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CAPABILITIES OF  $e^+e^-$  COLLISIONS FOR PRODUCING VERY HEAVY HIGGS BOSONS

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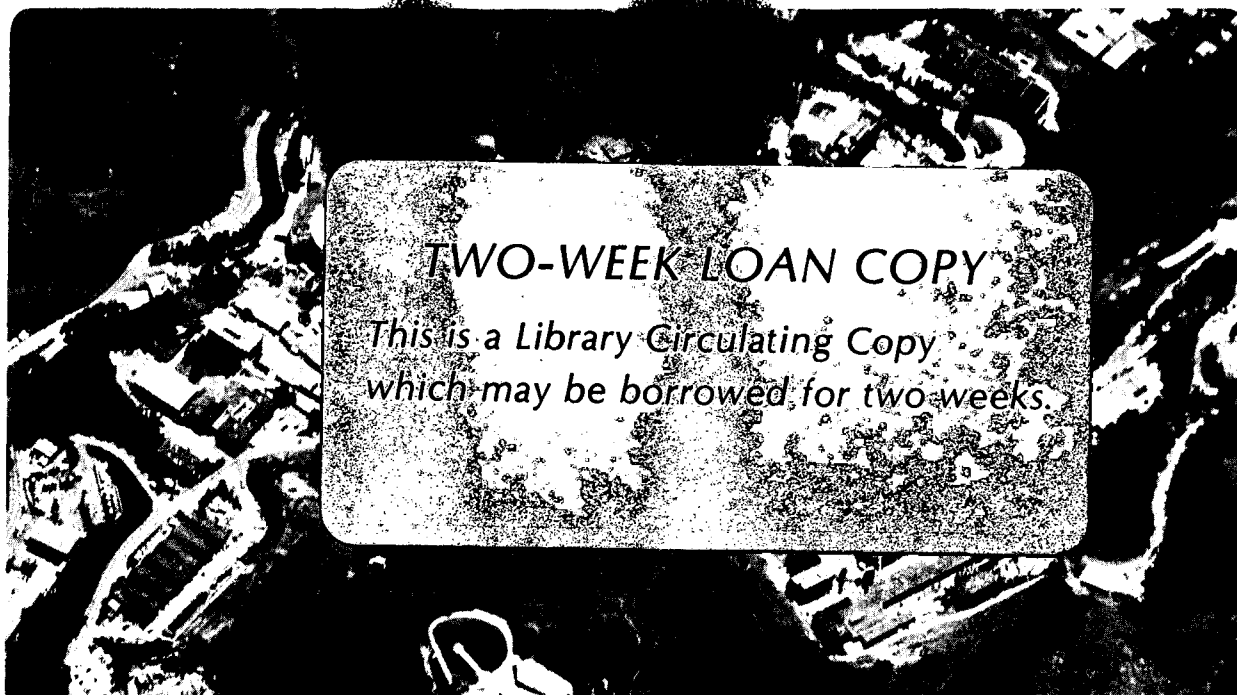
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S. Dawson and J.L. Rosner

June 1984



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EFI-84-27CAPABILITIES OF  $e^+e^-$  COLLISIONS FOR  
PRODUCING VERY HEAVY HIGGS BOSONS

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The process  $e^+e^- \rightarrow \nu\bar{\nu} + (\text{Higgs boson})$  is examined for production of such bosons at masses above  $0.4 \text{ TeV}/c^2$ . Possible backgrounds, such as  $e^+e^- \rightarrow (\text{soft photons}) + W^+W^-$ ,  $e^+e^- \rightarrow W^+W^-$ , and  $e^+e^- \rightarrow t\bar{t}$ , are examined. It is shown that to produce and detect Higgs bosons of masses  $(0.4, 0.6, 0.9) \text{ TeV}/c^2$  through this mechanism values of  $\sqrt{s}$  in excess of  $(1, 2, 4) \text{ TeV}^2$  will be required. We compare the rates for  $e^+e^- \rightarrow \nu\bar{\nu} + \text{Higgs}$  to those for the standard process  $e^+e^- \rightarrow Z + \text{Higgs}$ .

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The  $SU(2) \times U(1)$  theory of electroweak interactions<sup>1</sup> remains incomplete as long as the symmetry-breaking interaction is not fully understood. This problem may be postponed to center of mass energies of about  $1 \text{ TeV}$ , but not much beyond.<sup>2</sup> Both hadron-hadron and  $e^+e^-$  collisions have been advocated as a means of attaining this center of mass energy. Possibilities which have some hope for realization in this century include:

pp collisions at  $\sqrt{s} = 10\text{-}40 \text{ TeV}^{3,4}$ ; $e^+e^-$  collisions at  $\sqrt{s} = 1 \text{ TeV}$ .<sup>5</sup>

A detailed evaluation of the utility of hadron-hadron collisions at multi-TeV energies for the study of electroweak symmetry breaking has been presented recently.<sup>3</sup> It was concluded that one of the benchmarks of this program, the Higgs boson,  $H$ , can be observed in such collisions at  $\sqrt{s} = 40 \text{ TeV}$ , luminosity  $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ , if  $m_H \leq 0.7 \text{ TeV}/c^2$ . Since the major Higgs partial widths are expected to be,

$$\begin{aligned} \Gamma(H \rightarrow W^+W^-) &\approx 2\Gamma(H \rightarrow ZZ) \\ &\approx G_F M_H^3 / 8\pi\sqrt{2} = 40 \text{ GeV} (M_H/500 \text{ GeV})^3, \end{aligned} \quad (1)$$

a Higgs boson heavier than about  $0.7 \text{ TeV}/c^2$  will be hard to separate from nonresonant  $W^+W^-$  production, and  $q\bar{q}$  jets will provide an important background to any broad signal.<sup>6</sup> However, more optimistic estimates of how easily quark jets can be separated from  $W$  jets have recently been made,<sup>7</sup> and it may be possible to extend the detectable

Higgs boson mass range to 1 TeV/c<sup>2</sup> in hadron-hadron collisions with the parameters just mentioned.

In principle e<sup>+</sup>e<sup>-</sup> collisions can provide a source of heavy Higgs bosons somewhat more free of hadronic background than hadron interactions. The major mechanisms which dominate for Higgs masses above about 0.4 TeV/c<sup>2</sup> are

$$e^+e^- \rightarrow \nu\bar{\nu}H, \quad (2a)$$

$$e^+e^- \rightarrow e^+e^-H, \quad (2b)$$

where H is produced by W<sup>+</sup>W<sup>-</sup> or ZZ fusion<sup>8-11</sup> in process (2). The process

$$e^+e^- \rightarrow ZH, \quad (3)$$

useful for production of Higgs bosons below 0.4 TeV/c<sup>2</sup>, has too small a cross section to be of use above this mass. In the present note we point out that while cross sections for the process (2) remain appreciable up to quite high Higgs masses, backgrounds from processes such as

$$e^+e^- \rightarrow t\bar{t}, \quad (4)$$

$$e^+e^- \rightarrow W^+W^-, \quad (5)$$

and, most importantly,

$$e^+e^- \rightarrow (\text{soft photons}) W^+W^-, \quad (6)$$

limit detectable Higgs masses to (0.4, 0.6, 0.9) TeV/c<sup>2</sup> for s = (1, 2, 4) TeV<sup>2</sup>.

We calculate the cross section for reaction (2) exactly. The cross section for (2b) we estimate to be only a few percent of that for (2a), and we shall henceforth neglect it. The relevant Feynman diagram for (2) is shown in Fig. 1. The lepton 4-momenta are p<sub>1</sub>, p<sub>2</sub> (initial), and p<sub>1</sub>', p<sub>2</sub>' (final). The neutrino energies are E<sub>1</sub>', E<sub>2</sub>'. The final neutrino three-momenta p<sub>1</sub>' and p<sub>2</sub>' (in the e<sup>+</sup>e<sup>-</sup> center of mass) define an angle θ = cos<sup>-1</sup>(-p<sub>1</sub>' · p<sub>2</sub>'). The vector bosons coalescing to form the Higgs boson carry 4-momenta q<sub>i</sub> = p<sub>i</sub> - p<sub>i</sub>' (i = 1, 2). Then the cross section is

$$\sigma(e^+e^- \rightarrow \nu\bar{\nu}H) = (\alpha_{EM}/x)^3 M_W^2/8\pi \int dE_1' dE_2' \sin \beta d\beta d\alpha \times (1 + \cos \theta)/d_1^2 d_2^2, \quad (7)$$

where α<sub>EM</sub> ≈ 1/128 is the electromagnetic fine structure constant at M<sub>W</sub><sup>2</sup>, x = sin<sup>2</sup>θ<sub>W</sub>, β and α are polar and azimuthal Euler angles specifying the orientation of the three-body final state, and d<sub>i</sub><sup>2</sup> = M<sub>W</sub><sup>2</sup> - q<sub>i</sub><sup>2</sup>. (Further details may be found in Ref. 9.) The integrals in (7) are evaluated exactly using the program VEGAS.<sup>12</sup>

The resulting cross sections are shown in Fig. 2 for s = 1, 2, 4 TeV<sup>2</sup>. At ℓ = 10<sup>32</sup> cm<sup>-2</sup> s<sup>-1</sup>, a cross section of 10<sup>-5</sup> nb is needed to see 10 events in 10<sup>7</sup>s. This limits M<sub>H</sub> to less than (0.6, 0.9, 1.2) TeV/c<sup>2</sup> for s = (1, 2, 4) TeV<sup>2</sup> if we look for the Higgs by the WW fusion process of Eq. (2).

Also shown in Fig. 2 is the cross section for e<sup>+</sup>e<sup>-</sup> → ZH, given by the expression<sup>13</sup>

$$\sigma(e^+e^- \rightarrow ZH) = \pi \alpha_{EM}^2 [2K(K^2 + 3M_Z^2)(1 - 4x + 8x^2)] / [24\sqrt{s}(s - M_Z^2)^2 x^2(1 - x^2)], \quad (8)$$

where  $K$  is the c.m. three-momentum of either final particle,

$$K \equiv \{[s - (M_Z - M_H)^2][s - (M_Z + M_H)^2/4s]\}^{1/2}. \quad (9)$$

While this process is important for Higgs production at lower energies, we see that it does not provide large enough cross sections for production of Higgs bosons of masses in the several hundred GeV range. The cross sections (8) attain their maxima for given  $M_H$  at  $\sqrt{s}$  somewhat below  $2M_H$ , as shown in Table 1. Higgs bosons up to 400 GeV/c<sup>2</sup> may be detected via this process if we demand  $\sigma \geq 10^{-5}$ nb.

Three sources of background have been found which further reduce the highest accessible Higgs mass from WW fusion. These are the processes (4)-(6), which we discuss in turn.

The process  $e^+e^- \rightarrow t\bar{t}$  accounts for a cross section  $\sigma = (1.2, 0.6, 0.3) \times 10^{-37}$  cm<sup>2</sup> at  $s = (1, 2, 4)$  TeV<sup>2</sup>. Each top quark is likely to be degraded 10% of the time to an average of about 0.7 of its energy by primary semileptonic decays  $t \rightarrow b\ell^+\nu_\ell$ . Thus 20% of the  $t\bar{t}$  pairs in  $e^+e^- \rightarrow t\bar{t}$  should have observed effective mass  $\approx 0.7$  TeV/c<sup>2</sup> if  $\sqrt{s} = 1$  TeV. This corresponds to a signal of  $2.3 \times 10^{-38}$  cm<sup>2</sup>. The background at 0.6 TeV/c<sup>2</sup> is likely still to be appreciable, affecting the observation of  $H \rightarrow W^+W^-$ ,  $H \rightarrow ZZ$ . (It is probably possible to distinguish jets coming from lower-mass quarks from those due to W's or Z's.<sup>6,7</sup>) The  $t\bar{t}$  background is unlikely to affect the highest observable Higgs mass at  $s = 2, 4$  TeV<sup>2</sup>.

More important is the process  $e^+e^- \rightarrow W^+W^-$ , where the W loses energy by decays to  $\bar{c}s$  or  $\bar{t}b$ , followed by primary semileptonic decays of

c, b, or t. We use simplified forms, valid for  $s \gg M_W^2, M_Z^2$ , based on expressions given in Refs. 3, 14, and 15, to evaluate the cross sections

$$\begin{aligned} \sigma_T(e^+e^- \rightarrow W^+W^-) &\approx \pi\alpha^2/(4sx)\{z_0(1-z_0/3)^2 \\ &\quad (3/4 - (1-2x)/(4-4x) + (1-4x+8x^2)/(16(1-x)^2)) \\ &\quad - 2z_0 + \ln[(1+\beta_W z_0 - \epsilon_W/2)/ \\ &\quad (1-\beta_W z_0 - \epsilon_W/2)]\} \end{aligned} \quad (10)$$

$$\begin{aligned} \sigma_T(e^+e^- \rightarrow ZZ) &\approx \pi\alpha^2/(64sx^2(1-x)^2)\{\ln[(1+\beta_Z z_0 \\ &\quad - \epsilon_Z/2)/(1-\beta_Z z_0 - \epsilon_Z/2)] - z_0\} \\ &\quad \times \{1 + (4x-1)^4 + 6(4x-1)^2\} \end{aligned} \quad (11)$$

Here  $z_0$  is the cosine of the minimum c.m. angle  $\theta_{\min}$  observable in the detector,  $z_0 \equiv \cos \theta_{\min}$ ;

$$\epsilon_{W,Z} \equiv 4M_{W,Z}^2/s, \quad (12)$$

and

$$\beta_{W,Z} \equiv \sqrt{1 - \epsilon_{W,Z}}. \quad (13)$$

The WW and ZZ cross sections and their sum are plotted in Fig. 3 for  $s = 1$  TeV<sup>2</sup>. For reasonably large values of  $\theta_{\min}$  the logarithms in (10) and (11) vary very slowly with  $s$ , and the cross sections scale very nearly as  $1/s$ . As a result of the neutrino and electron poles, these cross sections are dominated by small angles of W or Z with respect to the beam direction. An angular cut  $\theta_{\min} = 15^\circ$  reduces the cross section for process (10) to  $(1, \frac{1}{2}, \frac{1}{4}) \times 10^{-3}$  nb at  $s = (1, 2, 4)$  TeV<sup>2</sup>. At the same time

this cut has very little effect on the process (2) for large Higgs mass, since the Higgs particle is moving slowly and decays isotropically.

We estimate the energy degradation of W's by assuming

$$\begin{aligned}
 B(W \rightarrow \bar{u}d) &= 0.3 \\
 B(W \rightarrow \bar{c}s) &= 0.3 \\
 B(W \rightarrow \bar{t}b) &= 0.1 \\
 B(W \rightarrow e\bar{\nu}) &= 0.1 \\
 B(W \rightarrow \mu\bar{\nu}) &= 0.1 \\
 B(W \rightarrow \tau\bar{\nu}) &= 0.1,
 \end{aligned} \tag{14}$$

presupposing an appreciable kinematic suppression of the  $t\bar{b}$  final state. We imagine each semileptonic decay of a c, b, or t to degrade the energy of the corresponding quark to 2/3 of its previous value, and to occur with a 10% probability. (We consider only primary semileptonic decays.) Then we estimate roughly 5% of each W to be degraded to 5/6 of its full energy. Thus 10% of the W pairs in  $e^+e^- \rightarrow W^+W^-$  will have observed effective mass  $0.8\sqrt{s}$ , and we might expect that a fraction of a percent of such pairs would have observed effective mass  $0.6\sqrt{s}$ . For the Higgs masses in question, these backgrounds appear manageable, though a more detailed calculation of W energy degradation in decays would be desirable. (The same remark applies to heavy quarks).

Most important of all is initial electron Bremsstrahlung in  $e^+e^- \rightarrow W^+W^-$ . The probability that a photon of energy between  $\epsilon$  and  $\epsilon + d\epsilon$  is radiated by  $e^+$  or  $e^-$  is<sup>16</sup>

$$\lambda(\epsilon) d\epsilon = \alpha A (\sqrt{s}/E_{WW})^{\alpha A} [1 + 13/12 \alpha A + \alpha/\pi (\pi^2/3 - 17/18)] d\epsilon/\epsilon, \tag{15}$$

where  $E_{WW}$  is the total c.m. energy of the WW subsystem,  $\epsilon = \sqrt{s} - E_{WW}$ , and

$$\alpha A = 2\alpha/\pi [2 \ln E_{WW}/m_e - 1]. \tag{16}$$

The expression (15) is the result of summing over multiple soft photons. The resulting cross section  $d\sigma/dE_{WW}$  per GeV of photon energy is obtained by multiplying (15) by (10) (with  $s$  in (10) replaced by  $E_{WW}^2$ ). We take  $\theta_{\min} = 15^\circ$ . The results are shown in Fig. 4. The cross sections rise with decreasing  $E_{WW}$  at low  $E_{WW}$  because of the behavior of  $\sigma(e^+e^- \rightarrow W^+W^-)$ , and with increasing  $E_{WW}$  at high  $E_{WW}$  because of the usual  $d\epsilon/\epsilon$  behavior of the Bremsstrahlung spectrum (15).

The values of  $d\sigma/dE_{WW}$  must be multiplied by the energy spread  $\Delta E_{WW}$  in  $E_{WW}$  to obtain a background cross section  $\sigma_B$  which can be compared with that for the process (2). A minimum estimate of this spread is  $\Delta E_{WW} \approx \Gamma_H$ ; we neglect additional effects due to instrumental resolution. The cross sections for signal and background are compared in Table 2.

In Table 2 we have underlined those cross sections corresponding to the maximum Higgs masses for each  $s$  for which the signal from  $e^+e^- \rightarrow \nu\bar{\nu}H$  exceeds the Bremsstrahlung background by at least 5 standard deviations. The maximum observable Higgs masses are approximately  $M_H = (0.4, 0.6, 0.9) \text{ TeV}/c^2$  for  $s = (1, 2, 4) \text{ TeV}^2$ . At these masses we expect the backgrounds from  $e^+e^- \rightarrow t\bar{t}$  and  $e^+e^- \rightarrow W^+W^-$  to be manageable.

Conclusion: we have considered Higgs production through both  $e^+e^- \rightarrow ZH$  and  $e^+e^- \rightarrow \nu\bar{\nu}H$  and find that the latter process is the

appropriate way to study Higgs bosons heavier than  $0.4 \text{ TeV}/c^2$ . However, an  $e^+e^-$  accelerator in excess of 1 TeV per beam is needed to probe Higgs masses up to the TeV range unless some means can be found to defeat the Bremsstrahlung background.

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$M_H(\text{GeV}/c^2)$	$E_{\text{cm}}(\text{GeV})$ at $\sigma^{\text{max}}$	$\sigma^{\text{max}}(e^+e^- \rightarrow ZH)$ (units of $10^{-39}\text{cm}^2$ )
300	510	21
400	710	9.7
500	920	5.7
600	1130	3.8
700	1340	2.7

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**Table 1** Maximum cross sections for production of Higgs bosons via  $e^+e^- \rightarrow ZH$ .

$M_H$ (TeV/c <sup>2</sup> )	$\Gamma_H$ (GeV)	$s = 1 \text{ TeV}^2$			$2 \text{ TeV}^2$			$4 \text{ TeV}^2$		
		$\sigma_s$	$d\sigma_B/dE_{WW}$	$\sigma_B$	$\sigma_s$	$d\sigma_B/dE_{WW}$	$\sigma_B$	$\sigma_s$	$d\sigma_B/dE_{WW}$	$\sigma_B$
0.4	31	<u>52</u>	1.5	<u>46</u>	111	0.95	29	184	0.64	20
0.5	60	26	1.2	70	72	0.68	41	144	0.44	27
0.6	104	12	1.0	102	<u>49</u>	0.53	<u>55</u>	97	0.33	34
0.7	165	4	0.9	151	27	0.43	71	74	0.26	42
0.8	246	1	1.0	246	15	0.38	93	50	0.21	52
0.9	350	—	—	—	9	0.35	121	<u>40</u>	0.18	<u>62</u>

**Table 2.** Comparison of signal ( $\sigma_s$ ) and Bremsstrahlung background cross sections ( $\sigma_B$ ) in Higgs production by  $e^+e^- \rightarrow \nu\nu H$ . Cross sections are in fb =  $10^{-39}\text{cm}^2$  or fb/GeV. Underlined entries correspond to maximum observable Higgs mass for a given  $s$ .

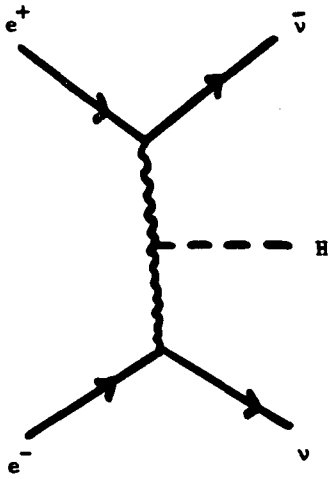


FIGURE 1

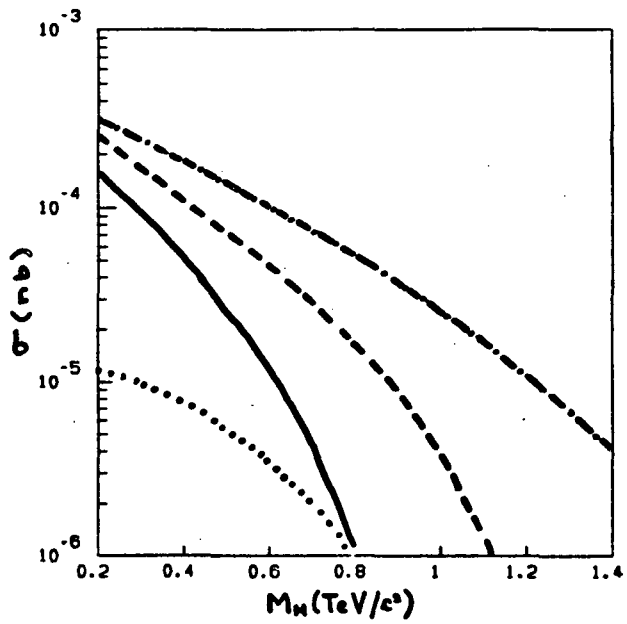


FIGURE 2

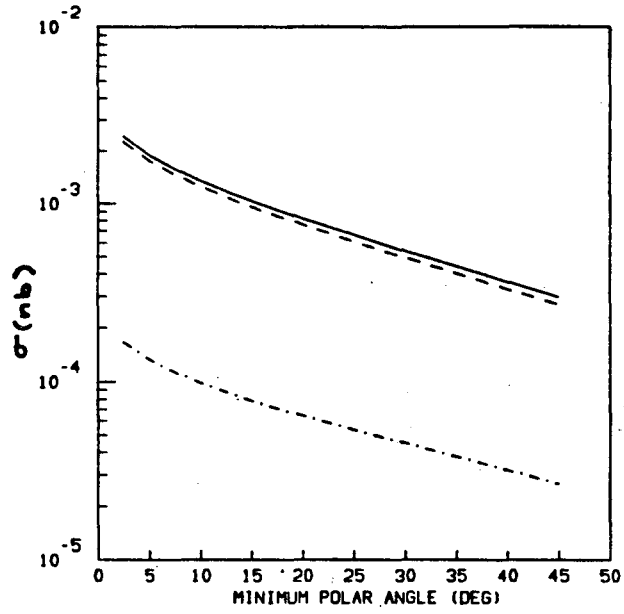


FIGURE 3

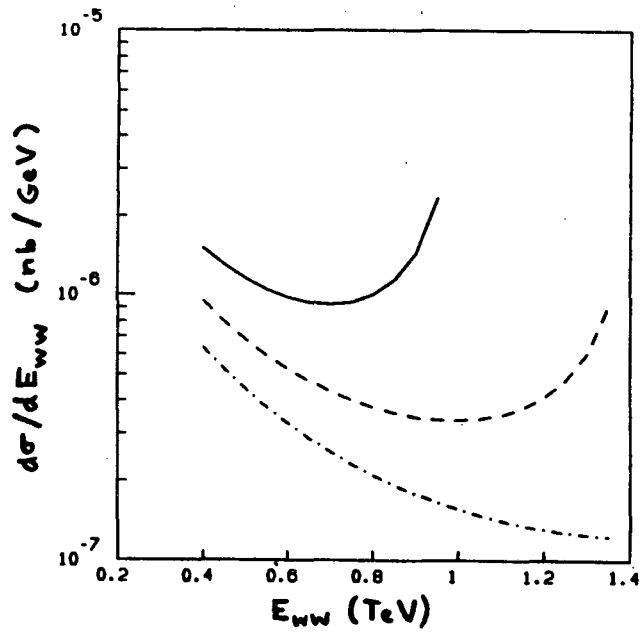


FIGURE 4

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