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PRODUCTION OF VERY MASSIVE HIGGS BONSONS

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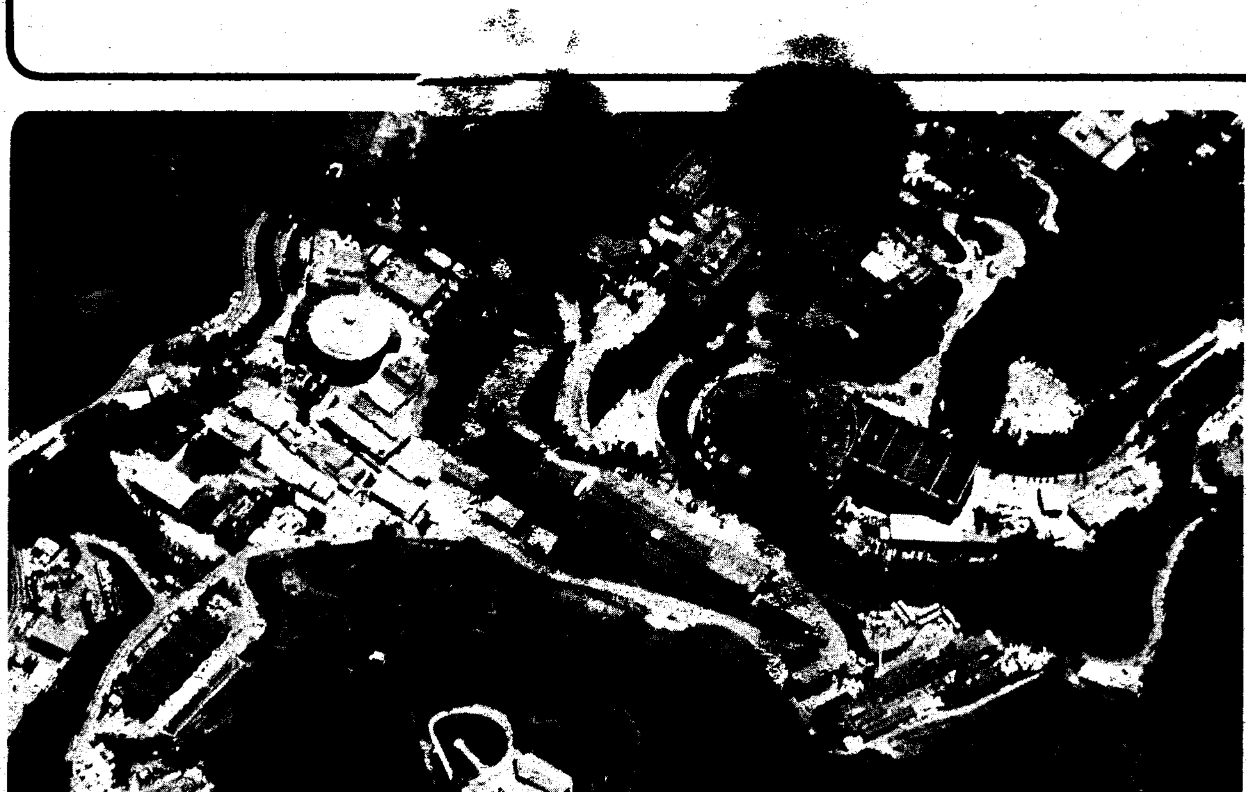

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Production of Very Massive Higgs Bosons

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Abstract

We compare Higgs boson production mechanisms at multi-TeV hadronic colliders. In addition to the previously investigated processes gluon + gluon → H and $q\bar{q} \to V^* \to VH, (V = W, Z)$, 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 $W^*W^* \to H$ is dominated by longitudinal W's and is the most important mechanism for $M_H > 6M_W$, if the top quark mass is about 30 GeV.

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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

$$\Gamma(H \to W^+W^-) \simeq \frac{G_F M_H^3}{8\pi\sqrt{2}} \simeq 40\mathrm{GeV}\left(\frac{M_H}{500\mathrm{GeV}}\right)^3 \qquad (1a)$$

$$\Gamma(H \to ZZ) \simeq \tfrac{1}{2}\Gamma(H \to W^+W^-) \qquad (1b)$$

Clearly, for $M_H > 10M_W$, 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 M_W 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 $M_H \simeq 6M_W$ and $m_t \simeq 30$ GeV the contribution from $W^*W^* \to H$ 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

$$\mathcal{M} = g_{VVH}\overline{u}(p_1')\gamma^\lambda(g_V + g_A\gamma_5)u(p_1)\,\overline{u}(p_2')\gamma_\lambda(g_V' + g_A'\gamma_5)u(p_2) \times (q_1^2 - M_V^2)^{-1}(q_2^2 - M_V^2)^{-1}, \quad (2)$$

where for $V = W$ we have

$$g_{WWH} = gM_W \quad (3a)$$

$$g_V = -g_A = \frac{g}{2\sqrt{2}} \quad (3b)$$

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

$$g_{ZZH} = \frac{gM_W}{\cos^2\theta_W} \quad (4a)$$

$$g_V = \frac{g}{\cos\theta_W}(\tfrac{1}{2}T_{3L} - Q\sin^2\theta_W) \quad (4b)$$

$$g_A = -\frac{g}{\cos\theta_W}\tfrac{1}{2}T_{3L} \quad (4c)$$

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

$$g_L = \tfrac{1}{2}(g_V - g_A), \quad (5a)$$

$$g_R = \tfrac{1}{2}(g_V + g_A), \quad (5b)$$

the spin averaged matrix element squared is

$$|\mathcal{M}|^2 = 64g_{VVH}^2[C_1 p_1\cdot p_2 p_1'\cdot p_2' + C_2 p_1\cdot p_2' p_1'\cdot p_2](q_1^2 - M_V^2)^{-1}(q_2^2 - M_V^2)^{-1} \quad (6)$$

where

$$C_1 = g_L^2 g_L'^2 + g_R^2 g_R'^2, \quad (7a)$$

$$C_2 = g_L^2 g_R'^2 + g_R^2 g_L'^2. \quad (7b)$$

We indicate $\hat{s} = (p_1 + p_2)^2$ and work in the c.m. of p_1 and p_2, defining

$$E_1' = \frac{\sqrt{\hat{s}}}{2}(1 - \eta), \quad (8a)$$

$$E_2' = \frac{\sqrt{\hat{s}}}{2}(1 - \varsigma), \quad (8b)$$

$$\cos\theta = -\hat{p}_1' \cdot \hat{p}_2' = 1 - 2\frac{\varsigma\eta - M_H^2/\hat{s}}{(1-\varsigma)(1-\eta)}. \quad (8c)$$

We assume that the incident quarks give a small fraction of their energy to the virtual vector bosons so $\eta, \varsigma \ll 1$ and $p_1 \cdot p_2 \simeq p_1 \cdot p_2' \simeq p_1' \cdot p_2 \simeq p_1' \cdot p_2' \simeq \hat{s}/2$. We find then

$$q_1^2 \simeq -\frac{\hat{s}}{2}(1 - \cos\alpha \sin\beta) \tag{9a}$$

$$q_2^2 \simeq -\frac{\hat{s}}{2}(1 - \cos(\alpha - \theta)\sin\beta) \tag{9b}$$

If the orientation of the three body final state is specified by Euler angles α, β, and γ in the usual way,

$$d\sigma_{VV} = \frac{g_{VVH}^2(C_1 + C_2)d\eta d\varsigma d\alpha d\cos\beta}{4\pi^4 \hat{s}^2[1 - \cos\alpha\sin\beta + \frac{1}{4}A_V]^2[1 - \cos(\alpha - \theta)\sin\beta + \frac{1}{4}A_V]^2} \tag{10}$$

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

$$\begin{aligned}
&\int d\alpha \int d\cos\beta [1 - \cos\alpha\sin\beta + \tfrac{1}{4}A_V]^{-2}[1 - \cos(\alpha - \theta)\sin\beta + \tfrac{1}{4}A_V]^{-2} \\
&\simeq \frac{128\pi}{\theta^3}\left[\frac{\theta^2 + A_V}{(\theta^2 + 4A_V)^{5/2}} \log\frac{\sqrt{\theta^2 + 4A_V} + \theta}{\sqrt{\theta^2 + 4A_V} - \theta} + \frac{\theta}{4A_V}\frac{\theta^2 - 2A_V}{(\theta^2 + 4A_V)^2}\right] \\
&\equiv J(\theta^2, A_V)
\end{aligned} \tag{11}$$

We see that for $\theta^2 \to 0, J \to 16\pi/3A_V^3$ while for $A_V \to 0, J \to 32\pi/\theta^4 A_V$. With our approximation $\eta, \varsigma \ll 1$, θ is a function only of the

product of η and ς. This enables us to do one integral. Setting $B_H = 4M_H^2/\hat{s}$, we obtain

$$\sigma_{VV} = \frac{g_{VVH}^2(C_1 + C_2)}{4\pi^4 \hat{s}^2}\frac{1}{4}\int d\theta^2 J(\theta^2, A_V)\log\frac{2}{\sqrt{\theta^2 + B_H}} \tag{12}$$

This final integration must be done numerically.

As a rough approximation, we replace J by

$$J(\theta^2, A_V) \simeq \frac{32\pi}{A_V}\left(\frac{1}{\sqrt{6}A_V + \theta^2}\right)^2 \tag{13}$$

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

$$\sigma_{VV} \simeq \frac{g_{VVH}^2}{16\sqrt{6}\pi^3 M_V^4}(C_1 + C_2)\log\frac{\hat{s}}{M_H^2}. \tag{14}$$

In particular, for $W^*W^* \to H$,

$$\sigma_{WW} \simeq \frac{1}{16\sqrt{6}M_W^2}\left(\frac{\alpha}{\sin^2\theta_W}\right)^3 \log\frac{\hat{s}}{M_H^2}. \tag{15}$$

Within our approximations, the cross sections for $ud \to duH, u\overline{u} \to \overline{u}uH, d\overline{d} \to \overline{d}dH$, and $\overline{u}\overline{d} \to \overline{d}\overline{u}H$ 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 $e^+e^- \to e^+e^-X$ must give a vanishing contribution to the cross section as their $q^2 \to 0$. This is clearly not so for the coupling WWH.

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

$$\sigma_{V^*} = \frac{g^2_{VVH}}{24\pi} \cdot \frac{g_V^2 + g_A^2}{(\hat{s} - M_V^2)^2} \cdot \frac{P_V}{\sqrt{\hat{s}}}\left(1 + \frac{P_V^2}{3M_V^2}\right) \tag{16}$$

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

$$\sigma_{W^*} = \frac{\pi}{6}\left(\frac{\alpha}{\sin^2\theta_W}\right)^2 \frac{M_W^2}{(\hat{s} - M_W^2)^2} \cdot \frac{P_W}{\sqrt{\hat{s}}}\left(1 + \frac{P_W^2}{3M_W^2}\right) \tag{17}$$

Heretofore, the standard production mechanism for heavy Higgs bosons in hadronic collisons has been resonant production from two gluons, $g + g \to H$. The cross section in hadronic colliders is[6]

$$\sigma_{eff} = \frac{4\pi^2}{M_H^3} \cdot 2 \cdot \frac{\Gamma(H \to gg)}{64} \tau \frac{d\mathcal{L}}{d\tau}, \tag{18}$$

where

$$\frac{d\mathcal{L}}{d\tau} = \int dx_1 \int dx_2 \delta(\tau - x_1 x_2) f_{1g}(x_1) f_{2g}(x_2) \tag{19}$$

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

$$\Gamma(H \to gg) = \frac{\sqrt{2}G_F \alpha_s^2}{8\pi^3} \frac{M_H^3}{9} |N|^2 \tag{20}$$

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

$$N_j = 3\int_0^1 dx \int_0^{1-x} dy \frac{1 - 4xy}{1 - xyM_H^2/m_j^2 - i\epsilon}. \tag{21}$$

Combining these results gives the expression of Georgi *et al.* [8]

$$\sigma_{eff} = \frac{\sqrt{2}G_F}{64} \frac{\pi}{}\left(\frac{\alpha_s}{\pi}\right)^2 \frac{|N|^2}{9} \tau \frac{d\mathcal{L}}{d\tau} \tag{22}$$

A fermion with $m_j \geq M_H$ gives $N_j \simeq 1$. For $M_H^2 > 4m_j^2$, N_j is complex.[9] With $\lambda_j = m_j^2/M_H^2$,

$$N_j = 3[2\lambda_j + \lambda_j(4\lambda_j - 1)f(\lambda_j)] \tag{23}$$

with

$$f(\lambda) = -2\left(\sin^{-1}\frac{1}{2\sqrt{\lambda}}\right)^2, \qquad \lambda > \tfrac{1}{4} \tag{24a}$$

$$f(\lambda) = \tfrac{1}{2}\left(\log\frac{\eta^+}{\eta^-}\right)^2 - \frac{\pi^2}{2} + i\pi\log\left(\frac{\eta^+}{\eta^-}\right), \qquad \lambda < \tfrac{1}{4} \tag{24b}$$

where

$$\eta^{\pm} = \tfrac{1}{2} \pm \sqrt{\tfrac{1}{4} - \lambda} \tag{25}$$

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

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 $\Lambda_{QCD} = 0.29$ 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 $Q^2 = 5\mathrm{GeV}^2$ 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 x and Q^2, different parameterizations lead to radically different forms for the gluon distribution function. However when evolved to high $Q^2 \simeq 10^6\,\mathrm{GeV}^2$, 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

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5. E. Eichten *et al.*, to be published.
6. See, for example, R. N. Cahn, Proceedings of the 10^{th} 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 $H \to gg$ to the partial width into a singlet color of gluon. The factor of 2 corrects for the identical particle effect in the decay $H \to gg$.
7. F. Wilczek, *Phys. Rev. Lett.* **39** (1977) 1304.
8. H. Georgi, *et al.*, *Phys. Rev. Lett.* **40** (1978) 692.
9. B. Lautrup and P. Olesen, *Phys. Lett* **22** (1966) 342.
10. For small vaues 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 σ_{WW} and σ_{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 σ_{WW} and σ_{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.

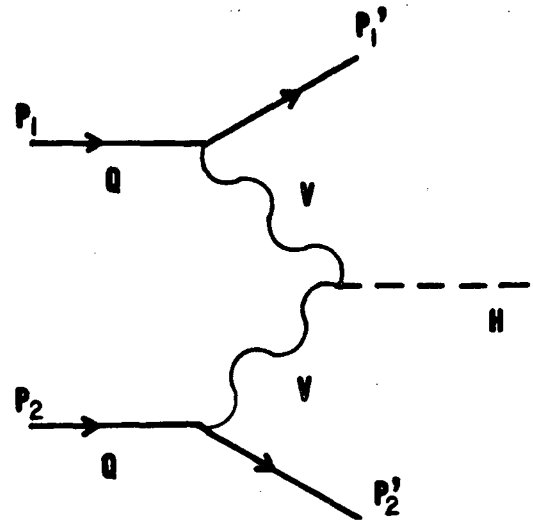

Figure 1

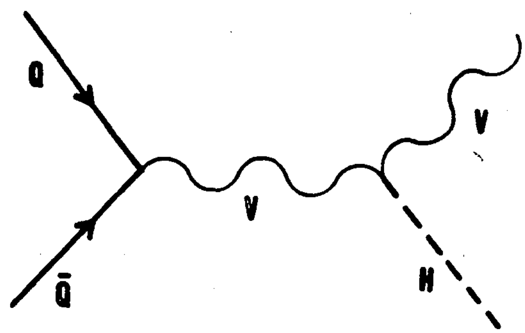

Figure 2

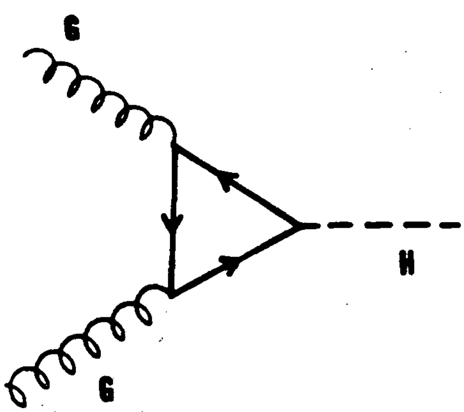

Figure 3

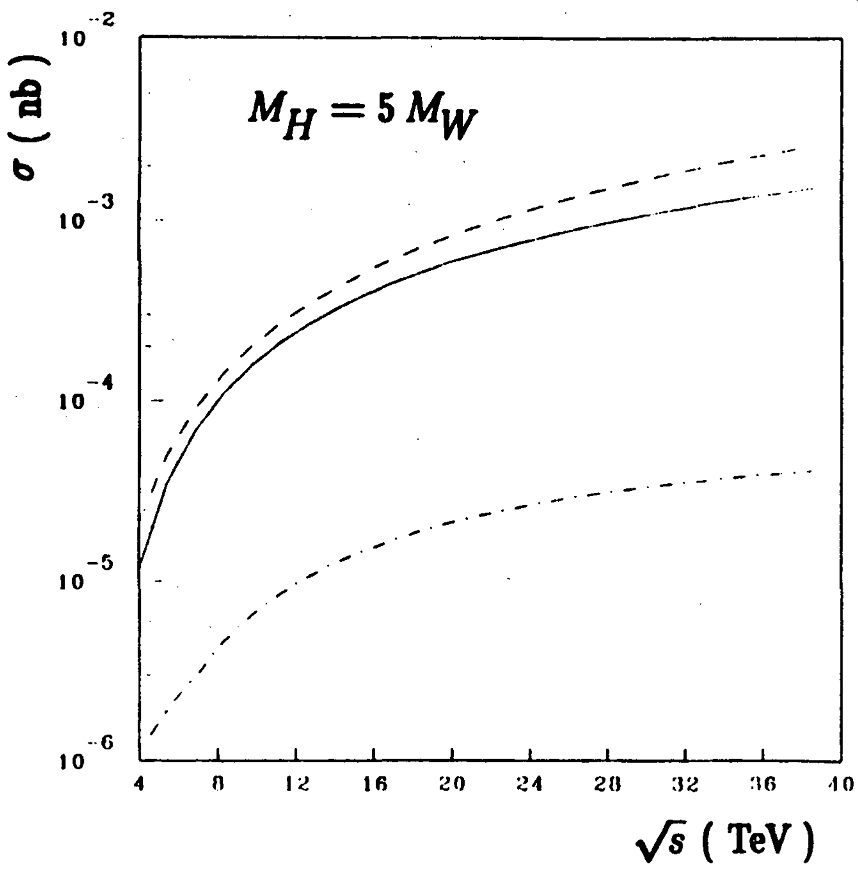

Figure 4

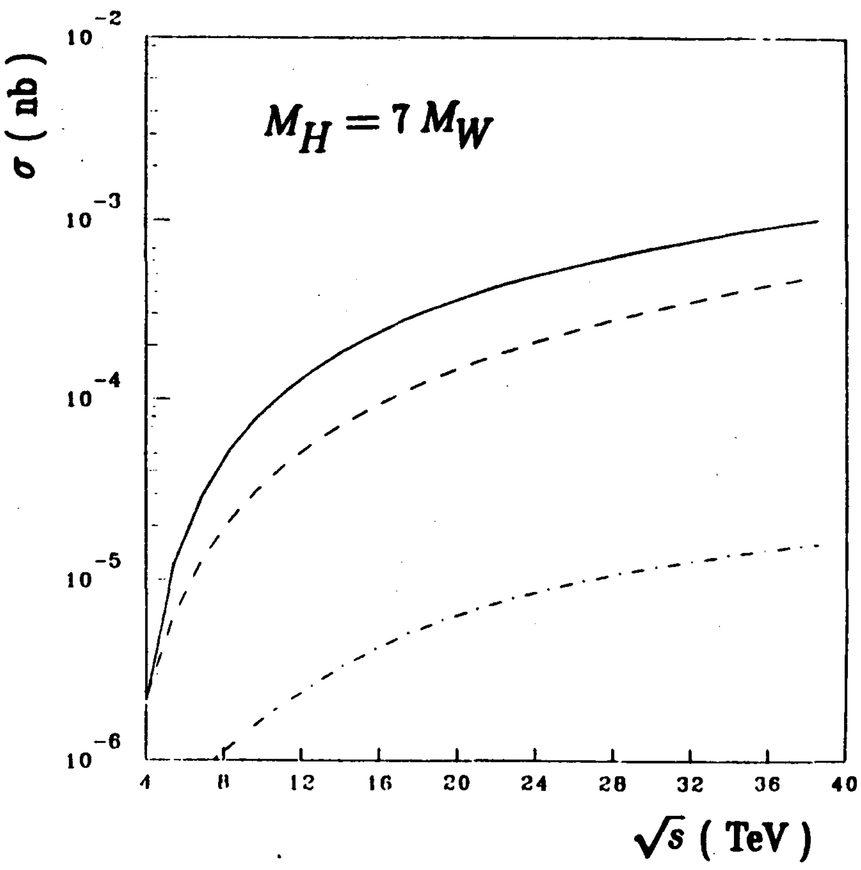

Figure 5

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