Feasibility Study of a Low Angle Cerenkov Detector for the NLC

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Abstract

This paper is a study on the feasibility of a low angle Cerenkov detector for the NLC. The detector is necessary to veto events which mimic certain supersymmetric signals. It consists of a ring of lead placed in front of a ring-shaped Cerenkov chamber. The entire apparatus is designed to sit within the beam pipe of the NLC. The focus of this study is to determine if this detector will be able to correctly distinguish signal from background, and to find the specific geometry which will optimize its abilities.

Contents

List of Figures

List of Tables

1 Introduction

The current picture of the natural world, as viewed from the vantage of high energy physics, is known to be incomplete. The Standard Model has been extensively tested, and experiments have produced wonderful agreement with theory. Yet still, mysteries abound. The existence of a Higgs particle is central to current theory, but as of yet it is unobserved. It is known that there are new physical phenomena at the TeV energy scale. To explore this new energy frontier it is necessary to construct colliders operating at TeV scale beam energies. The Large Hadron Collider (LHC) in Europe is one such machine, capable of making many new measurements. It has been the experience in the past that hadron colliders and electron-positron colliders are very complimentary to one another in probing new physical regimes (FNAL/SLAC). Both types of machines excel in different areas, and so it is necessary to have an electron machine capable of operating in the TeV range. The machine proposed to accomplish this is called the Next Linear Collider or NLC.

1.1 The NLC

The characteristics of the NLC as referred to in this paper come from a report submitted to Snowmass '96 [1]. The NLC is the next generation in linear collider technology. It will be an electron-positron collider designed to operate at higher energies and with a more sophisticated detector setup than any current linear collider. The NLC is envisioned to have multiple energy upgrades, with machine performance being greatly improved at each stage. Initially the NLC is expected to run at a nominal cms energy of 500 GeV with an overall length of 30.5 km, 17.6 km total linac length, and a luminosity of $5.5 \times 10^{33} s^{-1} cm^{-2}$. After several years of operation it is expected to be upgraded to a 19.1 km linac, running at 1 TeV with a luminosity of $1.1 \times 10^{34} s^{-1} cm^{-2}$. The NLC will have the ability to produce strongly polarized (80%) electron beams, and may even have positron beam polarization capability. This will allow the enhancement of certain decay channels, and the suppression of certain background signals. The NLC will also have a tunable beam energy, allowing runs at energies where selected cross sections are either minimized or enhanced. Extensive Monte Carlo simulation has demonstrated that a machine with the capabilities described here would be capable of seeing many interesting new physics processes. Furthermore, it has been demonstrated that for certain regions of supersymmetric parameter space the NLC would be capable of providing detailed measurements of Higgs particle and sparticle[2] masses as well as providing measurements of the physical parameters of non-Standard Model physics[3]. These are powerful indications that the NLC will prove to be an invaluable tool for high energy physics in the 21^{st} century.

1.2 Supersymmetry at the NLC

Our group at CU Boulder has been researching the abilities of the NLC as a tool for studying supersymmetry. Testing supersymmetric models is one of the critical goals of the NLC. We have primarily been studying minimal supersymmetric models in which R-parity is conserved. For more information on the particular models that we study see [4, 5]. R-parity is defined by the equation

$$R = (-1)^{3B+L+2S}$$

where B, L, and S represent baryon number, lepton number, and spin. Standard Model particles always have R = 1. Since supersymmetric particles differ from their Standard Model partners only by $\frac{1}{2}$ unit of spin, supersymmetric particles always have R = -1. If R-parity is a conserved quantity in a decay then it can be immediately seen that supersymmetric particles must always decay into an odd number of other supersymmetric particles and any number of Standard Model particles. This means that the lightest supersymmetric particle (LSP) must be a stable particle. One of the sparticles that is likely to be the LSP is the neutralino. The neutralino is a mixture of the Zino and the Higgsino, the superpartners to the Z boson and the Higgs, respectively. The neutralino only interacts weakly. Because of this it won't be detected in the calorimeter, and will carry off large amounts of energy unseen. This is the classic signature of supersymmetric decays in R-parity conserving models, large amounts of "missing" energy.

1.3 The Two Photon Background

It has been discovered that a certain type of interaction can lead to a significant background for supersymmetry studies at the NLC [6]. In general these are interactions of the form ($e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-e^+e^-$), hereafter referred to as "two photon" interactions. Figures 1 and 2 show the two lowest orders of Feynman diagrams contributing to the two photon events.

If three or four of the final state electrons can be seen then the event can be recognized as being a two photon event. However, there are many of these events where the two initial electrons deflect at very small angles (tens of mrad) and get lost down the beam pipe, while the other two deflect at large angles and get seen by the detector.

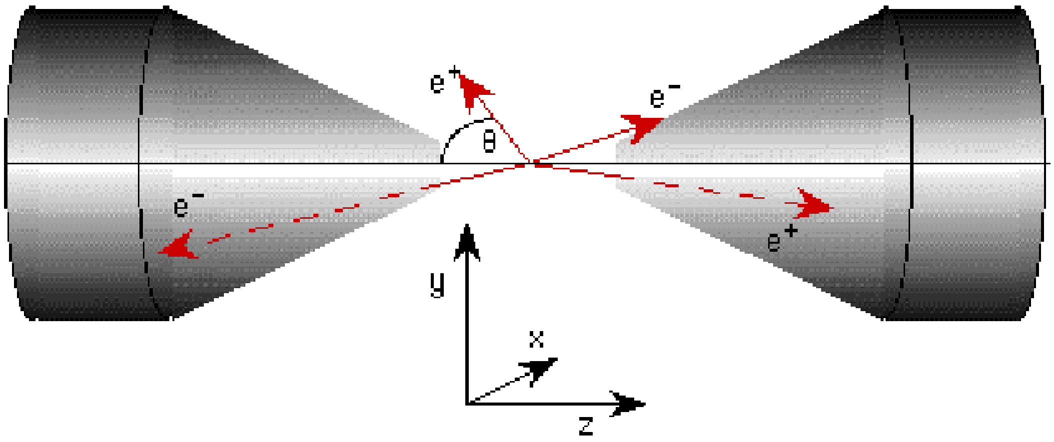

Figure 1: A typical two photon event. The two high energy electrons go down the beam pipe, and the low energy electrons go into the detector.

When this occurs it appears to be a possible supersymmetric event, because there are two final state leptons and a great deal of missing energy. This is extremely similar to many supersymmetric signals such as a selectron decay. It has also been demonstrated [7, 8] that if one could build a detector which sat at low angles (tens of mrad) within the beam pipe to find the low angle electrons then this two photon background can be observed, leading to a large reduction in the background on the supersymmetric signal. So all that must be done to solve this problem is to put a small detector within the beam pipe to catch these rogue leptons. Unfortunately it isn't quite that simple.

1.4 The Background for the Background

Now it is of interest to be able to detect electrons which are tens of mrad from the beam. The only problem is that there is a plethora of electrons in

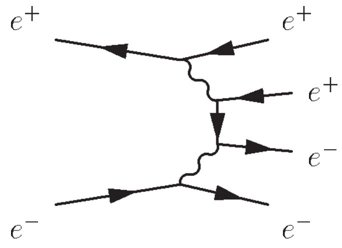

Figure 2: The production of lowest order $\gamma^*\gamma^*$ events.

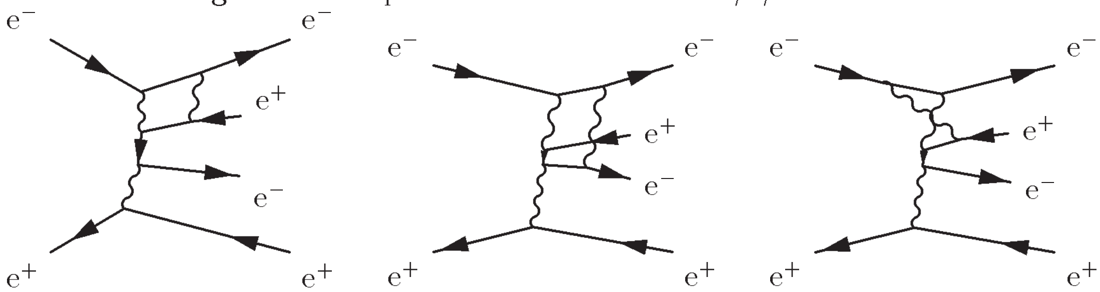

Figure 3: Next-to-lowest-order $\gamma^*\gamma^*$ processes include terms where an extra photon is exchanged such as these. There are nine diagrams total contributing at this level.

this region, and we only want to detect a tiny fraction of them. The problem comes from bremsstrahlung and beamsstrahlung photons created by the primary beam particles. These photons can pair produce electrons with sufficient angle and energy to obscure the electrons from the two photon events that we want to detect. Fortunately there is a sizeable energy difference between the electrons from these two processes. For a cms energy of 500 GeV, the two photon events create electrons with ∼230 GeV of energy, whereas those from the pair production have ∼3 GeV of energy. Nevertheless, there are about 30000 pair produced electrons per bunch crossing, which tends to obliterate the two photon signal. Luckily, the magnetic field confines these low energy electrons. The focus of this paper is to explore the possibility of designing a detector which can exploit the difference between the two photon and pair produced backgrounds and detect the electrons from the two photon events so that they will not be mistaken for a supersymmetric signal.

2 The Detector

The detector simulated in this paper consists of a flat ring of lead placed in front of a Cerenkov chamber. The entire apparatus has a diameter of about 10 cm and is designed to fit inside the beam pipe of the NLC, roughly 150 cm downstream from the interaction point.

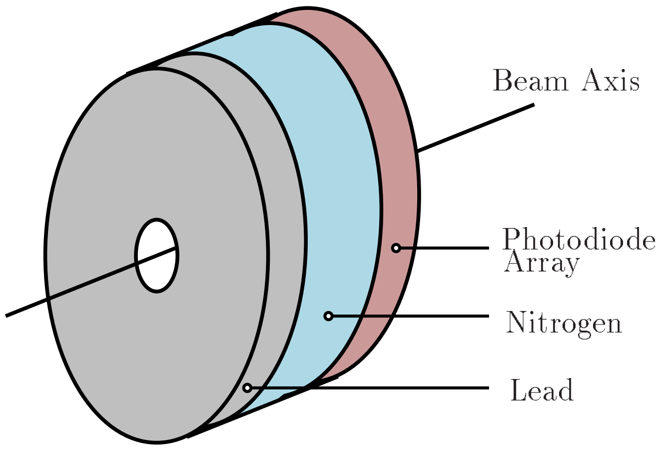

Figure 4: Simple schematic of the detector

2.1 How it Works

The idea behind the detector is simple and elegant. When an electron hits the lead it will initiate a shower of particles. These particles will have a distinct energy and spatial distribution when coming out the back of the lead which depends on the momentum of the incoming particle that started the shower. Figure 5 shows the energy distribution of electrons and positrons created by a 220 GeV electron passing through 8 radiation lengths of lead. Electrons at this energy are not confined to small radii by the magnetic field, and so this is precisely the distribution produced by two photon events, even at large radii from the z-axis (the beams run *nearly* parallel to the z-axis). Figure 6 shows the energy distribution of electrons and positrons created by one bunch worth of the low energy bremsstrahlung background, incident on 8 radiation lengths of lead; figure 7 shows this same distribution, but only for particles exiting the lead more than 3 cm away from the z-axis radially.

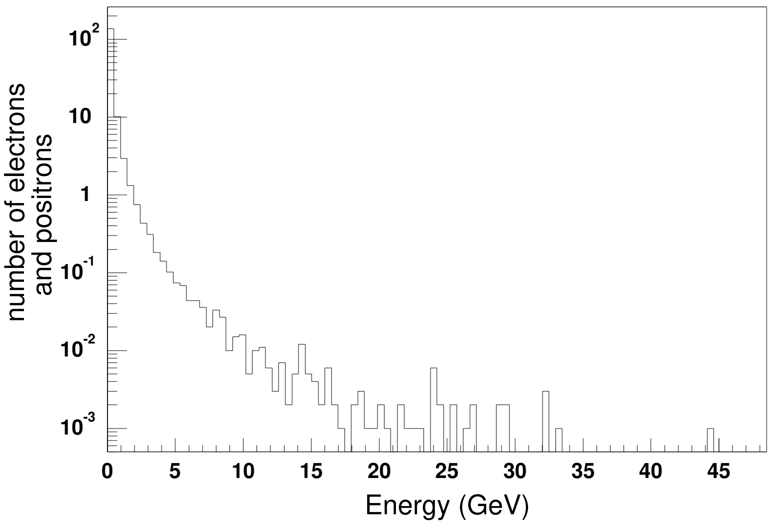

Figure 5: The energy distribution of the electrons and positrons created in the shower initiated by a typical two photon event.

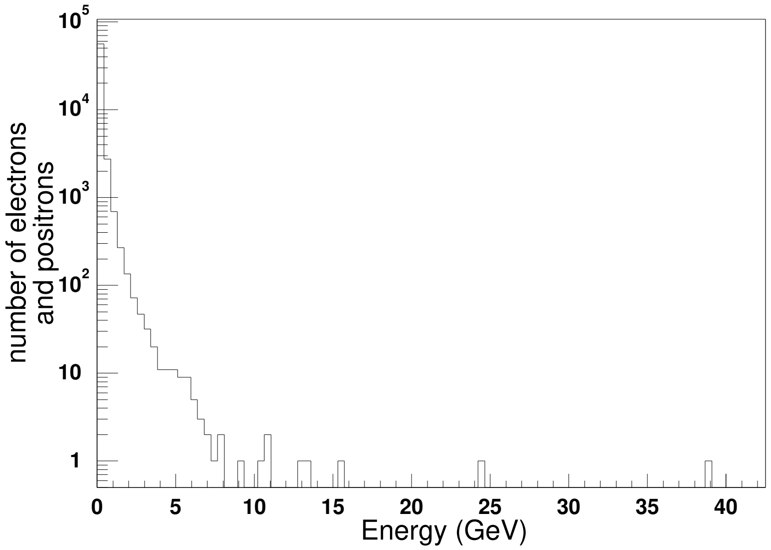

Figure 6: The energy distribution of electrons and positrons created by one bunch worth of bremsstrahlung background incident on 8 radiation lengths of lead.

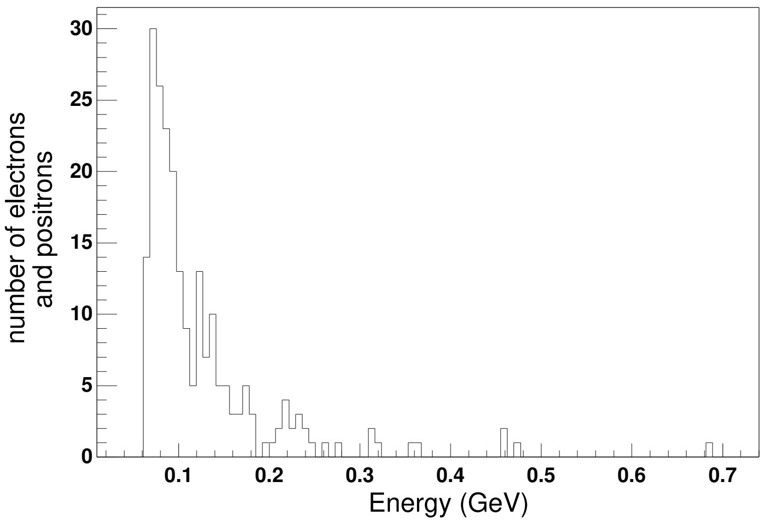

Figure 7: The energy distribution of electrons and positrons created by one bunch worth of bremsstrahlung background incident on 8 radiation lengths of lead. Here only particles with energy above threshold (E $\geq$ 66 MeV) and exiting the lead at radii greater than 3 cm are shown.

By varying the thickness of the lead and the pressure of the gas in the Cerenkov chamber we can "tune" the detector in such a way that only the high energy particles get detected. Only particles with energy above a certain threshold will emit Cerenkov light in the gas. This threshold energy is given by :

$$E_{th} = \frac{m}{\sqrt{1 - \frac{1}{n^2}}}$$

where m is the particle mass and n is the index of refraction of the medium in the Cerenkov chamber. We wanted a threshold energy somewhere in the tens to hundreds of MeV range. After checking the threshold energy for several gasses at various pressures we decided on nitrogen gas at a pressure of .1 atm. This causes E_{th} for an electron to be 66 MeV. By varying the thickness of the lead we tried to find a thickness for which the low energy electrons produced a minimal signal and for which the high energy electrons were easily detectable. We then proceeded to construct a computer simulation of the detector to test its abilities as a physics tool.

2.2 The Simulation

To simulate the properties of the detector we used a program called GEANT which simulates how radiation interacts with matter. We chose to use GEANT because it has been in use in the HEP community for years, and its reliability has been firmly established. We also generated Monte Carlo data for the two processes we are interested in, using the programs HERWIG and Guinea Pig.

2.2.1 The Pair Produced Background

First we simulated the electrons that are pair produced from the bremsstrahlung and beamstrahlung photons. We simulated the full amount of electron positron pairs that occur from the interaction of beamstrahlung and bremsstrahlung photons resulting from one bunch (10^{10}) of electrons colliding with one bunch (10^{10}) of positrons. We then plotted the spatial distribution of the electrons coming out of the back of the lead to determine how close to the beam we could get without our signal being swamped by background. Note that our simulation included the fact that the beams cross each other at a 20 mrad angle (both beams are at a 10 mrad angle relative to the z-axis). Tables 1 through 5 show the distribution of electrons coming out of the lead that are above the threshold energy, as a function of lead thickness, for 5 through 9 radiation lengths. The detector is situated 150 cm from the interaction point, along the beam direction. Thus an electron which was traveling at a 20 mrad angle to the beam initially would be 3 cm away from the beam upon reaching the detector. It is clear from the tables that between 0 cm and 3 cm from the beam there is too much background to be able to clearly see the two photon events. However, after 3 cm the background dies off quickly. Thus it may be possible to detect two photon events if an electron from the two photon process hits at an angle above 20 mrad. After performing this analysis for various thicknesses of lead from 1 radiation length to 10 radiation lengths, we found that the optimal thickness of lead in terms of reducing the background was 8 radiation lengths, which corresponds to about 4.5 cm.

radius in cm / angle in rad.	0 → .5	.5 → 1	1 → 1.5	1.5 → 2	2 → 2.5	2.5 → 3	3 → 3.5	3.5 → 4	4 → 4.5	4.5 → 5
$-\pi \to \frac{-3\pi}{4}$	9	9	9	15	28	9	9	4	0	0
$\frac{-3\pi}{4} \to \frac{-\pi}{2}$	6	34	52	55	38	38	23	14	0	0
$\frac{-\pi}{2} \to \frac{-\pi}{4}$	13	61	254	280	149	125	55	15	1	0
$\frac{-\pi}{4} \to 0$	10	102	4027	8338	419	100	48	18	2	0
$0 \to \frac{\pi}{4}$	38	474	9700	15504	865	152	31	3	0	0
$\frac{\pi}{4} \to \frac{\pi}{2}$	33	101	241	106	18	4	0	0	0	0
$\frac{\pi}{2} \to \frac{3\pi}{4}$	27	48	20	5	2	0	0	0	0	0
$\frac{3\pi}{4} \to \pi$	21	19	10	8	4	2	0	0	0	0

Table 1: Angular electron distribution for one bunch worth of pair produced background after passing through 5 radiation lengths of lead. For each of Tables 1-5, the detector is 150 cm away from the interaction point along the beam direction.

radius in cm / angle in rad.	0 → .5	.5 → 1	1 → 1.5	1.5 → 2	2 → 2.5	2.5 → 3	3 → 3.5	3.5 → 4	4 → 4.5	4.5 → 5
$-\pi \to \frac{-3\pi}{4}$	5	4	8	17	17	15	6	6	0	0
$\frac{-3\pi}{4} \to \frac{-\pi}{2}$	5	16	31	32	22	19	17	4	1	0
$\frac{-\pi}{2} \to \frac{-\pi}{4}$	6	53	170	180	127	69	39	13	1	0
$\frac{-\pi}{4} \to 0$	6	108	3434	7568	357	82	29	13	3	0
$0 \to \frac{\pi}{4}$	23	362	8125	13744	695	82	25	3	0	0
$\frac{\pi}{4} \to \frac{\pi}{2}$	23	66	155	79	24	2	0	0	0	0
$\frac{\pi}{2} \to \frac{3\pi}{4}$	10	30	5	5	0	0	0	0	0	0
$\frac{3\pi}{4} \to \pi$	9	5	3	7	4	2	0	0	0	0

Table 2: Angular electron distribution for one bunch worth of pair produced background after passing through 6 radiation lengths of lead.

radius in cm / angle in rad.	0 $\downarrow$ .5	.5 $\downarrow$ 1	1 $\downarrow$ 1.5	1.5 $\downarrow$ 2	2 $\downarrow$ 2.5	2.5 $\downarrow$ 3	3 $\downarrow$ 3.5	3.5 $\downarrow$ 4	4 $\downarrow$ 4.5	4.5 $\downarrow$ 5
$-\pi \rightarrow \frac{-3\pi}{4}$	2	3	4	8	11	6	7	1	0	0
$\frac{-3\pi}{4} \rightarrow \frac{-\pi}{2}$	5	14	21	16	20	9	12	4	0	0
$\frac{-\pi}{2} \rightarrow \frac{-\pi}{4}$	3	29	113	125	71	42	21	13	1	0
$\frac{-\pi}{4} \rightarrow 0$	4	65	2806	6464	249	67	14	7	2	0
$0 \rightarrow \frac{\pi}{4}$	21	230	6123	11516	523	66	12	12	0	0
$\frac{\pi}{4} \rightarrow \frac{\pi}{2}$	14	41	104	59	21	3	0	0	0	0
$\frac{\pi}{2} \rightarrow \frac{3\pi}{4}$	8	22	11	3	0	0	0	0	0	0
$\frac{3\pi}{4} \rightarrow \pi$	7	6	1	2	0	2	0	0	0	0

Table 3: Angular electron distribution for one bunch worth of pair produced background after passing through 7 radiation lengths of lead.

radius in cm / angle in rad.	0 $\downarrow$ .5	.5 $\downarrow$ 1	1 $\downarrow$ 1.5	1.5 $\downarrow$ 2	2 $\downarrow$ 2.5	2.5 $\downarrow$ 3	3 $\downarrow$ 3.5	3.5 $\downarrow$ 4	4 $\downarrow$ 4.5	4.5 $\downarrow$ 5
$-\pi \rightarrow \frac{-3\pi}{4}$	0	2	1	3	5	1	2	2	0	0
$\frac{-3\pi}{4} \rightarrow \frac{-\pi}{2}$	1	3	7	10	10	9	5	0	1	0
$\frac{-\pi}{2} \rightarrow \frac{-\pi}{4}$	0	31	85	86	44	40	18	5	0	0
$\frac{-\pi}{4} \rightarrow 0$	1	32	2085	5163	183	59	11	4	0	0
$0 \rightarrow \frac{\pi}{4}$	8	182	4449	8639	374	41	14	0	1	0
$\frac{\pi}{4} \rightarrow \frac{\pi}{2}$	4	25	46	34	6	3	0	0	0	0
$\frac{\pi}{2} \rightarrow \frac{3\pi}{4}$	0	6	6	1	2	0	0	0	0	0
$\frac{3\pi}{4} \rightarrow \pi$	4	2	0	2	2	0	0	0	0	0

Table 4: Angular electron distribution for one bunch worth of pair produced background after passing through 8 radiation lengths of lead.

radius in cm / angle in rad.	0 ↓ .5	.5 ↓ 1	1 ↓ 1.5	1.5 ↓ 2	2 ↓ 2.5	2.5 ↓ 3	3 ↓ 3.5	3.5 ↓ 4	4 ↓ 4.5	4.5 ↓ 5
$-\pi \to \frac{-3\pi}{4}$	1	1	3	1	1	1	1	1	0	0
$\frac{-3\pi}{4} \to \frac{-\pi}{2}$	2	3	7	3	7	2	4	4	1	0
$\frac{-\pi}{2} \to \frac{-\pi}{4}$	0	17	67	84	32	23	12	4	0	0
$\frac{-\pi}{4} \to 0$	0	29	1452	3958	129	21	8	2	3	0
$0 \to \frac{\pi}{4}$	1	139	3002	6561	273	18	6	1	0	0
$\frac{\pi}{4} \to \frac{\pi}{2}$	2	9	30	21	1	0	0	0	0	0
$\frac{\pi}{2} \to \frac{3\pi}{4}$	3	6	6	1	0	0	0	0	0	0
$\frac{3\pi}{4} \to \pi$	1	0	0	0	1	0	0	0	0	0

Table 5: Angular electron distribution for one bunch worth of pair produced background after passing through 9 radiation lengths of lead.

2.2.2 The Two Photon Events

To verify that we would be able to see the two photon events above the remaining background we studied the radiation pattern that they make after passing through the lead and hitting our detector. We carried out this analysis for one through ten radiation lengths of lead just as for the background. We ran a large number of two photon events through the simulated detector and then looked at the number of electrons that exited the lead with enough energy to radiate in the Cerenkov chamber, and normalized this distribution to a single particle. We found that these events produced between 100 and 200 electrons above threshold depending on the number of radiation lengths of lead that were used. Table 6 shows the number of secondary electrons exiting the lead with enough energy to emit Cerenkov radiation, as a function of initial particle energy and lead thickness.

Width of Pb (radiation lengths)	Energy of Incident $e^{\pm}$ (GeV)	Number of Outcoming $e^{\pm}$ above 66 MeV
5	180	122
	200	132
	220	143
	240	152
6	180	136
	200	151
	220	171
	240	177
7	180	138
	200	150
	220	166
	240	181
8	180	126
	200	140
	220	154
	240	171
9	180	108
	200	120
	220	133
	240	148
10	180	87
	200	99
	220	109
	240	123

Table 6: Outcoming number of particles as a function of lead width and energy of incident electron for two photon events, normalized to one incident particle.

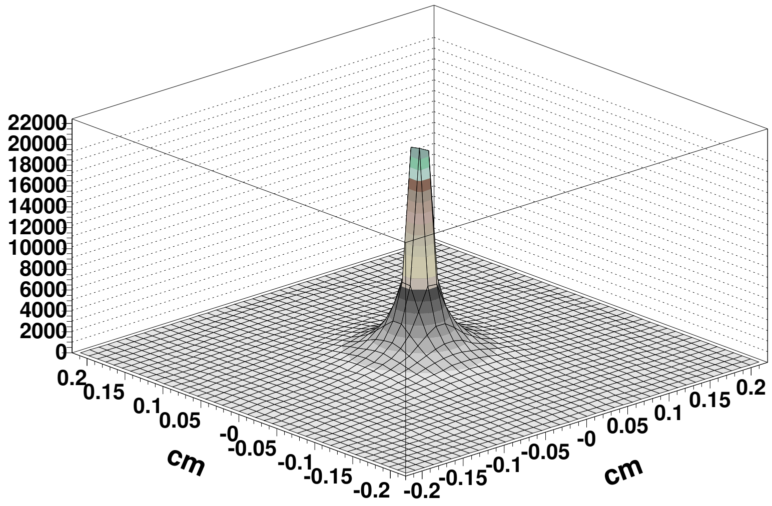

Figure 8: The radial distances of the particles created in a shower initiated by a two photon event. This distribution is unnormalized

This table shows that each time an electron from a two photon process hits the lead it creates roughly 150 secondary electrons which have sufficient energy to give off Cerenkov light. Thus if one of these high energy electrons from a two photon event hits the detector at a radius greater than 3 cm, it will produce a signal significantly stronger then the background in this region. This alone does not necessarily mean that these two photon events will be easy to detect, however. We also needed to study how spread out these particles are upon exiting the lead. Figure 8 shows the spatial distribution ($\sqrt{x^2 + y^2}$) of the particles exiting the lead for a shower initiated by a two photon event that hit the detector at x = y = 0. Figure 9 shows the same distribution for a shower initiated by the electrons produced from the beamstrahlung or bremsstrahlung photons . For the two photon events, the particles that exit the lead above threshold have an extremely tight radial distribution. The average radius of a particle produced in the shower is .45 mm, and 99% of the particles above threshold fall within a 1 mm radius of the particle initiating the shower. The bremsstrahlung and beamsstrahlung events are more spread out spatially. This is promising because it suggests

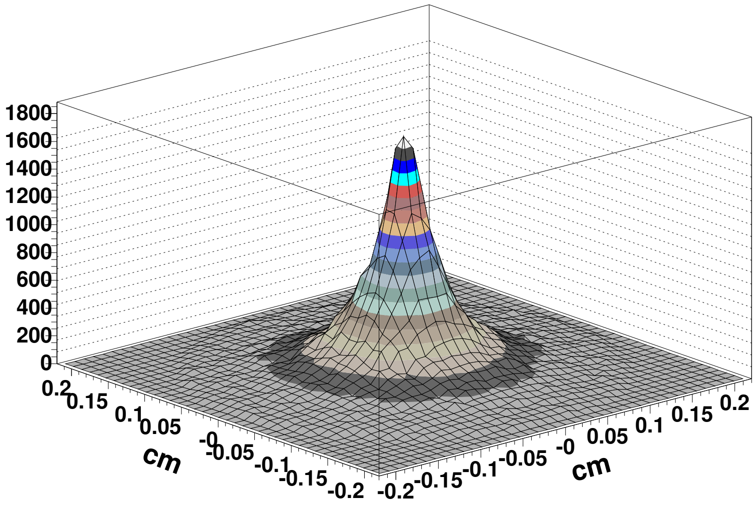

Figure 9: The radial distances of the particles created in a shower initiated by an electron from a bremsstrahlung event. This distribution is unnormalized.

that the radiation from a two photon event will be very dense and therefore much more easily distinguished from the background.

2.3 The Cerenkov Radiation

A particle which is emitting Cerenkov light gives off a certain number of photons per unit length it travels while it is radiating. Of these only a certain percentage are detected, depending on the efficiency of the detector. The number of detected Cerenkov photons, with wavelength between λ_1 and λ_2, that are emitted (per unit length) by a particle which is moving faster than the local speed of light is given by the relation:

$$\frac{dN}{d\ell} = 2\pi\alpha \left\{ \frac{2\gamma^2(n-1)-1}{\gamma^2} \right\} \int_{\lambda_1}^{\lambda_2} \epsilon(\lambda) \frac{d\lambda}{\lambda^2}.$$

Here N is the number of photons detected, α is the fine structure constant, γ is the energy of the particle divided by its rest mass, n is the index of refraction of the medium, and $\epsilon(\lambda)$ is the efficiency of the photoreceptors for detecting photons of wavelength λ. For our simulation we used nitrogen

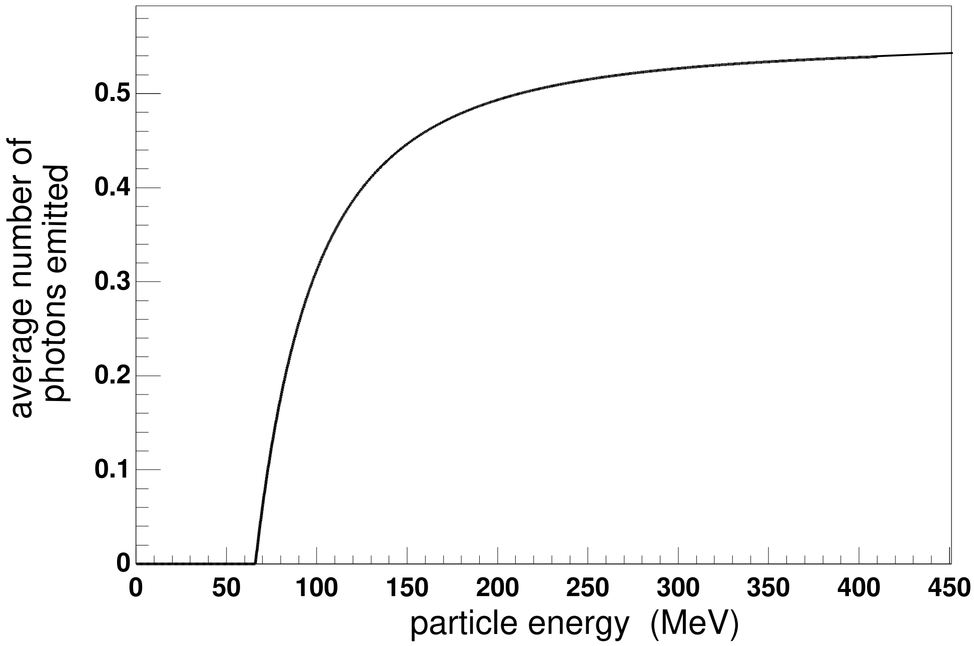

Figure 10: The number of photons detected from an electron above threshold energy traveling through a .1 atm nitrogen medium.

gas at a pressure of .1 atm. For nitrogen at this pressure, n = 1.000029199. The wavelengths of light we are interested in detecting are between 3000 and 5000 angstroms. For our detector efficiency we made a conservative estimate and let $\epsilon(\lambda)$ = constant = 50%. Were this detector to be used at the NLC the efficiency would likely be closer to 70% or 80% for λ between 3000 and 5000 angstroms. We used this relation to determine the number of photons that would be detected from a particle that exited the lead with enough energy to emit Cerenkov light. First we intergrated λ from 3000 to 5000 angstroms to obtain the number of photons detected per unit length traveled by the radiating particle. We then integrated over a 30 cm path (the nitrogen chamber will be about 30 cm thick) to obtain the total number of photons we expect to see emitted by an electron as a function of the electron energy. The results of this calculation are shown in figure 10.

The average number of photons emitted from an electron above threshold energy traveling through the nitrogen is roughly between .1 and .4 in the energy range we are interested in. Thus from a typical two photon event we expect to see in the neighborhood of 20 to 30 photons because there are approximately 150 electrons above threshold per two photon event. This is easily enough photons to give a signal in the detector.

3 Conclusion

3.1 Summary

One of the most troublesome backgrounds that mimics supersymmetric decays is known as the two photon background. We designed a low angle Cerenkov detector with the aim of being able to detect two photon decays at low angles from the beam, so that we could veto events that contained them. We created a computer model of this detector using the program GEANT. We then generated Monte Carlo data files for the two photon events as well as for the pair produced background which obscures them. We established that with the current detector design we will be able to detect the two photon events if they occur at angles larger then 20 mrad from the beam.

3.2 Future Areas of Study

There remain further areas to research in the study of the two photon background. We plan on continuing our work on this detector in hopes of further refining its capabilities. We hope to study different geometries as well as different Cerenkov energy thresholds in an effort to optimize it. Another thing that needs to be studied is precisely how and where the detector will sit within the NLC. We also need to add to our simulation of the detector a hole for the beam to pass through on the way to the beam dump, although we expect this to change our results in a negligible fashion. Another place where we would like to improve this study is in the simulation of the two photon data itself. Currently the program used to generate the Monte Carlo data only simulates lowest order processes. It is important that we learn the effect of the higher order processes on the number of events produced and their distribution. Another issue which we need to explore is the leaking of stray light into the photo detectors. When electrons hit the lead and create a shower they produce not only electrons coming out of the back of the lead, but also a large number of stray photons. Undoubtedly many of these photons have wavelengths in the 3000 to 5000 angstrom range, and so they will trigger the photo detectors if they cannot be filtered out beforehand. Unfortunately GEANT does not currently track particles with energies this low, and so we cannot be sure how many there are, nor can we simulate their effect on our results. We hope to be able to filter these photons out by means of two perpendicularly polarized glass plates placed in between the lead and the nitrogen chamber. Ideally this will block essentially all of the 1-20 eV stray photons from the shower while leaving the electrons unhindered on their way to the nitrogen. This idea remains unexplored and unsimulated, however, and will be one of our first projects in extending our research.

References

Note: All the papers with CU-HEP numbers can be found on the web at: http://hep-www.colorado.edu/SUSY/.

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