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Looking for colored leptons

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If leptons are composite objects containing colored preons one would expect the existence of heavy states with similar electroweak interactions which are color octets. These colored leptons should be produced (or have their effects felt) in a wide variety of interactions if they are not overly heavy. We examine the production mechanisms for and decay properties of these particles and find that they should be observable at CERN LEP, the Stanford Linear Collider, and other accelerator facilities.

I. INTRODUCTION

The possibility that quarks and leptons are composite objects consisting of sets of preons bound together by a new strong interaction has long been under discussion in literature.[1] In many models of this kind, color is a dynamical quantity as it is in the standard model. In such theories, the preons inside of leptons (be they fermions or bosons) may carry color although the composite state remains a color singlet. In all such composite-model approaches excited leptons must exist and several possibilities along these lines have been discussed by other authors.[2] We may have, for example, "radial excitations" in which the excited lepton l^* has the identical quantum numbers as l except for mass or l^* may be a "hyperfine excited state" with spin $\frac{3}{2}$. If the preons inside l have color, it is clearly possible that excited states of l could exist which are not color neutral. The representation of $SU(3)_c$ in which these colored leptons (chromoleptons)[3] find themselves is not clear but one obvious possibility is the **8**. This, for example, can occur if two preons carry a **3** of color and $3\times\bar{3}$ bound states form. The color-singlet part of this would be the usual lepton whereas the color-octet part would be the chromolepton l_8. Clearly, the l_8 mass is expected to be far greater than the corresponding l mass.

If l_8 is sufficiently light (10 GeV–1 TeV) how would these particles be produced or have their effects noticed at lower energies? This is the problem we will begin to address in this paper. We will assume that the l and l_8 have identical electroweak interactions and that the l_8 interaction with quarks is governed by the usual QCD Lagrangian augmented by the additional l_8 term. Since l and l_8 consist of the same preons, we also imagine a magnetic-dipole coupling between l and l_8:

$$\lambda\frac{g_s}{2M_8}\bar{l}\sigma_{\mu\nu}l_8^a G^{a\mu\nu}+\text{H.c.}\ , \tag{1.1}$$

where g_s is the usual strong coupling constant, M_8 is the l_8 mass, λ is a dimensionless parameter expected to be ~ 1, and $G^a_{\mu\nu}$ is the gluon field strength tensor. This coupling, e.g., allows for chromoleptons to decay into a normal lepton and a gluon: $l_8\to l+g$. It is just this coupling which can be used to look for l_8 production or the effects of l_8 exchange in high-energy reactions.

The outline of this paper is as follows. In Sec. II we consider the mass limits that can be placed on masses of chromoleptons by a simple analysis of present experiments. In Sec. III we consider a variety of production mechanisms for l_8's which can lead to new limits on the values of λ or M_8 or actual observation of l_8's. We concentrate on observing l_8's in e^+e^-, γe, and Z^0 decay reactions. Our conclusions and a discussion can be found in Sec. IV.

II. MASS LIMITS

From our knowledge of current experiments we can immediately establish a crude lower bound on the masses of chromoleptons. The data to be examined are e^+e^- interactions and the properties of the Z^0. Above threshold in e^+e^- annihilation, charged chromoleptons, make a huge contribution to R:

$$R_{e_8}=4\beta(3-\beta^2),\ \ \beta=(1-4M_8{}^2/s)^{1/2}\ . \tag{2.1}$$

This would imply immediately that $M_8\gtrsim 20$ GeV from the recent DESY PETRA data.[4] (The signal for e_8 pair production is also very clear: two jets plus an e^+e^- pair.) Neutral chromolepton production at present e^+e^- colliders is quite small since only Z^0 exchange can produce ν_8 pairs. We find, for example, that at $\sqrt{s}=45$ GeV

$$R_{\nu_8}\simeq 0.2\times\begin{cases}\beta(3-\beta^2)/2 & \text{if } \nu_8 \text{ is Dirac}\ ,\\ \beta^3 & \text{if } \nu_8 \text{ is Majorana}\ ,\end{cases} \tag{2.2}$$

which is presumably invisible from R measurements. The final state here is a pair of jets plus missing energy; recent searches at PETRA for monojets[5] should have observed some events of this kind unless ν_8 is also comparable to (or greater than) 20 GeV in mass.

Turning now to the data on the Z^0 width from the UA1 and UA2 Collaborations[6] we see that the data now constrain the width to a value quite close to the standard model. As is usually quoted, the number of new neutrinos, N_ν, is less than or equal to one. Hence, we would demand that

$$\frac{\Gamma(Z\to e_8\bar{e}_8)}{\Gamma(Z\to\nu\bar{\nu})},\frac{\Gamma(Z\to\nu_8\bar{\nu}_8)}{\Gamma(Z\to\nu\bar{\nu})}\le 1\ . \tag{2.3}$$

Now theoretically we find that

$$\frac{\Gamma(Z\to\nu_8\bar{\nu}_8)}{\Gamma(Z\to\nu\bar{\nu})}=\begin{cases}16\beta^3 \text{ (Majorana } \nu_8)\ ,\\ 4\beta(3+\beta^2) \text{ (Dirac } \nu_8)\ ,\end{cases} \tag{2.4}$$

$$\frac{\Gamma(Z\to e_8\bar{e}_8)}{\Gamma(Z\to\nu\bar{\nu})}=4\beta^3+2\beta(3-\beta^2)(-1+4\sin^2\theta_W)^2 \tag{2.5}$$

implying the limits ($\sin^2\theta_W=0.217$)

$$\begin{gathered}M_{\nu_8}\ge\begin{cases}42.7\text{ GeV (Majorana } \nu_8)\ ,\\ 46.3\text{ GeV (Dirac } \nu_8)\ ,\end{cases}\\ M_{e_8}\ge 38.6\text{ GeV}\ .\end{gathered} \tag{2.6}$$

In both cases striking signals should be observed; ν_8 pairs produce two jets plus missing energy while e_8 pairs produce two jets and two leptons with the appropriate equal invariant masses. To "explain" the observed usual (monojet and dijet) events, however, it is clear that the ν_8 masses would have to be tuned to a value very close to $M_Z/2$.

It seems reasonable to conclude from this analysis that e_8 and ν_8 are both fairly heavy (>40–45 GeV) and will not easily be pair produced in Z^0 decay if at all. We are thus forced to examine channels where single ν_8 or e_8 production occurs or where $\sqrt{s}$ values are sufficiently large for pair production of chromoleptons to occur. Note that for such large masses even single chromolepton production would be quite inhibited at top PETRA center-of-mass energies.

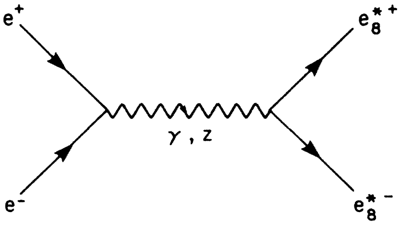

FIG. 1. Diagram for e_8 pair production in e^+e^- annihilation from single-γ or -Z^0 exchange.

III. PRODUCTION MECHANISMS

A. $e^+e^-\to e_8^+e_8^-$

Pair production of colored-octet chromoleptons can occur in a variety of ways with the most obvious being through the exchange of a single electroweak gauge boson (i.e., γ or Z) as shown in Fig. 1. Due to the additional color factors the e_8 pair-production cross section is eight times larger than that for normal leptons when we are far above threshold. Other production mechanisms can lead to much larger cross sections. A four-fermion contact interaction can result from a rearrangement of the preons, e.g., inside the electron which is expected in any composite model. For an interaction of the form

$$\frac{4\pi}{\Lambda^2}\bar{e}_8e_8\bar{e}e\ , \tag{3.1}$$

we find a cross section (relative to that for electroweak production) of $\sim(s/\Lambda^2\alpha)^2$ which can be quite large but depends sensitively on Λ. Note that if $\Lambda\gtrsim 5$–10 TeV, however, the contact interaction result is far smaller than the electroweak result. Such large values of Λ are not unreasonable given the present experimental limits and theoretical biases.

The process we will examine is shown in Fig. 2, with the resulting differential cross section ($z=\cos\theta$, θ being the angle between the e^- and e_8^- momenta)

$$\frac{1}{\sigma_{\text{pt}}}\frac{d\sigma}{dz}=\frac{3}{4}\lambda^4\left[\frac{\alpha_s}{\alpha}\right]^2\left[\frac{s}{tM^2}\right]^2\left[1-\frac{4M^2}{s}\right]^{1/2}\left[2(t+M^2)^2+4M^2/s(t+M^2)(u+M^2)+\left[\frac{M^2}{s}\right]^2[s(s-M^2)+(u+M^2)^2]\right] \tag{3.2}$$

with

$$\begin{gathered}t=-\tfrac{1}{2}s(1-\beta z)+M^2\ ,\\ u=-\tfrac{1}{2}s(1+\beta z)+M^2\ ,\end{gathered} \tag{3.3}$$

and $\beta=(1-4M^2/s)^{1/2}$. σ_{pt} is the $e^+e^-\to\mu^+\mu^-$ single-γ-exchange cross section, $\sigma_{\text{pt}}=4\pi\alpha^2/3s$, and M_8 is the chromolepton mass.

This result is plotted in Figs. 3 and 4 for $\sqrt{s}=100$ and 200 GeV, respectively, for various values of the e_8 mass; the results presented in these graphs must be rescaled by λ^4 for $\lambda\ne 1$. Note that, e.g., at $\sqrt{s}=100$ GeV and

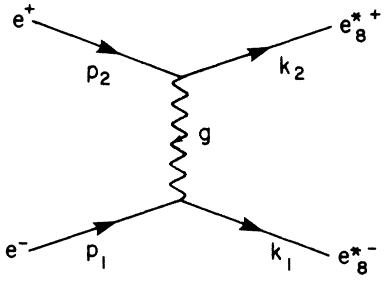

FIG. 2. Diagram for e_8 pair production in e^+e^- annihilation from single-gluon exchange.

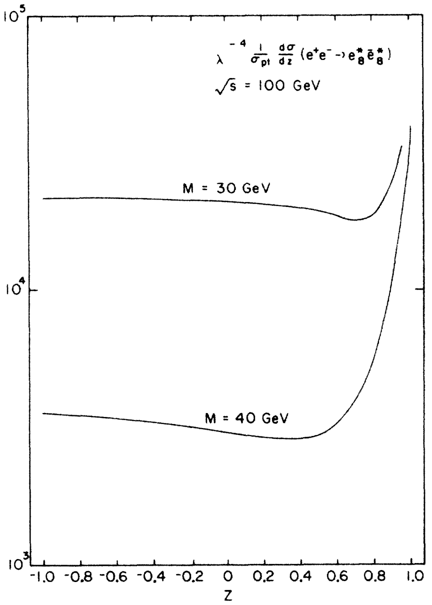

FIG. 3. Cross section for the process shown in Fig. 2 with $\sqrt{s}=100$ GeV.

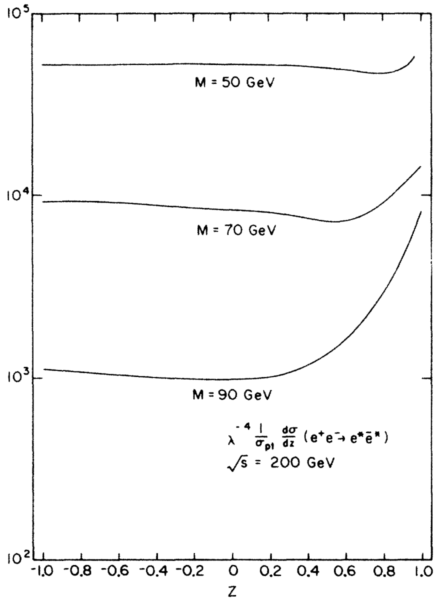

FIG. 4. Same as Fig. 3 but with $\sqrt{s}=200$ GeV.

$M_{e_8}=40$ GeV the cross section is quite large even for $\lambda \lesssim \frac{1}{5}-\frac{1}{10}$. (It is also important to note that the production mechanism being discussed is equally applicable to ν_8 production and yields an identical result if we assume that ν_8 is a Dirac particle.) At higher $\sqrt{s}$ values which are obtainable at CERN LEP II even higher-mass states can be reached provided λ is not too small. It should be noted that for $\lambda \simeq 1$ and $M \lesssim 50$ GeV at $\sqrt{s}=200$ GeV, unitarity violation occurs and our results are no longer reliable.

The final state to be observed here is two jets plus missing energy or two jets plus an e^+e^- pair. As noted above this results from the dominant two-body chromolepton decay modes

$$e_8 \to e+g, \quad \nu_8 \to \nu+g \ , \tag{3.4}$$

both of which occur with a width $\Gamma=\frac{1}{2}\lambda^2\alpha_s M_8$. Unless λ^2 is infinitesimal the track of the chromolepton is invisible and we observe only the decay products: lepton plus jet or jet plus missing energy. There will be a peak in the lepton + jet invariant mass equal to the mass of the decaying chromolepton.

B. $\gamma e \to g e_8$

Single chromolepton production can occur in γe collisions at high-$\sqrt{s}$ values, which might be obtainable at the Stanford Linear Collider (SLC) using the backward-Compton-scattering technique.[7] The process in question is shown in Fig. 5. The cross section for this process is given by

$$\frac{1}{\sigma_{pt}}\frac{d\sigma}{dz}=\frac{3}{8}\frac{\alpha_s}{\alpha}\lambda^2 f(x) \ , \tag{3.5}$$

where $z=\cos\theta$ (θ being the angle between the e and e_8 momenta), $x=M_8{}^2/s$, and

$$f(x)=x^{-1}(1-x)\left[(1-x)(1-z)\left[1-x+\frac{\beta(1-z)}{1-\beta z}\right]+4x\left[\frac{\beta(1-z)}{1-\beta z}\right]^2\right] \tag{3.6}$$

with

$$\beta\equiv\frac{1-x}{1+x} \ . \tag{3.7}$$

Figures 6 and 7 show the above cross-section ratio which must be multiplied by a factor of λ^2. The final state observed in this reaction is lepton plus two jets with a peak in the lepton plus jet invariant mass equal to M_8 which should be quite clear. Note that for $\lambda \simeq 1$ at $\sqrt{s}=100$ GeV, e_8 production for values of M_8 near 90 GeV is quite appreciably $\gtrsim \sigma_{pt}$. For small mass values the production rates are very large even for $\lambda \sim \frac{1}{10}$; remember that σ_{pt} with $L=10^{31}$ cm^{-2}sec^{-1} for $\sqrt{s}=100$ GeV yields $\sim$2700 events/yr. At $\sqrt{s}=200$ GeV even larger values of M_8 are obtainable even though σ_{pt} yields only $\simeq$690 events/yr at the same luminosity as above. For $M_8=190$ GeV we would expect $\sim$2700 events/yr with a very clear signature assuming $\lambda=1$. Chromoleptons of such large mass may be observable even for smaller values of λ.

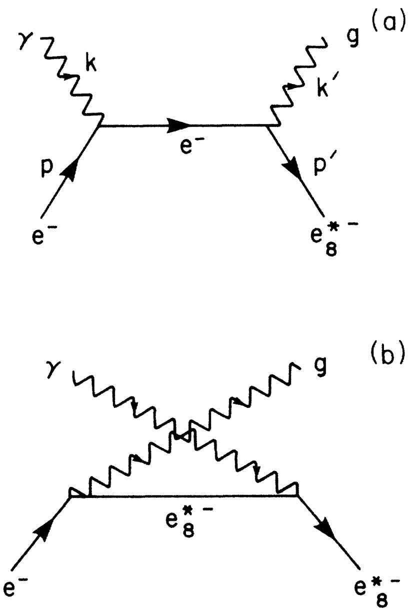

FIG. 5. Diagrams for single-e_8 production in γe collisions.

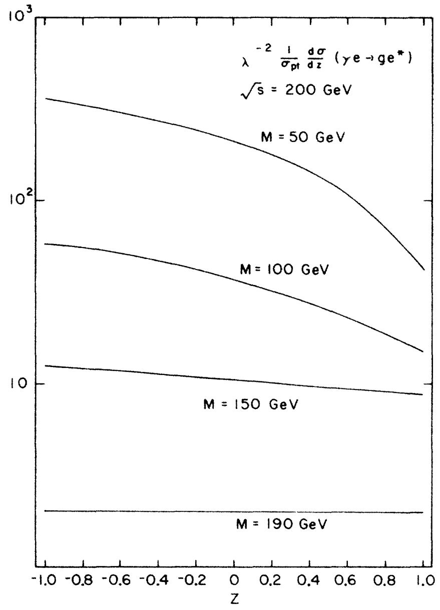

FIG. 7. Same as Fig. 6 but with $\sqrt{s}=200$ GeV.

C. $e^+e^-\to 2g$

Although this process is not one in which chromoleptons are produced in pairs or singly the reaction can only go through a chromolepton intermediate state and is thus a good probe for masses beyond that accessible at SLC or LEP. The relevant diagrams for this process are shown in Fig. 8. Unlike the previous two cases there are large backgrounds to this process since the observed final state is simply two jets—the usual e^+e^- hadronic final state. Unless one can distinguish quark- from gluon-initiated jets, observe a different jet angular distribution, or a deviation in the rate of the two-jet final state this process will be very difficult to detect.

The cross section for $e^+e^-\to 2g$ is given by

$$\frac{1}{\sigma_{\rm pt}}\frac{d\sigma}{dz}=6\left[\frac{\alpha_s}{\alpha}\right]^2\lambda^4 g(x,z)\,, \tag{3.8}$$

where $z=\cos\theta$, $x=4M_8{}^2/s$ with

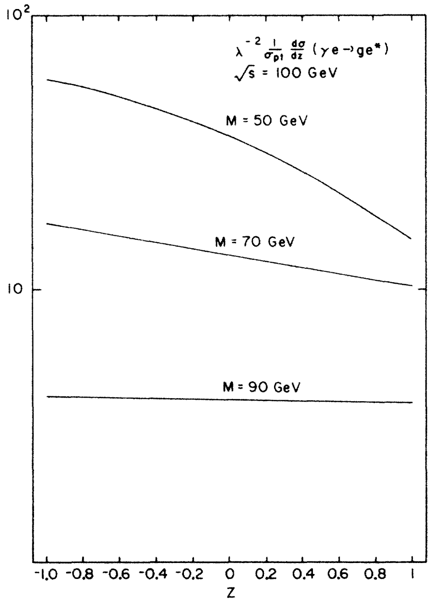

FIG. 6. Cross section for the process shown in Fig. 5 with $\sqrt{s}=100$ GeV.

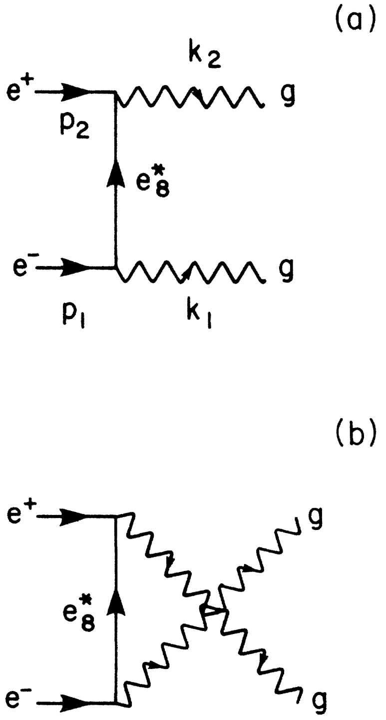

FIG. 8. Diagrams for $e^+e^-\to 2g$ through a virtual e_8.

$$g(x,z)=x^{-2}([(1-z^2+x]\{(1-z)^2[(1-z)+x/z]^{-2}+(+z)^2[(1+z)+x/2]^{-2}\}$$
$$+4x(1+z^2)[(1-z)+x/2]^{-1}[(1+z)+x/2]^{-1}) \; . \tag{3.9}$$

Note as $x\rightarrow\infty$ (i.e., $M^2\gg s$) we find the simpler approximation

$$\frac{1}{\sigma_{\rm pt}}\frac{d\sigma}{dz}=144\left[\frac{\alpha_s}{\alpha}\right]^2\lambda^4x^{-3}(1+z^2) \; . \tag{3.10}$$

Thus the two-jet final-state cross section would be, in this limit,

$$\frac{1}{\sigma_{\rm pt}}\frac{d\sigma}{dz}(e^+e^-\rightarrow 2 \text{ jets})$$
$$=\tfrac{9}{8}(1+z^2)\left[1+2\left[\frac{\alpha_s}{\alpha}\right]^2\lambda^4\left[\frac{\sqrt{s}}{M}\right]^6\right] , \tag{3.11}$$

where the 1 comes from $q\bar{q}$ production. If we demand that e_8 exchange not modify the usual two-jet cross section by more than 5% (10%) then we find the constraint (in this approximation)

$$4.43\;(3.94)\;\lambda^{2/3}\sqrt{s}<M_8 \; , \tag{3.12}$$

which is quite restrictive at present energies provided $\lambda\simeq 1$ and moderately restrictive for $\lambda\gtrsim\frac{1}{5}$ or so. Thus an accurate measurement of the two-jet cross section at the 5% level could be used to constrain λ and M_8. Figure 9 shows the exact result for $(1/\sigma_{\rm pt})d\sigma/dz$ for various values of x between 1 and 10^3 as a function of $z=\cos\theta$; the number on the right of each curve should multiply the scale of the curve. All of the results should be multiplied by λ^4 as well. For small-x values the cross section is quite enormous but decreases rapidly for increasing x; the situation gets most interesting near and above $x=100$ ($\sqrt{s}/M=\frac{1}{5}$). For example, at $x=100$ the exact expression tells us that e_8 exchange yields a 6.9% contribution to the *total* two-jet cross section for $\lambda=1$ whereas for $x=200$ we find only a 0.9% contribution to this same quantity for $\lambda=1$. This is probably the limit of detectability without a clear separation of gluon- and quark-initiated jet final states.

The limits obtained above are quite powerful; since R is known to better than 10% at $\sqrt{s}=40$ GeV from PETRA data we clearly arrive at the limit

$$160\lambda^{2/3}\text{ GeV}<M_8 \; , \tag{3.13}$$

which for $\lambda\simeq 1$ is clearly a significant improvement over the present limits from the Z^0 width and pair production at PETRA. A more accurate (5%) measurement of the two-jet cross section at 45 GeV (including corrections from Z^0 exchange) may provide a reasonable limit on M_8 even if $\lambda\simeq\frac{1}{10}$. For this value we obtain $M_8\gtrsim 43$ GeV, slightly better than that obtainable from Z^0 decay.

D. $X^0\rightarrow e_8eg\;(\nu_8\nu g)$

The last process we shall study is Z^0 decay into a single chromolepton which allows us to explore masses above the 38.6-GeV limit set by the present upper limit on the Z^0 width. The final state will be either e^+e^- + two jets or two jets plus missing P_T (dijets). In the first case there will be a peak in one of the lepton + jet invariant masses. We can use the results of this calculation in two ways to constrain λ and M_8. First, we can demand that the contribution of the e_8eg final state to the Z^0 width be less than or equal to that of an additional neutrino. Second, we can demand that the relative number of events of the kind described above be less than some prescribed limit. Both of these will be discussed below.

Figure 10 shows the diagrams for this process. Let $x_{1,2}=2E_{1,2}/M_z$; we then find

$$\frac{1}{\Gamma(Z\rightarrow e^+e^-)}\frac{d^2\Gamma}{dx_1dx_2}(Z\rightarrow e_geg)=\frac{4\alpha_s}{\pi}\lambda^2F(x_1,x_2,x_3,\delta)\delta^{-2} \; , \tag{3.14}$$

where $\delta\equiv M_8/M_z$, $x_3=2-x_1-x_2$, and

$$F=2(1-x_2)(1-x_1)^{-1}(1-x_1+\delta^2)^2$$
$$-(1-x_1)^{-2}(1-x_1+\delta^2)[(-x_1+\delta^2)(1-x_1-x_2-x_1x_2+\delta^2)+\delta^2(1-x_1-x_3-x_1x_3+\delta^2)]$$
$$-(1-x_2)^{-2}(1-x_2-\delta^2)[(1-x_2-\delta^2)(1-x_1-x_2-x_1x_2+\delta^2)-\delta^2(1-x_2-x_3-x_2x_3-\delta^2)] \; . \tag{3.15}$$

This expression, upon integration, is infrared divergent since the gluon can be infinitely soft; we render the ratio $\Gamma(Z\rightarrow e_8eg)/\Gamma(Z\rightarrow e^+e^-)$ finite by cutting off the gluon momenta at 2–8 % of M_z. This procedure has very little effect on the ratio of decay rates. Also since we expect to be able to see clearly defined jets with $\simeq$4 GeV energy at the SLC and LEP (Ref. 8) we choose the particular cutoff $E_g\gtrsim 4$ GeV in our results.

Figure 11 shows the ratio $R=\Gamma(Z\rightarrow e_8eg)/\Gamma(Z\rightarrow e^+e^-)$ as a function of δ for the above cutoff; both $e_8^-e^+g$ and $e_8^+e^-g$ final states are included in this figure. Note that the identical result is obtained for the ratio $\Gamma(Z^0\rightarrow\nu_8\nu g)/\Gamma(Z\rightarrow\nu\bar{\nu})$. The values on the graph need to be rescaled by the appropriate value of λ^2. Note that for $\delta\simeq 0.55$ and $\lambda^2=1$ the chromolepton production is comparable to e^+e^- pair production in Z^0 decay and de-

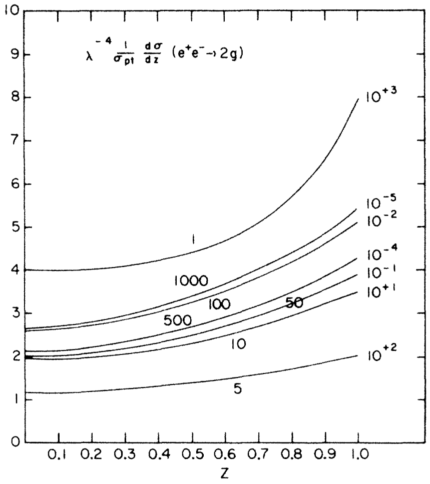

FIG. 9. Cross section for the process shown in Fig. 8. The number on the curve is the value of x defined in the text; the number on the right of the curve multiplies the values in the curve.

creases rapidly with increasing δ. It is clear that unless $\lambda > 1$ we cannot constrain λ and M_8 by using the total Z width along since single chromolepton production will be a less than 3% effect. If we demand the number of such events resulting from Z^0 decay into chromoleptons be small enough to be presently invisible R must be as low as $\simeq \frac{1}{20}$ or so. This would imply, for example, that for $\lambda = 1$, $M_8 \gtrsim 61.4$ GeV for charged chromoleptons. If the missing-p_T events are ascribed to ν_8 production we obtain a similar bound since at least some events of this kind are observed. As soon as we decrease λ below unity, however, our bound becomes quite poor compared with the bounds from PETRA using the two-jet final-state data.

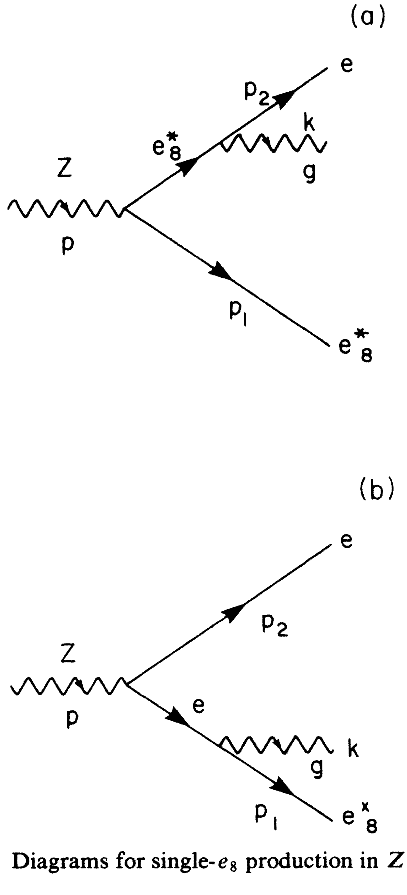

FIG. 10. Diagrams for single-e_8 production in Z^0 decay.

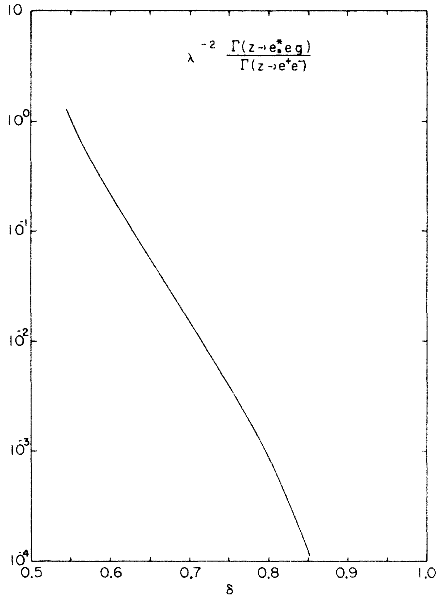

FIG. 11. Relative branching ratio for the process shown in Fig. 10.

IV. ANALYSIS AND CONCLUSION

We have considered a large number of processes in which chromoleptons are produced or have their effects observed indirectly. Observation of these particles and/or their effects depends critically on their masses and on the value of the parameter λ. For $\lambda > 1$, chromoleptons in the relevant mass ranges should be clearly seen in the next round of accelerators. For $\lambda < 1$, present experimental data constrains both λ and M_8; Fig. 12 shows the allowed regions of these parameters resulting from PETRA data as well as results from UA1 and UA2. For $\lambda \leq \frac{1}{10}$ the

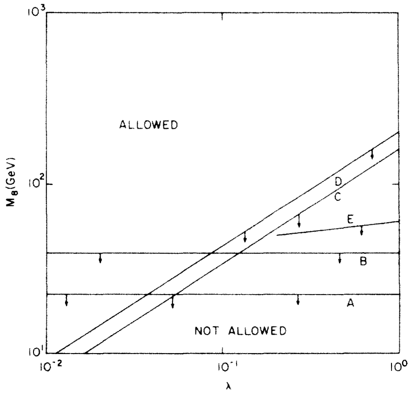

FIG. 12. Bounds on the coupling (λ) and mass (M_8) of colored leptons obtained in this paper.

best constraints come from the measurements of the Z^0 total width and the analysis that led to an upper limit on the number of additional ν species. For this case we find $M(e_8) \gtrsim 38.6$ GeV with comparable limits for ν_8 depending on whether ν_8 is a Dirac or Majorana particle.

For $\frac{1}{10} \lesssim \lambda \lesssim 1$ the best limits come from the modification e_8 exchange would produce in two-jet production in e^+e^- annihilation. A 10% R measurement by PETRA at $\sqrt{s}=40$ GeV forces $M_8 \gtrsim 170$ GeV for $\lambda=1$ which is quite restrictive compared to the limit obtained from Z^0 decays. It is clear that accurate measurements of R for $\sqrt{s} \geq M_z$ may reveal the existence of chromoleptons or place much more severe constraints than are presently possible from lower-energy data. Looking for events of the kind e^+e^- + two jets or two jets + missing energy at a Z^0 factory could be used to strengthen the bounds in the small λ region for masses $\gtrsim 40$ GeV.

The existence of chromoleptons seems to be a basic feature in a large class of composite models of quarks and leptons. If they exist then color-octet partners of both the neutrino and the electron are expected to be produced or have their effects felt in a large number of experiments. Chromolepton production signatures are quite clean. The observation of events of the kind described here and/or modifications of two-jet cross section in e^+e^- may be the first signal of compositeness.

It should be noted in closing that other processes in pp, $\bar{p}p$ (Ref. 9), and ep (Refs. 10 and 11) collisions can also be used to observe colored leptons. These will be discussed elsewhere.

ACKNOWLEDGMENT

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[6] For a review, see talk given by L. DiLella, at the 1985 International Europhysics Conference on High Energy Physics, Bari, Italy, 1985 (unpublished).

[7] See, for example the discussion in F. M. Renard, Z. Phys. C **14**, 209 (1982), and references therein.

[8] A. Firestone (private communication).

[9] D. Lust, E. Papantonopoulos, K. H. Streng, and G. Zoupanos, Max-Planck Report No. MPI-DAE/PTh 48/85, 1985 (unpublished); F. M. Renard, Montpellier Report No. PM/85-20, 1985 (unpublished).

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