Search for New Physics in High p_{T} Like-Sign Dilepton Events at CDF II

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We present a search for new physics in events with two high p_T leptons of the same electric charge, using data with an integrated luminosity of 6.1 fb^{-1}. The observed data are consistent with standard model predictions. We set 95% C.L. lower limits on the mass of doubly-charged scalars decaying to like-sign dileptons, $m_{H^{\pm\pm}} > 190 - 245$ GeV$/c^2$, assuming 100% BR to $ee, \mu\mu$ or $e\mu$.

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A wide variety of models of new physics predict events with two like-sign leptons, a signature which has very low backgrounds from the standard model. Examples include doubly-charged Higgs bosons [1], supersymmetry [2], heavy neutrinos [3], like-sign top quark production [4], and fourth-generation quarks [5].

CDF examined the like-sign dilepton data with integrated luminosity of 110 pb^{-1} in Run I [6] and 1 fb^{-1} in Run II [7], observing in Run II a slight excess of events above the standard model expectation (44 observed, 33.2 ± 4.7 expected).

In this Letter, we present a study of events with like-

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sign dileptons with an integrated luminosity of 6.1 fb^{-1} collected by the CDF II detector. We search for a localized excess of events in a model-independent manner by comparing the observed events to the standard model prediction using a Kolmogorov-Smirnov test in several kinematic variables and assessing the statistical consistency. In addition, we set limits on a specific model: pair production of doubly-charged scalars which decay to two like-sign charged leptons [1]. These limits supersede those from CDF in 240 pb^{-1} [8] and are stronger than those from D0 in 1.1 fb^{-1} [9] and CMS in 36 pb^{-1} [10] by an order of magnitude. A companion article [11] includes interpretations for like-sign top quark production and supersymmetric processes.

Events were recorded by CDF II [12, 13], a general purpose detector designed to study collisions at the Fermilab Tevatron $p\overline{p}$ collider at $\sqrt{s} = 1.96$ TeV. A charged-particle tracking system immersed in a 1.4 T magnetic field consists of a silicon microstrip tracker and a drift chamber. Electromagnetic and hadronic calorimeters surround the tracking system and measure particle energies. Drift chambers located outside the calorimeters detect muons. We examine data taken between August 2002 and September 2010, corresponding to an integrated luminosity of 6.1 fb^{-1}.

The data acquisition system is triggered by e or μ candidates [14] with transverse momentum [13], p_T, greater than 18 GeV/c. Electrons and muons are reconstructed offline and selected if they have a pseudorapidity [13], η, magnitude less than 1.1, p_T greater than 20 GeV/c and satisfy the standard CDF identification and isolation requirements [14]. An additional requirement is made to suppress electrons from photon conversions, by rejecting electron candidates with a nearly-collinear intersecting reconstructed track. Jets are reconstructed in the calorimeter using the JETCLU [15] algorithm with a clustering radius of 0.4 in azimuth-pseudorapidity space [13] and calibrated [16]. Jets are selected if they have $p_T \geq 15$ GeV/c and $|\eta| < 2.4$. Missing transverse momentum [17], $\not\!\!E_T$, is reconstructed using fully corrected calorimeter and muon information [14].

We select events with at least two isolated leptons (electrons or muons), two of which have the same electric charge. The leading lepton must have $p_T > 20$ GeV/c, $|\eta| < 1.1$ and be isolated in both the calorimeter and the tracker. The second lepton must satisfy the same requirements, with the exception that it needs only have $p_T > 10$ GeV/c. We require that the two leptons come from the same primary vertex and have a dilepton invariant mass $m_{\ell\ell}$ of at least 25 GeV/c^2 to reduce backgrounds from pair production of bottom quarks. Finally, we reject events with three or more leptons if they contain a pair of opposite-sign leptons or like-signed electrons in the window, $m_{\ell\ell} \in [86, 96]$ GeV/c^2. Like-signed electron pairs may be produced by the radiation of a hard photon, see below, which is negligible for muons. In each event, we calculate H_T, the scalar sum of the lepton p_T, the jet E_T and the missing transverse momentum.

Irreducible backgrounds to the like-sign dilepton signature with prompt like-sign leptons are rare in the SM; they are largely from WZ and ZZ production where one or two final state leptons are not seen in the detector. These backgrounds are modeled using simulated events generated by PYTHIA [18] with the detector response simulated with a GEANT-based algorithm CDFSIM [19].

The dominant reducible background comes from W+jets production or $t\bar{t}$ production with semi-leptonic decays, with one prompt lepton (e.g. $W \to \ell\nu$ or $t \to Wb \to \ell\nu b$) and a second lepton due to the semi-leptonic decay of a b- or c-quark hadron (e.g. $b + X \to c\mu\nu + X$) which is misidentified as a prompt lepton from real W or Z boson decay. This ("fake") background is described using a lepton misidentification model from inclusive jet data applied to W+jet events, validated in orthogonal jet samples and in events with like-sign dileptons but low invariant mass: $m_{\ell\ell} \in [15, 25]$ GeV/c^2.

The second largest source of background comes from the effective charge flip of an electron or positron due to hard photon radiation followed by asymmetric pair creation, such as $e^-_{\mathrm{hard}} \to e^-_{\mathrm{soft}}\gamma \to e^-_{\mathrm{soft}}e^-_{\mathrm{soft}}e^+_{\mathrm{hard}}$ where the track for the e^+_{hard} determines the charge. This mechanism is well-described by the detector simulation, and is validated in events with like-sign electron pairs which have a conversion-tagged electron. The major contributions via this mechanism are from Z/γ^*+jets and $t\bar{t}$ production with fully leptonic decays. Estimates of the backgrounds from Z/γ^*+jets processes are modeled using simulated events generated by PYTHIA normalized to data in opposite-sign events. The detector response for both Z+jets and $t\bar{t}$ processes is evaluated using CDFSIM, where, to avoid double-counting, the like-sign leptons are required to originate from the W or Z boson decays rather than from misidentified jets.

An additional contribution to the background is due to associated production of a W boson with a prompt photon. If the W boson decays to an electron (muon) and the photon converts too early to be identified as a conversion, the event can be reconstructed with a like-sign ee ($e\mu$) signature. The rate of $W\gamma$ production and the efficiency for finding conversions is validated in a sample of like-sign electron events with a conversion-tagged electron.

Backgrounds from charge-mismeasurement are insignificant, as the charge of a particle with momentum of 100 GeV/c is mismeasured at a rate less than 1×10^{-5} [20].

The dominant systematic uncertainty is the 50% uncertainty of the lepton misidentification rate, which is measured in the inclusive jet sample but may contain prompt leptons from $W \to l\nu$ and $Z \to \ell\ell$ boson decays. This gives a 20% uncertainty on the total background. Additional uncertainties are due to the jet en-

TABLE I: Predicted and observed event yields in like-sign lepton events. Uncertainties include statistical and systematic contributions. Entries written as — are negigible.

Process	Total $\ell\ell$	$\mu\mu$	ee	$e\mu$
$t\bar{t}$	0.1 ± 0.1	—	—	0.1 ± 0.1
$Z \to \ell\ell$	26.6 ± 3.4	—	17.0 ± 2.8	9.7 ± 2.1
WW, WZ, ZZ	28.4 ± 1.4	7.9 ± 0.9	6.0 ± 0.4	14.5 ± 0.8
$W(\to \ell\nu)\gamma$	16.2 ± 2.4	—	8.1 ± 1.8	8.0 ± 1.8
Fake Leptons	51.6 ± 24.2	8.2 ± 5.3	22.1 ± 8.9	21.3 ± 10.6
Total	123.0 ± 24.6	16.1 ± 5.4	53.3 ± 9.5	53.6 ± 10.9
Data	145	14	66	65

TABLE II: Results of KS-distance test for standard model prediction. The maximum KS distance and corresponding p-value are given for several kinematic distributions presented in this analysis.

Distribution	Total $\ell\ell$	ee	$\mu\mu$	$e\mu$
$m_{\ell\ell}$	0.11 (79%)	0.22 (47%)	0.23 (46%)	0.30 (59%)
$\not{E}_T$	0.19 (34%)	0.23 (27%)	0.24 (32%)	0.21 (69%)
N_{jets}	0.19 (56%)	0.31 (31%)	0.20 (57%)	0.21 (84%)
Lepton 1 p_T	0.16 (49%)	0.18 (47%)	0.25 (30%)	0.26 (60%)
Lepton 2 p_T	0.12 (66%)	0.21 (41%)	0.23 (33%)	0.40 (33%)
H_T	0.15 (45%)	0.22 (34%)	0.22 (32%)	0.24 (58%)

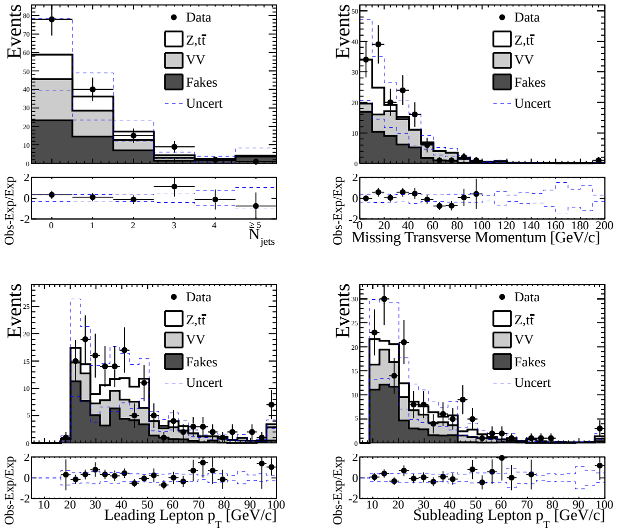

FIG. 1: Distribution of jet multiplicity, missing transverse momentum, leading lepton p_T and sub-leading lepton p_T in observed like-sign dilepton events and expected backgrounds. The VV contribution includes WW, WZ, ZZ and $W\gamma$.

ergy scale [16], contributions from additional interactions, and descriptions of initial and final state radiation [21] and uncertainties in the parton distribution functions [22, 23].

Table I shows the observed and predicted event yields. Figure 1 shows kinematic distributions of observed and predicted like-sign lepton events.

We calculate the maximum Kolmogorov-Smirnov (KS) distance for each the distributions $m_{\ell\ell}$, $\not{E}_T$, N_{jets}, lepton p_T and H_T. A large KS distance value would indicate a localized excess in one of these variables, though this test is not sensitive to discrepancies in the total yield. In each case, the standard model p-value (probability to observe a result at least this discrepant from the standard model) does not indicate significant deviation from the background-only hypothesis; see Table II.

This larger dataset does not show evidence of the excess seen in the previous analysis [7] that was based on 1 fb^{-1} of integrated luminosity. The background from misidentified leptons was calculated using a different technique, which gives a larger estimate of events with misidentified leptons in the original dataset than the previous analysis, though consistent within systematic uncertainties.

Observing no excess, we report our sensitivity in terms of limits on doubly-charged scalar bosons decaying to like-sign electron pairs, muon pairs or electron-muon pairs. Simulated events are generated with MADEVENT [24], showering and hadronization is performed by PYTHIA passed through the CDF II full detector simulation. Figure 2 shows the observed and expected standard model spectra in the $ee, \mu\mu$ and $e\mu$ channels.

The largest uncertainties on the signal model are due to energy resolution and lepton identification efficiencies, which are minor compared to the background uncertainties. In each case, we treat the unknown underlying quantity as a nuisance parameter and measure the distortion of the dilepton mass spectrum for positive and negative fluctuations.

The dilepton mass spectrum is in good agreement with the standard model prediction, and we calculate 95% C.L. upper limits on the production cross section of doubly-charged Higgs bosons, using frequentist statistics with the unified ordering scheme [25]. The Z/γ^* coupling and therefore production cross-section of the doubly-charged Higgs boson depends on whether it is a member of a singlet, doublet or triplet, as shown in Fig. 3 and Tables III and IV.

In summary, we present a search for new physics in events with two high p_T leptons of the same electric charge using data with an integrated luminosity of 6.1 fb^{-1}. The observed data are consistent with standard model predictions. We set 95% C.L. lower limits on the mass of doubly-charged scalars decaying to like-sign dileptons, $m_{H^{\pm\pm}} >$ 190-245 GeV/c^2, assuming 100% BR to $ee, \mu\mu$ or $e\mu$.

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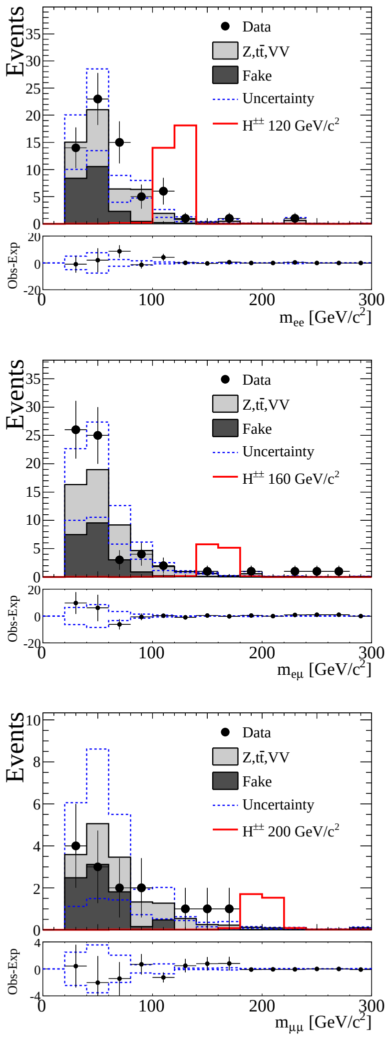

FIG. 2: The observed and expected standard model spectra in the $ee, \mu\mu$ and $e\mu$ channels. The doubly-charged Higgs boson signal is shown for a range of masses. The VV contribution includes WW, WZ, ZZ and $W\gamma$.

TABLE III: For various Higgs masses, the NLO cross sections for singlet (σ_1), doublet (σ_2), triplet (σ_3) production, expected and observed 95% C.L. limits in the $ee, e\mu$ and $\mu\mu$ channels. All cross-sections are in femtobarns and assume 100% BR to each channel.

$m_{H^{\pm\pm}}$	Theory			Observed			Expected		
(GeV/c^2)	σ_1	σ_2	σ_3	σ^{95}_{ee}	$\sigma^{95}_{e\mu}$	$\sigma^{95}_{\mu\mu}$	σ^{95}_{ee}	$\sigma^{95}_{e\mu}$	$\sigma^{95}_{\mu\mu}$
100	48	55	120	12	4.2	3.1	5.7	3.8	2.8
120	23	27	55	7.4	2.3	2.2	3.3	2.6	2.2
140	11	14	26	2.0	2.2	3.4	2.4	2.2	1.6
160	6.0	7.2	14	2.4	2.2	3.2	1.5	1.9	1.4
180	3.2	3.9	7.7	2.3	2.2	2.6	1.5	1.7	1.5
200	1.8	2.2	4.2	1.2	2.4	1.6	1.5	1.4	1.5
220	1.0	1.2	2.4	2.3	3.4	1.2	1.4	1.1	1.4
240	0.6	0.7	1.4	1.7	4.4	1.2	1.4	1.1	1.3
260	0.3	0.4	0.8	1.2	4.0	1.1	1.5	1.0	1.2

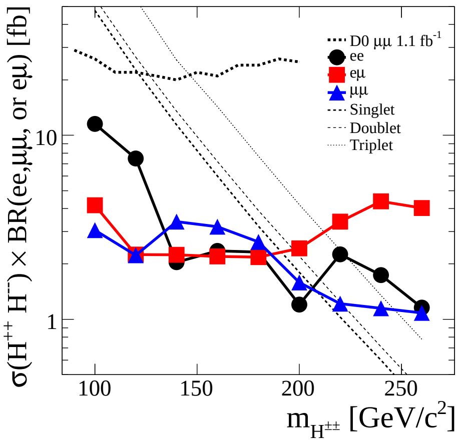

FIG. 3: Observed upper limits at 95% C.L. on the production cross-section for doubly-charged Higgs times the branching fraction to $ee, \mu\mu$ or $e\mu$ exclusively, compared to results from D0 [9]. Also shown are next-to-leading-order theoretical calculations of the cross-section, assuming the Higgs is a member of a singlet, doublet or triplet.

TABLE IV: Lower limits at the 95% C.L. on $H^{\pm\pm}$ masses by channel, for singlet, doublet and triplet theories. All in units of GeV/c^2. In each case, we assume 100% BR to each channel.

	Theory		
Channel	Triplet	Doublet	Singlet
ee	225	210	205
$e\mu$	210	195	190
$\mu\mu$	245	220	205

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