ASSOCIATE HIGGS BOSON AND HEAVY QUARK PRODUCTION IN HADRON COLLIDERS

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ABSTRACT

We calculated the production cross-section for the associated production of a Higgs boson with t and $\bar{t}$ quarks in hadron colliders. For Higgs masses in the 100 GeV/c^2 range, this is about 10 pb with experimental cuts implemented.

The success of the Glashow-Weinberg-Salam model of SU(2)×U(1) electroweak interactions has now focussed our attention on the mechanism of symmetry breaking. The standard model uses an elementary scalar doublet and a physical neutral Higgs boson, H^0, remains after symmetry breaking. Finding this 0^+ boson is undoubtedly of paramount importance to the future development of physics.

In the standard model the elementary scalar fields perform dual functions. It breaks the SU(2)×U(1) symmetry and thus gives masses to the gauge bosons. Furthermore, it also provides tree level masses to the fermions via Yukawa terms. This second function is not necessary for the breaking of gauge symmetry, but is a very economical way of giving fermion masses. Gauge invariance forbids fermion bare mass terms in the standard model. We shall call the above the standard Higgs boson, H^0, and its coupling to fermions is given by

$$Y_{Hff} = 2^{3/4} m_f G_F^{\frac{1}{2}} \tag{1}$$

where m_f is the mass of the fermion. This has the advantage that the Yukawa couplings are related to observed fermion masses but the price we pay is that the fermion masses are not calculable in the theory$^{1)}$. We emphasize that this is the result of the scalar field playing both roles.

The coupling in Eq. (1) dictates that the Higgs boson has substantial coupling only to the heaviest fermion such as the t-quark in the minimal 6-quark world. In addition, the Higgs couplings to gauge bosons $W^\pm$ and Z^0 are also large. Explicitly, they are proportional to the masses of the gauge bosons:

$$H^0W^+W^- \rightarrow igM_W g_{\mu\nu} \tag{2a}$$

$$H^0Z\,Z \rightarrow \frac{ig}{\cos\theta_W} M_Z\, g_{\mu\nu} \tag{2b}$$

This result derives from SU(2)×U(1) breaking and is independent of whether the H^0 provides masses for fermions. Equations (1) and (2) determine how we can produce the H^0 in sufficient quantities.

Although the couplings of H^0 to fermions and gauge bosons are determined, its mass, m_H, is largely unknown. Vacuum stability arguments give a lower bound$^{2)}$ of about 4 GeV/c^2 and perturbative unitarity gives a loose upper bound$^{3)}$

of a few TeV/c^2. Due to the property that the H^0 likes to couple to the heaviest particles around, different production mechanisms are optimal for different ranges of m_H. We find that the following reactions are appropriate for the ranges of m_H
indicated.:

(Ia)$^{4)}$ $Z^0 \rightarrow e^+e^-H^0$ or $\mu^+\mu^-H^0$

(Ib)$^{5)}$ $T(t\bar{t}) \rightarrow H^0\gamma$ for $10 < m_H < 60$ GeV/c^2

(IIa)$^{6)}$ $e^+e^- \rightarrow Z^0H^0$

(IIb)$^{7)}$ $p\overset{(-)}{p} \rightarrow H^0 + F + \bar{F} + X$ for $50 < m_H < 150$ GeV/c^2

where $F(\bar{F})$ denotes a hadron (conjugate) containing a heavy quark and

(IIIa)$^{8)}$ $p\overset{(-)}{p} \rightarrow H^0 + X$

for $150 < m_H < 0$ (TeV/c^2)

(IIIB)$^{6)}$ $p\overset{(-)}{p} \rightarrow H^0 + W^{\pm} + X$
$H^0 + Z^0 + X$

In principle, the Z^0 and toponium decays of (Ia,b) are the cleanest for finding Higgs below their masses. We have also conservatively estimated that for $m_H > 60$ GeV/c^2, the rates for Z^0 and toponium of mass 70 GeV decaying into H^0 will be too small to be useful. The associate production of Z^0H^0 in e^+e^- annihilation will have to await LEP II.

Here we report the first results of associated H^0 and heavy flavour hadron productions in hadron collisions$^{7)}$. The elementary parton subprocesses for associated production consist of two mechanisms: (i) one through the annihilation of the light quark q_j and the antiquark $\bar{q}_j$ into heavy quarks f_k and $\bar{f}_\ell$ plus a Higgs boson:

$$q_i + \bar{q}_j \rightarrow f_k + \bar{f}_\ell + H^0 \qquad (3a)$$

and (ii) the fusion of two gluons producing two heavy quarks and a H^0 via

$$g_a + g_b \rightarrow f_k + \bar{f}_\ell + H^0 \qquad (3b)$$

The first mechanism involves the annihilation of the light quarks and antiquarks and favours $p\bar{p}$ collisions. This mechanism is important only when $\sqrt{s} \lesssim 500$ GeV. The second one makes essential use of the large gluon content in the proton and/or antiproton; hence there is no difference between pp or $p\bar{p}$ colliders. The gluon-gluon mechanism is important at very high energies. This is in agreement with previous results on heavy quark productions[9]. We use the usual QCD-parton assumptions to calculate the production rate of H^0 and heavy quarks. For the quark-antiquark annihilation process, the cross-section is given by

$$\sigma(s,m_H,m_f) = \int_{x_{min}}^{1} dx_1 \int_{x_{2min}}^{1} dx_2\ \sigma(s,m_H,m_f)\left[u(x_1)\bar{u}(x_2) + d(x_1)\bar{d}(x_2)\right] \qquad (4)$$

with $s = x_1 x_2 s$ and x_1 and x_2 are respectively the fractions of momenta carried by the light quarks in their parent hadrons. σ is the cross-section for the subprocess calculated from the diagram of Fig. 2a. Numerical integrations are done by the Monte Carlo method. This is not the dominant process for high energies. Typically, it gives a production cross-section 10pb for associated production of H^0 and heavy quarks.

The large cross-section is given by the gluon fusion mechanism. The calculation proceeds as in the quark annihilation with quark distributions replaced by gluon distributions. In the Table, we give the production cross-section in picobarns for H^0 and t and $\bar{t}$ quarks at collider energies. The mass of the t quark we assume to be 35 GeV/c^2 and p is the beam energy of the pp or $p\bar{p}$ collider.

M_H(GeV/c^2) p(TeV)	50	100	200
1	1.5	0.176	2×10^{-2}
5	1000	180	26
10	7×10^{4}	1150	1012

We emphasize that the cross-section has theoretical uncertainty due to that in the small x behaviour of the gluon distribution function. We have used a scaling

$xG(x) = 3(1-x)^5$. A steeper distribution would give a larger production rate at very high collider energies*). This has also been done in our calculations.

We have also calculated various $p_\perp$ distributions. For example, for $m_H = 30$ GeV/c^2 and $m_f = 35$ GeV/c^2 the peak of the $p_\perp$ distribution of the H^0 is above 12 GeV for $\sqrt{s} = 2$ TeV. For details see Ref. 7).

Finally, we discuss the signal for the reaction. Since the H^0 will preferably decay into the heaviest quark available, if $m_H \lesssim 2m_t$, then we would get a four t-quark final state; i.e.,

$$\begin{array}{l} pp(\bar{p}) \to H^0 + t + \bar{t} \\ \qquad\quad \llcorner\!\!\!\longrightarrow\ t + \bar{t} \end{array}$$

If we tag on the semileptonic decay of the t which is about 10%, then we would get four large $p_\perp$ leptons plus four associated b-quark jets. This would be an unusual signature. However, the price one pays would be the small event rate. Using the Table we get:

$$\sigma(p\bar{p} \to H^0 t\bar{t})\ BR^4(t \to \ell\nu b) \simeq 0.1 \text{ to } 10^{-3} \text{ pb}$$

for $p\bar{p}$ in the LEP tunnel and SSC.

If one does not use large $p_\perp$ leptons from t-decay but the non-leptonic jet from the t-quark, then one would have four-jet final states. At the tevatron collider, this would be 1.5 pb for $m_H = 50$ GeV/c^2 and $m_t = 35$ GeV/c^2, and about 10 pb for $m_H = 10$ and $m_t = 35$ GeV/c^2. The production of H^0 with b-quarks is less kinematically suppressed both at the CERN $p\bar{p}$ collider and the tevatron collider. The four-jet cross-sections due to H^0 plus two b-quarks are 0.8 pb for SPS and 60 pb for the tevatron for $m_H = 20$ GeV/c^2.

We conclude that H^0 production is perhaps the most difficult when m_H is in the range 50 to 200 GeV/c^2. Associated production of H^0 with heavy quarks provides a handle and the final states contain spectacular signatures such as multijets and/or several large p_T leptons. Details are now being pursued.

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*) We have not imposed any cuts. If one uses a cut of greater than 100 GeV^2 on the invariant mass of the pair of quarks or that of one quark and Higgs boson, the cross-section decreases by about two orders of magnitude.

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