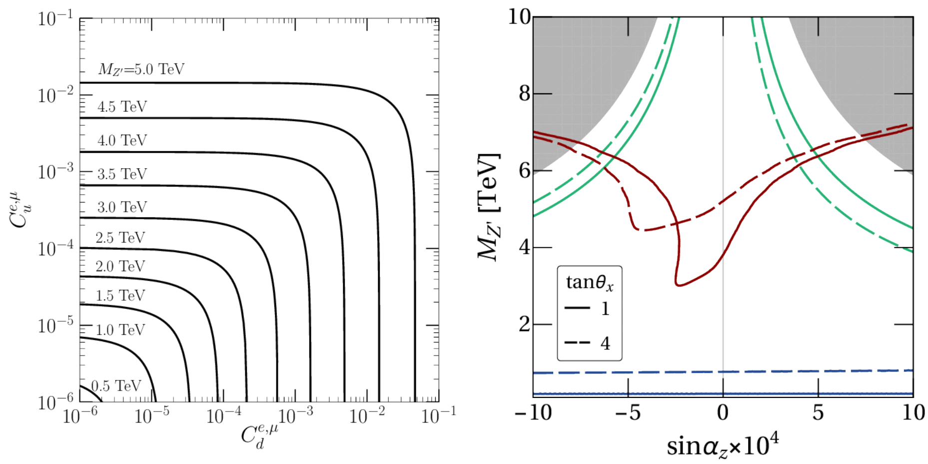

Figure 1: ***Left:*** Exclusion contours at 95% C.L. in the C_u^ℓ-C_d^ℓ, $(\ell \equiv e, \mu$ plane for different values of $M_{Z'}$, derived using ATLAS data for dilepton final states. ***Right:*** Consolidated bounds in the $(\sin\alpha_z$-$M_{Z'})$ plane. The shaded region is excluded from unitarity. The red and the blue colors indicate the limits set by direct detection and ν_μ-e scattering data, respectively. The green contours are obtained by setting $\Gamma_{Z'} = M_{Z'}/2$. The solid and dashed line-types correspond to $\tan\theta_x = 1$ and 4, respectively. Region above the red lines are allowed, the region above the blue lines and the interior of the green contours are allowed (details in [3]).

for resonant production of a Z' boson at the LHC and its subsequent decay into a pair of charged leptons can be conveniently expressed as [4, 5] (the sum is over all the partons):

$$\sigma\left(pp \to Z'X \to \ell^+\ell^- X\right) = \frac{\pi}{6s}\sum_q C_q^\ell w_q\left(s, M_{Z'}^2\right). \tag{8}$$

The coefficients,
$$C_q^\ell = \left[\left(g_L^q\right)^2 + \left(g_R^q\right)^2\right] \mathrm{BR}\left(Z' \to \ell^+\ell^-\right), \tag{9}$$

involve the fermionic couplings of Z'. The functions w_q contain information about the parton distribution functions and QCD corrections. Using the CT14NLO PDF set, we evaluate w_u and w_d, and translate the limit on the cross section into a bound in the C_u^ℓ-C_d^ℓ plane for different values of $M_{Z'}$ (fig. 1, left). We also express the limits in terms of our parameters (fig. 1, right).

In conclusion, we present a parametrisation of anomaly free Z' extensions which is completely model-independent. In our formalism, we do not a priori assume the smallness of the Z-Z' mixing angle α_z, and by careful variable counting we identify three independent variables, ($M_{Z'}$, α_z, $\tan\theta_x$), in terms of which we give bounds on the Z' parameter space.

References

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