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Associated production of Higgs bosons and Z particles

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We estimate the cross section for Higgs-boson production via bremsstrahlung from intermediate vector bosons produced in pp and $\bar{p}p$ collisions.

All elementary-particle interactions—weak, strong, and electromagnetic—are believed to be mediated by gauge theories. The detection of neutral-current interactions, the discovery of charmed particles, and many successes of quantum chromodynamics lend credence to this view. The spontaneous breakdown of the weak-electromagnetic gauge group can be accomplished in only one known way: with Higgs fields. At least one of these fields must survive as a physical particle which is neither too heavy[1] nor too light.[2] Its discovery would give a decisive proof of the validity of this picture of symmetry breakdown.

The Higgs particle is elusive and plays a negligible role in low-energy phenomenology.[3] This is because it couples to particles according to their mass, and is only very weakly coupled to the quark and lepton constituents of ordinary matter. It may be produced with a small cross section in proton-proton collisions. The dominant "strong-interaction" mechanism[4] is gluon-gluon annihilation, a process which involves the virtual participation of all heavy-quark flavors. In this paper, we discuss another mechanism for Higgs-particle production which may be more relevant to an experimental search. We consider the associated production of an intermediate vector boson ($W^\pm$ or Z) and a Higgs particle (H). This mechanism is basically a weak-interaction effect proceeding by the virtual production of an intermediate vector boson by quark-antiquark annihilation ($q\bar{q}\to W$), followed by the "bremsstrahlung" emission of a Higgs particle ($W\to W+H$).

The association of a $W^\pm$ or Z with H provides a dramatic experimental signal for H production. A non-negligible fraction of produced $W^\pm$ or Z's will be accompanied by an H, whose decay scheme is by its very nature as bizarre as is kinematically permitted.

We consider the simplest spontaneous broken gauge theory[5] involving exactly one physical Higgs boson. Our calculation of the associated production of a Higgs boson proceeds through the parton model. The elementary cross section for the process

$$q+\bar{q}\to(W^\pm \text{ or } Z)+H \tag{1}$$

is convoluted with the appropriate quark- and antiquark-distribution functions and integrated over all appropriate final-state variables. We find

$$\sigma(\overset{(-)}{p}p\to W\to W+H+X)$$
$$=\frac{G_F{}^2M_W{}^4}{24\pi}\int_{\tau_0}^1 dx_1\int_{\tau_0/x_1}^1 dx_2F_w(x_1;x_2)\times f_W(x_1x_2s;M_W)\,, \tag{2}$$

where $\tau_0\equiv(M_W+M_H)^2/s$, $\sqrt{s}$ is the center-of-mass energy, M_W is the appropriate vector-boson mass, M_H is the Higgs-particle mass,

$$F_{W^+}(x_1,x_2)=\tfrac{1}{3}[u(x_1)\bar{d}(x_2)+(x_1\leftrightarrow x_2)]\,,$$
$$F_{W^-}(x_1,x_2)=\tfrac{1}{3}[\bar{u}(x_1)d(x_2)+(x_1\leftrightarrow x_2)]\,, \tag{3}$$
$$F_Z(x_1,x_2)=2\times\tfrac{1}{3}\{[u(x_1)\bar{u}(x_2)+(x_1\leftrightarrow x_2)](\tfrac{1}{4}-\tfrac{2}{3}x_W+\tfrac{8}{9}x_W{}^2)+[d(x_1)\bar{d}(x_2)+(x_1\leftrightarrow x_2)]\times(\tfrac{1}{4}-\tfrac{1}{3}x_W+\tfrac{4}{9}x_W{}^2)\}\,,$$

where $\overset{(-)}{q}(x)$ is the probability of finding a quark (antiquark) q with momentum fraction x in the proton (or antiproton) and $x_W\equiv\sin^2\theta_W$, with θ_W the weak mixing angle, $M_Z\cos\theta_W=M_{W^\pm}$,

$$f_W(y,M_W)=\frac{1}{y}\left[1-\frac{(M_W+M_H)^2}{y}\right]^{1/2}\left[1-\frac{(M_H-M_W)^2}{y}\right]^{1/2}\left\{\left[1-\frac{(M_W+M_H)^2}{y}\right]\left[1-\frac{(M_H-M_W)^2}{y}\right]+12\frac{M_W{}^2}{y}\right\}\left[\frac{1}{(1-M_W/y)^2}\right] \tag{4}$$

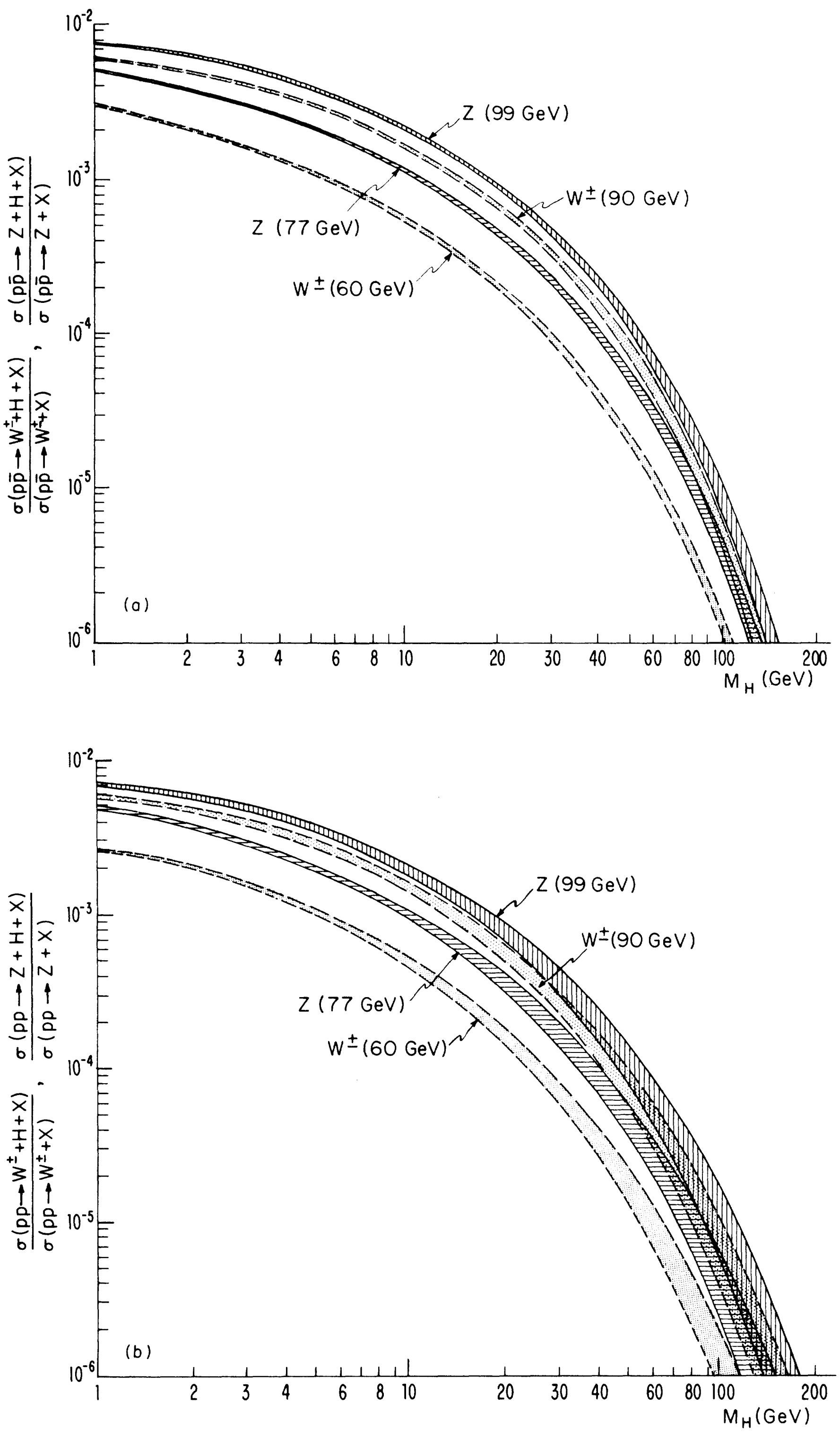

FIG. 1. Rate of associated production of the Higgs meson with $W^{\pm}$ or with Z, versus M_H, expressed as a fraction of total $W^{\pm}$ or Z production: (a) In $p\bar{p}$ collisions at $\sqrt{s}=540$ GeV. (b) In pp collisions at $\sqrt{s}=800$ GeV. Production with $W^{\pm}$ in indicated by the dotted bands, with Z indicated by slashes. Bands are shown for $M_W=60$ GeV ($M_Z=77$ GeV) [lower curves] and for $M_W=90$ GeV ($M_Z=99$ GeV) [upper curves]. Bands indicate the range of variation due to different quark-distribution-function parametrizations (Refs 6, 7, 8, and 9).

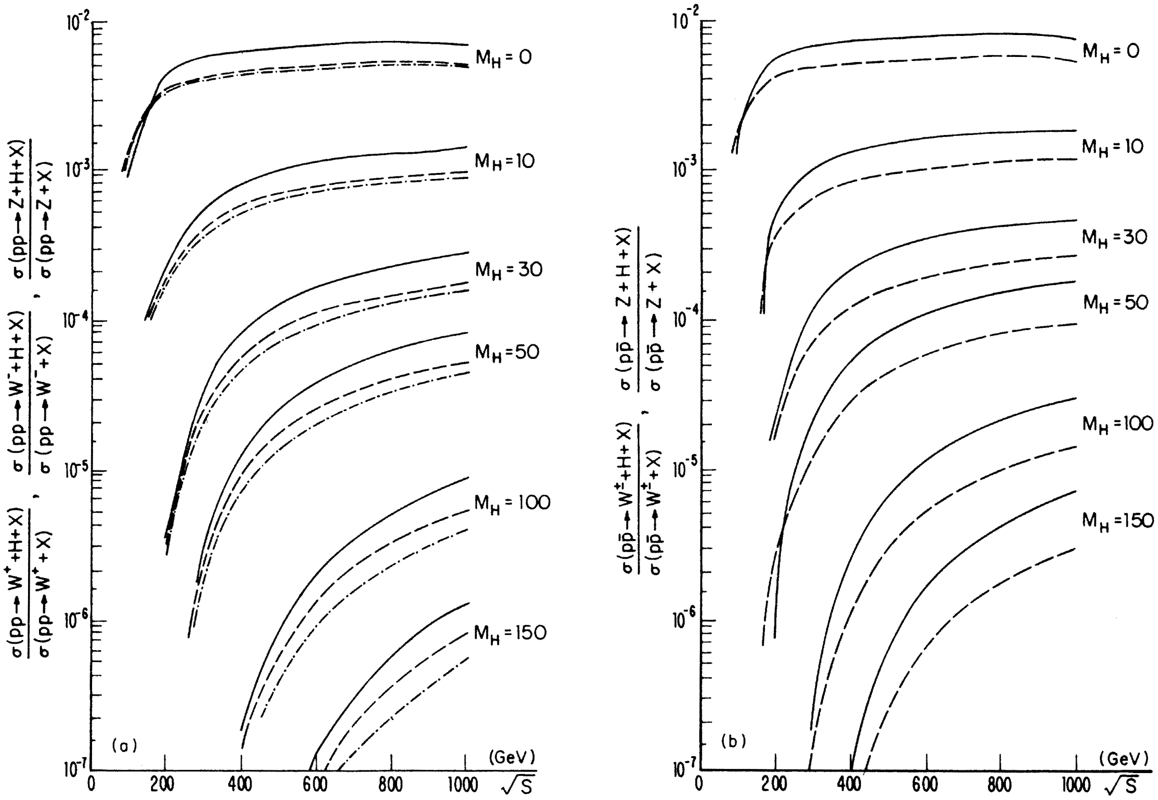

FIG. 2. Rate of associated production of the Higgs meson with W^+, W^-, or Z, versus energy $\sqrt{s}$, expressed as a fraction of total W^+, W^-, or Z production. (a) In $p\bar{p}$ collisions. (b) In pp collisions. Rates are shown for several M_H values, all using $M_W = 75$ GeV ($M_Z = 86.6$ GeV), corresponding to $x_W = 0.25$.

In our notation, $\sigma(p\overset{(-)}{p} \to W + X)$ is given by Eq. (2) with the replacement

$$f_W(x_1 x_2 s; M_W) \to \frac{24\sqrt{2}\pi^2}{G_F M_W^2}\,\delta(x_1 x_2 s - M_W^2)$$
$$\tau_0 \to \tau \equiv M_W^2/s\,. \tag{5}$$

Associated Higgs-particle production in $p\bar{p}$ and pp collisions, as a fraction of total weak-vector-boson production, is calculated for each of several different quark-distribution functions taken from the literature.[6-9] The results are indicated in Figs. 1(a) and 1(b), where bands represent the range of different parametrizations, the upper curves correspond to the choice $x_W = 0.17$ ($M_W = 90$ GeV, $M_Z = 99$ GeV); the lower curves to $x_W = 0.39$ ($M_W = 60$ GeV, $M_Z = 77$ GeV). For small Higgs-particle mass, up to about 10 GeV, the different parametrizations yield essentially equivalent results, agreeing within 5% or less. However, for increasing Higgs-particle mass the rate decreases significantly and so does the agreement between different parametrizations.

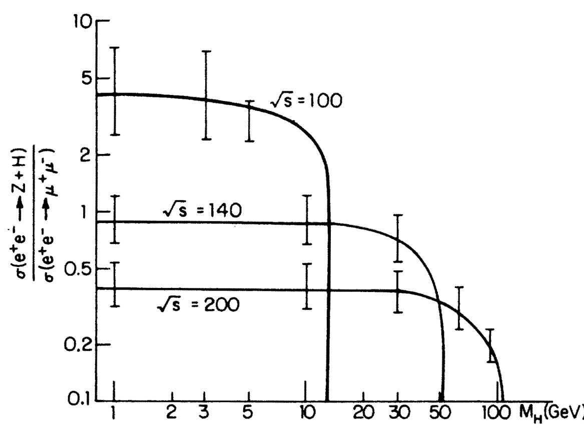

FIG. 3. Rate of associated production of the Higgs meson with Z, versus M_H, in e^+e^- collisions at various energies, expressed relative to the QED rate for $e^+e^- \to \mu^+\mu^-$. The curves shown are for $x_W = 0.25$ (corresponding to $M_W = 75$ GeV, $M_Z = 86.6$ GeV); the bars indicate the effect of a range of x_W values, $x_W = 0.22$ ($M_W = 80$ GeV, $M_Z = 90.6$ GeV) to $x_W = 0.29$ ($M_W = 70$ GeV, $M_Z = 82.9$ GeV).

Figures 2(a) and 2(b) show the dependence of the Higgs-particle production rate on energy for each of several Higgs-particle-mass values. Again, the rate falls strongly with increasing Higgs-particle mass. (Only one quark distribution was used here.[6]) The effect of different thresholds for different m_H is clearly seen.

It goes without saying that the cleanest laboratory test for associated Higgs-particle production is e^+e^- annihilation. The total cross section for the process

$$e^+e^- \to Z \to Z + H \tag{6}$$

is given by

$$\sigma(e^+e^- \to Z \to Z + H) = \frac{G_F{}^2 M_Z{}^4}{48\pi} f_Z(s, M_Z)(1 - 4x_W + 8x_W{}^2)\,, \tag{7}$$

where $f_Z(s, M_Z)$ is given by (4).

Figure 3 shows the rate of associated Higgs-particle production in e^+e^- experiments, relative to the QED rate for $e^+e^- \to \mu^+\mu^-$. At fixed energy this rate is essentially independent of M_H until close to threshold, when it drops rapidly. As the energy is increased, however, the relative rate decreases substantially.

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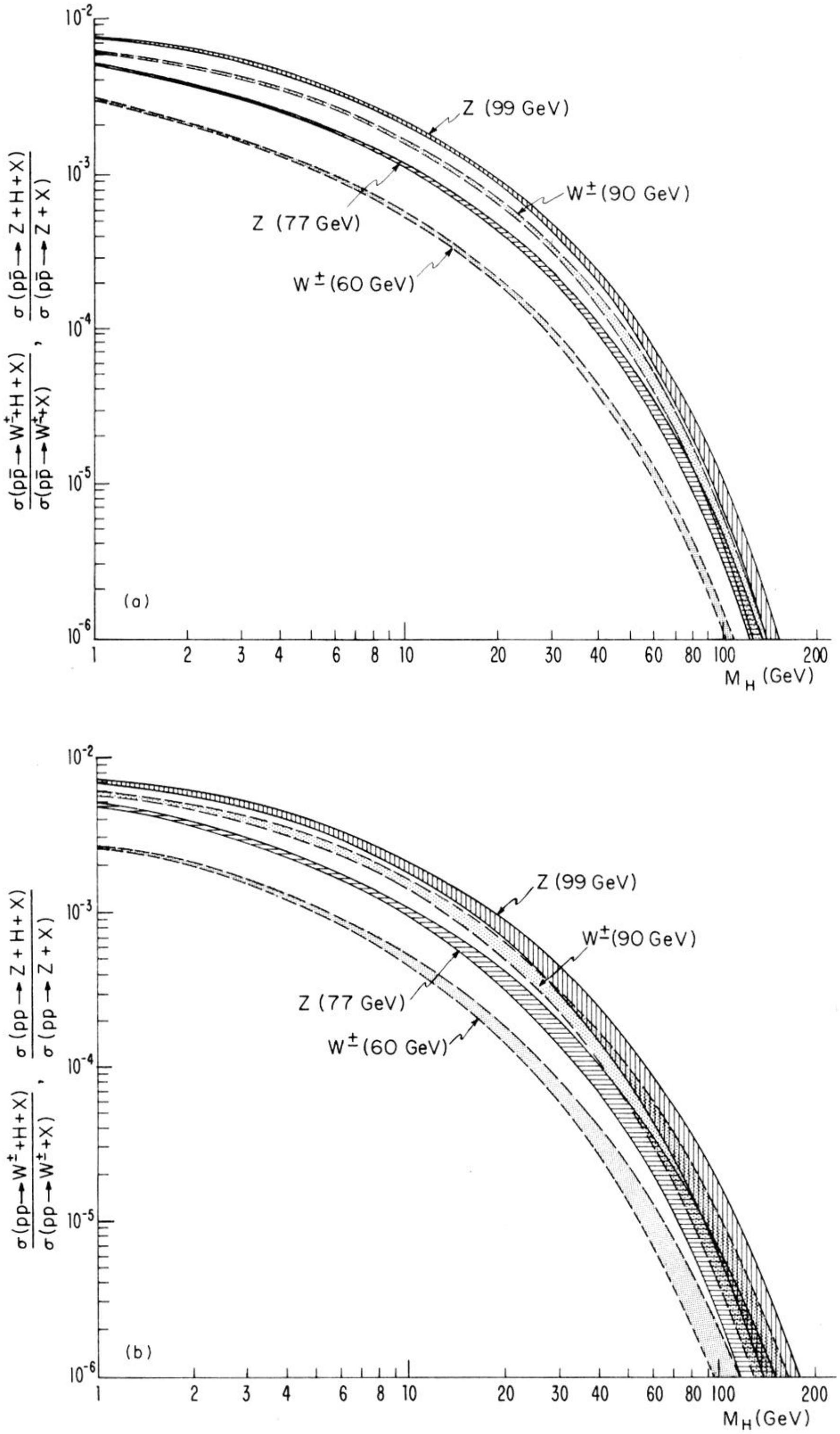

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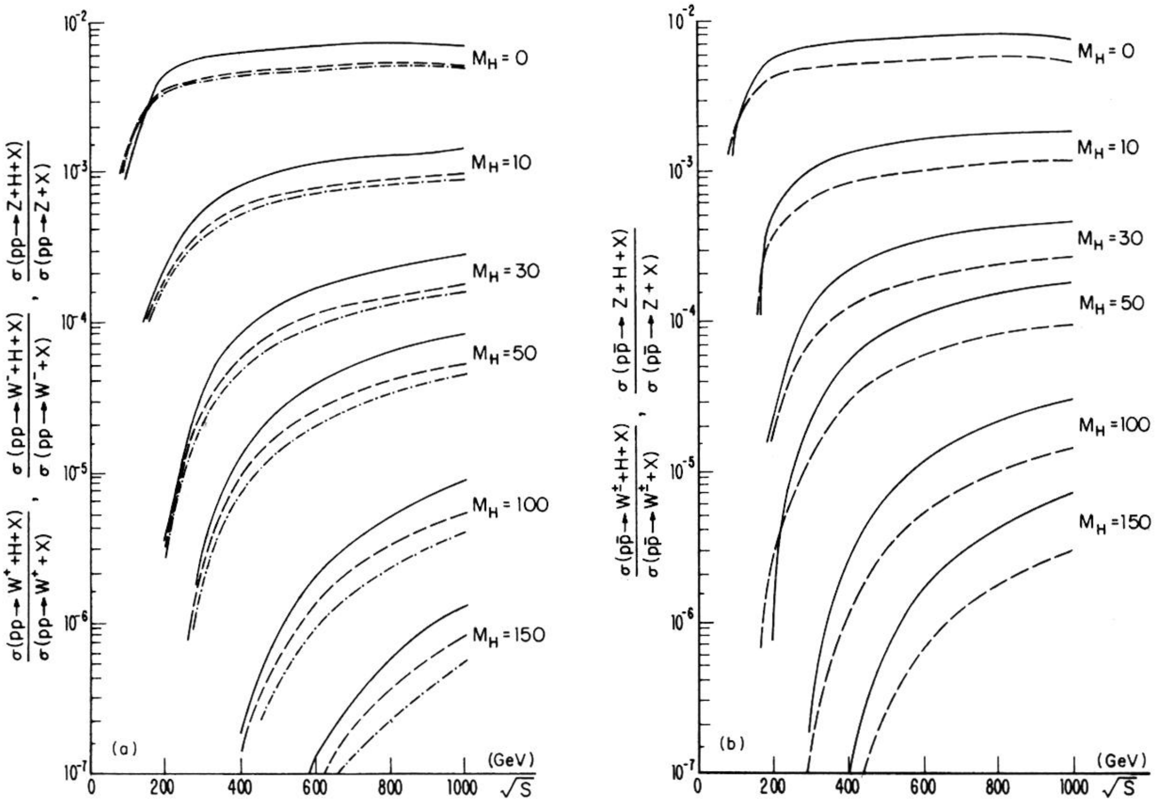

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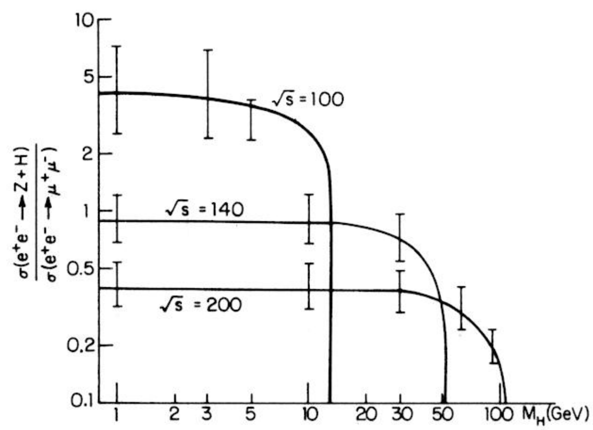

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