Effects of heavy unconventional scalars in leptonic interactions

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The contributions of virtual scalars in $e^+e^-\to\mu^+\mu^-$, $e^+e^-\to e^+e^-$, muon decays, and $\overset{(-)}{\nu}_e+e^-\to\overset{(-)}{\nu}_e e^-$ scattering are derived to obtain constraints on Yukawa couplings and masses of these scalars. Implications for anomalous $e^+e^-\gamma$ events in the $p\bar{p}$ collider are also discussed.

Recent investigations in supersymmetric gauge models have suggested that there could be more than one Higgs doublet in electroweak theories.[1] The coupling of the physical scalars to fermions need not be simply proportional to the fermions' masses. For two Higgs doublets there exist two physical charged Higgs bosons and three neutral ones. Production of these nonstandard Higgs bosons in e^+e^- collisions have been considered by various authors.[2] Suggestions have also been made that the anomalous $e^+e^-\gamma$ events recently observed in the $p\bar{p}$ collider at CERN could be due to the decay of either Z^0 (Ref. 3) or t-quarkonium (Ref. 4) into a scalar or an unconventional Higgs boson plus a photon. Being unconventional, the neutral Higgs boson can subsequently decay into an e^+e^- pair with a large branching ratio.

In this paper we investigate the constraints placed on the Yukawa couplings of both unconventional charged and neutral scalars as a function of their masses. We concentrate on flavor-conserving scalars. We use the reactions (a) $e^+e^-\to\mu^+\mu^-$, (b) $e^+e^-\to e^+e^-$, (c) muon decays, and (d) $\overset{(-)}{\nu}_e e\to\overset{(-)}{\nu}_e e$ scattering. The constraints are nontrivial for scalar masses around 50 GeV/c^2 and become loose as the masses increase. We shall take a general phenomenological approach and parametrize the effective coupling of the charged scalar χ^+ to $l\nu_l$ by the effective Lagrangian

$$\mathscr{L}=y_l'\,\bar{l}\nu_l\chi^+ + \text{H.c.}\ , \tag{1}$$

and similarly the neutral-scalar $\phi^0 l\bar{l}$ effective Lagrangian is taken to be

$$\mathscr{L}=y_l\bar{l}\,l\phi^0\ . \tag{2}$$

Since we are not considering *CP*-violating effects we can take y_l and y_l' to be real. In a gauge model where ϕ^0 and $\chi^\pm$ belong to the same multiplet $y_e=\sqrt{2}y_e'$. In general, the lowest-mass physical scalars could come from different multiplets and hence the Yukawa couplings need not be simply related. In the standard model $y_e'=0$ and

$$y_l=2^{1/4}G_F^{\ 1/2}m_l\ ,$$

where m_l is the mass of the lepton l. The subscript l for each lepton is kept for these Yukawa couplings since they need not be universal in their strengths. In the standard model they are not. However, in some models with discrete symmetries[5] imposed on the three families e-μ-τ universality holds, and thus

$$y_e=y_\mu=y_\tau\ . \tag{3}$$

We shall assume that the masses of $\chi^\pm$ and ϕ^0, denoted by M_χ and M_ϕ, respectively, are larger than 45 GeV/c^2; otherwise, they would have already been produced at DESY PETRA. Alternatively, if scalars are light they must have $y^2/(4\pi)\ll\alpha$ in order to escape detection. Then they behave like standard Higgs bosons and we are not considering them. For massive scalars only virtual effects can be discerned in the reactions (a)—(d) at present energies. We study them systematically below.

(a) $e^+e^-\to\mu^+\mu^-$. To the lowest order, only ϕ^0 contributes in the annihilation channel. The Feynman diagrams are depicted in Fig. 1. The cross section is given by[3]

$$\sigma=\frac{4\pi\alpha^2}{3}s\left[1+\frac{(g_v^{\ 2}+g_A^{\ 2})^2}{16s_W^{\ 4}c_W^{\ 4}}\frac{1}{(1-M_Z^{\ 2}/s)^2}+\frac{g_v^{\ 2}}{2s_W^{\ 2}c_W^{\ 2}}\frac{1}{(1-M_Z^{\ 2}/s)}+\frac{w_e^{\ 2}w_\mu^{\ 2}}{(1-M_\phi^{\ 2}/s)^2}\right], \tag{4}$$

where

$$w_l=\frac{y_l}{e},\quad s_W^{\ 2}=\sin^2\theta_W,\quad c_W^{\ 2}=\cos^2\theta_W \tag{5a}$$

and

$$g_V^{\ 2}=\tfrac{1}{4}(1-4s_W^{\ 2})^2,\quad g_A^{\ 2}=\tfrac{1}{4}\ . \tag{5b}$$

We assume the validity of the standard electroweak model and use the average values of $M_Z=92$ GeV/c^2 and

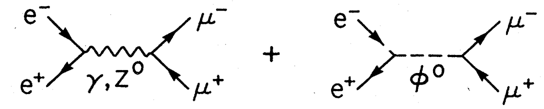

FIG. 1. Feynman diagrams contributing to $e^+e^-\to\mu^+\mu^-$ scattering including virtual-scalar ϕ^0 exchange.

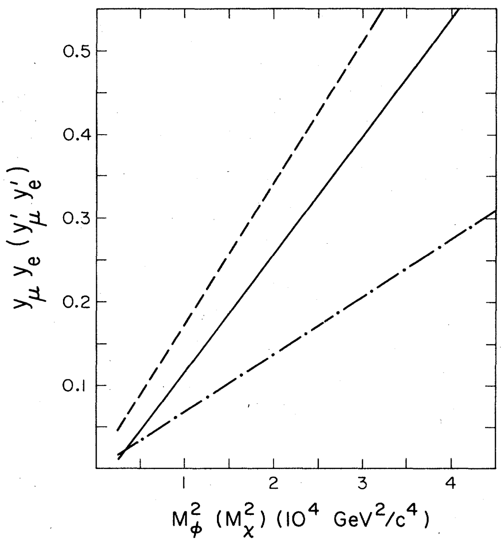

FIG. 2. Constraints on the Yukawa couplings $y_\mu y_e$ and $y'_\mu y'_e$ of the neutral and charged scalars ϕ and χ as functions of the masses squared. The solid line is from $e^+e^-\to\mu^+\mu^-$, the dashed line from muon decay with 5% measurement of η, and the dashed-dotted line is for 2% of measurement. Allowed parameters are to the right of the curves.

$\sin^2\theta_W=0.23$ given by the UA1 and UA2 experiments. Using the experimental result of Mark J (Ref. 6) we obtain the allowed values in $y_\mu y_e$-$M_\phi{}^2$ space. This is the area below the solid line plotted in Fig. 2. We have used the data[6] from PETRA at $\sqrt{s}=41.3$ GeV and allowed for a 5% error in the data to obtain this constraint. For $M_\phi=50$ GeV/c^2 we get $y_\mu y_e<0.010$ and for $M_\phi=1$ TeV/c^2 the limit is $y_\mu y_e<13$.

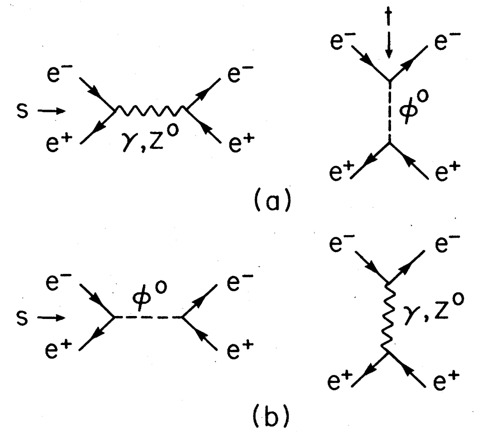

FIG. 3. Feynman diagrams for Bhabha scattering.

(b) $e^+e^-\to e^+e^-$. In this case the t-channel scalar-exchange scattering process can interfere with the s-channel annihilation process of γ and Z^0 exchanges [see Fig. 3(a)] and vice versa [Fig. 3(b)]. The interference between s- and t-channel ϕ exchange also takes place. In general, this is a more sensitive test for virtual-scalar effects than the previous case. The differential cross section is given explicitly as

$$
\begin{aligned}
\frac{d\sigma}{d\cos\theta}=\frac{\pi\alpha^2}{s}\Bigg[&\frac{1}{2}\left[\frac{3+\cos^2\theta}{1-\cos\theta}\right]^2+\frac{1}{2s_W{}^2c_W{}^2}\frac{(g_V{}^2+g_A{}^2)u^2+(g_V{}^2-g_A{}^2)t^2}{s(s-M_Z{}^2)}\\
&+\frac{1}{16s_W{}^4c_W{}^4}\frac{[(g_V{}^2+g_A{}^2)^2+4g_V{}^2g_A{}^2]u^2+(g_V{}^2+g_A{}^2)^2t^2}{(s-M_Z{}^2)^2}\\
&+\frac{1}{16s_W{}^4c_W{}^4}\frac{[(g_V{}^2+g_A{}^2)^2+4g_V{}^2g_A{}^2]u^2+(g_V{}^2+g_A{}^2)^2s^2}{(t-M_Z{}^2)^2}\\
&+\frac{1}{2s_W{}^2c_W{}^2}\frac{(g_V{}^2+g_A{}^2)u^2+(g_V{}^2-g_A{}^2)s^2}{t(t-M_Z{}^2)}\\
&+\frac{1}{2s_W{}^2c_W{}^2}(g_V{}^2+g_A{}^2)u^2\left[\frac{1}{s(t-M_Z{}^2)}+\frac{1}{t(s-M_Z{}^2)}\right]\\
&+\frac{(g_V{}^2+g_A{}^2)^2+4g_V{}^2g_A{}^2}{16s_W{}^4c_W{}^4}\frac{u^2}{(s-M_Z{}^2)(t-M_Z{}^2)}\\
&+w_e{}^4\left[\frac{u^2-s^2-t^2}{4(s-M_\phi{}^2)(t-M_\phi{}^2)}+\frac{s^2}{2(s-M_\phi{}^2)^2}+\frac{t^2}{2(t-M_\phi{}^2)^2}\right]\\
&-w_e{}^2\left[\frac{t^2}{s(t-M_\phi{}^2)}+\frac{s^2}{t(s-M_\phi{}^2)}+\frac{(g_V{}^2-g_A{}^2)t^2}{4s_W{}^2c_W{}^2(t-M_\phi{}^2)(s-M_Z{}^2)}+\frac{(g_V{}^2-g_A{}^2)s^2}{4s_W{}^2c_W{}^2(t-M_Z{}^2)(s-M_\phi{}^2)}\right]\Bigg],
\end{aligned}
$$

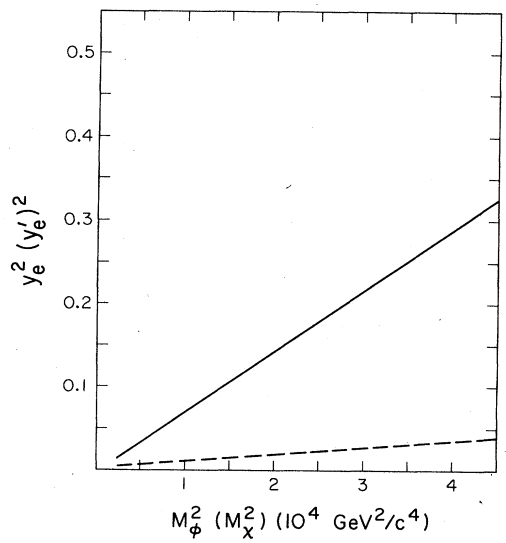

FIG. 4. Constrained Yukawa couplings y_e and y_e' as functions of $M_\phi{}^2$ and $M_\chi{}^2$. The solid line is given by $\bar{\nu}_e e \to \bar{\nu}_e e$ scattering and the dashed line by Bhabha scattering. Allowed parameters are to the right of the lines.

where s, t, and u are the Mandelstam variables. The first term is the lowest-order QED result and the terms not involving w_e are the standard-electroweak-model contribution.[7] We have written them in a form where one can identify the interference terms. Using the Mark J data[8] at $\sqrt{s}=34.6$ GeV we performed a fit to find the maximum allowed value for $w_e{}^2$ for a given M_ϕ. Notice that in this reaction a constraint on $y_e{}^2$ alone can be obtained. Figure 4 depicts the allowed region for $y_e{}^2$ and $M_\phi{}^2$ to be right of the dashed curve. For low masses of $m_\phi \simeq 50$ GeV/c^2, $y_e{}^2$ is constrained to be less than 0.003; and for large masses, e.g., $m_\phi = 1$ TeV/c^2, we obtain $y_e{}^2 < 0.91$. We mention in passing that since the lowest-order QED completely dominates at small angles the better place to look for the effects of these currents is at large angles. However, the data are poorer there.

We have not included radiative corrections in our analysis. The Mark J data we use have been corrected for QED radiative effects and acceptance.

Independent analysis on the effects of scalars in $e^+e^- \to \mu^+\mu^-$ and Bhabha scattering are also done by the CELLO Collaboration and by Hollick, Schrempp, and Schrempp.[9] Our results agree where they overlap and we take the analysis to higher values of M_χ and M_ϕ.

(c) $\mu^+ \to e^+ \nu_\mu \nu_e$. It is well known that the Michel spectrum of the e^+ for muon decays is sensitive to the presence of charged scalar currents. The precision measurement of the η parameter gives us knowledge of $y_e' y_\mu'$

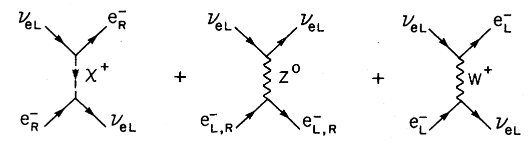

FIG. 5. Feynman diagrams for $\nu_e e^- \to \nu_e e^-$ scattering including virtual charged-scalar χ exchange.

and is crucial for testing the universality of the y_e's which could arise from discrete or family symmetries. The e^+ spectrum is[10]

$$\frac{dR}{dx}=\frac{G_F{}^5 m_\mu{}^5}{96\pi^3}\left\{\left[1+\left[\frac{M_W}{M_\chi}\right]^4\left[\frac{y_e' y_\mu'}{g^2}\right]^2\right]x^2(3-2x)\right.$$
$$\left.+\,12\left[\frac{M_W}{M_\chi}\right]^2\left[\frac{y_e' y_\mu'}{g^2}\right]\frac{m_e}{m_\mu}x(1-x)\right\}$$

with $x \equiv 2E_e/m_\mu$, where g is the SU(2) gauge coupling. As expected the charged-scalar- and W-exchange interference term has a coefficient of m_e/m_μ and vanishes in the limit $m_e \to 0$. Using the current value of η measurement,[11] where

$$\eta \equiv \frac{2\left[\dfrac{M_W s_W}{M_\chi}\right]^2 \dfrac{y_e' y_\mu'}{e^2}}{1+\left[\dfrac{M_W s_W}{M_\chi}\right]^4 \dfrac{y_e' y_\mu'}{e^2}} < 0.05\ ,$$

we rule out the area to the left of the dashed line in Fig. 2. At $M_\chi = 1$ TeV/c^2 we find $y_\mu' y_e' < 16$. The dotted-dashed line indicated the region $y_\mu' y_e' - M_\chi{}^2$ space that will be ruled out by a 2% measurement of η if no effects are found. This accuracy is within reach of current experiments.[12]

(d) $\overset{(-)}{\nu}_e + e^- \to \overset{(-)}{\nu}_e + e^-$. In this process an interference between the exchange of a charged scalar which flips helicity and the neutral-current exchange process can occur (see Fig. 5). The effect arises in general for any neutral-weak boson whose coupling to the right-handed electrons is not zero. This is the case for the Z^0 in the standard model. This is in addition to the known interference between the W and Z^0 terms. Since we assume that scalar particles do not couple to neutrinos then $\nu_\mu e \to \nu_\mu e$ plays no role in detecting the effects of these particles. The differential cross sections we obtain are (neglecting electron mass)

$$\frac{d\sigma}{dE'}(\nu_e e - \nu_e e)=\frac{2G_F m_e}{\pi}\left\{\frac{1}{4}+s_W{}^2+s_W{}^4\left[1+\left[1-\frac{E'}{E_\nu}\right]^2\right]-\left[2\left[\frac{y_e' M_W}{g M_\chi}s_W\right]^2-4\left[\frac{y_e' M_W}{g M_\chi}\right]^4\right]\left[1-\frac{E'}{E_\nu}\right]^2\right\}$$

and

$$\frac{d\sigma}{dE'}(\bar{\nu}_e e \to \bar{\nu}_e e) = \frac{2G_F m_e}{\pi}\left[\left[\tfrac{1}{4} + s_W{}^2 + s_W{}^4\right]\left[1 - \frac{E'}{E_{\bar{\nu}}}\right]^2 + s_W{}^4 - 2\left[\frac{y_e' M_W s_W}{g M_X}\right]^2 + 4\left[\frac{y_e' M_W}{g M_X}\right]^4\right],$$

where E' is the energy of the scattered electron and $E_{\nu(\bar{\nu})}$ is the incident neutrino (antineutrino) energy. The first three terms contain the usual W and Z^0 interference,[13] and the next terms are the X-Z^0 interference, and the contribution from X itself.

These reactions now play a similar role to Bhabha scattering in that they are sensitive only to the charged-scalar Yukawa coupling y_e'. Using the reactor data[14] and the standard-model parameters given above, the allowed values for $y_e'^2$ and $M_X{}^2$ are to the right of the solid line in Fig. 4. For $M_X = 1$ TeV/c^2 we get $y_e'^2 < 6.8$.

We see from the above that the most stringent limit currently available on the Yukawa couplings is given by Bhabha scattering. The value of $M_X = 50$ GeV/c^2 is of interest in relation to the anomalous $e^+e^-\gamma$ event from the $p\bar{p}$ collider.[15,16] Even allowing for the uncertainty in $\sin^2\theta_W$ and m_Z we get at best $y_e{}^2 < 0.01$. This rules out the unconventional Higgs coupling of strength determined by the top-quark mass, i.e., $y_e{}^2 \simeq 0.04$. Applying the above values we assess the possibility that the anomalous events originate from mixing of Z^0 and t-quarkonium which decays into unconventional Higgs plus a photon.[4] The only solution allowed by Bhabha scattering is maximal mixing with

$$y_e{}^2 B(\phi \to e^+e^-) = 0.002 \,.$$

This leads to a branching of ϕ into e^+e^- about 0.2. Although permissible phenomenologically, it is highly unlikely that any reasonable model can give such a large branching ratio for $\phi \to e^+e^-$. Furthermore, the invariant-mass plot of the e^+e^- pairs in the preliminary data does not support such a resonance interpretation.

Finally, the role that the muon $g-2$ plays in the study of unconventional scalars has to be discussed. In $g-2$ calculations additional theoretical issues concerning effective $\phi^0 Z^0\gamma$ and $\phi^0\gamma\gamma$ terms enter. These are highly model dependent. If we leave them out or if they are small, then the constraints on the Yukawa couplings are[17,18]

$$y_\mu{}^2 < 5\times 10^{-4} M_X{}^2$$

for charged scalars and a factor of 2 better for neutral scalars. This is certainly not competitive with Bhabha-scattering constraints.

We note in passing that similar considerations can be extended to the quark sector. Precision measurements of pion decays such as the branching ratio of $\pi_{e\nu}/\pi_{\mu\nu}$ can be used to limit the Yukawa couplings of charged scalars to quarks and leptons. However, the uncertainty in dealing with the radiative corrections involving hadrons which cannot be ignored hampers the accurate extraction of information on new weak currents from these measurements.

In conclusion, we have demonstrated the usefulness of leptonic interactions to constrain the Yukawa couplings of scalars. What we have considered can be carried through for pseudoscalars by inserting an $i\gamma_5$ for $L_{\rm eff}$ and can be extended to include the τ lepton. Optimistically, if effects are found, one can use Bhabha scattering and $\overset{(-)}{\nu}{}_e$ scattering to test whether y_e and y_e' are simply related. This is important in general and can be used to pin down the group structure of the scalar sector. Then, analyzing $e^+e^- \to \mu^+\mu^-$ and the η parameter in muon decays, one can test whether Yukawa couplings for these unconventional scalars or pseudoscalars to e and μ obey universality, as discussed by some models.

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