

# Indirect Leptoquark Searches at Polarized Lepton Colliders\*

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## ABSTRACT

We examine the utility of employing polarized lepton (electron and muon) beams to perform indirect searches for scalar leptoquarks. We find that polarization can extend the reach in excluding leptoquark masses for both  $e^+e^-$  and  $\mu^+\mu^-$  machines. Polarization can also provide a diagnostic tool for determining leptoquark couplings.

## I INTRODUCTION

Theories attempting to unify the leptons and quarks in some common framework often contain new states that couple to lepton-quark pairs, and hence are called leptoquarks[1]. Necessarily leptoquarks are color triplets, carry both baryon number and lepton number, and can be either spin-0 (scalar) or spin-1 (vector) particles. Perhaps the most well-known examples of leptoquarks appear as gauge bosons of grand unified theories[2]. To prevent rapid proton decay they must be very heavy and unobservable, or their couplings must be constrained by symmetries. Nonetheless, much work has been devoted to signals for the detection of leptoquarks at present and future colliders[3],[4],[5],[6],[7],[8]. One potentially attractive source of light leptoquarks is in  $E_6$  models where the scalar leptoquark can arise as the supersymmetric partner to the color-triplet quark that naturally resides in the fundamental representation  $\mathbf{27}$ . A recent review of the physics signals for leptoquarks can be found in Ref. [9].

At  $e^+e^-$  and  $\mu^+\mu^-$  colliders, pairs of leptoquarks can be produced directly via the  $s$ -channel  $\gamma$  and  $Z$  exchange. The reach for the leptoquark mass for this mode is essentially the kinematic limit, i.e.  $M_S < \sqrt{s}/2$ . However even if a leptoquark is too massive to be produced directly, it can contribute[5],[10],[11] indirectly to the process  $\ell^+\ell^- \rightarrow q\bar{q}$  by interfering with the Standard Model diagrams as shown in Fig. 1. By examining the overall rate and the angular distribution, indirect evidence for leptoquarks can be obtained. In this note, we examine the bounds which can be placed on the leptoquark mass in this way, paying special attention to assessing the potential advantage that polarized electron or muon beams might provide.

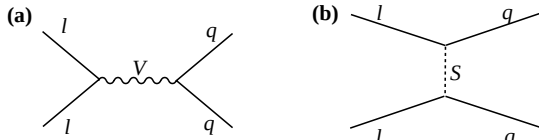


Fig.1. The Feynman diagrams for the process  $\ell^+\ell^- \rightarrow q\bar{q}$  include the (a) Standard Model diagrams involving  $s$ -channel  $V = \gamma, Z$  exchange, and (b) the hypothetical  $t$ -channel leptoquark  $S$  exchange.

The polarization of the beams of a lepton collider can serve two purposes in indirect leptoquark searches: (1) it can extend the reach of the indirect search by serving to enhance the fraction of initial leptons to which the leptoquark couples; (2) it can measure the left-handed and right-handed couplings of the leptoquark separately. Light leptoquarks (less than a few hundred GeV) must also satisfy strong constraints from flavor changing neutral current processes, so that leptoquarks must couple to a single generation of quarks and leptons. For the leptoquarks that might be detected at the multi-TeV machines considered here, the constraints from low energy processes do not necessarily apply, since (as shown below) the reach in leptoquark mass can exceed even 10 TeV, for which the FCNC effects should be very much suppressed.

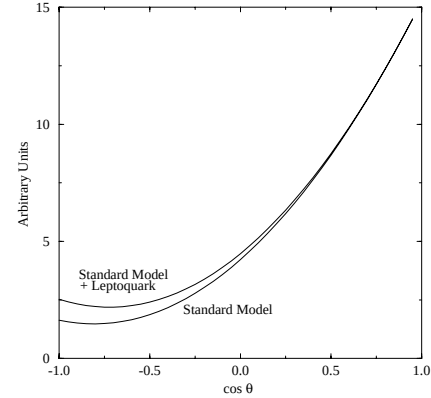


Fig.2. The angular distribution of  $\ell^+\ell^- \rightarrow q\bar{q}$  in the Standard Model and including the effects of a scalar leptoquark for  $M_S = 8$  TeV and  $\sqrt{s} = 4$  TeV.

The deviations from the Standard Model appear in the total cross section and the forward-backward asymmetry,  $A_{FB}$ [5]. In Fig. 2, the angular distribution of the  $q\bar{q}$  pair (the quark is taken to be  $Q = 2/3$ ) is shown in the Standard Model and in the presence of a scalar leptoquark. The total cross section and  $A_{FB}$  amount to integrating this distribution in one or two bins respectively. In order to maximize the sensitivity and following Choudhury[11], we bin the cross section in 18 bins with  $\Delta \cos \theta = 0.1$  in the range  $-0.9 < \cos \theta < 0.9$  and perform a  $\chi^2$ -analysis to calculate the statistical significance of any deviations from the Standard Model. Therefore this procedure is simply a generalization of the measurement of the total cross section and  $A_{FB}$ . The  $\chi^2$  is determined in the usual way from the number of events expected in each bin in the Standard Model,  $n_j^{\text{SM}}$ , and the number of events including the leptoquark,

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$n_j^{\text{LQ}}$ , expected in each bin, as

$$\chi^2 = \sum_{j=1}^{18} \frac{(n_j^{\text{LQ}} - n_j^{\text{SM}})^2}{n_j^{\text{SM}}} . \quad (1)$$

The additional piece in the Lagrangian that is of relevance to us can be parametrized in the form

$$\mathcal{L} = g S \bar{q} (\lambda_L P_L + \lambda_R P_R) \ell , \quad (2)$$

where  $g$  is the weak coupling constant (to set the overall magnitude of the interaction) and  $\lambda_{L,R}$  are dimensionless constants.  $P_L$  and  $P_R$  are the left- and right-handed projectors. The size of the interference effect will be determined by the three parameters  $M_S$ ,  $\lambda_L$  and  $\lambda_R$ .

Let us now concentrate on the interactions  $\ell^-(P^-)\ell^+(P^+) \rightarrow q\bar{q}$ , where the produced quark has  $Q = 2/3$ .  $P^-$  and  $P^+$  are the polarization of the colliding leptons, and can be either left- or right-handed (we choose to define them such that they are always positive). The amplitudes for the diagrams presented in Fig. 1 have been presented for the unpolarized case in Ref. [5], and is generalized to the case with polarization in Ref. [11]. So we do not repeat them here, and proceed directly to the results.

## II ELECTRON-POSITRON COLLIDER

The possibility of a multi-TeV  $e^+e^-$  collider has begun to be taken seriously, and the physics potential of such a machine has started to be assessed. It is expected that substantial polarization in the electron beam can be achieved, while the polarization of the positron beam might not be possible. Figure 3 shows the 95% c.l. bounds that could be achieved on a leptoquark with right-handed couplings ( $\lambda_L = 0$ ) at a  $\sqrt{s} = 4$  TeV  $e^+e^-$  collider, with nonpolarized beams and with 80% and 100% polarization of the electron beam. We have assumed integrated luminosity  $L_0$  and efficiency  $\epsilon$  for detecting the final state quarks so that  $\epsilon L_0 = 70\text{fb}^{-1}$ . This reflects the luminosity benchmark of  $L_0 = 100\text{fb}^{-1}$  and assumes that the tagging efficiency for charm quarks might be as high as 70% at the machine. Polarization from 80% to 100% roughly brackets the range that might reasonably be achievable for the electron beam. The option of polarizing the electron beam is clearly very useful, as it can lead to an increase in the bound by as much as a factor of two. Figure 4 shows the same bounds for the case where the leptoquark has left-handed couplings ( $\lambda_R = 0$ ). In this case the improvement is more modest but still nonnegligible.

In general a leptoquark would have both left- and right-handed couplings. The bounds that can be achieved are substantially larger than the collider energy, provided the leptoquark couplings are not too small compared to the weak coupling.

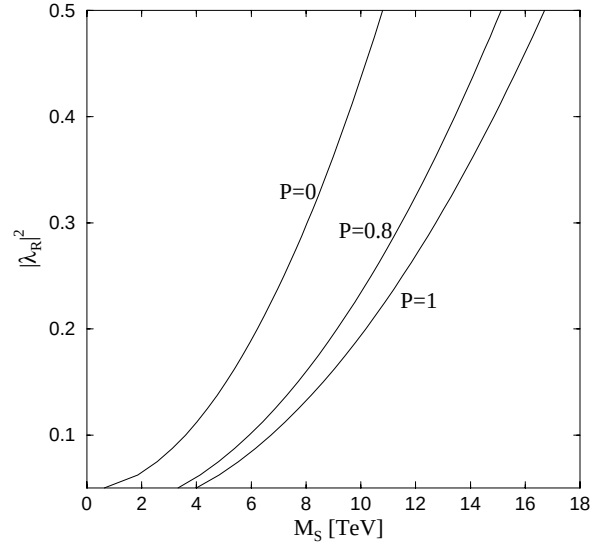


Fig.3. The 95% c.l. bounds on leptoquark mass and couplings at a  $\sqrt{s} = 4$  TeV  $e^+e^-$  collider for a leptoquark with right-handed couplings only ( $\lambda_L = 0$ ). The electron polarization  $P$  is set to 0%, 80% and 100%, and the positron is always unpolarized. The area above each curve would be excluded.

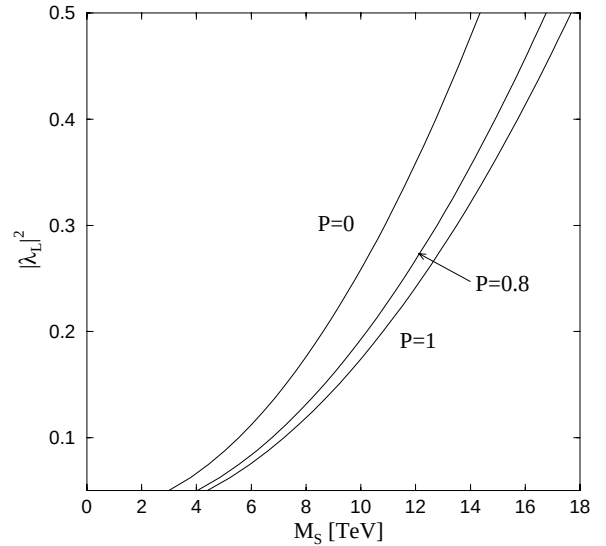


Fig.4. The 95% c.l. bounds on leptoquark mass and couplings at a  $\sqrt{s} = 4$  TeV  $e^+e^-$  collider for a leptoquark with left-handed couplings only ( $\lambda_R = 0$ ). The electron polarization  $P$  is set to 0%, 80% and 100%, and the positron is always unpolarized. The area above each curve would be excluded.

## III MUON COLLIDER

There is increasing interest recently in the possible construction of a  $\mu^+\mu^-$  collider[14],[15],[16],[17]. The expectation is that a muon collider with multi-TeV energy and the high luminosity can be achieved[18, 19]. Initial surveys of the physics po-

tential of muon colliders have been carried out[20],[21]. Both  $\mu^+$  and  $\mu^-$  beams can be at least partially polarized, but perhaps with some loss of luminosity. At the Snowmass meeting a first study of the tradeoff between polarization and luminosity at a muon collider was presented[22]. This analysis found that if one tolerates a drop in luminosity of a factor two, then one can achieve polarization of both beams at the level of  $P^- = P^+ = 34\%$ . (One could extend the polarization to 57% with a reduction in the luminosity by a factor of eight. This additional polarization does not prove useful if one must sacrifice so much luminosity, at least for the leptoquark searches studied here.) It might be possible to maintain the luminosity at its full unpolarized value if the proton source intensity (a proton beam is used to create pions that decay into muons for the collider) could be increased[22]. We have chosen to present results for each of these three possible scenarios below.

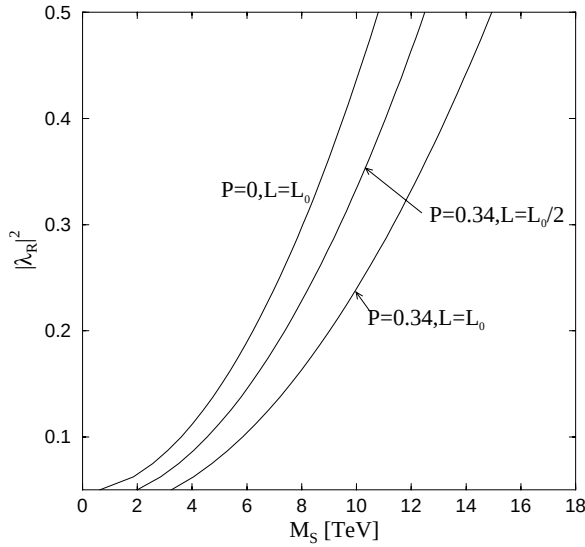


Fig.5. The 95% c.l. bounds on leptoquark mass and couplings at a  $\sqrt{s} = 4$  TeV  $\mu^+\mu^-$  collider for a leptoquark with right-handed couplings only ( $\lambda_L = 0$ ). The curves indicate the bounds for nonpolarized beams, both  $\mu^+$  and  $\mu^-$  having polarization  $P$  is set to 34% and no reduction in luminosity, and both  $\mu^+$  and  $\mu^-$  having polarization  $P$  is set to 34% and a reduction in luminosity of a factor of two. The area above each curve would be excluded.

In Fig. 5 the 95% c.l. bounds that can be obtained at a muon collider for a leptoquark with right-handed couplings are shown for three cases: (1) unpolarized beams with integrated luminosity such that  $\epsilon L_0 = 70\text{fb}^{-1}$ ; (2) both the  $\mu^+$  and  $\mu^-$  beams with 34% polarization with the same luminosity  $L_0$ ; and (3) both the  $\mu^+$  and  $\mu^-$  beams with 34% polarization but now including the expected reduction in luminosity  $L = L_0/2$ . One sees that even with the reduction of luminosity one obtains improved bounds with polarized  $\mu$  beams. In Fig. 6 the bounds that can be obtained at a muon collider for a leptoquark with left-handed couplings are shown. In this case the expected luminosity reduction associated with polarizing the muon beams does not result in an improved bound.

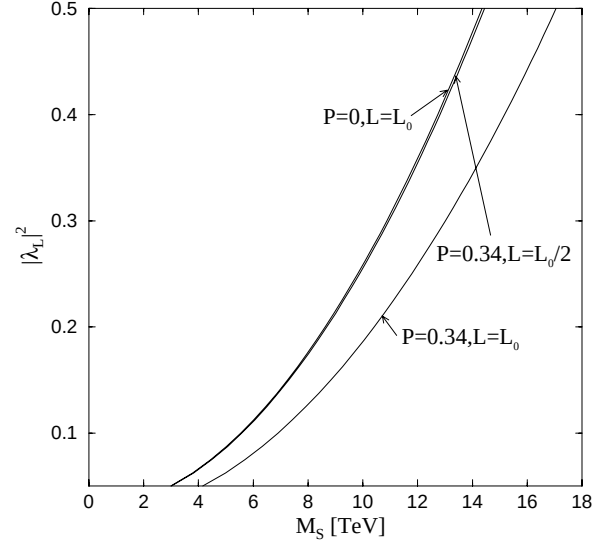


Fig.6. The 95% c.l. bounds on leptoquark mass and couplings at a  $\sqrt{s} = 4$  TeV  $\mu^+\mu^-$  collider for a leptoquark with left-handed couplings only ( $\lambda_R = 0$ ). The curves indicate the bounds for nonpolarized beams, both  $\mu^+$  and  $\mu^-$  having polarization  $P$  is set to 34% and no reduction in luminosity, and both  $\mu^+$  and  $\mu^-$  having polarization  $P$  is set to 34% and a reduction in luminosity of a factor of two. The area above each curve would be excluded.

#### IV CONCLUSIONS

We have performed a first study of the indirect search for leptoquarks at multi-TeV lepton colliders. It is known already that polarization can be advantageous at the NLC[9],[11], and we have shown by how much polarization is found to increase the lower bounds on scalar leptoquark masses at both multi-TeV  $e^+e^-$  machines and  $\mu^+\mu^-$  machines. Of particular interest is the utility of polarization in the case of muon colliders, for which partial polarization of both beams is possible but comes at the cost of loss in luminosity. If one can achieve 34% polarization in both muon beams, we find that this does improve the reach for leptoquarks if they couple to the right-handed muon, but does not either improve or disimprove substantially the reach for leptoquarks that couple to the left-handed muon. One should keep in mind that the expectations for the polarization and luminosity at a muon collider are very preliminary, and it might be possible to achieve polarization without significant reduction in the luminosity[22]. We find that polarizing the electron beam at an  $e^+e^-$  collider improves the reach in scalar leptoquark mass, assuming no loss of luminosity.

Finally one can assess the utility of polarizing both beams as opposed to polarizing just one beam. This can be done by comparing Figs. 3 and 5 for the right-handed leptoquark case and Figs. 4 and 6 for the left-handed leptoquark case. We summarize the bound for leptoquarks with interactions of order the weak coupling strength in Table I, for both left-handed couplings ( $|\lambda_L|^2 = 0.5, |\lambda_R|^2 = 0$ ) and right-handed couplings ( $|\lambda_R|^2 = 0.5, |\lambda_L|^2 = 0$ ). The 95% c.l. limits in the two

unknown parameter analysis, here translates into a 98.6% c.l. when only the leptoquark mass is unknown. For both cases one sees that the 34% polarization of both beams gives roughly the same bounds as a collider with one beam polarized at the 80-90% level.

Table I: Bounds on leptoquark masses at 98.6% confidence level, assuming either left-handed couplings ( $|\lambda_L|^2 = 0.5, |\lambda_R|^2 = 0$ ) or right-handed couplings ( $|\lambda_L|^2 = 0, |\lambda_R|^2 = 0.5$ ).

| Luminosity and Polarization( $\ell^-, \ell^+$ ) | Coupling | $M_S$ -Bound (TeV) |
|-------------------------------------------------|----------|--------------------|
| $L_0$ (0%,0%)                                   | Left     | 14.3               |
|                                                 | Right    | 10.8               |
| $L_0$ (80%,0%)                                  | Left     | 16.8               |
|                                                 | Right    | 15.1               |
| $L_0$ (100%,0%)                                 | Left     | 17.7               |
|                                                 | Right    | 16.7               |
| $L_0$ (34%,34%)                                 | Left     | 17.1               |
|                                                 | Right    | 14.9               |
| $L_0/2$ (34%,34%)                               | Left     | 14.4               |
|                                                 | Right    | 12.5               |

It should be emphasized that there are many uses for polarization at these machines, and the leptoquark search is just one entry on a long list of processes that should be studied to ascertain the full usefulness of including of polarization. Even without polarization we find the reach of a 4 TeV lepton collider is quite high: we find that leptoquarks with couplings of roughly electroweak strength can be ruled out well above 10 TeV, and discovered even if they have masses well above the collider energy. Whether nature provides us with leptoquarks of about 10 TeV is, however, another matter indeed.

## V ACKNOWLEDGEMENT

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