Theoretical Report of the W/Z/Higgs Working Group

Probing the W-Z-Higgs Sector of Electroweak Gauge Theories at the Superconducting Super Collider

John F. Gunion

Department of Physics, U.C. Davis, Davis CA. 95616

Group Members

Experimental Coordinator: A. Savoy-Navarro (Saclay)

G. Alverson (FNAL)	A. Mendez (U. Autonoma, Barcelona)
V. Barger (Wisconsin)	B. Milliken (Cal. Tech.)
H. U. Bengtsson (UCLA)	F. Olness (IIT)
P. le'Brun (FNAL)	F. Paige (BNL)
B. Cox (FNAL)	L. Price (ANL)
M.J. Duncan (Penn.)	S. Protopopescu (BNL)
F. Gilman (SLAC)	J. Pumplin (Michigan St.)
J.A. Grifols (U. Autonoma, Barcelona)	H. Reno (FNAL)
J. Hauptman (AMES)	W. Repko (Michigan St.)
D. Hedin (FNAL)	T. Sjostrand (Lund)
M.J. Herrero (LBL)	W. H. Smith (Nevis)
J. Kalinowski (U.C. Davis & Warsaw)	Y. Takaiwa (KEK & FNAL)
G. Kane (Michigan)	W.K. Tung (IIT)
B. Kayser (NSF)	E. Wang (LBL)
Z. Kunszt (Zurich)	S.S.D. Willenbrock (Wisconsin)
S. Linn (Florida St.)	P. Grosse-Wiesmann (SLAC)
S. Matsuda (Kyoto)	C. Young (Florida St.)

Summary

We review and summarize the procedures for exploring at the SSC the W-Z-Higgs sector of $SU(2)_L \times U(1)$ and extended gauge theory versions thereof, including supersymmetric and left-right symmetric models.

1. Introduction

In the standard $SU(2)_L \times U(1)$ model of electroweak interactions and in generalizations thereof (e.g. supersymmetric (SUSY) and extended gauge models) Higgs bosons, and the closely associated WW and ZZ pair channels, provide the most directly observable manifestations of the mechanism for spontaneous symmetry breaking and the underlying gauge nature of the interactions. The basic cross sections and event rates for the standard model (SM) are surveyed in ref. 1, (with the exception of the WW and ZZ scattering continuum processes), and, at first sight, seem more than adequate. However, a large number of backgrounds to observation of these channels have been identified. Recent work, both during and prior to the present summer study, has focused largely on establishing techniques for overcoming these backgrounds and increasing the reliability of both the signal and background calculations. This effort has produced a number of highly specific techniques for detecting the SM Higgs, which, at a theoretical level, will allow discovery throughout the range $m_{H^0} \lesssim 1\ TeV$, and probably somewhat beyond. However, prior to the present summer study, these techniques had not been examined in the presence of the full complexity of minimum bias QCD fragmentation and in the context of a realistic detector simulation—including resolution, hermeticity and similar considerations. During the UCLA Workshop on SM physics, the theoretical techniques were surveyed and an ambitious program for Monte Carlo and detector simulation begun.[2] In these proceedings we present a complete overview of WW, ZZ, and Higgs physics at the SSC. It is divided into two separate reports. The first one, given here, contains a survey of theoretical issues, with emphasis on recent ideas and progress in both the standard model and extended gauge theories. The second report focuses on experimental issues, including a review of the various SM Higgs discovery channels in light of the progress of the complete Monte Carlo and detector simulation program.

2. Theoretical Overview of Standard Model Higgs Detection

We begin by briefly reviewing the techniques advocated at the theoretical level for discovering a SM Higgs. As is well known there are two distinct Higgs mass regions of relevance at the SSC:

$$\begin{aligned} m_{H^0} &\leq 2m_W \\ m_{H^0} &> 2m_W. \end{aligned} \qquad (1)$$

Of course, the most important part of the first region is that portion which cannot be probed by e^+e^- colliders that are currently operating or under construction. Such m_{H^0} values are termed "intermediate". We focus on this latter region first.

Throughout this report we shall quote event rates and statistical significance based on the standard values,

$$\sqrt{s} = 40\ TeV \qquad L_{SSC\ year} = 10^4\ pb^{-1}, \qquad (2)$$

for the SSC energy and yearly luminosity.

The Intermediate Mass Region

In the intermediate mass region, decays to WW and ZZ pairs are not allowed, and the SM Higgs will decay primarily to the heaviest accessible fermion channel. For $m_t < m_W$ there could be a significant region of m_{H^0} for which this will be the $t\bar{t}$ channel. Under these circumstances backgrounds appear to be insurmountable.[3][4] For instance, a promising production channel was thought to be associated $W^{\pm}H^0$ production, using the leptonic W decay modes as a trigger. Unfortunately the backgrounds, particularly from $gg \to W^+b\bar{t} + gg \to W^-\bar{b}t$, and $t\bar{t}$ mass resolution problems explored in ref. 3 appear to make this channel unfeasible. New ideas for improving the $t\bar{t}$ pair mass resolution, while maintaining good b-t discrimination, would be required. Further progress in this direction was not made at this summer study.

The possibilities for using rare decay modes of the H^0 in the $2m_t < m_{H^0} < 2m_W$ situation have also been explored.[4] We briefly survey some of the conclusions; specific numbers assume $m_t = 40\ GeV$. We consider first inclusive H^0 production followed by rare decay. Possibly interesting modes include:

a) $\gamma\gamma$: at $m_{H^0} = 130\ GeV$ and for a 1% resolution in the photon pair invariant mass, we obtain a signal to background ratio of 60:1000 events. The $Z\gamma$ channel has about the same signal event rate but the background is roughly a factor of 8 larger at this same value of m_{H^0}.

b) $\Theta\gamma$: at $m_{H^0} = 130\ GeV$ we obtain a signal event rate of $\lesssim 3$ events per year, i.e. clearly hopeless.

c) WW^* and ZZ^*: event rates become significant for m_{H^0} values near $2m_W$. Final state modes in which one of the vector bosons decays hadronically while the other decays leptonically are masked by backgrounds that are difficult to overcome even when the WW/ZZ decay modes are on-shell; these will be discussed later in this review. If we consider WW^* with both the real and virtual W's decaying to $l\nu$ channels, mass reconstruction is impossible and WW (on-shell) continuum backgrounds are overwhelming. Only the ZZ^* channel with $Z \to l^+l^-$ and $Z^* \to l^+l^-$ or $\nu\nu$ allows for reconstruction of the m_{H^0} mass. In the case of the $\nu\nu$ mode, transverse mass, as described later in this review, would be used; but the on-shell continuum background overwhelms the signal at Higgs mass values in the intermediate range. The all-charged lepton mode would provide a clean signal but suffers from a very small branching ratio. Even at $m_{H^0} = 160\ GeV$ we obtain only 10 events per year.

d) $\tau^+\tau^-$: the event rate is significant, but backgrounds are probably large—additional study might be worthwhile.

Also considered were associated H^0 production modes followed by rare decay. Here the most promising case was $W, Z + H^0$ production followed by $H^0 \to \tau^+\tau^-$ decay. It deserves careful study, but was not pursued during this year's summer study.

The situation in the $2m_t < m_{H^0} < 2m_W$ region could be dramatically improved if there were a still heavier fourth generation of fermions. First, the "rare" decay mode $H^0 \to L^+L^-$, where L is the fourth generation lepton, could provide a very distinct signal. In ref. 4 it was found that the signal to Drell-Yan background ratio was $\gtrsim 1$ for $m_L \gtrsim 15\ GeV$, for 5% resolution in the L^+L^- channel, rising rapidly for higher values of m_L. Cross section times branching ratio for this H^0 decay mode is typically of order 1 to 10 *pb*. While the mass resolution is undoubtedly optimistic, given the complex nature of the L decays, the event rate would be high and discovery of the H^0 should be possible.

A second fourth generation scenario has recently been explored in refs. 5 and 6. Let us call the lighter (charge -1/3) quark of this fourth generation v. The v quarks can form spinzero bound states, η_v, which turn out to have a large branching ratio for the decay

$$\eta_v \to ZH^0. \qquad (3)$$

In addition, for most quark potentials, the gg fusion production cross section of the η_v is substantial.[5] Since the dominant decay of the H^0 in the H^0 mass range specified above is to $t\bar{t}$, the primary background to H^0 discovery in the channel (3) will be from the

$$gg \to Zt\bar{t} \qquad (4)$$

mixed QCD-Electroweak process. This has been computed in ref. 6, and compared to the signal cross section from reaction (3). Even allowing for pessimistic resolution in the $t\bar{t}$ channel, but noting that resolution in the $Zt\bar{t}$ invariant mass should be at least moderately good, ref. 6 concludes that, although the background is serious, simultaneous discovery of the η_v and an intermediate mass H^0 should prove possible.

Of course, in the last year, it has also become apparent that the $m_t > m_W$ possibility should be taken more seriously. We discuss this case in the absence of a fourth generation. A large top mass has a number of desirable effects in the $m_{H^0} < 2m_W$ region. Most importantly, $H^0 \to b\bar{b}$ decay will dominate over most of the $m_{H^0} < 2m_W$ region. Considering again the associated production channel $W^\pm H^0$, the gg induced background would be from $gg \to W^\pm cs$, assuming that the $gg \to W^\pm bt$ background is no longer relevant due to the high mass of the t. The $W^\pm cs$ background could then be eliminated and adequate event rate maintained if vertex tagging on the b at full luminosity is possible. Alternatively, a semi-leptonic decay of one of the b's could be tagged using a "high"-p_T lepton. Either way, we would be left with the irreducible background from $q\bar{q}' \to W^\pm b\bar{b}$. The studies of ref. 3 showed that a $b\bar{b}$ pair mass resolution of 10%, in combination with various other cuts, would yield signal/background larger than 1. A detailed study of $b\bar{b}$ mass resolution, in the presence of various triggers is required. Since the b decays yield fewer soft particles and neutrinos than the t decays, there is cause for optimism. The question of $b\bar{b}$ channel mass resolution, for a leptonic b trigger, is pursued in a contribution to these procedings, ref. 8, and various flavor identification issues are reviewed in ref. 9. These studies support the feasibility of H^0 discovery in the $b\bar{b}$ channel. Finally, we note that the absence of $H^0 \to t\bar{t}$ also implies a smaller H^0 width. In this case many of the rare decay modes of the H^0 discussed earlier might yield a viable signal. Particularly appealing is the decay mode $H^0 \to \gamma\gamma$,[10] in which excellent mass resolution, 1% as quoted earlier, is possible. Preliminary estimates indicate that the continuum photon-pair background no longer overwhelms the Higgs signal. Referring to the event numbers given earlier, the background is unchanged, whereas the $H^0 \to \gamma\gamma$ branching ratio, and associated event rate, will be at least a factor of 10 larger. The Higgs signal should be clearly observable. Further work is in progress.[10]

The $m_{H^0} > 2m_W$ Region

The mass region $m_{H^0} > 2m_W$ received the bulk of attention at this year's summer study. Here the main question is whether or not it is possible to overcome backgrounds to WW and ZZ pair detection in the region of a H^0 resonance. We review the theoretically advocated procedures.

The ideal mode from a background point of view is

$$H^0 \to Z(\to l^+l^-)Z(\to l^+l^-), \qquad l = e, \mu. \qquad (5)$$

It has been explored in refs. 11, 12, and 13. The final state is completely reconstructable, mass resolution is excellent, and hadronic effects are relevant only if special triggers are imagined, such as those discussed later. However, the branching ratio for this ZZ decay mode is only $\sim 3.6 \times 10^{-3}$. Nonetheless, for the standard SSC operating year of eqn. (2), the event rate is clearly adequate for $m_{H^0} \lesssim 0.5\ TeV$. For instance, at $m_{H^0} = 0.4\ TeV$, integrating over Z-pair masses within $\pm\Gamma_H/2$ of m_{H^0}, and requiring $|y_Z| < 2.5$ for both Z's, yields ~ 35 Higgs events in comparison to ~ 15 ZZ continuum background events (using results from ref. 1 corrected for the $\pm\Gamma_H/2$ restriction). We note that it is critical that the ZZ continuum be accurately normalized by measurements away from the Higgs resonance. In fact, optimized techniques for weighting on- and off-resonance data have been developed in ref. 14, and would lead to a high level of significance for such a Higgs signal. Beyond $m_{H^0} = 0.5\ TeV$ the mode (5) appears marginal, depending on the exact magnitude of the WW/ZZ fusion cross section. Discovery of a Higgs in this mode at somewhat higher mass might be possible by using[12] the predicted longitudinal, $\sin^2\theta^*$, distribution of the Z decays, originating from the H^0, to discriminate against ZZ continuum background, for which the Z's are mainly transverse, and decay with a $1+\cos^2\theta^*$ distribution. (The angle θ^* is the decay angle of the l^+l^- pair in the Z rest frame relative to the Z's direction of motion.) Such longitudinal decay analysis could possibly be done in combination with a cut on the total transverse momentum of the ZZ system. Such a cut discriminates against the $q\bar{q} \to ZZ$ background, which tends to have less energetic accompanying secondary jets than the spectator jets that are required as part of the WW/ZZ fusion mechanism for H^0 production. These latter produce an $< p_T >$ for the H^0 of order m_W.[13] In ref. 13 it is estimated that requiring $p_T^{ZZ} > 60\ GeV$, in addition to $|y_Z| < 1.5$ and $m_{H^0} - \Gamma_H < m_{ZZ} < m_{H^0} + \Gamma_H$, yields 9 signal events compared to 4.5 background events in a standard SSC year at $m_{H^0} = 0.6\ TeV$. Realistically, it seems likely that the all charged lepton channel will be very marginal by $m_{H^0} = 1\ TeV$ unless a specially designed, lepton-intensive interaction region with 10 times the standard SSC yearly luminosity is implemented.[15]

As a final point, we note that if the top mass is as heavy as $m_t = 150\ GeV$ then H^0 cross sections are dominated by gg fusion out to $m_{H^0} = 1\ TeV$. For instance, at $m_{H^0} = 0.7\ TeV$ the total H^0 cross section would be three times as large as predicted from WW/ZZ fusion alone,[7] while the $t\bar{t}$ branching ratio of H^0 decay would remain below 10%. (Plots of $\Gamma(H^0 \to t\bar{t})/\Gamma(H^0 \to ZZ + WW)$, for a variety of m_t values as a function of m_{H^0} are given in ref. 2.) Thus large top masses will substantially extend the range over which the mode (5) is viable.

The second discovery mode that has been explored in some detail[16] is

$$H^0 \to Z(\to l^+l^-)Z(\to \nu\bar{\nu}), \qquad l = e,\mu. \tag{6}$$

It retains the advantage of having no significant hadronic backgrounds, and has the additional advantage of a much larger branching ratio for ZZ decay in the indicated mode, $\sim 2.2 \times 10^{-2}$. Its disadvantage is the missing energy of the $\nu\bar{\nu}$ pair. The Higgs is revealed as an enhancement in the transverse mass spectrum:

$$m_T = 2\sqrt{p_T^2 + m_Z^2}. \tag{7}$$

The authors of ref. 16 argue convincingly that the ZZ continuum background will be smaller than the H^0 signal provided the observed Z is restricted to $|y_Z| \lesssim 1.5$, and an appropriate cut on m_T is made. In addition, due to the larger BR, event rates remain adequate out to and possibly beyond $m_{H^0} = 1\ TeV$. Only when $m_{H^0} \lesssim 0.4\ TeV$ does the m_T spectrum of the H^0 begin to merge into that from the continuum background. There the alternative charged lepton mode (5) is certainly viable. More quantitatively, one computes

$$\Sigma = \int_{m_T^{min}} \frac{d\sigma}{dm_T} dm_T \tag{8}$$

where m_T^{min} is some cutoff chosen to reduce the ZZ continuum background. For example, at $m_H = 0.8\ TeV$ the optimal value is $m_T^{min} = 0.7\ TeV$, yielding (after requiring $|y_Z| < 1.5$)

$$\Sigma_{signal} = 0.0054\ pb \qquad \Sigma_{background} = 0.0017\ pb, \tag{9}$$

which includes all branching ratios for the decay (6), and corresponds to a nominal $\sim 12\sigma$ effect in a standard SSC year, eqn. (2). As in the previous case, mode (5), absolute normalization of the ZZ continuum background is critical. In the present case the broader nature of the m_T bump makes it more difficult to move on and off resonance. However, the optimized techniques of ref. 14 were applied directly to this case, and, for a standard SSC year, yield high statistical significance for a $m_{H^0} = 0.8\ TeV$ signal in the m_T spectrum, even if the ZZ continuum normalization is uncertain by as much as a factor of 2, so long as its m_T shape is relatively certain. Finally, as in the previous case, large m_t tends to increase the cross section for H^0 production more than it decreases the branching ratio for H^0 decay to the channel of interest.

The final techniques suggested for Higgs discovery focus on the mixed hadronic-leptonic decay modes of the WW and ZZ final states. Clearly the relevant branching ratios are much larger than those appropriate to the previous channels. For instance, if we focus on the case

$$H^0 \to W(\to ud + cs)W(\to e\nu + \mu\nu), \tag{10}$$

the branching ratio for WW decay in the indicated channels is ~ 0.16. Backgrounds from

$$q\bar{q} \to WW \tag{11}$$

were given early consideration[1] . They do not cause major difficulty. The background from processes of the type

$$gg \to WW, \tag{12}$$

via fermion box diagrams, was considered in a contribution to these proceedings.[17] It yields a higher percentage of longitudinally polarized W's than does (11), but is not so large as to present a problem.

However, direct WW production processes are not the only background to the mixed mode decay of eqn. (10). Mixed QCD-Electroweak backgrounds of the type

$$qg \to q'gW;\ qq \to qq'W;\ gg \to q\bar{q}'W;\ .. \tag{13}$$

present a serious challenge.[18][19][20] Simply restricting the invariant mass of the 2-jet system to a narrow bin, say

$$.975m_W < m_{j_1j_2} < 1.025m_W, \tag{14}$$

corresponding to 5% resolution in the jj invariant mass, is totally inadequate for obtaining a reasonable signal to background ratio.[18][19] Techniques for singling out events in which the two jets come from a longitudinally polarized W are required. However, direct use of the rest frame decay angle, θ_{jj}^*, of the jj system is not possible. This is because the jjW backgrounds, (13), tend to accumulate at low p_T, and, thus, a substantial p_T cut must be imposed. This removes a large portion of the θ_{jj}^* range. In ref. 20 an alternative procedure was developed. We first imagine reconstructing the jjW mass, m_{WW}. This is done by measuring the transverse momenta of j_1, j_2, and l ($= e$ or μ) to determine that of the ν. The ν four-momentum can then be determined up to a two-fold ambiguity by requiring the invariant mass of l and ν to equal m_W. The solution with smallest mass, m_{WW}, for the WW system is then chosen. At the same time the angle of the leptonic W decay, θ_l^*, is determined. As part of the reconstruction process it is important to measure other jets in the event (such as the jets that are spectators in the WW fusion subprocess) so that the net transverse momentum of the W-pair system is determined to reasonable accuracy with respect to m_{WW}. Next, a cut on m_{WW} is imposed:

$$(m_H - \Delta m_H) < m_{WW} < (m_H + \Delta m_H), \qquad (15)$$

where $\Delta m_H = max(.05 m_H, \Gamma_H)$. Given our now complete determination of the WW system it is possible to impose the cuts

$$\frac{p_T^{min}}{m_{WW}} > r_{min} \qquad \frac{(p_T^{max} + p_T^{min})}{m_{WW}} > r_{sum}, \qquad (16)$$

which are found to be extremely effective in enhancing the percentage of jjW events in which the jj system comes from a longitudinal W. In particular, these latter cuts discriminate strongly against the jjW backgrounds of eqn. (13). Optimal values for r_{min} and r_{sum} are approximately 0.125 and 0.35, respectively. Here, the jet with largest transverse momentum has p_T^{max} and that with the smaller has p_T^{min}. As an example, with the additional cuts $|\cos(\theta_l^*)| < 0.5$ (to enhance the longitudinal leptonically decaying W's) and $|y^{j_1,j_2,l}| < 4$ (to guarantee that measureable tracks appear in the detector), one obtains, at $m_H = 0.8\ TeV$,

$$\sigma_{signal} = 0.04\ pb \qquad \sigma_{background} = 0.06\ pb, \qquad (17)$$

corresponding to a 16σ effect, for the yearly luminosity of eqn. (2). These cross sections include summation over both charges for the hadronically (and leptonically) decaying W.

A second technique for reducing backgrounds of the jjW type of eqn. (13) has also been explored.[21][18] In this approach the spectator jets in the WW/ZZ fusion subprocess are used as a trigger. The QCD-Electroweak processes, (13), are estimated to have spectator jets with much less transverse momentum, on average, than those accompanying the vector boson scattering processes of interest. Through appropriate cuts, such as requiring that each of the spectator jets have p_T of at least 60 GeV, a signal to background event ratio of order 460:490 (for a standard SSC year and including both WW and ZZ mixed modes) at $m_{H^0} = 0.4\ TeV$ is obtained. There appears to be no reason why this type of cut cannot be combined with the r_{min}-r_{sum} cuts of ref. 20, discussed above. Indeed these latter cuts will probably require measurement of the spectator jets in any case. Together a very favorable signal to background ratio might be achievable.

Comparing the detection modes (6) and (10), there are obvious advantages and disadvantages to both. Clearly the event rate, even after cuts, for the mixed mode decays is much higher. In addition, it is important to note that the only important background in the mixed mode case, from the QCD-Electroweak processes (13), can be experimentally determined by measurement on and off the W resonance in the $j_1 j_2$ system. One need not rely, as for the mode (6), only on observing an enhancement in the full Higgs system mass spectrum, m_T or $m_{j_1 j_2 W}$, depending on the mode. Use of the combined spectra in $m_{j_1 j_2}$ and $m_{j_1 j_2 W}$ would be particularly powerful in the statistics approach of ref. 14. One of the questions which was pursued at this summer study was the degree to which these advantages of the mixed mode are offset by the effects of beam, target, and jet fragmentation. The complexity of analysis of a realistic mixed mode event, in comparison to the obvious relative cleanliness of events of the type (6), could easily offset the above advantages. We shall return to these questions in the experimental report.

In the above discussion we have ignored the backgrounds that arise from

$$WW \to WW \qquad ZZ \to WW \qquad (18)$$

continuum scattering. These cannot really be separated from the Higgs resonance, since the latter is only one term in a complete gauge invariant set of amplitudes describing such scattering processes.

The contributions from the subprocesses (18) were computed in the effective-W approximation,[22] using spin averaged effective-W distributions and on-shell WW and ZZ scattering cross sections, in ref. 23, with the result that the enhancement in the m_{WW} spectrum from the H^0 was still significant. The spin averaging and various evolution and kinematical approximations can be removed by obtaining separately the distributions for W's and Z's with a given polarization, folding two such distributions with fixed polarizations together with the subprocess cross section for these same polarizations, and summing over different cases. Work in this direction has been begun in refs. 24 and 25. In particular, it appears from ref. 25 that the leading log formulae for effective-W distributions tend to be overestimates, especially for the transversely polarized W's.

The accuracy of the effective-W approximation, per se, in the context of the processes of the type

$$q_1 q_2 \to q_3 q_4 WW, \qquad (19)$$

can also be examined. Exact calculations of the reactions (19) are in progress by several groups.[26][27][28] There appears to be considerable sensitivity in the effective-W approach to the Coulomb exchange singularity in on-shell WW scattering.[26][27]

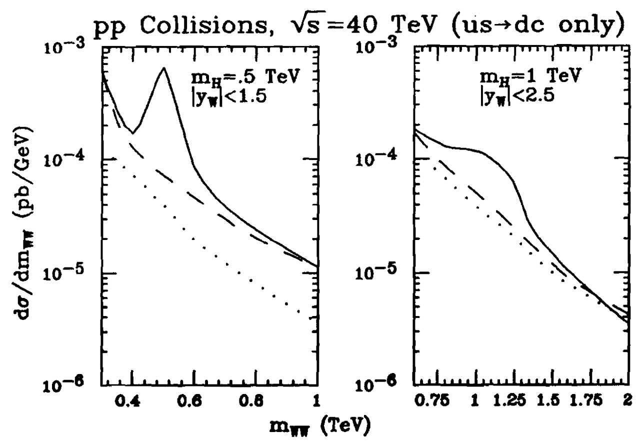

Figure 1: We give $d\sigma/dm_{WW}$ for pp collisions at $\sqrt{s} = 40\ TeV$. Only the single subprocess $us \to dcWW$ is included. We plot (solid lines) cross sections for the purely electroweak sector calculation in the cases: a) $m_H = 0.5\ TeV$ with $|y_W| < 1.5$; and b) $m_H = 1\ TeV$ with $|y_W| < 2.5$. In both cases, we also given curves for $m_H = \infty$ (dashed lines) and for the gluon exchange cross section (dotted lines), subject to the same W rapidity cuts. We have assumed that one W decays hadronically and the other leptonically, and thus have constrained both jets and the charged lepton from these decays to have $|y| < 4$.

This singularity is naturally regulated[26] in a complete calculation of the actual physical process (19). However, it was regulated in a somewhat *ad hoc* manner in the work of ref. 23. The partial results available from the exact calculations indicate that the Higgs enhancement in the m_{WW} spectrum from processes of the type (19) will, in fact, be clearly visible above the smooth background arising from this same subprocess set. And, as expected, the Higgs excess agrees with the exact on-pole calculations of ref. 29. However, the precise level of the smooth continuum, arising from the same calculations, is generally different from that given by the effective-W approach. A technique for regulating the effective-W on-shell amplitudes, that yields agreement with the exact results for all kinematical configurations, would be very valuable. Of course, the Coulomb exchange process is only present in WW scattering; WZ and ZZ continuum processes should yield better agreement between effective-W and exact calculations. Finally, it should be noted that the calculations of ref. 26 include the gluon exchange contribution to (19), and that a rapidity cut on the final W's is sufficient to keep this g exchange continuum process small. In fig. 1, we give the results of ref. 26. Further work is under way. (In particular, the corresponding results for the ZZ final state must be obtained in order to assess the impact of the above type of continuum backgrounds upon the purely leptonic final states, eqns. (5) and (6).) Additional discussion of the effective-W approach appears elsewhere in these proceedings.[30]

As a final note we must consider the possibility that the Higgs is very massive and that the primary physics of interest will be measurement of the WW, WZ and ZZ continuum production processes, in particular the vector boson scattering contributions. This will probably be impossible in the mixed mode channel due to the jjW backgrounds discussed above. The r_{min}-r_{sum} cuts are of no value until m_{WW} or m_{ZZ} masses are so large that a substantial fraction of the events contain longitudinal W's or Z's. By this time event rates after cuts are rather low. A similar problem is encountered in spectator triggering, which serves to enhance the vector boson scattering contributions. Event rates will be low when m_{WW} and m_{ZZ} are large enough that vector boson scattering is the dominant contribution to the continuum processes. However, further study is certainly warranted. In contrast, purely leptonic final states should allow detailed determination of the vector boson pair continuum processes. In particular, the purely leptonic mode (6) appears promising for observation of the ZZ continuum processes above $m_{ZZ} = 1\ TeV$ if the H^0 is not present. This was not studied in detail as part of the summer study but has been examined in ref. 31. It will be important to reexamine the high m_{WW}-m_{ZZ} regions using the exact calculations discussed in the preceding paragraph.

With this preparation, the reader could now turn to the discussion in our second report on the full Monte Carlo and detector simulation program. In the second part of this report we shall turn to a discussion of extended gauge theories and their impact upon Higgs discovery and the physics of the WW/ZZ sector.

3. Extended Gauge Theory Scenarios

Though it is clearly important to thoroughly investigate the standard model scenarios for Higgs discovery, it is probably true that most theorists believe that the actual Higgs sector will be more complicated. In particular, there are a variety of extended gauge models—such as supersymmetric, left-right symmetric, and string inspired E_6 theories— that yield an extremely rich spectrum of Higgs particles, as well as new mechanisms for producing them. It is the purpose of this section to give a brief overview of recent progress in understanding the techniques and modes for observing Higgs bosons in these more complex scenarios.

Supersymmetric Models

In order to illustrate the possibilities we will consider the minimal supersymmetric extension of the standard model, investigated in refs. 32 and 33. In this model there are 4 physical Higgs bosons, $H^\pm$, H_1^0, H_2^0, and H_3^0—H_1^0 and H_2^0 are scalars while H_3^0 is a pseudoscalar. By convention we take $m_{H_2^0} < m_{H_1^0}$. All parameters of the model are fixed by choosing values for $m_{H_1^0}$ and $m_{H_2^0}$ and a sector parameter, $\epsilon = \pm 1$ (with the + sign being preferred for a top mass above 40 GeV). In the minimal model considered in refs. 32 and 33 we have the constraints

$$\begin{aligned} m_{H_1^0} &\geq m_Z \\ m_{H_2^0} &\leq m_Z \\ m_{H_3^0} &= \sqrt{m^2_{H_1^-} + m^2_{H_2^0} - m^2_Z} \\ m_{H^\pm} &= \sqrt{m^2_W + m^2_{H_3^0}}. \end{aligned} \tag{20}$$

We shall consider the following representative choices for two of the parameters:

$$m_{H_2^0} = 0.01 m_Z \ or\ 0.5 m_Z \qquad \epsilon = +, \tag{21}$$

and vary $m_{H_1^0}$ or, equivalently, $m_{H^\pm}$. If H_2^0 were to lie very near to the Z in mass, then the results could be quite different from those we give, see ref. 33. We note that, for the choice $m_{H_2^0} = 0.5 m_Z$, the limit $m_{H_1^0} \to m_Z$ yields, from eqn. (20), the lower limit $m_{H^\pm} = 95\ GeV$. In addition, the angle β, which appears in several later formulae, takes on the value $\pi/2$ in that limit, but drops very rapidly, for increasing $m_{H^\pm}$, to $\pi/4$. For instance, by $m_{H^\pm} = 105\ GeV$ we have $\beta = 0.8\pi/2$, and the factor $\cot\beta$ which appears below is $\sim 1/3$. For the smaller value of $m_{H_2^0}$, all these statements move to lower $m_{H^\pm}$ masses. (For the preferred $\epsilon = +$ sector, $\cot\beta$ is always smaller than 1.)

Also important in discussing supersymmetric scenarios are the supersymmetric partners of the standard model particles. These include:

1. squarks, with generic symbol $\tilde{q}$;
2. gluinos, $\tilde{g}$;
3. sleptons and and sneutrinos, $\tilde{l}$ and $\tilde{\nu}$, respectively;
4. the neutralino partners of the γ, Z, H_1^0, and H_2^0, called $\tilde{\gamma}$, $\widetilde{H_0}$, $\widetilde{Z_+^0}$, and $\widetilde{Z_-^0}$, and represented as a group by the symbol $\widetilde{\chi^0}$;
5. the chargino partners of the $W^\pm$ and $H^\pm$, the $\widetilde{\chi_1^\pm}$ and $\widetilde{\chi_2^\pm}$, and represented as a group by the symbol $\widetilde{\chi^\pm}$.

In the following discussion we shall assume that the $\tilde{q}$'s and $\tilde{l}$'s are too heavy to participate in Higgs decays. Inclusion of such decay channels does not substantially modify any of our conclusions.[33][7] Currently the phenomenological constraints on the masses of the $\widetilde{\chi^0}$'s and $\widetilde{\chi^\pm}$'s are rather weak, and these particles could be either light or heavy. The implications of a particular model[34] in which they are light were explored in ref. 33. When light, they play a crucial role in the phenomenology of the Higgs sector, since they provide the dominant decay modes for all the Higgs, other than the light H_2^0.

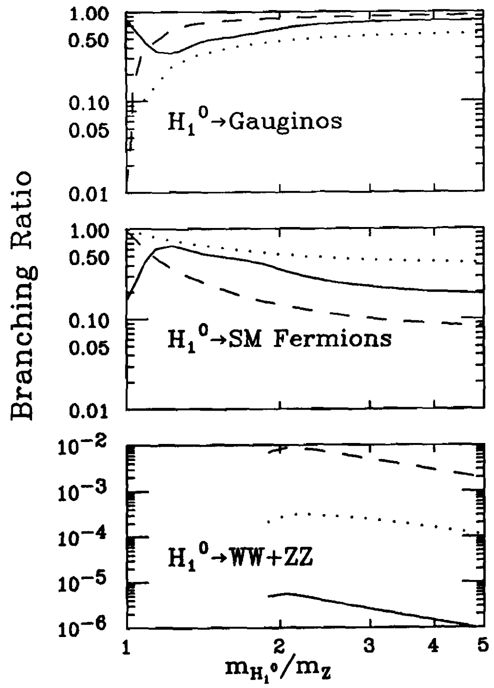

Figure 2: We plot the branching ratio for H_1^0 decay into the WW/ZZ, SM fermion, and neutralino/chargino (called gaugino) channels. We have taken the light mass model of ref. 33 for the latter particles. The different curves correspond to different values for the parameter $r_2 = m_{H_2^0}/m_Z$: solid for $r_2 = .01$; dashes for $r_2 = .5$; and dots for $r_2 = .99$. In all cases we have taken $\epsilon = +1$.

Neutral Higgs:

Turning first to the neutral Higgs sector, it turns out that the light H_2^0 is very similar in phenomenology to a SM Higgs of similar mass, and would, therefore, be most easily produced and detected at an e^+e^- collider.

In contrast, the heavier H_1^0 can differ greatly from the SM H^0. In particular, the H_1^0's coupling to the WW/ZZ channels becomes negligible for $m_{H_1^0} \gtrsim 2m_Z$. Thus it is both narrower and more weakly produced than a SM Higgs of the same mass. A heavy H_1^0 is produced primarily by gg and $t\bar{t}$ fusion; see the recent calculation of ref. 7. Such a H_1^0 will decay primarily to $t\bar{t}$ (if the channel is allowed) unless some of the neutralinos or charginos are light. The relative sizes of the important H_1^0 branching ratios are illustrated in fig. 2, in the case of the light chargino/neutralino model of ref. 33. (Additional plots can be found in that paper.) If the $t\bar{t}$ decays dominate, detection of H_1^0 will be very difficult. The case in which the neutralino/chargino channels are allowed was explored as part of the present summer study in ref. 35, using the model developed in ref. 33. It was found that the decay

$$H_1^0 \to \widetilde{Z}_{\pm}^0(\to l^+l^-\tilde{\gamma})\widetilde{H}_0(\to \gamma\tilde{\gamma}) \qquad (22)$$

should provide a detectable signal. The direct background from $\widetilde{Z}_{\pm}^0\widetilde{H}_0$ continuum pair production is very small. The largest background comes from

$$q\bar{q} \to l^+l^-\gamma + \vec{p}_T^{\,miss}, \qquad (23)$$

where $\vec{p}_T^{\,miss}$ is generated by fake missing momentum. This background can be controlled by a suitable set of cuts on the l^+l^- and $l^+l^-\gamma$ invariant masses, on the angles of of the l^+ and l^- with respect to the γ, and on the photon energy, E_γ. After these cuts one obtains, for the particular mass choice studied, $m_{H_1^0} = 0.4\ TeV$, the cross sections:

$$\sigma_{signal} = 0.024\ pb \qquad \sigma_{background} = 0.010\ pb. \qquad (24)$$

Techniques for further gains in signal/background are described in ref. 35.

Finally, the H_3^0 may be quite difficult to observe at the SSC,[33] but a more detailed study is warranted.

Charged Higgs:

The charged Higgs of the minimal SUSY model, or of any two-doublet version of the standard model, may present a considerable challenge. There are two distinct cases to consider:

$$m_{H^\pm} < m_t + m_b \qquad m_{H^\pm} > m_t + m_b. \qquad (25)$$

In the first case, a dominant production mode for the $H^\pm$ could be via $t\bar{t}$ production followed by t decay. Neglecting m_b we may write the relevant $H^-t\bar{b}$ coupling as

$$\frac{g}{2\sqrt{2}m_W} m_t(1+\gamma_5)\cot\beta. \qquad (26)$$

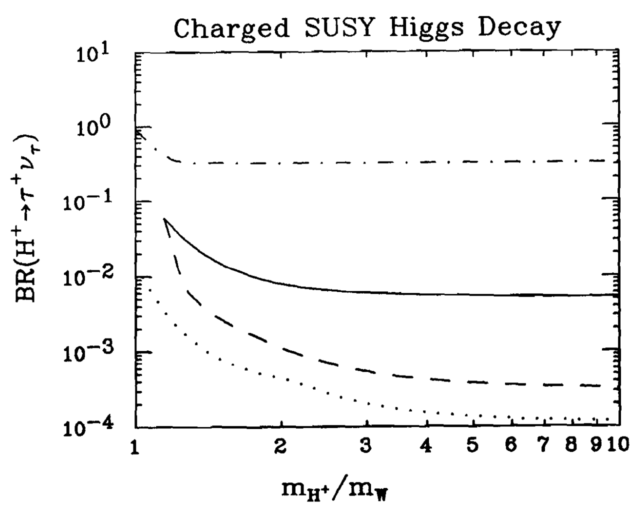

Figure 3: We give results for the $H^+ \to \tau^+\nu$ branching ratio in four cases: $m_{H_2^0} = 0.5m_Z$, $m_t = 40\ GeV$, and $\widetilde{\chi}^\pm$'s and $\widetilde{\chi}^0$'s heavy (solid line); $m_{H_2^0} = 0.5m_Z$, $m_t = 40\ GeV$, and $\widetilde{\chi}^\pm$'s and $\widetilde{\chi}^0$'s light according to the model of ref. 33 (dashed line); $m_{H_2^0} = 0.01m_Z$, $m_t \geq H^\pm$, and $\widetilde{\chi}^\pm$'s and $\widetilde{\chi}^0$'s heavy (dotdash line); and $m_{H_2^0} = 0.01m_Z$, $m_t \geq H^\pm$, and light $\widetilde{\chi}^\pm$'s and $\widetilde{\chi}^0$'s (dotted line). In all cases we have taken the squarks and sleptons heavy, so that $H^\pm$ decays to channels containing them are not allowed.

We then obtain[36]

$$\frac{\Gamma(t \to H^+ b)}{\Gamma(t \to W^+ b)} = \frac{p_{H^+}}{p_{W^+}} \frac{m_t^2(m_t^2 - m_{H^+}^2)}{(m_t^2 + 2m_W^2)(m_t^2 - m_W^2)} \cot^2\beta, \quad (27)$$

where p_{H^+} and p_{W^+} are the t rest frame momenta of the respective decays. Obviously the H^+ can be fully competitive with the W^+ mode, so long as $\cot\beta$ is not too small. (Note that in the minimal SUSY model it is not possible to have the ordering $m_{H^\pm} < m_t < m_W$, for which the $H^\pm$ decay mode would be completely dominant.) The size of $\cot\beta$ depends strongly on how near $m_{H^\pm}$ is to its minimum value. For instance, if m_t is of order 0.1 TeV and $m_{H_2^0} = 0.5 m_Z$ then $t \to H^+ b$ decay would be strongly suppressed by a small value of $\cot\beta$ since $m_{H^\pm}$ would have to be very near its minimum of 95 GeV.

However, for $m_{H_2^0} = 0.01 m_Z$ the situation is very different. First, $\cot\beta$ is generally not small unless $m_{H^\pm}$ is very near m_W; in fact $\cot\beta \gtrsim 0.95$ for $m_{H^\pm} \gtrsim 0.1$ TeV. In this case the $t \to H^+ b$ decay mode will be significant, and we must consider the dominant decay modes of the H^+ and H^- coming from the t and $\bar{t}$ decay. They are model dependent, and have been surveyed in ref. 7. In fig. 3 we present the branching ratios for one mode of particular interest, $H^\pm \to \tau\nu_\tau$, for a number of different cases that will concern us in the following discussions. If all gauginos, squarks and sleptons are sufficiently massive that channels containing them are phase space disallowed, then, for $m_{H_2^0} = 0.01 m_Z$, $H^\pm$ has a very substantial branching ratio to $\tau\nu_\tau$ modes, $\gtrsim 0.3$. (In a two-doublet non-SUSY version of the standard model this branching ratio is ~ 0.5, for $\cot\beta = 1$.) The corresponding final state signature, if both t and $\bar{t}$ decay to charged Higgs, would then consist of

$$2jet + \tau^+ + \tau^- + \vec{p}_T^{\,miss}. \quad (28)$$

The τ's are most easily detected via their single charged particle decay modes. Because of the strong production rate it is difficult to imagine competitive backgrounds, especially if a τ vertex trigger is available. For instance, if $m_t = 0.15$ TeV, $m_{H^\pm} = 0.1$ TeV and $m_{H_2^0} = 0.01 m_Z$, the $t \to H^+ b$ branching ratio is $\gtrsim 0.33$. Combined with a ~ 0.3 $H^+ \to \tau^+\nu$ branching ratio, we obtain a cross section times branching ratio for the final state of eqn. (28) of order $\sim 0.5 \times 10^3$ pb. On the other hand, if neutralinos and charginos are light then they provide the dominant $H^\pm$ decay channels. For $m_{H_2^0} = 0.01 m_Z$, the branching ratio for $H^+ \to \tau^+\nu$ decay is already $\lesssim 0.003$ by $m_{H^\pm} = 0.1$ TeV, in the minimal SUSY model of ref. 33, see fig. 3. There are few events in the $\tau\nu_\tau$ channel, and backgrounds from the $t \to W^+(\to \tau^+\nu)b$ type modes, which have a larger branching ratio, would appear to be overwhelming. However, searches for the $H^\pm$ in the gaugino/chargino channels could be successful. Further study is required.

If the top is lighter than the $H^\pm$ then the primary mechanism for $H^\pm$ production is from bt fusion. This has been computed, and the resulting phenomenological implications surveyed, in ref. 7. First, we note that the cross sections are surprisingly substantial. If we take $\cot\beta = 1$ in the coupling of eqn. (26), then for $m_t = 40$ GeV $\sigma(H^\pm)$ ranges from $\gtrsim 200$ pb, at $m_{H^\pm} = 0.1$ TeV, to $\gtrsim 0.3$ pb, at $m_{H^\pm} = 1.0$ TeV. (These are lower bounds coming from computation of the $bg \to H^\pm t$ cross section. The full computations in progress may yield larger numbers.[7]) Of course, for $m_{H_2^0} = 0.5 m_Z$ there will be considerable suppression from the small value of $\cot\beta$ near the $m_{H^\pm} = 0.1$ TeV region. This suppression would not be significant for $m_{H^\pm} \gtrsim 0.1$ TeV if $m_{H_2^0} = 0.01 m_Z$. Secondly, we note that in the bt fusion mechanism, the $H^\pm$ is always produced in association with a spectator t quark. This spectator t quark provides a very important signature for $H^\pm$ events, explored in ref. 7. One triggers on the secondary leptons coming from the spectator t decay. Using a p_T cut of order 10 GeV reduces standard model backgrounds that do not have a spectator t quark by a factor of order 70, while retaining approximately 45% of the charged Higgs signal. Thus a net improvement of signal/background by a factor of 30 is possible.

Turning to the $H^\pm$ decays for $m_t < m_{H^\pm}$, we find that, if all supersymmetric particle decay modes are phase space disallowed, the dominant decay of the $H^\pm$ will be (as one might expect) to bt channels. However, searches for $H^\pm$ in the tb decay mode will encounter enormous backgrounds from QCD 2-jet production. For instance, at $m_{H^\pm} = 0.5$ TeV ref. 7 obtains an $H^\pm$ cross section of $\gtrsim 4$ pb, neglecting possibly significant $\cot^2\beta$ suppression. In comparison the two jet cross section at this same jet-jet invariant mass is of order $d\sigma/dM_{jj} = 2 \times 10^3$ pb/GeV. For a mass resolution of 15% we obtain an effective cross section of 1.5×10^5 pb. Of this total, approximately 2% are gt or $g\bar{t}$ final states. If we imagine that a highly selective top quark jet trigger can be constructed, without sacrificing the 15% mass resolution (a somewhat questionable assumption given the results of ref. 37), then our effective background is of order 3×10^3 pb, ~ 1000 times larger than the signal. No further gain is possible using the stiff-lepton trigger on the t quark produced in association with the $H^\pm$, since gt production also occurs with an associated spectator t quark. Thus we would need to discriminate g jets from b jets at the level of 1/1000 in order to detect $H^\pm$ in the bt mode. No technique for differentiation has yet achieved such a factor.[9]

If the $\widetilde{\chi}^\pm\widetilde{\chi}^0$ decay modes for the $H^\pm$ are allowed, then, in the minimal SUSY model of ref. 33, they will dominate the $H^\pm$ decays, just as these gaugino modes dominated H_1^0 decays in the same situation (see fig. 2). A careful study of signatures and backgrounds, analogous to that performed for the neutral H_1^0 in ref. 35, should be undertaken. We have seen that backgrounds are not overwhelming in the latter case, and, perhaps, similar results will be found in the charged Higgs case.

However, if the the supersymmetric particles are heavy, we must search for an alternative to the bt decay mode of the $H^\pm$. The only possibility appears to be the $\tau\nu_\tau$ mode. We shall summarize the results of ref. 7 for this channel, for the case of $m_t = 40$ GeV. We first note that the cross section for $bt \to H^\pm$ fusion is $\propto \cot^2\beta$, whereas the $H^\pm \to \tau\nu_\tau$ branching ratio is $\propto \tan^4\beta$. Thus, $BR \times \sigma$ for $bt \to H^\pm \to \tau\nu_\tau$ is largest when $\cot\beta$ is small. We recall from our introduction to this section that larger values of $m_{H_2^0}$ yield smaller values of $\cot\beta$ at a given $m_{H^\pm}$. In fact, if we make the choice $m_{H_2^0} = 0.01 m_Z$, and all SUSY particles are heavy, the $H^\pm \to \tau\nu_\tau$ branching ratio is $\lesssim 0.001$ for $m_{H^\pm} \gtrsim 0.1$ TeV. Backgrounds to be enumerated shortly are overwhelming. Thus we focus on the case of $m_{H_2^0} = 0.5 m_Z$. The $H^\pm \to \tau\nu_\tau$ branching ratio appropriate to this case was presented in fig 3. It ranges from ~ 0.05 to ~ 0.005 over the 0.1 $TeV < m_{H^\pm} < 1.0$ TeV range, being already $\lesssim 0.01$ by $m_{H^\pm} = 0.15$ TeV. We imagine searching for the τ in one of its single charged particle decay modes: $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$, or $\tau \to \rho\nu$, with combined branching ratio of ≈ 0.67. There are two critical ingredients in overcoming backgrounds. The first is the spectatator t quark trigger discussed earlier. The second is a trigger on energetic τ's, perhaps a vertex detector. This latter is necessary in order to use the $e\nu\nu$ and $\mu\nu\nu$ modes. If no τ trigger is available, then backgrounds from $W \to e\nu, \mu\nu$ will generally swamp the spectra from $H^\pm$ decays, and only the $\pi\nu$ and $\rho\nu$ modes of τ decay would be useable, with consequent loss of effective event rate.

An impression of the results may be gained by considering two extreme cases. In the first we assume that $m_{H^\pm} \approx 0.1\ TeV$. For the $m_{H_2^0}$ choice being considered we find that $\cot\beta$ is small, and, at $m_t = 40\ GeV$, we find $\sigma(H^\pm) \sim 2\ pb$. In comparison, the cross section for single W production is of order $10^5\ pb$. The branching ratio for $W \to \tau\nu_\tau$ decay is of order 0.08. However, the W effective event rate is reduced via the stiff-lepton spectator t quark trigger, discussed earlier, by a factor of 70. Thus in a standard SSC year we obtain 10^6 events from the W background. The $H^\pm$ event number, after including the roughly 50% efficiency of the stiff lepton trigger, and the 0.05 branching ratio for the $\tau\nu_\tau$ mode, is of order 0.5×10^3—an impossibly small signal.

The second scenario we consider is that of $m_{H^\pm} = 1\ TeV$, again at $m_{H_2^0} = 0.5 m_Z$ and $m_t = 40\ GeV$. The value of $\cot\beta$ is substantial and we find a cross section of $\gtrsim 0.1\ pb$. However, combining this value with the 0.005 $\tau\nu_\tau$ mode branching ratio appropriate for heavy $H^\pm$, the stiff lepton trigger efficiency, and the 0.67 branching ratio for single charged particle τ decay, yields only ~ 2 events. Since additional cuts on the p_T of the charged particles arising from the τ decay are required in order to reduce the background from virtual W production of $\tau\nu_\tau$,[38] detection would not be possible.

For masses in the vicinity of $m_{H^\pm} = 0.5\ TeV$, the signal event rate would be roughly a factor of 10 larger than the 1 TeV case discussed above, and yet cuts on the single charged particle p_T should still be effective in eliminating the W induced background. This region has not been studied in detail, but some hope is warranted.

Of course, for $m_{H_2^0}$ near its upper limit of m_Z, the $BR \times \sigma$ for $H^\pm \to \tau\nu_\tau$ is substantially larger than for the case just considered. Detection over a wide range of $m_{H^\pm}$ would then appear to be feasible. On the other hand, if m_t is significantly larger than 40 GeV, then even though the $bg \to H^\pm t$ cross section is also larger,[7] the $BR \times \sigma$ for the $\tau\nu_\tau$ mode is smaller, and the $\tau\nu_\tau$ mode is more marginal than in the example analyzed.

Overall, we see that searches for the $H^\pm$ in the $\tau\nu_\tau$ channel could easily fail. However, the $\tau\nu_\tau$ mode is the only decay channel for which there is any possibility of detecting a SUSY $H^\pm$ when the tb decay mode is also allowed, and all supersymmetric particle channels are forbidden.

Summary:

In summary, it is clear that detection of the heavy neutral Higgs boson, H_1^0, and of the charged Higgs boson, $H^\pm$, can be very difficult in comparison to searches for the SM Higgs. Only in a limited number of special cases can their detectability be demonstrated or hoped for. These include the following.

1. The strongly produced top is heavy and decays to $H^\pm$, which, in turn, can be seen via decay either to $\tau\nu_\tau$ or to $\widetilde{\chi}^\pm\widetilde{\chi}^0$ modes (the latter dominate if allowed). For $m_t \sim 0.15\ TeV$ this typically requires a rather small mass for the H_2^0 in order to avoid suppression of the $t \to H^+ b$ decay mode relative to $t \to W^+ b$.
2. The top is light, single inclusive production cross sections for both the H_1^0 and $H^\pm$ are dominant, and the $\widetilde{\chi}^\pm/\widetilde{\chi}^0$ sector of the SUSY spectrum is light on the scale of $m_{H_1^0}$ and $m_{H^\pm}$. Then the the H_1^0 and $H^\pm$ decays will be dominated by final states containing the $\widetilde{\chi}^\pm/\widetilde{\chi}^0$ fermions. Backgrounds have been explicitly explored in the H_1^0 case, and shown to be surmountable.[35] We anticipate that similar results will emerge in a study of the $H^\pm$ case.
3. The top is light, but all supersymmetric $H^\pm$ decay channels are forbidden. Detection of $H^\pm$ in the $\tau\nu_\tau$ decay mode may be possible if $m_{H_2^0} \gtrsim 0.5 m_Z$ and if $H^\pm$ has a moderate mass of order $\sim 0.5\ TeV$. In this case, the $H^\pm$ cross section is sizeable, the branching ratio to $\tau\nu_\tau$ is significant, and special trigger techniques might succeed in controlling the background from $W^\pm$ production followed by decay to $\tau\nu_\tau$. Large top masses or small H_2^0 masses make the $\tau\nu_\tau$ channel unfeasible.

Left-Right Symmetric Models

Left-right (L-R) symmetric extended gauge groups are reviewed thorougly in ref. 39, contained in these proceedings. We present the highlights of this analysis here.

The minimal low energy symmetry group of a left-right symmetric model is

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}. \tag{29}$$

This group is broken down to $U(1)_{E\&M}$, in a minimal model, by three types of Higgs fields:

a) a bi-doublet, which we can call ϕ, that has left and right isospins given by $I_L = I_R = 1/2$ and has $B - L = 0$. It contains four complex Higgs fields—ϕ^0, $\phi^{0\prime}$, ϕ^- and $\phi^{+\prime}$. We consider the extreme in which only one of the neutral ϕ's, ϕ^0, acquires a vacuum expectation value which gives mass to the lighter neutral gauge boson, called Z_L, and to the charged gauge boson, W_L, of $SU(2)_L$.

b) a right-handed triplet Higgs field, called Δ_R, which has $I_L = 0, I_R = 1$, and $B - L = 2$. It has a doubly charged, a singly charged and a neutral member. The latter acquires a vacuum expectation value, v_R, that gives a large mass to the second massive neutral gauge boson, called Z_R, and also to the charged W_R of the $SU(2)_R$ group.

c) a left-handed triplet Higgs field, called Δ_L, which has $I_L = 1$, $I_R = 0$, and $B_L = 2$. Again, the neutral member could acquire a vacuum expectation value, v_L. But the experimental observation that $\rho \approx 1$ strictly limits the size of v_L and we shall take $v_L = 0$.

The Z_L and W_L are constrained to have the masses observed at the SppS. The phenonomenological constraints on W_R are stringent, requiring that m_{W_R} be at least $\sim 2\ TeV$. In contrast, the Z_R could be quite light, $m_{Z_R} \gtrsim 0.2\ TeV$. In the simplest L-R symmetric models the value of m_{Z_R} is closely tied to that of m_{Z_R}, and both would be heavy. However, a more complicated Higgs sector can easily decouple these two masses. We shall use language appropriate to this latter approach.

After symmetry breaking we find a considerable menagerie of Higgs particles. (There are no constraints on the masses of these Higgs intrinsic to the Lagrangian of the theory—only phenomenological ones as outlined below.)

1. The $H_{1,2}^0$ and $H^\pm$ which are not totally dissimilar from their SUSY counterparts and emerge from a mixture of neutral and charged members of the bi-doublet and R-triplet Higgs representations. For instance, $H_{1,2}^0$ are the mass eigenstates resulting from mixing the neutral Higgs of the bi-doublet, ϕ^0, and the neutral Higgs of the R-triplet, Δ_R^0. The Δ_R^0's vacuum expectation value, v_R, not only gives mass to the Z_R, but also also gives rise to a large number of phenomenologically important Higgs couplings. We shall return to detection of these Higgs shortly.

2. The $\phi^{0\prime}$ and Δ_L^0. The first is the second neutral member of the L-R Higgs bi-doublet, and must be very massive in order to avoid conflict with current limits on flavor changing neutral currents. We shall not discuss it further. The second is the neutral member of the L-triplet Higgs representation. Since we shall take $v_L = 0$, as explained above, all its couplings to gauge bosons are very small. In addition, quantum number considerations forbid it from having any couplings with quark-antiquark pairs. Thus all the standard production mechanisms are extremely suppressed. It is probably unobservable.

3. The Δ_R^{++}, Δ_R^{--}, Δ_L^{+}, Δ_L^{-}, Δ_L^{++} and Δ_L^{--}. These are remnants of the triplet Higgs representations, and are the most unique Higgs predicted in a typical L-R symmetric gauge model. However, they are not easily produced. They cannot be singly produced via gauge boson fusion, in the absence of W_R-W_L mixing, in the limit where m_{W_R} is large and $v_L = 0$. They also cannot be produced via gg fusion since they do not couple to quarks. The only direct process is pair-production via the Drell-Yan mechanism. For the doubly-charged Higgs of greatest interest, there are fewer than 10 pair events in an SSC year if the Higgs mass exceeds 100 GeV. Such a small number of events does, however, provide a clean signal since the only allowed decays of these doubly-charged Higgs are to like-sign lepton pairs. If the charged Higgs are heavier than 100 GeV they become extremely difficult to produce directly, and will probably not be detected except, possibly, as decay products of neutral Higgs, as discussed shortly.

We now return to the Higgs in category 1), above.

$H^{\pm}$:

For the $H^{\pm}$ we can, in large part, refer back to the SUSY discussion. The coupling to bt is as specified in eqn. (26), with $\cot\beta = 1$. The most dramatic difference with the SUSY model appears in the $\tau\nu_\tau$ coupling of the $H^{\pm}$ which is exactly 1/3 as large as that to bt. This anamalously large $\tau\nu_\tau$ coupling arises from a Dirac mass term that is peculiar to the L-R gauge theories. Thus, we have the two cases:

$$BR(H^{\pm} \to \tau\nu_\tau) = \begin{cases} 0.03; & m_t < m_{H^{\pm}} \\ 0.97; & m_t > m_{H^{\pm}}. \end{cases} \tag{30}$$

By referring to the SUSY discussion given earlier, we see that detection of the $H^{\pm}$ in the t and $\bar{t}$ decays of a strongly produced $t\bar{t}$ pair, should present no difficulty in the latter case, especially if $m_{H^{\pm}} < m_t < m_W$.

In the former case, we are in a situation somewhat analogous to the SUSY scenario in which all chargino/gaugino $H^{\pm}$ decays are forbidden, and only the $\tau\nu_\tau$ decay channel can provide a feasible signal—backgrounds in the bt channel being overwhelming. However, the L-R model yields considerably more favorable results than the $m_{H_2^0} = 0.5 m_Z$ SUSY case analyzed earlier. We parallel the two extreme cases considered near the end of the charged Higgs section of the SUSY discussion. First consider the $m_{H^{\pm}} \sim 0.1\ TeV$ case. Since $\cot\beta = 1$ for the L-R models, there is no suppression of the bt production cross section, while the $\tau\nu_\tau$ branching ratio in the L-R model is only a factor of 5/3 smaller than in SUSY, at small $m_{H^{\pm}}$. We obtain, for $m_{H^{\pm}} = 0.1\ TeV$ a $\tau\nu_\tau$ signal event rate of 3×10^4 per SSC year, vs. a background from $W_L(\to \tau\nu_\tau)$ of 10^6 events. While this is only a 3% effect, enhancement might be possible by using differences in the spectra of the τ's from W_L vs. $H^{\pm}$ decay. Further study would seem warranted. At $m_{H^{\pm}} = 1\ TeV$ L-R models predict a factor of 6 larger branching ratio for $m_{H^{\pm}} \to \tau\nu_\tau$ than does SUSY. After making the cuts described in ref. 39 on the p_T of the single charged particle from τ decay, we obtain a signal to background event ratio of 14/10—marginal but not clearly impossible. At intermediate values for $m_{H^{\pm}}$, detection should be possible since the background from W production can still be controlled by cuts, while the signal event rate will be substantial. A detailed study should be performed. Of course, if the W_R of the L-R model is light enough, its $\tau\nu_\tau$ decays will completely swamp those from an $H^{\pm}$. By scaling the $m_{W_R} = 1\ TeV$ results of ref. 38 we estimate that $m_{W_R} \gtrsim 2.5\ TeV$ is required in order to prevent the W_R from interfering with a $m_{H^{\pm}} \lesssim 1\ TeV$ signal.

$H_{1,2}^0$:

The phenomenology of this neutral sector is quite complex. We mention only a few highlights from ref. 39. There are two extreme cases that can be considered.

1. There is little mixing between the ϕ^0 of the bi-doublet and the Δ_R^0 of the R-triplet. In this case we drop the $H_{1,2}^0$ notation.

2. There is maximal mixing between the ϕ^0 and the Δ_R^0; by convention we take $m_{H_1^0} < m_{H_2^0}$.

In case 1), the ϕ^0 behaves much like a SM Higgs, and would first be discovered using the techniques outlined in section 2. Once found the exotic decays,

$$\phi^0 \to \begin{cases} Z_R Z_R \\ H^+H^-, \end{cases} \tag{31}$$

predicted in L-R models when mass allowed, could be searched for. The Δ_R^0 is only produced via $Z_R Z_R$ fusion, with small cross section unless m_{Z_R} is very near its phenomenological lower limit. Its decay channels are rather restricted. They include

$$\Delta_R^0 \to \begin{cases} Z_R Z_R \\ N_R N_R, \end{cases} \tag{32}$$

where N_R a massive Majorana neutrino, and a variety of Higgs pair decay modes,

$$\Delta_R^0 \to \begin{cases} H^+H^- \\ \Delta_R^{++}\Delta_R^{--} \\ \Delta_L^0\Delta_L^0 \\ \Delta_L^+\Delta_L^- \\ \Delta_L^{++}\Delta_L^{--}. \end{cases} \tag{33}$$

The $N_R N_R$ mode is only important if all other channels are forbidden; when allowed all other channels are comparable. Since the Higgs of eqn. (33) can be either light or heavy there are many alternatives to consider. We mention only two.[39]

a) If the Higgs pair modes are absent, and the $Z_R Z_R$ mode is allowed, then one can search for Δ_R^0 in the mode

$$\Delta_R^0 \to Z_R(\to l^+l^-) Z_R(\to N_R N_R); \tag{34}$$

in particular, since the N_R's are Majorana, 1/2 the time the $N_R N_R$ decays will produce leptons of the same sign. The net branching ratio for such $Z_R Z_R$ decays is .75%, yielding over 40 events in an SSC year for $\sigma(\Delta_R^0) \gtrsim 0.5\ pb$. This scenario is only possible if the Z_R is light so that both the Δ_R^0 cross section is substantial and the $Z_R Z_R$ decay mode is allowed.

b) If the doubly charged Higgs pair decay modes listed above are allowed, then

$$\Delta_R^0 \to \Delta_R^{++}(\to l^+l^+)\Delta_R^{--}(\to l^-l^-), \qquad (35)$$

and the corresonding mode involving Δ_L^{++} and Δ_L^{--} will provide a highly distinctive signature, with large branching ratio.

Turning to the maximal mixing case 2), we find that both H_1^0 and H_2^0 are, to first approximation, produced with 1/2 the SM Higgs cross section found at the same mass. They can both decay to $W_L^+W_L^-$, Z_LZ_L, and possibly to Z_RZ_R and Z_RZ_L. Widths to the first two channels are 1/2 those of a SM Higgs. The width of the Z_RZ_R channel is just as large when not phase space suppressed. In addition, all the Higgs pair modes of eqn. (33) are possible, as well as the decay $H_2^0 \to H_1^0H_1^0$. These Higgs pair modes, if allowed, can dominate H_1^0 decays if m_{Z_R} is small. However, only the $H_1^0 \to H^+H^-$ mode can be important at high m_{Z_R}. Thus we see that H_2^0 should be detectable using SM like modes and techniques, and that, in addition, the Z_RZ_R decay modes, especially that mentioned under case 1) for the Δ_R^0, could provide interesting signatures peculiar to L-R models. Similar statements apply to the lighter H_1^0, unless the Higgs pair modes dominate, in which case the doubly charged Higgs pair final states could lead to two resonant pairs of like-sign leptons. If such dramatic modes are not present, only a thorough survey of the decay modes of both H_1^0 and H_2^0 will distinguish this neutral Higgs sector of the L-R model from the corresponding one of a SUSY model or of a two Higgs doublet version of the SM.

Models Derived from Superstrings and E_6

The precise low energy manifestation of E_6 is still a subject of some debate, but several of the simplest possibilities deserve at least initial exploration. The investigations are at a very early stage, but a few interesting results have emerged. First, we note that once the low energy subgroup is specified, the Higgs sector is rather tightly constrained. However, in all cases, a full supersymmetric structure must be considered. We consider only one simple case—that in which the low energy group structure is based on a supersymmetric version of $SU(2)_L \times U(1) \times U(1)$. Due to the extra $U(1)$ there are two Z's, Z_1 and Z_2, where Z_1 must be close in mass to the SM Z and mixing between Z_1 and Z_2, parameterized by an angle α, cannot be too large. The Higgs sector is closely analogous to that considered for the minimal SUSY model, except for the addition of (at least) one neutral singlet Higgs, called N. In general, the 3 neutral scalar Higgs particles are mixed according to a highly constrained mass matrix. The resulting neutral eigenstates are H_2^0, H_1^0, and H_0^0, ordered according to increasing mass. Indeed, once m_{Z_2}, α, and the masses of the pseudoscalar, H_3^0, and the charged Higgs, $H^\pm$, are specified, all parameters of the Higgs sector are determined, much as in the general minimal SUSY case.

At first sight, it would appear that there is more freedom than in the minimal SUSY case. In fact, however, all masses are very tightly correlated. We illustrate this with a curve from ref. 40, fig. 4. This plot shows that fixing $m_{H_3^0}$, the pseudoscalar Higgs mass, in addition to m_{Z_2} and α, almost completely determines all remaining Higgs masses except for that of the lightest scalar H_2^0, in which case only an upper bound is predicted. Note, in particular, that either H_1^0 or H_0^0 is always approximately degenerate in mass with the Z_2, while the other one of these two, the $H^\pm$ and the H_3^0, in turn, have nearly equal masses. Detection of the Z_2 via its l^+l^- decay modes will presumably be straightforward, and the value of m_{Z_2} will fix a mass range on which to concentrate the search for one of the Higgs. This obviously greatly enhances the likelihood of detecting this particular Higgs.

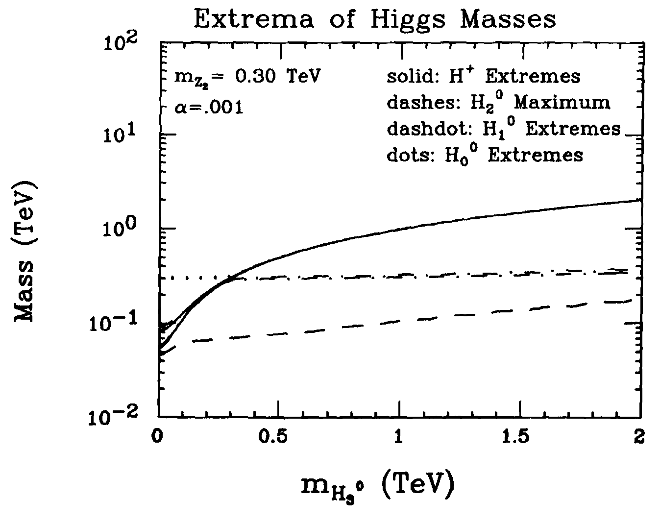

Figure 4: We plot the maximum and minimum allowed values of all Higgs masses as a function of the pseudoscalar mass $m_{H_3^0}$, for a typical choice of m_{Z_2} and α.

Constraints on the other Higgs masses are more theoretical in nature. Typically, a large portion of the $m_{H_3^0}$ mass range can be eliminated if bounds can be placed on one or more Lagrangian parameters, using renormalization group analyses. For instance, it is probable that the large $m_{H_3^0}$ region of fig. 4 should be regarded as violating these bounds, and that only values of $m_{H_3^0}$ below several hundred GeV should be considered. Note that in this case the light H_2^0 does indeed lie below the bound of ref. 41, but that without such restrictions that bound can be violated.

There will be correspondingly tight determinations of all the Higgs couplings, with associated implications for the production and detection of the Higgs particles. We anticipate some similarities to the SUSY results. Results will be available in the near future.

4. Conclusion

In conclusion, discovery of the standard model Higgs is clearly possible so long as $m_{H^0} > 2m_W$. Generally, at any such m_{H^0} at least one purely leptonic final state mode as well as the mixed hadronic-leptonic final state channel, should produce a clear signal for the Higgs. We have reviewed the theoretically proposed techniques for reducing the, sometimes severe, backgrounds to an acceptable level.

Discovery of a Higgs in the intermediate mass range— m_{H^0} below $2m_W$ but above the range accessible to e^+e^- machines (perhaps no more than ~ 40 GeV, unless LEP II is built, in which case $m_{H^0} \sim 85$ GeV might be reachable)— will depend crucially on the value of the top mass. If $2m_t < m_{H^0}$, detection could prove impossible. Backgrounds to detection in the dominant $t\bar{t}$ decay mode are severe. However, some rare decays, as summarized earlier, should not be completely dismissed without further study. Only the existence of a fourth generation will clearly allow for discovery of such a Higgs at the SSC. Both the $H^0 \to L^+L^-$ "rare" decay to fourth generation heavy leptons, and the decay of the spin 0 bound state of the fourth-generation, charge -1/3 quark, $\eta_v \to ZH^0(\to t\bar{t})$, provide viable discovery modes. On the other hand, if the top is heavy enough that $H^0 \to b\bar{b}$ decays are dominant at the actual value of m_{H^0}, discovery of the SM H^0 in both the $b\bar{b}$ and the $\gamma\gamma$ final states appears to be possible.

Extended gauge theory models always require a much more complicated Higgs sector than contained in the simple one-doublet version of the standard model. All models studied in detail to date predict that at least one of the neutral Higgs particles is either relatively light (and hence can be produced and detected at upcoming e^+e^- colliding beam facilities) or has couplings sufficiently like those of the SM Higgs that production and detection at the SSC will be possible (or both). On the other hand, the other members of a typical Higgs menagerie could be very elusive.

The minimal SUSY model is the most constrained. In that model, both the $H^\pm$ and the heavy H_1^0 are likely to be very difficult to search for unless the SUSY particle mass spectrum is such that they can decay to at least one channel containing a pair of gauginos with appropriate total charge. Current limits on gaugino masses, both charged and neutral, are not yet very restrictive. In addition, no good technique for finding the pseudoscalar H_3^0 has been proposed. Only the light H_2^0, with mass below m_Z, will be detectable with certainty, and then only at an e^+e^- facility.

In the left-right symmetric models, the $H^\pm$ is predicted to have an anomalously large $\tau\nu_\tau$ branching ratio, and discovery in this channel, while not easy, appears to be possible over a significant mass range.

However, at least two of the neutral Higgs of the L-R models are either too massive or too weakly coupled to be detectable. In addition, the truly unique doubly charged Higgs of the L-R models can only be directly produced at a detectable rate for masses below $\sim 0.1\ TeV$. They can also be indirectly produced as decay products of the H_1^0 and H_2^0 of the L-R model; the branching ratio is significant if m_{Z_R} is not too large. Regarding the H_1^0 and H_2^0 of the L-R models themselves, both should be detectable if the maximal mixing scenario described earlier obtains. On the other hand, the most natural version of the model would have little mixing between the ϕ^0 and Δ_R^0, and for a heavy Z_R the Δ_R^0 cross section would be too small to allow detection. The ϕ^0 would behave much like a SM Higgs in this situation.

The phenomenology of the E_6 based gauge theories is in its early stages. The simplest low energy gauge group produces a highly constrained spectrum of Higgs masses and couplings, and exhibits a number of similarities to the minimal SUSY model. The Higgs mass spectrum of this model is such that most, if not all, of the Higgs bosons lie below 1 TeV, and are, thus, in principle, accessible at the design SSC energy. Results for SSC phenomenology will be available shortly.[40]

Overall, we see that the SSC provides an excellent probe of the standard model Higgs boson, and may be capable of detecting enough of the Higgs bosons of a typical extended gauge theory to distinguish such models from the standard model and from one another.

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