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Colored scalars as flavor messengers in grand unified theories

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Summary. — We critically review the proton decay due to the scalar leptoquark exchanges within $SU(5)$ and flipped $SU(5)$ frameworks to address the issue of the model dependence of the relevant tree level operators. We quantify if, and when, it is necessary to have the leptoquark mass close to a grand unification scale. We summarize novel results regarding a possibility to have a collider accessible leptoquark without a rapid proton decay. The relevant state could be observed indirectly through its influence on physical processes such as the forward-backward asymmetry in $t\bar{t}$ production due to an antisymmetric set of couplings to a pair of up-quarks. The same leptoquark could affect the muon anomalous magnetic moment through the interaction of a lepton-quark nature. We accordingly investigate whether both sets of couplings can be simultaneously sizable without any conflict with matter stability.

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1. – Introduction

Scalar leptoquarks represent theoretically well-motivated source of new physics. Simply put, the leptoquark states take a quark into a lepton and vice versa. They are thus ubiquitous in any framework that unifies elementary fermions of the Standard Model (SM). We accordingly study these states in two different unification frameworks that correspond to the $SU(5)$ [1] and the flipped $SU(5)$ [2-4], *i.e.*, $SU(5) \times U(1)$, embeddings of the matter fields. These two scenarios are general enough to cover other possible (non)unifying schemes. Our aim is to present an excerpt from a comprehensive classification of scalar leptoquarks that simultaneously violate baryon (B) and lepton (L) numbers where a role these have in proton decay processes is addressed [5].

The leptoquark states that simultaneously violate B and L tend to mediate proton decay at tree level and are therefore taken to be very massive. However, it is possible to have a viable $SU(5)$ setup [6] with a very light leptoquark [7] that is in accord with the experimental limits on proton stability. The color triplet weak singlet scalar in

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question could then contribute to $t\bar{t}$ production [8] and explain the observed increase of the forward-backward asymmetry [9,10]. It could also have an impact on the muon anomalous magnetic moment [11] that could reconcile experimental [12] and theoretical results [13]. It might, however, (re)generate proton decay through the higher-order loop diagrams that yield an effective $d = 6$ set of operators and a class of tree-level $d = 9$ operators. A question then is whether one can simultaneously address the $t\bar{t}$ asymmetry and the muon anomalous magnetic moment by using the very same leptoquark [5].

This contribution is organized as follows. In sects. **2** and **3** we list all scalar leptoquarks associated with proton decay in $SU(5)$ and flipped $SU(5)$ and give examples of the Yukawa couplings to the SM fermions for leptoquarks from one representation. In sect. **4** we introduce the effective dimension-six operators for proton decay and calculate associated effective coefficients for certain leptoquark states. There we also present current experimental lower bounds on the color triplet leptoquark mass within phenomenologically realistic $SU(5)$ and flipped $SU(5)$ scenarios. In sect. **5** we study leptoquarks that do not contribute to proton decay at leading order. We conclude in sect. **6**.

2. – Leptoquarks in $SU(5)$

The scalars that couple to matter at tree-level in $SU(5)$ reside in 5-, 10-, 15-, 45- and 50-dimensional representations because the SM matter fields comprise $\mathbf{10}_i$ and $\overline{\mathbf{5}}_j$, where $i, j = 1, 2, 3$ represent family indices. Namely, $\mathbf{10}_i = (\mathbf{1}, \mathbf{1}, 1)_i \oplus (\overline{\mathbf{3}}, \mathbf{1}, -2/3)_i \oplus (\mathbf{3}, \mathbf{2}, 1/6)_i = (e^C_i, u^C_i, Q_i)$ and $\overline{\mathbf{5}}_j = (\mathbf{1}, \mathbf{2}, -1/2)_j \oplus (\overline{\mathbf{3}}, \mathbf{1}, 1/3)_j = (L_j, d^C_j)$, where $Q_i = (u_i \quad d_i)^T$ and $L_j = (\nu_j \quad e_j)^T$ [1]. Possible contractions of the matter field representations hence read $\mathbf{10} \otimes \mathbf{10} = \overline{\mathbf{5}} \oplus \overline{\mathbf{45}} \oplus \overline{\mathbf{50}}$, $\mathbf{10} \otimes \overline{\mathbf{5}} = \mathbf{5} \oplus \mathbf{45}$ and $\overline{\mathbf{5}} \otimes \overline{\mathbf{5}} = \overline{\mathbf{10}} \oplus \overline{\mathbf{15}}$.

The scalar leptoquark states that violate both B and L are $(\mathbf{3}, \mathbf{1}, -1/3)$, $(\mathbf{3}, \mathbf{3}, -1/3)$ and $(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$, if one *assumes* neutrinos to be Majorana particles. These states reside in **5**, **45** and **50**. However, if one allows for the possibility that neutrinos are Dirac particles there is another leptoquark—$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$—that is found in **10** of $SU(5)$ that violates both B and L and could thus also destabilize proton. Altogether, there are eighteen (fifteen) scalar leptoquarks that could mediate proton decay in case neutrinos are Dirac (Majorana) particles. Note that contributions to the up-quark, down-quark and charged lepton masses can come from both **5** and **45** whereas Majorana (Dirac) masses for neutrinos can be generated through **15** (**5**). Table I summarizes couplings to the matter of relevant states that reside in 45-dimensional representations. The couplings of the color triplets in 50-, 10- and 5-dimensional representations are spelled out in ref. [5].

Note that the $(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$ state always couples to the up-quark pair in an antisymmetric manner. Hence the absence of the tree-level proton decay. Moreover, if the Yukawa matrices are symmetric the $(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$ state would not destabilize matter whatsoever.

3. – Leptoquarks in flipped $SU(5)$

Another possibility to unify the SM matter into an $SU(5)$-based framework leads to the so-called flipped $SU(5)$ scenario [2-4]. The generator of electric charge in flipped $SU(5)$ is given as a linear combination of a $U(1)$ generator that resides in $SU(5)$ and an extra $U(1)$ generator as if both of these originate from an $SO(10) \to SU(5) \times U(1)$ decomposition. This guarantees anomaly cancelation at the price of introducing one extra state per family, *i.e.*, the right-handed neutrino ν^C. The transition between the $SU(5)$ and flipped $SU(5)$ embeddings is provided by the following set of transformations: $d^C \leftrightarrow u^C$, $e^C \leftrightarrow \nu^C$, $u \leftrightarrow d$ and $\nu \leftrightarrow e$.

TABLE I. – *Yukawa couplings of B and L violating scalars in* 45*-dimensional representation of* $SU(5)$*.* $a, b, c(i, j) = 1, 2, 3$ *are color (flavor) indices.* Y^{10}_{ij} *and* $Y^{\overline{5}}_{ij}$ *are Yukawa matrix elements.*

$SU(5)$	$Y^{10}_{ij}\mathbf{10}_i\mathbf{10}_j\mathbf{45}$	$Y^{\overline{5}}_{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\mathbf{45}^*$
$(\mathbf{3}, \mathbf{1}, -1/3)$ $\equiv$ Δ	$2^{1/2}[Y^{10}_{ij} - Y^{10}_{ji}]e^{C\,T}_i C u^C_{a\,j}\Delta_a$	$2^{-1}Y^{\overline{5}}_{ij}\epsilon_{abc}u^{C\,T}_{a\,i}Cd^C_{b\,j}\Delta^*_c$ $-2^{-1}Y^{\overline{5}}_{ij}u^T_{a\,i}Ce_j\Delta^*_a$ $2^{-1}Y^{\overline{5}}_{ij}d^T_{a\,i}C\nu_j\Delta^*_a$
$(\mathbf{3}, \mathbf{3}, -1/3)$ $\equiv$ $(\Delta^1, \Delta^2, \Delta^3)$	$2^{1/2}\epsilon_{abc}[Y^{10}_{ij} - Y^{10}_{ji}]d^T_{a\,i}Cd_{b\,j}\Delta^1_c$ $-2\epsilon_{abc}[Y^{10}_{ij} - Y^{10}_{ji}]d^T_{a\,i}Cu_{b\,j}\Delta^2_c$ $-2^{1/2}\epsilon_{abc}[Y^{10}_{ij} - Y^{10}_{ji}]u^T_{a\,i}Cu_{b\,j}\Delta^3_c$	$Y^{\overline{5}}_{ij}u^T_{a\,i}C\nu_j\Delta^{1*}_a$ $2^{-1/2}Y^{\overline{5}}_{ij}u^T_{a\,i}Ce_j\Delta^{2*}_a$ $2^{-1/2}Y^{\overline{5}}_{ij}d^T_{a\,i}C\nu_j\Delta^{2*}_a$ $-Y^{\overline{5}}_{ij}d^T_{a\,i}Ce_j\Delta^{3*}_a$
$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$ $\equiv$ Δ	$2^{1/2}[Y^{10}_{ij} - Y^{10}_{ji}]\epsilon_{abc}u^{C\,T}_{i\,a}Cu^C_{b\,j}\Delta_c$	$-Y^{\overline{5}}_{ij}e^{C\,T}_i Cd^C_{a\,j}\Delta^*_a$

The matter in flipped $SU(5)$ comprises $\mathbf{10}^{+1}_i$, $\overline{\mathbf{5}}^{-3}_i$ and $\mathbf{1}^{+5}_i$, where the superscripts correspond to the extra $U(1)$ charge. The SM hypercharge Y is defined through $Y = (Y(U(1)) - Y(U(1)_{SU(5)}))/5$, where $Y(U(1))$ and $Y(U(1)_{SU(5)})$ represent the quantum numbers of the extra $U(1)$ and the $U(1)$ in $SU(5)(\rightarrow SU(3)\times SU(2)\times U(1))$, respectively.

The scalar sector that can couple to matter directly is made out of $\mathbf{50}^{-2}$, $\mathbf{45}^{-2}$, $\mathbf{15}^{+6}$, $\mathbf{10}^{+6}$, $\mathbf{5}^{-2}$ and $\mathbf{1}^{-10}$. Representations that can generate contributions to the charged fermion masses and Dirac neutrino masses are $\mathbf{45}^{-2}$ and $\mathbf{5}^{-2}$, whereas Majorana mass for neutrinos can originate from interactions with $\mathbf{15}^{+6}$. Leptoquarks that violate B and L reside in $\mathbf{50}^{-2}$, $\mathbf{45}^{-2}$, $\mathbf{10}^{+6}$ and $\mathbf{5}^{-2}$. The relevant couplings to matter for $\mathbf{45}^{-2}$ are given in table II. All other color triplet couplings can be found in ref. [5].

4. – Proton decay

The dimension-six operators due to scalar exchange that violate B and L are

$$O_H(d_\alpha, e_\beta) = a(d_\alpha, e_\beta)\ u^T\ L\ C^{-1}\ d_\alpha\ u^T\ L\ C^{-1}e_\beta, \tag{1}$$

$$O_H(d_\alpha, e^C_\beta) = a(d_\alpha, e^C_\beta)\ u^T\ L\ C^{-1}\ d_\alpha\ e^{C\dagger}_\beta\ L\ C^{-1}u^{C*}, \tag{2}$$

$$O_H(d^C_\alpha, e_\beta) = a(d^C_\alpha, e_\beta)\ d^{C\dagger}_\alpha\ L\ C^{-1}\ u^{C*}\ u^T\ L\ C^{-1}e_\beta, \tag{3}$$

$$O_H(d^C_\alpha, e^C_\beta) = a(d^C_\alpha, e^C_\beta)\ d^{C\dagger}_\alpha\ L\ C^{-1}\ u^{C*}\ e^{C\dagger}_\beta\ L\ C^{-1}u^{C*}, \tag{4}$$

$$O_H(d_\alpha, d_\beta, \nu_i) = a(d_\alpha, d_\beta, \nu_i)\ u^T\ L\ C^{-1}\ d_\alpha\ d^T_\beta\ L\ C^{-1}\ \nu_i, \tag{5}$$

$$O_H(d_\alpha, d^C_\beta, \nu_i) = a(d_\alpha, d^C_\beta, \nu_i)\ d^{C\dagger}_\beta\ L\ C^{-1}\ u^{C*}\ d^T_\alpha\ L\ C^{-1}\ \nu_i, \tag{6}$$

$$O_H(d_\alpha, d^C_\beta, \nu^C_i) = a(d_\alpha, d^C_\beta, \nu^C_i)\ u^T\ L\ C^{-1}\ d_\alpha\ \nu^{C\dagger}_i\ L\ C^{-1}\ d^{C*}_\beta, \tag{7}$$

$$O_H(d^C_\alpha, d^C_\beta, \nu^C_i) = a(d^C_\alpha, d^C_\beta, \nu^C_i)\ d^{C\dagger}_\beta\ L\ C^{-1}\ u^{C*}\ \nu^{C\dagger}_i\ L\ C^{-1}\ d^{C*}_\alpha. \tag{8}$$

TABLE II. – *Yukawa couplings of B- and L-violating scalars in 45-dimensional representation of flipped $SU(5)$. $a, b, c(i, j) = 1, 2, 3$ are color (flavor) indices. Y^{10} and $Y^{\overline{5}}$ are Yukawa matrices.*

$SU(5) \times U(1)$	$Y^{10}_{ij}\mathbf{10}^{+1}_i\mathbf{10}^{+1}_j\mathbf{45}^{-2}$	$Y^{\overline{5}}_{ij}\mathbf{10}_i\overline{\mathbf{5}}^{-3}_j\mathbf{45}^{*\,+2}$
$(\mathbf{3}, \mathbf{1}, -1/3)^{-2}$		$2^{-1}Y^{\overline{5}}_{ij}\epsilon_{abc}d^{C\,T}_{a\,i}Cu^C_{b\,j}\Delta^*_c$
$\equiv$	$2^{1/2}[Y^{10}_{ij} - Y^{10}_{ji}]\nu^{C\,T}_i Cd^C_{a\,j}\Delta_a$	$-2^{-1}Y^{\overline{5}}_{ij}d^T_{a\,i}C\nu_j\Delta^*_a$
Δ		$2^{-1}Y^{\overline{5}}_{ij}u^T_{a\,i}Ce_j\Delta^*_a$
	$2^{1/2}\epsilon_{abc}[Y^{10}_{ij} - Y^{10}_{ji}]u^T_{a\,i}Cu_{b\,j}\Delta^3_c$	$Y^{\overline{5}}_{ij}d^T_{a\,i}Ce_j\Delta^{3*}_a$
$(\mathbf{3}, \mathbf{3}, -1/3)^{-2}$		$2^{-1/2}Y^{\overline{5}}_{ij}d^T_{a\,i}C\nu_j\Delta^{2*}_a$
$\equiv$	$-2\epsilon_{abc}[Y^{10}_{ij} - Y^{10}_{ji}]u^T_{a\,i}Cd_{b\,j}\Delta^2_c$	$2^{-1/2}Y^{\overline{5}}_{ij}u^T_{a\,i}Ce_j\Delta^{2*}_a$
$(\Delta^1, \Delta^2, \Delta^3)$	$-2^{1/2}\epsilon_{abc}[Y^{10}_{ij} - Y^{10}_{ji}]d^T_{a\,i}Cd_{b\,j}\Delta^1_c$	$-Y^{\overline{5}}_{ij}u^T_{a\,i}C\nu_j\Delta^{1*}_a$
$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)^{-2}$		
$\equiv$	$2^{1/2}[Y^{10}_{ij} - Y^{10}_{ji}]\epsilon_{abc}d^{C\,T}_{i\,a}Cd^C_{b\,j}\Delta_c$	$-Y^{\overline{5}}_{ij}\nu^{C\,T}_i Cu^C_{a\,j}\Delta^*_a$
Δ		

Here, $i(= 1, 2, 3)$ and $\alpha, \beta(= 1, 2)$ are generation indices, where all operators that involve a neutrino are bound to have $\alpha + \beta < 4$ due to kinematical constraints. $L(= (1 - \gamma_5)/2)$ is the left projection operator. The $SU(3)$ color indices are not shown due to a common $\epsilon_{abc}q_a q_b q_c$ contraction. This notation has already been introduced in ref. [14].

These operators allow us to extract relevant coefficients due to a particular leptoquark exchange [14]. Our convention for the charged fermion field redefinitions that yield the mass matrices in physical basis reads: $U^T_C M_U U = M^{\rm diag}_U$, $D^T_C M_D D = M^{\rm diag}_D$ and $E^T_C M_E E = M^{\rm diag}_E$. We introduce $U^\dagger D \equiv V_{UD} = K_1 V_{CKM} K_2$, where K_1 (K_2) is a diagonal matrix containing three (two) phases. In the neutrino sector we have $N^T_C M_N N = M^{\rm diag}_N$ ($N^T M_N N = M^{\rm diag}_N$) with $E^\dagger N \equiv V_{EN} = K_3 V_{PMNS} K_4$ ($V_{EN} = K_3 V_{PMNS}$) in the Dirac (Majorana) neutrino case. K_3 (K_4) is a diagonal matrix containing three (two) phases. V_{CKM} (V_{PMNS}) is the Cabibbo-Kobayashi-Maskawa (Pontecorvo-Maki-Nakagawa-Sakata) mixing matrix.

For example, the relevant coefficients for $\Delta \equiv (\mathbf{3}, \mathbf{1}, -1/3)$ from $\mathbf{45}$ are

$$a(d^C_\alpha, e_\beta) = \frac{1}{4m^2_\Delta}\,(D^\dagger_C Y^{\overline{5}\,\dagger} U^*_C)_{\alpha 1}\,(U^T Y^{\overline{5}} E)_{1\beta}, \tag{9}$$

$$a(d^C_\alpha, e^C_\beta) = \frac{1}{\sqrt{2}m^2_\Delta}\,(D^\dagger_C Y^{\overline{5}\,\dagger} U^*_C)_{\alpha 1}\,(E^\dagger_C (Y^{10} - Y^{10\,T})^\dagger U^*_C)_{\beta 1}, \tag{10}$$

$$a(d_\alpha, d^C_\beta, \nu_i) = \frac{1}{4m^2_\Delta}\,(D^\dagger_C Y^{\overline{5}\,\dagger} U^*_C)_{\beta 1}\,(D^T Y^{\overline{5}} N)_{\alpha i}. \tag{11}$$

TABLE III. – *Experimental bounds on selected partial proton decay lifetimes at* 90% *CL.*

Process	τ_p (10^{33} years)
$p \to \pi^0 e^+$	13.0 [15]
$p \to \pi^0 \mu^+$	11.0 [15]
$p \to K^0 e^+$	1.0 [16]
$p \to K^0 \mu^+$	1.3 [16]
$p \to \eta e^+$	4.2 [17]
$p \to \eta \mu^+$	1.3 [17]
$p \to \pi^+ \bar{\nu}$	0.025 [18]
$p \to K^+ \bar{\nu}$	4.0 [15]

The relevant coefficients for $\Delta \equiv (\mathbf{3}, \mathbf{1}, -1/3)^{-2}$ from $\mathbf{45}^{-2}$ in flipped $SU(5)$ are

$$a(d^C_\alpha, e_\beta) = \frac{1}{4m^2_\Delta}\,(D^\dagger_C Y^{\overline{5}\,*} U^*_C)_{\alpha 1}\,(U^T Y^{\overline{5}} E)_{1\beta}, \tag{12}$$

$$a(d_\alpha, d^C_\beta, \nu_i) = -\frac{1}{4m^2_\Delta}\,(D^\dagger_C Y^{\overline{5}\,*} U^*_C)_{\beta 1}\,(D^T Y^{\overline{5}} N)_{\alpha i}, \tag{13}$$

$$a(d^C_\alpha, d^C_\beta, \nu^C_i) = \frac{1}{\sqrt{2}m^2_\Delta}(D^*_C Y^{\overline{5}\,*} U^*_C)_{\beta 1}\,(N^\dagger_C (Y^{10} - Y^{10\,T})^\dagger D^*_C)_{i\alpha}. \tag{14}$$

The current experimental bounds on the partial proton lifetimes these operators contribute to are given in table III. We account for all these decay modes in our analysis.

4·1. *Leading-order contributions in* $SU(5)$. – Let us present predictions of the simplest of all possible renormalizable models based on the $SU(5)$ gauge symmetry. We demand that both **5** and **45** of Higgs contribute to the down-quark and charged lepton masses [19] to generate phenomenologically viable masses and mixing parameters. We take all mass matrices to be symmetric, *i.e.*, $M_{U,D,E} = M^T_{U,D,E}$. Note that the symmetric mass matrix assumption eliminates contributions to proton decay of all other color triplets besides the $(\mathbf{3}, \mathbf{1}, -1/3)$ from 5- and 45-dimensional representations.

For example, to find widths for the charged anti-leptons in the final state when the triplet state from 5-dimensional representation dominates we need to determine $a(d_\alpha, e_\beta)$, $a(d_\alpha, e^C_\beta)$, $a(d^C_\alpha, e_\beta)$ and $a(d^C_\alpha, e^C_\beta)$. If the Yukawa couplings are symmetric the relevant input for these coefficients reads

$$(U^T (Y^{10} + Y^{10\,T}) D)_{1\alpha} = -\frac{1}{\sqrt{2}v_5}\,(M^{\rm diag}_U V_{UD})_{1\alpha}, \tag{15}$$

$$(U^T Y^{\overline{5}} E)_{1\beta} = -\frac{1}{2v_5}\,(3V^*_{UD} M^{\rm diag}_D V^\dagger_{UD} U^*_2 + U_2 M^{\rm diag}_E)_{1\beta}, \tag{16}$$

$$(D^\dagger Y^{\overline{5}\,\dagger} U^*)_{\alpha 1} = -\frac{1}{2v_5}\,(3M^{\rm diag}_D V^T_{UD} + V^\dagger_{UD} U^*_2 M^{\rm diag}_E U^\dagger_2)_{\alpha 1}, \tag{17}$$

$$(E^\dagger (Y^{10} + Y^{10\,T})^\dagger U^*)_{\beta 1} = -\frac{1}{\sqrt{2}v_5}\,(U^T_2 M^{\rm diag}_U)_{\beta 1}, \tag{18}$$

where $U_2 = U^T E^*$ and v_5 represents a vacuum expectation value (VEV) of 5-dimensional representation. Our normalization is such that $|v_5|^2/2 + 12|v_{45}|^2 = v^2$, where v ($= 246\,\mathrm{GeV}$) stands for the electroweak VEV. v_{45} is the VEV in 45-dimensional representation. A connection between Yukawa couplings and charged fermion mass matrices is spelled out elsewhere [11]. For the $p \to e^+_\delta \pi^0$ channels we finally find

$$\Gamma(p \to e^+_\delta \pi^0) =$$
$$\frac{(m_p^2 - m_{\pi^0}^2)^2}{64\pi f_\pi^2 m_p^3} \frac{\alpha^2}{v_5^4 m_\Delta^4} \left| (V_{UD})_{11} \left[m_u + \frac{3}{4} m_d \right] + \frac{1}{4} \left(V_{UD}^\dagger U_2^* M_E^{\mathrm{diag}} U_2^\dagger \right)_{11} \right|^2$$
$$\times \left(\left| \frac{3}{2} \left(V_{UD}^* M_D^{\mathrm{diag}} V_{UD}^\dagger U_2^* \right)_{1\delta} + \frac{1}{2} \left(U_2 M_E^{\mathrm{diag}} \right)_{1\delta} \right|^2 + 4|m_u (U_2)_{1\delta}|^2 \right) (1 + D + F)^2,$$

where α and β are the so-called nucleon matrix elements. $F+D$ and $F-D$ combinations are extracted from the nucleon axial charge and form factors in semileptonic hyperon decays, respectively [20, 21]. We take in what follows $f_\pi = 130\,\mathrm{MeV}$, $m_p = 938.3\,\mathrm{MeV}$, $D = 0.80(1)$, $F = 0.47(1)$ and $\alpha = -\beta = -0.0112(25)\,\mathrm{GeV}^3$ [21].

In the previous example we assume that contributions to proton decay of the triplet in 5-dimensional representation dominate over contributions of triplets in 45-dimensional representation. We actually find that the 5-dimensional triplet dominates over the 45-dimensional triplet for moderate values of v_{45} [5]. The suppression factor for the partial lifetimes approximately reads $10^2 (v_{45}/v_5)^4$.

In order to incorporate $p \to \pi^+ \bar{\nu}$ and $p \to K^+ \bar{\nu}$ decay modes in our study we note that one is free to sum over the neutrino flavors in the final state. The relevant coefficients that enter widths for these decays are $a(d_\alpha, d_\beta, \nu_i)$ and $a(d_\alpha, d^C_\beta, \nu_i)$ when the exchanged state is the triplet in 5-dimensional representation. The upshot of our results is that widths for decays with neutral anti-lepton in the final state again depend only on U_2 as far as the mixing parameters are concerned. We again find that the contribution of the triplet in 5-dimensional representation towards $p \to K^+ \bar{\nu}$ and $p \to \pi^+ \bar{\nu}$ dominates over the 45-dimensional triplet contributions for moderate values of v_{45}.

We numerically analyze all the decay modes given in table III to find the current bounds on the triplet mass in $SU(5)$ with symmetric Yukawa couplings. We take values of quark and lepton masses at M_Z, as given in [22]. The CKM angles are taken from ref. [18]. We randomly generate one million sets of values for nine parameters of U_2 and five phases of V_{UD}. As it turns out, it is $p \to K^+ \bar{\nu}$ that dominates in all instances. The most and least conservative bounds for this channel read

$$m_\Delta > 1.2 \times 10^{13} \left(\frac{\alpha}{0.0112\,\mathrm{GeV}^3} \right)^{1/2} \left(\frac{100\,\mathrm{GeV}}{v_5} \right) \mathrm{GeV}, \tag{19}$$

$$m_\Delta > 1.5 \times 10^{11} \left(\frac{\alpha}{0.0112\,\mathrm{GeV}^3} \right)^{1/2} \left(\frac{100\,\mathrm{GeV}}{v_5} \right) \mathrm{GeV}. \tag{20}$$

To summarize, if one is to maximize contributions from the triplets in 5- and 45-dimensional representations towards proton decay within renormalizable $SU(5)$ framework with symmetric mass matrices the current bounds on the triplet mass scale are given in eqs. (19) and (20) if the color triplet in **5** of Higgs dominates in the most and least conservative scenario, respectively. Any $SU(5)$ scenario where the triplet scalar mass exceeds the most conservative bound of eq. (19) is certainly safe with regard to the proton decay constraints on the scalar mediated proton decay. If the triplet mass is below the least conservative bound of eq. (20) the $SU(5)$ scenario is not viable.

4˙2. *Leading-order contributions in flipped* $SU(5)$. – In the minimal flipped $SU(5)$ scenario it is sufficient to have only one 5-dimensional scalar representation present to generate realistic charged fermion masses. We accordingly present predictions of a flipped $SU(5)$ scenario with a single color triplet state. To be able to compare the flipped $SU(5)$ results with the case of ordinary $SU(5)$ we again take $M_{U,D,E} = M_{U,D,E}^T$.

We find that the decays with anti-neutrinos in the final state always dominate. To find corresponding decay widths for $p \to \pi^+\bar{\nu}$ and $p \to K^+\bar{\nu}$ we need to determine $a(d_\alpha, d_\beta, \nu_i)$ and $a(d_\alpha, d_\beta^C, \nu_i)$. In the minimal model with symmetric mass matrices the relevant input reads

$$(U^T(Y^{10} + Y^{10\,T})D)_{1\alpha} = -\frac{1}{\sqrt{2}v_5}\left(V_{UD}^* M_D^{\mathrm{diag}}\right)_{1\alpha}, \tag{21}$$

$$(D^T Y^{\bar{5}} N)_{\beta i} = -\frac{2}{v_5}\left(V_{UD}^T M_U^{\mathrm{diag}} U_2^* V_{EN}\right)_{\beta i}, \tag{22}$$

$$(D^\dagger Y^{\bar{5}\,*} U^*)_{\beta 1} = -\frac{2}{v_5}\left(V_{UD}^\dagger M_U^{\mathrm{diag}}\right)_{\beta 1}. \tag{23}$$

The sum over neutrino flavors in the final state eliminates dependence on any unknown rotations in the quark and lepton sectors leaving us with decay widths that depend only on known masses and mixing parameters. This makes minimal flipped $SU(5)$ with symmetric mass matrices very special. We find the following limit on the triplet mass that originates from experimental constraints on $p \to K^+\bar{\nu}$ channel

$$m_\Delta > 1.0 \times 10^{12} \left(\frac{\alpha}{0.0112\,\mathrm{GeV}^3}\right)^{1/2} \mathrm{GeV}. \tag{24}$$

The fact that $p \to \pi^+\bar{\nu}$ is also a clean channel means that the minimal flipped $SU(5)$ predicts ratio between $\Gamma(p \to \pi^+\bar{\nu})$ and $\Gamma(p \to K^+\bar{\nu})$. We find it to be

$$\Gamma(p \to \pi^+\bar{\nu})/\Gamma(p \to K^+\bar{\nu}) = 9.0. \tag{25}$$

This result represents firm prediction within the framework of the minimal flipped $SU(5)$.

5. – Higher-order contributions

The $(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$ state violates B and L but does not contribute to $d = 6$ proton decay operators at tree-level. We note that despite the absence of the tree-level contribution to proton decay of the $(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$ state, weak corrections lead to proton destabilizing $d = 6$ and $d = 9$ operators [5]. The effect of the $d = 9$ operators can be rendered adequately small even in the case of simultaneously large leptoquark *and* diquark couplings, a situation that is favored by observables in $t\bar{t}$ production and value of $(g-2)_\mu$. This is achieved by finely-tuned cancellation of two amplitudes. To the contrary, similar cancellation is impossible in the case of $d = 6$ operator for $p \to \pi^0\mu^+$ decay and we are required to suppress either all leptoquark couplings involving μ or all diquark couplings. We conclude that the proton decay lifetime constraint allows to fully address either $A_{FB}^{t\bar{t}}$ or $(g-2)_\mu$ observable with the $(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$ state, but not both.

6. – Conclusions

We classify the scalar leptoquarks present in $SU(5)$ and flipped $SU(5)$ grand unification frameworks that mediate proton decay. In both frameworks the considered leptoquark states reside in scalar representations of $SU(5)$ of dimension 5, 10, 45, and 50. We integrate out the above states at tree-level and parameterize their contributions in terms of effective coefficients of a complete set of $d = 6$ operators. The mass constraint on the color triplet state contained in 5- and 45-dimensional representations is then derived. The precise lower bound in $SU(5)$ depends on the value of the VEV of these representation. For the VEV of 100 GeV the least (most) conservative lower bound on the triplet mass that originates from the $p \to K^+\bar{\nu}$ channel is approximately 10^{11} GeV (10^{13} GeV). The corresponding bound is derived within the flipped $SU(5)$ framework to read 10^{12} GeV and proves to be both mixing and VEV independent. Moreover, flipped $SU(5)$ theory with symmetric mass matrices predicts $\Gamma(p \to \pi^+\bar{\nu})/\Gamma(p \to K^+\bar{\nu}) = 9$.

The two leptoquark states that do not contribute to proton decay at tree-level are $(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$ and $(\bar{\mathbf{3}}, \mathbf{1}, -2/3)^{+6}$ in the standard and flipped $SU(5)$ frameworks, respectively. We have estimated their contribution to dimension-six operators via box diagram and the tree-level contribution to dimension-nine operators. For the $(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$ state it has been found that if it is to explain both the anomalous magnetic moment of the muon and the $t\bar{t}$ forward-backward asymmetry, then the contribution of the dimension-six operator would destabilize the proton in $p \to \mu^+\pi^0$ channel. Therefore only one of the two puzzles can be addressed with this leptoquark state.

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REFERENCES

[1] Georgi H. and Glashow S. L., *Phys. Rev. Lett.*, **32** (1974) 438.
[2] De Rujula A., Georgi H. and Glashow S. L., *Phys. Rev. Lett.*, **45** (1980) 413.
[3] Georgi H., Glashow S. L. and Machacek M., *Phys. Rev. D*, **23** (1981) 783.
[4] Barr S. M., *Phys. Lett. B*, **112** (1982) 219.
[5] Dorsner I., Fajfer S. and Kosnik N., *Phys. Rev. D*, **86** (2012) 015013 (arXiv:1204.0674 [hep-ph]).
[6] Fileviez Perez P., *Phys. Lett. B*, **654** (2007) 189 (hep-ph/0702287).
[7] Dorsner I., Fajfer S., Kamenik J. F. and Kosnik N., *Phys. Lett. B*, **682** (2009) 67 (arXiv:0906.5585 [hep-ph]).
[8] Dorsner I., Fajfer S., Kamenik J. F. and Kosnik N., *Phys. Rev. D*, **81** (2010) 055009 (arXiv:0912.0972 [hep-ph]).
[9] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. D*, **83** (2011) 112003 (arXiv: 1101.0034 [hep-ex]).
[10] Abazov V. M. *et al.* (D0 Collaboration), *Phys. Rev. D*, **84** (2011) 112005 (arXiv: 1107.4995 [hep-ex]).
[11] Dorsner I., Drobnak J., Fajfer S., Kamenik J. F. and Kosnik N., *JHEP*, **11** (2011) 002 (arXiv:1107.5393 [hep-ph]).
[12] Bennett G. W. *et al.* (Muon g-2 Collaboration), *Phys. Rev. Lett.*, **92** (2004) 161802 (hep-ex/0401008).
[13] Jegerlehner F., *Acta Phys. Polon. B*, **38** (2007) 3021 (hep-ph/0703125).
[14] Nath P. and Fileviez Perez P., *Phys. Rep.*, **441** (2007) 191 (hep-ph/0601023).
[15] Miura M., *PoS ICHEP*, **2010** (2010) 408.

[16] Kobayashi K. *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. D*, **72** (2005) 052007 (hep-ex/0502026).
[17] Nishino H. *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. D*, **85** (2012) 112001 (arXiv:1203.4030 [hep-ex]).
[18] Nakamura K. *et al.* (Particle Data Group Collaboration), *J. Phys. G*, **37** (2010) 075021.
[19] Georgi H. and Jarlskog C., *Phys. Lett. B*, **86** (1979) 297.
[20] Claudson M., Wise M. B. and Hall L. J., *Nucl. Phys. B*, **195** (1982) 297.
[21] Aoki Y. *et al.* (RBC-UKQCD Collaboration), *Phys. Rev. D*, **78** (2008) 054505 (arXiv:0806.1031 [hep-lat]).
[22] Dorsner I., Fileviez Perez P. and Rodrigo G., *Phys. Rev. D*, **75** (2007) 125007 (hep-ph/0607208).