Joint production of quarkonium and a Higgs boson in e^+e^- interactions

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The exclusive joint production of a neutral Higgs boson H^0 and a heavy vector meson $V=\psi,\gamma, T$ in e^+e^- annihilation is analyzed. There is a realistic possibility of experimentally observing H^0 in such reactions because of the clear signature of the process and the good signal-to-background ratio.

Since the discovery of the $W^\pm$ and Z^0 gauge bosons, the only missing component in the standard $SU(2)\times U(1)$ model of the electroweak interaction is the Higgs boson H^0. The search for the Higgs boson is currently one of the most important problems in particle physics.

The difficulties in observing the H^0 bosons stem from the circumstance that the mass in the standard model can lie in a broad range from 7 to 1000 GeV (Refs. 1 and 2, for example). If the mass is relatively small ($M_H < 2M_W \simeq 160$ GeV), the characteristic decay modes of H^0 with a clear signature have relatively low branching ratios,[3] while the identification of the Higgs boson on the basis of the fundamental decay modes is complicated by the large hadronic background. It is thus preferable to observe the H^0 boson in exclusive reactions, rather than inclusive reactions, even if the cross sections for the H^0 production in the latter case is significantly larger.[4]

In the present letter we analyze the associative production of a Higgs particle with a heavy vector meson $V(V=\psi,\gamma T)$ in the reaction

$$e^+e^- \to H^0 + V. \tag{1}$$

The production in (1) has a clear signature because of the presence of the decay mode $V\to\mu^+\mu^-$, and a good signal-to-background ratio can be achieved in a certain kinematic region.

In first-order perturbation theory in the coupling constant of the electroweak interaction, process (1) is dominated by the diagrams in Fig. 1. The vertex representing the transition of the $Q\bar{Q}$ pair into a vector meson V with a momentum p is chosen in the form[5] $C_V\bar{u}(p/2)\hat{\epsilon}u(p/2)$, where u and $\bar{u}$ are spinors describing the quark and antiquark, ϵ_μ is the polarization vector of meson V, and the constant C_V is related to the wave function of the $V=(Q\bar{Q})$ ground state at the origin of coordinates, $\psi_V(0)$. This constant is determined from the width of the electromagnetic decay $V\to\mu^+\mu^-$:

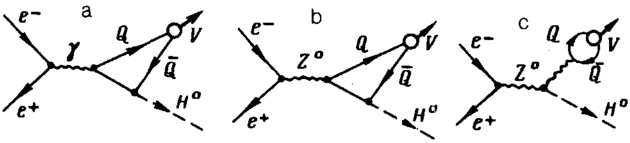

FIG. 1.

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$$C_V^2 = \frac{|\psi_V(0)|^2}{M_V^3} = \frac{1}{16\pi\alpha^2 e_Q^2}\,\frac{\Gamma}{M_V}\,. \tag{2}$$

The differential cross section for reaction (1) in the c.m. frame is

$$\frac{d\sigma}{d\Omega} = 6\alpha^2 C_V^2 G_F \sqrt{2} M_V^4 \frac{\lambda^{1/2}(s, M_V^2, M_H^2)}{s^2} \sum_{i,j} A_i^+ A_j\,, \tag{3}$$

where the A_i ($i = 1,2,3$) are matrix elements corresponding to the diagrams in Fig. 1, a–c:

$$|A_1|^2 = e_Q^2 D_1^2 E_V^2 (1 + \cos^2\theta + M_V^2/E_V^2 \sin^2\theta)\,, \tag{4a}$$

$$|A_2|^2 = (a_e^2 + v_e^2)(v_Q/e_Q)^2 s^2 D_2^2 |A_1|^2\,, \tag{4b}$$

$$|A_3|^2 = (a_e^2 + v_e^2) v_Q^2 M_z^4 s D_2^2 D_3^2 (1 + \cos^2\theta + E_V^2/M_V^2 \sin^2\theta)\,, \tag{4c}$$

$$A_1^+ A_2 + A_2^+ A_1 = 2v_e (v_Q/|e_Q|) s (s - M_z^2) D_2^2 |A_1|^2\,, \tag{4d}$$

$$A_1^+ A_3 + A_3^+ A_1 = -4 v_e v_Q |e_Q| M_z^2 s^{1/2} [(s - M_z^2)(M_V^2 - M_z^2) - \Gamma_z^2 M_z^2] D_1 D_2^2 D_3^2 E_V\,, \tag{4e}$$

$$A_2^+ A_3 + A_3^+ A_2 = -2(a_e^2 + v_e^2) v_Q^2 M_z^2 (M_V^2 - M_z^2) s^{3/2} D_1 D_2^2 D_3^2 E_V\,. \tag{4f}$$

Here

$a_e = 1/(2\sin 2\theta_W)$, $\quad D_1 = (s + M_H^2 - M_V^2)^{-1}$,

$v_e = (1 - 4\sin^2\theta_W)/(2\sin 2\theta_W)$, $\quad D_2 = |s - M_z^2 + i\Gamma_z M_z|^{-1}$,

$v_Q = (1 - 4|e_Q|\sin^2\theta_W)/(2\sin 2\theta_W)$; $\quad D_3 = |M_V^2 - M_z^2 + i\Gamma_z M_z|^{-1}$;

E_V is the energy of the meson V; and θ is the scattering angle.

Reaction (1) was studied in Ref. 6, where only the mechanism in Fig. 1c was taken into account. The results of our calculations show, however, that the mechanisms in Fig. 1, a and b, are no less important. To illustrate the situation, we show in Fig. 2 the relative contributions of the various terms $A_i^+ A_j$ to the total cross section

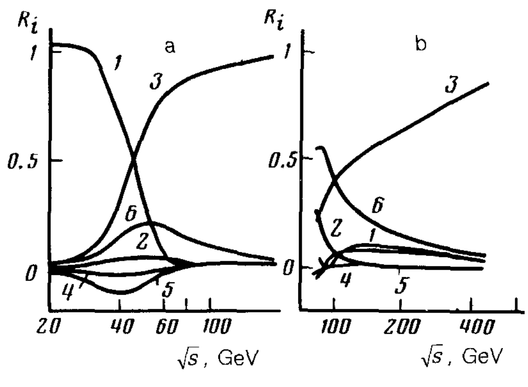

FIG. 2. Energy dependence of the relative contributions R_i from expressions (4a)–(4f) (curves 1–6, respectively) to the total cross section for reaction (1) at $M_H = 7$ GeV for the cases (a) $V = \gamma$ and (b) $V = T$, $M_T = 80$ GeV.

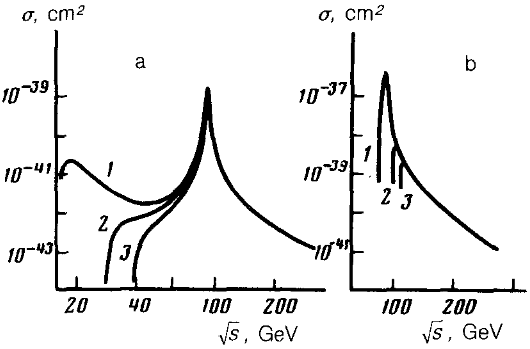

FIG. 3. Energy dependence of the total cross section for reaction (1) for the cases (a) $V=\gamma$ and (b) $V=T$, $M_T = 80$ GeV. 1,2,3—$M_H = 7,20$, and 30 GeV, respectively.

for reaction (1) as functions of $\sqrt{s}$ at $M_H = 7$ GeV for the cases $V=\gamma$ (Fig. 2a) and $V=T$ (Fig. 2b). It follows that we need to take into account all of the mechanisms discussed above. Figure 3 shows the $\sqrt{s}$ dependence of the cross sections for the cases $M_H = 7$, 20, and 30 GeV. The calculations show that, except near the threshold, the cross section is a weak function of the mass of the H^0 boson. We might also note that in the case[1)] $V=T$, the production of a Higgs particle near $\sqrt{s} = M_z$ occurs in an essentially isotropic manner in the c.m. frame.

In the course of the e^+e^- annihilation, there is the further possibility of the production of an H^0 boson jointly with excited states of quarkonium, which decay with a high probability through the channel $V+\ldots$. Because of the small energy released in such reactions, these processes are essentially indistinguishable from reaction (1), so that if the cross section is to be experimentally observable, we estimate it would have to be ~ 2 times larger than that calculated from (3) and (4).

Estimates of the cross sections for the background processes of the inclusive production of V mesons in e^+e^- annihilation indicate that there is essentially no background in the case $V=T$, and the same will be true in the case $V=\gamma$ if[7] $x = 2E_\gamma/\sqrt{s} \gtrsim 0.7$ in the case $V=J/\psi$, on the other hand, there is a strong background from the decays $B \to J/\psi + \ldots$.

We note in conclusion that the ratio of the cross section for the reaction $e^+e^- \to \gamma(T) + H^0$ to the total cross section for $e^+e^- \to$ hadrons is on the order of 10^{-7} (10^{-4}) at $M_V + M_H \lesssim \sqrt{s} \lesssim 2M_z$ and depends weakly on the mass of the H^0 boson. It thus appears realistic to search for the Higgs particle in such processes not only at the SLC and LEP installations, currently under construction, but also at the existing PEP and PETRA accelerators.

[1)] We are assuming that the known phenomenological relation $|\psi_V(0)|^2/M_V^2 = \text{const}$ holds even in the case of toponium, $T = (t\bar{t})$.

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