**Search for a Heavy Top-Like Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV at
the Tevatron**

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David J. Cox

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Approved:

Robin Erbacher, Chair

John Conway

Maxwell Chertok

Committee in Charge

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Abstract

We present the results of a search for pair production of a heavy top-like (t') quark decaying to Wq final states using data corresponding to an integrated luminosity of 5.6 fb^{-1} collected by the CDF II detector in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. A search for $t' \rightarrow Wb$ in events containing a lepton and four or more jets is conducted. By performing a fit to the two-dimensional distribution of total transverse energy versus reconstructed t' quark mass, we set upper limits on the $t'\bar{t}'$ production cross section and exclude a standard model fourth-generation t' quark decaying to Wb with mass below $358 \text{ GeV}/c^2$ at 95% CL.

To my mother Millicent Cox without whom none of this would've been possible.

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Chapter 1

Introduction

1.1 Introduction

In their effort to build a mathematical model that describes the fundamental forces and building blocks of the universe, physicists have constructed a standard model of particle physics (SM) that achieves a phenomenal degree of accuracy and predictive capability. The SM describes three of the four fundamental forces (the electromagnetic, weak and strong forces but not gravity which is too weak to impact particle physics events) as well as describing the fundamental attributes of the particles that comprise the matter we interact with on a daily basis.

Herein the SM will be briefly introduced and described emphasizing those aspects which are relevant to the expansion of the model to four generations and motivation for the addition of a fourth generation of quarks to the model will be introduced. The experimental search for such a fourth generation top-like quark (t') is the topic of this thesis.

1.1.1 Basics of the Standard Model

The SM describes three categories of particles; gauge bosons, leptons and quarks. Quarks are basic elementary particles which interact with the strong force, leptons are basic elementary particles which do not interact with the strong force and gauge bosons

generation	particles	charge	spin	$\sim$ mass
1st	u	$+\frac{2}{3}$	$\frac{1}{2}$	1.5 - 3.3 MeV / c^2
1st	d	$-\frac{1}{3}$	$\frac{1}{2}$	3.5 - 6 MeV / c^2
2nd	c	$+\frac{2}{3}$	$\frac{1}{2}$	1.27 GeV / c^2
2nd	s	$-\frac{1}{3}$	$\frac{1}{2}$	105 MeV / c^2
3rd	t	$+\frac{2}{3}$	$\frac{1}{2}$	173.3 GeV / c^2
3rd	b	$-\frac{1}{3}$	$\frac{1}{2}$	4.2 GeV / c^2

Table 1.1: Quark Properties

generation	particles	charge	spin	mass
1st	e	-1	$\frac{1}{2}$	$0.511 \text{ MeV} / c^2$
1st	ν_e	0	$\frac{1}{2}$	$< 2 \text{ eV} / c^2$
2nd	μ	-1	$\frac{1}{2}$	$105 \text{ MeV} / c^2$
2nd	ν_μ	0	$\frac{1}{2}$	$< 0.19 \text{ MeV} / c^2$
3rd	τ	-1	$\frac{1}{2}$	$1.777 \text{ GeV} / c^2$
3rd	ν_τ	0	$\frac{1}{2}$	$< 18.2 \text{ MeV} / c^2$

Table 1.2: Lepton Properties

particles	charge	spin	$\sim$ mass
γ	0	1	$< 1 \times 10^{-18} \text{ eV} / c^2$
g	0	1	$0 \text{ eV} / c^2$
$W^\pm$	± 1	1	$80.385 \text{ GeV} / c^2$
Z^0	0	1	$91.1876 \text{ GeV} / c^2$

Table 1.3: Boson Properties

are force mediators associated with one of the three fundamental forces described by the SM. In the SM there are six quark types (up and down, charm and strange, top and bottom), six lepton types (electrons, muons, taus and associated neutrinos) with each set being organized into generations or pairs of particles whose quantum numbers are duplicated in the other generations and are only distinguished from each other by their mass. The quarks are summarized in Table 1.1, the leptons in Table 1.2. For each of these particles there also exist anti-particles, and the quarks each come in three "colors" or color charges for a total of 36 quarks and 12 leptons. The gauge bosons are the force mediators, the photons (γ) mediate the electromagnetic force, the W and Z bosons the weak force and for the gluons (g) mediate the strong force, these are summarized in Table 1.3.

The electromagnetic interaction is probably the best known of the SM interactions and has a long history of investigation. It is described by quantum electrodynamics (QED), a gauge theory with an Abelian $U(1)$ symmetry. QED is formulated as a quantum field theory and is renormalizable and generally well-behaved, with higher order loop integrals manageable via perturbation theory because of the small coupling

constant $\alpha = \frac{e^2}{4\pi} \simeq \frac{1}{137}$ (1).

The theory of the weak interaction was originally developed by Fermi to describe the current-current interaction with $V - A$ currents. The initial theory was later developed in the framework of non-Abelian gauge theory with $SU(2)_L \times U(1)_Y$ which is now called the electroweak standard model, including the weak and electromagnetic interactions.

The strong interaction describes color interactions between quarks. It has the largest coupling constant of the known interactions and is responsible for keeping the quarks inside hadrons and mesons together. The corresponding field theory in the standard model is the non-Abelian gauge theory with $SU(3)_c$ color symmetry and is called quantum chromodynamics (QCD).

The guiding symmetry of the SM then is described by the simple direct product of the symmetry for the strong interactions $SU(3)_c$ and that describing the electroweak $SU(2)_L \times U(1)_Y$, or $G = SU(3)_c \times SU(2)_L \times U(1)_Y$. The quantum field theory that obeys that symmetry is the SM described previously and is characterized by three important principles, that it is a gauge theory, that it is renormalizable and that the symmetry breaking occurs spontaneously.

1.1.1.1 Quantum Electrodynamics: QED

The Lagrangian $\mathcal{L}$ describing the field of a single free fermion with mass m is expressed as

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi \quad (1.1)$$

where ψ is a 4-component spinor field of the fermion and $\partial_\mu = \partial/\partial x^\mu$ ($\mu = 0,1,2,3$). γ^μ are the 4 x 4 Dirac matrices and the summation over μ is implied via the standard conventions while the m is understood to be multiplied by a 4 x 4 unit matrix I . The gauge transformation of this system is described by

$$\psi \rightarrow \psi' = e^{i\phi}\psi = U_\phi\psi \quad (1.2)$$

Since ϕ is defined as constant everywhere in space-time, it follows immediately that the transformation is unitary, that is $U_\phi^\dagger U_\phi = 1$ and that it is Abelian, that is $U_{\phi_1}U_{\phi_2} = U_{\phi_2}U_{\phi_1}$. So the transformation 1.2 is global, unitary and Abelian, it is denoted by $U(1)$.

Making the global symmetry a local symmetry, by for example, introducing an x -dependent phase parameter $\phi(x)$. Then the kinetic term becomes no longer invariant, that is

$$\mathcal{L} \rightarrow \mathcal{L}' = \mathcal{L} - j^\mu(x) \partial_\mu \psi(x) \quad (1.3)$$

where $j^\mu(x) = \bar{\psi} \gamma^\mu \psi$ is the vector Noether current. In order to restore the invariance, ∂_μ must be replaced with the covariant derivative D_μ

$$D_\mu \equiv \partial_\mu - ieA_\mu \quad (1.4)$$

where A_μ is a vector field (spin 1) that transforms like

$$A_\mu \rightarrow A'_\mu \equiv A_\mu + \frac{1}{e} \partial_\mu \phi(x). \quad (1.5)$$

The Lagrangian therefore becomes

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi + e\bar{\psi}\gamma^\mu \psi A_\mu \quad (1.6)$$

which is invariant under the local transformation. A kinematic term is needed for the new field, which is added as

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (1.7)$$

where F is the electromagnetic field tensor, defined as:

$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu. \quad (1.8)$$

So the resultant total Lagrangian is

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}. \quad (1.9)$$

The field theory with $\mathcal{L}_{QED}$ is called quantum electrodynamics (QED), the Lagrangian obeys the global unitary and Abelian symmetry $U(1)$ and the interactions described 1.9 encompass the entirety of QED.

lepton family	Q	(T, T^3)	Y
ν_e, ν_μ, ν_τ	0	$(\frac{1}{2}, +\frac{1}{2})$	-1
e_L, μ_L, τ_L	-1	$(\frac{1}{2}, -\frac{1}{2})$	-1
e_R, μ_R, τ_R	-1	0	-2

Table 1.4: Quantum number assignment of lepton families in the GWS model

1.1.1.2 Electroweak Theory

The standard model electroweak theory is a non-Abelian gauge theory with $SU(2)_L \times U(1)_Y$ gauge symmetry. It represents as a unified whole the electromagnetic and weak interactions. Since in weak process only couplings between left-handed leptons and right-handed anti-leptons are observed the model is constructed representing each family of leptons by a left-handed doublet L and a right-handed singlet R or the $SU(2)$ group:

$$L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, R = e_R \quad (1.10)$$

and more completely the quantum numbers are represented as seen in 1.5. Where the weak hypercharge (Y) is related to the electromagnetic charge Q and the $SU(2)$ generators T

$$Q = T^3 + \frac{Y}{2}. \quad (1.11)$$

Then the Lagrangian is to be constructed with L and R which should be invariant under the $SU(2)_L$ and $U(1)_Y$ groups or

$$SU(2)_L : L \rightarrow L' = e^{-i\alpha^i(x)\tau^i/2}L, R \rightarrow R' = R, \quad (1.12)$$

$$U(1)_Y : L \rightarrow L' = e^{i/2\beta(x)}L, R \rightarrow R' = e^{i\beta(x)}R \quad (1.13)$$

This is constructed as

$$\mathcal{L}_F = \bar{L}i\gamma^\mu(\partial_\mu - ig\frac{\vec{\tau}}{2} \cdot \vec{A}_\mu + \frac{i}{2}g'B_\mu)L + \bar{R}i\gamma^\mu(\partial_\mu + ig'B_\mu)R \quad (1.14)$$

where A_μ^i ($i = 1, 2, 3$) and B_μ are gauge boson fields associated with $SU(2)_L$ and $U(1)_Y$, respectively. g and g' are the gauge coupling constants corresponding to $SU(2)_L$ and $U(1)_Y$, respectively. The covariant derivatives are given by

$$D_\mu = \partial_\mu - ig\frac{\vec{\tau}}{2} \cdot \vec{A}_\mu - ig'\frac{Y}{2}B_\mu. \quad (1.15)$$

The kinetic term of the gauge fields is given by

$$\mathcal{L}_G = -\frac{1}{4}F_{\mu\nu}^i F^{i\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \quad (1.16)$$

$$F_{\mu\nu}^i = \partial_\mu A_\nu^i - \partial_\nu A_\mu^i + g\epsilon_{ijk}A_\mu^j A_\nu^k \quad (1.17)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad (1.18)$$

where $F_{\mu\nu}^i$ ($i=1,2,3$) is the field strength tensor the gauge field corresponding to $SU(2)_L$ and $B_{\mu\nu}$ is the field strength tensors of the gauge field corresponding to $U(1)_Y$. In both 1.14 and 1.18 the mass terms do not appear as they would violate invariance requirements. In order to add mass to the fermions and gauge bosons spontaneous symmetry breaking, i.e. the Higgs mechanism is needed. Since a massless photon should be present after symmetry breaking it is necessary that

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}. \quad (1.19)$$

The simplest model to accomplish this is by adding a $SU(2)$ doublet of 2 complex scalar fields, ϕ with weak hypercharge $Y_\phi = +1$. The Lagrangian for the scalars is

$$\mathcal{L}_s = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) \quad (1.20)$$

with the potential term $V(\phi^\dagger \phi)$ given by

$$V(\phi^\dagger \phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (1.21)$$

where m^2 and λ are real constant parameters. Finally the coupling term between the fermions and scalars which are to provide the fermion mass is added. It is called the Yukawa interaction term

$$\mathcal{L}_Y = -G_e(\bar{L}\phi R + \bar{R}\phi^\dagger L) + h.c. \quad (1.22)$$

and the full set of the $SU(2)_L \times U(1)_Y$ gauge invariant Lagrangian of the GWS model is then just

$$\mathcal{L} = \mathcal{L}_F + \mathcal{L}_G + \mathcal{L}_s + \mathcal{L}_Y. \quad (1.23)$$

So far only the case for one family has been discussed. To extend the model with additional generations the different components must be extended. The fermion sector is extended simply, namely

$$\mathcal{L}_F = \mathcal{L}_F^{(e)} + \mathcal{L}_F^{(\mu)} + \mathcal{L}_F^{(\tau)} \quad (1.24)$$

Where both terms are the same as 1.14 with the appropriate substitution of fermion field terms L and R by $L_{e/\mu/\tau}$ and $R_{e/\mu/\tau}$ as appropriate. However, for the Yukawa term additional interaction terms are necessary

$$\mathcal{L}_Y = -G_{ij}\bar{L}_i\phi R_j + h.c. \quad (1.25)$$

where $i,j = e, \mu, \tau$ and after symmetry breaking the fermion mass terms are obtained

$$\mathcal{L}_F^{(mass)} = -\vec{\bar{l}} M \vec{r} + h.c. \quad (1.26)$$

where

$$\vec{\bar{l}} = \begin{pmatrix} \bar{e}_L & \bar{\mu}_L & \bar{\tau}_L \end{pmatrix} \quad (1.27)$$

$$\vec{r} = \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix} \quad (1.28)$$

and where M is the mass matrix, a 3 x 3 complex not necessarily hermitian matrix. In general it can be diagonalized by a transformation

$$U^\dagger M V = M_d \quad (1.29)$$

where M_d is a diagonal matrix and U and V are unitary matrices. Via redefining non-observable phases of the lepton fields once can further make the elements of M_d real and positive. Then $\mathcal{L}_F^{(mass)}$ can be rewritten as

$$\mathcal{L}_F^{(mass)} = -\vec{\bar{l}} M \vec{r}' + h.c. \quad (1.30)$$

where

$$\begin{pmatrix} e'_L \\ \mu'_L \\ \tau'_L \end{pmatrix} = U^\dagger \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} \quad (1.31)$$

$$\begin{pmatrix} e'_R \\ \mu'_R \\ \tau'_R \end{pmatrix} = V^\dagger \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix} \quad (1.32)$$

Then the prime states are the mass eigenstates which are not equal to current/weak eigenstates in general. The observed states are the mass eigenstates, so when the interactions in the generation space (mass) intergenerational mixing is allowed. It is

quark family	Q	(T, T^3)	Y
u_L, c_L, t_L	$+\frac{2}{3}$	$(\frac{1}{2}, +\frac{1}{2})$	$+\frac{1}{3}$
d_L, s_L, b_L	$-\frac{1}{3}$	$(\frac{1}{2}, -\frac{1}{2})$	$+\frac{1}{3}$
u_R, c_R, t_R	$+\frac{2}{3}$	0	$+\frac{4}{3}$
d_R, s_R, b_R	$-\frac{1}{3}$	0	$-\frac{2}{3}$

Table 1.5: Quantum number assignment of quark families

this mixing that leads to neutrino oscillations when massive neutrinos are included in the model.

Extending this to quarks is relatively straightforward. Three SU(2) doublets (corresponding to the left-handed quarks of each of the three generations) are added, with one up-type and one down-type quark in each doublet and 6 singlets, corresponding to the right-handed quarks of each generation. To allow for compactness the following notation is introduced

$$Q_{Li} = \begin{pmatrix} U_i \\ D_i \end{pmatrix}, \quad U_{Ri}, \quad D_{Ri} \quad (i = 1, 2, 3) \quad (1.33)$$

where i stands for the generation: $U_1 = u$, $D_1 = d$, etc. Then the Lagrangian can be written in terms of the quarks and their covariant derivatives as

$$\mathcal{L}_F = \sum_{i=1}^3 \bar{Q}_{Li} i \gamma^\mu (\partial_\mu - i g \frac{\vec{\tau}}{2} \cdot \vec{A}_\mu - \frac{i}{6} g' B_\mu) Q_{Li} \quad (1.34)$$

$$+ \sum_{i=1}^3 \bar{U}_{Ri} i \gamma^\mu (\partial_\mu - i \frac{2}{3} g' B_\mu) U_{Ri} \quad (1.35)$$

$$+ \sum_{i=1}^3 \bar{D}_{Ri} i \gamma^\mu (\partial_\mu + i \frac{1}{3} g' B_\mu) D_{Ri}. \quad (1.36)$$

The gauge field terms $\mathcal{L}_G$ and scalar field terms $\mathcal{L}_s$ are the same as the leptons. The Yukawa terms can be written as

$$\mathcal{L}_Y = - \sum_{i,j} (\Gamma_{i,j}^{(D)} \bar{Q}_{Li} \phi D_{Rj} + \Gamma_{i,j}^{(U)} \bar{Q}_{Li} \tilde{\phi} U_{Rj} + h.c.) \quad (1.37)$$

where the $\Gamma_{i,j}^{(D/U)}$ are Yukawa couplings which in general are unconstrained complex parameters and $\tilde{\phi}$ is defined from ϕ as $\tilde{\phi} = i \tau_2 \phi^*$, where ϕ^* is the complex conjugate

of ϕ . The mass matrices and flavor changing behavior in the quark sector functions similarly to the lepton sector.

1.1.1.3 Quantum Chromodynamics

In the standard model the theory of the strong interactions is quantum chromodynamics (QCD), a non-Abelian gauge theory with SU(3) color symmetry. The QCD Lagrangian for the interaction between quarks q and gluons A_μ^i for ($i=1,2,\dots,8$) is given by

$$\mathcal{L} = \bar{q}(i\not{D} - m)q - \frac{1}{4}F_{\mu\nu}^i F^{u\mu\nu} \quad (1.38)$$

and the quark field q and covariant derivative are given by

$$q = \begin{pmatrix} q^R \\ q^G \\ q^B \end{pmatrix} \quad (1.39)$$

$$D_\mu = \partial_\mu - ig_s \frac{\lambda^i}{2} A_\mu^i. \quad (1.40)$$

Here the superscripts R,G,B stand for red, green and blue respectively, g_s is the strong coupling constant and λ^i are the 3 x 3 Gell-Mann matrices. $F_{\mu\nu}$ are the field strength tensor for gluon fields A_μ^i and are given by

$$F_{\mu\nu}^i = \partial_\mu A_\nu^i - \partial_\nu A_\mu^i + g_s f_{ijk} A_\mu^j A_\nu^k \quad (1.41)$$

where f_{ijk} are the structure constants of the color $SU(3)_c$ group. There are several important consequences of the chosen structure of QCD. Firstly the extra term, which corresponds to the non-Abelian nature of QCD, compared to QED leads to gluon self-interactions. These in turn can be shown to lead to anti-screening in the coupling constants, or "asymptotic freedom," $\alpha_s(Q^2)$ decreases with increasing Q^2 , while for small Q^2 $\alpha_s(Q^2)$ becomes large.

This essentially divides QCD into two regions, for large values of Q^2 quarks and gluons behave as free particles ("asymptotic freedom") and perturbative calculations are valid. This corresponds to behavior such as deep inelastic scattering. For small Q^2 the quark-gluon coupling becomes large, perturbative calculations are invalid and the quarks and gluons are confined in hadrons ("confinement"). This is responsible for the observed lack of free quarks/gluons in nature. QCD then is the color SU(3) non-Abelian gauge theory of strong interactions.

1.1.1.4 The Higgs Mechanism

As mentioned previously, mass terms can not be directly added into the electroweak theory without violating gauge invariance. The way in which the standard model avoids this problem is via adding masses via spontaneous symmetry breaking through the Higgs mechanism.

Consider adding a complex doublet field $\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$ to the SU(2) gauge invariant Lagrangian. Then

$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) - \frac{1}{4} F_{\mu\nu}^i F^{i\mu\nu} - V(\phi^\dagger \phi) \quad (1.42)$$

and

$$D_\mu \phi = (\partial_\mu - ig \frac{\tau^i}{2} A_\mu^i) \phi, \quad (i = 1, 2, 3) \quad (1.43)$$

$$F_{\mu\nu}^i = \partial_\mu A_\nu^i - \partial_\nu A_\mu^i + g \epsilon_{ijk} A_\mu^j A_\nu^k, \quad (1.44)$$

$$V(\phi^\dagger \phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad (\mu^2 > 0) \quad (1.45)$$

. Then parametrize the field $\phi(x)$ in terms of the new real field $H(x)$ and $\xi^i(x)$ ($i = 1, 2, 3$) as

$$\phi(x) = \frac{1}{\sqrt{2}} e^{i\tau^i \xi^i(x)/2\nu} \begin{pmatrix} 0 \\ \nu + H(x) \end{pmatrix} \quad (1.46)$$

Then transform the fields according to a particular gauge transformation, the unitary gauge, as follows

$$\phi(x) \rightarrow \phi'(x) = U(x) \phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H(x) \end{pmatrix} \quad (1.47)$$

$$\vec{A}_\mu \rightarrow \vec{B}_\mu = U(x) \vec{A}_\mu U^{-1} - \frac{i}{g} (\partial_\mu U) U^{-1} \quad (1.48)$$

$$U(x) = e^{-i\tau^i \xi^i(x)/2\nu}. \quad (1.49)$$

Then the Lagrangian becomes

$$\mathcal{L} = (D_\mu \phi)'^\dagger (D^\mu \phi)' - \frac{1}{4} F_{\mu\nu}^i(B) F^{i\mu\nu}(B) + \mu^2 (\phi'^\dagger \phi') - \lambda (\phi'^\dagger \phi')^2. \quad (1.50)$$

If the Lagrangian is extrapolated in terms of the component fields of ϕ' then

$$\mathcal{L} = \frac{1}{2} \partial_\mu H \partial^\mu H - \mu^2 H^2 - \frac{1}{4} F_{\mu\nu}^i(B) F^{i\mu\nu}(B) + \frac{g^2 \nu^2}{8} B_\mu^i B^{i\mu} \quad (1.51)$$

$$+ \frac{g^2}{8} B_\mu^i B^{i\mu} H (2\nu + H) - \lambda \nu H^3 - \frac{\lambda}{4} H^4 - \frac{\nu^4}{4} \quad (1.52)$$

is obtained.

The three Goldstone boson $\xi^i(x)$ fields have disappeared, replaced by a triplet of massive vector fields B_μ^i and a single massive scalar. In other words the Goldstone bosons were "eaten" by the gauge bosons to make their longitudinal components. This is the same basic mechanism by which the Higgs mechanism works under other symmetries. When applied to the $SU(2)_L \times U(1)_Y$ theory, that is, electroweak theory it leads to the fermions obtaining mass through the Yukawa couplings and the creation of the massive gauge bosons ($W^\pm, Z$) and a new Higgs boson (H).

1.1.2 Limits on a fourth generation

One of the simplest ways to expand the SM is the addition of a fourth generation of chiral matter. This sort of expansion has been considered many times without a leading candidate emerging, creating a mistaken impression in some that it is ruled out or highly disfavored by experimental data. It makes sense to examine what limits current experimental results place on such a fourth generation (2).

Before the recent discovery of a new Higgs-like particle at mass 125 GeV (3, 4) the most clear cut limitation on a fourth generation was probably the result from the LEP experiment looking at Z decays. The LEP experiment measured the cross section for Z boson decays to invisible particles and were able to exclude quite strongly a fourth neutrino decay (see Figure 1.2). This limits requires any potential fourth generation neutrino to be sufficiently heavy that the Z boson cannot decay into two of them.

Under the assumption that the recently seen Higgs-like particle is indeed the Higgs boson of the SM, a simple addition of a fourth generation to the SM is strongly discouraged (5). Interesting models exist (for example the generic two-Higgs-doublet model with fourth-family SM fermions (6)) which contain standard fourth-generation quarks. Additionally for models which use vector-like quarks (for example the Beautiful Mirrors model described in 1.1.3.4) the constraints arising from the Higgs-like particle do not apply. Both of these sorts of models can include quarks which would have decay signatures identical to that searched for in this analysis.

Another limitation on a fourth generation arises from the impact of a fourth generation on precision electroweak oblique parameters. The precision electroweak oblique

parameters are parameterized as S , T and U defined as

$$S = -16\pi \frac{\Pi_{3Y}(m_Z^2) - \Pi_{3Y}(0)}{m_Z^2}, \quad (1.53)$$

$$T = 4\pi \frac{\Pi_{11}(0) - \Pi_{33}(0)}{s_W^2 c_W^2 m_Z^2}, \quad (1.54)$$

$$U = 16\pi \frac{[\Pi_{11}(m_Z^2) - \Pi_{11}(0)] - [\Pi_{33}(m_Z^2) - \Pi_{33}(0)]}{m_Z^2}, \quad (1.55)$$

where the weak-mixing angle θ_W is defined at the scale $\mu = m_Z$. Π_{11} and Π_{33} are the vacuum polarizations of isospin currents and Π_{3Y} is the vacuum polarization of one isospin and one hypercharge current. The SM global fit to these parameters from various measured electroweak observables (7) gives:

$$S = -0.04 \pm 0.11, \quad (1.56)$$

$$T = -0.03 \pm 0.13, \quad (1.57)$$

$$U = 0.18 \pm 0.14, \quad (1.58)$$

where a SM Higgs mass of 100 GeV is used (using different Higgs masses can have significant effects on the central values here).

The presence of a fourth generation enhances $B \leftrightarrow W^3$ mixing is enhanced leading to a positive contribution $\Delta S = 0.21$. Three important effects can mitigate this contribution. Firstly experimental constraints are comparatively insensitive to the $\Delta S \simeq \Delta T$ direction in oblique parameter space. Secondly splitting the fourth generation multiplet in a particular mass hierarchy can minimize this ΔS contribution, and finally a Majorana mass for the fourth generation neutrino reduces ΔS . Some specific parameterizations and their resultant contributions to S and T can be seen in Table 1.6 (2) and their relationship to the SM values and their errors in Figure 1.1 (2).

Limitations on the construction of a fourth generation also derive from previous direct searches for fourth generation particles. These experimental limits constrain fourth generation particles to be heavy relative to their third generation counterparts but leave ample room for reasonable constructions.

Lastly measurements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix describing inter-generational mixing in the known three generations of standard model quarks limit fourth generation constructions. These limitations emplace upper bounds on mixing between a fourth generation and the SM's three generations.

parameter set	m_{u4}	m_{d4}	m_H	ΔS_{tot}	ΔT_{tot}
(a)	310	260	115	0.15	0.19
(b)	320	260	200	0.19	0.20
(c)	330	260	300	0.21	0.22
(d)	400	350	115	0.15	0.19
(e)	400	340	200	0.19	0.20
(f)	400	325	300	0.21	0.25

Table 1.6: Examples of total contributions to ΔS and ΔT from a fourth generation. Here the lepton masses are fixed with $m_{\nu 4} = 100$ GeV and $m_{l4} = 155$ GeV

Figure 1.1: The 68% and 95% CL constraints on the (S, T) parameters from the LEP Electroweak Working Group. Shifts in theoretical value associated with changing Higgs mass shown in red, in blue the shifts associated with three of the fourth generation parameter choices in Table 1.6

Figure 1.2: LEP result measuring Z boson invisible decay cross section.

1.1.3 Fourth Generation Possibilities

Several theoretical models include a fourth generation of quarks or other heavy quark-like objects. Five will be briefly discussed here; "Flavor democracy" (8), "GUT $SO(1, 13)$ " (9), N=2 supersymmetric theories (7), "beautiful mirrors" (10) and the "Little Higgs" class of theories (11).

1.1.3.1 Flavor Democracy

In the democratic 4×4 limit all Yukawa couplings between lepton generations are equal and only the fourth generation of each lepton sector acquires mass. Democracy provides an alternative explanation (to for example the see-saw mechanism) for the smallness of neutrino masses since it doesn't require small Yukawa couplings for the neutrinos only that they be almost equal. In the flavor-democratic theory one naturally obtains the large mixing angles observed in neutrinos after breaking the symmetry. Flavor democracy would require an extra generation of quarks in order to have anomaly cancelation but otherwise constrains only leptons.

1.1.3.2 GUT $SO(1, 13)$

The GUT $SO(1, 13)$ theory is an attempt to unify all the internal degrees of freedom in the theoretical framework, i.e. construct a grand unified theory or GUT. It does this by considering spinors living in a $1 + 13$ dimensional space specifically a left-handed $SO(1, 13)$ Weyl spinor multiplet. Assuming some properties of the symmetry breaking and that the mass matrices are real and symmetric this theory then ends up with four families of quarks and leptons. In this theoretical model quark masses can lie between 200 GeV and 1 TeV, the fourth neutrino lies between 50 and 100 GeV in mass and the fourth lepton lies within the 50 to 200 GeV mass range. Fits performed to experimental data gave a best fit value of 285.2 GeV for the fourth generation up-like quark in this model.

1.1.3.3 N=2 Supersymmetry

N = 2 supersymmetry constructions enforce an even number of generations, mandating in practice three additional mirror families of chiral fermions. All of these matter

fermions originate at low-energy from effective Yukawa couplings and are chiral and have a natural mass range of roughly,

$$\frac{m_Z}{2} \lesssim M_f \lesssim \mathcal{O}(\langle H \rangle). \quad (1.59)$$

These extra families of fermions would have quark masses in the range of hundreds of GeV making them viable candidates to be seen in this search.

1.1.3.4 Beautiful Mirrors

In an effort to explain the discrepancy within the SM between the values for the weak mixing angle as obtained from the measurement of the leptonic and hadronic asymmetries at lepton colliders, the beautiful mirrors theory proposes the addition of additional bottom-like quarks. These additional bottom-like quarks significantly improve this disagreement and can be accompanied by top-like quarks which would be candidates to be seen in this search.

1.1.3.5 Little Higgs

Little Higgs models are an alternative to supersymmetric models which stabilize the light Higgs boson mass by introducing new particles that are not supersymmetric. These new particles can include particles with a wide variety of attributes including candidates for the top-like quark searched for in this work.

1.1.4 Overview

This work will continue in the next chapter by describing the Tevatron facility and the CDF II experiment. The third chapter will discuss event reconstruction at CDF. The fourth chapter will give an overview of techniques of event simulation. The fifth chapter will discuss the techniques used for reconstructing the top or t' mass of an event. The sixth chapter will describe the analysis method and the seventh and final chapter will discuss the results of this work.

Chapter 2

The Tevatron and the CDF II experiment

Figure 2.1: The Tevatron accelerator chain

2.1 Tevatron and Accelerator Complex

The Tevatron (12) was a proton-antiproton collider at the Fermi National Accelerator Laboratory (FNAL or Fermilab) that for much of its lifetime was the highest-energy particle collider operational in the world. Beginning with hydrogen it produces $p\bar{p}$ collisions at 1.96 TeV center of mass energy. Data gathered from these collisions form the basis of this study. In this section the main features of the Tevatron will be described. The main components can be seen in Figure 2.1.

2.1.1 Proton Source

The Fermilab Proton Source includes the pre-accelerator, 400 MeV linac and the 8 GeV booster. The Pre-accelerator serves as a source of negatively charged hydrogen atoms and accelerates these ions to an energy of 750 keV.

2.1 Tevatron and Accelerator Complex

These ions are then passed via transfer line to the linac. The linac is a series of radio frequency cavities (RFC) used as a linear accelerator and accelerates the ions to an energy of 400 MeV. The first section of the linac is the low energy drift tube linac (DTL) and makes up the first five of the RFCs. Each DTL cavity uses a large power amplifier tube to amplify the 201 MHz RF signal used in the cavities and accelerate the beam. The last 7 RFCs use klystron amplifiers which amplify an 805 MHz RF signal that is fed into side coupled cavity linac (SCL) modules. Every RF cycle in the DTL is used to accelerate beam but only one in four cycles in the SCL is used. The linac and the pre-accelerator can both accelerate beam once every 66 milliseconds (a 15 Hz repetition rate).

Hydrogen ions from the linac pass through a carbon foil, stripping them of their electrons and enter the booster. The booster is the first circular accelerator and consists of a series of magnets arranged around a 75-meter radius circle, with 19 RFCs interspersed. These RFCs accelerate the proton beam to 8 GeV and can accelerate beam once every 66 milliseconds.

2.1.2 Main Injector

The main injector is a circular synchrotron seven times as large as the booster divided up into 6 sections with 18 total accelerating cavities. It can accelerate the 8 GeV inputs to either 120 GeV or 150 GeV depending upon the intended destination. When being used to send beam to the antiproton source the beam is accelerated to 120 GeV. When being used to inject protons or antiprotons into the Tevatron, called a "shot", the beam energy is 150 GeV. The main injector can accept inputs as either protons from the booster or antiprotons from the antiproton source. It accelerates beam as fast as once every 2.2 seconds.

2.1.3 Antiproton Source

The antiproton source includes the target, debuncher, and accumulator. It receives 120 GeV protons from the main injector and collides them with a nickel alloy target, this collision produces a spray of secondary particles including antiprotons. Magnets are used to collect 8 GeV antiprotons from this spray which are then directed to the debuncher synchrotron.

The debuncher's primary purpose is to capture the antiprotons produced with a high momentum spread from the target. It also has beam-cooling systems that make the antiproton beam more manageable. The debuncher does not accelerate the 8 GeV inputted antiprotons but rather maintains their energy and then passes them to the accumulator.

The accumulator is also a synchrotron housed in the same tunnel as the debuncher. Like the debuncher it does not accelerate the antiprotons within it but maintain them at an 8 GeV energy, its purpose is to further cool the antiproton beam and then pass it to the recycler.

The recycler was originally designed to "recycle" the antiprotons from the Tevatron but this function was abandoned due to problems early in Run II of the Tevatron. Now it accepts transfers from the accumulator and cools the beam further than the accumulator can accomplish using a stochastic cooling system (like the debuncher and accumulator) and an electron cooling system. Like the debuncher and accumulator it does not accelerate the antiprotons but only maintains their energy at 8 GeV.

2.1.4 Tevatron

The Tevatron is the final and largest accelerator used to produce the proton and antiproton beams, and to focus them to collide at the B0 and D0 interaction points. It has a radius of 1 km and is a circular synchrotron with eight 53.1 MHz RFCs. It takes both protons and antiprotons from the main injector and accelerates them from 150 GeV to 980 GeV. Once accelerated, the Tevatron then stores these beams for hours at a time while collisions occur maintaining their energy until the instantaneous luminosity has fallen far enough, and the antiproton source has accumulated enough $\bar{p}$ to warrant another shot. The time while it maintains the beam is called a "store". The Tevatron is divided into six sectors labeled A through F. Each sector has five service buildings labeled 0 through 4. The CDF collision hall is located at the B0 section. The Tevatron typically delivers initial instantaneous luminosity of about $350 \text{ cm}^{-2} \text{ s}^{-1}$ and typically terminates a store with an instantaneous luminosity near $50 \text{ cm}^{-2} \text{ s}^{-1}$.

2.1 Tevatron and Accelerator Complex

Figure 2.2: The CDF II detector.

2.2 The Collider Detector at Fermilab - Detector Components

The Collider Detector at Fermilab Run II detector (CDF II or CDF) is an azimuthally and forward-backward symmetric apparatus weighing approximately 4,500 tons and including more than 1 million individual detector elements. It is a general purpose solenoidal detector which utilizes precision charged particle tracking with fast projective calorimetry and fine grained muon detection. Two schematics of the detector can be seen in Figure 2.2. The tracking systems are contained within a superconducting solenoid which generates a 1.4 T magnetic field parallel to the beam axis. The calorimetry and muon systems are outside of the solenoid.

2.2.1 Coordinates and Units

System components of the CDF detector are described in terms of a specialized set of coordinates and units. The basic coordinate system has the positive z -axis pointing in the direction of the proton beam provided by the Tevatron. ϕ is the angle measured relative to the vector pointing away from the center of the Tevatron and the polar angle θ is measured relative to the z axis. For convenience the pseudo-rapidity $\eta = -\ln(\tan \frac{\theta}{2})$ is typically used instead of the polar angle θ . The pseudo-rapidity closely approximates the Lorentz invariant rapidity $y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$ for particles with energy much larger than their mass, which is almost always true for particles produced at the Tevatron. η is useful because it is invariant to the reference frame used and because the density of produced particles is nearly uniform in η .

Instantaneous luminosity is defined as:

$$\mathcal{L} = f \frac{n_p n_{\bar{p}}}{4\pi\sigma_p\sigma_{\bar{p}}} \quad (2.1)$$

where $n_p(n_{\bar{p}})$ is the number of p ($\bar{p}$) in the bunches, f is the frequency of bunch crossings and the particle densities are parameterized by σ_p and $\sigma_{\bar{p}}$, is usually measured in units of $cm^{-2}s^{-1}$. Integrated luminosity defined as:

$$L = \int \mathcal{L}(t)dt \quad . \quad (2.2)$$

is usually measured in units of inverse *barns* (denoted b), where a single barn is numerically equal to 10^{-24}cm^2 . The analysis described in this dissertation is based on an integrated luminosity of 5.6 fb^{-1} .

2.2.2 Tracking Systems

Efficient and precise charged particle tracking is at the heart of the CDF detectors purpose. A catalog of applications of this tracking important to this analysis include

- Efficient and precise reconstruction of track momentum at both high and low p_T .
- The ability to combine tracks with information from EM calorimetry and / or muon chambers to provide efficient electron and muon identification with excellent purity both during triggering and in offline reconstruction.
- Precise reconstruction of track impact parameters and efficient reconstruction of tracks in dense jets allowing the ability to identify the delayed decay of B mesons and thereby tag jet flavor.

The tracking system includes the Central Outer Tracker (COT) (13), a cylindrical open cell drift chamber, Layer 00 (14), a single-sided silicon microstrip detector, the Silicon Vertex Detector (SVX) (15), a collection of five layers of double-sided silicon microstrip detectors and the Intermediate Silicon Layer (ISL) (16), a double-sided silicon microstrip detector. All of the tracking components are contained in a superconducting solenoid, 1.5 m in radius and 4.8 m in length, which generates a 1.4 T magnetic field parallel to the beam axis. This magnetic field causes charged particle tracks to bend based upon their momentum allowing the tracking system to perform measurements of the p_T of the particles.

2.2.2.1 Central Outer Tracker: COT

Covering the $|\eta| \leq 1.0$ region and radii between 40 and 137 cm the COT replaced the CTC of Run 0 and Run I and was designed to cope with the increased luminosity environment of Run II. The COT includes 30,240 sense wires that run the length (in z) of the chamber between the two end plates. Approximately half of the wires are in the four axial "superlayers", running along the z direction, and half are in the four

2.2 The Collider Detector at Fermilab - Detector Components

small angle (2°) stereo superlayers. Each superlayer is divided in ϕ into "supercells", with each supercell having sense wires and field wires configured for an approximately COT constant maximum drift distance of 0.88 cm. An image of the COT may be seen in Figure 2.3.

Figure 2.3: The COT system of the CDF II detector.

Charged particles traveling through the mixed argon / ethane gas produce electrons which are then accelerated by the voltage maintained on the field wires towards the sense wires. The sense wires span the length of the COT and register the current produced when electrons arrive at the wires as "hits". The cells in the axial superlayers provide information on the r and ϕ of the hit and the stereo superlayers allow reconstruction of the z position. The COT achieves a hit position resolution of approximately $140 \mu\text{m}$ and momentum resolution of $\sigma(p_T)/p_T^2 = 0.0015 (\text{GeV} / c)^{-1}$ (17). The COT also provides dE/dx information for the tracks.

2.2.2.2 The Silicon Detectors

The innermost component of the silicon detectors, the Layer00 detector, is attached to the beampipe at a radius of 1.1 cm and covers the range of $|n| < 4.0$. Covering the radius range of $2.4 \text{ cm} < r < 10.7 \text{ cm}$ for the range of $|n| < 2$ are the 5 layers of the SVX detector. The ISL is between the SVX detector and the COT and aids with track linking between the SVX and the COT. A diagrammatic view of the silicon detectors can be seen in Figure 2.4.

Each of the silicon detectors is made of doped silicon strips, single-sided in Layer00 and double-sided for the SVX and ISL layers. Charged particles entering the strips cause ionization which creates a pulse of current read out by integrated electronics readout chips. For the double-sided strips one side of the strip is arranged to provide position information in r and ϕ while the other side of the strip the crystals are set at either 90° or 1.25° angle stereo thus providing z position information. The entire system thus allows track reconstruction in three dimensions with impact resolution of $40 \text{ } \mu\text{m}$ including a $30 \text{ } \mu\text{m}$ contribution from the beamline and z_0 resolution of $70 \text{ } \mu\text{m}$ (17).

Figure 2.4: The Silicon Trackers of the CDF II detector.

2.2 The Collider Detector at Fermilab - Detector Components

Calorimeter Subsystem	CEM	CHA	PEM
η coverage	$ \eta < 1.1$	$ \eta < 0.9$	$1.1 < \eta < 3.6$
η segmentation	0.11	0.11	0.11
ϕ segmentation	15°	15°	15° or 7.5°
Energy absorbing layer	$\frac{1}{8}$ in. lead	1 in. iron	4.5 mm lead
Scintillating layer	5 mm	10 mm	4.5 mm
Total radiation lengths	$19\chi_0$	$4.5\lambda_0$	$21\chi_0$

Table 2.1: Calorimeter Summary: CEM, CHA and PEM

Calorimeter Subsystem	PHA	WHA
η coverage	$1.3 < \eta < 3.6$	$0.7 < \eta < 1.2$
η segmentation	0.2	0.25
ϕ segmentation	15° or 7.5°	15°
Energy absorbing layer	2 in. iron	2 in. iron
Scintillating layer	6 mm	10 mm
Total radiation lengths	$7\lambda_0$	$4.5\lambda_0$

Table 2.2: Calorimeter Summary: PHA and WHA

2.2.3 Calorimetry

Surrounding the tracking system outside of the solenoid are segmented electromagnetic and hadronic sampling calorimeters that measure the energy flow of interacting particles for $|\eta| < 3.64$. The central calorimeters (and endwall hadronic calorimeter) cover $|\eta| < 1.1(1.3)$. The plug calorimeters cover $1.1 < |\eta| < 3.64$. All of the CDF II calorimeters are scintillator-based: they work by having transiting particles interact with dense metal plates generating showers of particles which excite the scintillating material. The excited scintillating material then radiates photons as it returns to its ground state. Measuring these photons then provides a measure of the energy of the incident particle. Calibration of the calorimeters was conducted first using beams of particles with known energies and measuring the response of the calorimeter material. The calibration was maintained by studying the response to decay products from particles with known mass peaks (for example the Z boson). The properties of the calorimeters are summarized in Tables 2.1 and 2.2.

2.2.3.1 Central Electromagnetic Calorimeter: CEM

The Central Electromagnetic calorimeter (CEM) (18) covers the $|\eta| < 1.1$ region and full ϕ coverage. It is organized into projective towers each covering 15° in ϕ and 0.1 units in η . Each tower has 30 layers of $\frac{1}{8}$ in. thick lead and 31 layers of 5 mm SCSN-38 polystyrene scintillator for a total radiation length of $18 \chi_0$. Between the eighth lead layer and the ninth scintillator layer, at the depth corresponding to maximum average transverse shower development ($5.9 \chi_0$), a proportional strip chamber is inserted to determine shower position and transverse development by measurement of charge deposition on orthogonal strips and wires. The CEM achieves an energy resolution of $13.5\%/\sqrt{E_T} \oplus 2\%$ (17).

2.2.3.2 Central Hadron Calorimeter: CHA

The Central Hadron calorimeter (CHA) (19) covers the $|\eta| < 0.9$ region and full ϕ coverage. It is organized into projective towers each covering 15° in ϕ and 0.1 unit in η matching the CEM calorimeter which directly precedes it. Each tower has 32 layers of 2.5 cm thick steel and 1.0 cm thick doped PMMA scintillator for a total depth of $4.7 \lambda_0$. The CHA achieves an energy resolution of $75\%/\sqrt{E_T} \oplus 3\%$ (17).

2.2.3.3 Plug Electromagnetic Calorimeter: PEM

The Plug Electromagnetic calorimeter (PEM) (20, 21) covers the $1.1 < |\eta| < 3.6$ region using scintillator tiles. Each tower has 23 layers of 4.5 mm lead and 4 mm scintillator for a total radiation length of $21\chi_0$. The tiles of the first layer are made out of 10 mm thick scintillator, read out separately from the rest of the PEM and used as a pre-shower detector. Behind the 4th lead plate (approximately $6\chi_0$ in) a shower-max position detector (PES) composed of plastic scintillator strips is inserted. The PEM achieves an energy resolution of $16\%/\sqrt{E_T} \oplus 1\%$.

2.2.3.4 Plug Hadronic Calorimeter: PHA

The Plug Hadronic calorimeter (PHA) (20, 21) covers the $1.3 < |\eta| < 3.6$ region matching the PEM geometry. Each tower has 23 layers of 5.08 cm iron and 6 mm scintillator for a total depth of $7\lambda_0$. The PHA achieves a energy resolution of $74\%/\sqrt{E_T} \oplus 4\%$.

2.2.3.5 Endwall Hadronic Calorimeter: WHA

The Endwall Hadronic calorimeter (19) covers the $0.7 < |\eta| < 1.2$ region. Each tower has x layers of 5 cm thick steel and 1 cm thick doped PMMA scintillator for a total depth of $4.5 \lambda_0$. The WHA achieves an energy resolution of $75\%/\sqrt{E_T} \oplus 3\%$ (17).

2.2.4 Muon Detection Systems

Since muons deposit very little energy in the calorimeters and are relatively long-lived, muons produced at CDF typically transit through the detector leaving a characteristic minimum ionization trace. This ionizing trace shows as hits in the muon chambers. Because of this typical penetration the muon detection systems are the final layer of detectors at CDF. The muon chambers are a sandwich of drift chambers and plastic scintillation counters. The drift chambers form the basis for identification a muon and the scintillation counters are used to associate a given signal in the drift chambers with a particular bunch crossing, acting to identify muon signals from cosmic ray muons. The CMU and CMP systems both cover $|\eta| \leq 0.6$. The CMX system covers the range $0.6 \leq |\eta| \leq 1.0$ and the IMU system covers the range $1.0 \leq |\eta| \leq 1.5$ (17).

2.2.5 Cherenkov Luminosity Counter: CLC

The beam luminosity is measured using the Cherenkov Luminosity Counter (CLC) (22) counters which measure the average number of inelastic $p\bar{p}$ collisions per bunch crossing. The CLC consists of two modules that are located in the "3-degree holes" inside the CDF end-plug calorimeters in the forward and backward region of $3.7 < |\eta| < 4.7$. Each CLC detector includes 48 conical gas-filled Cherenkov counters. The counters surround the beam-pipe in three concentric layers with 16 counters in each layer. Charged particles traversing these modules coming from the $p\bar{p}$ interactions (primaries) will traverse the full length of the counter, emitting Cherenkov light and generating a large amplitude signal in the attached Photomultiplier Tubes (PMT). Particles from beam-halo interactions or from secondary interactions of prompt particles in detector material and the beam-pipe (secondaries) are softer, traverse at larger angles with shorter path lengths (thereby emitting less Cherenkov light) and their light will undergo a larger number of reflections before reaching the PMTs. Their signals are therefore significantly smaller than that of primaries and can be discriminated with suitable amplitude thresholds in

the electronics. Furthermore when two primaries traverse a single counter the resultant signal is twice that of a single particle allowing distinct peaks for the different particle multiplicities to be discerned in the output.

The instantaneous luminosity (L) can be expressed as

$$L = \frac{\mu \times f_{bc}}{\sigma_{in}}, \quad (2.3)$$

where μ is the average number of $p\bar{p}$ interactions per bunch crossing, f_{bc} is the Tevatron bunch crossing frequency (1.515×10^7 Hz) and σ_{in} (approx. 60 mb (23)) is the inelastic $p\bar{p}$ interaction cross-section. Multiple separate methods for measuring μ with the CLC exist, two are described here. First since μ is the mean of a Poisson distribution the probability of empty crossings is $P_0(\mu) = e^{-\mu}$. By measuring the fraction of empty crossings a measurement of μ can be made, and therefore the luminosity can be obtained. The disadvantage of this method is the small probability of empty crossings at high luminosity, making a precise measure of luminosity using this technique difficult. Second μ can be interpreted as

$$\mu = \frac{\bar{N}}{\bar{N}^s}, \quad (2.4)$$

where N is the measured average number of hits per bunch crossing and N^s is the average number of hits from a single $p\bar{p}$ collision (measurable at low luminosity).

The data used in this thesis corresponds to 5.6 fb^{-1} of measured integrated luminosity, the uncertainty on this luminosity is 5.9% with 4.4% from the acceptance and operation of the CLC (23) and 4.0% from the uncertainty on the calculation of the total $p\bar{p}$ inelastic cross section (24).

2.3 Triggering

In the high luminosity operating environment of the Tevatron it is necessary to parse the incoming data and read out the full detector systems on only a small proportion of the data in order to maintain functionality. To accomplish this CDF uses a multitiered triggering system with each tier completing progressively more thorough reconstruction and accepting progressively fewer events. CDF's triggering system has three levels. The level 1 (L1) trigger system is based on customized electronics, does relatively little reconstruction and is designed to target an accept rate below 28 kHz. The level 2 (L2)

trigger system is based on a PC, does moderate reconstruction and is designed to target an event acceptance rate below 900 Hz. The final level 3 (L3) trigger system uses a farm of PCs, does a more complete reconstruction and is designed with a 200 Hz acceptance rate target. A diagram of the trigger system can be seen in Figure 2.5. The extent of the cuts necessary to achieve these targeted acceptance rates is clearly heavily dependent on the instantaneous luminosity. The improvements in instantaneous luminosity achieved by the Tevatron during the later period of its running necessitated upgrades to the hardware used in the level 1 and 2 trigger system. Without these upgrades the trigger rates for some of the track based triggers important to this analysis would've inflated unacceptably.

2.3.1 eXtremely Fast Tracker Upgrade: XFT

The project to upgrade the tracking capabilities used in the L1 trigger system was called the eXtremely Fast Tracker upgrade (25). So called fake tracks, tracks that do not correspond to any physics object in the event, are a primary source of inflated trigger rates with luminosity and scale much faster with increased luminosity than the underlying physics rates. Prior to the XFT upgrade only the axial layers of the COT were used in constructing tracks for the L1 and L2 triggers. Adding the stereo information via the XFT upgrade allows for drastic improvements in rejection of fake tracks at both L1 and L2 and the possibility to do 3D reconstruction of tracks at L2.

2.3.1.1 XFT Hardware

The XFT system uses two primary pieces of hardware, the Stereo XFT Finder Module and the PULSAR module. The XFT system uses 36 finder boards, 12 boards for each superlayer. These boards receive input from the COT's XTC cards perform track segment finding and ϕ position and p_T measurements and send the data to the SLAM cards for use in the L1 trigger and to the three PULSAR boards for merging and concatenation before being transmitted to the L2 PC. Once the commissioning process for the XFT upgrade had begun it was determined that it was necessary to implement two additional functionalities at the PULSAR level, aborting events and truncated events. The abort functionality was implemented to speed the process of the L2 trigger by only sending the XFT information when it was going to be useful. Since most triggers do not need to use the 3D track reconstruction of the XFT this allows for

considerable time savings. Secondly testing revealed that for high COT occupancy events the resultant large amounts of data being transmitted by the XFT PULSARS to the L2 PC could cause problems. To resolve this a truncation system, whereby events in which the data size reached unacceptable levels were truncated and only partial data was transmitted to the L2 PC, was implemented.

2.3.1.2 XFT Impact

Implementation of the L1 component of the XFT upgrade allowed for a reduction in muon trigger rates by a factor of 3 to 5 and remains 97% efficient for real tracks. The addition at L2 of 3D reconstruction to demand that proposed muon tracks be fiducial to the detector with the associated stub allows for an additional factor of 2 to 4 reduction in trigger rates with greater than 99% efficiency. The overall impact of the upgrade therefore achieves a factor of 6-20 reduction in trigger rates while maintaining 96% efficiency. This improvement is thus very important to maintaining the utility of many track based triggers in the high luminosity environment of the late Tevatron.

2.3.2 Specific Triggers

There are a wide variety of triggers in use at CDF each designed to accept events matching different characteristics of interest to experimenters. This analysis is based upon the triggers designed to select events with exactly one lepton and several energetic jets. There are four primary types of triggers in this analysis: CEM electron triggers, CMX muon triggers, CMUP triggers, and triggers on $\cancel{E}_T$ used to gather "loose" leptons. The specific triggers involved in these categories change depending on the trigger table being used in a given physics run. Trigger requirements as they were at the end of running can be seen in Tables 2.3 2.4 2.5 2.6.

Figure 2.5: A diagram of the CDF Trigger system.

Trigger Level	Requirements
Level 1	$E_T > 8 \text{ GeV}$ Hits in four axial layers Track $p_T > 8.34 \text{ GeV} / c$ EM / Hadronic Calorimeter ratio > 0.125
Level 2	$0 < \eta < 1.317$ $E_T > 18 \text{ GeV}$ Hits in four axial layers Track $p_T > 8 \text{ GeV} / c$ EM / Hadronic Calorimeter ratio > 0.125
Level 3	$E_T > 18 \text{ GeV}$ EM / Hadronic Calorimeter ratio > 0.125 Track $p_T > 9.0 \text{ GeV} / c$ In the central calorimetry region $L_{shr} < 0.4$ $\Delta Z < 8$

Table 2.3: CEM trigger requirements

Trigger Level	Requirements
Level 1	CMU Stub $p_T > 6 \text{ GeV} / c$ Track $p_T > 4.09 \text{ GeV} / c$ CMP hit
Level 2	Stereo Confirmation Hits in 4 axial layers Track $p_T > 14.77 \text{ GeV} / c$
Level 3	$p_T > 18.0 \text{ GeV} / c$ CMUP Stub CMP stub quality pass CMU stub quality pass

Table 2.4: CMUP trigger requirements

Trigger Level	Requirements
Level 1	CMX Stub $p_T > 6\text{GeV} / c$ Track $p_T > 8.34\text{ GeV} / c$ Hits in 4 axial layers
Level 2	Stereo Confirmation Hits in 4 axial layers Track $p_T > 14.77\text{ GeV} / c$
Level 3	CMX Stub quality pass Track $p_T > 18.0\text{ GeV} / c$

Table 2.5: CMX trigger requirements

Trigger Level	Requirements
Level 1	$\cancel{E}_T > 25\text{ GeV}$
Level 2	Jet with $0 < \eta < 1.1$ and $E_T > 20\text{ GeV}$ $\cancel{E}_T > 30\text{ GeV}$ Two jets with $E_T > 15\text{ GeV}$
Level 3	$\cancel{E}_T > 35.0\text{ GeV}$

Table 2.6: $\cancel{E}_T$ trigger requirements

Chapter 3

Event Reconstruction

3.1 Tracks

Tracks passing through the CDF tracking systems can be exposed to significantly different sections of the tracking detector based on the geometry of the detector. To optimize track reconstruction CDF employs several algorithms depending on what parts of the detector a proposed track traveled through. This work uses the outside-in (OI) and inside-out (IO) track reconstruction algorithms described below.

3.1.1 Outside-in Track Reconstruction Algorithm: OI

Tracks that traverse at least half of the COT in the radial direction are reconstructed using the OI (26, 27) track reconstruction algorithm. An OI track begins with a "seed" of three hits in an outer COT layer. From these seeds a set of track segments are constructed by searching for hits that would match the expected position extrapolated from the set of three. The set of good track segments in the outermost axial superlayer of the COT (SL 8) is then extrapolated to expected positions in the next-innermost axial superlayer (SL 6) and if a good match is found the two segments form a track. The next step is to attempt to link segments from the two inner axial superlayers (SL 2 and 4) to these tracks or to segments in the outer superlayers that did not form tracks. Successfully linked segments form the axial tracks which are then passed to the next step where information from the stereo superlayers is used. The stereo information is added in a similar fashion to the axial construction where beginning with the outermost stereo superlayer (SL 7) its matches are sought between its segments and the axial tracks and the resultant modified track is then used to search for matches on the relatively inner stereo superlayers. For axial tracks that fail to be matched to stereo information with this algorithm, a second algorithm is used in which the stereo superlayers are searched for hits matching the position extrapolated from the axial track. With the full track defined the algorithm now performs a full fit using all the track's hits for the track parameters. For electron tracks with $p_T > 10\text{GeV}/c$ the tracking efficiency is greater than 98% (28).

3.1.2 Inside-out Track Reconstruction Algorithm: IO

The IO track algorithm (29) uses tracks found in the silicon detector subsystems to define a search area in the COT. The hits in this search area are then used to define a COT track. Then the COT track is used to refit the silicon hits and the parameters of this final fit define the IO track.

The initial silicon tracks are formed by seeds defined by two hits with 3D information consistent with a z -vertex candidate and a beam position estimate. The seeds define candidate tracks for a silicon hit search and those candidates consistent with four or more $r - \phi$ silicon hits become silicon tracks. Silicon tracks are then propagated from the collision point to obtain track parameters at the COT inner cylinder wall. The track parameters at the COT inner wall define a trajectory through the COT. At each layer of the COT the wires are searched for hits with sufficiently small ($< 1.4 + 0.006 \times (\text{layer number} - 1)$) azimuthal distance. If at least 6 axial and 2 stereo hits are found within this distance the hits are fit for the track parameters by a χ^2 minimization method constrained to the z_0 and d_0 of the original silicon track. With these new track parameters the track is propagated back towards the collision point and the fit is updated with each silicon hit forming the final IO track.

An attempt is made to construct a IO track from all silicon tracks reconstructed in the event. If the IO track is central and more than 15% of its COT hits are shared with an OI track or if the silicon track does not match to a IO track then the silicon track is discarded. The IO track algorithm achieves $> 95\%$ efficiency for high p_T tracks. (29).

3.2 Leptons

This work is searching for a t' quark via its decay to a final state involving at least one lepton. The reconstruction and identification of leptons by the detector is thus essential and will be described forthwith. For this search only electrons and muons are considered, as tau leptons present additional difficulties of reconstruction and were not used in this work.

3.2.1 Electrons

Electron (30) signatures in the detector are characterized by a track pointing to an electromagnetic calorimeter cluster. In order to ensure that objects identified as elec-

Electron Variables	Cut
E_T	$> 20 \text{ GeV}$
p_T	$> 10 \text{ GeV}/c$
N_{SL}^{axial} with 5 hits	≥ 3
N_{SL}^{stereo} with 5 hits	≥ 2
Fiducial	Yes
Hadronic / EM calorimeter energy	$< 0.055 + 0.00045 \times E$
$L_s hr$	< 0.2
E/p	< 2 (for $p_T < 50 \text{ GeV}$)
$ Z_{vertex} $	$< 60 \text{ cm}$
$ \Delta X $	$-3.0\text{cm} < Q_{trk} \Delta X < 1.5\text{cm}$
$ \Delta Z $	$< 3 \text{ cm}$
χ_{strip}^2	< 10
Conversion	No

Table 3.1: Electron ID Requirements

trons are reasonably purely electrons some additional quality requirements are made. These requirements are summarized in Table 3.1 (31). The efficiency of the electron id is measured by examining a data sample of Z bosons decaying to e pairs. By examining only candidate events within a narrow ($76\text{-}106 \text{ GeV} / c^2$) mass window the sample is assured a high purity of Z boson events. One of the electrons produced by the Z boson is required to pass the trigger requirements and have a track which masses to a calorimeter cluster in η and ϕ . For each such electron another electron is sought with the opposite using very loose requirements. The efficiency is then the number of these “probe” electrons that additionally pass all of the electron id requirements. The efficiency for central electrons is measured as 0.799 ± 0.002 in data events and as 0.814 ± 0.001 in MC (32). Efficiency as a function of η and ϕ can be seen in Figures 3.1 and 3.2.

3.2.2 Muons

Muon signatures in the CDF II detector (30) are characterized by a track pointing to a signal in one of the muon detectors, called a “stub”. In order to control the presence of fakes and ensure the purity of the sample several additional quality requirements are

Figure 3.1: Central Electron Efficiency for data and MC as a function of η .

Figure 3.2: Central Electron Efficiency for data and MC as a function of ϕ

Muon Variables	Cut
Cosmic Tag	No
p_T	$> 20\text{GeV}/c$
E_{EM}	$< 2 + \max(0, (p - 100) * 0.0115) \text{ GeV}$
E_{HAD}	$< 6 + \max(0, p - 100) * 0.028) \text{ GeV}$
$E_T^{isol.}/p_T$	< 0.1
$N_{SL}^{axial}with5hits$	≥ 3
$N_{SL}^{stereo}with5hits$	≥ 2
$ Z_{vertex} $	$< 60\text{cm}$
$ d_0 $	Tracks with no silicon: $< 0.2 \text{ cm}$, Tracks with silicon: $< 0.02 \text{ cm}$

Table 3.2: Muon ID Requirements

made. These requirements are summarized in Table 3.2 (33). Similarly to the process for the electrons the efficiency of the muon identification and reconstruction process is measured by examining a sample of events with Z bosons decaying to μ pairs. The events are selected by first requiring a muon that passes all trigger and identification cuts. Then a second candidate muon consisting of a muon stub and a track with at least 20 p_T fiducial to the muon detectors must be present. The event is also required to not be identified as a cosmic event, have both of the tracks reconstruct to the same vertex and have an invariant mass of the two tracks within the mass window. If all these requirements are met then the second candidate muon is used to test the efficiency of the muon ID requirements. Efficiencies for CMUP, CMX and BMU muons as a function of η can be seen in Figure 3.3.

3.2.2.1 CMUP

Muons incident on the CMUP (30) component of the muon detection system have additional quality requirements summarized in Table 3.3. CMUP muons are measured as having an efficiency of 0.8692 ± 0.004 in data events and 0.9411 ± 0.001 in MC (33).

3.2.2.2 CMX

Muons incident on the CMX (30) component of the muon detection system separate additional quality requirements summarized in Table 3.4. CMX muons are measured

Figure 3.3: Muon efficiency for data as a function of η .

CMUP Variables	Cut
$ \Delta x_{CMU} $	< 7 cm
$ \Delta x_{CMP} $	< 5 cm
Bluebeam muons	No for run < 154449

Table 3.3: CMUP ID Requirements

CMX Variables	Cut
$ \Delta x_{CMX} $	$< 6 \text{ cm}$
Run	> 150144
Miniskirt or keystone	No for run < 190697
Wedge 14 West	No for $190697 \leq \text{run} \leq 209760$

Table 3.4: CMX ID Requirements

Category	Description
BMU	Isolated forward muons with a stub in the BMU detector
CMU	Isolated CMU muons detector that are non-fiducial to the CMP
CMP	Isolated CMP muons detector that are non-fiducial to the CMU
CMIO	Stub-less muons that is non-fiducial to all muon detectors
CMXNT	Non-isolated CMX muon that either fails the COT exit radius cut or is in a CMX wedge that is bad for the trigger
SCMIO	Muons that fail one of the other muon selections but pass CMIO if you ignore the stub and CMIO non-fiduciality requirements.

Table 3.5: Loose muon subtypes

as having an efficiency of 0.9154 ± 0.006 in data events and 0.9238 ± 0.001 in MC (33).

3.2.2.3 Loose Muons

Muons that are not fiducial to the CMUP or CMX (30, 34) detectors and muons that fail the strict identification cuts of the CMX and CMUP muons are collected in a looser category of muons, the Loose muons. The requirements of the subcategories are described in Table 3.5. The efficiencies in data and MC by category are described in Table 3.6 (33, 35).

3.3 Jets

Quarks or gluons produced at CDF undergo interactions with other products producing $q\bar{q}$ pairs and gluons until all the color charge carrying particles are collected into color-singlet hadrons, this process is called hadronization. For high momentum produced

Category	Data Efficiency	MC Efficiency
BMU	0.9233 ± 0.005	0.9235 ± 0.001
CMU	0.8171 ± 0.012	0.9178 ± 0.001
CMP	0.8642 ± 0.009	0.9821 ± 0.002
CMIO	0.8718 ± 0.014	0.8469 ± 0.003
CMXNT	0.9335 ± 0.006	0.9435 ± 0.002
SCMIO	0.8798 ± 0.020	0.8990 ± 0.003

Table 3.6: Efficiencies of loose muon subtypes

particles these collections of particles are boosted into cones and the resultant cone of particles is called a "jet". Several algorithms exist for the reconstruction and estimation of the energy of a jet, this work uses an algorithm known as the JetClu (Jet Cluster) (37) with a cone size of $\Delta R \leq 0.4$.

The JetClu algorithm proceeds as follows:

- A list of calorimeter towers with $E_T > 1.0$ GeV (seed towers) is created, ordered by magnitude.
- Unbroken chains of contiguous seed towers with continuously decreasing tower E_T are grouped together as preclusters. If a tower is outside a 7×7 window of towers around the seed it is split off and used to form a new precluster.
- Preclusters are grown into clusters by finding the E_T weighted centroid and adding the energy from all towers with at least 100 MeV within the $\Delta R = 0.4$ cone of the centroid.
- A new centroid is calculated and the cluster is regrown using a cone about the new centroid until the centroid does not change.
- Overlapping jets are merged if they share $\geq 75\%$ of the smaller jet's energy. If they share less than the towers in the overlap region are assigned to the nearest jet.
- Final jet parameters are computed based on the final cone.

Jets at CDF are corrected for a variety of physical effects in order to more accurately derive at a the energy of the jet. These corrections and their uncertainties are described below (36).

3.3.1 Jet Energy Scale

3.3.1.1 Online / Offline calibrations

The calorimeter energy is calibrated for each system using well understood signals and regularly updated over time to account for changes to the calorimeter system.

3.3.1.2 Eta-dependent

Because the detector is not uniform in η the raw jet energies as measured in the calorimeter need to be corrected so as to make jet energy uniform under variations of η . This correction is performed using dijet events (where both jets should be equal). Systematic uncertainties for this correction are derived from varying the characteristics of other objects in the event and range from 1% in the central region to 7.5% for high η , low p_T jets.

3.3.1.3 Multiple Interactions

Since there are approximately six $p\bar{p}$ interactions per bunch crossing jet energies need to be corrected to account for the additional energy deposited by these interactions. The average calorimeter tower energy from soft interactions is measure in "minimum bias" events which contain two charged particles close to the beampipe. This average tower energy is subtracted from the towers contributing to a jet's energy. Systematic uncertainties are derived from using different observed data samples (lepton triggered and inclusive jet) to calculate the correction, giving approximately a 15% uncertainty for this correction.

3.3.1.4 Absolute

The most physically interesting object in the jet is the original parton that created the jet so the calorimeter response is also corrected to better model this original object. This correction is performed using dijet MC events. Systematic uncertainties for this

correction are assessed by comparing the observed data sample and MC EM calorimeter response for $W \rightarrow e\eta$ and $J/\psi \rightarrow ee$ events, giving a 3.5% uncertainty. $Z \rightarrow ee$ calibration events show a breakdown in simulation accuracy near the edges of calorimeter towers giving a 10% effect for these events. Finally differences in MC showering algorithms give a further 1% systematic.

3.3.1.5 Underlying Event

Interactions between the partons in the proton and the antiproton which are not directly involved in the collision are not modeled perfectly in MC, this uncertainty is the underlying event uncertainty. These effects are estimated by looking at tracks sensitive to radiation and estimating the differences between the observed data sample and MC as well as the differences between MC showering methods. This systematic gives up to 10% for low p_T jets and lower uncertainty for higher p_T jets. This is not used as a correction but only an systematic uncertainty on the jet energy scale.

3.3.1.6 Out-of-cone

The out-of-cone uncertainty corrects for differences between data and MC in how much energy escapes the jet cone. An annulus outside the jet cone in photon + jet events is compared between data and MC, from this a energy dependent uncertainty is derived ranging up to a 4% uncertainty for low p_T jets. This uncertainty is not used as a correction but only an systematic uncertainty on the jet energy scale.

3.3.1.7 Splash-out

Some energy is found to be missed even by the annulus outside of the jet cone used to measure the out-of-cone uncertainty, since this is small and difficult to measure in data half of the average value in MC (0.5 GeV) is taken as a systematic uncertainty. This uncertainty is not used as a correction but only an systematic uncertainty on the jet energy scale.

3.3.2 B-tagging

Since the top quark and the t' quark decays involve b quarks, and many background process do not, the identification of jets with b hadrons or b -tagging is an important

technique for this work. The principle of b -tagging is to take advantage of the discrepancy between the lifetime of b -hadrons and the hadrons of light flavor quarks. Since the b hadrons only decay via the weak interaction they have much longer lifetimes than light flavor hadrons. These lifetimes mean that b hadrons travel far enough in the detector to produce a discernible secondary vertex when they decay. This work uses the SECVTX b -tagging algorithm (39) to identify jets containing heavy flavor.

The first step in identifying secondary vertices is the identification of the primary vertex. A first estimate of the primary vertex position is found by fitting well-measured tracks to a common point of origin. Since at high luminosities more than one collision can occur on a given bunch crossing the z position of each vertex is calculated from the weighted average of the z coordinates of all tracks within 1 cm of a vertex from the first iteration. At this stage the typical resolution is 100 μm . The event primary vertex for the b -tagging is selected by identifying which of the vertices found by this technique is nearest the identified high-momentum electron or muon or the highest total scalar sum of transverse momentum of associated tracks (if no high momentum lepton is present). The position of this primary vertex is then determined by fitting tracks within a ± 1 cm window in z around this vertex. This fit begins by using all tracks within the z window and with impact parameter significance (relative to the beam line) $|d_0/\sigma_{d_0}| < 3$, where σ_{d_0} includes the uncertainty on both track and beam line positions. Here the beam line profile at the z of the original vertex is used as a constraint in the fit. The next step is to remove tracks contributing $\chi^2 > 10$ to the fit (or the track with the largest χ^2 if $\chi^2 / \text{degree of freedom} > 5$). The fit is then repeated using only the remaining tracks until a vertex with no tracks over the χ^2 cut is found. If no tracks survive the pruning stage then the beam line profile is used for the primary vertex position estimate.

With an event primary vertex position defined each jet can now be examined to determine if it is tagged with a secondary vertex. Here only the tracks included in a jet are considered in determining the tag on a jet. Poorly reconstructed tracks are rejected with a set of cuts on p_T , the number of silicon hits, the quality of silicon hits and the $\chi^2 / \text{degree of freedom}$ of the final track fit. Jets with at least two of these good tracks are defined as "taggable" and can produce displaced vertices.

For each taggable jet two passes are made to try and construct a secondary vertex. On the first pass tracks the algorithm attempts to reconstruct a secondary vertex which includes at least three tracks with $p_T > 0.5 \text{ GeV} / c$ and $|d_0/\sigma_{d_0}| > 2.5$ where

at least one of the tracks must have $p_T > 1 \text{ GeV} / c$. If the first pass is unsuccessful a second pass is performed where the track requirements are tighter ($p_T > 0.5 \text{ GeV} / c$, $|d_0/\sigma_{d_0}| > 2.5$, one track with $p_T > 1.5 \text{ GeV} / c$) but only two tracks are required to reconstruct a vertex.

Once a secondary vertex is found in a jet the two dimensional decay length of the secondary vertex L_{2D} is calculated by projecting onto the jet axis (in the $r-\phi$ view only) the vector pointing from the primary vertex to the secondary vertex. The sign of L_{2D} is defined by the absolute difference $|\phi|$ between the jet axis and the secondary vertex vector (positive for $< 90^\circ$, negative for $> 90^\circ$). b and c hadrons are expected to have large positive L_{2D} while random mismeasured tracks are expected to be less displaced from the primary vertex. To reduce fake rates a good secondary vertex is required to have $L_{2D}/\sigma_{L_{2D}} > 3$ (a positive tag) or $L_{2D}/\sigma_{L_{2D}} < -3$ (a negative tag). Here $\sigma_{L_{2D}}$ is the total estimated uncertainty on L_{2D} including the error on the primary vertex and is typically $190 \mu\text{m}$. The negative tags are useful for calculating the false positive tag rate. An illustration of the difference between a negative tagged and positive tagged jet can be seen in Figure 3.4. A tagged jet is defined to be a jet containing a good secondary vertex.

The tagging efficiency, or how often a heavy flavor jet is correctly tagged, is measured by first using a sample of jets whose heavy flavor fraction can be measured to determine a per-jet tag efficiency in data (38). Since these jets have substantially different energies, pseudorapidities and track multiplicity than the jets we're primarily interested in for this work this measurement of tag efficiency cannot be used directly, instead the measurement is repeated using a matching simulated sample. From this a ratio of efficiencies between data and simulation can be derived which is then used to correct the efficiency measured in simulation for jets matching the characteristics of interest. This ratio is measured to be 0.95 ± 0.04 (40). Efficiencies measured using this technique can be seen in Figures 3.5 and 3.6

The mistag rate or the rate at which a light flavored jet is tagged in the SecVtx algorithm is measured in inclusive jet data (38). Since the SecVtx algorithm is symmetric between positive and negative tags the negative tag rate is used as the first estimate of the mistag rate. Since some of the negative tags occur in jets which do have heavy flavor and since some of the mistags derive from K_S or Λ decays or interactions with detector material the negative tag rate must be corrected for these effects. Corrections

Figure 3.4: A diagram of a positive tag (top) and a negative tag (bottom).

Figure 3.5: SecVtx Tag efficiency as a function of Jet E_T (left), Jet η (right)

Figure 3.6: SecVtx Tag efficiency as a function of Number of vertices.

for these effects are derived from fits to pseudo- $c\tau$ spectra of tagged vertices. The net effect of these corrections is to increase the mistag rate by $20\% \pm 10\%$. The mistag rate is parameterized as a function of four jet variables (E_T , track multiplicity, η and ϕ) and one event variable ($\sum E_T$). The full five dimensional mistag matrix is used in this work but some projections can be seen in Figure 3.7.

Figure 3.7: SecVtx False Positive (mistag) rate as a function of Jet E_T (left) and Jet η (right).

3.4 Missing Transverse Energy: $\cancel{E}_T$

Since neutrinos rarely deposit energy in the detector their presence is inferred from imbalances in the transverse momentum in the event. The missing transverse energy is the negative transverse vector sum of unclustered calorimeter towers with more than 100 MeV of energy plus the negative transverse energy vector of each of the jets (where the energy used is corrected detector effects), electrons and muons (where energy is derived using the measured muon momentum). Since the $\cancel{E}_T$ depends upon many detector components it is vulnerable to systematic effects and requires significant correction for detector impacts, however despite these challenges the $\cancel{E}_T$ reconstruction still performs well as demonstrated in the distributions in Figures 3.8 3.9.

Figure 3.8: The $\cancel{E}_T$ distribution for all events (top) and electron events (bottom). All backgrounds are scaled to their expectations prior to the fitting process

Figure 3.9: The $\cancel{E}_T$ distribution for tight muon events (top) and loose muon events bottom. All backgrounds are scaled to their expectations prior to the fitting process

Chapter 4

Event Simulation

4.1 Event Simulation

In order to understand the characteristics of the data sample a simulation of the physically significant process present and the interaction of the products of those process with the detector is necessary. This simulation is done by generating *Monte Carlo* (MC) events. These events are randomly generated according to the probabilities theoretically predicted for various process and then passed through a simulation of the detector in order to simulate the data sample observed by the detector.

4.1.1 Event Generation

The basic generation of the hard scattering process in this work is done via two event generation packages and is dependent upon the initial state partons which are generated from a *parton distribution function* (PDF). The two event generation packages used are; the PYTHIA (43) program used to generate $t\bar{t}$ events, $t'\bar{t}'$ events and diboson events and the ALPGEN (44) program used to generate events involving a W or Z boson and jets.

4.1.1.1 Parton Distribution Functions

The first stage of generating an event is to determine the momentum of the initial state partons. The PDFs take as inputs the type and flavor of the parton and the momentum transfer of the interaction (Q^2) and provide a probabilistic distribution of the momentum of the initial state partons. PDFs can vary widely in how they are constructed and this work uses the CTEQ611 PDF.

4.1.1.2 PYTHIA

The PYTHIA program is based on a combination of analytical results and simplified Feynman diagrams, it's focus is on events with strong interactions and the production of multihadronic final states and is used in this work to generate some events and to simulate parton showering and hadronization in all events. For this work the PYTHIA program version 6.216 was used.

4.1.1.3 ALPGEN

The ALPGEN program performs at leading order in QCD and EW interactions the calculation of exact matrix elements for some process. The W and Z bosons can radiate potentially large amount of gluons making them difficult to model using PYTHIA's approximations. For these events ALPGEN's more exact method, implicitly including spin correlations and color effects is believed to produce more realistic modeling. For this work where ALPGEN was used the version was version 2.10 prime and the events so generated were passed to PYTHIA version 6.325 for the simulation of showering and hadronization.

4.1.2 Parton Showering and Hadronization

After the hard scattering process of a given MC sample has been generated it is necessary to simulate the other effects that are present in the sample. These include initial and final state radiation, effects from beam remnants and multiple scatterings and the impact of the hadronization process. For all of the MC samples in this work these effects are simulated using PYTHIA.

4.1.3 Detector Simulation

After event generation and associated showering and hadronization processes have been simulated it is necessary to simulate their interaction with the detector itself in order to determine what signal the detector would see for a simulated event. This is performed at CDF using a set of GEANT3 (45) routines and functions to model the various components of the CDF detector and to transfer the generated particles through them. The outputs of this simulation are then digitized like experimental data allowing the application of identical algorithms to MC and data.

4.1.4 Corrections

The simulation process described above is inexact in its modeling of the actual physical process. To account for some of the systematic aspects of this inaccuracy some corrections are applied.

4.1.4.1 Lepton Scale Factors

The rate at which leptons are successfully identified in the MC exceeds the rate of identification of leptons in data. This overabundance in MC has been found to be

relatively independent of kinematic factors and so a constant normalization scale factor is applied based on the kind of lepton in the event. The scale factors are determined by examining a sample of $Z \rightarrow ll$ events at an invariant mass near the pole mass of the Z boson. The efficiencies in both data and MC are measured by requiring one of the leptons to pass all trigger requirements and then determining how many of the second leptons pass the lepton ID requirements. The ratio the data versus MC efficiencies then determines the lepton ID scale factor. The lepton ID scale factor depends on lepton type and ranges from 0.92 to 0.99.

4.1.4.2 b Tagging Scale Factors

The simulation of b -tagging inexactly produces the observed behavior, over-estimating tagging efficiency. For most analysis the dependency of this over-estimation on jet energy is small enough to be ignored, however for this work due to the sensitivity of the analysis to fluctuations in the tails of the H_T distribution where events are dominated by jets with high E_T it was decided to use a jet E_T dependent b -tagging scale factor following work performed for the CDF search for a hypothesized W' boson (41). The tag scale factor as a function of jet E_T showing this E_T dependent scale factor can be seen in Figure 4.1.

Figure 4.1: The b -tag scale factor as a function of jet E_T . The dashed line is E_T dependent scale factor.

4.1.4.3 Triggering

For events with non-trigger muons it is necessary to apply a trigger turn on curve (42). This curve was determined by measuring the ratio of data events which pass the CMUP level 3 trigger and the $\cancel{E}_T$ trigger as a fraction of all level 2 CMUP events as a function of the vertex corrected $\cancel{E}_T$. This then is fit to the parameterized trigger turn on function and applied as a weight to MC events for this trigger. The fitted curve may be seen in Figure 4.2.

Figure 4.2: The $\cancel{E}_T$ turn-on as a function of vertex $\cancel{E}_T$.

Chapter 5

Mass Reconstruction

The t' quark is similar to the top quark in virtually every way except for its mass, this makes the reconstructed mass (M_{reco}) a very useful variable for discriminating between top and t' . The reconstruction technique used in this work is fundamentally the same as that developed for the top quark mass analysis (46). First the physics objects are fully corrected for the various systematic distortions known and uncertainties for those quantities that are allowed to vary are established. Then the four-vectors of the physics objects are inputted into a MINUIT (47) fitting program 24 times (corresponding to the various possible configurations of jets, leptons, missing energy that could reconstruct $t'\bar{t}'$ decay products. The mass from the fit with the lowest χ^2 is chosen as the M_{reco} of the event.

5.1 Inputs

The χ^2 fit used has six physics object inputs; the lepton, the four highest E_T jets in the event, the $\cancel{E}_T$ and the "unclustered energy". Each of these quantities receives corrections to account for systematic effects described in this work.

5.1.1 Leptons

The corrections on the lepton depend on the kind of lepton in the event. If the lepton is an electron then the electron energy is derived from the calorimeter, corrected for tower map response, while the angles are taken from the COT-only track. The electron mass is set to zero in the four-vector and the angles are assumed to be perfectly measured. The transverse momentum is given a p_T dependent uncertainty. Since the angles and mass are not allowed to vary this amounts to an uncertainty on the magnitude of the momentum vector.

If the lepton is a muon then the corrected four-vector uses the three vector of the COT-only track assigning a mass of zero. The angle and mass are treated as having no uncertainty and the transverse momentum is given an uncertainty, amounting again to an uncertainty on the magnitude of the momentum.

The lepton p_T distribution showing backgrounds and the $t'\bar{t}'$ signal can be seen in Figure 5.1.

Figure 5.1: The lepton p_T distribution showing backgrounds and $t'\bar{t}'$ signal for a mass of 360 GeV. The backgrounds are scaled to their expected values from the Method II process and the signal is scaled to approximately twice its theoretical value.

5.1.2 Jets

The jets of the event are first corrected with the generic jet corrections for calibrations, eta-dependency, multiple interactions and absolute energy scale described in the section of event reconstruction. The four jets with the highest E_T after these corrections are selected as the jet inputs for the event. As with the lepton the angles are treated as perfectly measured but the E , p and mass are treated as subject to uncertainties derived from the jet energy corrections.

The E_T of the four leading jets, showing backgrounds and $t'\bar{t}'$ signal distributions can be seen in Figures 5.2 5.3.

5.1.3 Unclustered Energy and $\cancel{E}_T$

Those jets beyond the leading four are identified as not belong to the t' decay chain, they are assumed to derive from sources other than the produced $t'\bar{t}'$. These jets are corrected in the same way as the leading four jets. The base unclustered energy of the event is defined as any energy seen in the calorimeter that is not associated with the primary lepton or a jet. The unclustered energy used as an input to the

Figure 5.2: Lead (left) and 2nd (right) jet E_T distributions showing backgrounds and $t'\bar{t}$ signal for a mass of 360 GeV. The backgrounds are scaled to their expected values from the Method II process and the signal is scaled to approximately twice its theoretical value.

Figure 5.3: 3rd (left) and 4th (right) jet E_T distributions showing backgrounds and $t'\bar{t}$ signal for a mass of 360 GeV. The backgrounds are scaled to their expected values from the Method II process and the signal is scaled to approximately twice its theoretical value.

fit is this base unclustered energy plus the energies of any jets beyond the leading four, corrected for those aspects of the jet energy corrections that would already be included by including the base unclustered energy (underlying event and out-of-cone). Each transverse component of the unclustered energy is assigned an uncertainty of $0.4\sqrt{\Sigma E_T^{unclus}}$.

The neutrino energy in the fit is calculated from the other fit quantities assuming a net event p_T of zero. Since only the p_T of the event balances only the neutrino p_T is calculated, this leaves the longitudinal momentum of the neutrino (p_z^ν) as a free parameter in the fit. Its initial value is calculated from the initial value of the lepton four-vector and the initial missing energy assuming they add to a W that has its pole mass. Since these conditions constitute a quadratic equation for the p_z^ν there are in general two solutions for the p_z^ν a separate fit is done for each.

5.2 MINUIT Fit

With the inputs fully prepared MINUIT is used to minimize a χ^2 with the pair produced quark mass as a free parameter. For each event this is done 24 times, corresponding to the 12 ways to assign the four leading jets to the four partons in $t'\bar{t}'$ or $t\bar{t}$ decay, times the 2 solutions for the neutrino longitudinal momentum, although some of these solutions are ignored since the solution is required to be consistent with the b-tagging information in the event. For each combination the following χ^2 is minimized:

$$\chi^2 = \sum_{i=l,jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} \quad (5.1)$$

$$+ \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t')^2}{\Gamma_{t'}^2} + \frac{(M_{bl\nu} - M_t')^2}{\Gamma_{t'}^2}.$$

Here σ_l and σ_{jet} are the lepton and leading jet p_T resolutions. $p_{x,y}^{UE}$ and $\sigma_{x,y}$ are the components of the composite unclustered energy and their resolutions. The variables $M_{jj}, M_{l\nu}, M_{bjj}$ and $M_{bl\nu}$ refer to the invariant mass of the sum of the four vectors denoted in the subscript. M_W and M_t' are the pole masses of the W and the t' quark. M_W is $80.41 \text{ GeV} / c^2$ and Γ_W is 2.12 GeV . M_t' is the free parameter that we're looking for initialized with a value of $175 \text{ GeV} / c^2$. 1.5 GeV is used for $\Gamma_{t'}$.

For data the jet-parton assignment (and p_z^ν solution) with the lowest χ^2 after minimization is selected for each event and the value of M_t' for that event is the M_{reco} for that event. For Monte Carlo a slightly more complex method is used to account for the relatively poor modeling of b-tagging. For Monte Carlo all 24 possible solutions

are used each being assigned a weight based on the probability of the b-tags being appropriately distributed.

5.3 Performance

The quality of the reconstruction varies with the χ^2 of the reconstruction as well as the number of jets. Most of the data (58%) fall into the area of best reconstruction with exactly four jets and a χ^2 less than 8. The remainder is distributed between; 5 or more jet events with $\chi^2 < 8$ (18%), exactly four jet events with $\chi^2 > 8$ (16%) and 5 or more jet events with $\chi^2 > 8$ (8%). For all of these categories the M_{reco} remains a powerful discriminant between background and signal sample as can be seen in Figure 5.4. The M_{reco} distribution showing backgrounds and $t'\bar{t}'$ can be seen in Figure 5.5.

Figure 5.4: Reconstructed mass distribution for four different categories of reconstruction.

Figure 5.5: M_{reco} showing backgrounds and $t'\bar{t}'$ signal for a mass of 360 GeV. The backgrounds are scaled to their expected values from the Method II process and the signal is scaled to approximately twice its theoretical value.

Chapter 6

Analysis Method

The pair production of t' quarks searched for in this work is characterized by a decay that is almost identical to that of the top quark. This has the advantage that tools originally developed for analyzing the top quark can be used with little difficulty to understand the signal and the disadvantage that the top quark thus represents a nearly irreducible background since it has an identical decay signature characterized only by a different energy. These two facts dominate the design of the analysis.

6.1 Description

Since the decay signature of the $t'\bar{t}'$ signal fundamentally the same as that of the $t\bar{t}$ background only shifted towards higher energies (or masses) it makes sense to perform a fit to the shape of kinematic variables sensitive to this. Two variables that are particularly sensitive to the energy or mass are the H_T , defined as the sum of the jet E_T s and the $\cancel{E}_T$, and the reconstructed mass. H_T distributions showing the separation between backgrounds and signal for this variable may be seen in Figure 6.1. Thus the method chosen is a binned likelihood fit in H_T and M_{reco} . Since the shape of the M_{reco} distribution for $t'\bar{t}'$ is particularly strongly dependent on the quality of the reconstruction (see Fig. 5.4) it makes sense to subdivide the sample further on this basis. The quality of the reconstruction depends most strongly on whether or not the parton assignments are correct in the selected fit, in the mass reconstruction only the leading four jets are examined, thus events with 5 or more jets (which can fail to include one of the decay products) tend to have a lower quality of reconstruction. From this for the final analysis a binned likelihood fit in H_T and M_{reco} is performed simultaneously to four sets of templates dependent upon the number of jets and the χ^2 of the mass reconstruction. The four template categories are:

- Exactly 4 jets, $\chi^2 < 8$
- Exactly 4 jets, $\chi^2 \geq 8$
- At least 5 jets, $\chi^2 < 8$
- At least 5 jets, $\chi^2 \geq 8$

Figure 6.1: H_T distribution showing backgrounds and $t'\bar{t}'$ signal for $m_{t'} = 360$ GeV. Here the backgrounds are scaled to their expected values from the Method II process and the $t'\bar{t}'$ is scaled to approximately twice its theoretical expectation.

6.2 Event Selection

The data used in this analysis was collected at the CDF II detector between March 2002 and February 2010 using inclusive high- p_T lepton (CEM, CMUP and CMX) and $\cancel{E}_T$ +jets triggers described earlier. The triggers used have a total integrated luminosity of 5.6 fb^{-1} . The event selection criteria are:

- One and only one isolated electron or muon with $p_T > 20 \text{ GeV} / c$
- $\cancel{E}_T \geq 20 \text{ GeV}$
- At least four jets with $E_T \geq 20 \text{ GeV}$
- At least one jet must be tagged as a b -jet (a b -tag)

Loose muon events are required to pass some additional criteria to ensure an efficiency of 100%, specifically:

- At least two jets are required to have $E_T > 25 \text{ GeV}$
- The two jets which satisfy the E_T requirement are required to be separated by a ΔR of at least 1.0
- One off the two jets satisfying the E_T requirement is required to be central ($|\eta| < 0.9$)

Vetoe conditions on conversions, cosmic rays, and dileptons as standardized by the top group are also required to be satisfied (48). 1,441 events satisfy these conditions.

6.3 Background Estimation

The dominant backgrounds in this sample are $t\bar{t}$ production and events with a W boson and QCD jets (W +jets). Smaller backgrounds include pure QCD jets, electroweak process and single top production.

6.3.1 Electroweak

The electroweak backgrounds consist of diboson production and the production of a Z boson with associated QCD jets. This background is fairly small, with only 28.5 ± 2.6 events expected. The largest component of this background is the production of a Z boson with associated jets closely followed by the contribution from the production

of two W bosons with the WZ and two Z boson production having relatively small contributions. The diboson MC is generated completely in PYTHIA. The Z boson with QCD jets MC is generated in ALPGEN with hadronization and showering modeled using PYTHIA.

6.3.2 Single Top

The production of a single top quark (s and t channels) is another small background with an expected contribution of only 24.4 ± 1.71 events. Both s and t channel production are almost equal in size. Single top MC is generated with MADEVENT with showering and hadronization handled in PYTHIA.

6.3.3 $t\bar{t}$

The production of a top quark pair is the dominant background with an expected contribution of $1,395.0 \pm 178.6$. $t\bar{t}$ MC is generated completely in PYTHIA with a top quark mass of 172.5 GeV. Since $t\bar{t}$ has the same decay products as the $t'\bar{t}'$ searched for in this work this background is nearly irreducible and we can only rely on analysis of the shape of the M_{reco} and H_T distributions to distinguish between $t\bar{t}$ and $t'\bar{t}'$ events. For both of these distributions the $t'\bar{t}'$ events due to the heavier t' quark mass are shifted towards higher energies, with the size of this shift varying with the size of the t' mass.

6.3.4 QCD

The expectation for QCD events is fairly low in this analysis with a contribution of only 71.5 ± 35.8 . QCD is very difficult to correctly model in MC so the QCD background is modeled using data which satisfies all of the acceptance criteria except some of the lepton id criteria crucial to excluding QCD. This data is collected using multiple jet energy triggers and then stitched together to give a continuous distribution. This results in a data sample that is large, totally dominated by QCD events and in agreement with the shape of the QCD dominated background regions.

6.3.5 W +jets

The W +jets background is the second largest background for this work but strongly secondary to the top background with an expectation of 248.1. Do to large uncertainties associated with the normalization of the W +jets background the normalization of the W + jets background is allowed to float freely in the final analysis fit. The W +jets

background is modeled as four separate samples modeling separately the contributions from a W boson plus; two b quark jets, two c quark jets, one c quark jets, light flavor jets. All of the MC samples were generated in ALPGEN with showering and hadronization handled in PYTHIA.

6.3.6 Method II

This work uses the Method II procedure (49, 50) developed in the CDF Top Group to calculate the expected normalization of the backgrounds. The Method II procedure is designed to compensate for the imperfection of MC models for poorly understood backgrounds by using the data to constrain the normalizations. Method II begins by assuming the data sample consists of electroweak, single top, $t\bar{t}$, QCD, and W +jets processes. Normalizations for electroweak, single top and $t\bar{t}$ processes are then calculated using measured or theoretical cross-sections, the luminosity and MC-estimated efficiencies.

Next the QCD (Non- W) fraction is estimated by using a fit to the $\cancel{E}_T$ spectrum. The non-QCD background is modeled with a template of W +jets MC, for fitting for the QCD fraction in the data without requiring a b -tag (pretag), or all non-QCD backgrounds, for fitting the QCD fraction in the data with at least one b -tag. The QCD background is modeled with data which satisfies almost all the acceptance criteria but fails some of the lepton id criteria. These two templates are fit to the data to derive an estimate of the QCD fraction for both pretag and tagged data.

Taking the MC-based normalization estimates for electroweak, single top and $t\bar{t}$ plus the data-based QCD normalization estimate the W +jets normalization for the pretag sample is then estimated as the difference between the number of events observed in data and the sum of the previous estimates.

$$N_{W+Jets}^{pretag} = N_{pretag} - N_{pretag} * F_{QCD}^{pretag} - N_{MC}^{pretag} \quad (6.1)$$

The tagged estimate of the W + jets normalization comes from this pretag estimate of the W +jets normalization. First the fraction of the W + jets background that is derived from heavy flavor is determined. Then separate normalizations for the heavy flavor (calculated using the tagging efficiency) and light flavor (using the mistag rate) are calculated from the pretag estimation.

Plots of various important quantities comparing data and MC with these background estimates can be seen in Figures 6.2 6.3 6.4

6.3 Background Estimation

Figure 6.2: Kinematic distributions for CEM Electrons + jets.

6.3 Background Estimation

Figure 6.3: Kinematic distributions for trigger muons + jets.

6.3 Background Estimation

Figure 6.4: Kinematic distributions for non-trigger muons + jets.

6.4 Templates

For every background and signal sample four 2D templates in H_T and M_{reco} are prepared corresponding to the four template categories of mass reconstruction χ^2 and number of jets. For M_{reco} there are 18 bins of 25 GeV each ranging from a minimum of 75 GeV to a maximum of 525 GeV. In terms of H_T there are 28 bins of 25 GeV each ranging from a minimum value of 125 GeV to a maximum value of 825 GeV. Events that fall outside of these ranges are moved into either the first or last bin.

There are thus $18 \times 28 \times 4 = 2016$ bins in the original construction of the templates that are to be simultaneously fit. This caused difficulties, with some bins having low MC statistics, imposing high MC statistical uncertainties on the fit. To solve this problem a bin merging algorithm was developed. The bin merging algorithm systematically merged bins for which the net MC statistical uncertainty on all the backgrounds was greater than 40% of the expected background in the bin. The merging continued recursively merging neighboring bins until all bins had less than 40% uncertainty from MC statistics. After this merging process there were 514 bins used in the final binned likelihood fit.

6.5 Fit Likelihood

The likelihood is defined as the product of the Poisson probabilities for observing n_i events in the bin i of (H_T, M_{reco}) :

$$\mathcal{L}(\sigma_{t'}|n_i) = \prod_i P(n_i|\mu_i) \quad . \quad (6.2)$$

The expected number of events in each bin, μ_i , is given by the sum over all sources indexed by j , which is summed over all lepton categories:

$$\mu_i = \sum_j L_j \sigma_j \epsilon_{ij} \quad . \quad (6.3)$$

Here the L_j are the integrated luminosities, the σ_j are the cross sections, and the ϵ_{ij} are the efficiencies per bin of (H_T, M_{reco}) .

The likelihood is calculated as a function of the $t'\bar{t}'$ cross section and Bayes' Theorem is used to convert it into a posterior density in $\sigma_{t'}$.

$$p(\sigma_{t'}|n_i) = \frac{\mathcal{L}(\sigma_{t'}|n_i)\pi(\sigma_{t'})}{\int \mathcal{L}(\sigma'_{t'}|n_i)\pi(\sigma'_{t'})d\sigma'_{t'}} \quad (6.4)$$

Here $\pi(\sigma_{t'})$ is the prior probability density for $\sigma_{t'}$ (which cancels out if it is constant). This posterior density can then be used to set an upper limit or measure the production rate of $t'\bar{t}'$.

In order to use this posterior density to calculate an upper limit the only free parameter in it can be the $\sigma_{t'}$. There are several other parameters however that must be addressed, these are dealt with via the profiling method (51), i.e. the likelihood is maximized with respect to these parameters. The production rates for W +jets in the 4-jet bin and in the ≥ 5 jet bins are two free unconstrained independent parameters in the fit (insulating the result from errors arising from the method in which their normalization estimates were derived). Other parameters, such as the $t\bar{t}$ production cross section, lepton ID data/MC scale factors, integrated luminosity are related to systematic errors and treated in the likelihood as nuisance parameters constrained within their expected distributions. These systematic errors fall into two categories morphing parameters or shape systematics, which affect both the normalization and shape of the templates, and non-morphing parameters or rate systematics, which affect only the normalization and not the shape of the templates.

Taking this into account the likelihood takes the following expression:

$$\mathcal{L}(\sigma_{t'}|n_i) = \prod_{i,k} P(n_i|\mu_i) \times G(\nu_k|\tilde{\nu}_k, \sigma_{\nu_k}) \times \prod_{e,j} P(n_i|\mu_i) \times f_X(\nu_j|\tilde{\nu}_j, \sigma_{\nu_j}) \quad (6.5)$$

where ν_k are the nuisance parameters used in the morphing parameters (constrained by gaussian terms to their expectation) and ν_j are the nuisance parameters used in non-morphing parameters (constrained by log normal terms to their expectations), such as $\sigma_{t\bar{t}}$, L_j and etc. $\tilde{\nu}_k, j$ are their central nominal values and $\sigma_{\nu_k, j}$ are their uncertainties.

The final component of the likelihood is the nuisance parameters associated with the impact of the finite MC statistics on our bin efficiency measurements. The measurement of the efficiency we make from the MC has a statistical error dependent upon the number of MC events in the bin. For many analysis with relatively few bins each of which has relatively many MC events this error is unimportant, but given the large number of bins used in this work the error becomes relevant. Barlow and Beeston (52) proposed a method for representing such systematic uncertainties by introducing a separate nuisance parameter multiplying the expected number of events from each source in each bin. Nominally these parameters have value 1 and they can be constrained according to the prior probability distribution function assumed for the number of MC events, in this work we assume a log-normal distribution so as to avoid the parameters tending to zero. Computational difficulties arise from the implementation of the full

Barlow-Beeston method (53), however since it is the overall statistical uncertainty on the predicted number of events from all sources rather than the uncertainty on each source that matters we can combine the uncertainties for each source as a single Barlow-Beeston type parameter. We then seek to minimize the contribution of this nuisance parameter by solving for the point at which the derivative of the natural log of the likelihood with respect to this parameter is zero. This is computationally tractable.

6.6 Systematics

In this section the various sources of systematic uncertainties and their effect on the result are described. First the systematics with an impact on the shape of the distributions and then the systematics which only affect the rates of the processes are described.

6.6.1 Shape Systematics

The shape systematics for this analysis include the jet energy scale, the W +jets Q^2 scale and the initial and final state radiation. The jet energy scale uncertainty applies to all MC samples. The W +jets Q^2 scale affects only the W +jets backgrounds and the initial and final state radiation is only significant applied to the $t\bar{t}$ background.

6.6.1.1 Jet Energy Scale

The sensitivity to t' depends on knowing accurately the distribution of (H_T, M_{reco}) . Therefore the largest source of uncertainty comes from the factor that has the greatest effect on the shape of the kinematic distribution, which is due to the jet energy scale. Jets in the data and Monte Carlo are corrected for various effects as described in 3.3.1, leaving some residual uncertainty.

This uncertainty results in possible shift in the H_T and M_{reco} distributions for both new physics and Standard Model templates. This effect is accounted for by generating templates with energies of all jets shifted upward by one standard deviation (+1 templates) and downward (-1 templates) respectively. From these templates we derive bin efficiencies $\epsilon_{ij}^{\pm}$ for upwards and downwards shifted templates as well as an efficiency ϵ_{ij}^0 from the nominal template.

With the templates generated the expectation value μ_i at each bin i is constructed via quadratic interpolation for $|\nu_{JES}| < 1$, where ν_{JES} is the nuisance parameter representing a relative shift in jet energy scale, and extrapolated linearly beyond that

range. Specifically the value of the efficiency for $|\nu_{JES}| < 1$ is determined by Lagrange interpolation as:

$$\epsilon_{ij} = \frac{\nu_{JES}(\nu_{JES} - 1)}{2} \epsilon_{ij}^- - (\nu_{JES} - 1)(\nu_{JES} + 1) \epsilon_{ij}^0 + \frac{\nu_{JES}(\nu_{JES} + 1)}{2} \epsilon_{ij}^+. \quad (6.6)$$

Outside of the $|\nu_{JES}| < 1$ region the efficiency is determined by straightforward linear extrapolation.

ν_{JES} enters the likelihood (6.5) as a gaussian constraint penalty term: $G(\nu_{JES}|0, 1) = \frac{1}{\sqrt{2\pi}} e^{-\nu_{JES}^2/2}$. This treatment of the systematic uncertainty was developed from the vertical template morphing method and is described more fully in (53).

6.6.1.2 W +jets Q^2 Scale

The effect of the choice of the appropriate Q^2 scale for W +jets production is evaluated by using the W +jets Monte Carlo samples generated with different Q^2 settings. Variant templates are constructed using MC samples generated with a half and double of the nominal Q^2 .

The Q^2 systematic is then incorporated into the likelihood in a manner similar to the Jet Energy Scale systematics, with an exception that it is only applied to W +jets template.

6.6.1.3 Initial and Final State Radiation

Making use of $t\bar{t}$ samples that simulate the effect of increasing and decreasing the initial and final state radiation in $t\bar{t}$ events shifted templates ("IFSR less" and "IFSR more") serve as +1 and -1 σ templates and are incorporated into the likelihood in the same way as the Jet Energy Scale and the W +jets Q^2 systematics. This morphing is only performed for $t\bar{t}$ template. In principle, the initial and final state radiation also affects the shapes of the t' H_T and M_{reco} distribution. However, the effect of this shift is tiny for t' . It changes the mean of the distribution by 2%. On the contrary, the effect from $t\bar{t}$ is non-negligible because it is a large background.

6.6.2 Rate Systematics

Rate systematics which affect this result include the integrated luminosity, the lepton ID scale factors, the PDF uncertainty, the theoretical uncertainty on the t' and top cross section and the uncertainty on the rate of b-tagging.

6.6.3 Integrated Luminosity

The integrated luminosity uncertainty is taken to be 5.8% (54), and represented by an additional log normal constrained parameter multiplying all contributions except for the QCD background and $W + \text{jets}$, which are normalized independently.

6.6.4 Lepton ID

The lepton ID scale factors and trigger efficiencies used are standard in the CDF Joint Physics Group (55), and applied to MC-based backgrounds only, except for $W + \text{jets}$, which floats independently. The uncertainty due to those is 1% and is applied in quadrature with the uncertainty due to the NLO theoretical cross sections.

6.6.4.1 PDF Uncertainty

The Parton Distribution Functions (PDFs) are not precisely known, and this uncertainty leads to a corresponding uncertainty in the predicted cross sections, as well as in the acceptance. The first is a major part of the NLO theoretical cross section and described in Sec. 6.6.4.2. The latter is estimated to be 1% from the $t\bar{t}$ cross section analyses, and is summed in quadrature with the uncertainty due to theory.

6.6.4.2 Theory Uncertainty

The theory uncertainty in the t' cross section is about 10% (see Table 7.1), which is mainly due to uncertainty in PDFs ($\sim 7\%$). The other effect comes from uncertainty in the choice of the Q^2 scale (57).

The theory uncertainty in $t\bar{t}$ cross section is taken as fully correlated with the one of t' and it is introduced into the likelihood as a single nuisance parameter: $\nu_{theory} = \nu_{theory}(m'_t)$, which is the same parameter used to constrain $t\bar{t}$ cross section to a theoretical value.

Cross sections for small electroweak backgrounds are also known with the precision of 10% and applied as independent nuisance parameters.

6.6.4.3 B-tag Uncertainty

The rate of b-tagging in top and t' is not perfectly modeled in MC and so a b-tagging scale factor is applied and an uncertainty therein. In addition this uncertainty is greater for jets with greater E_T . For jets with E_T below 100 GeV we follow the standard joint physics scale factor of 0.95 and uncertainty of 0.04 (56). For jets with E_T above 100

GeV we apply an E_T dependent asymmetric uncertainty of $+0.0005 * E_T$ or $-0.0015 * E_T$ following work used in the CDF search for a w' (41). This uncertainty is applied as a rate uncertainty in the same fashion as the PDF uncertainty.

Chapter 7

Results

The sensitivity of the method was tested by drawing pseudoexperiments from Standard Model distributions, i.e. assuming no t' contribution. The range of expected 95% CL upper limits with one standard deviation bandwidth is shown in Figure 7.5. The purple curve is the theory curve (57), the values of which are given in Table 7.1. The lower σ_{min} and upper σ_{max} limits are obtained using the CTEQ6M family of parton density functions with uncertainties, together with the study of the scale uncertainty (58).

From Figure 7.5 it follows that given no t' presence, this method is on average sensitive to setting an upper limit at 370 GeV t' mass.

The analysis fit on the data is performed and the resulting likelihoods for the t' mass points considered may be seen in Figures 7.1 7.2 7.3 7.4. From these it is concluded that no significant excess of events is seen and a mass limit may be set.

The red curve in Figure 7.5 shows the final result, expressed as a 95% CL upper limit on the t' production rate as a function of t' mass. Table 7.2 shows the individual calculated limits along with expected limits from pseudo-experiments.

Distributions of H_T and M_{reco} in four different categories of events are shown in Figure 7.6. The t' signal with mass of 360 GeV is normalized to the theoretical cross section value.

No significant excess is found and so based on these results a t' quark decaying via $t' \rightarrow Wb$ with mass below 358 GeV is excluded at 95% CL, given the true top mass is 172.5 GeV.

Figure 7.1: Likelihoods for t' masses of 180, 200, 220 and 240 GeV.

Figure 7.2: Likelihoods for t' masses of 250, 260, 280 and 300 GeV.

Figure 7.3: Likelihoods for t' masses of 320, 340, 350 and 360 GeV.

Figure 7.4: Likelihoods for t' masses of 380, 400, 450 and 500 GeV.

$m(t')$ (GeV)	σ_{min} (pb)	σ_{center} (pb)	σ_{max} (pb)
180.0	4.9938	5.7476	6.2396
200.0	2.7815	3.1898	3.4525
220.0	1.5926	1.8236	1.9710
240.0	0.9299	1.0647	1.1515
260.0	0.5499	0.6302	0.6828
280.0	0.3281	0.3769	0.4096
300.0	0.1968	0.2268	0.2475
320.0	0.1183	0.1370	0.1502
340.0	0.0711	0.0828	0.0914
360.0	0.0426	0.0500	0.0555
380.0	0.0255	0.0301	0.0337
400.0	0.0152	0.0181	0.0204

Table 7.1: Theory values of t' cross section for given mass (57).

Figure 7.5: Limits.

$m(t')$ (GeV)	expected limit (pb)	observed limit (pb)
180	$1.757^{+0.729}_{-0.519}$	1.814
200	$0.563^{+0.198}_{-0.178}$	0.581
220	$0.209^{+0.099}_{-0.058}$	0.242
240	$0.142^{+0.059}_{-0.041}$	0.139
250	$0.121^{+0.047}_{-0.036}$	0.113
260	$0.104^{+0.043}_{-0.029}$	0.106
280	$0.082^{+0.034}_{-0.025}$	0.088
300	$0.065^{+0.029}_{-0.018}$	0.076
320	$0.052^{+0.023}_{-0.013}$	0.062
340	$0.044^{+0.019}_{-0.011}$	0.057
350	$0.040^{+0.019}_{-0.010}$	0.053
360	$0.037^{+0.017}_{-0.010}$	0.054
380	$0.032^{+0.013}_{-0.009}$	0.052
400	$0.028^{+0.011}_{-0.008}$	0.049
450	$0.019^{+0.007}_{-0.006}$	0.031
500	$0.013^{+0.006}_{-0.003}$	0.020

Table 7.2: Expected and obtained limits on t' production cross section for given mass.

Figure 7.6: Log scale distributions of H_T and M_{reco} with $t'\bar{t}'$ signal of t' mass 400 GeV and no t' signal. All backgrounds set to their fitted normalizations results

Figure 7.7: Scatter plot of events in H_T and M_{reco}

Conclusions

8.1 Other Recent Fourth Generation Searches

In searches conducted at the CMS and ATLAS experiments at the Large Hadron Collider after the completion of this work exclusion limits have been set for a t' quark with a mass below 685 GeV (CMS) (59) and 404 GeV (Atlas) (60). The CMS result search included searches for $t'\bar{t}'$ production in addition to searches for mixed production of a single t' quark and a b' quark. The $t'\bar{t}'$ was assumed to decay to two b quarks and two W bosons as in this work. The Atlas search looked for $t'\bar{t}'$ production assuming each produced t' quark would decay to a b quark and a W boson. These searches thus set limits that are quite similar to that set in this work in applicability. These searches raise the lower limit on a t' quark mass to a region where perturbative calculations for the weak interactions start to fail.

8.2 Future of a Fourth Generation

The recent LHC searches and the push the limits on a fourth generation t' quark decaying to a W boson and a b quark into regions which are theoretically disfavored. It is still possible however that a fourth generation quark might be found with a different decay signal, recent theoretical constructions have included situations with relatively small 3rd-4th generation mixing (61) and other work (62) suggesting that a t' quark decaying to a Higgs boson and a top quark would be an interesting signal to search for. Future studies along the lines of this work seem less well motivated.

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