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BREMSSTRAHLUNG PRODUCTION OF HIGGS BOSONS IN e^+e^- COLLISIONS

K.J.F. Gaemers^{*)} and G.J. Gounaris⁺⁾

CERN -- Geneva

ABSTRACT

We discuss the production of Higgs bosons together with a heavy fermion pair in e^+e^- collisions. The ratio of the total cross-section for this process to the μ pair cross-section may vary between 10^{-6} and 10^{-4} at PETRA-PEP energies.

*) Address after 1 September: NIKHEF-H, Plantage
Muidergracht 4, Amsterdam C.

+) On leave from: University of Ioannina, Greece.

In all unified models¹⁾ of weak and electromagnetic interactions there are two basic ingredients which have defied experimental verification so far. In the first place there are, of course, the intermediate vector bosons. Secondly, there are the Higgs bosons, needed (among other things) to give a mass to the fermions (leptons - quarks) and intermediate vector bosons ($Z, W^\pm$). In order to generate the "correct" masses, the coupling of the Higgses to fermions must be proportional to the fermion mass, whereas for the intermediate vector bosons, it has to be proportional to their mass squared.

Several people have investigated ways in which the Higgs boson may be produced²⁾⁻⁵⁾, or shows up indirectly⁶⁾⁻⁸⁾ through other observable effects. In almost all proposals, one makes use of the fact that processes involving very heavy particles are more likely to produce the Higgs boson because of the above-mentioned proportionality of mass and coupling constant. An extensive review may be found in Ref. 2).

Here we consider in detail the reaction

$$e^+(p_+) + e^-(p_-) \rightarrow F(q_1) + \bar{F}(q_2) + H(q) . \quad (1)$$

We imagine that a pair of fermions $F\bar{F}$ is created through the usual one-photon mechanism whereafter one of these fermions emits a Higgs boson H . A different way in which the Higgs boson may be produced is through the production of a virtual Z which decays into a real Z and a Higgs particle. It is obvious that for this process to occur, one has at least to be able to produce the Z singly. The bremsstrahlung process we describe here has the advantage that heavy quarks and leptons are known to exist so that we can study directly their capability to radiate Higgs particles at presently available energies.

The total cross-section for reaction (1) can be expressed in terms of the following matrix element:

$$K_\mu = g_H \bar{u}(q_1) \left\{ \frac{\not{q}_1 + \not{q} + m}{(q_1 + q)^2 - m^2} \gamma_\mu + \gamma_\mu \frac{-\not{q}_2 - \not{q} + m}{(q_2 + q)^2 - m^2} \right\} v(q_2) \quad (2)$$

where g_H is the coupling constant of the Higgs boson (mass M) to the fermion (mass m). In the Weinberg-Salam model it is given by

$$g_H = m \sqrt{G_F \sqrt{2}} \quad (3)$$

with G_F the Fermi coupling constant. If we take a colourless fermion of unit charge, the cross-section for (1) is given by

$$\frac{d\sigma}{dE_1 dE_2} = \frac{\alpha^2}{12\pi s^2} \cdot \sum_{\text{spins}} -K_\mu K^\mu, \quad (4)$$

where E_1 and E_2 are the energies of F and $\bar{F}$, respectively, and $s = (p_+ + p_-)^2$. Introducing the scaling variables $x_i = 2E_i/\sqrt{s}$, ($i = 1, 2$), we get

$$\begin{aligned} \frac{d\sigma}{dx_1 dx_2} = & \frac{\alpha^2}{12\pi s} g_H^2 \left\{ \frac{(2-x_1-x_2)^2}{(1-x_1)(1-x_2)} + \right. \\ & + \frac{(2-x_1-x_2)^2}{(1-x_1)^2(1-x_2)^2} \cdot \frac{(s+2m^2)(4m^2-M^2)}{s^2} + \\ & \left. + \frac{2}{(1-x_1)(1-x_2)} \cdot \left[(M^2-4m^2)\left(x_1+x_2+\frac{M^2}{s}\right) + (8m^2-M^2) \right] / s \right\} \quad (5) \end{aligned}$$

We can obtain the energy spectrum of the produced Higgs boson by integrating (5) with respect to the variable $x_D = x_1 - x_2$, the result is

$$\begin{aligned} \frac{d\sigma}{dx_H} = & \frac{\alpha^2}{6\pi s} g_H^2 \left\{ x_H \ln \left| \frac{x_H+\beta}{x_H-\beta} \right| + \left[\frac{4}{x_H} \ln \left| \frac{x_H+\beta}{x_H-\beta} \right| + \frac{8\beta}{x_H^2-\beta^2} \right] \cdot \right. \\ & \cdot \frac{(s+2m^2)(4m^2-M^2)}{2s^2} + \frac{2}{x_H \cdot s} \ln \left| \frac{x_H+\beta}{x_H-\beta} \right| \cdot \\ & \left. \cdot \left[(M^2-4m^2) \cdot \left(2-x_H+\frac{M^2}{s}\right) + (8m^2-M^2) \right] \right\} \quad (6) \end{aligned}$$

Here $x_H = 2E_H/\sqrt{s}$ and β is the maximum value of $|x_1 - x_2|$ for the given value of x_H .

We will now present several results based on the formulae presented above. For present purposes we assume that g_H is given by (3). If other models predict a different value of g_H , one may, of course, rescale the results given below. In the table we give the total cross-sections for $F\bar{F}H$ and $F\bar{F}$ production, their ratio for a beam energy of 100 GeV and a range of values for m and M . From the numbers in this table one may deduce the cross-section for any other combination of energy and masses because the total cross-section for $F\bar{F}H$ has the form

$$\sigma = \frac{1}{s} \cdot (m^2 G_F) \cdot F\left(\frac{m^2}{s}, \frac{M^2}{s}\right) \quad (7)$$

where F is a dimensionless function of m^2/s and M^2/s .

We have assumed here that the fermion is colourless and has unit charge. These results apply directly to heavy leptons. For quarks one has to multiply the cross-section with $3Q^2$ (i.e., 1/3 or 4/3 depending on the flavour).

Now, in order to be more specific, we will look at the possibility for producing Higgs bosons at PETRA or PEP. At a beam energy of 20 GeV and fermion masses of 1.5, 1.8, 4.5 and 15 GeV we calculate the total cross-section ($F\bar{F}H$) as a function of the Higgs mass M , they are given in Fig. 1 (again for unit charge - no colour). From this figure one can see that with the heaviest fermions known at present, the production of Higgs bosons is small. If, however, a new flavour will be discovered with a mass of the order of 15 GeV or more, the prospects for finding the Higgs boson will be better. If we add the contributions of all known fermions (μ, u, d, s, c, τ, b) we find a total inclusive cross-section at 20 GeV of 2.1×10^{-40} cm² for $M = 5$ GeV, corresponding to $R = 4 \times 10^{-6}$.

In Fig. 2 we give the energy spectrum of the Higgs boson at a beam energy of 20 GeV and three different mass combinations. In Fig. 2a, we see clearly a bremsstrahlung spectrum, in Fig. 2b we see mainly the effects of phase space, whereas in Fig. 2c we have an intermediate situation. These structures may be useful as a test whether candidate events contain a Higgs particle. Notice that these will not change if all masses and energies are rescaled with the same factor.

In order to be able to detect a Higgs boson, one has to be able to look for a dramatic signature, since it follows from our calculations that the production rate will be very small. The decay properties of Higgs bosons have been studied in

detail in Ref. 2). From the results of this paper, it can be seen that it is not easy to give a unique signature since the decay properties of the Higgs depend very much on its mass.

If the Higgs is heavy enough, we may have typical four-jet events, where two jets come from the initial fermions and two jets come from the Higgs decaying into two quarks. In the same way we may also have typical four heavy-lepton events as well as two-jet - two-heavy-lepton ones, depending on the masses of the various quarks and leptons relative to the Higgs mass. If the Higgs is very light, one may notice it by the presence of $\mu^+\mu^-$ pairs with a low invariant mass accompanied by two hadron jets or two heavy leptons.

We conclude that the prospects of discovering the Higgs particle this way depend very much on the actual masses of the existing heavy quarks and leptons relative to the Higgs mass. These prospects are somewhat enhanced if heavy fermions of about ~ 20 GeV or more do exist, and if the Higgs mass is just above threshold for the appearance of a possible leptonic decay mode²⁾. On the other hand, if fermions much heavier than the presently discovered ones do not exist, then it seems rather unlikely that one will be able to find the Higgs particle without having the need to first produce the heavy intermediate boson. In this respect it should also be emphasized that even the discovery of the intermediate gauge boson will not automatically guarantee the discovery of the Higgs particle in its bremsstrahlung if it happens that it is too heavy.

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FIGURE CAPTIONS

Fig. 1 : Total cross-sections for $e^+e^- \rightarrow F\bar{F}H$ at $\sqrt{s} = 40$ GeV as a function of the Higgs mass, at fermion masses $m = 1.5, 1.8, 4.5$ and 15 GeV.

Fig. 2 : The Higgs energy spectrum at $\sqrt{s} = 40$ GeV for three mass combinations:

- a) $m = 1$ GeV $M = 1$ GeV
- b) $m = 15$ GeV $M = 1$ GeV
- c) $m = 0.5$ GeV $M = 0.1$ GeV

Table

$\sigma(e^+e^- \rightarrow F\bar{F}H)$ (cm²) and $R = \sigma(e^+e^- \rightarrow F\bar{F}H)/\sigma(e^+e^- \rightarrow F\bar{F})$ for various fermion and Higgs-particle masses at $\sqrt{s} = 200$ GeV

M (GeV)	m (GeV)	$\sigma(e^+e^- \rightarrow F\bar{F}) = 0.216 \times 10^{-35}$ cm ²										$\sigma(e^+e^- \rightarrow F\bar{F}) = 0.204 \times 10^{-35}$ cm ²
		5×10 ⁻⁴	0.1	0.5	1.0	1.5	1.8	4.5	15	20	60	
100	0.616×10 ⁻⁵⁰ 0.28 ×10 ⁻¹⁴	0.247×10 ⁻⁴⁵ 0.11 ×10 ⁻⁹	0.616×10 ⁻⁴⁴ 0.29 ×10 ⁻⁸	0.247×10 ⁻⁴³ 0.11 ×10 ⁻⁷	0.556×10 ⁻⁴³ 0.26 ×10 ⁻⁷	0.801×10 ⁻⁴³ 0.37 ×10 ⁻⁷	0.505×10 ⁻⁴² 0.23 ×10 ⁻⁶	0.591×10 ⁻⁴¹ 0.27 ×10 ⁻⁵	0.104×10 ⁻⁴⁰ 0.48 ×10 ⁻⁵			
30	0.102×10 ⁻⁴⁸ 0.47 ×10 ⁻¹³	0.407×10 ⁻⁴⁴ 0.19 ×10 ⁻⁸	0.102×10 ⁻⁴² 0.47 ×10 ⁻⁷	0.408×10 ⁻⁴² 0.19 ×10 ⁻⁶	0.920×10 ⁻⁴² 0.43 ×10 ⁻⁶	0.133×10 ⁻⁴¹ 0.62 ×10 ⁻⁶	0.851×10 ⁻³⁹ 0.39 ×10 ⁻⁵	0.116×10 ⁻³⁹ 0.54 ×10 ⁻⁴	0.230×10 ⁻³⁸ 0.11 ×10 ⁻³	0.223×10 ⁻³⁸ 0.11 ×10 ⁻²		
10	0.225×10 ⁻⁴⁸ 0.10 ×10 ⁻¹²	0.900×10 ⁻⁴⁴ 0.42 ×10 ⁻⁸	0.225×10 ⁻⁴² 0.10 ×10 ⁻⁶	0.906×10 ⁻⁴² 0.42 ×10 ⁻⁶	0.203×10 ⁻⁴¹ 0.95 ×10 ⁻⁶	0.297×10 ⁻⁴¹ 0.14 ×10 ⁻⁵	0.198×10 ⁻⁴⁰ 0.92 ×10 ⁻⁵	0.309×10 ⁻³⁹ 0.14 ×10 ⁻⁴	0.632×10 ⁻³⁹ 0.29 ×10 ⁻³	0.876×10 ⁻³⁸ 0.43 ×10 ⁻²		
3	0.362×10 ⁻⁴⁸ 0.17 ×10 ⁻¹²	0.145×10 ⁻⁴³ 0.67 ×10 ⁻⁸	0.365×10 ⁻⁴² 0.17 ×10 ⁻⁶	0.149×10 ⁻⁴¹ 0.69 ×10 ⁻⁶	0.344×10 ⁻⁴¹ 0.16 ×10 ⁻⁵	0.504×10 ⁻⁴¹ 0.23 ×10 ⁻⁵	0.370×10 ⁻⁴⁰ 0.17 ×10 ⁻⁴	0.632×10 ⁻³⁹ 0.29 ×10 ⁻³	0.128×10 ⁻³⁸ 0.59 ×10 ⁻²	0.183×10 ⁻³⁷ 0.90 ×10 ⁻²		
1	0.486×10 ⁻⁴⁸ 0.22 ×10 ⁻¹²	0.195×10 ⁻⁴³ 0.90 ×10 ⁻⁸	0.506×10 ⁻⁴² 0.23 ×10 ⁻⁶	0.216×10 ⁻⁴¹ 0.10 ×10 ⁻⁵	0.518×10 ⁻⁴¹ 0.24 ×10 ⁻⁵	0.773×10 ⁻⁴¹ 0.36 ×10 ⁻⁵	0.611×10 ⁻⁴⁰ 0.28 ×10 ⁻⁴	0.102×10 ⁻³⁸ 0.47 ×10 ⁻³	0.203×10 ⁻³⁸ 0.94 ×10 ⁻²	0.279×10 ⁻³⁷ 0.14 ×10 ⁻¹		
0.3	0.622×10 ⁻⁴⁸ 0.29 ×10 ⁻¹²	0.253×10 ⁻⁴³ 0.12 ×10 ⁻⁷	0.722×10 ⁻⁴² 0.33 ×10 ⁻⁶	0.329×10 ⁻⁴¹ 0.15 ×10 ⁻⁵	0.814×10 ⁻⁴¹ 0.38 ×10 ⁻⁵	0.122×10 ⁻⁴⁰ 0.56 ×10 ⁻⁵	0.967×10 ⁻⁴⁰ 0.45 ×10 ⁻⁴	0.150×10 ⁻³⁸ 0.69 ×10 ⁻³	0.293×10 ⁻³⁸ 0.13 ×10 ⁻²	0.394×10 ⁻³⁷ 0.19 ×10 ⁻¹		
0.1	0.746×10 ⁻⁴⁸ 0.34 ×10 ⁻¹²	0.320×10 ⁻⁴³ 0.15 ×10 ⁻⁷	0.103×10 ⁻⁴¹ 0.47 ×10 ⁻⁶	0.477×10 ⁻⁴¹ 0.22 ×10 ⁻⁵	0.117×10 ⁻⁴⁰ 0.54 ×10 ⁻⁵	0.176×10 ⁻⁴⁰ 0.81 ×10 ⁻⁵	0.134×10 ⁻³⁹ 0.62 ×10 ⁻⁴	0.200×10 ⁻³⁸ 0.92 ×10 ⁻³	0.389×10 ⁻³⁸ 0.18 ×10 ⁻²	0.491×10 ⁻³⁷ 0.24 ×10 ⁻¹		
3×10 ⁻²	0.882×10 ⁻⁴⁸ 0.41 ×10 ⁻¹²	0.433×10 ⁻⁴³ 0.20 ×10 ⁻⁷	0.147×10 ⁻⁴¹ 0.68 ×10 ⁻⁶	0.671×10 ⁻⁴¹ 0.31 ×10 ⁻⁵	0.162×10 ⁻⁴⁰ 0.75 ×10 ⁻⁵	0.241×10 ⁻⁴⁰ 0.11 ×10 ⁻⁴	0.181×10 ⁻³⁹ 0.84 ×10 ⁻⁴	0.252×10 ⁻³⁸ 0.12 ×10 ⁻³	0.468×10 ⁻³⁸ 0.22 ×10 ⁻²	0.545×10 ⁻³⁷ 0.27 ×10 ⁻¹		
1×10 ⁻²	0.101×10 ⁻⁴⁷ 0.47 ×10 ⁻¹²	0.581×10 ⁻⁴³ 0.27 ×10 ⁻⁷	0.193×10 ⁻⁴¹ 0.89 ×10 ⁻⁶	0.864×10 ⁻⁴¹ 0.40 ×10 ⁻⁵	0.211×10 ⁻⁴⁰ 0.97 ×10 ⁻⁵	0.315×10 ⁻⁴⁰ 0.15 ×10 ⁻⁴	0.225×10 ⁻³⁹ 0.10 ×10 ⁻³	0.294×10 ⁻³⁸ 0.14 ×10 ⁻²	0.555×10 ⁻³⁸ 0.26 ×10 ⁻²	0.693×10 ⁻³⁷ 0.34 ×10 ⁻¹

Fig. 1

Fig. 2