Z' Production in 331 Models

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We analyse the possibilities to detect a new Z' boson in di-electron events at LHC in the framework of the 331 model with right-handed neutrinos. For an integrated luminosity of $100 fb^{-1}$ at LHC, and considering a central value $M_{Z'} = 1500$ GeV, we obtain the invariant mass distribution in the process $pp \to Z' \to e^+e^-$, where a huge peak, corresponding to 800 signal events, is found above the SM background. The number of di-electron events vary from 10000 to 1 in the mass range of $M_{Z'} = 1000 - 5000$ GeV.

Keywords: 331 Models; Extra neutral gauge bosons; LHC physics

1. INTRODUCTION

In most of extensions of the standard model (SM), new massive and neutral gauge bosons, called Z', are predicted. The presence of this boson is sensitive to experimental observations at low and high energies, and will be of great interest in the next generation of colliders (LHC, ILC, TESLA) [1]. In particular, it is possible to study some phenomenological features associated to Z' through models with gauge symmetry $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$, also called 331 models. These models arise as an interesting alternative to explain the origin of generations [2–4], where the three families are required in order to cancel chiral anomalies. The electric charge is defined as a linear combination of the diagonal generators of the group

$$Q = T_3 + \beta T_8 + XI, \tag{1}$$

where β allow classify the different 331 models, $T_3 = 1/2\mathrm{diag}(1,-1,0)$, and $T_8 = (1/2\sqrt{3})\mathrm{diag}(1,1,-2)$. The two main versions corresponds to $\beta = -\sqrt{3}$ [2, 3] and $\beta = -\frac{1}{\sqrt{3}}$ [4]. In this work we search for Z' bosons in di-electron events produced in pp collisions at LHC collider in the framework of the 331 model with $\beta = -\frac{1}{\sqrt{3}}$, which we denote as the Foot-Long-Truan (FLT) model.

representation	Q_ψ	X_ψ
$q_{m^*L} = \begin{pmatrix} d_{m^*} \\ -u_{m^*} \\ J_{m^*} \end{pmatrix}_L \mathbf{3}^*$	$\begin{pmatrix} -\frac{1}{3} \\ \frac{2}{3} \\ \frac{1}{6}+\frac{\sqrt{3}\beta}{2} \end{pmatrix}$	$X^L_{q_{m^*}} = \frac{1}{6} + \frac{\beta}{2\sqrt{3}}$
$d_{m^*R}; u_{m^*R}; J_{m^*R} : \mathbf{1}$	$-\frac{1}{3}; \frac{2}{3}; \frac{1}{6}+\frac{\sqrt{3}}{2}\beta$	$X^R_{d_{m^*},u_{m^*},J_{m^*}} = -\frac{1}{3}, \frac{2}{3}, \frac{1}{6}+\frac{\sqrt{3}}{2}\beta$
$q_{3L} = \begin{pmatrix} u_3 \\ d_3 \\ J_3 \end{pmatrix}_L : \mathbf{3}$	$\begin{pmatrix} \frac{2}{3} \\ -\frac{1}{3} \\ \frac{1}{6}-\frac{\sqrt{3}\beta}{2} \end{pmatrix}$	$X^L_{q^{(3)}} = \frac{1}{6} - \frac{\beta}{2\sqrt{3}}$
$u_{3R}; d_{3R}; J_{3R} : \mathbf{1}$	$\frac{2}{3}; -\frac{1}{3}; \frac{1}{6}-\frac{\sqrt{3}\beta}{2}$	$X^R_{u_3,d_3,J_3} = \frac{2}{3}, -\frac{1}{3}, \frac{1}{6}-\frac{\sqrt{3}\beta}{2}$
$\ell_{jL} = \begin{pmatrix} \nu_j \\ e_j \\ E_j^{-Q_1} \end{pmatrix}_L : \mathbf{3}$	$\begin{pmatrix} 0 \\ -1 \\ -\frac{1}{2}-\frac{\sqrt{3}\beta}{2} \end{pmatrix}$	$X^L_{\ell_j} = -\frac{1}{2} - \frac{\beta}{2\sqrt{3}}$
$e_{jR}; E_{jR}^{-Q_1}$	$-1; -\frac{1}{2}-\frac{\sqrt{3}\beta}{2}$	$X^R_{e_j,E_j} = -1, -\frac{1}{2}-\frac{\sqrt{3}\beta}{2}$

TABLE I: *Fermionic content for three generations. We take $m^* = 1,2$ and $j = 1,2,3$*

2. THE FERMIONIC AND NEUTRAL GAUGE SPECTRUM

The fermion representations under $SU(3)_c \otimes$ $SU(3)_L \otimes U(1)_X$ read

$$\begin{aligned}
\widehat{\psi}_L &= \begin{cases} \widehat{q}_L : \left(\mathbf{3},\mathbf{3},X_q^L\right) = \left(\mathbf{3},\mathbf{2},X_q^L\right) \oplus \left(\mathbf{3},\mathbf{1},X_q^L\right), \\ \widehat{\ell}_L : \left(\mathbf{1},\mathbf{3},X_\ell^L\right) = \left(\mathbf{1},\mathbf{2},X_\ell^L\right) \oplus \left(\mathbf{1},\mathbf{1},X_\ell^L\right), \end{cases} \\
\widehat{\psi}_L^* &= \begin{cases} \widehat{q}_L^* : \left(\mathbf{3},\mathbf{3}^*,-X_q^L\right) = \left(\mathbf{3},\mathbf{2}^*,-X_q^L\right) \oplus \left(\mathbf{3},\mathbf{1},-X_q^L\right), \\ \widehat{\ell}_L^* : \left(\mathbf{1},\mathbf{3}^*,-X_\ell^L\right) = \left(\mathbf{1},\mathbf{2}^*,-X_\ell^L\right) \oplus \left(\mathbf{1},\mathbf{1},-X_\ell^L\right), \end{cases} \\
\widehat{\psi}_R &= \begin{cases} \widehat{q}_R : \left(\mathbf{3},\mathbf{1},X_q^R\right), \\ \widehat{\ell}_R : \left(\mathbf{1},\mathbf{1},X_\ell^R\right). \end{cases}
\end{aligned} \tag{2}$$

The second equality comes from the branching rules $SU(2)_L \subset SU(3)_L$. The X_p refers to the quantum number associated with $U(1)_X$. The generator of $U(1)_X$ conmute with the matrices of $SU(3)_L$; hence, it should take the form $X_p \mathbf{I}_{3\times 3}$, the value of X_p is related with the representations of $SU(3)_L$ and the anomalies cancellation. This fermionic content shows that the left-handed multiplets lie in either the $\mathbf{3}$ or $\mathbf{3}^*$ representations. The fermionic structure is shown in Tab. I in the framework of a three family model

For the scalar sector, we introduce the triplet field χ with vacuum expectation value (VEV) $\langle\chi\rangle^T = \left(0,0,\nu_\chi\right)$, which induces the masses to the third fermionic components. In the second transition it is necessary to introduce two triplets ρ and η with VEV $\langle\rho\rangle^T = \left(0,\nu_\rho,0\right)$ and $\langle\eta\rangle^T = \left(\nu_\eta,0,0\right)$ in order to give masses to the quarks of type up and down respectively [5].

In the gauge boson spectrum associated with the group $SU(3)_L \otimes U(1)_X$, we are just interested in the physical neutral sector that corresponds to the photon, Z, and Z', which are written in terms of the electroweak basis for any β as [6]

$$
\begin{aligned}
A_\mu &= S_W W_\mu^3 + C_W \left(\beta T_W W_\mu^8 + \sqrt{1-\beta^2 T_W^2} B_\mu \right), \\
Z_\mu &= C_W W_\mu^3 - S_W \left(\beta T_W W_\mu^8 + \sqrt{1-\beta^2 T_W^2} B_\mu \right), \\
Z'_\mu &= -\sqrt{1-\beta^2 T_W^2} W_\mu^8 + \beta T_W B_\mu, \qquad (3)
\end{aligned}
$$

where the Weinberg angle is defined as [6]

$$
S_W = \sin\theta_W = \frac{g_X}{\sqrt{g_L^2 + (1+\beta^2)\, g_X^2}} \qquad (4)
$$

and g_L, g_X correspond to the coupling constants of the groups $SU(3)_L$ and $U(1)_X$, respectively. It is important to note that the Z and Z' bosons in Eq. (3) are not true mass eigenstates, but there is a $Z-Z'$ mixing angle that rotate the neutral sector to the physical Z_1 and Z_2 bosons. However, the hadronic reactions are much less sensitive to the $Z-Z'$ mixing than lepton reactions [1]. Thus, the $Z-Z'$ mixing can be neglected and we identify the Z and Z' bosons as the physical neutral bosons.

3. THE NEUTRAL GAUGE COUPLINGS

Using the fermionic content from Tab. I, we obtain the neutral coupling for the SM fermions [6]

$$
\mathcal{L}_D^{NC} = \frac{g_L}{2C_W} \left[\overline{f}\gamma_\mu \left(g_v^f - g_a^f \gamma_5 \right) f Z^\mu + \overline{f}\gamma_\mu \left(\widetilde{g}_v^f - \widetilde{g}_a^f \gamma_5 \right) f Z^{\mu\prime} \right], \qquad (5)
$$

where f is $U=(u,c,t)$, $D=(d,s,b)$ for up- and down-type quarks, respectively and $N=(\nu_e,\nu_\mu,\nu_\tau)$, $L=(e,\mu,\tau)$ for neutrinos and charged leptons, respectively. The vector and axial-vector couplings of the Z boson are the same as the SM Z-couplings

$$
\begin{aligned}
g_v^{U,N} &= \frac{1}{2} - 2Q_{U,N} S_W^2, & g_a^{U,N} &= \frac{1}{2}, \\
g_v^{D,L} &= -\frac{1}{2} - 2Q_{D,L} S_W^2, & g_a^{D,L} &= -\frac{1}{2}, \qquad (6)
\end{aligned}
$$

with Q_f the electric charge of each fermion given by Tab. I; while the corresponding couplings to Z' are given by [7]

$$
\begin{aligned}
\widetilde{g}_{v,a}^{U,D} &= \frac{C_W}{2\sqrt{1-\beta^2 T_W^2}} \left[\frac{1}{\sqrt{3}} \left(diag\,(1,1,-1) + \frac{\beta T_W^2}{\sqrt{3}} \right) \right. \\
&\pm \left. 2Q_{U,D}\beta T_W^2 \right], \\
\widetilde{g}_{v,a}^{N,L} &= \frac{C_W}{2\sqrt{1-\beta^2 T_W^2}} \left[\frac{-1}{\sqrt{3}} - \beta T_W^2 \pm 2Q_{N,L}\beta T_W^2 \right], \qquad (7)
\end{aligned}
$$

where the plus sign (+) is associated with the vector coupling $\widetilde{g}_v$, and the minus sign (−) with the axial coupling $\widetilde{g}_a$. The above equations are written for $\beta = -1/\sqrt{3}$, which corresponds to the FLT model. On the other hand, the differential cross section for the process $pp(p\bar{p}) \longrightarrow Z' \longrightarrow f\bar{f}$ is given by [1]

$$
\frac{d\sigma}{dMdydz} = \frac{K(M)}{48\pi M^3} \sum_q P[B_q G_q^+ (1+z^2) + 2C_q G_q^- z], \qquad (8)
$$

where

$$
\begin{aligned}
M &= M_{ff} \\
z &= \cos\theta \\
K(M) &\simeq 1.3 \\
y &= 1/2 \log[(E+p_z)/(E-p_z)] \\
P &= s^2/[(s-M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2] \\
B_q &= [(\widetilde{g}_v^q)^2 + (\widetilde{g}_a^q)^2][(\widetilde{g}_v^f)^2 + (\widetilde{g}_a^f)^2] \\
C_q &= 4(\widetilde{g}_v^q \widetilde{g}_a^q)(\widetilde{g}_v^f \widetilde{g}_a^f) \\
G_q^\pm &= x_A x_B [f_{q/A}(x_A) f_{\bar{q}/B}(x_B) \pm f_{q/B}(x_B) f_{\bar{q}/A}(x_A)] \\
x &= M e^{\pm y}/\sqrt{z}.
\end{aligned}
$$

with M_{ff} the invariant final state mass, z the scattering angle between the initial quark and the final lepton in the Z' rest frame, $K(M)$ contains leading QED corrections and NLO QCD corrections, y the rapidity, E the total energy, p_z the longitudinal momentum, $\sqrt{s}$ the collider CM energy, $M_{Z'}$ and $\Gamma_{Z'}$ the Z' mass and total width, respectively. The parameters B_q and C_q contain the couplings from Eq. (7) for the initial quarks q and the final fermions f, while the parameter $G_q^\pm$ contains the Parton Distribution Functions (PDFs) $f(x)$, and the momentum fraction x. We can consider the Narrow Width Approximation (NWA), where the relation $\Gamma_{Z'}^2/M_{Z'}^2$ is very small, so that the contribution to the cross section can be separated into the Z' production cross section $\sigma(pp(\bar{p}) \to Z')$ and the fermion branching fraction of the Z' boson $Br(Z' \to f\bar{f})$

$$
\sigma(pp(\bar{p}) \to f\bar{f}) = \sigma(pp(\bar{p}) \to Z') Br(Z' \to f\bar{f}), \qquad (9)
$$

From the analysis of Ref. [7] we can estimate that $\Gamma_{Z'}^2/M_{Z'}^2 \approx 1 \times 10^{-4}$. Thus, the NWA is an appropriate approximation in our calculations.

4. Z'_{FLT} AT LHC

The design criteria of ATLAS at LHC could reveal a Z' signal at the TeV scale. The expected features of the detector are [8]

a. pp collisions at C.M. energy $\sqrt{s} = 14$ TeV,

b. Integrated luminosity $L = 100 fb^{-1}$,

c. Pseudorapidity below $|\eta| \leq 2.2$

d. Transverse energy cut $E_T \geq 20$ GeV.

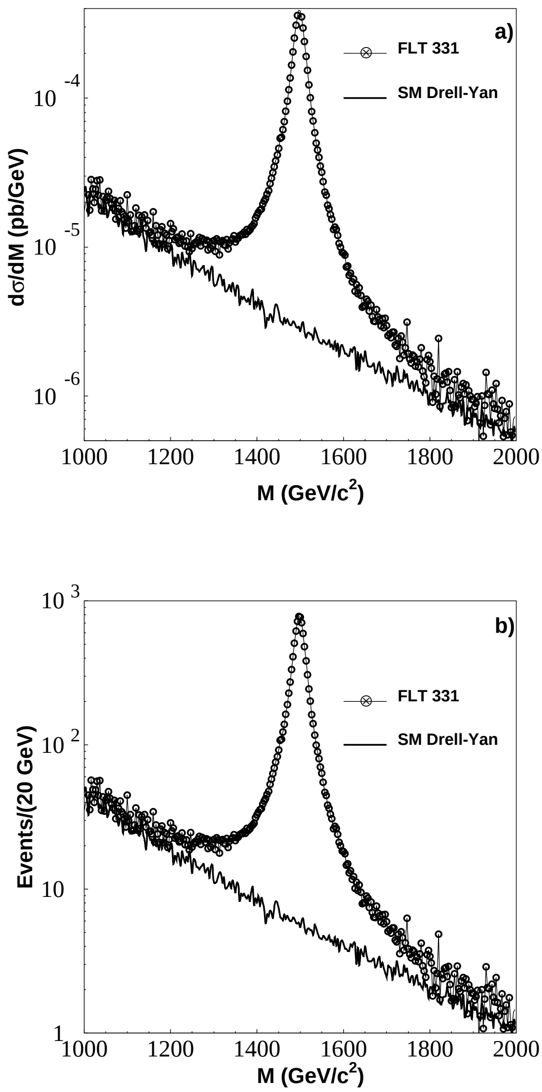

FIG. 1: The plot a.) shows the cross section distribution as a function of the invariant final state mass for $M_{Z'} = 1500$ GeV in LHC. The plot b.) shows the number of events.

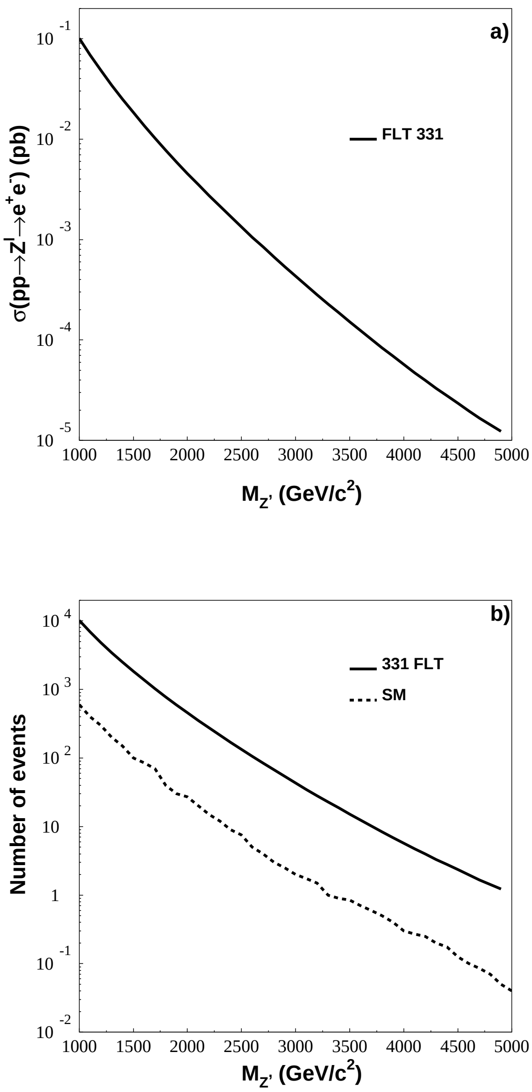

FIG. 2: The plot a.) shows the cross section as a function of $M_{Z'}$ in LHC. The plot b.) shows the number of events, where we plot the SM background.

For this study, we use the CalcHep package [9] in order to simulate $pp \to e^+e^-$ events with the above kinematical criteria. Using a non-relativistic Breit-Wigner function and the CTEQ6M PDFs [11], we perform a numerical calculation with the following parameters

$$\alpha^{-1} = 128.91, \quad S_W^2 = 0.223057, \quad \Gamma_{Z'} = 0.02 M_{Z'}, \qquad (10)$$

where the total width $\Gamma_{Z'} \approx 0.02 M_{Z'}$ is estimated from the analysis performed in the Ref. [7]. The plot in Fig. 1a shows the invariant mass distribution for the di-electron system as final state, where we have chosen a central value $M_{Z'} = 1500$ GeV, which is a typical lower bound for FLT models from low energy analysis at the Z-pole [10], and which lies into the expected detection range for LHC. The Fig. 1b shows the number of events for the expected luminosity of $100 fb^{-1}$. We also calculate the SM Drell-Yan spectrum in both plots with the same kinematical conditions, where we can see that the Z' signal exhibit a huge peak above the SM background with about 800 signal events.

On the other hand, we calculate the cross section for the same leptonic channel as a function of $M_{Z'}$, as shown by the plot in Fig. 2a. The Fig. 2b shows the number of events, where the SM background is found to be essentially negligible for all the selected range. For $M_{Z'} = 1$ TeV, we get a huge number of events, corresponding to 10000 signal events, while at the large mass limit $M_{Z'} = 5$ TeV, we find just 1 event per year.

5. CONCLUSIONS

In the framework of the FLT 331 model, we have analyzed the Z' production assuming the design criteria ATLAS detectors at LHC collider. For an integrated luminosity of $100 fb^{-1}$ in LHC and considering a central value of $M_{Z'} = 1500$ GeV, we find a narrow resonance with 800 signal events above the SM background. If the Z' mass increases, the number of events decreases from 10000 to 1 signal event in the $M_{Z'} = 1000 - 5000$ GeV range. It is important to note that the PPF model, corresponding to $\beta = -\sqrt{3}$ in Eq. 1, exhibit a typical lower bound $M_{Z'} = 4000$ GeV [10], which is near to the LHC discovery potential limit.

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