Search for a light Z' at LHC in a neutrinophilic U(1) model

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[1] Search for a light Z' at LHC in a neutrinophilic U(1) model, W. Abdallah, A.K. Barik, S.K. Rai and T. Samui, arXiv:2106:01362

The Model

- Extra $U(1)$ Gauge Boson Added

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Spin
H_1	1	2	$-1/2$	0	0
H_2	1	2	$-1/2$	$-q_x$	0
S	1	1	0	$2q_x$	0
N_L^i	1	1	0	q_x	$1/2$
N_R^i	1	1	0	q_x	$1/2$

.

Lagrangian

$$
\begin{aligned}
\mathcal{L} \supset\ & (D_\mu H_1)^\dagger D_\mu H_1 + (D_\mu H_2)^\dagger D_\mu H_2 + (D_\mu S)^\dagger D_\mu S - \mu_1 H_1^\dagger H_1 - \mu_2 H_2^\dagger H_2 \\
& -\mu_s S^\dagger S + i\,\overline{N}_L \gamma^\mu D_\mu N_L + i\,\overline{N}_R \gamma^\mu D_\mu N_R - \hat{M}_N \left(\overline{N}_L N_R + \overline{N}_R N_L\right) \\
& - \left\{ Y_\nu\, \bar{l}_L H_2 N_R + h.c. \right\} - \lambda_1 \left(H_1^\dagger H_1\right)^2 - \lambda_2 \left(H_2^\dagger H_2\right)^2 \\
& -\lambda_{12} H_1^\dagger H_1 H_2^\dagger H_2 - \lambda'_{12} \left| H_1^\dagger H_2 \right|^2 - \lambda_s \left(S^\dagger S\right)^2 - \lambda_{1s} H_1^\dagger H_1 S^\dagger S \\
& -\lambda_{2s} H_2^\dagger H_2 S^\dagger S - \left\{ Y_R S \overline{N}_R N_R^C + Y_L S \overline{N}_L N_L^C + \text{h.c.} \right\} \\
& + \left\{ \mu_{12} H_1^\dagger H_2 + \text{h.c.} \right\}
\end{aligned}
$$

The last term in the Lagrangian breaks the $U(1)_X$ symmetry explicitly. This soft-breaking term is needed to give mass to the pseudo-scalar after the symmetry breaking .

VEV

VEVs

$$H_1 = \begin{pmatrix} \frac{v_1 + \rho_1 + i\eta_1}{\sqrt{2}} \\ \phi_1^- \end{pmatrix}, H_2 = \begin{pmatrix} \frac{v_2 + \rho_2 + i\eta_2}{\sqrt{2}} \\ \phi_2^- \end{pmatrix}, S = \frac{v_s + \rho_s + i\eta_s}{\sqrt{2}}$$

$$v^2 = v_1^2 + v_2^2 \,, \tan\beta \; = \frac{v_2}{v_1}$$

Tadpole Equations.

$$\mu_1 - \mu_{12}\frac{v_2}{v_1} + \lambda_1 v_1^2 + \frac{\lambda_{12} + \lambda'_{12}}{2} v_2^2 + \frac{\lambda_{1s}}{2} v_s^2 = 0 \,,$$

$$\mu_2 - \mu_{12}\frac{v_1}{v_2} + \lambda_2 v_2^2 + \frac{\lambda_{12} + \lambda'_{12}}{2} v_1^2 + \frac{\lambda_{2s}}{2} v_s^2 = 0 \,,$$

$$\mu_s + \frac{\lambda_{1s}}{2} v_1^2 + \frac{\lambda_{2s}}{2} v_2^2 + \lambda_s v_s^2 = 0 \,.$$

Scalar Masses

- Pseudo-scalar mass $m_A = \sqrt{\frac{\mu_{12}}{v_1 v_2} v^2}$
- Charged scalar mass $m_{H^\pm} = \sqrt{\left(\frac{\mu_{12}}{v_1 v_2} - \frac{\lambda'_{12}}{2}\right) v^2}$

The CP-even scalar mass matrix in the $(\rho_1 \ \rho_2 \ \rho_s)^T$ basis is given by

$$M_H^2 = \begin{pmatrix} 2\lambda_1 v_1^2 + \mu_{12}\frac{v_2}{v_1} & (\lambda_{12} + \lambda'_{12}) v_1 v_2 - \mu_{12} & \lambda_{1s} v_1 v_s \\ (\lambda_{12} + \lambda'_{12}) v_1 v_2 - \mu_{12} & 2\lambda_2 v_2^2 + \mu_{12}\frac{v_1}{v_2} & \lambda_{2s} v_2 v_s \\ \lambda_{1s} v_1 v_s & \lambda_{2s} v_2 v_s & 2\lambda_s v_s^2 \end{pmatrix}$$

Gauge Boson Masses

$$\mathcal{L} \supset -\frac{1}{4} G^{a,\mu\nu} G^{a}_{\mu\nu} - \frac{1}{4} W^{b,\mu\nu} W^{b}_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} C^{\mu\nu} C_{\mu\nu} + \frac{1}{2} \tilde{g} B^{\mu\nu} C_{\mu\nu}$$

$\tilde{g}$ is the kinetic mixing parameter. The mixing angle of Z and Z'

$$\tan 2\theta' = \frac{2 g_z v^2 \left(g'_x + 2 g_x \sin^2 \beta \right)}{{g'_x}^2 v^2 + 4 g_x g'_x v_2^2 + 4 g_x^2 (v_2^2 + 4 v_s^2) - g_z^2 v^2}$$

The mass of the physical gauge bosons are

$$\begin{aligned} M^2_{Z',Z} &= \frac{1}{8} \left[g_z^2 v^2 + {g'_x}^2 v^2 + 4 g_x g'_x v_2^2 + 4 g_x^2 (v_2^2 + 4 v_s^2) \right] \\ &\pm \frac{1}{8} \sqrt{ \left({g'_x}^2 v^2 + 4 g_x g'_x v_2^2 + 4 g_x^2 (v_2^2 + 4 v_s^2) - g_z^2 v^2 \right)^2 + 4 g_z^2 \left(g'_x v^2 + 2 g_x v_2^2 \right)^2 } \end{aligned}$$

Redefined Parameters

$$g'_x = \frac{g_1 \tilde{g}}{\sqrt{1 - \tilde{g}^2}}, \qquad g_x \to g_x \sqrt{1 - \tilde{g}^2}.$$

Fermion Masses

The Lagrangian responsible for the masses and the mixing of leptons and quarks is essentially the Yukawa terms.

$$\mathcal{L} \supset -Y_l^{ij}\bar{l}_{Li}H_1^{\mathcal{C}}e_{Rj} - Y_d^{ij}\bar{q}_{Li}H_1^{\mathcal{C}}d_{Rj} - Y_u^{ij}\bar{q}_{Li}H_1 u_{Rj} + \mathrm{h.c.}$$

Couplings for	$h_i - f - \bar{f}$	$A - f - \bar{f}$	$H^{\pm} - f - \bar{f}'$
g_f	$Y_f^{\mathrm{SM}} \frac{Z^h_{i1}}{\cos\beta}$	$Y_f^{\mathrm{SM}} \tan\beta$	$Y_f^{\mathrm{SM}} \tan\beta$

In this model, neutrinos get masses via inverse sea-saw mechanism.

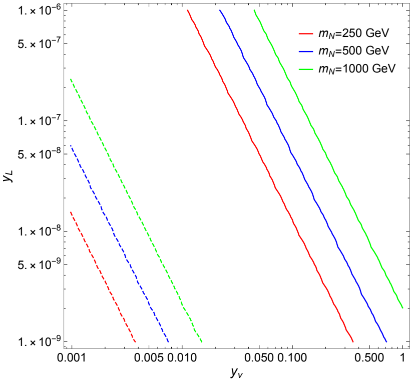
$$\mathcal{L} \;\supset\; -\, Y_\nu \overline{l_L} H_2 N_R - Y_R S \overline{N}_R N_R^C - Y_L S \overline{N}_L N_L^C - \hat{M}_N \overline{N}_L N_R + \text{h.c.}$$

The mass matrix in $\left(\nu_L \;\, N_R^C \;\, N_L\right)^T$ basis is given by

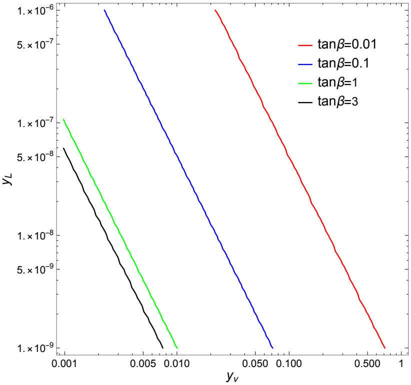
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & m_R & \hat{M}_N \\ 0 & \hat{M}_N^T & m_L \end{pmatrix},$$

where $m_D = v_2 Y_\nu/\sqrt{2}$, $m_R = \sqrt{2} v_s Y_R$ and $m_L = \sqrt{2} v_s Y_L$.

$$\begin{aligned} m_{\nu_\ell} &\simeq \frac{m_D^2\, m_L}{\hat{M}_N^2 + m_D^2}, \\ m_{\nu_{H,H'}} &\simeq \frac{1}{2}\left(\frac{\hat{M}_N^2\, m_L}{\hat{M}_N^2 + m_D^2} + m_R\right) \mp \sqrt{\hat{M}_N^2 + m_D^2}\,. \end{aligned}$$

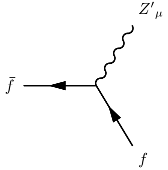


m_N=250 GeV
m_N=500 GeV
m_N=1000 GeV
y_L
y_ν

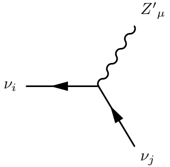


tanβ=0.01
tanβ=0.1
tanβ=1
tanβ=3
y_L
y_ν

Z' Couplings



$$i\left(\frac{e\,s_{\theta'}}{s_W\,c_W}\left(T^3 - Q_f\,s_W^2\right) + g_x'\,c_{\theta'}\left(T^3 - Q_f\right)\right)\gamma^\mu P_L - i\left(\frac{e\,s_{\theta'}}{s_W\,c_W}\,Q_f\,s_W^2 + g_x'\,c_{\theta'}\,Q_f\right)\gamma^\mu P_R$$



.

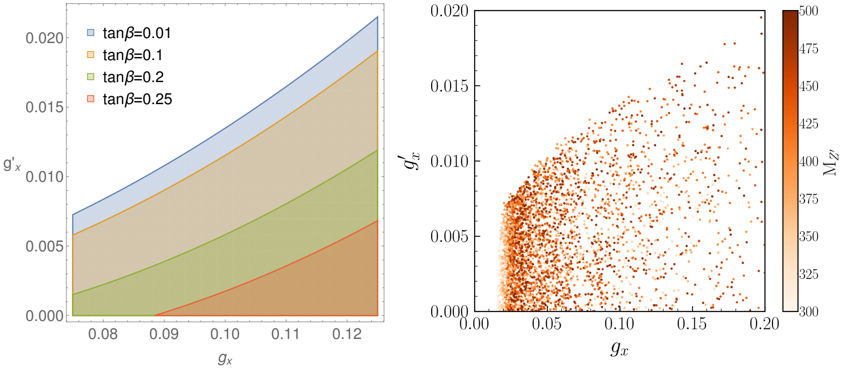
$$\frac{i}{2}\left(\left(\frac{e\,s_{\theta'}}{2\,s_W\,c_W} + \frac{g_x'}{2}\,c_{\theta'}\right)\sum_{k=1}^{3}\mathcal{N}_{ik}\mathcal{N}_{jk}^* + 2g_x\,c_{\theta'}\left(-\sum_{k=7}^{9}\mathcal{N}_{ik}\mathcal{N}_{jk}^* + \sum_{k=4}^{6}\mathcal{N}_{ik}\mathcal{N}_{jk}^*\right)\right)\gamma^\mu P_L$$

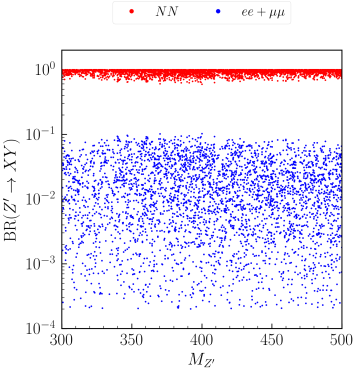
Experimental Constraints

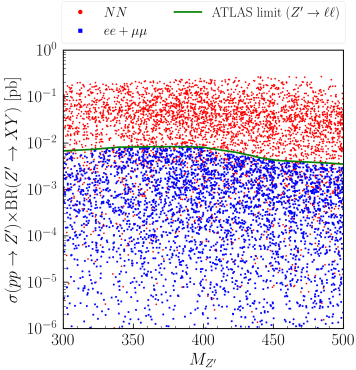
- LEP constraint on Z-Z' mixing, $\theta' < 10^{-3}$
- From higgs signals and production of unobserved scalars at colliders.
- From Searches for new Z' gauge boson .

λ_1	λ_2	λ_3	λ_4	λ_{1s}	λ_{2s}	μ_{12} (GeV^2)	tan β
0.1289	1.0	0.005	0.005	0.0	-0.5	10^4	0.01

- Masses of the scalars except SM like scalar are kept of order 1TeV.


tanβ=0.01
tanβ=0.1
tanβ=0.2
tanβ=0.25
0.020
0.015
0.010
0.005
0.000
g'$_x$
0.08
0.09
0.10
0.11
0.12
g_x
0.020
0.015
0.010
0.005
0.000
g'_x
0.00
0.05
0.10
0.15
0.20
g_x
500
475
450
425
400
375
350
325
300
$M_{Z'}$


NN
$ee+\mu\mu$
$\mathrm{BR}(Z' \to XY)$
$M_{Z'}$


NN
$ee+\mu\mu$
ATLAS limit $(Z' \to \ell\ell)$
$\sigma(pp \to Z')\times\mathrm{BR}(Z' \to XY)$ [pb]
$M_{Z'}$

Collider Analysis

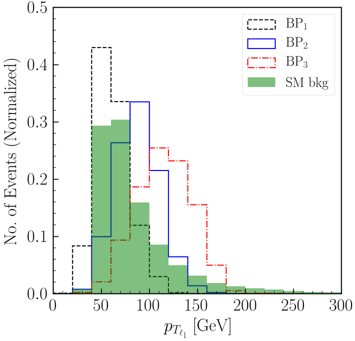
	BP1	BP2	BP3
$M_{Z'}$ (GeV)	300	400	500
$M_N = \hat{M}_{N_{11}}$ (GeV)	120	150	200
g_x	0.149	0.191	0.246
$g'_x \times 10^3$	7.02	9.52	9.52
$\tan\theta' \times 10^4$	9.87	7.20	4.52
$\sigma(p\,p \to Z')$ (fb)	215.5	148.2	67.7
BR $(Z' \to N\,N)$	0.987	0.985	0.990
BR$(N \to \ell^{\pm}\,W^{\mp}(\nu Z))$	0.75 (0.25)	0.67 (0.29)	0.60 (0.29)

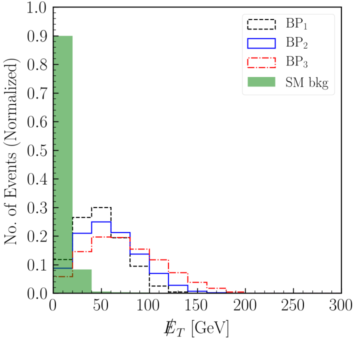
$4\ell + MET$

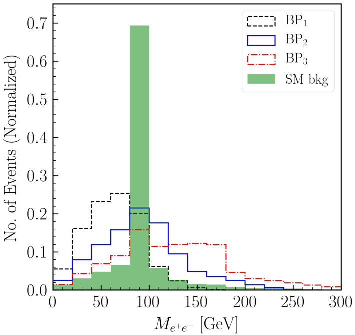
The major SM background for the $4\ell + MET$ final state comes from the following

$$pp \to VZ, \qquad pp \to t\bar{t}Z, \qquad pp \to VVV \;\; (V \equiv W^{\pm}, Z).$$

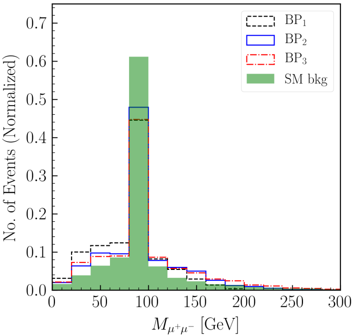
Signal	Cross-section (fb)	SM Background	Cross-section (fb)
BP1	0.688	ZZ	9.088
BP2	0.476	VVV	0.111
BP3	0.204	$W^{\pm}Z$	0.081
		$t\bar{t}Z$	0.014


BP$_1$
BP$_2$
BP$_3$
SM bkg
No. of Events (Normalized)
$p_{T_{\ell_1}}$ [GeV]


BP$_1$
BP$_2$
BP$_3$
SM bkg
No. of Events (Normalized)
$\not{E}_T$ [GeV]



No. of Events (Normalized)
$M_{e^+e^-}$ [GeV]
BP$_1$
BP$_2$
BP$_3$
SM bkg



No. of Events (Normalized)
$M_{\mu^+\mu^-}$ [GeV]
BP$_1$
BP$_2$
BP$_3$
SM bkg

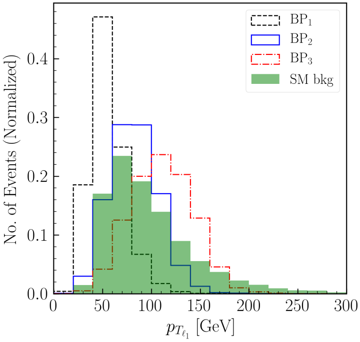
$\mathcal{L} = 100\ \text{fb}^{-1}$	SM-background				Signal		
Cuts	ZZ	VVV	$t\bar{t}Z$	$W^{\pm}Z$	BP1	BP2	BP3
$N_{\mu} \leq 2$	566.5	5.69	0.53	4.52	64.5	43.7	18.7
$(15 < MET < 200)$ GeV	107.3	4.8	0.47	3.97	60.07	41.66	18.04
$(20 < p_{T_{\ell_1}} < 200)$ GeV	103.7	4.19	0.38	3.97	60.01	41.66	18.02
$M_{\mu^+\mu^-} < 80$ GeV or $M_{\mu^+\mu^-} > 95$ GeV	35.35	2.74	0.25	3.6	56.17	38.5	16.6
Total Events after cuts	41.94				56.17	38.5	16.6
	Significance ($\mathcal{S}$)				7.38	5.67	2.42

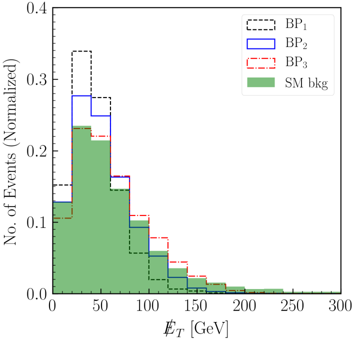
$3\ell + 2j + MET$

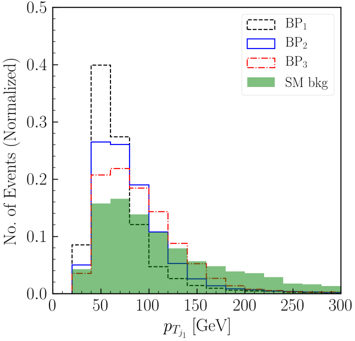
Signal	Cross-section (fb)	SM Background	Cross-section (fb)
BP1	1.723	ZZ	1.528
BP2	1.526	VVV	0.266
BP3	0.717	$W^{\pm} Z$	37.23
		$t\bar{t} + t\bar{t}\,Z$	1.745

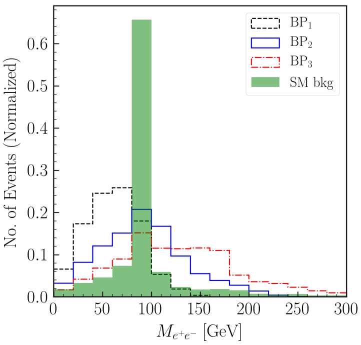
The main SM background comes from the following subprocesses

$$pp \to VZ, \qquad pp \to t\bar{t} + t\bar{t}\,Z, \qquad pp \to VVV \;\; (V \equiv W^{\pm}, Z).$$


BP$_1$
BP$_2$
BP$_3$
SM bkg
No. of Events (Normalized)
$p_{T_{\ell_1}}$ [GeV]


BP$_1$
BP$_2$
BP$_3$
SM bkg
No. of Events (Normalized)
$\not{E}_T$ [GeV]


0.5
0.4
0.3
0.2
0.1
0.0
No. of Events (Normalized)
BP$_1$
BP$_2$
BP$_3$
SM bkg
0
50
100
150
200
250
300
$p_{T_{j_1}}$ [GeV]


0.6
0.5
0.4
0.3
0.2
0.1
0.0
No. of Events (Normalized)
BP$_1$
BP$_2$
BP$_3$
SM bkg
0
50
100
150
200
250
300
$M_{e^+e^-}$ [GeV]

$\mathcal{L} = 100$ fb^{-1}	SM-background				Signal		
Cuts	$W^{\pm}Z$	$t\bar{t}$	ZZ	VVV	BP1	BP2	BP3
$N_\mu \leq 1$	2246.0	147.2	86.5	26.0	170.4	150.6	70.7
$(15 < MET < 200)$ GeV	2022.0	146.2	39.0	22.1	155.0	139.4	66.1
$p_T^{j_1} < 200$ GeV	1686.0	119.3	35.7	18.8	152.1	135.8	64.0
$(20 < p_{T_{\ell_1}} < 200)$ GeV	1608.0	118.7	34.6	17.2	151.4	135.7	63.7
$M_{e^+e^-} < 85$ GeV or $M_{e^+e^-} > 95$ GeV	228.0	97.3	4.9	2.2	124.9	96.0	49.0
Total Events after cuts	332.4				124.9	96.0	49.0
	Significance ($\mathcal{S}$)				6.48	5.04	2.63

Conclusion

- We consider a neutrinophilic model as an extension of the SM by introducing a $U(1)$ group which couples directly to only heavy neutral fermions, singlet under the SM.
- The neutrinos in the model get their mass from a standard inverse-seesaw mechanism .
- We study the phenomenology of having such a light Z' in the context of neutrinophilic interactions as well as the role of allowing kinetic mixing between the new $U(1)$ group with the SM hypercharge group.
- We find that although the di-lepton Drell-Yan channel is much suppressed here, the discovery prospects of observing a neutrinophilic Z' is significantly high in the $4\ell + MET$ and $3\ell + 2j + MET$ channels.

Thank You