Inclusive search for new physics with like-sign dilepton events in p(p)over-bar collisions at root s=1.96 TeV

A. Abulencia, J. Adelman, T. Affolder, T. Akimoto, M. G. Albrow, D. Ambrose, S. Amerio, D. Amidei, A. Anastassov, K. Anikeev, A. Annovi, J. Antos, M. Aoki, G. Apollinari, J. F. Arguin, T. Arisawa, A. Artikov, W. Ashmanskas, A. Attal, F. Azfar, P. Azzi-Bacchetta, P. Azzurri, N. Bacchetta, W. Badgett, A. Barbaro-Galtieri, V. E. Barnes, B. A. Barnett, S. Baroiant, V. Bartsch, G. Bauer, F. Bedeschi, S. Behari, S. Belforte, G. Bellettini, J. Bellinger, A. Belloni, D. Benjamin, A. Beretvas, J. Beringer, T. Berry, A. Bhatti, M. Binkley, D. Bisello, R. E. Blair, C. Blocker, B. Blumenfeld, A. Bocci, A. Bodek, V. Boisvert, G. Bolla, A. Bolshov, D. Bortoletto, J. Boudreau, A. Boveia, B. Brau, L. Brigliadori, C. Bromberg, E. Brubaker, J. Budagov, H. S. Budd, S. Budd, S. Budroni, K. Burkett, G. Busetto, P. Bussey, K. L. Byrum, S. Cabrera, M. Campanelli, M. Campbell, F. Canelli, A. Canepa, S. Carillo, D. Carlsmith, R. Carosi, S. Carron, M. Casarsa, A. Castro, P. Catastini, D. Cauz, M. Cavalli-Sforza, A. Cerri, L. Cerrito, S. H. Chang, Y. C. Chen, M. Chertok, G. Chiarelli, G. Chlachidze, F. Chlebana, I. Cho, K. Cho, D. Chokheli, J. P. Chou, G. Choudalakis, S. H. Chuang, K. Chung, W. H. Chung, Y. S. Chung, M. Ciljak, C. I. Ciobanu, M. A. Ciocci, A. Clark, D. Clark, M. Coca, G. Compostella, M. E. Convery, J. Conway, B. Cooper, K. Copic, M. Cordelli, G. Cortiana, F. Crescioli, C. C. Almenar, J. Cuevas, R. Culbertson, J. C. Cully, D. Cyr, S. DaRonco, M. Datta, S. D'Auria, T. Davies, M. D'Onofrio, D. Dagenhart, P. de Barbaro, S. De Cecco, A. Deisher, G. De Lentdecker, M. Dell'Orso, F. D. Paoli, L. Demortier, J. Deng, M. Deninno, D. De Pedis, P. F. Derwent, G. P. Di Giovanni, C. Dionisi, B. Di Ruzza, J. R. Dittmann, P. DiTuro, C. Dorr, S. Donati, M. Donega, P. D. J. Donini, T. Dorigo, S. Dube, J. Efron, R. Erbacher, D. Errede, S. Errede, R. Eusebi, H. C. Fang, S. Farrington, I. Fedorko, W. T. Fedorko, R. G. Feild, M. Feindt, J. P. Fernandez, R. Field, G. Flanagan, A. Foland, S. Forrester, G. W. Foster, M. Franklin, J. C. Freeman, I. Furic, M. Gallinaro, J. Galyardt, J. E. Garcia, F. Garberson, A. F. Garfinkel, C. Gay, H. Gerberich, D. Gerdes, S. Giagu, P. Giannetti, A. Gibson, K. Gibson, J. L. Gimmell, C. Ginsburg, N.

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We describe a search for anomalous production of events with two leptons (e or μ) of the same electric charge in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. Many extensions to the standard model predict the production of two leptons of the same electric charge. This search has a significant increase in sensitivity compared to earlier searches. Using a data sample corresponding to 1 fb^{-1} of integrated luminosity recorded by the CDF II detector, we observe no significant excess in an inclusive selection (expect 33.2 ± 4.7 events, observe 44) or in a supersymmetry-optimized selection (expect 7.8 ± 1.1 events, observe 13.)

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The standard model (SM) of particle physics successfully describes all experimental data taken in high energy collisions so far. Despite its successes, there are strong indications that this theory is only an effective low-energy model and new physics must be present at a higher energy scale. An excellent signature to search for deviations from the SM is production of two leptons with both leptons of the same electric charge. This signature occurs naturally in many extensions to the SM and occurs rather rarely in SM interactions.

An example of a model predicting like-sign dileptons is one with a Majorana particle that decays through SM-like bosons into leptons. Heavy Majorana neutrinos (ν_M) can be produced in $p\bar{p}$ collisions in association with a lepton through a virtual W boson ($p\bar{p} \rightarrow \nu_M \ell^{\pm} X$) [1]. This new particle can subsequently decay to a W and another lepton ($\nu_M \rightarrow W^{\pm}\ell^{\mp}$). Given the Majorana nature of this neutrino, i.e., that it is its own antiparticle, more than half of such events will contain like-sign dileptons in the final state. Another example is the class of models that predict new heavy analogs to the W and Z bosons. For instance, in supersymmetric extensions of the SM, a chargino-neutralino pair can be produced ($p\bar{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 X$) and decay into final states with three charged leptons ($\tilde{\chi}_1^{\pm} \rightarrow \ell^{\pm}\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$) [2]. Two of those three leptons will have the same charge.

The CDF and D0 Collaborations have previously investigated events with two same-charge leptons [3,4]. In this Letter, we present a more general search using data collected with the CDF II detector during the Tevatron's Run II data-taking phase at a center-of-mass energy of 1.96 TeV. We select events as inclusively as possible without optimizing for any particular new physics scenario. To avoid bias, we fix the final event selection criteria before examining the event yield in the signal region. The selection produces a relatively small sample that we investigate for deviations from SM predictions, both in the total number of events and in the shape of kinematic distributions. We use a data sample corresponding to 1 fb^{-1} of integrated luminosity collected between March 2002 and February 2006. This search has better acceptance and examines between a factor of 3 and a factor of 10 more integrated luminosity compared to earlier searches in the same channel, resulting in roughly a factor of 3 increase in the sensitivity to new physics.

The CDF II detector is a general purpose particle detector and is described in detail elsewhere [5]. It has a solenoidal charged particle spectrometer, consisting of 7–8 layers of silicon microstrip detectors and a cylindrical drift chamber immersed in a 1.4 T solenoidal magnetic field, a segmented sampling calorimeter, and a set of charged particle detectors outside the calorimeter used to identify muon candidates. The fiducial region of the silicon microstrip detector extends to $|\eta| \sim 2$ [6], while the drift chamber provides tracking for $|\eta| \lesssim 1$. The curvature resolution of the chamber is $\sigma_C = 3.6 \times 10^{-6}\ \mathrm{cm}^{-1}$ [7]. The curvature corresponding to a track with momentum of 100 GeV/c is $2.1 \times 10^{-5}\ \mathrm{cm}^{-1}$. The sign of the curvature of a track with 100 GeV/c of transverse momentum, and hence the charge of such a particle, is thus typically determined with a significance of better than 5 standard deviations.

We use data collected with a high-momentum central lepton trigger, which identifies events with an electron candidate with $E_T > 18$ GeV and $|\eta| \lesssim 1$ or a muon candidate with $p_T > 18$ GeV/c and similar η requirements. We select events with a pair of same-charge leptons (electrons or muons) regardless of other activity in the event. This analysis uses lepton candidates with $|\eta| \lesssim 1$. The tracks associated with the leptons have to share a common vertex; i.e., they come from the same $p\bar{p}$ interaction. We define the two highest-momentum charged leptons passing our selections as the leading and subleading lepton. We select leading and subleading electrons that fulfill the following requirements on the transverse component of the energy: $E_T > 20$ GeV and $E_T > 10$ GeV, respectively. We select muons that pass similar transverse momentum requirements. We remove photon-conversion electrons using a procedure described below. Cosmic-ray muons are identified and removed by looking for a track opposite to the reconstructed muon candidate which has timing information that is consistent with a particle moving toward the beam line rather than away from it. We also place a minimum requirement on the invariant mass of the lepton pair, $m_{\ell\ell} > 25\ \mathrm{GeV}/c^2$, to remove the large background from Drell-Yan and heavy quark production at low mass. The leptons must be isolated from other particles in the event, both in the calorimeter and in the tracking chamber. An electron (muon) is considered to be isolated in the calorimeter if the sum of the transverse energy within a cone $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.4$, minus the lepton E_T, is less than 10% of the lepton $E_T(p_T)$. Similarly, if the total transverse momentum of all other tracks within a cone $\Delta R \leq 0.4$ around the lepton is less than 10% of the candidate track p_T, the lepton is considered to be isolated in the tracking chamber.

SM backgrounds that produce like-sign dileptons in the final state include Drell-Yan dilepton production with a photon that is radiated off a final-state lepton and converts into an e^+e^- pair which fails our conversion identification algorithm (i.e., is not "tagged") as well as diboson production. The latter includes on- and off-shell ZZ and WZ production followed by decay into leptonic final states, as well as $Z\gamma$ and $W\gamma$ with the photon converting into two electrons inside the detector. In the following, we refer to the above Drell-Yan and $Z\gamma$ processes as $\ell\ell\gamma$ backgrounds and to the $W\gamma$ and WZ processes as WV. Events with $W(\rightarrow \ell\nu) + 1$ jet and $Z(\rightarrow \ell\ell) + 1$ jet where the jet is falsely identified as a lepton can also result in two lepton candidates with the same charge. Contributions from $t\bar{t}$, $b\bar{b}$ backgrounds are found to be negligible.

To estimate the background contribution from the $\ell\ell\gamma$ and diboson processes, we determine geometric and kinematic acceptance using Monte Carlo calculations followed by a GEANT-based simulation of the CDF II detector [8]. We use the Monte Carlo generator described in Ref. [9] for the $W\gamma$ background, MADEVENT for the WZ background [10], and PYTHIA for the other SM processes [11]. We use the CTEQ5L parton distribution functions to model the momentum distribution of the initial-state partons [12].

The expected number of events for each background component is determined as the product of the cross section, the luminosity of the sample, and the acceptance of the detector. The last is corrected for trigger efficiency and differences in lepton reconstruction efficiency between the data and the simulation. These efficiencies are derived via studies of $W(\to \ell\nu)$ and $Z(\to \ell^+\ell^-)$ events, and the differences are typically less than 10%.

Events with untagged photon conversions represent the dominant background to this search. To tag photon conversions, we take advantage of the kinematic condition that the trajectories of the electron and the positron from the photon are approximately parallel at the conversion point. We define the following variables: Δs is the distance in the transverse plane between the two tracks at the point that the two tracks are parallel, $\Delta\cot(\theta)$ is the difference in the cotangents of the polar angles between the two tracks, and Δz is the distance in the z dimension between the two points on the tracks used to compute Δs. A track pair is tagged as a photon conversion if $\Delta s < 1.1$ cm, $|\Delta\cot(\theta)| < 0.26$, and $\Delta z < 1.2$ cm. These thresholds are chosen to maximize the rejection power for conversions while having a negligible impact on the efficiency for nonconversion electrons. Conversion tagging will fail due to inefficiencies of the above selection or due to very asymmetric conversions, where the momentum of either the electron or the positron drops below our track selection threshold of $p_T > 500$ MeV$/c$.

Processes producing opposite-charge leptons, such as Drell-Yan dilepton production, can contribute to our backgrounds if one of the lepton tracks is poorly measured and its charge is incorrectly reconstructed. The charge of a particle is determined from the direction the particle curves in the magnetic field. We test our understanding of the charge misassignment mechanism by examining the modeling of the curvature uncertainty. The uncertainty on the curvature measured in the tracking chamber provides an estimate of the probability of incorrectly measuring the sign of a track's curvature. For this purpose, we select electrons from events with two electrons where one electron is identified based solely on its energy deposits in the calorimeter and examine the curvature uncertainty for this particle. We find that the uncertainty on the track curvature of this data sample is well described by our simulation of the detector. The estimated residual background from events containing a lepton with an incorrectly reconstructed charge is less than 0.1 events in the current sample.

Jets in W + jet and Z + jet events can be misidentified as leptons ("fakes") and paired with the lepton from the gauge boson decay to form a same-charge candidate event. We estimate this background by selecting a sample of events with one or more high-momentum leptons that pass our selection criteria, omitting events with same-sign lepton candidates. We determine the number of events in our final selection from this fake background by multiplying the number of isolated tracks in this sample by the misidentification probability ("fake rate"). This probability is measured in a sample triggered by at least one jet with $E_T > 50$ GeV and is defined as the number of identified leptons, divided by the total number of isolated tracks. We parametrize the fake rate as a function of p_T and η.

As a further means of controlling untagged photon conversions, we divide the electron candidates into two categories: with and without energy depositions in the silicon microstrip detector ("silicon hits"). Since most photon conversions occur either in the material of this detector or in the inner wall of the drift chamber, electrons with silicon hits are less likely to come from a conversion process. We consider the more pure category of electrons with silicon hits (e_{Si}) separately from those without (e). By considering these two classes independently rather than requiring all electrons to have silicon hits, we do not lose acceptance due to inefficiencies in the silicon microstrip detector but gain in statistical power.

We perform numerous tests to assure that we are able to model our backgrounds. These tests can be split into two categories: those that test the overall normalization of a background and those that test our ability to model detector performance. To probe the overall normalization of the diboson $Z\gamma$ background estimate, we select events with two leptons and a photon with transverse momentum thresholds of 20, 10, and 10 GeV$/c$, respectively. The predicted number of events for this selection is 258 ± 16 events, dominated by $Z\gamma$ production. We observe 258 events, in good agreement. Similarly, we probe the normalization of the $W\gamma$ background by selecting events with one lepton with $p_T > 20$ GeV$/c$, a photon with $E_T >$ 10 GeV, and $\not{E}_T > 15$ GeV. Using this selection, we expect 1493 ± 90 events, dominated by $W\gamma$ production. We observe 1540 events, in good agreement with our expectation. For both of the above measurements, we require the photon to be well separated from either the electron or muon, thereby effectively limiting the contribution from photons radiated in the material of the detector. We check our modeling of the material in the detector by selecting events with one electron, one photon, and $\not{E}_T < 20$ GeV. These are mostly Drell-Yan events in which one electron has lost most of its energy to a radiated photon. For this selection, we predict 243 ± 15 events and observe 269, thereby validating our understanding of the detector material. Other backgrounds are tested using dedicated selection criteria. We obtain good agreement between the observed and predicted events both in integral counts and kinematic distributions in all regions considered.

The uncertainty on the number of predicted background events is dominated by the uncertainty on the luminosity measurement (5%), the fake estimate (5%), and the conversion modeling (10%). Other uncertainties include those associated with the SM cross sections, lepton reconstruction, and the statistical uncertainty on the Monte Carlo acceptance calculation.

TABLE I. Event counts predicted (n_{pred}) and observed (n_{obs}), per category. The uncertainties for different channels are correlated. $n_{\ell\ell\gamma}$, n_{WV}, n_{ZZ}, and n_{fake} refer to the number of background events predicted in the $\ell\ell\gamma$, WV ($V = Z$ or γ), ZZ, and "fake" categories, respectively, and n_{pred} is the sum. e_{Si} and e refer to electron candidates with and without energy deposits in the silicon microstrip detector.

	n_{obs}	n_{pred}	$n_{\ell\ell\gamma}$	n_{WV}	n_{ZZ}	n_{fake}
$e_{\mathrm{Si}}e_{\mathrm{Si}}$	11	6.3 ± 1.0	3.2	1.4	0.4	1.3
ee	3	1.3 ± 0.3	0.9	0.1	0.0	0.2
$e_{\mathrm{Si}}e$	9	9.1 ± 1.8	6.4	1.6	0.1	1.0
$e_{\mathrm{Si}}\mu$	11	6.8 ± 0.8	0.8	2.8	1.1	2.1
$e\mu$	5	6.4 ± 1.2	3.4	1.9	0.2	0.9
$\mu\mu$	5	3.2 ± 0.3	0.1	1.4	0.8	0.8
Total	44	33.2 ± 4.7	14.9	9.3	2.5	6.4

TABLE II. Event counts with additional selection criteria for a SUSY-like physics scenario. The table headings are explained in the caption to Table I.

	n_{obs}	n_{pred}	$n_{\ell\ell\gamma}$	n_{WV}	n_{ZZ}	n_{fake}
$e_{\mathrm{Si}}e_{\mathrm{Si}}$	1	1.3 ± 0.3	0.4	0.6	0.0	0.4
ee	1	0.1 ± 0.1	0.0	0.1	0.0	0.0
$e_{\mathrm{Si}}e$	2	1.5 ± 0.3	0.1	1.2	0.0	0.2
$e_{\mathrm{Si}}\mu$	4	1.7 ± 0.2	0.0	1.0	0.1	0.7
$e\mu$	4	2.3 ± 0.5	0.6	1.4	0.0	0.2
$\mu\mu$	1	0.9 ± 0.1	0.0	0.5	0.1	0.4
Total	13	7.8 ± 1.1	1.1	4.7	0.2	1.8

New physics scenarios that lead to like-sign dilepton events, such as the ones mentioned in the introduction to this Letter, often have a WZ-like topology. As such, SM WZ production provides a reference point for the sensitivity of this analysis. The product of geometric acceptance, kinematic acceptance, and like-sign dilepton identification efficiencies ($\mathcal{A}_{\mathrm{geo}} \times \mathcal{A}_{\mathrm{kin}} \times \epsilon$) for leptonic decays for on-shell SM WZ production, given as a proxy for the sensitivity of this analysis, is 8.0%.

In Table I, we present the expected and observed number of events with two same-charge leptons in all different combinations of leptons considered. Combining all channels, we predict 33.2 ± 4.7 events and observe 44. The probability that 33.2 events with an uncertainty of 4.7 events fluctuate to 44 or more is 9%. Figure 1 shows the comparison between the predicted and observed events for several kinematic distributions of interest.

In Table II, we present the expected and observed number of events after imposing two additional requirements aimed at increasing the signal sensitivity for a supersymmetry (SUSY)-like physics scenario where the stable, neutral, and lightest supersymmetric particle escapes detection. We require a large transverse momentum imbalance ($\not\!\!E_T > 15$ GeV) and reject events in which the invariant mass of one of our selected leptons and another lepton of the same flavor and opposite charge are consistent with a Z boson ($66 < m_{\ell^+\ell^-} < 116\ \mathrm{GeV}/c^2$). We predict 7.8 ± 1.1 events and observe 13. The probability that 7.8 events with an uncertainty of 1.1 events fluctuate to 13 or more is 7%. The value of $\mathcal{A}_{\mathrm{geo}} \times \mathcal{A}_{\mathrm{kin}} \times \epsilon$ for WZ events, as described above but adding a $\not\!\!E_T > 15$ GeV requirement, is 7%.

In conclusion, we have performed a search for events with two leptons of the same electric charge using the CDF

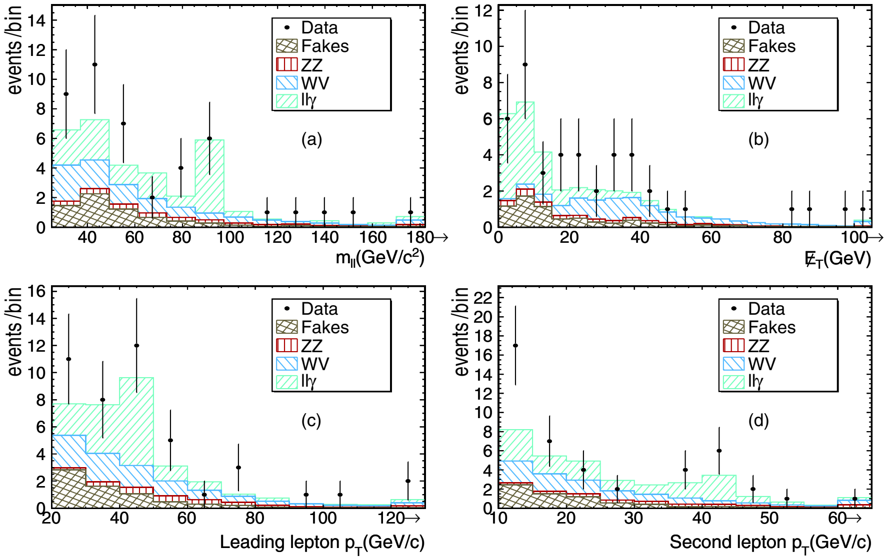

FIG. 1 (color online). Invariant mass distribution $m_{\ell\ell}$ of the selected leptons (a), $\not\!\!E_T$ (b), leading (c), and subleading (d) lepton transverse momentum in data and simulation. The rightmost bins are overflow bins. The peak at $m_{\ell\ell} \approx 90$ GeV is mostly due to Drell-Yan di-electron production with hard radiation off one electron, followed by an asymmetric conversion.

Run II data. We observe a slight excess in the number of predicted events in almost all lepton categories. However, the kinematic distributions do not show any anomalous deviation from expectations in any particular region of parameter space. Large future data sets expected at the Tevatron will reveal whether this observed slight excess persists.

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