ON THE BEHAVIOUR OF THE HIGGS RESONANCE

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Summary

The shape of the Higgs particle produced in pp collisions at $\sqrt{s} = 40\,\text{TeV}$ is studied, and the mass spectrum is found to depend rather strongly on the underlying production mechanism.

Among the more exciting prospects for the SSC is the possibility of detecting the Higgs particle predicted by the standard model ($SU(2) \times U(1)$). Over the last few years much effort has been spent in studying the behaviour of this resonance, in particular its signal and possible backgrounds. The task is made harder by the fact that the Higgs mass is an unknown parameter; different mass regimes necessitate different techniques for making the Higgs visible, and some mass windows seem next to hopeless. However, granted that the Higgs can be detected, what will it look like?

There are three major processes contributing to the production of the standard model Higgs in pp collisions, viz. $q\bar{q}$, gg and intermediate vector boson fusion. The cross-sections for these processes have been calculated and are readily available in the literature;[1,2,3] to study the shape of the resonance, one merely needs to substitute a Breit-Wigner shape for the delta function in mass of the zero-width approximation, i.e.

$$\delta(m^2 - m_H^2)dm^2 \to \frac{m_H \Gamma_H}{\pi} \frac{dm^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}, \qquad (1)$$

to take the finite width into account. With this substitution, the formulae for the cross-sections become:

$$\sigma(q\bar{q} \to H^0) = \pi \int \frac{dm^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \int dy \times \frac{1}{48} \left(\frac{\alpha_{em}}{x_W}\right)^2 \left(\frac{m^2}{m_W^2}\right)^2 \sum_i \frac{m_i^2}{m^2} \left(1 - 4\frac{m_i^2}{m^2}\right)^{\frac{1}{2}} \times \frac{m^2}{s} f_i^{(1)}\left(\frac{m}{\sqrt{s}} e^y, m^2\right) f_{-i}^{(2)}\left(\frac{m}{\sqrt{s}} e^{-y}, m^2\right) \sum_f \gamma_f \qquad (2)$$

$$\sigma(gg \to H^0) = \pi \int \frac{dm^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \int dy \times \frac{1}{512} \left(\frac{\alpha_S(m^2)}{\pi} \frac{\alpha_{em}}{x_W}\right)^2 \left(\frac{m^2}{m_W^2}\right)^2 |\eta|^2 \times \frac{m^2}{s} f_g^{(1)}\left(\frac{m}{\sqrt{s}} e^y, m^2\right) f_g^{(2)}\left(\frac{m}{\sqrt{s}} e^{-y}, m^2\right) \sum_f \gamma_f \qquad (3)$$

$$\sigma(W^+W^- \to H^0) = \pi \int d\tau \int \frac{dm^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \int dy \times \frac{1}{128\pi^2} \left(\frac{\alpha_{em}}{x_W}\right)^4 \left(\frac{m^2}{m_W^2}\right)^2 \left[\left(1 + \frac{m^2}{\tau s}\right) \ln \frac{\tau s}{m^2} - 2\left(1 - \frac{m^2}{\tau s}\right)\right] \times \sum_{i,j} f_i^{(1)}\left(\sqrt{\tau} e^y, m_W^2\right) f_j^{(2)}\left(\sqrt{\tau} e^{-y}, m_W^2\right) \theta(-e_i e_j) \sum_f \gamma_f, \qquad (4)$$

where i and j run over all quark and antiquark indices. The formula for $\sigma(Z^0 Z^0 \to H^0)$ is similar to eq. (4); the only changes are the inclusion of a factor $(1 - x_W)^{-3}$ for the weak charge, the substitution of $(v_i^2 + a_i^2)(v_j^2 + a_j^2)/16$ for $\theta(-e_i e_j)$, and the replacement of m_W^2 with m_Z^2 as the Q^2 scale in the structure functions. The function $|\eta|^2$ that appears in eq. (3) is the result of the integration over the quark loop; its value can be found e.g. in ref. 2. The quantity γ_f, denoting a scaled decay width, is defined as

$$\gamma_f = \begin{cases} N_c \frac{m_f^2}{m^2} \left(1 - 4\frac{m_f^2}{m^2}\right)^{\frac{3}{2}}, & f = q, l \\ \frac{1}{2d_f} \left(1 - 4\frac{m_f^2}{m^2} + 12\frac{m_f^4}{m^4}\right) \left(1 - 4\frac{m_f^2}{m^2}\right)^{\frac{1}{2}}, & f = V \end{cases}. \qquad (5)$$

Here, N_c is the number of colours, and $d_f = 1\,(2)$ for $f = W^\pm\,(Z^0)$.

The respective importance of these processes depends on parameters like the Higgs mass and the top quark mass and has been studied extensively in the literature; in Figs. 1 and 2 the contributions for two typical values of the top quark mass are shown. (All cross-sections in this paper were calculated with PYTHIA 4.7[4] using structure functions obtained from the evolution program by Wu-Ki Tung[5] with EHLQ set 2[2] as input distributions.) It should be noted that the cross-sections for $q\bar{q} \to H^0$ and $VV \to H^0$ are overestimates. For the first case this is true when m_q is comparable to or larger than m_{H^0}, and then a more reliable estimate is obtained from a calculation of the underlying gluon subprocess $gg \to q\bar{q}H^0$;[6] for the second case the overestimate is due to the effective W approximation, and the cross-section should probably be scaled down by a factor of 2.[7]

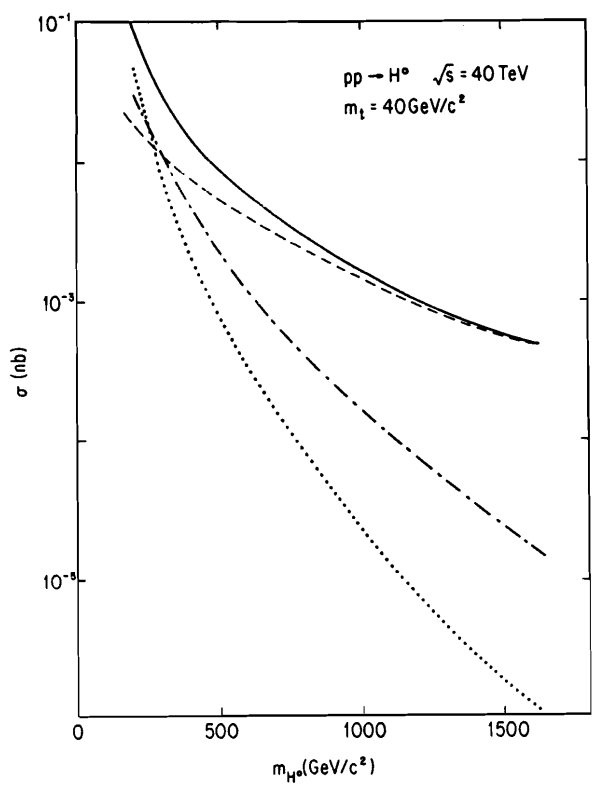

Fig. 1. The contributions to the cross-section for Higgs production at the SSC. Top quark mass is 40 GeV/c².
Full line: sum of all processes;
dashed line: $W^+ + W^-$, $Z^0 + Z^0 \to H^0$;
dash-dotted line: $q + \bar{q} \to H^0$;
dotted line: $g + g \to H^0$.

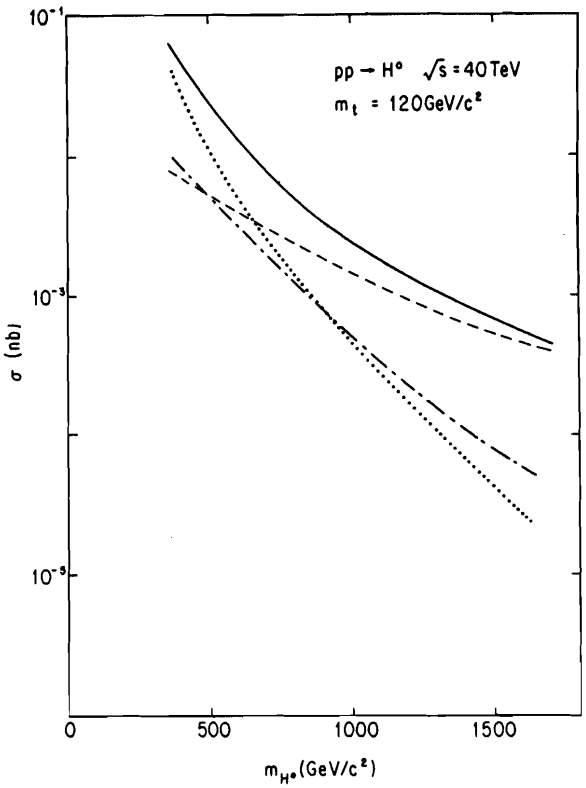

Fig. 2. Same as Fig. 1, but top quark mass is 120 GeV/c².

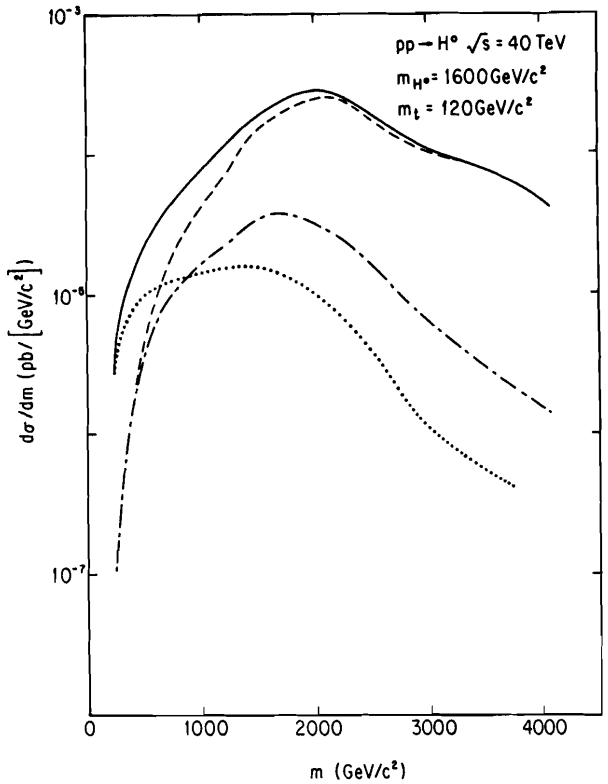

Fig. 4. Same as Fig. 3, but Higgs nominal mass is 1600 GeV/c².

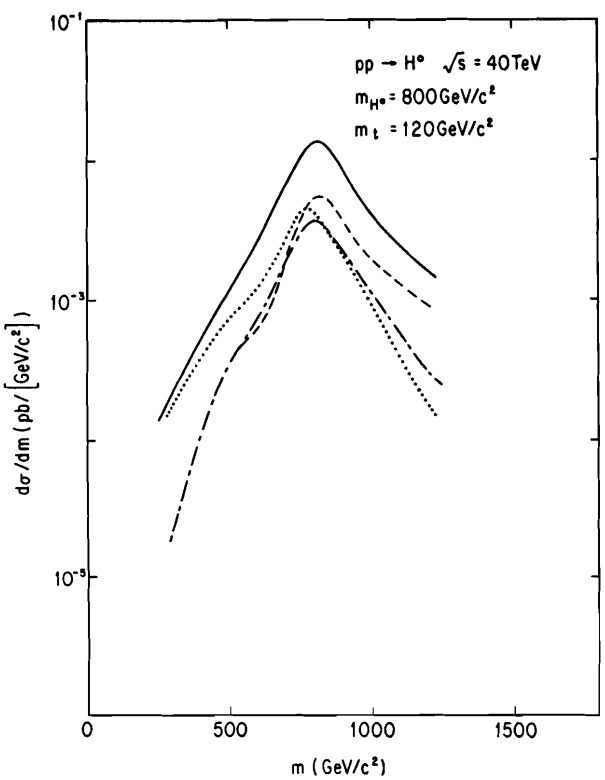

Fig. 3. The mass spectrum of Higgs particles produced at the SSC. Nominal Higgs mass is 800 GeV/c², top quark mass is 120 GeV/c².
Full line: sum of all processes;
dashed line: $W^+ + W^-$, $Z^0 + Z^0 \to H^0$;
dash-dotted line: $q + \bar{q} \to H^0$;
dotted line: $g + g \to H^0$.

A topic of more concern here is the actual shape of the Higgs. In Figs. 3 and 4 the mass spectrum of a Higgs with nominal mass of 800 and 1600 GeV/c², respectively, is shown (assuming a top quark mass of 120 GeV/c²). The interesting features, particularly noticeable for the case of $m_H = 1600\,\mathrm{GeV/c^2}$, are the absence of a peak in the mass distribution for the process $gg \to H^0$, and the peaking at a *higher* value than the nominal mass of the distribution for the process $VV \to H^0$. Both of these effects are kinematic in nature. The first is easily understood on the grounds that the gluon structure functions are very steeply falling; the peak disappears in the general sharp fall-off of the cross-section. The second effect comes about because of a curious interplay between the Breit-Wigner shape and the other mass dependent term in the cross-section for $VV \to H^0$; the total dependence on m^2 in this process is given by

$$\frac{m^4}{(m^2 - m_H^2)^2 + m_H^2\Gamma_H^2}\left[\left(1 + \frac{m^2}{\tau s}\right)\ln\frac{\tau s}{m^2} - 2\left(1 - \frac{m^2}{\tau s}\right)\right]. \tag{6}$$

With the definitions $\epsilon = m^2/\tau s$, $\epsilon_H = m_H^2/\tau s$ and $\gamma_H = m_H\Gamma_H/\tau s$, the resulting function $f(\epsilon)$ governing the mass shape becomes

$$f(\epsilon) = \frac{\epsilon^2[-(1+\epsilon)\ln\epsilon - 2(1-\epsilon)]}{(\epsilon - \epsilon_H)^2 + \gamma_H^2}, \tag{7}$$

the maximum of which depends on the values of ϵ_H and γ_H (see Fig. 5). The general trend is that for $\gamma_H \approx \epsilon_H$ there is a maximum around $\epsilon \approx 0.3$, relatively independent of the actual value of ϵ_H. A Higgs of mass 800 GeV/c² has a width $\Gamma_H \approx 240\,\mathrm{GeV/c^2}$, i.e. $\gamma_H \approx 0.3\epsilon_H$, while for a Higgs of mass 1600 GeV/c² the mass and width are comparable, so that $\gamma_H \approx \epsilon_H$. From Fig. 5 it can be seen, e.g., that for a fixed value of τ, such that $\tau s > 0.3m_H^2$, it becomes favourable to produce the Higgs with a higher mass than the nominal one, and as a result the peak of the distribution is shifted towards

higher mass values. The Higgs is consequently seen to be a chameleon-like object; depending on its surroundings, i.e. its mode of production, its actual appearance will change rather drastically.

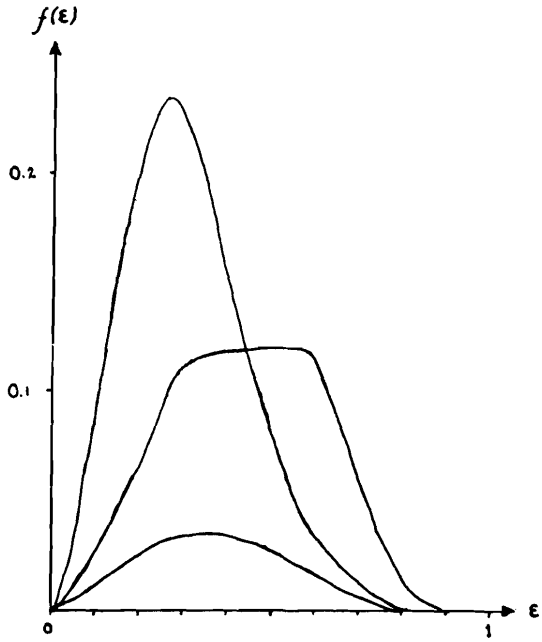

Fig. 5. The function $f(\epsilon)$ governing the mass shape. From top to bottom, the curves are for $\epsilon_H = \gamma_H = 0.25$; $\epsilon_H = 0.6$, $\gamma_H = 0.2$; $\epsilon_H = \gamma_H = 0.6$.

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