SIGNATURES AND TRIGGERING FOR NEW PHYSICS AT THE SSC†*

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Abstract

In this talk some of the signatures for new physics at future colliders are described, with emphasis on features that can help in constructing fast triggers to extract the physics from large backgrounds. The most emphasis is given to W pairs, with some discussion of the motivation, since the associated physics is the only kind where calculable Standard Model predictions exist. Several kinds of hypothetical new physics such as supersymmetry, technicolor, rare decays, etc. are briefly discussed.

INTRODUCTION

The need for triggering at future hadron colliders is painfully obvious, since the expected cross section for new physics is at the level of at most 10^{-11} of the total cross section. On the other hand, it is generally agreed that a trigger rate of 1 Hz. is "easy" to deal with; that corresponds to about 10^7 events per year, or a cross section of about 1 nb. at an integrated luminosity of 10^{40}. In most discussions the goal is to get the fast trigger, at essentially the hardware level, to the rate of 10^2 to 10^3 Hz., which means rejecting at the level of about 10^{-6} of a σ_{tot}. Another factor of 10^2 to 10^3 is done in fast software, at the msec. level. Of course, none of the new physics itself is expected to be present at even a rate of 1 Hz., but Standard Model backgrounds that mimic the new physics may be. The new physics has to be separated out in offline analysis. A lot of useful input to the trigger problem is available, in references 1,2,3,4 and some newer calculations.

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WW SCATTERING

In order to study experimentally why SU(2) is a broken symmetry rather than exactly conserved like the color and electromagnetic symmetries, how and why W bosons and fermions get mass, the existence of Higgs bosons, and the meaning of Higgs sector physics, it may be necessary to study WW scattering in the 1-1.5 TeV region[5,6]. It is understood[7,8,9] how to get beams of W's--essentially in a Weizacker-Williams approximation--so it is really possible to study W interactions. There are three kinds of sources of W pairs, shown in Fig. 1 a-c. The contributions of Fig. 1a are calculable[4] in the Standard Model. Those of Fig. 1b are calculable[10] if one knows the approximate mass of the heaviest quark, since it dominates the loop contributions. Only this one, of the various related contributions for $gg \to WW$, has been calculated. The contributions[6] of Fig. 1c can be further divided as in Fig. 2. The graphs involving only gauge bosons $W^{\pm}$, Z^0, and γ are known from the Standard Model. The graphs with a Higgs boson in the s or t channel are calculable for any given mass for the Higgs boson. It is important[6] to include all the graphs of Fig. 2 together in a gauge invariant set, as any one of them separately gives amplitudes growing as s. When M_{WW} is below about a TeV, these Standard Model calculations should be completely reliable. For larger M_{WW} new nonperturbative interactions could come in. Since it is deviations from the Standard Model predictions that will tell us what is happening, it is relevant to do the Standard Model calculations even at larger M as a basis for comparison with experiment. One complicating feature is that the Higgs' width can be written

$$\Gamma_H \approx \frac{1}{2} M_H^3$$

where M_H and Γ_H are in TeV. For $M_H = 1$ TeV, this gives $\Gamma_H = \frac{1}{2}$ TeV, etc.

The important point to remember is that whatever the result we will necessarily learn new physics from it. Fig. 3 shows some alternatives.[6] If the bottom line, labeled M_H<<1 TeV, is observed, we know that there is a light Higgs boson. If there is a Higgs boson of mass about 1 TeV, the curve labeled M_H=1 TeV will be observed. The curve labeled M_H>>1 TeV is the contribution from the gauge boson graphs of Fig. 2, beginning to rise with s since the cancellations from the last two graphs of Fig. 2 are suppressed. Figure 4 is instructive in terms of event rate, showing for two of the curves of Fig. 3 the expected event rate normalized to an integrated luminosity of 10^{40} and assuming perfect detection efficiencies. The vertical scale of Fig. 4 can be reduced appropriately if less luminosity is available or if less than 100% of the W pairs can be detected; the likelihood of detecting various branching ratios is discussed below. When deciding what can be observed, it should be kept in mind that the absolute normalization of the theoretical cross section cannot be calculated to better than about a factor of 2, so attention must be paid to how to decide whether a signal is present at that level.

DETECTING W'S

How can a pair of W's be detected after it is produced? There is of course background that will mimic W pairs, but before we turn to the backgrounds we want to find out whether it is possible at all to detect W's in a realistic situation, and what fraction of them we can hope to capture. The relevant branching ratios are approximately:

	$W^\pm$		Z^0
$q\bar{q}$	9/12	$q\bar{q}$	0.73
$e\nu$	1/12	e^+e^-	0.03
$\mu\nu$	1/12	$\mu^+\mu^-$	0.03
$\tau\nu$	1/12	$\tau^+\tau^-$	0.03
		$\nu\bar{\nu}$	0.18

There is essentially no doubt that it is possible to detect a ZZ pair with both Z's→ $\mu\mu$. If the Z→ ee mode is also detectable, the resulting branching ratio is $(.03+.03)^2=0.0036$ for the ZZ pair, not counting detector efficiencies. If that is all that is detectable, the vertical scale of Fig. 4 should be reduced by that factor.

There are six charge states to study, ZZ, ZW^+, ZW^-, W^+W^-, $W^\pm W^\pm$. Some of the branching ratios are

	Z	Z	
A	$\mu\mu$+ee	$\mu\mu$+ee	0.0036
B	$\mu\mu$+ee	$\nu\bar{\nu}$	$2\times.03\times.18=.01$
C	$\mu\mu$+ee	$q\bar{q}$	$2\times.03\times.73=0.44$
D	$\nu\bar{\nu}$	$q\bar{q}$	$2\times.18\times.73=.25$
E	$q\bar{q}$	$q\bar{q}$	$.73\times.73=.53$

	Z	$W^{\pm}$	
F	μμ+ee	qq	.06×.73=.044
G	μμ+ee	μν+eν	.06/6=.01
H	$\nu\bar{\nu}$	$q\bar{q}$	.18×.75=.14
I	$q\bar{q}$	μν+eν	.73/6=.12
J	$q\bar{q}$	$q\bar{q}$	.75×.73=.56

	$W^{\pm}$	$W^{\pm}$	
K	μν+eν	μν+eν	1/6×1/6=.028
L	μν+eν	$q\bar{q}$	2×1/6×3/4=.25
M	$q\bar{q}$	$q\bar{q}$	3/4×3/4=.56

Some modes are clearly unique and detectable. But many of them are background for each other! The physics of ZZ and of WZ are quite different; one has an s-channel Higgs and the other does not, for example. But several modes get contributions from both. So missing momentum on one side (from escaping neutrinos) plus $W \to q\bar{q}$ cannot be used to study ZZ interactions as it gets contributions from WZ; otherwise it might have been a good signature. Whether the two can be combined or more subtle cuts can be made has not been studied. Similar overlaps occur with modes C,F; D,H; E,M,J; I,L. Only modes A,B,G, and K are uniquely interpretable, and K may not be useful because there are two neutrinos. A and B together have a branching ratio of a little over 1% of ZZ pairs, G has 1% of WZ, and no W^+W^- mode is clearly interpretable.

I have not yet considered non-W-pair backgrounds. The most serious of these[11,12], production of W plus a $q\bar{q}$ that looks like a W, will be discussed by Gunion in his talk. My point has been that we do not yet even know how to get a unique, interpretable sample of W pairs in a given charge state at a level above about 1% of the W pair cross section. With more thought it may be possible to combine states in a useful way. As it stands, it will be necessary to reduce the vertical scale of Fig. 4 by about a factor of 25, assuming detector inefficiencies of only 50%.

For now, let us be optimistic that it will be possible to study some modes such as L above, which have $W \to q\bar{q}$. One of the useful tools that may help identify $W \to q\bar{q}$ is the opening angle distribution. There is a minimum opening angle, since conservation of energy and momentum do not allow a massive particle to decay into colinear massless ones, and most of the decays pile up near the minimum, as shown[6] in Fig. 5. The distribution is different for longitudinal and for transverse W's, which may either be a useful way to enhance the fraction of longitudinal W's, or a problem. The latter would occur if a cut on opening angle biased the projection of longitudinal W's.

The actual projection of the fraction of longitudinal W's is given by[6]

$$f_L = \int_0^1 \phi^*(\cos\theta^*)\ [2-5\cos^2\theta^*]d\cos\theta^*$$

where

$$\phi^* = f_L \phi_L^* + (1-f_L)\phi_T^*$$

and

$$\phi_L^* = \frac{3}{2}\,(1-\cos^2\theta^*)$$

$$\phi_T^* = \frac{3}{4}(1+\cos^2\theta^*).$$

Here $\theta*$ is the W decay angle in the W rest frame, and ϕ^*_L, ϕ^*_T are the decay distributions for longitudinal and transverse W's respectively. It is also possible to project f_L out by comparing the energies of the two fermions from W decay. To study WW interactions it will be crucial to determine the fraction of W pairs that have longitudinal W's, as a function of M, since the new physics is expected to be closely tied to the W polarization, because the Higgs mechanism operates by turning Goldstone bosons into longitudinal W's. It is extremely important not to make any cuts in the triggering process that bias the longitudinal projection.

Another very desirable goal is to separate Z's and $W^{\pm}$. Some Z's can be identified as $\mu\mu$ or ee, and some W's as $\mu\nu$ or $e\nu$. It may also be possible to use the 12 GeV separation of Z and $W^{\pm}$ to identify them by their mass in the $q\bar{q}$ mode; at least, mass resolutions of a few GeV, which would allow the separation to be made, are frequently mentioned.

The above questions need considerable further study. W pairs are the only physics where the mass scale to surely learn new physics is known, and the predictions to compare data with are calculable in the Standard Model. Whether it is possible to study W pairs experimentally in the relevant energy region has not yet been definitively established; the extent to which various decay modes can be detected is the major remaining question. It appears to be answerable in the near future.

Some of the properties of W pairs on which one can base a trigger are:

- isolated, hard, charged lepton
- large missing momentum (the distributions of the charged lepton and the neutrino are not symmetric, the neutrino being harder for V-A decay)
- the mass formed from the missing momentum and the charged lepton momentum is about M_W

for $W \to q\bar{q}$ there are two jet cores...although they overlap, they should be separable, with opening angle given by Fig. 5

HYPOTHETICAL NEW PHYSICS

Many possible kinds of new physics that might appear at higher energies have been studied in some detail. Unfortunately, there are no firm predictions for the mass scales where the new physics should appear, and no compelling arguments. Most workers believe that supersymmetry could only be relevant to understanding the electroweak scale if some supersymmetric partners have masses around or below M_W, and well below a TeV. Some technicolor particles that can be copiously produced are expected to have masses around 250 GeV or 160 GeV, and others around 1 TeV; the situation is analogous to the ordinary pseudoscalars (π,η,k) and vectors (ρ,ω,k^*) with the former considerably lighter than the latter. There are no widely accepted estimates for the masses of new quarks and leptons that might belong to a fourth generation or fit into multiplets of a higher symmetry. Arguments that heavier fermions would lead to radiative corrections that would contradict experiment for the ρ parameter, or for W masses, have been weakened as higher order calculations have been included[13], so all masses should be considered. Perhaps a useful guide would be to be able to look at least as far as the existing mass ratios suggest:

$$m_\tau/m_\mu \simeq 17, \qquad m_b/m_s \simeq 25, \qquad m_t/m_c \simeq 25(?)$$

So we should look for new fermions at least up to (say) 100 times the existing masses of (say) τ and b. Here I will only briefly remark on some issues for signatures and triggering for a few kinds of possible new physics, and list some of the questions that need to be considered in more detail at this workshop and future ones.

SUPERSYMMETRY

Very good analyses have already been done here; earlier work can be traced from ref. 14,15. Basically it is necessary to trigger on missing momentum. The Standard Model backgrounds have been studied. One problem needing more work is how to extrapolate to higher energies the missing momentum that will occur in any event, due to escaping particles that would normally be detected, detector losses, etc. The graphs I have looked at [b] suggest that the total transverse energy of an event with no large P_T activity scales approximately linearly in $\sqrt{s}$. At 40 TeV that would give $E_T \cong 1$ TeV. The E_T of an event with a hard collision is about twice that of a minimum bias event, so it should be about 2 TeV. UA1 has argued that their missing energy goes as the square root of E_T,

$$E_{miss} \cong 0.7\sqrt{E_T}.$$

Then to be safe any candidate for new physics is required to have 4× this "oneσ" amount. At 40 TeV, this gives $E_{miss} > 125$ GeV, an amount not so large as to make searches difficult. Basically, it means that supersymmetric partners of mass less than a few hundred GeV are difficult to search for because of this background, since they seldon give E_{miss} larger than the background. Better estimates of the relevant numbers can be obtained from Monte Carlos at this workshop and others.

HEAVY LEPTONS

Earlier calculations[4,17] of heavy lepton production were based on Fig. 6a. More recently, Willenbrock and Dicus[18] noted that _if_ a heavy lepton existed, then a heavy quark might also exist, and then production of L^+L^- through a heavy Higgs would have a large cross section, from Fig. 6b. Even more recently, calculations are underway[19] producing heavy leptons via beams of W's, analogous to the WW scattering processes. Just as the contribution of Fig. 1c dominated that of Fig. 1b, one would expect the contribution of Fig. 6c to dominate that of Fig. 6b. For a heavy Higgs it certainly does, while, for lighter Higgs they are comparable. Note the diagrams of Fig. 6c form a gauge invariant set and none can be omitted; large cancellations occur among them. The cross sections are remarkably large, allowing production of heavy leptons up to 2 TeV or so in some situations; hadron colliders are impressive sources of heavy leptons.

Considerable further study is needed on the signature for heavy leptons. Suppose L^+L^- are produced. Most likely each lepton decays to a $W^\pm$ and a neutral partner L^0; the neutral partner may decay itself, or escape the detector. If the L^0 escapes, the signature is a pair of $W^\pm$, which give missing momentum in their decay to $\ell^\pm\nu$, plus more missing momentum. It is not at all clear how to identify such events. From Fig. 6c some $L^\pm L^0$ events are produced, with only one $W^\pm$ and one L^0, so perhaps these events will be easier to find. Monte Carlo studies are badly needed to examine these signatures. Perhaps a useful approach would be to ask what kind of limits could be set on the masses of heavy leptons (that couple to Higgs or to W's) if no signal were observed.

TECHNICOLOR

Finally, it is interesting to look at signatures from technicolor. A few particles that would be produced copiously are shown below, with accompanying branching ratios[20], to suggest signatures.

PARTICLE	MASS(GEV)	DECAYS	
η_T	$240\sqrt{4/N}$	$t\bar{t}$	90%
		gZ	10%
$\pi_T^{\pm}$	"	$t\bar{b}$	75%
		$gW^{\pm}$	20%
π_T^0	"	$g\gamma$	70%
		gZ	30%
LQ	$160\sqrt{4/N}$	$t\tau, t\nu, b\tau, b\nu, c\mu, \ldots$	

Possible signatures are monojets from gZ with $Z \rightarrow \nu\bar{\nu}$, $g\gamma$, W+jet, etc. Note that for technicolor to be an explanation of some new signature, the whole pattern of these must occur.

IMPORTANT TRIGGERS

From consideration of all the above physics we can construct a list of desirable triggers. The goal presumably should be to simultaneously (i) get to a trigger rate ($\approx$10 Hz?), perhaps in two levels, which can be handled with reasonable detectors, and (ii) miss very little of any new physics that might occur.

W^+W^-
$W^{\pm}Z^0$
Z^0Z^0
$WW+E_{miss}$
$W+E_{miss}$
$j+E_{miss}$, $jj+E_{miss}$, etc.
$j\ell^{\pm}+E_{miss}$
jZ

isolated hard γ (from compositeness, from decay of π_T^0, from $\tilde{\gamma}\to\tilde{h}\gamma$, or ?)

τ's (isolated $\pi^\pm$ or $\pi^0\pi^\pm$ are likely to be τ's)

"isolated" μe with low mass (from rare decays such as $B\to\mu e$---isolation would only be partial, and Monte Carlo studies would be useful to judge how much)

$\ell j \ell j$ leptoquark states; $\ell=\ell^\pm$ or ν)

Additional interesting triggers can surely be added, but if most of the above ones can be done we will be very well off. For each trigger, we need to know what is the expected rate for interesting physics, what is the trigger rate due to backgrounds, and what fraction of the signal can be captured.

REFERENCES

1. Proceedings of the 1982 DPF Summer Study on Elementary Particle Physics and Future Facilities, ed. R. Donaldson, R. Gustafson, F. Paige; Snowmass, CO.

2. Summary Report of the PSSC Discussion Group Meetings, June 1984, ed. Phyllis Hale and B. Winstein; $p\bar{p}$ Options for the Supercollider, Proceedings of a DPF Workshop, ed. J. E. Pilcher and A. R. White, Feb. 1984

3. Proceedings of the 1984 Summer Study on the Design and Utilization of the SSC, ed. R. Donaldson and J. G. Morfin, Snowmass, CO.

4. E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. 56(1984)579.

5. For a recent discussion and references see M. S. Chanowitz and M. K. Gaillard, LBL-19470, and ref.6.

6. M. J. Duncan, G. L. Kane, and W. W. Repko, UM TH 85-18

7. G. L. Kane, "Windows for New Particles at Super Colliders," Invited talk at the Conference on the Physics of the XXI Century, Tucson, Dec.1983.

8. S. Dawson, Nucl. Phys. B249(1985)42

9. G. L. Kane, W. W. Repko, and W. B. Rolnick, Phys.Lett.148B(1984)367

10. H. Georgi, S. L. Glashow, M. E. Machcek, and D. V. Nanopoulos, Phys. Rev. Lett. 40(1978)692

11. W. J. Stirling, R. Kleiss, and S. D. Ellis, CERN TH 4209/85

12. J. F. Gunion, Z. Kunszt, and M. Soldate, Oregon Workshop on Super High Energy Physics preprint OITS-298

13. J. van der Bij, private communication

14. H. E. Haber and G. L. Kane, Phys.Rep. 117(1985)77

15. S. Dawson and A. Savoy-Navarro et al, ref.3; S. Dawson, LBL 20199

16. R. D. Field, Florida preprint UFTP-85-13

17. V. Barger, H. Baer, K. Hagiwara, and R. J. N. Phillips, MAD/PH/150

18. Scott D. Willenbrock and Duane A. Dicus, Texas preprint UTTG-03085

19. G. L. Kane and C.-P. Yuan, in preparation

20. Numerical values in this table are from S. Dimopoulos, G. L. Kane, and S. Raby, Nucl.Phys. B182(1981)77

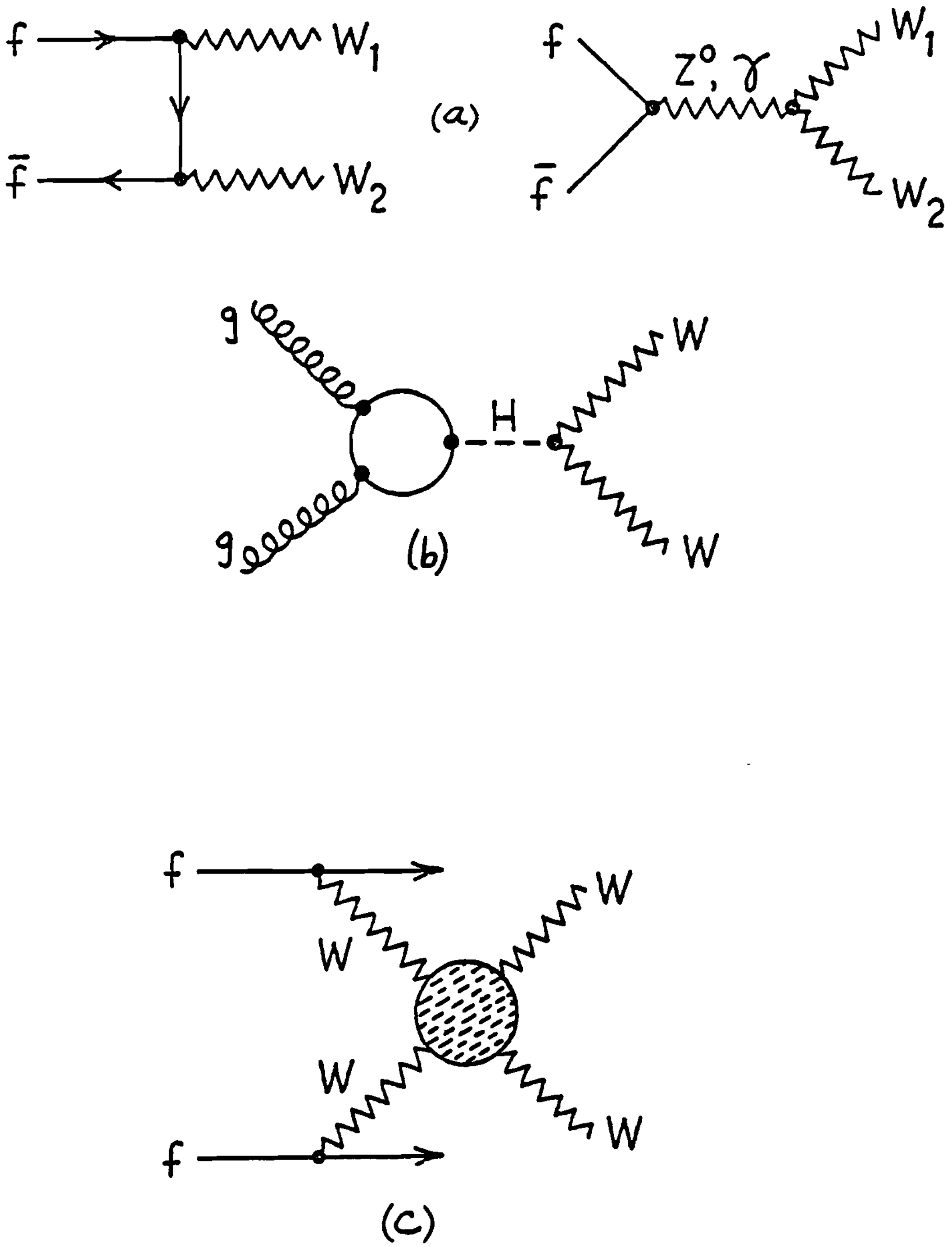

Figure 1. Three sources of W pairs at hadron colliders. The initial fermions or gluons are in hadrons.

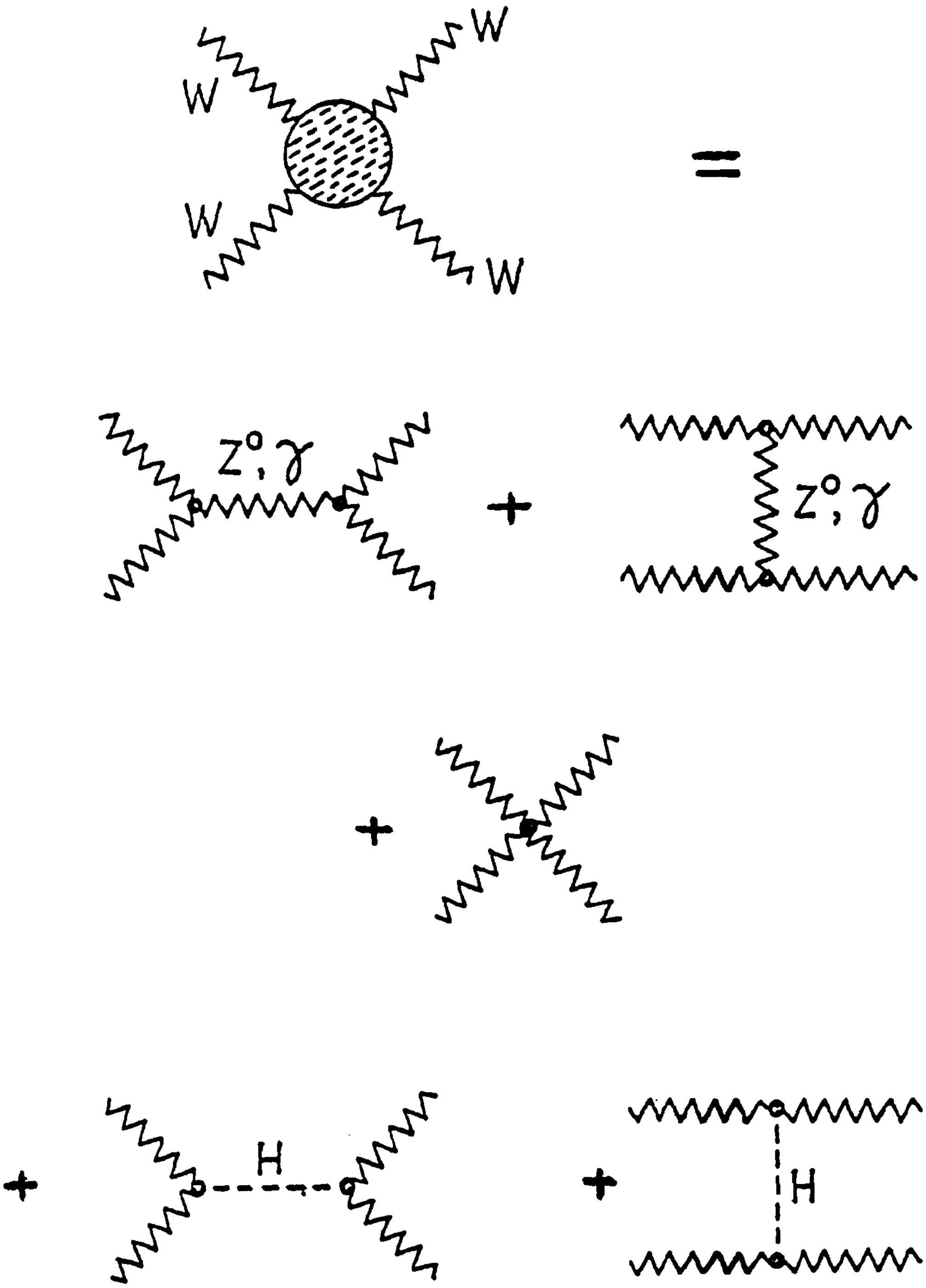

Figure 2. Contributions to Fig.1c. Each individual contribution gives an amplitude growing like s or faster; only the full (gauge invariant) set gives an amplitude that does not grow.

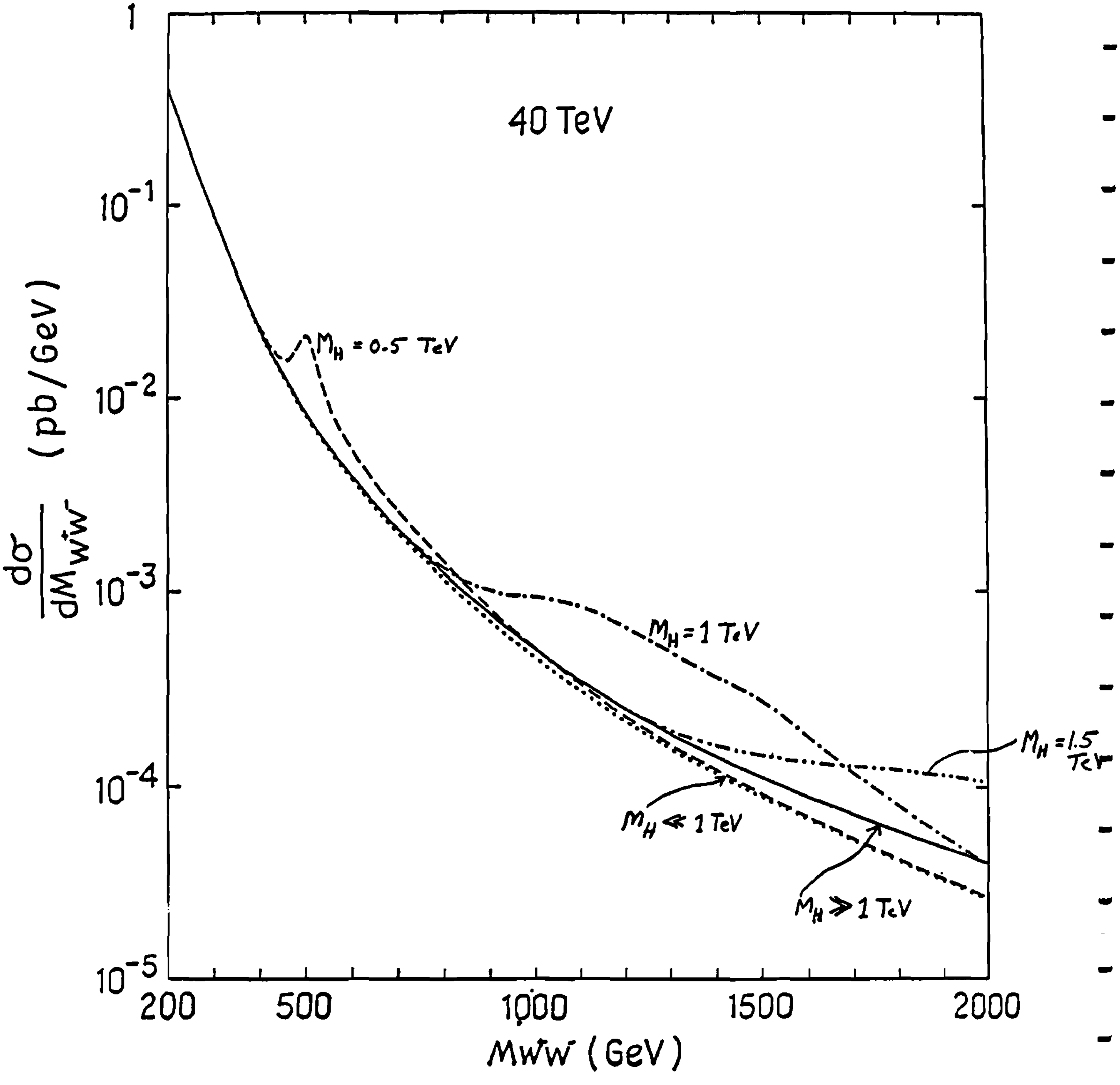

Figure 3. Cross sections for pp collisions at 40 TeV for W pair production. The graphs of Fig.1a give the curve labeled $M_H \ll 1$ TeV. The graphs of Fig.1 and the first three graphs of Fig.2 give the curve labeled $M_H \gg 1$ TeV. The full contributions for specific values of M_H give the other curves.

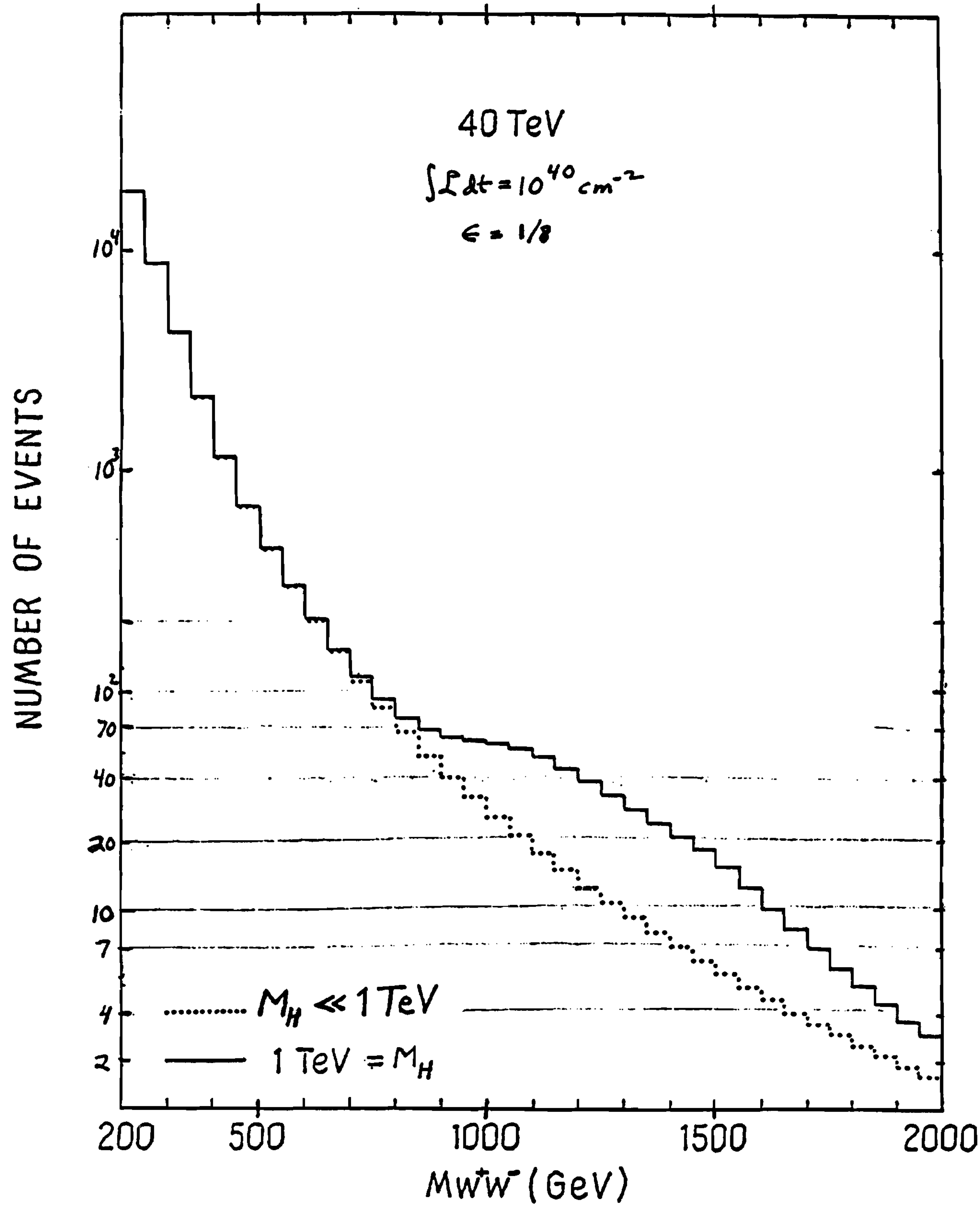

Figure 4. Two of the curves of Fig.3 are plotted, binned and normalized to an integrated luminosity of 10^{40}, assuming 1/8 of all W^+W^- pairs can be detected.

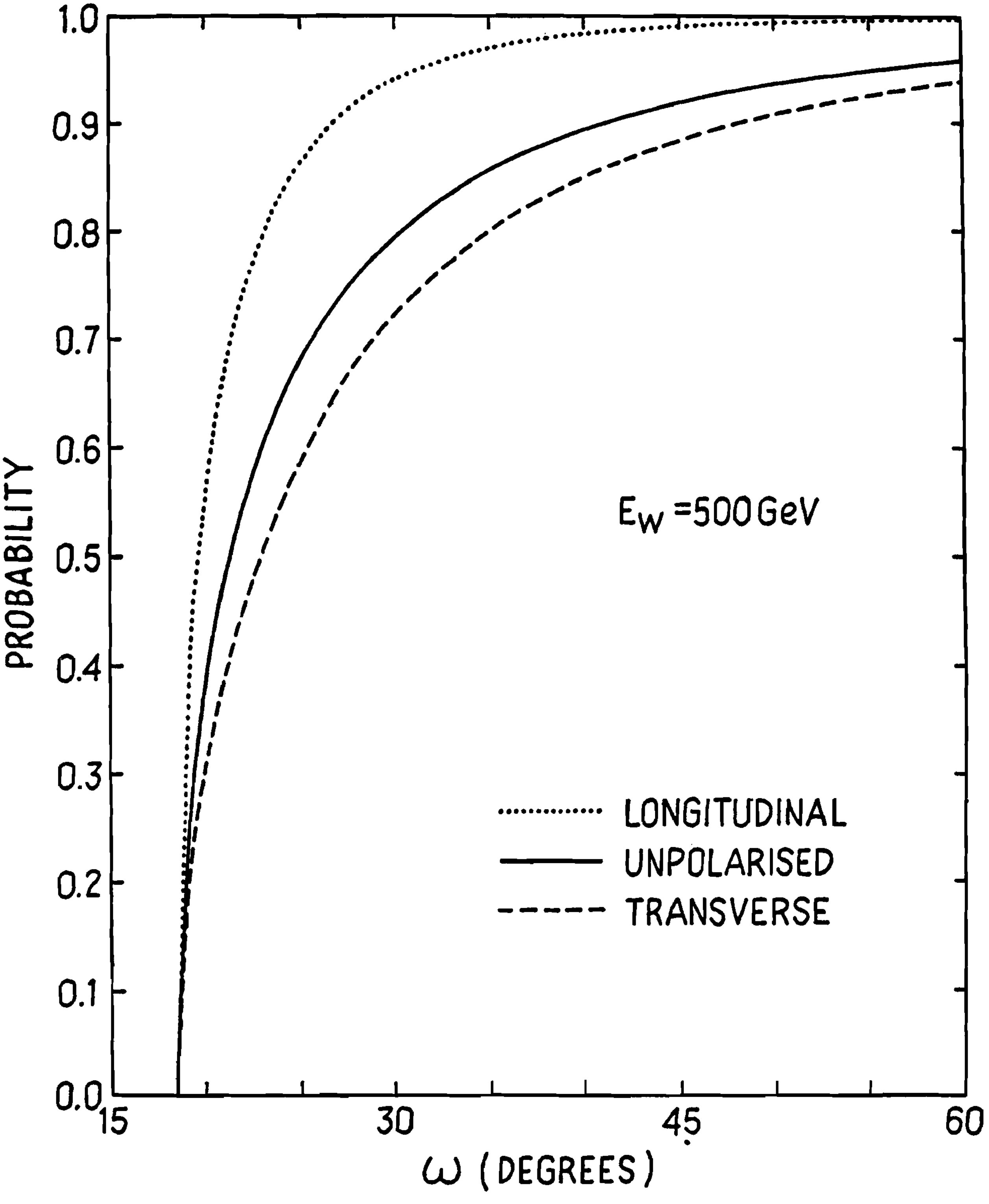

Figure 8. The probability that the opening angle between the fermions from $W \to f\bar{f}$ is less than the given opening angle ω is shown. Note that the opening angle for longitudinal W's is less than for transverse W's.

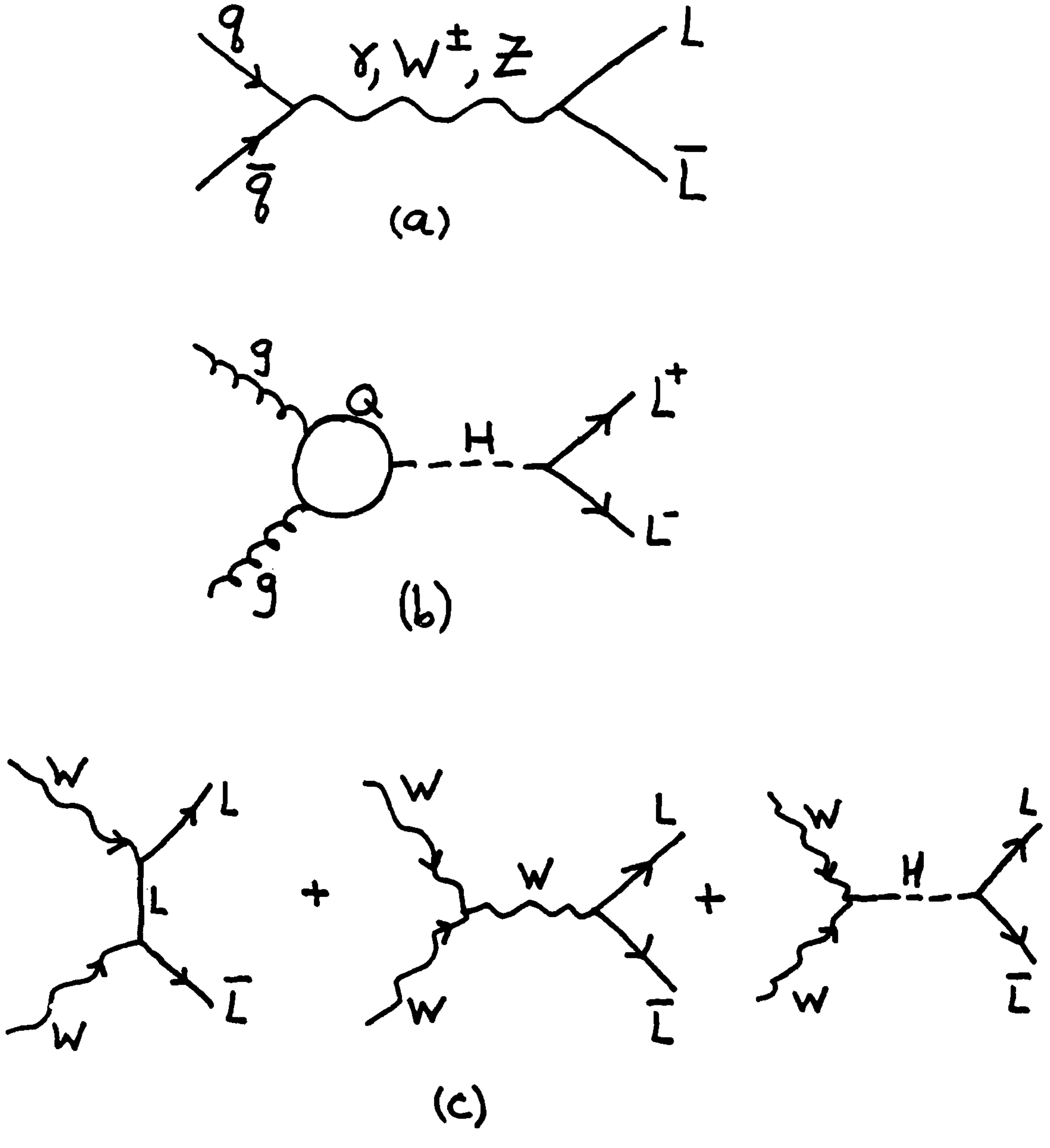

Figure 6. Contributions to heavy lepton production. The full set of graphs of c must be included to get an amplitude not growing with s. Large cancellations occur among the pieces.