What Can We Learn About Leptoquarks At LEP200?

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We investigate the discovery potential for first generation leptoquarks at the LEP200 $e^+e^-$ collider. We consider direct leptoquark searches using single leptoquark production via resolved photon contributions which offers a much higher kinematic limit than the more commonly considered leptoquark pair production process. Depending on the coupling strength of the leptoquark, search limits can be obtained to within a few GeV of $\sqrt{s}$. We also consider LQ limits that can be obtained from t-channel interferences effects in $e^+e^- \rightarrow$ hadrons.

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With the recent observation of an excess of high $Q^2$ events in $ep$ collisions by the H1 and ZEUS collaborations and the possibility that these events signal the existence of leptoquarks — colour (anti-)triplet, spin 0 or 1 particles which carry both baryon and lepton quantum numbers — there is considerable interest in the study of these particles. Leptoquarks appear in a large number of extensions of the standard model such as grand unified theories, technicolour, and composite models. The signature for leptoquarks is very striking: a high $p_T$ lepton balanced by a jet (or missing $p_T$ balanced by a jet, for the $\nu q$ decay mode, if applicable). Previous searches for leptoquarks have been performed by the H1 and ZEUS collaborations at the HERA $ep$ collider, by the D0 and CDF collaborations at the Tevatron $p\bar{p}$ collider, and by the ALEPH, DELPHI, L3, and OPAL collaborations at the LEP $e^+e^-$ collider.

In this communication we examine the information that can obtained about leptoquarks from $e^+e^-$ collisions at the LEP200 $e^+e^-$ collider at CERN. Information can be obtained primarily using three different approaches. In the first, LQ limits are obtained from LQ pair production. Limits can be obtained up to essentially $M_{LQ} \sim \sqrt{s}/2$. These limits have been surpassed considerably by the limits obtained at HERA and the Tevatron so we will not mention this approach again. The second approach is single leptoquark production in $e^+e^-$ collisions which utilizes the quark content of a Weizacker-Williams photon radiating off of one of the initial leptons. This process offers the advantage of a much higher kinematic limit than the LQ pair production process, is independent of the chirality of the LQ, and gives similar results for both scalar and vector leptoquarks. We will concentrate on the limits that can be obtained from this approach. The final approach is to search for deviations from standard model predictions for the $e^+e^- \rightarrow q\bar{q} \rightarrow hadrons$ cross section which might arise from t-channel leptoquark exchange. We find that measurements that can be made at LEP200 complements those from HERA and the Tevatron.

The most general $SU(3) \times SU(2) \times U(1)$ invariant scalar leptoquarks satisfying baryon and lepton number conservation have been written down Buchmüller et al. However, only those leptoquarks which couple to electrons can be produced in $e\gamma$ collisions so that we
only consider the production of leptoquarks coupling to first generation fermions. Further, for real leptoquark production the chirality of the coupling is irrelevant. For this case the number of leptoquarks reduces to four which can be distinguished by their electromagnetic charge; \(Q_{em} = -1/3, -2/3, -4/3, \) and \(-5/3\). In our calculations we will sometimes follow the convention where the leptoquark couplings are replaced by a generic Yukawa coupling \(g\) which is scaled to electromagnetic strength \(g^2/4\pi = \kappa\alpha_{em}\) with \(\kappa\) allowed to vary.

The process we are considering is shown in Fig. 1. The parton level cross section is trivial, given by:

\[
\sigma(\hat{s}) = \frac{\pi^2 \kappa \alpha_{em}}{M_s} \delta(M_s - \sqrt{\hat{s}})
\]

for scalar LQ’s. For vector LQ’s the cross section is a factor of two larger. Convoluting the parton level cross section with the quark distribution in the photon one obtains the expression

\[
\sigma(s) = \int f_{q/\gamma}(z, M_s^2) \sigma(\hat{s}) dz
= f_{q/\gamma}(M_s^2/s, M_s^2) \frac{2\pi^2 \kappa \alpha_{em}}{s}.
\]

This cross section depends on the LQ charge through \(f_{q/\gamma}\) since the photon has a larger \(u\) quark content than \(d\) quark content and hence has a larger cross section for LQ’s which couple to the \(u\) quark. For \(e^+e^-\) colliders the cross section is obtained by convoluting the expression for the resolved photon contribution to \(e\gamma\) production of leptoquarks, Eqn. (2), with the Weizsäcker-Williams effective photon distribution:

\[
\sigma(e^+e^- \rightarrow XS) = \frac{2\pi^2 \alpha_{em} \kappa}{s} \int_{M_s^2/s}^{1} \frac{dx}{x} f_{\gamma/e}(x, \sqrt{s}/2) f_{q/\gamma}(M_s^2/(xs), M_s^2).
\]

Fig. 1: The resolved photon contribution for leptoquark production in \(e\gamma\) collisions.
There exist several different quark distribution functions in the literature [21–25]. The different distributions give almost identical results for the $Q_{LQ} = -1/3, -5/3$ leptoquarks and for the $Q_{LQ} = -2/3, -4/3$ leptoquarks give LQ cross sections that vary by most a factor of two, depending on the kinematic region. We obtain our results using the GRV distribution functions [24] which we take to be representative of the quark distributions in the photon.

We next consider possible backgrounds [26]. The leptoquark signal consists of a jet and electron with balanced transverse momentum and possibly activity from the hadronic remnant of the photon. The only serious background is a hard scattering of a quark inside the photon by the incident lepton via t-channel photon exchange; $eq \rightarrow eq$. We plot the invariant mass distribution for this background in our plots of the LQ cross sections and find that it is typically smaller than our signal by two orders of magnitude. For the LQ invariant mass distribution we chose a 5 GeV invariant mass bin so that $d\sigma/dM = \sigma/5$ GeV. Related to this process is the direct production of a quark pair via two photon fusion

$$e + \gamma \rightarrow e + q + \bar{q}. \quad (4)$$

However, this process is dominated by the collinear divergence which is actually well described by the resolved photon process $eq \rightarrow eq$ given above. Once this contribution is subtracted away the remainder of the cross section is too small to be a concern [26]. Another possible background consists of $\tau$’s pair produced via various mechanisms with one $\tau$ decaying leptonically and the other decaying hadronically. Because of the neutrinos in the final state it is expected that the electron and jet’s $p_T$ do not in general balance which would distinguish these backgrounds from the signal. However, this background should be checked in a realistic detector Monte Carlo to be sure.

In Fig. 2 we show the single LQ production cross sections for $\sqrt{s} = 184, 190, \text{ and } 200 \text{ GeV}$. In Fig. 3 we use these cross sections to obtain estimates of the search limits on scalar leptoquarks that might be achieved at LEP200 as a function of mass and Yukawa couplings. In our results we assume $BR(LQ \rightarrow e + q) = 1$. If instead $BR(LQ \rightarrow e + q) = 0.5$
The cross sections for scalar leptoquark production due to resolved photon contributions in $e^+e^-$ collisions for (a) $\sqrt{s} = 184$ GeV, (b) 190 GeV, and (c) 200 GeV. $\kappa$ is chosen to be 1 and the resolved photon distribution functions of Glück, Reya and Vogt [24] are used. The dashed line is the $e[q]\gamma \rightarrow eq$ background. For the LQ invariant mass distribution we use a 5 GeV invariant mass bin so that $d\sigma/dM = \sigma/5$ GeV.

and $BR(LQ \rightarrow \nu + q) = 0.5$ the second LQ decay mode would have an even more dramatic signature than the one we consider; a high $p_T$ monojet balanced against a large missing $p_T$. Thus, in this case the sum of the two possible decays would give similar limits. We define our limits as the combination of LQ mass and coupling that would result in 10 $e-\text{jet}$ events with the correct topology for a given integrated luminosity for the four LEP experiments combined. Because we do not know for certain what the total integrated luminosity will be at these energies we use the following four values of integrated luminosity to obtain results; a pessimistic 200 pb$^{-1}$ (4 × 50), an expected (for the 184 GeV run) 400 pb$^{-1}$ (4 × 100), an expected (for the 190 GeV run) 1000 pb$^{-1}$ (4 × 250), and an optimistic 2000 pb$^{-1}$ (4 × 500).

The limits are relatively insensitive to the exact value of the luminosity at large values of the Yukawa coupling but become fairly sensitive as the strength of the Yukawa coupling decreases. Because the vector LQ cross section is twice that of the scalar LQ cross section we can obtain the vector LQ limits for a given luminosity by using the curves for the next higher luminosity for the scalar case. (ie. the limits for vector LQ’s with 200 pb$^{-1}$ is given by the curve for the scalar case with 400 pb$^{-1}$.) The limits that can be obtained from single LQ production are quite competitive with limits obtained by the Tevatron experiments [3,4].

In certain regions of the parameter space (small values of the Yukawa coupling) the limits
**Fig. 3:** Exclusion regions for the LQ coupling, $g$ as a function of $M_{LQ}$. The region above and to the right of the curved lines would be excluded by the nonobservation of at least 10 single LQ events for a given integrated luminosity. The region above the horizontal lines defines the region that could be excluded using the contributions of $t$-channel scalar LQ exchange in $e^+e^- \rightarrow \text{hadrons}$. In all cases the solid line is for $L=200$ pb$^{-1}$, the dotted line for $L=400$ pb$^{-1}$, the dashed line is for $L=1000$ pb$^{-1}$, and the dot-dot-dashed line is for $L=2000$ pb$^{-1}$.

are also competitive with HERA results, in some cases they are even more stringent. We note that these limits are extracted at the kinematic limit where $x \rightarrow 1$ and the hadronic remnant of the photon has vanishing energy. In this kinematic region the factorization into struck parton and remnant is questionable with the quark distribution functions subject to higher twist effects. Nevertheless, despite these qualifications, we believe our estimates to be fairly robust and are not likely to be changed substantially by a more rigorous scrutinization.
Finally, we comment on the sensitivity of the process $e^+e^- \rightarrow \text{hadrons}$ to LQ's via t-channel LQ exchange. In Fig. 3 we include limits based on comparing deviations expected from LQ exchange to the 1-sigma statistical errors assuming standard model cross sections. We include these results primarily to remind the reader that precision results can put stringent limits on new physics. For LQ's coupling to u-quarks the limits are rather weak but the limits on LQ's coupling to d-quarks the limits are rather stringent. Thus, cross section measurements can be sensitive to the existence of LQ's up to many times $\sqrt{s}$, depending on the LQ coupling. If the recent HERA results are confirmed by better statistics LEP200 measurements could play an important role in understanding the basis for these anomalies. Having said this we stress that we only wish to draw attention to the fact that these measurements are potentially useful. Our analysis is hopelessly naive, not having taken into account experimental acceptances and systematic errors. To further emphasize this, a recent analysis by the OPAL collaboration \cite{19} using measurements of $e^+e^- \rightarrow \text{hadrons}$ taken at 133 GeV, 161 GeV, and 172 GeV and employing a one-sided likelihood fit obtains more stringent limits than ours for LQ's coupling to the u-quark but weaker limits for LQ's coupling to the d-quark. The difference is due to the fact that the experimental measurements are in the wrong direction to the changes expected from u-type LQ's but in the right direction for d-type LQ's.

In this communication we have pointed out that information about LQ's that can be obtained at LEP200 complements measurements made at other colliders such as HERA and the Tevatron. We have used the resolved photon contributions to single leptoquark production and t-channel leptoquark exchange to estimate potential limits on leptoquark masses and couplings. If the recent HERA results are confirmed, measurements at LEP200 could play an important role in understanding the underlying physics. Finally, we remind the reader that our results are of course only theorist's estimates which should be examined more closely and carefully than has been described here.
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