Search for Doubly Charged Higgs Bosons with Lepton-Flavor-Violating Decays involving Tau Leptons

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We search for pair production of doubly charged Higgs particles ($H^{\pm\pm}$) followed by decays into electron-tau ($e\tau$) and muon-tau ($\mu\tau$) pairs using data (350 pb^{-1}) collected from $\bar{p}p$ collisions at $\sqrt{s}$ = 1.96 TeV by the CDF II experiment. We search separately for cases where three or four final-state leptons are detected, and combine results for exclusive decays to left-handed $e\tau$ ($\mu\tau$) pairs. We set an $H^{\pm\pm}$ lower mass limit of 114 (112) GeV/c^2 at the 95% confidence level.

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The Standard Model (SM) Higgs mechanism provides a framework in which particles can acquire mass while preserving local gauge invariance. The complex scalar Higgs doublet of the SM is just one of many viable implementations, and many extensions to the SM contain Higgs triplets [1, 2, 3]. For example the left-right symmetric $(SU(2)_L \times SU(2)_R \times U(1)_{B-L})$ extension of the electroweak force [2] casts parity violation as a low-energy phenomenon by invoking a right-handed weak interaction broken above the electroweak scale. This model predicts small but nonzero neutrino masses (consistent with recent experiments [4, 5]) related to the suppression of the right-handed weak current [2]. Another model with an extended Higgs sector is the Higgs triplet model [3], which predicts a massive left-handed Majorana neutrino without requiring a right-handed neutrino. An important phenomenological feature of the above models is the prediction of doubly charged Higgs bosons ($H^{\pm\pm}$) as part of a Higgs triplet. Doubly charged Higgs bosons couple to Higgs and electroweak gauge bosons and either left-handed or right-handed charged leptons (ℓ), and are respectively denoted $H_L^{\pm\pm}$ or $H_R^{\pm\pm}$ [6].

The only significant production mode at the Fermilab Tevatron is predicted to be $q\bar{q}\to\gamma^*/Z\to H^{++}H^{--}$, and the leptonic decay modes dominate for $H^{\pm\pm}$ in the mass range $m(H^{\pm\pm})<(m(W^\pm)+m(H^\pm))$[7]. Lepton-flavor-violating (LFV) decay modes are allowed, and may be particularly large (e.g., the branching fraction for the $\mu\tau$ mode may be near 1/3) in the Higgs triplet model if the mass hierarchy of the quarks and charged leptons also holds for the neutrino sector[8].

The $H_L^{\pm\pm}$ ($H_R^{\pm\pm}$) is excluded below 99 GeV/c^2 (97 GeV/c^2) at the 95% C.L. by previous searches at LEP [9], assuming production cross sections according to the left-right symmetric models [2] and 100% branching ratio to any one dilepton decay channel. Recent searches from the Fermilab Tevatron have resulted in 95% C.L. lower mass limits of 136, 133, and 115 GeV/c^2 for $H_L^{\pm\pm}$ in the $\mu\mu$, ee, and $e\mu$ channels, respectively, and a lower mass limit of 113 GeV/c^2 for the $H_R^{\pm\pm}$ in the $\mu\mu$ channel [10].

We present the first results from hadron colliders on $H_L^{++}H_L^{--}$ pair production and subsequent decay through LFV channels involving taus. We use data corresponding to an integrated proton-antiproton luminosity of $\approx$350 pb^{-1} [11] collected at $\sqrt{s}$ = 1.96 TeV by the CDF II experiment at the Fermilab Tevatron, and set mass limits in the left-right symmetric model [2, 7] for exclusive decays in the $e\tau$ and $\mu\tau$ channels. We present limits on the cross section times branching ratio squared, $\sigma \times B^2$, which can be interpreted in the context of various models [7].

CDF II [12, 13], a cylindrical detector with concentric layers, has inner silicon strip detectors (SVX) and a wire drift chamber (COT) for tracking inside a solenoidal coil. The COT provides tracking in the pseudorapidity region $|\eta|\lesssim 1.3$, while the SVX covers the region $|\eta|\lesssim 1.9$. At radii outside the solenoid coil, sampling electromagnetic and hadronic calorimeters cover the region $|\eta|<3.6$ with a projective tower geometry. In the central region ($|\eta|\leq 1.0$), the electromagnetic calorimeter (CEM) has an embedded multi-wire proportional chamber (CES), with anode wires parallel to the beam direction, and orthogonal cathode strips. The CES has 2 cm strip/wire spacing and provides $\approx$ 2 mm spatial resolution of electromagnetic showers. The region $1.1\leq|\eta|\leq 3.6$ is covered by the "plug" electromagnetic (PEM) and hadronic calorimeters. At the largest radii there are scintillator and drift tube muon detectors in the region $|\eta|<1.5$.

We use several sets of selection criteria to characterize lepton candidates. All "tight" leptons must be in the central region, while "loose" leptons satisfy $|\eta|<1.3$. Tight electrons [14] have tracks in the COT matched to energy clusters in both the CEM and CES. They pass requirements on the electromagnetic to hadronic calorimeter deposition ratio, the CEM energy to COT track momentum ratio, and a tower-to-tower energy sharing variable. Loose electrons only have tracks matched to CEM or PEM clusters with electromagnetic to hadronic calorimeter deposition ratios consistent with the electron hypothesis. Tight muons [10] are minimally ionizing in the calorimeters and have tracks in the COT that extrapolate to hits in the outer muon detectors. Loose muons are simply isolated tracks, as described below. In order to suppress background from jets misidentified as leptons, an electron or muon is selected to be isolated by requiring that the sum of the transverse momenta of all other tracks in a cone of angle 0.4 radians with respect to the lepton's direction be less than 2 GeV/c.

Identification of hadronically decaying taus (τ_h) is fully described elsewhere [14]. In tau reconstruction, all tracks are assumed to correspond to charged pions, and all trackless CES/CEM clusters are assumed to correspond to π^0 mesons. A tight τ_h must have 1 or 3 localized tracks, and can have additional localized π^0 candidates. The localization is defined by a variable size "signal cone" (between 3° and 10°, depending on the tau's momentum) around the highest p_T track associated with the τ_h. The region between the signal cone and a larger 30° cone serves as an isolation annulus in which the summed p_T of all tracks must be less than 2 GeV/c and the summed E_T of all π^0 mesons must be less than 0.5 GeV. The 4-momentum of a τ_h is taken to be the vector sum of the 4-momenta of the tau's tracks and π^0 candidates in the signal cone. The charge of a τ_h is the sum of the

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charges of its tracks, and must equal ±1. A loose τ_h is the same as a tight τ_h in the region $|\eta|<1.0$, but has additional acceptance for $1.0<|\eta|<1.3$. Since the CES does not cover the latter region, π^0 related cuts are dropped, and the energy of a loose τ_h is estimated from the plug calorimeters.

To increase signal acceptance, systems of one or three isolated, localized tracks in the region $|\eta|<1.3$ are also considered as loose lepton candidates. For such candidates, the signal and isolation cone sizes are 10° and 30° respectively. These "isolated track systems" (ITSs) have acceptance for e, μ, and τ leptons. The efficiencies of lepton reconstruction, identification, and isolation requirements are measured in data using electrons from decays of Υ mesons, electrons and muons from decays of Z bosons, and taus from W bosons.

We require at least three reconstructed isolated charged leptons to suppress large cross-section backgrounds such as dijets, γ + jets, and $W(\rightarrow \ell\nu_\ell)$+ jets. Events are classified according to the number of isolated high p_T leptons detected, and separate selections are used for the 3-ℓ and 4-ℓ signatures. The data are collected by lepton plus isolated track triggers [15]. These triggers require one central lepton (e or μ) and a second central isolated track. The integrated luminosities of the $e\tau$ and $\mu\tau$ samples are 350 pb^{-1} and 322 pb^{-1}, respectively. Trigger efficiencies for electrons (muons) are estimated from events with photon conversions and $Z\rightarrow ee$ ($J/\psi\rightarrow\mu\mu$ and $Z\rightarrow\mu\mu$) decays. The efficiency for the isolated track is measured from a jet sample. The overall trigger efficiencies are $\approx 95\%$ for $H^{\pm\pm}$ masses in the range 80-130 GeV/c^2. The specific lepton requirements for the $e\tau$ and $\mu\tau$ searches are summarized in Table I.

We use CTEQ5L parton density functions (PDFs) in the PYTHIA generator [16] and a GEANT-based [17] detector simulation, scaled to next-to-leading order (NLO) cross sections [7], to estimate the signal and background processes. Our signal MC samples scan the $H^{\pm\pm}$ mass range 80-130 GeV/c^2 at 10 GeV/c^2 intervals. The potential SM backgrounds for both the 3-ℓ and 4-ℓ searches are: $Z/\gamma^*\rightarrow$ leptons produced in association with $\geq$1 hadronic jet(s) or photon(s); ZZ and WZ with both bosons decaying leptonically; $t\bar{t}$ with leptonically decaying W bosons; W bosons decaying leptonically produced in association with $\geq$2 hadronic jets; and "QCD" events (no leptons, $\geq$3 hadronic jets). For the $e\tau$ signature, γ + hadronic jets events are also a potential background, while cosmic ray muons are a potential background in the $\mu\tau$ channel. The backgrounds with the larger production cross sections (e.g., QCD, W) are suppressed by multiple powers of the lepton misidentification rates ($\approx 10^{-2}$ for jet$\rightarrow\tau$, and $\approx 10^{-4}$ for jet$\rightarrow e,\mu$).

Event selection for the 3-ℓ events begins with the removal of events that are consistent with cosmic ray muons [18] or low-mass Drell-Yan lepton pairs ($M(e^+e^-)<30$ GeV/c^2; $M(\mu^+\mu^-)<30$ GeV/c^2). Also, events consistent with $Z+\gamma$ production with the photon misidentified as an electron are efficiently removed by requiring at least 20 GeV of missing transverse energy ($\not\!\!E_T$) [13]. Signal events with at least one τ decaying to an electron typically have $\not\!\!E_T$ >20 GeV, due to the significant fraction of the τ's energy carried off by the two neutrinos, while $Z+\gamma$ events are typically well measured, and thus have small $\not\!\!E_T$. Similarly, in the 4-ℓ search, events consistent with having four final-state electrons must have at least 20 GeV of $\not\!\!E_T$. No attempt is made to reconstruct the full $H^{\pm\pm}$ mass, but we do require the presence of a like-sign $e\tau$ or $\mu\tau$ pair with an invariant mass in the range 30-125 GeV/c^2. This selection is nearly 100% efficient for signal but reduces diboson and top backgrounds.

To further reduce backgrounds, in particular Z + jets, we impose a requirement on the scalar sum of the lepton transverse energies and $\not\!\!E_T (Y_T)$. The Y_T requirement depends on whether an event is tagged as a Z boson decay. It is more efficient to remove events consistent with Z boson decays by Y_T than by a direct mass cut, because some of the signal has oppositely charged leptons in the Z mass range, but large Y_T values compared to Z + jets events. The Y_T cut values for tagged and untagged events, as well as the mass window used in Z boson tagging, are optimized by running pseudoexperiments and choosing the sets of cut values that result in the best expected limits on H^{++}. The $e\tau$ search uses Y_T cuts of 190 GeV for untagged events and 300 GeV for events tagged as Z boson candidates, defined as an e^+e^- pair in the mass range 71-111 GeV/c^2. The $\mu\tau$ search uses Y_T cuts of 190 GeV for untagged events, and 350 GeV for events tagged as Z boson candidates, defined as a $\mu^+\mu^-$ pair in the mass range 76-116 GeV/c^2. In the $\mu\tau$ analysis, a muon with a severely mismeasured p_T may lead to spuriously high Y_T. We minimize the mismeasurement risk by imposing additional cuts on the highest p_T tracks in the events.

Events with four isolated leptons have less background than trilepton events, so less restrictive cuts are applied. We first require $Y_T>120$ GeV. Events tagged as Z bosons are required to have $\not\!\!E_T>20$ GeV in the $e\tau$ search and $Y_T>150$ GeV in the $\mu\tau$ search. As with Y_T and Z-veto for the 3-ℓ channels, pseudoexperiments were conducted with various values of both cuts, and the cuts that resulted in the best expected limits were chosen for each analysis. The acceptances for the 3-ℓ and 4-ℓ channels are roughly equal, and the combined acceptance grows approximately linearly with $H^{\pm\pm}$ mass from 8% at 85 GeV/c^2 to 14% at 135 GeV/c^2. Observed and expected event yields for signal and background for the 3-ℓ and 4-ℓ searches are shown in Table II. The signal event yields assume $\sigma\times B^2 = 89.4 fb$, corresponding to exclusive decays of 110 GeV/c^2 $H^{\pm\pm}$ to $e\tau$ ($\mu\tau$) pairs in models [2] and [3]. The Z + jets process is the most significant single background, with $0.15^{+.11}_{-.07}(stat)$ expected events for each of the combined (3-ℓ + 4-ℓ) $\mu\tau$ and $e\tau$

searches. The combined background from WZ and ZZ production amounts to 0.12±0.02 (0.20±0.02) events for the $e\tau$ ($\mu\tau$) search. $t\bar{t}$ background is $0.01^{+0.02}_{-0.01}$ ($0.06^{+0.02}_{-0.01}$) events in the $e\tau$ ($\mu\tau$) search. Cosmic ray, γ + jets, and QCD backgrounds are negligible and determined from data.

Systematic uncertainties on backgrounds from NLO cross section uncertainties are 4% for Z and W boson production processes and 8% for diboson and top quark production processes [19]. A 6% uncertainty applies to the integrated luminosity of our dataset. A 28% (21%) systematic uncertainty is used for the $W \to \ell\nu_\ell$ ($Z \to \ell\ell$) background predictions to account for imperfect knowledge of the jet$\to\tau_h$ misidentification rate. Imperfect simulation of the track curvature resolution is accounted for by a 0.1 event systematic uncertainty on the combined backgrounds for the $\mu\tau$ search. The combined systematic uncertainty for all backgrounds amounts to 0.04 (0.11) events for the $e\tau$ ($\mu\tau$) search. The total uncertainties on backgrounds, shown in Table II, are statistically dominated. Systematic uncertainties on the signal cross section include NLO cross section uncertainties (7.5%) [7], luminosity (6%) [11], and parton density function (PDF) uncertainty (5%) [20]. The uncertainty on signal acceptance (6.1%) is driven by uncertainties on track isolation efficiency (4.5% and 6% for 3-ℓ and 4-ℓ channels, respectively), and π^0 isolation efficiencies (1.5% and 2% for 3-ℓ and 4-ℓ channels, respectively).

We find that the background predictions agree with data in all control samples, including samples in the kinematic region Y_T<150 GeV enriched with QCD, Z boson, and W boson events. To check our predictions in the high-Y_T regime while keeping the analysis "blind," we check the number of events that pass all analysis selections except track isolation for the second tight lepton (Table I). After finalizing all selection requirements and our limit setting procedure, we search the signal regions in both the 3-ℓ and 4-ℓ channels. We observe no events in either the 3-ℓ or 4-ℓ channels for both the $\mu\tau$ and $e\tau$ searches, which is consistent with the SM backgrounds of $0.24^{+0.27}_{-0.24}$ $e\tau$ events and 0.39±0.23 $\mu\tau$ events. Limits are set using a Bayesian method based on a Poisson likelihood, with a flat prior for signal cross section and Gaussian priors for uncertainties on signal, background acceptance, and integrated luminosity. The 3-ℓ and 4-ℓ channels are treated as separate measurements, taking into account correlated systematic uncertainties [14]. We set an upper $\sigma\times B^2$ limit for the process $p\bar{p}\to H_L^{++}H_L^{--}\to e^+\tau^+e^-\tau^-$ of 74 fb at the 95% C.L., which corresponds in models [2] and [3] to a mass limit of 114 GeV/c^2. The process $p\bar{p}\to H_L^{++}H_L^{--}\to\mu^+\tau^+\mu^-\tau^-$ is excluded above a cross section of 78 fb at the 95% C.L., corresponding to a mass limit of 112 GeV/c^2 in the same models. The exclusion curves are shown in Fig. 1.

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Signature	Lepton	Flavor	E_T (P_T)	$\|\eta\|$
3-ℓ	1^{st} (tight)	e	> 20 GeV	< 1.0
	2^{nd} (tight)	τ_h or e	> 15 GeV	< 1.0
	3^{rd} (loose)	τ_h or e	> 10 GeV	< 1.3
4-ℓ	4^{th} (loose)	Isolated Track	> 10 GeV/c	< 1.3

TABLE I: Kinematic and geometric lepton requirements (cut values) for the $e\tau$ search. For the $\mu\tau$ search, the first lepton changes from e to μ, and the third lepton changes from τ_h or e to isolated track.

$e\tau$	Selection	Exp. Signal	Background	Data
3-ℓ	Lepton ID	2.94±0.11	37.8±1.3	34
	M_{LS}, M_{OS}	2.89±0.11	35.4±1.2	29
	Y_T/Z veto	2.4±0.09	9.65±0.66	8
	Y_T	1.97±0.08	$0.24^{+0.27}_{-0.24}$	0
4-ℓ	Lepton ID	1.61±0.07	0.18±0.06	0
	Y_T/Z veto	1.60±0.07	$0.04^{+0.05}_{-0.04}$	0
$\mu\tau$	Selection	Exp. Signal	Background	Data
3-ℓ	Lepton ID	3.06±0.04	30.0±1.4	28
	M_{LS}, M_{OS}	2.99±0.04	24.6±1.26	20
	Y_T/Z veto	2.35±0.04	6.6±0.86	7
	Y_T	1.80±0.03	0.27±0.22	0
4-ℓ	Lepton ID	1.65±0.03	0.25±0.08	0
	Y_T/Z veto	1.64±0.03	0.14±0.05	0

TABLE II: Cumulative effect of selection requirements on signal (110 GeV/c^2, $\sigma \times B^2 = 89.4 fb$) and background in the 3-ℓ and 4-ℓ searches. M_{LS} (M_{OS}) represent the invariant mass requirements on the like (opposite) sign leptons. The Z veto refers to the additional Y_T requirement on Z boson tagged events. The uncertainties are combined statistical and systematic.

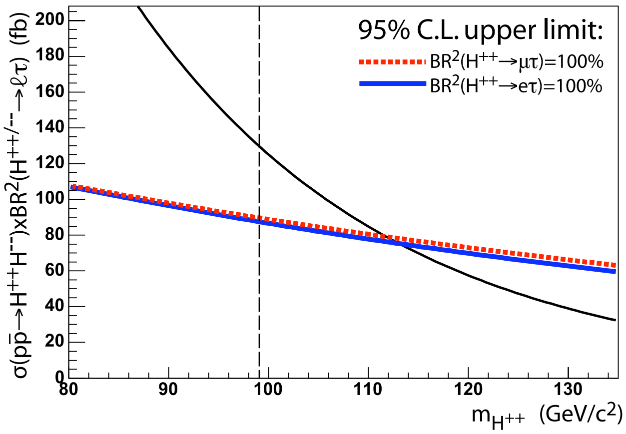

FIG. 1: Theoretical production cross sections for the pair production of left-handed $H^{\pm\pm}$, and 95% C.L. limit curves for $\sigma(p\bar{p} \to H^{++}H^{--} \to) \times B^2(\ell^+\tau^+\ell^-\tau^-)$, for $\ell = e$(solid), μ(dashed). The vertical dashed line corresponds to limits from experiments at LEP2 for exclusive $H_L^{\pm\pm}$decays to any one dilepton channel [9].

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