A Model with New Signatures of Exotic Chiral Fermions
Coupling with Scalar Leptoquarks

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Abstract

In this paper, the possibility to have new physics is considered at the scale of the electroweak
symmetry breaking (EWSB) in a completely new framework. A new non-standard minimal chi-
ral fermion extension of the Standard Model (SM) which renders the complete model free from
anomalies is included. The new fermionic matter coupled with scalar leptoquarks (SLQ) develop-
ing new signals for exotic fermions that could be evaluated in the Large Hadron Collider (LHC).
Analysis based on the cross-section final states shows that the channels $D_{-1/3}\overline{D}_{-1/3} \rightarrow jj + \xi$ and
$D_{-1/3}\overline{D}_{-1/3} \rightarrow 2l^- 2l^+ + jj$ have an apparent narrow window $M_{D_{-1/3}} \sim 240 – 300$ GeV still allowed
by direct and indirect constraints and then interesting for analysis to the new run of the LHC.

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I. INTRODUCTION.

The Standard Model (SM) has achieved great success in the last decades. After the discovery of the Higgs boson [1], the main focus of the LHC experiments is to discover signs of new physics. Searches based on more detailed models, like supersymmetry, in their decay chains that lead to easy-to-see signatures have not exhibited any particular deviation from the SM predictions. The LHC is ending the technical pause and has restarted a new run at a higher center of mass energy close to 14 TeV. The new run will allow the experiments to access higher mass scales, but also processes that gave too flimsy cross-sections to be detected during the 8 TeV run.

The focus of this paper is on one of such cases, where the new fields are new chiral fermions that mixes with scalar leptoquaks producing new signatures and decay chains capable of being detected by the LHC. The new interactions of the exotic quarks contrast with models containing this kind of chiral fermions, in which the decays are mediated via electroweak interactions with SM fermions [2]-[4]. Therefore, the new framework with SLQ will provide new channel searches for the exotic fermions considered here. Concerning to Leptoquaks, they are highly motivated by more elaborate theories and are expected to exist in various extensions of the SM such as in the Pati-Salam model [5], grand unification theories based on SU(5) [6] and SO(10) [7] and lately, they offered the possibility to explain one of the last experimental deviations at the LHC [8].

This paper presents the prospects and exclusions limits for a particular extension of the SM which contains a minimal set (into the $SU(2)_L \otimes U(1)_Y$ gauge group) of exotic chiral fermions mixing with SLQ at the energies of the EWSB. The new chiral fermions form nontrivial multiplets of the SM symmetry group $SU(2)_L \otimes U(1)_Y$ of the electroweak interactions. In addition, a second scalar doublet is introduced in order to give mass for the exotic fields and together with a discrete symmetry $Z_4$ keep under control the SM predictions.

II. GENERALITIES OF THE MODEL.

The complete model is parametrized through an effective Lagrangian $\mathcal{L}_{Eff}$ as follows,

$$\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \mathcal{L}_{NF} + \mathcal{L}_{LQ-Q}$$ (1)
where $\mathcal{L}_{SM}$ represents the SM-Lagrangian, $\mathcal{L}_{NF}$ the Lagrangian of the new field (Exotic and SLQ) and $\mathcal{L}_{LQ-Q}$ contain all the interactions among exotic fermions, SM-fermions and SLQ. The minimal non-standard chiral fermion extension is for the quark sector:

$$
\psi^Y_L \equiv \begin{bmatrix} D_L \\ Y_L \end{bmatrix} \sim (3, 2, -5/6), \quad D_R \sim (3, 1, -1/3), \quad Y_R \sim (3, 1, -4/3),
$$

and for the lepton sector,

$$
\xi^Y_L \equiv \begin{bmatrix} E^3e_L \\ E^2e_L \end{bmatrix} \sim (1, 2, 5/2), \quad E^3e_R \sim (1, 1, 3), \quad E^2e_R \sim (1, 1, 2),
$$

In addition, two scalar leptoquarks are introduced in order to offer new possible channels for the decays of the exotic quarks.

$$
\tilde{S}_u \sim (3, 1, -2/3) \\
S_{1/2} \sim (3, 2, 1/6)
$$

Due to the chiral structure of the new fermionic matter, bare mass terms common in models with vector-like fermions are absent here. Therefore, we consider two Higgs doublet for breaking the electroweak symmetry, $\phi_{1,2} \sim (2, 1)$ \cite{9} -\cite{11}, with vacuum expectation values $\langle \phi_{1,2} \rangle = [0 \ v_{1,2}/\sqrt{2}]^T$. The first Higgs doublet, $\Phi_1$, is assumed to have a tree level couplings to the SM quarks fields, while the second one, $\Phi_2$, with the exotic quarks fields as is done in \cite{4}. For supporting this we take into account the existence of a discrete symmetry $Z_4$ remaining from some physics at very high energy scale, such that the fields transforming non-trivially have charges as shown in table \cite{11}. In addition, the model is assumed into an special scenario of the two Higgs doublet model which entails to have a benchmark point in which the Higgses decoupled. In this setting, the mixing angle $\alpha$ in (7) takes a zero value forbidden in this way tree-level interactions between the exotic and SM fermions and thereby protects the production of the SM-Higgs through gluon fusion.

The Yukawa Lagrangian invariant under $SU(3) \otimes SU(2) \otimes U(1) \otimes Z_4$ reads,
Table I  Charges of the fields transforming nontrivially under \(Z_4\), where \(w_n = e^{i\frac{2\pi}{4}}\).

| \(\Phi_1\) | \(q_L\) | \(L_L\) | \(S_{1/2}\) | \(Z_4\) | \(w_2\) | \(w_2\) | \(w_2\) | \(w_2\) |
|---|---|---|---|---|---|---|---|---|
| \(-\frac{1}{2}\) | \(-1\) | \(-2\) | \(-S_{1/2}\) | \(w_2\) | \(w_2\) | \(w_2\) | \(w_2\) |

\[-L_LQ_Y = y_{uij}^u \overline{q}_{iL} \Phi_1 u_{jR} + y_{ij}^d \overline{q}_{iL} \Phi_1 d_{jR} + y^Y \overline{\psi}_L \Phi_2 Y_R + y^D \overline{\psi}_L \Phi_2 D_R + h.c. \] (5)

\[-L_Y^L = y_{ij}^e \overline{t}_{iL} \Phi_1 l_{jR} + y_{ij}^\nu \overline{t}_{iL} \Phi_1 l_{jR} + x^A \overline{\xi}_L \Phi_2 E^3 e_R + x^B \overline{\xi}_L \Phi_2 E^2 e_R + h.c. \] (6)

where, in Eqs.(5) and (6) the first-second lines correspond to the SM-Exotic Yukawa Langrangian for quark and lepton sectors respectively. Regarding the scalar sector, the mass eigenstates of the Higgses \(H^0\) and \(h^0\) reads,

\[h^0 = H s_\alpha + h c_\alpha\]

\[H^0 = H c_\alpha - h s_\alpha\] (7)

Equations (5), (6) and (7) give the interaction terms between the exotic fermions and the Higgses, where in the mass eigenstates reads,

\[L_{QH} = \sum_i \frac{\sqrt{2m_{\bar{q}i}}}{v_{s_\beta}} \overline{\bar{q}}_{iL} \bar{q}_{iR} (H s_\alpha + h c_\alpha) + \sum_{\eta} \frac{\sqrt{2M_{\bar{Q}}} v_{c_\beta}}{v_{s_\beta}} \overline{\bar{Q}}_{\eta L} \bar{Q}_{\eta R} (H c_\alpha - h s_\alpha) \] (8)

in (8) the standard relations between the vevs \(tg\beta = \frac{v_2}{v_1}\) have been used. The exact decoupling limit is reached taking \(\alpha = 0\), in which the contributions to the SM-Higgs production coming from exotic quarks \((h\bar{Q}Q)\) are absent. The Lagrangian \(L_{QH}\) in this limit takes the form,

\[L_{QH} = \sum_i \frac{\sqrt{2m_{\bar{q}i}}}{v_{s_\beta}} \overline{\bar{q}}_{iL} \bar{q}_{iR} h + \sum_{\eta} \frac{\sqrt{2M_{\bar{Q}}} v_{c_\beta}}{v_{c_\beta}} \overline{\bar{Q}}_{\eta L} \bar{Q}_{\eta R} H \] (9)

where \(i\) run over the SM-fermions and \(\eta\) on the new fermions. Equation (9) shows that the fermion masses are strongly dependent of the \(\beta\) angle. It imposes upper bounds on large
masses through demand perturvature of the Yukawa couplings $y^2 \lesssim 4\pi$. The still allowed values of $\beta$ depends on the type of two Higgs doublet model (I,II,III IV) that is used as scalar sector. In addition, $\beta$ has been strongly suppressed by electroweak measurements, in which, the so-called alignment limit suggest that $\cos(\beta) \leq 0.4$ in order to keep all the SM predictions into the 95% CL [10]. The above considerations impose an upper limit on the masses of the exotics fermions in $M_Q \sim 300$ GeV, which leads to expect that the exotic fermions into this new framework will be manifests at the scale of the EWSB. Other experimental limits have already been imposed in many works for the $Y_{-4/3}, D_{-1/3}$ exotic quarks masses assuming a completely different decay chains and branching ratios to the current work [12][13].

The idea to look for new physics at the EWSB scales motivate the construction of models containing new decay channels so far unexplored for the exotic fermions. The interaction Lagrangian in equation (10) allows the decay of all the exotic fermions always through the interaction with a SLQ,

$$-\mathcal{L}_{\text{LQ}} = \lambda_d \bar{d}_R S_{1/2}^T \epsilon L_L + \lambda_D \bar{D}_R S_{1/2}^T \epsilon L_L + \lambda_q \nu_R \tilde{u}_u + \lambda_A \bar{E}_R^{2e,c} Y_R \tilde{S}_u + h.c. \quad (10)$$

where, $\epsilon$ represents two dimensional antisymmetric matrix, $\lambda_d$ and $\lambda_D$ are matrices in flavor space and $\lambda_A$ and $\lambda_q$ are complex numbers. The fields $L$ and $u_R$ represent the left-handed SM-lepton doublets and SM-u-type right handed quarks respectively. Expanding the $SU(2)$ components yields

$$-\mathcal{L}_{\text{LQ}} = \lambda_d^{\nu} \bar{d}_R S_{1/2}^{-1/3} \nu_L + \lambda_D^{\nu} \bar{D}_R S_{1/2}^{2/3} \nu_L + \lambda_q \bar{\nu}_R \tilde{u}_u + \lambda_A \bar{E}_R^{2e,c} Y_R \tilde{S}_u + h.c. \quad (11)$$

where, the charge subscript for the fermions is omitted whereas the subscript in the leptoquaks represent the electric charges. From Lagrangian (11), the possibilities for the $D_{-1/3}$ decay through a SLQ $S_{1/2}^{2/3}$ and $S_{1/2}^{-1/3}$ entails two very different collider signatures which leads to relax the limits on the masses of the exotic quarks.

### III. OBLIQUE PARAMETERS.

In order to suppress possible contributions to the $STU$ parameters due to the new fermionic matter, the scenario is chosen nearly degenerate for the doublet of quarks and
leptoquarks. For leptons, a narrow split between the masses of the doublet is allowed in order to open the $E^{3e} \rightarrow E^{2e}W^+$ on-shell decay. Then it is shown that a few scenarios with $M_W \leq M_{E^{3e}} - M_{E^{2e}} \leq M_Z$ GeV are in complete agreement with the last fit for STU \cite{14}. Taking the formulas in Ref \cite{15}, each pair of fermions $(\psi_1, \psi_2)$, with masses $(m_1, m_2)$, whose left-handed components form a doublet $\Psi \equiv (\psi_{1L} \psi_{2L})^T \sim (2, Y)$ of hypercharge $Y$, and their right-handed components are singlets $\psi_{1R}, \psi_{2R}$, gives the following contribution to the oblique parameters

$$S_\Psi = \frac{N_C \Psi}{6\pi} \left[ 1 - 2Y \ln \frac{x_1}{x_2} + \frac{1 + 8Y}{20x_1} + \frac{1 - 8Y}{20x_2} \right],$$

$$T_\Psi = \frac{N_C}{8\pi s_W^2 c_W^2} F(x_1, x_2),$$

$$U_\Psi = -\frac{N_C \Psi}{2\pi} \left\{ \frac{x_1 + x_2}{2} - \frac{(x_1 - x_2)^2}{3} + \left[ \frac{(x_1 - x_2)^3}{6} - \frac{1}{2} \frac{x_1^2 + x_2^2}{x_1 - x_2} \right] \ln \frac{x_1}{x_2} + \frac{1}{6} f(x_1, x_1) + \frac{x_2 - 1}{6} f(x_2, x_2) + \frac{1}{6} \frac{x_1 + x_2}{x_1 + x_2 - 1} - \frac{(x_1 - x_2)^2}{6} \right\} f(x_1, x_2) \right\}$$

in which $N_C = 3(1)$ is the color degree of freedom of quarks (leptons),

$$F(x_1, x_2) = \frac{x_1 + x_2}{2} - \frac{x_1 x_2}{x_1 - x_2} \ln \frac{x_1}{x_2},$$

$$f(x_1, x_2) = \begin{cases} 
-2\sqrt{\Delta} \left[ \arctan \frac{x_1 - x_2 + 1}{\sqrt{\Delta}} - \arctan \frac{x_1 - x_2 - 1}{\sqrt{\Delta}} \right] & (\Delta > 0) \\
0 & (\Delta = 0) \\
\sqrt{-\Delta} \ln \frac{x_1 + x_2 - 1 + \sqrt{-\Delta}}{x_1 + x_2 - 1 - \sqrt{-\Delta}} & (\Delta < 0)
\end{cases}$$

with $x_i = m_i^2/M_Z^2$, and $\Delta = 2(x_1 + x_2) - (x_1 - x_2)^2 - 1$.

The mass of the new fermionic matter should be greater than $M_Z$ in order to avoid $O(M_Z^4/M_i^4)$ corrections to the above equations. Therefore, from now on, the new matter is assumed to satisfy the $M_i > M_Z$ condition, in addition, the mass hierarchy in the doublets makes it always to satisfy $\Delta > 0$. Regarding the $S$ parameter, the mass hierarchy between the exotic leptons implies an offsetting negative contributions from the quarks fields in which is taking the benchmark point with $M_Y > M_D$. For example, with $M_{E^{3e}} = 250$ GeV, $M_{E^{2e}} = 160$ GeV, $M_Y = 250$ GeV and $M_D = 240$ GeV gives $S = -0.05$ (in this case $T = 0.15$ and $U = 0.9$), which show that the $U$ parameter strongly forbids non-degenerate doublets. In figure \cite{1}, each graph represents the case in which the lepton masses are varied in steps
of $\Delta M = M_{E^3e} - M_{E^2e} = 10, 50 \text{ and } 80 \text{ GeV}$ (left, middle and right) keeping the quark masses fixed in $M_Y = 250 \text{ GeV}$ and $M_D = 240 \text{ GeV}$. The radio of each circle represents the value taken by the $U$ parameter when the lepton masses are varied from $M_{E^3e} = 250 \text{ GeV}$ and $M_{E^2e} = 240 \text{ GeV}$ for the most outer circle, until $M_{E^3e} = 120 \text{ GeV}$ and $M_{E^2e} = 110 \text{ GeV}$ for the most inter circle, in which $\Delta M = M_{E^3e} - M_{E^2e} = 10, 50 \text{ and } 80 \text{ GeV}$ for the left, middle and right graphs respectively.

![Diagram](image)

**Figure 1** The radio of each circle represents the value taken by the $U$ parameter when the lepton masses are varied from $M_{E^3e} = 250 \text{ GeV}$ and $M_{E^2e} = 240 \text{ GeV}$ for the most outer circle, until $M_{E^3e} = 120 \text{ GeV}$ and $M_{E^2e} = 110 \text{ GeV}$ for the most inter circle, in which $\Delta M = M_{E^3e} - M_{E^2e} = 10, 50 \text{ and } 80 \text{ GeV}$ for the left, middle and right graphs respectively.

From Fig. (1) it can be inferred that all the doublets shall be nearly degenerate in order to keep the electroweak parameters under control.

**IV. \(D_{-1/3}\) QUARK PHENOMENOLOGY.**

The most simple decay chain of the non-standard fermions present in this model is for the $D_{-1/3}$ quark. Therefore, in order to test the discovery potential of the model or the possible scenarios in which it is potentially excluded, it is introduced the possible signatures for the $D_{-1/3}$ quark at the LHC8. The main production channel is QCD through gluon fusion, followed by the production via the decay of $H$ in a pair $D_{-1/3}\bar{D}_{-1/3}$, which, subsequently $D_{-1/3}$ decay in two leptons and a jet through a scalar leptoquark as mediator Fig. (2). Limits on scalar leptoquarks masses are less stringent than for the other class of leptoquarks [16]. Although in this work there are new channels for the scalar leptoquarks which have new couplings with exotic fermions, here, the latest fit on their masses has been taken $M_{SLQ} \sim 1$
TeV as a benchmark point. The FeynRules package [17] has been used to simulate the complete model (SM and new interactions) obtaining a UFO [18] sampled model containing all the exotic fermions, heavy scalar and scalar leptoquarks as the BSM particles. The necessary coupling terms to be implemented include: the effective $H - h gg$ couplings, $HVV$ couplings, $HQQ$ Yukawa couplings and the leptoquark-quark-lepton interactions $LQ - Q L$.

![Feynman diagrams](image)

**Figure 2** Feynman diagrams for the $D_{-1/3}$ decays through a $S^{2/3}_{1/2}$ and $S^{-1/3}_{1/2}$ scalar leptoquaks.

| Parameters | S1: $D_{-1/3} \bar{D}_{-1/3} \rightarrow jj + \not q$ | S2: $D_{-1/3} \bar{D}_{-1/3} \rightarrow 2l^- 2l^+ + jj$ |
|------------|---------------------------------|---------------------------------|
| $M_H$      | 1 TeV                           | 1 TeV                           |
| $M_{E2e}, M_{E3e}$ | (180, 200) GeV       | (180, 200) GeV       |
| $M_D, M_Y$ | (220-300, 300) GeV              | (220-300, 300) GeV              |
| $M_{SLQ}$  | 1 TeV                           | 1 TeV                           |
| $g_{SLQ-lQ}$ | 1 (S1A, S1B)                  | 1 (S2A, S2B)                  |
| $g_{SLQ-lq}$ | $10^{-3}$ (S1A, S1B)         | $10^{-3}$ (S2A, S2B)         |
| $\cos(\beta)$ | 0.35                          | 0.35                          |

**Table II** Representative points in the model parameter space and the relevant mass spectrum used in the analysis.

Let us calculate now the signal cross-section for the completely decay chain for the scenarios S1, S2 in [33], where $g_{SLQ-lQ}$, $g_{SLQ-lq}$ and $\cos(\beta)$ represent the couplings of the SLQ with one lepton and an exotic quark ($D_{-1/3}$ or $Y_{-4/3}$), the coupling of the SLQ with one lepton and a SM quark and the value of $\cos(\beta)$ in which $\beta = v_2/v_1$. For each scenario, two complete different frameworks (S1A, S1B and S2A, S2B) are taken. The A label means that the SLQ
coupled with the first two families of leptons and quarks of the SM, whereas the quark $D_{-1/3}$ coupled with the three families of SM-leptons and one SLQ. The B label means that the SLQ coupled just with the third family of quarks and leptons of the SM, whereas the quark $D_{-1/3}$ coupled with only the third family of SM-leptons and one SLQ.

![Graph](image)

**Figure 3** Cross-section of the $D_{-1/3} \overline{D}_{-1/3}$ pair production and decay and direct (left) and indirect (right) constraints for each decay channel at the LHC8.

In spite of not having direct limits for both of the possible final states signals of $D_{-1/3}$, searches in SUSY brings us upper limits for the squarks cross-sections when they decay in jets plus missing energy, in which, the squarks decays have almost the same final state of $D_{-1/3}$ when it decays through $S_{1/2}$. On the other hand, searches containing four leptons serves as an idea of the size of the cross-section for the $D_{-1/3}$ decay through $S_{2/3}$ in relation to that observed so far.

**A. $D_{-1/3} \overline{D}_{-1/3} \rightarrow jj + \notin$ Channel.**

In [19], the last upper bounds on cross-sections have been imposed for pair-produced squarks, each decaying to a quark and a neutralino. The topology of the decays are equal for squarks and $D_{-1/3}$ when it decays through a $S_{1/2}$ leptoquak enabling it impose upper limits on the $pp \rightarrow D_{-1/3} \overline{D}_{-1/3} \rightarrow jj + \notin$ cross-sections. In Fig. (3) (left) is the cross-section for the scenarios S1A and S1B along with the fifth-order polynomial fit of the cross-section.
for pair-produced squarks decaying in quarks and a massless neutralino in the LHC at 8 TeV. From it, the scenario S1A is completely excluded, whereas the scenario S1B allows a narrow window of masses (240-300) GeV still in agreement with the experimental limits.

**B. $D_{-1/3} \bar{D}_{-1/3} \rightarrow 2l^- 2l^+ + jj$ Channel.**

Unlike the previous case, the decay through a $S^{2/3}_{1/2}$ leptoquark has not associated direct limits. Nevertheless, the four leptons as a final state lets consider searches in four leptons as indirect constraints on the size of $D_{-1/3} \bar{D}_{-1/3} \rightarrow 2l^- 2l^+ + jj$ cross-section. Here, we calculate the sum of all the bins of the four lepton mass invariant graph, figure 13 in [20] from 200 GeV to 600 GeV divided by the luminosity $L = 20.3 fb^{-1}$. An arbitrary factor of $\epsilon = 10$ has been introduced to recompense the signal loss due to the cuts and then obtaining the $\sigma(M_{4l}) \cdot (\epsilon = 10)$ fit. In Fig. (3) (right) is the cross-section for the scenarios S2A and S2B along with the $\sigma(M_{4l}) \cdot (\epsilon = 10)$ fit. From it, we can roughly say that the scenario S2B is strongly excluded whereas the scenario S2B allows a narrow window of masses (270-300) GeV still in agreement with the setting made here.

**V. CONCLUSIONS**

In this work, the analysis of signatures at the LHC at 8 TeV of a complete renormalizable chiral fermion extension of the SM, which, embeds quarks and leptons with exotic charges and scalar leptoquaks has been considered. The exotic fermions mix with scalar leptoquaks via Yukawa couplings with ordinary leptons keeping the usual couplings of the leptoquaks with SM fermions, even though new coulings with exotic fermions are introduced for the scalar leptoquars considered here. Due to the chirality of the new fermions, an extra scalar doublet has been introduced in order to give the mass of them through the Higgs mechanism as done in [4], where, a benchmark point in complete agreement with the last fit for the 2HDM was taken into account.

The analysis are based on the comparison of the size of final states cross-sections for the two possibles decays of the quark $D_{-1/3}$ with direct and indirect constraints. The direct constraints are coming from supersymmetry searches of squarks which have the same final state signature of $D_{-1/3}$ decaying in $S_{1/2}^{-1/3}$ and a ordinary lepton. On the other hand, indirect
constraints are coming from the complete background for the four lepton final state, which, can bring us an idea of how large the model signatures are from the experimental data at 8 TeV. Two benchmark points are analysed for each scenario, in one (SB) the SLQ couples with the two first families of SM fermions whereas $D_{-1/3}$ couples with the third SM leptons plus a SLQ, the other sub scenario (SA) is when the SLQ only couples with the third family of SM fermions and $D_{-1/3}$ with a lepton of the third SM family and a SLQ.

Concerning to the $D_{-1/3}\overline{D}_{-1/3} \rightarrow jj + \notin$ channel, constraints coming from supersymmetry searches exclude completely the scenario S1A, whereas allow a narrow window of masses into the experimental limits (240-300) GeV. For the $D_{-1/3}\overline{D}_{-1/3} \rightarrow 2l^{-}2l^{+} + jj$ channel, the fit made here shows that the cross-section is too large for the scenario S2A. Nevertheless, the scenario S2B left a narrow window of masses (280-300) GeV still in agreement with the indirect constraint. Both scenarios can be easily tested by the new run of the LHC thus leading to provide new channels to search exotic physics at the LHC energies.

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