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ELECTROWEAK INTERACTIONS AT THE SSC:

INTRODUCTORY REMARKS

MULTI W AND Z PRODUCTION

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ABSTRACT

This report is a partial summary of the work of the electroweak interaction study group† at the Workshop on $p\bar{p}$ Options for the Super Collider, University of Chicago, February 13-17, 1984. Included are general remarks concerning the topics studied and a discussion of multi intermediate vector boson production as a probe of the gauge and scalar sectors of the electroweak theory.

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INTRODUCTION

The central issue in electroweak interactions to be addressed by the SSC is the nature of electroweak symmetry breaking. It follows simply from unitarity of the S-matrix that if a Higgs particle (or some similar manifestation of the symmetry breaking phenomenon) is not found at a mass scale below a TeV, tree unitarity will break down for the $J = 0$ partial wave WW scattering amplitude, and longitudinally polarized W's will develop strong interactions. There are also arguments related to the so-called "gauge hierarchy" problem: i.e., the instability of scalar masses against large radiative corrections, which suggest that the mechanism for electroweak symmetry breaking must entail qualitatively new physics. Examples (technicolor, supersymmetry, compositeness) are addressed by the "new particles and interactions" group. One possibility we must face is that the first manifestation of new physics will be confined to the W-W sector - either a broad s-wave resonnance (the Higgs particle) or a more complicated and rich structure in WW scattering in the TeV c.m. energy region. To observe this requires sufficient energy to overcome the reduction in energy of the quark beams relative to the proton beams and of W beams relative to quark beams and sufficient luminosity to yield a measurable event rate. Rough estimates to be discussed below indicate that for $\mathcal{L} = 10^{33}$ and $\sqrt{s} = 40$ TeV, observation of such phenomena will be difficult but possibly feasible. While a scenario of this type may be regarded as the most pessimistic, it should be pointed out that one is looking for a rather distinctive signature, namely multi-W and Z events. While other new phenomena (technicolor, supersymmetry) may have higher cross sections their signals are apt to be harder to extract from the background. Whatever the new physics, we cannot escape the reality that the nucleon shares its energy among constituents, which, until the new physics scale is reached, scatter with cross sections falling as $1/s$. Thus if, for example, quarks themselves develop strong interactions at a scale of a TeV, it means that their cross sections will level off at - or grow mildly from - a level of at most a few picobarns. The multi WW phenomena we have considered is just one illustration of the general problem. The fact that it is a difficult one must not deter us, however, from attempting to uncover the origin of electroweak symmetry breaking which is the missing link of our otherwise successful gauge theories and undoubtedly a crucial key in attempts to proceed beyond them.

We must of course continue to test as stringently as we can the gauge sector of the electroweak theory. One tool is WW production via the usual gauge interactions. Another is searching for heavier bosons which might mediate additional gauge interactions not detected at low energies. We have thus focussed our attention primarily on multi-W and Z processes and heavy W and Z production. Other topics, such as the role of the SSC as a W factory have not been addressed in detail and are worthy of further study.

MULTI W AND Z PRODUCTION

We have considered three sources of multiple W,Z events: $q\bar{q}$ annihilation into W,Z (and γ) pairs which proceeds via the conventional gauge couplings, decay of a "light" ($2M_W<M_H<$ 1 TeV) Higgs boson into W^+W^- or ZZ, and multi-W and Z production from the strong interactions which occur among them if $M_H>1$ TeV. Note that if the Higgs mass is below $2M_W$ it will be virtually impossible to observe at a hadron collider. For $M_H \lesssim 40$ GeV the Higgs particle should be accessible to SLC and LEP I via $Z \to H + \ell^+\ell^-$ (or possibly $(t\bar{t})_{J=1} \to H+\gamma$); for $M_H \lesssim 100$ GeV it could be accessible to LEP II via $e^+e^- \to Z+H$ (which seems to leave a small window of inaccessibility!)

<u>$q\bar{q}$ annihilation into vector pairs</u>. The annihilation processes

$$q\bar{q}' \to W^+W^-,\ W^{\pm}Z,\ ZZ \text{ or } W^{\pm}\gamma \tag{1}$$

can in principle provide precision tests of the gauge sector of the electroweak theory. A first check of the predicted cross sections will be provided by TeV I. Further studies of the WWZ and WWγ couplings will be performed at LEP. The question is then what the SSC can be expected to add to these studies.

The number of W^+W^- events[1] expected from pp collisions, with $\sqrt{s}$ = 40 TeV for an integrated luminosity $\int dt\mathcal{L} = 10^{40}$ cm^{-2} are shown in Table 1 for various rapidity cuts and leptonic decay requirements. Also shown are the percentages of events with W W center of mass energies above .5 and 1 TeV ($\tau = 1.6\times10^{-4}$ and 6.3×10^{-4}, respectively). Since the bulk of events occur for low parton

<u>Table 1. Number of events $q\bar{q}' \to W^+W^-$ for $\int dt\mathcal{L} = 10^{40}$ cm^{-2}</u>

	Total	1 leptonic decay	2 leptonic decays	percent events with $\sqrt{s}_{WW}$ greater than .5 TeV	1 TeV
Total	2×10^6	2.6×10^5	5.1×10^4	9%	1.3%
y<2.5	10^6	1.3×10^5	2.6×10^4	4.5%	0.5%
y<1.5	5×10^5	6.5×10^4	1.3×10^4	2%	0.3%

momentum fractions, $p\bar{p}$ collisions would not appreciably enhance the standard model W-pair yield. While QCD jet background appears to be sufficiently severe as to require leptonic decay signatures, this still leaves a reasonable event sample for some level of study. We have not carried out a study of the sensitivity to deviations from the standard model attainable with a given event sample. For comparison, the cross section at LEP II with $\sqrt{s}$ = 200 GeV is about 0.01nb as compared with 0.2nb for pp collisions with $\sqrt{s}$ = 40 TeV. It has been estimated[2] that a year's running at LEP II ($\int dt\mathcal{L} \sim 10^{39}$ cm^{-2}) would allow a distinction between $g_{ZWW} = 0$ and the standard model value, if one leptonic decay is required. While the event rate at either $p\bar{p}$ or pp will be considerably higher, there are additional uncertainties in parton model distributions as well as the considerable jet-jet and W-jet background. An "interesting" level of accuracy might be about 5% on the value of g_{WWZ}, which would be sensitive[3] to the effects of a very heavy Higgs sector. The ZZ production rate (which does not probe the ZWW coupling) is suppressed[1] relative to WW production by a factor of about 7. The ZW process, which does probe g_{WWZ} and could provide a clean $Z \to \ell^+\ell^-$ signal, has a total cross section between those for ZZ and WW, but has a lower rate[1] than ZZ for y<1.5.

Another interesting process is $q\bar{q}' \to W\gamma$ which has an angular distribution sensitive to the anomalous magnetic moment κ of the W.[4] Figure 1 shows[5] the γ-W c.m. angular distributions expected for the gauge theory value $\kappa=1$ and the value $\kappa=0$, and the expected event rates for $0 \leq |\cos\theta| \leq 0.2$ and $0.7 \leq |\cos\theta| \leq 0.95$ from 10^{40} pp/cm^2 at $\sqrt{s} = 40$ TeV. Again we have not made quantitative estimates of sensitivity levels attainable with a given event sample. If the theory is renormalizable deviations from $\kappa=1$ are expected to be very small[3] ($\lesssim$ %). Rough checks of the WWγ coupling will be provided by TeV I, LEP II and perhaps LEP I which could probably distinguish[6] between $\kappa=0$ and $\kappa=1$ running at $\sqrt{s} = 70$ GeV.

In conclusion much more study is needed to determine what event rates are required, which is the only issue here relevant to the pp vs. $p\bar{p}$ option, for a meaningful study of the gauge sector, and indeed if such a study if feasible at a hadron collider.

<u>"Light" Higgs production</u>: The three mechanisms expected to be important sources of Higgs production in a hadron collider are depicted in Figure 2, and the corresponding cross sections for $pp \to H+X$ ($\hookrightarrow W^+W^-$) (with no rapidity cut) are shown in Figure 3. The dominant mechanisms, namely gluon fusion[7] and W^+W^- bremsstrahlung[8], are the same for pp and $p\bar{p}$ collisions. The $q\bar{q}$ annihilation process has the possibly more distinctive signature of a three -(W,Z) final state.[10] However the event rates are low and some number of leptonic decays will no doubt be required to eliminate backgrounds from 3 jet, W+2 jet and WW-jet events.

The Higgs width grows with its mass as

$$\Gamma_H = 0.48 \text{ TeV } (M_H/\text{TeV})^3 \qquad (2)$$

reflecting the fact that the HW_LW_L coupling (W_L = longitudinally polarized W) becomes strong as the Higgs mass approaches a TeV. This means that the W^+W^- continuum from $q\bar{q}$ annihilation, if binned in units of Γ_H, becomes an important source of background (See Figure 3). Even discounting QCD jet background, a bump in the W^+W^- invariant mass distribution will be difficult if not impossible to observe for M_H greater than a few hundred GeV. There are other signals of a Higgs as the source of WW and ZZ events which one may be able to exploit. One is an anmalously high Z/W production ratio. The Higgs decay branching ratio is

$$\frac{\Gamma(H\to ZZ)}{\Gamma(H\to WW)} = \tfrac{1}{2} \qquad (3)$$

to be compared with $\sigma(ZZ)/\sigma(WW) \simeq 1/7$ from $q\bar{q}$ annihilation. Another characteristic feature is that a heavy Higgs particle decays predominantly into longitudinally polarized vector bosons, as it is these components which develop strong couplings to the Higgs particle. The predominance of longitudinally polarized vectors (V=W or Z) in the final state grows with the Higgs mass as[9]:

$$\frac{\Gamma(H\to V_L V_L)}{\Gamma(H\to V_T V_T)} = \frac{1}{4} \left[\left(\frac{M_H}{M_{W,Z}} \right)^2 - 2 \right]^2, \qquad (4)$$

while the VV continuum from $q\bar{q}$ annihilation is dominated by transversely polarized vector bosons. The decay products of a longitudinally polarized vector boson are preferentially emitted perpendicular to the line of flight of the parent:[9]

$$\frac{1}{\Gamma}\,\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{2}\,\sin\theta^*$$

Polarization measurements will presumably be feasible only for $Z\to\ell^+\ell^-$. Imposing a rapidity cut $y<1.5$ and taking $m_t = 30$ GeV, we get for an integrated luminosity $\int dt\,\mathcal{L} = 10^{40}\ \mathrm{cm}^{-2}$, 50,000 to 2000 events $H\to ZZ$ for $M_H \simeq (.2-1)$ TeV. Requiring one lepton decay reduces the event sample to 6000-260 and two leptonic decays give 200-8 events. Since the Z+jet background is also dominated by transversely polarized Z's, one leptonic decay per event may be sufficient to detect an anomalously high yield of longitudinal Z's.

"Heavy" Higgs Sector : For M_H <1 TeV the longitudinal bosons become strongly coupled and M_H is to be interpreted as a parameter characterizing the scale of these strong interactions rather than as the "mass of a particle", although it may still roughly coincide with the position of a broad resonance in the $W_L^+W_L^-$ and Z_LZ_L s-wave scattering channels. The task in this case is to observe [10] the strong W_L and Z_L interactions. It appears that colliding beams of $W_L^\pm$ are most efficiently produced by bremsstrahlung as in Fig. 2a for $q\bar{q}'\to q\bar{q}'+H$. To estimate rates in the "Heavy Higgs" case we must replace the cross section for $W_L^+W_L^-\to H\to$ (W_LW_L or Z_LZ_L) by the unkown total W_LW_L scattering cross section. Fig. 4 shows estimates for $pp\to Z_LZ_L$ + 2n (W_L,Z_L) assuming a) a non-resonant cross section

$$\sigma = \frac{G_F^2}{8\pi}\,\Lambda^2\,(1+s/\Lambda^2), \qquad \Lambda \geq 1\ \mathrm{TeV}$$

(for Λ <4 TeV this estimate is undoubtedly pessimistic).
b) a Breit-Wigner for M_H = 1 TeV, and
c) an interpolation between b) for s <1 TeV and a) for s>> 1 TeV (with Λ=1).
All these choices are constrained to reproduce the Born approximation for $\sqrt{s}\lesssim$ a few hundred GeV, as required [10] by the symmetries of the theory. At larger s they must be interpreted as a sum over all even partial waves and all multi W_L,Z_L channels.

Superimposed in Fig. 4 are various backgrounds: 2 jets required to simulate a Z (assuming a background reduction factor of 1/7 for each such requirement), Z + jet with the above requirement, and $q\bar{q}\to ZZ,WW$. Inspection of Fig. 4 indicates that one leptonic decay may not be a sufficient condition for a reasonable signal to background ratio unless the factor 1/7 can be considerably improved upon.

The integrated cross section a) - c) yield 2500-7500 multi W and Z events with total invariant mass above 500 GeV for an integrated luminosity of $10^{40}\ \mathrm{cm}^{-2}$. With one or two leptonic decays required, the event rates for Z_LZ_L are 200-300, and 5-10 respectively, if the two body channels remain dominant up to 4 TeV center of mass energy for $W_L^+W_L^-$ scattering. A conservative estimate [10] of the multiplicity is obtained by fitting 2n-body rates to their calculable lower energy values and cutting off the growth in multiplicity at the scale Λ. This gives 10-60 4-body events. It is quite possible, however, that high multiplicity events become dominant for c.m. energies above a TeV, in which case the signal to background ratio should be enhanced.

As is the case for "light" Higgs, additional signals for a strongly interacting $W_L Z_L$ sector are an enhanced Z/W production ratio and an enhanced V_L/V_T ratio, as compared with the $q\bar{q}' \to VV$ and V+jet backgrounds.

The lessons of this exercise are that a) there are no significant differences between pp and $p\bar{p}$ cross sections, and b) high luminosity will be needed to extract a meaningful signal if the key to the electroweak symmetry breaking sector is hidden in strong interactions among W and Z bosons.

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11. Figure compiled with the collaboration of S. Dawson and I. Hinchliffe.

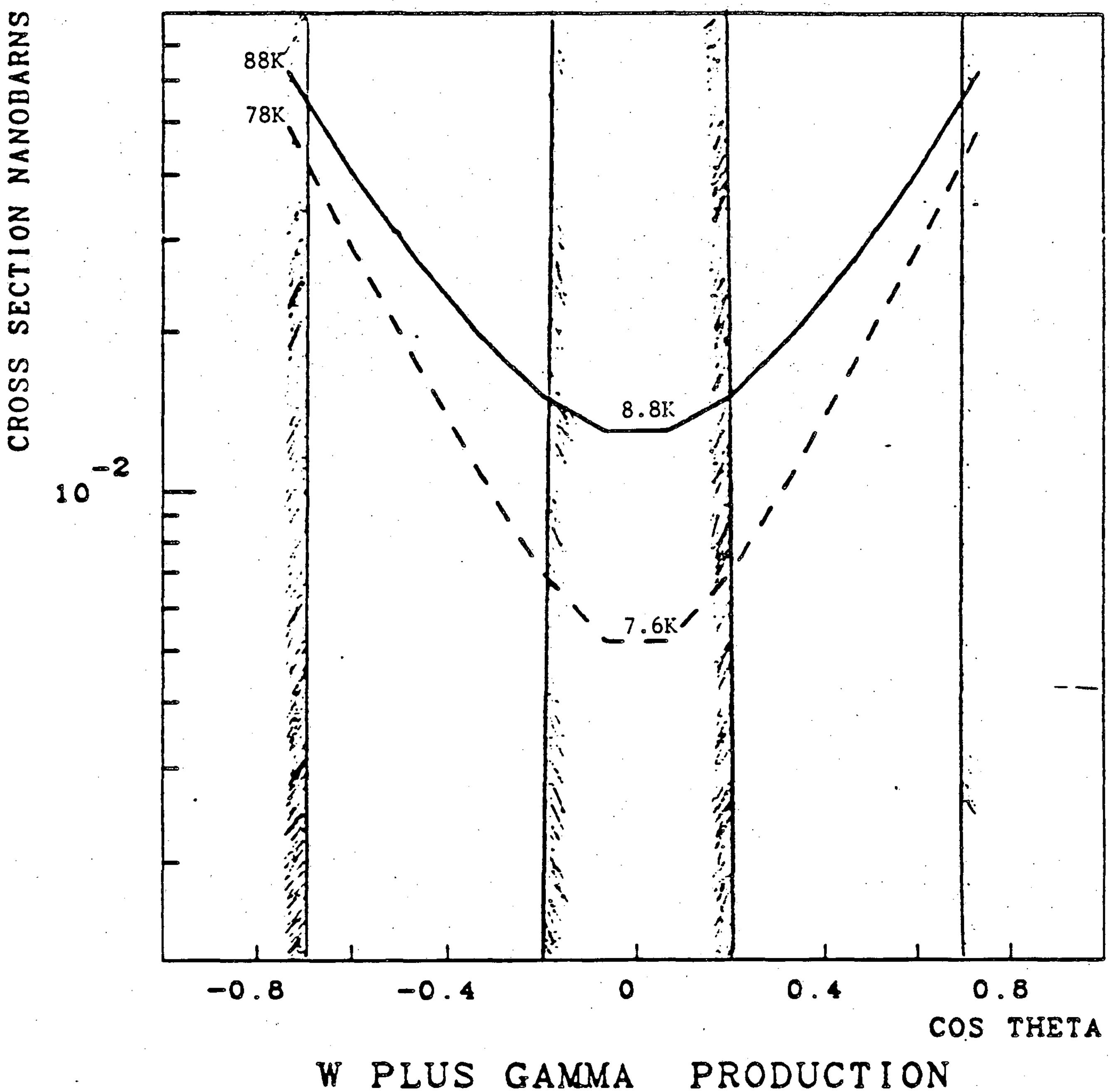

Fig. 1. Differential cross section $d\sigma/d\cos\theta$ for $pp \to W^- + \gamma$ for $\sqrt{s}$ = 40 TeV, where θ is the scattering angle in (W-γ) c.m. frame.[5] Total events for $\int dt\mathcal{L} = 10^{40}$ cm^{-2} are shown for $|\cos\theta|<0.2$ and $0.7<|\cos\theta|<0.95$.

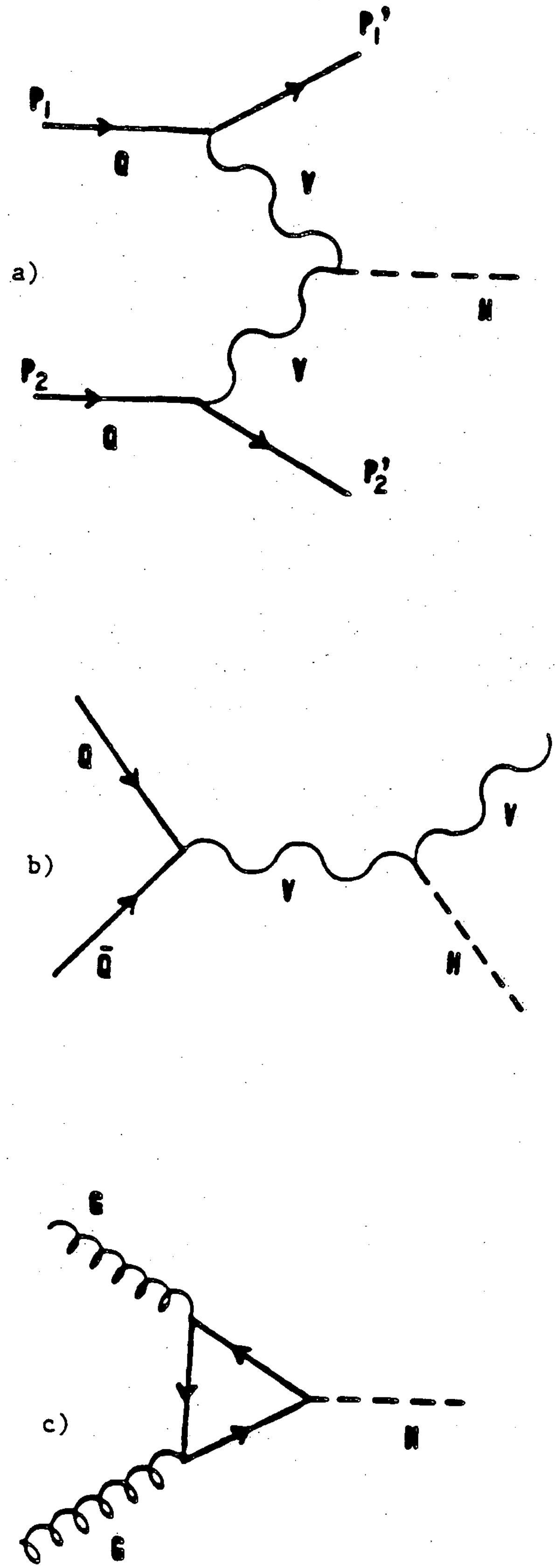

Fig. 2. Mechanisms for Higgs production in hadron colliders: a) vector boson bremsstrahlung, b) associated production with vector bosons, c) gluon fusion, (V=W or Z).

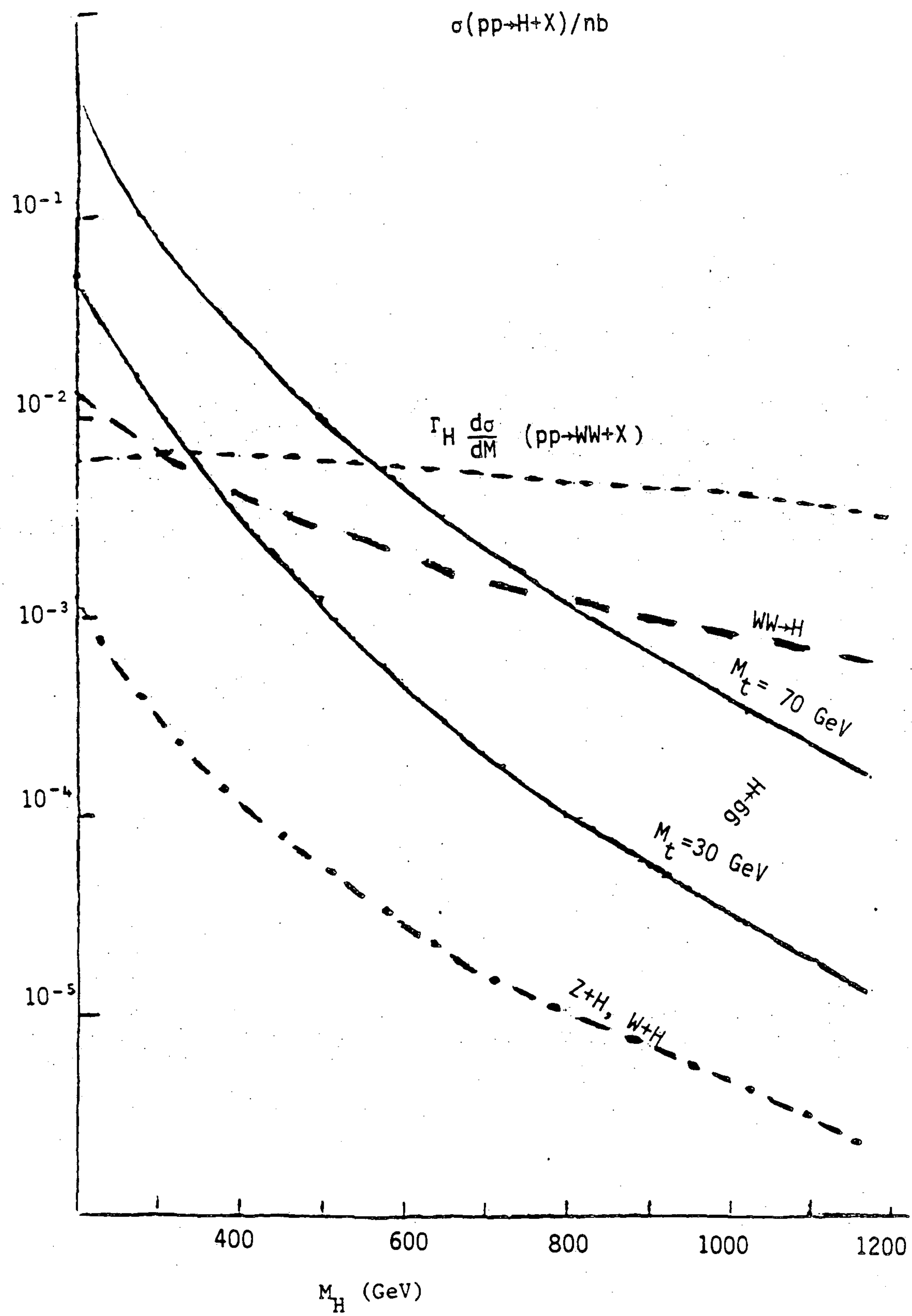

Fig. 3. Cross sections for pp→H+X as a function of Higgs mass for the three production mechanisms of Fig. 2. The background from the WW continuum is also shown (no cuts on y imposed).[11)]

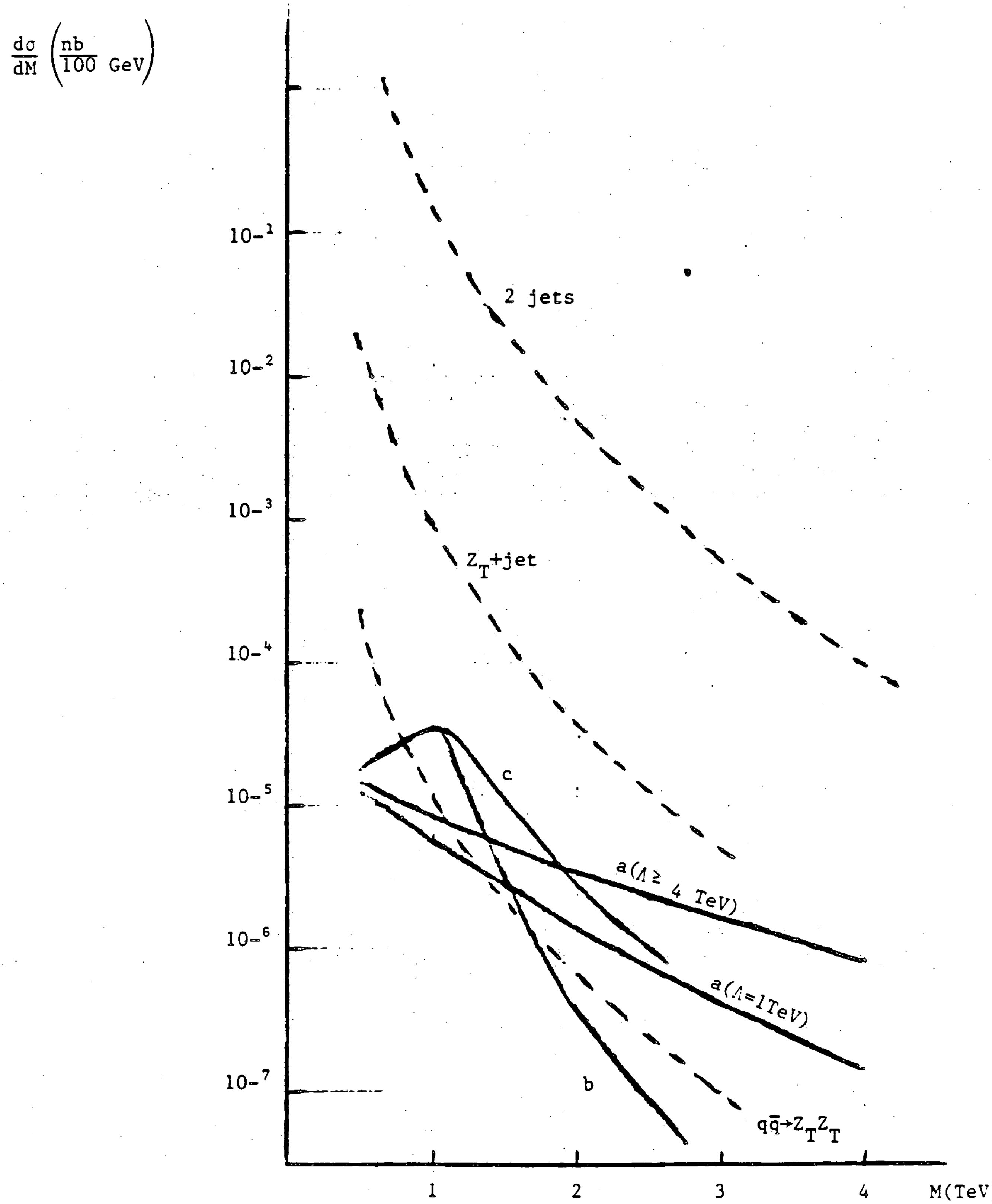

Fig. 4. Crude estimates in the "Heavy Higgs" scenario for $pp \to Z_L Z_L + X$ via the strong rescattering subprocesses $qq' \to qq' + W_L W_L \to \bar{q}q' + Z_L Z_L + 2n(V_L)$ (solid lines; see text) as a function of the $W_L W_L$ invariant mass. Dashed lines show various sources of background for 2-Z events, assuming 14% of jets resemble a Z.[11)]

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