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Leptoquark Search at e^+e^- Colliders

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Abstract

We investigate the possibility of detecting a scalar leptoquark, coupling to the electron and the top, at a linear collider. For coupling strength equalling the weak coupling constant, the present mass bounds are of the order of 300 GeV. We demonstrate that at the NLC, one could detect such particles if their mass were less than a few TeV's.

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In the otherwise glorious success of the Standard Model (SM), there remains the "aesthetic drawback" of the arbitrary assignment of quark and lepton fields. Theories that venture beyond the SM do offer hints of a pattern [1, 2] albeit at the cost of new fields that mediate new interactions between the quarks and leptons. Leptoquarks are but a kind. Transforming as the fundamental representation of the $SU(3)_c$ gauge group, these can be either (pseudo-)scalars or (axial-)vectors.

Some phenomenogical constraints (at least for leptoqaurks coupling to the first two generations) are obvious. The stability of the proton dictates that if the mass (m) and the coupling (f) be such that $m/f \lesssim 10^{16}$ GeV, then a leptoquark may not have a diquark coupling[3]. Bounds[4] from flavour changing neutral current processes ($m/f \gtrsim 10^5$ GeV) are evaded only if we assume that these couple to only one flavour of leptons and quarks each[5]. Furthermore, the requirement that the leptonic decay modes of the pseudoscalar mesons be not enhanced stipulates that either $m/f \gtrsim 10^5$ GeV or the leptoqaurk couples chirally[6]. Bounds from atomic parity violation are somewhat weaker[5].

Inspite of such constraints, there has been a recent surge of interest in the subject[1]. The reasons are twofold. On the one hand, there do exist symmetries and models wherein the above constraints are comfortably evaded while allowing a rich phenomenology; on the other, recent experiments have begun to provide us with direct probes[7]. For coupling strengths similar to the weak gauge coupling, these searches give lower bounds of the order of a few hundred GeV.

There could exist though one class of leptoquarks that would easily evade the aforementioned constraints without any further assumptions. We focus here on a scalar particle (S) that couples the electron only with the quarks of the third generation. In the SM, the ordinary Yukawa coupling for the top quark is almost the same as the weak gauge coupling. If this be the case here too, one could look forward to interesting new features. In a recent work, Bhattacharyya *et al.* [8], have investigated such a scenario. They conclude that the

[1]For a representative list of recent work, please see ref.[8]

strongest bounds can be inferred from the leptonic partial widths of the Z, and for the above choice of coupling strengths, are of the order of 300 GeV.

In this letter we point out that at the next generation of linear colliders (such as CLIC,JLC,TESLA,VLEPP *etc.*) a significant improvement can be made. While direct production obviously limits us to the kinematic bound, one could probe larger masses by considering interactions involving virtual leptoquarks. With the discovery of the top quark and the determination of its mass[9], a simple experiment suggests itself.

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

$$\mathcal{L}_Y = g\, S\, \bar{t}(h_L P_L + h_R P_R) e \tag{1}$$

where g is the weak coupling constant and $h_{L,R}$ are dimensionless constants.

Let us now concentrate on the interaction $e^-(p_1, \lambda) e^+(p_2, \overline{\lambda}) \longrightarrow t(p_3)\bar{t}(p_4)$. Here $\lambda, \overline{\lambda}$ denote the polarization of the electron and the positron respectively. Within the SM, the interaction proceeds *via* two tree–level s-channel diagrams, the amplitude for which can be expressed as

$$\mathcal{M}_{SM} = \sum_i \frac{g^2}{s - m_i^2} \bar{u}(p_3)\, \gamma_\mu \left(v_i^{(t)} + a_i^{(t)} \gamma_5 \right)\, v(p_4)\;\; \bar{v}(p_2, \overline{\lambda})\, \gamma_\mu \left(v_i^{(e)} + a_i^{(e)} \gamma_5 \right)\, u(p_1, \lambda) \tag{2}$$

where the sum runs over the photon and the Z and

$$\begin{aligned}
v_\gamma^{(e)} &= -\sin\theta_W & a_\gamma^{(e)} &= 0 \\
v_Z^{(e)} &= \frac{-1 + 4\sin^2\theta_W}{4\cos\theta_W} & a_Z^{(e)} &= \frac{1}{4\cos\theta_W} \\
v_\gamma^{(t)} &= \frac{2\sin\theta_W}{3} & a_\gamma^{(t)} &= 0 \\
v_Z^{(t)} &= \frac{1 - 8\sin^2\theta_W/3}{4\cos\theta_W} & a_Z^{(t)} &= \frac{-1}{4\cos\theta_W}
\end{aligned} \tag{3}$$

With the introduction of the leptoquark, we have an additional t–channel diagram :

$$\mathcal{M}_{LQ} = \frac{g^2}{t - m_S^2} \bar{u}(p_3)\; (h_L P_L + h_R P_R)\; u(p_1, \lambda)\;\; \bar{v}(p_2, \overline{\lambda})\; (h_L^* P_R + h_R^* P_L)\; v(p_4). \tag{4}$$

The very fact that the additional contribution is a t–channel one as opposed to the s–channel "background", points to the possibility of a significant modification in the angular distribution. That this is indeed so is borne out by a glance at the differential cross section. For reasons of compactness, we first define:

$$
\begin{aligned}
A_{ij} &= (1+\lambda\overline{\lambda})\left\{v_i^{(e)}v_j^{(e)} + a_i^{(e)}a_j^{(e)}\right\} - (\lambda+\overline{\lambda})\left\{v_i^{(e)}a_j^{(e)} + a_i^{(e)}v_j^{(e)}\right\} \\
B_{ij} &= (1+\lambda\overline{\lambda})\left\{v_i^{(e)}a_j^{(e)} + a_i^{(e)}a_j^{(e)}\right\} - (\lambda+\overline{\lambda})\left\{v_i^{(e)}v_j^{(e)} + a_i^{(e)}v_j^{(e)}\right\} \\
C_{ij} &= v_i^{(t)}v_j^{(t)} + a_i^{(t)}a_j^{(t)} \\
D_{ij} &= v_i^{(t)}a_j^{(t)} + a_i^{(t)}v_j^{(t)} \\
Q_i &= |h_L|^2(1+\lambda)(1+\overline{\lambda})\left(v_i^{(e)} - a_i^{(e)}\right)\left(v_i^{(t)} + a_i^{(t)}\right) \\
&+ |h_R|^2(1-\lambda)(1-\overline{\lambda})\left(v_i^{(e)} + a_i^{(e)}\right)\left(v_i^{(t)} - a_i^{(t)}\right) \\
R_i &= |h_L|^2(1+\lambda)(1+\overline{\lambda})\left(v_i^{(e)} - a_i^{(e)}\right)\left(v_i^{(t)} - a_i^{(t)}\right) \\
&+ |h_R|^2(1-\lambda)(1-\overline{\lambda})\left(v_i^{(e)} + a_i^{(e)}\right)\left(v_i^{(t)} + a_i^{(t)}\right) \\
F &= \frac{1}{4}\left[|h_L|^2(1+\lambda) + |h_R|^2(1-\lambda)\right]\left[|h_L|^2(1+\overline{\lambda}) + |h_R|^2(1-\overline{\lambda})\right] .
\end{aligned}
\tag{5}
$$

Finally we have, in terms of the Mandelstam variables,

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{3\pi\alpha^2}{s^2\,\sin^4\theta_W}\Bigg[& 2\sum_{ij}\frac{A_{ij}C_{ij}(u^2+t^2-2m_t^4) + B_{ij}D_{ij}s(t-u) + 4v_i^{(t)}v_j^{(t)}A_{ij}m_t^2 s}{(s-m_i^2)(s-m_j^2)} \\
& + \sum_i \frac{Q_i(t-m_t^2)^2 + R_i m_t^2 s}{(t-m_S^2)(s-m_i^2)} + F\left(\frac{t-m_t^2}{t-m_S^2}\right)^2\Bigg] .
\end{aligned}
\tag{6}
$$

A straightforward integration of the above expression would obviously give us an indication of the observability at a collider of a given beam energy. A more sensitive test could be to compare the observed forward–backward asymmetry with the SM expectation. Much more can be achieved though by comparing the angular distributions. To do this, one would divide the angular width of the experiment into bins and compare the observed number of events n_j in each with the SM prediction n_j^{SM}. A χ^2 test can be devised as

$$\chi^2 = \sum_{j=1}^{\text{bins}} \left(\frac{n_j^{SM} - n_j}{\Delta n_j^{SM}} \right)^2 \tag{7}$$

The number of events obviously is obtained by integrating eqn.(6) over the part of the phase space corresponding to the particular bin and is given by

$$n_i = \sigma_i \epsilon L \tag{8}$$

where ϵ is the detector efficiency and L is the machine luminosity. The error in eqn.(7) is a combination of the statistical and systematic ones *viz.*

$$\Delta n = \sqrt{(\sqrt{n})^2 + (\delta_{\text{syst}} n)^2}. \tag{9}$$

To make our results quantitative, we choose to investigate for C.M. energies of 500 GeV and 1000 GeV. For the integrated luminosity we assume the oft-quoted figure[10] of 10 fb^{-1}. For experimental simplicity, we delimit ourselves to be at least 20° away from the beam pipe. The efficiency (ϵ) for the top-reconstruction is taken to be 15% and we make a conservative estimate of $\delta_{\text{syst}} = 0.05$. Dividing the angular region into 10 equal-sized bins[2], we then perform the χ^2 test as in eqn(7). To avoid spurious results, we reject a bin from the analysis if either (i) the difference between the SM expectation and the measured number of events is less than one or (ii) the SM expectation is less than one event while the measured number is less than three.

For reasons of clarity, we do not attempt to present our results as a function of all three of the parameters m_S, h_L, h_R. We rather choose to present these as bounds in the two–parameter space of mass and one of the couplings, keeping the other zero. The interpretation is straightforward. Any combination of the two parameters *above* the curves (*i.e.* away from the origin) can be ruled out at 95% C.L.[3] Since we are dealing with one–sided bounds, this

[2] We find that the sensitivity of the results to the binning is rather weak for bin cardinality between 6 and 20.

[3] If the value of one of the parameters were known, then a 98.6% C.L. bound on the other is given by the corresponding projection on the axis.

corresponds to $\chi^2 > 4.61$ in eqn.(7). Figure 1 shows the bounds for the "left–handed" leptoquark for both $\sqrt{s} = 500$ GeV and 1000 GeV.

If $|h_L| = 1$, we would then be able to detect (with unpolarized beams) the corresponding particle at NLC500 if its mass were less than 2.4 TeV, and at NLC1000 if $m_S < 3.75$ TeV. This should be compared with the current bounds of $m_S \gtrsim 300$ GeV as obtained in ref.[8].

In Fig. 1, we also indicate the bounds that would be accessible if beam polarization were achieved, a distinct possibility at the NLC. Since polarizing positrons is a relatively difficult proposition, we have chosen $\overline{\lambda} = 0$ in eqn.(6). For simplicity, we present curves only for $\lambda = 0.5$ and $\lambda = 1.0$ (*i.e.* 50% and 100% left–polarized electron beams). A glance at the figure shows that this would improve the detection capability by a significant factor.

A corresponding analysis for the right–chirally coupled field can be made as easily and we present the results thereof in Fig. 2. In this case, we would obviously do better with a right–polarized electron beam and hence we present our results for $\lambda = 0, -0.5, -1.0$. A comparison of Figs. 1 and 2 show that, for unpolarized beams, the obtainable limits for the right–chiral field are weaker compared to those for the left–chiral one. This can easily be traced to the significant difference between the left–handed and the right–handed couplings of the t–quark to Z leading to a different level of "background". This difference obviously narrows down as the extent of beam polarization increases. We summarize our results in Table 1.

Until now, we have restricted ourselves to the case where only one of $h_{L,R}$ is non-zero. This was motivated by the consideration that if the leptoquark is relatively light, then its coupling to the first two generations must necessarily be chiral. For our case, this constraint is obviously not so strict. In Figs. 3 and 4, we present the 95% C.L. bound in the h_L–h_R plane (for representative values of $m_S = 3$ TeV and $m_S = 4$ TeV) that can be achieved at the NLC500 and NLC1000 respectively. The curves for 100% beam polarization have been dispensed with as these would obviously be parallel to the coordinate axes.

To conclude, we point out that the present constraints on a scalar leptoquark that couples the electron and the top are indirect and relatively weak. However at the next linear collider, significant improvement can be made in constraining the properies of such particles. Indeed, for a coupling strength close to the weak coupling constant, such a collider would be able to detect such particles such particles of masses upto about four times the center of mass energy.

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[10] See *e.g.* , Summary of the Working Group 6, *Proc. ECFA Workshop on e^+e^- Linear Colliders, Garmisch-Partenkirchen, 1992*, ed. R. Settles, p. 484 (MPI-PhE/93-14, ECFA 93-154).

Energy	Limit of Observability (TeV)					
	$\lvert h_L\rvert = 1, \quad \lvert h_R\rvert = 0$			$\lvert h_R\rvert = 1, \quad \lvert h_L\rvert = 0$		
	$\lambda = 0$	$\lambda = 0.5$	$\lambda = 1.0$	$\lambda = 0$	$\lambda = -0.5$	$\lambda = -1.0$
$\sqrt{s} = 500$ GeV	2.39	2.75	3.02	1.95	2.50	3.10
$\sqrt{s} = 1000$ GeV	3.75	4.31	4.73	2.98	3.76	4.66

Table 1: Limits of observability (98.6% C.L.) for scalar leptoquarks coupling chirally to the electron and the top-quark with a strength equalling the weak coupling constant. λ is the electron polarization, the positron beam being unpolarized.

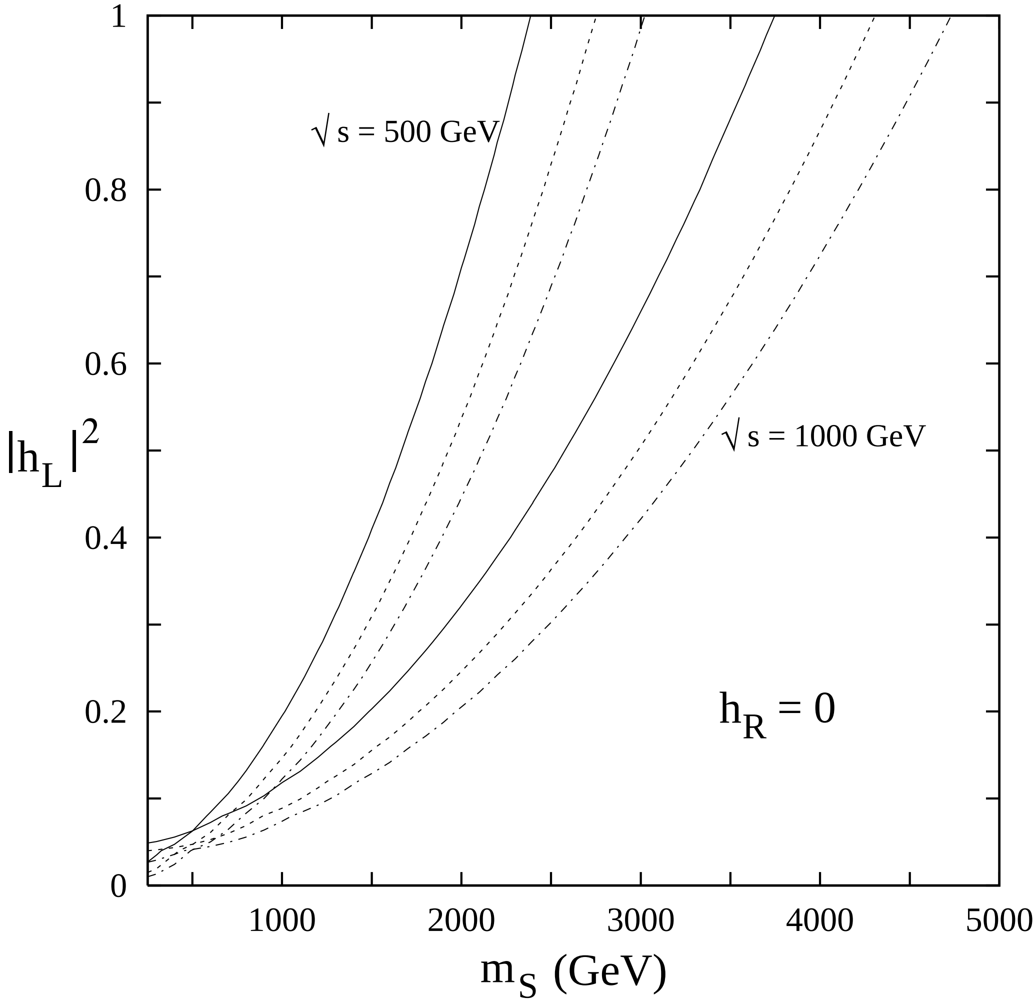

Figure 1: Contours of detectability in the m_S–h_L plane for $h_R = 0$ (left set : NLC500, right set : NLC1000). The parameter space *above* the curves can be ruled out at 95% C.L. The solid, dashed and dot-dashed curves are for electron polarization 0, +0.5 and +1.0 respectively (the positron is unpolarized).

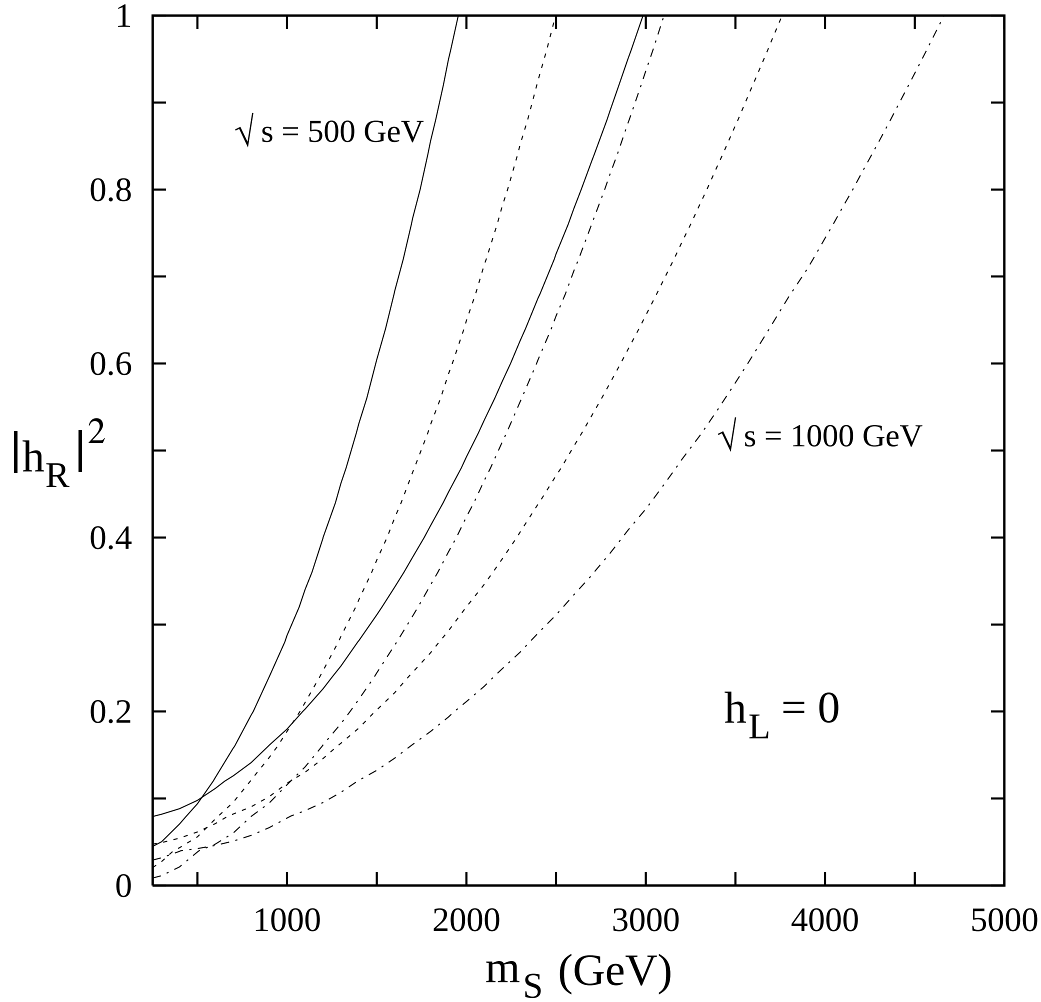

Figure 2: Contours of detectability in the m_S–h_R plane for $h_L = 0$ (left set : NLC500, right set : NLC1000). The parameter space *above* the curves can be ruled out at 95% C.L. The solid, dashed and dot-dashed curves are for electron polarization 0, -0.5 and -1.0 respectively (the positron is unpolarized).

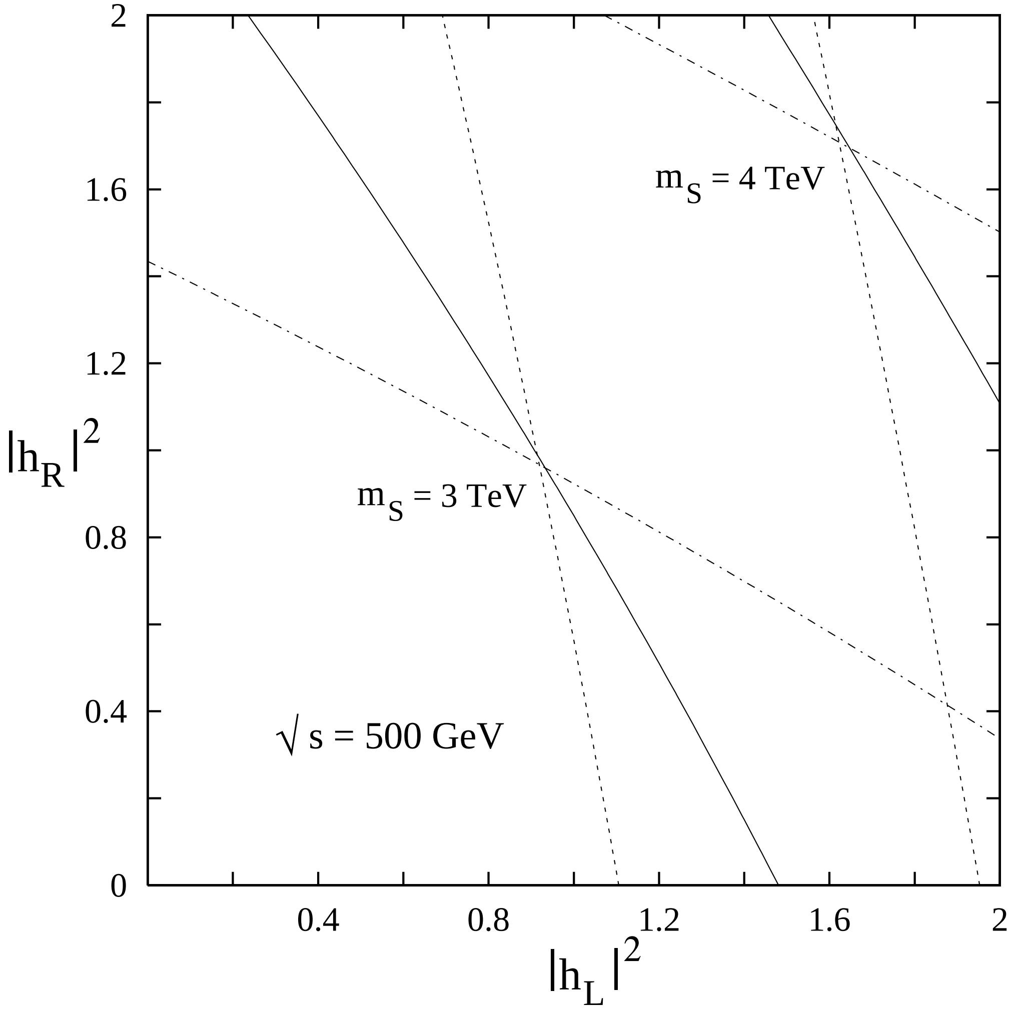

Figure 3: Contours of detectability in the h_L–h_R plane at NLC500. The parameter space *above* the curves can be ruled out at 95% C.L. The solid, dashed and dot-dashed curves are for electron polarization 0, +0.5 and −0.5 respectively (the positron is unpolarized).

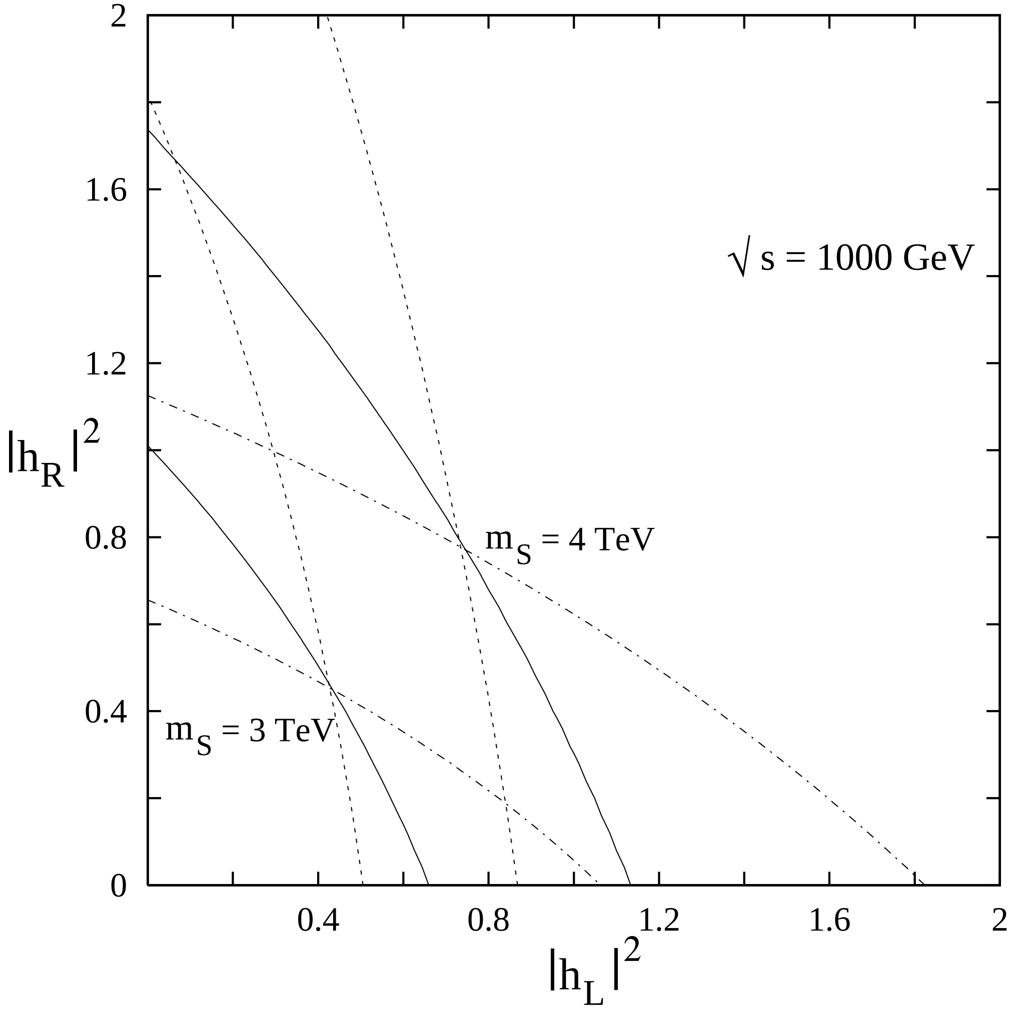

Figure 4: As in Fig. 3, but for NLC1000.

This figure "fig1-2.png" is available in "png" format from:

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