New Bounds on Leptoquarks

Miriam Leurer

Department of Nuclear Physics
The Weizmann Institute
Rehovot 76100
ISRAEL

Abstract

We show that FCNC processes are unavoidable for leptoquarks that couple to left handed quarks, and derive new FCNC bounds from neutral meson mixing. Despite being induced only at one loop, these processes lead to significant bounds since the leptoquark contributions do not suffer from GIM cancellations. Studying the implications of these bounds we find that (i) The $D^0 - \bar{D}^0$ mixing bound is the first significant FCNC bound from the up sector. Combining it with FCNC bounds from the down sector we arrive at a bound on the first generation couplings. (ii) The $K^0 - \bar{K}^0$ and $D^0 - \bar{D}^0$ mixings bound $g^2/M$ while all other processes bound $g/M$. The combined neutral meson mixing bound is therefore dominant for the heavier leptoquarks, and leads to exclusion of large regions in parameter space which were previously allowed.

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It is well known that $K^0 - \bar{K}^0$ mixing is a sensitive probe for beyond-standard models \[1\]. In this talk we will show that $D^0 - \bar{D}^0$ mixing has become a probe almost as sensitive as that of $K^0 - \bar{K}^0$ mixing.

We will study here the bounds on light scalar leptoquarks. Since for many of us leptoquarks are associated with the GUT scale, we will start by explaining how can a leptoquark be light. Basically, there are three conditions that light leptoquarks should obey: They should not couple to diquarks, and they should couple chirally and diagonally. We will now explain in some detail the meaning of these conditions:

- Diquark couplings are forbidden, since they, together with the lepton-quark couplings lead to nucleon decay. The bound on the leptoquark mass is then extremely strong, of the order of the scale of grand-unified theories.

- When we say that a leptoquark couples chirally, we mean that it couples either to left-handed (LH) or to right-handed (RH) quarks, not to both. A nonchiral leptoquark induces the following four-Fermi interaction:

\[
\mathcal{L}_{eff} = \frac{g_L g_R}{2M^2} \bar{u}_R d_L \bar{e}_R \nu_L
\]

Here $g_L$ and $g_R$ are the leptoquark couplings to LH and RH quarks respectively and $M$ is its mass. The above interaction contributes to $\pi \rightarrow e\nu$ decay and, in contrast to the standard model interaction, it is not chiral and its amplitude is not helicity suppressed. The amplitude is therefore enhanced by $m_\pi/m_e$ relative to the standard model amplitude and, in addition, it is possible to show that there is further enhancement by $m_\pi/(m_u + m_d)$ \[2\]. The enhanced effect of the interaction (1) leads to unacceptable deviations from lepton universality in $\pi$ decays, unless one strongly constrains the leptoquark parameters with the 95% CL bound as strong as $M^2/g_L g_R \geq (170 \text{ TeV})^2$. The chirality requirement enables us to circumvent this bound.

- Leptoquarks couplings are called “diagonal” when the leptoquark couples to a single leptonic generation and to a single quark generation. If the leptoquarks couple nondiagonally they induce flavour changing neutral current (FCNC) processes in both the leptonic sector and the quark sector, leading to strict bounds on the leptoquark parameters \[3\], \[4\]. To avoid these bounds we impose diagonality of the couplings.

The first important point we want to make here is that diagonality is not really possible for leptoquarks that couple to left-handed quarks. The fact that the CKM matrix \[5\] is not trivial implies that one cannot diagonalize the leptoquark interactions simultaneously in the up and the down quark sectors. For example, if the couplings to the up sector are diagonal, and the leptoquark couples only to the first generation up quark, then the couplings in the down sector are not diagonal: The leptoquark couples “mainly” to the down quark, but there are also some coupling to the strange quark (suppressed by $\sin \theta_C$) and some coupling to the bottom quark (suppressed by $V_{13}$, where $V$ is the CKM matrix). Similarly, if the leptoquark couplings to the down quark are diagonal, then its couplings to the up quark sector are almost diagonal, but not strictly so. Therefore FCNC processes are unavoidable for leptoquarks that couple to LH quarks. We will now examine these leptoquarks more closely and will strive to make their couplings as close to diagonal as possible, so that the
bounds from FCNC processes will be minimal. These minimal FCNC bounds are *utterly unavoidable* and turn out to be very significant for heavier leptoquarks (above a few hundred GeV) [8].

There are three scalar leptoquarks that can couple to LH quarks, \( S \), an SU(2)_W scalar carrying weak hypercharge \( Y = 1/3 \); \( D \), an SU(2)_W doublet with \( Y = -7/6 \); and \( T \), an SU(2)_W triplet with \( Y = 1/3 \). Their couplings are given by:

\[
\mathcal{L}_S = \sum_i \left( g_i e^c u^i_L - g'_i \nu^c d^i_L \right) S^{(1/3)}
\]

\[
\mathcal{L}_D = \sum_i \left\{ g_i \bar{e} u^i_L D^{(-5/3)} + g'_i \bar{e} d^i_L D^{(-2/3)} \right\}
\]

\[
\mathcal{L}_T = \sum_i \left\{ \sqrt{2} g_i \bar{\nu} u^i_L T^{(-2/3)} + (g_i \bar{e} u^i_L + g'_i \bar{\nu} d^i_L) T^{(1/3)} + \sqrt{2} g'_i \bar{\nu} d^i_L T^{(4/3)} \right\},
\]  

(2)

where the \( g_i \)'s and \( g'_i \)'s are related by a CKM rotation: \( g'_i = g_j V_{ji} \), with \( V \) the CKM mixing matrix. In order to present our bounds we define the overall strength of the Yukawa couplings to be \( g \) with \( g = \sqrt{\sum_i |g_i|^2} \), and give our final results as bounds in the \( g - M \) plane.

Since leptoquarks that couple to the first generation, are currently of the most interest [7], we will assume from now on that the leptoquarks \( S, D \) and \( T \) couple to the first generation of leptons "mainly" to the first generation of quarks, that is, we will assume that the second generation couplings are suppressed by \( O(\sin \theta_C) \) and the third generation couplings by \( O(|V_{13}| + |V_{12} \cdot V_{23}|) \). Since the third generation couplings are so suppressed, they will actually have no effect, so we shall ignore them and reduce to a two generation picture. Then the couplings can be parametrized by:

\[
g_1 = g \cos \theta \quad \text{and} \quad g_2 = -g \sin \theta \\
g'_1 = g \cos(\theta_C - \theta) \quad \text{and} \quad g'_2 = g \sin(\theta_C - \theta).
\]  

(3)

The angle \( \theta \) describes the deviation from diagonality in the up sector, while \( (\theta_C - \theta) \) describes the deviation from diagonality in the down sector. \( \theta \) therefore determines the division of the FCNC problems between the two quark sectors. Our purpose is to find "the best" \( \theta \), the one which will soften all bounds as much as possible.

At this point we reach the main issue of this talk: *Up till now no significant FCNC bounds were known to arise from the up sector*. The best \( \theta \) choice was obviously \( \theta = \theta_C \), FCNC were then hidden in the up sector, and could not provide any observable signature. However, we want to show here that there is a new class of FCNC bounds, arising from neutral meson mixings and including a significant bound on the up quark sector couplings. One could, at first thought, discard neutral meson mixings as unimportant, since leptoquarks induce them only at one loop, in contrast to other leptoquark bounds that arise already at tree level. However, such an approach is mistaken: After all, \( K^0 - \bar{K}^0 \) and \( D^0 - \bar{D}^0 \) mixing arise in the standard model too only at one loop. Moreover, the GIM mechanism of the standard model leads to a suppression of \( e.g. \ K^0 - \bar{K}^0 \) mixing by \((m_c/M_W)^2\), while for the leptoquarks contribution there is no suppression of this kind. We therefore should expect that neutral meson mixing will supply us with significant bounds on the leptoquarks parameters.
Actually, the fact that the leptoquark contributions arise only at the one loop level is in some ways advantageous: Tree level processes induced by the leptoquarks lead to bounds on $g/M$, while the one loop $K^0 - \bar{K}^0$ and $D^0 - \bar{D}^0$ mixings lead to bounds on $g^2/M$. Therefore, the neutral meson mixing bounds will always become the dominant bounds at some high mass region.

Table 1 summarizes our bounds on the $S$, $D$ and $T$ leptoquarks that couple to the first generation of leptons and “mainly” to the first generation of quarks. These bounds arise from universality in $\pi$ decay, from atomic parity violation [8], and from FCNC processes: Rare $K$ decays and $K^0 - \bar{K}^0$ mixing in the down sector and $D^0 - \bar{D}^0$ mixing in the up sector. All the bounds are at the 95% CL. For a detailed derivation of these bounds see [8].

Our task is to combine the FCNC bounds from both sectors to a bound on the overall coupling $g$. The bounds from the up sector apply to the coupling constant combination $|g_1 g_2|$, and those from the down sector to $|g_1' g_2'|$, namely:

$$f_u(M) \geq |g_1 g_2| = g^2 |\sin(2\theta)/2|$$
$$f_d(M) \geq |g_1' g_2'| = g^2 |\sin 2(\theta_C - \theta)/2| ,$$

where $f_u(M)$ is the $D^0 - \bar{D}^0$ mixing bound and is linear in $M$, and $f_d(M)$ is the dominant FCNC bound from the down sector: At low masses $f_d(M)$ arises from rare $K$ decays and is then quadratic in $M$, at higher masses it comes from $K^0 - \bar{K}^0$ mixing and so is also linear in $M$. Equation (4) makes it clear that any choice of $\theta$ will lead to bounds on $g^2$. The “best” angle $\theta(M)$ that leads to the softest bounds, is given by saturating both inequalities in (4), then:

$$\frac{f_u(M)}{f_d(M)} = \left| \frac{\sin 2\theta}{\sin 2(\theta_C - \theta)} \right| .$$

Solving equation (5) for the “best” angle $\theta$, and substituting this angle into any of the two
inequalities of (4) we get a bound on the overall coupling $g$. Since $\theta$ is small ($\theta \leq \frac{2}{3}\theta_C$), the overall coupling is equal, to a very good approximation, to $g_1$ and $g'_1$. We therefore interpret the bound on $g$ as a bound on the couplings to the first generation.

Figures 1(a–c) describe the combined FCNC bounds for each of the leptoquarks $S$, $D$ and $T$ and compare them to the conventional bound (in the first row of table 1). The FCNC bounds become stronger than the conventional bound at $M = 3300$ GeV for $S$, at $M = 270$ GeV for $D$ and at $M = 710$ GeV for the $T$ leptoquark.
Figure 1(a–c). Bounds on the couplings and masses of first generation leptoquarks that couple to LH quarks, $S$, $D$ and $T$. The regions above the lines are excluded. The full line in each figure is our new FCNC bound, the dashed line is the “conventional” bound arising from universality in leptonic $\pi$ decays or atomic parity violation. We took the direct CDF bounds [9] into account and therefore the mass ranges are above 82 GeV for $S$ and above 113 GeV for $D$ and $T$.

Our new bounds are important for various proposals for leptoquark searches, particularly for indirect searches in accelerators [10]: We exclude leptoquarks with coupling $g = e$ (where $e$ is the electromagnetic coupling) at masses 930 GeV, 340 GeV and 710 GeV for $S$, $D$ and $T$, respectively. Comparing these results with recently proposed methods [10] for indirect leptoquark searches we find that our bounds already exclude large parts of the parameter space that could be penetrated by these methods. Our results are also interesting
for the direct searches at HERA: At the moment, our bounds are better than the first results from HERA for all masses, but in the future HERA will improve on our bounds at masses below $\sim 300$ GeV.

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