Lawrence Berkeley National Laboratory
Recent Work

Title
PRODUCTION OF VERY MASSIVE HIGGS BOSONS

Permalink
https://escholarship.org/uc/item/2qc8p9vm

Authors
Cahn, R.N.
Dawson, S.

Publication Date
1983-12-01
Submitted for publication

PRODUCTION OF VERY MASSIVE HIGGS BOSONS

R.N. Cahn and S. Dawson

December 1983
DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.
Production of Very Massive Higgs Bosons

R. N. Cahn

and

Sally Dawson

Lawrence Berkeley Laboratory, Univ. of California
Berkeley, California 94720

Abstract

We compare Higgs boson production mechanisms at multi-TeV hadronic colliders. In addition to the previously investigated processes gluon + gluon → H and q̅q → V* → VH, (V = W, Z), we consider Higgs boson formation by pairs of virtual W's or Z's, a process analogous to two photon collisions in e+e− scattering. The Higgs production process W*W* → H is dominated by longitudinal W's and is the most important mechanism for MH > 6MW, if the top quark mass is about 30 GeV.

I. Introduction

The standard Glashow-Weinberg-Salam\(^1\) model of electroweak interactions has been extremely successful at predicting low energy phenomena. With the recent discovery 2 of the W and Z gauge bosons, the only particle of the theory remaining to be discovered is the Higgs boson, a neutral spin-zero particle. The Higgs is required for the spontaneous symmetry breaking which gives rise to masses in the theory. Unfortunately, although the couplings of the Higgs boson to quarks and leptons are predicted, its mass is not.

We shall consider here the possibility that the Higgs boson is very massive, in fact with a mass several times that of the W. The dominant decay of such a Higgs boson is into W or Z pairs. The partial widths are predicted to be

\[
\Gamma(H \rightarrow W^+W^-) \approx \frac{G_FM_H^2}{8\pi\sqrt{2}} \approx 40\text{GeV} \left(\frac{M_H}{500\text{GeV}}\right)^3 \quad (1a)
\]

\[
\Gamma(H \rightarrow ZZ) \approx 4\Gamma(H \rightarrow W^+W^-) \quad (1b)
\]

Clearly, for MH > 10MW, the width of the Higgs boson is so great that its detection becomes quite improbable. For Higgs boson masses above threshold for the WW decay but not in excess of 7-8 MW there is a chance that the Higgs boson could be found in experiments at a multi-TeV hadronic collider. The best signature may be furnished by the leptonic decay of one of the W's or Z's.\(^3\)
II. Basic Production Cross-Sections

In the standard electroweak model, the Higgs boson can be produced from quark anti-quark interactions, Figs. 1 and 2, or from gluon gluon interactions, Fig. 3. Previously, it has been assumed that the dominant mechanism is gluon fusion. However, for a heavy Higgs boson, this is no longer the case. For $M_H \approx 6M_W$ and $m_t \approx 30$ GeV the contribution from $W^+W^- \rightarrow H$ is about equal to that from gluon fusion, and for larger Higgs masses it dominates.

We compute the amplitude for the diagram in Fig. 1 as

$$M = g_{VVH}U(p_1')\gamma^\mu(g_V + g_A\gamma_5)u(p_1)U(p_2')\gamma^\nu(g_V' + g_A'\gamma_5)u(p_2)$$

$$\times (q_1^2 - M_V^2)^{-1}(q_2^2 - M_V^2)^{-1},$$

where for $V = W$ we have

$$g_{WWH} = g_{WW}$$

$$g_V = -g_A = \frac{g}{2\sqrt{2}}$$

where $g = e/\sin \theta_W$. For $V = Z$ we have

$$g_{ZZH} = \frac{g_{MZ}}{\cos^2 \theta_W}$$

$$g_V = \frac{g}{\cos \theta_W}(T_{3L} - Q \sin^2 \theta_W)$$

$$g_A = -\frac{g}{\cos \theta_W}T_{3L}$$

where $T_{3L}$ and $Q$ are the third component of weak isospin and the charge of the quark. With

$$g_L = \frac{1}{4}(g_V - g_A),$$

$$g_R = \frac{1}{4}(g_V + g_A),$$

the spin averaged matrix element squared is

$$|M|^2 = 64g_{VVH}^2[C_1 p_1 \cdot p_2 p_1' \cdot p_2' + C_2 p_1 \cdot p_2 p_1' \cdot p_2](q_1^2 - M_V^2)^{-1}(q_2^2 - M_V^2)^{-1}$$

where

$$C_1 = g_L^2 s_L^2 + g_R^2 s_R^2,$$

$$C_2 = g_L^2 s_L^2 + g_R^2 s_R^2.$$
We assume that the incident quarks give a small fraction of their energy to the virtual vector bosons so \( \eta, \zeta < 1 \) and \( p_1 \cdot p_2 \approx p_1' \cdot p_2' \approx p_1' \cdot p_2' \approx \hat{\delta}/2 \). We find then

\[
q_1^2 \approx -\frac{\hat{\delta}}{2}(1 - \cos \alpha \sin \beta) \quad (9a)
\]

\[
q_2^2 \approx -\frac{\hat{\delta}}{2}(1 - \cos(\alpha - \theta) \sin \beta) \quad (9b)
\]

If the orientation of the three body final state is specified by Euler angles \( \alpha, \beta, \) and \( \gamma \) in the usual way,

\[
d\sigma_{VV} = \frac{g^2 V_{VH}(C_1 + C_2) d\eta d\alpha d\beta}{4 \pi \hat{\delta}^2 [1 - \cos \alpha \sin \beta + \hat{\delta} A_V]^2 [1 - \cos(\alpha - \theta) \sin \beta + \hat{\delta} A_V]^2} \quad (10)
\]

with \( A_V = 4 M_W^2 / \hat{\delta} \). For \( A_V \ll 1, \theta \ll 1 \), the integral is dominated by the region \( \alpha \approx 0, \beta \approx \pi/2 \). Using the small angle approximation we find

\[
\int d\alpha \int d\cos \beta [1 - \cos \alpha \sin \beta + \hat{\delta} A_V]^{-2} [1 - \cos(\alpha - \theta) \sin \beta + \hat{\delta} A_V]^{-2} \approx \frac{128 \pi}{\hat{\delta}^3} \left[ \frac{\theta^2 + A_V}{(\theta^2 + 4 A_V)^{3/2}} \log \frac{\sqrt{\theta^2 + 4 A_V} + \theta}{\sqrt{\theta^2 + 4 A_V} - \theta} \right]
\]

\[
\equiv J(\theta^2, A_V) \quad (11)
\]

We see that for \( \theta^2 \to 0, J \to 16 \pi / 3 A_V^3 \), while for \( A_V \to 0, J \to 32 \pi / \hat{\delta}^4 A_V \). With our approximation \( \eta, \zeta \ll 1, \theta \) is a function only of the product of \( \eta \) and \( \zeta \). This enables us to do one integral. Setting \( B_H = 4 M_H^2 / \hat{\delta} \), we obtain

\[
\sigma_{VV} = \frac{g^2 V_{VH}(C_1 + C_2)}{4 \pi \hat{\delta}^2} \frac{128 \pi}{\sqrt{2} A_V} \log \frac{2}{\sqrt{\theta^2 + B_H}} \quad (12)
\]

This final integration must be done numerically.

As a rough approximation, we replace \( J \) by

\[
J(\theta^2, A_V) \approx \frac{32 \pi}{A_V} \left( \frac{1}{\sqrt{6 A_V + \theta^2}} \right)^2 \quad (13)
\]

which has the correct limiting behavior and which allows us to do the final integration in a crude analytic approximation:

\[
\sigma_{VV} \approx \frac{g^2 V_{VH}(C_1 + C_2)}{16 \sqrt{6 A_V}} \log \frac{\hat{\delta} A_V}{M_H^2}. \quad (14)
\]

In particular, for \( W^+ W^- \to H \),

\[
\sigma_{WW} \approx \frac{1}{16 \sqrt{6} M_H^4} \left( \frac{\alpha}{\sin^2 \theta_W} \right)^3 \log \frac{\hat{\delta} A_V}{M_H^2}. \quad (15)
\]

Within our approximations, the cross sections for \( ud \to duH, u\bar{u} \to \bar{u}uH, d\bar{d} \to \bar{d}dH, \) and \( \bar{u}d \to \bar{d}uH \) are equal.

The relatively large cross section can be traced to the longitudinally polarized \( W \)'s which couple with full strength to make the Higgs boson.
The longitudinally polarized photons contributing in $e^+e^- \rightarrow e^+e^-X$ must give a vanishing contribution to the cross section as their $q^2 \rightarrow 0$. This is clearly not so for the coupling $WWH$.

The production of Higgs bosons from $q\bar{q} \rightarrow W^* \rightarrow WH$ and $q\bar{q} \rightarrow Z^* \rightarrow ZH$ has been studied by Hinchliffe \textsuperscript{4} and by Eichten \textit{et al.} \textsuperscript{5}. The basic cross section for $q\bar{q} \rightarrow V^* \rightarrow VH$ is

\begin{equation}
\sigma_{V^*} = \frac{g^2_{\nu VH}}{24\pi} \cdot \frac{g^2_{\nu} + g^2_{\lambda}}{(s - M^2_{\nu})^2} \cdot \frac{P_V}{\sqrt{s}} \left(1 + \frac{P^2_V}{3M^2_{\nu}}\right)
\end{equation}

where $P_V$ is the c.m. momentum of the final vector boson (or the Higgs boson). For $q\bar{q} \rightarrow W^* \rightarrow WH$ in particular, this gives

\begin{equation}
\sigma_{W^*} = \frac{\pi}{6} \left(\frac{\alpha}{\sin^2 \theta_W}\right)^2 \frac{M^2_W}{(s - M^2_W)^2} \cdot \frac{P_W}{\sqrt{s}} \left(1 + \frac{P^2_W}{3M^2_W}\right)
\end{equation}

Heretofore, the standard production mechanism for heavy Higgs bosons in hadronic collisions has been resonant production from two gluons, $g + g \rightarrow H$. The cross section in hadronic colliders is \textsuperscript{8}

\begin{equation}
\sigma_{eff} = \frac{4\pi^2}{M^2_H} \cdot \frac{\Gamma(H \rightarrow gg)}{64 \cdot \frac{dL}{d\tau}}
\end{equation}

where

\begin{equation}
\frac{dL}{d\tau} = \int dx_1 \int dx_2 \delta(\tau - x_1x_2)f_{1g}(x_1)f_{2g}(x_2)
\end{equation}

with $\tau = M^2_H/s$ and where $f_{1g}$ and $f_{2g}$ are the gluon distributions in the incident hadrons. The partial width for $H \rightarrow gg$ is determined by the heaviest fermions which contribute to the triangle diagram \textsuperscript{7}, and

\begin{equation}
\Gamma(H \rightarrow gg) = \frac{\sqrt{2}G_F \alpha^2 s}{8\pi^3} \frac{M^3_H}{9}|N|^2
\end{equation}

where $N$ is a sum of contributions, $N_j$, from quarks $j = 1, 2, \ldots$.

\begin{equation}
N_j = 3 \int_0^1 dx \int_0^{1-x} dy \frac{1 - 4xy}{1 - xyM^2_H/m^2_j - i\epsilon}.
\end{equation}

Combining these results gives the expression of Georgi \textit{et al.} \textsuperscript{8}

\begin{equation}
\sigma_{eff} = \frac{\sqrt{2}G_F}{64} \frac{\pi}{\pi} \alpha^2 \left|N\right|^2 \frac{dL}{d\tau}
\end{equation}

A fermion with $m_j \geq M_H$ gives $N_j \approx 1$. For $M^2_H > 4m^2_j$, $N_j$ is complex. \textsuperscript{9} With $\lambda_j = m_j^2/M^2_H$,

\begin{equation}
N_j = 3[2\lambda_j + \lambda_j(4\lambda_j - 1)f(\lambda_j)]
\end{equation}

with

\begin{equation}
f(\lambda) = -2\left(\sin^{-1} \frac{1}{2\sqrt{\lambda}}\right)^2, \quad \lambda > \frac{1}{4}
\end{equation}

\begin{equation}
f(\lambda) = \frac{i}{4}\left(\log \frac{\eta^+}{\eta^-}\right)^2 - \frac{\pi^2}{2} + i\pi \log\left(\frac{\eta^+}{\eta^-}\right), \quad \lambda < \frac{1}{4}
\end{equation}
where

\[ \eta^\pm = \mp \sqrt{4 - \lambda} \]  

(25)

The actual value of \( N = \sum N_j \) is sensitive to the mass of the heaviest quarks. For \( M_H > m_j, \lambda < 1 \) and \( N_j \) is nearly proportional to \( \lambda \) so \( \sigma_{\text{eff}} \) varies roughly as \( 1/M_H^2 \). On the other hand, \( \sigma_{WW} \) varies roughly as \( \log s/M_H^2 \), so for large \( M_H^2 \) we may expect \( W^*W^* \to H \) to compete with \( gg \to H \).

III. Collider Cross-sections

To obtain predictions for hadronic cross-sections, we have integrated our results from the previous section with the parton distribution functions of Ref. 5, which have \( A_{QCD} = 0.29 \) GeV and a relatively hard distribution of gluons. These distribution functions have been constructed by making a fit to the deep inelastic scattering data at \( Q^2 = 5 \) GeV\(^2\) and then evolving the structure functions to high \( Q^2 \) using the Altarelli-Parisi equations. This procedure is guaranteed to yield distribution functions which are sensible at TeV energies.

At low \( z \) and \( Q^2 \), different parameterizations lead to radically different forms for the gluon distribution function. However when evolved to high \( Q^2 \approx 10^6 \) GeV\(^2\), the differences between different forms of the gluon distribution functions tend to decrease, leaving uncertainties of factors of two in hadronic cross sections involving gluons in the initial state.

Our results are shown in Figs. 4 and 5 for Higgs boson masses of five and seven times the \( W \) mass respectively. The top quark mass is fixed to be 30 GeV.\(^{10} \) The incident particles are protons. In Fig. 4, we see that for \( M_H = 5M_W \), the contributions from virtual \( W \) and \( Z \) pairs are comparable to those from gluon fusion, while for \( M_H = 7M_W \) (Fig. 5), their contribution exceeds that gluon fusion. In all cases which we have considered, \( (2M_W < M_H < 7M_W) \), the contribution from \( WH \) and \( ZH \) production is smaller than the gluon fusion and \( VV \) processes.

IV. Conclusion

Resonant formation of Higgs bosons by pairs of virtual \( W \)'s or \( Z \)'s is a significant contributors at multi-TeV energies. It surpasses gluon fusion for Higgs boson masses greater than 6 \( M_W \). Production of very heavy Higgs bosons in association with a \( Z \) or \( W \) has a cross section about an order of magnitude smaller, but the presence of the gauge boson in the final state may provide a distinctive signature.

Acknowledgments

We thank H. Georgi, who participated in the initiation of this work and I. Hinchcliffe, who provided the parton distributions.
References


4. I. Hinchliffe, presentation to the Woods Hole Panel meeting at SLAC, May 19, 1983.

5. E. Eichten *et al.*, to be published.

6. See, for example, R. N. Cahn, *Proceedings of the 10th SLAC Summer Institute on Particle Physics*, p. 27. The factor of $1/64$ arises from requiring that the gluon pair be a color singlet and from relating the partial width for $H \rightarrow gg$ to the partial width into a singlet color of gluon. The factor of 2 corrects for the identical particle effect in the decay $H \rightarrow gg$.


10. For small values of $m_t/M_H$, the cross section for gluon fusion scales approximately as $\sigma_{eff} \sim m_t^3$.

---

Figure Captions

1. Higgs boson production from virtual vector boson pairs, $(V = W$ or $Z)$. The initial state quark (or anti-quark) momenta are $p_1$ and $p_2$ and the corresponding final state momenta are $p'_1$ and $p'_2$. The momenta of the virtual vector bosons are $q_1$ and $q_2$.

2. Production of a Higgs boson together with a vector boson, $(V = W$ or $Z)$. The particles in the initial state are a quark and an anti-quark.

3. Production of a Higgs boson from a pair of gluons.

4. The cross-section for the production of Higgs bosons in a pp collider as a function of center of mass energy of the pp system. The Higgs boson mass is taken to be $5M_W$. The solid line is the contribution from $\sigma_{WW}$ and $\sigma_{ZZ}$, Eq. (12). The dashed line is the contribution from gluon fusion, Eq. (22), with $m_t = 30$ GeV. The dash-dotted line is the cross-section for the sum of $WH$ and $ZH$ production, Eq. (17).

5. The cross-section for the production of Higgs bosons in a pp collider as a function of center of mass energy of the pp system. The Higgs boson mass is taken to be $7M_W$. The solid line is the contribution from $\sigma_{WW}$ and $\sigma_{ZZ}$. The dashed line is the contribution from gluon fusion with $m_t = 30$ GeV. The dash-dotted line is the cross-section for the sum of $WH$ and $ZH$ production.
Figure 4

$M_H = 5 M_W$

Figure 5

$M_H = 7 M_W$
This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.