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San Juan de Pasto, 12 de diciembre de 2023

Señores:
Asamblea de profesores
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Por medio de la presente informo de las actividades desarrolladas durante mi comisión académica en el evento **8th ComHEP: Colombian Meeting on High Energy Physics**, que tuvo lugar en la Universidad del Tolima, en Ibagué (Colombia) del 4 al 07 de diciembre del 2023.

- Presenté la charla titulada: **Classification for Alternative 3-3-1 models with exotic electric charges.**
- Y participé de las actividades realizadas en esta conferencia, que incluyeron charlas y conferencias.

El resumen de la charla: We report the most general classification of 3-3-1 models with $\beta=\sqrt{3}$. We found several solutions where anomaly cancellation occurs among fermions of different families. These solutions are particularly interesting as they generate non-universal heavy neutral vector bosons. Non-universality in the SM fermion charges under an additional gauge group generates Charged Lepton Flavor Violation (CLFV) and Flavor Changing Neutral Currents~(FCNC); we discuss under what conditions the new models can evade constraints coming from these processes. In Addition, we also report LHC constraints.

Anexo: Certificado de participación y la charla expuesta.

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COMHEP
8th Colombian Meeting on High Physics
4 to 7 December 2023
Ibagué (Tolima), Colombia

This is to certify that

Yithsbey Giraldo Usuga

Participated as a speaker with the talk “**Classification for Alternative 3-3-1 models with exotic electric charges** ”

in the 8th Colombian Meeting on High Energy Physics,
from 4th to 7th December of 2023

Carlos Eduardo Vera
Universidad del Tolima Colombia
On behalf of the Organizing Committee

COMHEP

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Classification for Alternative 3-3-1 models with exotic electric charges

In collaboration with E. Suarez, W. A. Ponce, E. Rojas and R. H. Benavides

Yithsbey Giraldo

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December 6, 2023

Universidad de Nariño

8th ComHEP: Colombian Meeting on High Energy Physics

Alternative 3-3-1 models with exotic electric charges

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(Dated: November 30, 2023)

We report the most general classification of 3-3-1 models with $\beta = \sqrt{3}$. We found several solutions where anomaly cancellation occurs among fermions of different families. These solutions are particularly interesting as they generate non-universal heavy neutral vector bosons. Non-universality in the SM fermion charges under an additional gauge group generates Charged Lepton Flavor Violation (CLFV) and Flavor Changing Neutral Currents (FCNC); we discuss under what conditions the new models can evade constraints coming from these processes. In Addition, we also report LHC constraints.

I. INTRODUCTION

Models with exotic fermions based on the gauge group symmetry $SU(3) \otimes SU(3) \otimes U(1)$ (hereafter 3-3-1 models for short) have been proposed since the early 1970s [1–11]; however, many of these models lacked important properties of what is known nowadays as 3-3-1 models. For a model to be interesting from a modern perspective [12], it must be chiral, the triangle anomalies must be canceled out only with a number of generations multiple of 3, and most importantly, it must contain the Standard Model (SM).

In the 1990s, non-universal models without exotic lep-

β does not exist in the literature, and therefore a work in this line is necessary. It is important to notice that there are solutions for arbitrary β [49]; however, this solution does not account for all the possible models for a given β. As we will see, the parameter β cannot be arbitrarily large, from the matching conditions $|\beta| \lesssim \cot\theta_W \sim 1.8$. This condition constitutes a very important restriction regarding the possible realizations of the 3-3-1 symmetry at low energies as it limits the number of possible non-trivial cases to a countable set.

In section II, we review the basics of the 3-3-1 models. In section III, we propose sets of fermions corresponding to families of quarks and leptons with the left-handed

Overview

Abstract

- We present a comprehensive classification of 3-3-1 models with $\beta = \sqrt{3}$.
- We have identified multiple solutions where anomaly cancellation takes place across fermions from distinct families.
- These solutions are particularly intriguing as they give rise to non-universal heavy neutral vector bosons.
- Non-universality in the charges of Standard Model fermions under an additional gauge group leads to Charged Lepton Flavor Violation (CLFV) and Flavor Changing Neutral Currents (FCNC); we explore the conditions under which the new models can circumvent constraints arising from these processes.
- We provide an overview of constraints from the LHC.

Introduction

- Models with exotic fermions based on the gauge group symmetry $SU(3) \otimes SU(3) \otimes U(1)$ (hereafter 3-3-1 models for short) have been proposed since the early 1970s. These models must be chiral, the triangle anomalies must be canceled out only with a number of generations multiple of 3, and most importantly, it must contain the Standard Model (SM).
- In the 1990s, non-universal models without exotic leptons gained popularity as they were very convenient in addressing flavor problems
- Pleitez and Frampton proposed the non-universal 3-3-1 models as examples of electroweak extensions with lepton number violation, where the number of families is determined by anomaly cancellation. It has exotic electric charges in the quark sector and corresponds to what is known in the literature as $\beta = \sqrt{3}$. The parameter β cannot be arbitrarily large, from the matching conditions $|\beta| \lessapprox \cot\theta_W \sim 1.8$.

3-3-1 Models

The most complete electric charge operator for this electroweak sector is

$$Q = \alpha\, T_{L3} + \beta\, T_{L8} + X\mathbf{1}, \tag{1}$$

assuming $\alpha = 1$, the $SU(2)_L$ isospin group of the SM is fully covered in $SU(3)_L$.
The parameter $\beta = \frac{2b}{\sqrt{3}}$ is a free parameter that defines the model (β is proportional to b present in the electric charge of the exotic vector boson K_μ). The X values are determined through anomaly cancellation. The 8 gauge fields A^a_μ of $SU(3)_L$ can be expressed as

$$\sum_a \lambda_a A^a_\mu = \sqrt{2}\begin{pmatrix} D^0_{1\mu} & W^+_\mu & K^{(b+1/2)}_\mu \\ W^-_\mu & D^0_{2\mu} & K^{(b-1/2)}_\mu \\ K^{-(b+1/2)}_\mu & K^{-(b-1/2)}_\mu & D^0_{3\mu} \end{pmatrix}, \tag{2}$$

$b = 3/2$ (i.e., $\beta = \sqrt{3}$).

3-3-1 Models

- 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 $(1, 3^*, 0)$.
- Set $S_{Q1} = [(d, u, Q_1^{5/3}) \oplus u^c \oplus d^c \oplus Q_1^c]_L$ with quantum numbers $(3, 3^*, 2/3)$; $(3^*, 1, -2/3)$; $(3^*, 1, 1/3)$ and $(3^*, 1, -5/3)$, respectively.
- Set $S_{Q2} = [(u, d, Q_2^{-4/3}) \oplus u^c \oplus d^c \oplus Q_2^c]_L$ with quantum numbers $(3, 3, -1/3)$; $(3^*, 1, -2/3)$; $(3^*, 1, 1/3)$ and $(3^*, 1, 4/3)$, respectively.
- Triplets and anti-triplets of exotic leptons; for example, $S_{E1} = [(N_1^0, E_4^+, E_3^{++}) \oplus E_4^- \oplus E_3^{--}]_L$ with quantum numbers $(1, 3^*, 1)$; $(1, 1, -1)$ and $(1, 1, -2)$, respectively.
- $S_{E2} = [(E_5^+, N_2^0, E_6^-) \oplus E_5^- \oplus E_6^+]_L$ with quantum numbers $(1, 3, 0)$; $(1, 1, -1)$ and $(1, 1, 1)$, respectively.

Irreducible anomaly free sets

Contribution to the anomalies for each family of quarks S_{Q_i}, leptons S_{L_i} and exotics S_{E_i}, for 3-3-1 models with $\beta = \sqrt{3}$.

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

AFSs for $\beta = \sqrt{3}$. We have classified the AFS according to the content of quark families, i.e., Q_i^I, Q_i^{II}, and Q_i^{III}. Combinations of these sets with three SM quark and three SM lepton families can be considered as 3-3-1 models.

i	Vector-like lepton set (L_i)	One quark set (Q_i^I)	Two quarks set (Q_i^{II})	Three quarks set (Q_i^{III})
1	$S_{E2} + S_{L2}$	$S_{E2} + 2S_{L1} + S_{Q1}$	$S_{L1} + S_{L2} + S_{Q1} + S_{Q2}$	$3S_{L1} + 2S_{Q1} + S_{Q2}$
2	$S_{E1} + S_{L1}$	$S_{E1} + 2S_{L2} + S_{Q2}$	$S_{L1} + S_{L3} + S_{Q1} + S_{Q2}$	$3S_{L2} + S_{Q1} + 2S_{Q2}$
3	$S_{E2} + S_{L3}$	$S_{E1} + S_{L2} + S_{L3} + S_{Q2}$		$3S_{L3} + S_{Q1} + 2S_{Q2}$
4		$S_{E1} + 2S_{L3} + S_{Q2}$		$2S_{L2} + S_{L3} + S_{Q1} + 2S_{Q2}$
5				$S_{L2} + 2S_{L3} + S_{Q1} + 2S_{Q2}$

Collider 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 X: Alternative embeddings of the SM fields for some of the models in Table VIII. 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. LHC constraints are obtained from Table IX for embeddings in which we can choose the same Z' charges for the first two families, otherwise, we leave the space blank. *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}. This feature will be helpful to distinguish between the different embeddings. The embedding also defines the content of exotic particles in each case.*

Conclusions

1. Since that for 3-3-1 models, the absolute value of the parameter β must be less than $\beta \lessapprox \cot\theta_W = 1.8$ (for $\sin^2\theta_W = 0.231$ in the $\overline{\text{MS}}$ renormalization scheme at the Z-pole energy scale), and the values of β are further limited by the requirement that the vector boson charges be integers, the possible values of this parameter are reduced to a few cases.
2. We have constructed three sets of lepton families, S_{Li}, two quark families, S_{Qi}, and two exotic lepton families S_{Ei}, and we calculated their contribution to anomalies. In our analysis, we obtained 14 irreducible AFSs, from which we built 33 non-trivial 3-3-1 models (without considering the different embeddings) with at least three quark and three lepton families for each case. Each of these embeddings constitutes a phenomenologically distinguishable model; however, we limited our analysis of the possible embeddings to a few cases.
3. In the same way, from our analysis of the 3-3-1 models with $\beta = \sqrt{3}$ we report the couplings of the SM fields to the Z' boson for all the possible quark and lepton families and the corresponding lower limits on the Z' mass.
4. We also discuss the conditions under which the reported models avoid FCNC and CLFV. We also observed that strongly coupled models appear naturally and require a high value for the Z' mass. They can be helpful in specific phenomenological approaches based on models with strong dynamics.

THANK YOU!