Alternative 3-3-1 models and Collider constraints

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Outline

- The triangle anomalies must be canceled out only with a number of generations multiple of 3 (For example a 3-3-1 model of E_6 is not interesting in that sense)
- it must contain the standard model (SM).
- There is a lot of literature about 3-3-1 models. Which typically reduces to those models with nonexotic charges.
- By embedding this group in a larger one, it is possible to explain the charge quantization.

3-3-1 models

The so-called 3-3-1 models are based on the gauge group $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$. For the 3-3-1 models, the most general electric charge operator in the extended electroweak sector is

$$Q = T_{L3} + \beta T_{L8} + X\mathbb{1}, \qquad (1)$$

where $T_{La} = \lambda_a/2$, with $\lambda_a,\ a = 1, 2, \ldots, 8$ are the Gell-Mann matrices for $SU(3)_L$ normalized as $\mathrm{Tr}(\lambda_a\lambda_b) = 2\delta_{ab}$ and $\mathbb{1} = \mathrm{Diag}(1, 1, 1)$ is the diagonal 3×3 unit matrix.

In general, we have for any set of generators T^a of a symmetry $SU(N)$ with $N \leq 3$, a set of generators $-T^{a*}$, which satisfy the exact group algebra. This set of generators spawns the so-called conjugate representation of $SU(N)$.

$$\{T^a, T^b\} = if^{abc}T^c \longrightarrow \{-T^{a*}, -T^{b*}\} = if^{abc}(-T^{c*}) \tag{2}$$

We can obtain the charges of the SM doublets as a linear combination of the generators in the standard representation (i.e, T^a), or as the linear combination of the generators in the conjugated one (i.e, $-T^{a*}$). In each case the value of the X charge is different.

3-3-1 models

- For $\beta = 1/\sqrt{3}$, all the exotic particles have electrical charges like the SM.
- For $\beta = \sqrt{3}$, particles with exotic charges appear in the triplet third component.

$$3_L = \begin{pmatrix} 0 \\ -1 \\ -2 \end{pmatrix}, \quad 3_L^* = \begin{pmatrix} -1 \\ 0 \\ +1 \end{pmatrix} \tag{3}$$

$$3_Q = \begin{pmatrix} +2/3 \\ -1/3 \\ -4/3 \end{pmatrix}, \quad 3_L^* = \begin{pmatrix} -1/3 \\ +2/3 \\ +5/3 \end{pmatrix} \tag{4}$$

For $\beta = \sqrt{3}$ the electric charges of the triplet and the anti-triplet) are: $Q_{\text{QED}}(3) = \text{Diag}(1 + X, X, -1 + X)$ and $Q_{\text{QED}}(3^\star) = \text{Diag}(-1 + X, X, 1 + X)$, respectively.

3-3-1 lepton and quark generations.

To reproduce the SM we account for all the possible lepton S_{L_i} and quark S_{Q_i} families consistent with the SM, i.e.,

- Each family requires one quark doublet q_i and one lepton doublet ℓ_i.
- Three singlets under $SU(2)$ with charges $2/3$ u_i and d_i and e_i correspond to the right-hand components of the doublets of $SU(2)$.
- The $SU(2)$ singlets can correspond to $SU(3)$ singlets or the third component of a $S(3)$ triplet.

Lepton families S_{L_i}

- Lepton generation $S_{L1} = [(\nu_e^0, e^-, E_2^{--}) \oplus e^+ \oplus E_2^{++}]_L$ with quantum numbers $(1,3,-1); (1,1,1)$ and $(1,1,2)$ respectively.
- Set $S_{L2} = [(e^-, \nu_e^0, E_1^+) \oplus e^+ \oplus E_1^-]_L$ with quantum numbers $(1,3^*,0)$; $(1,1,1)$ and $(1,1,-1)$, respectively.
- Set $S_{L3} = [(e^-, \nu_e^0, e^+)]_L$ with quantum numbers $(1,3^*,0)$.

Quark families S_{Q_i}

For $\beta = \sqrt{3}$ the electric charges of a triplet (or anti-triplet) are: $Q_{\text{QED}}(3) = \text{Diag}(1 + X, X, -1 + X)$ and $Q_{\text{QED}}(3^\star) = \text{Diag}(-1 + X, X, 1 + X)$, respectively.

- Set $S_{Q1} = [(d, u, Q_2) \oplus u^c \oplus d^c \oplus Q_2^c]_L$ with quantum numbers $(3, 3^*, 2/3)$; $(3^*, 1, -2/3)$; $(3^*, 1, 1/3)$ and $(3^*, 1, -5/3)$, respectively.
- Set $S_{Q2} = [(u, d, Q_1) \oplus u^c \oplus d^c \oplus Q_1^c]_L$ with quantum numbers $(3, 3, -1/3)$; $(3^*, 1, -2/3)$; $(3^*, 1, 1/3)$ and $(3^*, 1, 4/3)$, respectively.

Exotic families and fermionic dark matter candidates

It is advantageous to cancel anomalies by introducing triplets and anti-triplets of exotic leptons, for example:

- First exotic lepton set, $S_{E1} = [(N_1^0, E_4^+, E_3^{++}) \oplus E_4^- \oplus E_3^{--}]_L$ with quantum numbers $(1, 3^*, 1)$; $(1, 1, -1)$ and $(1, 1, -2)$, respectively.
- Second exotic lepton set, $S_{E2} = [(E_5^+, N_2^0, E_6^-) \oplus E_5^- \oplus E_6^+]_L$ with quantum numbers $(1, 3, 0)$; $(1, 1, -1)$ and $(1, 1, 1)$, respectively.

In these triplets, it is possible to identify fermionic dark matter candidates.

Anomalies

Table 1 shows the contribution of the sets to each of the anomalies.

$$A = \mathrm{Tr}\left[T^a \left\{T^b, T^c\right\}\right] = 0. \tag{5}$$

Anomalías	S_{L1}	S_{L2}	S_{L3}	S_{Q1}	S_{Q2}	S_{E1}	S_{E2}
$[SU(3)_C]^2 \otimes U(1)_X$	0	0	0	0	0	0	0
$[SU(3)_L]^2 \otimes U(1)_X$	-1	0	0	2	-1	1	0
$[\mathrm{Grav}]^2 \otimes U(1)_X$	0	0	0	0	0	0	0
$[U(1)_X]^3$	6	0	0	-12	6	-6	0
$[SU(3)_L]^3$	1	-1	-1	-3	3	-1	1

Table: Anomalías para campos fermiónicos del modelo 331 con $\beta = \sqrt{3}$

New 3-3-1 models

i	Just lepton families S_{Lj}	one quark family S_{Qj}	two quark families S_{Qj}	three quark families S_{Qj}
	$S_{E2} + S_{L2}$ $S_{E1} + S_{L1}$ $S_{E2} + S_{L3}$	$S_{E2} + 2S_{L1} + S_{Q1}$ $S_{E1} + 2S_{L2} + S_{Q2}$ $S_{E1} + S_{L2} + S_{L3} + S_{Q2}$ $S_{E1} + 2S_{L3} + S_{Q2}$	$S_{L1} + S_{L2} + S_{Q1} + S_{Q2}$ $S_{L1} + S_{L3} + S_{Q1} + S_{Q2}$	$3S_{L1} + 2S_{Q1} + 1S_{Q2}$ $3S_{L2} + 1S_{Q1} + 2S_{Q2}$ $3S_{L3} + 1S_{Q1} + 2S_{Q2}$ $2S_{L2} + 1S_{L3} + 1S_{Q1} + 2S_{Q2}$ $1S_{L2} + 2S_{L3} + 1S_{Q1} + 2S_{Q2}$

Table: Anomaly free sets (AFS) for $\beta = \sqrt{3}$.

LHC Constraints

We consider the ATLAS search for high-mass dilepton resonances in the mass range of 250 GeV to 6 TeV in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV during Run 2 of the LHC with an integrated luminosity of 139 fb^{-1} [1]. This data was collected from searches of Z' bosons decaying dileptons. We obtain the mass lower limit from the intersection of the theoretical predictions with the upper limit on the cross-section at a 95% confidence level. We use the expressions given in Ref. [2, 3, 4] to calculate the theoretical

Upper limit on the cross-section at a 95% confidence level [1].

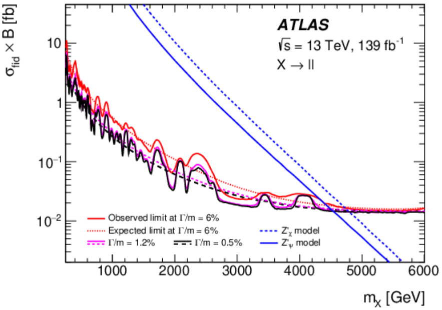

Figure: Mass lower limit from the intersection of the theoretical predictions with the upper limit on the cross-section at a 95% confidence level [1].

Particle content first generation	LHC-Lower limit in TeV
$S_{L3} + S_{Q1}$	7.3
$S_{L3} + S_{Q2}$	6.4

Table: The lepton families S_{L_1} and S_{L_2} are strongly coupled (For S_{L_1} and S_2 the lehf-handed doubled ℓ and the right-handed charged singled e have couplings larger than 1, respectively). Therefore only S_{L_3} is phenomenologically viable for the first family. Depending on the quark content, i.e., S_{Q_1} or S_{Q_2}, we have two different constraints.

Model	j	SM Lepton Embeddings	Universal —	2 + 1	— Quark Configuration	— LHC-Lower limit
$M3 = Q_3^{III}$(Minimal)	-	$[3S_{L3}^{\bar{\ell}+e'^+}]$	✓	×	$2S_{Q2}+S_{Q1}$	6.4 TeV
$M4 = Q_4^{III}$	-	$[2S_{L2}^{\bar{\ell}+e^+}+S_{L3}^{\bar{\ell}+e'^+}]$	×	✓	$2S_{Q2}+S_{Q1}$	6.4 TeV
$M6 = (Q_1^I + Q_1^{II})^j$	1	$[3S_{L1}^{\ell+e^+}]+S_{L2}+S_{E2}$	✓	×	$2S_{Q1}+S_{Q2}$	SC
	2	$[2S_{L1}^{\ell+e^+}+S_{L2}^{\bar{\ell}+e^+}]+S_{L1}+S_{E2}$	×	✓	$2S_{Q1}+S_{Q2}$	SC
$M17 = (Q_2^I + Q_3^I + Q_4^I)^j$	1	$[3S_{L2}^{\bar{\ell}+e^+}]+3S_{L3}+3S_{E1}$	✓	×	$3S_{Q2}$	SC
	2	$[3S_{L3}^{\bar{\ell}+e'^+}]+3S_{L2}+3S_{E1}$	✓	×	$3S_{Q2}$	6.4 TeV
	3	$[2S_{L2}^{\bar{\ell}+e^+}+S_{L3}^{\bar{\ell}+e'^+}]+S_{L2}+2S_{L3}+3S_{E1}$	×	✓	$3S_{Q2}$	6.4 TeV
	4	$[S_{L2}^{\bar{\ell}+e^+}+2S_{L3}^{\bar{\ell}+e'^+}]+2S_{L2}+S_{L3}+3S_{E1}$	×	✓	$3S_{Q2}$	6.4 TeV
$M10 = (Q_1^I + Q_2^{II})^j$	1	$[3S_{L1}^{\ell+e^+}]+S_{L3}+S_{E2}$	✓	×	$2S_{Q1}+S_{Q2}$	SC
	2	$[2S_{L1}^{\ell+e^+}+S_{L3}^{\bar{\ell}+e'^+}]+S_{L1}+S_{E2}$	×	✓	$2S_{Q1}+S_{Q2}$	7.3 TeV

Table: The lepton sets in square brackets (blue) contain the standard model fields. The superscripts correspond to the particle content of the SM, where ℓ ($\bar{\ell}$) stands for a left-handed lepton doublet embedded in a $SU(3)_L$ triplet (anti-triplet), and e'^+ (e^+) is the right-handed charged lepton embedded in a $SU(3)_L$ triplet (singlet). The check mark ✓ means that at least two (2+1) or three (universal) families have the same charges under the gauge symmetry. The cross × stands for the opposite. To avoid a strongly coupled model in the Lepton sector, it is necessary to embed the first Lepton family (electron and electron neutrino) in S_{L3}.

¿ Why could these models be attractive?

Even the Universal embeddings are capable of having clear signatures.

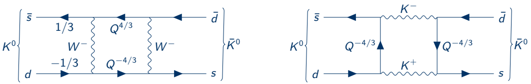

Figure: Exotic quark contribution to the $K^0 - \bar{K}^0$ mixing.

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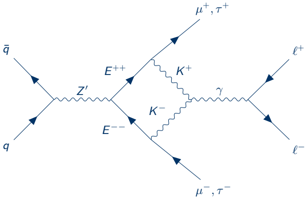

Figure: Doubly charged exotic lepton contribution to the process $q\bar{q} \to Z' \to E^{++}E^{--} \to \ell^+\ell^-\gamma \to \ell^+\ell^-\mu^+\mu^-(\tau^+\tau^-)$.

Conclusions

- Several $SU(3)_L$ generations have been proposed.
- We report the list of the minimal anomaly-free sets for 3-3-1 models with $\beta = \sqrt{3}$
- We have fully accounted for the possible 3-3-1 models with $\beta = \sqrt{3}$ and their corresponding LHC constraints.
- These models are suitable for studying flavor physics and strongly coupled extension models.

Frame Title

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- J. Erler, P. Langacker, S. Munir, and E. Rojas, "Z' Bosons at Colliders: a Bayesian Viewpoint," *JHEP*, vol. 11, p. 076, 2011.
- C. Salazar, R. H. Benavides, W. A. Ponce, and E. Rojas, "LHC Constraints on 3-3-1 Models," *JHEP*, vol. 07, p. 096, 2015.
- R. H. Benavides, L. Muñoz, W. A. Ponce, O. Rodríguez, and E. Rojas, "Electroweak couplings and LHC constraints on alternative Z' models in E_6," *Int. J. Mod. Phys. A*, vol. 33, no. 35, p. 1850206, 2018.