The Higgs Mechanism and Electroweak Symmetry Breaking at e^+e^- Linear Colliders

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The next e^+e^- linear collider is expected to provide critical measurements of the Higgs mechanism. The expected sensitivity of these measurements is summarized. These complement those of the LHC significantly.

1. Introduction

The LHC (or the Tevatron) should initiate the experimental measurements of the particle(s) associated with electroweak symmetry breaking (EWSB). These discoveries will likely provide a limited view of the nature of the Higgs mechanism. A Linear Collider will be a crucial tool in advancing the understanding that the LHC/Tevatron begins. Our current model of the electroweak interaction is precise and agrees with LEP/SLC/Tevatron measurements to high precision. The recent measurements of WW production at LEP2, shown in Figure 1, illustrates this very convincingly.

The many measurements of electroweak processes can be expressed as a measurement of the remaining free parameter of the Standard Model, the Higgs mass (M_H). Figure 2 shows the Summer 2001 plot of the change in the χ^2 of the fit to the electroweak data as a function of this mass. This curve says the Standard Model Higgs, if it exists, has a mass less than 190 GeV/c^2 with 90% confidence. The shaded region has been ruled out by direct searches at LEP2, where $M_H > 113.5\,\text{GeV}/c^2$. The suggestion one can draw from these measurements and theoretical considerations is that the data is in excellent agreement with a light Standard Model Higgs boson.

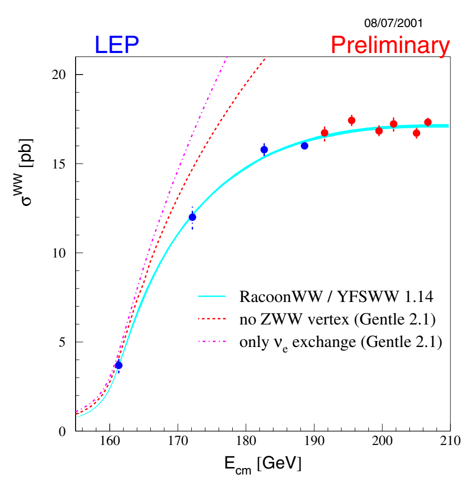

Figure 1: LEP2 measurement of the WW cross-section versus $\sqrt{s}$ for different W couplings [1].

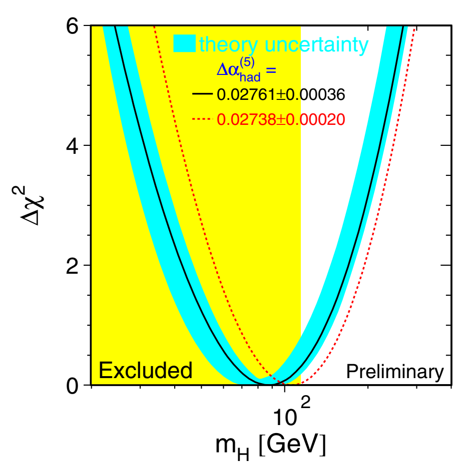

Figure 2: $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ versus $m_{\rm H}$ curve from the LEP Electroweak Working Group fit. The vertical band shows the 95% CL exclusion limit on $m_{\rm H}$ from the direct search [1].

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Table I Linear Collider Parameters. (*The NLC and JLC-X band parameters are not identical, but are similar.) [6]

	TESLA	JLC-C	NLC/JLC-X*
L_{design} (10^{34})	3.4 → 5.8	0.43	2.2 → 3.4
E_{CM} (GeV)	500 → 800	500	500 → 1000
Eff. Gradient (MV/m)	23.4 → 35	34	70
RF freq. (GHz)	1.3	5.7	11.4
Δt_{bunch} (ns)	337 → 176	2.8	1.4
bunches/train	2820 → 4886	72	190
Beamstrahlung (%)	3.2 → 4.4		4.6 → 8.8

This is the story in the context of the Standard Model. However, the Standard Model is not favored, as we know. If the Higgs is found in this range, we should not be too surprised that its properties are nearly Standard Model-like, even if it does not arise from the Standard Model. This will place a premium on measurements with precision, those capable of discriminating between Standard Model-like and Standard Model-exact. Discovery of the Higgs will be of limited value without detailed measurements of its properties. The 500 GeV Linear Collider, and its higher energy upgrades, are the tools needed to complete these precision studies. [2]

Accelerator designers have been hard at work all over the world. Table I lists a recent set of parameters for three possible approaches. What is shown here is that each plan could deliver 1000 fb^{-1} of integrated luminosity within a few years of operation. The expected impact of such facilities on the study of the Higgs boson has been thoroughly detailed. [3, 4, 5]

The Next Linear Collider, as it is being conceived, has a number of options. The 'standard package' would provide e^+e^- collisions, initially at a center-of-mass energy of 500 GeV, with about 80% electron polarization. This might be enhanced in a number of ways:

- Energy upgrades to 1.5 TeV
- Positron polarization
- Gamma-gamma collisions
- e^+e^- and $e^-\gamma$ collisions
- Giga-Z (precision measurements at the Z pole), and WW threshold running

Each of these enhancements requires a development program, and the realization of each will depend on the physics motivation, as well as the success of development.

Experimentation at a linear collider has the advantage of some particularly special experimental conditions. First of all, the interactions are elementary, without the complications of spectator partons. For example, in the reaction $e^+e^- \rightarrow Z^0H^0$, the only final state particles (neglecting beamstrahlung) come from the Z^0 and the H^0. This is quite different from hadronic colliders. Furthermore, the cross sections for many processes tend to be of similar size. This is illustrated in Figure 3. For example, $\sigma(e^+e^- \rightarrow Z^0H^0) \sim 1/2\sigma(e^+e^- \rightarrow d\bar{d})$. This means the processes of interest are not buried beneath a large background. The electron beam is highly polarized, at about 80%, with handedness switchable from train to train. This capability can be used to control the competing processes. Finally, the beam environment of the linear collider makes possible exceptional detectors. The vertex detection can be exquisite with a beampipe about 1 cm in radius, and hit resolutions of about 3 μm. This has been demonstrated by the performance of the SLD vertex detector operating with 307 million pixels [7]. With jet flow calorimetry, the jet energy resolution should be roughly $30\%/\sqrt{E}$. Silicon/tungsten calorimetry is being seriously proposed as the central elements of jet energy flow measurements by the TESLA and NLC groups [3, 4], having been proven in the e^+e^- colliders starting with the SLD luminosity monitor [8], and proposed at Snowmass 96 for the EM calorimeter [9].

2. Electroweak Symmetry Breaking

There are many models of electroweak symmetry breaking. These include the Standard Model which provides excellent agreement to the electroweak precision measurements, as discussed

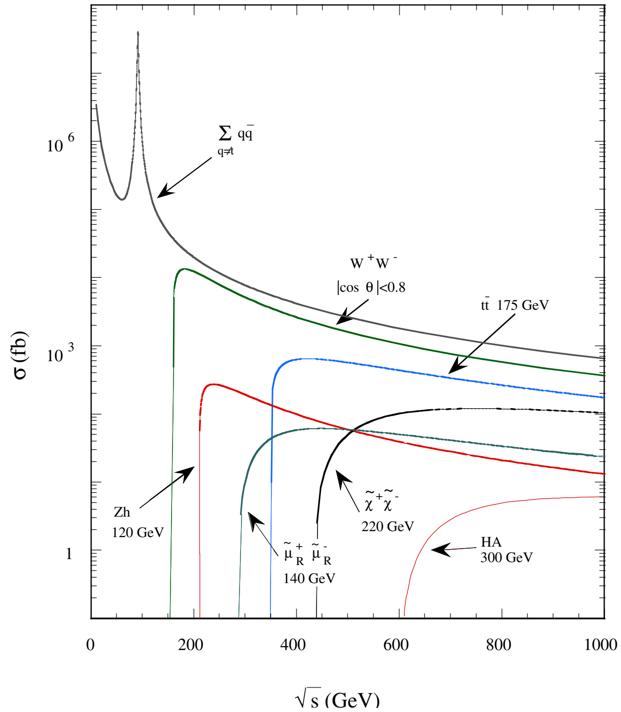

Figure 3: Cross sections at the linear collider [4]

above, and implies a Higgs mass below 200 GeV/c^2. However, the Standard Model is theoretically incomplete, and therefore disfavored. Other models can produce Standard Model-like Higgs bosons, with more acceptable theoretical properties. These include the MSSM model, non-exotic extended Higgs sector models (such as the Higgs Two Doublet Model) and strong coupling models. The MSSM model would expect the lightest Higgs to be very light, below 135 GeV/c^2. The other models would also produce detectable effects at the linear collider, although perhaps in quite different manifestations.

Taken at face value, the electroweak precision measurements suggest there should be a relatively light Higgs boson. If this boson is discovered, it will be crucial to measure its properties. The key to revealing the origin of EWSB is the measurement of the full nature of this "Higgs." The linear collider is capable of a significant clarification of this question. The program will include the mass measurement, the measurement of the total width, the measurement of particle couplings (including weak vector bosons, fermions, and $\gamma\gamma$), determination of the spin-parity-charge conjugation quantum numbers, and measurement of the Higgs self-couplings. A physics program at the linear collider would capitalize on the special advantages enumerated above, to make precise statements on all of these properties. Table II presents an example of the precision possible with a 500 GeV linear collider. Many of the properties of the Higgs boson could be measured with great precision. In the following we will discuss these.

2.1. Higgs Production

The principal production mechanisms for the Higgs boson at the linear collider are the Higgstrahlung process ($e^+e^- \to Z^0H^0$), and the WW fusion process ($e^+e^- \to \nu\overline{\nu}H^0$). The cross-sections for each of these is illustrated in Figure 4. The Higgstrahlung process has the advantage of allowing the detection of the Higgs from the recoiling Z, independent of the Higgs decay mode. Even invisible decays of the Higgs are measurable.

Table II Example of Precision of Higgs Measurements at the Next Linear Collider. $M_H = 140\,\mathrm{GeV}/c^2$, 500 fb^{-1} at 500 GeV. [3][4]

Mass measurement	$\delta M_H \approx 60 MeV \approx 5\times 10^{-4} M_H$
Total width	$\delta\Gamma_H/\Gamma_H \approx 3\%$
Particle couplings	
$t\bar{t}$	(needs higher $\sqrt{s}$ for 140 GeV, except through $H \to gg$)
$b\bar{b}$	$\delta g_{Hbb}/g_{Hbb} \approx 2\%$
$c\bar{c}$	$\delta g_{Hcc}/g_{Hcc} \approx 22\%$
$\tau^+\tau^-$	$\delta g_{H\tau^+\tau^-}/g_{H\tau^+\tau^-} \approx 5\%$
WW*	$\delta g_{HWW}/g_{HWW} \approx 2\%$
ZZ	$\delta g_{HZZ}/g_{HZZ} \approx 6\%$
gg	$\delta g_{Hgg}/g_{Hgg} \approx 12\%$
$\gamma\gamma$	$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma} \approx 10\%$
spin-parity-charge conjugation	establish $J^{PC} = 0^{++}$
self-coupling	$\delta\lambda HHH/\lambda HHH \approx 32\%$ (statistics limited)

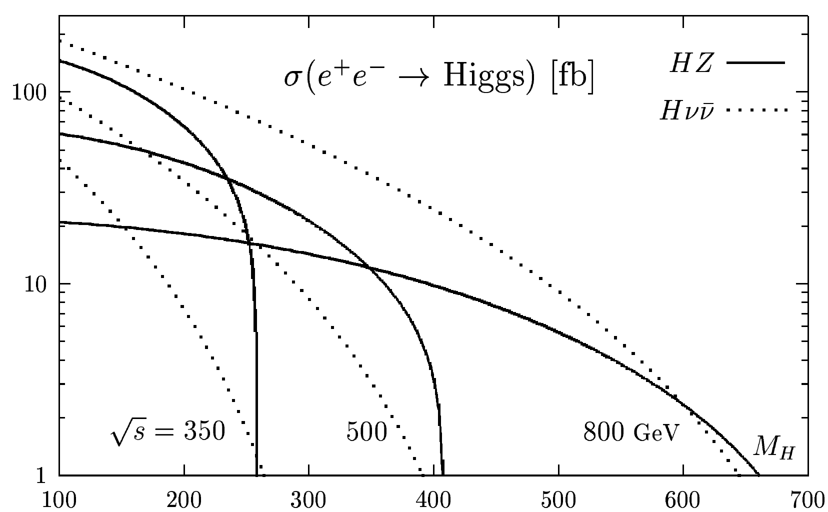

Figure 4: Higgs production cross sections versus the mass of the Higgs boson for $\sqrt{s} = 350$, 500, and 800 GeV.[4]

Table III Precision of the Mass Measurement ($500 fb^{-1}$ at 350 GeV, ref: [4])

M_H	δM_H (recoil)	δM_H (recon and fit)
120 GeV		40 MeV (3.3×10^{-4})
150 GeV	90 MeV	70 MeV (2×10^{-4})
180 GeV	100 MeV	80 MeV (4×10^{-4})

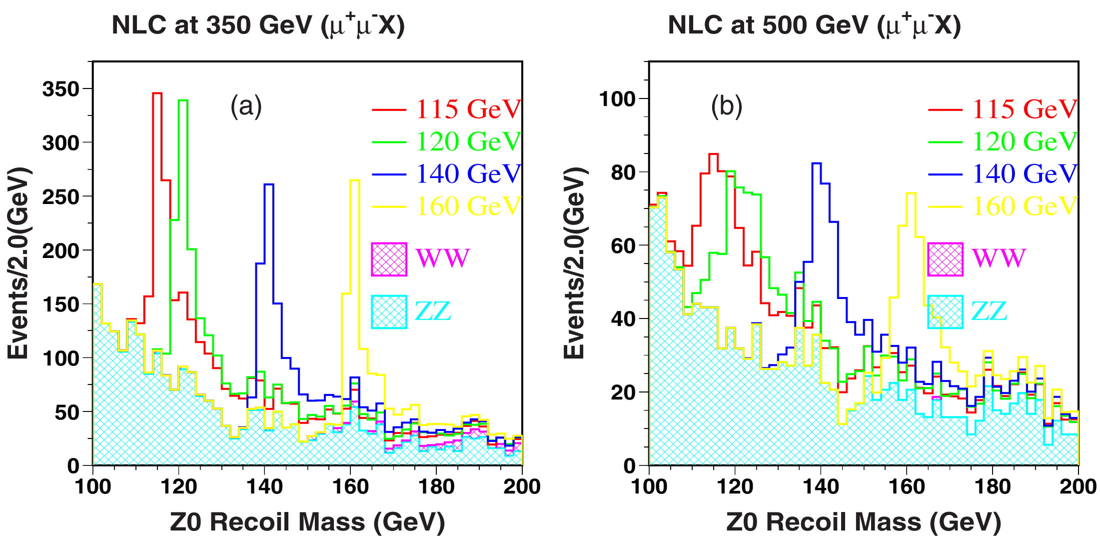

Figure 5: Recoil mass distributions.[3]

2.2. Higgs Mass and Width Measurements

The linear collder is capable of a mass measurement with better than 100 MeV/c^2 precision. The expectations are summarized in Table III. This may be achieved simply by measuring the recoiling mass from the dilepton decay of the Z^0, as illustrated in Figure 5, or (for better precision) with reconstruction of the recoiling system, and a constrained fit. With the constraint, the precision will be a few parts in ten-thousand.

The total width of the Higgs can be measured to a few percent precision either through the Higgsstrahlung process, or through WW fusion. The cross section for either of these processes reveals the partial width to that gauge boson, and the measurement of the branching ratio is then used to extract the total width:

$$\Gamma_{\text{tot}} = \Gamma_{VV}/BR(H \to VV), V = W \text{ or } Z$$

The sensitivity of such an analysis is shown in Table IV

Table IV Precision of the Higgs Width Measurement ($500 fb^{-1}$ at 350 GeV, ref: [4])

M_H	WW fusion	Higgs-strahlung
120 GeV	6.1%	5.6%
140 GeV	4.5%	3.7%
160 GeV	13.4%	3.6%

Table V Precision of the Higgs ZZ and WW Couplings ($500 fb^{-1}$ at 500 GeV, ref: [3])

ZZ Couplings		
M_H	cross section	branching ratio
120 GeV	6.5%	
140 GeV	6.5%	
160 GeV	6%	8.5%
200 GeV	7%	4%

WW Couplings		
M_H	cross section	branching ratio
120 GeV	3.5%	4.5%
140 GeV	6%	2%
160 GeV	17%	1.5%
200 GeV		3.5%

Table VI Precision of the Higgs Branching Ratios ($500 fb^{-1}$ at 500 GeV, ref: [3])

M_H	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to \tau^+\tau^-$
120 GeV	2.9%	39%	18%	17.9%
140 GeV	4.1%	45%	23%	10%

2.3. Higgs Couplings

The measurement of the Higgs couplings to fermions and bosons tests the Standard Model predictions with great sensitivity. Table V lists the precision of the coupling measurement to the gauge bosons.[3] These may be extracted either from the Higgs production cross sections, or from the Higgs branching ratios.

The Higgs branching ratios to fermions has an expected sensitivity shown in Table VI [3]. These sensitivities have been studied by several different investigators. The precision to charm and glue is somewhat uncertain due to the assumptions of vertex detection and channel separation. The numbers quoted here have been chosen on the side of the more conservative, as reflected in Reference [11].

The coupling of the Higgs to the photon is of particular interest as it arises from loops dominated by the top quark. Figure 6 illustrates the mass spectrum possible at a linear collider [4] and Figure 7 illustrates the fractional error possible in the branching ratio measurement [3].

The top quark coupling is the largest in the Standard Model. It may be directly measured through the process $e^+e^- \to t\bar{t}H$. The cross section for this process, however, is small, as illustrated in Figure 8 [3]. This will probably require higher than 500 GeV energy, or very high luminosity.

2.4. Higgs Spin-parity and Charge Conjugation (J^{PC})

The spin(J), parity(P), and charge conjugation(C) quantum numbers are important properties of the Higgs boson to confirm. Observation of the decay of the Higgs to two photons would rule out $J = 1$ and indicates $C = +1$. The threshold cross section in the process $e^+e^- \to Z^0H^0$ rises as β for $J = 0$, and generally as a higher power of β for non-zero spin. This is illustrated in Figure 9.[3] The production and decay angles in the Higgsstrahlung process is a sensitive test of the J^P of

Table VII Precision of the Higgs Branching Ratios ($500 fb^{-1}$ at 350 GeV, ref: [4])

M_H	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to \tau^+\tau^-$
120 GeV	2.4%	8.3%	5.5%	5.0%
140 GeV	2.6%	19%	14.%	8.%
160 GeV	6.5%			

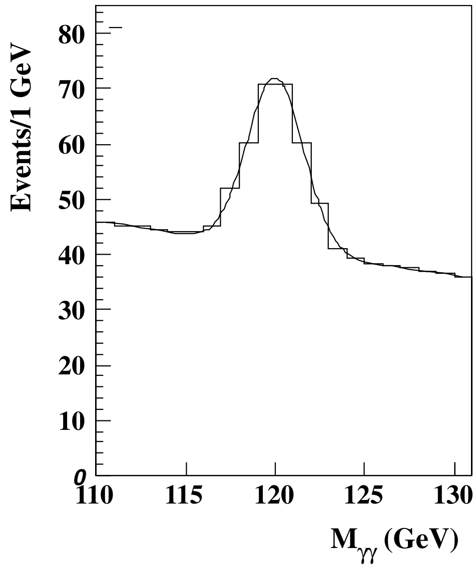

Figure 6: Gamma-gamma mass distribution.[4]

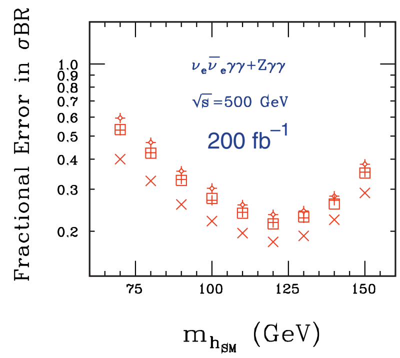

Figure 7: Higgs to gamma gamma branching ratio fractional error.[3]

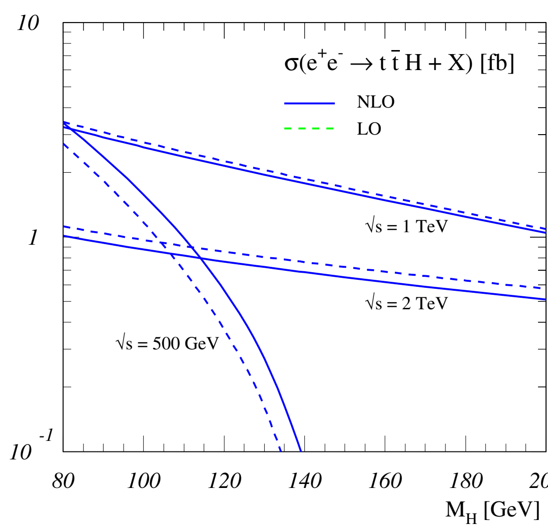

Figure 8: Cross section for $e^+e^- \to t\bar{t}H + X$ [3].

the Higgs; Figure 10 presents the polar angular distribution and compares it with production of particles of other quantum numbers. The right side of Figure 9 illustrates the power to separate the 0^{++} and 0^{-+} hypotheses.[3]

2.5. Higgs Self-couplings

An important test of the Standard Model is the self-coupling of the Higgs. The Higgs potential $V = \lambda(|\phi|^2 - 1/2v^2)^2$ must include triple (λ_{HHH}) and quartic (λ_{HHHH}) self couplings. The effects of the triple couplings might be detectable at 500 GeV. The expected precision for 1000 fb^{-1} is 17% for m_H = 120 GeV and 23% for m_H = 140 GeV.[4]

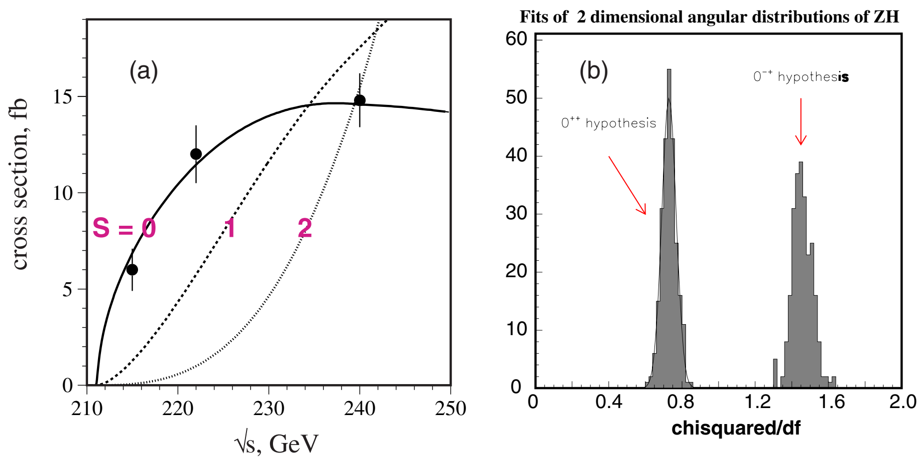

Figure 9: Threshold energy dependence on spin and spin analysis [3].

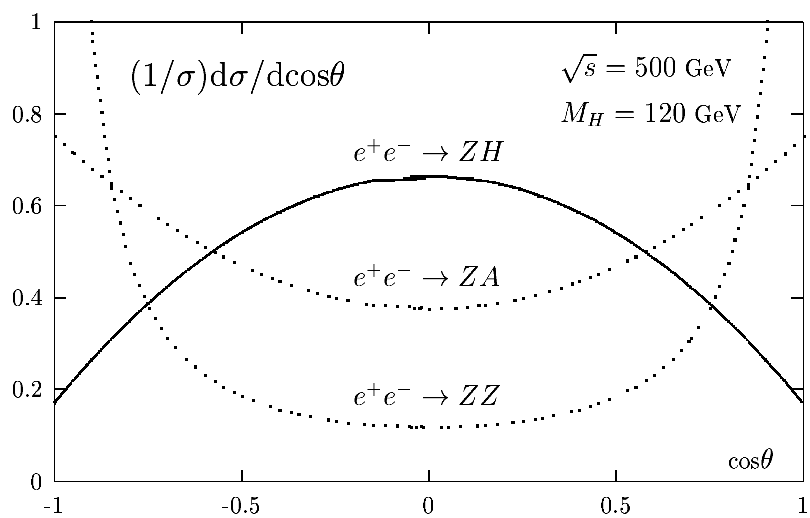

Figure 10: Angular distributions [4].

3. Interpretation: Is It the Standard Model Higgs?

What interpretation would one be able to deduce from the measurements that might follow the 1000 fb^{-1} of running at the linear collider. Table II presented one realistic possible outcome. The question is: would it be possible to determine whether or not this Higgs boson was consistent with the Standard Model. This question would be addressed through a detailed comparison to the expectations of the Standard Model. Does the hZZ coupling saturate the Z coupling sum rule? The Standard Model hZZ coupling should satisfy the relation:

$$g_{Zhh} = \left(\frac{M_Z g_{ew}}{2cos^2\theta_W} \right)^2$$

Are the branching ratios consistent with the Standard Model? Is the width consistent? Have other Higgs bosons or super-partners also been discovered? If none have, these precision measurements may be the only guide to the full nature of EWSB.

4. Susy Higgs Measurements

If additional Higgs bosons exist, finding them and determining their properties will provide vital data to the EWSB story. Unfortunately, the evidence for these states may be hard to obtain, further strengthening the case for precision measurements. Figure 11 shows the range in tanβ-M_A space over which the MSSM branching ratios deviate significantly from the Standard Model.[3] For M_A less than several hundred GeV, the branching ratio deviations would be detectable. For larger values for M_A, "decoupling" sets in, and the MSSM light Higgs looks much like a Standard Model Higgs.

Another illustration of this is shown in Figures 12 and 13 [4]. These plots show the deviation of the fermion couplings to the 120 GeV Higgs, for various values of M_A in MSSM, and the precision expected at the linear collider with 500 fb^{-1}. The conclusion of this analysis is that for $M_A < 600$ GeV, one would likely be able to distinguish the Standard Model from MSSM. Again, for large values of M_A, "decoupling" sets in.

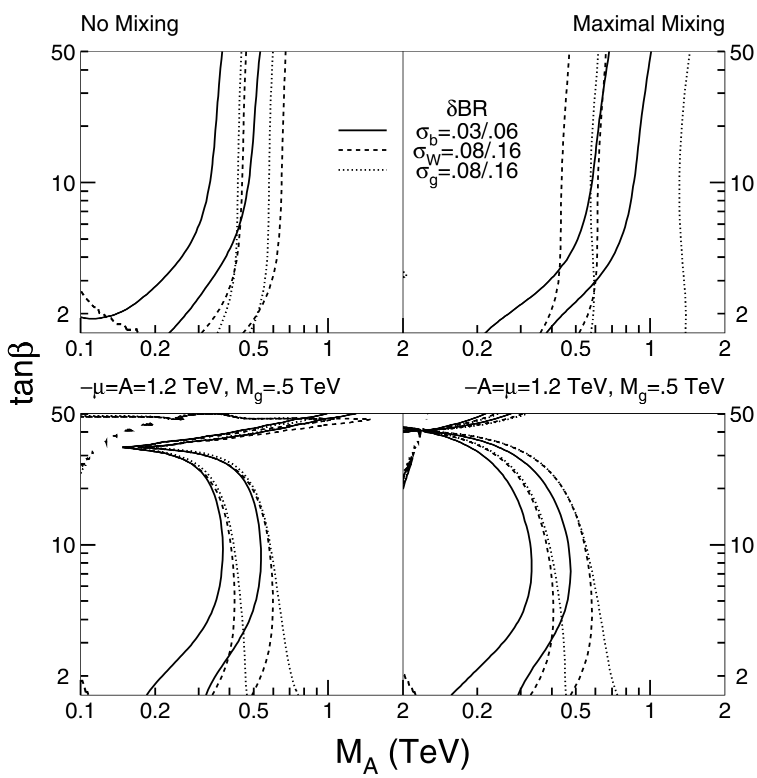

Figure 11: Comparison of branching ratios with M_A [3].

5. Strong Coupling Gauge Models

Electroweak symmetry breaking might not be mediated by fundamental scalars (despite the excellent agreement of data with the Standard Model). Instead, a new stong interaction could provide the Higgs mechanism. In this case, the linear collider would also provide critical information; for example, the Giga-Z run would constrain strong coupling composite 'Higgs' masses to < 500 GeV. In this scenario, bound states of new fermions would be expected at the TeV scale. The absorption of primordial Higgs particles into the longitudinal components of the W and Z

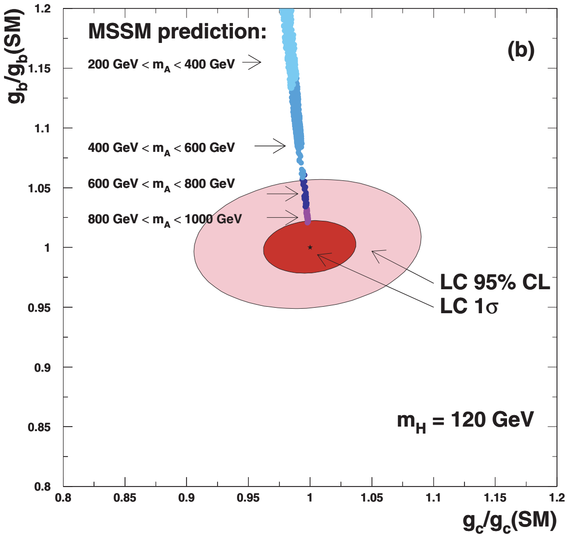

Figure 12: HFITTER results for g_b versus g_c [4].

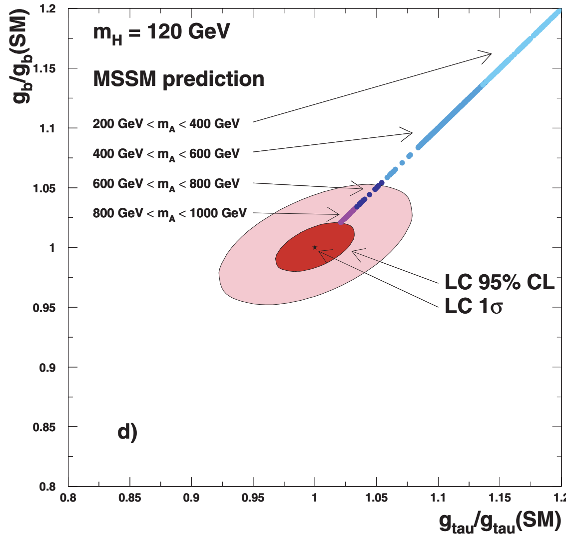

Figure 13: HFITTER results for g_b versus g_τ [4].

would modify the WW and ZZ scattering. The LHC would observe a broad resonance, and the linear collider would measure significance deviations in the $e^+e^- \to W^+W^-$ cross section.

Another effect of the strong coupling would be observable modifications to the $WW\gamma$ coupling. The linear collider could be very effective in detecting these modifications; for example, for $\kappa_{\gamma,Z}$, the 500 GeV linear collider is 10-20 times more precise than the LHC. Also, anomalous top couplings to the Z and γ are expected, and these would only be observable at the linear collider.

6. Other scenarios

Any other scenario for new physics must be consistent with the precision electroweak measurements. Many new scenarios in agreement with the precision electroweak data have been investigated; they generally require new physics which would be detectable at the linear collider [10]. Several of these combine a heavy higgs with another new physics element. One example of the new physics is a light $SU(2) \times SU(2)$ multiplet. This introduces new observable particles. Another is a Z', which is observable. Another extra dimensions, which are detectable. And yet another new particles with large a up/down flavor asymmetry. This leads to Giga-Z effects. Again and again, many possible “conspiracy scenarios” require some new physics to which the linear collider is sensitive.

7. Linear Collider Enhancements

The physics program of the linear collider might be enhanced by a number of options. These include the possibility of running at the WW threshold, of running with very high luminosity at the Z^0 pole, to produce about 10^9 polarized Z^0s, and the option of developing a gamma-gamma collider. Each of these enhancements would contribute to our investigation of the nature of electroweak symmetry breaking. For example, the W mass could be measured with 6 MeV precision with one year of running at threshold with both beams polarized.

7.1. Precision Studies at the Z^0

Some scenarios for the outcome of high energy measurements at the LHC and the linear collider would motivate higher precision studies of the Z^0. For example, if a light Higgs is found, and nothing else, it would be extremely valuable to know the electroweak loop corrections more precisely than they are known today. At the Giga-Z facility, the Standard Model Higgs mass could be confirmed through electroweak corrections to 7%, with a measurement of $\sin^2\theta_W$ to 0.000013, and knowledge of the W mass to 6 MeV and the top mass to 100 MeV.[4] This could play a key role in understanding the nature of the Higgs spectrum.

Several studies have demonstrated the value of this. In one investigation of the "Topcolor" seesaw model with $M_\chi = 5$ TeV, it is shown that if the electroweak measurements are to be explained by a conspiracy between a heavy Standard Model Higgs and other new physics, that other new physics will generally be detectable at the LC in this way [10].

7.2. The Gamma-gamma Collider

One option for the linear collider is the formation of the collision of two backscattered photon beams. One particularly valuable role for this Gamma–gamma collider would be the s-channel production of the Higgs boson ($\gamma\gamma \to H \to X$). Production of the Higgs at the Gamma-gamma collider establishes the charge conjugation of the Higgs to be positive and rules out spin one. In addition, the CP even (H) and CP odd (A) states can be produced separately using polarized photons. This could be very significant if there two particles have similar masses and other similar properties, as is expected for much of the MSSM parameter space.

8. Complementarity with LHC

The linear collider is sure to add value to the data of the LHC, providing the "enabling technology" for full interpretation of the LHC results. How it does will certainly depend on the physics, but in many scenarios it has been shown that this will be the case. It can add precision to the LHC discoveries, such as is the case for a light Higgs boson. If SUSY parameters fall in the $\tan\beta/M_A$ wedge, it will be crucial to explore this blind spot. It may add valuable asymmetry measurements to the WW/ZZ resonances discovered at the LHC. Extra neutral gauge bosons might appear, and require the data only obtained from a linear collider. Or the very high precision measurements possible at the Z pole might be critical to understanding a relatively barren LHC program. Even in the scenario where the LHC is rich with new physics, such as a light SUSY sector, the linear collider will be needed to fully interpret these signals.

9. Run Parameters

The linear collider has a broad role in elucidating new physics. One issue that must be considered is whether or not it is possible to devise a run plan that measures what one would like to know within a reasonable time. This has been studied and shown to be possible [3]. If one constrains the amount of running to that needed to accumulate 1000 fb^{-1} at 500 GeV, yet allows the collider to operate at several energy thresholds, one can achieve the physics goals, even in a rich scenario with many new, interesting states [3].

10. Conclusions

The linear collider will be a powerful tool for studying the Higgs Mechanism and electroweak symmetry breaking. The current status of electroweak precision measurements strongly suggests that the physics will be rich and greatly advance our understanding of the elementary particles and interactions. If Nature turns out to be more complicated than the simplest models, the precision offered by a linear collider could be critical.

11. Acknowledgements

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