Search for anomalous production of multiple leptons in association with W and Z bosons at CDF

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This paper presents a search for anomalous production of multiple low-energy leptons in association with a $W$ or $Z$ boson using events collected at the CDF experiment corresponding to 5.1 fb$^{-1}$ of integrated luminosity. This search is sensitive to a wide range of topologies with low-momentum leptons, including those with the leptons near one another. The observed rates of production of additional electrons and muons are compared with the standard model predictions. No indications of phenomena beyond the standard model are found. A 95% confidence level limit is presented on the production cross section for a benchmark model of supersymmetric hidden-valley Higgs production. Particle identification efficiencies are also provided to enable the calculation of limits on additional models.

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I. INTRODUCTION

The signature of multiple leptons is common in many models of physics beyond the standard model (SM) with light mass scales and couplings to the electroweak sector, such as the Next-to-Minimal Supersymmetric Model [1], little Higgs models [2], and R-parity violating MSSM models [3]. Some of these new physics scenarios propose explanations for the nature of dark matter [4] as well as the existence of other, yet-undiscovered particles in long
difficulty in identifying them in non-isolated topologies. In addition to predicting large numbers of leptons, these models also often predict that clusters of leptons are produced spatially close to each other. These clusters are often referred to in the literature as “lepton jets” \[5\]. Due to the unique characteristics of these models, they could have evaded previous searches for an excess of leptons, such as diboson searches \[6\] and SUSY-inspired multi-lepton searches \[7\]. The high multiplicity of leptons can lead to low lepton momenta, well below the usual cutoff of 10-20 GeV. Additionally, collimated lepton jets will fail the standard requirement that leptons be isolated in the detector. As an example, Figure 1 shows a typical decay chain in a model in which the Higgs decays to a light hidden sector resulting in events with a high multiplicity of leptons \[8\].

![FIG. 1: An example of multiple low-\(p_T\), non-isolated lepton production. A Higgs decays to a pair of lightest supersymmetric neutralinos \((N_1)\) which then cascade through a dark sector to a lightest dark sector particle \((\tilde{\nu}_d)\) and a number of dark photons \((\gamma_d)\). The dark photons then decay back into the SM in the form of leptons \((\ell^\pm)\). This model is adapted from Ref. \[9\]. Note that this diagram shows only the decay of the Higgs, while this analysis as a whole would be sensitive to the associated production of a Higgs with a W or Z boson.](image)

This paper presents a signature-based search for anomalous production of multiple electrons and/or muons in association with W and Z bosons. Previous searches for lepton jets at the Tevatron \[9\] and at the LHC \[10\] have focused on searching for clusters of leptons with specific requirements on the size of the clusters. These searches have resulted in no evidence for lepton jets. We have performed a more general search, sensitive to a wide range of scenarios that predict multiple electrons and muons. Note that hadronic decays of tau leptons are not included in this search due to the additional difficulty in identifying them in non-isolated topologies.

The data used here correspond to 5.1 fb\(^{-1}\) of integrated luminosity at a center-of-mass energy of \(\sqrt{s} = 1.96\) TeV collected using the CDF detector at Fermilab between December 2004 and January 2010. Within the events containing leptonically decaying W and Z bosons, we search for additional ‘soft’ leptons with no isolation requirements and with momentum greater than 3 GeV for muons and 2 GeV for electrons \[11\].

II. ANALYSIS STRATEGY

The analysis strategy and the structure of this paper are as follows. The baseline data sets for this analysis consist of leptonically decaying W and Z boson events selected with high transverse momentum \(p_T\) leptons \[12\]. The kinematic distributions are used to validate the W and Z boson selections. The selection of these events is described in Section V.

After the W or Z boson reconstruction, additional low-\(p_T\) electrons and muons are identified in the events with no isolation requirements. Purely data-driven techniques are used to develop the soft lepton identification algorithms. The selection of soft leptons is more fully described in Section V.

The numbers of additional electrons and muons are counted in the inclusive W and Z data sets, where the SM predicts few events with multiple leptons. The observed event count is compared to the SM expectations in bins of additional lepton multiplicity. These results are described in Section VII.

III. THE CDF II DETECTOR

The CDF II detector is a cylindrically-symmetric spectrometer designed to study \(p\bar{p}\) collisions at the Fermilab Tevatron. The detector has been extensively described in detail elsewhere in the literature \[13\]. Here the detector subsystems relevant for this analysis are described.

Tracking systems are used to measure the momenta of charged particles, to reconstruct primary and secondary vertices, and to trigger on and identify leptons with large transverse momentum. Silicon strip detectors (SVX) \[15\] and the central outer tracker (COT) \[16\] are contained in a superconducting solenoid that generates a magnetic field of 1.4 T. The silicon strip system provides up to 8 measurements in the \(r-\phi\) and \(r-z\) views and helps to reconstruct tracks in the region \(|\eta| < 2\) \[12\]. The COT is an open-cell drift chamber that makes up to 96 measurements along the track of each charged particle in the region \(|\eta| < 1\). Sense wires are arranged in 8 alternating axial and \(\pm2^\circ\) stereo super-layers. The resolution in \(p_T\), \(\sigma_{p_T}/p_T\), is \(\approx 0.0015 p_T\text{(GeV)}\) for tracks with only COT measurements, and \(\approx 0.0007 p_T\text{(GeV)}\) for tracks with both silicon and COT measurements.

Calorimeters are segmented with towers arranged in a projective geometry. Each tower consists of an electromagnetic and a hadronic compartment \[17\]. The
central hadronic calorimeter (CEM) and central
hadronic calorimeter (CHA) cover the central region
(|\eta| < 1.1), while the plug electromagnetic calorimeter
(PEM) and plug hadronic calorimeter (PHA) cover the
‘end plug’ region (1.1 < |\eta| < 3.6). In this analysis,
a high-\(E_T\) electron is required to be identified in
the central region, where the CEM has a segmentation
of 15° in \(\phi\) and \(\approx 0.1\) in \(\eta\) \[14\], and an \(E_T\) resolution of
\(\sigma(E_T)/E_T \approx 13.5\%/\sqrt{E_T}\) (GeV) \(\pm 2\%\) \[17\]. Two additional
systems in the central region with finer spatial
resolution are used for electron identification. The
central strip system (CES) uses a multi-wire proportional
chamber to make profile measurements of electromagnetic
showers at a depth of 6 radiation lengths (approximately
shower maximum) \[17\]. The central preshower
detector (CPR) is located just outside the solenoid coil
on the front face of the CEM. In 2004 the CPR was
upgraded from the Run I configuration of wire proportional
chambers to a fast scintillator system \[19\]. This analysis
only uses data collected after the CPR upgrade.

Muons are identified using the central muon sys-
tems \[20\]: CMU and CMP for the pseudo-rapidity region
of \(|\eta| < 0.6\), and CMX for the pseudo-rapidity region
of \(0.6 < |\eta| < 1.0\). The CMU system uses four layers of pla-
nar drift chambers to detect muons with \(p_T > 1.4\) GeV.
The CMP system consists of an additional four layers of planar
drift chambers located behind 0.6 m of steel out-
side the magnetic return yoke, and detects muons with
\(p_T > 2.2\) GeV. The CMX system detects muons with
\(p_T > 1.4\) GeV with four to eight layers of drift chambers,
depending on the direction of the muon.

The luminosity is measured using two sets of gas
Cerenkov counters \[21\], located in the region \(3.7 < |\eta| < 4.7\).
The total uncertainty on the luminosity is estimated
to be 5.9%, where 4.4% comes from the acceptance and
operation of the luminosity monitor and 4.0% from the
calculation of the inelastic \(p\bar{p}\) cross-section \[22\].

A three-level online event selection (trigger) sys-
tem \[23\] selects events to be recorded for further anal-
ysis. The first two trigger levels consist of dedicated fast
digital electronics analyzing a subset of the complete de-
tector information. The third level, applied to the full
set of detector information from those events passing the
first two levels, consists of a farm of computers that re-
construct the data and apply selection criteria consistent
with the subsequent offline event processing.

IV. W AND Z BOSON SAMPLE SELECTION

Events for this analysis are selected with three different
triggers \[23\]. Approximately half the events are selected
with a trigger requiring a high-\(p_T\) central electron in the
CEM (\(E_T > 18\) GeV, \(|\eta| < 1.0\)). In addition, two muon
triggers, one requiring hits in both the CMP and CMU
and the other requiring hits in the CMX, collect events
with central muons (\(p_T > 18\) GeV, \(|\eta| < 1.0\)).

Further selection criteria are imposed on triggered
events offline. Electron (muon) candidates are required
to have \(E_T > 20\) GeV (\(p_T > 20\) GeV). They must ful-
fill several other identification criteria designed to select
pure samples of high-\(p_T\) electrons (muons) \[13\], including
an isolation requirement that the energy within a cone of
\(\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.4\) around the lepton direction is
less than 10% of the \(E_T\) (\(p_T\)) of the electron (muon).

In order to reduce the electron background from photon
conversions, the electron(s) from the W or Z boson decay
are required to pass a conversion filter. Electron candidates
with an oppositely-charged partner track consist-
stant with having originated from a photon conversion are removed \[24\]. However, the electron candidate is kept
if its partner conversion track also has another partner
track, since the three tracks are assumed to originate
from an electron which radiates a photon which subse-
quently converts.

In order to reduce the background from mesons decay-
ing to muons within the tracking chamber, the muon(s)
from the W or Z boson decay must pass a decay-in-flight
(DIF) removal algorithm. The DIF algorithm requires the \(\chi^2\) per degree of freedom of the fitted track to be
less than 3 and requires that the impact parameter of the
track be less than 0.02 cm. Additionally, for tracks with
\(p_T > 300\) GeV, it requires \(N_{\text{transitions}} > 30\), where
\(N_{\text{transitions}}\) is the number of times the pattern of track
hits crosses the fitted track \[25\]. Muons consistent with
cosmic rays are vetoed \[27\].

To select W boson events we require \(E_T > 25\) GeV
and that the highest-energy lepton and the \(E_T\) have
\(m_T > 20\) GeV \[12\]. In order to remove events where the \(E_T\)
while the other is

For electrons, the loose selection accepts elec-
trons with \(E_T > 12\) GeV and has relaxed identifica-
tion requirements with respect to the centroid shape in
the CES and \(E/p\bar{p}\), the ratio of calorimeter energy to track
momentum \[27\]. Finally, the invariant mass of the lep-
ton pair is required to be within the range of \(76\) GeV
\(\leq m(l,l) \leq 106\) GeV, consistent with the mass of the Z
boson.

The distributions of \(m_T\) in W boson events and the
dilepton invariant mass in Z boson events are shown in
Figure \[2\] for both electron- and muon-triggered events.
In total, 4,722,370 W boson events and 342,291 Z boson
events are obtained from 5.1 fb \(^{-1}\) of data. Good
agreement with predictions is observed across most of the
distributions. In the W \(m_T\) distributions, a disagree-
ment occurs at low mass, where the distribution shifts
from being QCD-dominated to electroweak-dominated,
and is accounted for by the QCD normalization syste-
V. SOFT LEPTON IDENTIFICATION

The identification of low-$p_T$, or “soft”, leptons is a main focus of this analysis. Likelihood-based methods are used to identify soft electrons and muons. The identification algorithms are described here, along with the methods used to validate them and evaluate their systematic uncertainties.

A. Soft electrons

Soft electrons are identified using a likelihood method trained on a signal sample from photon conversions and a background sample from other tracks with electron sources removed.

1. Identification algorithm and candidate selections

A preselection is applied to all soft electron candidates requiring good track quality as well as track extrapolation to the CES, CPR, and calorimeter. Only tracks with $|\eta| < 1$ are considered for the soft electron identification.

After this preselection, a likelihood-based calculator is used to identify electrons. The likelihood calculator uses seven discriminating variables: the energy loss as the track traverses the tracking chamber, the electromagnetic and hadronic calorimeter energies, the energies deposited in the preradiator and the showermax detector, and the two-dimensional distance ($\Delta x, \Delta z$) between the extrapolated position of the track and the shower in the CES. The calorimeter variables are calculated using a narrow, two-tower-wide section of the calorimeter.

Some of the variables used in the soft electron identification are modeled very badly in the MC, and so the likelihood is trained on data without resorting to the simulation. For each of the above variables $x_i$, a fit is performed to the ratio of the distribution in the electron sample and the distribution in the non-electron background (“fake”) sample. For each candidate, the value of each of these fit functions is multiplied together to get the final likelihood ($L_{\text{electron}}$):

$$Q = \prod_i \frac{P(x_i|\text{real})}{P(x_i|\text{fake})}, \quad L_{\text{electron}} = \frac{Q}{1 + Q}.$$  

The distribution of the likelihood in the real and fake samples is shown in Figure 3. A candidate is identified as an electron if it passes the requirement $L_{\text{electron}} > 0.99$.

FIG. 2: (a) The transverse mass ($m_T$) of the highest-$p_T$ lepton and the $E_T$ in the electron-triggered $W$ boson sample. (b) The dilepton invariant mass in the electron-triggered $Z$ boson sample. (c) The $m_T$ of the highest-$p_T$ lepton and the $E_T$ in the muon-triggered $W$ boson sample. (d) The dilepton invariant mass in the muon-triggered $Z$ boson sample. The estimation of the QCD contribution to these distributions is described in Section VI A. The points represent the observed data and the filled histograms are the SM estimates.
or an identified high-
any event that contains an identified heavy quark decay
addition, to reduce the contamination from real electrons,
within $\Delta$
from using a muon-triggered sample, any track that is
removed from the training sample. To reduce the bias
likelihood function. All tracks in the events that, along
the likelihood.

In order to avoid any bias from the trigger, the lower-
training samples as functions of
$\mathcal{E}$
electron is ignored.

Photon conversions are used as a pure sample of elec-
trons to train the likelihood function. In events selected
using an 8 GeV electron trigger, pairs of tracks are found
that correspond to a photon converting into $e^+e^-$ \cite{24}. In order to avoid any bias from the trigger, the lower-
momentum track of the conversion pair is used to train
the likelihood.

Events from the 18 GeV muon trigger are used to select
a sample of non-electron tracks with which to train the
likelihood function. All tracks in the events that, along
with another track, form a possible photon conversion are
removed from the training sample. To reduce the bias
from using a muon-triggered sample, any track that is
within $\Delta R < 0.7$ of an identified muon is also ignored. In
addition, to reduce the contamination from real electrons,
any event that contains an identified heavy quark decay
or an identified high-$p_T$ electron is ignored.

The efficiency and fake rate are calculated in these
training samples as functions of $p_T$, $\eta$, and track iso-
lation. The same sample used for training is also used
to measure the efficiency, due to the larger backgrounds
present in other independent samples. The separation in
identification rate between electrons and non-electrons
after the likelihood selection is shown in Figure 3 (right).
The efficiency in terms of $p_T$ and $\eta$, after the track and
CES shower have been identified, is shown in Table I.

![Figure 3](image)

**FIG. 3:** (a) The likelihood distributions for electrons (closed
squares) and non-electrons (open circles) after all preselection
criteria. Only those candidates with a likelihood $> 0.99$ are
identified as electrons. (b) The efficiency as a function of $p_T$
for the identification of electrons (closed squares) and tracks
misidentified as electrons (open circles) after the likelihood
selection.

2. Training samples and efficiency and misidentification rate measurements

Photons are used as a pure sample of electrons to train the likelihood function. In events selected using an 8 GeV electron trigger, pairs of tracks are found that correspond to a photon converting into $e^+e^-$. In order to avoid any bias from the trigger, the lower-momentum track of the conversion pair is used to train the likelihood.

Events from the 18 GeV muon trigger are used to select a sample of non-electron tracks with which to train the likelihood function. All tracks in the events that, along with another track, form a possible photon conversion are removed from the training sample. To reduce the bias from using a muon-triggered sample, any track that is within $\Delta R < 0.7$ of an identified muon is also ignored. In addition, to reduce the contamination from real electrons, any event that contains an identified heavy quark decay or an identified high-$p_T$ electron is ignored.

The efficiency and fake rate are calculated in these training samples as functions of $p_T$, $\eta$, and track isolation. The same sample used for training is also used to measure the efficiency, due to the larger backgrounds present in other independent samples. The separation in identification rate between electrons and non-electrons after the likelihood selection is shown in Figure 3 (right).

The efficiency in terms of $p_T$ and $\eta$, after the track and CES shower have been identified, is shown in Table I.

### TABLE I: Efficiency to identify soft ($2 \text{ GeV} < p_T < 20 \text{ GeV}$) electrons as a function of candidate $p_T$ and $\eta$.

| $p_T$ range (GeV) | $[2, 2.5]$ | $[2.5, 3]$ | $[3, 6]$ | $[6, 12]$ | $[12, 20]$ |
|-------------------|------------|------------|---------|----------|-----------|
| $0 < |\eta| < 0.2$ | 0.90 | 0.99 | 0.99 | 0.90 | 0.99 |
| $0.2 < |\eta| < 0.6$ | 0.94 | 0.99 | 0.99 | 0.99 | 0.99 |
| $0.6 < |\eta| < 1$ | 0.95 | 0.99 | 0.99 | 0.99 | 0.99 |

This identification rate is applied as a weight to each candidate track in the MC to find the predicted number of identified electrons.

### 3. Validation and systematic uncertainty determination

The efficiency and fake rate parametrizations are checked on a data set triggered on jets having $E_T > 50$ GeV. The parametrizations use the $p_T$, $\eta$ and isolation of candidates in order to account for any kinematic differences between the training sample and the validation sample. First, the same electron removal that was used for the fake training sample (Section V A 2) is applied to the tracks in the jet sample. The likelihood distribution of all candidate tracks in the jet sample is then fit to templates from the real and fake likelihood training samples to obtain the fraction of real and fake electrons in the jet sample. The jet sample is found to consist of 2.5% real electrons, mostly coming from photon conversions from which only one electron was reconstructed. The predicted identification rate is then checked for agreement with the measured identification rate.

The disagreement between the calculated and observed identification rates is measured to be 1.6%. However, we observe larger disagreement in the shapes of the calculated and observed distributions in $p_T$ and $\eta$. We assign a systematic uncertainty of 15%, which is sufficient to cover the observed disagreement \cite{24}. This systematic uncertainty is applied separately to the electron identification and misidentification rates.

### B. Soft muons

Soft muons are identified using a method similar to that described in Ref. \cite{25}. The inputs to the algorithm are derived from a sample of muons arising from $J/\psi$ decays in a muon calibration dataset.
1. Identification algorithm and candidate selections

The soft muon identification algorithm relies on matching tracks identified in the COT to track segments reconstructed in the muon chambers (muon stubs). Matching is done in the extrapolated position along the muon chamber drift direction (x), the longitudinal coordinate along the chamber wires (z) when available, and the difference in slope between the extrapolated COT track and the reconstructed muon chamber track segment (dQ/df). Tracks are paired with muon chamber track segments based on the best match in x for those track segments within 50 cm of an extrapolated COT track.

Soft muon candidates are required to extrapolate to within the physical boundaries of a muon chamber, have good track quality, have at least one hit in the SVX, |d0| < 0.3 cm where d0 is the impact parameter with respect to the beamline, and z0 < 60 cm where z0 is the z position of the track at the interaction point.

A $\chi^2$ is built from the track-to-stub matching variables $x_i$ described above (dx, dz, and dQ/df). This $\chi^2$ is normalized to have mean 0 and variance 1 for real muons, independent of the number n of track-stub matching variables $x_i$ used:

$$\chi^2 = \sum_i \frac{(x_i - \mu_i)^2}{\sigma_i^2}, \quad Q_{\text{muon}} = \frac{\chi^2 - n}{\sigma(\chi^2)},$$

where $\mu_i$ and $\sigma_i^2$ are the expected mean and variance of the distribution of $x_i$, and $\sigma(\chi^2)$ is the expected standard deviation of $\chi^2$.

In the final selection, we require that all identified soft muons must have a track segment in each muon chamber to which the track extrapolates and that |$Q_{\text{muon}}$| < 3.5 (see Fig. 4).

2. Efficiency and misidentification rate measurements

The efficiency of the soft muon identification is measured using a pure sample of muons obtained from $J/\psi \rightarrow \mu\mu$ decays. These events are obtained using an online trigger requiring the presence of a muon with $p_T > 8$ GeV. The $J/\psi$ is reconstructed by requiring that the trigger muon make a vertex with another track of opposite charge that has associated muon chamber hits. All track requirements listed in Sec. V B 1 are applied to both tracks. The $J/\Psi$ candidate mass is required to satisfy $3.03 < m(\mu\mu) < 3.15$ GeV, and the sidebands of the mass distribution are used to evaluate the background under the mass peak.

The misidentification rates of pions and kaons are measured in $D^+ \rightarrow D^0\pi^+$ decays where the $D^0$ decays as $D^0 \rightarrow K^-\pi^+$. These events are obtained from a trigger that requires the presence of a vertex containing two tracks and are reconstructed requiring masses $1.835 < m(K\pi) < 1.895$ GeV and $m(D^*) - m(D^0) < 170$ MeV. The sidebands of the $m(D^*) - m(D^0)$ distribution are used to evaluate the background under the mass peak.

The misidentification rate of protons is measured using a sample of protons obtained from $\Lambda \rightarrow p\pi$ decays. These events are taken from the same dataset as that from which the $D^*$ sample is obtained. The reconstructed $\Lambda$ mass is required to satisfy $1.111 < m(p\pi) < 1.121$ GeV. The sidebands of the mass distribution are used to evaluate the background under the mass peak.

Figure 4 (left) shows the distribution of muon scaled $\chi^2$, $Q_{\text{muon}}$, using the samples described above. Good separation is obtained between muons and other particle species.

![Figure 4](image-url)
TABLE II: Efficiency to identify soft muons as a function of candidate $p_T$ and $\eta$.

| $p_T$ range (GeV) | [3, 4] | [4, 5] | [5, 6] | [6, 7] | [8, 10] | [10, 12] | [12, 16] | [16, 20] |
|-------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| $-1.5 < \eta < -0.7$ | 0.739 | 0.626 | 0.567 | 0.419 | 0.342 | 0.127 | 0.237 | 0.174 |
| $-0.7 < \eta < -0.55$ | 0.593 | 0.556 | 0.581 | 0.480 | 0.438 | 0.299 | 0.356 | 0.344 |
| $-0.55 < \eta < -0.45$ | 0.740 | 0.788 | 0.833 | 0.751 | 0.783 | 0.608 | 0.644 | 0.659 |
| $-0.45 < \eta < -0.15$ | 0.816 | 0.901 | 0.896 | 0.782 | 0.821 | 0.701 | 0.570 | 0.659 |
| $-0.15 < \eta < 0.15$ | 0.777 | 0.796 | 0.784 | 0.667 | 0.657 | 0.525 | 0.424 | 0.616 |
| $0.15 < \eta < 0.45$ | 0.832 | 0.918 | 0.913 | 0.799 | 0.815 | 0.698 | 0.568 | 0.659 |
| $0.45 < \eta < 0.55$ | 0.768 | 0.782 | 0.840 | 0.741 | 0.582 | 0.758 | 0.529 | 0.659 |
| $0.55 < \eta < 0.7$ | 0.625 | 0.573 | 0.556 | 0.461 | 0.450 | 0.409 | 0.237 | 0.256 |
| $0.7 < \eta < 1.5$ | 0.750 | 0.617 | 0.593 | 0.428 | 0.327 | 0.146 | 0.173 | 0.174 |

Separate systematic uncertainties are estimated for the true muon identification efficiency and the misidentification rate. The invariant mass sideband subtraction technique used to obtain the muon efficiency matrix introduces uncertainties arising from the statistics of the $J/\psi$ sample. These uncertainties vary from 2% - 70%, depending on the bin in $p_T$ and $\eta$. In addition, the maximum variation in efficiency of 8% arising from the difference between isolated and non-isolated candidates is used as an uncertainty representing the maximum possible difference between the $J/\psi$ sample environment and the $W/Z$ environment. This is added in quadrature to the statistical uncertainty arising from the sideband subtraction method to obtain a final muon efficiency uncertainty of 8% - 70%.

The misidentification systematic uncertainty is obtained by selecting muon-free regions in samples triggered on high-$p_T$ jets and taking the difference between observed and predicted soft muon misidentification rates. In this jet sample, at least 3 jets are required with $E_T > 15$ GeV and $|\eta| < 2.0$. In order to reduce the contamination from real muons, any jet that contains an identified heavy quark decay is rejected, as is any track that has impact parameter significance $d_0/\sigma(d_0) > 2$. In a sample having an online trigger requiring the presence of a jet with $E_T > 100$ GeV, a difference of 4.8% is observed between the observed and predicted soft muon identification rates. A conservative estimate of twice this difference is used as the systematic uncertainty on the soft muon misidentification rate.

C. Application of soft lepton identification to $W/Z$ samples

Additional selection criteria are applied to soft lepton candidates in the high $p_T$ $W$ and $Z$ boson data samples to reduce the amount of background in the search sample. Any track that is already identified as a high-$p_T$ electron or muon in the $W$ or $Z$ boson selection is ineligible to be identified as a soft muon. To reject badly measured tracks, each track is required to have at least one hit in the silicon detector. For electron candidates, this hit is required to be within the first two layers of the silicon detector to help reject photon conversions. Each track is required to be inside of a reconstructed jet having $|\eta| < 2.0$ and transverse energy of $E_T > 5$ GeV, so that the heavy flavor fraction fit described later in Section VIIB can be applied. (Note that the ‘jet’ could be composed entirely of leptons, or even entirely of a single lepton.) Any track that is identified as a conversion partner is rejected. The track candidate must have a distance along the beamline $|\Delta z| < 5$ cm from the high-$p_T$ trigger lepton. If the trigger lepton is the same flavor as the soft lepton, the invariant mass $M$ is calculated of the candidate and trigger, and the following mass ranges are rejected:

- $M < 5$ GeV to suppress the $J/\psi$ and $b\bar{b}$ backgrounds.
- $9 < M < 10$ GeV if the candidate track has opposite charge to the trigger lepton. This rejects $\Upsilon$ events.
- $80 < M < 100$ GeV if the candidate track has opposite charge to the trigger lepton. This rejects $Z$ events.

These additional selection criteria have a small effect on the benchmark model chosen for this analysis, cutting
out 4.5% of the signal leptons generated.

VI. BACKGROUND PREDICTION

The main SM backgrounds in this analysis are from $W + \text{jets}$, Drell-Yan, QCD multijet, top quark, and diboson production processes. The cross section and differential distributions of electroweak backgrounds from hard scattering processes are modeled using the ALPGEN MC program, except for the top production and diboson production backgrounds, which are modeled by PYTHIA. PYTHIA is used to model the parton showering in all samples. These MC events are analyzed using a GEANT based detector simulation. The samples generated by ALPGEN are $W/Z + N_p$ partons (light flavor) and $W + q \bar{q} + N_p$ partons, where $q = c, b$ (heavy flavor). The interface with the parton showering generates a double counting of heavy flavor events which is corrected using the MLM matching method.

The relative contributions from the various background sources can be seen qualitatively in Figure 2. The cross sections used for every sample are described in [24]. The final background predictions are summarized later in Section VII. The QCD multijet background requires a different treatment since it is not possible to simulate it using MC. It is derived using data as explained below.

A. QCD multijet background fraction

The $W$ boson is identified by the presence of a high energy lepton and missing transverse energy. Events containing jets may emulate this signature; a dijet event, for example, may have large $E_T$ arising from the energy mis-measurement of one jet while the other jet in the event can mimic an electron by leaving a track in the COT associated with an electromagnetic energy deposit. The contribution from these QCD multijet processes is estimated by using a data-derived model [33]. This is accomplished by defining an object that is similar to an electron, but has a much larger rate of contamination from jets; we refer to this as an “anti-selected electron”. An anti-selected electron is required to pass the same kinematic requirements as an electron, but must fail at least two of the identification requirements.

The number of events arising from the QCD multijet background is obtained by fitting the $E_T$ distribution of the data using two templates: an electroweak template obtained from $W + \text{jets}$, $Z + \text{jets}$ and diboson MC, and a QCD template. The QCD template is obtained from the anti-selected electron sample after subtracting the expected $W$ boson contamination using the MC. The total number of events is kept constant and the fraction from each template is obtained from the fit.

After the fit is performed across the $E_T$ distribution, the number of QCD events in the $W$ boson signal region is calculated by applying the selection of $E_T > 25$ GeV. The MC electroweak contribution and the data-derived QCD template are scaled to the result obtained from this $E_T$ fit. Figure 5 shows the result of this fit in the electron-triggered dataset. A similar fit is performed in each muon-triggered dataset. A systematic uncertainty of 26% is applied to the QCD normalization, as found in [32].

![Figure 5](image_url)  
**FIG. 5:** The fit to the $E_T$ distribution of events with $m_T > 20$ GeV and $\Delta(\phi/E_T,l) > 0.5$, in the electron-triggered dataset. The “electroweak” template is obtained from Monte Carlo and the “QCD” template is obtained from the anti-selected electron data sample. The systematic uncertainty of 26% found in [32] is shown.

B. Heavy flavor background fraction

The leptonic decay of heavy flavor quarks creates a significant background contribution to the soft leptons of this analysis. This background is estimated using the data in the $W/Z +$ exactly one soft muon channel, which should be dominated by SM processes. A fit is performed in two distributions of soft muons which are sensitive to the heavy flavor fraction: $p_T^\mu$, which is the momentum of the muon transverse to the direction of the jet in which it is found, and $d_0/\sigma(d_0)$, which is the significance of the muon’s impact parameter with respect to the beamline. A simultaneous fit is performed of these two distributions to a sum of templates from heavy flavor, light flavor, and Drell-Yan processes, as shown in Figure 6. These templates were acquired from the MC background samples. The result of this fit is used to normalize the contributions of the three types of processes in the higher-multiplicity sample. The uncertainty resulting from the fit, ranging from 5% to 34% in the various samples, is used as a systematic uncertainty on this normalization.
C. Normalization of soft electron multiplicities

The heavy flavor fit described in Section VI B normalizes all of the data to the $W/Z+1\mu$ channel. However, we find a mismatch in the $W/Z+1e$ channel, which has a large contribution from photon conversions. The difference between the predicted and observed numbers in the $W/Z$ plus exactly one electron channel is 34% in the $W$ boson sample and 31% in the $Z$ boson sample. This is used as a systematic uncertainty for the normalization of all other MC with at least one additional identified electron [24].

VII. RESULTS

Using the soft lepton identification techniques described in Section V, we count the numbers of $W$ and $Z$ boson events with multiple additional leptons. Figures 7 and 8 show the multiplicity of additional electrons ($N_e$) and muons ($N_\mu$) in these events, with the SM expectation and observed data overlaid. The two-dimensional histograms of $N_\mu$ vs. $N_e$ are presented in slices of $N_e$ for ease of viewing. These expected and observed event counts are also presented in Tables III and IV for ease of comparison with predictions from other models. The sources of systematic uncertainties are summarized in Table V with references to the sections in which they are described and evaluated. Good agreement with the SM expectation is observed across the distributions.

In particular, very few multi-muon events are observed. This is the region where many lepton jet models would be expected to show an excess, since a potential signal in the multi-electron region would be more likely to be hidden by the large background contribution from photon conversions. Only three events containing 3 muons beyond the $W$ selection are observed, which is consistent with the SM expectation of 2.9 events. No events are observed containing four or more additional muons.

A. Benchmark model

This is a general signature-based search, and as such is applicable to many different models. We choose an example model from the representative lepton jet models presented in Ref. [8]. The benchmark model chosen for this analysis is an adaptation of the ‘Neutralino Bench-
FIG. 7: Multiplicity of additional electrons and muons after the W boson selection. The two-dimensional histogram of $N_e$ vs. $N_\mu$ is presented in slices of $N_e$ for ease of viewing. Both hard and soft leptons (but not the initial lepton used for the W boson selection) are counted. Note that the distributions combine the electron- and muon-triggered events.

mark Model,' in which the Higgs decays principally to a pair of the lightest supersymmetric particles, which then decay through a dark sector to lepton jets. A MC sample of signal events was generated from this model using Pythia. The signal from this model to which this analysis is most sensitive is associated production of a W or Z boson and a Higgs boson, which has a cross section of 389 fb. This cross section would result in 1647 $W^+ \text{Higgs}$ events and 322 $Z^+ \text{Higgs}$ events in the data sample of this analysis before applying any selection criteria.

The particular parameters of the model \cite{34} were chosen to create a ‘typical’ model of this class. The MSSM parameters ($\mu$, $m_{1/2}$, $m_A$, $\tan(\beta)$ and $\sin(\alpha)$) avoid previous limits from searches for supersymmetry while making the lightest supersymmetric partner ($\chi_0^0$) the favored Higgs decay channel. The Higgs has a mass near that favored by precision measurements. The branching fractions for $\chi_0^0$ decaying into the dark neutralinos ($\chi_{d}$) and
FIG. 8: Multiplicity of additional electrons and muons after the Z selection. The two-dimensional histogram of $N_\mu$ vs. $N_e$ is presented in slices of $N_e$ for ease of viewing. Both hard and soft leptons (but not the initial leptons used for the Z boson selection) are counted. Note that the distributions combine the electron- and muon-triggered events.

dark photons ($\gamma_d$) simply model the sort of cascade decay illustrated in Figure 1. The mass of the dark photon is chosen in order to make the additional leptons that are produced approximately half muons and half electrons. These parameters are summarized in Table VI.

We set a 95% confidence level limit on the production of this benchmark model. The limit is set at $0.312 \times \sigma$, or $112$ fb. The model can be ruled out at the standard cross section at a confidence level of 99.7%. Both of these limits are set in the Bayesian framework using the mclimit tools running over the combined $W$ and $Z$ channels in Figures 7 and 8 (Tables III and IV).

B. Application to other models

In addition to the benchmark model discussed in Section VII A, limits can be set on a wide range of alternate
TABLE III: Summary of predicted and observed event counts by number of additional electrons ($N_e$) and muons ($N_\mu$) after the $W$ boson selection. The prediction of a model described in Section VII A is also shown for comparison. Bins with less than 0.25 expected events in both signal and background and 0 observed events are not shown.

| $N_e$ | $N_\mu$ | Predicted SM Background | Predicted Dark Higgs Signal | Observed |
|-------|---------|-------------------------|-----------------------------|----------|
| 0 0   |         | 4623512 ± 315244         | 158                         | 4673896  |
| 0 1   |         | 6463 ± 807              | 42                          | 6498     |
| 0 2   |         | 109 ± 24               | 21                          | 70       |
| 0 3   |         | 2.1 ± 0.79             | 8.0                         | 2        |
| 0 4   |         | 0.029 ± 0.019          | 2.8                         | 0        |
| 0 5   |         | 0.00026 ± 0.00023      | 0.83                        | 0        |
| 1 0   |         | 46055 ± 11387          | 27                          | 37778    |
| 1 1   |         | 824 ± 230              | 11                          | 425      |
| 1 2   |         | 23 ± 7.8               | 6.4                         | 8        |
| 1 3   |         | 0.58 ± 0.27            | 2.6                         | 0        |
| 1 4   |         | 0.010 ± 0.0074         | 0.95                        | 0        |
| 1 5   |         | 0.00011 ± 0.00011      | 0.29                        | 0        |
| 2 0   |         | 3600 ± 1085            | 7.1                         | 3184     |
| 2 1   |         | 129 ± 43               | 3.8                         | 86       |
| 2 2   |         | 4.9 ± 1.8              | 2.3                         | 1        |
| 2 3   |         | 0.13 ± 0.067           | 0.97                        | 1        |
| 2 4   |         | 0.0031 ± 0.0024        | 0.37                        | 0        |
| 3 0   |         | 491 ± 185              | 1.9                         | 366      |
| 3 1   |         | 23 ± 9.3               | 1.2                         | 5        |
| 3 2   |         | 0.85 ± 0.42            | 0.72                        | 1        |
| 3 3   |         | 0.028 ± 0.017          | 0.30                        | 0        |
| 4 0   |         | 79 ± 38                | 0.47                        | 50       |
| 4 1   |         | 3.9 ± 2.1              | 0.28                        | 2        |
| 5 0   |         | 13 ± 7.6               | 0.096                       | 5        |
| 5 1   |         | 0.74 ± 0.49            | 0.058                       | 0        |
| 6 0   |         | 2.0 ± 1.5              | 0.015                       | 0        |

In general, any model that predicts significant numbers of 3-muon events can be ruled out, since only three such events are observed in the sample, consistent with the SM background. However, models that produce multiple electrons can more easily be accommodated, since photon conversions result in a much higher background in that region.

VIII. CONCLUSIONS

This analysis expands the reach of previous searches for additional leptons by allowing leptons to be reconstructed from a much lower $p_T$ threshold and with no requirement of isolation. This greatly increases the acceptance to find lepton jets or similar excesses of leptons from effects beyond the SM. No indication of such new effects is seen in the data sample. A 95% confidence level limit is set on an example benchmark model of supersymmetric Higgs production, and a framework is provided to set limits on a class of other models.

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TABLE IV: Summary of predicted and observed event counts by number of additional electrons ($N_e$) and muons ($N_\mu$) after the $Z$ selection. The prediction of a model described in Section [VIA] is also shown for comparison. Bins with less than 0.25 expected events in both signal and background and 0 observed events are not shown.

| $N_e$ | $N_\mu$ | Predicted SM Background | Predicted Dark Higgs Signal | Observed |
|------|--------|-------------------------|-----------------------------|---------|
| 0    | 0      | 215219 ± 36886          | 7.6                         | 211448  |
| 0    | 1      | 255 ± 52                | 1.2                         | 270     |
| 0    | 2      | 3.2 ± 0.89              | 0.54                        | 4       |
| 1    | 0      | 2145 ± 447              | 1.0                         | 1975    |
| 1    | 1      | 30 ± 8.1                | 0.27                        | 20      |
| 1    | 2      | 0.51 ± 0.18             | 0.15                        | 0       |
| 2    | 0      | 175 ± 50                | 0.28                        | 176     |
| 2    | 1      | 4.2 ± 1.5               | 0.10                        | 5       |
| 3    | 0      | 23 ± 9.0                | 0.070                       | 18      |
| 3    | 1      | 0.71 ± 0.31             | 0.031                       | 1       |
| 4    | 0      | 3.4 ± 1.8               | 0.019                       | 2       |
| 5    | 0      | 0.52 ± 0.35             | 0.0044                      | 0       |

TABLE V: Sources of systematic uncertainties. Their size is measured both as a percentage and as the number of events in a benchmark-signal-rich region, defined as a $W$ or $Z$ boson plus at least 3 additional muons with $p_T > 3$ GeV. Note that, although some of the systematics are large, they have little effect in the signal region due to there being negligible SM background.

| Systematic Source                                      | Size          | Effect in Large S/B Region (Events) |
|--------------------------------------------------------|---------------|-------------------------------------|
| Trigger Efficiency [24]                                | ±(1.6 - 5.9)% | ±0.06                               |
| QCD fraction (Sec. [VIA])                              | ±26%          | 0                                   |
| Soft $e$ real rate (Sec. [VIA3])                       | ±15%          | ±0.04                               |
| Soft $\mu$ real rate (Sec. [VIA3])                     | ±15%          | ±0.11                               |
| Soft $\mu$ fake rate (Sec. [VIB3])                     | ±(8-70)%      | ±0.64                               |
| Soft $\mu$ fake rate (Sec. [VIB3])                     | ±10%          | ±0.34                               |
| Soft $e$ normalization (Sec. [VIC])                    | ±(31-39)%     | ±0.24                               |
| Heavy Flavor Fraction (Sec. [VIB])                     | ±(5-34)%      | ±0.25                               |

TABLE VI: Parameters used for the benchmark model based on that in Ref. [8]. The first five parameters are the inputs to the MSSM including the branching fractions for $\chi_0 \rightarrow \chi_d + N\gamma_d$ [34].

| Parameter     | Value     |
|---------------|-----------|
| $\mu$         | 149 GeV   |
| $m_{\chi_1}$  | 13 GeV    |
| $m_{\chi_2}$  | 286 GeV   |
| $\tan(\beta)$ | 3.5       |
| $\sin(\alpha)$| -0.28     |
| $m_{\chi_0}$  | 10 GeV    |
| $m_H$         | 120 GeV   |
| $m_{\chi_d}$  | 1 GeV     |
| $m_{\gamma_d}$| 300 MeV   |

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TABLE VII: Summary of kinematic requirements to find various objects. These numbers can be used to set limits on many models that predict production of additional leptons.

| Object | Requirements | Number Observed |
|--------|--------------|-----------------|
| W      | $p_T(e/\mu) > 20$ GeV | 4,722,370 |
|        | $|\eta(e)| < 1.1, |\eta(\mu)| < 1.5$ | |
|        | $E_T > 25$ GeV | |
|        | $m_T(l, E_T) > 20$ GeV | |
|        | $d\phi(l, E_T) > 0.5$ | |
| Z      | $p_T(e/\mu) > 20$ GeV | 342,291 |
|        | $p_T(e_2) > 12$ GeV, $p_T(\mu_2) > 10$ GeV | |
|        | $|\eta(e)| < 1.1, |\eta(\mu)| < 1.5$ | |
|        | $76$ GeV $< m(l_1, l_2) < 106$ GeV | |
| soft e | $p_T(e) > 2$ GeV | See Tables [I] and [IV] |
|        | $|\eta(e)| < 1$ | |
|        | $\mathcal{L} > 0.99$ (Efficiency in Table [I]) | |
| soft $\mu$ | $p_T(\mu) > 3$ GeV | See Tables [I] and [IV] |
|        | $|\eta(\mu)| < 1.5$ | |
|        | $|\mathcal{L}| < 3.5$ (Efficiency in Table [I]) | |

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[12] The CDF II detector uses a cylindrical coordinate system in which $\phi$ is the azimuthal angle, $r$ is the radius from the nominal beam line, and $z$ points in the proton beam direction. The transverse $(r-\phi)$ plane is perpendicular to the $z$ axis. Transverse momentum and energy are the respective projections of momentum measured in the tracking system and energy measured in the calorimeter system onto the $r-\phi$ plane, and are defined as $p_T = p \sin \theta$, and $E_T = E \sin \theta$. Here, $\theta$ is the polar angle measured with respect to the interaction vertex. Missing $E_T$ ($\vec{E}_T$) is defined by $\vec{E}_T = - \sum_\mathbf{i} E_{T_i} \hat{\mathbf{n}}_i$, where $i$ is the calorimeter tower number for $|\eta| < 3.6$, and $\hat{\mathbf{n}}_i$ is a unit vector perpendicular to the beam axis and pointing at the $i$th tower. The transverse mass $m_T$ is defined as the invariant mass of the sum of the transverse projection of the momentum vector of one decay product and the missing energy vector $\vec{E}_T$. The pseudorapidity $\eta$ is defined as $-\ln(\tan(\theta/2))$, where $\theta$ is measured with respect to the origin of the detector. We define the magnitude $E_T = |\vec{E}_T|$.
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