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Term Paper
8.311: Particle Physics
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Supersymmetry Detection and Precision Measurements at a Linear Collider

ABSTRACT

Supersymmetry is perhaps the strongest candidate to explain phenomena outside the standard model. In this paper I will motivate the need for such extra-standard model theory, as well as provide a theoretical overview of supersymmetry. I will discuss the design of a next-generation linear collider and detector systems and detail how such a collider can lead to the discovery of supersymmetry and detailed measurements of its properties.

I. Why Search for Supersymmetry?

I.1 The Standard Model and its Failings

For more than thirty years the study of physics at high energies has been dominated by what is known as the "Standard Model" of particle physics. This theory is based on the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry group [1]. The Standard Model separates all elementary particles into two groups: fermions and bosons. Fermions consist of quarks and leptons (and their anti-partners;) all of which carry half-integer spin. It is these particles (particularly the up and down quarks, and the electron) that come together to form mesons, baryons, and atoms that comprise "ordinary" matter. All other elementary particles (the ones with integer spin) are known as bosons. These include the photon, the W and Z bosons, and the gluons. These are the particles that mediate the electromagnetic, weak, and strong forces, respectively. Fermions interact with each other by emitting and absorbing bosons. Furthermore, the Standard Model assumes the symmetry is spontaneously broken to the $SU(3)_C \times U(1)_{em}$ symmetry by an $SU(2)_L$ doublet of spin-zero (scalar) fields. This field has associated boson, the Higgs boson, which also endows fermions and heavy bosons with their mass. While the Higgs has not yet been found, this should not be taken as a failing in the theory, but rather a failing in our experimental prowess. There is ample reason to believe that Higgs will indeed be observed once the Large Hadron Collider (LHC) is up and running [2].

For all intents and purposes, the Standard Model has been an unmitigated success. To date, no experiment has been performed that contradicts the theoretical predictions of the Standard Model. This leads to the obvious (and reasonable) question of why we are bothering to search for a "better" physical model (supersymmetry) when our old theory has not been proven wrong. Why try and fix our yet-unbroken theory? The reason we should search for extra-standard-model physics is that, at a theoretical level, the standard model is incomplete. It is not and indeed cannot be the fundamental description of nature. Perhaps most damaging in general (and probably least damaging with regards to this paper) is that the theory does not even attempt to explain the gravitational force. Also, the theory correctly predicts electroweak symmetry breaking (EWSB), but we really have no clue what the mechanism for this is. Furthermore, the standard model does not explain the seemingly arbitrary value of particle masses and mixing parameters. It seems content to describe these without any underlying motivation. It has been said that, "nature abhors a vacuum;" well, physicists abhor arbitrariness. Aesthetically, the Standard Model seems incomplete.

However, there is one particular failing of the Standard Model that is of great importance to the topic at hand.

This failing revolves around a problem that arises in quantum field theories when one tries to work with elementary spin-zero fields (such as the Higgs,) and it is the primary motivation for supersymmetry (from here on SUSY) searches. The radiative corrections to the mass of such scalar bosons diverge quadratically with internal loop momentum (see fig. 1) [3].

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Figure 1 in Martin, Stephen P. A Supersymmetry Primer. ArXiv:hep-ph/9709356 v3 (1997).
http://arxiv.org/abs/hep-ph/9709356

fig. 1: quadratic divergences in the Higgs

Unlike the corrections to fermion and heavy boson masses (which are logarithmic in nature) these divergences cannot be normalized over. According to the theory then, the physical mass of the Higgs boson would be:

$$m_H^2 = m_0^2 + \delta m_H^2$$

where m_0 is the first order Higgs mass term. While we do not know the exact mass of the physical Higgs, we do know it cannot be too large. If we liberally estimate this upper limit to be 500 GeV, then for this to be accurate at the GUT cutoff scale we must add two numbers, both exceeding 10^{30} GeV^2, to get an answer around 10^6 GeV^2. This implies that the two right-hand elements must be precise to 1 part in 10^{24}. This sort of sensitivity is, simply put, impossible [4]. If our model of the universe is to be correct, it must protect against these quadratic divergences. We must be able to accurately predict the physical Higgs mass without resorting to the sort of fine-tuning required above. Fortunately, SUSY does exactly this. After a brief introduction to SUSY theory, I will proceed to show just how we can handle these divergences.

I.2 A Primer on Supersymmetry

The topic of this paper is an experimental search for SUSY, and as such most of the technical aspects of SUSY theory (such as its Lagrangian formulation and group algebra) fall outside of our scope (for a more thorough treatment, see ref. 3,4.) However, it is important to understand the basics of SUSY theory especially the *physicality* of the theory; that is, what will we be looking for when we search for evidence of SUSY. At the most basic level, SUSY theorizes that every fundamental particle-every quark, lepton, and boson-has an associated superpartner. With the exception of spin, a SUSY particle will carry the same quantum numbers (charge, weak-isospin, color, etc.) as its partner. The spin however, is where the two differ, and they invariably differ by exactly 1/2 unit. SUSY quark partners (squarks) and SUSY lepton partners (sleptons) will have spin 0, and they will be bosons. The SUSY W, B, and gluon (Wino, Bino, and gluino respectively) will all have spin 1/2 and thus they will all be fermions. The Higgs superpartner is special and deserves its own explanation. The Standard Model predicts the Higgs will be a $SU(2)_L$ doublet with spin 0. In SUSY, we require two doublets (Higgsinos) also with spin 1/2 [3].

It is important to note that, because of EWSB, the above particles are not necessarily mass eigenstates of SUSY theory. Taking our cues from the Standard Model, we would expect that the wino, bino, and Higgsino gauge eigenstates should mix to form the spin 1/2 mass eigenstates. This is crucial because it is the mass eigenstates that we look for in the detector. For the remainder of this paper, when we talk about detecting these gauginos, we will usually refer to charginos, ($\chi_i^{\pm}$) and neutralinos (χ_i^0), the mass eigenstates of mixtures of winos, binos, Higgsinos. Most SUSY models predict that the gluino, squarks, and sleptons are indeed gauge and mass eigenstates of the theory.

I.2.a R Parity

Before we can discuss the decay chains of SUSY particles, we need to introduce the concept of R parity or matter parity. Currently, the most plausible supersymmetric models all postulate that R parity is conserved for all interactions (Standard Model and SUSY.) R parity is a multiplicative quantum number defined as:

$$P_R = (-1)^{3(B-L)+2s}$$

where B, L, and s are the baryon, lepton, and spin quantum numbers, respectively [5]. It is easy to see that all standard model particles and the standard model Higgs, carry even R parity ($P_R = +1$.) All squarks, sleptons, gauginos, and Higgsinos (all sparticles) carry odd R parity ($P_R = -1$.) The conservation of R parity carries a number of interesting consequences and three of them are of vital importance to our study. First, in our experimental collider environment, any reaction that produces sparticles must produce an even amount of them. In other words, all sparticles must be pair-produced. Second, the lightest supersymmetric particle

(LSP) must be absolutely stable. R parity conservation prevents the LSP from decaying into any SM particle, and, of course, the LSP cannot decay into a heavier sparticle. Finally, all sparticles (besides the LSP) must eventually decay into an odd number of other sparticles. This means that *all* sparticles we manage to create will eventually decay into an LSP [3].

R parity conservation may seem like an arbitrary constraint on SUSY theories, simply to make our lives simpler; and as we will see, this does make the prospect of discovering SUSY much less daunting. Indeed it is possible to formulate SUSY without R parity conservation. However, these outlying theories notwithstanding, the desire to conserve R parity is well motivated by experiment. Recent experiments have placed a lower limit on the lifetime of the proton at 10^{33} years [6]. A consequence of R parity is that the proton, like the LSP, is absolutely stable over the lifetime of the universe, which seems to be the case. Moreover, one of the biggest problems with SUSY models without R parity conservation is that they predict much shorter lifetimes for the proton. Also, the idea of a stable LSP provides an attractive candidate for the non-baryonic dark matter that we know makes up around 25% of the energy density in the universe. Hence, for the majority of this paper, we will ignore models that do not conserve R parity.

I.3 Supersymmetric Decays

It is vitally important for us to understand sparticle decays, since it is ultimately these decays that we will search for. Our knowledge will allow us to reconstruct specific interactions from the signals in our detector. In our treatment, we will assume that the lightest neutralino (χ_1^0) is the LSP and therefore all sparticles decays will ultimately contain the χ_1^0 in the final state. We will subsequently discuss sparticle decays in terms of how important the processes are in our experimental challenges. With this in mind we will start with neutralinos and charginos, then move on to sleptons and finally squarks gluinos.

As we stated above, the charginos ($\chi_i^\pm$) and neutralinos (χ_i^0) are mass eigenstates that are mixtures of the charged and neutral winos, the bino, and the Higgsinos. As long as the decay products are not more massive than the original sparticle, a neutralino or chargino can decay into a lepton + slepton, quark + squark, or a lighter neutralino + Higgs or Standard Model gauge boson. Neutralinos and chargino can also participate in three-body decays, where one of the products is a sparticle and two are standard model particles. An example would be neutralino decaying into a lighter neutralino plus a fermion pair. As we will see later, the decays of charginos and neutralinos are the primary sector for our SUSY discovery searches.

Sleptons and sneutrinos (l˜,υ~) also participate in two-body decays. Sleptons can decay into a charged lepton plus a neutralino or a neutrino plus a chargino. Sneutrinos decay into a charged lepton and a chargino or a neutrino and a neutralino. These decays will play an important role in determining the mixing ratios for charginos and neutralinos, especially when we employ polarized beams for our interactions.

Squark and gluino decays will not play a dominant role in SUSY discover at a linear collider. However, for completeness purposes, we will not ignore them. Squarks will decay into quark + gluino with the highest probability, since this decay will have QCD-scale coupling. More rare decays include direct squark to quark plus neutralino and squark to anti-quark plus chargino. Similarly the dominant gluino decay will yield quark plus squark. These decays (especially those of the gluino) play a more prominent role in hadron colliders [4].

I.4 How SUSY "Fixes" the Standard Model

We noted above that the main motivation for SUSY theories are the quadratic radiative corrections to the scalar Higgs mass in the Standard Model. The Standard Model presents an unacceptable sensitivity for the Higgs mass. SUSY provides a rather ingenious way around this problem. We illustrate this with an example. Imagine a Higgs-mass correction of the type in figure 1a. The Higgs radiates a quark-antiquark pair and this loop integral leads to the aforementioned quadratic divergence. When we introduce supersymmetry however, we must also introduce a squark-antisquark loop to the corrections to the Higgs mass. When we integrate around this loop, we obtain exactly the same correction to the mass (because the quantum numbers and couplings are the same) except of course for the difference in spin, which introduces a factor of (-1) to the loop integral. Therefore the two corrections *exactly cancel* each other and thus we have eliminated the extreme sensitivity so damaging to the Standard Model [3]. To date, SUSY serves as the most probable theory for extra-Standard Model physics.

II. The Linear Collider

II.1 Motivation

Thus far, the scientific community has yet to observe any signals from SUSY particles. Currently, the highest energy collisions are obtained at the Tevatron at Fermi National Laboratory. The Tevatron collides protons and anti-protons at a center-of-mass energy ($\sqrt{s}$) of about 2 TeV. Within the next couple of years however, the Large Hadron Collider (LHC) at CERN is expected to turn on and will provide 14 TeV proton-proton collisions. With such a high-energy machine nearing completion it is not unreasonable to ask why we are discussing linear-collider (LC) SUSY searches. Certainly, the argument goes, if SUSY does indeed exist, it will be found at the LHC. We should be focusing our energy on hadronic, not leptonic, SUSY searches.

Yes it is true that the completion of an LC such as the one we discuss is years, perhaps decades, away. Still, the LHC and an LC should not be viewed as in direct competition. Indeed it would be silly to place all of our eggs in the LHC's basket. An LC and the LHC provide complementary approaches to discovering new physics. Neither could claim sole ownership of the extra-Standard Model landscape. The LHC may or may not discover SUSY. If it does not, an LC would provide our best shot at discovery, or in the absence of discover, our best shot at disproving SUSY. If the LHC is able to detect signals of SUSY, an LC may prove to be even more necessary to carry out precision measurements that would be far too complicated in the environment of a hadron collider.

Indeed a linear collider has many features that make it an ideal tool for discovering and measuring new physics. While we will go into more detail in our analysis section, a couple of these properties are worth mentioning here. First, and perhaps most important, is the "clean" environment produced in e^+e^- collisions. Hadronic collisions tend to be messy, with numerous spectator particles clouding the actual collision signal. The signal to background ratio is much lower for hadronic collisions than for e^+e^- collisions. Furthermore, partons interact via QCD forces, which are not as well understood as electroweak forces. This makes precision measurements much more difficult at a place like the LHC. Finally, electron and positron beams are much more versatile than proton beams. Electron beams can be tuned to precise energies, and furthermore they can be polarized, allowing for asymmetry measurements unavailable at the LHC [7].

It is with these factors in mind that we propose a design for a linear collider facility. We will take our design cues from the proposed Next Linear Collider (NLC,) which will deliver electron-positron collisions at a center of mass energy between .5 and 1.5 TeV.

II.2 The Accelerator

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Figure 1.5 in NLC Physics Working Group. Physics and Technology of the Next Linear Collider. FERMILAB-PUB-96/112 (1996).
http://arxiv.org/PS_cache/hep-ex/pdf/9605/9605011.pdf

Fig.2 Schematic of a high-energy LC [8]

From a physics standpoint, and for the purposes of this paper, it is not vital to understand the workings of the accelerator complex. As long as electrons and positrons are delivered to our detectors at high energy and known polarization, and as long as these beams interact, we can make our measurements with no knowledge of how these beams arrived. As such we will not discuss in detail in inner workings of beam dynamics, positron production, klystrons etc. However, it is important to have a general idea how, and more importantly why, we use a linear accelerator to provide these beams.

Figure 2 provides a schematic view of the NLC facility. The entire structure will be between 30 and 40 km long and will accelerate electrons and positrons to energies ranging from 250 - 750 GeV. The main accelerator contains many thousands of superconducting RF resonant cavities. These cavities are cooled by liquid helium and are driven in such a way as to create a high-frequency oscillating electric field inside the cavity. The main idea is that an electron (or positron) bunch enters each cavity and are accelerated a small amount by this electric field. After passing through the entire length of the accelerator (approximately 10,000 of these cavities,) the electron (or positron) bunch has been boosted to the desired energy. Dipole and quadrapole magnets are used to steer and focus the beam, creating tightly packed bunches to collide. Each bunch contains about 10^{10} particles and bunches are separated by approximately 1.5 nanoseconds. These bunches arrive at the interaction point where they collide with each other and hopefully, we are able to find the signals of interesting novel physics.

II.3 The Detector

For our purposes, the detector is the most vital part of our facility. Our experimental search for SUSY can only be as good as our detector. We must take great care in designing a detector that will optimize our chances of finding SUSY signals. Figure 3 [8] shows a cross-sectional view of our proposed detector. While the dimensions are not "set in stone," this should give a good idea about what our detector will resemble. Of course, figure 3 only shows one quadrant of the detector. In reality the detector will cover the full 2π range in ϕ and up to .99 in $\cos\theta$. In the next few subsections, we will describe the different detector systems starting at the beam pipe and moving radially outward. The capabilities of each system will also be described in the subsections. Our motivations will become clearer in the analysis section, where we will describe the physics goals for our detector.

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Figure 2.49 in NLC Physics Working Group. Physics and Technology of the Next Linear Collider. FERMILAB-PUB-96/112 (1996).

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Fig.3: cross-section of detector systems

II.3.a The Inner Tracking System

One of the nice features of an e^+e^- detector is that the physical dimensions of the electron and positron bunches are relatively small, allowing the beam pipe at the interaction point also to be small (~1 cm.) This allows us to place our innermost tracking system very close to the primary interaction point [9]. This innermost tracking system (often referred to as the vertex detector) is used for precision secondary-vertex and flavor tagging. These tasks require very fine spatial resolution. Our design calls for 3-5 layers of 20-micron by 20-micron charged-coupled devices (CCDs.) This system is expected to achieve impact parameter resolution at high momentum of better than 3μm.

II.3.b Central and Forward Tracking

It would be fiscally impractical (an unnecessary) to extend this CCD region too far. Outside of the inner vertex detector, we have a region of central tracking. This region is used to track charged particles as they fly from the central interactions. Designs for central tracking systems fall into two categories: gaseous and solid-state. Gaseous systems, such as the TPC at STAR, provide excellent momentum resolution, but such a system would be ill equipped to handle the extremely small bunch separation (1.2 ns) in our accelerator. So for our detector we suggest central tracking using 5 cylindrical layers of silicon strips, which would provide 5 micron spatial resolution and would be much better suited to handle the rapid collision rate of our machine. These layers would extend to $\cos\theta = .9$. This system should provide us with excellent momentum resolution, even at low angles. Taking into account the radius of our central tracking system (~50 cm) and the strength of our magnetic field (~4 T), we should expect $\delta p_T/P_T = 2 \times 10^{-4}$ at 100 GeV at $\cos\theta = .9$ [8].

As we will see later on, it is of vital importance that we are able to track charged particles in the far forward direction of our detector. Many of the processes we will look for involve missing energy and we must be careful to separate the events with true missing energy from those in which standard model particles escape detection in the forward direction. For this we suggest another series of silicon detectors (disks) in the far forward direction. This should provide us with momentum resolution on the order of $\delta p_T/P_T^2 = 5 \times 10^{-4}$ [8], all the way down to $\cos\theta = .99$. However, we believe that this can be improved upon and much of the R&D effort should be put into high-precision forward tracking.

II.3.c The Electromagnetic Calorimeter

Just outside of the tracking chamber would sit our electromagnetic calorimeter (Ecal.) The Ecal is important for measure the shape and energy of electromagnetic showers, which in turn allows us to reconstruct hadronic and leptonic final states. This is the principle way to identify the energy of a particle in our detector. As we shall see, our discovery searches as well as our precision measurements will require very good energy resolution. For our Ecal we recommend 25 radiation lengths (X_o), which should be able to fully contain the electromagnetic showers giving us a good energy measurement. We suggest SiW-Ecal, with 40 sampling layers and a full thickness of around 20 cm. The towers should have angular segmentation of 30 to 40 mrad^2. This option will cost more than a traditional sampling calorimeter but will provide much better energy resolution. With this type of Ecal we should expect energy resolution in the rang of $\sigma_E/E = 10\%/\sqrt{E}$ [10]. For the same reasons that we require good forward tracking, we also require our Ecal to extend beyond the barrel, over the end caps as well. This will provide energy measurements to $\cos\theta = .99$.

II.3.d The Magnet

The magnet coil system will sit outside of the Ecal. The technical details of the magnet are not pertinent to this paper. Suffice to say that it will create a solenoidal magnetic field inside the coil. For purposes of our experiments, a field of 4 T should be large enough for our tracking purposes. Such a field is well matched to our small-volume tracker. And fields of this magnitude should not be too costly or technologically problematic. The magnetic coil is superconducting and will be 2-3 X_o thick. An advantage to the small size of our detector is that we should be able to easily maintain a homogenous field throughout, which will prove invaluable when making precision measurements [8].

II.3.e The Hadronic Calorimeter and Muon System

The hadronic calorimeter (Hcal) sits outside of the magnet. The Hcal works in conjunction with the Ecal to measure the energy of hadronic jets too energetic to deposit all of their energy in the Ecal. These jets become very important in the hadronic decays of sparticles. To this end it is built in much the same fashion as the Ecal. However, to fully contain the energy showers of these jets it must be much thicker. To keep costs to a reasonable level it is impractical to make the Hcal out of the same material as the Ecal. With an unlimited budget, this would probably be a good plan, and would lead to better energy resolution of jets, but it is not what we advocate here. We suggest using an iron scintillating sampling calorimeter. We suggest having about 100 samples, extending around 150 cm after the magnets system. We do not expect the energy resolution to be as precise as the Ecal, but we can expect $\sigma_E/E \sim 40\%/\sqrt{E}$ [8].

The entire detector will be wrapped in a iron flux return what will also include ten layers of muon detectors. Muons tend to penetrate material more than electrons and even jets. It is important for our purposes to be able to identify high-energy muons, tag them, and measure their transverse momentum to some extent. The energy resolution of our muon system will not be as precise as the calorimeters, but it should be sufficient for our purposes.

III. Analysis

III.1 Intro

In this section we will discuss the various way SUSY will manifest itself in our detector and how best we can use our detectors to discover SUSY. As we have shown above, a .5 - 1.5 TeV e^+e^- collider is a very powerful tool for searching for physical phenomena outside of the Standard Model. With such a powerful tool at our disposal, we would be remiss if we were to limit ourselves to simply the discovery of SUSY. We ought to, and indeed we do, have more ambitious goals for our experiments. If and when SUSY is discovered, there will be a wealth of new particles to study. The scientific community will demand precision measurements of sparticle masses, mixing parameters, decay ratios, and interaction strengths. A TeV-scale linear collider will be at the forefront of such measurements. With this in mind, we organize this section into two main parts. First we will discuss discovery searches, which will naturally become the main focus for our LC if the LHC finds no evidence of SUSY. Second we will discuss opportunities for precision measurements once SUSY has been discovered, either at our LC or at the LHC. Since we are unsure of how SUSY will manifest itself, we, for the most part, will focus on the minimal supergravity model of SUSY (mSugra.) This model has the least amount of free parameters, with all of the SUSY interactions being described in terms of two mass terms m_0 and $m_{1/2}$, a universal trilinear coupling A_0, and $\tan\beta$, the ratio of vacuum Higgs expectation values. The mSugra model also assumes R parity is conserved and that the LSP is a neutralino. For a more thorough discussion of the mSugra model see Ref. 3,4.

III.2 Discovery Searches

The first point we must make is that SUSY may still exist even if it is not discovered at the LHC. While it is true that the LHC will run at a much higher energy than the NLC, the SUSY searches it will run will be much more difficult. The primary detection channel for the LHC is gluino production. It is likely that the gluino is very massive even in comparison to the lighter charginos and neutralinos. Furthermore, as we have stated earlier, the analysis will be much more difficult to perform at the LHC, as the environment is much messier. So if SUSY is not discovered at the LHC we must do our best to search for it at our LC. However, the two machines combined will be able to search for the lightest SUSY Higgs over the entire mSugra parameter space. If evidence of SUSY is not found at either facility, than the mSugra model must be ruled out [8]. Figure 4 shows a comparison between the reaches of both machines in parameter space.

More optimistically, we must discuss what exactly a SUSY signal will look like in our detector. The main channels for discovery in our environment are the pair production of light charginos ($\chi_1^{\pm}$), and production of the light neutralinos χ_1^0 and χ_2^0. To give an idea of what kind of rate we will be looking at, we note that if mSugra theory is correct, the cross section for $e^+e^- \to \chi_1^+\chi_1^-$ is approximately .75 pb [8]. Which means for one year of running at desired luminosity, we should be looking at event numbers of the order of 10^4. For chargino pair production, a classic signal would be when one of the pair decays into a lepton and the LSP, while the other decays hadronically into two jets plus the LSP. The chargino will decay this way around 66% of the time. The LSPs travel unobserved through our detectors, carrying with them energy and momentum that will be noticeably absent. This "missing energy" from the jet-jet invariant mass distribution is indeed the most striking signal for SUSY [11]. Another striking signal from the chargino pair production would be for both charginos to decaying into a lepton plus an LSP. Charginos decay this way around 22% of the time. This would lead to a topology of two acollinear leptons with "missing" energy. Similar types of decays would lead to similar signals from neutralino production. For example, χ_2^0 will decay to $l^+ + l^-$ + LSP around 33% of the time. Figure 5 shows theoretical cross-sections for different SUSY processes at .5 TeV for two sets of mSugra parameters [7].

III.2.a Backgrounds

It becomes obvious now why we insisted on excellent calorimetry in our detector and made sure that our calorimeters covered even down to small angels. Since our main signals for SUSY involved "missing" energy, we must be able to accurately reconstruct the energy for interactions. This leads nicely into a discussion of our main backgrounds, that is, backgrounds that mimic the missing energy so endemic to our discovery searches. Far and away the biggest background source that we will have will be $e^+e^- \to W^+W^-$ reactions [11]. W pairs can mimic our signals because they too can decay either leptonically or hadronically creating dilepton and jet events with missing energy. Often this energy is carried away by highly energetic neutrinos which we have no hope of tracking in our detectors. Furthermore, the products from these interactions tend to travel down the beam pipe where we cannot detect them. But wait, didn't we say earlier that a

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Figure 2.37 in NLC Physics Working Group. Physics and Technology of the Next Linear Collider. FERMILAB-PUB-96/112 (1996).

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Fig. 4: The top plot shows the reach in mSugra parameter space of the NLC for single beam energy of 250, 500, and 750 GeV. The bottom plot shows the same for the LHC. The shaded areas are excluded by theory or experimental limits [8].

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Figure 2.25 in NLC Physics Working Group. Physics and Technology of the Next Linear Collider. FERMILAB-PUB-96/112 (1996).

http://arxiv.org/PS_cache/hep-ex/pdf/9605/9605011.pdf

Fig. 5: Cross-sections for different SUSY sub-processes at two different sets of mSugra parameters [8].

main strength of the LC was its "clean" environment, relatively free of background events, providing for easier analysis? Indeed we did, and we shall see that it is not hard to separate the Standard Model backgrounds from the SUSY events. To do so we employ a series of cuts on our data. These cuts are as follows:

- $|\cos\theta_{thrust}| < 0.85$
- $E_{back} > 0$
- # of particles per jet > 4
- $E_{for} < .4E_{CM}$

The first cut separates SUSY events, which tend to be isotropic, from the WW events that tend to be peaked in the beam direction. In the second cut E_{back} is the energy in the hemisphere with lower energy. This cut ensures that there is energy in both hemispheres of the detector. This cut eliminates events in which both W decay into neutrinos + X, and both of those neutrinos fly off in the same direction, or where the resultant lepton travels down the beam pipe. The third cut eliminates events where the jets come from taus or leptons and enhances hadronic (quark or antiquark) jets. The final cut is probably the most important, eliminating all events without missing energy. These cuts lead to a striking amplification of the signal over the background [7]. Indeed some simulations suggest that the ratio may be more than 30 to 1. Figure 6 shows a simulation of energy distribution for SUSY and Standard Model processes, as well as the SUSY signals after these cuts have been made [11].

Figure removed for copyright reasons.

Figure 7 in Bagger, J. A. Supersymmetry at LHC and NLC. ArXiv:hep-ph/9709355 v1 (1997). http://arxiv.org/abs/hep-ph/9709335

Fig. 6: Energy distribution for SUSY (solid) and SM (dashed) processes (above.) The optimized SUSY distribution (below.)

III.2.b R Parity Violating Searches

Although we have stressed that R parity conservation is very well motivated, we must concede that it is possible for SUSY to exist without R parity conservation. In these models, some other mechanism is employed to protect against proton decay. Either we allow for baryon number or lepton number conservation to be violated, but not both. If indeed R parity is not conserved, our high-energy linear collider becomes an optimum environment for discovering SUSY. Unlike in the signals above, when R parity is not conserved, the "LSP" will decay into standard model particles inside our detector. Instead of missing energy, we will find that the invariant mass spectrum of our final state reflects the mass of the decaying sparticle [12]. The tunable beam energy at our collider allows us to take advantage of the "threshold effect." We can measure process cross-sections as a function of energy. If a new particle exists, our cross section measurement will spike and then plateau just above the energy threshold for pair production of the new particle. If the new particle is spin 1/2, this rise in cross-section will be proportional to β, the velocity of the SUSY particle. If the new particle is spin 0, the rise will be proportional to β^2. While this type of measurement will be less precise as far as knowing what we are looking at, we can easily see production of some particle that previously went undetected. Because the LHC collides protons on protons, this sort of analysis is not readily available at the required energies. That is, it is the annihilation of particle and anti-particle that fuels the resonance-like production of the "new" particle. LHC will not collide particles on anti-particles at high energies. Thus, in the unlikely event of R parity violation, our collider will present the best chance of discovering SUSY.

III.3 Precision Measurements

As we have stated, the LHC has a tremendous advantage over our LC as it is slated to begin taking data within the next few years. It is quite possible that SUSY will be discovered there and discovered in dramatic and unambiguous terms. One might think that prevent us from realizing our LC, as it would "no longer be needed." Of course this couldn't be further from the truth. In many ways a linear e^+e^- collider represents the perfect machine for precisely determining all of the many physical quantities that will be opened by the discovery of SUSY. In this section we will outline, in general terms, the ways in which we will use the LC for precision measurements. When making these precision measurements, two features of the LC (aside from its "clean" environment) present themselves as particularly useful: the tunable beam energy and the beam polarization. During the following discussion we will assume that the beam is fully tunable, allowing us run each beam at any energy below maximum, with relative ease in tuning, and precise knowledge of the energy. We will also assume minimum of 80% polarization in the electron beam. Polarizations of this magnitude are routinely achieved at the SLC and we see no reason why we shouldn't expect similar results. In fact, advances in technology may even allow us higher polarizations, perhaps in the 95% range. Furthermore, in the future it may be possible to polarize the positron beam. While we do not assume this capability in this paper, we believe that this should be a primary area of R&D for accelerator physics in the coming years.

III.3.a Mass Measurements

One of the most basic measurements we will need to make on any newly discovered particle is its mass. Our detector systems provide an excellent opportunity to make precision mass measurements for SUSY particles. As an illustrative example we will consider the mass of a selectron. We expect copious selectron/spositron production in our machine for CM energies above the threshold, and for the most part these selectrons will decay into the lightest neutralino plus a Standard Model electron ($(se)^- \to \chi_1^0 + e^-$.) In this decay, the resulting electron has a unique energy in the rest from of the selectron. When we measure the energy of the electron in our detector frame, we will get a box-type distribution (see figure 7) with clear upper and lower bounds. If E_{max} is the upper bound and E_{min} is the lower bound, they are governed by the equation:

$$E_{max,min} = (1 \pm \beta)\gamma E_{e,CM}$$

where

$$E_{e,CM} = (m_{se}/2)*(1 - (m_\chi^2/m_{se}^2))$$

and

$$\beta = (1 - (4m_{se}^2/s))^{1/2}$$

$$\gamma = (\sqrt{s})/m_{se}^2.$$

From this we can calculate the mass of the selectron using

$$m_{se} = (\sqrt{s})((E_{max}E_{min})/(E_{max} + E_{min})^2)^{1/2}.$$

With good statistics, we should be able to measure the mass of the selectron with a relative uncertainty of $\delta m/m = 1\%$ [7]. Obviously, this type of measurement is not limited to selectrons, but can be used for all SUSY particles that have two-body decays. Moreover, since the mass splittings for SUSY may be as high as tens of GeVs, we can tune our beam to enhance the production of specific sparticles. This would allow us to focus on one or two particular sparticles at a time, greatly simplifying our analysis.

Figure removed for copyright reasons.

Danielson, M. N., *et al.* Supersymmetry at the NLC. Report presented at the 1996 Snowmass conference. (1996). http://www.slac.stanford.edu/pubs/snowmass96/PDF/SUP117.PDF

Fig. 7: Energy distribution for the lone electron in the decay of a s electron [7].

III.3.b Measurements Using Polarization

Our LC provides a unique analysis tool in that it can provide highly polarized electron (and possibly positron beams.) This becomes important when measuring production cross-sections for different SUSY particles. Left-handed electrons enhance production via the SU(2)-like couplings and right-handed electrons enhance production via the U(1)-like couplings. Furthermore, our main source of background (W^+W^- pair production) is severely repressed for right-handed electron beams. This would allow us to make even cleaner measurements for some SUSY processes (see figures 9 and 10 [8].)

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Figure 2.25 in NLC Physics Working Group. Physics and Technology of the Next Linear Collider. FERMILAB-PUB-96/112 (1996).
http://arxiv.org/PS_cache/hep-ex/pdf/9605/9605011.pdf

Fig 9: cross sections for various SUSY processes as a function of electron polarization. $P_L = 1$ corresponds to 100% left handed electrons

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Figure 2.3 in NLC Physics Working Group. Physics and Technology of the Next Linear Collider. FERMILAB-PUB-96/112 (1996).
http://arxiv.org/PS_cache/hep-ex/pdf/9605/9605011.pdf

Fig. 10: Cross sections for various standard model processes as a function of electron polarization.

Furthermore, for charginos and neutralinos, which are admixtures of winos, binos, and Higgsinos, we can employ polarized beams to measure the mixing of each species in the mass eigenstates. This will allow us to unravel all of the first-order Feynman diagrams behind these particle interactions. This is one of the easier ways to test SUSY independent of model parameters. For example in chargino pair production, we can look at the left- and right-handed cross sections. If the left-handed cross section (σ_L) is much higher than the right-handed cross section (σ_R), than the chargino is primarily a wino. This is because only right-handed electrons can produce wino pairs as well as Higgsino pairs, while the left-handed electrons can only pair-produce Higgsinos. A comparison of σ_L to σ_R would allow us to determine with good precision the ratio of Higgsino to wino in the chargino. These types of measurements that take advantage of the "left-handedness" of the weak force will be unavailable to experimenters at the LHC, and they are critical to fully understanding supersymmmetry [8].

IV Conclusion

In this paper we have discussed the use of a linear e^+e^- collider for the study of supersymmetry. Our collider will have a center of mass energy between .5 and 1.5 TeV. Such a collider presents itself as being the ideal environment for such a study. We have also elaborated on the detector for such a collider, and which SUSY signals we should expect to manifest themselves in our detectors. Finally we have discussed a plan for discovery searches and for precision measurements of SUSY. The bottom line is that such a facility provides an excellent opportunity for studying SUSY, and as such it should be seen not as a direct competitor to the LHC, but as a collaborative piece of the puzzle. Both facilities have their relative strengths and weaknesses, and we feel that proper study of extra-Standard Model physics requires a variety of approaches.

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