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# Exotic states in BSM physics: The 331 model, a case of study

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**Summary.** — We present the relevant phenomenology of the so-called 331 model. The gauge group of this model is $SU(3)_c \times SU(3)_L \times U(1)_X$, implying the presence of extra vector and scalar bosons as well as fermions. We also discuss some interesting theoretical aspects of the model, the most important being connected with the cancellation of anomalies.

## 1. – Introduction

The experimental discovery of a scalar resonance done in 2012 by the ATALS and CMS Collaboration at the LHC [1,2] fills the particle content of the Standard Model (SM) of particle physics. However the SM seems to be unable to sustain certain experimental evidences that do not fit in its current formulation. Moreover, there are theoretical problems that suggest that the SM should be thought of as a low-energy theory, embedded in a larger model at scales higher than the electroweak one. We briefly present some of these evidences, without any pretension of completeness.

In the SM neutrinos are massless particles. This is clearly in contrast with experimental evidences of neutrino oscillations [3, 4]. In fact the measured flavour oscillations imply that neutrinos have to be massive particles.

The experimental evidence of dark matter [5-7], known since more than four decades, is still an unanswered question. A possible explanation is the presence of a weakly interacting massive particle (WIMP). Such a particle is predicted in various extensions of the SM.

As a final remark, let us remind that there is no explanation in the SM for $n_{f_L} = n_{f_Q} = 3$. The electroweak precision measurements on the $Z$ resonance [8] are in agreement with $n_{f_L} = 3$ but the SM does not provide any arguments for $n_{f_L} = n_{f_Q}$. We will come back to this issue in the next section.

## 2. – The 331 Model

We consider an extension of the SM obtained starting from a larger gauge group. The gauge symmetry of the so-called 331 model is

$$SU(3)_c \times SU(3)_L \times U(1)_X, \tag{1}$$

where the $U(1)$ factor is not the SM hypercharge by itself. In fact $SU(3)_L$ has two diagonal generators, hence the electromagnetic charge operator is given by

$$\mathbb{Q} \equiv \mathbb{Y} + \mathbb{T}_3 = \beta^{em}\mathbb{T}_8 + \mathbb{X} + \mathbb{T}_3.$$

The generators of $SU(3)_L$ are usually identified with the Gell-Mann matrices of dimension three. The 331 model is actually a class of models, parametrized by the possible values of $\beta^{em}$. Although at this stage this is a free parameter, we will see that in order to fulfil some basic requirements, such as the quantization of the electromagnetic charge, $\beta^{em}$ can take only few values.

The enlarged gauge symmetry implies that we must extend the matter content of the model. Scalars and fermions are in fact arranged in triplets, being in the fundamental (or anti-fundamental) representation of $SU(3)$. In the quark sector we have

$$Q_1 = \begin{pmatrix} u \\ d \\ D \end{pmatrix}, \quad Q_2 = \begin{pmatrix} c \\ s \\ S \end{pmatrix}, \quad Q_{1,2} \in (\mathbf{3}, \mathbf{3}, X_{Q_{1,2}}), \tag{2}$$

$$Q_3 = \begin{pmatrix} b \\ t \\ T \end{pmatrix}, \quad Q_3 \in (\mathbf{3}, \bar{\mathbf{3}}, X_{Q_3}), \tag{3}$$

whereas the leptons are arranged as

$$L = \begin{pmatrix} l \\ \nu_l \\ E_l \end{pmatrix}, \quad L \in (\mathbf{1}, \bar{\mathbf{3}}, X_L), \quad l = e,\ \mu,\ \tau. \tag{4}$$

We have not written explicitly the $U(1)_X$ quantum number for the fermions. We notice that the first two families of quarks belong to the fundamental of $SU(3)_L$ whereas the third one belong to the anti-fundamental. In the lepton sector there is not such a difference. The three families of leptons belong to the same representation of $SU(3)_L$. We will explain the reason for this different treatment in a moment. Before that, let us remark that we have not written the right-handed fermions, which are of course present in the 331 model.

The asymmetry in the $SU(3)_L$ representation of quarks and leptons lies in the need for anomaly cancellation within the 331 model. In fig. 1 the loop diagram involved in the $(SU(3)_L)^3$ anomaly is shown schematically. The fermion lines correspond to quarks and leptons charged under $(SU(3)_L)^3$, precisely the ones in eqs. (2)–(3). This anomaly vanishes because of the equal number of fundamental and anti-fundamental

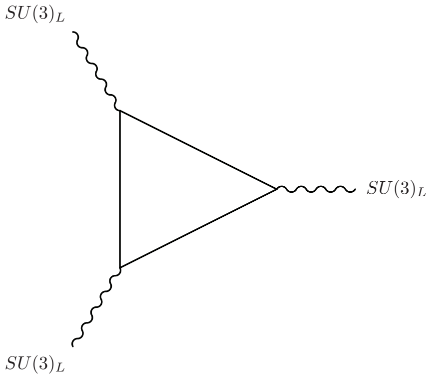


Fig. 1. – Schematic representation of the loop diagram involved in the $(SU(3)_L)^3$ anomaly.

representations, if one takes into account the colour multiplicity for the quarks. Anomaly cancellation in the 331 model then forces

$$n_{f_L} = n_{f_Q} = 3\kappa, \tag{5}$$

giving an explanation for the equal number of quark and lepton families. Anomaly cancellation in the 331 model happens among the three families of fermions, differently from the SM case.

The scalar sector consists of three triplets

$$\chi = \begin{pmatrix} \chi^A \\ \chi^B \\ \chi^0 \end{pmatrix} \in (1,3,X_\chi), \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{-B} \end{pmatrix} \in (1,3,X_\rho), \quad \eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta^{-A} \end{pmatrix} \in (1,3,X_\eta). \tag{6}$$

Here again we have left their $U(1)_X$ quantum numbers unspecified. The electromagnetic charges of the $A$- and $B$-states are $Q^A = \frac{1}{2} + \frac{\sqrt{3}}{2}\beta^{em}$, $Q^B = -\frac{1}{2} + \frac{\sqrt{3}}{2}\beta^{em}$. They depend of course on $\beta^{em}$ as the electric charge of the extra fermionic degrees of freedom. The neutral component of each triplet can take a vacuum expectation value (vev). In this way the gauge symmetry is spontaneously broken, in complete analogy with the electroweak symmetry breaking in the SM. The spontaneous symmetry breaking chain is

$$SU(3)_L \times U(1)_X \xrightarrow{v_\chi} SU(2)_L \times U(1)_Y \xrightarrow{v_\rho,\, v_\eta} U(1)_{em}. \tag{7}$$

Let us consider the effects of spontaneous symmetry breaking (SSB) on the gauge bosons of the 331 model. After the first breaking, when $\chi$ gets vev, three gauge bosons became massive. They are $Z'_\mu, Y^{\pm A}_\mu, V^{\pm B}_\mu$. The $Z'_\mu$ is a mixture of $X_\mu$ and $W^8_\mu$, whereas

$$Y^{\pm A}_\mu = \frac{1}{\sqrt{2}}(W^4_\mu \mp i\, W^5_\mu), \quad V^{\pm B}_\mu = \frac{1}{\sqrt{2}}(W^6_\mu \mp i\, W^7_\mu). \tag{8}$$

The mass of $Z'_\mu$ is given by [9]

$$M^2_{Z'} = \frac{g^2 v^2_\chi \cos\theta_W}{3(1-(1+(\beta^{em})^2\sin^2\theta_W))}(1+\cdots). \tag{9}$$

TABLE I. – *Electric charges of new particles for different choices of* $\beta^{em}$.

| particle | $Q(\beta^{em})$ | $\beta^{em}=-\frac{1}{\sqrt{3}}$ | $\beta^{em}=\frac{1}{\sqrt{3}}$ | $\beta^{em}=-\sqrt{3}$ | $\beta^{em}=\sqrt{3}$ |
|---|---|---|---|---|---|
| $D,S$ | $\frac{1}{6}-\frac{\sqrt{3}\beta^{em}}{2}$ | $\frac{2}{3}$ | $-\frac{1}{3}$ | $\frac{5}{3}$ | $-\frac{4}{3}$ |
| $T$ | $\frac{1}{6}+\frac{\sqrt{3}\beta^{em}}{2}$ | $-\frac{1}{3}$ | $\frac{2}{3}$ | $-\frac{4}{3}$ | $\frac{5}{3}$ |
| $E$ | $-\frac{1}{2}+\frac{\sqrt{3}\beta^{em}}{2}$ | $-1$ | $0$ | $-2$ | $1$ |
| $V$ | $-\frac{1}{2}+\frac{\sqrt{3}\beta^{em}}{2}$ | $-1$ | $0$ | $-2$ | $1$ |
| $Y$ | $\frac{1}{2}+\frac{\sqrt{3}\beta^{em}}{2}$ | $0$ | $1$ | $-1$ | $2$ |

From eq. (9) we obtain that, given the value of the Weinberg angle, $|\beta^{em}| \le \sqrt{3}$ if the $Z'_\mu$ mass has to be positive definite. Moreover this parameter enters the electromagnetic charge of the particles, which can be at most fractional. Hence we have $\beta^{em} = 0, \pm 1/\sqrt{3}, \pm 2/\sqrt{3}, \pm 3/\sqrt{3}$. In table I we give the electromagnetic charge for the extra fermions/gauge bosons in some interesting cases.

Recently a phenomenological analysis has been done for the case $\beta^{em} = \sqrt{3}$. The phenomenological analysis concerns the production of *dileptons* at the LHC [10]. This version of the model in fact has the almost unique feature to accommodate a vector boson of charge 2. Moreover, by inspection of table I, one recognizes that the extra leptonic degree of freedom can be thought of as the right-handed component of each charged lepton. Among the various versions of the 331 model, this is the scenario in which the amount of extra fermions can be minimized.

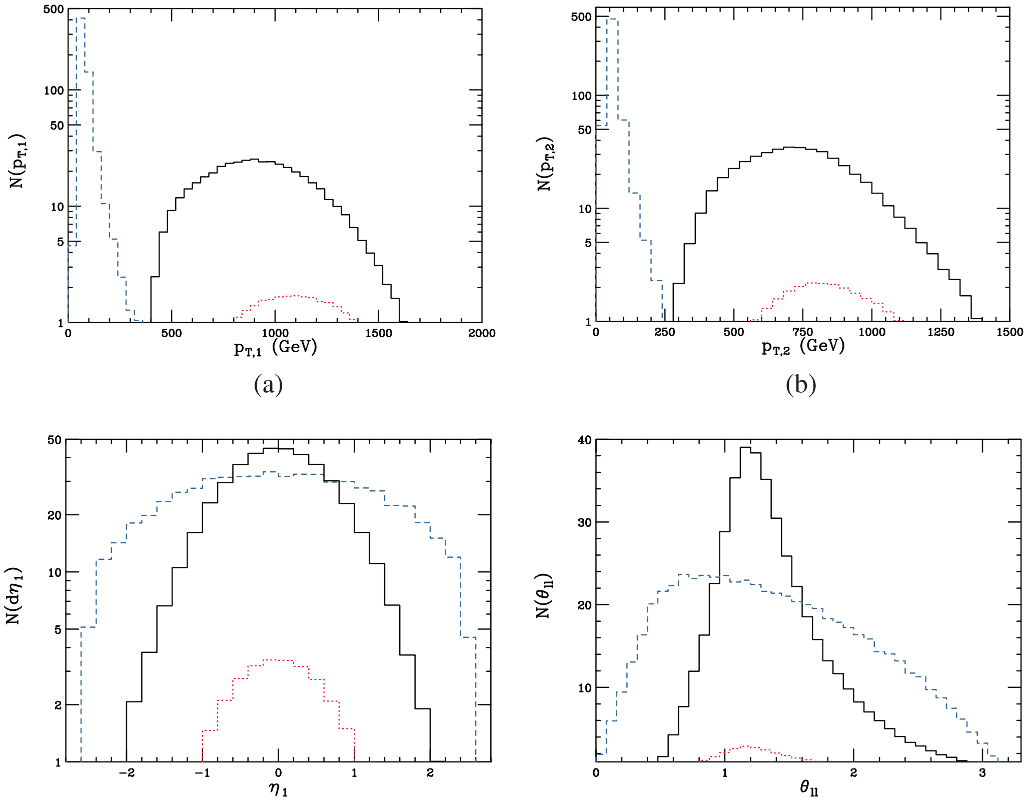
## 3. – Same-sign leptons phenomenology

Here we present the result of a phenomenological analysis of same-sign lepton pair production at the LHC [10]. In the SM this signature is absent and at the LHC the relevant background is given by $pp \to ZZ \to 2\ell^+ 2\ell^-$. The 331 model has an interesting scenario where the same-sign production of lepton pairs is allowed. In particular it can happen through the decay of a doubly charged vector $Y^{\pm\pm}$ or a doubly-charged scalar $H^{\pm\pm}$. We note that a scalar particle with charge two is predicted by various models of beyond-Standard-Model (BSM) physics. Conversely, a doubly charged vector boson is almost unique in BSM physics.

The phenomenological analysis presented in [10] considers the process

$$pp \to B^{++}B^{--} \to 2\ell^+ 2\ell^- \tag{10}$$

at the LHC. Here $B^{\pm\pm}$ stands for either the scalar or the vector boson with charge two. The mass of these particles has been taken to be $m_{Y^{\pm\pm}} \simeq m_{H^{\pm\pm}} \sim 870\ GeV$ and their branching fractions in leptons are $\mathrm{Br}(Y^{\pm\pm} \to \ell^\pm \ell^\pm) = \mathrm{Br}(H^{\pm\pm} \to \ell^\pm \ell^\pm) = 1/3$. The cross-section for the signal is $\sigma(pp \to YY \to 4\ell) \simeq 4.3$ fb and $\sigma(pp \to HH \to 4\ell) \simeq 0.3$ fb whereas the cross-section of the dominant background is $\sigma(pp \to ZZ \to 4\ell) \simeq 6.1$ fb, both at $\sqrt{s} = 13$ TeV. In fig. 2 we give the distribution of the transverse momentum of the hardest (a) and next-to-hardest lepton (b), the rapidity of the leading lepton (c) and polar angle between the same-sign pair (d). By inspection of the distributions and/or



(a) (b)

(c) (d)

Fig. 2. – Distribution of the $p_T$ of hardest (a) and next-to-hardest (b) lepton, $\eta$ of the leading lepton (c) and $\theta$ of the same-sign pair (d). The black solid line is the $Y^{\pm\pm}$, the red dotted line is the $H^{\pm\pm}$ and the blue dashed line is the $Z$ pair, respectively.

calculating the significances for, *e.g.*, 300 fb$^{-1}$ of integrated luminosity we conclude that the LHC will be sensitive to the spin-1 doubly charged state predicted by the 331 model.

## 4. – Conclusions

There are theoretical and phenomenological reasons to consider extensions of the SM. The search for physics BSM is usually driven by models that extend the field content or the gauge symmetry. The 331 models are a class of models that is able to predict the number of fermionic families by the anomaly cancellation. There are various versions, each of which has a different way to construct the SM hypercharge out of the generators of $SU(3)_L \times U(1)_X$. This makes the phenomenology of the 331 model very rich. This extension of the gauge symmetry can also be thought of as the remnant of a Grand-Unified Theory (GUT) at energies lower than the GUT scale. We have presented the results of a phenomenological analysis that explores the possibility to have doubly charged bosonic resonances, with signature not allowed by the SM.

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