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Decays of Heavy Vector Mesons into Higgs Particles

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ABSTRACT

Estimates are presented for the decay of vector mesons composed of heavy quarks into states containing a Higgs boson. If the decays are kinematically allowed, they are probably experimentally accessible when the quark mass $m_q \gtrsim 4$ GeV.

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Present-day gauge theories of the weak interactions require the existence of scalar particles (Higgs mesons) with characteristic properties. Discovery of such particles would be weighty evidence in favor of such theories. Because these mesons are thought to be very weakly coupled, all processes hitherto considered for production and detection gave poor prospects for experimental success.[1] In this note we would like to point out that this situation can be much improved if e^+e^- colliding-beam machines produce particles analogous to the J/ψ but with larger mass.[2]

Let us briefly recall the relevant properties of Higgs mesons. For definiteness we shall discuss the original model of Weinberg and Salam[3] with new quarks and leptons added sequentially. In this model the coupling of the Higgs meson H to a quark q or lepton ℓ of mass m is given by

$$\mathscr{L}_{\text{int.}} = 2^{\frac{1}{4}} G_F^{\frac{1}{2}} m H (q\bar{q} \text{ or } \ell\bar{\ell}) \quad . \tag{1}$$

The close connection between the Higgs coupling strength and the fermion mass is characteristic. It immediately suggests that the use of particles containing heavy quarks in the search for Higgs particles will be profitable. For instance, if the mass m of the quark is 7.6 GeV, then the Higgs coupling already has 1/10 the strength of the electromagnetic coupling. (Actually, if we remember that quarks are fractionally charged, the ratio is even larger). The mass of the Higgs particle itself is unfortunately not predicted in the model.

It is easy to compute the ratio of the processes $V \to \mu\mu$, $V \to H\gamma$ (where V is a vector meson formed from quarks of mass m_q), assuming that V is weakly bound and that non-relativistic mechanics is appropriate. Calculation of the Feynman diagrams shown in Figure 1 yields:

$$\frac{\Gamma(V \to H\gamma)}{\Gamma(V \to \mu\mu)} = \frac{G_F m_q^2}{\sqrt{2}\,\pi\alpha}\sqrt{1 - \frac{m_H^2}{m_V^2}} \tag{2}$$

which for $m_q = 4.5\ \mathrm{GeV}^2$ is .007 times the phase-space factor. Since colliding beam machines may produce tens of thousands of V particles and the branching ratio for $V \to \mu\mu$ should be a few percent, it is not inconceivable that the monochromatic photons from $V \to H\gamma$ could be detected.

If several such events are collected, it would be interesting to look at the decay modes of H. We would expect that of known particles H decays almost exclusively to charmed final states and $\tau^+\tau^-$ pairs,[4] if 9 GeV $\gtrsim m_H \gtrsim$ 4 GeV.[5] The ratio of decays into charm-bearing final states (which might be $D\bar{D}n\pi$, $J/\psi\pi\pi$, ...) to decays into τ's should be about 3 (for 3 colors) times the square of the mass ratio, i.e. $\sim 3 \times (1.3)^2/(1.8)^2 \simeq 1.6$. Since $\tau \to e\nu\bar{\nu}$ and $\tau \to \mu\nu\bar{\nu}$ each about 20% of the time, we expect $H \to \tau^+\tau^- \to \ell\,\bar{\ell}' + \nu$'s about 10% of the time, giving the very distinctive decays $V \to \gamma\mu\mu$, $\gamma\mu e$, γee with a monochromatic photon. If neutral heptons[6] exist and have masses $\gtrsim$ 2 GeV, they might dominate H decays and lead to spectacular multi-lepton final states.

Decays of lighter Higgs mesons are discussed in Ref. 1. There is, however, a potentially important process which was not considered in that paper. This is the 'loop-annihilation' process depicted in Fig. 2. (It is formally similar to the $H \rightarrow \gamma\gamma$ process which was considered.) In this process the Higgs boson couples to a virtual heavy quark which annihilates into two color gluons. Since through this process light quarks may be produced in Higgs decay without the appearance of their small masses, we expect this to be the dominant process for light quark production even though it is suppressed by several powers of the strong interaction coupling. The effective vertex for the loop-annihilation process depicted in Fig. 2 is $HG_{\mu\nu}G_{\mu\nu}$, i.e. of dimension 5. Therefore for a heavy quark q of mass m_q we expect the Feynman integral to be well enough convergent in the ultraviolet so that the integral is proportional to $1/m_q$ for large m_q. However, the vertex coupling the Higgs to q is also proportional to m_q, so that the total amplitude is <u>independent</u> of the m_q when m_q is large. So this process in principle would allow the detection of effects of arbitrarily heavy quarks. It may be calculated with some confidence using renormalization group methods, and in principle allows us to measure experimentally the number of heavy quark flavors.

The result is[7]

$$\frac{\Gamma(H \to GG)}{\Gamma(H \to \mu\mu)} = \left(\frac{m_H}{m_\mu}\right)^2 \left(\frac{g^2}{4\pi^2}\right)^2 \frac{4}{9\left(1 - \frac{4m_\mu^2}{m_H^2}\right)^{3/2}} N^2 \tag{3}$$

where N is the number of heavy quark flavors. The denominator is directly measurable, but the numerator would have to be determined indirectly by comparing say the total $\mu\mu$ branching ratio to that expected from tree-graph processes, or making some plausible conjecture as to how the two-gluon final state is realized physically.

Another, closely related, mechanism for Higgs production is illustrated by the quark diagram in Fig. 3. It is difficult to be quantitative here, but roughly speaking we would expect that the ratio of inclusive decay into Higgs mesons to inclusive decay into real photons to be comparable to the ratio in Eq. (2). If the charge of the quark is -1/3, we might even expect the relative rate for inclusive Higgs production to be up a factor $3^2 = 9$ from Eq. (2). On the other hand, notice that the final hadron state X in $V \to H + X$ has charge conjugation $C = -$, and in some models for 'Zweig's rule'[8] would be extra suppressed relative to $V \to \gamma + X$ $(C = +)$ (we do not expect this, however). In any case, the most likely channel for the Higgs decay with hadrons would be $V \to H + \omega$.

We have discussed so far only the original Weinberg-Salam model, where all particles acquire mass from a single Higgs multiplet. The coupling of Higgs particles in more complicated models is difficult to survey in a general way. Indeed, the requirements of gauge invariance and renormalizability alone allow any number of scalar particles with almost arbitrary masses and couplings. We will mention one possibility. It is possible that the W-bosons acquire the bulk of their mass through Higgs particles which do not couple to quarks (to lowest order). Then the coupling of the quarks to the Higgs bosons which do give them mass would be larger than envisaged in Eq. (1). (The vacuum expectation values would be smaller so that the contribution of the 'quark-coupling' Higgs to the W-mass is smaller, but the product of Yukawa coupling to quarks times vacuum expectation value is fixed to be the quark mass.) For this reason our estimate Eq. (2) has the nature of a lower bound. It might conceivably be possible to identify the X(2800)[9] with such a Higgs particle, although there is at present no sufficient reason for such a radical step.

There is one general relation between the mass m_H of the Higgs particle, the mass m_q of the quark, and the Yukawa coupling g_Y between them, which follows from the requirement that the Higgs self-coupling not be strong.[10] It is

$$m_H \lesssim m_q/2\pi g_Y \quad . \tag{4}$$

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REFERENCES

[1] J. Ellis, M. Gaillard, D. Nanopoulos, Nucl. Phys. B106, 292 (1976), and references therein.

[2] Such particles may be suggested by the findings of S. Herb, et al., Phys. Rev. Lett. 39, 252 (1977).

[3] S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in Proc. Eighth Nobel Symposium, ed. N. Svartholm (Stockholm, 1968).

[4] M. Perl, et al., Phys. Rev. Lett. 35, 1489 (1975), Phys. Lett. 63B, 466 (1976).

[5] There are arguments by A. Linde, JETP Lett. 23, 73 (1976), and S. Weinberg, Phys. Rev. Lett. 36, 294 (1976), indicating $m_H \gtrsim 4$ GeV. See also P. Frampton, Phys. Rev. Lett. 37, 1378 (1976). However these arguments involve the assumption that the simple H^4 form of the Higgs interaction survives at high momenta, which may not be correct.

[6] Eg. T. P. Cheng, L.-F. Li, Phys. Rev. Lett. 38, 381 (1977).

[7] The result is readily extracted from the calculation of L. Resnick, M. Sudaresan, P. Watson, Phys. Rev. D8, 172 (1973). We have ignored a small correction due to the renormalization of 'effective mass'.

[8] G. Zweig (1964, unpublished) and in Symmetries in Elementary Particle Physics (Academic, New York, 1965), p. 192.

[9] J. Heintze, Proc. 1975 Stanford Lepton-Photon Symposium (SLAC, Stanford, Cal.).

[10] For the quark mass we have $m_q = g_Y \langle\phi\rangle$, while $\langle\phi\rangle$ is determined by the Higgs mass m_H and self-coupling λ to be $\langle\phi\rangle = m_H/\lambda^{\frac{1}{2}}$, thus requiring $\lambda/4\pi^2 \leq 1$ leads to Eq. (4).

FIGURE CAPTIONS

Fig. 1:	Comparison of the radiative decay $V \rightarrow H\gamma$ (a) and the leptonic decay $V \rightarrow \mu^+\mu^-$ (b).
Fig. 2:	'Loop-annihilation' contribution to Higgs decay.
Fig. 3:	Comparison of the inclusive decay $V \rightarrow H + X$ (a) and the inclusive radiative decay $V \rightarrow \gamma + X$ (b).

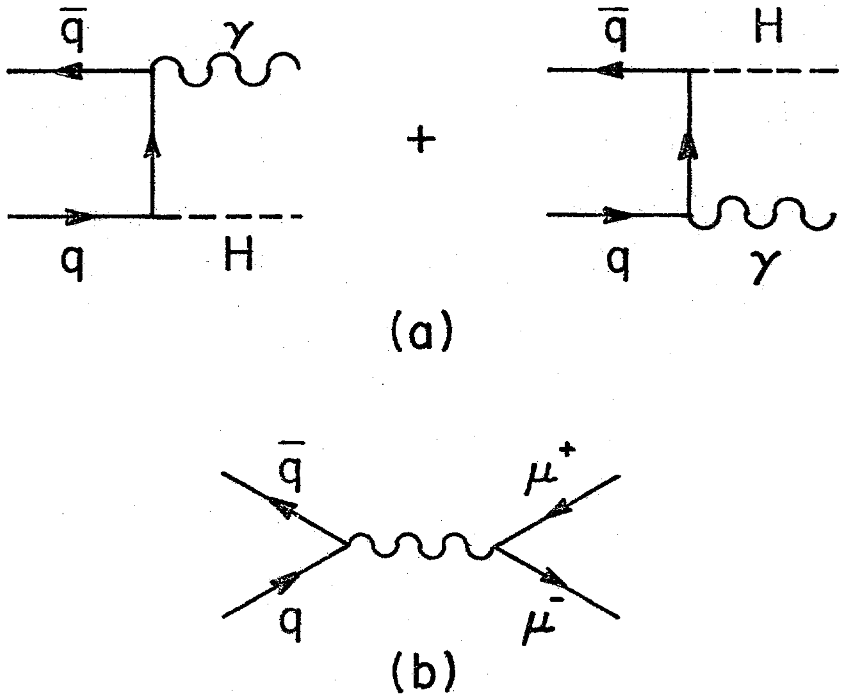

Fig. 1

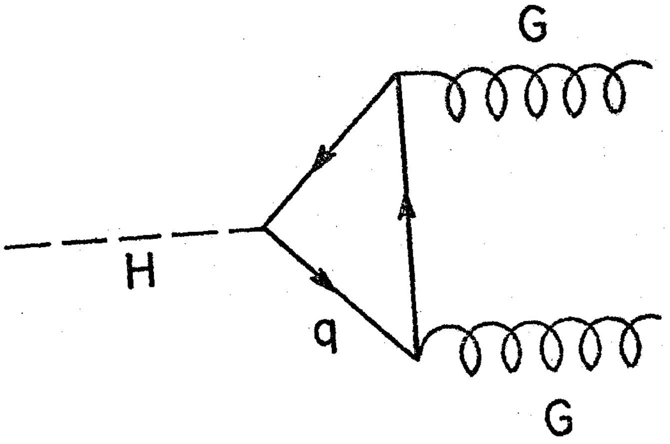

Fig. 2

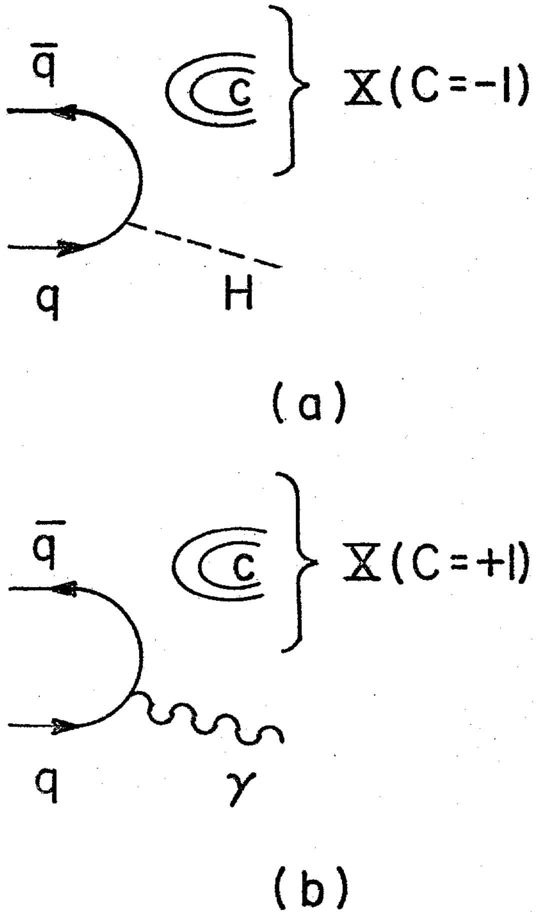

Fig. 3