Higgs Bosons from Two-Gluon Annihilation in Proton-Proton Collisions

H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
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We estimate the cross section for Higgs-boson production in proton-proton collisions. We find that most of the cross section comes from a two-gluon annihilation process, in which the gluons couple to Higgs bosons via heavy-quark loops.

Today's recipe for elementary particle physics calls for four basic ingredients: leptons, quarks, gauge bosons with spin 1, and Higgs bosons with spin 0. Alas, there is no direct evidence for the existence of the Higgs boson even though theory demands that there be at least one such particle, H. We show that the inclusive cross section for

$$p + p \to H + \text{anything}, \qquad (1)$$

though small, may permit the discovery of Higgs bosons at proposed (or even existing) colliding pp facilities. Moreover, since we find that H's are produced primarily by virtual gluon-gluon collisions, their discovery could shed light on the gluonic constituency of hadrons.

In the parton model, the obvious mechanism for Higgs-meson production is quark-antiquark annihilation illustrated in Fig. 1(a). The contribution of this process to the produced-Higgs-boson rapidity distribution, $d\sigma_H/dy$, is

$$\tfrac{1}{6}\pi \sum_Q g_Q^{\,2} \tau m_H^{-2}[F_Q(\tau^{1/2}e^y)F_{\overline{Q}}(\tau^{1/2}e^{-y}) + (Q \leftrightarrow \overline{Q})], \qquad (2)$$

where m_H is the H mass, $s^{1/2}$ is the center-of-mass energy, $\tau = m_H^{\,2}/s$, Q ($\overline{Q}$) stands for any quark (antiquark) flavor, $F_{Q(\overline{Q})}$ is its distribution function in the proton, and g_Q is the Yukawa coupling constant of H to Q. In (2), we have ignored kinematic dependence on the quark masses which reduces the contribution from heavy quarks.

To be definite, we discuss the simplest spontaneously broken gauge theory[1] which involves a single physical Higgs boson. Its coupling constant to the different quark flavors is prescribed, so that

$$g_Q = m_Q 2^{1/4} G_F^{\;1/2}, \qquad (3)$$

where G_F is the Fermi coupling constant and m_Q is the quark mass renormalized at the momentum m_H.

For a particular contribution to $\sigma(H)$ to be significant, it is necessary that g_Q, F_Q, and $F_{\overline{Q}}$ are all sizable. There are many light quarks in the proton, and not a few light antiquarks.[2] But, the very small current-algebra masses[3] of the light quarks makes their contribution to (2) very small. While H does couple strongly to heavy quarks, the chance to find simultaneously a heavy quark in one protnon and a heavy antiquark in the other is negligible. Thus, the contribution of quark-antiquark annihilation [Fig. 1(a)] to Higgs-boson production is very small.

Illustrated in Fig. 1(b) is another mechanism for Higgs-boson production which depends upon the coupling of H to two gluons.[4] This coupling leads to a two-gluon annihilation contribution to $d\sigma_H/dy$ which is

$$\frac{\pi}{32}\left(\frac{\alpha_s}{\pi}\right)^2 \frac{G_F}{\sqrt{2}}\frac{N^2}{9}\tau F_G(\tau^{1/2}e^y)F_G(\tau^{1/2}e^{-y}), \qquad (4)$$

where $F_G(\xi)$ is the gluon distribution function in the proton, α_s is the quantum chromodynamics coupling constant evaluated at m_H, and N is a function of m_H and the quark masses obtained from the triangle graph in Fig. 1(b). Roughly, N is the number of quark flavors Q satisfying $m_Q \gtrsim 0.2 m_H$ The remarkable feature of the induced coupling of H to gluons is that it counts all heavy-quark flavors,[5] even those so heavy that the corresponding new hadrons are inaccessible. In the numerical estimates below, we use $N = 3$. The number of heavy quarks, and thus the

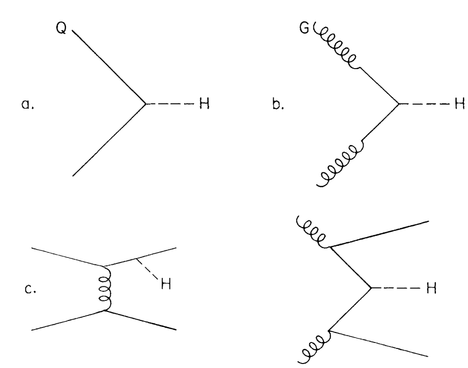

FIG. 1. Mechanisms contributing to H production in pp scattering: (a) quark-antiquark annihilation; (b) gluon-gluon annihilation; (c) other mechanisms.

production cross section of Higgs bosons, could be considerably larger.

Loosely but correctly we say that about half of the proton's momentum resides on gluons: F_G is expected to be large. More precisely, what is known[6] from experimental data is

$$\int_0^1 \xi F_G(\xi) d\xi \simeq \tfrac{1}{2}. \quad (5)$$

We know of no valid theoretical prediction for the shape of F_G. As an *Ansatz*, we use the functions

$$F_G^{(n)}(\xi) = \tfrac{1}{2}(n+1)\xi^{-1}(1-\xi)^n, \quad (6)$$

which satisfy (5) for any n, and we limit ourselves to values of n such that $8 \geq n \geq 4$. Simplistic arguments[7] suggest the value $n = 5$. Fortunately, for a wide range of values of m_H, our results do not depend critically on the value of n.

Other mechanisms should be included in a serious parton-model estimate of inclusive H production. A few are illustrated in Fig. 1(c). The evaluation of these and other similar diagrams is complicated and we have not done it. However, we believe that their effect is small for the same reasons that direct quark-antiquark annihilation into H is small. We assume that $d\sigma_H/dy$ is dominated by the two-gluon contribution (4). The effects which we ignore can only increase the cross section.

In Fig. 2, we display our predictions for $d\sigma_H/dy$ (at $y = 0$) as a function of the Higgs boson mass m_H. The bands represent three different values of energy: $s^{1/2} = 27.4$ GeV (corresponding to 400-GeV protons incident on a stationary target), $s^{1/2} = 60$ GeV, and $s^{1/2} = 400$ GeV. We obtain bands, not lines, because we have left the shape of F_G somewhat unspecified. Any F_G satisfying (5) which may be approximated by a linear combination with positive coefficients of $F_G^{(n)}$ $(8 \geq n \geq 4)$ yields a result lying within the bands.

In order to discover H, we must both produce it and detect it. The experimental signature indicating that a Higgs boson was produced depends crucially on its mass.[8] If $m_H \lesssim 4$ GeV, H will decay predominantly into hadrons via two gluons or $\bar{s}s$. It would appear in $\overline{K}K$ or other hadronic final states as a very narrow but rarely produced resonance. Unfortunately, its branching ratio into muon pairs would only be a few percent.

Things are quite different if $\sim 11 \text{ GeV} \geq m_H \geq \sim 4$ GeV. In this case, the $\tau\bar{\tau}$ and $c\bar{c}$ decay modes are kinematically accessible and dominant. Conventional hadron decay modes, as well as the decay into muon pairs, are negligible. One must search for the anomalous production of $\tau\bar{\tau}$ pairs,

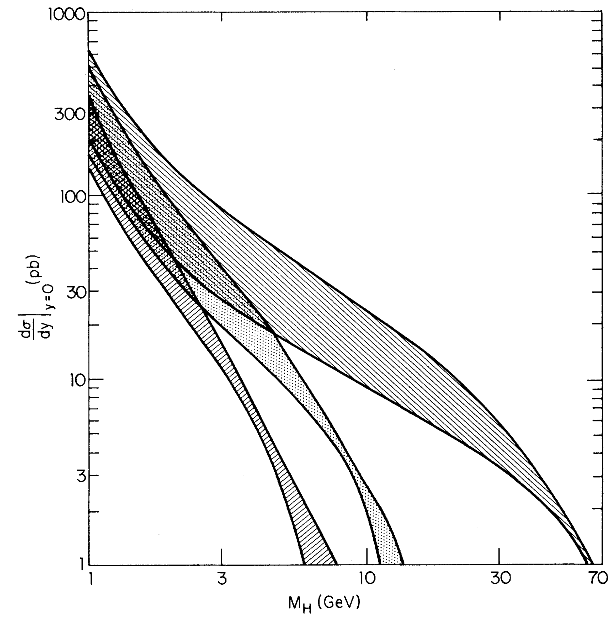

FIG. 2. $d\sigma_H/dy|_{y=0}$ as a function of H mass. Each shaded band represents a different center-of-mass energy; $s^{1/2} = 27.4$ GeV (slash up to the right), $s^{1/2} = 60$ GeV (dot), and $s^{1/2} = 400$ GeV (slash up to the left).

making use of the known decay pattern of τ. Other mechanisms for $\tau\bar{\tau}$ production (the Drell-Yan process, or the decays of upsilon[9]) will produce roughly equal numbers of $\tau\bar{\tau}$ pairs and $\mu\bar{\mu}$ pairs. Whether these can be disentangled from $\tau\bar{\tau}$ pairs arising from H decay is a difficult experimental question.

For m_H greater than ~11 GeV, H can decay into hadrons containing the upsilon constituents. Until a next new hadronic or leptonic threshold is encountered (corresponding to yet another flavor of lepton or quark), these decay modes of H will be predominant. Possibly, the new upsilon-related hadrons are stable. If so (and this will be known when larger e^+e^- machines become operative), the detection of H will be relatively straightforward. On the other hand, the upsilon constituents may be just another flavor of quark which enjoys weak couplings to other flavors. In this case, the new hadrons decay by weak cascades producing multilepton or multi-strange-particle final states. These may provide an effective signal for the detection of the Higgs boson.

The observation of Higgs bosons is evidently an essential test of the theory of spontaneous symmetry breakdown. We have shown that the induced coupling of such particles to gluons substantially increases their production in pp collisions, and leaves the possibility of even more enhancement due to the existence of unobserved quark flavors. Nonetheless, the experimental difficulty in detecting Higgs bosons, even if they are copiously produced, remains formidable.

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[1]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Elementary Particle Physics*, edited by N. Swartholm (Almquist and Wiksells, Stockholm, 1968), p. 367.

[2]Evidence for the presence of a significant antiquark distribution in the proton comes primarily from neutrino and antineutrino data. See, for example, M. Holder *et al.*, Phys. Rev. Lett. 39, 433 (1977).

[3]H. Georgi and H. D. Politzer, Phys. Rev. D 14, 1829 (1976); S. Weinberg, Harvard University Report No. HUTP-77/A057 (to be published); H. D. Politzer, Nucl. Phys. B117, 397 (1976).

[4]F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).

[5]Explicitly, $N = |\sum_Q I_Q|$, where

$$I_Q = 3\int_0^1 dx \int_0^{1-x} dy\, (1-4xy)[1-(xy m_H^2/m_Q^2)]^{-1}.$$

See L. Resnick, M. K. Sundaresan, and P. J. S. Watson, Phys. Rev. D 8, 172 (1973). Fundamental fermions transforming according to higher representations of color SU(3) than triplets would also contribute to N if they exist and get their masses from the Higgs-boson vacuum expectation value.

[6]The glue fraction at small q^2 (= 3.5 GeV^2) ~ 30%; see H. D. Politzer, Nucl. Phys. B122, 237 (1977). We are interested in F_G at $q^2 \sim m_H^2$. Equation (5) is roughly correct for large m_H.

[7]Y. Matveev *et al.*, Lett. Nuovo Cimento 7, 719 (1973); S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31, 1153 (1973).

[8]For a review of the phenomenology of Higgs particles, see J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B106, 292 (1976).

[9]S. W. Herb *et al.*, Phys. Rev. Lett. 39, 252 (1977); W. R. Innes *et al.*, Phys. Rev. Lett. 39, 1240, 1640(E) (1977).

Statistical Analysis of Preequilibrium α-Particle Spectra and Possible Local Heating

T. Nomura, H. Utsunomiya, T. Motobayashi, T. Inamura, and M. Yanokura
Cyclotron Laboratory, The Institute of Physical and Chemical Research, Wako-shi, Saitama 351, Japan
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It is shown that energy spectra of preequilibrium α-particle emission in ^{209}Bi + ^{14}N reactions are reproduced well by the statistical formula of Ericson when nuclear temperature is treated as a parameter depending on the emission angle. The resultant temperature shows monotonical decrease with increasing angles, indicating the cooling-down process of the associated composite system.

In reactions induced by heavy ions such as ^{12}C, ^{14}N, and ^{16}O at bombarding energies well above the Coulomb barrier, α particles are known to be emitted with large probability. The α-particle emission occurs predominantly in the forward direction with strong enhancement of the high-energy part when compared to an evaporation spectrum observed in compound reactions.[1,2] As a possible origin of such α-particle emission, Britt and Quinton[1] suggested the breakup of an incident projectile in an interaction with the surface of a target nucleus. A recent work of Inamura *et al.*[3] indicated that this reaction originates from initial channel spins localized just above the critical angular momentum for complete fusion. In other words, the relevant entrance angular momenta lie between those of the grazing collision and those of close collisions leading to rapid formation of a compound nucleus. This is a feature similar to deeply inelastic reactions, in which relaxation phenomena become important because of long interaction times.[4] This suggests the possibility of attributing the above α-particle emission to evaporation from a locally excited nuclear system recently proposed for preequilibrium phenomena by Weiner and Weström.[5]

In this Letter, the same phenomenon is shown to be significant even at low incident energies in the ^{209}Bi + ^{14}N reaction. We further present simple statistical analysis for the energy spectra following the idea of Ref. 5 and discuss possible energy relaxation process of a composite system in heavy-ion reactions.

A self-supporting ^{209}Bi target of about 1 mg/cm^2 thickness was bombarded with 85- and 95-MeV ^{14}N ions from the cyclotron at the Institute

