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# Leptoquark-boson signals at $e^+e^-$ colliders

J. L. Hewett* and T. G. Rizzo*
*Center for Particle Theory, University of Texas, Austin, Texas 78712*

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We examine the production of scalar-leptoquark-boson ($S$) pairs in $e^+e^-$ annihilation along with indirect limits of leptoquark-boson properties from existing $e^+e^-$ data and that which can be obtained in the near future from the Stanford Linear Collider and the CERN collider LEP.

Leptoquark bosons are a common feature[1] of many theories that go beyond the standard model (SM). Leptoquark bosons carry both baryon and lepton number, couple to lepton plus quark, and are triplets under $SU(3)_c$. Other than these particular features their other quantum numbers (e.g., spin, weak isospin $T$, and electric charge $Q$) are very model dependent, thus making unique predictions of their production cross sections and other properties difficult. In what follows we will for simplicity limit ourselves to leptoquark bosons with spin zero ($S$), $Q=-\frac{1}{3}$, or $\frac{2}{3}$, with $T=0$ or $\frac{1}{2}$.

What limits currently exist on $S$? If $S$ is sufficiently light then $S$ can be pair produced in $e^+e^-$ annihilation as shown in Fig. 1. The $t$-channel quark-exchange diagram is model dependent due to the unknown value of the $qlS$ coupling $(A+B\gamma_5)$. If we *neglect* this diagram as well as the $Z$-exchange contribution (which is a clear oversimplification and an underestimate as we will see below) the total $S$ pair production cross section is given by $[\beta\equiv(1-4m_S{}^2/s)^{1/2}]$

$$\frac{\sigma(e^+e^-\to S\bar{S})}{\sigma(e^+e^-\to\mu^+\mu^-)}=\tfrac{3}{4}Q^2\beta^3\ , \tag{1}$$

implying that the present data from the SLAC and DESY storage rings PEP and PETRA on the $R$ ratio (Ref. 2) constrains $m_S\gtrsim 15$ GeV depending only on the charge $Q$. This limit is model independent in the sense that it depends only on the charge $Q$, and the assumption of spin-zero leptoquark bosons. Including the $t$-channel and $Z$-exchange diagrams can improve this limit but leads to a constraint on $m_S$ which depends upon the parameters $A$ and $B$ as well as the isospin properties of the leptoquark boson $S$. In addition, the UA1 Collaboration[3] has recently announced a limit on the mass of leptoquark bosons, assuming a unit probability of decay into $\mu$+jet, of 32 GeV. This constraint is quite dependent on the details of the model; only the above $e^+e^-$ limit is fairly model independent. We will return to the production of leptoquark pairs below.

To get a limit on $m_S$ we first consider the process $e^+e^-\to q\bar{q}$ as shown in Fig. 2. We see that the existence of leptoquark bosons leads to a new $t$-channel contribution as well as the usual $s$-channel $\gamma$ and $Z$ exchange. $S$ exchange clearly modifies the $q\bar{q}$ production cross section as well as the forward-backward asymmetry $A_{FB}$, depending on $m_S$ as well as the $qlS$ couplings ($A$ and $B$) discussed above. The differential cross section for $e^+e^-\to q\bar{q}$ is given by

$$\frac{d\sigma}{dz}=\frac{3\pi\alpha^2}{2s}\left[\sum_{ij}s^2A_{ij}[\tilde{B}_{ij}(1+z^2)+2\tilde{E}_{ij}z]+\frac{2t^2}{t-m_S{}^2}\sum_i P_i[k(\tilde{v}_e^i\tilde{v}_q^i-\tilde{a}_e^i\tilde{a}_q^i)+k'(\tilde{v}_e^i\tilde{a}_q^i-\tilde{a}_e^i\tilde{v}_q^i)]+k^2\frac{t^2}{(t-m_S{}^2)^2}\right], \tag{2}$$

where $t=-\frac{1}{2}s(1-z)$ with

$$k\equiv\frac{|A|^2+|B|^2}{e^2},\quad k'\equiv\frac{2\,\mathrm{Re}(A^*B)}{e^2}\ , \tag{3}$$

and

$$\begin{aligned}A_{ij}&=\frac{(s-M_i{}^2)(s-M_j{}^2)+(\Gamma_iM_i)(\Gamma_jM_j)}{[(s-M_i{}^2)^2+(\Gamma_iM_i)^2][(s-M_j{}^2)^2+(\Gamma_jM_j)^2]}\ ,\\ \tilde{B}_{ij}&=(\tilde{v}_i\tilde{v}_j+\tilde{a}_i\tilde{a}_j)_e(\tilde{v}_i\tilde{v}_j+\tilde{a}_i\tilde{a}_j)_q\ ,\\ \tilde{E}_{ij}&=(\tilde{v}_i\tilde{a}_j+\tilde{v}_j\tilde{a}_i)_e(\tilde{v}_i\tilde{a}_j+\tilde{v}_j\tilde{a}_i)_q\ ,\\ P_i&=\frac{s-M_i{}^2}{(s-M_i{}^2)^2+(\Gamma_iM_i)^2}\ .\end{aligned} \tag{4}$$

Here $z$ is the angle between the $e^-$ and outgoing $q$. The couplings $\tilde{v}_i$ and $\tilde{a}_i$ are normalized via the interaction Lagrangian

$$\mathcal{L}=e\bar{f}\gamma_\mu(\tilde{v}_i-\tilde{a}_i\gamma_5)fZ_i^\mu \tag{5}$$

and the sum over $i=(0,1)$ labels the sum over the neutral gauge bosons $\gamma$ and $Z$, respectively.

Clearly, the existence of the second and third terms in Eq. (2) will cause a drastic modification of the production cross section and the angular distribution if $k\simeq|k'|\simeq 1$ and $m_S\simeq 100$ GeV or less. This can be most easily seen from Fig. 3 which shows the limit on $m_S$ as a function of $k$ $(=k')$ over a large range of $k$ values. In obtaining the curve on the left (right) we have

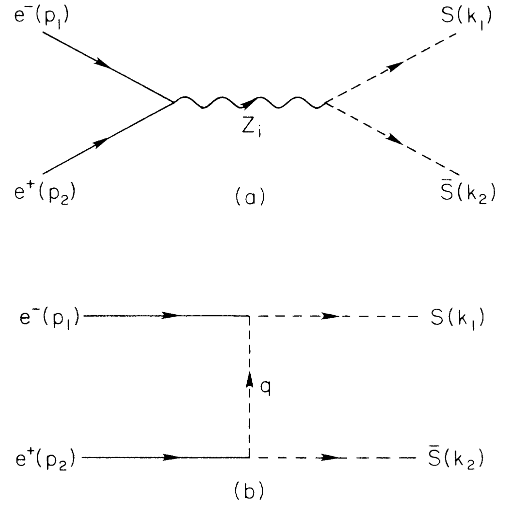

FIG. 1. Diagrams leading to the pair production of a scalar leptoquark boson in $e^+e^-$ annihilation.

demanded that neither the total cross section nor the forward-backward asymmetry ($A_{FB}$) differ from their standard-model (SM) predictions by more than 10% (5%) for quarks of either $\frac{2}{3}$ or $-\frac{1}{3}$ electric charge at $\sqrt{s}=40$ GeV. If less stringent limits were imposed it would upset the good agreement with the SM observed for charm and bottom production at PEP and PETRA.[2,4] In obtaining these limits we note that varying $k'$ over the range $-k \le k' \le k$ for fixed $k$ does not significantly modify the limits shown in the figure. As we increase the severity of the constraints from 10 to 5 % the limits on $m_S$ for a given $k$ value get significantly stronger especially for larger values of $k$. It should be noted that $A_{FB}$ provides the most stringent constraint on $m_S$ for a given value of $k$.

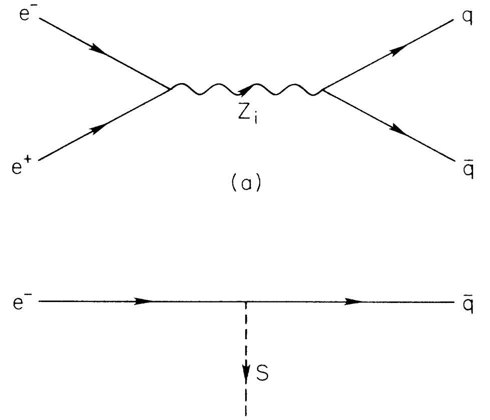

FIG. 2. Diagrams contributing to the process $e^+e^- \to q\bar{q}$ in the presence of leptoquark bosons.

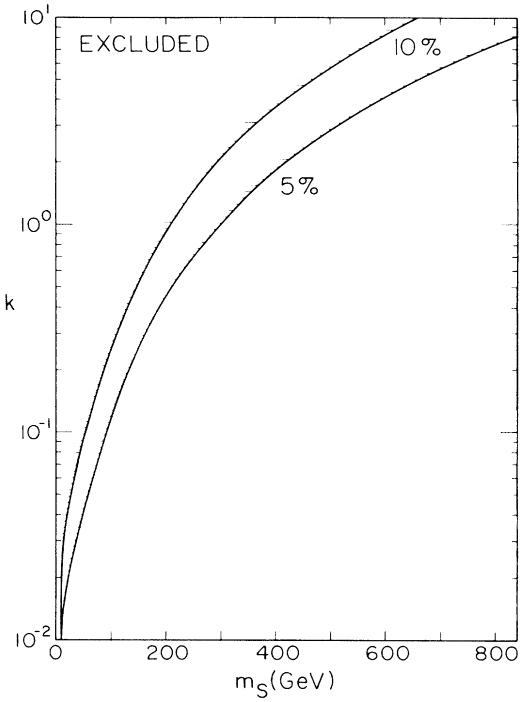

FIG. 3. Constraints on $m_S$ as a function of $k$ for two allowed values of the deviation from the SM total cross section and forward-backward asymmetry. Results for both $Q=\frac{2}{3}$ and $-\frac{1}{3}$ quarks are included.

Note that for very small $k$ values, $S$ masses as low as 10 GeV are allowed by our constraints but these do not satisfy the direct production limit which follows from Eq. (1). Clearly, for these small values of $k$ ($k \le 0.05$) Eq. (1) provides an adequate approximation to the true cross section. Thus it is clear that for $k \lesssim 0.04$ all values of $m_S \gtrsim 15-20$ GeV will satisfy both the constraint from direct production and that which follows from quark production. For $k>10$ leptoquark-boson couplings become very strong and pertubation theory becomes questionable and so we will not consider this possibility further.

Can $m_S$ be constrained by the recent measurements of the ratio of the $Z$ and $W$ total widths $\Gamma_Z/\Gamma_W$ by the UA2 Collaboration at the CERN collider?[5] To be concrete we consider an isodoublet (or isosinglet) pair of leptoquark bosons with $Q=\frac{2}{3}$ and $-\frac{1}{3}$. One can then calculate the shift in the $Z$ and $W$ decay width ($\Delta\Gamma_Z$ and $\Delta\Gamma_W$) as a function of $m_{2/3}$ and $m_{-1/3}$ using the couplings of the SM. Since constraints of $\Gamma_Z/\Gamma_W$ have gotten quite tight recently[6] and $m_t > 46$ GeV (Ref. 7) we use the limit $\Gamma_Z/\Gamma_W < 1.07(\Gamma_Z/\Gamma_W)_{\rm SM}$ in our analysis. Our calculation shows that $\Gamma_Z/\Gamma_W$ does not lead to any new constraint on either $m_{2/3}$ or $m_{-1/3}$ for isodoublet (or isosinglet) leptoquark bosons.

It is clear that as this data improves and new data from $e^+e^-$ annihilation is obtained at larger values of $\sqrt{s}$ the limits on leptoquark bosons obtained above can be substantially improved.

Given these constraints on $k$ and $m_S$ we turn our attention to the calculation of $S\bar{S}$ production. The relevant diagrams for this process are shown in Fig. 1. Using the above notation and defining the $(\gamma,Z)S\bar{S}$ coupling by the Lagrangian

$$\mathcal{L}_{ZS\bar{S}}=ie\tilde{C}_i(k_1-k_2)_\mu S^\dagger SZ_i^\mu \ , \tag{6}$$

we arrive at the differential cross section

$$\frac{d\sigma}{dz}=\frac{3\pi\alpha^2}{4}\beta^3 s(1-z^2)\left[\sum_{ij}(\tilde{v}_i\tilde{v}_j+\tilde{a}_i\tilde{a}_j)\tilde{C}_i\tilde{C}_j A_{ij}+\tfrac{1}{4}(k^2+k'^2)t^{-2}+t^{-1}\sum_i \tilde{C}_i P_i(\tilde{v}_i k-\tilde{a}_i k')\right] . \tag{7}$$

Here $t\equiv m_S{}^2-\frac{1}{2}s(1-\beta z)$ and $\beta$ is defined above. The existence of the $t$-channel-exchange diagram modifies the angular distribution away from the $(1-z^2)$ expected for the pair production of scalars in $e^+e^-$ annihilation and also modifies the $\beta^3$ threshold factor. Thus, whereas the production of ordinary scalars in $e^+e^-$ does not lead to a $A_{FB}$, the additional $t$-channel exchange can lead to significant values of $A_{FB}$.

Figure 4(a) shows the ratio ($R$) of the total cross section $\sigma$ as a (function of $k$) to that expected in the SM ($\sigma_{\mathrm{SM}}$) for a pair of color-triplet, spin-0 bosons (i.e., when only the $s$-channel contribution is present) for $\sqrt{s}=100$ GeV, $m_S=30$ GeV with four different assignments of $T_3$ and $Q$. An example of such color-triplet scalars are the squarks which exist in all supersymmetric theories. Note that from Fig. 3 for $m_S=30$ GeV we have $k\le 0.055$. For either charge the ratio is closest to unity in the isodoublet case with larger deviations observed for the isosinglet case. Figure 4(b) shows $A_{FB}$ for the same situation as in Fig. 4(a) for the same range of $k$. (Here, and in what follows, $k'=k$ will be assumed for purposes of demonstration.)

Note that for two cases $|A_{FB}|$ is quite large $(\geq 0.13)$, which is striking for the production of spin-0 particles and is a clear signal for $S\bar{S}$ production. Similarly, in two cases, the ratio $\sigma/\sigma_{\mathrm{SM}}$ differs from unity at the 15–20% level which should be easily observable. For both quantities, as expected, the deviations from the SM grow rapidly with $k$.

Figures 5(a) and 5(b) parallel Figs. 4(a) and 4(b) except we take $\sqrt{s}=200$ GeV and $m_S=60$ GeV and that larger $k$ values are now possible. In this case we see that over a reasonable range of $k$ substantial deviations from the expectations of the SM occurs for both $R$ and $A_{FB}$ for all quantum number choices. Note that the models which produced the largest deviations in Fig. 4 do not necessarily produce the largest deviations in Fig. 5 and vice versa. We also note that in Fig. 5(b) the $A_{FB}$ for the quantum number assignment $Q=-\frac{1}{3}$, $T_3=0$ actually undergoes a sign oscillation as $k$ is increased away from zero. This is not seen in the case of the other models, nor is it seen for any of the models in Fig. 4(b).

It is interesting to note that for very large $\sqrt{s}$ (e.g., 1 TeV) and large values of $m_S$ (e.g., 0.3 TeV) the larger allowed $k$ values tend to drastically increase $\sigma$ so that $R$ lies in the range 20–380 and $A_{FB}$ is large and positive (0.75–0.90). These are very distinct signals for the production of leptoquark-boson pairs at such a high-energy collider.

In Fig. 6 we show $R=\sigma/\sigma_{\mathrm{SM}}$ as a function of $\sqrt{s}$ for $Q=-\frac{1}{3}$ and $T_3=-\frac{1}{2}$ with the maximal allowed values of $k$ as given in Fig. 3 for several values of $m_S$, i.e., $m_S=20$ GeV $(k=0.04)$, $m_S=40$ GeV $(k=0.07)$, $m_S=60$ GeV $(k=0.10)$, and $m_S=80$ GeV $(k=0.20)$. Figure 7 shows $A_{FB}$ for the same values of the parameters. Qualitatively similar results are obtained for both $R$ and $A_{FB}$ assuming the other quantum number choices for $S$ discussed above. We note that since $k$ can be larger for leptoquark bosons of greater mass, $R$ grows significantly with increasing $m_S$ for the cases shown in the figure. Similar results are shown in Fig. 7 for $A_{FB}$; $A_{FB}$ grows increasingly large as $m_S$ is increased reflecting the growth in $k$. Note that for large $k$, $A_{FB}$ becomes large and positive which merely reflects the dominance of the $t$-channel-exchange diagram in this case. Thus in the $50\le\sqrt{s}\le 250$ GeV region both $R$ and $A_{FB}$ will provide very good probes for leptoquark bosons because of the large deviations from SM predictions for spin-0 color triplet production.

These deviations grow larger still if even greater masses can be probed by a $\sqrt{s}=0.5-1.0$ TeV $e^+e^-$ collider. In Figs. 8 and 9 we show $R$ and $A_{FB}$, respectively, over this energy range for the exemplary $S$ quantum numbers $Q=-\frac{1}{3}$ and $T_3=-\frac{1}{2}$. For such large masses $R$ becomes quite enormous $(\geq 10-100)$ and $A_{FB}$ also becomes quite large and positive. (The large cross section would be very helpful since event rates at large $\sqrt{s}$ $e^+e^-$ colliders are not expected to be large unless very high luminosities can be obtained.) As $m_S$ (and correspondingly $k$) are further increased $A_{FB}$ becomes closer to unity, independent of the values of $Q$ and $T_3$, because of the $t$-channel exchange. The production is pushed closer to the forward direction and more than compensates for the overall $1-z^2$ factor appearing in the production cross section [Eq. (7)]. Note that in all cases for fixed $m_S$, $A_{FB}$ increases as $\sqrt{s}$ is increased which again shows the $t$-channel dominance for large $k$ values.

It is clear from the above analysis that for $\sqrt{s}\geq 50$ GeV, leptoquark bosons lead to nonzero $A_{FB}$ and large $R$ providing a unique signature via production alone.

The decay signatures of leptoquark bosons are quite distinct and have been discussed in detail in earlier work.[8] Since the two decay modes are $S\rightarrow lq$ and $\nu q'$, pair production always produces two jets plus leptons. If the leptons are neutrinos there will be a large missing-energy signal along with the jets similar to a supersymmetry signal for squark production. If one $S$ decay involves a charged lepton then missing $p_T$ ($\not p_T$) will still be present. In the case where two charged leptons occur along with the jets, an invariant-mass distribution should show double peaking in the lepton-plus-jet combination. It is clear that large production cross sections and unique signatures should make leptoquark bosons easy to spot in $e^+e^-$ annihilation. Note that the relative branching ratio for the $\nu q'$ and $lq$ final states will depend on the details of the model and will not be further discussed here.

In conclusion we have analyzed the limits that existing $e^+e^-$ data place on the mass and couplings of lepto-

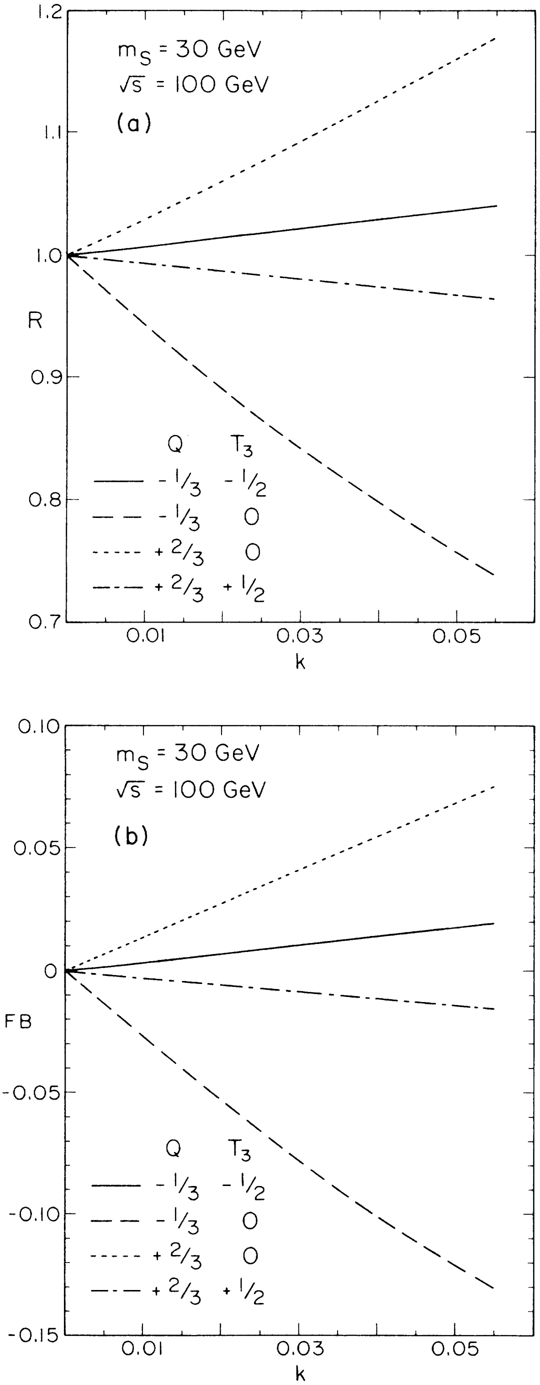

FIG. 4. Values of $R=\sigma/\sigma_{SM}$ (a) and $A_{FB}$ (b) for $m_S=30$ GeV, $\sqrt{s}=100$ GeV as functions of $k$ for four different quantum number assignments of the leptoquark boson.

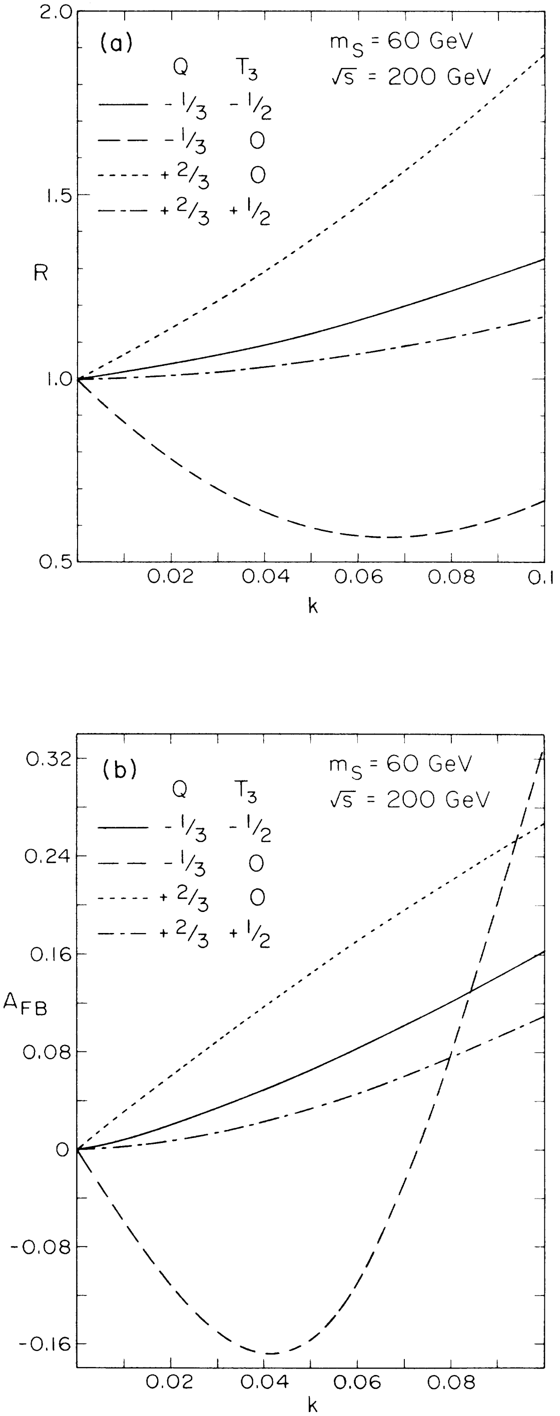

FIG. 5. Same as Fig. 4 but for $m_S=60$ GeV and $\sqrt{s}=200$ GeV.

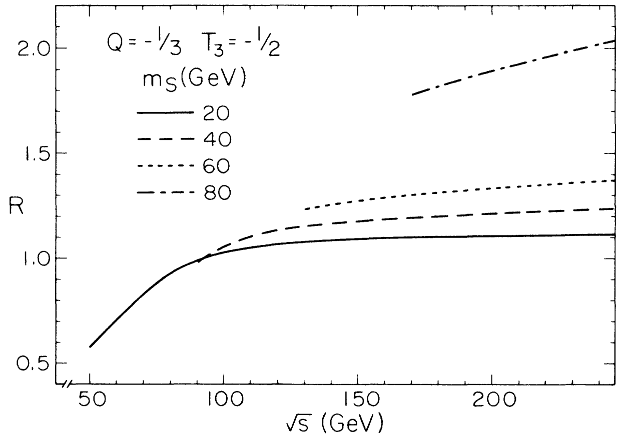

FIG. 6. $R=\sigma/\sigma_{SM}$ vs $\sqrt{s}$ for $Q=-\frac{1}{3}$, $T_3=-\frac{1}{2}$ with maximal values of $k$; $m_S=20$ GeV ($k=0.04$), $m_S=40$ GeV ($k=0.07$), $m_S=60$ GeV ($k=0.10$), and $m_S=80$ GeV ($k=0.20$). Here $50\leq\sqrt{s}\leq 200$ GeV.

quark bosons with various electroweak quantum numbers. Using these constraints we have calculated the production cross section and the forward-backward asymmetry for leptoquark-boson pairs in $e^+e^-$ annihilation. For large $k$ values we found that the constraints on $m_S$ are quite severe whereas for $k\leq 0.04$ all values of $m_S \gtrsim 15-20$ GeV are found to satisfy all of the existing constraints. $A_{FB}$ is found to be a far more sensitive probe of leptoquark production than total-cross-section measurements when $k$ is small. For large $k$ the cross section was found to be greatly enhanced because of the $t$-channel quark exchange and $A_{FB}$ was always very large in magnitude. Clearly both $\sigma$ and $A_{FB}$ can be used to separate leptoquark-boson pair production from the pair production of ordinary color-triplet scalars. The decay signature for leptoquark bosons is 2 jets $+l^+l^-$, $l+\not{p}_T$, or $\not{p}_T$ and is unique if a charged lepton is observed in the final states and is clearly distinguishable from other scenarios such as supersymmetry.

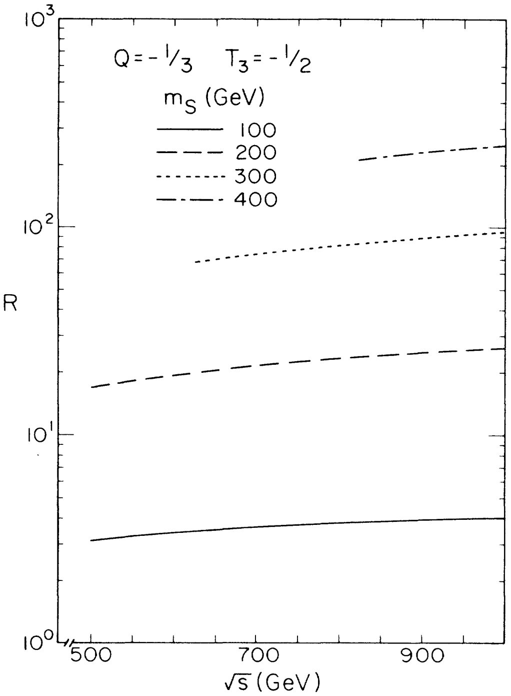

FIG. 8. Same as Fig. 6 but for $m_S=100$ GeV ($k=0.25$), $m_S=200$ GeV ($k=0.9$), $m_S=300$ GeV ($k=2.0$), and $m_s=400$ GeV ($k=3.6$) and $0.5\leq\sqrt{s}\leq 1.0$ TeV.

Leptoquark-boson production may provide us with a unique signal for physics beyond the standard model.

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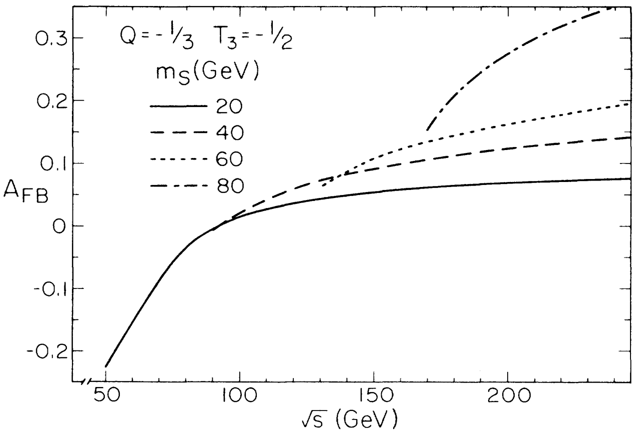

FIG. 7. Same as Fig. 6 but for $A_{FB}$.

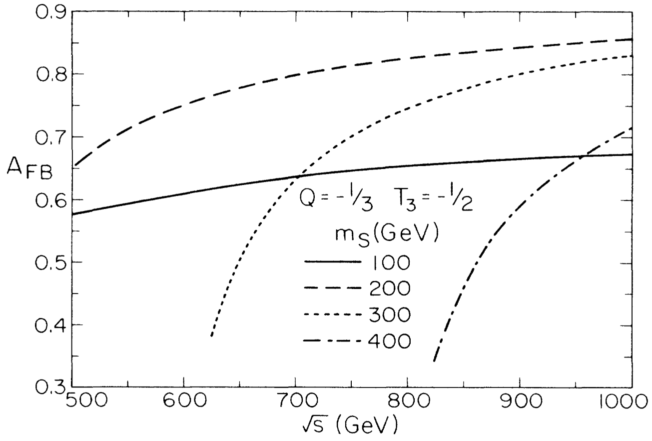

FIG. 9. Same as Fig. 8 but for $A_{FB}$.

[*] Permanent address: Ames Laboratory, Iowa State University, Ames, IA 50011.

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