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ASSOCIATED PRODUCTION OF HEAVY HIGGS BOSON WITH TOP QUARKS

Z. KUNSZT* **

Institute for Theoretical Physics, University of Bern, Bern, Switzerland

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Associated production of a heavy Higgs boson ($m_{\mathrm{H}} > 100$ GeV) with top quarks at Juratron energies is studied. It is natural to differentiate between the "light" ($2m_{\mathrm{t}} < m_{\mathrm{H}} < 2m_{\mathrm{W}}$) and "heavy" ($m_{\mathrm{H}} > 2m_{\mathrm{W}}$) Higgs search. It is assumed that the mass value of the top quark is in the interval $m_{\mathrm{t}} \approx 30$–$80$ GeV. m_{W} is the W-boson mass. If $m_{\mathrm{H}} < 2m_{\mathrm{W}}$ a dangerous background is given by the QCD production of four top quarks. We have calculated the cross sections for both the Higgs production and the background reaction. The disappointing result found is that the background is overwhelmingly large. However the Higgs search in this mass region is not hopeless. The associated production of the Higgs boson with a W-boson may have a clear experimental signature, its background given by the reaction $\mathrm{p} + \bar{\mathrm{p}} \to \mathrm{W} + \mathrm{t} + \bar{\mathrm{t}}$ might be suppressed. The difficulty with this mechanism is that the rate is rather low. If $m_{\mathrm{H}} > 2m_{\mathrm{W}}$ the background is different and its contribution is expected to be small. The associated production of a Higgs boson with a pair of top quarks might be a useful method in the Higgs search in this case.

1. Introduction

One of the most remarkable results of the CERN $\mathrm{p}\bar{\mathrm{p}}$ collider has been the demonstration of the viability of the $\mathrm{p}\bar{\mathrm{p}}$ collider scheme [1]. Its operation with high luminosity has led to the very clean discovery of the W- and Z-bosons [2–3] and the verification of the existence of large-p_{T} hadronic jets [4–5]. However the discovery of the W- and Z-bosons with mass values as predicted by the theory [6] still does not constitute proof that spontaneously broken gauge theories have something to do with reality. The two most characteristic phenomena of such theories, the self-coupling of vector bosons and the existence of the Higgs particle, can not yet be tested. In principle the self-coupling of vector bosons can be measured at the Tevatron and at LEP II although at energies close to the two-gauge boson production threshold it may be difficult to separate the contribution of the triple ZWW gauge coupling from the contributions of the quark (neutrino) exchange.

* Supported by Schweizerischer Nationalfonds.
** Permanent address: Central Research Institute for Physics of the Hungarian Academy of Sciences, Budapest, Hungary.

An important goal at Juratron [7] (or SSC) will be to provide a decisive experimental test of these fundamental phenomena of the elektroweak theory.

The experimental difficulty in the Higgs boson [8–9] search is that it gives very weak effects at low and moderate energies. Its mass value can vary from ≈ 15 MeV up to ≈ 500 GeV without affecting the agreement of the theory with available experimental data. The upper limit is obtained by observing [10–11] that the self-coupling of the Higgs field and of the longitudinally polarized vector bosons increases quadratically with the Higgs mass. Consequently if $m_H > 600$ GeV large corrections [12] are induced to the lowest-order relations between the mass parameters of the $SU(2)_L \times U(1)_Y$ theory.

The huge range allowed for the Higgs mass at present will be reduced significantly by future experiments at LEP. Toponium ($m \approx 80$ GeV?) and Z-boson spectroscopy could test the existence of Higgs bosons with mass values up to 80 GeV, while at LEP II the reaction $e^+e^- \to Z + H$ could give an observable signal up to $m_H \approx 100$ GeV [13]. The Higgs search at Juratron (or SSC) will become significant if $m_H > 100$ GeV [14]*.

The decay properties of the Higgs boson depends strongly on its mass value. It appears natural to differentiate between the "light" Higgs search with $2m_t < m_H < 2m_W$ and the "heavy" Higgs search with $m_H > 2m_W$.

Heavy Higgs bosons can be produced at a relatively large rate via the reactions (see fig. 1)

$$\begin{aligned} p + \bar{p} &\to g^* + g^* + \text{partons} \\ &\to \text{H (via heavy quark loop)} + \text{hadrons [15]}, \end{aligned} \tag{1a}$$

$$p + \bar{p} \to W + H + \text{hadrons [16]}, \tag{1b}$$

$$p + \bar{p} \to t + \bar{t} + H + \text{hadrons [17,26]}, \tag{1c}$$

$$p + \bar{p} \to W^* + W^* + \text{partons} \to H + \text{hadrons [18]}. \tag{1d}$$

If $m_H < 2m_W$ the dominant decay mode of the Higgs boson is $H \to t + \bar{t}$, and therefore the most important backgrounds are given by reactions where the top quarks are produced via QCD mechanisms (see fig. 2). Therefore one must consider

* The importance of exploring the mass range $2m_t < m_H < 2m_W$ in the heavy Higgs search was emphasized in this paper.

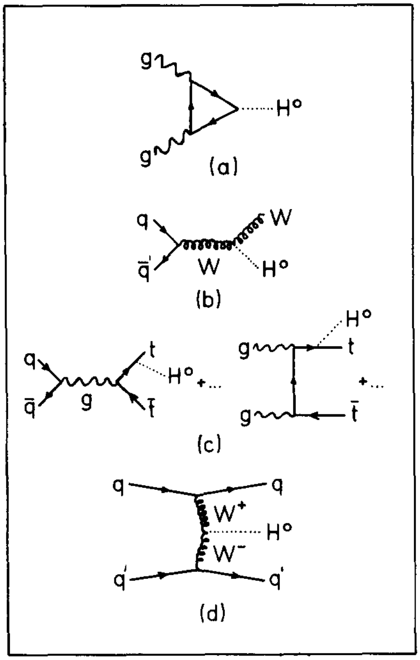


Fig. 1. (a) Production of a Higgs boson from the fusion of a pair of gluons. (b) Production of a Higgs boson via bremsstrahlung from a W-boson. (c) Examples of Feynman diagrams describing the production of a Higgs boson via bremsstrahlung from a top quark. (d) Production of a Higgs boson from the fusion of a pair of virtual gauge bosons.

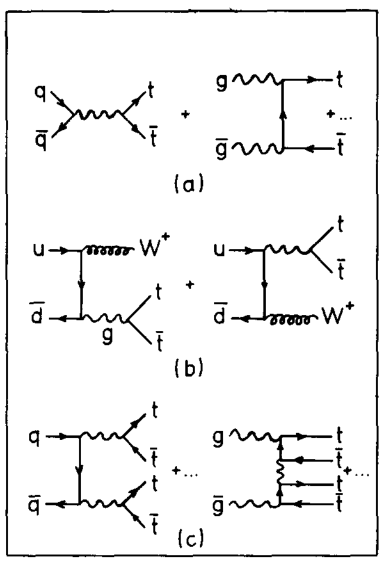


Fig. 2. (a) Examples of Feynman diagrams describing the production of a pair of top quarks. (b) Feynman diagrams describing the production of a pair of top-antitop quarks in association with gauge bosons. (c) Examples of Feynman diagrams describing the production of two pairs of top-antitop quarks. The total number of diagrams for $q\bar{q}$ annihilation and gg fusion is 14 and 72, respectively. If identical quark effects are neglected they are reduced to 7 and 36.

the production processes as follows:

$$p + \bar{p} \to t + \bar{t} + \text{hadrons [19]}^{\star}, \tag{2a}$$

$$p + \bar{p} \to W + t + \bar{t} + \text{hadrons}, \tag{2b}$$

$$p + \bar{p} \to t + \bar{t} + t + \bar{t} + \text{hadrons}. \tag{2c}$$

The first and fourth Higgs production mechanisms (1a) and (1d) are higher order in the weak coupling constant than the top pair production in QCD eq. (2a), and therefore the reaction (2a) gives an overwhelming background. In the case of the second and third mechanism it is hard to guess the relative size of the background. An order of magnitude estimate is obtained by the ratio of the coupling constants:

$$O\left(\frac{\alpha m_t^2}{4\alpha_s^2 \sin^2\theta_w m_W^2}\right) \simeq O(1).$$

Therefore only an explicit calculation can decide whether the background problem can be tamed or not. We have performed all the necessary cross-section calculations and the quantitative comparison of the rates of the Higgs production mechanism (1b), (1c), with the rates of the background reactions equations (2b), (2c). This constitutes the main result of this paper.

If $m_H > 2m_W$ the dominant decay of the Higgs boson is into W- or Z-pairs. Therefore the background to the production mechanisms of eqs. (1a)–(1d) is given by the reactions (see fig. 3)

$$p + \bar{p} \to V + \bar{V} + \text{hadrons [20]}, \tag{3a}$$

$$p + \bar{p} \to V' + V + \bar{V} + \text{hadrons}, \tag{3b}$$

$$p + \bar{p} \to t + \bar{t} + V + \bar{V} + \text{hadrons}, \tag{3c}$$

where V denotes the W- or Z-boson. The cross section of the gluon fusion mechanism is lower in the gauge coupling but is higher order in the strong coupling constant in comparison with the cross section of the background reaction (3a). The order of magnitude estimate for the cross section ratio is

$$O(\alpha_s^2/\alpha) \simeq O(1).$$

The exact calculation has revealed a larger rate for the background. However, the resonant peak of the Higgs production might rise above the background.

In case of the Higgs production in association with a W-boson or a pair of top quarks the background reactions have cross sections of higher order in the gauge

* In [19] Kunszt et al. give the calculation of the cross section of the heavy quark pair production with hard gluon bremsstrahlung.

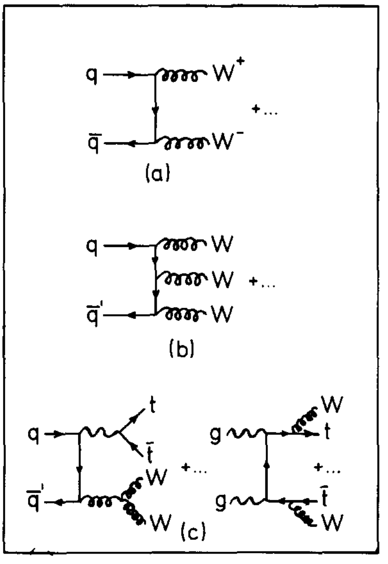


Fig. 3. (a) An example of a Feynman diagram describing the production of a pair of W-bosons. (b) An example of a Feynman diagram describing the production of three W-bosons. (c) Examples of Feynman diagrams describing the production of a pair of W-bosons in association with a top quark-antitop quark pair.

coupling constant and therefore they are expected to give negligible contribution. The fourth mechanism is very special [18]. At large Higgs mass the longitudinally polarized W-bosons have an enhanced coupling to the Higgs boson and therefore the relative order of the cross sections of this reaction when it is compared with the cross section of W- or Z-pair production is $O(\alpha_w(m_H/m_W)^2)$.

It is $\simeq O(1)$ if $m_H > 6\ M_W$. This is a manifestation of the increasing self-interaction of the longitudinally polarized gauge bosons and the physical Higgs boson mentioned above. The production mechanisms (1a), (1b) and (1d) of very heavy Higgs bosons have been discussed in great detail recently by Eichten et al. [21] and so we have studied only the production mechanism (1c).

In sect. 2 we briefly describe the cross-section calculations performed for reactions (1c), (3b) and (3c). In sect. 3 we present the results obtained for the associated production of Higgs production and for the QCD production of four top quarks. Sect. 4 contains a short discussion of the experimental implications of the results. Finally the appendix contains a few cross-section formulae.

2. Cross-section calculations

We shall consider only the associated production of the Higgs boson with a W-boson and with a pair of top quarks (eqs. (1b) and (1c)). The corresponding background reactions (eqs. (2b), (2c) and (3b), (3c)) will also be studied. Cross sections of the production mechanism when the Higgs boson is produced in association with a W- or Z-boson were first calculated by Glashow et al. [16]. Recently Eichten et al. [21, 22] carried out a detailed study at high energies ($\sqrt{s} = 5$–40 TeV) with large Higgs boson mass values. If $2m_t < m_H < 2m_W$ the background reaction to W + H production is the associated production of W with a pair of top quarks. The relevant parton subprocess

$$u + \bar{d} \to W^+ + t + \bar{t} \tag{4}$$

is described by two Feynman diagrams only (see fig. 2b). The invariant matrix element can be easily calculated, the relatively simple expression obtained is listed in the appendix. If $m_H > 2m_W$ the background reaction is given by the triple gauge boson production (see fig. 3b). However it is expected to be harmless since it is higher order in the weak interaction coupling constants $\alpha_w = \alpha/\sin^2\theta_w$ (where θ_w is the Weinberg angle).

The cross-section calculations for the production of the standard Higgs boson in association with a heavy quark pair (eq. (1c)) are more involved. In this case there are two parton subprocesses* (see fig. 1c):

$$q + \bar{q} \to t + \bar{t} + H, \tag{5a}$$

$$g + g \to t + \bar{t} + H. \tag{5b}$$

The cross sections of these parton reactions have been calculated in two independent papers [17, 26]. However they did not publish the long expression obtained for the gluon fusion subprocess (5b). I have repeated the calculation for both reactions. The expression obtained for the invariant matrix element of $q\bar{q}$ annihilation, eq. (5a), agrees with those given in ref. [26]. The dominant subprocess is the gluon fusion of eq. (5b). In the Feynman gauge this reaction is described by ten Feynman diagrams when two diagrams describe the ghost contributions. I have calculated the invariant matrix element square with REDUCE. The expression obtained is about two pages long so that it is not reproduced here. The analytic expression has been checked by a completely numerical program. Gauge invariance can be tested easily also with the numerical program.

If $2m_t < m_H < 2m_W$ the background of the QCD production of four top quarks (eq. (2c) and fig. 2c) is described again by two parton subprocesses, quark-antiquark annihilation and gluon-gluon fusion:

$$q + \bar{q} \to t + \bar{t} + t + \bar{t}, \tag{6a}$$

$$g + g \to t + \bar{t} + t + \bar{t}. \tag{6b}$$

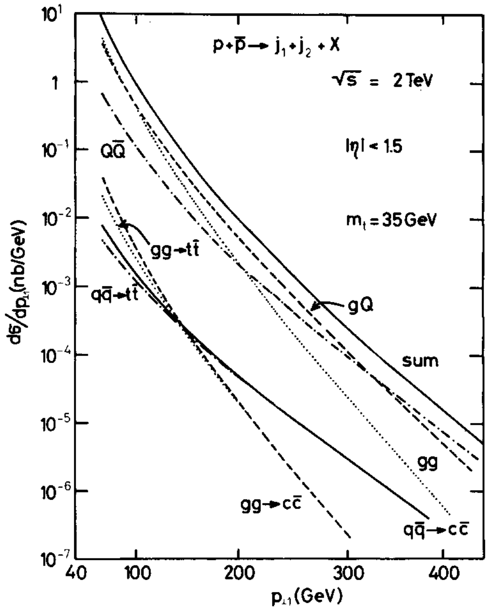
* I assume that the intrinsic top component of the proton wave function is negligible.

In all the parton reactions studied so far identical particle effects have proved to be small ($\lesssim 1$–2%) as far as only total cross sections, transverse momentum, invariant mass and other distributions have been considered, such that averaging has been made over the jet flavours. I assume that in our case as well the identical particle effects remain small, i.e. the two top quarks in the final state have been treated as if they could be distinguished. With this approximation the number of Feynman diagrams describing reactions (6a) and (6b) are reduced by a factor of two. Still the calculation is rather lengthy: there are seven Feynman diagrams for $q\bar{q}$ annihilation and (in the physical gauge) 36 Feynman diagrams for gluon-gluon fusion (see fig. 2c). In the first case again the invariant matrix element square has been calculated with the help of REDUCE, and the algebraic expression has been checked again with a completely numerical program. The analytic formula is about 2 pages long so I do not give it here. In the case of gluon-gluon fusion the invariant matrix element has been calculated only by a completely numerical program. Here it seems appropriate to remark that the complexity of the numerical program grows only linearly with the number of Feynman diagrams, while the complexity of the algebraic calculation grows quadratically. In the case of finite quark masses the double poles in the denominators do not cancel by zeros in the nominators as in the massless case. Consequently one expects that the analytic expression is very lengthy. The numerical calculation can also be used to check gauge invariance and known properties of helicity amplitudes very easily. However, the evaluation of the invariant matrix element square requires non-negligible computer time. In our case the calculation of the weight for one event (in the Monte Carlo evaluation of phase space integrals) required 0.3 sec CPU time on the IBM 3081. I did not make special effort to increase the speed of the program.

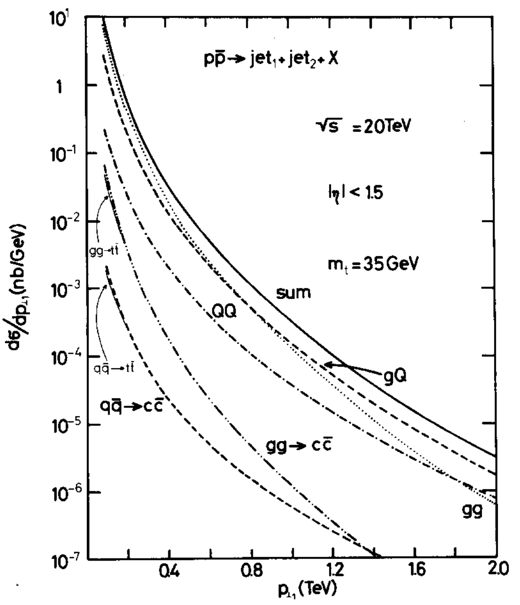
If $m_H > 2m_W$ the background is given by the production of one pair of top quarks and one pair of gauge bosons (see eq. (3c) and fig. 3c). Again this background is higher order in the gauge coupling constant therefore it is expected to be small.

In order to obtain physical cross sections the parton subprocesses have to be folded with quark and gluon wave functions. I have used the parametrization of ref. [23] with $\Lambda = 0.4$ GeV. Their parametrization describes all deep inelastic scattering data and it has given an acceptable description of the jet data at $\sqrt{s} = 540$ GeV. The main ambiguity is given by the scale of the Q^2-evolution of the wave function and the QCD running coupling constant $\alpha_s(Q^2)$. In the calculations where heavy quarks and Higgs or gauge bosons have been involved I always used $Q = 1/2E_{\text{parton}}$ where E_{parton} denotes the centre-of-mass energy of the relevant parton subprocess. For large-p_T jet production the normalization $Q = 1/2p_{T\max}$ has been used.

In order to illustrate the huge rate of jet production and the rate of two top quarks production with large transverse momentum, in figs. 4a and 4b two jet production cross sections are plotted as a function of the transverse momenta of the jets at two different energies $\sqrt{s} = 2$ TeV and $\sqrt{s} = 20$ TeV in the pseudorapidity interval



(a)



(b)

Fig. 4. (a) Transverse momentum distribution of one of the jets for two-jet production in proton-antiproton collisions at $\sqrt{s} = 2$ TeV in the pseudorapidity interval $|\eta| < 1.5$. The contribution gQ denotes the contribution of all parton subprocesses when one of the initial partons is a gluon. Large-p_T production of heavy quark flavours is also indicated. For the mass value of the top quark $m_t = 35$ GeV has been used. (b) The same as fig. 4a but with $\sqrt{s} = 20$ TeV.

$|\eta| < 1.5$, with $m_t = 35$ GeV for the top quark mass. As we can see in figs. 4a and 4b for transverse momenta $p_T < 150$ GeV finite top mass effects become negligible. It is also remarkable that the heavy flavour production rate with large p_T is about three orders of magnitude smaller than the production rate of gluon or light quark jets at the same transverse momenta.

3. Differential and integrated cross sections

In order to understand the relative contributions of the associated production of the Higgs boson with a pair of top quarks and the background of the QCD production of four top quarks I have computed differential and integrated cross sections for these reactions at various values of the mass parameters and the incoming energy. I have also made a comparison with the contributions of the other three mechanisms of heavy Higgs production discussed in sect. 1 (see eqs. (1a), (1b) and (1d)).

Let us consider first the production of Higgs bosons if $m_H > 2m_W$. In figs. 5a and 5b I plotted total cross-section values of the reactions equations (1a)–(1d) as a function of the Higgs boson mass m_H for proton-proton collisions at energy $\sqrt{s} = 40$ TeV with top quark mass $m_t = 30$ GeV (fig. 5a) and $m_t = 70$ GeV (fig. 5b). Only the result for $t + \bar{t} + H$ production is new. The curves for the other production mechanisms have been calculated recently by Eichten et al. [21, 22]. At lower values of m_H, $gg \to H^0$ is dominant while at higher values $W^*W^* \to H$ has the largest rate. The special reason of the large rate in the latter case has been discussed in the introduction. The gluon fusion mechanism $gg \to H^0$ has a large background due to the continuum production of W^+W^- (or Z^0Z^0), and therefore very good energy resolution in the electron channel is needed to observe the resonant signal*. At moderate value of the Higgs mass the associated production with a top quark pair competes in rate with the gluon fusion $gg \to H^0$ with a crossover at $m_H \simeq 0.9$ TeV. If the top quark mass is higher the cross sections of these reactions increase but the increase is larger in case of $gg \to H^0$. The experimental signature is much better with a top quark pair in the final state. Therefore the mechanism given by equation (1c) is expected to be a useful method in the heavy Higgs search. In fig. 6 I have plotted the cross sections for eqs. (1a) and (1c) by requiring that in the final state the pseudo-rapidities of the heavy particles (W, Z, top) must be less than 1.5. The background of the continuum production of W-pairs and of W-pairs in association with top quark pairs is also indicated. The cross section for the latter has not been calculated; the curve with the question mark represents only an educated guess. The cleanest experimental signal is given by WH or ZH production. (Triple gauge boson

* One of the two W's can decay into jets while the other into a lepton pair $\ell\nu$. If the missing momentum of the neutrino and the momenta of the electron and the jets are measured with high resolution the sharp resonant peak will rise above the background of the continuum production. (I thank J. Ellis for emphasizing this point to me.)

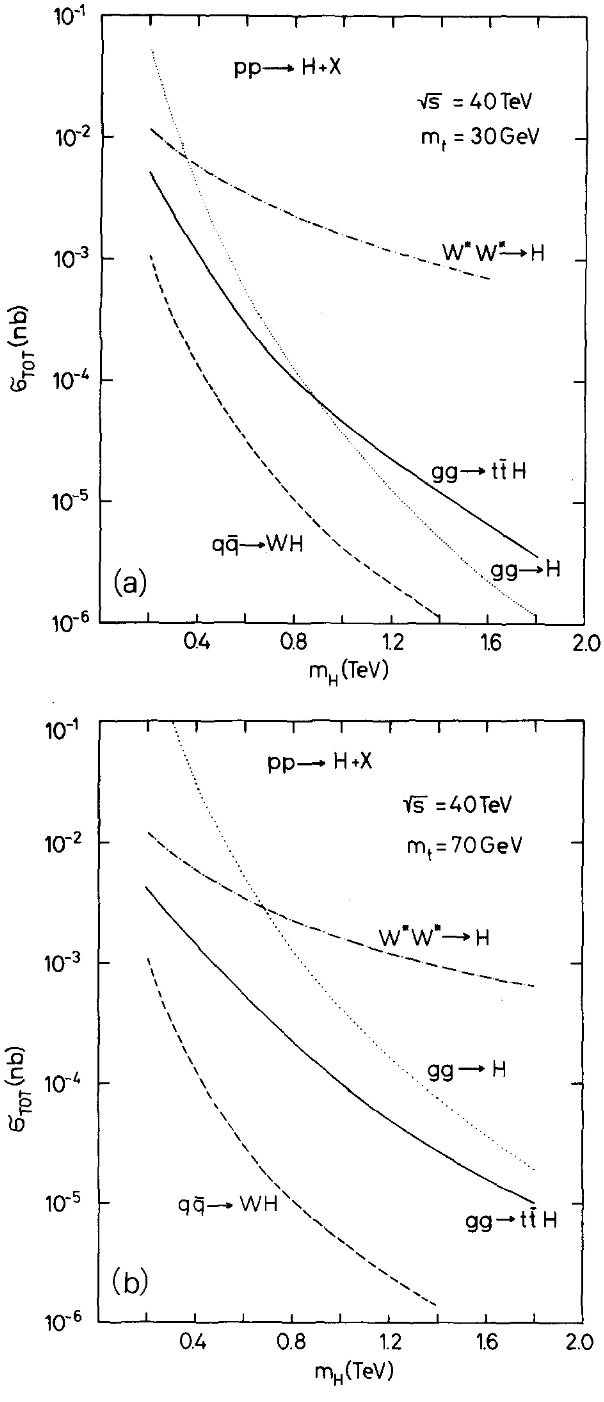


Fig. 5. (a) Total cross-section values for pp collision at $\sqrt{s} = 40$ GeV and with top mass $m_t = 30$ GeV as a function of the Higgs mass for the four production mechanisms given in fig. 1a–d. The curves for the reactions $W^*W^* \to H$, $gg \to H$ and $q\bar{q} \to \overline{W}H$ have been calculated by Eichten et al. [21]. (b) The same as fig. 5a but with $m_t = 70$ GeV.

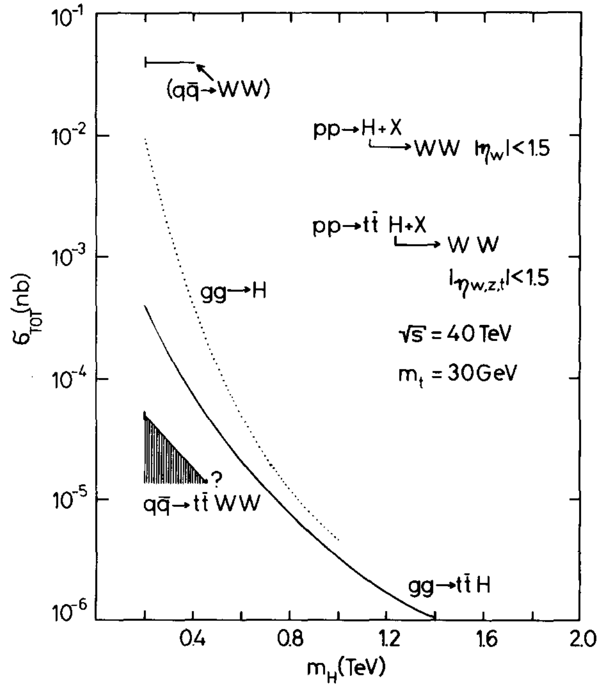


Fig. 6. Cross-section values via the two-gluon fusion mechanism of eqs. (1a) and (1c) in proton-proton collisions at $\sqrt{s}=40$ TeV and with $m_t=30$ GeV as a function of the Higgs boson mass. It was required that the rapidity values of the W-, Z- bosons and top quarks in the final state be less than 1.5. The value of the W-pair production cross section [21] (with the same rapidity cut) is also given while the curve with the question mark indicates the tentative value of the cross section of the associated production of one W-boson pair, one top quark pair.

production is higher order in the gauge coupling.) Unfortunately the cross section is the smallest in this case (≈ 0.1–0.01 pb), and so to have high luminosity is vital.

If the mass range $2m_t < m_H < 2m_W$ is considered the background problem becomes more severe. The continuum production of top quark pairs (eqs. (2a), (2b), (2c), figs. 2a, 2b, 2c) via the QCD mechanism has a formidably large rate. A simple comparison of cross-section values obtained in refs. [15] and [19] reveals immediately that for gg → H the background is overwhelming (its rate is more than two orders of magnitude larger than the signal). Unfortunately the background problem has been found severe also in case of reaction equation (1c). In fig. 7 total cross-section values are plotted for the Higgs production mechanism equation (1c) and for the background reaction equation (2c) as a function of the incoming energy with mass values $m_t = 35$ GeV and $m_H = 120$ GeV. As m_t is increased the background decreases. This is illustrated by plotting cross-section values for the reaction equation (2c) also with top quark mass $m_t = 70$ GeV. As we can see in fig. 7 the background is two orders of magnitude larger. One may try to suppress the contribution of the

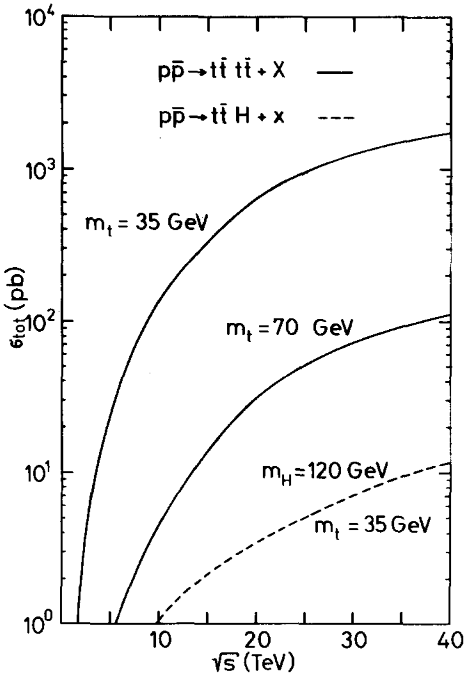


Fig. 7. Total cross-section values for the associated production of the Higgs bosons with a pair of top-antitop quarks and for the QCD production of two top quark pairs at $m_t = 35$ GeV and $m_H = 120$ GeV. In the case of four-top-quark production cross-section values are also given with $m_t = 70$ GeV.

background with suitable cuts in the invariant mass, rapidity, transverse momentum, etc. by exploiting the resonant signal of the Higgs production. Unfortunately it turned out that most of the distributions are rather similar (see figs. 8a, 8b, 9a, 9b, 10a, 10b). The main contribution to the integrated cross section of four-top-quark production comes from the threshold region, furthermore with four top quarks in the final state we have twelve different possible pairings of the top pairs for invariant mass distributions. Therefore the significance of the resonance effect is strongly diluted. With ≈ 5–10% resolution in the invariant mass the background is reduced only by a factor of ≈ 2. This is illustrated in fig. 10b where the invariant mass distribution of a $t\bar{t}$ pair is plotted. It is strongly peaked at mass values around the Higgs mass ≈ 100–130 GeV. The striking similarity of the rapidity distributions (figs. 8a and 8b), transverse momentum distributions (figs. 9a, 9b), is also rather disappointing. My conclusion is that if $2m_t < m_H < 2m_W$ it appears impossible to find a clear signal of the Higgs bosons via the associated production with a top quark pair.

In order to compare my calculation with the result obtained earlier in refs. [17, 26] I have evaluated differential cross sections also at Tevatron energies $\sqrt{s} = 2$ TeV. I have assumed the following values for the mass parameters: $m_H = 30$ GeV, $m_t = 35$

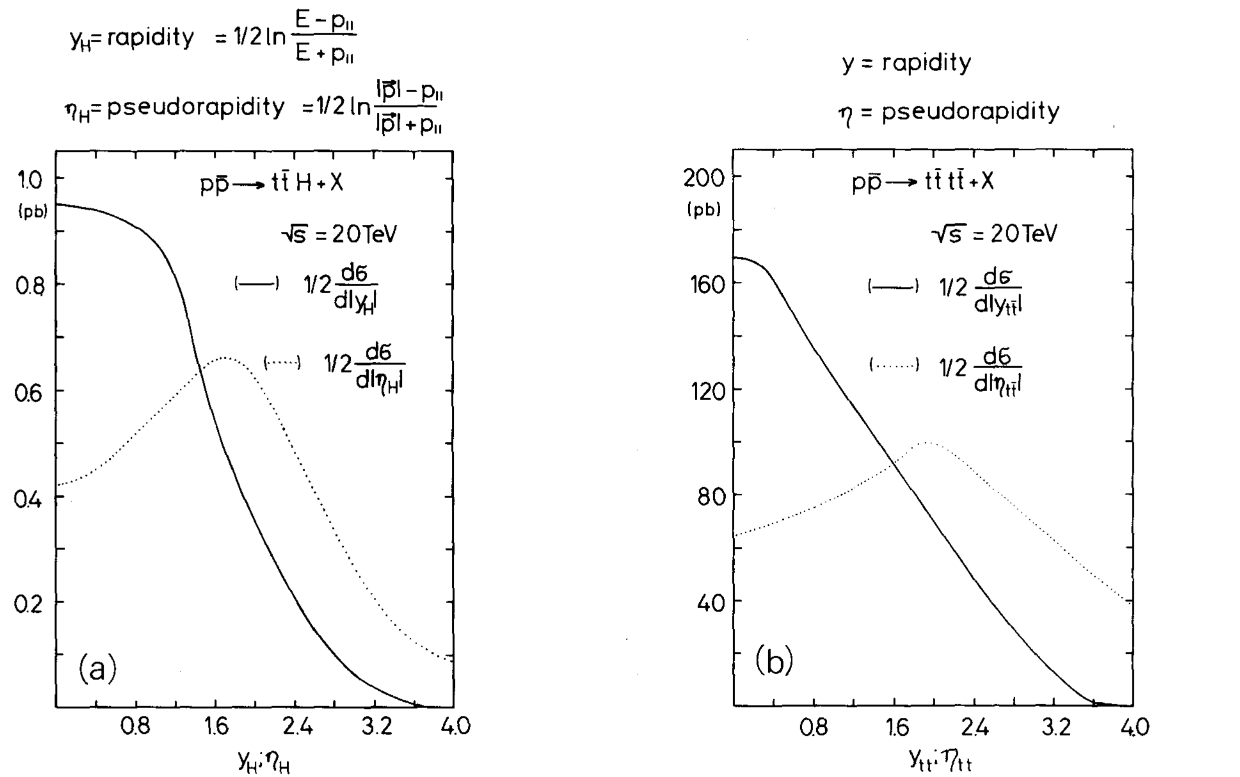


Fig. 8. (a) Rapidity and pseudorapidity distributions of the Higgs boson produced in association with a pair of top quarks in proton-antiproton collisions at $\sqrt{s}=20$ TeV with $m_H=120$ GeV and $m_t=35$ GeV. (b) Rapidity and pseudorapidity distributions of a pair of top quarks produced in the reaction $p\bar{p} \to t\bar{t}t\bar{t}$ + hadrons at $\sqrt{s}=20$ TeV energy and with $m_t=35$ GeV. An averaging is made over all possible choice of pairs of the final partons.

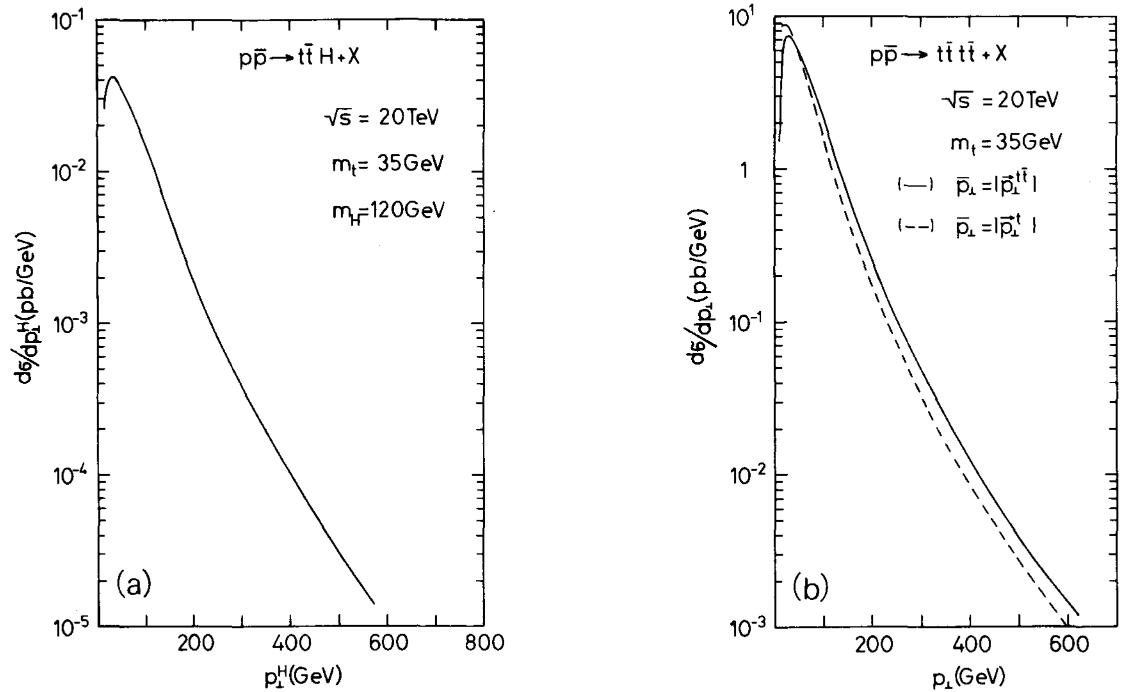


Fig. 9. (a) Transverse momentum distribution of the Higgs boson produced in association with a pair of top quarks at $\sqrt{s}$ = 120 GeV, $m_t = 35$ GeV and $m_H = 120$ GeV. (b) Transverse momentum distributions of one of the top quarks and of one pair of top quarks produced in the reaction $p + \bar{p} \to t + \bar{t} + t + \bar{t} +$ hadrons at $\sqrt{s}$ = 20 TeV energy with $m_t = 35$ GeV.

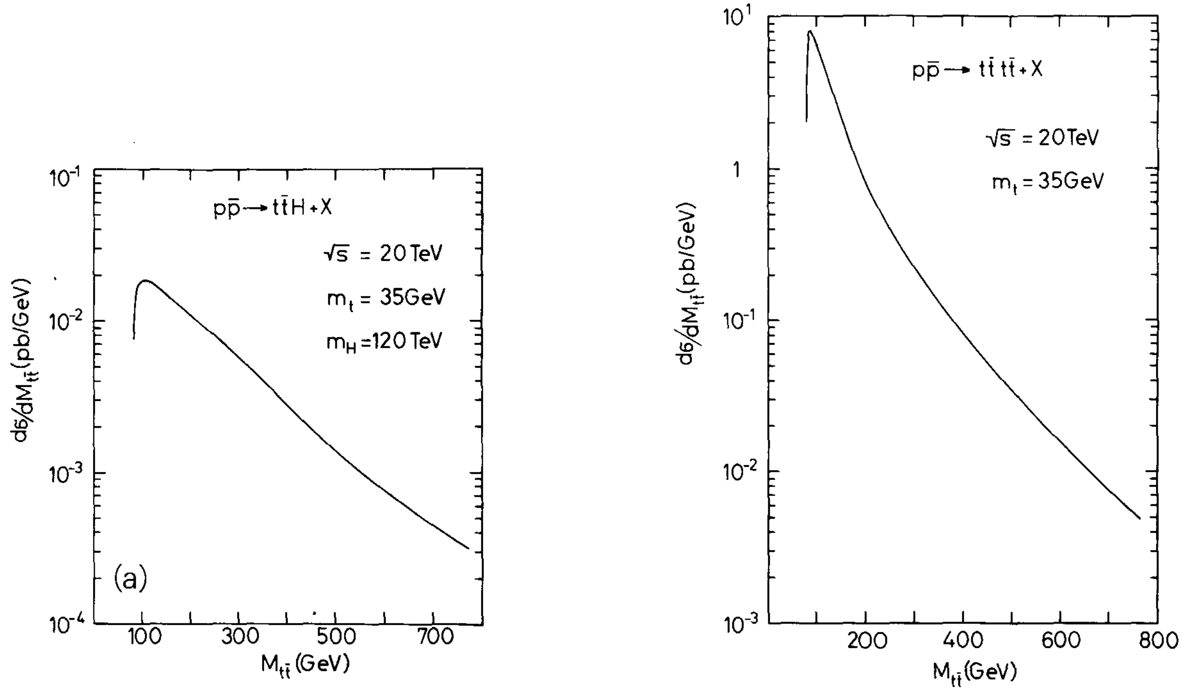


Fig. 10. (a) Invariant mass distribution of the pair of top-antitop quarks produced in association with a Higgs boson in proton-antiproton collision at $\sqrt{s} = 20$ TeV energy with mass values $m_t = 35$ GeV and $m_H = 120$ GeV. (b) Invariant mass distribution of a pair of top quarks produced in the reaction $p + \bar{p} \to t\bar{t}t\bar{t} + \text{hadron}$ at $\sqrt{s} = 20$ TeV and with $m_t = 35$ GeV. An averaging is made over all possible choice of pairs of the final partons.

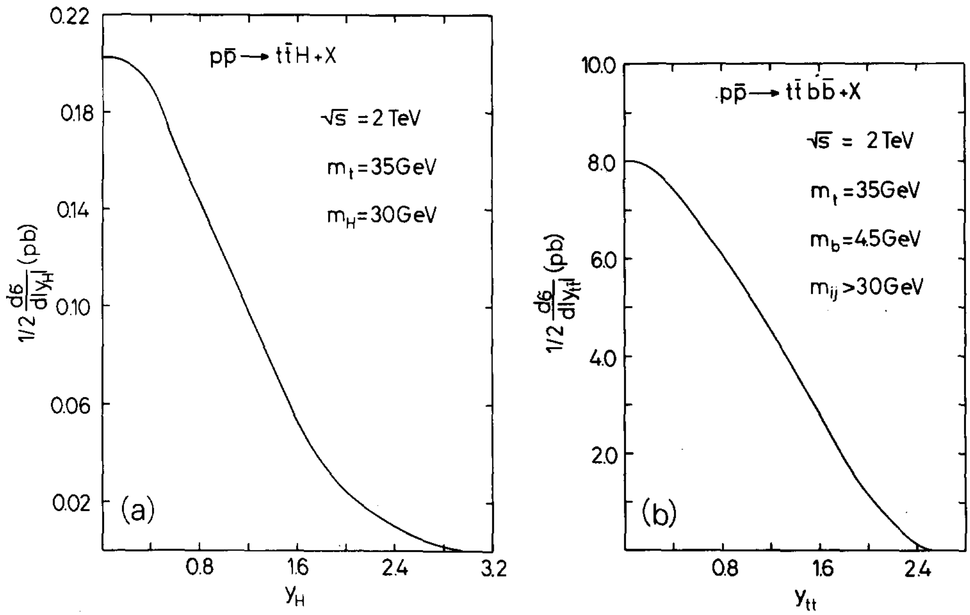


Fig. 11. (a) Rapidity distribution of the Higgs boson produced in association with a top pair in $p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV energy with mass values $m_t = 35$ GeV and $m_H = 30$ GeV. (b) Rapidity distribution of the pair of bottom quarks produced in association with a pair of top quarks in proton-antiproton collisions at $\sqrt{s} = 2$ TeV energy and with mass values $m_t = 35$ GeV, $m_b = 4.5$ GeV. It is required that the invariant mass of the bottom pair be larger than 30 GeV.

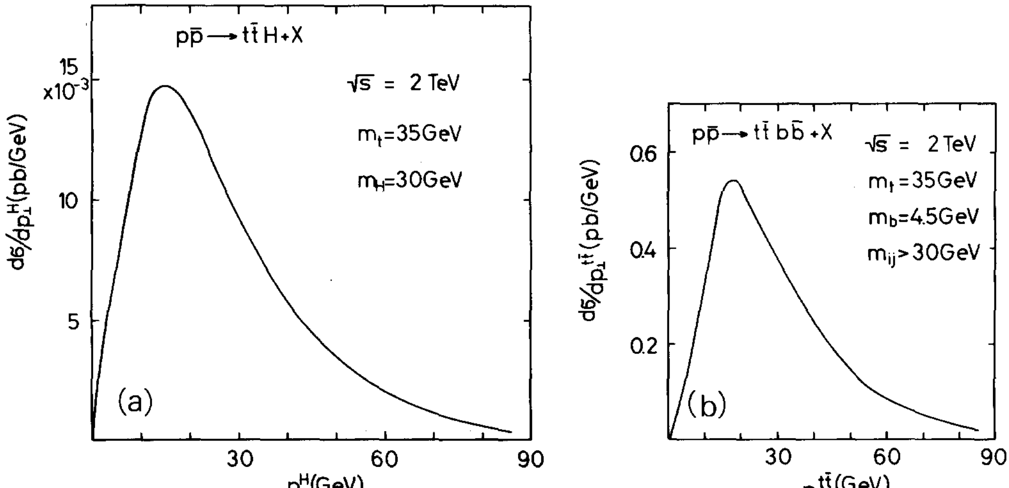


Fig. 12. (a) Transverse momentum distribution of the Higgs boson produced in association with a top and antitop quark in proton-antiproton collisions at $\sqrt{s} = 2$ TeV with $m_H = 30$ GeV and $m_t = 35$ GeV. (b) Transverse momentum distribution of the bottom-antibottom pair produced in association with a top and an antitop quark in proton-antiproton collisions at $\sqrt{s} = 2$ TeV with $m_t = 35$ GeV and $m_b = 4.5$ GeV. It is required that the invariant mass of the bottom-antibottom pair be larger than 30 GeV.

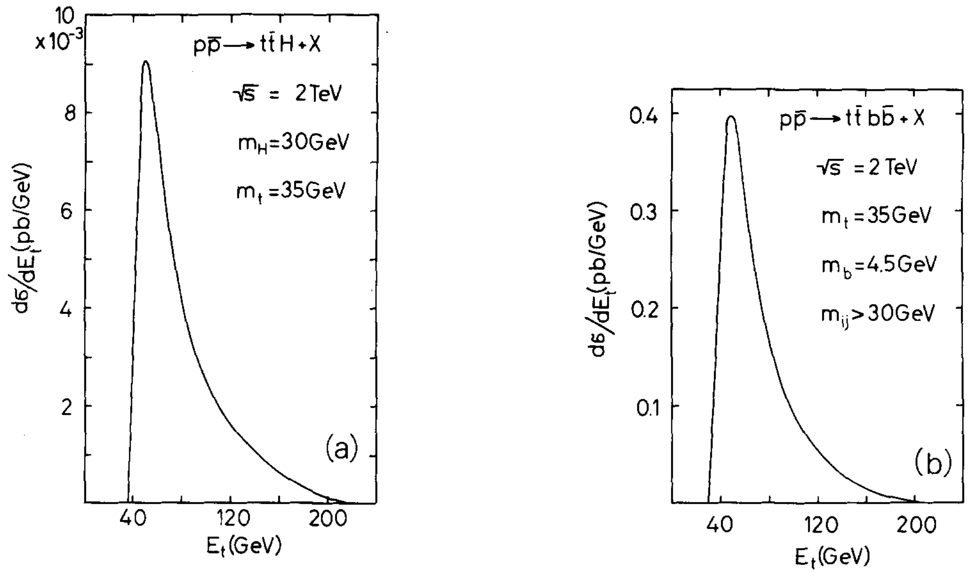


Fig. 13. (a) Energy distribution of a top quark produced in association with a Higgs boson and an antitop quark at $\sqrt{s} = 2$ TeV with $m_{\mathrm{H}} = 30$ GeV and $m_{\mathrm{t}} = 35$ GeV. (b) Energy distribution of a top quark produced in association with one antitop quark and one bottom-antibottom quark pair in proton-antiproton collisions at $\sqrt{s} = 2$ TeV with $m_{\mathrm{t}} = 35$ GeV and $m_{\mathrm{b}} = 4.5$ GeV. It is required that the invariant mass of the bottom-antibottom pair be larger than 30 GeV.

GeV and $m_{\mathrm{b}} = 4.5$ GeV. In this case the dominant decay of the Higgs boson is $\mathrm{H}^0 \to \mathrm{b}\bar{\mathrm{b}}$ and the background reaction is

$$\mathrm{p} + \bar{\mathrm{p}} \to \mathrm{t} + \bar{\mathrm{t}} + \mathrm{b} + \bar{\mathrm{b}} + \text{hadrons}. \tag{7}$$

It has been required that the invariant mass of the quark pairs be larger than 30 GeV. In figs. 11a, 11b, 12a, 12b, 13a, 13b rapidity, transverse momentum and top energy distributions are plotted both for the Higgs production and the background reaction equation (7). Again we can see remarkable similarity between the distributions of the two reactions. Therefore contrary to ref. [26] I conclude that reaction equation (1c) will not give an observable signal for the Higgs boson at the Tevatron*.

In the mass range $2m_{\mathrm{t}} < m_{\mathrm{H}} < 2m_{\mathrm{W}}$ the only known mechanism which gives an observable signal for the production of a Higgs particle is the reaction equation (1b).

* The distribution for the top energy is steeper and the rapidity distribution has no peak around $|y| \approx 2.2$, contrary to the curves given in ref. [26]. The p_{T}-distribution of the Higgs boson has a similar shape. The overall normalization of the cross sections found in ref. [17] is smaller by a factor of ≈ 12 when it is compared with those of ref. [26]. I confirm the results of ref. [17].

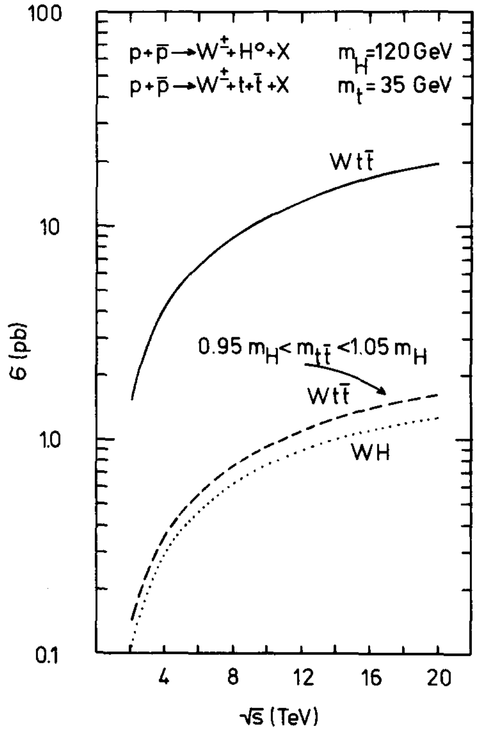


Fig. 14. Total cross-section values for Higgs production in association with a W-boson (dotted line) and in association with a top quark pair (solid line) in proton-antiproton collisions as a function of the incoming energy with $m_t = 35$ GeV and $m_H = 120$ GeV. The dashed line indicates the factor of ≈ 12 reduction if it is required that the invariant mass of the top quark pair be in the interval $0.95\ m_H < m_{t\bar{t}} < 1.05\ m_H$.

The total cross sections for this reaction and for its background equation (2b) are plotted in fig. 14 as a function of the incoming energy. The dashed curve illustrates the reduction of the background if we require that the invariant mass of the top pair be in the mass interval $0.95\ m_H < m_{t\bar{t}} < 1.05\ m_H$. Unfortunately the cross-section value is the smallest for this mechanism and therefore very large luminosity is needed.

4. Conclusion

In high-energy proton-(anti)proton collisions heavy Higgs bosons (with subsequent decay into top-antitop quarks or WW, ZZ pairs) can be produced at a relatively large rate. However their decay modes give a weak experimental signature which might be easily overwhelmed by continuum production of top quark pairs and gauge boson pairs. If $m_H > 2m_W$ the dominant decay mode is gauge boson pair production and the background problem is less serious. This mass range has been recently studied by Eichten et al. [21,22]. I have supplemented their results with the cross-section calculation of the associated production of a Higgs boson with a pair of top quarks. The production rate is reasonably large and (if top jets can be easily recognized) the experimental signature is clean since the background of the continuum production of one top and one gauge bosons pair is expected to be small. If the mass of the Higgs boson is lighter, $2m_t < m_H < 2m_W$, the associated production of a Higgs boson with a top quark pair does not seem to be a useful method in the Higgs search*. The continuum production of four top quarks gives an overwhelming background. In this mass region the most promising mechanism is when the Higgs boson is produced in association with a W-boson. The background of the continuum production of $t+\bar{t}+W$ can be suppressed to an acceptable level. The production rate in this case is rather low (see fig. 14) but it might be measurable.

In the mass range $2m_t < m_H < 2m_W$ the experimental search of the standard Higgs boson is rather difficult.

I would like to thank John Ellis for many interesting discussions and suggestions.

Appendix

For reference I list here partial decay width formulae for the standard Higgs boson decay into a top quark pair and gauge boson pair, respectively.

$$\Gamma(H \to t\bar{t}) = \frac{3\alpha m_H}{8\sin^2\theta_w} \frac{m_t^2}{m_W^2}\left(1 - \frac{4m_t^2}{m_H^2}\right)^{3/2} = \frac{3G_F}{4\pi\sqrt{2}} m_H m_t^2 \left(1 - \frac{4m_t^2}{m_H^2}\right)^{3/2}, \tag{A.1}$$

where $\sin\theta_w$ denotes the Weinberg angle and G_F is the Fermi coupling constant. For the decay into a gauge boson pair we have

$$\Gamma(H \to WW) = \frac{G_F}{8\pi\sqrt{2}} m_H^3 \left(1 - \frac{4m_W^2}{m_H^2} + \frac{12m_W^4}{m_H^4}\right)\left(1 - \frac{4m_W^2}{m_H^2}\right)^{1/2}, \tag{A.2}$$

$$\Gamma(H \to ZZ) = \frac{G_F}{8\pi\sqrt{2}} \frac{1}{2} m_H^3 \left(1 - \frac{4m_Z^2}{m_H^2} + \frac{12m_Z^4}{m_H^4}\right)\left(1 - \frac{4m_Z^2}{m_H^2}\right)^{1/2}. \tag{A.3}$$

Next we give the cross section for the reaction

$$u(p_1) + \bar{d}(p_2) \to W(k_3) + t(k_4) + \bar{t}(k_5), \tag{A.4}$$

* If m_t were only slightly smaller than m_W the decay mode $H \to W + W^*$ (virtual) [24] could compete with the $H^0 \to t+\bar{t}$ decay mode giving a significantly improved experimental signature. This narrow mass interval has been recently discussed in ref. [25].

where u, d, t, denote quarks while p_1, p_2, k_3, k_4, k_5 denote the four-momentum of the particles. It is convenient to introduce the variables

$$k_1 = -p_1, \qquad k_2 = -p_2, \qquad \sum_i^5 k_i = 0, \tag{A.5a}$$

$$x = (k_1 + k_3)^2, \qquad y = (k_2 + k_3)^2, \qquad s = (k_4 + k_5)^2, \tag{A.5b}$$

$$t = 2k_1k_4, \qquad u = 2k_2k_4. \tag{A.5c}$$

The cross-section formula is

$$\mathrm{d}\sigma = \frac{1}{2s}\int \prod_{i=1}^{3}\left(\frac{\mathrm{d}^3k_j}{(2\pi)^3 2E_j}\right)(2\pi)^4\delta^{(4)}\left(\sum k_i\right)|M|^2, \tag{A.6a}$$

where

$$|M|^2 = C|T|^2, \tag{A.6b}$$

$$C = \tfrac{1}{4}\times\tfrac{2}{9}(4\pi\alpha_s)^2\left(\frac{4\pi\alpha\cos^2\theta_C}{8\sin^2\theta_w}\right)16\times 4, \tag{A.6c}$$

where $\cos\theta_C$ is the Cabibbo angle α_s is the QCD coupling constant and α is the fine-structure constant. $|T|^2$ has the rather simple expression

$$\begin{aligned}|T|^2 = {} & \frac{m_W^4}{xys} - \frac{m_W^2 m_t^2}{x^2y^2s}(x-y)^2 + \left[x^2+y^2+2s(s-x-y)\right]\frac{m_t^2}{xys^2} \\ & + \frac{m_W^2}{x^2y^2s^2}\left[2s^2xy - \tfrac{1}{2}s^2(x^2+y^2) - sxy(x+y) - s(x-y)(tx-uy) - (tx-uy)^2\right] \\ & + \frac{1}{xys}\left[s(s+t+u-x-y) + t(t-y) + u(u-x) + \tfrac{1}{2}(x^2+y^2)\right].\end{aligned} \tag{A.7}$$

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