Signals for Virtual Leptoquark Exchange at HERA

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Abstract

We study the effects of virtual leptoquarks on charged current and neutral current processes at the \( ep \) collider HERA. We present the areas of parameter space that can be excluded at HERA by searching for deviations from Standard Model expectations. The best results are obtained by examining the ratio of neutral current to charged current cross sections, \( R = \frac{\sigma_{NC}}{\sigma_{CC}} \), where, with \( 200 \text{ pb}^{-1} \) of integrated luminosity for unpolarized \( e^- \) and \( e^+ \) beams, HERA can search for leptoquarks with masses up to \( \sim 800 \text{ GeV} \), with leptoquark coupling strengths of order \( \alpha_{em} \).

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Many theories which go beyond the Standard Model (SM) are inspired by the symmetry between the quark and lepton generations and try to relate them at a more fundamental level. As a result, many of these models contain new particles, called leptoquarks, which naturally couple to a lepton-quark pair. Examples of such theories include models with quark-lepton substructure, the strong-coupling version of the SM, horizontal symmetries, grand unified theories based on the gauge groups SU(5), SO(10), as well as the Pati-Salam SU(4), and superstring inspired $E_6$ models. In all these theories, leptoquarks carry both baryon and lepton number, and are triplets under SU(3)$_C$; their other quantum numbers (e.g., spin, weak isospin, and electric charge) vary between the different models. These particles need not be heavy; in fact, leptoquarks can have a mass $\lesssim 100\text{ GeV}$ and still avoid conflicts with rapid proton decay and dangerously large flavor changing neutral currents. This is particularly true in models where each generation of fermions has its own leptoquark(s) which couples only within that generation. Models where the leptoquarks can possess flavor non-diagonal couplings are much more constrained.

By its nature, the high-energy ep collider HERA is especially well-suited to study leptoquarks. Direct production can occur via an $s$-channel resonance at enormous rates with distinctive peaks in the $x$-distribution. Indeed, HERA experimental searches are expected to reach a discovery limit (with a $5\sigma$ signal and an integrated luminosity of 200 pb$^{-1}$) of $\sim 250\text{ GeV}$ when the leptoquark coupling strength is of order $0.01\alpha_{em}$, and up to the kinematic limit if the coupling is equal to $\alpha_{em}$. If leptoquarks are too massive to be produced directly at HERA, perhaps they can be detected through their indirect effects via virtual exchange by searching for deviations from SM expectations for certain processes. This is similar in nature to the detection of the SM $Z$-boson at PEP/PETRA. Several authors have examined such effects on the neutral current asymmetries that can be formed with polarized electron beams, and have found that departures from the SM are small, even for leptoquarks of low mass (e.g., $\sim 400\text{ GeV}$) and large couplings. Here, we systematically investigate these possible indirect effects on charged current as well as neutral current processes. We find that the best results are obtained by examining the ratio $R = \sigma_{NC}/\sigma_{CC}$, where discovery limits can reach leptoquark masses of order...
800 GeV for electromagnetic coupling strengths (with 200 pb$^{-1}$ of integrated luminosity per $e^+, e^-$ beam). Taking the ratio of neutral to charged current cross sections is also advantageous because several systematic uncertainties, as well as those from a lack of detailed knowledge of the parton distributions, will cancel. Such a ratio has historically played a great role\cite{8} in our knowledge of SM interactions from traditional low-energy neutrino scattering. As such, it is only natural that such a ratio be used to probe new interactions in the high-energy regime at HERA.

Present bounds from the LEP experiments\cite{9} on a leptoquark mass are $m > M_Z/2$; single leptoquark production from $Z$ decay could extend\cite{10} the LEP search reach to masses of $\sim 70$ GeV. It is also possible, using the high statistics available at LEP, to study the virtual effects of leptoquarks via flavor changing $Z$ decays\cite{11}. Any such limits will, however, be more model dependent than those quoted above. At hadron colliders, leptoquarks may be produced\cite{12} either singly through their unknown $q\ell(LQ)$ couplings via $qg$ fusion, or in pairs by $gg$ fusion and $q\bar{q}$ annihilation. UA2 has placed\cite{13} limits on scalar leptoquark pair production by searching for the possible final states $e^+e^- + 2$ jets and $e\nu + 2$ jets with the result that $m > 67$ GeV at 95\% C.L. assuming the branching fraction $B(LQ \to eq) = 50\%$. As one varies this branching fraction from 10\% to 100\%, the UA2 bounds range from the LEP result of $m > M_Z/2$ up to $m > 74$ GeV. Constraints in the leptoquark mass-coupling plane may also be obtained by examining $t$-channel leptoquark exchange in the process $e^+e^- \to q\bar{q}$. Such effects are hidden at LEP I due to the $Z$-boson resonance, but data from PEP/PETRA allow\cite{14} for leptoquark coupling strengths to be of order electromagnetic strength, or larger, for the mass range of interest here.

For definiteness, we will concentrate on the leptoquark present in superstring-inspired $E_6$ models\cite{15}. These leptoquarks, which we will denote by $S$, are scalar, charge $-1/3$, baryon number $= +1/3$, lepton number $= +1$, weak iso-singlets, and are the supersymmetric partner of the exotic color triplet fermion which appears in the $27$ representation of $E_6$. Their interactions are governed by the $E_6$ superpotential terms

$$
\lambda_L L S \bar{c} Q + \lambda_R S u \bar{c} e e + \lambda ' \nu \bar{c} S d e ,
$$

(1)
where $L$ and $Q$ represent the left-handed lepton and quark doublets, respectively, and the superscript $c$ denotes the charge conjugate states. The Yukawa couplings, *i.e.*, the $\lambda$’s, are *a priori* unknown and for simplicity we set $\lambda_L = \lambda_R$ in our numerical calculations. We make the assumption that the right-handed neutrino is too heavy to be produced at HERA and hence ignore any contributions from the $\lambda'$ term. If $\nu^c$ is light enough to be produced, the signature from its subsequent decay would be distinguishable from that of the SM charged current events considered here. The total leptoquark decay width (assuming the right-handed neutrino does not contribute) is

$$\Gamma_S = \frac{m_S}{16\pi} (2\lambda_L^2 + \lambda_R^2).$$  \hspace{1cm} (2)$$

For calculational purposes, we parameterize the $\lambda$’s by

$$\frac{\lambda_{L,R}^2}{4\pi} = F_{L,R} \alpha,$$ \hspace{1cm} (3)

and take $F_L = F_R \leq 1$.

First we consider the contributions of leptoquark exchange on neutral current (NC) events. These $e^\pm q \rightarrow e^\pm q$ and $e^\pm \bar{q} \rightarrow e^\pm \bar{q}$ events are generated by $t$-channel $\gamma$ and $Z$ exchange in the SM, and by $s$- and $u$-channel leptoquark exchange. The Feynman diagrams responsible for these mechanisms are presented in Fig. 1a-b. The differential cross section for a left-handed polarized electron and an unpolarized proton is

$$\frac{d\sigma(e^-p)}{dxdy} = \frac{2\pi\alpha^2}{sx^2y^2} \left( \sum_{q=u,d} [b_{LL}^2(q) + b_{LR}^2(q)(1-y)^2]xq(x) \right)$$

$$+ \sum_{q=u,d} [b_{LR}^2(q) + b_{LL}^2(q)(1-y)^2]\bar{xq}(x)$$

$$+ F_L b_{LL}(u) sxy \left\{ \frac{\left(\hat{s} - m_S^2\right)xu(x)}{\left[\left(\hat{s} - m_S^2\right)^2 + (m_S\Gamma_S)^2\right]} + \frac{(1-y)^2\bar{x\bar{u}}(x)}{[u - m_S^2]} \right\}$$

$$+ \frac{1}{4} F_L (F_L + F_R) \left( \frac{t^2 xu(x)}{\left[\left(\hat{s} - m_S^2\right)^2 + (m_S\Gamma_S)^2\right]} + \frac{u^2 y^2 \bar{x\bar{u}}(x)}{[u - m_S^2]^2} \right),$$

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and for a left-handed polarized positron and an unpolarized proton,

\[
\frac{d\sigma(e^+_Lp)}{dx dy} = \frac{2\pi\alpha^2}{sx^2y^2} \left( \sum_{q=u,d} [b^2_{RL}(q) + b^2_{RL}(q)(1 - y)^2]xq(x) \right) + \sum_{q=u,d} [b^2_{RR}(q) + b^2_{RL}(q)(1 - y)^2]x\bar{q}(x) + F_R b_{RR}(u) sxy \left\{ \frac{(1 - y)^2 xu(x)}{[u - m^2_S]} + \frac{(\hat{s} - m_S^2) x\bar{u}(x)}{[\hat{s} - m_S^2]^2 + (m_S\Gamma_S)^2]}) \right\} + \frac{1}{4} F_R (F_L + F_R) \left\{ \frac{u^2 y^2 xu(x)}{[u - m^2_S]^2} + \frac{t^2 x\bar{u}(x)}{[\hat{s} - m_S^2]^2 + (m_S\Gamma_S)^2]}) \right\}.
\]

The corresponding cross sections for right-handed polarized e’s are obtained by

\[
\frac{d\sigma(e^+_R p)}{dx dy} = \frac{d\sigma(e^+_L p)}{dx dy} \quad \text{with} \quad L \leftrightarrow R.
\]

Here \(q(x)\) and \(\bar{q}(x)\) represent the quark and anti-quark distribution functions, \(\hat{s} = xs\), \(t = -Q^2\), \(u = -\hat{s} + Q^2\), \(Q^2 = sxy\), and \(x\) and \(y\) are the usual scaling variables. The functions \(b_{ij}\) are given by

\[
b_{ij} = -Q^q + \frac{\sqrt{2}G_F M_Z^2 C^f_C \frac{t(t - M_Z^2)}{N_C}}{\pi\alpha} \left\{ \frac{t(t - M_Z^2)}{(t - M_Z^2)^2 + (M_Z\Gamma_Z)^2} \right\},
\]

with \(Q^q\) being the electric charge of the incoming parton, \(C^f_L = T^f_{3L} - Q^f \sin^2 \theta_w\), \(C^f_R = -Q^f \sin^2 \theta_w\), and \(T^f_{3L}\) is the value of the fermion’s third component of weak isospin. These expressions agree with those of Ref. [3] and also with the SM contributions of Ref. [10, 17].

The Feynman diagrams representing the SM and s-, u-channel leptoquark contributions to charged current (CC) events, \(e^\pm q \rightarrow \nu q\) and \(e^\pm \bar{q} \rightarrow \nu \bar{\nu}\), are depicted in Fig. 2a-b. The differential cross section for a left-handed polarized electron is
\[
\frac{d\sigma(e^- p)}{dxdy} = \frac{2\pi \alpha^2}{s x^2 y^2} \left( b_{LL}^2 x u(x) + b_{LL}^2 (1 - y)^2 x \bar{d}(x) \right) + F_L b_{LL} s x y \left\{ \frac{(s - m_S^2) x u(x)}{[(s - m_S^2)^2 + (m_S \Gamma_S)^2]} + \frac{(1 - y)^2 x \bar{d}(x)}{[u - m_S^2]} \right\} \\
+ \frac{F_L^2 t^2 x u(x)}{4[(s - m_S^2)^2 + (m_S \Gamma_S)^2]} + \frac{F_L^2 u^2 y^2 x \bar{d}(x)}{4[u - m_S^2]^2},
\]

and for a right-handed polarized positron,
\[
\frac{d\sigma(e^+ p)}{dxdy} = \frac{2\pi \alpha^2}{s x^2 y^2} \left( b_{LL}^2 (1 - y)^2 x d(x) + b_{LL}^2 x \bar{u}(x) \right) + F_L b_{LL} s x y \left\{ \frac{(1 - y)^2 x d(x)}{[u - m_S^2]} + \frac{(s - m_S^2) x \bar{u}(x)}{[(s - m_S^2)^2 + (m_S \Gamma_S)^2]} \right\} \\
+ \frac{F_L^2 t^2 x \bar{u}(x)}{4[(s - m_S^2)^2 + (m_S \Gamma_S)^2]} + \frac{F_L^2 u^2 y^2 x d(x)}{4[u - m_S^2]^2}.
\]

Here, the SM contributions agree with that in Ref. [17]. The leptoquark exchange
diagrams also contribute to \(e_R^+\) and \(e_L^-\) scattering, (note that there are no SM contributions to these processes), with
\[
\frac{d\sigma(e_R^- p)}{dxdy} = \frac{2\pi \alpha^2}{s x^2 y^2} \left( b_{LL}^2 (1 - y)^2 x d(x) + b_{LL}^2 x \bar{u}(x) \right) + F_L b_{LL} s x y \left\{ \frac{(1 - y)^2 x d(x)}{[u - m_S^2]} + \frac{(s - m_S^2) x \bar{u}(x)}{[(s - m_S^2)^2 + (m_S \Gamma_S)^2]} \right\} \\
+ \frac{F_L^2 t^2 x \bar{u}(x)}{4[(s - m_S^2)^2 + (m_S \Gamma_S)^2]} + \frac{F_L^2 u^2 y^2 x d(x)}{4[u - m_S^2]^2}.
\]

For charged current processes, \(b_{LL}\) is defined as
\[
b_{LL} = \frac{G_F M_W^2}{\sqrt{2} \alpha \pi} \frac{t(t - M_W^2)}{(t - M_W^2)^2 + (M_W \Gamma_W)^2}.
\]

In order to ensure that the NC and CC events are cleanly separated and
identified we impose cuts on the scaling variables \(x\) and \(y\), as well as on the transverse
momentum of the out-going lepton. We have found that restricting $x$ to lie in the range $0.1 \leq x \leq 1.0$ satisfies the above condition, while yielding the greatest sensitivity to the indirect leptoquark effects. For a given value of $x$, we then restrict $y$ to lie in the range

$$\max(0.1, y_{\text{min}}) \leq y \leq \min(1.0, y_{\text{max}}),$$  \hspace{1cm} (13)

where,

$$y_{\text{max,min}} = \frac{1}{2} \left[ 1 \pm \sqrt{1 - \frac{4(p_{T}^{\text{cut}})^2}{xs}} \right]. \hspace{1cm} (14)$$

In order to fully distinguish the two types of events, we impose the realistic cuts

$$p_{T}(e) > 5 \text{ GeV}$$  \hspace{1cm} (15)

for the out-going $e^{\pm}$ in the NC events, and

$$p_{T}(\nu) > 20 \text{ GeV}$$  \hspace{1cm} (16)

on the missing transverse momentum in CC events. In the circumstance that a more sophisticated detector triggering system is developed, we also ran a test case with a cut on the CC missing transverse momentum of $p_{T}(\nu) > 10 \text{ GeV}$, and found that our results did not significantly change. We then integrate the above differential cross sections over these $x$ and $y$ ranges to obtain our results.

We perform a $\chi^2$ analysis in searching for virtual leptoquark effects and comparing them to SM expectations for various asymmetries, total cross sections, and the ratio $R = \sigma_{NC}/\sigma_{CC}$. We assume that most of the systematic uncertainties cancel for the asymmetries and in $R$, and only include the statistical errors for these quantities, which are given by

$$\delta A = \frac{1 - A^2}{\sqrt{1 - A}} \frac{1}{\sqrt{2N_{\alpha}}},$$  \hspace{1cm} (17)

for the asymmetries defined as $A = (\sigma_{\alpha} - \sigma_{\beta})/(\sigma_{\alpha} + \sigma_{\beta})$ with $N_{\alpha} = \mathcal{L} \sigma_{\alpha}$ being the number of events for $\sigma_{\alpha}$ for a value of the integrated luminosity $\mathcal{L}$, and

$$\frac{\delta R}{R} = \frac{1}{\sqrt{N_{NC}}} \oplus \frac{1}{\sqrt{N_{CC}}},$$  \hspace{1cm} (18)
where the ‘⊕’ signifies that the errors are to be added in quadrature, and \( N_{NC,CC} \) is the number of neutral current and charged current events, respectively. In the case where we examine possible deviations in the total cross sections, we also include the systematic errors associated with the luminosity determination, giving

\[
\frac{\delta \sigma}{\sigma} = \frac{1}{\sqrt{N}} \oplus \frac{\delta L}{L},
\]

where we take \[19\] the value \( \delta L/L = 5\% \). Finally, we also use the sum of neutral current and charged current asymmetries in order to increase the statistics in searching for deviations from the SM. In this case, we calculate \( \chi^2 \) for the neutral current (\( \chi^2_{NC} \)) and for the charged current (\( \chi^2_{CC} \)) processes separately, and then add

\[
\chi^2_{TOT} = \chi^2_{NC} + \chi^2_{CC}.
\]

We then determine 90% and 95% C.L. deviations based on the value of \( \chi^2_{TOT} \).

We present our results for the HMRS-B parton distributions of Ref. [21]. We have checked that the limits obtained from the asymmetries and the ratio of cross sections are insensitive to the choice of distribution functions as expected, but the bounds from the total cross sections can change by as much as 10% as the distribution function parameterizations are varied. In our numerical calculations, we use the values [20] \( M_Z = 91.175 \text{ GeV}, \Gamma_Z = 2.487 \text{ GeV}, M_W = 80.14 \text{ GeV}, \Gamma_W = 2.15 \text{ GeV}, \alpha(M_Z) = 1/128, \) and \( x_w = 0.233 \).

We examine the effects using both unpolarized and polarized e± beams. In the latter case, we define the polarized cross sections as

\[
\sigma^\pm(+) = \frac{1}{2}(1 + P)\sigma(e_L^\pm p) + \frac{1}{2}(1 - P)\sigma(e_R^\pm p),
\]

\[
\sigma^\pm(-) = \frac{1}{2}(1 - P)\sigma(e_L^\pm p) + \frac{1}{2}(1 + P)\sigma(e_R^\pm p),
\]

which takes into account that there will be only a finite degree of polarization. We take \( P = 80\% \) and assume 125 pb\(^{-1}\) of integrated luminosity for each polarized e± beam. For the unpolarized case, we set \( P = 0 \) in the above equations. Generally, we find that the use of polarized beams does not increase the leptoquark search reach over the unpolarized case (for a similar value of \( L \)).
We begin the discussion of our results by examining the six different neutral
current asymmetries that can be formed from various combinations of the polarized
$e^\pm$ beams. Out of these six asymmetries, $A_{LR}^\pm$, which is defined as

$$A_{LR}^\pm = \frac{\sigma^-(+P) - \sigma^+(-P)}{\sigma^-(+P) + \sigma^+(-P)}, \quad (22)$$
yields the best leptoquark search limits. These limits are shown in the leptoquark
coupling-mass parameter plane in Fig. 3, represented by the dotted (dashed-dotted)
curve in the upper left-hand corner which corresponds to the 90\% (95\%) C.L. Here,
and in all of our results below, the discovery region lies to the left of the curves.
It is clear from the figure that these types of measurements do \textbf{not} yield useful
limits, reaching leptoquark masses of only $m_S \sim 325$ GeV, even with electromagnetic
coupling strengths. This confirms the results of previous authors\cite{3,7}.

We next discuss the limits that are obtainable from measurements of the total
cross sections. Summing over both the neutral and charged current unpolarized cross
sections, we find that the 90\% (95\%) C.L. discovery reach lies to the left of the
solid (dashed) curves in Fig. 3, for 200 pb$^{-1}$ of integrated luminosity per $e^-, e^+$
beam. We find that the 5\% uncertainty in the luminosity determination completely
dominates the statistical errors, such that improved searches from this technique are
not possible, even with substantial increases in the total integrated luminosity. Of
course, measurements involving only cross sections are also severely hampered by
the rest of the systematic errors as well as the uncertainties arising from the lack of
knowledge of the parton distributions.

A slightly more useful quantity in searching for indirect leptoquark effects is
the (unpolarized) charge asymmetry $A^{\pm}$, given by

$$A^{\pm} = \frac{\sigma(e^-p) - \sigma(e^+p)}{\sigma(e^-p) + \sigma(e^+p)}. \quad (23)$$

In Fig. 4 we show the 90\% (solid curves) and 95\% (dashed curves) C.L. discovery
regions obtainable from the charge asymmetry for (a) 200 pb$^{-1}$ and (b) 500 pb$^{-1}$ of
integrated luminosity per beam. Where possible, we present the results from neutral
current and charged current events separately, as well as those obtained from the sum of both types of events. As can be seen by comparing Figs. 3 and 4, the charge asymmetry can exclude a slightly larger region of parameter space than cross section measurements alone.

It is, of course, possible to measure other quantities that are essentially independent of systematic uncertainties. We find two such quantities that provide much stronger search limits than any of the observables discussed so far. The first of these is the neutral current-charged current asymmetry, defined as

$$A_{ZW} = \frac{\sigma_{NC} - \sigma_{CC}}{\sigma_{NC} + \sigma_{CC}},$$

and the second is the ratio $R = \sigma_{NC}/\sigma_{CC}$. Here, $\sigma_{NC}$ and $\sigma_{CC}$ represent the total neutral current and charged current cross sections, summed over both electron and positron beams. The discovery regions in the leptoquark coupling-mass plane, based on measurements of these two observables, are displayed in Figs. 5 and 6 (note the scale change on the $m_S$ axis compared to Figs. 3 and 4). Figures 5 and 6a show the results from unpolarized $e^\pm$ beams for integrated luminosities of 20, 200, and 500 pb$^{-1}$ per beam, while Fig. 6b presents the bounds obtainable from polarized beams, with 125 pb$^{-1}$ per $e^\pm_{L,R}$ beam. Comparing Figs. 6a and 6b, we see that although the total integrated luminosity (summed over all beams) is larger in the polarized case, it is the unpolarized measurements which yield the largest discovery region! Note also that the search regions resulting from measurements of $R$ and $A_{ZW}$ are essentially equivalent. However, due to slightly different systematic uncertainties associated with identifying NC versus CC events, the asymmetry $A_{ZW}$ may not be as clean a measurement as the ratio $R$. The region that can be explored with 200 pb$^{-1}$ per unpolarized beam is $m_S \lesssim 800$ GeV for large leptoquark-electron-quark couplings ($F \sim 1$), and $F \gtrsim 0.13$ for $m_S \sim 314$ GeV, based on measurements of these two quantities.

In summary, we have performed a careful analysis of the effects of virtual leptoquarks at HERA. We found that measurements of the standard neutral current asymmetries using polarized beams, of the charge asymmetries, or of the neutral
current and charge current total cross sections are either plagued by systematic uncertainties or are simply not very sensitive to the parameters of the theory. However, it is possible, by examining ratios and asymmetries between NC and CC cross sections, to eliminate the large systematic errors and to probe a sizable region of the leptoquark parameter space. In principle, HERA can search for leptoquarks up to a mass of 800 GeV for large leptoquark-electron-quark couplings, and for leptoquark-electron-quark couplings \( \gtrsim 0.13\alpha_{\text{em}} \) for leptoquarks with mass \( m_S > \sqrt{s} \).

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FIGURE CAPTIONS

Figure 1. Feynman diagrams contributing to the neutral current events (a) $e^\pm q \to e^\pm q$ and (b) $e^\pm \bar{q} \to e^\pm \bar{q}$, in the Standard Model and with leptoquark exchange.

Figure 2. Feynman diagrams contributing to the charged current events (a) $e^- q \to \nu q'$ and (b) $e^+ q \to \nu q'$ in the Standard Model and with leptoquark exchange.

Figure 3. Discovery region in the $m_S - F$ plane at HERA by neutral current plus charged current total cross section and by the asymmetry $A_{LR}^\pm$, for the integrated luminosities as shown. The 90% (95%) C.L. discovery region corresponds to the area to the left of the solid (dashed) curves for the cross section measurements and to the dotted (dashed-dotted) for the asymmetry.

Figure 4. Discovery region in the $m_S - F$ plane at HERA by the charge asymmetry, $A^{-+}$, for the charged current ($A_{CC}^{\pm}$), the neutral current ($A_{NC}^{\pm}$) and the sum ($A_{CC}^{\pm} + A_{NC}^{\pm}$) for (a) $\mathcal{L} = 200$ pb$^{-1}$ and (b) 500 pb$^{-1}$. The area to the upper left of the solid (dashed) curves can be excluded at the 90% (95%) C.L.

Figure 5. Search region in the $m_S - F$ plane at HERA by the neutral-charged current asymmetry, $A_{ZW}$ for various values of $\mathcal{L}$ as shown. The area to the upper left of the solid (dashed) curves can be excluded at the 90% (95%) C.L.

Figure 6. Discovery region in the $m_S - F$ plane at HERA from the ratio, $R$, with (a) unpolarized $e^\pm$ and (b) polarized $e^\pm$ beams, for different integrated luminosities as shown. The area to the upper left of the solid (dashed) curves can be excluded at the 90% (95%) C.L.