1. INTRODUCTION

1.1 Overview

Since time immemorial, mankind has struggled to discover deeper and more fundamental laws associated with the natural phenomena that is observed in nature. In the 20th century this struggle turned to the science of particle physics as the focus of the search for a Grand Unified Theory of all the constituents of matter and their associated forces [1]. More so, the task of testing theories against experimental data and picking the ones that are the most consistent with what is observed, and rejecting those that fail such tests, has lead to the formation of what is known as the Standard Model, here after denoted by SM, of particle physics [2].

Much as Dmitri Mendeleev's table of periodic elements allowed us to understand and predict an enormous amount of phenomena in chemistry, the SM has proven to be overwhelmingly successful for phyics. However, just as we now know that Mendeleev's table was not the fundamental theory of atoms, we believe the SM is not the fundamental theory of particles and their forces and thus must be modified or extended in some way.

Any new theory of particle physics must be capable of making predictions about observable new phenomena, and it is these predictions that we turn our attention to in this thesis. Many contending theories predict that there should exist, as yet undiscovered, new particles and/or interactions. They also predict that in experiments where we collide high energy particles one could produce one or more collisions (or events) that "differs" from expectations of the SM.

While scientists have been performing such experiments for many years [3], history suggests that many discoveries come from the application of a new tool which allows scientists to consider information previously unavailable. In our case, we have collisions of high energy particles, at the time the highest available to man, and a detector surrounding the collision that is able to measure the time of arrival of photon (the particles of light) to a precision of just over a half a nanosecond. This tool provides a new window of opportunity to search for compelling extensions of the SM, for example theories of the Higgs boson and Supersymmetry (SUSY), that predict new particles that have a significantly long lifetime (many nanoseconds) and produce photons in such a way that they arrive at the detector a few nanoseconds later than expectations. In other words the photons would appear to arrive at the detector "delayed". The details of example theories that might produce such a set of events, how they will decay and interact with our detector, as well as our methods and results of searching for such events in this unique signature, constitutes the majority of the remaining pages of this thesis.

While there are compelling theoretical reasons to look for this experimental signature, in point of fact, the model we are testing is the SM. In order to do this we must first understand the predictions of the SM and thereby understand the model itself in some more detail. In the next section we will present a discussion of the SM of particle physics and some of its known limitations, specifically with an eye towards potential solutions and extensions as well as ways of testing these extensions. Said colloquially, "Once you know the 'rules' of the game we can see if nature has 'changed' any of them."

1.2 Outline of the Dissertation

Before we go further, it is useful to give a more complete description about the full path laid out in this thesis. Once we are done with our description of the SM, detailed in Section 1.3.1, we will describe more about some of the models of new physics of most interest to us from both a theoretical and experimental point of view. These models include both the Higgs mechanism and SUSY, both of which will be described in Section 1.3.2. With these ideas, in Section 1.4, we look at previous

This thesis follows the style of Physical Review D.

searches for evidence for specific SUSY models as well as places which are not yet covered by previous experiments. Of particular interest will be a preliminary search from the Fermilab Tevatron in 2008, the worlds highest energy proton antiproton particle accelerator, that produced what could be naively interpreted as evidence for new physics. We will discuss this original observation, and in the bulk of the this thesis, do a thorough and systematic study to see if this potential hint is really evidence for new physics.

In Chapter 2 we present the experimental tools used in this analysis, including the Fermilab Tevatron collider as well as the Collider Detector at Fermilab (CDF) which surrounds the collision point and records the activities of the resulting interactions. In particular we describe the relevant subsystems used at CDF in the timing measurement. Chapter 2 also describes the various object identification that is performed from the information read out from the CDF detector as well as laying out many of the various useful data samples used in this analysis. In Chapter 3 the new calibration procedure is detailed in order to ensure that we have accurate and reliable timing information associated with photons in this analysis. Chapter 4 details non-collision backgrounds and new selection requriements used to minimize their presence in our final sample of events. In Chapter 5 we turn our attention to the various SM backgrounds and the pathological event reconstruction which results in both an underestimation of the backgrounds to the search described in Section 1.6 as well as the methods we use to mitigate many of these effects. Chapter 6 focuses on the development and validation of a new data-driven background estimation from SM sources. Finally, Chapter 7 presents the results of the search and compares them directly to the 2008 result. Chapter 8 ultimately summarizes these results as well as proposing possible extensions to the search which could be performed in the future. With this path in mind we begin our description of the SM of Particle Physics.

1.3 Theory

In this section we provide an overview of the prevailing theory of particle physics known as the SM. With this basis we next draw attention to known experimental and theoretical shortcomings of the SM, in particular, the Higgs mechanism of electroweak symmetry breaking, with an eye towards potential extensions to the SM. In Section 1.3.2 we put forward one potential extension to the SM known as SUSY. We provide a general overview of this theory with attention drawn toward the potential experimental ramifications of such an extension. SUSY is posited as a real symmetry in nature, and while there is clear evidence that this would have to be a broken symmetry, what is not clear is what mechanism breaks this symmetry. In order to make predictions about what we will see in experiments we need to select one of many mechanisms of SUSY breaking that are favored for one reason or another. To allow us to make specific predicitions we detail the aspects of one particular 'flavor' of symmetry breaking known as Gauge Mediated Supersymmetry Breaking (GMSB) in Section 1.3.3. Finally, since there are many versions of GMSB, we detail many of the important parameters of this model. This allows to understand both the basic theoretical underpinnings of collider based searches that have already been performed, presented in Section 1.4, as well as what areas are not yet covered. Said in a slightly different way, if the Higgs mechanism and SUSY (or theories like them) were true in nature, what type of collisions might we expect to see in high energy experiments that we would not otherwise observe? With a clear vision of what our models predict would show up in experiments, we have a clear motivation of what types of events to look for.

1.3.1 The Standard Model of Particle Physics

The SM of particle physics is a theory that describes the known elementary particles and their interactions [1]. The SM asserts that the material which makes up the observable universe is made of elementary particles interacting through fields as well as the particles associated with those interaction fields. This theory successfully describes three of the fundamental forces: the strong nuclear force, the weak nuclear force, and the electromagnetic force; the three of which are responsible for the vast majority of interactions (gravity is excluded) between elementary particles [2].

As shown in Figure 1.1 the SM contains three generations of spin $\frac{1}{2}$ (e.g. $\frac{1}{2}$,$\frac{3}{2}$,$\frac{5}{2}$...) particles called fermions that make-up the basic constituents of atomic matter. For every fermion there is an associated, so called, "anti-fermion" that possesses the same mass but opposite quantum numbers. All fermions interact with each other via the exchange of the gauge bosons representing the fundamental forces listed on the right hand side of Figure 1.1. The fundamental forces are mediated by four integer spin (e.g. 1,2,3..) vector gauge bosons particles which act as the carriers of the various interactions between the particles. These bosons are the photon (electromagnetic force), the gluon (strong force), and the W and Z bosons (weak force). The last particle of the SM is the Higgs boson, which as of this writing was just reported as potentially being observed [4].

In mathematical terms, the SM interactions can be described by a local symmetry group of $SU(3)_C \times SU(2)_L \times U(1)_Y$, where $SU(3)_C$ describes the strong force interaction through the coupling of the quarks to the $SU(3)$ gluon particles that carry "color charge" (hence the subscript C) in a theoretical framework known as Quantum Chromodynamics (QCD) [5, 6]. The $SU(2)_L \times U(1)_Y$ terms correspond to the electromagnetic and weak interaction, or electroweak (EWK) theory [7–9] and the couplings to the photon and the W and Z boson with the subscript L denoting the weak current and Y denoting "weak hypercharge". However, we observe the weak force and the electromagnetic force as separate; thus the $SU(2)_L \times U(1)_Y$ symmetry is observed to be broken [9]. The most common thought is that this symmetry is spontaneously broken by a fundamental scalar field, the Higgs field [10]. This symmetry breaking mechanism, while not verified in experiment yet, gives rise to the

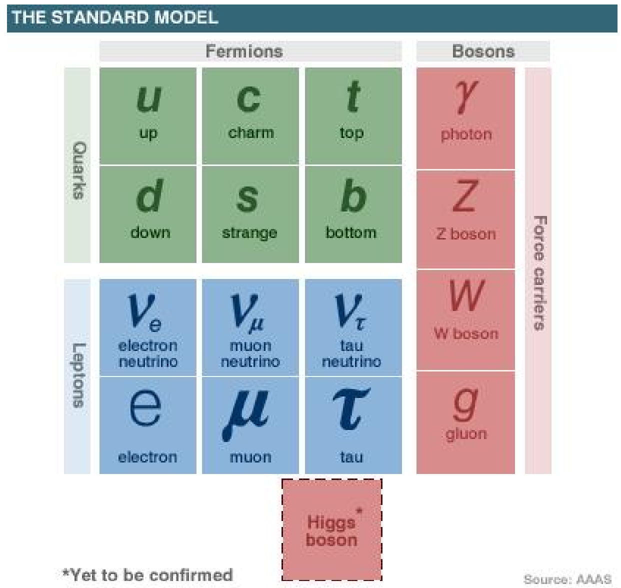

Fig. 1.1. The particles that comprise the Standard Model are arranged into three generations and the interactions between them are communicated by the exchange of the force carrying particles.

familiar mass eigenstates for the gauge bosons, such as the W and Z, and establishes the correlation between charge as we conventionally know it (Q) and "weak hypercharge". These quantities are thus what we measure experimentally [3] and summary of their names, symbols, and masses is given in Table 1.1.

The mechanism by which EWK symmetry breaking occurs will be discussed further in the next section, but has long been thought to be by the Higgs mechanism [10]. While the effects of a Higgs mechanism have been verified to a high degree of measurements [3], and there is some evidence that the particle corresponding to fundamental scalar field (namely, the Higgs boson itself), has been observed [4], the mechanism of EWK symmetry breaking has not be verified. For now it is sufficient to remark that the Higgs field can be thought of as a sort-of viscous fluid that all particles have to constantly travel through and the resulting *drag* is what can be thought of as the particle's mass. This field gives rise to a Higgs boson whose couplings to the particles is proportional to their mass [11].

Particle	**Symbol**	**Mass** (MeV/c^2)
Quarks		
Up	u	1.5 - 5
Down	d	3 - 9
Charm	c	1100 - 1400
Strange	s	60 - 170
Top	t	172000
Bottom	b	4100 - 4400
Leptons		
Electron	e	0.511
Electron neutrino	ν_e	∼0 (but not identically 0)
Muon	μ	105.7
Muon neutrino	ν_μ	∼0 (but not identically 0)
Tau	τ	1777.1
Tau neutrino	ν_τ	∼0 (but not identically 0)
Bosons		
Photon	γ	0
W	W	80400
Z	Z	91200
Gluon	g	0

Table 1.1
Table of the Standard Model particles, their symbols, and their measured mass.

While the SM is seen as a very successful theory in both precision measurement as well as predicting new particles [12], there are several theoretical and experimental shortcomings that suggest that it is simply a low-energy approximation to a more fundamental theory. Examples of experimental results that do not immediately fall into the SM come from a variety of measurements. One such example is the observation of neutrino oscillations [13] suggesting that the neutrinos are not in fact massless as predicted by the SM. Another such measurement is the $\sim 3.4\sigma$ deviation from SM prediction of the muon magnetic moment, $g-2$, observed in experiment [14]. Perhaps the most astounding is that current cosmological observations imply that the visible matter in the universe that is described by the content of the SM only constituents ∼5% of the known universe [15, 16].

In addition to these experimental results, an important potential theoretical shortcoming of the SM lies with the Higgs mechanism itself. For instance, the calculation of the Higgs mass in the theory leads to radiative corrections that cause the mass to diverge and is known as the "hierarchy" or "naturalness" problem [17]. These problems are so named because the values computed for the Higgs mass are wildly larger ($\sim 10^{14}$ GeV) then what is observed for the electroweak scale breaking ($\sim 10^{2}$ GeV) thus putting a large "hierarchy" into the theory and making the predicitions lack "naturalness". Without some sort of "ultra-violet cutoff" to the diverging mass calculation this will cause the theory to become not self-consistent. This problem is discussed further in the following section.

1.3.2 Higgs / Supersymmetry Theory

Higgs

To understand this Higgs problem, and a potential solution, we next describe the EWK theory. The EWK theory requires four gauge bosons (W^+, W^-, Z, γ) all of which would have to be massless in order that the SM be invariant under gauge transformations [7–9]. However, it is experimentally known that while this is true for the photon, the W and Z bosons are massive [3] and any straightforward attempt to simply add a mass term breaks the gauge symmetry and is thus not allowed. As mentioned before, there is an elegant solution known as spontaneous symmetry breaking known or the Higgs mechanism [10]. Put simply, the Higgs mechanism allows one to introduce massive gauge bosons for the weak interaction without breaking the $SU(2)_L \times U(1)_Y$ invariance.

The Higgs mechanism is the ansatz that there is a fundamental scalar field, known as the Higgs field, which makes the gauge invariant theory undergo a spontaneous symmetry breaking as the Higgs potential reaches a non-zero value for the introduced scalar field. Figure 1.2 is a schematic drawing of what the Higgs potential looks like (colloquially referred to as the "mexican hat" potential) and thus provides a sense why the non-zero value for the potential spontaneously breaks the symmetry. Namely, since the minimum of the potential is no longer located at the center of this representation for the potential, the symmetry is broken when the particles go to the low-energy state. In the SM this spontaneous symmetry breaking generates the mass terms for all the particles including the gauge bosons.

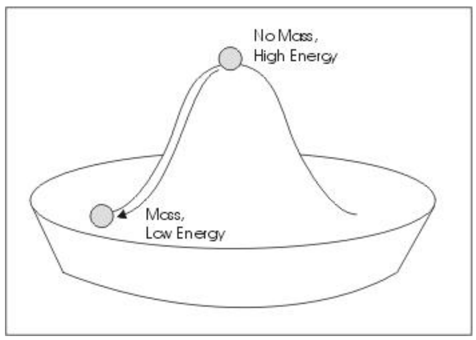

Fig. 1.2. Schematic of the Higgs potential energy demonstrating how the particles of the SM obtain their mass.

In addition to giving mass to the gauge bosons, the Higgs mechanism also predicts a fundamental spin-0 particle known as the Higgs boson [10] with an unspecified mass. It is in the calculation of this particles mass where aforementioned hierarchy problem arises. Specifically, the hierarchy problem can be seen when radiative corrections to the Higgs mass are calculated and have the basic form shown in Equation 1.1. Here, m^2_{Bare} is known as the "bare" Higgs mass and δm^2_H is the sum of the corrections due to such radiative corrections shown in Figure 1.3. We find

$$m^2_H = m^2_{Bare} + \delta m^2_H \tag{1.1}$$

where δm_H^2 can be written for a fermion of mass m_f as

$$\delta m_H^2 \approx \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + m_f^2) + ... \tag{1.2}$$

and λ_f is the coupling constant of the Higgs boson and Λ is the cut-off energy of the theory [1]. Unlike the fields describing all the other known particles, whose masses are protected by symmetry principles [1] that ensure the radiative corrections are only logarithmically divergent, the Higgs mass diverges quadratically when taking diagrams like Figure 1.3 into account [17]. In order to yield a Higgs mass of the order of 100 GeV, which is favored by the SM [18, 19] to preserve EWK symmetry breaking, the bare Higgs mass is forced to be the same order of magnitude as the corrections, thus forcing the theory to be "fine-tuned" to an uncomfortable number of digits to keep the Higgs mass from becoming non-physical.

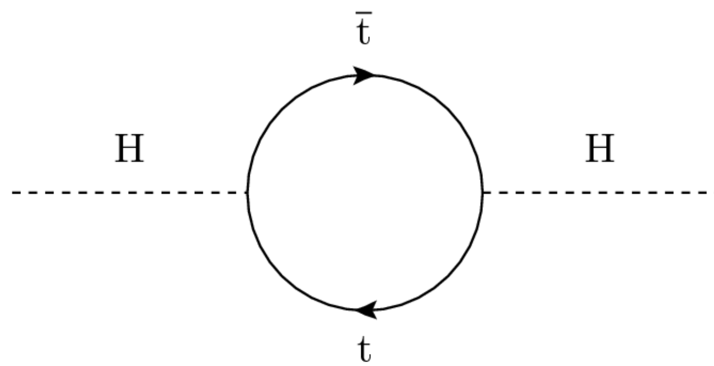

Fig. 1.3. An example of the one-loop quantum corrections from fermion loops (top quark shown here) to the Higgs mass leads that lead to a divergent Higgs boson mass without "fine tuning" in the theory. This is known as the "hierarchy" problem and presents a compelling reason to believe that the SM Higgs may not be the complete theory of EWK symmetry breaking.

Since it seems unlikely that the theory of EWK symmetry breaking requires this remarkable fine-tuning of one of its physical parameters, physicists have sought other solutions which might reveal a more fundamental understanding. One particularly elegant solution comes by extending the symmetry of the theory further to a symmetry that relates the gauge particles (bosons) and the matter particles (fermions). This theory is known as SUSY and offers a solution to the hierarchy problem as well as having many other advantages. In particular, SUSY offers intriguing solutions to other shortcomings of the SM such as an explanation of the previously mentioned anomalous muon magnetic moment and the “dark matter” question [14–16]. While a complete discussion is beyond the scope of this thesis, it is worthwhile to note that SUSY (or something like it) is required for most grand unified models such as String Theory [20].

On the flip side, it is important to note that the SUSY solution to the hierarchy problem is not without its potential downside. For example, it more than doubles the number of particles; as such it can hardly be said to be an “elegant solution” just on the surface. Furthermore, none of these new particles have been observed, although this makes this theory wonderfully testable at high energy experiments. With this in mind we move towards a description of SUSY, eventually coming back to how it helps solve the Higgs problem.

Supersymmetry

Since SUSY is a compelling theory for many reasons, many independent of the Higgs mechanism, we describe it in some detail here. As we will see, SUSY is not just a single theory but a set of theories each of which have different advantages and disadvantages. We will focus on ones that help the Higgs mechanism, have the potential to solve other problems, and give experimental predictions that can be tested in high energy collisions.

The basic proposal of SUSY [21] is that nature posseses a symmetry law that relates elementary particles of integer spin to particles of half integer spin. Said differently, SUSY implies that for every type of boson there exists a corresponding fermion partner and vice versa. Mathematically, this transformation can be achieved by having an operator Q that is an anti-commuting spinor [21–23] such that

$$Q\,|Boson\rangle = |Fermion\rangle\,, Q\,|Fermion\rangle = |Boson\rangle \tag{1.3}$$

where the theory is invariant under Q transformations. This requirement is satisfied by introducing additional supersymmetric fields which correspond to the supersymmetric partners of the SM particles and thus preserve the symmetries of the SM. The consequence of this is that the number of elementary particles is essentially (at least) doubled for the Minimal Supersymmetric Standard Model (MSSM).

To simplify our description, we adopt the standard naming convention for the supersymmetric partners of the SM particles. For the partners of the fermions (leptons and quarks), we keep the same name but add an "s" to the front; they are thus referred to as "squarks" and "sleptons". The partners of the bosons (gauge bosons) receive an "ino" as a suffix and thus become "gauginos". Additionally, as can be seen in Figure 1.4, the symbols for the squarks, sleptons, and gauginos are the same as the corresponding fermion and boson with the addition of a "~" denoting the supersymmetric version of the particle with a few special cases described below.

The representation of the SUSY algebra that produces the particle content of MSSM are the so called 'supermultiplets' which effect the mixing between the EWK and mass eigenstates of the gauginos. The supermultiplets also contain both fermion and boson states for SM and SUSY particles in such a way that the number of degrees of freedom for fermions is the same as for bosons. As shown in Figure 1.4, SUSY theories require a minimum of two complex Higgs doublets rather than just one ordinary SM Higgs [22, 23]. The supersymmetric partner to these Higgs doublets (higgsinos) mix with the supersymmetric EWK gauge particles (gauginos) because of the effects of the EWK symmetry breaking, [21–23], such that the neutral ones combine to form four mass eigenstates called the "neutralinos" ($\tilde{\chi}^0_i, i = 1, 2, 3, 4$) and the charged ones combine to form the "charginos" ($\tilde{\chi}^{\pm}_i, i = 1, 2$) shown in Figure 1.4 where the num-

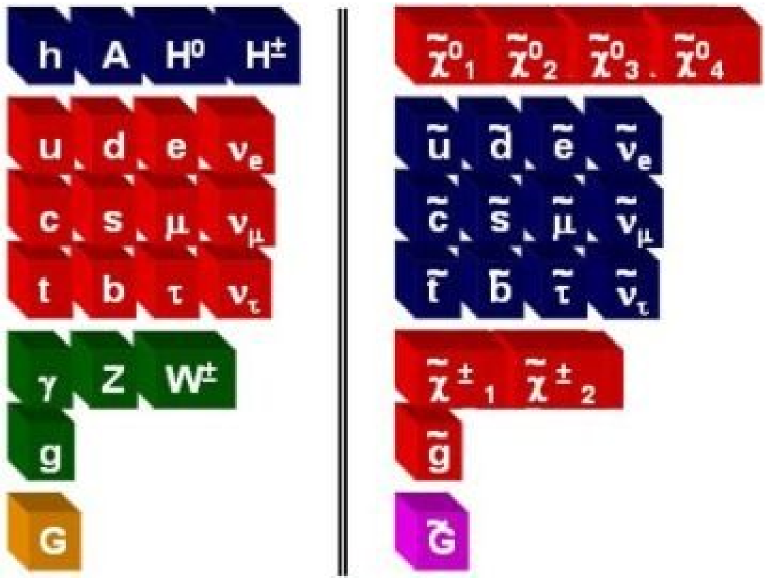

Fig. 1.4. The particles of the Minimal Supersymmtric Standard Model (MSSM) extension to the SM of particle physics.

bering i corresponds to the ordering of the mass eigenstates. Additionally SUSY also postulates the Gravitino, $\tilde{G}$, the SUSY partner to the as-yet-undiscovered spin 2 Graviton [21].

With a basic understanding of SUSY we can now come back to how SUSY can help solve the hierarchy problem before moving on to how SUSY and the Higgs can potentially be observed in high energy collider experiments. SUSY can solve the hierarchy problem because the SUSY particles must be included in the loop diagram corrections to the Higgs mas as shown in Figure 1.5. Each gives corrections similar to those in Equation 1.2 but with opposite sign since they are now scalar and fermion loops, such as

$$\delta m_H^2 \approx -\frac{\lambda_{\tilde{f}}^2}{4\pi^2}(\Lambda^2 + m_{\tilde{f}}^2) + ... \tag{1.4}$$

These correction terms thus are enticingly close to being exactly what is needed to cancel out the quadratic divergences from δm_H^2 and thus elegantly solves the hierarchy problem [24].

However, this solution comes at a cost; namely this theory introduces a large number of new fundamental particles, none of which have been discovered as of the writing of this thesis [3]. Furthermore, if SUSY was a perfect symmetry the SUSY particles would have the exact same masses as their SM counterparts and thus would have been detected long ago [3]. Since SUSY provides a compelling solution to the hierarchy problem, and there are other reasons to think SUSY might still be correct in nature, a great deal of effort has gone into consider more sophisticated versions of SUSY. In particular the resonable assumption that SUSY is a broken symmetry like EWK theory. If this is the case, then our next task is to understand the mechanism of SUSY breaking. We start by considering that a spontaneous SUSY breaking takes place via some other field, since none of the fields in MSSM can develop a non-zero vacuum expectation without spoiling the gauge invariance of the theory.

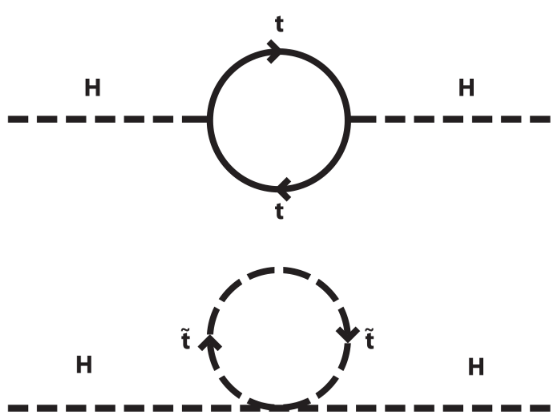

Fig. 1.5. One-loop quantum corrections to the Higgs mass leads to a divergent mass in the theory known as the "hierarchy" problem. In SUSY extensions to the SM the quantum corrections for fermions and their bosonic "SUSY-partners" have opposite signs and thus can lead to a cancellation that prevents the Higgs mass from becoming divergent.

While the exact mechanism of SUSY breaking is not yet understood, a common and well motivated method of SUSY breaking is known as “hidden sector” symmetry breaking [25]. Hidden sector symmetry breaking is the idea that there is an ensemble of, as-yet-unobserved, quantum fields and particles that cause the breaking of SUSY. These quantum fields and particles would exist at much higher energies, would not directly interact with the known lower energy SM fields, and thus remain “hidden”. Only through a weak coupling of this “hidden sector” to the MSSM particles are the SUSY breaking terms introduced.

This description of SUSY breaking thus has two sectors, known as the “visible” sector (to which all the ordinary matter belongs) and the “hidden” sector (containing new fields and particles). The two sectors interact through the exchange of some “messenger” field that mediate the information about how the SUSY breaking occurs. While there are many hidden sector variations of SUSY [21,24], historically there have been two main competing theories for what the mediating interaction between the “hidden” sector and the “visible” sector may be. The first one of these approaches assumes that the mediation is due to gravitational interactions and is commonly referred to as minimal Supergravity (mSUGRA) symmetry breaking [26, 27]. The second possibility assumes that the mediation is due to the gauge interactions and is referred to as Gauge Mediated Supersymmetry Breaking (GMSB) [29–31].

While many searches for both types of models (and many other variations) have been performed [3], and yielded null results up to the time of the writing of this thesis, the majority of collider searches have focused on mSUGRA type models owing to the prediction of a heavy dark matter candidate [28]. GMSB models provide a compelling alternative to mSUGRA models as well as having advantages such as natural suppression of “flavor” violating interactions [29–31]. “Flavor” is a common term to explain the assigning of quantum numbers to the various particles in the SM such as lepton number, baryon number, isospin, etc. Simple flavor conservations have been observed in SM interactions [3], such as lepton number conservation, and thus any theory that can avoid "flavor" violation that has not been previously observed is seen as favorable.

1.3.3 Gauge Mediated Symmetry Breaking

We begin with a more detailed description of GMSB. However, berfore proceeding to a discussion of its implication on observable at collider experiments we remark that even with the specification of the hidden sector breaking mechanism we are left with a huge number of free parameters in the model and we will have to further reduce them with either theoreical ideas or experimental constriants. One such example is a new conservation law postulated (and typically assumed) known as "R-parity" which simply states the number of SUSY particles in an interaction is conserved for reasons we will describe in a moment.

In GMSB models SUSY breaking originates in a "hidden sector", which is not further specified, and "mediates" the breaking through "messenger fields" to the "visible" sector. This type of breaking mechanism causes the fields that couple to the messenger field to acquire a vacuum expectation value, denoted as $<F>$, and thus give the masses to the MSSM fields dynamically via loop corrections [24]. A schematic view of this SUSY breaking mechanism, commonly referred to as "soft" SUSY breaking, is shown in Figure 1.6. An appealing consequence of this solution to SUSY breaking is that since it is spontaneously broken in the hidden sector, with no direct coupling to the SM particles, one can avoid quadratic divergences of the SUSY breaking terms [25] which plagued the Higgs mechanism of EWK symmetry breaking.

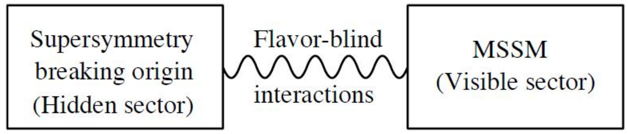

Fig. 1.6. Schematic of Gauge Mediated Supersymmetry Breaking (GMSB).

With all these new particles and couplings one would naively expect a host of new interactions that would allows for the known SM particles to decay away. Since we do not observe this in nature, in addition to the known conservation laws, there must be additional mechanisms to prevent the known stable particles from decaying away. For this reason, it is typically assumed that there is a new conservation law in SUSY. In particular a value known as "R-parity" is introduced where R is a quantum multiplicative number and defined as

$$R = (-1)^{3(B-L)+2s} \tag{1.5}$$

where B, L, and s represent the baryon, lepton, and spin of the particle respectively [32]. The reason for the introduction of this conservation principal is that in the most general MSSM models there are terms introduced into the theory that allows the violation of baryon and lepton number. Interestingly, if R-Parity is violated in the most general of ways such that all B and L violating terms are allowed this would imply that the proton would become unstable and decay in a very short period of time [33]. While this phenomenological consequence of proton decay can be avoided by introducing additional terms into the SM, it is generally thought to be more theoretically appealing to simply posit R-Parity conservation [34] since both baryon and lepton number conservation have been tested to a high degree of precision [3]. This quantity is designed to be $R = +1$ for SM particles and $R = -1$ for their SUSY counterparts. R-Parity being postulated to be conserved implies a number of important phenomenological consequences for searches for sparticles at high energy colliders:

1. Any initial state created in laboratories using pairs of SM particles (such as colliders) has $R = +1$ and thus any SUSY particles created must be created in pairs.

2. All individual SUSY particles, which have $R = -1$, will decay (except the lightest supersymmetric particle) into a state that contains an odd number of SUSY particles.

3. The lightest supersymmetric particle (LSP) must be stable and cannot decay further into SM particles, thus making it a candidate for dark matter if it is also electrically neutral [16].

GMSB models also offer distinctive phenomenological features that make them appealing for searches at particle colliders. One of these features is that the weakly interacting Gravitino ($\tilde{G}$) has a mass range of $\sim$eV/c^2 to $\sim$GeV/c^2 [29] and thus becomes the LSP. Another feature is the next-to-lightest SUSY particle (NLSP) is often the neutralino ($\tilde{\chi}_1^0$) which can decay almost exclusively to via $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ making for a very distinctive signature in high energy collider experiments. While not all versions of GMSB models have this distinctive signature, in this thesis we have chosen to focus on variations which do.

We start by listing some of the parameters of GMSB to aid in understanding quantitative predictions of the model and comment on the constraints that help us choose these parameters as well as bound their values. This will aid in our understanding of previous searches performed at collider experiments which assume certain constraints based on these model parameters. Furthermore, since a great deal of data has been gathered on the masses and other characteristics of the SM particles, we list some of the current experimental constraints that help us choose these parameters as well as bound their values. It is worth noting that we will limit ourselves to models that have predictions that can be tested at our experiment and denote which parameters this places limits on.

For GMSB models the hidden sector particles are assumed to be at a mass scale denoted as $\sqrt{F}$ and the messenger sector mass scale is given as M_{mess}. To avoid flavor breaking we require $M_{mess} > \sqrt{F}$, meanwhile M_{mess} is bounded on the other side as being below the Plank scale in order to realize SUSY breaking and help solve the hierarchy problem [35]. Thus, these values must be of the order of $\sqrt{F} \approx$10 TeV/c^2 and $M_{mess} \approx$100 TeV/c^2 [35]. With this the number of free parameters in the minimal GMSB model are reduced from over one hundred free parameters of the MSSM to 6 free parameters which are:

1. N_{mess}**:**

   The number of messenger fields. We note that while this can have any value in principle, phenomenologically low values ($\leq$ 2) of N_m lead to the next-to lightest stable particle (NLSP) being the neutralino $\tilde{\chi}_1^0$.

2. $\Lambda = \frac{F}{M_{mess}}$**:**

   The mass scale of the visible sector of SUSY breaking. For sparticles with masses on the order of the EWK scale Λ is on the order of $\frac{100\ \text{TeV}}{\sqrt{N_{mess}}}$.

3. M_{mess}**:**

   The overall messenger scale of the messenger sector. All the masses of the SUSY particles depend on M_{mess} logarithmically while the lifetime of the NLSP, which is important in this analysis, depends quadratically on M_{mess}.

4. tan β**:**

   The ratio of the vacuum expectation values of the Higgs. Large values of tanβ remove the $\tilde{\chi}_1^0$ from being the NLSP and thus remove the final state $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ so we don't explore those scenarios any further.

5. sgn(μ):

   This is the sign of the Higgs and Higgsino supersymmetric mass parameter μ. The absolute value of μ is determined by the EWK breaking condition. Sgn(μ) is correlated with the sign of the MSSM correction to the anomalous magnetic moment of the muon, $g-2$, which is thus favored to be positive to account for this discrepancy [35].

6. C_{grav}:

   Represents the ratio between the scale of SUSY breaking (F_0), a generic term true in all SUSY models, and the scale of the intrinsic SUSY breaking parameter ($\frac{F_0}{F}$). This parameter contributes to the tuning of the Gravitino mass and the NLSP lifetime.

Even though this parametrization of MSSM adopted within GMSB considerably simplifies the possible phenomenological scenarios, even a six-dimensional space is too broad to be covered by any single study at a high energy experiment. For this reason, great effort has been made to create sets of combinations of the parameters that all have similar "types" of final states and phenomenologies at colliders. At this point we will shift our focus away from general and minimal GMSB theory and focus more on collider phenomenology of two different GMSB model types that have been previously searched for, as well as collider signatures which we are sensitive to but have yet to be studied. This will help provide the final pieces of focus for where we will concentrate our effort, in particular in high energy collision events that produce a photon and a Gravitino in the final state.

1.3.4 GMSB Collider Phenomenology

In order to help simplify the GMSB parameter space we will refer to two types of models each of which have a unique collider phenomenology. Both models have $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ in their final state and their production and decay can be characterized as:

$$p\bar{p} \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 + X \rightarrow \gamma\tilde{G}\gamma\tilde{G} + X \tag{1.6}$$

where X is any other particles produced in the original interaction (if any). For now we have not specified the production mechanism of the $\tilde{\chi}_1^0$ pairs, but note that they can be directly produced or produced the the decay of other, heavier particles and this divides the various ways they produce this final state. Equally important, from the perspective of the detection of these final states, is a second bifurcation of the types into two subtypes which affect how they will detected, in particular the lifetime of the $\tilde{\chi}_1^0$ before it decays via $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$. We will discuss both separately. The goal of understanding these differences in the phenomenology is to aid us in understanding the previous search results presented in the next section as well as our future search strategy.

Before proceeding to the phenomenology of GMSB models, it is useful to introduce the notion of how measurements are made in high energy experiments. These ideas will be explained in much greater detail in Sections 2.1 and 2.2. The basic idea of how we produce high energy collisions comes from when two beams of energetic particles (e.g. protons and antiprotons) are made to intersect each other at a large center of mass energy. We surround the points where the beams are made to collide with large multi-purpose detectors (such as the CDF detector) that are capable of recording information relevant to the subsequent particles produced in the collisions. This information includes such quantities as collision location and collision time, as well as the 4-momentum, particle type and arrival time of the produced particles in the detector. Since the collision occurs with approximately no momentum in the plane transverse to the collision we can infer, by conservation of momentum, that the vector sum of the transverse momenta of the inital and final state particles should be approximately zero. Particles that do not interact with the calorimeter, such as neutrinos and Gravitinos (if they exist), will not deposit energy in the calorimeter so they can be inferred from the transverse energy imbalance of the detected particles in the collision. The measured missing transverse energy ($\not{E}_T$) is defined as the negative of the vector sum of the transverse energy measured in the detector. From this information it is possible, in principle, to reconstruct and identify the particles produced in the collision as a way to search for new particles such as those predicted in SUSY models. From this perspective, the production of sparticces in Equation 1.6 gives the $\gamma\gamma + \not{E}_T + X$ final state, in principle, in a detector.

An important caveat to this description is the finite size of the detector which makes the lifetime of the $\tilde{\chi}_1^0$ particularly important as it affects when and how the photon is produced. The $\tilde{\chi}_1^0$ lifetime ($\tau_{\tilde{\chi}_1^0}$) given by [36]:

$$c\tau_{\tilde{\chi}_1^0} = 48\pi \frac{m_{3/2}^2 M_{Pl}^2}{m_{\tilde{\chi}_1^0} |P_{1\gamma}|^2} \tag{1.7}$$

where $m_{3/2} = \frac{|F|}{\sqrt{3}M_{Pl}}$, F is related to the value of the superpaticle masses and M_{Pl} is the Plank mass [21]. For theoretically reasonable squark masses, such that SUSY may still contribute to solving the hierarchy problem, between 2 TeV and 10 TeV [21] bounds the typical lifetime ranges to be 0.4 ns $< \tau_{\tilde{\chi}_1^0} <$ 180 ns for the $\tilde{\chi}_1^0$. This allows us to divide the possible production of $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma \tilde{G}\tilde{G}$ into three possible search prospects [37]. Namely:

1. $\tau_{\tilde{\chi}_1^0} <$ 1 ns:

   In this case the photons from the decay of the $\tilde{\chi}_1^0$ are produced so close to the original collision position that we are not able to distinguish them from photons directly produced in the collision.

2. 1 ns $< \tau_{\tilde{\chi}_1^0} <$ 50 ns:

In this case the final state $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ occurs at a displaced spatial location from the collision which produced the $\tilde{\chi}_1^0$ and causes the arrival time of the photon to frequently be delayed relative to expectations from promptly produced photons. This scenario will be discussed in greater detail in the following section.

3. $\tau_{\tilde{\chi}_1^0} > 50$ ns:

   In this scenario both $\tilde{\chi}_1^0$ pairs can travel a large enough distance before decaying that they typically leave the detector entirely. SUSY in this channel would not produce photons in a detector surrounding the collision point. Thus this scenerio be indistinguishable in typical collider experiments from other versions of SUSY (e.g. mSUGRA) and thus we don't consider it further.

These possibilities are what determine the last important part of the GMSB phenomenology in a detector. If GMSB models are correct, then a small fraction of high energy collisions should produce sparticles which will decay down to photons and $\not{E}_T$ in the final state. The question then becomes whether the neutralinos will, typically, produce two promptly produced photons, one delayed photon, or no photons in the detector. As there have been many searches for the first scenerio as well as searches for other models of SUSY, and there are compelling reasons to believe the second scenario is most likely, it is the second scenario that is the focus of this thesis where the $\tilde{\chi}_1^0$ has a long enough lifetime to produce a photon whose reconstructed time of flight will arrive later ("delayed") than a photon promtly produced by the collision.

To quantify what is meant by "prompt" and "delayed" we consider the production and decay of a $\tilde{\chi}_1^0$ in a detector, see Figure 1.7, and write down a standard photon timing variable used known as corrected time of arrival [38], defined as:

$$t_{corr} \equiv (t_f - t_i) - \frac{|\vec{x_f} - \vec{x_i}|}{c} \tag{1.8}$$

where t_f is the arrival time of the photon at the calorimeter, t_i is the time of the collision, and $|\vec{x_f} - \vec{x_i}|$ is the distance between the collision point and the position where the photon his observed. In a perfect detector, for a promptly produced photon t_{corr}=0 ns. For a $\tilde{\chi}_1^0$ with a finite lifetime we would have t_{corr} >0 ns and we would describe this photon as being "delayed" and use the notation $\gamma_{delayed}$.

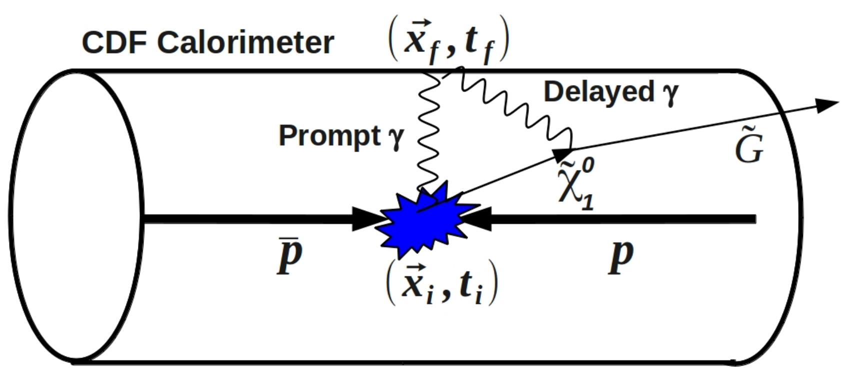

Fig. 1.7. A schematic of production of long-lived $\tilde{\chi}_1^0$ at the Tevatron decaying to a Gravitino ($\tilde{G}$) and a photon (γ) inside the CDF detector with the photon arriving with a delayed time.

Coming back to the GMSB phenomenology, we can now understand our two production mechanisms in Equation 1.6 and our two decay mechanisms which give us four different final states with photons. A summary of the various scenarios described above and their resulting final states is given in Table 1.2 [37]. We next describe more details about each of these four scenarios.

The most commonly discussed production models in the literature are ones where $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ is produced at the end of a long decay chain, represented by the top row of Table 1.2. An agreed upon convention was arrived at during the 2001 Snowmass Workshop on the Future of Particle Physics and is known as the Snowmass Points and Slopes (SPS) convention [39]. These are a set of benchmark points and parameters in which the MSSM parameters correspond to different general types of scenarios in

	$\tau_{\tilde{\chi}_1^0} < 1$ ns	$\tau_{\tilde{\chi}_1^0} \sim 5$ ns
$\tilde{\chi}_1^0\tilde{\chi}_1^0 + X$ Production	$\gamma\gamma$+$\not\!\!E_T + X$	$\gamma_{delayed}$+$\not\!\!E_T + X$
Exclusive $\tilde{\chi}_1^0\tilde{\chi}_1^0$ Production	Exclusive $\gamma\gamma$+$\not\!\!E_T$	Exclusive $\gamma_{delayed}$+$\not\!\!E_T$

Table 1.2
Table of various final states for $\tilde{\chi}_1^0$ lifetimes of interest in this analysis where X is any other particles produced in the original interaction (if any).

SUSY for use in experimental searches. Of particular importance to us is parameter set eight, known as SPS-8, which describes benchmark set of relationships that have fixed mass relationships between the sparticles. This further simplifies the models and we are left with two free parameters: (1) The mass of one of the particles (all others are derived relative to it) and (2) the lifetime of the NLSP. Since the masses of the sparticles and their couplings are well specified, this uniquely determines their production cross sections in different types of high energy collisions, as well as their branching fractions and final state topologies.

A typical example of the production and resulting decay chain from an SPS-8 scenario for proton antiproton collisions at a center of mass energy of $\sim$2 TeV is shown in Figure 1.8 on the left hand side where the dominant production mode is chargino pair production [37]. This diagram was chosen as it is at the limits of the sensitivity of what could be produced at the Tevatron. Similar production and decay diagrams occur at LEP and the LHC (each with slightly different diagrams) and searches for these final states have been performed at LEP [40], the Tevatron [41], and the LHC [42] for various mass and lifetime combinations which would produce the $\gamma\gamma$+$\not\!\!E_T$ final state as well as other ways of searching for long-lived neutralinos. All have shown no evidence for GMSB SUSY in this scenario. However, these all assume SPS-8 type relations which keep the production cross-section high but also place constraints on the possible masses of the sparticles. These limits will be described in the next section.

While the SPS-8 relations are most frequently used, a second and equally important type of production mechanism comes from models where only the $\tilde{\chi}_1^0$ and the $\tilde{G}$ have masses low enough to be produced in collider experiments [43] represented by the bottom row of Table 1.2. This scenario is referred to as the Light Neutralino and Gravitino (LNG) scenario in the literature and is important because it releases these SPS-8 type relations that are only there to help restrict the number of different search strategies for experimentalists. In these models the large direct sparticle production rates, which originally made them appealing from an experimental perspective, vanish. Said differently, the previous limits from LEP, the Tevatron, and the LHC are not applicable to these scenarios because the production mechanisms which were favored in SPS-8 models no longer produce events, thus the limits are no longer relevant. An exciting production mechanism of SUSY particles in LNG scenarios is shown on the right hand side of Figure 1.8 [43]. It shows sparticles produced in collisions is through the production of the lightest Higgs (h^0) which then decays to $\tilde{\chi}_1^0$ pairs if the masses are in a favorable configuration. The phenomenology of $h^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$ in LGN models, where sparticle production is dominated by (h^0) events decaying to $\tilde{\chi}_1^0$ pairs, is significantly different from those seen in SPS-8 models which produce $\tilde{\chi}_1^0$ pairs at the end of long decay chains; the final state is $\gamma\gamma\tilde{G}\tilde{G}$ plus little else giving $\gamma\gamma$+$\not\!\!E_T$ if the lifetime is short and a $\gamma_{delayed}$+$\not\!\!E_T$ if the lifetime is $\sim$5 ns. It is topologies like this will be the focus for this thesis as they are not excluded in any substantive way.

1.4 Previous Collider Searches and Model Constraints

Now that we have finished describing the basic properties of GMSB SUSY phenomenology, detailed four different phenomenological scenarios, and alluded to some previous results, we now highlight a few of the searches previously performed for each in a little more detail. After we have completed this description and have a better understanding of which regions are most advantageous to study, we will highlight

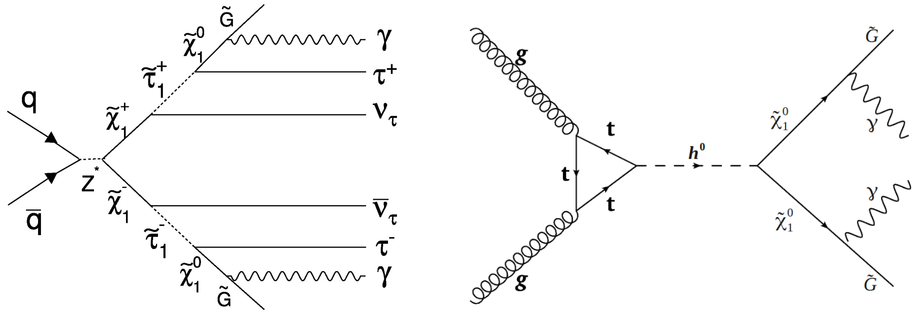

Fig. 1.8. Two example Feynmann diagrams illustrating SUSY $\tilde{\chi}_1^0$ pair production event that, in the simplest GMSB models, can produce one or more photons $+\not{E}_T$ in high energy particle collisions.

an unpublished preliminary result that was performed in 2008 and a very intriguing excess that was found in the exclusive $\gamma_{delayed}+\not{E}_T$ final state. The bulk of this thesis is dedicated to following up on this result.

The results of various searches from LEP and the Tevatron are shown in Figure 1.9 for SPS-8 type scenarios. This figure demonstrates the parameter space that has been constrained as a function of neutralino lifetime versus mass. A few words are in order about the searches that produced these results. We begin with the e^+e^- results from the Apparatus for Large Electron Positron PHysics (ALEPH) which are a combination of direct searches for $\tilde{\chi}_1^0$'s as well as indirect searches for sleptons and charginos. In the direct searches for low lifetime $\tilde{\chi}_1^0$'s at ALEPH the channel $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}\gamma\tilde{G} \rightarrow \gamma\gamma+\not{E}_T$ was used where the neutralino lifetime was assumed to be less than 1 ns. This implies that the photons were required to originate directly from the beam line. In the case where the lifetime was assumed larger (1 ns$< \tau_{\tilde{\chi}_1^0} <$ 10 ns) the direct searchs at ALEPH used photon "pointing" methods [40] which are complementary to the delayed photon methods previous described. In this method, photon pointing measures the way the photon interacts with the detector and searches photon candidates for evidence that they come directly from the beam line ("points" to the beam line). No evidence for SUSY was observed in these searches. These searches were only sensitive up to neutralino masses less than 100 GeV, the limiting factor being the center-of-mass energy of LEP which was only 205 GeV. We also note that while these scenarios were based on an SPS-8 like production, only the gauginos and sleptons were assumed to be light here.

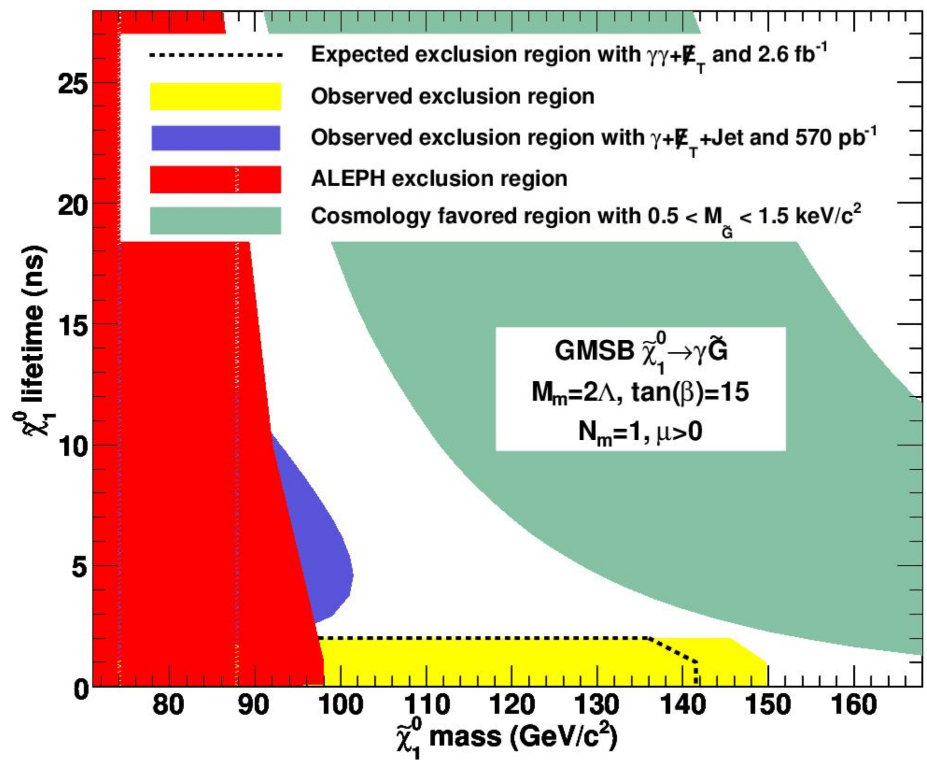

Fig. 1.9. The predicted and observed exclusion regions from the ALEPH detector at LEP as well as the previous GMSB photon searches at CDF. The green shaded bands shows the cosmologically favored region where $0.5 < m_{\tilde{G}} < 1.5$ keV/c^2 [41].

A complementary set of searches were performed at the Fermilab Tevatron which focus on SPS-8 models where diagrams like the LHS of Figure 1.8 dominate. The low lifetime search was published in 2010 and assumed both $\tilde{\chi}_1^0$'s would decay inside the detector and the final state would appear as $\gamma\gamma + \not{E}_T + X$ where the X was required in the form of significant extra energy. The long lifetime search was performed in 2007 in the $\gamma_{delayed} + \not{E}_T + jet$ final state [41]. The low lifetime result ($\tau_{\tilde{\chi}_1^0}$ <1 ns), shown in yellow, as well as a long lifetime search (1 ns < $\tau_{\tilde{\chi}_1^0}$ <20 ns), shown in blue using the delayed photon methods, are the result searches performed at CDF [41]. Figure 1.10 shows the results of a search for GMSB SUSY that was performed at the Tevatron's DØ experiment in the $\gamma\gamma$+$\not\!\!E_T$ using more luminosity, but who's final state is only sensitive for lifetimes less than ∼1 ns [44].

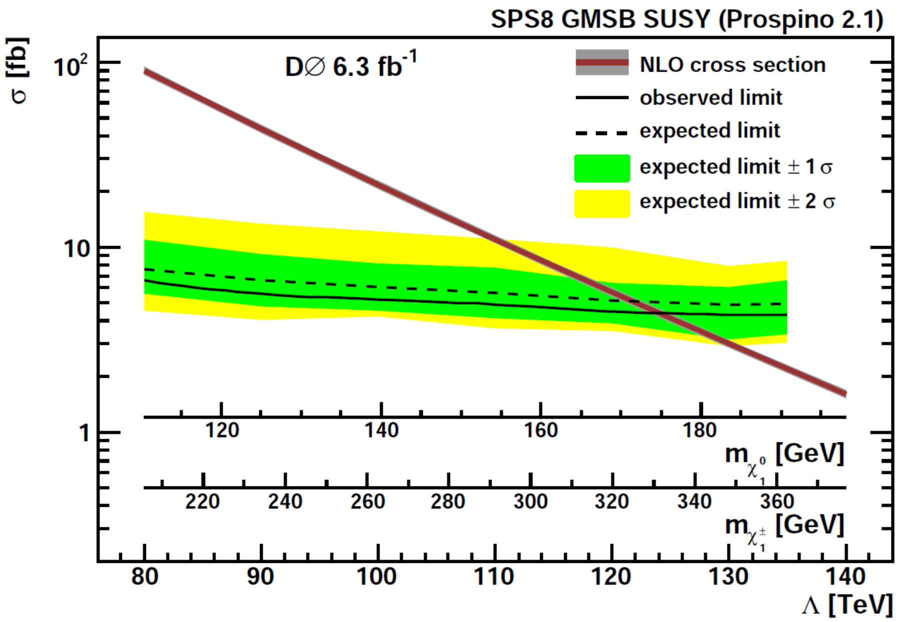

Fig. 1.10. The predicted cross section and the 95% confidence limit expected and observed exclusion limit as a function of Λ from a search in $\gamma\gamma$ + $\not\!\!E_T$ performed at the DØ experiment in 2010. This search assumes SPS-8 model parameters and thus makes the dominant production of SUSY particles gaugino pair production. The corresponding masses are shown for the lightest chargino $\chi_1^\pm$ and neutralino χ_1^0 [44].

A similar result at 3.5 times higher collision energies but with proton proton collisions and focusing on SPS-8 scenarios was done at the LHC in 2011 [42] as shown in Figure 1.11. These searches are different in that the sparticles are most often produced through strong production of squarks and gluinos. This search looked for the $\gamma\gamma$+$\not\!\!E_T$ + X in final state produced from squarks and gluinos, which decay down and eventually produce the photons, $\not\!\!E_T$ and other final state particles and these other high energy particles are required as part of the search. No evidence for SUSY is observed and limits are set in this scenario for $\tilde{\chi}_1^0$ lifetimes up to 3 ns for a neutralino mass $>$ 200 GeV/c^2 with 200 pb^{-1} of data as shown in Figure 1.11. While this search is directly comparable to the LEP and Tevatron results in that it assumes SPS-8 relationships, it is very different in that it presumes a squark-gluino production unlike the searches at the Tevatron which assume gaugino pair production. The comparison between the limited value as we move even slightly outside the SPS-8 assumptions as SPS-8 is only designed to simplify the displaying of results in terms of a model that is well specified. There is no compelling reason to believe that this particular set of choices is more likely to be observed in nature. Thus, while the parameter spaces shown for the searches are the same, the production mechanism assumptions for the LHC searches are different. We can think of them as being two different types of searches: ones where squarks/gluinos are too heavy to be produced (Tevatron and LEP are applicable only) and ones where squarks/gluinos are accessible (LHC, Tevatron and LEP are all applicable, but the LHC results are most sensitive).

While the searches described above exclude a great deal of minimal GMSB model scenarios, many of these limits may not apply if the assumptions made in the SPS mass hierarchies are relaxed. Thus, as we move out of the narrow SPS-8 interpretation these results can be considered to be covering different regions, or in some sense are complementary. However, we are left with the inescapable fact that no evidence for GMSB SUSY has been observed in any of these three searches. That being said, we also notice that these searches cover models in only the top half of Table 1.2 where the masses of all but the $\tilde{\chi}_1^0$ and Gravitino are out of reach of the collider production energies. Before continuing, it is important note that there has been a search for exclusive $\gamma\gamma+\not\!\!E_T$ at CDF which did not uncover evidence for anomalous production [45].

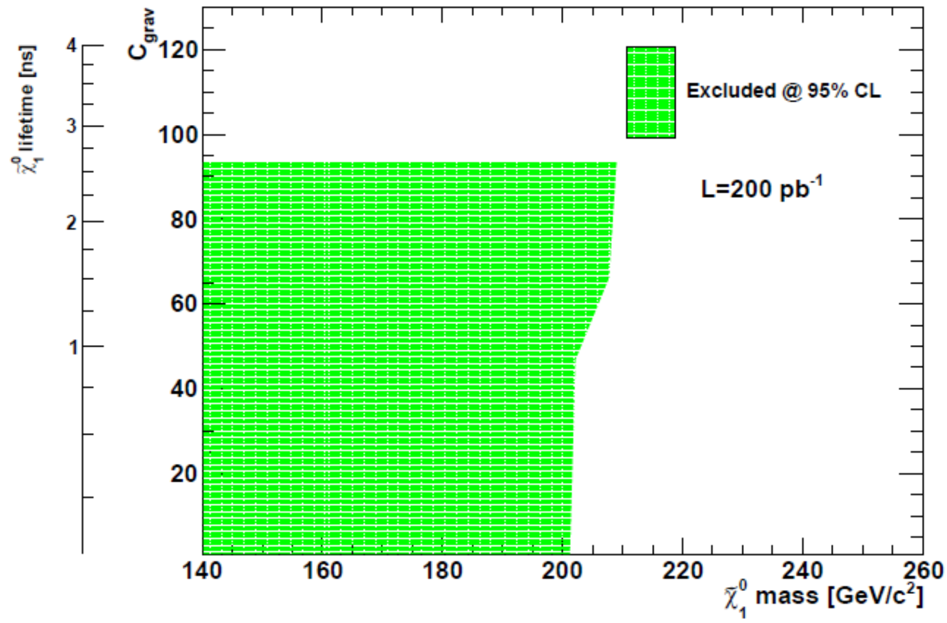

Fig. 1.11. The observed exclusion regions from a GMSB search performed at the LHC in 2011 for lifetimes up to ∼3 ns for neutalino mass > 200 GeV/c^2 with 200 pb^{-1} of data. This $\gamma\gamma + \not{E}_T + X$ results are interpreted using SPS-8 model parameters which are dominated by squark-gluino production. This result is complementary to the searches performed at the Tevatron and LEP for low lifetime neutralinos in this scenario.

With these results in mind, we note that there have been no published results on LNG searches for long-lived neutralinos making this a new and important window of opportunity. This provides a clear motivation to do a first search in the exclusive $\gamma_{delayed} + \not{E}_T$ final state as was first recommended in References [37] and [43]. With clear vision of what types of models to focus on, we will go into more detail about a preliminary search in this final state.

1.5 Overview of Searches for Long Lived Neutral Particles that Decay to Photons

Having motivated our search in the exclusive $\gamma_{delayed}$+$\not\!\!E_T$ final state, we turn to the details of how the search is done. We come back to the variable used to calculate t_{corr}, as defined in Equation 1.8 and consider what it will look like in a real detector. We then do a cursory summary of the typical backgrounds and their corrected time distributions as well as methods we will use in the exclusive $\gamma_{delayed}$+$\not\!\!E_T$ to measure and/or reject these backgrounds. This discussion will be especially useful as we look at some preliminary results in the next section. Note that this discussion follows the work done in [38] which was the first search for delayed photons by CDF in the $\gamma_{delayed}$+$\not\!\!E_T + Jet$ analysis.

For a promptly produced photon, with perfect measurements, $t_{corr} = 0$ ns. Since our detector is not in fact perfect this measurement has an intrinsic resolution which we have measured to be ~0.65 ns and is thus well described by a Gaussian centered at $t_{corr} = 0$ as shown in Figure 1.12 (LHS). We refer to this distribution as the "right vertex" corrected time because it represents the timing distribution when we have correctly identified the origin of the collision which we measure experimentally as a "vertex". Photons from the decay of a long-lived $\tilde{\chi}_1^0$ would have $t_{corr} > 0$ and thus arrive at a time that is "delayed" relative to expectations from the SM as shown in Figure 1.12 (RHS). The t_{corr} variable allows for good separation between nanosecond-lifetime $\tilde{\chi}_1^0$'s and promptly produced SM photons [38]. This will be described in more detail in Section 2.2.3.

Unfortunately, there are other sources of events with large t_{corr} events which make our search more complicated. Specifically, the presence of other collisions occurring in the data-taking window that do not have anything to do with the produced photon, as seen in Figure 1.13, can lead to ambiguity in the selection of x_0 and t_0. When the incorrect initial interaction point (vertex) is selected in an event we call this a "wrong vertex" event. As will be discussed in Section 5.1, this results in the "smearing" out of the Gaussian distribution of the t_{corr} variable. The resulting

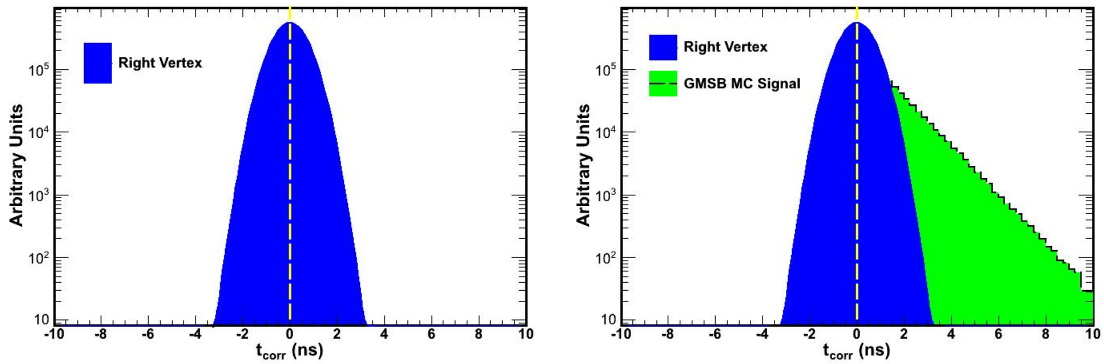

Fig. 1.12. Monte Carlo example of the corrected time variable, t_{corr}, for both promptly produced photons (LHS) as well as photons from a simulated long-lived $\tilde{\chi}_1^0$ (RHS).

RMS of the t_{corr} distribution becomes ~2.0 ns where this number comes mostly from the variation in the time of collision between the protons and antiprotons, as well as timing resolution of the systems involved in measuring the initial and final positions. With this understanding of right and wrong vertices, we can see that when we select a single vertex for use in an event we will have some chance of having correctly assigned the t_0 and x_0 and some chance of having selected incorrectly. Thus the resulting corrected timing distribution will be the combination of the right and wrong vertex Gaussians as shown in Figure 1.14 where we include what a signal from $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ would look like as well with a long lived $\tilde{\chi}_1^0$.

The second major background to our signal is from photon candidates that have nothing to do with the collision and originates from sources external to the detector, typically from 'cosmic rays'. These events are discussed in more detail in Section 4.2. For now it is sufficient to remark that since these events have nothing to do with the collision they effectively show up randomly in time and thus present a 'flat' background signature in the t_{corr} distribution, as shown in Figure 1.14. A signal region, where we have the potential for separation between new physics and background sources, is readily seen between about 2 ns and 7 ns. Other regions are

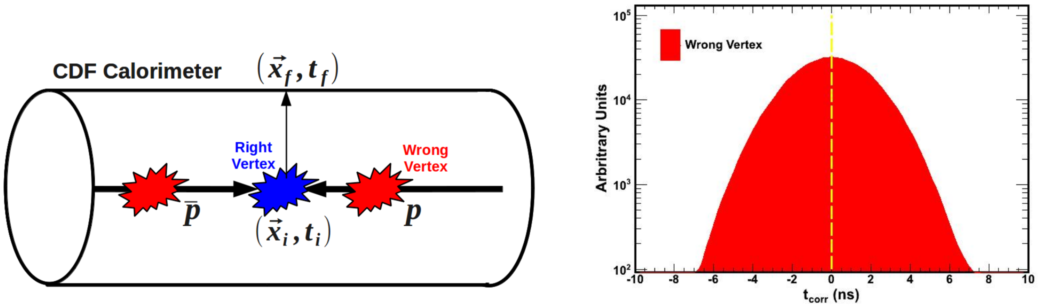

Fig. 1.13. (LHS) Schematic showing how selecting a incorrect collision (i.e. wrong vertex) can cause an errant calculation of the time-of-flight ($\frac{|\vec{x_f}-\vec{x_i}|}{c}$) thus leading to a t_{corr} described by a (RHS) Gaussian with an RMS ~2 ns for wrong vertices.

dominated by right vertex, wrong vertex, or cosmic rays. Each of which can be used to estimate the background rate in the signal region using data.

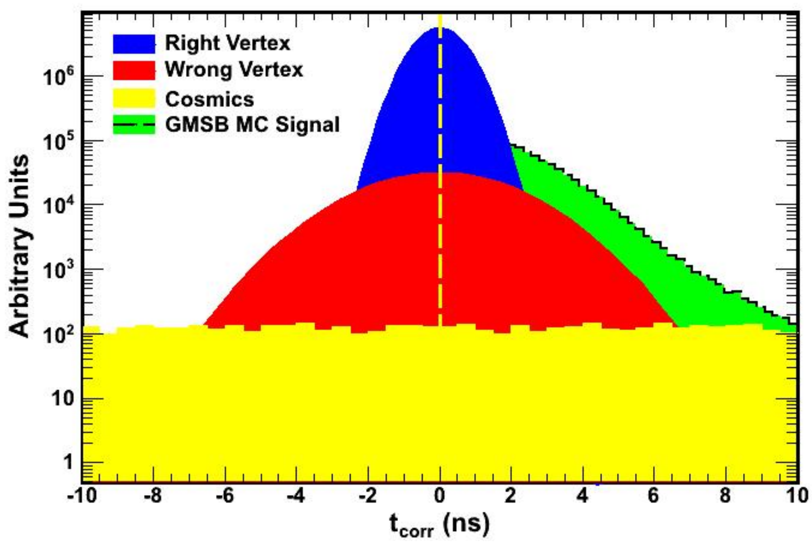

Fig. 1.14. A toy simulation of t_{corr} including GMSB signal events along with a set of collision and non-collision background events. Here the right vertex (blue), wrong vertex (red), and cosmic ray (yellow) distributions are shown.

In the next section we present an overview of a preliminary search in the exclusive γ+$\not\!\!E_T$ final state, but using simple background estimation technique and no rejection against subtle, yet insidious, backgrounds with large times.

1.6 2008 Preliminary Result

In 2008 a preliminary search looking for events that contain a single photon (identified using criteria described in Section 2.4.3) and $\not\!\!E_T$ (defined in Section 2.4.6) and little other activity in the detector was performed. This previous analysis focued on a search for new phenomena know as Large Extra Dimension [46] as it can have the γ+$\not\!\!E_T$ final state. No evidence for new physics was observed and the result was published in reference [47]. This search differed from the exclusive $\gamma_{delayed}$+$\not\!\!E_T$ final state in that the arrival time of the photon was not considered as a way to discriminate between SM and new phenomenon.

Following the publication of this result, even though this search was not optimized for a search for GMSB, the corrected time distribution for the sample of events was examined using the simple prescription assuming the symmetry in the t_{corr} distribution around t_{corr} = 0 ns, shown in Figure 1.14 for both the right and wrong vertex distributions. By exploiting the seemingly benign fact that only GMSB MC signal events were asymmetrically distributed about t_{corr}= 0 ns it seemed very straightforward to predict the number of events expected between 2 ns < t_{corr} < 7 ns (signal region) by using the number of events from -7 ns < t_{corr} < -2 ns. In fact this had been done in the first delayed photon search for $\gamma_{delayed}$+$\not\!\!E_T$ + Jet with the data being consistent with background expectations alone [41]. It was expected that this should have sensitivity based on a simplified, although independent, estimate of the sensitivity in the region 120 GeV/c^2 < m_{h^0} < 160 GeV/c^2, 30 GeV/c^2 < $m_{\tilde{\chi}_1^0}$ < 80 GeV/c^2, and 1 ns < $\tau_{\tilde{\chi}_1^0}$ < 20 ns [43].

The results of this prelimnary search are shown in Figure 1.15. What can be seen in the corrected time distribution is a statistically significant excess of events in the

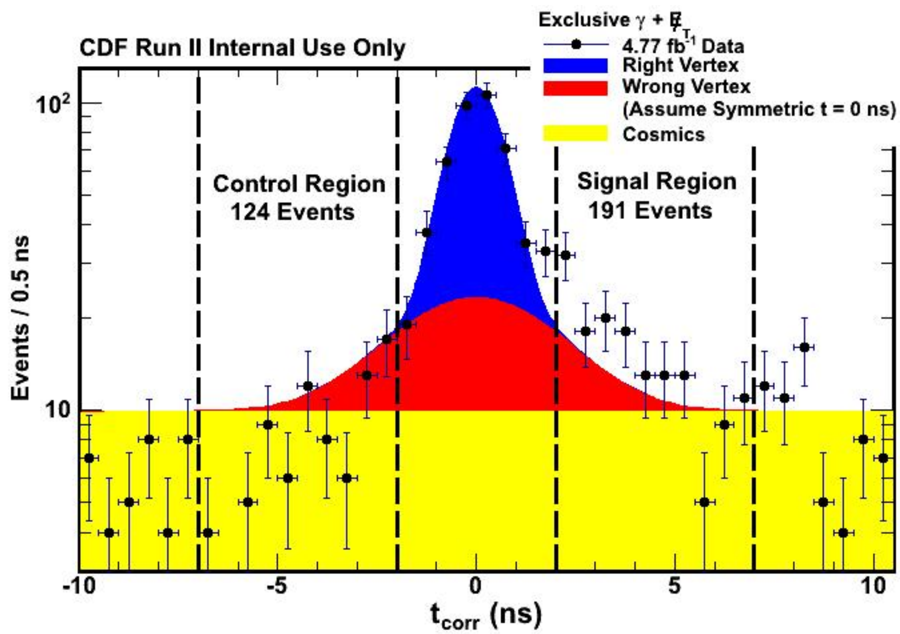

Fig. 1.15. The result of a preliminary search for delayed photons performed in 2008 in the exclusive γ+$\not\!\!E_T$ final state showing an excess of events in the region 2 ns$< t_{corr} <$ 7 ns above simple background estimation techniques.

region 2 ns$< t_{corr} <$7 ns relative to expectations. There are 191 events are observed in the signal region with a background prediction of only 124 events. Clearly, this is a very interesting result and demands a follow up with more data as well as cross-checks to the underlying assumptions of the analysis.

In many ways, this thesis is the follow up to this reported excess. As discussed before it is possible that this result hints at the discovery of SUSY and possibly even the Higgs boson. However, extraordinary claims require extraordinary evidence. In particular we will describe the results of a thorough and systematic search for other sources of events which might produce large time photons in the exclusive γ+$\not\!\!E_T$ final state, as well as a study of the the validity of the background estimation techniques assumptions. In the next section we will lay out the outline for this analysis as we follow up on the intriguing excess observed and describe the new methods we developed for rejecting biased sources of SM events as well as for predicting the number of events from SM sources in the signal region.

1.7 Outline of the Search

This analysis is constructed to follow up on the intriguing excess that was observed in the exclusive $\gamma_{delayed}+ \not\!\!E_T$ final state. We focus on doing a search in as model-independent a method as possible. For this reason, we do not focus on GMSB or Higgs specifically, rather we focus on the model of the production of a heavy neutral object that decays, after a few nanoseconds, to a photon plus something that leaves the detector without depositing any energy. While this signature is embodied in $h^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}\gamma\tilde{G}$, we use nothing about this decay except that the $\gamma_{delayed}+\not\!\!E_T$ final state should not be accompanied by any other high energy final state particle.

That being said, this interpretation is amenable to GMSB SUSY scenarios where the $\tilde{\chi}_1^0$ has long enough lifetime to produce a delayed photon and assume that only $\tilde{\chi}_1^0$ pairs are produced in the final state thus making the most sensitive channel the exclusive $\gamma_{delayed}+ \not\!\!E_T$ [37]. Due to the length requirements (of the time spent as a Ph.D. student, not dissertation page length), we have focused on a full follow-up of the preliminary result rather than the interpretation of any final result in terms of a new physics prediction. Our analysis strategy is to study a large number of high energy proton antiproton collisions and to select interactions where the collisions produced $\gamma+\not\!\!E_T$ and little other activity in the detector. We next examine the corrected time distribution of those photons in order to look for evidence that the photons' source is non-SM in origin. As previously mentioned, the dominant backgrounds for the exclusive $\gamma_{delayed}+ \not\!\!E_T$ final state comes from cosmic rays that interact with the detector producing a fake photon signal in coincidence with a collision as well as wrong vertex events where we incorrectly assign the initial time and time of flight for the photon found in the detector.

One of the most important facts uncovered during the study of the SM backgrounds using Monte Carlo techniques is that the wrong vertex timing distribution is not symmetric about $t_{corr} = 0$ ns. This makes the analysis far more complicated because this leads to the necessity to develop a new method for estimating the mean of the wrong vertex of our final sample of exclusive $\gamma + \not\!\!E_T$ events. A significant portion of this analysis is dedicated to understanding the causes of bias in wrong vertex events, and with that understanding now fully in hand it is not hard to create biased samples. For example, the top part of Figure 1.16 shows the corrected timing distribution for a very pure sample of events of known SM origin, $W \to e\nu \to e + \not\!\!E_T$, using the assumption of a symmetric background timing distribution and the identical selection criteria as the 2008 preliminary result but choosing electrons instead of photons. Clearly the assumption that the wrong vertex timing distribution is symmetric about $t_{corr} = 0$ ns does not accurately model the data. SM backgrounds do not necessarily have the same number of events in the control region as the signal region. The bottom of Figure 1.16 shows the timing distribution if we release the assumption that wrong vertex distribution is symmetric about 0.0 ns, but keep the Gaussian description of the data and allow the fit to find a value of the mean that best matches the data. What we can see here is the double Gaussian assumption of the corrected time distribution does accurately model the SM background and in this case has a wrong vertex mean ($< t^{WV}_{corr} >$) of 0.45 ns. While we now understand why the mean does not have to be zero, the distribution should be well approximated by a Gaussian with an RMS of 2 ns. The observed fact that $< t^{WV}_{coor} >$ is not zero complicates the analysis. We need new ways of predicting the number of events from SM sources in the signal region.

With the knowledge that SM collisions can have biased times, it is important to do a systematic study of all types of events that have such a bias. With this in mind, a major focus of this thesis revolves around two important and related tasks. The first of these tasks is to understand and mitigate the contributing factors that

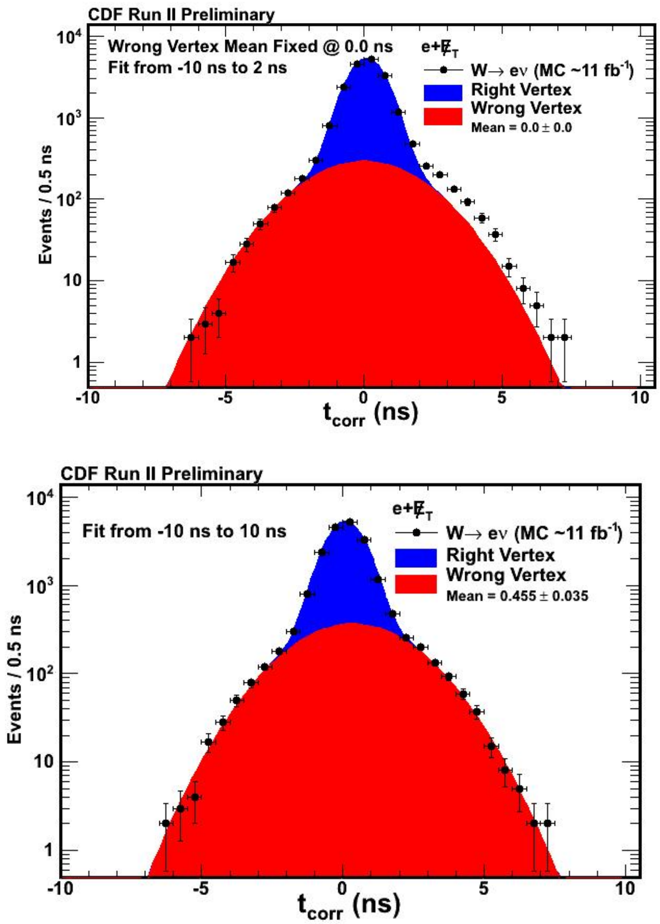

Fig. 1.16. The t_{corr} distribution for a pure sample of SM W→ $e\nu \rightarrow e+\not\!\!E_T$ events in data where we ignore the electron track and allow the algorithms to pick the highest ΣP_T vertex. In this case, the wrong vertex is often selected and we see the timing distribution as being the sum of right vertex and wrong vertex events. In the top plot we show a fit to the data in the region -7 ns $< t_{corr} <$ 2 ns where we assume $< t_{corr}^{WV} >=$ 0 ns. We can see that this is clearly not a good description of the data. The bottom plot shows the fit when we fit over the entire timing distribution and allow $< t_{corr}^{WV} >$ to float in the fit. The agreement between the data and the double Gaussian prediction is excellent.

cause SM backgrounds to give large times. As we will see, we have uncovered a good understanding of the effects that both produce large values of $< t_{corr}^{WV} >$ as well as effects that can cause t^{WV}_{coor} distribution to be asymmetric around zero. We will describe the methods to mitigate these factors and leave our data with only sources which are symmetric and have small mean values. The second task is to develop a method to predict the number of events in the signal region from SM sources now that the simple background method doesn't work. Specifically, to measure $< t^{WV}_{corr} >$ from data in a reliable way.

New features to this analysis since the preliminary result in 2008 are as follow:

1. **Adding Additional Data**:

   We have added 25% more data than was used in the initial 2008 result giving us 6.3 fb^{-1} of data analized. The data sample is described in Section 2.3.

2. **Robust Timing Calibrations**:

   A new and more robust set of timing calibration procedure has been developed that does not suffer from the wrong assumptions of previous methods. This procedure is described in detail in Chapter 3.

3. **Additional Cosmic Ray Rejection**:

   Two new rejection parameters are implemented in order to help reject the dominant background from cosmic rays that interact with the detector producing a fake photon candidate in coincidence with a collision. This is described in Chapter 4.

4. **Identification and Minimization of Pathological Event Reconstruction**:

   A systematic set of studies have been done to identify and minimize many pathological reconstruction problems in SM events that lead to a positively biased event times when a wrong vertex is selected. As a result, a suite of new rejection methods have been implemented. These studies and rejection methods are detailed in Chapter 5.

5. **New Data-Driven Background Estimation**:

   Finally, a new background estimation method is developed and presented which shows that it is possible to derive the underlying wrong vertex mean and thus make a proper prediction of the number of events we expect in the signal region from SM sources. The details, validation, and results of this background estimation method is shown in Chapter 6.

With all these new tools will will have a robust and reliable search that will be able to answer many of the questions about the search results from 2008. These results will be presented in Chapter 7 along with a comparison to the 2008 preliminary result.