Search for a Fourth-Generation Quark More Massive than the $Z^0$ Boson in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

by

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2000

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Para os meus pais
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Chapter 1

Introduction

The Standard Model (SM) of Particle Physics with three generations of quarks and leptons is in excellent agreement with all experimental data available today. There is no experimental indication that an extra fermion generation exists. However, the SM does not explain either the fermion family replication or the fermion mass hierarchy. Several theoretical models have been proposed to solve shortcomings in the Standard Model through the introduction of extra quarks and leptons, while grand unification, supersymmetry, supergravity and superstrings predict or can accommodate extra fermion states.

This dissertation reports on a search for a fourth-generation quark with charge $-1/3$ ($b'$) more massive than the $Z^0$ boson. We use 87.8 $\text{pb}^{-1}$ of $\bar{p}p$ collisions at $\sqrt{s} = 1.8 \text{ TeV}$ obtained with the Collider Detector at Fermilab (CDF) between 1994 and 1996. We search for $b'$ quarks, pair-produced by the strong interaction, that would decay by flavor-changing neutral current into a $b$ quark and a $Z^0$ boson. We study the decay mode $b'b' \rightarrow b\bar{b}Z^0Z^0$ where one $Z^0$ decays into $e^+e^-$ or $\mu^+\mu^-$ and the other decays hadronically, giving a signature of two leptons plus jets.

The thesis is organized as follows. In the remainder of this chapter, we motivate the search for this quark in this decay mode. Theoretical estimations and current experimental limits are presented. Chapter 2 gives a brief description of the experimental apparatus. The main components of the Fermilab accelerator system and the CDF detector are briefly discussed. The remaining chapters cover the steps necessary to analyze the data and draw
conclusions about the existence of this new quark. Chapter 3 describes the data sample and the event selection done to enhance the signal relative to the background. Chapter 4 is devoted to the calculation of the acceptance and efficiencies for the $b'$ quark signal. Both detector and selection effects are included. The systematic uncertainties that affect the final acceptance calculation are examined in Chapter 5. The background estimation in the $Z^0 + \text{jets}$ channel is discussed in Chapter 6. Chapter 7 presents the final results of the search. These include the calculation of an exclusion limit, some cross-checks, and a few comments. Finally, we conclude with a short summary of the dissertation in Chapter 8.

1.1 The Standard Model

The Standard Model (SM) of elementary particles and their fundamental interactions describes all phenomena currently observed in high energy physics experiments. According to the SM, the universe consists of a set of elementary particles that are the basic building blocks of matter and interact through four forces known as the electromagnetic, strong, weak and gravitational forces. Each force is carried by intermediate interaction particles. The matter particles, listed in Table 1.1, are spin-1/2 fermions and are classified into leptons and quarks. There are six leptons ($l$): the electron ($e$), the muon ($\mu$) and the tau ($\tau$) with electric charge $-1$; and their respective neutrinos $\nu_e, \nu_\mu, \nu_\tau$ with neutral electric charge. There are also six different flavors of quarks: up, down, charm, strange, bottom and top. The quarks differ from the leptons by having fractional charge and an additional quantum number known as color, which can take three different values: red, green and blue.

The forces between the particles above are listed in Table 1.2 together with their respective intermediate particles. The electromagnetic, the weak and the strong forces are mediated by the exchange of spin-1 bosons. The photon ($\gamma$) is the exchanged particle in the electromagnetic interaction. The strong interaction is mediated by eight gluons, and the three weak bosons ($W^\pm$ and $Z^0$) are the corresponding intermediate bosons of the weak interactions. The gravitational interactions are mediated by the graviton, a spin-2 boson. The strength of each force is characterized by a coupling constant. At low energies the
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<td>t</td>
<td>2/3</td>
<td>173.8 ± 5.2</td>
</tr>
<tr>
<td></td>
<td>Bottom quark</td>
<td>b</td>
<td>-1/3</td>
<td>4.1 - 4.4</td>
</tr>
</tbody>
</table>

Table 1.1: The Standard Model lepton and quark generations. The particles masses are from reference [1].

The electromagnetic coupling strength is given by the fine structure constant, \( \alpha \approx 1/137 \). The weak interactions are characterized by a coupling of the order of \( \alpha_W \approx 10^{-5} \) at energies much lower that the masses of the intermediate weak bosons. The strong force coupling constant \( \alpha_s \) varies from a value of \( \sim 1 \) at large distances down to the asymptotic limit \( \alpha_s \rightarrow 0 \) for vanishingly small distances. Gravity (\( \alpha_G \approx 10^{-38} \)) is too weak to play an important role in the particle physics processes studied in this thesis and will not be discussed any further.

<table>
<thead>
<tr>
<th>Force</th>
<th>Particle</th>
<th>Charge (e)</th>
<th>Mass (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>Photon (( \gamma ))</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Strong</td>
<td>Gluon (( g ))</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Weak</td>
<td>Charged ( W ) Boson (( W^± ))</td>
<td>±1</td>
<td>80.3</td>
</tr>
<tr>
<td></td>
<td>Neutral ( Z ) Boson (( Z^0 ))</td>
<td>0</td>
<td>91.2</td>
</tr>
<tr>
<td></td>
<td>Gravitational Graviton (( G ))</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1.2: The Standard Model fundamental forces and corresponding gauge bosons.

The charged lepton interactions are mediated by the electromagnetic and weak forces, while neutrinos, being electrically neutral, only participate in weak interactions.
Quarks carry both color and electric charge and therefore participate in interactions involving the strong, electromagnetic and weak forces. All particles mentioned above have an associated antiparticle with equal mass and spin but opposite charge. For instance, the electron has an antiparticle called the positron \((e^+\)) ; the antiquarks are denoted by \(\bar{u}, \bar{d}, \bar{s}, etc.\) The neutral particles like the photon, \(Z^0\), and gluon are identical to their antiparticles.

The Standard Model is a quantum field theory that is based on the gauge symmetry \(SU(3)_C \times SU(2)_L \times U(1)_Y\). This gauge group includes the symmetry group of the strong interactions \(SU(3)_C\), and the symmetry group of the electroweak interactions \(SU(2)_L \times U(1)_Y\). In the SM, the electroweak symmetry is spontaneously broken \(SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{em}\), where \(U(1)_{em}\) is the group symmetry of the electromagnetic interaction. This symmetry-breaking is implemented by the Higgs mechanism which provides the non-zero masses to the weak bosons \(W^\pm\) and \(Z^0\), and predicts the existence of a new electrically-neutral scalar particle, the Higgs boson. The Higgs boson has yet to be confirmed experimentally and the mechanism for the electroweak symmetry breaking remains one of the great open questions of the SM.

In the SM with \(SU(2)_L \times U(1)_Y\) as the gauge group of electroweak interactions, the fermions can be grouped into three generations (or families) as shown in Table 1.1. Each generation is a replica of the others except for the particle masses. Each contains a charged and neutral lepton, and an up-type and a down-type quark. The fermions are assigned to left-handed doublets and right-handed singlets as follows:

\[
\begin{align*}
\begin{pmatrix}
\nu_e \\
e_L
\end{pmatrix},
\begin{pmatrix}
u_u \\
u_R, u_R, d_R
\end{pmatrix},
\begin{pmatrix}
u_\mu \\
\mu_L, c_R, s_R
\end{pmatrix},
\begin{pmatrix}
u_\tau \\
\tau_L, t_R, b_R
\end{pmatrix},
\end{align*}
\]

The quark mass eigenstates are not the same as the weak interaction eigenstates. The \(3 \times 3\) matrix relating them is known as Cabibbo-Kobayashi-Maskawa (CKM) matrix.
The mixing is expressed in terms of an unitary matrix operating on the charge $-1/3$ quarks. The matrix contains four independent parameters: three angles and one phase.

$$
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
= 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}_{\text{weak}}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}_{\text{mass}}
$$

1.2 Quarks beyond the SM

The Standard Model describes the fermion family replication but cannot explain why there is exactly three families and what is the origin of the mass hierarchy observed among the fermions. Extra fermion families could be added to the SM without much modification. The idea of a fourth generation has been considered from a number of different perspectives, such as,

- The scenario of dynamical electroweak symmetry breaking due to heavy-quark condensation [2]. In some models [3, 4] the top-quark mass is not large enough to be responsible for the electroweak symmetry breaking. Heavier quarks that couple to top would be required.

- A minimal four-family supergravity model [5].

- Supersymmetric models [6, 7] with four fermion families.

- Models that attempt to solve the strong-CP problem without axions can introduce a non-chiral doublet of quarks or non-chiral singlets [8].

- It has been shown that extending the SM with one extra generation can allow unification of the gauge couplings at the unification scale without supersymmetry [9].

- It has been argued [10] that flavor democracy, which requires that the Yukawa couplings of all fermions of a particular type with the Higgs boson before the diagonalisation of the mass matrix are equal, can be achieved in a four-generation model with
a heavy neutrino without requiring any large hierarchy among Yukawa couplings of
the fermions of different types. This is no longer possible in a three-family model due
to the high mass of the top quark and the relatively low masses of the other fermions.

In this thesis, we consider a new charge $-1/3$ quark ($b'$) belonging to a standard
sequential fourth generation.

\[
\begin{pmatrix}
  u \\
  d \\
  c \\
  s \\
  t \\
  b \\
  b'
\end{pmatrix}
\]

(1.1)

We assume that the $b'$ quark is lighter than the $t'$ quark, its partner in a SU(2) doublet.
Nevertheless, our results should also apply to vector-like quarks, both doublets and singlets,
with little or no modification.

1.2.1 Production and Decay of the $b'$ Quark

Fourth-generation $b'$ quarks can be pair-produced in $p\bar{p}$ collisions through $gg$ fusion
and $qq$ annihilation with the same cross section, for a given mass, as top quarks. The
tree-level diagrams for strong $b'b'$ production are shown in Figure 1.1.

![Figure 1.1: Feynman diagrams for pair production of the $b'$ quark.](image)

Each quark can decay via the the Standard Model charged current (CC), or via loop
induced flavor-changing neutral currents (FCNC). In general, CC transitions are by far more
important because the FCNC's are higher-order processes and can be suppressed by the
Glashow-Iliopoulos-Maiani (GIM) mechanism. However, if a $b'$ quark exists and is lighter than both the $t$ and $t'$ quarks, the charged-current decays $b' \rightarrow tW^-$ and $b' \rightarrow t'W^-$ are kinematically forbidden. The leading charged-current decay mode will then be $b' \rightarrow cW^-$, shown in Figure 1.2, which is doubly Cabibbo-suppressed. That is, the CKM matrix element $V_{cb'}$ is expected to be very small because it represents the mixing between two non-adjacent families (for instance, the corresponding coefficient between the first and third families is $V_{ub} = 0.0018$ to $0.0045$ [1]).

![Figure 1.2: Charge current weak decay of a $b'$ quark lighter than both $t$ and $t'$.](image)

On the other hand, the loop induced FCNC $b' \rightarrow bV^0$ shown in Figure 1.3, where $V^0$ is a neutral vector boson, carries the CKM coefficients

$$V_{ub}V_{ub} \approx -V_{lb}V_{lb}$$

(1.2)

and therefore has more or less the same CKM coefficients as the forbidden tree level transition $b' \rightarrow tW^-$ (since the processes corresponding to $V_{ub}V_{ub}$ and $V_{cb}V_{cb'}$ would also be very Cabibbo suppressed). Box diagrams involving two $W$ bosons also contribute, but it has been argued that these can be ignored [13]. In this situation FCNC decays can dominate [11, 12, 13] provided $|V_{cb'}|/|V_{ub}|$ is less than roughly $10^{-2}$ to $10^{-3}$, depending on the $b'$ and $t'$ masses [13]. This is a reasonable assumption when compared with the equivalent quantity for three generations $|V_{ub}|/|V_{cb}| = 0.08 \pm 0.02$ [1].

The $b' \rightarrow b\gamma$, $b' \rightarrow b + \text{hadrons}$ and $b' \rightarrow bZ^0$ width obtained with $m_t = 175 \text{ GeV}/c^2$ are shown in Figure 1.4 as function of the $b'$ and $t'$ masses.\footnote{The theoretical predictions for the different FCNC branching ratios were performed before the discovery} From these calculations, we
conclude that if \( m_{\nu} > m_{Z} + m_{b} \), the dominant FCNC decay mode is \( b' \rightarrow bZ^{0} \) [13] as long \( b' \rightarrow bH \) is kinematically suppressed or forbidden [16].

For \( m_{t} < m_{\nu} < m_{t} + m_{W} \), the decay mode \( b' \rightarrow tW^{*} \) becomes available but is suppressed by three-body phase space, and the \( b' \rightarrow bZ^{0} \) channel can still dominate over the CC decay for \( b' \) masses up to about 230 GeV/c^2 [11, 17].

1.2.2 Experimental Limits

The LEP experiments have established with high statistical precision that the number of light neutrinos (i.e., \( m_{\nu} < m_{Z/2} \)) is three. This excludes the possibility of existence of a fourth generation of fermions with a zero or small mass neutrino. However, if a fourth-generation neutrino is heavier than \( m_{Z/2} \), it would not show up in the “neutrino counting” experiment at LEP, and therefore the existence of an extra fermion generation is not excluded.

The direct experimental limits on the \( b' \) quark mass come from several sources. A summary of these limits is given in Figure 1.5. The experimental signatures of the \( t' \) and \( b' \) quark decays via charged currents to bottom and charm are very similar to the top quark signatures that have been studied at CDF and DØ. Therefore, on the assumption of the top quark [12, 13], therefore the authors assumed that \( m_{t} = m_{\nu} + 10 \) GeV. We thank Robin Stuart for providing the program for the calculation with \( m_{t} = 175 \) GeV/c^2.
Figure 1.4: Theoretical prediction of the FCNC $b'$ width in arbitrary units.
predominant CC decay, the dilepton and the lepton + jets (without $b$-tagging in the $b'$ case) mass limits will apply with little modification to the lighter of $b'$ or $t'$. In 1990, CDF used this argument to publish a lower limit on the $b'$ mass of 72 GeV [15]. If the CC transition $b' \rightarrow cW^-$ is the exclusive $b'$ decay, the lower mass bound of 128 GeV found in a DØ top quark search [22] also applies to the $b'$ quark [1].

Several experiments have searched explicitly for $b'$ quarks decaying via FCNC. The most stringent limit comes from the DØ Collaboration, which searched in the $b'\overline{b} \rightarrow \gamma gb\overline{b}$ and $b'\overline{b} \rightarrow \gamma\gamma b\overline{b}$ channels, excluding a $b'$ quark mass up to $m_Z + m_b$ for a FCNC branching fraction larger than 50% [19]. Previous lower mass limits, carried out at $e^+e^-$ colliders, had been established by the AMY, VENUS, MARK II and LEP I collaborations [18].

CDF has excluded a long-lived $b'$ quark with mass up to 148 GeV/c$^2$ and a lifetime of $\tau \approx 3.3 \times 10^{-11}$ sec, assuming $BR(b' \rightarrow bZ^0) = 100\%$ [20]. CDF has also carried out a

Figure 1.5: Summary of $b'$ mass excluded regions. Light boxes indicate previously excluded regions. The box with vertical dashes indicates the previously excluded region for a long-lived quark.
preliminary search for very long-lived charged massive particles [21]. These would be heavy quarks produced in $p\bar{p}$ collisions and that would leave the detector without decaying. The lower mass limit for a stable charge $-1/3$ quark is 195 GeV/$c^2$. These limits are only valid for the special case when the fourth generation is almost completely decoupled from the other three.

1.2.3 The $b'$ Signature

As mentioned before, under some reasonable assumptions on the sizes of the relevant Kobayashi-Maskawa matrix elements, the flavor-changing neutral current decay of $b'$ can be the dominant decay mode. In this case, for a $b'$ quark more massive than the $Z^0$ boson the theoretical prediction for $BR(b' \rightarrow bZ)$ is close to 100%. Therefore, we search for pair-produced $b'$ quarks decaying via FCNC into $bZ^0$. One $Z^0$ decays into leptons and the other decays hadronically, as shown in Figure 1.6. The signature is two high transverse momentum ($p_T$) leptons from the $Z^0$ decay, two high-$p_T$ jets from the second $Z^0$, and two $b$ jets with $p_T$ which scales with the $b'$ mass being considered.

$$b' \bar{b}' \rightarrow bZ + \bar{b}Z \rightarrow q\bar{q} \rightarrow \ell^+\ell^-$$

Figure 1.6: The $b'$ decay mode under study.
Chapter 2

Experimental Apparatus

The Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, is a major facility dedicated to the study of high-energy physics. The laboratory holds a particle accelerator complex that includes the accelerator which provides the most energetic collisions per nucleon in the world, the Tevatron. The Tevatron produces proton (p) and antiproton (\(\bar{p}\)) collisions with a center of mass energy of \(\sqrt{s} = 1.8\text{ TeV}\). The debris from the collisions are studied by two large multi-purpose particle detectors, the Collider Detector at Fermilab (CDF) and the DØ detector. The data used to search for \(b \bar{b}f\) production were collected with the CDF detector between 1994 and 1996.

2.1 Fermilab Accelerator Complex

In order to obtain beams of particles at high energies several stages are necessary. In a short description of this process, we will follow the path of the protons and antiprotons paths from their creation until their annihilation in the interaction point. A schematic diagram of the Fermilab accelerator complex is shown in Figure 2.1. The process starts with the production of \(H^-\) ions from a bottle of hydrogen gas. The ions are accelerated by a Cockroft-Walton electrostatic accelerator to an energy of 750 keV before being delivered to a 145 m linear accelerator, the Linac, which accelerates the ions to an energy of 400 MeV. The \(H^-\) ions pass through a copper foil and lose their two electrons. The resulting bare protons
are then injected into another accelerator, the Booster ring. The Booster, a synchrotron with a radius of 75 m, boosts the protons to an energy of 8 GeV and gathers the protons into bunches. The proton bunches are extracted and delivered to the Main Ring.

The Main Ring is a 1 km radius synchrotron with conventional magnets that is able to accelerate protons up to an energy of 150 GeV. After reaching 150 GeV, the protons are coalesced into a single bunch and injected into the Tevatron ring. The Tevatron is a synchrotron accelerator with the same radius as the Main Ring and located just below it. The Tevatron uses superconducting magnets operating at the liquid helium temperature to produce the large magnetic fields required to attain 900 GeV energies per beam.

The Main Ring serves a second major purpose. It provides 120 GeV protons to be used in the production of antiprotons. The antiproton production is rather complex. The 120 GeV protons from the Main Ring are extracted and collide with a tungsten target. Antiprotons are selected from the resulting particles, focused with a lithium lens, and injected into the Debuncher. The Debuncher reduces the antiproton momenta spread using stochastic cooling. From the Debuncher, the antiprotons are transferred to the Accumulator, a ring that stores them at an energy of 8 GeV. Here, they are “stacked” at a rate of $\sim 4 \times 10^{10}$ antiprotons per hour, until approximately $10^{12}$ antiprotons have been collected. When a large number of antiprotons has been stored, six bunches of approximately $2 \times 10^{11}$ protons are injected from the Main Ring into the Tevatron. Then, six bunches of $\sim 5.5 \times 10^{16}$ antiprotons from the Accumulator are transferred into the Main Ring and accelerated to an energy of 150 GeV. When this energy is reached, the antiproton bunches are injected into the Tevatron in the opposite direction of the protons. Many antiprotons are lost in the transfer process from the Accumulator to the Tevatron, and therefore the antiproton bunches at the Tevatron are composed of only $\sim 3 \times 10^{10}$ particles. The proton and antiproton beams travel in counter-rotating helical paths sharing the same beam pipe, while being accelerated up to 900 GeV. The $p\bar{p}$ collisions take place at the B0 and D0 interaction regions where the CDF and DØ detectors are located respectively. The transverse beam profile, in the collision region, is characterized by a gaussian distribution in the horizontal and vertical
Figure 2.1: Schematic diagram of the Fermilab accelerator complex. The Main Ring and the Tevatron are both inside the same tunnel. The Tevatron is located below the Main Ring and both have the same 1 km radius [25].

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directions with a width of $\sigma_x \approx \sigma_y \approx 35 \mu m$. The bunch crossing at the interaction region occurs at every 3.5 $\mu$s, corresponding to the Tevatron typical instantaneous luminosity of $1-2 \times 10^{-31} \text{ cm}^{-2}\text{s}^{-1}$.

### 2.2 Collider Detector at Fermilab

The Collider Detector at Fermilab is a multi-purpose apparatus designed to detect and study the particles produced in high-energy $p\bar{p}$ collisions. Extensive descriptions of the CDF detector can be found in the literature [26, 27]. Here, we will briefly describe the components that were the most relevant for this analysis. A schematic cross-section view of the CDF detector is shown in Figure 2.2. The detector has an overall forward-backward and cylindrical symmetry, and therefore only a quarter is shown. The CDF coordinate system uses $(\theta, \phi, z)$, where the proton beam is in the $z$ direction and $\theta$ and $\phi$ are the polar and azimuthal angles. The origin of the coordinate system is located at the nominal interaction point shown on the lower righthand corner of Figure 2.2. The detector pseudorapidity is defined in terms of the polar angle as $\eta = -\log[\tan(\theta/2)]$.

The CDF detector is composed of a variety of smaller specialized components. Most of these are integrated into the four major systems of the detector: tracking, calorimetry, muon chambers and trigger.

Surrounding the nominal interaction point and inside a 1.4 T solenoidal magnetic field, the silicon vertex detector (SVX), the vertex time projection chamber (VTX), and the central tracking chamber (CTC) provide tracking information. The SVX, positioned immediately outside the beampipe and inside the VTX, delivers precise track reconstruction in the plane transverse to the beam and is used to identify secondary vertices from the decay of $b$ hadrons. The VTX is used to measure the position of the primary interaction vertex along the $z$ axis. The CTC is a cylindrical drift chamber that covers the pseudorapidity range $|\eta| < 1.1$.

Outside the solenoid, electromagnetic (CEM, PEM, FEM) and hadronic (CHA, WHA, PHA, FHA) calorimeters surround the tracking volume and are used to identify
Figure 2.2: Schematic diagram of a quarter of the CDF detector. The interaction point is located at the lower righthand corner. The detector components are described in the text. The coordinate system used by CDF is also shown.
electrons, photons and jets over the range $|\eta| < 4.2$. Outside the calorimeters, three systems of drift chambers (CMU, CMP, CMX) in the region $|\eta| < 1.0$ provide muon identification. A three-level trigger selects the inclusive electron and muon events used in this analysis. Each of these systems is described in more detailed below.

### 2.2.1 Tracking System

The silicon vertex detector (SVX), the vertex time projection chamber (VTX), and the central tracking chamber (CTC) provide the tracking information at CDF. They are located inside a uniform 1.4 T magnetic field oriented along the beam direction that is produced by a superconducting solenoidal coil [28]. The coil is 3 m in diameter and 4.8 m in length with an overall radial thickness of 0.85 radiation lengths. The charged particles pass through the uniform solenoidal field with a helical trajectory. The transverse momentum of these particles is then derived from their trajectory curvature as measured by the tracking systems.

The SVX [29, 30, 31, 32] is a silicon micro-strip vertex detector that provides tracking information in the plane transverse to the beam and is used to identify secondary vertices from the decay of $b$ hadrons. Positioned immediately outside the beryllium beampipe and inside the VTX, the SVX is the tracking detector closest to the interaction point. The detector is composed of two similar barrels aligned end-to-end along the beam pipe and symmetrically positioned relative to the nominal interaction point, $z = 0$. One such barrel is shown in Figure 2.3. The total active length of the detector is 51 cm, corresponding to a pseudorapidity coverage of $|\eta| < 1.9$. Since the actual $p\bar{p}$ interaction position is distributed around the nominal interaction point according to a gaussian distribution of width $\sim 30$ cm, the SVX has a geometrical acceptance for $p\bar{p}$ collisions of roughly 60%.

Each barrel consists of four layers of silicon micro-strip detectors position at a radii of 2.86, 4.26, 5.69 and 7.87 cm from the beam axis. The layers are divided into twelve azimuthal wedges of 30$^\circ$, each housing one ladder with silicon detectors. Each ladder accommodates three single-sided silicon detectors of 8.5 cm in length. The silicon detectors
have axial strips with a 60 $\mu$m pitch on the three inner layers and 55 $\mu$m pitch on the outermost layer. The resolution for a single hit in the SVX detector is 13 $\mu$m, while the track impact parameter in the $r - \phi$ plane relative to the beam position can be measured with a precision of 17 $\mu$m. This good resolution allows the detection of secondary vertices from $b$ hadron decays. For this reason, the SVX has become an essential tool in the quest for new physics. The impact parameter information provided by the SVX is used in this thesis in the algorithm that allows the identification of the $b$ hadrons from the $b'$ quark decay. The SVX tracking is done in conjunction with the information from the CTC.

The Vertex Time Projection chamber (VTX) [33] is used to measure the position of the primary interaction vertex along the $z$ axis. The VTX, with a 8 cm inner radius and 22 cm outer radius, lies between the SVX and the CTC. It covers the region in $z$ between $z = \pm 1.4$ m corresponding to a pseudorapidity $|\eta| < 3.2$. The detector consists of octagonal.

Figure 2.3: Diagram of one SVX barrel.
time projection chamber modules with radial wires and it is capable of finding the event vertex to within ±1 mm. The event primary vertex distribution, as measured by the VTX, is described by a gaussian of width ~ 30 cm.

The Central Tracking Chamber (CTC) [34] is a large cylindrical drift chamber that covers the pseudorapidity range of |\eta| < 1.1. It is 3.2 m long in the z-direction, centered at z = 0, with an inner radius of 31.0 cm and an outer radius of 132.5 cm. It consists of 84 concentric cylindrical layers of sense wires that are grouped into nine superlayers. Five of the superlayers are called axial superlayers and contain twelve layers of sense wires parallel to the z axis. These are interleaved with four stereo superlayers each of which contain six layers of sense wires tilted ± 3° with respect to the beam axis. Figure 2.4 shows a diagram of the CTC endplate featuring the nine superlayer geometry. The superlayers are divided into cells tilted 45° relative to the radial direction to compensate for the Lorentz angle of the ionization drift velocity. This gives electron drift trajectories perpendicular to the radial direction so that the maximum drift distance is less than 40 mm, corresponding to a drift time of about 800 ns. The gas mixture used is argon-ethane-alcohol in a 49.6%:49.6%:0.8% proportion and the drift field is ~ 1350 V/cm. The axial superlayers provide information about track momentum in the r-\phi plane. The stereo layers allow for the reconstruction of the track momentum along the z direction, and therefore, together with the axial layers, provide tracking in three dimensions. The CTC measures momentum with a resolution of \( \frac{\delta p_T}{p_T} = 0.002 \text{ GeV}^{-1} \cdot p_T \) without beam constraint or SVX information.

2.2.2 Calorimeters

Electromagnetic and hadronic calorimeters are positioned outside the tracking chambers and the solenoid, covering 2\pi in azimuth and |\eta| < 4.2 in pseudorapidity. They are divided into three major |\eta| regions: central, endplug, and forward. In each region the electromagnetic calorimeter precedes the corresponding hadron calorimeter with respect to the nominal interaction point. The calorimeters are segmented in azimuth and pseudora-
Figure 2.4: Diagram of CTC endplate emphasizing the nine superlayers.
pidity in a projective tower geometry that points back to the interaction point. Some of the calorimeters' characteristics are summarized in Table 2.1.

The central electromagnetic calorimeter (CEM) \([35, 36, 37, 38, 39]\) is divided projective towers assembled into wedges as shown in Figure 2.5. Each tower is 15° wide in azimuth and 0.1 units wide in \(\eta\). The towers are composed of alternating layers of lead and scintillator with a total thickness of 18 radiation lengths. The energy resolution is \(\sigma(E)/E = 13.5\% / \sqrt{E \sin \theta}\) where \(E\) is measured in GeV. In each CEM tower, wire proportional strip chambers (CES) are located at the depth corresponding to the approximate shower maximum \((6 \cdot X_0)\). The CES provides shower shape and position information in both \(z\) and \(r-\phi\). Proportional chambers (CPR) are located between the solenoid and the CEM. They sample the early development of electromagnetic showers in the solenoid coil. The CPR measures only the \(r-\phi\) position of showers.

The central hadronic calorimeter (CHA) \([40]\) is located immediately behind the CEM and is contained in the same physical wedges. It shares the same tower geometry and segmentation as the electromagnetic calorimeter. The wall hadronic calorimeter (WHA) complements the CHA as shown in Figure 2.2. The WHA has a significantly different shape because it covers the edge of the cylindrically shaped central region. Together, the CHA and the WHA provide hadronic coverage in the region \(|\eta| < 1.3\). Both calorimeters are made up of alternating layers of iron and plastic scintillator. Their energy resolution and absorption thickness are given in Table 2.1.

The plug electromagnetic calorimeter (PEM) \([41]\) and the plug hadronic calorimeter (PHA) cover the polar angle region between roughly 10° and 30° with respect to the beamline. They are located immediately next to the central calorimeters extending the total coverage in the central region to \(|\eta| < 2.4\). The plug calorimeters are composed of two identical modules located on each end of the CDF detector as shown in Figure 2.2. The tower size in the plug is 5° wide in \(\phi\) and 0.1 units wide in \(\eta\). Both the PEM and PHA use the same projective geometry and segmentation. The active region is gas proportional chambers with a 50/50 mixture of argon-ethane gas. The proportional tube arrays are in-
Figure 2.5: Schematic of a single central calorimeter wedge. Each wedge is composed of 10 towers. A single tower covers a region of $\Delta \eta = 0.1$ and $\Delta \phi = 15^\circ$. Wire proportional strip chambers are located at shower maximum. The top diagram shows the position of the central electromagnetic and hadronic calorimeter wedge relative to the interaction point and the central muon chambers. The $z$-axis corresponds to the beam axis, the $x$-axis to the azimuthal direction and the $y$-axis to the radial direction. The bottom diagram shows the details of the CEM light collection system.
Calorimeter Subsystem | Geometric Coverage | $\Delta \eta \times \Delta \phi$ segmentation | Energy Resolution (GeV) | Absorption Thickness
---|---|---|---|---
CEM | $0.0 < |\eta| < 1.1$ | $0.1 \times 15^\circ$ | $13.7\%/\sqrt{E_T} \oplus 2\%$ | $18 X_0$
PEM | $1.1 < |\eta| < 2.4$ | $0.09 \times 5^\circ$ | $22\%/\sqrt{E} \oplus 2\%$ | $18-21 X_0$
FEM | $2.2 < |\eta| < 4.2$ | $0.1 \times 5^\circ$ | $26\%/\sqrt{E} \oplus 2\%$ | $18 X_0$
CHA | $0.0 < |\eta| < 0.9$ | $0.1 \times 15^\circ$ | $50\%/\sqrt{E_T} \oplus 3\%$ | $4.5 \lambda_0$
WHA | $0.7 < |\eta| < 1.3$ | $0.1 \times 15^\circ$ | $75\%/\sqrt{E} \oplus 4\%$ | $4.5 \lambda_0$
PHA | $1.3 < |\eta| < 2.4$ | $0.09 \times 5^\circ$ | $106\%/\sqrt{E} \oplus 6\%$ | $5.7 \lambda_0$
FHA | $2.4 < |\eta| < 4.2$ | $0.1 \times 5^\circ$ | $137\%/\sqrt{E} \oplus 3\%$ | $7.7 \lambda_0$

Table 2.1: Summary of the CDF calorimeter properties. Tower segmentation is listed under the column $\Delta \eta \times \Delta \phi$. Energy resolutions are for incident electrons and photons in the electromagnetic calorimeters, and for incident isolated pions in the hadronic calorimeters. $E_T = E \sin \theta$ is the transverse energy. The symbol $\oplus$ signifies addition in quadrature. Thicknesses are given in radiation lengths ($X_0$) for electromagnetic calorimeters, and in interaction lengths ($\lambda_0$) for hadronic calorimeters.

Table 2.1: Summary of the CDF calorimeter properties. Tower segmentation is listed under the column $\Delta \eta \times \Delta \phi$. Energy resolutions are for incident electrons and photons in the electromagnetic calorimeters, and for incident isolated pions in the hadronic calorimeters. $E_T = E \sin \theta$ is the transverse energy. The symbol $\oplus$ signifies addition in quadrature. Thicknesses are given in radiation lengths ($X_0$) for electromagnetic calorimeters, and in interaction lengths ($\lambda_0$) for hadronic calorimeters.

The forward electromagnetic calorimeter (FEM) and the forward hadronic calorimeter (FHA) [42] are physically separated from the rest of the CDF detector. They are composed of two identical modules located in both the proton and antiproton beam directions, positioned approximately 6.5 m from the interaction point. The forward detectors cover the small angle region between 10° and 1.7° relative to the beamline, extending the calorimeter coverage up to $|\eta| < 4.2$. Their construction and energy resolution are similar to the corresponding plug calorimeters.

2.2.3 Muon Detectors

Outside the calorimeters, three systems of drift chambers provide muon identification information. These are the central muon chambers (CMU), the central muon upgrade chambers (CMP) and the central muon extension chambers (CMX). The muon chambers are used to identify muons and make a crude measurement of their transverse momentum.
at the trigger level. This information, combined with a matching extrapolated CTC track, provides accurate muon transverse momentum measurement. The geometric coverage and position resolution for each chamber is summarized in Table 2.2. A fourth muon system located in the detector forward region, the forward muon chamber (FMU), was not used in this analysis, and therefore is not described here.

Table 2.2: Coverage and resolution of muon chambers.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Geometric Coverage</th>
<th>Radial Position</th>
<th>Typical Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMU</td>
<td>0.03 &lt;</td>
<td>η</td>
<td>&lt; 0.63</td>
</tr>
<tr>
<td>CMP</td>
<td>0.00 &lt;</td>
<td>η</td>
<td>&lt; 0.55</td>
</tr>
<tr>
<td>CMX</td>
<td>0.65 &lt;</td>
<td>η</td>
<td>&lt; 1.00</td>
</tr>
<tr>
<td>FMU</td>
<td>2.40 &lt;</td>
<td>η</td>
<td>&lt; 4.20</td>
</tr>
</tbody>
</table>

Figure 2.6: Coverage in the η − φ plane of the central muon chambers used in this analysis. These are the CMU, the CMP and the CMX chambers.

All three muon systems consist of four-layer drift chambers. The CMU chambers
are located immediately outside the CHA and are segmented as $\Delta \eta \times \Delta \phi = 0.1 \times 12.6^\circ$ corresponding to each 15° wedge of the CHA as shown in Figure 2.5. With its 4.5 interaction lengths ($\lambda_0$) of iron, the CHA acts as a hadron absorber for the CMU chambers. The CMP chambers are located behind an additional 0.6 m ($3.5\lambda_0$) of steel. This additional steel reduces the rate of hadronic punchthrough by a factor of 30. By requiring a positive identification by both the CMU and a CMP chambers, the number of fake muons can be significantly reduced. The muon chambers do not cover all the central region of the CDF detector resulting in some $\eta$ and $\phi$ gaps as shown in Figure 2.6. The CMU system covers approximately 84% of solid angle for $|\eta| < 0.6$ while 63% is covered by the CMP. The CMU-CMP simultaneous coverage is 53%.

The CMX chambers extend muon coverage to the region $0.6 < |\eta| < 1.0$, covering 71% of the solid angle in that region. The position of the CMX is shown in Figure 2.2. The CMX drift chambers are arranged as four free-standing conical arches. Scintillators on both faces of the CMX provide trigger information.

2.2.4 Beam-Beam Counters

Minimum bias events account for almost all the $p\bar{p}$ interactions at the Tevatron. These events are characterized by a large number of particles that leave the interaction point at small angles relative to the beamline. The luminosity of the accelerator delivered to CDF is monitored by measuring the rate of the minimum bias events using small-angle scintillating planes called beam-beam counters (BBC). The BBC are located on the front face of each of the forward electromagnetic calorimeters, covering the range $3.2 < |\eta| < 5.9$.

Coincidental signals from both BBCs are required to fall within a 15 ns window around the Tevatron bunch crossing signal. These provide the Level 0 CDF trigger and a measurement of the instantaneous luminosity. The total delivered luminosity at CDF is found by integrating this instantaneous luminosity over time. During the data taking run from 1994 to 1995, the total luminosity at CDF was measured to be $87.8 \pm 3.6$ pb$^{-1}$.
2.2.5 Trigger System

The event rate delivered by the Tevatron (~ 280 kHz) is too large for all events to be recorded and processed by the CDF online data acquisition system. CDF uses a three-level trigger system, to reduce the rate of events to a manageable level (~ 6 Hz) while maximizing the selection of interesting events. Each of the trigger levels consists of a logical OR of a number of triggers designed to find several types of interesting events. Each successive trigger level is more sophisticated and takes a longer time to reach a decision but processes a smaller number of events. The CDF Level 1 and Level 2 triggers are implemented in hardware, while the Level 3 trigger is implemented in software which allows more flexibility.

The hardware implementation of the Level 1 trigger allows for a quick decision on whether to process the event any further. The decision is made within the 3.5 μs between bunch crossings, to minimize the amount of deadtime, i.e. time during which the detector does not acknowledge new interactions. The Level 1 triggers relevant for this analysis are the central muon and calorimeter triggers. These select events with muon tracks in the central muon chambers or significant calorimeter energy for the electron triggers. The three Level 1 central muon triggers use fast outputs from the CMU, CMP, and the CMX. They require a pair of hits in two parallel muon drift tubes. No tracking information is used at this level. The calorimeter triggers use fast outputs from the central calorimeters. In these triggers, the energy in the electromagnetic and hadronic calorimeter are separately summed into trigger towers, defined as Δη × Δφ = 0.2 × 15°. These towers are required to have an energy above a given threshold. For a typical instantaneous luminosity of 10 × 10^{30} cm^{-2} s^{-1}, the Level 1 trigger reduces the event rate from approximately 280 kHz to ~ 1 kHz.

The Level 2 trigger implements more sophisticated algorithms than Level 1 by making more extensive use of trigger signals coming from the calorimeter, tracking, and muon systems. A hardware calorimeter-cluster finder searches for a seed tower above a certain threshold and then adds in neighboring towers which are above a lower threshold. The $E_T$, mean $\phi$, and mean $\eta$ are calculated for each cluster. The central fast tracker (CFT) [44] is a hardware processor that uses information from the five axial CTC superlayers to iden-
tify high-momentum tracks in $r$-$\phi$. The CFT is able to measure the transverse momentum with a resolution of $\delta P_T/P_T \approx 0.035 \text{ GeV}^{-1} \cdot P_T$, and has an efficiency of $93.5 \pm 0.3\%$ for tracks with $p_T$ above 10 GeV/$c$. Track segment information, including azimuthal position and $P_T$, from the CMU, CMP and CMX chambers is also available. Dedicated hardware extrapolates tracks found by the CFT to the CEM calorimeter clusters and to the muon chamber segments, forming electron and muon candidates respectively. For flexibility, the final Level 2 decision is made in a programmable module. Depending on the complexity of the event, the Level 2 trigger processing can take from $\sim 20 \mu s$ up to hundreds of microseconds. During this time, the detector ignores any subsequent crossing. For a typical instantaneous luminosity of $10 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, the Level 2 trigger incurs a deadtime of about 4%, and outputs events at a rate of approximately 20 to 35 Hz.

The Level 3 trigger is a fully software-based trigger which runs on a farm of Silicon Graphics processors. It bases its decision on data read out from the entire detector. It executes a simplified version of the offline event reconstruction code, including calorimeter clustering and tracking. All events that pass the Level 3 trigger are stored on 8 mm magnetic tapes with a typical output rate of about 5-8 events per second. The Level 3 trigger and the DAQ incur a dead time of about 10%.
Chapter 3

Event Selection

In this analysis, we search for pair-production of $b'$ quarks that decay by FCNC into $bZ^0$, where one $Z^0$ decays into $e^+e^-$ or $\mu^+\mu^-$ and the other decays hadronically. These events contain two high transverse momentum ($p_T$) leptons from the $Z^0$ decay, two high-$p_T$ jets from second $Z^0$, and two $b$-jets whose $p_T$ scales with the $b'$ mass. We select events satisfying a high-$p_T$ lepton trigger and containing a well-identified muon or electron in the central region. Inclusive $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ samples are selected by requiring one primary lepton that satisfies tight lepton identification cuts and a second lepton satisfying looser identification cuts, with a dilepton invariant mass close to the $Z^0$ mass. From these events, we define as our $b'$ signal sample those with three or more jets in which at least one jet is identified as corresponding to a $b$ quark.

In this chapter we describe in detail the requirements imposed on our data. In the first section, we define the inclusive high-$p_T$ electron and muon samples which are the starting point of the analysis. The second section describes the $Z^0$ selection in both the electron and muon channels, including the lepton identification requirements. Finally, we present the jet selection criteria including the $b$-tag requirement, and the optimization studies that motivated them. A detailed discussion of the background processes will be presented in Chapter 6.
3.1 Data Sample

This search uses the data resulting from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected with the CDF detector from 1994 to 1995\(^1\) which corresponds to an integrated luminosity of $\int \mathcal{L} dt = 87.8 \pm 3.6$ pb\(^{-1}\). The data set consists of events that passed the inclusive high-$p_T$ central electron and muon triggers and is similar to the one used for the CDF top analysis.

3.1.1 High-$p_T$ Electron Sample

Electrons produce a unique signature in the CDF detector. They are distinguished by a cluster of electromagnetic energy with most of the energy deposited in a single electromagnetic tower. In the case of central electrons, a CTC track points to the cluster and the shower profile is mapped by the proportional strip chambers (CES) inside the calorimeter. This additional information results in a better identification of central electrons as compared to plug electrons. The electron signal is characterized by a set of variables, described briefly below:

$E_T$ Transverse energy deposited in the electromagnetic calorimeters towers associated with the cluster to which the track points.

$P_T$ Transverse momentum of the track associated with the electromagnetic cluster. The momentum is measured from the track curvature in the CTC.

$E_{had}/E_{em}$ The ratio of energy deposited in the hadronic calorimeters (CHA or WHA) to the electromagnetic calorimeters (CEM or PEM) in the towers corresponding to the electron cluster.

$E/P$ The ratio of the calorimeter energy in the cluster to the total track momentum as measured by the CTC.

\(^1\)The 1994-1995 CDF data collection period is known as Run 1b.
\( |\Delta z| \) The distance in the \( r-\phi \) plane between the CES shower position and the extrapolated CTC track. Only for CEM electrons.

\( |\Delta z| \) The distance in the \( r-z \) plane between the CES shower position and the extrapolated CTC track. Only for CEM electrons.

\( \chi^2_{strip} \) The \( \chi^2 \) from the comparison between the CES shower profile and the expectation from test beam electron data. Only for CEM electrons.

\( L_{shr} \) Comparison of the lateral shower profile in the CEM and expectations from test beam electron data. This variable is defined by

\[
L_{shr} = 0.14 \sum_i \frac{E_{i}^{obs} - E_{i}^{test}}{\sqrt{(0.14\sqrt{E})^2 + \sigma_{E_{i}^{test}}^2}}
\]

where the sum is over the towers adjacent to the seed tower, \( E_{i}^{obs} \) is the energy observed in tower \( i \), \( E_{i}^{test} \) is the energy expected to be observed from test beam electron data, \( \sigma_{E_{i}^{test}}^2 \) is the uncertainty in \( E_{i}^{test} \) and 0.14\( \sqrt{E} \) is the calorimeter energy resolution.

\( |z_v - z_e| \) The distance along the \( z \)-axis between the event primary vertex and the electron track. If there is more than one primary vertex (due to multiple interactions), this is the distance to the closest vertex.

\( I_{cal} \) Transverse calorimeter energy in a cone of radius \( R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.4 \) centered on the electron cluster but excluding the transverse energy associated to the electron cluster, \( I_{cal} = E_T^{cone} - E_T^{electron} \).

The inclusive high-\( p_T \) central electron sample is collected using the multilevel trigger system\(^2\) described in Section 2.2.5. The Level 1 trigger identifies a central electromagnetic cluster as an electron candidate if it has \( E_T > 8 \) GeV. The Level 2 central electron trigger requires an energy cluster with \( E_T > 16 \) GeV associated to a CTC track reconstructed by the Central Fast Tracker (CFT) with \( p_T > 12 \) GeV. The hadronic energy in the cluster is

\(^2\)The Level 2 trigger described here is known as the CEM_16_CFT_12 trigger; and the Level 3 trigger is the ELEA.CEM.18.
required to be less than 12.5% the electromagnetic energy. Finally, the software trigger at Level 3 requires a central electromagnetic cluster with $E_T > 18$ GeV matched to a CTC track with $p_T > 13$ GeV plus some additional cuts. The inclusive high-$p_T$ electron sample contains about 750,000 events.

3.1.2 High-$p_T$ Muon Sample

Muons are minimum-ionizing particles that can traverse large amounts of matter before stopping. Therefore, the muon signature in the CDF detector is a high-$p_T$ CTC track with little electromagnetic or hadronic energy deposited in the calorimeters that points to a track segment ("stub") in the muon chambers. Since the muon chambers do not cover all the CDF detector, we define a second muon category called CMIO. The CMIO muons, are consistent with a minimum-ionizing particle but were not detected by the muon chambers. These muons have a CTC track which does not extrapolate to a muon chamber, and they deposit very little energy in the calorimeters. The muon signal is characterized by the following set of variables:

- $P_T$ Transverse momentum of the muon track as measured in the CTC.
- $E_{had}$ Energy deposited in the hadronic calorimeter tower traversed by the muon track.
- $E_{em}$ Energy deposited in the electromagnetic calorimeter tower traversed by the muon track.
- $|\Delta x|$ The distance in the $r-\phi$ plane between the muon chamber stub position and the extrapolated CTC track.
- $d_0$ Impact parameter, defined as the distance of closest approach, in the $r-\phi$ plane, between the muon track and the beam axis, $r = 0$.
- $|z_v-z_\mu|$ The distance along the $z$-axis between the event primary vertex and the muon track. If there is more than one primary vertex (due to multiple interactions), this is the distance to the closest vertex.
$I_{cal}$ Transversed calorimeter energy in a cone of radius $R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.4$ centered on the muon but excluding the transverse energy in the calorimeter tower transversed by the muon.

The CDF muon detector system has a rather complex geometry, resulting in a correspondingly complicated trigger system. The muon candidates are categorized by the name of the muon chamber that detected them. Muons with stubs in both the CMU and CMP chambers are called CMUP. Muons reconstructed in only one of the chambers are called CMU, CMP or CMX.

The events are required to pass the Level 1 muon triggers and at least one of the Level 2 triggers listed in Table 3.1. The Level 2 triggers require the stubs in the muon detectors to match a CTC track reconstructed by the CFT, with $p_T > 12$ GeV. The match must be to within $5^\circ$ in azimuthal angle. The CMUP triggers select events covered by both the CMU and CMP detectors. The candidates that fall in the $\eta$ gaps of the CMP but cross the CMU chambers are selected with the CMNP triggers. The CMX triggers cover the higher-rapidity region, $0.6 < |\eta| < 1.0$. Several of the muon triggers have very high event rates and it was necessary to prescale the data. This means that only a percentage of the triggered events are kept. The prescale factor is set dynamically using an algorithm that is based on the instantaneous luminosity during data taking. The $b'$ events are expected to have a large number of jets; therefore we have used triggers that require the presence of a jet with $E_T > 15$ GeV in addition to the muon. These triggers help to recover some of the efficiency lost due to the prescaling. We do not use missing-energy triggers because these triggers contribute little to our acceptance and are difficult to model.

The Level 3 trigger requires a reconstructed CTC track with $p_T > 18$ GeV/c matched to a muon chamber stub. The distance between the extrapolated track and the muon stub, $|\Delta x|$ must be less than 10 cm for CMU or CMUP muons and 25 cm for CMX muons. The inclusive high-$p_T$ muon sample contains about 570,000 events.
Table 3.1: List of high-$p_T$ L2 muon triggers used. The second column shows the number of events and the percentage that passed the corresponding trigger after the $Z^0$ selection described in Section 3.2. The percentage is relative to the total number of $Z^0$ events.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Prescale</th>
<th>Data events</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMNP.CFT.12.5Deg.V*</td>
<td>0.40</td>
<td>343</td>
<td>12</td>
</tr>
<tr>
<td>CMUP.CFT.12.5Deg.V*</td>
<td>1.</td>
<td>1915</td>
<td>65</td>
</tr>
<tr>
<td>CMNP.JET*</td>
<td>1.</td>
<td>88</td>
<td>3</td>
</tr>
<tr>
<td>CMUP.JET*</td>
<td>1.</td>
<td>175</td>
<td>6</td>
</tr>
<tr>
<td>CMU.CMP.JET*</td>
<td>0.37</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>CMNP.CFT.12.5Deg.M*</td>
<td>0.25</td>
<td>402</td>
<td>14</td>
</tr>
<tr>
<td>CMUP.CFT.12.5Deg.M*</td>
<td>0.96</td>
<td>1751</td>
<td>60</td>
</tr>
<tr>
<td>CMX.CFT.12.5Deg.V*</td>
<td>0.43</td>
<td>543</td>
<td>18</td>
</tr>
<tr>
<td>CMX.JET*</td>
<td>1.</td>
<td>108</td>
<td>4</td>
</tr>
<tr>
<td>CMX.CFT.12.5Deg.M*</td>
<td>0.30</td>
<td>200</td>
<td>7</td>
</tr>
<tr>
<td>CMX.CFT.12.5Deg.E*</td>
<td>0.50</td>
<td>571</td>
<td>19</td>
</tr>
</tbody>
</table>

3.2 $Z^0$ Selection

From the inclusive lepton sample described above, we select $Z^0 \rightarrow l^+l^-$ events. In order to increase the search sensitivity, we select $Z^0$ events using rather loose lepton identification requirements. Inclusive dielectron and dimuon samples are selected by requiring one primary lepton that satisfies tight lepton identification cuts and a second lepton satisfying looser identification cuts.

The events are required to be from a "good run", meaning that all the components in the detector were in good working condition \(^3\). The primary vertex of the event, $|z_{\text{vertex}}|$, is required to be within 60 cm along the beam axis of the nominal interaction position. This assures that the interaction occurred close to the detector center and therefore that its products traversed the instrumented regions of the detector.

\(^3\)CDF code flag used was: BADRUN = 15 or -1.
3.2.1 Electron Channel

We start by selecting a first electron detected by the central calorimeter (CEM) with $E_T \geq 20 \text{ GeV}$. To ensure that the electron shower energy is well-measured we require that the shower position is within the fiducial region of the calorimeter. This region excludes the calorimeter boundaries and inactive towers\(^4\). A detailed description of this cut can be found in reference [46]. The fiducial cut efficiency is about 84% for central electrons.

This first electron is required to pass tight electron identification requirements on the variables defined in Section 3.1.1:

- $E_T \geq 20 \text{ GeV}$
- $E_{\text{had}}/E_{\text{em}} \leq 0.05$
- $E/P \leq 1.8$
- track strip matching:
  - $|\Delta z| \leq 1.5 \text{ cm}$
  - $|\Delta z| \leq 3.0 \text{ cm}$
- $L_{\text{shr}} \leq 0.2$
- $\chi^2_{\text{strip}} \leq 10.0$
- $|z_v - z_e| \leq 5.0 \text{ cm}$

These cuts ensure a large reduction of fakes due to charged hadrons. To increase the acceptance, we do not impose any energy isolation requirement on this first electron. A large source of background electrons is photon conversions to $e^+e^-$ pairs in the detector material. The electrons from photon conversions are removed using an algorithm that is $0.907 \pm 0.038$ efficient [47]. The primary electron candidate is removed if there is a nearby opposite-charged track passing the following cuts:

---

\(^4\)The fiducial cuts are implemented by the CDF offline code subroutine FIDELE.
• The separation of the two tracks in the \( r - \phi \) plane at the tangency point is \(|\delta (r - \phi)| < 0.3 \text{ cm}\)

• The difference in polar angle at the tangency point is \(|\delta \cot \theta| < 0.06\)

• The conversion radial position, after the cuts above, is \(-20 < R_{\text{conv}} < 50 \text{ cm}\)

Often, the partner track of a conversion electron is missed. In this case, the primary electron is considered to be from a conversion and removed if the following conditions are met:

• The number of expected VTX hits is at least three.

• The ratio of observed VTX hits to the number expected is less than 0.2.

For events that have one high-\( P_T \) electron that passes all the cuts above, we require a second electron with \( E_T \geq 10 \text{ GeV} \) that can be in the central or plug calorimeters. No other fiducial requirements are imposed. This second electron must satisfy the following loose electron identification criteria:

• \( E_T \geq 10 \text{ GeV} \)

• \( E/P < 2.0 \) (if in the CEM)

• \( E_{\text{had}}/E_{\text{em}} < 0.12 \)

Furthermore, in order to reduce hadronic backgrounds, this second electron must pass a calorimeter isolation requirement. The calorimeter transverse energy inside a cone of radius \( \sqrt{\eta^2 + \phi^2} = 0.4 \) centered on the electron direction, excluding the electron transverse energy, must be less than 20\% the transverse energy associated with the electron,

\[
\text{iso} = \frac{E_{\text{cone, electron}} - E_T}{E_T} < 0.2.
\]

We accept events for the \( Z^0 \rightarrow e^+e^- \) data sample if the reconstructed invariant mass of the identified electron pair is between 75 and 105 GeV/\( c^2 \). After this selection there are 6287 \( Z^0 \) events remaining. Figure 3.1 shows the \( \eta \) distribution for the second-leg electrons.
of the events that have passed our \(Z^0\) selection requirements. The events are distributed in the central and plug calorimeters as shown in Table 3.2. Only 8% of the events that have both electrons in the CEM have a second electron that fails the tight cuts. About 60% of the \(Z^0 \rightarrow e^+e^-\) events have one of the electrons in the plug calorimeter. The forward calorimeter is not used in this analysis because its contribution to the signal acceptance is only about 3% and there is some concerns of large QCD backgrounds in that area of the detector. Figure 3.2 shows the \(Z^0\)-mass peak observed in the dielectron invariant mass distribution after all the \(Z^0\) selection cuts have been applied to the data.

<table>
<thead>
<tr>
<th>Observed (Z \rightarrow e^+e^-) data events</th>
<th>central - central</th>
<th>central - plug</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>tight (Z)</td>
<td>2410</td>
<td>3680</td>
<td>6287</td>
</tr>
<tr>
<td>loose (Z)</td>
<td>197</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Number of observed events in the \(Z^0 \rightarrow e^+e^-\) data divided by the second-leg electron calorimeter. The loose \(Z^0\) column indicates the number of central \(Z^0\) events in which the second electron did not pass the tight cuts but passed the loose ones.

### 3.2.2 Muon Channel

The dimuon selection starts by requiring one CTC track with \(p_T \geq 20 \text{ GeV/c}\) that passed the high-\(p_T\) muon trigger and has a matching stub in the CMU or CMX muon chambers. These include the muons from the CMUP, CMU and CMX categories described in Section 3.1.2. To ensure that the track corresponds to a muon and to reduce backgrounds, we impose the muon identification criteria given below:

- \(p_T \geq 20 \text{ GeV/c}\)
- \(E_{\text{em}} \leq 2 \text{ GeV}\)
- \(E_{\text{had}} \leq 6 \text{ GeV}\)
- \(E_{\text{em}} + E_{\text{had}} \geq 0.1 \text{ GeV}\)
Figure 3.1: $\eta$ distribution of the second-leg electron in $Z^0 \rightarrow e^+e^-$ events. The contributions from the two calorimeters used are indicated with different hashes. 

Figure 3.2: Dielectron invariant mass after $Z^0$ selection cuts.
• $|\Delta z| = 2.0 \text{ cm (5.0 cm)}$ in CMU (CMP and CMX)

• $d_0 \leq 0.3 \text{ cm}$

• $|z_0 - z_v| \leq 5.0 \text{ cm}$

For events that have one high-$p_T$ muon that passes the above cuts, we require a second muon with $p_T \geq 10 \text{ GeV}/c$. Besides the muon categories that were valid for the first muon, we accept other two looser categories of muons: the CMP and the CMIO muons. The lepton identification requirements for this second muon are less stringent than for the first muon. If it was detected by the muon chambers, the following criteria are applied:

• Muon type: CMU, CMP, CMUP or CMX

• $p_T \geq 10 \text{ GeV}/c$

• $E_{had} \leq 10 \text{ GeV}$

• $E_{em} \leq 5 \text{ GeV}$

• $|\Delta z| \leq 5 \text{ cm}$.

For CMIO muons, the identification requirements are more stringent because there is no confirmation from a muon chamber. The rapidity cut ensures that the track goes through most of the tracking chamber.

• $p_T \geq 10 \text{ GeV}/c$

• $E_{had} \leq 6 \text{ GeV}$

• $E_{em} \leq 2 \text{ GeV}$

• $|\eta| \leq 1.2$
Similarly to the electron case, a calorimeter energy isolation cut is imposed on the second muon. The muon is accepted if

\[ \text{iso} = \frac{E_{\text{cone}} - E_{\text{muon}}}{P_{T_{\text{muon}}}} < 0.2, \]

where \( E_{\text{cone}} \) is the calorimeter energy in a cone of radius of 0.4 centered in the muon track, \( E_{T_{\text{muon}}} \) is the transverse energy found in the calorimeter tower associated with the muon track and \( P_{T_{\text{muon}}} \) is the muon transverse momentum.

We accept events if the reconstructed \( \mu\mu \) invariant mass is between 75 and 105 GeV/c\(^2\). After this selection there are 2940 \( Z^0 \) events remaining in the muon data sample. From these, 2904 have opposite-sign muons and 36 have like-sign muons. Figure 3.3 shows the invariant mass distribution of the 2940 \( Z^0 \) events. The events with CMIO muons compose a large percentage of the total number accepted, as shown in Table 3.3.

![CDF preliminary](https://example.com/fig3.3.png)

**Figure 3.3**: Dimuon invariant mass after \( Z^0 \) selection cuts.

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<table>
<thead>
<tr>
<th>Muon type</th>
<th>First Leg</th>
<th>Second Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMU only</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>CMP only</td>
<td>N/A</td>
<td>12</td>
</tr>
<tr>
<td>CMUP</td>
<td>63</td>
<td>24</td>
</tr>
<tr>
<td>CMX</td>
<td>27</td>
<td>19</td>
</tr>
<tr>
<td>CMIO</td>
<td>N/A</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 3.3: Distribution of the muon data events by muon category. The numbers are given in percentage of $Z^0$ events.

### 3.3 Jet Selection

Our $b'$ signal contains four quarks in the final state, of which at least two are $b$ quarks. In this analysis, quarks are identified as hadronic jets using a calorimeter energy clustering algorithm [48] with a cone size of $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4$. The algorithm begins by grouping pre-clusters of contiguous calorimeter towers with $E_T > 1 \text{ GeV}$. Towers with $E_T > 0.1 \text{ GeV}$ inside a $\Delta R < 0.4$ cone centered on the pre-cluster are associated into a cluster. A new center for the cluster is calculated and an iterative procedure is performed until the cluster configuration is stable. The jet energy is the sum of the individual tower transverse energy within the cluster cone. The jet energy can be corrected for several effects: (i) calorimeter non-linearities, (ii) out-of-cone energy loss, (iii) loss of low-$p_T$ tracks curled by the magnetic field, (iv) undetected energy from muons and neutrinos in the jet, (v) detector boundary effects, (vi) energy from the underlying event (soft interactions between spectator partons in the event). These corrections are more crucial for analyses where the best possible determination of the jet energy is important. In this analysis, these jet-corrections are not applied, which results in an underestimation of the actual parton energies by approximately 30%.

Since some of the jets can be merged, or lost due to inefficient coverage of the detector, we only require the presence of three jets in our $Z^0$ sample. In order to optimize our sensitivity to a $b'$-quark signal we make a jet selection that depends on the $b'$ mass.

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being considered. Each event is required to have at least three jets within $|\eta| < 2.0$, two of which with $E_T > 15$ GeV. For $b'$ masses above 120 GeV/c$^2$, the third jet is required to have $E_T > 15$ GeV. For $m_{b'} \leq 120$ GeV/c$^2$, the $E_T$ requirement on the third jet is relaxed to $E_T > 7$ GeV since the $b$ jets for $b'$ masses near the $m_Z + m_b$ threshold have low momentum.

The $p_T$ of the $b'$ decay products is expected to increase with the $b'$ mass. We define the variable $\sum E_T^{jets}$ as the summed transverse energy of jets with $E_T > 15$ GeV and $|\eta| < 2.0$. Motivated by the studies described in section 3.3.2, we require this quantity to scale with the $b'$ mass according to the equation $\sum E_T^{jets} \geq m_{b'} c^2 - 60$ GeV. Figure 3.4 shows the $\sum E_T^{jets}$ distribution for ee and $\mu\mu$ events passing the 3-jet requirement for $b'$ masses above 120 GeV/c$^2$. Also shown are the distributions expected from the main Standard Model background ($Z^0 + jets$)$^5$ and from the decay of a 150 GeV/c$^2$ $b'$ quark$^6$. The number of events passing each major selection criterion for each leptonic channel is shown in Table 3.4.

<table>
<thead>
<tr>
<th>$m_{b'}$ (GeV/c$^2$)</th>
<th>$Z^0 \rightarrow e^+e^-$</th>
<th></th>
<th>$Z^0 \rightarrow \mu^+\mu^-$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 jets $\sum E_T^{jets}$ b-tag</td>
<td>3 jets $\sum E_T^{jets}$ b-tag</td>
<td>3 jets $\sum E_T^{jets}$ b-tag</td>
<td>3 jets $\sum E_T^{jets}$ b-tag</td>
</tr>
<tr>
<td>100</td>
<td>34 31 0</td>
<td>32 29 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>34 24 0</td>
<td>32 22 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>34 20 0</td>
<td>32 21 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>9 8 0</td>
<td>8 6 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>9 8 0</td>
<td>8 5 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>9 7 0</td>
<td>8 4 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>9 4 0</td>
<td>8 4 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>9 2 0</td>
<td>8 4 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>9 1 0</td>
<td>8 3 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>9 1 0</td>
<td>8 3 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>9 1 0</td>
<td>8 2 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>210</td>
<td>9 1 0</td>
<td>8 0 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4: Events observed in data after each main selection requirement in both the electron and the muon channels. The 3 jets requirement is different for $m_{b'} \leq 120$ GeV/c$^2$ and $m_{b'} > 120$ GeV/c$^2$ and the $\sum E_T^{jets}$ cut scales with the $b'$ mass.

$^5$The background is discussed in detail in Chapter 6.

$^6$The signal Monte Carlo simulation is described in Chapter 4 together with the efficiencies and acceptance calculation.
Figure 3.4: $\sum E_T^{jets}$ distribution for events with at least 3 jets with $E_T > 15$ GeV and $|\eta| < 2$, before the $b$-tagging requirement. The expected SM background is shown shaded. The expected signal event distribution for a $b'$ quark mass of 150 GeV/$c^2$ is shown as a solid line. The vertical dashed line represents the $\sum E_T^{jets}$ cut for this specific $b'$ mass. Events to the right of this line are accepted.

3.3.1 Silicon Vertex $b$-tag

A $b$-quark jet can be distinguished from other jets due to the relatively long lifetime of the $b$ quark. With a lifetime of about 1.5 psec, a $B$ hadron created in the high-$p_T$ collision can travel a few millimeters before decaying. The displacement between the decay vertex and the event primary vertex can be measured by the Silicon Vertex Detector. This measurement provides a means to identify or "tag" $b$-quark jets. This identification is accomplished by the SVX $b$-tagging algorithm [49] developed for the top quark analyses.

Since a $b'$ signal should be rich in $b$ quarks, we require the events in the $Z^0$ sample that pass the above jet selection criteria to have at least one jet positively identified by the SVX $b$-tagging algorithm. A summary of the event statistics in our selection process is shown.
in Table 3.4. We do not observe any events in the electron data sample after the final $b$-tag requirement, but there is one $\mu\mu$ event in which the highest-$E_T$ jet is found to be consistent with a $b$-quark. This muon event passes all our selection criteria for $m_\mu \leq 120$ GeV/c$^2$; however, it has a third jet with $E_T = 8.3$ GeV which fails the third-jet $E_T$ requirement for larger $b'$ masses.

The candidate event has the number 15532 and it is from run number 64275. Figures 3.5 and 3.6 show the CTC and calorimeter display for this event. The event passes the muon triggers that requires a central high-$p_T$ muon and a CFT track (CMUP.CFT*) and the corresponding jet trigger (CMUP.JET*). The muon that fired the trigger was detected by both the CMU and CMP muon chambers and passes the tight muon identification cuts, while the second muon is a CMIO. The invariant mass of the two muons is 94 GeV, consistent with originating from a $Z^0$ decay. The two most energetic jets ($E_T(j_1) = 56.7$ GeV, $E_T(j_2) = 20.3$ GeV) have an invariant mass within our $Z^0$ mass window. So, an extra cut on the jets invariant mass would not reject the event. It really looks like an event with two $Z^0$ bosons! Some more information about this event is given in Table 3.5.

<table>
<thead>
<tr>
<th>Run# 64275</th>
<th>Event# 15532</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T$ (GeV)</td>
<td>$p_T$ (GeV/c)</td>
</tr>
<tr>
<td>$\mu_1$</td>
<td>38.8</td>
</tr>
<tr>
<td>$\mu_2$</td>
<td>56.3</td>
</tr>
<tr>
<td>jet$_1$</td>
<td>56.7</td>
</tr>
<tr>
<td>jet$_2$</td>
<td>20.3</td>
</tr>
<tr>
<td>jet$_3$</td>
<td>8.3</td>
</tr>
<tr>
<td>$\sum E_T^{jets}$</td>
<td>77 GeV</td>
</tr>
<tr>
<td>$m(jet_1,jet_2)$</td>
<td>97 GeV</td>
</tr>
<tr>
<td>$m(\mu_1,\mu_2)$</td>
<td>94 GeV</td>
</tr>
<tr>
<td>$E_T$</td>
<td>7.1 GeV</td>
</tr>
<tr>
<td>$z_{vertex}$</td>
<td>-18 cm</td>
</tr>
<tr>
<td>$b$-tag</td>
<td>jet$_1$</td>
</tr>
</tbody>
</table>

Table 3.5: Characteristics of the muon event that passed the $b'$ selection criteria.
Figure 3.5: Central tracker image of $b'$ candidate event.

Figure 3.6: Calorimeter image of $b'$ candidate event.
3.3.2 Cuts Optimization

Our selection criteria were motivated by a thorough study of $sgn/\sqrt{bkg}$ distributions. The $b'$ signal Monte Carlo used in this calculation is described in Section 4.1. The background estimations are reported in Chapter 6. Figure 3.3.2 shows the $sgn/\sqrt{bkg}$ as a function of the $E_T^{jets}$. The study was performed before and after the $b$-tag requirement, but subsequently to the other selection criteria. Each curve in the plot corresponds to a different $b'$ mass. The arrows indicate were the $E_T^{jets}$ cut is applied for a given mass. We show the results for masses from 100 GeV to 200 GeV. We observed that the $E_T^{jets}$ cut improves the $sgn/\sqrt{bkg}$ independently of the $b$-tag requirement. We also observe that the $b$-tag boosts our sensitivity by at least a factor of two for almost every $b'$ mass. In the case of a 100 GeV $b'$ quark, the $b$-tag requirement actually results in a slightly lower $sgn/\sqrt{bkg}$, but we benefit from the fact that the background is reduced to almost zero. This way, we can calculate a limit without subtracting background and therefore are not affected by the uncertainties in the background estimation.
Figure 3.7: $\frac{\text{sgn}}{\sqrt{\text{bkg}}}$ as a function of $\sum E_T^{\text{jets}}$ for all $b'$ masses. The arrows show the position of the $\sum E_T^{\text{jets}}$ cut; events to its right are accepted. The curves show $b'$ masses in 10 GeV steps from 100 GeV to 200 GeV. The leftmost arrow corresponds to a 100 GeV $b'$ while the rightmost arrow is for 200 GeV. Top: Calculation done after the 3-jet requirement and before the $b$-tag. Bottom: Calculation done after all selection besides the $\sum E_T^{\text{jets}}$ cut. Both plots are normalized to the Run 1b luminosity.
Figure 3.8: $\text{sgn}/\sqrt{\text{bkg}}$ as a function of $\sum E_T^{\text{jets}}$ for all $b'$ masses. The arrows show the position of the $\sum E_T^{\text{jets}}$ cut; events to its right are accepted. The curves show $b'$ masses in 10 GeV steps from 100 GeV to 200 GeV. The leftmost arrow corresponds to a 100 GeV $b'$ while the rightmost arrow is for 200 GeV. Top: Calculation done after the 3-jet requirement and before the $b$-tag. Bottom: Calculation done after all selection besides the $\sum E_T^{\text{jets}}$ cut. Both plots are normalized to the Run 1b luminosity.
Chapter 4

Acceptance and Efficiencies

This section describes the computation of the fraction of $b'b'$ events that can be identified using the selection criteria from the previous chapter. The acceptance and detection efficiencies calculation is factorized into independent terms as follows:

$$A \cdot \epsilon = A_Z \cdot \epsilon_Z \cdot \epsilon_{jet} \cdot \epsilon_{b-tag},$$

where $A_Z$ is the detector geometrical acceptance for a $Z^0 \rightarrow l^+l^-$ from a $b'b'$ event, $\epsilon_Z$ is the detection efficiency for the $Z^0$, $\epsilon_{jet}$ is the overall jet requirement efficiency and $\epsilon_{b-tag}$ the efficiency for $b$-tagging at least one jet in the event. These acceptance and detection efficiencies are determined from a combination of data and Monte Carlo simulation.

4.1 Signal Monte Carlo

We used the HERWIG v5.6 Monte Carlo generator program [50] to study the acceptance of the detector and the kinematic selection cuts. The standard version of HERWIG does not have the possibility to generate the $b'b' \rightarrow bZ^0\bar{b}Z^0$ process. Since both top and $b'$ are produced by the same hadronic processes of gluon-gluon fusion and $q\bar{q}$ annihilation, we have generated top quarks as if they were $b'$ quarks. The subroutine that handles the standard charged-current decays of heavy quarks was replaced with another subroutine that allows 2-body neutral-current decays of top (our $b'$) into $\gamma$ and gluons [51]. The subroutine was then modified to make the $b' \rightarrow bZ^0$ neutral-current decay. One $Z^0$ is required to decay...
into muons or electrons while the other is allowed to decay through any available decay channel. The CLEO QQ Monte Carlo program [53] is used to decay the $b$ quarks generated by HERWIG. This step is necessary to ensure the proper lifetime and decay of the $b$ hadrons. These events are passed through a fast simulation of the CDF detector$^1$. Each event was subjected to the same selection requirements as the data.

We generated Monte Carlo samples of $b'b' \rightarrow bZbZ$ with the MRSD0$'$ structure functions [52]. We made samples at twelve different $b'$ masses between 100 and 210 GeV$/c^2$ in steps of 10 GeV$/c^2$. The sample size varies from 60,000 ($m_{b'} = 100$ GeV) to 30,000 events in order to allow a similar statistical uncertainty for all $b'$ masses after event selection requirements have been imposed. These large samples led to a small Monte Carlo statistical error and allowed a comprehensive study of the systematic uncertainties.

4.2 $Z^0$ Acceptance

The $Z^0$ acceptance is the geometrical acceptance for detecting a $Z^0 \rightarrow l^+l^-$ decay from the $b'b'$ event. This acceptance includes the $z_{\text{vertex}}$ efficiency, the efficiency for having both leptons in the fiducial region of the detector, and the $Z^0$ mass cut efficiency.

4.2.1 $z_{\text{vertex}}$ Efficiency

As we saw in Chapter 3, we require the primary vertex of the event to be within 60 cm of the nominal interaction position, $|z_{\text{vertex}}| < 60$ cm, in order to keep the events well-contained in the fiducial region of the detector. The event primary vertex distribution is described by a gaussian of width $\sigma_z = 29$ cm and is not expected to vary with the physics process being studied. Therefore, the $b'$ Monte Carlo samples, used to determine the geometrical acceptance, were simulated with a primary vertex drawn from a truncated gaussian with $\sigma_z = 29$ cm and the requirement that $|z_{\text{vertex}}| < 60$ cm. The $z_{\text{vertex}}$ efficiency was obtained from an independent CDF data sample.

$^1$We used the QFL' v3.61 program for the CDF detector simulation.
The efficiency was measured from $W \rightarrow \mu \nu$ data to be $\varepsilon_{z_{\text{vertex}}} = 0.949 \pm 0.023$ [54], which includes statistical (0.1%) and systematic uncertainties. The systematic uncertainties of $\pm 0.8\%$ and $\pm 2.3\%$ were assigned to the assumptions that the $z_{\text{vertex}}$ efficiency does not depend on the total integrated luminosity and on the number of jets in the event, respectively.

4.2.2 Geometrical Acceptance

The geometrical acceptance for the $b'$ signal is determined from the Monte Carlo samples described in Section 4.1, using a method similar to the one used in the CDF top dilepton analysis [56]. The method involves matching muon or electron objects that have been reconstructed by the detector simulation with the corresponding generator-level particle. The geometrical acceptance $\varepsilon_{\text{geom} \cdot p_T}$ is defined as the fraction of the total events in the signal Monte Carlo simulation that pass the requirements below.

In the electron channel, each event must have:

- One reconstructed electron candidate with $E_T > 20$ GeV, in the central calorimeter and passing the fiducial criteria.
- A second electron-candidate object in the central or plug calorimeters with $E_T > 10$ GeV. No fiducial requirement is made on this second electron.
- The reconstructed track for both simulated electron objects above must lie within a cone of $\Delta R < 0.11$ around the momentum direction of a generator-level electron, where $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.

In the muon channel, each event must have:

- One muon object candidate with $p_T > 20$ GeV/c detected by the CMU (with or without CMP confirmation) or the CMX muon chambers.
- A second muon candidate which can be a CMU, CMP, CMUP, CMX or CMIO with $p_T > 10$ GeV/c.
• The reconstructed track for both muon objects above must lie within a cone of $\Delta R < 0.11$ about the momentum direction of a generator-level muon.

For this purpose, the minimum requirements to reconstruct an object as an electron candidate are a calorimeter cluster with $E_T > 5$ GeV and $E_{had}/E_{em} < 0.125$. Every stub in any of the muon chambers that is matched to a CTC track, and every track with $p_T > 10$ GeV/c that is not matched to a muon stub or calorimeter cluster (CMIO muons) is considered a muon candidate. So, $\epsilon_{geom, p_T}$ is the acceptance before the lepton identification requirements of Section 3.2 have been imposed. This acceptance does not include the $z_{vertex}$ efficiency which was obtained from data in Section 4.2.1.

The $\epsilon_{geom, p_T}$ values are shown, as a function of the $b'$ mass, in Figure 4.1 and Table 4.10 for electrons and Table 4.11 for muons. The geometrical acceptance for the first electron is slightly larger than the one for the first muon because the rapidity coverage of the central calorimeter ($|\eta| < 1.1$) is slightly larger than the central muon chambers ($|\eta| < 1.0$). However, the second electron can also be in the plug calorimeter which extends the rapidity coverage in the electron channel up to $|\eta| = 2.4$. So, the geometrical acceptance for a pair of electrons is significantly larger than for a pair of muons. Its ratio varies from 1.44 to 1.24 for $b'$ masses of 100 GeV/$c^2$ to 210 GeV/$c^2$. $\epsilon_{geom, p_T}$ increases with the $b'$ mass because heavier $b'$ pair production requires more violent collisions, which result in more central events. This also explains why the relative geometrical acceptances in the electron and muon channels is not constant as a function of the $b'$ mass.

4.2.3 $Z^0$-mass Cut Efficiency

The $Z^0$-mass cut efficiency, $\epsilon_{Z massa}$, is defined as the fraction of Monte Carlo events passing the geometrical requirements above which have two leptons with an invariant mass in the $Z^0$ mass window $75$ GeV/$c^2$ $M_{1+1-} < 105$ GeV/$c^2$. These two leptons are required to be matched with a generator level electron or muon. Table 4.10 and Table 4.11 show this efficiency as a function of the $b'$ mass for electrons and muons, respectively.

We observe that the $Z^0$-mass cut efficiency decreases as a function of the $b'$ mass.
This effect arises because the two leptons, which have passed the geometrical criteria above, were not required to originate from the $Z^0$ decay. Therefore, events in which one of the $Z^0$ leptons was lost due to a geometrical inefficiency can pass the geometrical requirements as long as other same-type lepton was observed. This third lepton can, for instance, originate from the weak decay of a $b$ quark. The number of such leptons rises with the $b'$ mass due to the increase of the event centrality. Therefore, the probability of having a second lepton that is not from the $Z^0$ decay passing the geometrical cuts also increases with the $b'$ mass. It is interesting to notice that $\epsilon_{Z-\text{mass}}$ shows a trend opposite to $\epsilon_{\text{geom-}p_T}$, as the above reasoning would suggest.

The $Z^0$ acceptance is calculated by multiplying the $Z^0$-mass cut efficiency, the geometrical acceptance and the $z_{\text{vertex}}$ efficiency.

$$\mathcal{A}_Z = \epsilon_{z_{\text{vertex}}} \cdot \epsilon_{\text{geom-}p_T} \cdot \epsilon_{Z-\text{mass}}$$  \hspace{1cm} (4.2)$$

The $Z^0$ acceptance is shown, as a function of the $b'$ mass, for the electron channel in Figure 4.7 and Table 4.12, and for the muon channel in Figure 4.8 and Table 4.13. The $Z^0$ acceptance rises steadily with the $b'$ mass due to the factors explained above.

Figure 4.2 shows the acceptance for the two detectors of the second leg electron relative to the total $Z^0$ acceptance, as a function of the $b'$ mass. Events from more massive $b'$ quarks have a larger percentage of electrons in the central calorimeter. This agrees with the statement of an increased event centrality for more massive $b'$ quarks. In Figure 4.3, we show the same fractional acceptance but for each muon category. In this case, all the muon categories correspond to a central $\eta$ region and therefore no significant trend is observed as a function of the $b'$ mass. This information on the relative $Z^0$ acceptance will be crucial to calculate the $Z^0$ detection efficiency.
Figure 4.1: Geometrical acceptance calculated from the $b'$ signal Monte Carlo. The points labeled "geometry-$P_T$" correspond to the geometrical acceptance for two electrons or muons as defined in 4.2.2. Top: Electron channel. Bottom: Muon channel.
Figure 4.2: Acceptance for the two detectors of the second leg electron relative to the total $Z^0 \rightarrow e^+e^-$ acceptance, as a function of the $b'$ mass.

Figure 4.3: Acceptance for the several categories of the second leg muon relative to the total $Z^0 \rightarrow \mu^+\mu^-$ acceptance, as a function of the $b'$ mass.
4.3 $Z^0$ Detection Efficiency

The $Z^0$ detection efficiency includes all the detector effects other than geometrical that reduce the acceptance for $Z^0 \rightarrow l^+l^-$ events from $b'$ decays. These include the trigger efficiency, the lepton identification efficiencies and the lepton isolation efficiency.

4.3.1 Trigger Efficiency

In the electron channel, we use a trigger that requires a CTC track found by the Central Fast Tracker (CFT) [44]. The electron trigger efficiency is obtained solely from data. We use electron candidates that passed other triggers that do not require a CFT track and measure the probability that these electrons will pass the CFT trigger used in this analysis. We find that the central electron trigger efficiency is $\epsilon_{\text{trigger}} = (91.95 \pm 0.12)\%$ [57].

In the muon channel, we use triggers that require one jet in addition to the high-$p_T$ muon. These triggers are very efficient for our signal because each event has at least three high-$p_T$ jets. The overall trigger efficiency in the muon channel depends on the kinematics of the event because of these jet triggers and therefore it has to be obtained using a trigger simulation. The trigger simulation takes into consideration the values for the muon trigger efficiencies measured from $Z^0 \rightarrow \mu^+\mu^-$ data, $\epsilon_{\text{CMU/CMP}} = 0.863^{+0.027}_{-0.031}$ and $\epsilon_{\text{CMX}} = 0.696^{+0.045}_{-0.049}$ [55], the jet trigger efficiency as a function of the jet $E_T$ [60], and the trigger prescale values in Table 3.1. The efficiency is determined after all the jet selection criteria have been applied. The results, shown in Table 4.1, do not depend on the $b'$ mass. The average trigger efficiency per event is $0.8140 \pm 0.0013$, where the uncertainty is statistical only.

4.3.2 Lepton Identification Efficiencies

The lepton identification efficiencies, $\epsilon_{\text{lepton-id}}$, were obtained from data [61] the $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ data samples. We start by looking for a lepton that passes

---

2The trigger simulation package used was SIM.MUTRIG [58]. This simulation is the same as the one used for the measurement of the top cross-section [59].
Table 4.1: The muon trigger efficiency obtained from the trigger simulation as a function of the $b'$ mass. The trigger efficiency calculation is done after the jet requirements.

<table>
<thead>
<tr>
<th>$m_\nu$ [GeV/c$^2$]</th>
<th>$\varepsilon_{\text{trigger}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.814 ± 0.005</td>
</tr>
<tr>
<td>110</td>
<td>0.813 ± 0.005</td>
</tr>
<tr>
<td>120</td>
<td>0.815 ± 0.004</td>
</tr>
<tr>
<td>130</td>
<td>0.804 ± 0.004</td>
</tr>
<tr>
<td>140</td>
<td>0.814 ± 0.004</td>
</tr>
<tr>
<td>150</td>
<td>0.818 ± 0.004</td>
</tr>
<tr>
<td>160</td>
<td>0.812 ± 0.004</td>
</tr>
<tr>
<td>170</td>
<td>0.811 ± 0.004</td>
</tr>
<tr>
<td>180</td>
<td>0.818 ± 0.004</td>
</tr>
<tr>
<td>190</td>
<td>0.812 ± 0.004</td>
</tr>
<tr>
<td>200</td>
<td>0.815 ± 0.004</td>
</tr>
<tr>
<td>210</td>
<td>0.822 ± 0.005</td>
</tr>
</tbody>
</table>

The efficiencies for the individual electron identification cuts are shown in Table 4.2. We emphasize that the requirements on the plug electron are very loose. Besides the 10 GeV $E_T$ requirement, we only have the additional requirement that $E_{\text{had}}/E_{\text{em}} \leq 0.12$, which is very efficient. Thus, the electron identification efficiency for plug electrons is close to 100%. The total electron identification efficiency for the different types of electrons are shown in Table 4.3. These values do not include the conversion removal algorithm.
overefficiency [47] which is included separately. The muon identification efficiencies for the different muon categories are shown in Table 4.4. These values are in good agreement with results from other studies [62, 63].

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Central tight</th>
<th>Central loose</th>
<th>Plug</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{had}/E_{em} \leq 0.05$</td>
<td>0.944(3)</td>
<td>0.987(2)</td>
<td>0.995(1)</td>
</tr>
<tr>
<td>$E_{had}/E_{em} \leq 0.12$</td>
<td>0.895(5)</td>
<td>0.908(5)</td>
<td></td>
</tr>
<tr>
<td>$E/P \leq 1.8$</td>
<td>0.895(5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E/P \leq 2.0$</td>
<td>0.972(2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta z</td>
<td>\leq 1.5 \text{ cm}$</td>
<td>0.945(4)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta z</td>
<td>\leq 3.0 \text{ cm}$</td>
<td></td>
</tr>
<tr>
<td>$L_{shr} \leq 0.2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\chi^2_{strip} \leq 10.0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>z_0 - z_o</td>
<td>\leq 5.0 \text{ cm}$</td>
<td>0.996(1)</td>
</tr>
</tbody>
</table>

Table 4.2: Electron identification selection efficiencies for each individual cut.

<table>
<thead>
<tr>
<th>Category</th>
<th>Central</th>
<th>Plug</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose $\epsilon$</td>
<td>$0.901 \pm 0.004$</td>
<td>$0.995 \pm 0.001$</td>
</tr>
<tr>
<td>Tight $\epsilon$</td>
<td>$0.804 \pm 0.006$</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3: Electron identification efficiency for each electron category.

### 4.3.3 Isolation Efficiency

We require the second $Z^0$ lepton to pass the calorimeter isolation cut, $iso < 0.2$, described in Section 3.2. The isolation efficiency due to the jet activity in $b'$-signal events was calculated directly from the signal Monte Carlo simulation, for each type of electron and muon. The efficiency is measured using the $Z^0$ second lepton from events that passed the jet requirement, $\epsilon_{iso}^{MC} = N_{iso}/N_{jet}$. The electron isolation efficiency for each detector is shown in Table 4.5 as a function of the $b'$ mass, and the average isolation efficiency for muons is
shown in Table 4.6. Heavier $b'$ quarks will result in larger jet activity and centrality of the event, therefore the lepton isolation efficiency decreases with the increase of the $b'$ mass.

<table>
<thead>
<tr>
<th>$m_{\psi}$ [GeV/$c^2$]</th>
<th>$\varepsilon_{iso}^{MC}(central)$</th>
<th>$\varepsilon_{iso}^{MC}(plug)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.953 ± 0.003</td>
<td>0.983 ± 0.002</td>
</tr>
<tr>
<td>110</td>
<td>0.939 ± 0.003</td>
<td>0.980 ± 0.002</td>
</tr>
<tr>
<td>120</td>
<td>0.919 ± 0.003</td>
<td>0.975 ± 0.002</td>
</tr>
<tr>
<td>130</td>
<td>0.920 ± 0.003</td>
<td>0.973 ± 0.002</td>
</tr>
<tr>
<td>140</td>
<td>0.918 ± 0.003</td>
<td>0.972 ± 0.002</td>
</tr>
<tr>
<td>150</td>
<td>0.915 ± 0.003</td>
<td>0.969 ± 0.002</td>
</tr>
<tr>
<td>160</td>
<td>0.918 ± 0.003</td>
<td>0.973 ± 0.002</td>
</tr>
<tr>
<td>170</td>
<td>0.911 ± 0.003</td>
<td>0.972 ± 0.002</td>
</tr>
<tr>
<td>180</td>
<td>0.913 ± 0.003</td>
<td>0.974 ± 0.002</td>
</tr>
<tr>
<td>190</td>
<td>0.913 ± 0.003</td>
<td>0.970 ± 0.003</td>
</tr>
<tr>
<td>200</td>
<td>0.916 ± 0.003</td>
<td>0.976 ± 0.002</td>
</tr>
<tr>
<td>210</td>
<td>0.914 ± 0.003</td>
<td>0.980 ± 0.002</td>
</tr>
</tbody>
</table>

Table 4.5: Isolation efficiency for an unbiased electron due to the jet activity in a $b'$ signal event.

Multiple interactions, minimum bias events and underlying events add some level of isotropic energy in the calorimeters. To include this factor in our overall isolation efficiency we have computed a scaling factor between the isolation efficiency observed in the $Z^0 \rightarrow e^+e^- (\mu^+\mu^-)$ data and in a HERWIG $Z^0 \rightarrow e^+e^- (\mu^+\mu^-)$ Monte Carlo,

$$SF_{iso} = \frac{\varepsilon_{iso}^{data}}{\varepsilon_{iso}^{Z^0MC}}.$$  \hspace{1cm} (4.3)
Table 4.6: Isolation efficiency for an unbiased muon due to the jet activity in a $b'$ signal event, averaged over all five muon categories and weighted by the numbers of events.

For this purpose, the isolation efficiency is computed with the events that pass the $Z^0$ selection criteria including lepton identification, but before any jet requirement. The results for central and plug electrons are shown in Table 4.7. The scale factor for each detector is different because of the different $|\eta|$ coverage. For central muons, the average isolation efficiency in the $Z^0$ Monte Carlo is $0.998\pm0.001$ while in the data we measure $0.985\pm0.003$. Thus, in the muon case, we take a scale factor $SF_{iso} = 0.987\pm0.003$, independent of the muon type.

Table 4.7: Isolation efficiency measured after the $Z^0$ selection in the data and in the $Z^0 \rightarrow e^+e^-$ Monte-Carlo. $SF_{iso}$ is the ratio between both measurements.

<table>
<thead>
<tr>
<th>$Z \rightarrow e^+e^-$</th>
<th>Central</th>
<th>Plug</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>$0.985\pm0.002$</td>
<td>$0.951\pm0.003$</td>
</tr>
<tr>
<td>Monte-Carlo</td>
<td>$0.998\pm0.002$</td>
<td>$0.997\pm0.002$</td>
</tr>
<tr>
<td>$SF_{iso}$</td>
<td>$0.987\pm0.003$</td>
<td>$0.954\pm0.004$</td>
</tr>
</tbody>
</table>

The corrected isolation efficiency for a given lepton in detector $x$ is obtained by
multiplying the efficiency from the \( b' \) Monte Carlo by the data scale factor.

\[
\varepsilon_{iso}^\pi = \varepsilon_{iso}^{MC,\pi} \times SF_{iso}^\pi
\]  

(4.4)

The overall isolation efficiency for the \( b' \) events has to take into consideration the fact that there are two leptons in the event and each has a probability \( \varepsilon_{iso}^\pi \) of passing this cut. It is incorrect to consider that the event isolation efficiency is \( \varepsilon_{iso}^\pi \) because the isolation cut is done only on the second lepton. This approach would neglect the fact that when both leptons pass tight cuts, one passes isolation and the other fails isolation, the event always passes our cuts. The correct treatment of the event isolation efficiency needs to convolve the lepton identification, trigger and isolation efficiencies. This is explained in detail in Section 4.3.4.

### 4.3.4 \( Z^0 \) Efficiency Calculation

The \( Z^0 \) efficiency is composed of all the efficiencies mentioned in this section. Its calculation is rather complex because of the large number of different lepton categories and the existence of different levels of lepton identification cuts (tight and loose) for the first and second \( Z^0 \) leptons.

#### 4.3.4.1 Electron Channel

The overall \( Z^0 \rightarrow e^+e^- \) event detection efficiency can be separated in two terms.

\[
\varepsilon_Z = F_{cc} \cdot \varepsilon_Z^{cc} + F_{cp} \cdot \varepsilon_Z^{cp}
\]  

(4.5)

The first term accounts for events with both \( Z^0 \) electrons in the central calorimeter, while the second term accounts for events with one central and one plug electron. \( F_{cc} \) and \( F_{cp} \) are the fraction of \( Z^0 \) events in which the second leg falls into the central and plug calorimeter, respectively. These fractions were obtained from our studies of the geometrical acceptance, the results of which are shown in Figure 4.2.

In the case that the second electron is in the plug calorimeter the \( Z^0 \) efficiency, \( \varepsilon_Z^{cp} \), is simply the product of all the detection efficiencies. These are the event trigger efficiency
\( \epsilon_T \), the central electron identification efficiency for first leg electrons \( c_1 \), the plug electron identification efficiency \( p \), the correction factor for the overefficiency of the conversion removal algorithm \( \epsilon_{\text{conv}} = 0.987 \pm 0.004 [47] \) and the isolation efficiency for plug electrons \( \epsilon_{\text{iso}} ^p \).

\[
\epsilon_Z^p = \epsilon_T \cdot c_1 \cdot \epsilon_{\text{conv}} \cdot p \cdot \epsilon_{\text{iso}} ^p \tag{4.6}
\]

In the case that both electrons are in the central calorimeter, either electron can be used for the \( Z^0 \) first leg. This factor makes the \( Z^0 \) efficiency for central-central events, \( \epsilon_Z^{CC} \), rather complicated,

\[
\epsilon_Z^{CC} = \epsilon_T \cdot c_1 \cdot \epsilon_{\text{conv}} \cdot \epsilon_{\text{iso}} (2c_2 - \epsilon_T \cdot c_1 \cdot \epsilon_{\text{conv}} \cdot \epsilon_{\text{iso}}), \tag{4.7}
\]

where we have introduced \( c_2 \), the central electron identification efficiency for second leg electrons and \( \epsilon_{\text{iso}} \), the isolation efficiency for central electrons. In this case, each central electron has 24 possible outcomes from which only the following nine are accepted:

1. \( \epsilon_1 = \epsilon_T \cdot \epsilon_{\text{conv}} \cdot c_1 \cdot \epsilon_{\text{iso}} \)
2. \( \epsilon_2 = \epsilon_T \cdot \epsilon_{\text{conv}} \cdot c_1 \cdot (1 - \epsilon_{\text{iso}}) \)
3. \( \epsilon_3 = \epsilon_T \cdot \epsilon_{\text{conv}} \cdot (c_2 - c_1) \cdot \epsilon_{\text{iso}} \)
4. \( \epsilon_4 = (1 - \epsilon_T) \cdot \epsilon_{\text{conv}} \cdot c_1 \cdot \epsilon_{\text{iso}} \)
5. \( \epsilon_5 = (1 - \epsilon_T) \cdot \epsilon_{\text{conv}} \cdot (c_2 - c_1) \cdot \epsilon_{\text{iso}} \)
6. \( \epsilon_6 = \epsilon_T \cdot (1 - \epsilon_{\text{conv}}) \cdot c_1 \cdot \epsilon_{\text{iso}} \)
7. \( \epsilon_7 = \epsilon_T \cdot (1 - \epsilon_{\text{conv}}) \cdot (c_2 - c_1) \cdot \epsilon_{\text{iso}} \)
8. \( \epsilon_8 = (1 - \epsilon_T) \cdot (1 - \epsilon_{\text{conv}}) \cdot c_1 \cdot \epsilon_{\text{iso}} \)
9. \( \epsilon_9 = (1 - \epsilon_T) \cdot (1 - \epsilon_{\text{conv}}) \cdot (c_2 - c_1) \cdot \epsilon_{\text{iso}} \)

From the above, only electrons satisfying the conditions 1 and 2 can be used for the first \( Z^0 \) leg. Only electrons passing condition 1 can be used for both legs. Electrons that satisfy
any of the nine conditions can be used for the second leg of the $Z^0$ event. Therefore, the $Z^0$ efficiency for central-central electrons is given by,

$$
\epsilon^Z_{C} = \epsilon_1^2 + 2\epsilon_1(\epsilon_2 + \epsilon_3 + \epsilon_4 + \epsilon_5 + \epsilon_6 + \epsilon_7 + \epsilon_8 + \epsilon_9)
$$

(4.8)

$$
+ 2\epsilon_2(\epsilon_3 + \epsilon_4 + \epsilon_5 + \epsilon_6 + \epsilon_7 + \epsilon_8 + \epsilon_9)
$$

(4.9)

$$
= \epsilon_T \cdot c_1 \cdot c_{conv} \cdot \epsilon_{iso}(2c_2 - \epsilon_T \cdot c_1 \cdot c_{conv} \cdot \epsilon_{iso})
$$

(4.10)

The overall $Z^0 \rightarrow e^+e^-$ event detection efficiency obtained in this way is shown, as a function of the $b'$ mass, in Table 4.8. Its average value is $\epsilon_Z = 0.734 \pm 0.002$, where the uncertainty is statistical only.

<table>
<thead>
<tr>
<th>$m_Y$ [GeV/c²]</th>
<th>$\epsilon^Z_{C}$</th>
<th>$\epsilon^Z_{P}$</th>
<th>$\epsilon_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.767 ± 0.010</td>
<td>0.707 ± 0.006</td>
<td>0.741 ± 0.007</td>
</tr>
<tr>
<td>110</td>
<td>0.763 ± 0.010</td>
<td>0.705 ± 0.006</td>
<td>0.737 ± 0.007</td>
</tr>
<tr>
<td>120</td>
<td>0.756 ± 0.010</td>
<td>0.701 ± 0.006</td>
<td>0.732 ± 0.007</td>
</tr>
<tr>
<td>130</td>
<td>0.756 ± 0.010</td>
<td>0.700 ± 0.006</td>
<td>0.733 ± 0.007</td>
</tr>
<tr>
<td>140</td>
<td>0.756 ± 0.010</td>
<td>0.699 ± 0.006</td>
<td>0.732 ± 0.007</td>
</tr>
<tr>
<td>150</td>
<td>0.755 ± 0.010</td>
<td>0.697 ± 0.006</td>
<td>0.731 ± 0.007</td>
</tr>
<tr>
<td>160</td>
<td>0.755 ± 0.010</td>
<td>0.700 ± 0.006</td>
<td>0.733 ± 0.007</td>
</tr>
<tr>
<td>170</td>
<td>0.753 ± 0.010</td>
<td>0.700 ± 0.006</td>
<td>0.733 ± 0.007</td>
</tr>
<tr>
<td>180</td>
<td>0.754 ± 0.010</td>
<td>0.701 ± 0.006</td>
<td>0.733 ± 0.007</td>
</tr>
<tr>
<td>190</td>
<td>0.754 ± 0.010</td>
<td>0.698 ± 0.006</td>
<td>0.732 ± 0.007</td>
</tr>
<tr>
<td>200</td>
<td>0.755 ± 0.010</td>
<td>0.702 ± 0.006</td>
<td>0.735 ± 0.008</td>
</tr>
<tr>
<td>210</td>
<td>0.754 ± 0.010</td>
<td>0.705 ± 0.006</td>
<td>0.736 ± 0.008</td>
</tr>
</tbody>
</table>

Table 4.8: $Z^0$ efficiency in the electron channel. The first two columns give the efficiency for central-central and central-plug events. The last column is the averaged efficiency over both detectors.

### 4.3.4.2 Muon Channel

The overall event selection efficiency for a $Z^0 \rightarrow \mu^+\mu^-$ event is defined in a similar way as in the electron case,

$$
\epsilon_Z = \epsilon_T \times (\epsilon_{lepton-id} \otimes \epsilon_{iso})
$$

(4.11)
where $\epsilon_T$ is the trigger efficiency per event, $\epsilon_{\text{lepton-id}}$ is the muon identification efficiency of Section 4.3.2, and $\epsilon_{\text{iso}}$ is the isolation efficiency of Section 4.3.3. The lepton identification efficiency and the isolation efficiency are convoluted because there are two muons per event and there are different levels of cuts (i.e., tight and loose) applied to each muon.

In order to calculate this quantity we divide the events into eleven different combinations depending on the muon types: CMU, CMP, CMUP, CMX and CMIO. The first $Z^0$ leg has to satisfy tight lepton identification cuts and no isolation cut while the second leg needs to pass loose lepton identification cuts and an isolation requirement. Furthermore, the $Z^0$ first leg cannot be a CMP or CMIO muon. Therefore, each combination of detectors falls into one of the following 3 categories:

**CASE I** For CMU-CMU, CMUP-CMUP and CMX-CMX combinations, both muons can be used for the $Z^0$ first leg. Each muon has six possible outcomes from which only the following three are accepted:

1. It passes tight cuts and isolation, $\epsilon_1 = \epsilon_{\text{tight}} \cdot \epsilon_{\text{iso}}$
2. It passes tight cuts but fails isolation, $\epsilon_2 = \epsilon_{\text{tight}} \cdot (1 - \epsilon_{\text{iso}})$
3. It fails tight cuts but passes loose cuts and isolation, $\epsilon_3 = (\epsilon_{\text{loose}} - \epsilon_{\text{tight}}) \cdot \epsilon_{\text{iso}}$

In this case, the efficiency $(\epsilon_{\text{lepton-id}} \otimes \epsilon_{\text{iso}})$ is given by:

$$\epsilon_T^A = \epsilon_1^A \left( \epsilon_1^A + 2\epsilon_2^A + 2\epsilon_3^A \right) + 2\epsilon_2^A \cdot \epsilon_3^A \quad (4.12)$$

$$= \epsilon_{\text{tight}}^A \cdot \epsilon_{\text{iso}}^A \left( 2\epsilon_{\text{loose}}^A - \epsilon_{\text{tight}}^A \cdot \epsilon_{\text{iso}}^A \right) \quad (4.13)$$

where $A$ denotes the general detector common to both muons.

**CASE II** For CMU-CMUP, CMU-CMX and CMUP-CMX combinations both muons can still be used for the first leg, however they are not indistinguishable as in CASE I because they are from different detectors. Each muon still has the same three possible outcomes that are accepted but it has to satisfy the cuts corresponding to its own detector.
In this case, if we denote each general detector by $A$ and $B$, the efficiency ($\epsilon_{\text{lepton-id}} \otimes \epsilon_{\text{iso}}$) is given by:

$$\epsilon_{II}^{A-B} = 2 \left( \epsilon_1^A \left( \epsilon_1^B + \epsilon_2^B + \epsilon_3^B \right) + \epsilon_2^A \left( \epsilon_1^B + \epsilon_2^B \right) + \epsilon_3^A \left( \epsilon_1^B + \epsilon_2^B \right) \right)$$

(4.14)

$$= 2 \left( \epsilon_{\text{tight}} \cdot \epsilon_{\text{loose}} \cdot \epsilon_{\text{iso}} + \epsilon_{\text{tight}} \cdot \epsilon_{\text{loose}} \cdot \epsilon_{\text{iso}}^A - \epsilon_{\text{tight}} \cdot \epsilon_{\text{loose}} \cdot \epsilon_{\text{iso}} \cdot \epsilon_{\text{iso}}^A \right) \epsilon_{\text{iso}}^B$$

(4.15)

**CASE III** If one muon is a CMP or a CMIO it cannot be used for the first leg and things are much simplified. The convolution of the lepton identification and isolation efficiencies is given by,

$$\epsilon_{III}^{A-B} = \epsilon_{\text{tight}} \cdot \epsilon_{\text{loose}} \cdot \epsilon_{\text{iso}}^B$$

(4.16)

where $A$ denotes the detector of the first-leg muon.

The overall combined lepton identification and isolation efficiency for $Z^0$ events can be obtained by multiplying the efficiencies above by the corresponding event fractions $F_A^B$ for detectors $A$ and $B$,

$$(\epsilon_{\text{lepton-id}} \otimes \epsilon_{\text{iso}}) = F_U^U \cdot \epsilon_U^U + F_X^X \cdot \epsilon_X^X + F_{UP}^U \cdot \epsilon_{UP}^U +$$

$$+ F_U^U \cdot \epsilon_{UP-U}^U + F_X^X \cdot \epsilon_{UP-X}^X + F_{UP}^U \cdot \epsilon_{UP-X}^U +$$

$$+ F_U^P \cdot \epsilon_{III-P}^U + F_{U}^{IO} \cdot \epsilon_{III-IO}^U + F_{UP}^P \cdot \epsilon_{III}^P \cdot \epsilon_{UP-IO}^U +$$

$$+ F_X^P \cdot \epsilon_{III-P}^X + F_{IO}^{IO} \cdot \epsilon_{III}^X \cdot \epsilon_{IO-IO}^X$$

(4.17)

where we made the abbreviations: CMU = U, CMP = P, CMUP = UP, CMX = X and CMIO = I. The event fractions $F_A^B$ where determined using the $b'$ Monte Carlo described in Section 4.1 after the $Z^0$ mass cut has been applied. The differences between these fractions and the event fractions obtained after all cuts are within the statistical uncertainty.

### 4.4 Jet Selection Efficiencies

The jet selection efficiency is determined from the Monte Carlo samples described in Section 4.1. This efficiency is composed of two components, the 3-jet cut efficiency.
Table 4.9: The $\varepsilon_{\text{lepton-id}} \otimes \varepsilon_{\text{iso}}$ includes the lepton-id and isolation efficiencies. The $Z^0$ efficiency is obtained by multiplying the trigger efficiency by the first column.

<table>
<thead>
<tr>
<th>$m_{\bar{b}}$ [GeV/c²]</th>
<th>$\varepsilon_{\text{lepton-id}} \otimes \varepsilon_{\text{iso}}$</th>
<th>$\varepsilon_{Z^0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.847 ± 0.007</td>
<td>0.690 ± 0.007</td>
</tr>
<tr>
<td>110</td>
<td>0.836 ± 0.008</td>
<td>0.679 ± 0.007</td>
</tr>
<tr>
<td>120</td>
<td>0.826 ± 0.008</td>
<td>0.673 ± 0.007</td>
</tr>
<tr>
<td>130</td>
<td>0.822 ± 0.008</td>
<td>0.661 ± 0.007</td>
</tr>
<tr>
<td>140</td>
<td>0.818 ± 0.007</td>
<td>0.666 ± 0.007</td>
</tr>
<tr>
<td>150</td>
<td>0.822 ± 0.008</td>
<td>0.673 ± 0.007</td>
</tr>
<tr>
<td>160</td>
<td>0.825 ± 0.008</td>
<td>0.670 ± 0.007</td>
</tr>
<tr>
<td>170</td>
<td>0.821 ± 0.008</td>
<td>0.666 ± 0.007</td>
</tr>
<tr>
<td>180</td>
<td>0.822 ± 0.008</td>
<td>0.672 ± 0.007</td>
</tr>
<tr>
<td>190</td>
<td>0.826 ± 0.008</td>
<td>0.671 ± 0.007</td>
</tr>
<tr>
<td>200</td>
<td>0.818 ± 0.008</td>
<td>0.667 ± 0.007</td>
</tr>
<tr>
<td>210</td>
<td>0.822 ± 0.009</td>
<td>0.675 ± 0.008</td>
</tr>
</tbody>
</table>

Table 4.9: The $\varepsilon_{\text{lepton-id}} \otimes \varepsilon_{\text{iso}}$ includes the lepton-id and isolation efficiencies. The $Z^0$ efficiency is obtained by multiplying the trigger efficiency by the first column.

and the $\sum E_T^{jets}$ cut efficiency: $\varepsilon_{\text{jet}} = \varepsilon_{3-\text{jet}} \cdot \varepsilon_{\Sigma E_T}$. The 3-jet cut efficiency is defined by $\varepsilon_{3-\text{jet}} = \frac{N_{3-\text{jet}}}{N_Z}$, where $N_Z$ is the number of Monte Carlo events that pass the $Z^0$ selection and $N_{3-\text{jet}}$ is the subset of such events that also pass the 3-jet requirement. The $\sum E_T^{jets}$ cut efficiency, $\varepsilon_{\Sigma E_T} = \frac{N_{\Sigma E_T}}{N_{3-\text{jet}}}$, is calculated with the events that have passed the 3-jet criteria, where $N_{\text{jet}}$ is the number of events that passed all the selection cuts but the $b$-tag requirement. The calculation of these efficiencies is done separately for $b'$ events in the $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ channels. The results are presented in Table 4.10 and Figure 4.4 for electrons, and in Table 4.11 and Figure 4.5 for muons. The step observed in the efficiency for $b'$ masses between 120 GeV/c² and 130 GeV/c² is due to the different requirement on the energy of the third jet for $m_{\bar{b}} \leq 120$ GeV/c² and more massive $b'$ quarks.

The overall jet efficiency is higher in the muon channel than in the electron due to several factors. First, the muon sample is composed of events that are more central than the electron ones because the muon selection requires muons to be within $|\eta| < 1.1$, while electrons can have $|\eta|$ up to 2.4. More central events result from more violent collisions, and therefore the jet energy present in the event is higher. Furthermore, the centrality...
Figure 4.4: Jet selection efficiencies, as a function of the $b'$ mass, for events in the electron channel. Left: 3-jet efficiency; Right: $\sum E_T^{jets}$ efficiency.

Figure 4.5: Jet selection efficiencies, as a function of the $b'$ mass, for events in the muon channel. Left: 3-jet efficiency; Right: $\sum E_T^{jets}$ efficiency.
of the event will result in a better acceptance for the jets, which will be less likely to fail the $|\eta| < 2$ cut. Besides that, jets and electrons look very similar in our detector. They are distinguished by the relative energy deposited in the hadronic and electromagnetic calorimeters. It is possible that, if one electron is lost, a jet will fake an electron which will pass our $Z^0$ selection. In this case, the event will lack one jet and therefore it will be less likely to pass the 3-jet requirement. Another possibility is that a jet and an electron overlap in the calorimeters in such a way that they are indistinguishable. In this case, the jet could be incorporated in the electron and thus be removed from our jet counting.

<table>
<thead>
<tr>
<th>$m_{\nu}$</th>
<th>$E_{\text{jet}}$ cut</th>
<th>$E_{\text{jet}}$ cut</th>
<th>$E_{\text{jet}}$ cut</th>
<th>$E_{\text{jet}}$ cut</th>
<th>$E_{\text{jet}}$ cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>65.0 ± 0.2</td>
<td>88.3 ± 0.2</td>
<td>25.9 ± 0.5</td>
<td>97.4 ± 0.2</td>
<td>15.3 ± 0.4</td>
</tr>
<tr>
<td>110</td>
<td>65.7 ± 0.2</td>
<td>87.9 ± 0.2</td>
<td>43.9 ± 0.5</td>
<td>90.5 ± 0.3</td>
<td>27.1 ± 0.5</td>
</tr>
<tr>
<td>120</td>
<td>67.0 ± 0.2</td>
<td>87.2 ± 0.2</td>
<td>57.0 ± 0.5</td>
<td>84.6 ± 0.3</td>
<td>36.2 ± 0.5</td>
</tr>
<tr>
<td>130</td>
<td>67.0 ± 0.2</td>
<td>86.8 ± 0.2</td>
<td>46.8 ± 0.5</td>
<td>94.7 ± 0.3</td>
<td>43.3 ± 0.5</td>
</tr>
<tr>
<td>140</td>
<td>67.7 ± 0.2</td>
<td>86.8 ± 0.2</td>
<td>54.6 ± 0.5</td>
<td>91.5 ± 0.3</td>
<td>45.8 ± 0.5</td>
</tr>
<tr>
<td>150</td>
<td>68.4 ± 0.2</td>
<td>86.3 ± 0.2</td>
<td>59.2 ± 0.5</td>
<td>89.0 ± 0.3</td>
<td>47.9 ± 0.5</td>
</tr>
<tr>
<td>160</td>
<td>69.4 ± 0.3</td>
<td>85.9 ± 0.2</td>
<td>62.8 ± 0.5</td>
<td>86.9 ± 0.3</td>
<td>48.7 ± 0.5</td>
</tr>
<tr>
<td>170</td>
<td>69.4 ± 0.3</td>
<td>85.7 ± 0.2</td>
<td>65.1 ± 0.5</td>
<td>85.3 ± 0.3</td>
<td>50.2 ± 0.5</td>
</tr>
<tr>
<td>180</td>
<td>70.2 ± 0.3</td>
<td>86.1 ± 0.2</td>
<td>67.5 ± 0.5</td>
<td>82.9 ± 0.3</td>
<td>52.1 ± 0.5</td>
</tr>
<tr>
<td>190</td>
<td>70.5 ± 0.3</td>
<td>86.0 ± 0.2</td>
<td>69.0 ± 0.5</td>
<td>82.0 ± 0.3</td>
<td>51.5 ± 0.5</td>
</tr>
<tr>
<td>200</td>
<td>70.5 ± 0.3</td>
<td>85.4 ± 0.2</td>
<td>69.7 ± 0.5</td>
<td>80.3 ± 0.3</td>
<td>52.2 ± 0.5</td>
</tr>
<tr>
<td>210</td>
<td>71.2 ± 0.3</td>
<td>85.4 ± 0.2</td>
<td>71.1 ± 0.5</td>
<td>79.3 ± 0.3</td>
<td>53.1 ± 0.5</td>
</tr>
</tbody>
</table>

Table 4.10: Acceptance calculated directly from the signal $b'$ Monte Carlo for events in the electron channel. Note that the geometry-$p_T$ does not include the $z_{\text{vertex}}$ efficiency and the $b$-tag does not include the $b$-tag scale factor.

4.5 $b$-tag Efficiency

The $b$-tag efficiency was calculated from the $b'$ signal Monte Carlo and adjusted by a scale factor obtained from data, $\epsilon_{b-tag} = \epsilon_{b-tag}^{MC} \times S_{b-tag}^{\text{event}}$. We define the event $b$-tag efficiency obtained from the Monte Carlo as $\epsilon_{b-tag}^{MC} = \frac{N_{b-tag}}{N_{jet}}$, where $N_{jet}$ is the number of

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Table 4.11: Acceptance calculated from the signal $b'$ Monte Carlo for events in the muon channel. Note that the geometry-$p_T$ does not include the $z_{vertex}$ efficiency and the $b$-tag does not include the $b$-tag scale factor.

<table>
<thead>
<tr>
<th>$m_Y$ [GeV/$c^2$]</th>
<th>signal acceptance/efficiencies [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>geometry-$p_T$</td>
</tr>
<tr>
<td>100</td>
<td>45.6 ± 0.2</td>
</tr>
<tr>
<td>110</td>
<td>46.4 ± 0.3</td>
</tr>
<tr>
<td>120</td>
<td>48.3 ± 0.3</td>
</tr>
<tr>
<td>130</td>
<td>49.2 ± 0.3</td>
</tr>
<tr>
<td>140</td>
<td>50.8 ± 0.3</td>
</tr>
<tr>
<td>150</td>
<td>52.2 ± 0.3</td>
</tr>
<tr>
<td>160</td>
<td>53.1 ± 0.3</td>
</tr>
<tr>
<td>170</td>
<td>53.9 ± 0.3</td>
</tr>
<tr>
<td>180</td>
<td>54.6 ± 0.3</td>
</tr>
<tr>
<td>190</td>
<td>56.3 ± 0.3</td>
</tr>
<tr>
<td>200</td>
<td>56.7 ± 0.3</td>
</tr>
<tr>
<td>210</td>
<td>57.5 ± 0.3</td>
</tr>
</tbody>
</table>

events that passed all the selection criteria besides the $b$-tag requirement and $N_{b-tag}$ is the subset of $N_{jet}$ that in addition passed the $b$-tag cut. We observe that as expected, the $b$-tag efficiency is strongly dependent on the $b'$ mass because for small $b'$ mass the $E_T$ of the $b$ jets is considerably lower. Table 4.10 and Table 4.11 show the $b$-tag efficiencies obtained directly from the signal Monte Carlo as a function of the $b'$ mass.

The detector simulation produces a better tracking efficiency than the one for data. To account for this we include a track degradation scale factor [64] calculated using data,

$$SF_{b-tag}^{deg} = \frac{\epsilon_{b-tag}^{data}}{\epsilon_{b-tag}^{MC}} = 0.87 \pm 0.07$$

On the other hand, it has been found that the $b$-tagging efficiency in Monte Carlo events is actually smaller than for real data. This is due to several other factors in the detector simulation which we correct for by introducing another scale factor [65, 66]. In our analysis, we used the SECVTX scale factor determined for the $W + 3$ jets top events, $SF_{b-tag}^{W} = 1.22 \pm 0.12$. The heavy flavor content in $t\bar{t} \rightarrow bW\bar{b}W$, is smaller than in $b\bar{b}$ events because in the latter about 15% of the events have four $b$-jets, where the extra two jets come from
a $Z^0$ decay. This effect should be very small (less than 2%) but difficult to determine and therefore we have neglected it. The overall $b$-tag scale factor per event is given by,

$$SF_{b-tag}^{\text{event}} = SF_{b-tag}^{\text{deg}} \times SF_{b-tag}^{\text{W}} = 1.06 \pm 0.10$$  \hspace{1cm} (4.19)$$

The final event $b$-tag efficiency is given by $\epsilon_{b-tag} = \epsilon_{b-tag}^{\text{MC}} \times SF_{b-tag}^{\text{event}}$. The numbers obtained are consistent with the expectations. For large $b'$ masses, we expected a $b$-tag efficiency slightly larger than the one for $t\bar{t}$ ($\epsilon_{t\bar{t}} = 0.505 \pm 0.051$ [67]) because each $b'$ event has at least two high-$p_T$ $b$ quarks just like a top event but, in addition 15% of the $b'$ events have a $Z^0$ which decays into $b\bar{b}$. In these events there are four high-$p_T$ $b$ quarks.

![Graph](image_url)

Figure 4.6: $b$-tag efficiency as a function of the $b'$ mass including the $b$-tag scale factor. Left: Electron channel. Right. Muon channel.

### 4.6 Total Acceptance $\times$ Efficiency ($A \cdot \epsilon$)

The total acceptance $\times$ efficiency is the product of all independent acceptances and efficiencies calculated in this Chapter,

$$A \cdot \epsilon = \epsilon_{\text{vertex}} \cdot \epsilon_{\text{geom}} \cdot \epsilon_{Z-\text{mass}} \cdot \epsilon_{Z} \cdot \epsilon_{3-\text{jet}} \cdot \epsilon_{\Sigma E_T} \cdot \epsilon_{b-tag}$$  \hspace{1cm} (4.20)$$
The total acceptance × efficiency is given in Table 4.12 and Figure 4.7 for electrons, and in Table 4.13 and Figure 4.8 for muons.

<table>
<thead>
<tr>
<th>$m_{\nu}$ [GeV/c²]</th>
<th>$(A \cdot \epsilon)$ [%]</th>
<th>$\epsilon_{\text{e+e-}} \cdot \epsilon_{\text{geo-P_T}}$</th>
<th>$\epsilon_{\text{Z}}$</th>
<th>$\epsilon_{\text{Z}} \cdot \epsilon_{\text{e+e-}}$</th>
<th>$\epsilon_{\text{Z}} \cdot \epsilon_{\text{e+e-}} \cdot \epsilon_{\text{jet}}$</th>
<th>$\epsilon_{\text{Z}} \cdot \epsilon_{\text{e+e-}} \cdot \epsilon_{\text{jet}} \cdot \epsilon_{\text{b-tag}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>61.7 ± 0.2</td>
<td>54.5 ± 0.2</td>
<td>40.3 ± 0.1</td>
<td>10.2 ± 0.1</td>
<td>1.65 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>62.4 ± 0.2</td>
<td>54.9 ± 0.2</td>
<td>40.4 ± 0.2</td>
<td>16.1 ± 0.1</td>
<td>4.62 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>63.6 ± 0.2</td>
<td>55.4 ± 0.2</td>
<td>40.6 ± 0.2</td>
<td>19.9 ± 0.2</td>
<td>7.62 ± 0.11</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>63.6 ± 0.2</td>
<td>55.2 ± 0.2</td>
<td>40.4 ± 0.2</td>
<td>17.9 ± 0.2</td>
<td>8.22 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>64.3 ± 0.2</td>
<td>55.8 ± 0.2</td>
<td>40.9 ± 0.2</td>
<td>20.4 ± 0.2</td>
<td>9.91 ± 0.13</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>64.9 ± 0.2</td>
<td>56.0 ± 0.2</td>
<td>41.0 ± 0.2</td>
<td>21.6 ± 0.2</td>
<td>10.9 ± 0.14</td>
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</tr>
<tr>
<td>160</td>
<td>65.9 ± 0.2</td>
<td>56.6 ± 0.3</td>
<td>41.5 ± 0.2</td>
<td>22.6 ± 0.2</td>
<td>11.6 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>65.9 ± 0.2</td>
<td>56.5 ± 0.3</td>
<td>41.4 ± 0.2</td>
<td>23.0 ± 0.2</td>
<td>12.2 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>66.6 ± 0.2</td>
<td>57.3 ± 0.3</td>
<td>42.0 ± 0.2</td>
<td>23.5 ± 0.2</td>
<td>12.9 ± 0.16</td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>66.9 ± 0.2</td>
<td>57.5 ± 0.3</td>
<td>42.1 ± 0.2</td>
<td>23.8 ± 0.2</td>
<td>13.0 ± 0.16</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>66.9 ± 0.3</td>
<td>57.2 ± 0.3</td>
<td>42.0 ± 0.2</td>
<td>23.5 ± 0.2</td>
<td>13.0 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>210</td>
<td>67.6 ± 0.3</td>
<td>57.7 ± 0.3</td>
<td>42.5 ± 0.2</td>
<td>24.0 ± 0.2</td>
<td>13.4 ± 0.17</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.12: Acceptance × efficiency for the $b'$ signal in the electron channel. The two last columns show the final $(A \cdot \epsilon)$ before and after $b$-tag.
Figure 4.7: Acceptance $\times$ efficiency ($A \cdot \epsilon$), in the electron channel, as a function of the $b'$ mass after the successive selection criteria.
Figure 4.8: Acceptance $\times$ efficiency ($A \cdot \epsilon$) in the muon channel, as function of $b'$ mass after the successive selection criteria.
Table 4.13: Acceptance × efficiency for the $b'$ signal in the muon channel. The two last columns show the final $(A \cdot \epsilon)$ before and after $b$-tag.
Chapter 5

Systematic Uncertainties

The efficiency and acceptance calculations described in the previous chapter depend on many particulars that can introduce a bias into the final result. Uncertainties in the detector response and Monte Carlo description of nature are among the most important ones. While we try to correct for most of these factors, some remain without being fully understood and therefore they can be seen as irreducible. In this chapter, we account for all the systematic uncertainties that we know affect the final results in our acceptance calculation. We describe in some detail the estimation of the systematic uncertainty due to the jet energy scale, gluon radiation and the parton distribution function. We finish with a summary of all the systematic uncertainties considered in the determination of the $b'$ acceptance.

5.1 Jet-Energy Scale

The calorimeter jet-energy measurement has a large relative uncertainty due to the detector calibration and stability, fragmentation effects and the underlying event. The $b'$ kinematic efficiency is strongly dependent on the jet-energy scale because of the requirement at low $b'$ mass of a jet with $E_T > 7$ GeV, which is near the detector threshold, and the $\sum E_T^{jets}$ cut. To estimate the systematic uncertainty introduced by the jet-energy scale, we vary the energy of the jets in the Monte Carlo simulation by a factor of $\pm 10\%$. The
effects of the variation of the jet $E_T$ on the kinematic distributions are shown in Figures 5.1 and 5.2. Figure 5.1 shows the jet-$E_T$ and multiplicity distributions for events from 100 GeV $b'$-quarks. With the decrease in jet-$E_T$, the jets that were produced near the threshold of the jet-$E_T$ cut are lost. Since a large percentage of events for low $b'$ masses only have three jets, this results in a considerable loss of events. Figure 5.2 shows the $\Sigma E_T^{jets}$ and multiplicity distributions for 150 GeV $b'$-quark events. For heavier $b'$ quarks, most events have at least four jets and most jets have large $E_T$ relative to the cut threshold. In this case, the jet-energy scale has the largest impact on the $\Sigma E_T^{jets}$ distribution, resulting in a significant variation in the number of events that pass the kinematic cuts.

![Figure 5.1: Jet-$E_T$ scale impact on kinematic distribution for $m_{b'} = 100$ GeV in the muon channel. Left: third-jet $E_T$ distribution; Right: jet multiplicity distribution. The plots were made after the 3-jet requirement but before the $\Sigma E_T^{jets}$ cut.](image)

We recalculate the efficiencies, for the twelve $b'$ masses from 100 to 210 GeV/$c^2$, using the Monte Carlo samples with the ±10% variations of jet $E_T$. From these, the jet-energy scale systematic uncertainty, $\Delta_{1/2}^{js}$, is defined by the following equation,

$$\Delta_{1/2}^{js} = \frac{1}{2} \times \frac{\epsilon_{110\%} - \epsilon_{90\%}}{\epsilon_{default}}$$

(5.1)
Figure 5.2: Jet-$E_T$ scale impact on kinematic distribution for $m_Y = 150$ GeV in the muon channel. Left: $\sum E_T^{jets}$ distribution. The vertical line shows the place of the cut; Right: jet multiplicity distribution. The plots were made after the 3-jet requirement but before the $\sum E_T^{jets}$ cut.
where $\epsilon_{\text{default}}, \epsilon_{\text{110}}, \epsilon_{\text{90}}$ are the overall $b'$ acceptance times efficiency calculated with the default jet-energy scale, and the jet-energy scale varied by $\pm 10\%$ and $-10\%$, respectively.

Several efficiencies for these variations of jet-$E_T$ are shown in Figure 5.3 and 5.4, for the electron and muon channels respectively. In these plots, the top graphs show the value of the efficiencies for the three cases of jet-$E_T$ and the bottom graphs show the systematic uncertainty on the corresponding efficiency. The systematic uncertainties due to the jet-energy scale, on the 3-jet cut and the $\sum E_T^{jets}$ cut efficiencies change as a function of the $b'$ mass in opposite directions, mainly because of the scaling of the $\sum E_T^{jets}$ cut. Consequently, the variation in the combined jet-selection efficiency is fairly flat with the $b'$ mass. The muon trigger and isolation efficiency do not show any appreciable dependence on the jet-energy scale.

The effect on the $b$-tag efficiency is anti-correlated with the effect on the jet-selection efficiencies. This can be understood in the following way. If the jet-energy scale is lowered, fewer events will pass the jet selection. However, the ones that pass have jets with larger $E_T$ which are more likely to be tagged by the SVX $b$-tagging algorithm. So, the jet-selection efficiency decrease is partially compensated by an increase in the $b$-tag efficiency.

We use the total efficiency to make our best estimation of the jet-energy scale systematic uncertainty. The use of the total efficiency accounts for all the correlations mentioned above. We estimate that in the electron channel the this systematic uncertainty is 16% for $b'$ masses of 100 GeV, 13% for $m_{\nu} = 110$ GeV and 12% for higher $b'$ masses. In the muon channel, the systematic uncertainty is 13%, 12% and 11% for the same $b'$ masses.

### 5.2 Gluon Radiation

The Monte Carlo generator includes the modeling of gluon radiation from initial-state (ISR) and final-state (FSR) partons. The emission of these gluons increases the jet multiplicity and therefore it affects the overall efficiency determination for signal events. An example of $b'$ production with an additional gluon from ISR is shown in Figure 5.5.

Traditionally at CDF, the PYTHIA Monte Carlo program [72] has been used to
Figure 5.3: Jet-energy scale effect on several efficiencies in the electron channel. Each efficiency is plotted for three variations of jet-$E_T$ scale. The line graph shows the half of the percent difference between the 90% and the 110% cases. The bottom-right plot shows the collective effect on the total efficiency.
Figure 5.4: Jet-energy scale effect on several efficiencies in the muon channel. Each efficiency is plotted for three variations of jet-$E_T$ scale. The line graph shows the half of the percent difference between the 90% and the 110% cases. The bottom-right plot shows the collective effect on the total efficiency.
estimate the effects of the amount of gluon radiation in the Monte Carlo model, even when the signal acceptances are calculated with HERWIG. This happens because it is possible to turn off initial and final state radiation in PYTHIA while it is not possible in HERWIG. However, since the Monte Carlo programs are different, it is not clear that the results obtained with PYTHIA apply to the gluon radiation model in HERWIG.

In our analysis, we used the HERWIG generator, the same program used to calculate the acceptances, to estimate the gluon radiation systematic uncertainty. We devised a method that effectively works the same way as the "switch" in PYTHIA to turn initial and final state radiation on and off. In the Monte Carlo simulation, we used the particle generation codes to identify the partons originating from the initial/final state of the hard collision that produces the $b'$ quarks. We then selected the events whose ISR/FSR partons had all $p_T < 7$ GeV. This way, we obtained a sample virtually free of ISR/FSR because the low-$p_T$ partons are not seen in the detector. Using this ISR/FSR "free" sample, we
calculated the total efficiency and compared it with the previously calculated values for the samples with standard gluon radiation. We then define the systematic uncertainty due to ISR or FSR, $\Delta_{1/2}^{ISR/FSR}$, to be

$$\Delta_{1/2}^{ISR/FSR} = \frac{1}{2} \times \frac{\varepsilon_{on} - \varepsilon_{off}}{\varepsilon_{on}}$$  \hspace{1cm} (5.2)$$

The method was applied separately for the initial and final-state gluon radiation.

The presence of gluon radiation increases the jet multiplicity and therefore increases the efficiency of the three-jet requirement. This effect is more pronounced at low $b'$ mass because the $b$ quarks from low-mass $b'$ decay are produced near threshold and therefore are detected with low efficiency. The jets resulting from gluon radiation have a very small content of heavy flavor. Therefore, the $b$-tagging efficiency on events which third-jet comes from gluon radiation is very small. So, the effect of gluon radiation on the $b$-tagging efficiency for a low mass $b'$ is anti-correlated with the effect on the jet-selection efficiencies. The plots in Figures 5.6 and 5.7 show the effect of ISR on several efficiencies, in the electron and muon channels. In general, the gluon radiation adds some amount of jet-energy to the event. This results in a small increase of the $\sum E_T^{jets}$ efficiency. On the other hand, the presence of extra jets decreases the lepton isolation efficiency because the probability of an overlap between a jet and a lepton is larger. We take the collective effect on the total efficiency as our best estimation of the ISR systematic uncertainty. In the electron channel, we estimate a systematic uncertainty varying from 19% for $m_{b'} = 100$ GeV, to 6% for $m_{b'} \geq 130$ GeV. In the muon channel, the uncertainty varies from 18% for $m_{b'} = 100$ GeV, to 6% for $m_{b'} \geq 120$ GeV.

The final-state gluon radiation systematic uncertainty is calculated in the a similar way to the initial-state radiation systematic. The initial-state radiation has a much stronger effect on our acceptance calculations than the final-state radiation. The FSR gluons originate from a more massive object and therefore they carry less momentum than the ISR gluons. Table 5.1 shows the percentage of the $b'$ Monte Carlo events that have ISR/FSR energetic enough to be seen in the detector. This number is fairly constant for all $b'$ masses. The bottom right plots in Figure 5.8 and Figure 5.9 show the overall effect of the FSR on
Figure 5.6: Initial-state gluon radiation effect on several efficiencies in the electron channel. Each efficiency is plotted for ISR on and ISR off. The line graph shows the half-percentage difference between the two cases. The bottom-right plot shows the collective effect on the total efficiency.
Figure 5.7: Initial-state gluon radiation effect on several efficiencies in the muon channel. Each efficiency is plotted for ISR on and ISR off. The line graph shows the half-percentage difference between the two cases. The bottom right plot shows the collective effect on the total efficiency.
the total efficiency. We use the values shown in the line plot to estimate this systematic uncertainty.

<table>
<thead>
<tr>
<th>$m_{\nu}$ [GeV/c$^2$]</th>
<th>Events with ISR/FSR partons with $p_T &gt; 7$ GeV [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ISR</td>
</tr>
<tr>
<td>110</td>
<td>66</td>
</tr>
<tr>
<td>120</td>
<td>65</td>
</tr>
<tr>
<td>140</td>
<td>65</td>
</tr>
<tr>
<td>160</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 5.1: Percentage of $b'$ Monte Carlo events that have ISR/FSR energetic enough to be seen in the detector.

5.3 Parton Distribution Function

The parton distribution function used in the signal Monte Carlo has some influence on the final-state kinematics of the simulated events. The Monte Carlo samples used for the $b'\bar{b}'$ acceptance calculation were created with the MRSD0' parton distribution function [52] (PDF). To study the effect of the PDF choice, we created new Monte Carlo samples using different parton distribution functions: GRV 94HO, MTB1, CTEQ 2MS and HMRS B [73]. These structure functions were chosen because they yield results that agree within $3\sigma$ with the CDF measurement of the $W$ charge asymmetry [27].

Using these new samples, we calculated the signal acceptance times efficiency for $m_{\nu} = 100$ GeV and $m_{\nu} = 140$ GeV. The variation of the product of the $Z^0$ acceptance and the kinematic efficiencies was always within ±5%. The largest variation was 4.8% between the HMRS B and the MRSD0' for $m_{\nu} = 100$ GeV. We have also observed that in general the choice of the PDF had a larger influence at the lower $b'$ mass. We will however assume a 5% systematic uncertainty independent of the $b'$ mass. The PDF systematic uncertainty should be similar in both the muon and electron channel.
Figure 5.8: Final-state gluon radiation effect on several efficiencies in the electron channel. Each efficiency is plotted for FSR on and FSR off. The line graph shows the half-percentage difference between the two cases. The bottom right plot shows the collective effect on the total efficiency.
Figure 5.9: Final-state gluon radiation effect on several efficiencies in the muon channel. Each efficiency is plotted for FSR on and FSR off. The line graph shows the half-percentage difference between the two cases. The bottom right plot shows the collective effect on the total efficiency.
5.4 $b$-tagging

The Silicon Vertex detector $b$-tagging efficiency is measured from the signal Monte Carlo. Since the Monte Carlo simulation is not perfect, the efficiency is corrected by a scale factor, $SF_{b\text{-tag}}$ that accounts for the difference in the $b$-tagging efficiency when the tagging algorithm is applied to data or Monte Carlo events. The correct value of the scale factor and its associated uncertainty have been a source of much controversy within CDF. In this analysis, we used the latest measurement of the scale factor which has recently been adopted by the collaboration. Its value per $b$-jet is $1.25 \pm 0.13$ [65, 66].

The uncertainty includes ±0.07 for statistical uncertainty from both the data and Monte Carlo, plus the systematic uncertainty from QCD. A systematic uncertainty of ±0.04 has been assigned to a potential $E_T$-dependence of the scale factor. Finally, a ±0.02 systematic uncertainty results from the uncertainty in the rate of gluon splitting in the HERWIG Monte Carlo used to calculate $SF_{b\text{-tag}}$. All these errors are added linearly resulting in a very conservative systematic uncertainty estimation of ±10%.

5.5 Total Systematic Uncertainty

The most important systematic uncertainties that affect the determination of the $b'$ acceptance were described in the previous sections. We show in Tables 5.2 and 5.3 the summary of our estimate for all systematic uncertainties. The uncertainty in the luminosity measurement has been recently reevaluated by the CDF collaboration [74]. The luminosity was measured using two telescopes of beam-beam counters to an accuracy of 4.1%. Other systematic uncertainties independent of the $b'$ mass originate from lepton identification, lepton isolation cut, primary vertex cut and the trigger efficiency. We assign a systematic uncertainty of 4% to the electron identification efficiency. The muon identification uncertainty of 5% includes the effect of the cosmic ray removal algorithm (3% uncertainty). The trigger efficiency uncertainty is particularly large in the muon channel due to the use of prescaled triggers and jet triggers. The systematic uncertainties due to the signal Monte
Carlo statistics are shown in Table 5.4. The uncertainties are larger for small \( b' \) masses due to the lower \( b \)-tag efficiency. The large Monte Carlo samples allowed us to make a better estimation of the gluon radiation and the jet-energy scale systematics.

The total systematic uncertainty on the \( b' \) acceptance times efficiency is given in Tables 5.2 and 5.3. The total uncertainty is larger for low mass \( b' \) quarks due mainly to the large uncertainty arising from the Monte Carlo modeling of the initial state radiation. The values change in the electron channel from 28.5% for \( m_{\psi} = 100 \text{ GeV}/c^2 \) to 19.2% for \( m_{\psi} = 210 \text{ GeV}/c^2 \) and in the muon channel from 27.4% to 19.2% for the same \( b' \) masses.

<table>
<thead>
<tr>
<th>( Z^0 \rightarrow e^+e^- ) channel</th>
<th>Systematic uncertainties [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\psi} ) [GeV/c^2]</td>
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</tr>
<tr>
<td>Luminosity</td>
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</tr>
<tr>
<td>Jet-energy scale</td>
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</tr>
<tr>
<td>Gluon radiation: ISR</td>
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</tr>
<tr>
<td>FSR</td>
<td>3</td>
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<tr>
<td>PDF</td>
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</tr>
<tr>
<td>Z-vertex</td>
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</tr>
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<td>Trigger</td>
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<tr>
<td>Lepton-id</td>
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</tr>
<tr>
<td>Isolation</td>
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</tr>
<tr>
<td>( b )-tag</td>
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<tr>
<td>MC statistics</td>
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</tr>
<tr>
<td>Total</td>
<td>28.5</td>
</tr>
</tbody>
</table>

Table 5.2: Summary of our estimate for all systematical uncertainties that affect the determination of the \( b' \) total acceptance in the electron channel.
Table 5.3: Summary of our estimate for all systematical uncertainties that affect the determination of the $b'$ total acceptance in the muon channel.

<table>
<thead>
<tr>
<th>$Z^0 \rightarrow \mu^+\mu^-$ channel</th>
<th>Systematic uncertainties [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m_{\nu}$ [GeV/$c^2$]</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4.1</td>
</tr>
<tr>
<td>Jet-energy scale</td>
<td>14</td>
</tr>
<tr>
<td>Gluon radiation: ISR</td>
<td>18</td>
</tr>
<tr>
<td>FSR</td>
<td>3</td>
</tr>
<tr>
<td>PDF</td>
<td>5</td>
</tr>
<tr>
<td>Z-vertex</td>
<td>2.4</td>
</tr>
<tr>
<td>Trigger</td>
<td>5</td>
</tr>
<tr>
<td>Lepton-id</td>
<td>5</td>
</tr>
<tr>
<td>Isolation</td>
<td>4</td>
</tr>
<tr>
<td>b-tag</td>
<td>10</td>
</tr>
<tr>
<td>MC statistics</td>
<td>2.8</td>
</tr>
<tr>
<td>Total</td>
<td>27.4</td>
</tr>
</tbody>
</table>

Table 5.4: Systematic uncertainty due to the signal Monte Carlo statistics for both the electron and muon samples.

<table>
<thead>
<tr>
<th>$m_{\nu}$ [GeV/$c^2$]</th>
<th>Monte Carlo statistical uncertainties [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before b-tag</td>
</tr>
<tr>
<td></td>
<td>$Z^0 \rightarrow e^+e^-$</td>
</tr>
<tr>
<td>100</td>
<td>0.99</td>
</tr>
<tr>
<td>110</td>
<td>0.92</td>
</tr>
<tr>
<td>120</td>
<td>0.79</td>
</tr>
<tr>
<td>130</td>
<td>0.85</td>
</tr>
<tr>
<td>140</td>
<td>0.78</td>
</tr>
<tr>
<td>150</td>
<td>0.77</td>
</tr>
<tr>
<td>160</td>
<td>0.78</td>
</tr>
<tr>
<td>170</td>
<td>0.79</td>
</tr>
<tr>
<td>180</td>
<td>0.79</td>
</tr>
<tr>
<td>190</td>
<td>0.79</td>
</tr>
<tr>
<td>200</td>
<td>0.82</td>
</tr>
<tr>
<td>210</td>
<td>0.81</td>
</tr>
</tbody>
</table>

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Chapter 6

Background

The pair production of $b'$ quarks and their subsequent decay into $bZ^0$ results in a very distinct signature: a lepton pair with an invariant mass close to $m_Z$, four jets and at least two $b$ quarks. The only non-negligible background to the $b' \rightarrow bZ$ process is from $Z^0$ production with associated QCD hadronic jets. An example of one such process is given in Figure 6.1.

Figure 6.1: Sample Feynman diagram for $Z^0$ production associated with 3 jets.

The signature of $Z^0 +$ multijets events is similar to the $b'$ signal under study. There are, however, two major differences. First, the background events usually have a very low content of heavy flavor as opposed to the two $b$ jets from the $b'$ quark decays. Second, the jets from $Z^0 +$ multijets events are usually less energetic than the ones in the $b'$ signal.
The selection criteria discussed in Chapter 3 were designed to reduce the background by exploiting these differences. Additionally, the $Z^0 + \text{multijets}$ processes are higher-order QCD processes and therefore their production cross section is small. After the $b$-tag requirement we expect a very small contribution from background. Thus, we assume that all detected events are signal and do not subtract background in the limit calculation. The background estimates described in this chapter are only used to understand event rates, the shape of kinematic distributions and establish the selection criteria.

This background is estimated using a combination of the VECBOS [70] and HERWIG Monte Carlo programs. We have made a Monte Carlo sample of inclusive $Z^0$ plus three or more jets generated with VECBOS + HERWIG and simulated with the fast CDF detector simulation program. VECBOS makes the calculation of the leading-order matrix elements for the $Z^0 + 3$ partons process. We use the MRSDO' parton distribution functions [52], and the QCD renormalization and factorization scales of $Q^2 = \langle p_T \rangle^2$, where $\langle p_T \rangle$ is the average $p_T$ of the generated partons. In addition, the $Z^0 + \text{partons}$ events are generated with following input parameters:

- **Outgoing partons:**
  - $p_T > 6 \text{ GeV/c}$
  - $|\eta| < 2.5$
  - $\Delta R > 0.4$ between partons

- **One lepton with:**
  - $p_T > 12 \text{ GeV}$
  - $|\eta| < 2.5$

After the VECBOS generation, a partial higher-order correction to the tree-level diagrams is obtained by including gluon radiation and hadronic fragmentation using the HERWIG shower simulation algorithm [68]. The $Z^0$ boson events with hadron showers are then introduced into QFL (v3.61) for the CDF detector response simulation, and the resulting jets are identified and selected the same way as in the data and signal Monte Carlo simulation.
We have generated about 37.5 million weighted events which after the unweighting procedure were reduced to approximately 82500 events; using the cross section reported by VECBOS, these correspond to a total luminosity of 4.36 fb\(^{-1}\). We use this luminosity to normalize the background Monte Carlo. It is well known that the VECBOS cross section has a very large uncertainty. However, we do not include the background estimations in the limit calculation and therefore the overall normalization is not of great importance.

We compare the \(Z^0 + \text{jets}\) background with the data distributions after imposing the following minimal 3-jet selection:

- 2 jets \(E_T > 15 \text{ GeV}, |\eta| < 2\)
- 3rd jet \(E_T > 7 \text{ GeV}, |\eta| < 2\)

Figure 6.2 and Figure 6.3 show the jet-\(E_T\) distributions from the background Monte Carlo and data in the electron and muon channels, respectively. The \(E_T\) distribution from the two most energetic jets is shown in the left histogram. The right histogram shows the \(E_T\) of the third jet in the event. Figure 6.4 and Figure 6.5 compare the jet multiplicity in the background and data after the 3-jet cut. There is very good agreement between data and background in all these distributions. The agreement is actually even good in the overall normalization. This is not surprising because other studies have shown that similar Monte Carlo samples, generated with the same \(Q^2 = \langle p_T \rangle^2\), agree well with the \(Z^0 \rightarrow e^+e^- + \text{jets}\) data from CDF [71].

As we have seen in Chapter 3, our event selection cuts depend on the \(b'\) mass being considered, and they were devised to reduce the background content in the final data samples. The number of background events, in the electron and muon channel, that survive each main selection criteria is given in Table 6.1 and Table 6.2, for the cuts corresponding to the different \(b'\) masses indicated. The background expectations, after the 3-jet and the \(\sum E_T^{\text{jets}}\) cuts, are compared to the number of events observed in the electron and muon data in Figure 6.6. The number of events decreases for more massive \(b'\) quarks because the \(\sum E_T^{\text{jets}}\) cut increases with the \(b'\) mass. The discontinuity from \(m_{b'} = 120 \text{ GeV}/c^2\) to

92
Figure 6.2: Comparison of the jet-$E_T$ distributions of background and data, in the electron channel. The left plot shows the distribution for the two most energetic jets, while the right plot shows the third most energetic jet in the event.

Figure 6.3: Comparison of the jet-$E_T$ distributions of background and data, in the muon channel. The left plot shows the distribution for the two most energetic jets, while the right plot shows the third most energetic jet in the event.
Figure 6.4: Comparison of the multiplicity distributions of the background Monte Carlo sample with electron data after the minimal 3-jet cut.

Figure 6.5: Comparison of the multiplicity distributions of the background Monte Carlo sample with muon data after the minimal 3-jet cut.
$m_{\nu} = 130$ GeV/$c^2$ is due to the different $E_T$ requirement on the third jet. The agreement between the background expectations and the data is very good.

<table>
<thead>
<tr>
<th>$m_{\nu}$ (GeV/$c^2$)</th>
<th>Background in the $Z^0 \rightarrow e^+e^-$ channel</th>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-jet</td>
<td>3-jet + $\sum E_T$</td>
</tr>
<tr>
<td>100</td>
<td>36.1 ± 0.7</td>
<td>1.09 ± 0.12</td>
</tr>
<tr>
<td>110</td>
<td>30.2 ± 0.6</td>
<td>0.94 ± 0.12</td>
</tr>
<tr>
<td>120</td>
<td>24.9 ± 0.6</td>
<td>0.81 ± 0.11</td>
</tr>
<tr>
<td>130</td>
<td>11.4 ± 0.4</td>
<td>0.44 ± 0.08</td>
</tr>
<tr>
<td>140</td>
<td>9.8 ± 0.4</td>
<td>0.38 ± 0.07</td>
</tr>
<tr>
<td>150</td>
<td>8.3 ± 0.3</td>
<td>0.33 ± 0.07</td>
</tr>
<tr>
<td>160</td>
<td>6.8 ± 0.3</td>
<td>0.27 ± 0.06</td>
</tr>
<tr>
<td>170</td>
<td>5.3 ± 0.3</td>
<td>0.21 ± 0.06</td>
</tr>
<tr>
<td>180</td>
<td>4.5 ± 0.2</td>
<td>0.18 ± 0.05</td>
</tr>
<tr>
<td>190</td>
<td>3.6 ± 0.2</td>
<td>0.14 ± 0.05</td>
</tr>
<tr>
<td>200</td>
<td>2.9 ± 0.2</td>
<td>0.12 ± 0.04</td>
</tr>
<tr>
<td>210</td>
<td>2.4 ± 0.2</td>
<td>0.09 ± 0.04</td>
</tr>
</tbody>
</table>

Table 6.1: Number of expected background events in the electron channel after each specified cut, normalized to the data luminosity; errors are statistical only.

Since VECBOS does not generate heavy flavor, we estimate the $b$-tag rate in $Z^0$ plus jet events directly from data using a technique developed for the top analysis\(^1\) [69]. In this method, we assume that the observed $b$-tag rate in an inclusive jet sample is the same as in the $Z^0$ + jets background, and apply the $b$-tag rates measured in the inclusive jet sample, parametrized by the event $\sum E_T^{jets}$ and the $E_T$ and track multiplicity of each jet, to the jets of the background events that pass all the other selection criteria. This technique overestimates the background because the inclusive jet sample contains heavy-quark contributions from direct production, gluon splitting and flavor excitation while heavy quarks in $Z^0$ + jets events are produced mainly from gluon splitting. The background expectations after the $b$-tag requirement are shown in Table 6.1 and Table 6.2. We expect approximately one background event per lepton channel for $m_{\nu} < 130$ GeV/$c^2$ and less than half event for

\(^1\)We estimate the $b$-tag rate directly from data using the $b$-tag background parametrization method (SEC.FAKE) [69] instead of the SECVTX algorithm.
Figure 6.6: Expected number of events from signal and background before the $b$-tag requirement compared to data as function of $b'$ mass. The errors are statistical only. Top: $Z^0 \rightarrow e^+e^-$ channel; Bottom: $Z^0 \rightarrow \mu^+\mu^-$ channel.
The background in the $Z^0 \to \mu^+\mu^-$ channel can be further divided into selection criteria.

### Table 6.2: Number of expected background events in the muon channel after each specified cut, normalized to the data luminosity; errors are statistical only.

<table>
<thead>
<tr>
<th>$m_\gamma$ [GeV/c$^2$]</th>
<th>3-jet</th>
<th>3-jet + $\sum E_T$</th>
<th>3-jet + $\sum E_T + b$-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>25.0 ± 0.6</td>
<td>1.01 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>21.2 ± 0.5</td>
<td>0.91 ± 0.11</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>17.6 ± 0.5</td>
<td>0.80 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>7.7 ± 0.3</td>
<td>0.40 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>6.9 ± 0.3</td>
<td>0.38 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>5.8 ± 0.3</td>
<td>0.32 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>4.8 ± 0.2</td>
<td>0.27 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>3.7 ± 0.2</td>
<td>0.21 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>2.9 ± 0.2</td>
<td>0.17 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>2.5 ± 0.2</td>
<td>0.15 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>2.1 ± 0.2</td>
<td>0.13 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>210</td>
<td>1.6 ± 0.2</td>
<td>0.10 ± 0.04</td>
<td></td>
</tr>
</tbody>
</table>

A final possible background is $W + $ jets events in which the $W$ decays into $e\nu$ and there is an extra fake electron. The invariant mass of both "electrons" can fall in the $Z^0$ mass window producing a false $Z^0$ event. This kind of event should have higher missing transverse energy, $E_T$, than a $Z^0$ event due to the presence of the neutrino. To check this contamination of our $Z^0 \to e^+e^-$ sample we plot the $E_T$ distribution for data and compared it with the $Z^0 +$ jets Monte Carlo in Figure 6.7. To use our Monte Carlo, we required the presence of at least three jets in the event: two jets with $E_T > 15$ GeV and the third with $E_T > 7$ GeV, with $|\eta| < 2$ for all the three jets. The Monte Carlo and data distributions are very similar, therefore we conclude that this background does not constitute a major contribution to our data sample.
Figure 6.7: Comparison of the missing $E_T$ in data and in our $Z^0 +$ jets background.
Chapter 7

Search Results

The major goal of every search analysis is to find a signal of new physics. However, more often than not, it is found that the data are consistent with the Standard Model expectations and do not support the new physics hypothesis being considered. Unfortunately, this analysis is not an exception to this rule.

In this chapter, we will start by comparing the number of events observed in our data sample with the $b'$ signal expectations. Given that the $b'$ quark hypothesis is not confirmed, we will calculate an upper limit on $\sigma_{pp \rightarrow b'b'} \times [BR (b' \rightarrow bZ^0)]^2$. Making reasonable assumptions for $BR (b' \rightarrow bZ^0)$, a lower limit on $b'$ mass is derived. The limit is obtained using a Bayesian calculation and checked against frequentist methods. In both cases we take in consideration the correlation between the acceptance uncertainties of the muon and electron channels. We finish with a short discussion of the final results.

7.1 Signal Estimation

For each leptonic channel studied, the expected number of signal events for a given $b'$ mass is calculated using the equation

$$N_{\nu\bar{\nu}}^{\text{exp}}(m_\nu) = \sigma_{pp \rightarrow \nu\bar{\nu}}(m_\nu) \times [BR (b' \rightarrow bZ^0)]^2 \times F [BR (Z^0)] \times (A \cdot \epsilon) \times \int L dt,$$

(7.1)

where the theoretical $b'$ pair-production cross section $\sigma_{pp \rightarrow \nu\bar{\nu}}(m_\nu)$ at a certain $b'$ mass is equal to the top cross section $\sigma_{pp \rightarrow t\bar{t}}(m_t)$ at the same mass, $m_t = m_\nu$. Also, $(A \cdot \epsilon)$ is
the total acceptance times efficiency from Table 7.1, ∫ L dt is the integrated luminosity, and
\( \mathcal{F}[BR(Z^0)] \) is a function of the \( Z^0 \) branching ratio,

\[
\mathcal{F}[BR(Z^0)] = 2 \times BR(Z^0 \rightarrow \text{anything}) \times BR(Z^0 \rightarrow l^+l^-) = 6.73\% \quad (7.2)
\]

In this equation, the factor of two accounts for the presence of two \( Z^0 \) bosons in the final state, doubling the probability that one will decay into electrons or muons.

<table>
<thead>
<tr>
<th>( m_Y ) (GeV/c^2)</th>
<th>( (A \cdot \epsilon) )</th>
<th>( (A \cdot \epsilon) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z^0 \rightarrow e^+e^- )</td>
<td>( Z^0 \rightarrow \mu^+\mu^- )</td>
<td>( Z^0 \rightarrow e^+e^- )</td>
</tr>
<tr>
<td>100</td>
<td>1.65</td>
<td>1.59</td>
</tr>
<tr>
<td>110</td>
<td>4.62</td>
<td>4.21</td>
</tr>
<tr>
<td>120</td>
<td>7.62</td>
<td>6.37</td>
</tr>
<tr>
<td>130</td>
<td>8.22</td>
<td>6.76</td>
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<tr>
<td>140</td>
<td>9.91</td>
<td>8.27</td>
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<td>9.20</td>
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<td>160</td>
<td>11.7</td>
<td>9.77</td>
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<tr>
<td>170</td>
<td>12.2</td>
<td>10.3</td>
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<tr>
<td>180</td>
<td>13.0</td>
<td>10.4</td>
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<tr>
<td>190</td>
<td>13.0</td>
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<tr>
<td>200</td>
<td>13.0</td>
<td>11.0</td>
</tr>
<tr>
<td>210</td>
<td>13.5</td>
<td>11.4</td>
</tr>
</tbody>
</table>

Table 7.1: Final acceptance times efficiency in the electron and muon channels as a function of the \( b' \) mass. These numbers are reproduced from Table 4.12 and Table 4.13.

The number of expected signal events after the main selection requirements is given in Tables 7.2 and 7.3 for the electron and muon channels respectively. After all the selection criteria, the number of \( b' \) events that we expect to observe in the electron channel, within the \( b' \) mass range studied, varies from 17.5 ± 0.3 to 1.34 ± 0.02. In the muon channel, we expect a range of 15.3 ± 0.3 to 1.15 ± 0.02 signal events depending on the \( b' \) mass. The decrease of the \( b' \) signal expectations as a function of the \( b' \) mass is due to the decrease of the \( b' \) pair-production cross section \( \sigma_{pp \rightarrow b'b'}(m_Y) \).

The signal expectations are shown in Figure 7.1 together with the events observed in the \( Z^0 \) data sample given in Table 3.4. After the 6-tag requirement, we do not observe
Expected signal events ($Z^0 \rightarrow e^+e^-$ channel) after each main selection requirements.

<table>
<thead>
<tr>
<th>$m_\nu$ [GeV/c$^2$]</th>
<th>Selection cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-jet</td>
</tr>
<tr>
<td>100</td>
<td>63.0 ± 0.6</td>
</tr>
<tr>
<td>110</td>
<td>64.6 ± 0.6</td>
</tr>
<tr>
<td>120</td>
<td>54.0 ± 0.4</td>
</tr>
<tr>
<td>130</td>
<td>28.4 ± 0.2</td>
</tr>
<tr>
<td>140</td>
<td>22.3 ± 0.2</td>
</tr>
<tr>
<td>150</td>
<td>16.8 ± 0.1</td>
</tr>
<tr>
<td>160</td>
<td>12.6 ± 0.2</td>
</tr>
<tr>
<td>170</td>
<td>9.28 ± 0.07</td>
</tr>
<tr>
<td>180</td>
<td>7.06 ± 0.05</td>
</tr>
<tr>
<td>190</td>
<td>5.26 ± 0.04</td>
</tr>
<tr>
<td>200</td>
<td>3.91 ± 0.03</td>
</tr>
<tr>
<td>210</td>
<td>3.00 ± 0.02</td>
</tr>
</tbody>
</table>

Table 7.2: Expected number of signal events in the electron channel after each main selection requirements. The 3-jet requirement is different for $m_\nu \leq 120$ GeV/c$^2$ and $m_\nu > 120$ GeV/c$^2$ and the $\sum E_T^{jets}$ cut scales with the $b'$ mass. The errors are statistical only.
<table>
<thead>
<tr>
<th>$m_{\mu}$ [GeV/c²]</th>
<th>Expected signal events ($Z^0 \rightarrow \mu^+\mu^-$ channel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Selection cuts</td>
</tr>
<tr>
<td></td>
<td>3-jet</td>
</tr>
<tr>
<td>100</td>
<td>54.3 ± 0.6</td>
</tr>
<tr>
<td>110</td>
<td>51.3 ± 0.5</td>
</tr>
<tr>
<td>120</td>
<td>41.7 ± 0.3</td>
</tr>
<tr>
<td>130</td>
<td>22.2 ± 0.2</td>
</tr>
<tr>
<td>140</td>
<td>17.5 ± 0.1</td>
</tr>
<tr>
<td>150</td>
<td>13.4 ± 0.1</td>
</tr>
<tr>
<td>160</td>
<td>9.92 ± 0.08</td>
</tr>
<tr>
<td>170</td>
<td>7.30 ± 0.06</td>
</tr>
<tr>
<td>180</td>
<td>5.48 ± 0.04</td>
</tr>
<tr>
<td>190</td>
<td>4.11 ± 0.03</td>
</tr>
<tr>
<td>200</td>
<td>3.13 ± 0.02</td>
</tr>
<tr>
<td>210</td>
<td>2.44 ± 0.02</td>
</tr>
</tbody>
</table>

Table 7.3: Expected number of signal events in the muon channel after each main selection requirements. The 3-jet requirement is different for $m_{\mu} \leq 120$ GeV/c² and $m_{\mu} > 120$ GeV/c² and the $\sum E_T^{jets}$ cut scales with the $b'$ mass. The errors are statistical only.
any candidate events in the electron channel. In the muon channel, there is one candidate event that passes our cuts for $b'$ masses below 130 GeV/$c^2$. The event has a third jet with $E_T = 8.3$ GeV which fails the jet-$E_T$ requirement of $E_T > 15$ GeV for $m_\ell > 130$ GeV. Therefore, we do not observe any events for the cuts corresponding to $m_\ell > 130$ GeV. Also shown in Figure 7.1 is the $Z^0 + \text{jets}$ background estimations from Table 6.1 and Table 6.2. We expect from both lepton channels approximately two background events for $m_\ell \leq 120$ GeV/$c^2$ and less than one event for $m_\ell > 120$ GeV/$c^2$, in agreement with the number of events observed in the data. Since the data are consistent with the Standard Model background and not with the $b'$ quark signal that we were searching for, we proceed to calculate an upper limit on the $b'$ pair-production cross section times branching ratio.

## 7.2 Limit Calculation

Since the number of observed events is small, they are distributed according to Poisson statistics. In a given channel, the probability of observing a certain number of events $n_0$ when $\mu$ are expected is given by

$$P(n_0; \mu) = \frac{e^{-\mu} \mu^{n_0}}{n_0!}. \quad (7.3)$$

In our analysis we treat all observed events as candidate events and do not subtract background. In this case, the total number of expected events is the same as the number of events from the signal, $\mu = N_{b'b}^{\text{exp}}$. To simplify the equations that follow, we redefine $\epsilon$ as the product between the total acceptance times efficiency and the leptonic branching ratio of the $Z^0$, $\epsilon = 2(A \cdot \epsilon)BR(Z^0 \rightarrow l^+l^-)$. We also define the total number of $b'$ events produced which decay into the $b\bar{b}Z^0Z^0$ channel as $N_{b'b}^{ZZ} = \mathcal{L}\sigma_{b'b}BR(b' \rightarrow bZ^0)^2$. This way, we can write,

$$\mu = N_{b'b}^{\text{exp}} = \epsilon N_{b'b}^{ZZ}. \quad (7.4)$$

In order to incorporate the systematic uncertainties on the acceptance into the upper limit estimation, the Poisson distribution is convoluted with the acceptance probability.
Figure 7.1: Expected number of events as function of $b'$ mass after all selection criteria. Also shown are the data and the expected background. The errors are statistical only. Top: Electron channel; Bottom: Muon channel.
distribution, which is assumed to be a Gaussian with mean $\epsilon$ and width $\sigma_\epsilon$. Thus, the probability distribution function (pdf) for the number of observed events is given by

$$
\hat{P}(n_0; eN_{\gamma^*}) = \int_0^\infty P(n_0; e'N_{\gamma^*}) \otimes G(e'; \epsilon, \sigma_\epsilon) \, de'.
$$

(7.5)

If we make two independent measurements of the same quantity, i.e. using the electron and muon channels, the joint likelihood of observing $n_1$ followed by $n_2$ events is

$$
\mathcal{L} = \hat{P}(n_1, e_1; eN_{\gamma^*}) \hat{P}(n_2; e_2N_{\gamma^*}).
$$

(7.6)

In this case, the correlation between the systematic uncertainties of the two measurements needs to be taken into account. We assume that the uncertainty in the acceptance can be decomposed into two parts, a fully correlated uncertainty $\sigma_{\epsilon e}$ and totally uncorrelated uncertainty $\sigma_{\epsilon u}$:

$$
G(e_1'; e_1, \sigma_{\epsilon e}) = G(e_1^c; e_1^c, \sigma_{\epsilon e}^c) \cdot G(e_1^u; e_1^u, \sigma_{\epsilon u}^c).
$$

(7.7)

For the purpose of the limit calculation we consider that the following uncertainties are fully correlated between the two lepton channels:

- Luminosity
- Jet energy scale
- Gluon radiation
- Parton distribution function
- $z_{\text{vertex}}$ efficiency
- Isolation efficiency
- $b$-tag efficiency

while the following uncertainties are considered totally uncorrelated,

- Trigger efficiency

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• Lepton identification

• Monte Carlo statistics

From the systematic uncertainties in Tables 5.2 and 5.3 we obtain the correlated and uncorrelated uncertainty values shown in Table 7.4.

<table>
<thead>
<tr>
<th>$m_{\psi}$ (GeV/c²)</th>
<th>correlated $(\delta \sigma_{e\bar{e}})$[%]</th>
<th>uncorrelated $(\delta \sigma_{e\bar{e}})$[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Z^0 \rightarrow e^+e^-$</td>
<td>$Z^0 \rightarrow \mu^+\mu^-$</td>
</tr>
<tr>
<td>100</td>
<td>28.1</td>
<td>26.3</td>
</tr>
<tr>
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<tr>
<td>200</td>
<td>18.6</td>
<td>18.0</td>
</tr>
<tr>
<td>210</td>
<td>18.6</td>
<td>18.0</td>
</tr>
</tbody>
</table>

Table 7.4: Correlated and uncorrelated systematic uncertainties in both lepton channels as a function of $b'$ mass.

7.2.1 Combined Limit - Bayesian Approach

The application of Bayesian methods to the determination of confidence level limits has been extensively described in the literature [75, 76]. Here, we extend the method to the calculation of combined limits. In this method, we consider the same likelihood function as in Equation 7.6, which includes the proper treatment of the systematic uncertainties correlations:

$$L(f) = \int_0^\infty \int_0^\infty d\epsilon_{e} d\epsilon_{\mu} P(n_{e}; \epsilon_{e}, f) \otimes G(\epsilon_{e}', \epsilon_{e}, \sigma_{ee}) P(n_{\mu}; \epsilon_{\mu}, f) \otimes G(\epsilon_{\mu}', \epsilon_{\mu}, \sigma_{\epsilon\mu}) \quad (7.8)$$

To simplify the notation, we define $N_{\psi\bar{\psi}} \equiv f$. The quantity $f$ must be common to both channels and represents the physical quantity that is to be measured. In our case, we can...
take $f$ as the number of $b'$ events produced and decaying in the $b\bar{b}Z^0Z^0$ channel$^1$. The luminosity will be factored out to obtain the 95% C.L. limit on $\sigma_{pp\to \nu\bar{\nu}} \times BR(b' \to bZ^0)^2$.

Using Bayes's theorem, we can write the posterior probability distribution function for $f$ as

$$\mathcal{P}(f|n_e,n_\mu) = \frac{\mathcal{L}(f)\mathcal{P}(f)}{\int_0^{\infty} \mathcal{L}(f')\mathcal{P}(f')df'}$$

(7.9)

where $\mathcal{P}(f)$ is the prior probability distribution function. The 95% confidence level limit $f_{95\%}$ is obtained by integrating the posterior pdf between 0 and the $f = f_{95\%}$ value that satisfies the equation,

$$0.95 = \int_0^{f_{95\%}} \mathcal{P}(f'|n_e,n_\mu)df'.$$

(7.10)

Considering an uniform prior pdf for $f$, $\mathcal{P}(f) = 1$ for $f \geq 0$ and $\mathcal{P}(f) = 0$ for $f < 0$, we have

$$0.95 = \frac{\int_0^{f_{95\%}} \mathcal{L}(f'\mu)n_e,n_\mu df'}{\int_0^{\infty} \mathcal{L}(f')df'}$$

(7.11)

The combined 95% C.L. upper limit on $\sigma_{pp\to \nu\bar{\nu}} \times [BR(b' \to bZ^0)]^2$ is then given by

$$\left(\sigma_{pp\to \nu\bar{\nu}} \times BR(b' \to bZ^0)\right)_{95\%C.L} = \frac{N_{\nu\bar{\nu}}^{ZZ,95\%}}{\int \mathcal{L}dt}$$

(7.12)

where $N_{\nu\bar{\nu}}^{ZZ,95\%} = f_{95\%}$ is the limit on the number of signal events determined by Bayesian method above. The limit on $\sigma_{pp\to \nu\bar{\nu}} \times [BR(b' \to bZ^0)]^2$ is shown in Table 7.5 and Figure 7.2, together with the theoretical prediction, as a function of the $b'$ mass. Since the $b'$ production cross section for a given mass should be similar to the top quark cross section at the same mass, the theoretical curve is the next-to-leading-order (NLO) calculation of the top pair-production cross section [77]. In addition, the theoretical prediction assumes that $b'$ decays 100% of the time into $bZ^0$. The limit on $\sigma_{pp\to \nu\bar{\nu}} \times [BR(b' \to bZ^0)]^2$ is the main result of this thesis.

One should recall that this limit was obtained without subtraction of background, i.e. the event observed in the muon channel for $m_\nu \leq 120$ GeV/c$^2$ is considered a candidate

---

$^1$In a more general treatment, where the branching ratios into each channel are different, the branching ratios should be combined together with the acceptance for each specific channel. In that case, $f$ would be taken as the actual production cross section.
signal event. This fact produces a somewhat higher limit in that $b'$ mass range and explains the bump observed in the $\sigma_{pp \rightarrow b'b\bar{b}} \times BR(b' \rightarrow bZ^0)^2$ limit plot.

Using this NLO cross section calculation and assuming that $BR(b' \rightarrow bZ^0) = 100\%$, we can convert the 95% upper limit on the $\sigma_{pp \rightarrow b'b\bar{b}} \times [BR(b' \rightarrow bZ^0)]^2$ into a $b'$ mass exclusion limit. We exclude the existence of a $b'$ quark with a mass between 100 and 199 GeV/c$^2$.

<table>
<thead>
<tr>
<th>$M_{b'}$ (GeV/c$^2$)</th>
<th>$\sigma_{pp \rightarrow b'b\bar{b}} \times BR(b'b\bar{b} \rightarrow bZbZ)$ (pb)</th>
<th>$\beta(b' \rightarrow bZ) = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>37.4</td>
<td>102.</td>
</tr>
<tr>
<td>110</td>
<td>10.6</td>
<td>61.6</td>
</tr>
<tr>
<td>120</td>
<td>6.51</td>
<td>38.9</td>
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<tr>
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<td>3.76</td>
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<td>5.83</td>
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<td>180</td>
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<td>2.26</td>
</tr>
<tr>
<td>210</td>
<td>2.26</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Table 7.5: The combined 95% CL upper limit on $\sigma_{pp \rightarrow b'b\bar{b}} \times BR(b'b\bar{b} \rightarrow bZbZ)$ obtained using both the high-$p_T$ electron and muon data. This is the main result of this thesis.

In Figure 7.3, we present the 95% CL upper limit on the $b' \rightarrow bZ^0$ branching ratio. The curve is obtained from the 95% CL limit on the $\sigma_{pp \rightarrow b'b\bar{b}} \times [BR(b' \rightarrow bZ^0)]^2$ and assuming the theoretical NLO pair-production cross section from Ref. [77]. The branching ratio limit excludes a $b'$ quark that decays into $bZ^0$ with a branching ratio larger than the 95% upper limit independently of the existence of other decay modes. This statement is actually conservative because the search is also sensitive to other $b'$ decay channels such as $b' \rightarrow bH$ or $b' \rightarrow cW^-$ as long $BR(b' \rightarrow bZ)$ is not negligible, since the hadronic decays of the $H$ or $W$ are kinematically similar to those of the $Z$. The most interesting case is the
decay $b' \rightarrow bH$ where the Higgs is light. As long as the $BR(b' \rightarrow bZ^0)$ is not negligible this signal should be covered by our search for most of the parameter space because such a Higgs boson would decay predominately into $b\bar{b}$. However, if we conservatively assume no sensitivity to these decay modes, the excluded mass range can be obtained directly from Figure 7.3. For instance, for $BR(b' \rightarrow bZ) \geq 50\%$, we exclude a $b'$ mass from 104 GeV to 152 GeV. A more detailed account of this issue is given in Section 7.4.

![Figure 7.2: The 95% confidence level upper limit on $pp \rightarrow b'b'b'X$ production cross section times the $b' \rightarrow bZ^0$ branching ratio squared (solid). The dashed curve shows the predicted $\sigma_{pp \rightarrow b'b'} \times [BR(b' \rightarrow bZ^0)]^2$ with the NLO production cross section from Ref. [77] and $BR(b' \rightarrow bZ^0) = 1.$](image)

### 7.3 Verification with Frequentist Methods

There is some disagreement about the preferred method for calculating upper limits: Bayesian or frequentist. In this section, we check the $b'$ limit, obtained above with the Bayesian calculation, using a frequentist approach.

In this approach, the upper limit at a confidence level $\alpha$ is defined such that, if
Figure 7.3: The 95% CL upper limit on the $b' \rightarrow bZ^0$ branching ratio obtained assuming the pair production cross section from Ref. [77] and using the Bayesian approach described in the text.

If an experiment is repeated a very large number of times, the fraction of experiments that observe a value equal or smaller than the measured value is less than $1 - \alpha$, if the real value of the quantity being measured is above the upper limit.

We consider the same joint likelihood as in the Bayesian method, Equation 7.6. This likelihood can be evaluated using Monte Carlo techniques. We have used an improved version of the POISSON program [78] to perform the calculation. In this version we have implemented the algorithm explained below to account for correlated uncertainties with different magnitude for each channel, and have also increased the precision of the calculation.

The Monte Carlo calculation throws a large number of pseudo-experiments for a given rate of events $N^{ZZ}_{b'b'} = N_0$. In each pseudo-experiment, the acceptance in each channel, $i$, is drawn from two Gaussian distributions as shown in Equation 7.7. To calculate the correlated part of the uncertainty for each pseudo-experiment we start by drawing one random number from a Gaussian of zero mean and unit width. This number is then multiplied by the relative correlated systematic uncertainty $\delta \sigma_{b'}$ corresponding to each channel,
\( \delta'_{\xi} = 1 + \delta \sigma_{\xi} \cdot G(0; 1) \). In this way we create two random numbers that are drawn from Gaussians of different widths but are totally correlated. The uncorrelated fraction of the uncertainty is drawn from different Gaussian distributions for each channel, \( \delta'_{\xi} = G(1; \delta \sigma_{\xi}) \). The acceptance \( \epsilon'_{i} \) for each pseudo-experiment is then obtained from \( \epsilon'_{i} = \epsilon_{i} \cdot \delta_{\xi} \cdot \delta_{\xi'} \) where \( \epsilon_{i} \) is the acceptance mean value for channel \( i \).

### 7.3.1 Frequentist Method - Total Rate

The mean number of expected observed events for each channel \( \mu_{i} \) is determined from the above acceptance. The number of observed events for each pseudo-experiment \( n'_{i} \) is drawn from a Poisson distribution with mean \( \mu_{i} \). We use the total rate of events from both channels to set the 95% CL limit\(^{2} \). Therefore, we compare the sum of \( n'_{i} \) from both channels \( n' = n'_{1} + n'_{2} \), with the total number of events observed in the data (zero or one depending on the \( b' \) mass). By performing a large number of pseudo-experiments using this procedure, we determine the fraction of pseudo-experiments that have \( n' \) less or equal to the number observed in the data for a given value of \( N_{\nu'\nu}^{ZZ} \). The 95% CL upper limit corresponds to the \( N_{\nu'\nu}^{ZZ} \) rate for which this fraction is smaller or equal to 0.05.

The combined 95% C.L. upper limit on \( \sigma_{pp\to\nu'\nu} \times [BR(\nu' \to bZ^{0})]^{2} \) is again given by

\[
\left( \sigma_{pp\to\nu'\nu} \times [BR(\nu' \to bZ^{0})]^{2} \right)_{95\% C.L.} = \frac{N_{\nu'\nu}^{ZZ,95\%}}{L dt}^{2}
\]  

(7.13)

The limit on the \( \sigma_{pp\to\nu'\nu} \times [BR(\nu' \to bZ^{0})]^{2} \) obtained by the frequentist approach is shown on the left plot of Figure 7.5. In the right plot of the same figure, we present the 95% CL upper limit on the \( BR(\nu' \to bZ^{0}) \).

The limit obtained by this method is compared to the Bayesian limit in Table 7.5 and Figure 7.4 for several values of \( b' \) mass. The results from both methods are very consistent, but as expected the Bayesian method yields a more conservative limit. The largest difference between the two methods is observed for \( m_{\nu} = 100 \text{ GeV/c}^{2} \) because the systematic uncertainty is considerably larger for this particular mass (Table 7.4).

\(^{2}\)The method presented here corresponds to method 4 of Ref. [78].
Figure 7.4: Comparison of the 95% CL upper limit on $\sigma \cdot BR(b' \rightarrow bZ^0)^2$ obtained using the Frequentist and Bayesian approaches. The theoretical curve assumes $BR(b' \rightarrow bZ^0) = 100\%$. 

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Figure 7.5: Left: 95% CL upper limit on $\sigma \cdot BR(b' \to bZ^0)^2$ obtained using the Frequentist approach applied to the total rate of events. The theoretical curve assumes $BR(b' \to bZ^0) = 100\%$. Right: 95% CL upper limit on the $b' \to bZ^0$ branching ratio obtained assuming the theoretical cross section from [77].

From the frequentist total-rate analysis, we can exclude the existence of a $b'$ quark with a mass between 100 and 200 GeV/$c^2$. Remember that, the Bayesian method yields a slightly weaker excluded mass range, $100 \leq m_{b'} \leq 199$ GeV/$c^2$.

7.3.2 Frequentist Method - Unique Measurements

An alternative frequentist method of calculating the limit using the information from multiple channels is to consider the measurements as unique, ignoring the total rate of observed events [78].

The method is very similar to the previous one. The measurements are assumed to be distinguishable, as above, but the limit is calculated using the probability of the outcome considering the individual observations from each channel instead of using the total rate of observed events. We use the likelihood function in Equation 7.6 and in the Monte Carlo pseudo-experiment ask for the fraction of the pseudo-experiments that would observe $n_1$. 

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events in channel 1 and $n_2$ events in channel 2. This method will potentially give different upper limits if the data set is arbitrarily divided into separate measurements [78].

As an exercise, we have applied this method in our analysis and obtain a somewhat different 95% C.L. upper limit on $\sigma_{p\bar{p} \to b' \bar{b}' z^0} \times BR(b' \to b z^0)^2$. The result is compared with the two previous methods in Table 7.6. Figure 7.6 compares this method with the frequentist method that uses the total rate of events. We observe that for the $b'$ masses where we have one candidate event, the total rate method is considerably more conservative than the unique-measurements method described in this section. The candidate event seems to have a very small effect on the upper limit when the outcome of the pseudo-experiments are considered individually and the information about the total rate is ignored.

<table>
<thead>
<tr>
<th>$M_{b'}$ (GeV/c^2)</th>
<th>$\sigma_{p\bar{p} \to b' \bar{b}' z^0} \times BR(b' \to b z^0)^2$ (pb)</th>
<th>95% CL</th>
<th></th>
<th>Theory $\beta(b' \to b z) = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
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<td>2.10</td>
<td>2.16</td>
<td>2.26</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Table 7.6: Upper limit on $\sigma_{p\bar{p} \to b' \bar{b}' z^0} \times BR(b' \to b z^0)^2$ at 95% C.L. obtained using both the high-$p_T$ electron and muon data. The calculation was performed using the three methods described in the text. Column one shows the limit obtained with the frequentist method assuming unique measurements, column two shows the frequentist limit using the total rate of events. The Bayesian upper limit is given in column three.

Following the same procedure as before we can derive $b'$ mass exclusion regions. Assuming $BR(b' \to b z^0) = 100\%$, we exclude a $b'$ mass from 100 to 201 GeV/c^2. For
$BR(b' \rightarrow bZ) \geq 50\%$, the exclusion region is reduced to $100 \leq m_{b'} \leq 155 \text{GeV}/c^2$. It is interesting to note that the mass lower limit is nearly independent of the method used to calculate the limit, varying only by 2 GeV/c$^2$. This happens because there are no observed events for high $b'$ masses. We conclude that the method described in this section is the least conservative of the methods studied. In particular, it seems to be too "optimistic" when applied to searches that yield a non-zero number of observed events.

We choose the Bayesian method to present the final result of this analysis, because it is a robust technique and it yields the most conservative result. It is important to notice, however, that the $b'$ mass excluded region depends weakly on the method used to calculate the limit.

![Graph](image-url)

Figure 7.6: Comparison of the 95% CL upper limit on $\sigma \cdot BR(b' \rightarrow bZ)^2$ obtained using the two different frequentist methods. The Frequentist(1) curve corresponds to the method where the total rate of observed events is not taken into consideration. The Frequentist(2) curve shows the upper limit with the total rate method described in Section 7.3. The theoretical curve assumes $BR(b' \rightarrow bZ^0) = 100\%$.

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Figure 7.7: Left: 95% CL upper limit on $\sigma \cdot BR(b' \rightarrow bZ^0)^2$ obtained using the Frequentist approach applied to the individual rate of events. The theoretical curve assumes $BR(b' \rightarrow bZ^0) = 100%$. Right: 95% CL upper limit on the $b' \rightarrow bZ^0$ branching ratio obtained assuming the theoretical cross section from reference [77].

7.4 Final Considerations

7.4.1 The Light Higgs Possibility

If a light Higgs boson, i.e. $m_H < 150$ GeV/$c^2$, exists, the branching ratio for $b' \rightarrow bH$ might not be negligible, depending on the $b'$ mass. In this case, the assumption of $BR(b' \rightarrow bZ^0) = 100\%$ used to establish a lower limit on the $b'$ mass would not be valid. On the other hand, the limit on $\sigma_{pp \rightarrow b'b} \times [BR (b' \rightarrow bZ^0)]^2$ calculated above would actually be improved. In this section, we will give some preliminary indication of the sensitivity of our results to the existence of such Higgs boson.

The branching ratio of the $b' \rightarrow bH$ decay has been calculated as a function of the $b'$ mass [16]. It was shown that $BR (b' \rightarrow bH)$ depends strongly on the CKM mixing angles and the Higgs, top, $b'$ and $t'$ masses. Fortunately, the branching ratio calculation was performed for $m_t = 175$ GeV/$c^2$ and, in addition, the ratio $r = BR (b' \rightarrow bH)/BR (b' \rightarrow bZ^0)$ is independent of the CKM mixing angles and mostly independent of the $t'$ mass. The ratio $r$ can have a wide range of values depending on the Higgs and $b'$ masses, but unfortunately
the $b' \rightarrow bH$ branching ratio was determined only for four values of Higgs mass, $m_H = 20, m_Z, 150$ and $200 \text{ GeV}/c^2$. For $m_H < m_Z$, the Higgs decay mode will dominate. Due to phase space suppression, for Higgs masses above the $Z^0$ mass, the $b' \rightarrow bZ^0$ decay dominates up to a specific $b'$ mass above which $b' \rightarrow bH$ prevails. In the special case that $m_H = m_Z$, the branching ratios from both channel are similar up to $m_{b'} \approx 140 \text{ GeV}/c^2$.

The latest results from LEP II have established a preliminary lower limit on the Higgs mass of $105.6 \text{ GeV}/c^2$ at 95% confidence level [79]. Taking this experimental bound on the Higgs mass and interpolating the values given in Ref. [16], we find that the $b' \rightarrow bZ^0$ decay mode should dominate $b' \rightarrow bH$ for $b'$ masses up to $160-170 \text{ GeV}/c^2$. Since we have found at 95% C.L. that $BR(b' \rightarrow bZ^0) < 50\%$ for $104 \text{ GeV} < M_{b'} < 152 \text{ GeV}$, we can conclude that a $b'$ quark decaying by FCNC is excluded in that mass range independently of the existence of a Higgs boson.

If a Higgs boson exists and it has a mass below $\sim 130-140 \text{ GeV}/c^2$, it will predominately decay into $b\bar{b}$. For heavier Higgs masses, the dominant decay will be $H \rightarrow W^+W^-$ or $H \rightarrow WW$. All these decay modes produce jets in the final state. So, as long the $BR(b' \rightarrow bZ^0)$ is not negligible, our search should be sensitive to the process $b'\overline{b} \rightarrow b\overline{b}Z^0H$.

To demonstrate this, we have studied our acceptance to the process $b'\overline{b} \rightarrow b\overline{b}Z^0H$. We have made Monte Carlo samples for three different values of the Higgs mass, $m_H = 100, 125$ and $150 \text{ GeV}/c^2$, and different values of $b'$ masses. The acceptance times efficiency, $(A \cdot \epsilon)_{ZH}$ for this mode were calculated using the same procedure as described in Chapter 4. Table 7.7 shows the ratio $(A \cdot \epsilon)_{ZH}/(A \cdot \epsilon)_{ZZ}$ where $(A \cdot \epsilon)_{ZH}$ is the total acceptance times efficiency for the $b'\overline{b} \rightarrow b\overline{b}Z^0Z^0$ process given in Table 7.1. The ratio was calculated only in the muon channel because it is not expected to be different in the electron channel. To obtain the final relative search sensitivity between the $Z^0H$ and $Z^0Z^0$ channels, the numbers in Table 7.7 have to be divided by a factor of two to account for the fact that the $Z^0H$ decay mode only has one $Z^0$ in the final state.

Eventually, knowing these acceptance for the $Z^0H$ decay mode, one could determine confidence level limits for different Higgs masses. Unfortunately, this is not possible
due to the lack of theoretical information on the ratio $r = BR(b' \rightarrow bH) / BR(b' \rightarrow bZ^0)$.

However, to get some feeling for how this light Higgs would affect the cross section times branching ratio and the $b'$ mass limits, we can perform the exercise shown in Figure 7.8. We calculate the 95% C.L. limit on the $\sigma_{pp \rightarrow b'b} \times [BR(b' \rightarrow bZ^0)]^2$, assuming that $BR(b' \rightarrow bH) = BR(b' \rightarrow bZ^0) = 0.5$, i.e. $r = 1$, independent of the $b'$ mass. If one would neglect the $Z^0H$ acceptance, the limit would be the conservative result, shown in the left plot of Figure 7.8, that we had already obtained in the previous section. On the other hand, if we assume the acceptance in the $Z^0H$ channel to be 1.4 times the acceptance in the $Z^0Z^0$ channel (a reasonable number for a low-mass Higgs), we get the plot on the right of Figure 7.8. The theoretical expectation for the $pp \rightarrow b'bX$ production cross section times the $b' \rightarrow bZ^0$ branching ratio squared is 25% the value for $BR(b' \rightarrow bZ^0) = 1$. However, the 95% confidence level upper limit on $\sigma_{pp \rightarrow b'b} \times [BR(b' \rightarrow bZ^0)]^2$ was improved due to the acceptance in the $Z^0H$ channel. In this case, we would be able to exclude a $b'$ quark with

<table>
<thead>
<tr>
<th>$m_{b'}$ (GeV/c²)</th>
<th>Ratio of $(A \cdot \epsilon)<em>{ZH}$ to $(A \cdot \epsilon)</em>{ZZ}$</th>
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Table 7.7: Ratio of the final acceptance times efficiency for $b'b \rightarrow b\bar{b}Z^0H$ process to the one for $b'b \rightarrow b\bar{b}Z^0Z^0$, in the $Z^0 \rightarrow \mu^+\mu^-$ channel. The $Z^0$ leptonic branching ratio function, $F[BR(Z^0)]$ is not included. The dashes indicate $m_{b'}$ and $m_H$ combinations for which the decay $b' \rightarrow bH$ is kinematically forbidden.
a mass between 100 GeV/$c^2$ and 170 GeV/$c^2$, assuming that the quark would decay 100% of the time by FCNC.

![Graph](image)

Figure 7.8: The 95% confidence level upper limit on $p\bar{p} \rightarrow b'\bar{b}X$ production cross section times the $b' \rightarrow bZ^0$ branching ratio squared assuming that $BR(b' \rightarrow bH) = BR(b' \rightarrow bZ^0) = 0.5$. Left: Neglecting the acceptance for the $Z^0H$ decay channel; Right: Considering that the acceptance in the $Z^0H$ decay mode is 1.4 times the acceptance in the $Z^0Z^0$ channel.

### 7.4.2 The $b' \rightarrow tW^*$ Decay

Since the $b'$ mass exclusion range extends above the top mass, we need to worry about the validity of the assumption that $BR(b' \rightarrow bZ^0) = 100\%$. For $b'$ masses above the top mass, the decay channel $b' \rightarrow tW^*$ is kinematically allowed. However, it is highly suppressed by three-body phase space. In Figure 7.9 we show the ratio $BR(b' \rightarrow tW^*)/BR(b' \rightarrow bZ^0)$ as a function of the $b'$ mass. The FCNC decay clearly dominates for $b'$ masses up to 190 GeV/$c^2$. For larger masses, the ratio depends highly on the $t'$ mass considered. For a $b'$ mass of 200 GeV/$c^2$, the ratio varies from 40% for a $b'$-$t'$ non-chiral doublet, to 2% for $m_{t'} = 260$ GeV/$c^2$. The electroweak precision data constrains the mass splitting of extra fermions and boson doublets. At 1$\sigma$ and 2$\sigma$ levels, this constraint gives $|m_{t'} - m_{t'}| < 38$ GeV and 93 GeV respectively [80], assuming no extra SU(2) doublets. If the extra quark is a
non-chiral isosinglet, $b' \to b Z^0$ occurs at tree-level resulting in a CC to FCNC ratio much smaller than 1% \cite{11, 81}. We conclude that, for the entire $b'$ mass range excluded, there is some parameter space for which the assumption that $BR(b' \to b Z^0) = 1$ is reasonable.

![Graph](image)

Figure 7.9: Comparison of the charge current and FCNC rates in $b'$ decays as function of the $b'$ mass. The case of a non-chiral isosinglet quark is not shown because the ratio is much smaller than 1% \cite{11, 81}.
Chapter 8

Conclusions

The current precision electroweak data severely constrain the existence of extra generations of fermions. Nevertheless, extra quarks are still allowed in the Standard Model and in its most popular extensions.

In this analysis, we have searched for an extra quark \( b' \) with charge \(-1/3\). We have searched for \( b'\)-quark pair production in \( p\bar{p} \) collisions at \( \sqrt{s} = 1.8 \) TeV, using 87.8 pb\(^{-1}\) of data collected with the Collider Detector at Fermilab. The favored \( b' \) decay mode depends on the CKM matrix mixing angles. The flavor-changing neutral current decays will dominate for a large set of reasonable values of the fourth-generation mixing angles. We have assumed that both \( b' \) quarks would decay by FCNC into \( b' \rightarrow b Z^0 \) and studied the decay mode \( b' \bar{b} \rightarrow b weaken\ 4\) decay into \( e^+e^- \) or \( \mu^+\mu^- \) and the other decays hadronically, giving a signature of two leptons plus jets. We found one event in the muon data sample that passed all the selection criteria for a \( b' \) event. However, this is also consistent with expectations from the Standard Model background. In the absence of a signal, a 95% confidence level upper limit on \( \sigma_{p\bar{p}\rightarrow b'b'} \times [BR (b' \rightarrow b Z^0)]^2 \) was established as a function of the \( b' \) mass. This limit is the major final result of the analysis. From this, \( b' \) mass range exclusion regions can be derived for the theoretical model of choice. The search is also sensitive to other \( b' \) decay channels such as \( b' \rightarrow b H \) or \( b' \rightarrow c W^- \) as long \( BR (b' \rightarrow b Z) \) is not negligible, since the hadronic decays of the \( H \) or \( W \) are kinematically similar to those of the \( Z \). The acceptance for \( b' \bar{b} \rightarrow b weaken\ 4\) is 1.8 to 0.5 times the acceptance for \( b' \bar{b} \rightarrow b weaken\ 4\).
depending on the Higgs and $b'$ masses and not including the $BR(Z \to l^+l^-)$. However, if we conservatively assume no sensitivity to these decay modes, we exclude a $b'$ mass from 104 GeV to 152 GeV for $BR(b' \to bZ) \geq 50\%$. Assuming that $BR(b' \to bZ) = 100\%$, we are able to exclude at 95\% C.L. $b'$ masses from 100 GeV/c$^2$ up to 199 GeV/c$^2$.

The $b'$ mass region excluded by this search is compared to the previously existing limits in Figure 8.1. The exclusion region in the flavor-changing neutral current channel was extended by more than a factor of two. The limit for a long-lived quark with a lifetime of $\tau \approx 1$ cm was also extended since this search should apply to such quarks as well. Since the branching ratios of different FCNC decay channels are related by Standard Model parameters, it would be possible to derive limits on those channels using the results of this search.

![Figure 8.1: Summary of the search results. Light boxes indicate previously excluded regions. The box with vertical dashes indicates the previously excluded region for a long-lived quark. The dark box shows the $b'$ mass range excluded by this search. The dark dashed boxes indicate exclusions that can be inferred from the results of this search.](image-url)
After this search is legitimate to ask: Is there still room for a $b'$? Where could it be hiding? While the mass limits are reaching very large discouraging values, it is important to notice that the most important result from these searches is actually the limit on the branching ratio and not on the mass. For instance, the mass limit in the charged-current mode assumed that $b'$ would decay 100% of the time into $cW$. If the CC and FCNC branching ratios are actually comparable then that limit does not apply anymore. So, for instance, there is room for a $b'$ quark with a mass of close to the CC limit but that would decay mostly by $b' \rightarrow cW$. Of course, a $b'$ quark heavier than 128 GeV/$c^2$ that decays mostly by the charged current is also still allowed. It is important to note that this region of the parameter space is difficult to exclude because of the top quark decay background.

The next run of the Tevatron, scheduled to begin in Spring 2001, will bring at least a factor of 20 more data. Besides the increased luminosity, the CDF detector has undergone a major upgrade that will result in an increased acceptance for the $b'$ signal. The search for $b' \rightarrow bZ$ will mostly benefit from the increase in the $b$-tag efficiency. Most importantly, the next run will allow the search for a $b'$ quark in the charge current mode to be extended. With a better understanding of the top signal, it will be possible to extend the $b' \rightarrow cW$ limit close to the top mass. With that result in hand, the window for a light $b'$ quark will definitively be closed.
Appendix

The $b'$ Search Article
Search for a Fourth-Generation Quark More Massive than the Z0 Boson in p\bar{p} Collisions at $\sqrt{s} = 1.8$ TeV


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26 University of Michigan, Ann Arbor, Michigan 48109
27 Michigan State University, East Lansing, Michigan 48824
28 University of New Mexico, Albuquerque, New Mexico 87131
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30 Osaka City University, Osaka 588, Japan
31 University of Oxford, Oxford OX1 3RH, United Kingdom
32 Università di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy
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34 Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore di Pisa, I-56100 Pisa, Italy
35 University of Pittsburgh, Pittsburgh, Pennsylvania 15260
36 Purdue University, West Lafayette, Indiana 47907
37 University of Rochester, Rochester, New York 14627
38 Rockefeller University, New York, New York 10021
39 Rutgers University, Piscataway, New Jersey 08855
40 Texas A&M University, College Station, Texas 77843
41 Texas Tech University, Lubbock, Texas 79409
42 Istituto Nazionale di Fisica Nucleare, University of Trieste, Udine, Italy
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We present the results of a search for pair production of a fourth-generation charge $\frac{1}{3}$ quark ($b'$) in $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions using 88 pb$^{-1}$ of data obtained with the Collider Detector at Fermilab. We assume that both quark decays via the flavor-changing neutral current process $b' \rightarrow Z^0 b b'$ and that the $b'$ mass is greater than $m_Z + m_b$. We studied the decay mode $b b' \rightarrow Z^0 Z^0 b b'$ where one $Z^0$ decays into $e^+ e^-$ or $\mu^+ \mu^-$ and the other decays hadronically, giving a signature of two leptons plus jets. An upper limit on the $\sigma(p\bar{p} \rightarrow b'b' \rightarrow Z^0 Z^0 b b')$ is established as a function of the $b'$ mass. We exclude at 95% confidence level a $b'$ quark with mass between 100 and 199 GeV/c$^2$ for $b(b' \rightarrow Z^0 b') = 100\%$.

PACS numbers: 13.85.Rm, 13.85.Qk, 14.65.-q

The standard model (SM) with three generations of quarks and leptons is in excellent agreement with all experimental data available today. There is no strong reason to believe that an extra fermion generation exists. However, the SM does not explain either the fermion family replications or the fermion mass hierarchy. Several models have been proposed to solve shortcomings in the SM specifically through the introduction of extra quarks and leptons. In addition, grand unification, supersymmetry, supergravity, and superstrings predict or can accommodate extra quarks [1]. An extensive discussion of such models can be found in a recent review [2].

In general, flavor-changing neutral current (FCNC) processes in the standard model are highly suppressed. However, if a fourth-generation charge $\frac{1}{3}$ quark ($b'$) exists and is lighter than both the $t'$ [its partner in an SU(2) doublet] and the top quark ($t$), the charged-current (CC) decays $b' \rightarrow tW^+$ and $b' \rightarrow t'W^-$ are kinematically forbidden. The leading charged-current decay mode will then be $b' \rightarrow cW^-$, which is doubly Cabibbo-suppressed. In this situation loop-induced FCNC decays can dominate [2-4] provided $|V_{cb}|/|V_{ub}|$ is less than roughly $10^{-3}$ to $10^{-1}$, depending on the $b'$ and $t'$ masses [4]. If $m_{b'} > m_Z + m_b$, the dominant FCNC decay mode is $b' \rightarrow Z^0 b b'$ [4] as long as $b' \rightarrow b H$ is kinematically suppressed or forbidden [5]. For $m_{b'} < m_{b'} < m_t + m_w$, the decay mode $b' \rightarrow tW^+$ becomes available but is suppressed by three-body phase space, and the $b' \rightarrow bZ^0$ channel can still dominate over the CC decay for $b'$ masses up to about 230 GeV/c$^2$ [2,6].

Several experiments have searched explicitly for $b'$ quarks decaying via FCNC [7]. The most stringent limit comes from the D0 Collaboration, which searched in the $b'b' \rightarrow ggbb$ and $b'b' \rightarrow γγbb$ channels, excluding a $b'$ quark mass up to $m_{Z} + m_b$ for a FCNC branching fraction larger than 50% [8]. CDF has excluded a long-lived $b'$ quark with mass up to 148 GeV/c$^2$ and a lifetime of $\tau = 3.3 \times 10^{-11}$ sec, assuming $b(b' \rightarrow Z^0 b') = 100\%$ [9]. If the CC decay $b' \rightarrow cW^-$ dominates, the lower mass bound of 128 GeV found in a D0 top quark search [10] also applies to the $b'$ quark [11].

In this Letter, we report on a search for a $b'$ quark using 88 ± 4 pb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected with the CDF detector from 1994 to 1995. Fourth-generation $b'$ quarks can be pair-produced in $p\bar{p}$ collisions through $gg$ fusion and $q\bar{q}$ annihilation with the same cross section, for a given mass, as the top quark. We search for pair-produced $b'$ quarks decaying via FCNC into $bZ^0$, where one $Z^0$ decays into leptons and the other decays hadronically. The signature is two high transverse momentum ($p_T$) leptons from the $Z^0$ decay, two high-$p_T$ jets from the second $Z^0$, and two $b$ jets whose $p_T$ scales with the $b'$ mass.

A detailed description of the CDF detector can be found elsewhere [12]. We briefly describe the components most relevant for this analysis. Inside a 1.4 T solenoidal magnetic field, the silicon vertex detector (SVX), the vertex time projection chamber (VTX), and the central tracking chamber (CTC) provide tracking information. The SVX, positioned immediately outside the beampipe and inside the VTX, consists of four layers of silicon microstrip detectors and covers $|z| < 25$ cm [13]. It provides precise track reconstruction in the plane transverse to the beam and is used to identify secondary vertices from the decay of $b$ hadrons. The VTX is used to measure the position of the primary interaction vertex along the $z$ axis. The CTC is a cylindrical drift chamber that covers the pseudorapidity range $|\eta| < 1.1$ and consists of 84 layers that are grouped in nine alternating superlayers of axial and stereo wires. Outside the solenoid, electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, surround the tracking volume and are used to identify electrons and jets over the range $|\eta| < 4.2$. The electron energy is measured in the central electromagnetic calorimeter (CEM) (|$\eta| < 1.1$) and the end-plug electromagnetic calorimeter (PEM) (1.1 < $|\eta|$ < 2.4). Outside the calorimeters, three systems of drift chambers in the region $|\eta| < 1.0$ provide muon identification.

We select events satisfying a high-$p_T$ lepton trigger, containing a well-identified muon or electron in the central region, whose primary vertex is within 60 cm of the nominal interaction position. A trigger that requires one jet with $E_T > 10$ GeV, in addition to the lepton, is also used for muon events. Inclusive $Z^0 \rightarrow e^+ e^-$ and $Z^0 \rightarrow \mu^+ \mu^-$ samples are selected by requiring one primary lepton that satisfies tight lepton identification cuts and a second lepton satisfying loose identification cuts [14]. Dielectron events are selected by requiring at least one tight electron with transverse energy $E_T > 20$ GeV in the CEM and a second loose electron with $E_T > 10$ GeV in either the CEM or PEM calorimeters. Dimuon events are required to have one tight muon with transverse momentum $p_T > 20$ GeV/c in the central region and a second loose muon with $p_T > 10$ GeV/c. A calorimeter isolation cut is imposed on the second lepton. We accept events if the reconstructed $ee$ or $\mu\mu$ invariant mass is between 75 and 127.
105 GeV/c^2. After this selection there are 6287 (2940) Z^0 events remaining in the electron (muon) data sample.

In order to optimize our sensitivity to a b' quark signal we make a jet selection that depends on the b' mass being considered. Hadronic jets are selected using a clustering algorithm [15] with a cone size of $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4$. Each event is required to have at least three jets within $|\eta| < 2.0$, two of which with $E_T > 15$ GeV. For b' masses above 120 GeV/c^2, the third jet is required to have $E_T > 15$ GeV. For $m_{b'} < 120$ GeV/c^2, the $E_T$ requirement on the third jet is relaxed to $E_T > 7$ GeV since the b' jets for b' masses near the $m_Z + m_b$ threshold have low momentum. We define the variable $\sum E_T^{jets}$ as the summed transverse energy of jets with $E_T > 15$ GeV and $|\eta| < 2.0$ and require this quantity to be larger than $m_{b'} - 60$ GeV. Figure 1 shows the $\sum E_T^{jets}$ distribution for e^+e^- and $\mu^+\mu^-$ events passing the three-jet requirement for b' masses above 120 GeV/c^2. Also shown are the distributions expected from SM background and from a b' quark with a mass of 150 GeV/c^2 (see below).

We further require at least one jet to be tagged as a b quark by the SVX b-tagging algorithm developed for the top quark analysis [16]. The number of events passing each major selection criterion for each leptonic channel is shown in Table I. One $\mu\mu$ event passes all our selection criteria for $m_{b'} \approx 120$ GeV/c^2. This event has a third jet with $E_T > 8.3$ GeV which fails the third-jet $E_T$ requirement for larger b' masses.

The signal acceptance and detection efficiencies are estimated from a combination of data and Monte Carlo simulation. We have generated bZ^0 → bZ^0Z^0 Monte Carlo samples for different b' masses between 100 and 210 GeV/c^2 using the HERWIG program [17] with MRSD' structure functions [18]. One Z^0 is required to decay into muons or electrons while the other is allowed to decay through any available decay channel. The CLEO QQ Monte Carlo program [19] is used to model the decays of b hadrons. These events are passed through a simulation of the CDF detector and are subjected to the same selection requirements as the data.

The electron trigger efficiency is determined from data to be $(92 \pm 1)$%, while the muon trigger efficiency per event $(82 \pm 4)$% is obtained from a combination of data and simulation. The efficiencies of the lepton identification cuts are determined using a Z^0 → e^+e^- (\mu^+\mu^-) data sample with an unbiased selection on one of the leptons. The $Z^0 → e^+e^-$ and $Z^0 → \mu^+\mu^-$ geometric and kinematic acceptance was obtained from the HERWIG Monte Carlo program. The total Z^0 detection efficiency times acceptance, including the isolation efficiency, is $(41 \pm 3)$% for $e^+e^-$ and $(30 \pm 3)$% for $\mu^+\mu^-$ and is nearly independent of the b' mass.

The event b-tag efficiency rises with $m_{b'}$ from 17% for $m_{b'} = 100$ GeV/c^2 to values between 50% and 57% for masses above 150 GeV/c^2. The total acceptance times efficiency, not including the $B(Z → l^+l^-)$, increases from 1.7% (1.6%) to 14% (11%) for the electron (muon) channel as $m_{b'}$ increases from 100 to 210 GeV/c^2 (Table II). This increase is due to the fact that a more massive b' leads to a more central event with more energetic jets in which, in addition, the b-tag algorithm is more efficient.

The dominant systematic uncertainties on the acceptance times efficiency arise from the jet energy scale and gluon radiation [14]. By varying parameters in the Monte Carlo simulation we estimate that the systematic uncertainty due to the jet energy scale in the electron (muon) channel is 16% (14%) for $m_{b'} = 100$ GeV/c^2 and less than 13% for higher masses. The presence of gluon radiation increases the jet multiplicity and therefore increases the efficiency of the three-jet requirement. This effect is more pronounced at low b' mass because the b quarks from low-mass b' decay are produced near threshold and therefore are detected with low efficiency. We estimate the systematic uncertainty due to this effect to be 19% (18%) in the electron (muon) channel for $m_{b'} = 100$ GeV/c^2 and less than 9% for a heavier b'. Other important systematic uncertainties arise from the b-tag efficiency (10%), parton distribution function (5%), total integrated luminosity.

### Table I

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The number of events and yields are listed in Table II.
TABLE II. Total acceptance ($A$) times efficiency ($e$) and relative systematic uncertainties ($\delta_{\text{rel}}$) in the electron and muon channels. 95% C.L. upper limit on the pair-production cross section times the branching ratio of $b' \rightarrow bZ^0$ squared, and theoretical pair-production cross section [20].

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<th>$A \times e$ (%)</th>
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(1.1%), lepton identification efficiency (4% for electrons, 5% for muons), isolation efficiency (4%), and trigger efficiency (1% for electrons, 5% for muons). The total uncertainty on the acceptance times efficiency is shown as a function of $b'$ mass in Table II.

The only non-negligible background is from $Z^0$ events with associated QCD hadronic jets. This background is estimated using a combination of the VECBOS [21] and HERWIG Monte Carlo programs. VECBOS calculates the leading-order matrix elements for $Z^0 +$ three partons events using the MRSD' structure functions [22]. A partial higher-order correction to the tree-level diagrams is obtained by including gluon radiation and hadronic fragmentation using HERWIG. These $Z^0$ events are then passed through a simulation of the CDF detector. We estimate the $b$-tag rate in $Z^0 +$ jet events directly from data using a technique developed for the top analysis [23]. We apply the $b$-tag rates measured in an inclusive jet sample to the $Z^0 +$ jets events that pass all the other selection criteria. This method overestimates the background because the inclusive jet sample contains heavy-quark contributions that are not present in $Z^0 +$ jets events. We expect approximately two background events for $m_{b'} > 120$ GeV/$c^2$ and less than one event for $m_{b'} > 120$ GeV/$c^2$, in agreement with the number of events observed in the data.

Under the assumption that the observed $\mu \mu$ event is from signal, that is, without subtracting background, we obtain a conservative 95% confidence level upper limit on the $\sigma_{p\bar{p} \rightarrow b'b}\times [B(b'b' \rightarrow bZ^0)^2]$. The limit is presented as a function of the $b'$ mass in Table II. We have used a Bayesian method to calculate the limit and treat the number of expected signal events as a Poisson distribution convoluted with a Gaussian systematic uncertainty. Using the theoretical next-to-leading-order (NLO) $b'$ pair production cross section [20] and assuming that $B(b'b' \rightarrow bZ^0)$ is 100%, we exclude at 95% confidence level $b'$ masses from 100 to 199 GeV/$c^2$, as shown in Fig. 2. This search is also sensitive to other $b'$ decay channels such as $b' \rightarrow bH$ or $b' \rightarrow cW$ as long as $B(b'b' \rightarrow bZ^0)$ is not negligible, since the hadronic decays of the $H$ or $W$ are kinematically similar to those of the $Z$. The acceptance for $b'b' \rightarrow bZH$ is 1.7 to 0.5 times the acceptance for $b'b' \rightarrow bZ$, depending on the Higgs and $b'$ masses and not including the $0(Z \rightarrow l^+l^-)$. However, if we conservatively assume no sensitivity to these decay modes, we exclude a $b'$ mass from 104 to 152 GeV for $B(b'b' \rightarrow bZ) \geq 50%$.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science, Sports and Culture of Japan; the National Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; and the Bundesministerium fuer Bildung und Forschung, Germany.


[13] The CDF coordinate system uses $(\theta, \phi, z)$, where the proton beam is in the $z$ direction and $\theta$ and $\phi$ are, respectively, the polar angle and the azimuthal angle. The transverse momentum of a particle is $p_T = p \sin \theta$.


[22] The QCD renormalization and factorization scales are set by the $<p_T^2>$ of the generated partons. The outgoing partons are generated with a minimum $p_T$ of 6 GeV/c, $|\eta| < 2.5$, and $d\phi > 0.4$ between partons.

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