A Search for Associated
Chargino-Neutralino
Production in $p\bar{p}$ Collisions at
$\sqrt{s} = 1.96$ TeV

Thesis submitted in accordance with the requirements of the University of
Liverpool for the Degree of Doctor of Philosophy by

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Abstract

This thesis describes a search for associated production of the supersymmetric particles $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ in proton-antiproton collisions at a centre of mass energy of 1.96 TeV, collected by the CDF experiment at Fermilab. The leptonic decay of these particles leads to a “trilepton” signature with three charged leptons and large missing energy. The search for this signature was carried out in three different channels, using 346 pb$^{-1}$ of data gathered between March 2003 and August 2004. In this data sample, we observe zero events, consistent with the Standard Model background prediction, and thus use the data to constrain the supersymmetric parameter space.
To the late, great Professor Paul Booth. Truly a larger than life character, he inspired me to begin this research in the first place, and was never anything but supportive and kind.
Acknowledgments

Thanks must firstly go to my supervisor, Beate Heinemann. Her quick thinking and clear explanations have helped me through more difficult patches than I care to remember; it is hard to imagine how CDF would function without her. Thanks also for the support of my official supervisors in Liverpool: Paul Booth (sadly no longer with us), and Mike Houlden, who provided useful feedback during the writing of this thesis.

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The CDF multilepton group was a great help as we struggled together to find signs of supersymmetry. Thanks to all, and in particular to Alon Attal for useful discussions towards the end of my analysis work. The SUSY and exotic physics groups also provided much valuable input: thanks go to Peter Wittich, Stephan Lammel, Song Ming Wang and Teruki Kamon.

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rience, and helped to make the three hours spent commuting each day more bearable. The “Fermi posse” has grown too large for me to name them all individually, but I should mention my contemporaries and neighbours in the cubicles, Matt, Nicola and Ben, Sam for his patient help with my coding nightmares, and Tamsin, Marilyn, James and Paul for being generally ace. The rest of you know who you are; suffice to say that I couldn’t have asked to be randomly thrown together with a nicer bunch of people.

Finally, thanks to PPARC for funding me for three years and offering me the opportunity to work on cutting-edge physics at one of the premier labs in the world.
Declaration

No portion of the author's work described in this thesis has been submitted in support of an application for another degree or qualification in this, or any other, institute of learning.
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Chapter 1

Introduction

Particle physics is the science of the fundamental constituents of matter and their interactions. As recently as the start of the twentieth century only one of the fundamental particles, the electron, was known. Over the last hundred years, experiments at higher and higher energies have allowed us to burrow ever-deeper into matter, uncovering first the nucleus, then protons and neutrons, and finally (so far, at least) quarks. Indeed, particle physics is also known as “high energy physics”, emphasizing the fact that we must constantly push the energy frontier to make discoveries.

But experimental progress has always gone together with theoretical advances. Sometimes experiment throws a surprise for the theorists, such as the muon of which Rabi famously remarked, “Who ordered that?” At other times the theorists lead the way. Dirac correctly predicted the existence of antimatter, and Weinberg, Glashow and Salam’s unification of the electromagnetic and weak nuclear forces preceded the discovery of the W and Z bosons at CERN by some 15 years. In fact the theorists have probably had the upper hand since the completion of the Standard Model with the theory of the strong nuclear interaction in the 1970s.

The Standard Model (described in Section 2.1) has been an astonishingly
successful theory, and late-twentieth-century experimental particle physics may be seen largely as an exercise in ticking off its predictions. Parameters determined by the theory have been verified to an extraordinary degree of accuracy, particularly at the Large Electron Positron (LEP) collider at CERN in the 1990s. Although theorists did not anticipate the third generation of particles ushered in with the tau lepton, it was no great surprise that it was completed with another neutrino, and the bottom and top quarks.

Yet, the experimentalists keep pushing. The energies produced in particle collisions have continued to grow exponentially, and the Tevatron, at which the work for this thesis was carried out, will soon be surpassed by CERN's new Large Hadron Collider. Behind this massive investment lies the conviction that the Standard Model is not a complete theory, nor an elegant one; a principle of surprising importance to physicists. It leaves many important questions unanswered, and requires several parameters to be put in by hand, as discussed in Section 2.1.5.

The analysis presented here pursues one promising route beyond the Standard Model: the theory known as supersymmetry, described in Section 2.2. To produce evidence for "new physics" one must be rigorous and microscopically focused. We pursue just one type of decay of a particular class of supersymmetric particles, and compare it to all the possible confounding processes. Chapter 3 describes the CDF experiment, the elaborate experimental apparatus used to acquire the necessary data. Chapter 4 explains how we begin to make sense of that data, turning thousands of channels of raw electronic read-outs into a coherent picture of a collision. In Chapter 5, we sift from the confusion of that collision the leptons that we seek, and in Chapter 6 describe the background processes that may lead us astray. Chapter 7 details our attempts to isolate our signal at the expense of these backgrounds, Chapter 8 summarizes the
systematic uncertainties affecting this procedure, and Chapter 9 presents the results.

Without wishing to spoil the conclusion, it is fair to say that the road to discovery is paved with null results. Some have said that the decade since the discovery of the top quark at the Tevatron has seen a lull in experimental particle physics. I invite them to sit in on a meeting of the CDF exotic physics group in conference season and repeat that claim!
Chapter 2

Theory

The Standard Model (SM) of particle physics is in agreement with experimental measurements to an extraordinary degree of accuracy. However it contains several problems which cannot be resolved without the introduction of new physics.

This chapter briefly reviews the Standard Model and its successes and limitations. A new model, supersymmetry (SUSY), is introduced, and motivated by it providing solutions to two of the problems inherent in the SM. In particular the Minimal Supersymmetric Standard Model (MSSM) and minimal supergravity model (mSUGRA) are introduced. Finally, the particular channel investigated in this analysis is described.

2.1 The Standard Model

The Standard Model is a description of the fundamental particles and their interactions. In the SM the fundamental particles can be divided into leptons and quarks, which make up all matter; and gauge bosons, which mediate the interactions between matter. The SM describes three of the four fundamental forces: electromagnetism (EM), the weak force and the strong force. The
fourth force, gravity, is not described in the SM framework, but at laboratory energies it is many orders of magnitude weaker than the others and can be ignored.

The matter particles are all fermions, with half-integer spin. There are three generations of fermions, each containing a charged lepton, a neutral, almost-massless neutrino, and an up-type and down-type quark with charge +2/3 and -1/3 of the elementary charge $e$, respectively. Each particle has a corresponding antiparticle with the same mass but opposite additive quantum numbers. All charged fermions participate in the electromagnetic interaction, but neutrinos only feel the effects of the weak interaction. Only quarks are affected by the strong interaction as they have an additional "colour charge". Quarks combine to form hadrons, which are combinations with no net colour. The known types of hadrons are mesons, made up of a quark combined with an antiquark, and baryons, comprising three quarks. Table 2.1 [2] summarises the properties of the fermions.

Each fundamental force is mediated by the exchange of gauge bosons. The electromagnetic force is carried by massless photons; the weak force by massive bosons, $Z^0$ and $W^\pm$; and the strong force by eight massless gluons. Gravitons are proposed to mediate the gravitational force, but have not yet been observed. Table 2.2 [2] summarises the properties of the gauge bosons.

In the SM, particles get their mass via the Higgs mechanism [3]. The postulated spin-0 Higgs boson has not yet been observed, but is excluded by LEP at the 95% confidence level for masses below 114.4 GeV/$c^2$ [4]. The Higgs boson is the last remaining particle predicted by the SM which has not been observed in experiments.

The SM is a quantum field theory description of the fundamental particles and interactions, in which the particles emerge as quanta of the field variables.
## Chapter 2: Theory

### Fermions

<table>
<thead>
<tr>
<th>Fermion Type</th>
<th>Mass</th>
<th>Charge</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 electron</td>
<td>0.511 MeV/c²</td>
<td>-1</td>
<td>1/2</td>
</tr>
<tr>
<td>electron neutrino</td>
<td></td>
<td>0</td>
<td>1/2</td>
</tr>
<tr>
<td>2 muon</td>
<td>106 MeV/c²</td>
<td>-1</td>
<td>1/2</td>
</tr>
<tr>
<td>muon neutrino</td>
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</tr>
<tr>
<td>3 tau</td>
<td>1.78 GeV/c²</td>
<td>-1</td>
<td>1/2</td>
</tr>
<tr>
<td>tau neutrino</td>
<td></td>
<td>0</td>
<td>1/2</td>
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<tr>
<td>Quark</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1 up</td>
<td>1.5 - 3.0 MeV/c²</td>
<td>2/3</td>
<td>1/2</td>
</tr>
<tr>
<td>down</td>
<td>3 - 7 MeV/c²</td>
<td>-1/3</td>
<td>1/2</td>
</tr>
<tr>
<td>2 charm</td>
<td>1.25 ± 0.09 GeV/c²</td>
<td>2/3</td>
<td>1/2</td>
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<tr>
<td>strange</td>
<td>95 ± 25 MeV/c²</td>
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<td>1/2</td>
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<tr>
<td>3 top</td>
<td>174.2 ± 3.3 GeV/c²</td>
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<td>bottom</td>
<td>4.20 ± 0.07 GeV/c²</td>
<td>-1/3</td>
<td>1/2</td>
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**Table 2.1: Properties of the fermionic particles [2].**

### Force Gauge Bosons

<table>
<thead>
<tr>
<th>Force Type</th>
<th>Gauge Boson</th>
<th>Mass</th>
<th>Charge</th>
<th>Spin</th>
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<tr>
<td>Electromagnetic</td>
<td>photon</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>gluon</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Weak</td>
<td>W⁺⁻</td>
<td>80.403 ± 0.029 GeV/c²</td>
<td>±1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Z⁰</td>
<td>91.1876 ± 0.00021 GeV/c²</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Gravitational</td>
<td>graviton</td>
<td>0</td>
<td>0</td>
<td>2</td>
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</tbody>
</table>

**Table 2.2: Properties of the gauge bosons [2].**
It combines the theories of electroweak unification and quantum chromodynamics (QCD). It is based on the symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, where $C$ denotes colour, $L$ chirality and $Y$ weak hypercharge. The $SU(3)_C$ group describes the strong interactions of the quarks and gluons, which carry colour charge. The $SU(2)_L \otimes U(1)_Y$ group describes the electromagnetic and weak interactions, which are unified in the model.

There is one coupling constant for each group: $\alpha_S$ for the strong interaction, $\alpha$ for the EM interactions, and $g$ for the weak interaction.

### 2.1.1 Quantum Electrodynamics

Quantum Electrodynamics (QED) [5] was developed in the late 1940s and early 1950s to describe the electromagnetic interactions of electrons and photons. It is the simplest example of a gauge theory, and was the prototype for modern quantum field theories.

Since QED is a gauge theory, it is invariant under a change of quantum mechanical phase. Global $U(1)$ gauge invariance requires the conservation of electromagnetic charge, while the imposition of local gauge invariance necessitates the introduction of a gauge field. This field describes the interactions between the charged particles, and the quantum of the field is the photon, $\gamma$.

The strength of the interaction between the photon and charged fermions is given by the coupling constant $\alpha$, which depends on the momentum transfer, $q^2$, in an interaction. Thus the coupling constant is said to "run". At $q^2 = 0$, the coupling constant is the fine structure constant, $\alpha = e^2/4\pi\hbar c = 1/137$ while at the scale of the $Z$ boson, $\alpha \simeq 1/128$. 
2.1.2 Electroweak Unification

The electroweak theory [6] was proposed by Weinberg [7], Glashow [8] and Salam [9] to unify the QED description of electromagnetism with the weak interaction. In this framework the electromagnetic and weak interactions are two manifestations of the same fundamental electroweak interaction, with the symmetry broken at low energies. The huge difference in strength between the weak and EM interactions is explained by the fact that the gauge bosons of the weak interactions are massive (see Section 2.1.4), and thus its effect is short-range, while the EM interaction is mediated by the massless photon. Electroweak unification predicted the $W$ and $Z$ bosons, which were subsequently discovered at CERN [10] [11].

In the electroweak theory, invariance under local gauge transformations requires the introduction of four massless gauge fields. These are arranged in a triplet, $W^{i=1,2,3}_\mu$, associated with weak isospin, $I$; and a singlet, $B_\mu$, associated with weak hypercharge, $Y$. The $B_\mu$ field couples to fermions with a strength $g'$, while the $W_\mu$ field couples only to left-handed chirality states with a strength $g$.

The physical electroweak bosons are linear combinations of these gauge fields. The $W^\pm$ bosons arise from combinations of the $W^1_\mu$ and $W^2_\mu$ fields:

$$W^\pm_\mu = \frac{1}{\sqrt{2}} (W^1_\mu \pm i W^2_\mu) \quad (2.1)$$

while the photon corresponds to the field $A_\mu$ and the $Z$ boson to the field $Z_\mu$ which are given by:

$$Z_\mu = \cos \theta_w W^3_\mu - \sin \theta_w B_\mu \quad (2.2)$$

$$A_\mu = \sin \theta_w W^3_\mu + \cos \theta_w B_\mu \quad (2.3)$$
2.1 The Standard Model

The weak mixing angle, $\theta_w$, relates the weak and electromagnetic coupling constants:

$$g \sin \theta_w = g' \cos \theta_w = e$$  \hspace{1cm} (2.4)

2.1.3 Quantum Chromodynamics

Quantum Chromodynamics (QCD) [6] was developed in 1973 and is the gauge theory of the strong interaction. In this theory quarks must be invariant under local $SU(3)$ gauge transformations of colour charge. This requires the introduction of eight massless gauge fields, associated with gluons. Unlike in QED, the force carriers (gluons) themselves carry (colour) charge and so may interact with each other. This leads to a decreasing strength of the coupling constant, $\alpha_s$, with increasing energy scale, i.e. the strength of the strong force increases with distance.

As two quarks move apart, gluons exchanged between the quarks interact with each other as well as with the quarks. The increasing force binds the quarks together in a hadron until the energy density is enough to create a $qq$ pair, leading to the creation of two new hadrons. Hence quarks appear only in bound colour-singlet states, a phenomenon known as quark confinement.

2.1.4 Higgs Mechanism

Local gauge invariance in the electroweak sector leads to the introduction of the massless $W$ and $B$ fields. But the short-range nature of the weak force implies that it is mediated by massive gauge bosons. The $W$ and $Z$ bosons are given mass through a procedure involving spontaneous symmetry breaking and the Higgs mechanism [6]. To achieve this, a scalar doublet self-interacting field $\phi$ is introduced, with a potential given by:
By choosing $\mu^2 < 0$ and $\lambda > 0$ this potential has an infinite number of states with the same (minimum) energy:

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

(2.5)

These states do not respect the $SU(2)_L \otimes U(1)_Y$ gauge symmetry, and so the symmetry is spontaneously broken at the energy scale of the vacuum expectation value, $v$. The introduction of this field gives rise to a massive scalar Higgs boson (H) and three massless Goldstone bosons.

The three degrees of freedom associated with the Goldstone bosons are used to give the longitudinal polarisation of the $W$ and $Z$ bosons. Mass terms appear only for the $W$, $Z$ and $H$ fields, while the $A_\mu$ field associated with the photon remains massless. The theory predicts correctly the mass ratio of the $W$ and $Z$ bosons, but does not predict the mass of the Higgs, as $\lambda$ is a free parameter.

The fundamental fermion fields interact with the Higgs doublet field, and its non-zero vacuum expectation value causes them to acquire mass terms in the final SM Lagrangian.

### 2.1.5 Successes and Limitations of the Standard Model

Experiments carried out at high-energy physics laboratories have measured many of the properties of the SM to great accuracy. These include the masses of the $W$ and $Z$ bosons, the weak mixing angle and the branching ratios of decays of the $Z$ to quarks and leptons. The SM is a very successful theory at the electroweak scale, but it requires the masses and coupling constants of
the quarks and leptons to be put in by hand, and many unanswered questions remain. These include:

- Why are there three fermion generations, and why does each have the same structure?
- Why are there two types of particles, bosons and fermions, which behave in fundamentally different ways?
- What is the relationship between the strong and electroweak forces? Can these forces be unified at some high energy scale?
- How can gravity be incorporated into the theory?
- What is the solution to the “hierarchy problem”? (see Section 2.2.1)
- What is the mechanism by which charge-parity (CP) symmetry is broken, and why is the universe matter-dominated?
- How do neutrinos acquire mass?

2.2 Supersymmetry

Supersymmetry [12] is the most-studied theoretical framework for physics beyond the SM. It introduces a symmetry between fermions and bosons, which predicts the existence of additional particles that differ from their SM partners by half a unit of spin. This section motivates the introduction of supersymmetry, describes the Minimal Supersymmetric Standard Model and discusses one possible supersymmetry breaking mechanism, mSUGRA, which predicts the mass spectrum of all the SUSY particles (sparticles) from only five parameters.
2.2.1 Motivation for Supersymmetry

The Hierarchy Problem

The hierarchy problem is a major challenge to the SM, arising from the 16 order of magnitude difference between the scale of the electroweak interactions ($\sim M_Z$) and gravitational interactions ($M_P$, the Planck mass).

Consider the first order perturbative correction to the Higgs boson mass, a single fermion loop, as shown in Figure 2.1 This correction is given by:

$$\Delta m_H^2 = \frac{|\lambda_F|^2}{16\pi^2} [-2\Lambda_{UV}^2 + 6m_F^2 \ln \frac{\Lambda_{UV}}{m_F} + ...] \quad (2.7)$$

where $m_F$ is the fermion mass, $\lambda_F$ its coupling strength to the Higgs, and $\Lambda_{UV}$ the momentum cut-off used to regulate the loop integral, which can be interpreted as the energy scale at which new physics enters to alter the high-energy behaviour of the theory. The first term of the equation diverges quadratically with the cut-off, so if we choose $\Lambda_{UV} \sim M_P$, then the radiative correction to the Higgs mass is of the order of the Planck mass.

However the SM requires the Higgs mass to be less than 1 TeV in order to remain a perturbative theory. To achieve this the quadratic corrections must be cancelled, which can only be achieved by fine-tuning the parameters to an order of $10^{-16}$. This is highly unnatural, and regarded as unacceptable by many theorists. This is the hierarchy problem, which has led to suggestions
that the SM is embedded in a richer structure which somehow cuts off the divergence at a much lower scale.

To see one way this might work, consider the introduction of an additional loop contribution involving a scalar particle to the Higgs mass correction, as shown in Figure 2.2.

If this scalar has mass $m_S$ and coupling $\lambda_S$ this introduces an additional correction:

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \left[ \Lambda_{UV}^2 - 2m^2 \ln \frac{\Lambda_{UV}}{m_S} + \ldots \right]$$

(2.8)

Hence by choosing $\lambda_S = |2\lambda_F|^2$ the quadratic divergence can be cancelled, and a complete cancellation at all orders can be achieved by requiring $m_S \simeq m_F$.

This solution to the hierarchy problem requires that each fermion has a bosonic partner, and vice versa; exactly what is proposed by supersymmetry via an anti-commuting spinor operator $Q$ that interchanges fermions and bosons:

$$Q|\text{boson} = |\text{fermion}; Q|\text{fermion} = |\text{boson}$$

(2.9)
Unification of Gauge Couplings

It is theoretically desirable for the strong force to be unified with the electroweak force at some large energy scale, $M_{GUT}$, above which there is only one "Grand Unified Force". The three gauge couplings in the SM can be extrapolated to high energies using the Renormalisation Group Equations, but in the SM they do not become equal at any energy, as shown in Figure 2.3.

However in supersymmetric theories the new particles introduced change the evolution of the couplings and if the SUSY particles have a mass of the order of $1 \text{ TeV}/c^2$, the couplings can be made to unify at an energy scale of around $10^{16} \text{ GeV}$, as in Figure 2.4.
2.2 Supersymmetry

b) MSSM, $\mu_{\text{SUSY}} = m_z$

\begin{align*}
\frac{1}{\alpha_1} & \quad \frac{1}{\alpha_2} & \quad \frac{1}{\alpha_3}
\end{align*}

Figure 2.4: Extrapolation of the SM gauge couplings to high energies within the framework of SUSY with SU(5) unification. $\alpha_1$ is the electromagnetic coupling constant, $\alpha_2$ the weak and $\alpha_3$ the strong.

2.2.2 The Minimal Supersymmetric Standard Model

The MSSM, as its name suggests, is the simplest incorporation of SUSY into the SM, requiring the minimal number of new particles and interactions while preserving the SM gauge group.

The fermions have spin-0 “sfermion” partners known as squarks and sleptons, while the gauge bosons’ partners are spin-1/2 gauginos, named the photino, gluino, wino and zino. The MSSM requires two Higgs doublets to cancel anomalies and give mass to both the up-type and down-type quarks. The Higgs bosons’ partners are the spin-1/2 higgsinos.

The MSSM includes terms which allow violation of baryon number ($B$) and lepton number ($L$). To avoid this undesirable feature another symmetry called R-parity can be introduced. R-parity can be written as:
\[ R = (-1)^{3B+L+2s} \]  

where \( s \) is the particle spin. It is +1 for all SM particles and -1 for all sparticles. R-parity is then required to be conserved as a multiplicative quantum number, which has several consequences for SUSY phenomenology:

- Sparticles can only be pair-produced from SM particles, never produced singly.
- The lightest supersymmetric particle (LSP) cannot decay. If it is also uncharged then it would be undetectable and make an excellent candidate for dark matter. This is a further motivation for SUSY as a beyond SM theory.
- SUSY particles will decay into states with an odd number of LSPs, usually one, so R-parity conserving SUSY searches will typically be concerned with high values of missing energy.

2.2.3 Supersymmetry Breaking and mSUGRA

No supersymmetric particles have yet been observed. This implies that SUSY cannot be an exact symmetry, as the sparticles would then be equal in mass to their corresponding particles and would have been observed. A mechanism must therefore be provided for SUSY to be broken at some high energy scale. Several such breaking mechanisms have been devised. These mechanisms can also be used to reduce the large number of free parameters in the MSSM (over 100) to a more manageable number for experimental searches. In this analysis we study gravity-mediated SUSY breaking, in particular the minimal supergravity model (mSUGRA). We also assume R-parity conservation.
Supersymmetry is based on local invariance under SUSY transformations. This implies invariance under local co-ordinate change, which is the underlying principle of general relativity, so gravity is naturally included. Supersymmetry is broken in the “hidden sector” and transmitted to the “visible sector” by gravitational interactions.

In this model it is assumed that the gauge couplings unify at an energy scale of about $10^{16}$ GeV and further that at this energy scale the masses of all scalar particles unify at $m_0$, and the masses of the gauginos unify at $m_{1/2}$. These two parameters are free parameters of the theory. Additionally three other parameters must be set: the trilinear interaction term between the scalars, $A_0$; the ratio of the two Higgs vacuum expectation values, $\tan \beta$; and the sign of the Higgsino mixing parameter, $\mu$.

### 2.2.4 Particle Spectrum

Once these parameters have been chosen, mSUGRA predicts the complete evolution of the masses of the sparticles. This section describes the spectrum of particles in the mSUGRA framework.

**Higgs**

Since there are two complex $SU(2)_L$ Higgs doublets in the MSSM, there is a total of eight degrees of freedom in the Higgs sector. Three of them become the longitudinal modes of the $W$ and $Z$, as in the SM Higgs mechanism. The remaining five are assigned to one CP-odd neutral scalar, $A$, two charged scalars, $H^+$ and $H^-$, and two CP-even neutral scalars $h$ and $H$.

The masses of all the Higgs particles can be derived in terms of $\tan \beta$ and $M_A$, the mass of the pseudo-scalar Higgs boson.
Sleptons

Below the electroweak breaking scale, fields with different $SU(2)_L \otimes U(1)_Y$ quantum numbers can mix if they have the same $SU(3)_C \otimes U(1)_{EM}$ quantum numbers. Thus the left-handed and right-handed charged sleptons can mix. The gauge interactions of the sfermions are the same as the SM fermions, so a left-handed slepton couples to the $W$ boson while a right-handed slepton does not. The sleptons of the first two generations have mass eigenstates which are roughly equal to the left and right-handed eigenstates. However, the mass eigenstates of the stau, $\tilde{\tau}_1$ and $\tilde{\tau}_2$, are mixtures of $\tilde{\tau}_R$ and $\tilde{\tau}_L$, and at the electroweak scale the lighter of these eigenstates becomes the lightest slepton.

Charginos and Neutralinos

The charged higgsinos ($H^\pm$) and winos ($W^\pm$) mix to form two mass eigenstates known as charginos, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$. Whether the charginos are wino-like or Higgsino-like affects their interaction with other particles, and thus their cross-sections and branching ratios.

The photino ($\tilde{\gamma}$), the zino ($\tilde{Z}$) and the two neutral higgsinos ($H^{0}_{1,2}$) mix to give the four neutralino mass eigenstates, $\tilde{\chi}^0_{1,2,3,4}$. The first neutralino eigenstate is the LSP in the mSUGRA framework. As mentioned this is a good dark matter candidate, and so it is possible to relate cosmological constraints to limits on the mSUGRA parameter space.

2.3 The Trilepton Signal

The associated production of the lightest chargino, $\tilde{\chi}_1^\pm$, and the second lightest neutralino, $\tilde{\chi}^0_2$, and subsequent decay to a final state with three leptons and missing energy is one of the most promising channels for SUSY discovery at
2.3 The Trilepton Signal

The Tevatron [13]. The closest analogous process in the SM is $WZ$ production, which has a $p\bar{p}$ production cross-section of 1.98 pb at $\sqrt{s} = 1.96$ TeV. If we assume $m_{\tilde{\chi}^\pm}$ and $m_{\tilde{\chi}^0}$ to be of the order of $M_W$ and $M_Z$, we expect the rates of production of the two processes to be comparable. Under mSUGRA the charginos and neutralinos generally follow the mass relationship $m_{\tilde{\chi}^\pm} \approx m_{\tilde{\chi}^0} / 2$.

The associated production of $\tilde{\chi}^\pm$ and $\tilde{\chi}^0$ can occur via quark-antiquark annihilation in the $s$-channel through $W$ boson exchange, or squark exchange in the $t$-channel, as shown in Figure 2.5. The cross-section depends on $m_{\tilde{\chi}^\pm}$ and $m_{\tilde{\chi}^0}$, and hence on the mSUGRA parameters described in Section 2.2.3. If the squarks are much heavier than the gauginos, the $s$-channel process dominates, but light squarks allow destructive interference between the two channels, suppressing the cross-section by as much as 40%.

Figure 2.6 [14] shows typical cross sections for the production of various sparticles, as a function of the mass of the sparticles. This shows that the cross section for chargino-neutralino production is one of the highest at the Tevatron, especially if the chargino and neutralino have masses of only a few hundred GeV/$c^2$. The cross section is of the order $10^{-1}$ to 1 pb at the Tevatron centre of mass energy.

As in $WZ$ production, a variety of possible decay modes are available, leading to different final states. The branching fractions are a complicated
function of the SUSY parameter space. In this analysis, we search for the final state with three charged leptons (as well as two $\chi^0_1$ and a neutrino) as this is a distinctive signature with little SM background. The two LSPs and neutrino escape detection but their directions are uncorrelated so the missing energy can vary from a small to a substantial amount. Figure 2.7 shows the possible decays of the chargino and neutralino to this final state, which can proceed either via virtual $W$ and $Z$ bosons, or virtual sleptons. If the slepton masses are smaller than the chargino and neutralino masses the decay can occur via real sleptons, with a similar diagram. Low slepton masses mean the decay occurs more often through real or virtual sleptons and so the branching fraction to the trilepton final state is enhanced.

In this analysis we search only for electrons and muons, but this also includes the contribution from leptonic decays of the tau. Hadronic decays of the tau are difficult to distinguish from quark or gluon jets. As $\tan \beta$ increases, the mixing between the left and right-handed staus produces an increasing mass

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**Figure 2.6:** Production cross sections for various sparticles as a function of their masses. Associated chargino-neutralino production is shown in magenta. Leading order (LO) and next to leading order (NLO) cross sections are shown.
2.3 The Trilepton Signal

Figure 2.7: Decay modes of charginos (left) and neutralinos (right) which result in the final state of three charged leptons, two LSPs and a neutrino. The top row shows the decay via virtual W and Z bosons, and the bottom row via excited sleptons.

difference between the two stau mass eigenstates, and the decay via the lighter stau begins to dominate, increasing the branching ratio to tau leptons. Since we search for electrons and muons, this search is more sensitive to low tan β scenarios.

2.3.1 Existing Limits

Direct Searches

At LEP, pair production of $\tilde{x}_1^\pm$ would have been possible if $\sqrt{s} > 2m_{\tilde{\chi}_1^\pm}$. As no such events were observed, the LEP experiments set a model-independent limit of $m_{\tilde{x}_1^\pm} > 103.5$ GeV/$c^2$ [15]. LEP also derived a mass limit on $\tilde{x}_1^0$ within mSUGRA from the chargino mass bound, and excludes $m_{\tilde{x}_1^0} < 59$ GeV.

The DØ collaboration at Fermilab has published a limit on chargino-neutralino production using various different final states, including some which are sensitive to tau leptons [16]. By combining these channels they achieve a
Figure 2.8: Limits on the cross-section for associated chargino and neutralino production with leptonic final states from DØ. Three model lines are shown. The top line corresponds to models with heavy squark masses and low slepton masses, the middle line to low slepton masses in mSUGRA, and the bottom line to large m₀ with the chargino and neutralino decaying via virtual gauge bosons. The shaded bands show PDF and scale uncertainties.

Indirect Constraints

Constraints on the SUSY parameter space can be derived indirectly from other data including the following:

- The Wilkinson microwave anisotropy probe (WMAP) has produced a stringent limit on the density of dark matter in the universe [17]. It is often assumed that in the context of mSUGRA the entire dark matter density is made up by the lightest neutralino. Different regions of the mSUGRA parameter space predict a different dark matter density, depending crucially on annihilation cross sections for SUSY particles in the
2.3 The Trilepton Signal

early universe. Thus the data can be used to locate favourable regions of the SUSY parameter space.

- The branching ratio of the decay $b \rightarrow s\gamma$. Since this decay occurs at loop level in the SM, the SUSY contribution to the branching ratio could a priori be of similar magnitude. However, the current experimental value [18] agrees very well with the SM prediction, allowing constraints on SUSY to be placed.

- The anomalous magnetic moment of the muon, $(g-2)_{\mu}$ [19]. There is currently a small discrepancy between the measured value and the SM prediction, which has led to some discussion of whether new physics could be involved.

- Electroweak parameters such as the mass of the $W$ boson, which can be modified by contributions from supersymmetric particles.

Many theoretical papers have used such data to predict likely regions of SUSY parameter space and values of sparticle masses. Two examples are shown in Figures 2.9 [20] and 2.10 [21].

2.3.2 Signal Monte Carlo Sample

We must choose a particular region in the mSUGRA parameter space at which to generate our signal Monte Carlo. As well as considering the direct limits and indirect constraints described above, we must take into account the expected number of signal events we could observe at each point. This depends on the production cross section, the leptonic branching fraction, and the acceptance of the CDF detector.

A scan was performed in the five-dimensional mSUGRA parameter space, evaluating the production cross section times the leptonic branching ratio at
Figure 2.9: (a) $\chi^2$ curves showing likely values for $m_{1/2}$ with $\tan\beta = 10$ and different values of $A_0$. (b) $\chi^2$ curves showing likely values for $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_2^0}$ based on the values of $m_{1/2}$ shown in (a).

Figure 2.10: (a) A likelihood map in mSUGRA parameter space marginalised down to the two parameters $m_0$ and $m_{1/2}$. (b) A likelihood distribution for the masses of the chargino and the lightest slepton. The likelihood (relative to the likelihood in the highest bin) is shown by reference to the bar on the right of each plot.
Figure 2.11: Production cross section times leptonic branching ratio in the $m_0 - m_{1/2}$ plane for $A_0 = 0$, $\mu > 0$ and $\tan \beta = 5$ (arbitrary units).

As a benchmark point we chose:

- $m_0 = 100$ GeV/c$^2$
- $m_{1/2} = 180$ GeV/c$^2$
- $\tan \beta = 5$
- $A_0 = 0$
- $\mu > 0$

This gives a chargino mass of about 113 GeV/c$^2$, just above the LEP limit.

The next to leading order (NLO) production cross section, calculated with the PROSPINO [22] package, is 0.642 pb and the branching ratio to three leptons is 22.3%. We generated 125,000 Monte Carlo events at this point, using the PYTHIA [23] generator. This signal sample was used for the optimisation of
Chapter 2: Theory

kinematic cuts and to obtain the expected number of signal events given in Chapter 9.

Chapter 3

The CDF Experiment at the Tevatron Collider

In present, the Tevatron particle accelerator resides inside Fermilab's 50-

year-old Laboratory near Chicago. It is the highest energy particle collider at

the world, producing proton-proton collisions at 1.96 TeV. Since its initial

production of the LEP, the Tevatron particle accelerator has

been upgraded and improved until the current LEP. Part of the detector

programmes is LEP, which aims to observe and understand

the properties of the collider and the design of the CDF

detector.

The large collisions were achieved in October 1995, with the target of

producing 30 fb⁻¹ [200-600 (GeV)⁻¹]. CDF's continuum as integrated was

above 200 pb⁻¹ in a beam at mass-energy of 1.4 TeV, with instantaneous

integrated in excess of 3.6 fb⁻¹ year⁻¹. This allowed the discovery of the

top quark and, through and with the help of a combination of the mass of the tau

lepton and the weak mixing angle,

Bottom quark and charm the second one and the other two are seen in

proactively in Run II. The Tevatron's search for more energy was

unsuccessful.
Chapter 3

The CDF Experiment at the Tevatron Collider

At present, the Tevatron proton-antiproton collider at the Fermi National Accelerator Laboratory, near Chicago, is the highest energy particle collider in the world. Its centre of mass energy of 1.96 TeV will remain the highest achievable until the start of the Large Hadron Collider programme at CERN in 2007. Two general purpose detectors are sited on the Tevatron ring: CDF and DØ. This chapter describes the operation of the collider and the design of the CDF detector.

The first collisions were achieved in October 1985, and during the period of data-taking from 1992-1996 (“Run 1”), CDF collected an integrated luminosity of 109 pb$^{-1}$ at a centre of mass energy of 1.8 TeV, with instantaneous luminosities in excess of $2 \times 10^{31}$ cm$^{-2}$ s$^{-1}$. This allowed the discovery of the top quark and $B_c$ meson, and precision measurements of the mass of the $W$ boson and the weak mixing angle.

Between 1996 and 2001 the accelerator and detectors were significantly upgraded prior to “Run II”. The Tevatron’s centre of mass energy was increased
to 1.96 TeV, and the frequency of $p\bar{p}$ interactions was increased. The instantaneous luminosity was expected to increase tenfold, to $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$. While this was not achieved at turn-on, after recent improvements the design luminosity was achieved in August 2006 and is now regularly exceeded.

To handle the increased luminosity, the CDF collaboration completed major upgrades of tracking detectors, muon detectors and the trigger system; new forward calorimeters were also installed. Up to the end of 2005, Run II of CDF collected an integrated luminosity of 1488 pb$^{-1}$, 1193 pb$^{-1}$ of which was recorded to tape, and it expects to collect 4.8 fb$^{-1}$ by 2009.

Figure 3.1 [24] shows the luminosity delivered and recorded to tape at CDF during Run II, demonstrating the continuous improvements achieved.
3.1 The Fermilab Accelerator Complex

The Fermilab accelerator complex is shown schematically in Figure 3.2. The Tevatron is a circular proton synchrotron with a radius of 1 km, into which protons and antiprotons are injected in opposite directions. The steps in the acceleration of protons and the production and acceleration of antiprotons are described in this section.

3.1.1 Proton Acceleration

The accelerator chain begins with hydrogen gas. A pulsed ion source converts the hydrogen into \( H^- \) ions, which are accelerated to 750 keV across a series of voltage gaps in a Cockroft-Walton accelerator. From here they pass into a 145 m-long linear accelerator (the Linac) and are boosted through a series of oscillating electric fields to an energy of 400 MeV.

The ions are then passed through a carbon foil to strip away the electrons,
and the remaining protons are passed into the Booster ring, the first of six synchrotrons in the accelerator chain. In this 475 m ring the protons are accelerated to 8 GeV in a period of 0.033 seconds. The magnetic field used to keep the protons in the ring must be increased as the protons are accelerated. The Booster also collects the protons together into bunches, and transfers between six and eight of these bunches at a time into the Main Injector, a larger ring with a circumference of two miles.

The Main Injector was completed in 1999 and is dual purpose. As well as accelerating protons to 150 GeV and injecting them into the Tevatron it accelerates some protons to 120 GeV for fixed target experiments and antiproton production. The six to eight bunches received from the Booster are combined into a single bunch.

3.1.2 Antiproton production

The 120 GeV protons supplied by the Main Injector are focused on to a nickel target, producing a spray of many different particles. For every million protons only around 20 antiprotons are produced. These are collected and focused using a cylindrical lithium lens, and antiprotons of approximately 8 GeV are selected using a charge-mass spectrometer. Since the incident protons are bunched, the antiprotons are also produced in bunches, and they have a spread of energies. They are then injected into the Debuncher ring and undergo a process known as “stochastic cooling” to reduce the transverse beam size and energy spread. Next, they are stored in the Accumulator ring and “stacked” to $10^{12}$ particles per bunch, which takes up to 12 hours. They are then delivered to the Main Injector for acceleration to 150 GeV and injection into the Tevatron.

The Main Injector also includes an Antiproton Recycler which allows additional storage of antiprotons. An important improvement in 2005 which
helped set new luminosity records was the introduction of electron cooling of antiprotons in the Recycler. A continuous, high-intensity beam of electrons is used to manipulate the speed of individual antiprotons and produce denser antiproton bunches.

At the beginning of a “store” the Tevatron receives protons and antiprotons from the Main Injector at 150 GeV and accelerates them to 980 GeV. Since the protons and antiprotons have opposite charge, the same magnetic field is used to keep them in the ring, travelling in opposite directions in slightly different orbits. This magnetic field is produced by about 1000 superconducting magnets, cooled to 4K in order to deliver a magnetic field of 4.2 T.

Once the required energy is reached, thirty-six bunches of protons and antiprotons are brought into collision. Each proton bunch contains about $2.7 \times 10^{11}$ protons and each antiproton bunch $3 \times 10^{10}$ antiprotons. The bunches are spaced by an interval of 396 ns, and are focused at the two experimental interaction points by low beta quadrupole magnets to achieve maximum luminosity.

3.2 The CDF Detector

The CDF detector is described in more detail elsewhere [25]. It is a general-purpose solenoidal detector comprising a series of sub-detectors that provide precision particle tracking, calorimetry, muon identification and luminosity measurement. The detector is forwards-backwards and azimuthally symmetric and is designed to measure the position and momentum of charged and neutral particles over a large range of solid angle, allowing the study of a broad range of final states resulting from $p\bar{p}$ collisions. Figure 3.3 shows a 3-dimensional cut-away of the CDF detector, with the main sub-detectors indicated.
Figure 3.3: A schematic diagram of the CDF detector, showing the silicon tracking systems (L00, SVXII, ISL), central outer tracker (COT), central and plug electromagnetic calorimeters (CEM, PEM), central and wall hadronic calorimeters (CHA, WHA), central muon, central muon upgrade and central muon extension detectors (CMU, CMP, CMX) and barrel muon detector (BMU).
3.2 The CDF Detector

3.2.1 Co-ordinate System and Nomenclature

In the co-ordinate system used at CDF the nominal interaction point is at (0,0,0), the geometrical centre of the detector. The $z$-axis is taken to be along the proton direction (eastward at CDF), the $x$-axis points horizontally outward from the centre of the ring (northward at CDF) and the $y$-axis points vertically upwards. In cylindrical co-ordinates $(r, \phi, z)$ the $z$-axis is the same, and $\phi$ is the angle measured from the plane of the Tevatron. In spherical co-ordinates $(r, \varphi, \theta)$ the polar angle, $\theta$, is measured from the proton direction. The coordinate system is shown schematically in Figure 3.4.

A proton (or antiproton) consists of three valence quarks and a "sea" of softer quarks and gluons. A typical collision occurs between one quark or gluon from a proton and another from an antiproton. Although the momentum of these colliding constituents varies, the collision is usually boosted relative to the lab frame along the beam direction. The detector segmentation is thus designed to be invariant under Lorentz boosts along the $z$ direction, and the Lorentz invariant co-ordinate $\eta$, or pseudorapidity, is used to describe particle kinematics and define the angular segmentation of the detector. Pseudorapidity is the relativistic limit of rapidity, $y$, and these variables are defined.
as:

\[
y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (3.1)
\]

\[
\eta = -\ln \tan \frac{\theta}{2} \quad (3.2)
\]

Remnants of the proton and antiproton are scattered forwards in the collision. This means that the total momentum in the event cannot be measured; but the components of momentum and energy perpendicular to the beam direction are useful variables. These are known as the transverse momentum, \( P_T \), and transverse energy, \( E_T \). For particles with large momenta compared to their masses \( E_T \) and \( P_T \) are almost identical, but conventionally \( E_T \) is used to refer to the energy measured by calorimeters and \( P_T \) for the momentum measured by the tracking systems.

### 3.2.2 Tracking Systems

The tracking detectors are used to measure the direction and momentum of charged particles produced in the interaction. They consist of three systems of silicon detectors and a drift chamber, inside a solenoid providing a 1.4 T magnetic field. This causes charged particles to travel in a curved path, with the curvature determined by their momentum. The solenoid is made of an Al-stabilized NbTi superconductor operated at liquid helium temperatures. Figure 3.5 shows a longitudinal cross section through one quadrant of the CDF tracking volume.
3.2 The CDF Detector

CDF Tracking Volume

Figure 3.5: A quadrant of the CDF tracking system.

Silicon Detectors

The silicon tracking system is the closest system to the beam pipe, spanning radii from 1.35 cm to 29 cm. It consists of eight cylindrical layers split into three subdetectors: Layer 00 (LOO), the Silicon Vertex Detector (SVX II) and the Intermediate Silicon Layers Detector (ISL) in order of increasing radius. With lengths from 90 cm to nearly 2 m, the detector provides tracking coverage out to $|\eta| \leq 2$.

Layer 00 [26] consists of single-sided radiation-tolerant silicon strip detectors assembled on a low-mass carbon fiber structure and mounted on the beam pipe.

SVX II [27] spans radii between 2.4 and 10.7 cm and consists of three identical cylindrical barrels, each 29 cm long. They comprise five layers of double-side microstrip silicon detectors split into 12 wedges in $\phi$. Three of the layers have 90° stereo while two have 1.2° small angle stereo.
ISL [28] consists of a single layer at a radius of 23 cm in the central region ($|\eta| \leq 1$) and two layers at 20 and 29 cm in the forward region. It is used to link tracks in the Central Outer Tracker to SVX II, and to provide silicon standalone tracking in the forward region, with coverage out to $|\eta| \leq 2$.

Figure 3.6 shows the relative positioning of the silicon sub-detectors in the $r-z$ view.

Central Outer Tracker

The Central Outer Tracker (COT) [29] is a large open cell drift chamber 3.1 m long, extending from a radius of 40 cm to 137 cm. This is the main tracking detector for CDF in the central region ($|\eta| \leq 1$).
3.2 The CDF Detector

Figure 3.7: (a) One sixth of a COT end plate showing the arrangement of slots which hold the field and sense wires. (b) an example of a drift cell in COT Superlayer 2.

It contains 96 concentric cylindrical layers of sense wires grouped into 8 "super-layers". Half these layers have wires parallel to the beam direction (axial), while half are tilted at ±2° to the beam direction (stereo). This allows three dimensional tracking with a momentum resolution of $\frac{\delta P_T}{P_T} = 0.08\%$ for tracks with $P_T > 10 \text{ GeV/c}$.

Small drift cells and a gas mixture that allows a fast drift velocity are used to limit drift times to less than 100 ns. The basic drift cell consists of two gold-on-mylar cathode planes, 1.76 cm apart. Lines of alternating sense and potential wires spaced by 3.8 mm run down the middle. Figure 3.7 shows the arrangement of wires in the eight superlayers, as well as a close-up of one drift cell within a superlayer.
Chapter 3: The CDF Experiment at the Tevatron Collider

3.2.3 Time of Flight System

The Time of Flight detector (TOF) [30] is situated between the COT and the solenoid. It measures the time of arrival of a particle at the detector (with respect to the collision time) with a resolution of 100 ps. The TOF comprises 216 scintillator bars measuring $4 \times 4 \times 276$ cm, each with a photomultiplier tube mounted on the end.

3.2.4 Calorimeters

The calorimeters lie outside the solenoid and are designed to cover almost all the solid angle. They use a projective tower geometry with towers with a constant size of 0.11 in $\eta$ pointing towards the nominal interaction point. Each tower consists of an inner lead-scintillator electromagnetic (EM) calorimeter and a steel-scintillator hadron calorimeter on the outside. The central calorimeters cover $|\eta| < 1.1$ and the plug calorimeters $1.1 < |\eta| < 3.6$. There is an uninstrumented "chimney" region between $0.77 < \eta < 1.0$, $75^\circ < \phi < 90^\circ$ to make room for cryogenic equipment needed to run the solenoid. The plug calorimeters are completely new detectors in Run II.

Electromagnetic calorimeters allow the measurement of the energy of electrons or photons. When a high-energy electron or photon enters the calorimeter, it causes an electromagnetic shower that deposits most of its energy inside the calorimeter. This energy can then be measured, and thus the energy of the incident particle can be inferred.

An electromagnetic shower is caused by a chain reaction of pair production ($\gamma \rightarrow e^+e^-$) and bremsstrahlung ($e^\pm \rightarrow \gamma e^\mp$). Initially, more and more particles are produced, and so the average energy per particle falls until further multiplication ceases. The shower then decays through ionization losses of the electrons and Compton scattering of the photons. The point at which
the shower contains the largest number of particles is known as the shower maximum.

Hadron showers arise when an incident hadron collides inelastically, producing secondary hadrons which can repeat the process. Hadrons may begin showering in the electromagnetic calorimeters but are only fully absorbed by the deeper hadronic calorimeters.

Central Electromagnetic Calorimeter (CEM)

The CEM [31] is split into two halves (East and West), and contains 24 azimuthal wedges each covering $15^\circ$ in azimuthal angle. Each wedge consists of 31 layers of 5 mm thickness plastic scintillator as a sampling medium and 30 layers of 3.2 mm thickness lead absorber. The towers are approximately 18 radiation lengths deep and the scintillators are read out by wavelength shifting fibres which direct the light to photomultiplier tubes. The energy resolution of the CEM is $\sigma(E_T)/E_T = 13.7\% / \sqrt{E_T} \oplus 1.5\%$.

The Central Electromagnetic Shower detector (CES) is installed inside the CEM at the shower maximum (approximately 6 radiation lengths into the CEM, or 184 cm from the beamline) to give accurate information about the position and profile of the shower inside the calorimeter. It is a proportional strip and wire chamber using cathode strips to provide the z position and anode wires for the $\phi$ position with a resolution of 2 mm for particles with an energy of 50 GeV.

Further information on the shower is provided by the Central Preradiator detector (CPR), which is mounted in front of the calorimeter, 168 cm from the beamline, and samples the early development of the shower.

Figure 3.8 shows the typical layout of a single CEM wedge.
Central and Endwall Hadronic Calorimeter (CHA, WHA)

Each CEM wedge is backed by a CHA [32] wedge consisting of 32 layers of 2.5 cm thick steel between 1 cm thick layers of plastic scintillator with an energy resolution of $\sigma(E_T)/E_T = 50%/\sqrt{E_T} \oplus 3\%$. The towers are approximately 4.5 interaction lengths deep.

The WHA overlaps with the CHA between $0.7 \leq |\eta| \leq 0.9$ and extends to $|\eta| \leq 1.3$. It comprises 15 layers of 5.1 cm thick steel absorber alternating with plastic scintillator and has an energy resolution of $\sigma(E_T)/E_T = 75%/\sqrt{E_T} \oplus 4\%$.

Plug Calorimeters (PEM, PHA)

The plug calorimeter was constructed in a similar fashion to the central calorimeter system, with towers divided into inner EM and outer hadronic...
sections, read out in the same way as the central systems. The azimuthal segmentation is 7.5°, finer than in the central region. Figure 3.9 shows the segmentation of the plug calorimeter.

The PEM [33] comprises 23 layers of 4.5 mm thick lead, and 23 layers of 4 mm thick scintillator, while the PHA has 23 layers of alternating iron (2.5 cm) and scintillator (6 mm). The energy resolution of the PEM is $\sigma(E_T)/E_T = 16%/\sqrt{E_T} \oplus 1\%$, and the towers have a thickness of approximately 21 radiation lengths. The resolution of the PHA is $\sigma(E_T)/E_T = 80%/\sqrt{E_T} \oplus 5\%$ and its depth is about 7 interaction lengths.

The PEM also has a shower maximum detector, the Plug Electromagnetic Shower detector (PES) [34]. It is divided into eight azimuthal sectors, each
consisting of two layers (U and V) of 5 mm pitch scintillator strips. These provide two-dimensional position measurement with a position resolution of 

\[
\frac{38}{E(\text{GeV})} + 0.4 \text{ mm for } 10 < E < 180 \text{ GeV.}
\]

3.2.5 Muon Detectors

Muons are minimum ionising particles which penetrate through the calorimeters, so chambers are placed on the outside of the detector to identify them. The detectors used in this analysis are the central muon chamber (CMU), the central muon chamber upgrade (CMP) and the central muon extension (CMX). The CMU and CMP together cover 94% of the solid angle in the range \(|\eta| < 0.6\), with a large overlap. The CMX covers 74% of the solid angle in the range \(0.6 < |\eta| < 1.0\). The barrel muon detector (BMU) provides coverage in the region \(1 < |\eta| < 1.5\) but is not used in this analysis. A track reconstructed in these detectors is known as a muon stub. Figure 3.10 shows an \(\eta - \phi\) view of the coverage of the muon detectors.

Central muon chamber (CMU)

The CMU [35] lies behind the towers of the CHA, which acts as a hadron absorber for this detector. Only muons with \(P_T > 1.4 \text{ GeV}/c\) reach the CMU. It is divided into azimuthal wedges of 12.6°, each divided into three towers comprising four layers of drift chambers. Each layer has four drift tubes with a 50 μm-diameter stainless steel sense wire in the centre of each cell. The second and fourth layers are offset by 2 mm from the first and third, and the wires in the first and third (second and fourth) are ganged together in the readout. Each pair uses a time-to-digital converter (TDC) to measure the \(\phi\) position of the muon, and an analogue-to-digital converter (ADC) on each end to measure \(z\) position by charge division. Figure 3.11 shows the layout of these
layers in the $r - \phi$ plane.

Central muon upgrade (CMP)

Although most hadrons are absorbed in the CHA, about 0.5% will penetrate into the CMU, giving a fake muon background. This effect is reduced by the installation of an additional detector, the CMP, behind 60 cm of steel, provided in part by the return yoke of the solenoid. The CMP is a four-sided box with fixed length in $z$ placed around the outside of the central detector, so its coverage in $\eta$ varies with azimuth. Muons of $P_T > 2.5$ GeV/c can reach this detector.

Central muon extension (CMX)

The CMX extends muon coverage to $|\eta| < 1.0$. It consists of two 120° arches at each end of the central detector, with the uninstrumented regions filled by a 30°
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Figure 3.11: A CMU module in the $r-\phi$ view, showing the four layers of drift chambers. The sense wires are shown as black dots.

"keystone" at the top and a 90° "miniskirt" in the lower gap: CMX wedges 5-6 and 15-20 respectively. There is also a gap on the east side "chimney region" for cryogenic access to the solenoid, as in the CEM (see Section 3.2.4).

3.2.6 Luminosity Counters (CLC)

The luminosity at a hadron collider is determined from the rate of inelastic $p\bar{p}$ collisions, which have a large cross section. Two gas Cherenkov Luminosity Counters (CLC) [36], positioned between the beam-pipe and the plug calorimeters ($3.7 < |\eta| < 4.7$), are used to measure this rate and thus determine the Tevatron's luminosity. Each CLC consists of 48 thin, long, conical gas-filled Cherenkov counters arranged in three concentric circles. This construction has several advantages. Primary particles from the $p\bar{p}$ interaction travel along the axis of the cone and produce a large signal, while particles produced in the beam pipe and plug calorimeter cross at a different angle and produce less light. The Cherenkov counters are also not sensitive to low momentum particles, or particles coming from beam halo interactions, which hit the counter
The luminosity is given by:

\[ L = \frac{N_{pp}}{\sigma_{inel}} = \frac{f \times \mu}{\sigma_{inel}} \tag{3.3} \]

where \( N_{pp} \) is the number of inelastic \( pp \) collisions, \( \sigma_{inel} \) is the inelastic scattering cross section, \( f \) is the frequency of bunch crossing and \( \mu \) is the average number of interactions per beam crossing, given by the CLC hit rate (about 5-6). The inelastic cross section is taken to be \( \sigma_{inel} = 60.7 \pm 2.3 \text{ mb} \): the error-weighted average of values measured by the CDF [37] and E710/E811 [38] [39] collaborations. The luminosity is always quoted with a systematic uncertainty of 6%: 4.4% from the acceptance and operation of the luminosity monitor and 4.0% from the uncertainty on the inelastic cross section.

### 3.2.7 Triggers

The collision rate in a hadron collider is many times greater than the rate at which data can be stored to tape. CDF has a collision rate essentially equivalent to the bunch crossing rate of 2.53 MHz, but a tape writing speed of less than 50 Hz. Thus a trigger system is needed to efficiently extract the most interesting events.

This is achieved at CDF with a three-tier trigger system, with each level providing a rate reduction sufficient to allow the next level to operate with minimum dead time. Level 1 uses custom designed hardware to look for physics objects such as EM calorimeter clusters or muon stubs. It makes a decision based on counting of these objects within 4 \( \mu \)s, passing events to Level 2 at a rate of 50 kHz. The Level 2 hardware performs a partial reconstruction of the event; adding jet clustering, improved track momentum resolution, finer matching between muon stubs and central tracks, and information from the
CES. It passes 300 events per second to the Level 3 processor farm which fully reconstructs events using all the detector information.

There are many specified trigger paths, and events which pass any one of them are reconstructed using the latest calibrations and written to tape at a rate of up to 50 Hz. Each event has a size of about 250 kB.
Chapter 4

Event Reconstruction and Preselection

This chapter describes the analysis strategy, the collection of the dataset used in this analysis and the offline corrections applied to events before they can be used.

4.1 Analysis Strategy

Figure 4.1 shows the transverse momentum at generator level of the three leptons in the signal MC sample described in Section 2.3.2. Since the highest $P_T$ lepton usually has $P_T > 20$ GeV/c we opt to use a data sample triggered on high-$P_T$ leptons.

In particular this analysis was carried out using a trigger for central electrons with $E_T > 20$ GeV, as described in Section 4.2. The analysis was designed to be complementary to searches using other triggers, such as a high-$P_T$ muon trigger, and low-$P_T$ dilepton triggers. These separate searches are combined for the final limit presented in Chapter 9.

The second lepton in the event can be another central electron, an electron...
in the forward (plug) region of the detector, or a muon. Each of these possible search channels is treated separately, as described in Chapter 7. These channels will be referred to as central-central (CC), central-plug (CP) and $e\mu$ respectively.

The analysis was blind, meaning that the number of events in the signal region, defined in Chapter 7, was not written out by the analysis code until cross-checks confirmed that we understood the modelling of our backgrounds.

4.2 Trigger Sample

The dataset used requires a central electron to pass the high $P_T$ electron trigger, ELECTRON_CENTRAL.18. The requirements at each level of the trigger (as described in Section 3.2) are as follows:

- At Level 1, the “eXtremely Fast Tracker” (XFT) [40], an online tracking algorithm, constructs tracks that have hits in several layers in the
COT and measures their transverse momentum. The $E_T$ and the ratio of energy deposited in hadronic ($E_{\text{had}}$) and electromagnetic ($E_{\text{em}}$) calorimeters are also measured for each tower. The Level 1 trigger condition is fulfilled if a tower has $E_T > 8$ GeV and $E_{\text{had}}/E_{\text{em}} < 0.125$ (this cut is only applied for $E_T < 14$ GeV), and an XFT track pointing at the tower has hits in three or more layers and $P_T > 8.34$ GeV/c.

- At Level 2, a clustering algorithm forms energy clusters in the calorimeter associated with electrons. The trigger condition is fulfilled if a cluster is found with $E_T > 16$ GeV and $E_{\text{had}}/E_{\text{em}} < 0.125$, and an XFT track with $P_T > 8.34$ GeV/c points at the seed tower.

- At Level 3, electromagnetic energy clusters known as EMObejects are constructed using the seed tower and one or two adjacent towers. The Level 3 trigger requires a central EMObeject with $E_T > 18$ GeV, $E_{\text{had}}/E_{\text{em}} < 0.125$ and a central track with $P_T > 9$ GeV/c, as well as some additional requirements based on the full reconstruction of the event.

The efficiency of each level of the trigger to select electrons with $E_T > 20$ GeV has been studied in detail [1]. The L1 trigger, L1.CEM8, is measured to have an efficiency greater than 99.9% and is taken as 100% efficient.

The L2 trigger, L2.CEM16, has an efficiency parametrized by:

$$\epsilon(L2.CEM16) = 0.9989 - 1465.0 \times \exp(-0.5229 \times E_T).$$

Figure 4.2 shows this efficiency as a function of electron $E_T$.

The L3 trigger, L3.CEM18, has an efficiency given by:

$$\epsilon(L3.CEM18) = 1 - 2.784 \times \exp(-1.749 \times (E_T - 17.86)).$$

The total tracking trigger efficiency (from XFT, L2 and L3), is measured in seven run periods; weighting it according to the luminosities in our sample we obtain $\epsilon(TRK) = 0.966 \pm 0.001$. 
Figure 4.2: The Level 2 calorimeter trigger efficiency as a function of electron $E_T$ [1]. A constant minus an exponential is fitted to the data to model the turn-on of the trigger.
In the case of events with two electrons with $E_T > 20$ GeV, the efficiency will be:

$$\epsilon_{\text{trig}}^{\text{ee}} = \epsilon_{\text{trig}}^{1\text{st}} + \epsilon_{\text{trig}}^{2\text{nd}} - \epsilon_{\text{trig}}^{1\text{st}} \times \epsilon_{\text{trig}}^{2\text{nd}}.$$ 

For electrons with $E_T < 18$ GeV the efficiency is zero. Monte Carlo events are weighted with the efficiency for one (or two) central electron(s) to meet the trigger requirements (dependent on $E_T$), in order to emulate the trigger efficiency in the data. In the case of an event with three electrons above 20 GeV the efficiency is taken to be 100%.

### 4.3 Good Run List

Each run is assigned a number of bits representing the operational status of subdetectors and triggers, to ensure optimal data quality. For this analysis "good" status for the COT, calorimeter, CES and muon systems is required. When plug electrons are used, good status for the silicon system is also required, since tracks rely on the silicon detector for $|\eta| > 1.2$. After making this good run requirement the ELECTRON CENTRAL.18 sample corresponds to a luminosity of 346 pb$^{-1}$ when good silicon is not required, and 318 pb$^{-1}$ when it is.

### 4.4 Tracking Algorithms

Four main tracking algorithms are used to group hits in individual layers of the tracking system into tracks which can be used in a physics analysis.

- COT Pattern Recognition Algorithm [41]
Chapter 4: Event Reconstruction and Preselection

Hits in individual superlayers are grouped together into segments of tracks containing three or more hits in consecutive wires. $r - \phi$ tracks are constructed by linking together segments in the four axial superlayers, and segments or hits in the stereo layers are then added to form 3D tracks.

- Outside-In (OI)

The “outside-in” tracking algorithm is used in the central region. COT tracks, as described above, are extrapolated into the silicon detectors adding hits progressively. Hits within $\pm 1\sigma$ of the extrapolated track in each silicon layer are added to form new track candidates. The candidate with the greatest number of silicon hits is chosen.

- Standalone Silicon Tracking [42]

An “inside-out” tracking algorithm is used to construct tracks using only the silicon tracking systems, in particular SVX II. This is useful for low $P_T$ tracks which do not reach the outer layers of the COT, and more importantly for this analysis for $1 < |\eta| < 2$, beyond the coverage of the COT, but covered by the SVX II detector. The algorithm works similarly to the COT algorithm: $r - \phi$ tracks are fitted to candidates with hits in 4 or 5 of the axial layers, and then hits in the stereo layers are added to reconstruct 3D tracks.

- PHOENIX Tracking [43] [44]

PHOENIX tracking is an alternative algorithm used for electrons in the plug, which uses the energy and position measurements from the PEM as a seed for the silicon tracking system. The efficiency is about 80% at $|\eta| \sim 1.2$, falling to 40% at $|\eta| \sim 2.6$ due to the $\eta$ coverage of the silicon tracking. It has a higher efficiency than standalone tracking for almost
all values of \( \eta \), as shown in Figure 4.3. The primary event vertex and the position of the highest energy cluster give two position measurements, and the magnitude of the curvature (which is determined by the momentum of the electron) is estimated from the total \( E_T \) of the cluster. Two seed tracks are then created, as the charge cannot be determined, and the OI tracking algorithm is applied to both hypotheses. If tracks are found for both charge hypotheses, a \( \chi^2 \) fit is used to discriminate which track is used.

4.5 Jet Clustering and Corrections

Jets are reconstructed from energy deposits in the calorimeter using an iterative fixed cone jet clustering algorithm, based on the original UA1 JETCLU algorithm \cite{45}. We use cones with \( \Delta R \equiv \sqrt{\Delta \phi^2 + (\Delta \eta)^2} = 0.4 \).

Standard methods have been developed at CDF to correct measured jet
energies to energies which can be compared to theory [46]. These corrections compensate for several effects that may distort the measured jet energy: the response of the calorimeter to different particles; non-linear response of the calorimeter to particle energies; uninstrumented regions of the detector; spectator interactions; and energy radiated outside the jet clustering cone. For this analysis we apply the following corrections:

- Online/offline calibrations which give the correct overall calorimeter energy scale.
- Relative corrections which make the jet energy response uniform in $\eta$ across different calorimeter towers. Jets outside $0.2 < |\eta| < 0.6$ are scaled to jets inside this region, because the CEM and CHA are the best understood calorimeters and the selected region is far away from any cracks.
- Absolute corrections which correct the jet energy measured in the calorimeter for any non-linearity and energy loss in the uninstrumented regions of each calorimeter.

Corrections are applied only for jets with $E_T > 8$ GeV and $|\eta| < 3.6$ as the corrections outside this range are not well known.

### 4.6 Missing Energy Corrections

Particles may escape detection altogether, leading to an imbalance in the energy measured in the detector. As noted in Section 3.2.1, it is not possible to measure the momentum along the beam direction, but the transverse component of energy should balance. Hence a "missing" transverse energy component indicates the escape of an undetected particle from the detector.
The missing tranverse energy (MET) is calculated using all calorimeter deposits up to $|\eta| \leq 3.6$. The raw MET is defined as the negative vector sum of the transverse energies in the calorimeters, summed over all towers (CEM, CHA, WHA, PEM, PHA) above a threshold of 0.1 GeV.

Since the energy deposits in the calorimeters from jets are corrected, as described in Section 4.5, the missing energy must be correspondingly corrected. For each jet the difference between its raw and corrected energy is added vectorially to the raw missing energy.

Additionally, muons deposit little of their energy in the calorimeter, and so contribute to the raw missing energy defined above. However if they are detected in the muon chambers and matched to a track we can substitute the track's momentum for the energy deposited by the muon, and thus correct the missing energy for this effect.

The missing energy after applying these corrections is the variable described as MET for the rest of this thesis.
Chapter 5

Lepton Selection

This analysis depends on identifying three leptons (electrons or muons) in an event. This chapter outlines the variables used to select electrons and muons, and describes the sets of cuts used to identify the three leptons in our events.

5.1 Electron Identification

Several variables are used to identify electrons. They are described here, and the exact cuts on each variable are given in Tables 5.1 and 5.2.

- Fiducial requirement

  Central (plug) electrons are required to lie within $|\eta| < 1.1$ ($1.2 < |\eta| < 2.0$). The $x$ and $z$ position of the electron within a CEM tower is measured using the CES detector. Fiduciality requirements are demanded to ensure that the electron is in a well-instrumented region of the detector:

  1. $|X_{CES}| < 21$ cm ($|X_{CES}|$ is measured from the centre of the tower).

  2. $9 < |Z_{CES}| < 230$ cm.

  3. The “chimney” region, described in Section 3.2.4, in tower 7, $0.77 < \eta < 1.0$, $75^\circ < \phi < 90^\circ$, and $|Z_{CES}| > 193$ cm is excluded.
Plug electrons are only included up to $|\eta| < 2.0$ because the tracking efficiency falls off beyond this, as shown in Figure 4.3, allowing greater background contamination.

- Event vertex

The position of the primary vertex, $z_0$, is the distance in $z$ from the nominal interaction point ($z = 0$) to the point where the track associated with the electron passes closest to the beamline. To ensure the tracks are fiducial to the tracking systems $|z_0|$ is constrained to be less than 60 cm.

- Electromagnetic energy clusters

An electromagnetic energy cluster, or EMobject, is constructed from a seed tower and one or two adjacent towers. For electrons we use the energy deposited in the electromagnetic calorimeter, $E_{em}$. The transverse energy, $E_T$, is the component of the energy perpendicular to the beamline, given by $E_{em} \sin \theta$. For central electrons $\theta$ is the polar angle provided by the best COT track pointing to the EM cluster, while for the plug, $\theta$ is the polar angle of the electron calculated using the PES. A correction factor for tower response and edge effects is also applied, depending on the position of the cluster in the tower. For plug electrons a slightly more complicated set of corrections is applied [47].

- Ratio of hadronic to electromagnetic energy

Electrons are expected to deposit most of their energy in the electromagnetic calorimeter, with a small amount of leakage into the hadronic calorimeter. Hence an upper limit is placed on the ratio of the energy deposited in the hadronic calorimeter to that deposited in the electromagnetic calorimeter, $E_{had}/E_{em}$. 

5.1 Electron Identification
Chapter 5: Lepton Selection

- Track transverse momentum

A track is associated with each electron candidate, and the $P_T$ of an electron refers to the transverse momentum of the associated track. For central electrons a COT track is used, while for plug electrons a PHOENIX track is used for electrons with $E_T > 15$ GeV, and a silicon standalone track for lower energy electrons (these tracking algorithms are described in Section 4.4). To ensure a well-measured COT track, requirements are placed on the number of axial and stereo superlayers which have at least five COT hits, $N_{ax}$ and $N_{st}$.

- Calorimeter isolation

The leptons in this analysis are required to be isolated from other deposits of energy in the calorimeter, in order to suppress background from jet and $b\bar{b}$ production. The isolation energy is defined with reference to a cone of $\Delta R < 0.4$ built around the electron’s seed cluster position. It is the sum of the $E_T$ in this cone, excluding the energy of the electron’s own cluster. We also subtract a small leakage correction dependent on electron $E_T$ to account for the fact that the isolation energy increases with increasing electron energy.

- Shower profile

The variables $\chi^2_{strip}$ and PES $5 \times 9$ are used to describe the profile of electromagnetic showers for central and plug electrons respectively, and determine whether they are consistent with the profile expected for an electron.

$\chi^2_{strip}$ is the $\chi^2$ fit value between the CES shower profile in the $r - z$ view and the profile measured using test beam electrons. It is used to discriminate between electromagnetic showers from prompt photons and...
electrons, and those coming from jets, where neutral pions can decay to two photons.

The PES $5 \times 9$ ratio performs the same role for the plug. A five-strip window is constructed around the PES cluster, and also a nine-strip window containing two more strips on each side. The PES $5 \times 9$ ratio is simply the ratio of the energy in the five strip window to that in the nine strip window. It is measured for both the U and V wires.

- Consistency with electromagnetic shower deposition

The variables $L_{shr}$ and PEM $3 \times 3\chi^2$ compare the energy distribution between the seed tower and neighbouring towers (for central and plug electrons respectively), to examine their consistency with the distribution expected from a genuine electromagnetic shower.

$L_{shr}$ is defined as:

$$L_{shr} = 0.14 \frac{\sum_i (M_i - P_i)}{\sqrt{0.14E_{em}^2 + \sum_i (\Delta P_i)^2}}$$  \hspace{1cm} (5.1)

where the sums are over all adjacent towers in the same wedge, $M_i$ is the measured energy deposit and $P_i$ is the predicted energy deposit from test beam data, with an uncertainty $\Delta P_i$.

PEM $3 \times 3\chi^2$ compares the energy distribution for nine towers in a $3 \times 3$ square about the seed tower to the distribution for test beam electrons.

- $E/P$

$E/P$ is the ratio of the EM cluster transverse energy to the transverse momentum of the associated track. For an electron this ratio is normally expected to be unity. If an electron radiates a photon in the inner
tracking volume, the measured track $P_T$ will correspond to the momentum of the electron after radiating the photon. However, in the case of highly energetic electrons, the radiated photon will be nearly collinear with the electron and will generally enter the same tower in the calorimeter. Hence the $P_T$ of the track will be less than the $E_T$ measured in the calorimeter.

Imposing an upper limit on the $E/P$ ratio maintains a high efficiency for electrons which have emitted a bremsstrahlung photon, but rejects other background from QCD.

- $Q\Delta x$ and $\Delta z$
  These variables describe the distance between the extrapolated COT track and best-matching CES cluster in the $r-\phi$ and $r-z$ planes. Before cutting on $\Delta x$ it is multiplied by the charge of the track, $Q$, as bremsstrahlung introduces a charge-dependent asymmetry in the CES cluster.

Table 5.1 shows two sets of cuts on these variables for central electrons, which will be referred to as the "tight" and "loose" cuts. Table 5.2 shows cuts for plug electron identification.

### 5.1.1 Conversion Rejection

We do not wish to select electrons which arise from a radiated photon converting into an electron-positron pair. To remove conversions we take the track of the electron candidate and attempt to form a conversion pair with another oppositely-signed track in the event. Two variables are calculated:

- $\Delta XY$, the distance between the two tracks in the x-y plane at the radial location where they are parallel.
5.1 Electron Identification

<table>
<thead>
<tr>
<th>Tight cuts</th>
<th>Loose cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$P_T &gt; 8$ GeV/$c$</td>
<td>$P_T &gt; 4$ GeV/$c$</td>
</tr>
<tr>
<td>$N_{ax} \geq 3, N_{st} \geq 2$</td>
<td>$N_{ax} \geq 3, N_{st} \geq 2$</td>
</tr>
<tr>
<td>$z_0 &lt; 60$ cm</td>
<td>$z_0 &lt; 60$ cm</td>
</tr>
<tr>
<td>$E_{had}/E_{em} &lt; 0.055 + 0.00045.E$</td>
<td>$E_{had}/E_{em} &lt; 0.055 + 0.00045.E$</td>
</tr>
<tr>
<td>$\text{Iso}/E_T &lt; 0.1$</td>
<td>$\text{Iso}/E_T &lt; 0.1$</td>
</tr>
<tr>
<td>$E/P &lt; 2$ or $P_T &gt; 50$ GeV/$c$</td>
<td>$E/P &lt; 2$ or $P_T &gt; 50$ GeV/$c$</td>
</tr>
<tr>
<td>$\chi_{strip}^2 &lt; 10$</td>
<td>$\chi_{strip}^2 &lt; 10$</td>
</tr>
<tr>
<td>$L_{shr} &lt; 0.2$</td>
<td>$L_{shr} &lt; 0.2$</td>
</tr>
<tr>
<td>$-3 &lt; Q\Delta x &lt; 1.5$ cm</td>
<td>$-3 &lt; Q\Delta x &lt; 1.5$ cm</td>
</tr>
<tr>
<td>$</td>
<td>\Delta z</td>
</tr>
</tbody>
</table>

Table 5.1: Variables and cuts for central electron identification.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Plug cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiduciality</td>
<td>$1.2 &lt;</td>
</tr>
<tr>
<td>Transverse energy</td>
<td>$E_T &gt; 8(5)$ GeV</td>
</tr>
<tr>
<td>Track</td>
<td>$E_T &gt; 15$ GeV: PHOENIX</td>
</tr>
<tr>
<td></td>
<td>$E_T &lt; 15$ GeV: standalone</td>
</tr>
<tr>
<td>Had/EM</td>
<td>$E_{had}/E_{em} &lt; 0.05$</td>
</tr>
<tr>
<td>Isolation</td>
<td>$\text{Iso}/E_T &lt; 0.1$</td>
</tr>
<tr>
<td>E/P</td>
<td>$E/P &lt; 3$ (if standalone)</td>
</tr>
<tr>
<td>Shower profile</td>
<td>$\text{PES} 5 \times 9 (U and V) &gt; 0.65$</td>
</tr>
<tr>
<td>Consistency with EM shower</td>
<td>$\text{PEM} 3 \times 3\chi^2 &lt; 10$</td>
</tr>
</tbody>
</table>

Table 5.2: Variables and cuts for plug electron identification.
• $\Delta \cot \theta$, the difference between the $\cot \theta$ of the tracks.

If $|\Delta XY| < 0.1$ and $|\Delta \cot \theta| < 0.02$, the electron is taken to be a conversion and is rejected.

### 5.1.2 Efficiency of Selection

The efficiency of the electron identification cuts has been derived for data and Monte Carlo in several separate studies. For high-$P_T$ electrons, $Z \rightarrow ee$ candidates in a small mass window are used, while for lower-$P_T$ electrons we select low invariant mass Drell-Yan events by requiring two oppositely-charged electrons back-to-back in $\phi$. One of the electrons is required to pass all the tight cuts, while the other is a "probe" electron passing only minimal cuts. The number of probe electrons is used as the denominator in the efficiency measurements.

For plug electrons the efficiency is broken down into the tracking efficiency (efficiency to find a track given a well-identified plug cluster) and the calorimeter (PEM) efficiency (efficiency to pass plug identification requirements given a track passing kinematic cuts).

The efficiency of the electron identification cuts in data is not perfectly simulated in Monte Carlo. Hence scale factors, $\epsilon_{\text{DATA}}/\epsilon_{\text{MC}}$, are derived. When counting Monte Carlo events, each event is multiplied by the relevant scale factors for the electrons found in the event. Table 5.3 shows the scale factors used for each class of electron described.

A scale factor is also required because the efficiency of the conversion filter is not perfectly simulated. This was the subject of a separate study [52]. For the conversion cuts used in this analysis, the scale factor is calculated to be $1.581 - 0.0152 \times E_T$ where $E_T$ is the transverse energy of the seed electron in GeV. When this function falls below 1, a value of 1 is used. The uncertainty
5.2 Muon Identification

Muons are identified by tracks matched to stubs in the various muon chambers. In this analysis three different types of muons are used depending on which chamber the stub is found in. CMUP muons are those which have a stub in both the CMU and CMP detectors, while CMX muons have a stub in the CMX detector. CMIO muons do not have a stub but are isolated tracks with little energy deposition in the calorimeter. The following variables are used in muon identification:

- Fiducial requirement

CMUP muons are required to be fiducial to both the CMU and CMP detectors, CMX muons to the CMX detector, and CMIO muons are required to not satisfy either of the preceding fiduciality requirements. This means that for CMUP and CMX muons the extrapolated track must pass through all four chambers of the muon detector, enabling a stub to be reconstructed, while CMIO muons must pass through a region not covered by muon chambers, as otherwise a stub would be expected.

### Table 5.3: Electron identification scale factors for each category of electron.

<table>
<thead>
<tr>
<th>Electron type</th>
<th>Scale factor</th>
<th>Systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight central (&gt; 20 GeV) [48]</td>
<td>1</td>
<td>0.5%</td>
</tr>
<tr>
<td>Loose central (&gt; 8 GeV) [49]</td>
<td>1</td>
<td>2%</td>
</tr>
<tr>
<td>Loose central (&gt; 5 GeV) [50]</td>
<td>1</td>
<td>20%</td>
</tr>
<tr>
<td>Plug (PHOENIX) [48]</td>
<td>0.949</td>
<td>2.8%</td>
</tr>
<tr>
<td>Plug (standalone) [51]</td>
<td>$E_T$ dependent</td>
<td>11%</td>
</tr>
</tbody>
</table>

Of this scale factor is 28.8%.
(they can pass through either the CMU or CMP detector, but not both).

- $P_T$

Muons deposit little energy in the calorimeter, so the $P_T$ of the track associated with the muon is used as a measure of its energy. As for electrons, the track is required to be well-measured by imposing cuts on the number of axial and stereo superlayers with five or more COT hits.

- $E_{\text{had}}, E_{\text{em}}, E_{\text{tot}}$

Muons are minimum ionising particles (MIPs), and so are not expected to deposit much energy in the electromagnetic or hadronic calorimeters. An upper limit is required on the energy deposited in each calorimeter to distinguish muons from other particles. A lower limit is also required on the total energy deposited in the EM and hadronic calorimeters, as a MIP is expected to deposit some energy in the calorimeter. This cut is a check that the muon hit the calorimeter, and thus that the $E_{\text{had}}$ and $E_{\text{em}}$ cuts are effective.

- Isolation

An isolation cone of $\Delta R < 0.4$ is constructed around the muon track. The isolation is defined as the $P_T$ sum in the cone excluding the energy of the cluster associated with the muon. Requiring isolated muons is effective in removing background such as soft muons produced in jets, for example from $b\bar{b}$ decays.

- Impact parameter

The impact parameter, $d_0$, is the closest distance between the extrapolated track and the interaction point. The track is required to originate
from close to the interaction point to reduce contamination from cosmic rays.

Table 5.4 shows the cuts used on these variables to identify CMUP, CMX and CMIO muons.

<table>
<thead>
<tr>
<th>Stubbed muon cuts</th>
<th>CMIO muon cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMUP/CMX fiducial</td>
<td>Not CMUP or CMX fiducial</td>
</tr>
<tr>
<td>$P_T &gt; 8 \text{(5)} \text{ GeV/}c$</td>
<td>$P_T &gt; 10 \text{ GeV/}c$</td>
</tr>
<tr>
<td>$E_{\text{cm}} &lt; 2 \text{ GeV (for } P_T &lt; 100 \text{ GeV/}c)$</td>
<td></td>
</tr>
<tr>
<td>$P_T &lt; 20 \text{ GeV}: E_{\text{had}} &lt; 3.5 + P_T/8 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>$P_T &gt; 20 \text{ GeV}: E_{\text{had}} &lt; \max(6, P_T - 100 \times 0.028) \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{tot}} &gt; 0.1 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>$\text{Iso}/P_T &lt; 0.1$</td>
<td></td>
</tr>
<tr>
<td>$z_0 &lt; 60 \text{ cm}$</td>
<td></td>
</tr>
<tr>
<td>$d_0 &lt; 0.2 \text{ cm}$</td>
<td></td>
</tr>
<tr>
<td>$d_0 &lt; 0.02 \text{ cm (if } P_T &gt; 20 \text{ GeV and has silicon hits)}$</td>
<td></td>
</tr>
<tr>
<td>$N_{\mu} \geq 2, N_{ax} \geq 3$</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4: Criteria for the selection of muon candidates used in this study.

5.2.1 Cosmic Ray Rejection

High energy cosmic muons passing through the detector generate hits in the muon chambers and COT, but they should not be mistakenly identified as muons created in the interaction. As well as the cut on $d_0$ described above, the timing of the COT hits is used to reject pairs of aligned muons [53].

Two fits are made to the timing information for the pair of muons: one takes them to be both outgoing (i.e. non-cosmic) while the other tries a reverse timed fit for one muon. If the reverse fit (i.e. considering one muon to be
ingoing) has a lower \( \chi^2 \) then the muon pair is considered to be a cosmic ray and rejected.

### 5.2.2 Efficiency of Selection

The efficiency for a muon to pass these identification cuts has been measured in separate studies in a similar way to electrons. For high-\( p_T \) CMUP and CMX muons (> 20 GeV/c), \( Z \rightarrow \mu^+\mu^- \) events with \( 80 \text{ GeV}/c^2 < M_{\mu\mu} < 100 \text{ GeV}/c^2 \) are used; one muon is required to pass all the cuts (CMUP or CMX) and the other is used as a probe. The probe is required to pass the fiducial requirements and not be tagged as a cosmic. For muons with \( p_T < 20 \text{ GeV}/c \), muon pairs in the \( J/\psi \) and \( \Upsilon \) mass regions are used as well as in the \( Z \) mass window. The muons from \( J/\psi \) and \( \Upsilon \) are not isolated so the isolation efficiency is measured separately in Drell-Yan events.

The efficiency of muon identification in data is not perfectly simulated in Monte Carlo. Hence scale factors, \( \epsilon_{\text{DATA}}/\epsilon_{\text{MC}} \), are derived. When counting Monte Carlo events, each event is multiplied by the relevant scale factors for the muons found in the event.

Table 5.5 shows the scale factors used for each class of muon described.

<table>
<thead>
<tr>
<th>Muon type</th>
<th>Scale factor</th>
<th>Systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMUP (&gt; 20 GeV) [54]</td>
<td>0.881</td>
<td>1.1%</td>
</tr>
<tr>
<td>CMUP (&lt; 20 GeV) [55]</td>
<td>0.846</td>
<td>5.9%</td>
</tr>
<tr>
<td>CMX (&gt; 20 GeV) [54]</td>
<td>0.997</td>
<td>0.7%</td>
</tr>
<tr>
<td>CMX (&lt; 20 GeV) [55]</td>
<td>0.906</td>
<td>5.5%</td>
</tr>
<tr>
<td>CMIO [55]</td>
<td>1</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table 5.5: Muon identification scale factors for each category of muon.
Chapter 6

Estimation of Background Contributions

The background contribution to the trilepton signal is broken down into three categories:

1. Standard Model processes that produce three leptons in the final state; these are dominated by $WZ$, $ZZ$ and $t\bar{t}$ production.

2. Standard Model processes that produce two leptons in the final state (dominated by Drell-Yan), where a third electron is produced by the conversion of a radiated photon.

3. Standard Model processes that produce two leptons in the final state, where a third "fake" lepton arises from the misidentification of an object produced in jet fragmentation.

The Standard Model backgrounds and Monte Carlo samples used to estimate them are described in Section 6.1 and the method for estimating the background due to fake leptons is described in Section 6.2.
6.1 Standard Model Background Processes

6.1.1 SM Processes with Three-Lepton Final States

The major SM backgrounds that produce three leptons in the final state are diboson production ($WZ$ and $ZZ$) and top pair-production. $WZ$ production, where the $Z$ decays to two charged leptons and the $W$ to a charged lepton and a neutrino, gives the same final state of three charged leptons with missing $E_T$ as the signal. However, two of the leptons should reconstruct to the $Z$ mass.

$ZZ$ production can give a four-lepton final state, and fake missing $E_T$ can arise from detector effects. In particular, if one muon is not identified then we can not correct the missing energy properly.

In top pair production, each top quark decays to a bottom quark and a $W$ boson. The bottom quark then decays to a charm quark and another $W$. If each of the $W$ bosons decays leptonically then we can have a final state with four charged leptons and significant missing $E_T$ from neutrinos. However there will also be additional quark jets in the event, and the leptons arising from semi-leptonic b-decay are within a jet, and so will usually be rejected by the isolation requirement.

We estimate these backgrounds by generating large Monte Carlo samples, detailed in Table 6.1. For top production and $ZZ$ we use the PYTHIA generator [23], but for $WZ$ we use MADGRAPH [56] as PYTHIA does not include the contribution from virtual photons ($\gamma^*$). In the following discussion the $Z$ in $WZ$ and $ZZ$ implicitly includes the $\gamma^*$ contribution.

6.1.2 SM Processes with Two-Lepton Final States

For the $ee$ channels the overwhelming background with two leptons in the final state is from $Z \rightarrow ee$. For the $e\mu$ channel $Z \rightarrow \tau\tau$ dominates, but $WW$
production is also significant. The Monte Carlo samples used to simulate these backgrounds are detailed in Table 6.1. The background from \( \bar{b}b \) production was shown to be negligible [57].

These processes can give rise to three identified leptons when a photon is radiated from the initial or final state and it converts to an electron-positron pair. In the central region we apply a filter to reject such conversion pairs (see Section 5.1.1), but it is not 100% efficient. In the plug region we do not apply any conversion filter as the identification of tracks is poorer. To estimate the background from conversions we use a Monte Carlo sample of \( Z + \gamma \) production (see Table 6.1). This contains both initial and final state radiation while the \( Z \to ee \) and \( Z \to \tau \tau \) samples contain only FSR. For events to which the conversion filter is applied, the MC is scaled by the factor described in Section 5.1.1.

<table>
<thead>
<tr>
<th>Background</th>
<th>Generator</th>
<th>Events</th>
<th>( \sigma \times BR/\text{pb} )</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z \to ee )</td>
<td>PYTHIA</td>
<td>( 3 \times 10^6 )</td>
<td>355 \times 1.4</td>
<td>( M_{ee} &gt; 20 \text{ GeV}/c^2 )</td>
</tr>
<tr>
<td>( Z \to \tau \tau )</td>
<td>PYTHIA</td>
<td>882,000</td>
<td>355 \times 1.4</td>
<td>( M_{\tau \tau} &gt; 20 \text{ GeV}/c^2 )</td>
</tr>
<tr>
<td>( WW )</td>
<td>PYTHIA</td>
<td>420,000</td>
<td>1.273</td>
<td>( M_{WW} &gt; 30 \text{ GeV}/c^2 )</td>
</tr>
<tr>
<td>( WZ \to \ell \ell \ell )</td>
<td>MADGRAPH</td>
<td>120,000</td>
<td>0.0208 \times 1.34</td>
<td></td>
</tr>
<tr>
<td>( ZZ \to \ell \ell \ell \ell )</td>
<td>PYTHIA</td>
<td>161,000</td>
<td>0.0151</td>
<td>( M_{ZZ} &gt; 10 \text{ GeV}/c^2 )</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>PYTHIA</td>
<td>959,000</td>
<td>6.7 (NLO)</td>
<td>( m_t = 178 \text{ GeV}/c^2 )</td>
</tr>
<tr>
<td>( Z + \gamma \to \ell \ell \gamma )</td>
<td>Baur [58]</td>
<td>425,000</td>
<td>8.62 \times 1.4</td>
<td>( M_{ee} &gt; 20 \text{ GeV}/c^2 )</td>
</tr>
<tr>
<td></td>
<td>Baur (( \mu ))</td>
<td>443,000</td>
<td>8.61 \times 1.4</td>
<td>( M_{\mu\mu} &gt; 20 \text{ GeV}/c^2 )</td>
</tr>
<tr>
<td></td>
<td>MADGRAPH (( \tau ))</td>
<td>199,000</td>
<td>6.42 \times 1.4</td>
<td>( M_{\tau\tau} &gt; 20 \text{ GeV}/c^2 )</td>
</tr>
</tbody>
</table>

Table 6.1: Monte Carlo samples used for background studies. The second number given under \( \sigma \times BR \) is the \( k \)-factor used to scale from leading order to next-to-leading order cross sections.
6.2 Fake Lepton Background

The background processes described in Section 6.1 produce at least three real leptons. It is also possible for a non-leptonic object to be falsely identified as a lepton. QCD processes create jets and tracks that may pass the electron and muon identification cuts described in Chapter 5. A SM process giving two real leptons in association with such a "fake" lepton can look like a genuine three lepton event. Monte Carlo simulation does not accurately reproduce this behaviour, as the modelling of jet fragmentation is not perfect, so we developed a method of estimating the fake lepton background from data [59].

The method is in two stages. First the probability for a jet or track arising from QCD to pass the lepton identification requirements is determined. Then this probability, or "fake rate", is applied to data events containing such jets or tracks.

6.2.1 Determination of Fake Rate

The fake rate is defined with reference to a denominator object: an object produced by QCD which has a probability of faking a lepton by passing the lepton identification requirements. The denominator object is inclusive, i.e. all fake leptons are a subset of the relevant denominator object.

For electrons the denominator object is a jet with $E_T > 4$ GeV, and $|\eta| < 1.1$ for central electrons, or $1.2 < |\eta| < 2.0$ for plug electrons. For muons the denominator object is an isolated track passing all the track quality requirements for muon identification, described in Section 5.2. For each category of muon the track is required to pass the same chamber fiducial requirement as the muon (see Section 5.2). We require the $E_T$ in a cone of $\Delta R < 0.4$ around the track (subtracting the towers hit by the track) to be less than 4 GeV, and also require $E_{\text{tower}}/P_T < 1$ to reduce contamination from real
6.2 Fake Lepton Background

electrons.

The numerator in the fake rate is the number of denominator objects which pass all the identification requirements for a particular class of lepton. In the case of electrons, the electron object must be within \( \Delta R < 0.4 \) of the denominator jet, while for muons the track associated with the muon object must be the denominator track. Separate fake rates are defined for each lepton category described in Chapter 5. Each fake rate is measured as a function of the \( E_T (P_T) \) of the denominator jet (track). In the case of the plug electron fake rates, the dependence on \( \eta \) is also determined.

To measure the fake rate accurately we need large samples of the denominator objects. These are provided by data samples triggered on jets. Four samples were used, triggered on jets with a threshold energy of 20 GeV (JET20), 50 GeV (JET50), 70 GeV (JET70) and 100 GeV (JET100). The same good run list was applied as for the main dataset (see Section 4.3). To remove trigger bias we do not consider the highest \( E_T \) jet in each event.

Figure 6.1 shows the fake rate for tight and loose central electrons as a function of jet \( E_T \). The fake rate measured in each jet sample is shown separately. Clearly there is some dependence on the sample, so we take the (unweighted) average of the four samples and quote a systematic error of 50% to cover this spread, shown by the dotted lines on the plot. We then fit a function of the form \( f(x) = a + e^{bx+c} \). The fake rates are shown, together with the fits, in Figure 6.2. The fit gives a good description of the data at all values of \( E_T \). For tight central electrons the fake rate is of the order \( 10^{-4} \) and for loose central electrons it is 5-10 times higher.

In the plug region the tracking coverage is strongly dependent on \( \eta \), so we first plot the fake rate as a function of \( \eta \), shown in Figure 6.3. Two fake rates are shown, for electrons with a PHOENIX track and those with a stand-alone
Chapter 6: Estimation of Background Contributions

Figure 6.1: Tight (left) and loose (right) electron fake rates versus jet $E_T$ for the JET20, JET50, JET70 and JET100 samples.

Figure 6.2: Tight (left) and loose (right) electron fake rates versus jet $E_T$ for the average of all four jet samples. Also shown is an exponential fit to the fake rate.
6.2 Fake Lepton Background

Figure 6.3: PHOENIX (PHX) and standalone electron fake rate versus \( \eta \). For PHOENIX a cut of \( E_T > 15 \) GeV is applied while for standalone the cut is \( E_T > 5 \) GeV.

For the electron with stand-alone tracking, at \( |\eta| > 1.3 \) the fake rate is approximately independent of \( \eta \) but there is a significant enhancement at \( 1.2 < |\eta| < 1.3 \). Hence we determine the fake rate separately in these two regions. There is also an up and down alternation in the fake rate in higher \( \eta \) bins due to the tower structure of the calorimeter.

Figure 6.4 shows the \( E_T \) dependence of the fake rate for PHOENIX electrons and for the two \( \eta \) regions for electrons with stand-alone tracking. Again all four jet samples are shown, the average is taken and the 50% systematic is shown. Figure 6.5 shows the averages and fits (in this case a first order polynomial).

The PHOENIX fake rate is of order \( 10^{-3} \) and the standalone fake rate is an order of magnitude lower (for \( |\eta| > 1.3 \)).

An additional complication for electrons is that the energy of the denominator jet is not necessarily the same as the energy that would be measured for the "electron" if it passed the identification cuts. To account for this we plotted the ratio of electron \( E_T \) to jet \( E_T \) for jets which fake electrons. This is...
Figure 6.4: PHOENIX (left) and standalone (right) plug electron fake rates versus jet $E_T$ for all four jet samples. Also shown is the average of the four samples and the 50% systematic uncertainty. The upper left plot shows the fake rate for PHOENIX electrons, the upper right for standalone plug electrons with $\eta > 1.3$ and the bottom right plot for standalone plug electrons with $\eta < 1.3$. 
6.2 Fake Lepton Background

Figure 6.5: PHOENIX (left) and standalone (right) plug electron fake rates versus jet $E_T$ (in GeV) for the average of all four jet samples. Also shown is a straight line fit to those data used for parameterizing the fake rate. The upper right plot shows the fake rate for standalone electrons for $\eta > 1.3$ and the bottom right plot for $\eta < 1.3$. 
shown in Figure 6.6, with a Gaussian fit. We use this function when applying the fake rate (see Section 6.2.2).

Figures 6.7 and 6.8 repeat this procedure for each category of muon. A first order polynomial is used to fit the $P_T$ dependence of the fake rate. In each case the fake rate rises with increasing track $P_T$. The fake rates for stubbed muons (CMUP and CMX) are from order $10^{-3}$ to $10^{-2}$, while the CMIO fake rate is of order $10^{-1}$.

Table 6.2 summarises the fake rates measured for each lepton category.

### 6.2.2 Application of Fake Rate

We then apply these fake rates to our dataset to determine the contribution of fakes to the background. Possible contributions to the signal from fakes are:

1. A real central tight electron, a real second lepton and a fake third lepton.

2. A real central tight electron, a fake second lepton and a real third lepton.
Figure 6.7: CMUP (top left), CMX (top right) and CMIO (bottom) fake rates for the JET20, JET50, JET70 and JET100 data. The solid line is the fit to the average of the samples and the dotted lines indicate the 50% variation of this fit which is taken to be the systematic error.
Chapter 6: Estimation of Background Contributions

Figure 6.8: CMUP (upper left), CMX (upper right) and CMJO (lower left) muon fake rates versus $P_T$ and the fits to those data.
6.2 Fake Lepton Background

<table>
<thead>
<tr>
<th>Type</th>
<th>function</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM loose $e$</td>
<td>$e^{b+cE_T}$</td>
<td>$-$</td>
<td>$-7.98$</td>
<td>$0.022$</td>
</tr>
<tr>
<td>CEM tight $e$</td>
<td>$a + e^{b+cE_T}$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$-7.94$</td>
<td>$-0.194$</td>
</tr>
<tr>
<td>PHX $e$</td>
<td>$a + b_{Pr}$</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$-$</td>
</tr>
<tr>
<td>PEM tight $e$, $\eta &gt; 1.3$</td>
<td>$a + b_{Pr}$</td>
<td>$7.4 \times 10^{-5}$</td>
<td>$1.1 \times 10^{-6}$</td>
<td>$-$</td>
</tr>
<tr>
<td>PEM tight $e$, $\eta &lt; 1.3$</td>
<td>$a + b_{Pr}$</td>
<td>$4.3 \times 10^{-4}$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>CMUP $\mu$</td>
<td>$a + b_{Pr}$</td>
<td>$8.6 \times 10^{-4}$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$-$</td>
</tr>
<tr>
<td>CMX $\mu$</td>
<td>$a + b_{Pr}$</td>
<td>$8.2 \times 10^{-4}$</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$-$</td>
</tr>
<tr>
<td>CMIO $\mu$</td>
<td>$a + b_{Pr}$</td>
<td>$-1.4 \times 10^{-2}$</td>
<td>$3.7 \times 10^{-3}$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

Table 6.2: Fake rate parameterizations for the five lepton categories.

3. A real central tight electron and two fake leptons.

4. Three fake leptons.

Contributions 3 and 4 are negligible in comparison to 1 and 2 due to the small fake rate. To estimate the fake background we select events with at least one central tight electron, and also note any other identified leptons in the event. We now look for any denominator objects in these events which are separated from all the identified leptons (we do not want to double-count real leptons as fake leptons). For each such denominator object we treat it as if it were a lepton but weight the entire event by the corresponding fake rate. In the case of electrons, as mentioned in the previous section, we take the energy of the “electron” to be the measured energy of the jet multiplied by a factor randomly sampled from the appropriate Gaussian distribution of electron $E_T$ divided by jet $E_T$.

We then pass the event through the kinematic cuts described in Chapter 7. In case 3 we must find at least two denominator objects and the event is weighted by the product of the two fake rates.
Chapter 6: Estimation of Background Contributions

One further complication is that the muon denominator object (an isolated track that is not associated with any identified lepton) can easily be generated by a real electron that passes through an uninstrumented region of the calorimeter. We do not wish to double-count real leptons as fakes so we wish to remove these false denominator objects. This was done by requiring CMIO denominator objects (and also CMIO muons themselves) to pass the same fiduciality requirements as electrons in the CES. Figure 6.9 shows the CES co-ordinates for such tracks, demonstrating that the electron fiduciality requirements ($|X_{CES}| < 21$ cm and $9 < |Z_{CES}| < 230$ cm) are appropriate to remove this effect.

We impose this requirement only on the second muon in the event, i.e. in the $e\mu$ channel, and allow the third lepton to be a muon which is not CES-fiducial. The rationale for this is that while many events with a tight central electron also have a second electron (from $Z \rightarrow ee$), few events with two leptons also have a third real electron, in comparison to those which have a fakeable object coming from QCD.
Figure 6.9: CES co-ordinates for isolated tracks not associated with an identified lepton.
Chapter 7

Event Selection

7.1 Lepton selection and Channels

Having chosen the dataset and identified the major sources of background, a series of cuts on kinematic variables was devised to isolate the signal. As mentioned in Section 4.1 this is done in three separate channels, defined by the type of the leading two leptons in the event.

The first lepton (central electron) is required to have $E_T > 20 \text{ GeV}$, the second electron (muon) in the event to have $E_T (P_T) > 8 \text{ GeV}$, and the third electron (muon) to have $E_T (P_T) > 5 \text{ GeV}$.

7.2 Kinematic Variables

Having selected the leading two leptons in an event as above, the following kinematic variables were studied:

1. The invariant mass of the leading two leptons, shown in Figure 7.1 for each channel. The data agree well with the MC expectation apart from at low mass. We select events with an invariant mass greater than 20 GeV/c$^2$ to be reasonably far from the $J/\Psi$ and $\Upsilon$ resonances. Also
several of the MC samples we use (detailed in Table 6.1) are generated with \( M_H > 20 \text{ GeV}/c^2 \), so it is convenient to require this for the data. For the ee channels we also exclude events with invariant mass between 76 and 106 GeV/c\(^2\) to remove \( Z \rightarrow ee \) events.

2. The difference in azimuthal angle, \( \Delta \phi \), between the first two leptons, shown in Figure 7.2 after the cut on the invariant mass, is required to be less than 2.8 rad in order to remove di-jet QCD contributions (which are mostly back-to-back), Drell-Yan events that are not rejected by the invariant mass cut and \( Z \rightarrow \tau\tau \) events (for the e\(\mu\) channel).

3. We require the missing transverse energy in the event, shown in Figure 7.3 for events that pass the above two cuts, to be greater than 15 GeV. This selection removes remaining Drell-Yan events while keeping most of the signal.

4. Events with more than one jet (excluding those within \( \Delta R < 0.4 \) of an identified lepton) with corrected \( E_T > 20 \text{ GeV} \) are also removed, to reduce the \( t\bar{t} \) background. A distribution of the number of jets is shown in Figure 7.4 for events surviving the three preceding cuts.

The selection on each of these variables is applied sequentially in the order listed here. The cut values were chosen to retain high efficiency for the signal while reducing the major backgrounds, as seen in Figure 7.5, which shows the number of signal and background events surviving after each cut. We kept the cuts simple and intuitive so as not to be biased towards the exact kinematics of any given signal point.

The events which survive all the kinematic selections on the first two leptons and additionally contain a third lepton constitute the signal (cut 5 in Figure 7.5). The same mass cuts are applied to the third lepton with the first
Figure 7.1: The invariant mass of the leading two leptons in the central-central channel (top left), central-plug channel (top right) and $\mu\mu$ channel (bottom left), comparing data and backgrounds. The bottom right plot shows the distribution for the signal MC in each of the three channels.
Figure 7.2: The azimuthal angle (radians) between the leading two leptons in the central-central channel (top left), central-plug channel (top right) and e\(\mu\) channel (bottom left), comparing data and backgrounds. The bottom right plot shows the distribution for the signal MC in each of the three channels. The legend is as for Figure 7.1.
Figure 7.3: The missing transverse energy in the central-central channel (top left), central-plug channel (top right) and eµ channel (bottom left), comparing data and backgrounds. The bottom right plot shows the distribution for the signal MC in each of the three channels.
7.2 Kinematic Variables

- Central-central
  - Data
  - Fake lepton
  - $Z \rightarrow ee$
  - $Z \rightarrow \tau \tau$
  - $t\bar{t}$
  - $WZ$
  - $ZZ$
  - $WW$
  - $Z + \gamma$
  - $W + \gamma$

- Central-plug

- Electron-muon

- Signal
  - $CC$
  - $CP$
  - $\mu\nu$
Chapter 7: Event Selection

Figure 7.5: The number of events remaining after each cut (as described in Table 7.1) for the central-central channel (top left), central-plug channel (top right) and $e\mu$ channel (bottom left). The signal in each channel is indicated in black.
and second, i.e. the invariant mass with either must be greater than 20 GeV, and the Z window is rejected if the leptons are of the same type (cuts 6 and 7 in Figure 7.5).

Table 7.1 summarises the requirements for the signal region. This region is kept blind, meaning that the data in this region are not examined until after checks have been performed on the modelling of the background outside the signal region. These are described in the next section.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cut Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{T}(\ell_1)$</td>
<td>$&gt; 20$ GeV</td>
</tr>
<tr>
<td>$E_{T}(\ell_2)$</td>
<td>$&gt; 8$ GeV</td>
</tr>
<tr>
<td>$E_{T}(\ell_3)$</td>
<td>$&gt; 5$ GeV</td>
</tr>
<tr>
<td>$M_{t_1 t_2}$</td>
<td>$M &gt; 20$ GeV/$c^2$; for ee: $76 &lt; M &lt; 106$ GeV/$c^2$</td>
</tr>
<tr>
<td>$M_{t_1 t_3} / M_{t_2 t_3}$</td>
<td>$M &gt; 20$ GeV/$c^2$, $76 &lt; M &lt; 106$ GeV/$c^2$ (if same type)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi_{t_1 t_2}</td>
</tr>
<tr>
<td>$\not{E}_T$</td>
<td>$&gt; 15$ GeV</td>
</tr>
<tr>
<td>$N_{\text{jet}}(E_T &gt; 20)$</td>
<td>$\leq 1$</td>
</tr>
</tbody>
</table>

Table 7.1: The kinematic selections that define the signal region.

### 7.3 Control Regions

To gain confidence in the event selection and our understanding of the backgrounds we define a number of control regions. These are regions which fail one or more of the kinematic cuts defined above, in which we can compare data with the SM expectation without compromising our blind analysis.

The control regions are illustrated in Figure 7.6. For the $e\mu$ channel we do not apply a Z-veto cut, so we combine control regions A and E, G and H and J. We also compare the data to the SM prediction.
after an inclusive dielectron selection in the Z-mass range (control region Z). In each case we compare the number of events with two and with three leptons between the data and the SM prediction.

Figure 7.6: Illustration of the control regions.
7.3 Control Regions

7.3.1 Dilepton Control Regions

For each of the control regions shown in Figure 7.6 we compare data with the SM expectation before requiring a third lepton. Tables 7.2, 7.3 and 7.4 show the expected number of SM background events, the fake prediction from data, and the number of observed data events in each control region for each channel. We quote a statistical error from MC statistics, and a systematic error as described in Chapter 8. The agreement is good, giving us confidence in our understanding of the SM backgrounds and the fake rate.

The ee dilepton control regions are dominated by Drell-Yan production so the control regions are not very sensitive to the other backgrounds or the fake rate. However the $e\mu$ control regions have significant contributions from several backgrounds. Figure 7.7 shows the composition of the background and the number of data events in these control regions, displaying excellent agreement.

![Electron-muon](image)

Figure 7.7: Example control regions. Bin 1 is $A + E$, Bin 2 $G + I$, Bin 5 $A^2 + F$. 
Table 7.2: Number of expected and observed events in the dilepton control regions for the central-central channel, with statistical and systematic uncertainties on the total expectation.

<table>
<thead>
<tr>
<th>Control Region</th>
<th>Total MC</th>
<th>Fake</th>
<th>Total BG</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>64.8</td>
<td>14.1</td>
<td>79.0 ± 2.0</td>
<td>93</td>
</tr>
<tr>
<td>A2</td>
<td>13.0</td>
<td>2.0</td>
<td>15.0 ± 0.8</td>
<td>15</td>
</tr>
<tr>
<td>E</td>
<td>275.7</td>
<td>3.4</td>
<td>279.0 ± 4.0</td>
<td>290</td>
</tr>
<tr>
<td>F</td>
<td>30.9</td>
<td>0.6</td>
<td>31.4 ± 1.3</td>
<td>37</td>
</tr>
<tr>
<td>G</td>
<td>1121.2</td>
<td>33.0</td>
<td>1154.1 ± 8.2</td>
<td>1215</td>
</tr>
<tr>
<td>H</td>
<td>20.7</td>
<td>1.3</td>
<td>21.9 ± 1.1</td>
<td>31</td>
</tr>
<tr>
<td>I</td>
<td>6646.4</td>
<td>4.7</td>
<td>6651.1 ± 19.6</td>
<td>6867</td>
</tr>
<tr>
<td>J</td>
<td>102.1</td>
<td>0.2</td>
<td>102.3 ± 2.4</td>
<td>96</td>
</tr>
<tr>
<td>Z</td>
<td>8031.4</td>
<td>10.5</td>
<td>8041.9 ± 21.6</td>
<td>8218</td>
</tr>
</tbody>
</table>

Table 7.3: Number of expected and observed events in the dilepton control regions for the central-plug channel, with statistical and systematic uncertainties on the total expectation.

<table>
<thead>
<tr>
<th>Control Region</th>
<th>Total MC</th>
<th>Fake</th>
<th>Total BG</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>23.8</td>
<td>4.4</td>
<td>28.2 ± 1.2</td>
<td>30</td>
</tr>
<tr>
<td>A2</td>
<td>4.9</td>
<td>0.6</td>
<td>5.4 ± 0.5</td>
<td>3</td>
</tr>
<tr>
<td>E</td>
<td>190.2</td>
<td>1.7</td>
<td>191.9 ± 3.4</td>
<td>143</td>
</tr>
<tr>
<td>F</td>
<td>21.0</td>
<td>0.2</td>
<td>21.2 ± 1.1</td>
<td>18</td>
</tr>
<tr>
<td>G</td>
<td>557.5</td>
<td>13.3</td>
<td>570.7 ± 6.0</td>
<td>582</td>
</tr>
<tr>
<td>H</td>
<td>10.4</td>
<td>0.5</td>
<td>10.9 ± 0.8</td>
<td>10</td>
</tr>
<tr>
<td>I</td>
<td>5531.0</td>
<td>4.8</td>
<td>5535.8 ± 18.7</td>
<td>5659</td>
</tr>
<tr>
<td>J</td>
<td>75.3</td>
<td>0.2</td>
<td>75.4 ± 2.2</td>
<td>73</td>
</tr>
<tr>
<td>Z</td>
<td>6619.8</td>
<td>8.1</td>
<td>6627.9 ± 20.4</td>
<td>6654</td>
</tr>
</tbody>
</table>

7.3.2 Inclusive Z Cross Section

We use the events with two electrons in control region Z to measure the \( Z \to ee \) cross section times branching ratio. For central-central we find \( \sigma = 257 ± 3 \) pb.
Table 7.4: Number of expected and observed events in the dilepton control regions for the $e\mu$ channel, with statistical and systematic uncertainties on the total expectation.

<table>
<thead>
<tr>
<th>Control Region</th>
<th>Total MC</th>
<th>Fake</th>
<th>Total BG</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A + E</td>
<td>18.9</td>
<td>2.3</td>
<td>21.2 ± 1.0 ± 1.4</td>
<td>23</td>
</tr>
<tr>
<td>A2 + F</td>
<td>8.8</td>
<td>0.6</td>
<td>9.4 ± 0.4 ± 0.7</td>
<td>13</td>
</tr>
<tr>
<td>G + I</td>
<td>38.9</td>
<td>7.3</td>
<td>46.2 ± 2.2 ± 3.8</td>
<td>47</td>
</tr>
<tr>
<td>H + J</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8 ± 0.1 ± 0.2</td>
<td>0</td>
</tr>
</tbody>
</table>

and for central-plug $\sigma = 252 \pm 3$ pb, for $66 < M_Z < 106$ GeV/$c^2$. These are in excellent agreement with the value measured by CDF in 72 pb$^{-1}$ of data using both the electron and muon channels: $254.9 \pm 3.3$ (stat.) $\pm 4.6$ (sys.) $\pm 15.2$ (lum.) pb [60]. This gives confidence in the lepton selection and scale factors, the luminosity calculation and the Drell-Yan Monte Carlo.

7.3.3 Trilepton Control Regions

The control regions presented in Section 7.3.1 demonstrate a good understanding of the backgrounds and kinematic selection cuts. However, it is also important to correctly predict events with a third lepton. We attempt this in all regions apart from A and A2. A is the signal region, and hence blind, and A2 is very close to the signal and could have significant contributions from squark and gluino cascade decays of neutralinos and charginos.

The background expectations and observations for all other regions after the third lepton requirement are given in Table 7.5. The regions inside the $Z$ window and outside the $Z$ window are summed to improve the statistics.

In the central-plug channel, and to a lesser extent the central-central, the data seems a little higher than expected. We additionally studied control regions where we placed no tracking requirement on the third electron. This
Trilepton control regions with no tracking requirement on third central and central-plug channels combined. From left regions A, A2, E, F, G, H, I, J, Z.
7.3 Control Regions

display and found them consistent with what we expect from our selection. Example events are shown in Figure 7.9 for the central-central channel and Figure 7.10 for the central-plug.

![Figure 7.9: Example event displays showing the $r - \phi$ view for trilepton events in control region Z in the central-central channel. The arrow indicates the direction of missing $E_T$.](image-url)
Figure 7.10: Example event displays showing the $r - \phi$ view for tri-lepton events in control region $Z$ in the central-plug channel. The arrow indicates the direction of missing $E_T$. 
Chapter 8

Systematic Uncertainties

The systematic uncertainties on the signal and background predictions are divided into three categories: those correlated between signal and background, those affecting background alone and those affecting signal alone. The systematic uncertainties in each category are described in this section, and the effect on the signal and background for each channel is shown in Tables 8.1 and 8.2.

8.1 Correlated Uncertainties

Luminosity Measurement

The luminosity measured at CDF is assigned a 6% systematic uncertainty, as described in Section 3.2.6.

Lepton ID Scale Factors

As described in Sections 5.1.2 and 5.2.2, MC events are scaled by the ratio of the efficiency of lepton identification in data and MC. These ID scale factors for each class of lepton are given in Tables 5.3 and 5.5. For each event the scale factor uncertainties for each type of lepton (electron or muon) identified...
in the event are summed separately, and then added together in quadrature.

Jet Energy Scale and MET Uncertainty

The jet energy correction procedure described in Section 4.5 has an associated systematic error [46]. The jet energy scale is varied up and down by the systematic error provided and the effect on the signal and background prediction is determined. The uncertainty on the jet energy scale also leads to uncertainty in the measurement of missing transverse energy, through the correction procedure described in Section 4.6. This effect is also included in the jet energy scale systematic.

Trigger Efficiency

The uncertainty on the efficiency of the high-\(p_T\) electron trigger is 0.4\% [1], and this applies to all signal and background events. However, it is negligible compared to other uncertainties.

Conversion Scale Factor

The uncertainty of 28.8\% on the conversion finding efficiency scale factor described in Section 5.1.1 applies to all the events in which the conversion filter is used.

Parton Distribution Functions

Parton distribution functions (PDFs) describe the distribution of momenta of the various quarks and gluons which make up a proton or antiproton. Various parametrizations exist, and a systematic uncertainty on the acceptance for the signal and for each background can be obtained by varying the function
This was done using the CTEQ6M series [61], following the procedure described in [62].

8.2 Uncertainty on Signal

Initial and Final State Radiation

In order to study the systematic uncertainty due to the simulation of initial and final state radiation (ISR, FSR) of gluons or quarks in the signal Monte Carlo, we generated MC samples identical to the one described in Section 2.3.2 but with more or less ISR. As we only select events with leptons in the final state, we are insensitive to the uncertainty coming from FSR. The larger of the differences between the correct signal sample and the other samples is taken as the uncertainty on the acceptance.

Theory Cross Section

We use the uncertainty on the NLO cross-section as given by PROSPINO as an estimate of the systematic uncertainty on the cross section. This uncertainty is found to be 7%. The uncertainty on theoretical cross section of the signal is not considered for the limit on the cross section times branching ratio but is relevant for the extraction of a limit on the chargino mass.

8.3 Uncertainty on Background

Fake Rate

As stated in Section 6.2.1, we assign an uncertainty of 50% on the fake lepton background estimated from the data.
Chapter 8: Systematic Uncertainties

Monte Carlo Backgrounds

The cross sections for the backgrounds have all been evaluated at NLO. We quote an uncertainty of 10% [63] on $t\bar{t}$ production. In the other processes we evaluate the NNLO contribution by varying the renormalisation scale by a factor of two in MCFM.

Table 8.1 shows the effect of each systematic uncertainty on the signal prediction, and Table 8.2 on the background. The largest sources are the luminosity, the lepton ID scale factors and the lepton fake rate.

<table>
<thead>
<tr>
<th>Source</th>
<th>Central-central</th>
<th>Central-plug</th>
<th>$e\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Lepton ID</td>
<td>9.6%</td>
<td>11.8%</td>
<td>10.8%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1.7%</td>
<td>2.5%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.4%</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Conversion scale factor</td>
<td>6.1%</td>
<td>2.2%</td>
<td>1.3%</td>
</tr>
<tr>
<td>PDF</td>
<td>0.8%</td>
<td>0.8%</td>
<td>0.9%</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>4.5%</td>
<td>12.0%</td>
<td>6.8%</td>
</tr>
<tr>
<td>Theory Cross Section</td>
<td>7%</td>
<td>7%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 8.1: Sources of systematic uncertainties and the effect on the signal expectation for each channel
## 8.3 Uncertainty on Background

Table 8.2: Sources of systematic uncertainties and the effect on the predicted background for each channel

<table>
<thead>
<tr>
<th>Source</th>
<th>Central-central</th>
<th>Central-plug</th>
<th>eμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>4.6%</td>
<td>4.7%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Lepton ID</td>
<td>6.9%</td>
<td>12.0%</td>
<td>9.5%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>4.6%</td>
<td>3.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Conversion scale factor</td>
<td>5.0%</td>
<td>3.7%</td>
<td>0.5%</td>
</tr>
<tr>
<td>PDF</td>
<td>2.2%</td>
<td>2.2%</td>
<td>2.4%</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>3.2%</td>
<td>3.1%</td>
<td>3.3%</td>
</tr>
<tr>
<td>Fake rate</td>
<td>13.0%</td>
<td>9.7%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Theory Cross Section</td>
<td>4.9%</td>
<td>5.2%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>

The table shows that the central uncertainties vary between different sources, with some being higher than others. The eμ column indicates the predicted uncertainty for the eμ channel.
Chapter 9

Results

This section describes the results observed when the analysis was unblinded and the interpretation of these results. The results of other search channels for the trilepton signal at CDF are described and combined limits on the cross section times branching ratio for chargino-neutralino production and the mass of the chargino are set.

9.1 Expected and Observed Events

After performing the cross-checks described in 7.3 the analysis was unblinded, i.e. the data in the signal region defined in Table 7.1 were examined. The number of events expected from the backgrounds and from the signal can then be compared to the number of events observed in the data.

Table 9.1 shows the estimated signal and background for each channel in the signal region. The dominant backgrounds are $WZ$, $Z\gamma$ and fake leptons (one background of each type described in Chapter 6); $t\bar{t}$ is also significant for the $e\mu$ channel.

For the central-central channel we expect $0.29\pm0.08\pm0.05$ Standard Model background events in 346 pb$^{-1}$ and observe zero events. For the central-plug...
Table 9.1: Background and signal expectation after all cuts, and the observed number of events in data. The first uncertainty is statistical, the second systematic as discussed in Chapter 8.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Central-central</th>
<th>Central-plug</th>
<th>eµ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z + γ</td>
<td>0.11</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.08</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>Fake lepton</td>
<td>0.07</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>t£</td>
<td>0.01</td>
<td>0.004</td>
<td>0.02</td>
</tr>
<tr>
<td>Total BG</td>
<td>0.29 ± 0.08 ± 0.05</td>
<td>0.09 ± 0.02 ± 0.02</td>
<td>0.13 ± 0.02 ± 0.02</td>
</tr>
<tr>
<td>Signal</td>
<td>0.57 ± 0.03 ± 0.08</td>
<td>0.16 ± 0.02 ± 0.03</td>
<td>0.52 ± 0.03 ± 0.07</td>
</tr>
<tr>
<td>Observed</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

channel we expect 0.09 ± 0.02 ± 0.02 Standard Model background events in 318 pb⁻¹ and observe zero events. For the eµ channel we expect 0.13 ± 0.02 ± 0.02 Standard Model background events in 346 pb⁻¹ and observe zero events.

There is some overlap between the signal regions of the three channels which was estimated using the signal MC. A total of 0.07 events are common to central-central and central-plug, 0.17 to central-central and eµ and 0.04 to central-plug and eµ.

The total number of expected signal events for this particular point in the SUSY parameter space is thus 0.97 events, but we gain more statistical power by regarding the three channels as separate rather than summing the exclusive signal and background predictions in each channel.

9.2 Results From Other Search Channels

As well as the three channels described here, several other similar searches for the trilepton signal were performed at CDF, using common analysis tools such as the fake rate described in Section 6.2. Each analysis requires two isolated
leptons and large missing $E_T$. The differences between the analyses come in the trigger used to collect the data, and the types of leptons that were selected:

- A trigger for high-$P_T$ muons ($P_T > 18 \text{ GeV/cm}$) was used as an alternative to the high-$P_T$ electron trigger used for this analysis. Three channels were defined by the type of the second lepton (muon, central electron or plug electron) just as in this analysis. The third lepton in the event was required to be an identified electron or muon [64].

- A low-$P_T$ dilepton trigger was the basis of another class of analysis. The idea is that lowering the $P_T$ requirement on the first lepton will increase the acceptance of the analysis. Both $\mu\mu$ [65] and $ee$ [66] dilepton triggers were used. In the case of the $ee$ low-$P_T$ analysis, the requirement for the third lepton was relaxed to just an isolated track.

- A further class of analysis did not require a third lepton at all, but demanded that the leading two leptons were of the same charge [67]. This was broken down into $ee$, $e\mu$ and $\mu\mu$ channels.

These analyses are summarized in Table 9.2, together with the number of SM expected and observed events in each channel. In all cases, the number of observed events are consistent with the Standard Model expectation.

9.3 Combined Limit on Chargino-Neutralino Production

As no evidence of supersymmetry has been observed in any of the analyses, the results are combined to obtain a limit on the cross section times branching ratio for a range of points in the parameter space of the model. Two scenarios
9.3 Combined Limit on Chargino-Neutralino Production

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>$\mu + \tau$ [low-pt]</th>
<th>$\mu + \ell$ [high-pt]</th>
<th>$\mu e(CEM)+ \ell$</th>
<th>$\mu e(PLUG)+ \ell$</th>
<th>$ee$</th>
<th>$e\mu$ LS</th>
<th>$\mu \mu$ LS</th>
<th>$ee+$ track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$312 \text{ pb}^{-1}$</td>
<td>$745 \text{ pb}^{-1}$</td>
<td>$765 \text{ pb}^{-1}$</td>
<td>$680 \text{ pb}^{-1}$</td>
<td>$704 \text{ pb}^{-1}$</td>
<td>$704 \text{ pb}^{-1}$</td>
<td>$704 \text{ pb}^{-1}$</td>
<td>$607 \text{ pb}^{-1}$</td>
</tr>
<tr>
<td>Expected number of signal events</td>
<td>$0.17 \pm 0.04$</td>
<td>$1.61 \pm 0.22$</td>
<td>$0.83 \pm 0.06$</td>
<td>$0.64 \pm 0.01$</td>
<td>$0.91 \pm 0.16$</td>
<td>$0.92 \pm 0.09$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected number of SM background events</td>
<td>$0.13 \pm 0.03$</td>
<td>$0.64 \pm 0.18$</td>
<td>$0.42 \pm 0.08$</td>
<td>$0.36 \pm 0.07$</td>
<td>$2.60 \pm 0.30$</td>
<td>$3.50 \pm 0.60$</td>
<td>$0.73 \pm 0.08$</td>
<td>$0.40 \pm 0.10$</td>
</tr>
<tr>
<td>Number of observed events</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 9.2: Results of the analyses used for the combined limit. The first uncertainty is statistical, the second systematic.

were explored, obtaining the limit for the benchmark point in the mSUGRA scenario, and also investigating an mSUGRA-inspired MSSM scenario with the slepton masses set to the same value. In order to avoid double-counting of events, an exclusive acceptance for each channel was calculated, assigning events selected by more than one channel to the channel with the highest $S/\sqrt{B}$. An estimate for the exclusive background in each channel was made by scaling the background by the ratio of exclusive signal acceptance to total acceptance. This assumes that the overlap between channels is the same for the backgrounds as for the signal.

9.3.1 Procedure for Setting Limit

The procedure to calculate the combined limit on the cross section times branching ratio uses a modified frequentist approach [68] designed to easily combine independent searches for the same particle where the expected signal and background levels are small enough to require the use of Poisson statistics. The method also incorporates the effects of systematic uncertainties and their correlations across channels and between signal and background for the same channel.
In order to discriminate between signal-like and background-like results it is necessary to define a statistical variable that distinguishes between these. A good choice is the likelihood ratio (LR), defined for each channel as the ratio of the probabilities of obtaining the observed outcome under a signal plus background hypothesis to that under a background-only hypothesis. Let $s_i$ be the expected number of signal events in channel $i$, $b_i$ the estimated background in that channel, and $d_i$ the number of data events observed. The LR for each channel, $X_i$, is then given by:

$$X_i = \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!} \cdot \frac{e^{-b_i}b_i^{d_i}}{d_i!}$$  \hspace{1cm} (9.1)

For $n$ channels the LR is given by the product of the LRs of each channel:

$$X = \prod_{i=1}^{n} X_i$$  \hspace{1cm} (9.2)

The LR may then be used to compute confidence levels (CL). The confidence level for excluding the simultaneous presence of signal and background is the probability that, given the presence of signal and background at their hypothesized levels, the likelihood ratio would be less than or equal to that observed in the data. This is given by a sum of Poisson probabilities:

$$CL_{s+b} = P_{s+b}(X \leq X_{obs}) = \sum_{X(\{d_i\}) \leq X(\{d_i\})} \prod_{i=1}^{n} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!}$$

where $X(\{d_i\})$ is the LR computed for the observed set of candidates in each channel $\{d_i\}$ and the sum runs over all possible outcomes $\{d_i\}$ that lead to a LR less than or equal to that observed. The value $1 - CL_{s+b}$ may be used to quote exclusion limits, but it has the problem that if too few candidates are
9.3 Combined Limit on Chargino-Neutralino Production

observed to account for the estimated background, then the limits will be very
wrong, and even the background itself may be excluded at high confidence
level.

To remedy this problem it is necessary to calculate the CL for the back-
ground only hypothesis, $CL_b = P_b(X \leq X_{\text{obs}})$. The value of $CL_b$ gives the
probability that background processes alone would give rise to fewer than or
equal to the number of observed candidates. The CL used to quote limits in
the modified frequentist approach is given by

$$CL_4 = \frac{CL_{2+b}}{CL_4}$$

(9.3)

An upper limit, $N_{\text{Lim}}$, on the number of signal events is given when

$$CL_s \leq 0.05 \lor N > N_{\text{Lim}}$$

(9.4)

The task of summing the terms in equation 9.3 can be formidable: for $n$
channels each with $m$ possible outcomes there are $O(n^m)$ terms to compute. A
computer program (MCLIMIT) has been provided by the authors of the method,
allowing the sum to be performed using the probability distribution functions
for the LR. Statistical and systematic uncertainties on signal and background
estimations are taken into account by averaging over possible values of the
signal and background assuming the errors follow a Gaussian distribution with
the tails cut off at zero, so that negative values of $s$ and $b$ are not allowed.
Correlations between uncertainties are also taken into account by the method.

9.3.2 Results of Combined Limit

We find that by combining all the analyses listed in Table 9.2 for the benchmark
SUSY point described in Section 2.3.2 we can exclude values of cross section
times branching ratios of up to 0.225 pb at a 95% CL, which means that we are not able to exclude this point. An independent cross check using a Bayesian approach [69] was performed and the results found to be consistent within 10%.

However, we do not expect this point to be the one for which we have the best sensitivity, and so we also calculate the acceptance for the analyses at a series of other SUSY points. For each point a sample was generated using a combination of ISAJET and PYTHIA in an mSUGRA-like scenario with $\tan\beta = 3$, $A_0 = 0$, $\mu > 0$, $m_0 = 60, 78, 80, 82$ GeV/$c^2$ and $m_{1/2}$ ranging between 160 and 200 GeV/$c^2$. Slepton mixing was turned off by setting the slepton masses to be equal, as in the results published by D0 [16]. Some values of the theoretical cross section, $\sigma \times BR$ and masses considered in this study are shown in Figures 9.1 and 9.2, as a function of $m_0$, $m_{1/2}$ and the chargino mass.

The NLO cross section for each point was calculated using the NLO program PROSPINO [22]. The observed limit on $\sigma \times BR$ is plotted as a function of the chargino mass in Figure 9.3, for $m_0 = 60$ GeV/$c^2$. The expected limit is better than the observed limit because slightly more events were observed than expected from background. The shaded bands correspond to $\pm1\sigma$ and $\pm2\sigma$ uncertainties on the expected limit calculation. The limit curve has been fitted to avoid discontinuities due to poor statistics.

According to these results we can exclude masses of the $\tilde{\chi}_1^\pm$ above 127 GeV/$c^2$ for values of $\sigma \times BR \approx 0.25$ pb, compared to the expected limit of approximately 140 GeV/$c^2$. The limit obtained in the mSUGRA scenario with slepton mixing is shown in Figure 9.4 for comparison. Both the observed and expected limits are worse in this scenario due to the enhancement of the decay of the chargino and neutralino into final states with tau lepton. This reduces
Figure 9.1: The NLO theoretical values of the cross sections (left), the branching ratio into three leptons, and $\sigma \times BR$ (right) as a function of $m_0$ and $m_{1/2}$ taken from PROSPINO and ISAJET.
Figure 9.3: Branching fractions (left) and some sparticle masses (right) for the Monte Carlo points with (top row) and without (bottom row) slepton mixing.
the acceptance because of the branching ratio of $\tau \rightarrow e, \mu$ and the lower momenta of the electrons and muons in the final state. Limits as a function of the mass of the selectron and of the difference between the selectron and the chargino masses are shown in Figure 9.5.

To test the robustness of the limit-setting procedure, the limit was recalculated with all the systematic uncertainties set to zero. The limit improved by only about 3%, demonstrating that the systematic uncertainties have little effect.

Figure 9.3: The excluded cross section limit plotted as a function of the chargino mass for $m_0=60$ GeV/c$^2$ (black solid line) in an mSUGRA-like scenario with slepton mixing turned off.
Figure 9.4: The excluded cross section limit plotted as a function of the chargino mass for $m_0=60$ GeV/c$^2$ (black solid line) with slepton mixing turned on.
9.3 Combined Limit on Chargino-Neutralino Production

Figure 9.5: The excluded cross section limit plotted as a function of the selectron mass (top) and the difference between chargino and selectron masses (bottom) for $m_0=60$ GeV/c$^2$ for an mSUGRA-like scenario (left) and with slepton mixing turned off (right).
Chapter 10

Conclusion

This thesis describes a search for associated production of the supersymmetric particles $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ in the trilepton channel at CDF Run II. A search strategy was devised to select SUSY candidates while rejecting the major Standard Model backgrounds. The modelling of these backgrounds was shown to be well understood, and systematic uncertainties were determined.

In 346 pb$^{-1}$ of data, the observed number of events was consistent with the Standard Model prediction. Since no evidence of supersymmetry was found, the results were used to set a limit in SUSY parameter space. It was possible to exclude $\tilde{\chi}_1^\pm < 127 \text{ GeV/c}^2$ for certain SUSY scenarios. An update to this analysis, employing the same methods and using 1 fb$^{-1}$ of data, has just been completed, and CDF hopes to collect 8 fb$^{-1}$ of data before Run II ends.

Searching for new physics can be a frustrating endeavour. So far, the Tevatron has failed to storm the bastion of the Standard Model, but the Large Hadron Collider now looms large. Theorists tell us there simply must be something in the energy range it will access; so even if nothing is found, that will be a very interesting result! Exciting times are ahead, and I look forward to reporting on them in my new job as a scientific journalist.
Bibliography


