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Searching for Scalar Leptoquarks at the LHC/FCC and a Muon Collider

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We present the search strategies for two different leptoquark models at the present and future colliders. A model containing a singlet and a doublet scalar leptoquark can generate neutrino mass at one-loop while contributing to the muon $g-2$ experimental measurement. Signatures of this model, in benchmark scenarios that simultaneously satisfy neutrino mass and oscillation data, muon $g-2$ excess as well as CLFV bounds, are studied from the pair production at the LHC/FCC, with complementary final states that distinguish the leptoquark mass eigenstates. A non-trivial mixing exists between the singlet and the doublet, which can be probed by an asymmetric pair production. Next, we consider a singlet and a triplet scalar leptoquark separately, motivated by their contribution to B-decay ratios and associated observables. A benchmark-independent study is performed for the 5σ probe of a very minimal set of Yukawa couplings at the LHC/FCC from the single production of leptoquarks. A complementary study from the pair production is performed at a multi-TeV muon collider, which leads to cleaner signal and better reach.

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1. Introduction

The various shortcomings of the Standard Model (SM) of particle physics necessitates the introduction of hypothetical particles Beyond the Standard Model (BSM), of which leptoquarks (LQ) are some well-studied examples. These colour-charged scalar or vector bosons couple to a quark and a lepton at the same time, thus facilitating explanations of flavour anomalies, $(g-2)$ measurement, and neutrino mass generation, among others. Motivated by such usefulness, we study the collider phenomenology of two different scenarios containing scalar LQs.

2. $\widetilde{R}_2 + S_1$ LQs together: probes at LHC/FCC

We extend the SM with two scalar leptoquarks: $\widetilde{R}_2\,(3,2,1/6) = (\widetilde{R}_2^{2/3},\, \widetilde{R}_2^{-1/3})^T$ and $S_1\,(\bar{3},1,1/3)$, which are doublet and singlet under $SU(2)_L$, respectively [1]. The relevant part of the Lagrangian looks like:

$$-\mathscr{L} \supset \mathcal{Y}_1^L\, \overline{\boldsymbol{Q}}{}_L^c\, S_1\,(i\sigma_2)\,\boldsymbol{L}_L + \mathcal{Y}_1^R\, \overline{u}{}_R^c\, S_1\, \ell_R + \mathcal{Y}_2\, \overline{d}_R\, \widetilde{R}_2^T\,(i\sigma_2)\,\boldsymbol{L}_L \; + \kappa\, H^\dagger \widetilde{R}_2\, S_1 \; + h.c., \tag{1}$$

where the $\kappa\, H^\dagger \widetilde{R}_2\, S_1$ term induces non-trivial mixing between the two LQ multiplets, with a mixing angle $\tan 2\theta_{LQ} = \frac{-\sqrt{2}\kappa v}{m^2(S_1) - m^2(\widetilde{R}_2^{1/3})}$. After electroweak symmetry breaking (EWSB), the $Q = 1/3$ components of the LQ multiplets mix, creating the mixed LQ mass eigenstates $X_{1,2}^{-1/3}$, where $X_1^{-1/3}$ is mostly singlet and $X_2^{-1/3}$ is mostly doublet. The $\widetilde{R}_2^{+2/3}$ remains a pure doublet mass eigenstate.

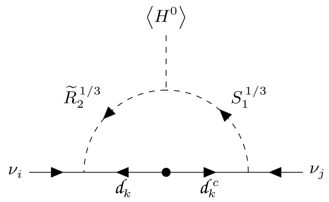
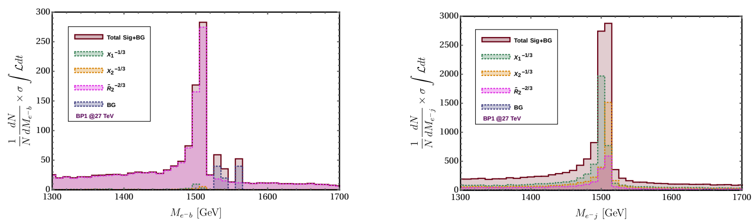


Figure 1: One-loop neutrino mass generation with the $\widetilde{R}_2 + S_1$ model.

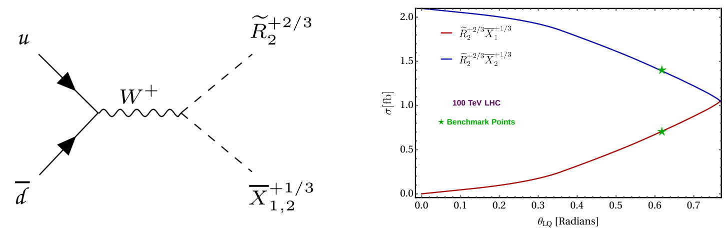
This mixing allows the generation of neutrino mass at one-loop via the Feynman diagram shown in Figure 1 [2, 3]. The same setup, with the correct choice of Yukawa couplings, can successfully enhance the $(g-2)_\mu$ [4]. In our work, we carefully identify three sets of Yukawa couplings with varying strengths as our benchmark points (BP), that simultaneously satisfy neutrino mass, oscillation data, $(g-2)_\mu$, and charged lepton flavour violating bounds, keeping masses of the the LQs ~ 1.5 TeV and $\theta_{LQ} \sim -0.618$ radians [1]. A `pythia8`-based simulation is performed on these points, with cross-generation final states to distinguish and reconstruct the pure and mixed LQ eigenstates, at three LHC/FCC energies of 14 TeV, 27 TeV, and 100 TeV.



(a) (b)

Figure 2: Reconstruction of LQ masses for BP1 at the 27 TeV LHC.

With the advantage of having different decay modes for $\widetilde{R}_2^{+2/3}$ compared to $X_{1,2}^{-1/3}$, one can distinguish the pure state from the mixed state accross the three BPs, via their pair production at the LHC/FCC. However, the significant mixing required for generating neutrino mass leads to overlapping of final states for $X_{1,2}^{-1/3}$ themselves, and hence it is extremely challenging to distinguish between them in such a scenario. This is illustrated for BP1 at a future LHC energy of 27 TeV, where Figure 2(a) shows a clean invariant mass peak for $\widetilde{R}_2^{+2/3}$, while an overlapping peak for $X_{1,2}^{-1/3}$ is shown in Figure 2(b). As a possible way of discerning between $X_{1,2}^{-1/3}$ and probing the mixing angle, we propose the $W^{\pm}$-boson mediated asymmetric pair production of the type $pp \to \widetilde{R}_2^{+2/3} X_{1,2}^{+1/3}$ at the 100 TeV FCC, shown in Figure 3(a). Owing to the $W^{\pm}$ only coupling to the doublet part of the LQ, the process involving $X_2^{-1/3}$ shows higher cross-section, and this difference has correlation with the mixing angle, as depicted in Figure 3(b). A high-luminosity analysis of final states from these processes can possibly lead to the distinction of these mixed LQ states.



(a) (b)

Figure 3: (a) Asymmetric pair production of LQs. (b) θ_{LQ} dependence of cross-section at the 100 TeV FCC.

3. S_1 and S_3 LQs separately: probes at LHC/FCC and a muon collider

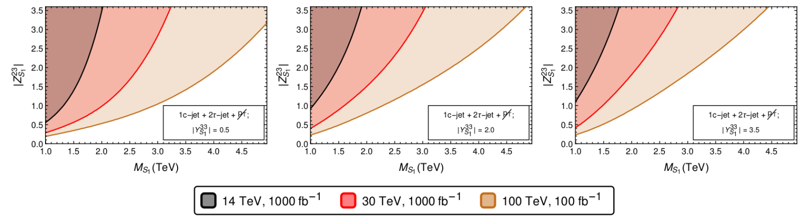
Compared to the previous scenario, we also study a more minimal model with two LQs: $S_1(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ (singlet) and $S_3(\bar{\mathbf{3}}, \mathbf{3}, 1/3) \equiv (S_3^{4/3}, S_3^{1/3}, S_3^{-2/3})^T$ (triplet) considered one at a time [5]. The relevant Lagrangians look like:

$$\mathcal{L}_{S_1} \supset \overline{Q^c}^i \, i\tau_2 Y_{S_1}^{i\alpha} L^\alpha \, S_1 + \overline{u_R^c}^i \, Z_{S_1}^{i\alpha} \ell_R^\alpha \, S_1 + \text{h.c.}\,, \quad (2)$$

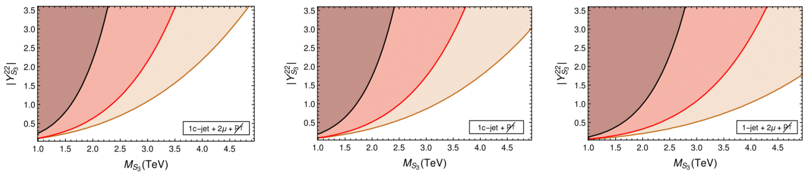
$$\mathcal{L}_{S_3} \supset \overline{Q^c}^i \, Y_{S_3}^{i\alpha} \, i\tau_2 \, \boldsymbol{\tau} \cdot \mathbf{S_3} \, L^\alpha + \text{h.c.}\,, \quad (3)$$

Here, with a benchmark of only two non-zero Yukawa couplings $Y_{S_1}^{33}$ and $Z_{S_1}^{23}$, S_1 explains the $R(D)/R(D*)$ anomaly [6]. Similarly, with the two non-zero couplings $Y_{S_3}^{22}$ and $Y_{S_3}^{32}$, the S_3 could explain the then-existent $R(K)/R(K*)$ anomaly [7]. While the latter anomaly is now alleviated [8], the thrust results of our work involve benchmark-independent reach studies in the LQ Mass vs Yukawa plane, which are utilizable to look for such Yukawa coupling structures over TeV-scale LQ masses. Our study involves single production of the LQs via quark-gluon fusion at the LHC/FCC, the event rates of which are predominantly dependent on the Yukawa couplings. Counting signal events from cross-generation final states against SM and model backgrounds, we present these reach plots at LHC/FCC energies of 14, 30, and 100 TeV respectively, in Figure 4. For the reach plots of S_1 in Figure 4(a), we fix the coupling $Y_{S_1}^{33}$ at three different values, to evaluate the 5σ discovery contours for M_{S_1} against the coupling $Z_{S_1}^{23}$. For S_3, three plots are presented in Figure 4(b) for three of the triplet excitations, in the M_{S_3} vs $Y_{S_3}^{22}$ plane. Evidently, S_3 signal is comparetivly cleaner as a result of muons in the final states, providing better reach at the hadron colliders.

As a complementary probe, we study the pair production of S_3 at a multi-TeV muon collider as well [9, 10]. The t-channel production modes shown in Figure 5(a) are purely Yukawa coupling dependent. The significant deficit of hadronic QCD background and the subsequent cleaner signal, lead to comparatively better reach than the hadron collider counterparts. As seen from Figure 5(b), it is possible to obtain 5σ probes of $Y_{S_3}^{22} < 0.5$ for $M_{S_3} \leq \frac{\text{COM energy}}{2}$ at the muon collider, establishing our claim for higher precision opportunity.

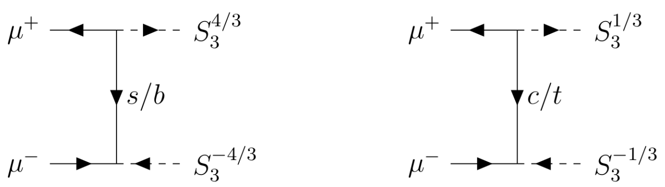


(a)

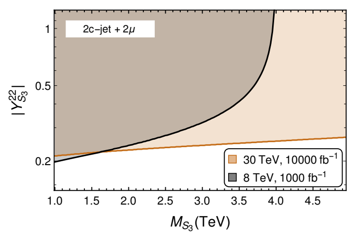


(b)

Figure 4: LHC/FCC reach with energies of 14, 30, and 100 TeV, in the M_{LQ} vs Yukawa plane for (a) S_1 and (b) S_3.



(a)



(b)

Figure 5: (a) t-channel production of LQ pairs at the muon collider. (b) 5σ contours in the M_{S_3} vs $Y^{22}_{S_3}$ plane at muon collider energies of 8 and 30 TeV.

4. Summary

Leptoquarks are useful sets of BSM extensions that can contribute to various observations that the SM lacks answers for. A combination of $\widetilde{R}_2$ and S_1 leptoquarks together can generate neutrino mass and explain the $(g-2)_\mu$ anomaly, with a significant mixing leading to discernible final state phenomenology at the LHC/FCC from their symmetric and asymmetric pair production. On the other hand, the S_1 and S_3 leptoquarks separately can be motivated by charged- and neutral-current B-anomalies, explained with minimal choices of two non-zero Yukawa couplings, which can be probed from single production at the LHC/FCC. A multi-TeV muon collider provides a more precise and efficient alternative for S_3, probing < 0.5 values of the Yukawa couplings for a much larger mass range compared to the LHC/FCC.

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