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Search for Doubly Charged Higgs in Lepton Flavor Violating Decays involving Taus

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Abstract

We search for the pair production of doubly charged Higgs particles followed by the lepton-flavor violating decay of each Higgs into dileptons ($H_L^{++}H_L^{--} \rightarrow l^+l'^+l^-l'^-$) using 350 pb^{-1} of data collected at $\sqrt{s} = 1.96$ TeV by the CDF II experiment at the Fermilab Tevatron. Both three and four-body signatures are investigated, and the results of the searches are combined. Assuming exclusive same-sign dilepton decays, we derive lower mass limits of 113.6 GeV/$c^2$and 112.1 GeV/c^2at the 95 % confidence level for the $H_L^{\pm\pm}$ in the $e\tau$ and $\mu\tau$ channels respectively.

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Many extensions of the Standard Model (SM) include enhanced Higgs sectors[1, 2, 3]. The left-right symmetric $(SU(2)_L \times SU(2)_R \times U(1)_{B-L})$ extensions of the SM, for example, cast parity violation as a low-energy phenomenon by positing a right-handed weak interaction broken above the electroweak scale. These models predict small but nonzero neutrino masses that are related to the suppression of the right-handed weak current[4]. An important phenomenological feature of these models is the prediction of doubly-charged Higgs bosons ($H^{\pm\pm}$) as a part of a Higgs triplet. In supersymmetric frameworks these bosons may be as light as 100 GeV/c^2, and may decay primarily to leptons[10].

The doubly-charged Higgs Bosons are annotated as $H^{\pm\pm}_L$ and $H^{\pm\pm}_R$ according to their exclusive coupling to left or right handed particles, respectively. The only significant production mode at the Tevatron is $p\bar{p} \to \gamma^*/Z \to H^{++}H^{--}$[10]. The $H^{\pm\pm}$ can couple to charged leptons, W's, and singly-charged Higgs. At masses below 160GeV, the bosonic decay-modes are phase-space suppressed. The flavor composition for leptonic decays is theoretically unrestricted. In this search we are interested in the lepton flavor violating (LFV) decay modes $H^{\pm\pm} \to l^{\pm}\tau^{\pm}$, with l as an electron or muon. The partial width for flavors l and $l^{'}$ is $\Gamma_{ll'} = h^2_{ll'} m(H^{\pm\pm})/(8\pi)$. The relevant experimental bounds on phenomenological couplings $h_{ll'}$ derive from unseen decays of muons and taus[7]. We are interested in the range $h_{l\tau}$ >10^{-5}, resulting in prompt decays with $c\tau < 10\mu m$.

The $H^{\pm\pm}$ is excluded to 100 GeV/c^2 assuming 100% branching ratio to any one dilepton decay channel [12, 13]. Recent searches from the Tevatron have resulted in more stringent limits on the ee, $e\mu$, and $\mu\mu$ channels [14, 15]. We search for pair production of $H^{\pm\pm}$ followed either by LFV decays into electrons and taus or LFV decays into muons and taus using 350 pb^{-1} of data collected at $\sqrt{s}$ = 1.96 TeV by the CDF II experiment at the Fermilab Tevatron. We set the world's highest mass limits for $10^{-5} < h_{llprime}$ <0.5. The mass limits assume the $H^{\pm\pm}$ production model [4], and exclusive decays into the e+τ or μ+τ channels.

The CDF detector consists of (ordered by increasing radius) silicon and drift tracking chambers, sampling electromagnetic (EM) and hadronic calorimeters, and outer drift chamber muon detectors. The EM calorimeter has an embedded multiwire proportional chamber which enables better spacial resolution of developing EM showers. This subdetector, called the 'shower max detector' is useful for the identification of electrons and photons, and allows reconstruction of π^0's associated with hadronic tau decays.

We require at least three isolated leptons in our signature in order to suppress hadronic backgrounds such as γ+Jets and W$\to l\nu_l$+Jets. The events are classified according to the number of isolated high-P_T leptons reconstructed (3 or 4) and separate analyses are carried out for the '3-lepton' and '4-lepton' signatures. The data for the exclusive eτ search is collected by an electron + isolated track trigger[5], which requires one energy cluster with E_T >8 GeV in the EM calorimeter with a matching track of at least 8 GeV/c in P_T, as well as a second track of at least 5 GeV/c with tau-style track isolation (described later, and in detail in [5]), both in central (pseudorapidity $|\eta| < 1$) region. The integrated luminosity of the eτ sample is (350$\pm$ 21) pb^{-1}. For the $\mu\tau$ analysis, data is collected by a muon + isolated track trigger[5], which is identical to the electron + track trigger, except for the substitution of the electron with a muon (reconstructed as a track with 8 GeV/c in P_T with corresponding hits in the outer muon chambers). The integrated luminosity of the $\mu\tau$ sample is (322$\pm$ 19) pb^{-1}. The luminosity is determined by measuring the rate of inelastic collisions, and the associated uncertainty has equal parts from the uncertainties on inelastic cross section and on the acceptance of the luminosity counters.

The base lepton requirements for the exclusive electron+tau decay mode are one tight central electron with E_T >20 GeV and track P_T >10 GeV/c, one loose central electron or hadronic tau-candidate with E_T > 15 GeV, and another loose electron or hadronic tau-candidate with E_T > 10 GeV in the pseudorapidity region $|\eta|$ < 1.3. For the exclusive muon+tau decay mode, the base letpon requirements are a tight central muon with P_T > 20 GeV/c, one loose central electron or hadronic tau-candidate with E_T > 15 GeV, and another lepton of any flavor with E_T > 10 GeV. Tight muons are required to have tracks that extrapolate to hits in the outer muon detectors. Tight electrons are required have track-cluster matching, EM to hadronic calorimeter deposition ratios (Em fraction), energy to momentum ratios, and lateral shower profiles consistent with those of electrons. Loose electrons are identical to tight electrons but have less stringent track-cluster matching and lateral shower profile requirements. Hadronic tau candidates must have 1 or 3 localized tracks, and possibly some associated π^0's reconstructed in the shower max detector. The localization is defined by a 3-D angle about the highest P_T track associated with the tau. The default value for this angle is 10°, but the angle is adjusted according to the measured boost of the tau candidate. The cone defined by the angle is called the 'signal cone'. Hadronic tau candidates must have reconstructed masses and charges consistent with taus. In order to suppress hadronic backgrounds, all lepton candidates are required to be isolated. Both muons and electrons are required have less than 2 GeV/c of tracking activity within a 3-D angle of 23° of the direction defined by the track associated with the lepton. For track isolation, the tau must have less than 2 GeV/c of tracking activity between the signal cone and a larger, 30° cone. Hadronic tau candidates must also have less than 0.5 GeV of π^0 activity between the signal cone and the larger, 30° cone. All lepton candidates must pass track quality requirements. The tracks must all pass within 2mm of the beam line, and must also pass within 5cm of each other at the beam line. Tracks must have a sufficient number of hits in the drift chamber in order to ensure a good measurement of momentum. For the muon+tau analysis, a more stringent requirement is made on the curvature resolution of the highest P_T track in the event in order to avoid mismeasurement of very high-Pt tracks. The efficiency associated with this requirement is taken from data and is 99.3%. The efficiencies of lepton reconstruction, ID and isolation requirements are measured in data from leptonic decays of Υ's, Z's and W's, and corresponding efficiencies in MC are adjusted by scale factors if necessary. Trigger efficiency for the electron leg is measured using a photon conversion sample and parametrized as a function of electron E_T and P_T. The efficiency for the track leg is measured from a jet sample and parametrized as a function of track curvature and isolation. The trigger efficiency for the muon leg is taken from a $Z \rightarrow \mu^+\mu^-$ sample.

After lepton ID, the event-level cuts for the muon+tau and electron+tau searches are very similar. If an event has three isolated leptons, we look for a fourth isolated lepton. The requirements here are identical to those of the third lepton candidate of the muon+tau analysis. If the fourth object is a well-reconstructed tau or electron, the corresponding energy-momentum measurement is used rather than track momentum. Events with four isolated leptons have fewer backgrounds than trilepton events. Accordingly, less restrivtive cuts apply to such events.

Events that pass three lepton selection, but do not have an additional isolated track must pass several event-level cuts. Various candidate event-level quantities have been studied, and the most potent one has been found to be the scalar sum of lepton E_T's plus the missing transverse energy ($\not\!\!E_T$): $\mathrm{H}_T \equiv \Sigma(\not\!\!E_T + P_T^{leptons})$. The effectiveness of the H_T cut reflects the fact that the $H^{++}H^{--}$ are pair produced with considerable momentum in the rest frame due to an overall β^3/Q^2 term in the production cross section, where β and Q^2 are the boson velocity and the total energy respectively in the center of mass frame.[8]. The cut value of 190 GeV has been optimized for significance in the three-lepton signature. In order to suppress backgrounds form Drell-Yan processes, we veto any event with opposite-sign (OS) same flavor leptons which make an invariant mass $M_{OS} < 30\ \mathrm{GeV}/c^2$. In order to suppress Z-based backgrounds, if the OS mass is in the range $71\ \mathrm{GeV}/c^2 < M_{OS} < 111\ \mathrm{GeV}/c^2$ for a pair of muons or electrons, we require the H_T to be at least 300 GeV. To reduce $Z+\gamma$ backgrounds, trielectron events are required to have at least 20 GeV of $\not\!\!E_T$. This requirement is 100% efficient on signal. Finally, given that the maximal mass reach for $\mathrm{H}^{\pm\pm}$ is 115 GeV/c^2, we require a mass window for the like-sign(LS) leptons in the event: $30\ \mathrm{GeV}/c^2 < M_{LS} < 125\ \mathrm{GeV}/c^2$. This range is 100% efficient for signal, but is useful for controlling diboson backgrounds. The effects of these cuts on signal and sum backgrounds are summarized in table 1.

Events with four isolated tracks have very little backgrounds, yet, it is possible to reduce the already low backgrounds while leaving the signal unaffected. At the event-level, we require 20 GeV of $\not\!\!E_T$ if the highest mass reconstructed with OS particles is less than 120 GeV/c, or if the event is consistent with having four electrons. If the event is consistent with a $Z \rightarrow \mu\mu$+X, we require an H_T of 150 GeV, otherwise, and H_T cut of 120GeV is applied. These cuts are nearly 100% efficient on signal, but reduce backgrounds by a factor of 60%. The effects of these cuts on signal and background are summarized in table 2.

The combined analysis acceptance for the 3-lepton and 4-lepton channels grows linearly with $H^{\pm\pm}$ mass from 8% at $M_{H^{\pm\pm}} = 85$ GeV/c^2 to 14% at $M_{H^{\pm\pm}} = 135$ GeV/c^2.

The potential SM backgrounds listed in order of significance are Z/γ^* →leptons produced in association with hadronic jets or photons, ZZ* and WZ* with both bosons decaying leptonically, $t\bar{t}$ with leptonically decaying W's, W decaying leptonically produced in association with a hadronic Jet, and QCD (three or more hadronic jets). For the electron+tau signature, direct γ+ hadronic jets is also a potential background, while cosmic rays are a potential background for the muon+tau case.

The $Z \to ll$+Jets process contributes 0.15 ± 0.15 events for both the muon+tau and electron+tau searches - representing almost half of the total backgrounds. We use a Pythia MC sample consisting of over 700 separate runs, with each run representative of beam and detector conditions present during a given period of data taking. The events that fail the Z-Veto in data define a control region for this background. Comparisons of event yields and relevant kinematical quantities show that the MC predictions of jet→ τ_h fake rate, as well as kinematical distributions for the Z and recoil jets, are sufficiently accurate. We use Pythia samples to estimate the ZZ* and ZW, $t\bar{t}$, and W+jets backgrounds. The ZZ* process contributes mostly in the 4-lepton channel. The WZ* and top process is only significant in the three-track channel. All other backgrounds are negligable. The γ+Jets contribution is obtained by estimating the number of untagged conversions given the number of tagged conversions. The QCD backgrounds are determined by extrapolating along the track isolation of the leading lepton. The background from cosmic rays is suppressed by the requirements that any pair of muons be consistent with outgoing particles that originate at the same location and at the same time as the rest of the leptons in the event. For both the $\mu\tau$ and $e\tau$ analyses, W+jets backgrounds are estimated at 0± 0.15 events with Monte Carlo simulations. The total acceptance of the analysis is well below 10^-6 for W+jets MC, therefore we estimate backgrounds using events that pass kinematical selections but fail some lepton ID cuts, such as isolation, and scale down with the pass/fail ratio of the lepton ID cuts. Care is taken to account for any correlation between the cuts that are loosened, and other analysis cuts. This method is also applied to QCD, photon+jets, and cosmic ray backgrounds, which also have very small acceptances. To account for any discrepancies in the fake rates of jet→ τ_h in data and MC, the overall normalization of the MC is fixed in a W-enriched control region.

Systematic uncertainties on backgrounds come from data/MC scale factors and NLO cross section uncertainties for diboson and top processes (8%), and luminosity (6%). Systematic uncertainties on signal cross section include NLO errors (7.5%), luminosity (6%), and PDF uncertainty (5%). The errors on acceptance (6%) are driven by uncertainties on track isolation efficiency (4.5% and 6% for 3 and 4-lepton channels respectively).

After checking background predictions in various control regions (those dominated by QCD, Z, W, as well as the region $H_T < 150$ GeV), we look in the signal regions for both 3-lepton and 4-lepton channels. We observe 0 events in both the 3-lepton and 4-lepton channels for both the $\mu\tau$ and $e\tau$ searches. Limits are set using a Baysean method with a flat prior for signal cross section and Gaussian priors for uncertainties on signal and background acceptance and integrated luminosity. The 3 and 4-lepton channels are treated as separate measurements, taking into account correlated systematic uncertainties. In the calculation of the mass limit, we use NLO and PDF uncertainties for the signal cross section. We set an upper cross section limit for the process $p\bar{p} \to H_L^{++}H_L^{--} \to e^+\tau^+e^-\tau^-$ to 73.5 fb at the 95% confidence limit (C.L.), which corresponds to a mass of 113.6 GeV/c^2. The $p\bar{p} \to H_L^{++}H_L^{--} \to \mu^+\tau^+\mu^-\tau^-$ process is excluded above cross sections of 78 fb at the 95% C.L., corresponding to a mass of 112.1 GeV/c^2. The exclusion curves are shown in figure 1.

In conclusion, we have searched for the process $p\bar{p} \to H_L^{++}H_L^{--} \to l^+\tau^+l^-\tau^-$ using ≈ 350 pb$^-1$ of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV. The observation of 0 events in both searches are consistent with the SM backgrounds of 0.24±0.27 events and 0.39±0.23 We set a 95% C.L. lower limit on the $H_L^{\pm\pm}$ mass to be 113.6 (112.1) GeV/c^2 assuming exclusive electron+tau (muon+tau) decays, taking into account NLO and PDF uncertainties.

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3-lepton Signal and Backgrounds			
$e\tau$	Data	Bkg	$H^{++} \to e\tau$
Lepton ID	34	37.8±1.3	2.94±.11
M_{LS}, M_{OS}	29	35.4±1.2	2.89±.11
Z-Veto	8	9.65±0.66	2.4±0.09
H_T	0	0.24±0.27	1.97±0.08
$\mu\tau$	Data	Bkg:	$H^{++} \to \mu\tau$
Lepton ID	28	30.0±1.4	3.06±
M_{LS}, M_{OS}	20	24.6±1.26	2.99±0.04
Z-Veto	7	6.6±0.86	2.35±0.04
H_T	0	0.27±0.125	1.80±0.03

Table 1: 3-lepton signal and background summary. The signal yields are for a 110 GeV$/c^2 H^{++}$.

4-lepton Signal and Backgrounds			
$e\tau$	Data	SumBkg	$H^{++} \to e\tau$
Lepton ID	0	.18±.06	1.61±0.07
Z-Veto	0	0.05±0.05	1.61±0.07
ZZ→eeee cut	0	0.04±0.05	1.60±0.07
$\mu\tau$	Data	SumBkg	$H^{++} \to \mu\tau$
Lepton ID	0	.25±.08	1.65±0.03
Z-Veto	0	0.14±0.05	1.64±0.03

Table 2: 4 Track Signal and Background Tally. The Signal yields are for a 110 GeV$/c^2 H^{++}$. The ZZ→eeee cut requires 20 GeV of $\not\!\!E_T$ if the event is consistent with having four electrons.

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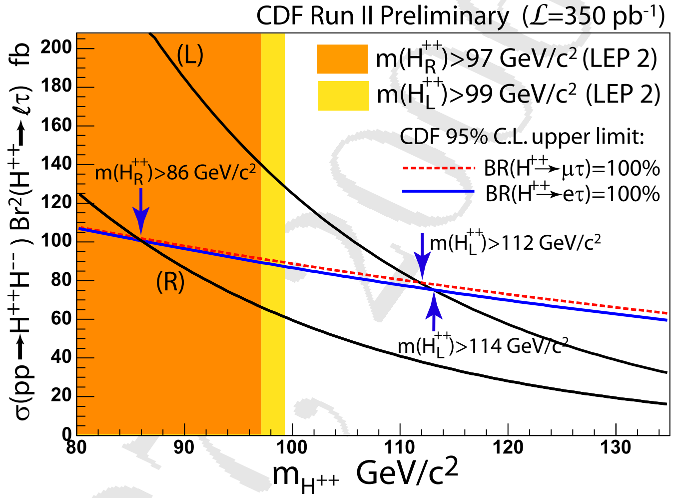

Figure 1: 95% C. L. limit curves for $p\bar{p} \to H^{++}H^{--} \to l^+\tau^+l^-\tau^-$. The vertical lines correspond to limits from experiments at LEP2[12, 13] The arrows show the limits for the two analyses that assume exclusive electron+tau, and exclusive muon+tau decays.

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