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# Gauge model for testing compositeness in electron-positron collisions

Y. A. Coutinho, J. H. Lopes, J. A. Martins Simões, and M. C. Pommot Maia*
*Universidade Federal do Rio de Janeiro, Instituto de Física 21941 Rio de Janeiro, Brasil*

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We present a composite scenario based on the $SU_L(2)\otimes U(1)_Y\otimes SU_L^*(2)$ group. New interactions are predicted at the usual electroweak scale. New heavy fermions can be produced in a renormalizable model. A new type of light excited neutrinos can occur and are shown to be naturally consistent with the recent results from the CERN $e^+e^-$ collider LEP on the $Z$ width.

## I. INTRODUCTION

The $e^+e^-$ collisions at the CERN collider LEP and at SLAC are expected to achieve at least two fundamental goals in elementary-particle physics: to improve the data from the standard model predictions and to verify the consistency of some of its extensions. The standard model is being tested at the level of its quantum corrections, and some remaining question marks, such as the Higgs sector, the top quark, the Kobayashi-Maskawa parameters, are expected to be settled. It is also generally believed, although not experimentally motivated, that some unanswered questions such as the origin of the families' replication needs some theoretical extension of the standard model. Here a wide number of suggestions is possible but none has, so far, been confirmed by experiment.

In this paper we will concentrate our attention on the idea of compositeness. At first sight it is a very appealing suggestion since the regularities in the family behavior seems to suggest a common origin from some deeper structure. However, the experimental restriction on distances of the order of $10^{-16}$–$10^{-17}$ cm renders very difficult the task of theoretical models. The most popular approach consists in the hypothesis of a new scale of interactions that simulates an effective four-fermion interaction at low energies of the same type as the old Fermi theory for weak interactions. This implies in an effective coupling $g^2/\Lambda$, and if $g^2\simeq 1$ we have the bound $\Lambda \geq 1$ TeV. As in Fermi's theory this violates unitarity at energies of the order of $\Lambda$, and heavy objects such as an excited lepton with this mass cannot be correctly described by this model.

Recently,[1] we have developed a new approach to test the hypothesis of compositeness, which was suggested some years ago.[2] Here we briefly review the model and discuss some new consequences of it. For more details, we address the reader to Refs. 1 and 2.

## THE $SU_L(2)\otimes U(1)_Y\otimes SU_L^*(2)$ MODEL

Our starting point is very simple. If the idea of compositeness is correct, the standard electroweak $SU_L(2)\otimes U_Y(1)$ model must be considered as an effective theory. In this context, a more fundamental dynamical model must be found, and it has to reproduce the fermion mass spectrum, the now known families, $P$ and $CP$ violation, and all the well-established features of the standard model. Nowadays we have no convincing model to explain the dynamics of the subcomponents, and, although an important point, this is not the subject of the present paper. The idea of compositeness we are presenting here is based, instead, on macrocharacteristics of matter. The success of the standard model allows us to go one step further in the direction of testing the hypothesis of compositeness. Even if the $SU_L(2)\otimes U_Y(1)$ model is to be considered as an effective theory in the compositeness scenario, its validity remains unquestionable. Not only its agreement with experiment is untouchable but also its theoretical completeness of being renormalizable and anomaly-free must be considered. These properties can be used as a guide to find a fundamental aspect of compositeness that is not answered in most models: What is the behavior of the excited states of the now known matter? Following the success of the standard $SU_L(2)\otimes U_Y(1)$ model we were led to speculate that excited matter must behave according to some new gauge group. We have chosen a new $SU_L^*(2)$ that acts on excited fermions.[1-3] The motivations for this choice are the following: First, we consider only the massive $W$ and $Z$ as composite (not the photon) and look for their excited states ($W^*,Z^*$). As the usual $W$ and $Z$ are associated with the $SU_L(2)$, we propose a new[1,2] $SU_L^*(2)$ to generate $W^*$ and $Z^*$. Second, it is well known that a Higgs doublet gives a charged-to-neutral-current ratio identical to 1, in close agreement with experiment. So, we propose a new Higgs doublet $\Phi^*$ (with a vacuum parameter $v^*$) that is a doublet for $SU_L^*(2)$. With this choice we have agreement with low-energy phenomenology in a natural way. The usual fermions are singlets under $SU_L^*(2)$, and we have the possibility of including new excited fermions as doublets under $SU_L^*(2)$ [and singlets under $SU_L(2)$]. The same procedure must be applied to each family. These quantum numbers are summarized in Table I. Lepton number is supposed to be the same for the usual and excited fermions. This implies no mixing between different families and no flavor-changing neutral effects such as $\mu\rightarrow 3e$, but we can have $E\rightarrow 3e$, $M\rightarrow 3\mu$, etc.

The main advantage of this model is the possibility of predictions for the new excited boson masses and couplings. This is related with our model having five unknown parameters: three coupling constants $g$, $g'$, $g^*$ as-

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TABLE I. Quantum numbers for fermions and Higgs bosons under SUS*.

| | $\nu_L$ | $\nu_R$ | $e_L$ | $e_R$ | $N_L$ | $N_R$ | $E_L$ | $E_R$ | $\Phi^+$ | $\Phi^0$ | $\Phi^{*+}$ | $\Phi^{*0}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $I_3$ | $\frac{1}{2}$ | 0 | $-\frac{1}{2}$ | 0 | 0 | 0 | 0 | 0 | $\frac{1}{2}$ | $-\frac{1}{2}$ | 0 | 0 |
| $I_3^*$ | 0 | 0 | 0 | 0 | $\frac{1}{2}$ | 0 | $-\frac{1}{2}$ | 0 | 0 | 0 | $\frac{1}{2}$ | $-\frac{1}{2}$ |
| $Y$ | $-1$ | 0 | $-1$ | $-2$ | $-1$ | 0 | $-1$ | $-2$ | 1 | 1 | 1 | 1 |
| $Q$ | 0 | 0 | $-1$ | $-1$ | 0 | 0 | $-1$ | $-1$ | 1 | 0 | 1 | 0 |

sociated with $SU_L(2)\otimes U_Y(1)\otimes SU_L^*(2)$ (from now on called SUS*), respectively, and two vacuum parameters $v$ and $v^*$ associated to the Higgs doublets $\Phi$ and $\Phi^*$. Of course, $v$ and $v^*$ can be unrelated but in the composite scenario it is natural to consider $\Phi$ as a composite object and $\Phi^*$ as their first excited state. So, we suppose that their vacuum parameters have the same order of magnitude ($v \simeq v^*$). In this paper we will choose them as equal so that the ratio $R=(v^*/v)^2$ is equal to one. If we take the values of $\alpha(M_W)$, $G_f$, $M_W$, $M_Z$ as inputs we can determine $M_{W^*}$, $M_{Z^*}$, and all the vector couplings uniquely.[1,2]

In Figs. 1 and 2 we show the new vector-boson masses as functions of the observed $W$ and $Z$ masses. With the experimental values $M_Z=91.1\pm0.1$ GeV and $M_W=80.5\pm0.7$ GeV we can have variations for $M_{Z^*}$ and $M_{W^*}$ of a factor 2. For the values $M_Z=91.1$ GeV and $M_W=80.5$ GeV we have $M_{Z^*}=151$ GeV and $M_{W^*}=142$ GeV.

One of the most important consequences of our SUS* is the fact that new vector gauge bosons are coupled to ordinary matter with coupling parameters much smaller than the usual standard-model values. The same property implies that excited matter have a small coupling with the known vector bosons. This is not imposed by hand but it is a natural consequence of our model.

The general Yukawa coupling in this model generates fermion masses and mixes the known leptons $(e,\nu_e)$ with their possible excited states $(E,N)$.

The most general SUS*-invariant Yukawa Lagrangian is

$$\mathcal{L}_Y=f_{11}\bar{L}\Phi e_R+f_{12}\bar{L}\Phi E_R+f_{21}\bar{L}^*\Phi^* e_R+f_{22}\bar{L}^*\Phi^* E_R+h_{11}\bar{L}\tilde{\Phi}\nu_R+h_{12}\bar{L}\tilde{\Phi}N_R+h_{21}\bar{L}^*\tilde{\Phi}^*\nu_R+h_{22}\bar{L}^*\tilde{\Phi}^*N_R\ . \tag{1}$$

As is well known, the Higgs mechanism cannot fix the fermionic masses, and so we must consider the present experimental[4] bound for the excited lepton masses $M_{E,N}>50$ GeV. With no CP violation we have only mixing parameters: $\alpha$ for $(\nu,N)$ and $\beta$ for $(e,E)$.

We have the following interactions for charged currents:

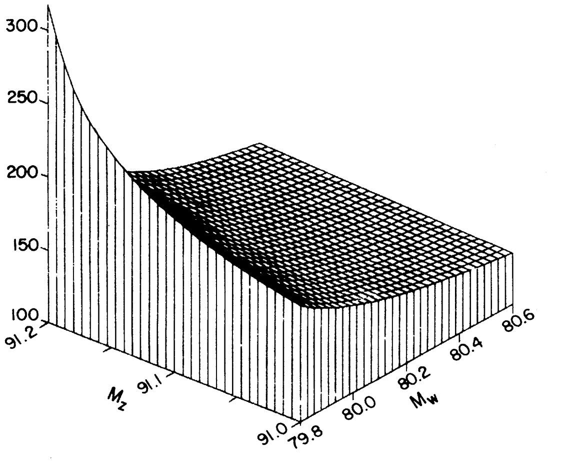

FIG. 1. The new-charged-vector-boson mass as a function of the known $M_W$, $M_Z$. The other input parameters are $\alpha(M_W)$ and $G_F$.

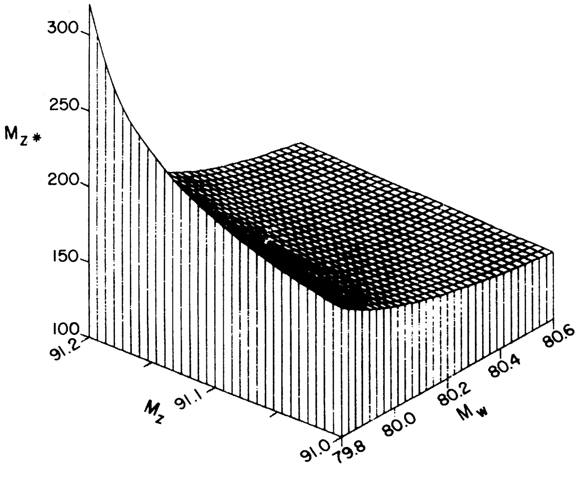

FIG. 2. The new-neutral-vector-boson mass.

TABLE II. Neutral couplings for ordinary and excited matter with the $Z$. A mixing angle $\sin\alpha \simeq \sin\beta \simeq 0.1$ and $M_Z=91.1$ GeV was taken.

| $M_W$ | $V_\nu$ | $V_N$ | $V_{\nu N}$ | $V_e$ | $A_e$ | $V_E$ | $A_E$ | $V_{eE}$ |
|---|---|---|---|---|---|---|---|---|
| 80.0 | 0.182 | −0.015 | 0.020 | −0.014 | −0.182 | 0.183 | 0.015 | 0.020 |
| 80.2 | 0.182 | −0.020 | 0.020 | −0.016 | −0.182 | 0.185 | 0.020 | 0.020 |
| 80.4 | 0.181 | −0.024 | 0.021 | −0.019 | −0.181 | 0.186 | 0.024 | 0.021 |
| 80.6 | 0.180 | −0.028 | 0.021 | −0.022 | −0.180 | 0.187 | 0.028 | 0.021 |
| 80.8 | 0.180 | −0.032 | 0.021 | −0.025 | −0.180 | 0.187 | 0.032 | 0.021 |
| 81.0 | 0.179 | −0.035 | 0.022 | −0.027 | −0.179 | 0.187 | 0.035 | 0.022 |

$$\begin{aligned}\mathcal{L}^{cc}=&-\frac{g}{2\sqrt{2}}[\bar{\nu}\gamma^\mu(1-\gamma^5)e\cos\alpha\cos\beta-\bar{\nu}\gamma^\mu(1-\gamma^5)E\cos\alpha\sin\beta\\&\quad-\bar{N}\gamma^\mu(1-\gamma^5)e\sin\alpha\cos\beta+\bar{N}\gamma^\mu(1-\gamma^5)E\sin\alpha\sin\beta]W_\mu\\&-\frac{g^*}{2\sqrt{2}}[\bar{\nu}\gamma^\mu(1-\gamma^5)e\sin\alpha\sin\beta+\bar{\nu}\gamma^\mu(1-\gamma^5)E\sin\alpha\cos\beta\\&\quad+\bar{N}\gamma^\mu(1-\gamma^5)e\cos\alpha\sin\beta+\bar{N}\gamma^\mu(1-\gamma^5)E\cos\alpha\cos\beta]W^*_\mu+\text{H.c.}\end{aligned}\tag{2}$$

After rotation in the neutral vector fields, the neutral interactions are described by the Lagrangian

$$\begin{aligned}\mathcal{L}^{\text{NC}}=&-[\bar{\nu}\gamma^\mu(V_\nu-A_\nu\gamma^5)\nu+\bar{N}\gamma^\mu(V_N-A_N\gamma^5)N+\bar{\nu}\gamma^\mu(V_{\nu N}-A_{\nu N}\gamma^5)N+\bar{e}\gamma^\mu(V_e-A_e\gamma^5)e\\&\quad+\bar{E}\gamma^\mu(V_E-A_E\gamma^5)E+\bar{e}\gamma^\mu(V_{eE}-A_{eE}\gamma^5)E]Z_\mu\\&\quad+[\bar{\nu}\gamma^\mu(V^*_\nu-A^*_\nu\gamma^5)\nu+\bar{N}\gamma^\mu(V^*_N-A^*_N\gamma^5)N+\bar{\nu}\gamma^\mu(V^*_{\nu N}-A^*_{\nu N})N+\bar{e}\gamma^\mu(V^*_e-A^*_e\gamma^5)e\\&+\bar{E}\gamma^\mu(V^*_E-A^*_E\gamma^5)E+\bar{e}\gamma^\mu(V^*_{eE}-A^*_{eE}\gamma^5)E]Z^*_\mu+\text{H.c.}\end{aligned}\tag{3}$$

For $M_Z=91.1$ GeV and $M_W=80$ GeV we calculate $g^2=0.422$, $g^{*2}=1.923$, and $g'^2=0.138$.

The neutral couplings are given in Tables II and III. The most stringent bound on the mixing angles is given by the $(g-2)$ factor and implies $\sin\alpha,\beta\simeq 0.1$.

## III. CONSEQUENCES IN ELECTRON-POSITRON COLLISIONS

With the previous interactions we can readily compute the contribution of a new $Z^*$ to $e^+e^-\to\mu^+\mu^-$. The result is shown in Fig. 3 for $\sin\alpha=\sin\beta=0.1$. The second peak is smaller than the first since $Z^*$ has smaller couplings with the ordinary fermions.

In order to compare our predictions with the ones from the standard model we show in Fig. 4 the $Z$ width difference, $\Delta\Gamma=\Gamma_{\text{SM}}-\Gamma_{\text{SUS}*}$, calculated for ordinary neutrinos and electrons, as a function of the mixing angle. In Fig. 5 we have the same kind of comparison for the hadronic and total widths. It is worth mentioning that the hadronic case is constant since we included no mixing in the quark sector for ordinary and excited quarks. From those results we conclude that, although the coupling constants in our model are smaller than the equivalent ones in the standard case, the overall effect is not stringent enough to permit us at low energy to distinguish between them. Also from the two figures it is clear that the mixing angle has not a decisive role, at least at this level. In the total width we have included also the possibility of the $Z$ decaying in the new channels $N\bar{\nu}$, $E\bar{e}$, $N\bar{N}$. These channels can be suppressed by a small mixing or by a heavy excited lepton mass. For example we show in Fig. 6 the contribution of the channel $Ee$ for $M_E=60$

TABLE III. The same as Table II but for the $Z^*$.

| $M_W$ | $V^*_\nu$ | $V^*_N$ | $V^*_{\nu N}$ | $V^*_e$ | $A^*_e$ | $V^*_E$ | $A^*_E$ | $V^*_{eE}$ |
|---|---|---|---|---|---|---|---|---|
| 80.0 | 0.036 | 0.355 | −0.032 | 0.068 | −0.036 | −0.251 | −0.355 | −0.032 |
| 80.2 | 0.042 | 0.325 | −0.029 | 0.076 | −0.042 | −0.207 | −0.325 | −0.029 |
| 80.4 | 0.047 | 0.306 | −0.026 | 0.081 | −0.047 | −0.178 | −0.306 | −0.026 |
| 80.6 | 0.051 | 0.293 | −0.025 | 0.085 | −0.051 | −0.156 | −0.293 | −0.025 |
| 80.8 | 0.055 | 0.283 | −0.023 | 0.089 | −0.055 | −0.139 | −0.283 | −0.023 |
| 81.0 | 0.059 | 0.275 | −0.022 | 0.092 | −0.059 | −0.124 | −0.275 | −0.022 |

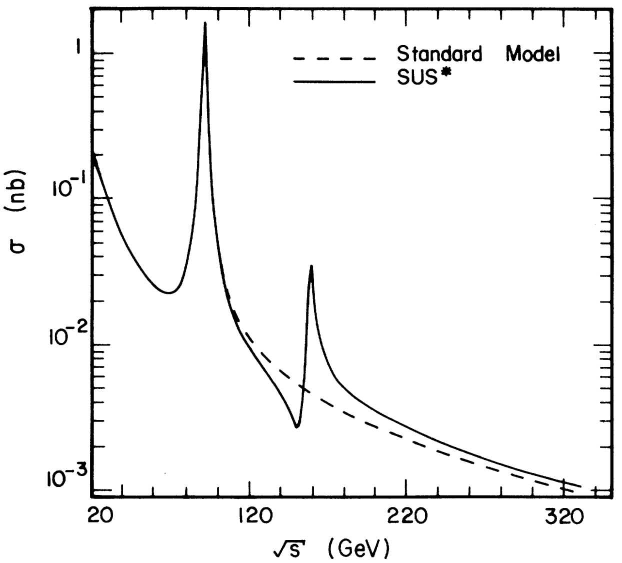

FIG. 3. Total cross section for $e^+e^-\to\mu^+\mu^-$. Input parameters are $M_W=80$ GeV, $M_Z=91.1$ GeV that implies $M_{Z^*}=177.3$ GeV. A total width for $Z^*$ of 2.6 GeV was considered. The same parameters are considered in Figs. 4–8.

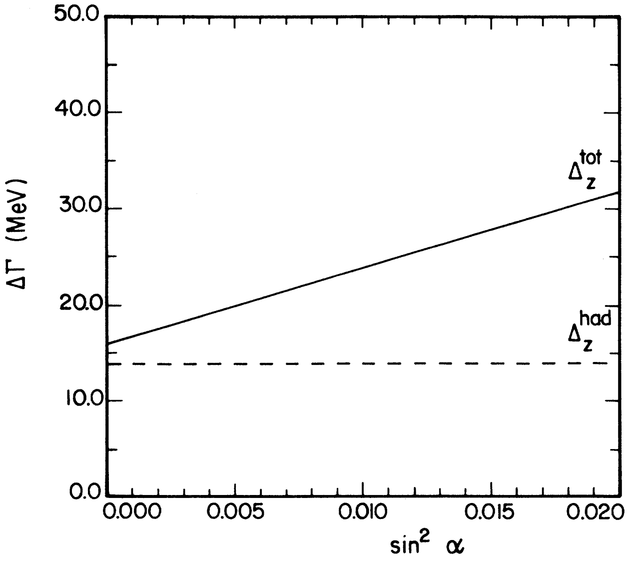

FIG. 5. The $Z$ decay into hadrons and the total width. The new channels $N\bar{\nu}$, $E\bar{e}$, $N\bar{N}$ were considered with $M_E=60$ GeV and $M_N=0$ GeV.

GeV. It is possible the inclusion of very massive excited states by the seesaw mechanism.[5]

One of the most attractive possibilities of the SUS* model is the case of excited neutrinos ($N$) with small mass. We shown in Fig. 6 the contribution for $Z\to N\bar{\nu}$, $N\bar{N}$ considering $M_N\simeq 0$. The new $N\bar{N}$ channels are practically independent of the mixing angle. Again the general feature of a small coupling between ordinary and excited matter gives this small number. The recent bound[6] on three standard families for the $Z$ decay obtained at CERN allows this type of new neutrinos of the SUS* model.

Another attractive feature of the SUS* model is that we can compute cross sections for new lepton production

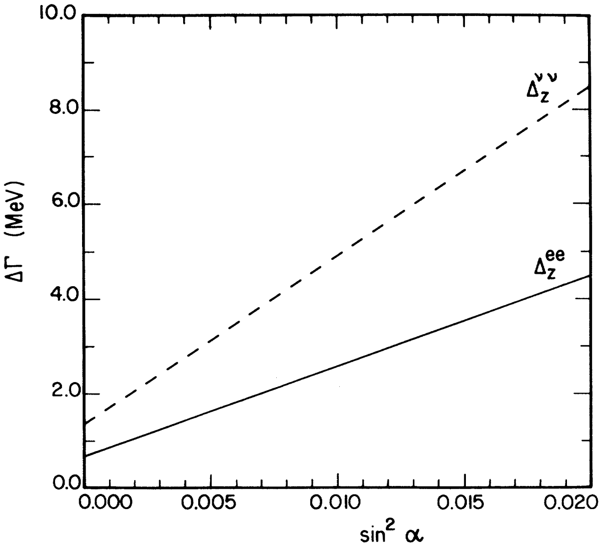

FIG. 4. The $Z$ decay in neutrinos and electrons. The plot is the difference $\Delta=$standard model $-$SUS*.

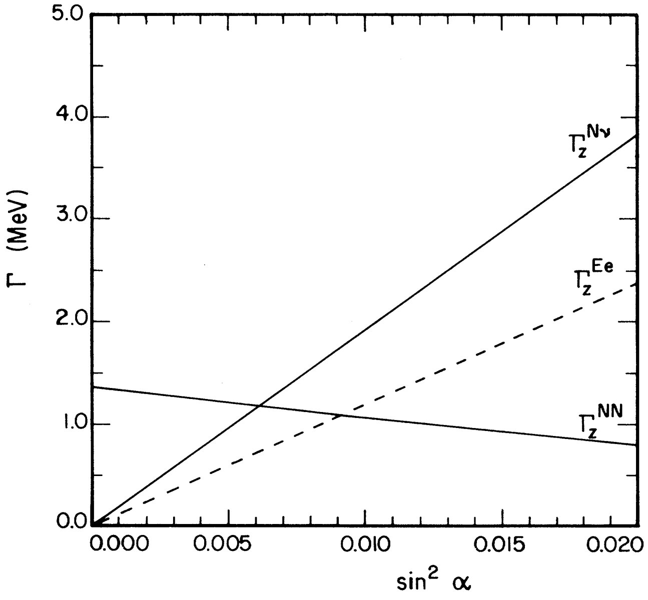

FIG. 6. New channels for the usual $Z$ decay. We have taken $M_E=60$ GeV and $M_N=0$ GeV.

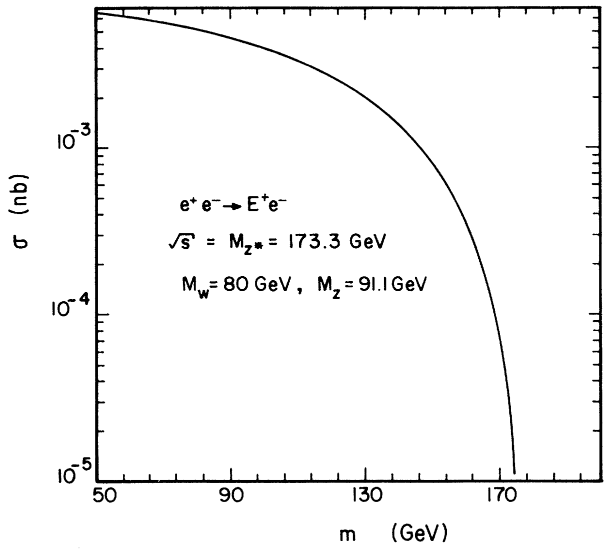

FIG. 7. Total cross section for excited-lepton production in $e^+e^-$ as a function of their mass. Charged and neutral heavy leptons give similar results.

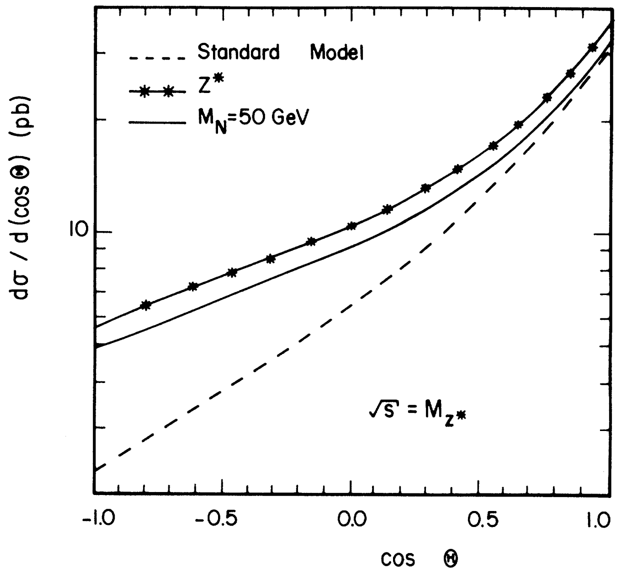

FIG. 9. Angular distribution for $e^+e^- \to W^+W^-$. The new SUS* effects are shown for a $Z^*$ and an excited-neutrino exchange.

with arbitrary masses. There is no unitarity violation since this is a completely renormalizable model. The interaction Lagrangians given by Eqs. (2) and (3) imply contributions to the reactions $e^+e^- \to E^+e^-$, $E^+e^-$, $N\bar{N}$, $N\bar{\nu}$. We have contributions from the $s$ and $t$ channels that are explicitly given in the appendix. In Figs. 7 we have the total cross section for $e^+e^- \to E^+e^-$ as a function of $M_E$. We have a similar curve for $N\bar{\nu}$ production. In Fig. 8 we show the energy dependence for the same processes for $M_E = M_N = 60$ GeV.

The reaction $e^+e^- \to W^+W^-$ is expected to give the first experimental test of the trilinear vector-boson coupling in the standard model. In the SUS* model we have two new contributions for this process: the $Z^*$ exchange and the excited neutrino exchange. This second contribution can be zero if there is no mixing. After a long calculation[7] we have the results shown in Fig. 9 for the angular distribution of $W^+W^-$ pair. There, the starred line is the result considering just the $Z^*$ contribution, and the solid line is what we get when, in addition to the

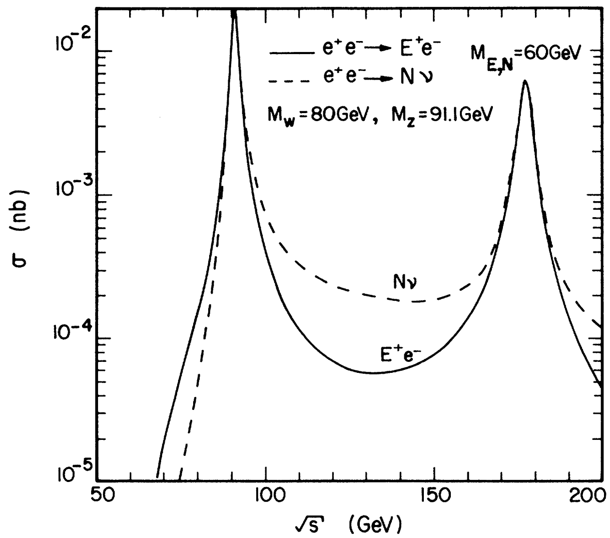

FIG. 8. Total cross section for excited-lepton production in $e^+e^-$ as a function of the c.m. energy. The curves are for $M_E = M_N = 60$ GeV.

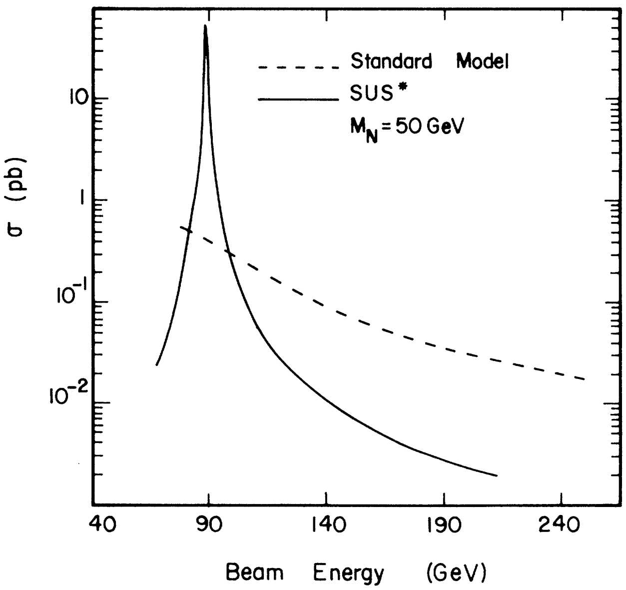

FIG. 10. Higgs-boson production via $e^+e^- \to Z^* \to ZH$.

$Z^*$ contribution, we include a new heavy neutrino (50 GeV).

Another very distinctive signature of the SUS* model is the contribution to Higgs-boson production in $e^+e^- \to ZH$. As the $Z^*$ is heavier than the usual $Z$ we can have a contribution[7] through $e^+e^- \to Z^* \to ZH$, which enhances the standard model contribution by a factor 100 at the $Z^*$ peak. This is shown in Fig. 10.

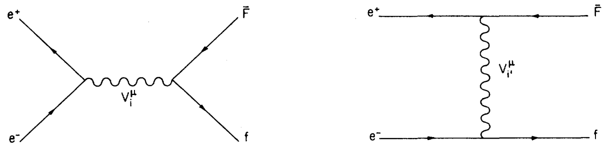

FIG. 11. Feynman diagrams for $e^+e^- \to \bar{F}f$.

## IV. CONCLUSIONS

In this paper we have explored the possible existence of excited matter. Instead of the old-fashioned, four-fermion phenomenological interactions we have extended the standard model to $\mathrm{SU}_L(2)\otimes \mathrm{U}(1)_Y \otimes \mathrm{SU}_L^*(2)$. A somewhat similar group was recently considered[8] but it introduces a new arbitrary scale of symmetry breaking and has a neutral to charged-current ratio different from one. In the composite scenario we have only one electroweak mass scale and new effects can be uniquely predicted in $e^+e^-$ collisions.

## ACKNOWLEDGMENTS

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## APPENDIX

We give here the general expression for the production of usual fermion $f$ and excited fermion $F$ from $e^+e^-$ annihilation into virtual vector bosons.

For the coupling of fermions $f_a$ and $f_b$ with the vector boson $V_i$, we write the general interaction term

$$\mathcal{L}_{abi} = -\bar{f}_a \gamma_\mu (V_{abi} - A_{abi}\gamma^5) f_b V_i^\mu . \tag{A1}$$

The cross section for the process $e^+e^- \to \bar{F}f$ receives contributions of the general form (see Fig. 11)

$$\begin{aligned}\frac{d\sigma}{d\Omega}(i,j,i',j') = \frac{s}{128\pi^2}(1-\chi^2)(1-\chi^4) \Bigg\{ & [2A_{ij}(1+\alpha\cos^2\theta)+2B_{ij}(1+\alpha)\cos\theta]\Delta_i(s)\Delta_j^*(s) \\ & + \left[4\left[\frac{1}{1+\chi^2}\right](C_{i'j'}-D_{i'j'})+(C_{i'j'}+D_{i'j'})[1+(1+\alpha)\cos\theta+\alpha\cos^2\theta]\right]\Delta_{i'}(t)\Delta_{j'}^*(t) \\ & + \{[1+(1+\alpha)\cos\theta+\alpha\cos^2\theta][E_{ij'}\Delta_i(s)\Delta_{j'}^*(t)+E_{i'j}\Delta_{i'}(t)\Delta_j^*(s)]\} \Bigg\} .\end{aligned} \tag{A2}$$

This expression is calculated under the assumptions $m_e = m_f = 0$ and the definitions

$$s = (p_1 + p_2)^2 , \tag{A3}$$

$$\chi = \frac{M_F}{\sqrt{s}} , \tag{A4}$$

$$t = -\frac{s}{2}(1-\chi^2)(1-\cos\theta) , \tag{A5}$$

$$\alpha = \frac{1-\chi^2}{1+\chi^2} , \tag{A6}$$

$$A_{ij} = (V_{eei}V_{eej} + A_{eei}A_{eej})(V_{fFi}V_{fFj} + A_{fFi}A_{fFj}) , \tag{A7}$$

$$B_{ij} = (V_{eei}A_{eej} + A_{eei}V_{eej})(V_{fFi}A_{fFj} + A_{fFi}V_{fFj}) , \tag{A8}$$

$$C_{i'j'} = (V_{efi'}V_{efj'} + A_{efi'}A_{efj'})(V_{eFi'}V_{eFj'} + A_{eFi'}A_{eFj'}) , \tag{A9}$$

$$D_{i'j'} = (V_{efi'}A_{efj'} + A_{efi'}V_{efj'})(V_{eFi'}A_{eFj'} + A_{eFi'}V_{eFj'}) , \tag{A10}$$

$$\begin{aligned}E_{ij'} = & (V_{fFi}V_{efj'} + A_{fFi}A_{efj'})(V_{eei}V_{eFj'} + A_{eei}A_{eFj'}) \\ & + (V_{fFi}A_{efj'} + A_{fFi}V_{efj'})(V_{eei}A_{eFj'} + A_{eei}V_{eFj'}) ,\end{aligned} \tag{A11}$$

$$\Delta_i(q^2) = \frac{1}{q^2 - M_i^2 - i\Gamma_i M_i} . \tag{A12}$$

For instance, in the process $e^+e^- \to \bar{N}\nu$ we have sixteen terms of this kind since $i$ and $j$ can be $Z$ or $Z^*$ and $i'$ and $j'$ can be $W$ and $W^*$.

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*Present address: Fermi National Accelerator Laboratory, P.O. Box 500, Batavia IL 60510.

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