Are there really any experimental limits on a light Higgs boson?

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The experimental evidence regarding a light Higgs boson is reviewed. It is shown that a light Higgs boson with almost any mass between 14 MeV/c^2 and 1 GeV/c^2 is still allowed by existing data. The only limit in this range comes from B-decay data which, for sufficiently large values of the top-quark mass, excludes a Higgs boson with a mass between $2m_\mu$ and ~ 700 MeV/c^2. Discussions of light-Higgs-boson emission in the decays of K, π, μ, τ, η', and Υ are also given.

I. INTRODUCTION

One of the most important ingredients of the standard model of electroweak interactions is the phenomenon of spontaneous symmetry breaking affecting the masses of the W and Z bosons. In the simplest realization of this phenomenon, one electroweak doublet of fundamental bosons breaks SU(2)$\times$U(1) to U(1) electromagnetism. A neutral scalar boson (the Higgs boson) is a physical remnant of this effect. If there is more than one Higgs doublet involved then there will be more physical bosons: we shall refer to the lightest neutral one as the light Higgs boson. The mass of this particle is not strictly fixed by the theory. The lower limit on its mass (~ 14 MeV/c^2) is obtained[1] from observing the decay of an excited state of ^{4}He. We shall be interested in this paper in light Higgs bosons with a mass ranging from 14 MeV/c^2 to ~ 1 GeV/c^2. It is worth noting that such a particle plays a crucial role in a possible joint solution to the solar-neutrino and dark-matter problems.[2] We shall assume standard couplings of the Higgs boson to quarks even if there is more than one Higgs doublet.

In the case of a single Higgs doublet, a theoretical lower limit on the light-Higgs-boson mass (>7 GeV/c^2) is obtained[3] from a one-loop analysis of the Higgs potential. This lower limit, however, vanishes if the heaviest fermion in the standard model has a mass of order 80 GeV/c^2, or if there are more undiscovered heavy fermions (such as in a fourth generation). The top quark remains a candidate for this heavy fermion. If there is more than one Higgs doublet then, in general, no lower limit on the light-Higgs-boson mass can be derived since there are more parameters in the Higgs potential. Finally, the Higgs potential is quite constrained at the tree level in supersymmetric two-Higgs-doublet models and a light Higgs boson is certainly possible. At the one-loop level, all squarks, sleptons, and gauginos enter with opposite signs for bosons and fermions so that the lower limit on the light-Higgs-boson mass depends, in detail, on this spectrum.[4] To summarize, there is no hard theoretical lower limit on the light-Higgs-boson mass. A light Higgs boson always seems possible with some fine-tuning of the parameters in the theory. It will require an exhaustive experimental search to rule out the existence of such a particle. In this paper we comment on the present status of this search.

Since the existence of a Higgs boson is so crucial to our understanding of the electroweak interactions it is imperative that a critical and conservative view be taken when comparing theoretical estimates with experimental data. We believe that ruling out a light Higgs boson must necessarily rest on a combination of accurate data and hard theoretical predictions.

II. PROPERTIES OF LIGHT HIGGS BOSONS

To understand the validity of the experimental searches for light Higgs bosons it is necessary to examine the properties of these particles. Because it couples to mass, a light Higgs boson will decay predominantly into the heaviest states that are kinematically available. If the Higgs-boson mass m_h is less than $2m_\mu$ then the only decay modes are $h\to\gamma\gamma$ and $h\to e^+e^-$, and the lifetime decreases from $\sim 10^{-5}$ sec for $m_h \lesssim 2m_e$ to $\sim 10^{-11}$ sec for $m_h \approx 2m_\mu$ (Ref. 5). The width for $h\to e^+e^-$ is given by[5]

$$\Gamma(h\to e^+e^-)=\frac{G_F m_e^2}{4\pi\sqrt{2}}m_h\left[1-\frac{4m_e^2}{m_h^2}\right]^{3/2}, \qquad (1)$$

whereas the width for $h\to\gamma\gamma$ is[6]

$$\Gamma(h\to\gamma\gamma)=\frac{G_F m_h^3}{8\pi\sqrt{2}}\left[\frac{\alpha}{4\pi}\right]^2\left[7-\tfrac{4}{3}\sum_f Q_f^2\right]^2 . \qquad (2)$$

The first term in the large parentheses in Eq. (2) arises from the W-boson loop and the second from all possible fermion loops (both leptons and quarks). Thus for $2m_e < m_h \le 2m_\mu$, $\Gamma(h\to\gamma\gamma)/\Gamma(h\to e^+e^-)\lesssim\frac{1}{3}$ reaching its maximum value at $m_h=2m_\mu$. For $2m_\mu \le m_h < 2m_\pi$, the dominant decay mode is $h\to\mu^+\mu^-$, and the lifetime decreases rapidly as the mass of the Higgs boson increases: the width for $h\to\mu^+\mu^-$ is given by Eq. (1) with m_e replaced by m_μ. The expected decay branching ratios

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for $m_h > 2m_\pi$ are subject to some uncertainties. It has recently been shown[7] that final-state interactions enhance the rate for $h \to \pi\pi$ so that the branching ratio for $h \to \mu^+\mu^-$ is $\sim(10^{-1}-10^{-2})$ for $2m_\pi \le m_h < 2m_K$.

III. HIGGS-BOSON PRODUCTION IN K DECAYS

The decay $K \to \pi h$ can be used to search for a Higgs boson with $m_h < 350$ MeV/c^2. However, theoretical estimates for its branching ratio have varied from 10^{-3} to 10^{-8}. The problem has been to incorporate PCAC (partial conservation of axial-vector current), known $\Delta I = \frac{1}{2}$ enhancements, and to correctly evaluate the matrix elements of the quark–Higgs-boson Lagrangian. The relevant graphs are shown in Figs. 1 and 2.

The most recent, and probably most reliable, estimate of the amplitude for $K \to \pi h$ is that of Chivukula and Manohar[8] who used chiral perturbation theory to obtain

$$A(K_L^0 \to \pi^0 h) = A(K^+ \to \pi^+ h)$$

$$= \left[(-1.5\times 10^{-10}) \left[1 + \frac{m_\pi^2 - m_h^2}{m_K^2} \right] + B(0.68\times 10^{-10}) + \sum_i \eta_i \right] \text{GeV} . \quad (3)$$

The first two terms in this expression can be associated with Fig. 1. The parameter B is undetermined in the effective Lagrangian and reflects unknown hadronic contributions which, unfortunately, can only be determined in processes involving at least one Higgs boson. The last term is the contribution from the quark graphs of Fig. 2 with η_i given by

$$\eta_i = \frac{m_K^2}{2v} \frac{3\alpha}{16\pi \sin^2\theta_W} V_{is}^* \frac{m_i^2}{m_W^2} V_{id} . \quad (4)$$

The V_{ij} are elements of the Kobayashi-Maskawa (KM) mass matrix and the sum runs over all quarks: $\eta_u \ll \eta_c \approx 0.72\times 10^{-10}$ GeV. The size of the presumed top (or any further very massive) quark contribution depends sensitively on the interplay between its mass and its mixing angles with the s and d quarks. We shall discuss this in some detail below. First, we shall deal with the situation where only the u and c quarks contribute.

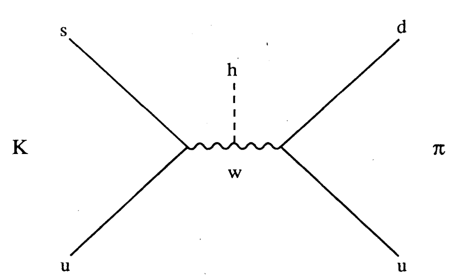

FIG. 1. The tree-level contribution to the decay $K \to \pi h$.

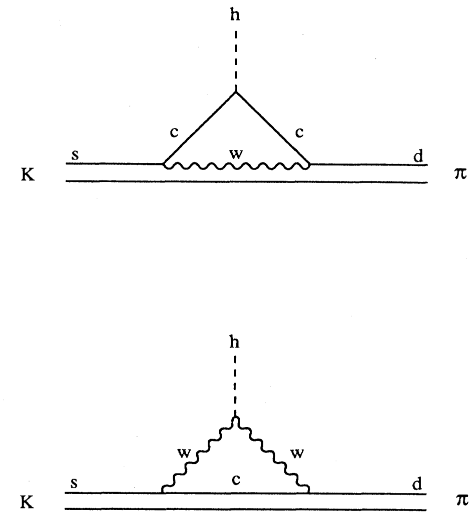

FIG. 2. One-loop contributions to the decay $K \to \pi h$.

The branching ratios for kaon decays into massless Higgs bosons are given by

$$R(K^+ \to \pi^+ h) = \left[\frac{A}{10^{-10}} \right]^2 7.5\times 10^{-6} \quad (5a)$$

and

$$R(K_L^0 \to \pi^0 h) = \left[\frac{A}{10^{-10}} \right]^2 3\times 10^{-5} . \quad (5b)$$

Because B is unknown, the possibility exists that the terms in Eq. (3) cancel; thus regardless of what quarks contribute, no unambiguous limits on the existence of light Higgs bosons can be derived from kaon decay. For example, ignoring η_t and taking $B \approx 1$ implies that the branching ratio for $K^+ \to \pi^+ h$ ($K_L^0 \to \pi^0 h$) is $\approx 7.5\times 10^{-8}$ (3×10^{-7}).

Willey[9] has recently emphasized that η_t might be the dominant contribution to Eq. (3). For example, the most recent Particle Data Group[10] compilation quotes the following limits on the relevant KM matrix elements: $0.036 < V_{ts} < 0.052$ and $0.002 < V_{td} < 0.018$. If these are inserted in Eq. (4), one finds $\eta_t \gtrsim 0.2\eta_c(m_t/40 \text{ GeV}/c^2)^2$. Thus, for $m_t \sim 80$ GeV/c^2, $\eta_t \sim \eta_c$ and the general conclusions above are not significantly altered. However, a more stringent limit can be derived from the measured B_d^0-$\bar{B}_d^0$ mixing:[11] $\Delta M_B/\Gamma_B = 0.73\pm 0.18$. Let us assume that the dominant contribution to the mixing results from the graphs shown in Fig. 3. Note that this assumption ignores contributions from possible fourth-generation and/or supersymmetric particles, etc., so in this sense it is very model dependent.[12] One thereby obtains the estimate

$$\Delta M_B/\Gamma_B = \frac{G_F^2 m_B \tau_B}{6\pi^2} f_B^2 B_B |V_{tb}^* V_{td}|^2 m_t^2 , \quad (6)$$

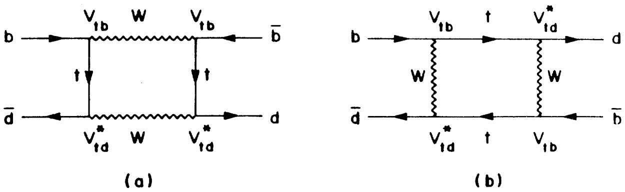

FIG. 3. Box graphs with t-quark exchange contributing to B_d^0-$\bar{B}_d^0$ mixing.

where τ_B is the B lifetime and f_B is its decay coupling constant. B_B is a parameter reflecting unknown bound-state effects. With reasonable estimates of these parameters one can derive $\eta_t \gtrsim \eta_c[m_t/(20\ \mathrm{GeV}/c^2)]$. In this case with $m_t \sim 80\ \mathrm{GeV}/c^2$, η_t dominates the one-loop quark operator contribution to Eq. (3). If now $B \approx 1$, then the theoretical estimate for $R(K \to \pi h)$ increases by at least an order of magnitude and a light Higgs boson with 80 MeV $< m_h < m_K - m_\pi$ would indeed be ruled out by the data discussed below. However, from a critical and conservative point of view, we are still in an ambiguous situation since there is no constraint on the parameter B. One need only have $B \approx -3$ to negate any limit from present experimental data.

A variety of limits on the existence of light Higgs bosons derived from kaon decays have appeared in the literature. We comment on these limits immediately below.

A. Limits from K^+ decays

(1) Willey[9] argues that Higgs bosons with 50 $\mathrm{MeV}/c^2 < m_h < 2m_\mu$ are ruled out from existing data[13,14] on $K^+ \to \pi^+ e^+ e^-$. However, the data of Cence *et al.*[13] do not provide a limit on Higgs bosons lighter than $\sim 100\ \mathrm{MeV}/c^2$ because such a Higgs boson would live sufficiently long to have failed the experimental decay vertex requirement.[15] Thus we find $R(K^+ \to \pi^+ h)R(h \to e^+e^-) < 2.7\times 10^{-7}$ (90% C.L.) for 100 $\mathrm{MeV}/c^2 < m_h < 2m_\mu$. The data of Bloch *et al.*[14] imply $R(K^+ \to \pi^+ h)R(h \to e^+e^-) < 3.5\times 10^{-7}$ (90% C.L.) for 140 $\mathrm{MeV}/c^2 < m_h < 2m_\mu$. Comparing these limits with Eqs. (5a) and (3), remembering that the branching ratio for $h \to e^+e^-$ is ≥ 0.75 in this region, we see that no definitive limits on light Higgs bosons can be inferred.

(2) Yamazaki *et al.*[16] searched for $K^+ \to \pi^+ h$ without placing any requirements on the properties of the particle recoiling against the π^+. The 90%-C.L. upper limit for the branching ratio for this decay is 1.5×10^{-6} for $0 < m_h < 80\ \mathrm{MeV}/c^2$, and rises slowly as m_h increases to 120 MeV/c^2. Comparing this result with Eq. (5a), we again see that there is no limit on light Higgs bosons.

(3) Asano *et al.*[17] searched for $K^+ \to \pi^+ X$ where X corresponds to the absence of detected charged and neutral particles. Their limit of $R(K^+ \to \pi^+ X) < 4\times 10^{-8}$ (90% C.L.) is applicable to light-Higgs-boson emission only if the lifetime of the Higgs boson is greater than $\sim 10^{-9}$ sec, which holds for $m_h < 5\ \mathrm{MeV}/c^2$: for shorter-lived Higgs bosons, i.e., for $m_h > 5\ \mathrm{MeV}/c^2$, the experimental limit is considerably larger, namely, $R(K^+ \to \pi^+ X) < 1.4\times 10^{-6}$ (90% C.L.) for all $m_h < 100\ \mathrm{MeV}/c^2$. Again, this provides no limit on light Higgs bosons.

(4) The experiment of Baker *et al.*[18] found $R(K^+ \to \pi^+ h)R(h \to e^+e^-) < 8\times 10^{-7}$ (90% C.L.) for a short-lived ($< 10^{-11}$ sec) neutral particle with mass < 100 MeV/c^2. However, this is not a useful constraint on the amplitude for Higgs-boson emission in kaon decay because Higgs bosons in this mass region live longer than 10^{-11} sec.

B. Limits from K_L^0 decays

Chivukula and Manohar[8] claim that, barring accidental cancellations in the amplitude of Eq. (3), existing kaon data exclude the existence of light Higgs bosons for all masses less than 350 MeV/c^2. For $2m_e < m_h < 2m_\mu$, they use the measured branching ratio $R(K_L^0 \to \pi^0 h)R(h \to e^+e^-) \leq R(K_L^0 \to \pi^0 e^+ e^-) < 2.3\times 10^{-6}$ (90% C.L.) (Ref. 19). However, Higgs bosons lighter than $\sim 40\ \mathrm{MeV}/c^2$ would not have decayed until after they traveled beyond the decay volume in the experiment of Ref. 19 and so would have been cut by the analysis. Higgs bosons lighter than $\sim 80\ \mathrm{MeV}/c^2$ would have decayed far enough downstream of the kaon decay point to cause the reconstructed π^0 mass to fall outside the experimental cuts: the π^0 mass was calculated from the measured photon energies and the kaon decay point, which was taken as the charged particle (in this case, the e^+e^-) vertex. Thus these data are only relevant for Higgs bosons with 80 $\mathrm{MeV}/c^2 < m_h < 2m_\mu$. For $2m_\mu < m_h < 2m_\pi$, they use the measured branching ratio $R(K_L^0 \to \pi^0 \mu^+ \mu^-) < 1.2\times 10^{-6}$ (90% C.L.) (Ref. 19). Comparing these limits with Eqs. (5b) and (3), we again see that they cannot be used to exclude light Higgs bosons in these ranges. For $m_h > 2m_\pi$ any constraint on light Higgs bosons from this limit on the $K_L^0 \to \pi^0 \mu^+ \mu^-$ branching ratio is further weakened by the small branching ratio of the Higgs bosons into $\mu^+\mu^-$ (Ref. 7).

In summary, the present kaon-decay data show no indication of the existence of a light Higgs boson. At the present level of accuracy they provide constraints on the allowable range of the parameter B in Eq. (3) rather than hard evidence against the existence of a light Higgs boson. More sensitive searches would either discover a light Higgs boson or argue against their existence in the absence of a fine-tuned cancellation in Eq. (3). Improved sensitivity to Higgs bosons with $2m_\mu < m_h < 2m_\pi$ should be available soon from kaon decay data from AGS Experiment 787 (Ref. 20), and AGS Experiment 791 (Ref. 21).

IV. HIGGS-BOSON PRODUCTION IN B DECAYS

An expression for the branching ratio $B_1 \equiv \Gamma(B \to hX)/\Gamma(B \to e\nu X)$ has been derived in Refs. 22 and 8. This expression implies that the branching ratio $B_2 \equiv \Gamma(B \to hX)/\Gamma(B \to \mathrm{all})$ may be fairly large although it is very sensitive to the top-quark mass ($\propto m_t^4$), the bottom-quark mass, and various mixing angles: a fourth generation of quarks would also contribute with unknown mixing angles. There is an additional uncertainty due to the fact that the calculation for B_1 has been done to the one-loop level but the experimental measurement for $\Gamma(B \rightarrow e\nu X)/\Gamma(B \rightarrow \text{all})$, which is sensitive to all higher-order corrections, is used to estimate B_2. Claims have been made in the literature[8,22] using B-decay data[23] to rule out light Higgs bosons in various mass ranges.

In fact, there are no limits for $m_h < 2m_\mu$ because such a light Higgs boson would live so long that the e^+e^- from its decay would not be associated with the B-decay vertex in the experiments. Higgs bosons with $2m_\mu < m_h < 2m_\pi$ decay predominantly into $\mu^+\mu^-$. The experimental upper limits[23] for the branching ratio $B_3 \equiv \Gamma(B \rightarrow \mu^+\mu^- X)/\Gamma(B \rightarrow \text{all}) \geq B_2 R(h \rightarrow \mu^+\mu^-)$ are

$$B_3 \leq 0.007 \quad (95\% \text{ C.L.}) \text{ for } 300 \text{ MeV}/c^2 < m_h \lesssim 5 \text{ GeV}/c^2 \text{ (JADE)} ,$$

$$B_3 \leq 0.007 \quad (95\% \text{ C.L.}) \text{ for } 400 \text{ MeV}/c^2 < m_h \lesssim 5 \text{ GeV}/c^2 \text{ (Mark J)} ,$$

$$B_3 \leq 0.008 \quad (90\% \text{ C.L.}) \text{ for } 500 \text{ MeV}/c^2 < m_h \lesssim 3.2 \text{ GeV}/c^2 \text{ (CLEO) (Ref. 24)} ,$$

$$B_3 \leq 0.02 \quad (95\% \text{ C.L.}) \text{ for } 2m_\mu < m_h \lesssim 5 \text{ GeV}/c^2 \text{ (TASSO)} .$$

The first three experiments imposed cuts on the minimum value of the muon momenta and their opening angle implying a minimum value of m_h to which they were sensitive. The resulting limits on light Higgs bosons from B decay as a function of m_t is shown in Fig. 4. The cusp near $m_h = 300 \text{ MeV}/c^2$ is caused by the limit from JADE becoming inapplicable: for $2m_\mu < m_h < 2m_\pi$, the branching ratio for $h \rightarrow \mu^+\mu^-$ is large so the excluded region extends to lighter m_t. Grinstein, Hall, and Randall[22] point out that even though there are stringent limits on the branching ratio for $B \rightarrow hK$, theoretical uncertainties in the expected rate for this decay prevent it being used to exclude light Higgs bosons with any mass. Thus even though the branching ratio for $B \rightarrow hX$ is expected to be fairly large, theoretical uncertainties substantially reduce the range of light-Higgs-boson masses that can be excluded and imply that this range depends strongly on the mass of the top quark. As in the case of kaon decays, more sensitive searches would be very useful.

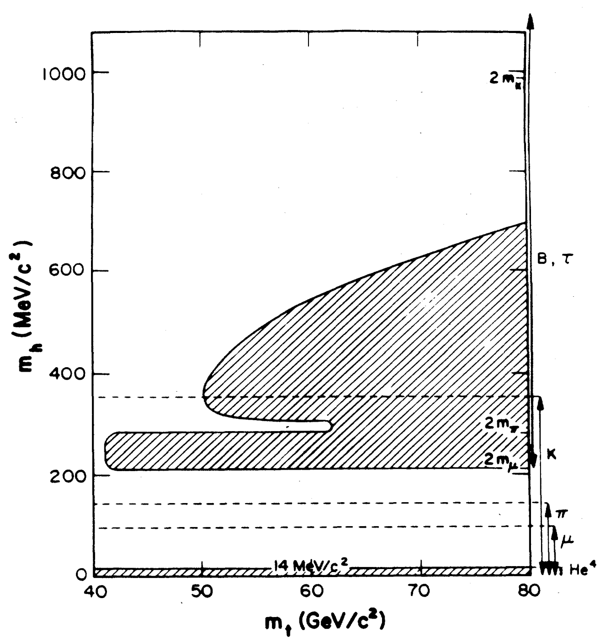

FIG. 4. The ranges (hatched) of light-Higgs-boson masses that are definitively excluded by existing data as a function of the mass of the top quark. The symbols to the right of the graph show the ranges of light-Higgs-boson masses that particular particle decays can probe.

V. HIGGS-BOSON PRODUCTION IN π^+ DECAYS

The rate for Higgs-boson production in charged-pion decay, where the Higgs boson is emitted from the virtual W, is given by

$$d\Gamma(\pi^+ \rightarrow e^+\nu_e h) = \frac{\sqrt{2} f_\pi^2 G_F^3}{m_\pi (2\pi)^3} [m_\pi^2 (m_\pi^2 - m_h^2) - 2m_\pi^3 E_- + m_\pi^2 (E_+^2 - E_-^2)] dE_- dE_+ , \quad (7)$$

where $E_\pm = E_\nu \pm E_e$. Integrating Eq. (7) over phase space gives a branching ratio for this decay of

$$R(\pi^+ \rightarrow e^+\nu_e h) = 6.5 \times 10^{-9} [(1 - 8x + x^2)(1 - x^2) - 12x^2 \ln x] ,$$

where $x \equiv (m_h^2)/(m_\pi^2)$. The data of Eichler *et al.*[25] would seem to rule out Higgs bosons with $2m_e < m_h < 80 \text{ MeV}/c^2$ but a definitive statement must await a detailed study of the effects of the acceptance of the SINDRUM detector.[26]

VI. HIGGS-BOSON PRODUCTION IN CHARGED-LEPTON DECAYS

The rate for the decay of a charged lepton L into a lighter charged lepton l plus a Higgs boson and two neutrinos is given by

$$d\Gamma(L^+\to l^+\nu\bar{\nu}h)=\frac{G_F^3\mathbf{p}_l\mathbf{p}_h}{48\pi^5\sqrt{2}m_L}\{A_1^2(Q^2p_l\cdot p_L+2Q\cdot p_lQ\cdot p_L)+A_2(Q^2p_l\cdot p_h+2Q\cdot p_lQ\cdot p_h)$$
$$+A_3^2[7Q^2(2p_h\cdot p_Lp_l\cdot p_h-m_h^2p_l\cdot p_L)+4p_h\cdot p_LQ\cdot p_lQ\cdot p_h-2m_h^2Q\cdot p_lQ\cdot p_L]\}$$
$$\times dE_hdE_ld\cos\theta_{hl}\ , \qquad (8)$$

where p_x is a four-vector, $\mathbf{p}_x$ is a three-vector, $Q=p_L-p_l-p_h$, and the coefficients A_1, A_2, and A_3 are given by

$$A_1=2\left[\sqrt{2}-\frac{m_L^2}{m_h^2-2m_LE_h}\right],$$
$$A_2=\frac{2m_L^2A_1}{m_h^2-2m_LE_h},$$
$$A_3=\frac{m_L}{m_h^2-2m_LE_h}.$$

The branching ratios for different lepton species are shown in Fig. 5 as a function of Higgs-boson mass. The branching ratio is smaller than present sensitivities for muon decay from SINDRUM (Ref. 25) and the Crystal Box Collaboration[27] and for τ decay.[28]

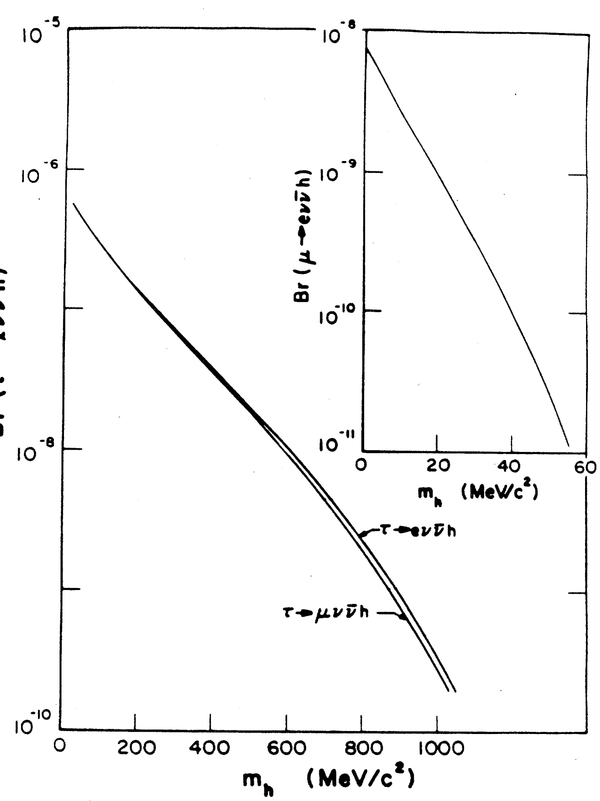

FIG. 5. The branching ratios for $\tau\to\mu\nu\bar{\nu}h$, $\tau\to e\nu\bar{\nu}h$, and $\mu\to e\nu\bar{\nu}h$ as a function of the mass of the light Higgs boson.

VII. HIGGS-BOSON PRODUCTION IN η' DECAYS

Dzhelyadin *et al.*[29] claim to exclude Higgs bosons with $m_h<409$ MeV/c^2 from a search for $\eta'\to\eta\mu^+\mu^-$. Since this experiment was sensitive only to Higgs bosons decaying into muon pairs, it was completely insensitive to $m_h<2m_\mu$. In addition, the experimental result does not limit light Higgs bosons with $m_h>2m_\pi$ because the estimate of the $h\to\mu^+\mu^-$ branching ratio in Ref. 29 is not correct.[7] Finally, the expected branching ratio for $\eta'\to\eta h$ is theoretically uncertain[30] making any definitive statement based on this decay, even for $2m_\mu<m_h<2m_\pi$, unreliable.

VIII. HIGGS-BOSON PRODUCTION IN Υ DECAYS

An extensive search for a monochromatic photon from $\Upsilon\to h\gamma$ has been conducted by the CUSB Collaboration for $m_h>\sim750$ MeV/c^2 (Ref. 31). This search has the advantage of being independent of the decay modes of the Higgs boson. No evidence for such monochromatic photons has been found. A first-order calculation leads to the expectation of a branching ratio for $\Upsilon\to h\gamma$ of $\sim3\times10^{-4}$ for a wide range of Higgs-boson masses.[32] The one-loop QCD radiative corrections to this process have been calculated[33] giving

$$\frac{\Gamma(\Upsilon\to h\gamma)}{\Gamma(\Upsilon\to\mu^+\mu^-)}=\left[\frac{G_Fm_b^2z}{\sqrt{2}\pi\alpha}\right]\left[1-\frac{4\alpha_s}{3\pi}\alpha_H(z)\right], \qquad (9)$$

where $z\equiv1-m_h^2/m_\Upsilon^2\approx1$ and $\alpha_H(1)=7+6\ln2-\pi^2/8\approx10$. The part of Eq. (9) in the first large parentheses is the result obtained by Wilczek.[32] For $\alpha_s(m_\Upsilon^2)=0.15$, the one-loop correction is 63% of the tree-level contribution. Thus the use of a perturbation expansion is suspect, so no definitive limits can be deduced from the data.

There are several calculations in the literature which study the relativistic corrections to this process.[34] Only the results of Biswas, Goyal, and Pasupathy and Aznauryan, Grigoryan, and Matinyan are applicable to a light Higgs boson with $m_h<1$ GeV/c^2, while all are applicable to the region $m_h\sim7$–9 GeV/c^2. Four of the calculations find that there is a large suppression of the rate for $m_h\sim8$ GeV/c^2. On the other hand, Biswas, Goyal, and Pasupathy find a large enhancement in this region. Even for $m_h\ll1$ GeV/c^2, Aznauryan, Grigoryan, and Matinyan predict a factor of ~2 suppression in the ratio $\Gamma(\Upsilon\to h\gamma)/\Gamma(\Upsilon\to e^+e^-)$.

Clearly the theoretical expectation for this process is in serious doubt, especially for light Higgs bosons, due to both the radiative and relativistic corrections. Hopefully this distressing theoretical situation will improve with additional study. However, until a reliable estimate of the expected branching ratio for $\Upsilon \rightarrow h\gamma$ is available, no limits on light Higgs bosons can be set from this decay.

IX. CONCLUSIONS

We have examined many possible constraints on the existence of light Higgs bosons. Many of the claims in the literature excluding Higgs bosons within certain mass ranges are not valid and others rest on unreliable theoretical calculations. At present, only light Higgs bosons with $m_h < 14$ MeV/c^2 and the region $2m_\mu \leq m_h < 700$ MeV/c^2 for certain values of m_t as shown in Fig. 4 are unambiguously excluded. Existing data on π^+ decay may soon extend the limit up to ~ 80 MeV/c^2, independent of m_t. More sensitive searches in K, Υ, and B decays may either discover a light Higgs boson or further restrict the theoretical scenarios in which a light Higgs boson could exist.

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