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LEPTOQUARKS AT FUTURE LEPTON COLLIDERS *

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In this talk I summarize the capability of future lepton colliders to discover leptoquarks and to determine their electroweak quantum numbers. This analysis is an updated discussion based on the results presented in the Snowmass 1996 New Phenomena Working Group report as well as some more recent work that has appeared in the literature as a result of the HERA high-Q^2 excess.

1. Introduction and Background

The observation of a possible excess of both neutral and charged current events at HERA[1] has brought the discussion of leptoquarks(LQs) and their properties off the back burner, though they have been subjects of study for quite some time[2,3]. For more than a decade any discussion of leptoquark models has been historically based on the classic work by Buchmüller, Rückl and Wyler (BRW)[2]. As these authors showed, LQs can be either spin-0 (scalars) or spin-1 (vectors) and may carry fermion number, $F = 3B + L = 0$ or ± 2. In that paper the authors provided a set of basic assumptions under which consistent leptoquark models can be constructed; these can be restated as:

(a) LQ couplings must be invariant with respect to the Standard Model (SM) gauge interactions,
(b) LQ interactions must be renormalizable,
(c) LQs couple to only a single generation of SM fermions,
(d) LQ couplings to fermions are chiral,
(e) LQ couplings separately conserve Baryon and Lepton numbers,
(f) LQs only couple to the SM fermions and gauge bosons.

Amongst these assumptions, both (a) and (b) are can be considered sacrosanct whereas (c)-(e) are data driven[2,3] by a host of low energy processes as discussed by Davidson, Bailey and Campbell and by Leurer. Assumption (f) effectively requires that the leptoquark be the only new component added to the SM particle spectrum,

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which seems quite unlikely in any realistic extended model, and is perhaps the least tenable. Assuming the validity of (a)-(f), the possible set of LQ models is quite restricted and we arrive at the relatively short list shown in Table 1 as obtained years ago by BRW:

Attempts to explain the HERA data have led to new types of LQs not obtainable from the BRW analysis; this occurs as follows. Since the HERA excess appears in the e^+p channel and not in e^-p we would be forced to conclude that our HERA associated LQ has $F = 0$. Furthermore, since vector LQs have a far larger cross section at the Tevatron than do scalars[4] and, since neither CDF nor D0 have observed LQ pair production[5], we must conclude the HERA LQ is a scalar. One of the difficulties associated with the LQ interpretation of the HERA excess is then immediately obvious from Table 1 in that all $F = 0$ scalars have a branching fraction(B_ℓ) into ej of unity, something already excluded by CDF/D0 searches if the LQ mass is anywhere near 200 GeV. This necessitates the construction of LQ models that go beyond[6] those considered by BRW and this can only be done by dropping (at least) one of the BRW assumptions, *e.g.*, assumption (f). Thus we should remember that the BRW list is not necessarily an exhaustive one and be prepared for LQs with other possible quantum numbers. The BRW set does, however, provide a fertile testing ground for the ability of colliders to distinguish the various possibilities from one another.

2. Leptoquark Pair Production

As is well known, though hadron colliders provide a high mass reach for searches they are incapable of determining the electroweak quantum numbers of the LQs once they are discovered. However, it is possible that from the cross section and angular distributions the spin of the LQ may be determined. Before the turn on of a first generation lepton collider it is likely that the LHC will have probed the LQ mass range up to $\simeq 1.3 - 1.5$ TeV for scalars and $2.1 - 2.5$ TeV for vectors[7] in the pair production channel. (Here we have accounted for the new NLO pair production cross section results obtained by Krämer *et al.*[8]). Thus we should already know if a LQ will be kinematically accessible at the first generation lepton collider.

At planned lepton colliders, which have smaller values of $\sqrt{s}$ than the LHC, the pair production cross section and angular distribution in e^+e^- or $\mu^+\mu^-$ collisions alone already tells us much about both the LQ spin and electroweak quantum numbers. Fig. 1 from the recent analysis of Rückl, Settles and Spiesberger(RSS)[9], shows that LQ pair production cross sections at lepton colliders are large and give quite reasonable rates assuming canonical luminosities in the 50-100 fb^{-1} range. (We note that these results assume that the strength of the Yukawa coupling, λ, at the eq vertex is quite weak in comparison to electroweak couplings. If this is *not* the case then LQ pair production will also occur through $t(u)-$channel quark exchange as well as $s-$channel γ and Z exchange. This can result in a significant change in the overall production rate as well as the angular distribution.) We also see from this figure the rather strong variations in the cross section due to both LQ spin and

Table 1. Quantum numbers and fermionic couplings of the BRW leptoquark states as well as the minimal $SU(5)$ representation into which it can be embedded. No distinction is made between the $SU(5)$ representation and its conjugate.

	Leptoquark	SU(5) Rep	Q	Coupling	B_ℓ
Scalars					
$F=-2$	S_{1L}	**5**	1/3	$\lambda_L\,(e^+\bar{u}),\ \lambda_L\,(\bar{\nu}\bar{d})$	1/2
	S_{1R}	**5**	1/3	$\lambda_R\,(e^+\bar{u})$	1
	$\widetilde{S}_{1R}$	**45**	4/3	$\lambda_R\,(e^+\bar{d})$	1
	S_{3L}	**45**	4/3	$-\sqrt{2}\lambda_L\,(e^+\bar{d})$	1
			1/3	$-\lambda_L\,(e^+\bar{u}),\ -\lambda_L\,(\bar{\nu}\bar{d})$	1/2
			−2/3	$\sqrt{2}\lambda_L\,(\bar{\nu}\bar{u})$	0
$F=0$	R_{2L}	**45**	5/3	$\lambda_L\,(e^+u)$	1
			2/3	$\lambda_L\,(\bar{\nu}u)$	0
	R_{2R}	**45**	5/3	$\lambda_R\,(e^+u)$	1
			2/3	$-\lambda_R\,(e^+d)$	1
	$\widetilde{R}_{2L}$	**10/15**	2/3	$\lambda_L\,(e^+d)$	1
			−1/3	$\lambda_L\,(\bar{\nu}d)$	0
Vectors					
$F=-2$	V_{2L}	**24**	4/3	$\lambda_L\,(e^+\bar{d})$	1
			1/3	$\lambda_L\,(\bar{\nu}\bar{d})$	0
	V_{2R}	**24**	4/3	$\lambda_R\,(e^+\bar{d})$	1
			1/3	$\lambda_R\,(e^+\bar{u})$	1
	$\widetilde{V}_{2L}$	**10/15**	1/3	$\lambda_L\,(e^+\bar{u})$	1
			−2/3	$\lambda_L\,(\bar{\nu}\bar{u})$	0
$F=0$	U_{1L}	**10**	2/3	$\lambda_L\,(e^+d),\ \lambda_L\,(\bar{\nu}u)$	1/2
	U_{1R}	**10**	2/3	$\lambda_R\,(e^+\bar{d})$	1
	$\widetilde{U}_{1R}$	**75**	5/3	$\lambda_R\,(e^+u)$	1
	U_{3L}	**40**	5/3	$\sqrt{2}\lambda_L\,(e^+u)$	1
			2/3	$-\lambda_L\,(e^+d),\ \lambda_L\,(\bar{\nu}u)$	1/2
			−1/3	$\sqrt{2}\lambda_L\,(\bar{\nu}d)$	0

quantum number choices.

This sensitivity can be seen more clearly from Table 2 which shows the cross sections and polarization asymmetries for all the scalar LQs in the BRW scheme given in Table1 assuming degenerate multiplets. It is easy to see that from the cross section and polarization asymmetry it will be quite simple to distinguish the various models. We remind the reader again that there can be more LQ quantum number assignments than are obtainable from simply following the BRW assumptions[6] and some confusion may thus occur in quantum number extractions if care is not exercised.

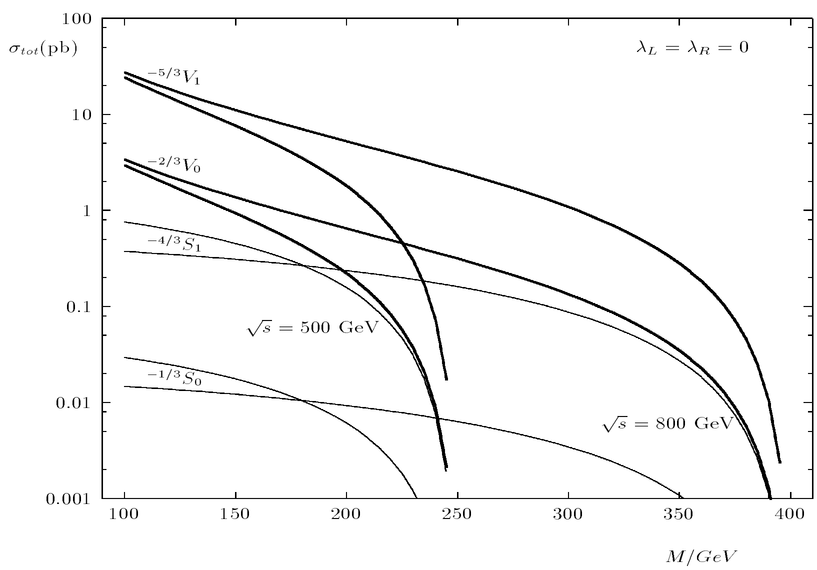

Fig. 1. Total cross sections for leptoquark pair-production at fixed center-of-mass energies as a function of the leptoquark mass M assuming vanishing Yukawa couplings and including corrections due to beamstrahlung and ISR from the analysis of RSS. Here S or V refer to the LQ spin, the upper(lower) index is the corresponding electric charge(weak isospin).

The search reach for LQs in the pair production mode in e^+e^- collisions has been most thoroughly studied in the recent RSS analysis. These authors perform a very detailed simulation study including all SM backgrounds, detector cuts and smearing, decay and hadronization effects as well as including beamstrahlung and initial state radiation(ISR). Table 3 from the RSS analysis shows the expected search

Table 2. Cross sections for the three scalar leptoquark pair decay channels in fb at a 500 GeV NLC assuming complete leptoquark multiplets with a common mass of 200 GeV. The polarization asymmetry in the $\ell\ell jj$ channel is also given. In all cases $\tilde{\lambda} \ll 1$ is assumed.

Leptoquark	$\ell\ell jj$	$\ell\nu jj$	$\nu\nu jj$	$A_{\ell\ell jj}^{LR}$
S_{1L}	1.88	3.77	1.88	-0.618
S_{1R}	7.53	0.0	0.0	-0.618
$\widetilde{S}_{1R}$	120.4	0.0	0.0	-0.618
S_{3L}	192.2	3.77	1.88	0.931
R_{2L}	181.0	0.0	80.4	0.196
R_{2R}	261.4	0.0	0.0	-0.141
$\widetilde{R}_{2L}$	47.6	0.0	33.2	0.946

reach for all BRW type LQs. In almost all cases we see that the reach approaches the kinematic limit for pair production of $\simeq \sqrt{s}/2$ in both the $eejj$ and $e\nu jj$ mode. The reach is seen to be usually somewhat less in the $\nu\nu jj$ channel. It appears that LQs will not be missed at a lepton collider.

It may also be possible to *indirectly* probe the existence of LQs in $e^+e^- \to q\bar{q}$ processes since t-channel LQ exchange can contribute significantly–provided the Yukawa coupling is sufficiently large. Here one looks for deviations in both the total cross section as well as the angular distribution in a manner resulting from the t-channel exchange. Fig. 2 from the updated analysis of Hewett[10], a part of the DPF study in Ref. 3, shows the region in LQ mass vs LQ Yukawa coupling space that can be probed by this technique for the case of the E_6-type LQs, *i.e.*, $S_{1L,R}$. Note that even for $(\lambda/e)^2 = 0.1$ the reach is of order $2\sqrt{s}$ which is more than 4 times that obtainable from direct pair production. Comparable reaches are also obtainable for other LQ types. The OPAL Collaboration[11] has recently performed this type of analysis with real data at LEPII and have obtained interesting constraints.

3. Single Leptoquark Production

In order to directly probe beyond the kinematic reach associated with pair production it is necessary to consider single LQ production which occurs via $\gamma\ell$ collisions[12] and whose rate depends on the square of the Yukawa coupling, λ. The photon in this case can either be the result of Weizsäcker-Williams(WW) emission at a conventional lepton collider or it arises from a backscattered laser(BL) beam and both possibilities have been examined in the literature. One of the most complete studies of both these processes has recently been performed by Doncheski and Godfrey[12,13]. Fig. 3 from that analysis shows the event rate for these processes assuming electromagnetic strength Yukawa couplings for a number of different collider options. Table 4 shows the corresponding search reach in each of these cases obtained by the same authors under the same set of assumptions. An important ingredient in this analysis is the inclusion of contributions to the cross section which arise due to the hadronic content of the photon; specifically, Doncheski and Godfrey make use of the parton densities of Glück, Reya and Vogt(GRV)[14]. Note that the

Table 3. *Discovery limits for leptoquarks (masses in GeV) at* $\sqrt{s} = 500$ *GeV* ($\mathcal{L} = 20\ fb^{-1}$) *and* $\sqrt{s} = 800$ *GeV* ($\mathcal{L} = 50\ fb^{-1}$) *requiring a* 5σ *effect from the analysis of RSS. I, II and III label the channels* $eejj$, $e\nu jj$ *and* $\nu\nu jj$ *respectively.* N_{bg} *is the number of background events passing the cuts in a given channel. Dashes indicate cases where the corresponding search is not possible,* $*$ *means no sensitivity to masses above 100 GeV with the cuts considered.*

		$\sqrt{s} = 500$ GeV			$\sqrt{s} = 800$ GeV		
	Search	I	II	III	I	II	III
	$5\sqrt{N_{bg}}$	18	61	251	21	60	375
States	B_{eq}	Mass reach in GeV					
$^{-1/3}S_0$	2/3	202	$*$	$*$	318	$*$	$*$
	1/2	183	$*$	$*$	289	$*$	$*$
	1	217	–	–	350	–	–
$^{-4/3}\tilde{S}_0$	1	242	–	–	387	–	–
$^{2/3}S_1$	0	–	–	225	–	–	275
$^{-1/3}S_1$	1/2	183	$*$	$*$	289	$*$	$*$
$^{-4/3}S_1$	1	244	–	–	389	–	–
$^{-2/3}S_{1/2}$	1/2	230	221	179	369	359	$*$
	0	–	–	218	–	–	239
	1	240	–	–	384	–	–
$^{-5/3}S_{1/2}$	1	244	–	–	389	–	–
$^{1/3}\tilde{S}_{1/2}$	0	–	–	198	–	–	146
$^{-2/3}\tilde{S}_{1/2}$	1	237	–	–	379	–	–
$^{-1/3}V_{1/2}$	1/2	241	237	220	385	380	266
	0	–	–	236	–	–	326
	1	245	–	–	392	–	–
$^{-4/3}V_{1/2}$	1	247	–	–	395	–	–
$^{2/3}\tilde{V}_{1/2}$	0	–	–	236	–	–	326
$^{-1/3}\tilde{V}_{1/2}$	1	244	–	–	390	–	–
$^{-2/3}V_0$	2/3	241	233	195	385	373	200
	1/2	238	234	212	380	376	244
	1	244	–	–	390	–	–
$^{-5/3}\tilde{V}_0$	1	247	–	–	396	–	–
$^{1/3}V_1$	0	–	–	241	–	–	352
$^{-2/3}V_1$	1/2	238	234	212	380	375	244
$^{-5/3}V_1$	1	248	–	–	396	–	–

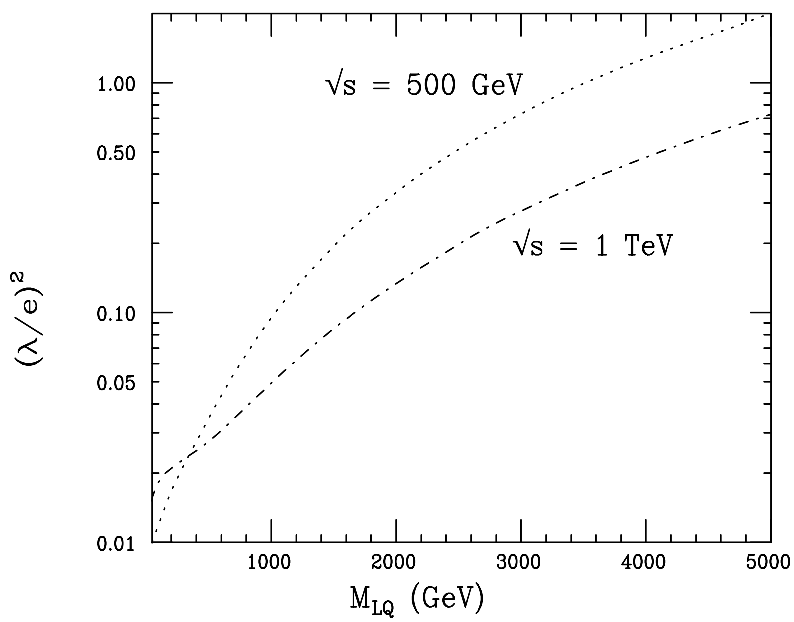

Fig. 2. 95% CL indirect discovery region(to the left of the curves) at a 500 GeV and 1 TeV e^+e^- collider with integrated luminosities of 50 and 100 fb^{-1} from the analysis of Hewett.

contribution from these subprocesses are uncertain by about a factor of two given the uncertainties in the photon distribution functions.

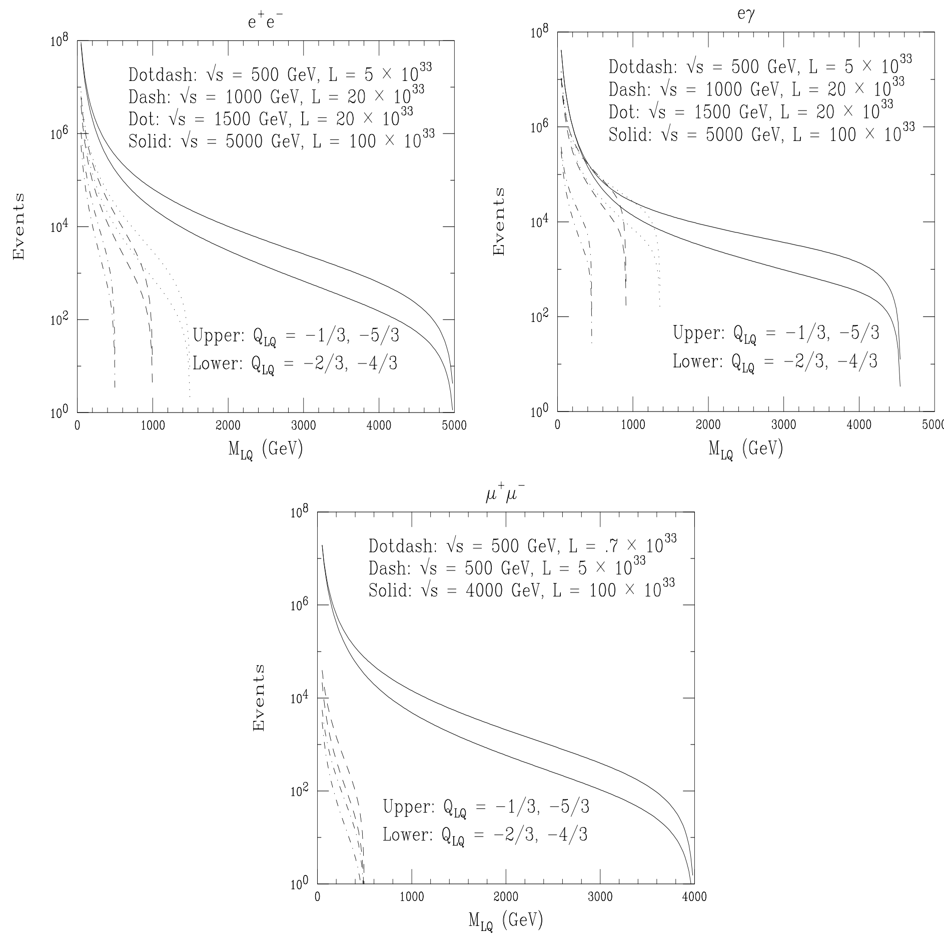

Fig. 3. Event rates for single leptoquark production in e^+e^-(WW), $e\gamma$(BL), and $\mu^+\mu^-$(WW) collisions from Doncheski and Godfrey. The center of mass energies and integrated luminosities are given by the line labelling in the figures.

A similar analysis in Table 5 from Ref. 6 directly compares the production rates obtainable via the WW and BL processes. From either of these analyses we see that the search reach in the $\gamma\ell$ mode is essentially $\simeq 0.9\sqrt{s}$ for Yukawas of strength $0.1e$ or greater, independently of the LQ type.

Is it possible to distinguish the various LQ types in the γe mode once they are observed? Doncheski and Godfrey[12,13] have performed a very extensive analysis in the attempt to answer this question. Here, since the Yukawa coupling itself is *a priori* unknown, the cross section measurement itself cannot be used to identify the LQ, and we are thus forced to rely only upon various asymmetries to probe LQ properties. The first asymmetry examined by Doncheski and Godfrey employs

Table 4. Leptoquark discovery limits for e^+e^-(WW), $e\gamma$(BL), and $\mu^+\mu^-$(WW) colliders from the analysis of Doncheski and Godfrey. The discovery limits are based on the production of 100 LQ's for the centre of mass energies and integrated luminosities given in columns one and two. The results were obtained using the GRV distribution functions and the LQs are labeled by their electric charges.

e^+e^- Colliders					
$\sqrt{s}$ (TeV)	L (fb^{-1})	Scalar		Vector	
		-1/3, -5/3	-4/3, -2/3	-1/3, -5/3	-4/3, -2/3
0.5	50	490	470	490	480
1.0	200	980	940	980	970
1.5	200	1440	1340	1470	1410
5.0	1000	4700	4200	4800	4500

$e\gamma$ Colliders					
$\sqrt{s}$ (TeV)	L (fb^{-1})	Scalar		Vector	
		-1/3, -5/3	-4/3, -2/3	-1/3, -5/3	-4/3, -2/3
0.5	50	450	450	450	440
1.0	200	900	900	910	910
1.5	200	1360	1360	1360	1360
5.0	1000	4500	4400	4500	4500

$\mu^+\mu^-$ Colliders					
$\sqrt{s}$ (TeV)	L (fb^{-1})	Scalar		Vector	
		-1/3, -5/3	-4/3, -2/3	-1/3, -5/3	-4/3, -2/3
0.5	0.7	250	170	310	220
0.5	50	400	310	440	360
4.0	1000	3600	3000	3700	3400

Table 5. Rates for single scalar leptoquark production in γe collisions at a 500 GeV NLC assuming complete leptoquark multiplets with a common mass of 200 GeV and an integrated luminosity of $50 fb^{-1}$. In all cases $\lambda/e = 0.1$ is assumed and a p_T cut on the quark jet of 10 GeV has been applied. The charged lepton branching fraction for the produced multiplet is also given.

Leptoquark	Backscattered Laser	Weizsäcker-Williams	B_ℓ
S_{1L}	212.	56.8	0.5
S_{1R}	212.	56.8	1
$\widetilde{S}_{1R}$	109.	24.4	1
S_{3L}	430.	106.	$\simeq 0.75$
R_{2L}	332.	79.5	1
R_{2R}	381.	92.6	1
$\widetilde{R}_{2L}$	49.1	13.1	1

only the electron beam polarization and corresponds to the conventional left-right asymmetry given by:

$$A^{+-} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\lambda_L^2 - \lambda_R^2}{\lambda_L^2 + \lambda_R^2}.$$

Assuming that LQs are chirally coupled this divides the various models in the BRW classification into three distinct bins depending on whether the particular LQ type couples only to the left- or right-handed electron or can couple to either helicity:

e_L^-**:** $\tilde{R}_{2L}$, S_{3L}, U_{3L}, $\tilde{V}_{2L}$

e_R^-**:** $\tilde{S}_{1R}$, $\tilde{U}_{1R}$

e_U^-**:** $U_{1L,R}$, $V_{2L,R}$, $R_{2L,R}$, $S_{1L,R}$

Here "e_U^-" means this LQ type can couple to either helicity as shown in Table 1. Of course, this is just convention since the polarization will pick out just one of these two states.

Doncheski and Godfrey showed that one can go further and trivially distinguish whether the LQs are scalar or vector. This could be accomplished in two ways. In the first case one can study the angular distributions of the leptoquark decay products. In the second they employ the double polarization asymmetry:

$$A_{LL} = \frac{(\sigma^{++} + \sigma^{--}) - (\sigma^{+-} + \sigma^{-+})}{(\sigma^{++} + \sigma^{--}) + (\sigma^{+-} + \sigma^{-+})}$$

where the first index refers to the electron helicity and the second to the quark helicity, the quark arising from the internal structure of the photon. Because scalars only have a non-zero cross section for σ^{++} and σ^{--}, for scalar LQs one finds that the parton level asymmetry for eq collisions is $\hat{a}_{LL} = +1$. Similarly, since vectors only have a non-zero cross section for σ^{+-} and σ^{-+} for vector LQs $\hat{a}_{LL} = -1$. To obtain the observable asymmetries we convolute the parton level cross sections with the polarized photon distribution functions. Doing so will reduce the asymmetries from their parton level values of ± 1 so one must determine whether the observable asymmetries resulting from this convolution can be used to distinguish between the leptoquark types. The complete expressions for the double longitudinal spin asymmetry A_{LL} are given in Doncheski and Godfrey[12]. These authors show in detail that out to masses of order $\simeq 0.75\sqrt{s}$, vector and scalar LQs are easily distinguished as are LQs with the same chirality of their couplings.

4. Leptoquarks in e^-e^- Collisions

LQs might also be pair produced in e^-e^- collisions provided one's model is sufficiently complex[15]. (It is obvious that an e^-e^- collider can also be run in the γe mode with the advantage that both beams can be polarized.) Since the initial state in e^-e^- collisions has $L = 2$, the two LQs produced in the final state must be distinct in that one must have $F = 0$ and the other will have $F = 2$. This implies that any model that predicts LQ production in this channel must have LQs of more than one species, such as the $SU(15)$ or the 331 models of Frampton[15], with the production resulting from $t-$ or $u-$channel quark exchange. In some models, such as the 331 case, an $s-$channel exchange of a $L = 2$ gauge boson also contributes; depending upon mass relations this exchange may be resonant and lead to a very large cross section. If the two LQs have different masses, $M_1 < M_2$, this mode may allow an extension of the search reach obtainable in e^+e^- collisions provided $M_1 + M_2 < \sqrt{s} < 2M_2$.

5. Summary and Outlook

Lepton colliders in the $e^+e^-/\mu^+\mu^-$, γe and e^-e^- modes provide unique ways to both discover LQs of all types *and* to obtain detailed information about their electroweak quantum numbers–something not possible at present or future hadron colliders. The phenomenology of LQ models is particularly rich, particularly if one goes beyond the BRW scheme. Analyses have become increasingly complex and have evolved in sophistication to the point where detector considerations are becoming increasingly important. Although much work has been done, there is still a lot of work to be done in the future.

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