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Present and Future Searches for Leptoquarks

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Abstract

We review the present searches for scalar leptoquarks and the potential of the CERN Large Hadron Collider (LHC) to unravel the existence of first generation leptoquarks.

1 Introduction

Many extensions of the Standard Model (SM) treat quarks and leptons in the same footing and, consequently, allow the existence of particles, called leptoquarks, that mediate quark-lepton transitions. The class of theories exhibiting leptoquarks includes composite[1,2], grand unified[3], and technicolor[4] models.

A natural hypothesis for theories beyond the SM is that they exhibit the gauge symmetry $SU(2)_L \otimes U(1)_Y$ above the electroweak symmetry breaking scale v, therefore, we imposed this symmetry on the leptoquark interactions. In order to avoid strong bounds coming from the proton lifetime experiments, we required baryon (B) and lepton (L) number conservation. The most general effective Lagrangian for leptoquarks satisfying the above requirements and electric charge and color conservation is given by[5]

$$\mathcal{L}_{eff} \quad = \quad \mathcal{L}_{F=2} \; + \; \mathcal{L}_{F=0} \; , \tag{1}$$

$$
\begin{aligned}
\mathcal{L}_{F=2} &= g_{1L}\ \bar{q}^c_L\ i\tau_2\ \ell_L\ S_{1L} + g_{1R}\ \bar{u}^c_R\ e_R\ S_{1R} + \tilde{g}_{1R}\ \bar{d}^c_R\ e_R\ \tilde{S}_1 \\
&\quad + g_{3L}\ \bar{q}^c_L\ i\tau_2\ \vec{\tau}\ \ell_L \cdot \vec{S}_3\ , \\
\mathcal{L}_{F=0} &= h_{2L}\ R^T_{2L}\ \bar{u}_R\ i\tau_2\ \ell_L + h_{2R}\ \bar{q}_L\ e_R\ R_{2R} + \tilde{h}_{2L}\ \tilde{R}^T_2\ \bar{d}_R\ i\tau_2\ \ell_L
\end{aligned}
$$

where $F = 3B + L$, q (ℓ) stands for the left-handed quark (lepton) doublet, and we omitted the flavor indices of the leptoquark couplings to fermions. The leptoquarks $S_{1R(L)}$ and $\tilde{S}_1$ are singlets under $SU(2)_L$, while $R_{2R(L)}$ and $\tilde{R}_2$ are doublets, and S_3 is a triplet.

Low-energy experiments lead to strong indirect bounds on the couplings and masses of leptoquarks. The main sources of indirect constraints are:

- Leptoquarks can give rise to Flavor Changing Neutral Current (FCNC) processes if they couple to more than one family of quarks or leptons [6,7]. In order to avoid strong bounds from FCNC, we assumed that the leptoquarks couple to a single generation of quarks and a single one of leptons.
- The analyses of the decays of pseudoscalar mesons put stringent bounds on leptoquarks unless their coupling is chiral [6].
- Leptoquarks that couple to the first family of quarks and leptons are strongly constrained by atomic parity violation [8]. In this case, there is no choice of couplings that avoids the strong limits.
- The analyses of the effects of leptoquarks on the Z physics through radiative corrections lead to limits on the masses and couplings of leptoquarks that couple to top quarks [9].

As a rule of a thumb, the low-energy data constrain the masses of leptoquarks to be larger than 0.5—1 TeV when their Yukawa coupling is equal to the electromagnetic coupling e [9,10].

2 Present Bounds on Leptoquarks

Since leptoquarks are an undeniable signal of physics beyond the SM, there have been several direct searches for them in accelerators.

Recently the LEP Collaborations [11] used their $\sqrt{s} = 161$ and 172 GeV data to obtain the constraint $M_{lq} \gtrsim 131$ GeV for leptoquarks coupling to first family quarks and electrons. The searches for scalar leptoquarks decaying exclusively into electron-jet pairs at the Tevatron constrained their masses to be $M_{lq} \gtrsim 225$ GeV [12].

Using the $e^- p$ data, the experiments at HERA [13] placed limits on leptoquark masses and couplings, establishing that $M_{lq} \gtrsim 216-275$ GeV depending on their types and couplings. These constraints are stronger for $F = 2$ leptoquarks since these can be formed by e^-–valence quark collisions in $e^- p$ interactions. On the other hand, $e^+ p$ collisions at HERA exhibited an intriguing excess of neutral current events at large Q^2 ($\gtrsim 1.5 \times 10^4$ GeV^2) [14]. H1 observes 18 events for lepton–jet invariant masses between 187.5 and 212.5 GeV, while only 1.5 events are expected. ZEUS found 5 events for $x > 0.55$ and $y > 0.25$ when 2 events are expected. These rates are certainly incompatible with the standard model.

At this point it is natural to verify whether this excess can be explained by scalar leptoquarks with the interactions given by Eq. 1. For simplicity let us assume that the leptoquarks couple either to u or d quarks but not to s. From the event rates, the leptoquark must be $F = 0$, otherwise its signal would have already been observed in the $e^- p$ run. Combining the HERA rates and the atomic parity violation bounds we obtain that branching ratio to charged leptons (B_e) must satisfy the limit [15]

$$B_e \gtrsim 0.1\text{–}0.2 \qquad \text{for } e^+ u \text{ leptoquarks} \;, \tag{2}$$

$$B_e \gtrsim 0.2\text{–}0.4 \qquad \text{for } e^+ d \text{ leptoquarks} \;. \tag{3}$$

The HERA data suggests that the leptoquark mass is around 200 GeV, which is within the mass range explored by DØ and CDF. The Tevatron data for leptoquark masses around 200 GeV constrains the charged lepton branching ratio (B_e) to be

$$B_e \lesssim 0.5\text{–}0.7 \;. \tag{4}$$

Therefore the HERA data can be interpreted as being the signal for scalar leptoquarks provided the B_e lies in the window defined by Eqs. (2), (3), and (4). It is important to notice that leptoquarks whose interactions are totally described by Eq. (1) can **not** explain the HERA data since all leptoquarks that couple to e^+u and e^+d pairs possess $B_e = 1$.

3 Future LHC Bounds

In the near future, the direct search for leptoquarks with masses above a few hundred GeV can be carried out only at the CERN Large Hadron Collider [16]. We studied the capability of the LHC to unravel the existence of scalar leptoquarks through the final state topology two jets plus a pair e^+e^- [17]. This was accomplished by a careful analyses of the signal and backgrounds using the event generator PYTHIA [18]. We performed our analyses for first generation leptoquarks whose interactions are described by the most general effective Lagrangian that is invariant under $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ given by Eq. (1).

In hadronic colliders, leptoquarks can be single or pair produced through the processes $q+g \to S_{lq}+\ell$, $q+\bar{q} \to S_{lq}+\bar{S}_{lq}$, and $g+g \to S_{lq} + \bar{S}_{lq}$, where $\ell = e^{\pm}$ (ν) and we denoted the scalar leptoquark by S_{lq}. When the leptoquark decays into a $e^{\pm}$–q pair, the final state presents a pair e^+e^- and jets after hadronization. The cross sections for pair production are model independent because the leptoquark–gluon interaction is determined by the $SU(3)_C$ gauge invariance. On the other hand, the single production is model dependent once it involves the the unknown Yukawa coupling of leptoquarks to a lepton–quark pairs.

At the parton level, the single production of leptoquarks leads to a final state exhibiting a pair e^+e^- and q $(\bar{q})$. After the parton shower and hadronization the final state usually contains more than one jet, and consequently, the backgrounds for single and pair productions of leptoquarks are basically the same. In our analyses we kept track of the $e^{\pm}$ (jet) carrying the largest transverse momentum, that we denoted by e_1 (j_1), and the $e^{\pm}$ (jet) with the second largest p_T, that we called e_2 (j_2).

Within the scope of the SM, there are many sources of backgrounds leading to jets accompanied by a pair e^+e^-: QCD processes, which depend exclusively on the strong interaction; electroweak processes, which contains the Drell-Yan production of quark or lepton pairs and the single and pair productions of electroweak gauge bosons; and the production of top quark pairs.

The signals for leptoquark production and their associated backgrounds exhibit different kinematical distributions for the hardest leptons and jets. For instance [17], the transverse momentum distributions of the $e_{1(2)}$ and $j_{1(2)}$ for the signal exhibit a larger fraction of very hard jets and leptons than the backgrounds. The invariant mass of pairs e^+e^- is usually quite large for single and pair productions of leptoquarks, while this spectrum for the background is concentrated at small invariant masses and around the mass of the Z. Furthermore, the signal events present a clear peak in the invariant mass (M_{ik}) distribution of e_i–j_k pairs, as expected.

Taking into account the features of the signal and backgrounds above described, we imposed the following set of cuts:

(C1) The leading jets and $e^{\pm}$ should be in the pseudorapidity interval $|\eta| < 3$.

(C2) The leading leptons (e_1 and e_2) should have $p_T > 200$ GeV.

(C3) We reject events where the invariant mass of the pair e^+e^- ($M_{e_1 e_2}$) is smaller than 190 GeV.

(C4) In order to further reduce the $t\bar{t}$ background we required that *all* the invariant masses $M_{e_i j_k}$ are larger than 200 GeV.

leptoquark	$\mathcal{L} = 10$ fb^{-1}	$\mathcal{L} = 100$ fb^{-1}
S_{1L} and S_3^0	1.1	1.5
S_{1R}, $\tilde{S}_{1R}$, R_{2L}^1,R_{2R}^2, and $\tilde{R}_2^1$	1.3	1.7

Table 1: 95% CL limits on the leptoquark masses in TeV that can be obtained from the search for leptoquark pairs for two integrated luminosities.

We demonstrate in Ref.[17] that the cuts C1—C4 effectively suppress all the backgrounds to leptoquark production at the LHC, consequently, the leptoquark searches are background free. Therefore, the LHC will be able to exclude at 95% CL the regions of parameter space where the number of expected signal events is larger than 3 for a given integrated luminosity.

The limits on leptoquarks coming from the leptoquark pair searches depend exclusively on their branching ratio into a charged lepton and jet (B_e) since they are produced by strong interaction processes that are the same for all leptoquark species. We show in Table 1 the 95% CL limits on the leptoquark masses that can be obtained from their pair production at the LHC for two different integrated luminosities. As we can see, this search will be able to exclude leptoquarks with masses up to 1.5 (1.7) TeV for $B_e = 0.5$ (1) and an integrated luminosity of 100 fb^{-1}.

We also analyzed the search for leptoquarks through the existence of an excess of events presenting a e-jet invariant mass in the range $|M_{lq} \pm \Delta M|$ after we imposed the cuts C1–C4 . These events originate from the single production of leptoquarks, as well as their pair production, consequently having a larger cross section than the pair or single production alone. However, this search is model dependent since the single production involves the couplings of the leptoquark to fermions.

Fig. 1 contains the 95% CL excluded regions in the plane κ–M_{lq}

($\kappa\alpha_{em} \equiv \lambda^2/4\pi$) from the single leptoquark search. As expected, the excluded region is independent of κ for masses up to the reach of the leptoquark pair searches. At higher masses the signal is dominated by the single production and consequently the bounds on leptoquarks that couple to d quarks (S_3^+, R_{2R}^2, $\tilde{R}_2^1$, and $\tilde{S}_{1R}$) are the weakest ones for a fixed value of κ. Since the leptoquarks S_{1R}, R_{2L}^1, and R_{2R}^1 couple to u quarks and have $B_e = 1$ they are the ones that possesses the most stringent limits. In fact, for leptoquark Yukawa couplings of the electromagnetic strength ($\kappa = 1$) and an integrated luminosity of 100 fb^{-1}, the LHC can exclude S_{1L} and S_3^0 leptoquarks with masses smaller than 2.6 TeV; while S_3^+, R_{2R}^2, $\tilde{R}_2^1$, and $\tilde{S}_{1R}$ leptoquarks with masses smaller than 2.4 TeV can be ruled out; and S_{1R}, R_{2L}^1, and R_{2R}^1 leptoquarks can be excluded up to masses of 2.9 TeV.

Our conclusions are that the LHC will be able to discover leptoquarks with masses smaller than 1.5–1.7 TeV irrespective of their Yukawa couplings through their pair production for an integrated luminosity of 100 fb^{-1}. Furthermore, the single leptoquark search can extend the reach of the LHC, allowing the discovery of leptoquarks with masses up to 2–3 TeV depending on their couplings to fermions.

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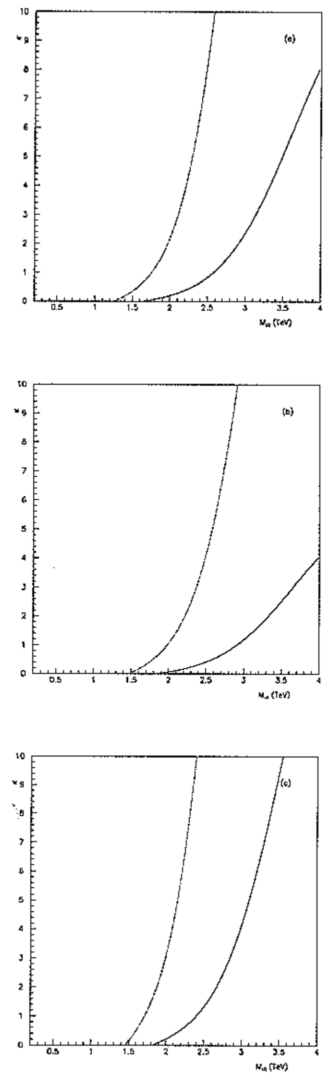

Figure 1: 95% excluded regions in the plane κ–M_{lq} from the single leptoquark analysis for an integrated luminosity of 10/100 fb^{-1} (solid/dotted line) and the leptoquarks: (a) S_{1L} and S_3^0; (b) S_{1R}, R_{2L}^1, and R_{2R}^1; (c)S_3^+, R_{2R}^2, $\tilde{R}_2^1$, and $\tilde{S}_{1R}$.