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Leptoquark mass limits from single leptoquark production at LEP and LEP200

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Abstract

We investigate the discovery potential for first generation leptoquarks at the LEP and LEP200 e^+e^- colliders. We consider single leptoquark production via resolved photon contributions which offers a much higher kinematic limit than the more commonly considered leptoquark pair production process. This process also has the advantage that it is independent of the leptoquark chirality, is almost insensitive to whether the leptoquark is scalar or vector, and only depends on the leptoquark charge. We estimate that from the nonobservation of energetic $e-jet$ events that cannot be explained as backgrounds, the limits at LEP for all types of leptoquarks are $M_{LQ} > 90$ GeV. For the just completed $\sqrt{s} = 161$ GeV run at LEP200 we estimate potential scalar leptoquark mass limits of $M_{LQ} > 130$ GeV for $Q_{LQ} = -2/3, -4/3$ and $M_{LQ} > 148$ GeV for $Q_{LQ} = -1/3, -5/3$ and for vector LQ's the limits are ~ 140 and ~ 154 GeV respectively. Ultimately, LEP200 should be able to achieve discovery limits for leptoquarks of ~ 188 GeV for the $\sqrt{s} = 190$ GeV runs. In all cases we assume electromagnetic strength coupling.

There is considerable interest in the study of leptoquarks (LQs) — colour (anti-)triplet, spin 0 or 1 particles which carry both baryon and lepton quantum numbers. Such objects appear in a large number of extensions of the standard model such as grand unified theories, technicolour, and composite models. Quite generally, 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 νq decay mode, if applicable). Searches for leptoquarks have been performed by the H1 [1] and ZEUS [2] collaborations at the HERA ep collider, by the D0 [3] and CDF [4] collaborations at the Tevatron $p\bar{p}$ collider, and by the ALEPH [5], DELPHI [6], L3 [7], and OPAL [8] collaborations

at the LEP e^+e^- collider. The LQ limits obtained by the LEP experiments have for the most part considered LQ pair production although DELPHI considered single LQ production via the process $Z \rightarrow LQ + e + jet$. In this letter we consider 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 [9–14]. 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. The cross section depends on the LQ charge 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 than for LQ's which couple to the d quark. Although the limits

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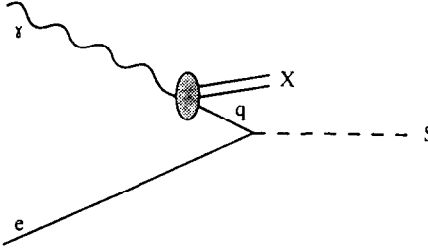


Fig. 1. The resolved photon contribution for leptoquark production in $e\gamma$ collisions.

we obtain for searches at LEP200 are slightly lower than direct limits that can be obtained at HERA it is still useful to confirm the HERA limits elsewhere.

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. [15]. However, only those leptoquarks which couple to electrons can be produced in $e\gamma$ collisions and 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 follow the convention adopted in the literature [12] where the leptoquark couplings are replaced by a generic Yukawa coupling g which is scaled to electromagnetic strength $g^2/4\pi = \kappa\alpha_{em}$ and allow κ to vary.

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

$$\sigma(\hat{s}) = \frac{\pi^2 \kappa \alpha_{em}}{M_s} \delta(M_s - \sqrt{\hat{s}}). \quad (1)$$

Convoluting the parton level cross section with the quark distribution in the photon one obtains the expression

$$\begin{aligned} \sigma(s) &= \int f_{q/\gamma}(z, M_s^2) \hat{\sigma}(\hat{s}) dz \\ &= f_{q/\gamma}(M_s^2/s, M_s^2) \frac{2\pi^2 \kappa \alpha_{em}}{s}. \end{aligned} \quad (2)$$

We note that the interaction Lagrangian used in Ref. [13] associates a factor $1/\sqrt{2}$ with the leptoquark-lepton-quark coupling. Thus, one should compare our results with κ to those in Ref. [13] with 2κ . We give results with κ chosen to be 1.

For e^+e^- colliders the cross section is obtained by convoluting the expression for the resolved photon contribution to $e\gamma$ production of leptoquarks, Eq. (2), with the Weizsäcker-Williams effective photon distribution

$$\begin{aligned} \sigma(e^+e^- \rightarrow XS) &= \frac{2\pi^2 \alpha_{em} \kappa}{s} \\ &\times \int_{M_s^2/s}^1 \frac{dx}{x} f_{\gamma/e}(x, \sqrt{s}/2) f_{q/\gamma}(M_s^2/(xs), M_s^2) \end{aligned} \quad (3)$$

with the Weizsäcker-Williams effective photon distribution given by [16]:

$$\begin{aligned} f_{\gamma/e}(x, E) &= \\ &\frac{\alpha_{em}}{2\pi} \left\{ \frac{[1 + (1-x)^2]}{x} \ln \left[\frac{E^2 (1-2x+x^2)}{m_e^2 (1-x+x^2/4)} \right] \right. \\ &\left. + x \ln \left(\frac{(2-x)}{x} \right) + \frac{2(x-1)}{x} \right\}. \end{aligned} \quad (4)$$

There exist several different quark distribution functions in the literature [17–21]. 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 [20] which we take to be representative of the quark distributions in the photon.

Before proceeding to our results we consider possible backgrounds [22]. 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

$$e + \gamma \rightarrow e + q + \bar{q}. \quad (5)$$

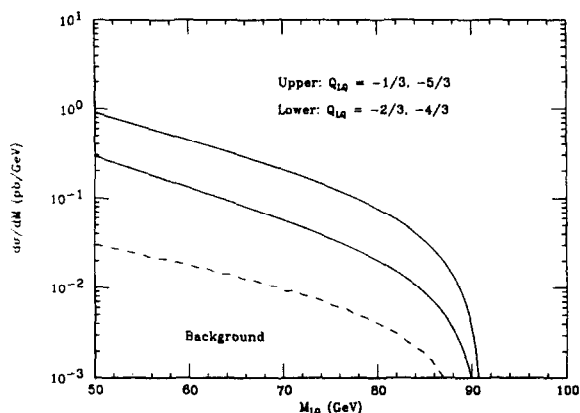


Fig. 2. The cross sections for scalar leptoquark production due to resolved photon contributions in e^+e^- collisions for $\sqrt{s} = 91.17$ GeV. κ chosen to be 1 and resolved photon distribution functions of Glück, Reya and Vogt [20] are used. The dashed line is the $e[q]\gamma \rightarrow eq$ background. For the LQ invariant mass distribution we use a 5 GeV invariant mass bin so that $d\sigma/dM = \sigma/5$ GeV.

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 [22]. Another possible background consists of τ 's pair produced via various mechanisms with one τ 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. The remaining backgrounds originate from heavy quark pair production with one quark decaying semileptonically and only the lepton being observed with the remaining heavy quark not being identified as such. All such backgrounds are significantly smaller than our signal in the kinematic region we are concerned with.

In Fig. 2 we show the cross sections for $\sqrt{s} = 91.17$ GeV. In our results we assume $BR(LQ \rightarrow e + q) = 1$. We interpret the non-observation of any $e - jet$ events that cannot be explained away as a background by any of the LEP experiments, to signify that a LQ does not exist up to the leptoquark mass that would produce at least 3 $e - jet$ events with the integrated luminosities of the combined LEP experiments. Assuming $BR(LQ \rightarrow e jet) = 1$ this leads to LQ search

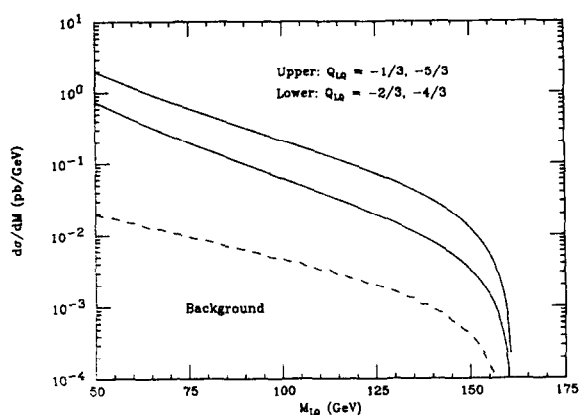


Fig. 3. The cross sections for leptoquark production due to resolved photon contributions in e^+e^- collisions for $\sqrt{s} = 161$ GeV. See Fig. 2 for details.

limits of $M_{LQ} > 90$ GeV for all first generation leptoquark types. If instead $BR(LQ \rightarrow e + q) = 0.5$ 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 limits similar to the one given above.

In Fig. 3 we show the cross sections for $\sqrt{s} = 161$ GeV, the energy of the most recent LEP200 run. For an integrated luminosity of 10 pb^{-1} per LEP experiment we interpret the non-observation of any $e - jet$ events with the correct topology for the LQ mass that would result in 3 events as scalar LQ search limits of $M_{LQ} > 130$ GeV for $Q_{LQ} = -2/3, -4/3$ and $M_{LQ} > 148$ GeV for $Q_{LQ} = -1/3, -5/3$ and 140 GeV and 154 GeV respectively for the vector leptoquarks. These limits represent a significant improvement over the LEP limits given above and are quite competitive with similar published limits obtained by the Tevatron experiments [3,4].

Figs. 4 and 5 give the cross sections for $\sqrt{s} = 175$ GeV and $\sqrt{s} = 190$ GeV respectively. At present we do not know for certain what the total integrated luminosities will be for each of these energies. We use the currently planned 25 pb^{-1} at $\sqrt{s} = 175$ GeV and 500 pb^{-1} at $\sqrt{s} = 190$ GeV for each of the LEP experiments. Again, using the criteria that none of the experiments see any $e - jet$ events that could otherwise be explained, we obtain search limits up to ~ 170 GeV for $\sqrt{s} = 175$ GeV and ~ 188 GeV for $\sqrt{s} = 190$ GeV.

Table 1

Mass limits and discovery limits for leptoquarks at LEP and LEP200. Our results are based on the non-observation of any leptoquark candidates when 3 are expected for the given LQ mass. We take $\kappa = 1$ and assume $BR(LQ \rightarrow e + q) = 1$. Our results are given in GeV

\sqrt{s} (GeV)	L (pb^{-1})	Scalar LQ		Vector LQ	
		$Q = -2/3 - 4/3$	$Q = -1/3 - 5/3$	$Q = -2/3 - 4/3$	$Q = -1/3 - 5/3$
91.17	720	90	90	90	91
161	40	130	148	140	154
175	100	154	167	162	170
190	2000	187	188	188	189

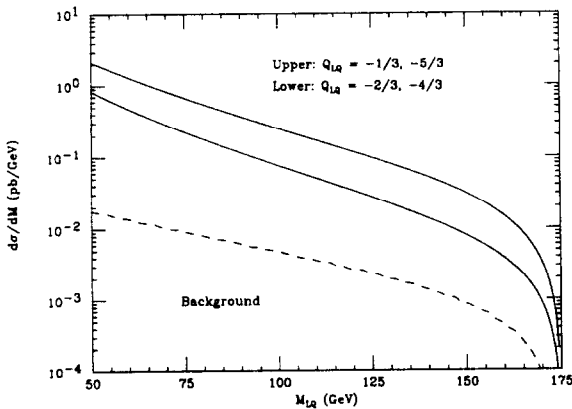


Fig. 4. The cross sections for leptoquark production due to resolved photon contributions in e^+e^- collisions for $\sqrt{s} = 175$ GeV. See Fig. 2 for details.

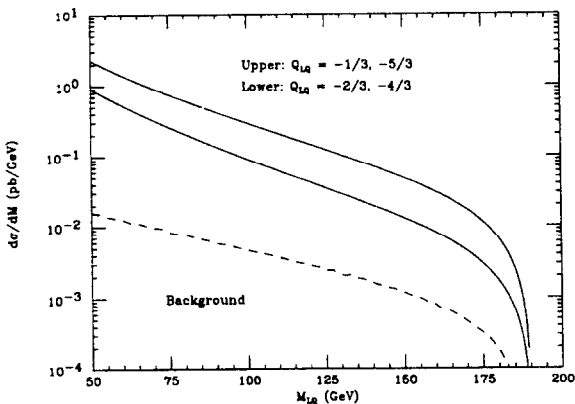


Fig. 5. The cross sections for leptoquark production due to resolved photon contributions in e^+e^- collisions for $\sqrt{s} = 190$ GeV. See Fig. 2 for details.

The search limits for the different charge and spin assumptions are summarized in Table 1.

In this letter we have used the resolved photon con-

tributions to single leptoquark production to estimate potential limits on leptoquark masses. This production mechanism has the advantage that it can produce both scalar and vector leptoquarks with roughly the same cross section and of being insensitive to the chiral properties of the leptoquarks. It's only dependence on LQ properties is on the LQ charge because the photon has a larger u -quark than d -quark content. The potential limits we obtain from the non-observation of LQ's at $\sqrt{s} = 161$ GeV are competitive with published limits of the Tevatron collaborations. In general, the limits obtainable at LEP200 will be slightly lower than direct limits that can be obtained at HERA [1,2]. Nevertheless, limits obtained in searches at LEP200 should complement those obtained at HERA and the Tevatron for two reasons: First, LQ's will have very dramatic and distinct signatures at LEP200 in contrast to the Tevatron and HERA where their presence are determined by statistical enhancements over the SM backgrounds. Second, the limits obtained at LEP200 tend to be less dependent on the properties of the LQ's than results obtained at ep and hadron colliders. 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. For example, we have not included detector acceptances in our estimates, perhaps over simplistically assuming that the LQ decay products will decay isotropically in the detector resulting in fairly high detection efficiencies. In addition, a detailed detector Monte Carlo of possible backgrounds should be performed. Finally, we point out 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 dis-

tribution 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.

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