PHYSICAL REVIEW D VOLUME 19, NUMBER 3 1 FEBRUARY 1979

Higgs-boson production at large transverse momentum in quantum chromodynamics

Risto Raitio
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305 and Research Institute for Theoretical Physics, University of Helsinki, Helsinki, Finland

Walter W. Wada
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305 and Department of Physics, The Ohio State University, Columbus, Ohio 43210

(Received 17 October 1978)

We estimate the Higgs-boson production cross sections $d\sigma/dy$ and $d\sigma/dydq_T^2$ at $y=0$ in $p(\bar{p})p$ collisions by calculating the subprocess gluon + gluon → Higgs boson + heavy-quark-antiquark pair.

The problem of Higgs-boson (H) production was studied earlier.[1-4] Because of the lower bounds on the mass of H that have been proposed,[5] it appears that the possibility of its production and detection would be restricted to energetic e^+e^- annihilation[2,4] and pp collisions of several hundred GeV (Ref. 3) of the next-generation proton-storage-ring facilities. In Ref. 3 the two-gluon analog diagram of the Drell-Yan mechanism [Fig. 1(a)] arising from the fusion of two gluons into H through the quark triangle diagram is calculated. While this subprocess obviously gives relatively large cross sections, it only contributes at small transverse momenta (q_T) of the produced H, say $\langle q_T\rangle \sim 300$ MeV, in which kinematic region the background problems are most severe. Therefore, we find it desirable to investigate also other processes that might give measurable cross sections in the $1 \lesssim q_T \lesssim 10$-GeV region. The process that we have investigated in this work is the external and internal bremsstrahlung production of H off a heavy-quark-antiquark pair from two-gluons in pp collisions. The relevant diagrams are given in Fig. 2. The resulting cross section is of order α_s^2, same as that of Ref. 3 [Fig. 1(a)]. To this order there are other diagrams that can lead to nonvanishing q_T, such as that in Fig. 1(b). However, because of the small heavy-quark content of the nucleon, these are expected to be dominated by the process under consideration (Fig. 2). In this paper we calculate the differential cross sections $d\sigma/dy$ and $d\sigma/dydq_T^2$ at $y=0$, where y refers to the rapidity of H, for $p(\bar{p})+p \to H+$ anything arising from the subprocess gluon + gluon → H + heavy-quark pair.

We assume the simplest spontaneously broken gauge theory[6] involving one physical H. Its coupling constant to quarks is given by

$$g_H = m_Q 2^{1/4} G_F^{1/2}, \tag{1}$$

where m_Q is the quark mass and G_F is the Fermi coupling constant. The fact that g_H is proportional to m_Q determines that the couplings of H only to heavy quarks c, b, and t are appreciable. The amplitude corresponding to the diagrams of Fig. 2 for

$$g^a(p_1) + g^b(p_2) \to H(q) + Q(k_1) + \bar{Q}(k_2)$$

is of the form

$$g^2 g_H \epsilon_\mu(p_1)\epsilon_\nu(p_2) T_{ab}^{\mu\nu}, \tag{2}$$

with

$$T_{ab}^{\mu\nu} = T_aT_bA_1^{\mu\nu} + T_bT_aA_2^{\mu\nu} + T_aT_bA_3^{\mu\nu} + T_bT_aA_4^{\mu\nu} + T_aT_bA_5^{\mu\nu} + T_bT_aA_6^{\mu\nu} + if_{abc}T_c(A_7^{\mu\nu} + A_8^{\mu\nu}), \tag{3}$$

where g is the gauge coupling constant of quantum chromodynamics (QCD), a and b refer to the octet of gluons, $T_a = \frac{1}{2}\lambda_a$ with λ_a the Gell-Mann matrices, and f_{abc} are the structure constants in $[T_a, T_b] = if_{abc}T_c$. It is straightforward to construct the amplitudes $A_1^{\mu\nu}, \cdots, A_8^{\mu\nu}$ in accordance with the diagrams in Fig. 2. These are given in the Appendix.

Assuming on-shell gluons in the protons, the square of the amplitude (2) should be summed over only the transverse polarizations of the gluons.

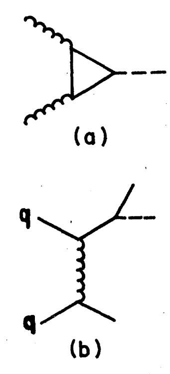

FIG. 1. Diagrams of order $\alpha_s G_F^{1/2}$ for H production in hadron collisions.

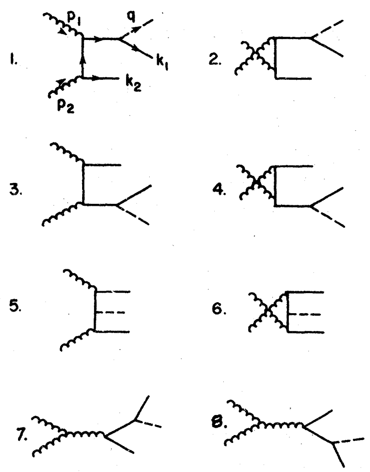

FIG. 2. Diagrams for gluon + gluon $\to H$ + heavy-quark-antiquark pair.

Contrary to QED in which the photon is always coupled to a conserved charge current, because of diagrams (7) and (8) in Fig. 2 in which self-couplings of gluons take place, the gauge-invariance conditions familiar in QED, $p_{1\mu}T_{ab}^{\mu\nu}=p_{2\nu}T_{ab}^{\mu\nu}=0$, in fact do not occur. As was pointed out previously,[7] this has the consequence that the condition in the Feynman gauge, $\sum^{\lambda}\epsilon_{\mu}^{\lambda}\epsilon_{\nu}^{\lambda}=-g_{\mu\nu}$, would introduce spurious contributions coming from the longitudinal polarizations. A method to circumvent the complications resulting from this was proposed previously,[8] according to which the terms in $A_7^{\mu\nu}$ and $A_8^{\mu\nu}$ proportional to p_1^{μ} and p_2^{ν} are to be dropped, since the difference between $T_{ab}^{\mu\nu}$ of (3) and $\tilde{T}_{ab}^{\mu\nu}$ thus obtained is proportional to $p_1^{\mu}\epsilon_{\mu}(p_1)$ and $p_2^{\nu}\epsilon_{\nu}(p_2)$ and the amplitude is unchanged for the physical polarizations. It is then found that $p_{1\mu}\tilde{T}_{ab}^{\mu\nu}=p_{2\nu}\tilde{T}_{ab}^{\mu\nu}=0$, allowing usage of the Feynman gauge for physical gluons. The square of the amplitude (2) should be averaged over the physical polarizations and the octet degrees of freedom of the gluons.

The coupling constant α_s $(=g^2/4\pi)$ of QCD should depend upon Q^2, where Q is an appropriate mass scale of the system. It may be approximated by[8]

$$\alpha_s(Q^2)=\frac{4\pi}{9\ln(Q^2/\Lambda^2)}, \quad (4)$$

where $\Lambda = 500$ MeV. If one takes Q^2 to be equal to the mass square of the three particles produced, $\alpha_s(Q^2)$ is found to be in the range 0.2–0.3 for $Q^2 = 25$–$100\ \mathrm{GeV}^2$. Because of the considerable uncertainty in assigning the value for Q^2 in (4) in the present situation, we have adopted the value for α_s commonly used in QCD calculations, i.e., $\alpha_s \approx 0.3$.[9]

The cross section for $p+p\to H+$ anything is now obtained by convoluting the differential cross section for $g+g\to H+Q+\bar{Q}$ over the gluon distribution functions according to

$$d\sigma=\int dx_1dx_2F(x_1)F(x_2)d\sigma(x_1p_1,x_2p_2,k_1,k_2,q), \quad (5)$$

where p_1 and p_2 are the c.m. momenta of the protons, and $F(x)$ is the gluon distribution function which is taken to be

$$F(x)=3\frac{(1-x)^5}{x}, \quad (6)$$

corresponding to $\langle x_{\mathrm{gluon}}\rangle = 0.5$.

The resulting cross sections $d\sigma/dy$ (at $y=0$) are shown in Fig. 3 as functions of $\sqrt{s}$ at two Higgs-boson mass values $m_H = 5$ and 10 GeV (Refs. 10 and 11). Contributions from three quarks c, b, and t with masses 1.5, 5, and 15 GeV, respectively, are summed. Of these, c and b quark contributions are found to be approximately equal, while that of the heaviest quark is roughly 5% of the total. Thus additional heavier quarks, if they exist, should increase

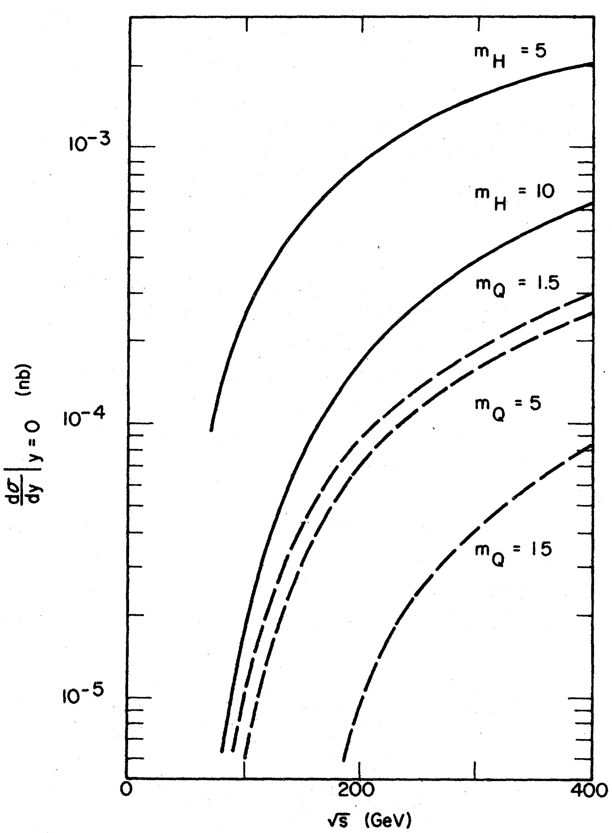

FIG. 3. The cross section $d\sigma/dy$ at $y=0$ in nb for $pp\to H+$ anything as a function of $\sqrt{s}$ with Higgs masses $m_H = 5$ and 10 GeV, and $\alpha_s = 0.3$. The dashed line shows for $m_H = 10$ GeV the different quark contributions with the quark masses 1.5, 5, and 15 GeV indicated.

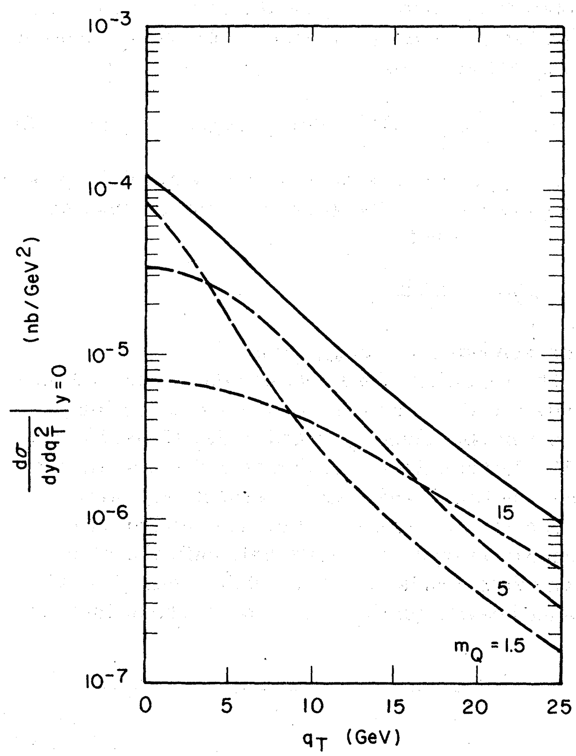

FIG. 4. The differential cross section $d\sigma/dydq_T^2$ in nb/GeV^2 at $y=0$ for $pp \to H+$anything at $\sqrt{s}=400$ GeV with $m_H=10$ GeV and $\alpha_s=0.3$. The dashed line shows the various quark contributions with the quark masses in GeV indicated.

the cross section only slightly. The differential cross section $d\sigma/dyq_T^2$ (at $y=0$) for $m_H=10$ GeV and $\sqrt{s}=400$ GeV is shown in Fig. 4.

A comparison of $d\sigma/dy$ obtained with that arising from the triangle diagram[3] shows that the present cross section for H production arising from the bremsstrahlung off heavy quarks is smaller by one or two orders of magnitude at all $\sqrt{s}$. This disadvantage may perhaps be compensated for by the relatively large q_T, as seen in Fig. 4.

As has been emphasized by the previous authors,[1-4] the most serious problem in the search for the Higgs boson is the experimental signal for its identification. Its decays into pairs of leptons, hadrons, and photons have been discussed previously.[1-4] An interesting situation arises if $m_H \gtrsim 10$ GeV. It is then expected that the Higgs boson decays predominantly into a pair of $b\bar{b}$ jets. For an appreciable q_T, say $q_T \gtrsim 5$ GeV/c, these $b\bar{b}$ jets will be accompanied by a pair of heavy-quark-antiquark jets with corresponding transverse momenta. The structure of these events in momentum space is noncoplanar. If the meson pairs from the decay containing heavy quarks, i.e., $b\bar{u}$, $\bar{b}u$, etc., are stable, then the signal for the Higgs boson is expected to be relatively clean.

Finally, we would like to mention that our cross-section values are sensitive to the largely unknown gluon structure function. These uncertainties are typically factors of 2 (squared in this case).

In summary, it seems to us that the production of the Higgs particle in multihundred-GeV proton rings at large transverse momenta may possibly provide another avenue for its search.

We thank S. J. Brodsky, J. Ellis, P. H. Frampton, and E. Takasugi for useful discussion. We are grateful to Professor S. D. Drell for the warm hospitality extended to us at the Stanford Linear Accelerator Center Theory Group where this work was carried out. The work of R. R. was supported by the U. S. Department of Energy under Contract No. EY-76-C-03-0515 and by the Academy of Finland. The work of W. W. W. was supported in part by the Department of Energy under Contract No. EY-76-C-02-1545.*000.

APPENDIX

Amplitudes $A_1^{\mu\nu}$, $A_3^{\mu\nu}$, and $A_5^{\mu\nu}$ are given below. The corresponding amplitudes in which the two gluons are crossed, $A_2^{\mu\nu}$, $A_4^{\mu\nu}$, and $A_6^{\mu\nu}$, respectively, are obtained by the simultaneous interchanges $\mu \leftrightarrow \nu$ and $p_1 \leftrightarrow p_2$.

$$A_1^{\mu\nu} = \bar{u}(k_1)\frac{\not{q}+2m_Q}{2(q\cdot k_1)+m_H^2}\gamma^\mu \frac{-\not{p}_2\gamma^\nu+2k_2^\nu}{2(p_2\cdot k_2)}v(k_2), \quad A_3^{\mu\nu} = \bar{u}(k_1)\frac{2k_1^\mu-\gamma^\mu\not{p}_1}{2(p_1\cdot k_1)}\gamma^\nu\frac{\not{q}-2m_Q}{2(q\cdot k_2)+m_H^2}v(k_2),$$

$$A_5^{\mu\nu} = \bar{u}(k_1)\frac{2k_1^\mu-\gamma^\mu\not{p}_1}{2(p_1\cdot k_1)}\frac{\not{p}_2\gamma^\nu-2k_2^\nu}{2(p_2\cdot k_2)}v(k_2),$$

$$A_7^{\mu\nu}+A_8^{\mu\nu} = \frac{1}{2(p_1\cdot p_2)}[(-p_1+p_2)^\rho g^{\mu\nu}+(2p_1+p_2)^\nu g^{\mu\rho}-(p_1+2p_2)^\mu g^{\nu\rho}]$$

$$\times\bar{u}(k_1)\left[\frac{\not{q}+2m_Q}{2(q\cdot k_1)+m_H^2}\gamma_\rho-\gamma_\rho\frac{\not{q}-2m_Q}{2(q\cdot k_2)+m_H^2}\right]v(k_2).$$

[1]J. Ellis, M. K. Gaillard, and D. V. Nanpoulos, Nucl. Phys. B106, 292 (1976), and references therein.
[2]F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).
[3]H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos, Phys. Rev. Lett. 40, 692 (1978).
[4]P. H. Frampton and W. W. Wada, Phys. Rev. D 19, 271 (1979).
[5]S. Weinberg, Phys. Rev. Lett 36, 294 (1976); A. D. Linde, Zh. Eksp. Teor. Fiz. Pis'ma Red. 23, 73 (1976) [JETP Lett. 23, 64 (1976)]; Phys. Lett. 70B, 306 (1977); P. H. Frampton, Phys. Rev. Lett. 37, 1378 (1976).
[6]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No.* 8), edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.
[7]R. Cutler and D. Sivers, Phys. Rev. D 17, 196 (1978).
[8]H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos, Harvard report, 1978 (unpublished).
[9]G. Altarelli, G. Parisi, and R. Petronzio, Phys. Lett. 76B, 356 (1978); H. Fritzsch and P. Minkowski, *ibid.* 73B, 80 (1978); K. Kajantie and R. Raitio, Nucl. Phys. B139, 72 (1978).
[10]The trace of the squared matrix element was obtained by the computer program REDUCE. The x_1, x_2, and phase-space integrations were carried out by the Monte Carlo program SHEP.
[11]We have approximated the numerators in the square of the sum of the amplitudes by setting quark mass $m_Q=0$. We checked the case for $d\sigma/dy$ ($y=0$) using $m_Q=5$ GeV at $\sqrt{s}=400$ GeV. The result was a 27% increase of cross section compared to the $m_Q=0$ case. For other quark masses considered the effect upon $d\sigma/dy$ was smaller.