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Search for doubly-charged Higgs boson pair production in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for pair production of doubly-charged Higgs bosons in the processes $q\bar{q} \to H^{++}H^{--}$ decaying through $H^{\pm\pm} \to \tau^\pm\tau^\pm, \mu^\pm\tau^\pm, \mu^\pm\mu^\pm$. The search is performed in $p\overline{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV using an integrated luminosity of 7.0 fb^{-1} collected by the D0 experiment at the Fermilab Tevatron Collider. The results are used to set 95% C.L. limits on the pair production cross section of doubly-charged Higgs bosons and on their mass for different $H^{\pm\pm}$ branching fractions. Models predicting different $H^{\pm\pm}$ decays are investigated. Assuming $\mathcal{B}(H^{\pm\pm} \to \tau^\pm\tau^\pm) = 1$ yields an observed (expected) lower limit on the mass of a left-handed $H_L^{\pm\pm}$ boson of 128 (116) GeV and assuming $\mathcal{B}(H^{\pm\pm} \to \mu^\pm\tau^\pm) = 1$ the corresponding limits are 144 (149) GeV. In a model with $\mathcal{B}(H^{\pm\pm} \to \tau^\pm\tau^\pm) = \mathcal{B}(H^{\pm\pm} \to \mu^\pm\tau^\pm) = \mathcal{B}(H^{\pm\pm} \to \mu^\pm\mu^\pm) = 1/3$, we obtain $M(H_L^{\pm\pm}) > 130$ (138) GeV.

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Doubly-charged Higgs bosons ($H^{\pm\pm}$) appear in models with an extended Higgs sector such as the Little Higgs model [1], Left-Right symmetric models [2], and in models with $SU(3)_c \times SU(3)_L \times U(1)_Y$ (3-3-1) gauge symmetry [3].

The $H^{\pm\pm}$ bosons could be pair-produced and observed at a hadron collider through the process $q\bar{q} \to Z/\gamma^* \to H^{++}H^{--} \to \ell^\pm\ell'^\pm$ ($\ell, \ell' = e, \mu, \tau$). The decay into like-charge lepton pairs violates lepton flavor number conservation. The decays $H^{\pm\pm} \to \tau^\pm\tau^\pm$ are predicted to dominate in some scenarios, such as the 3-3-1 model of Ref. [4]. In a Higgs triplet model that is based on a seesaw neutrino mass mechanism, a normal hierarchy of neutrino masses leads to approximately equal branching fractions for $H^{\pm\pm}$ boson decays to $\tau\tau$, $\mu\tau$, and $\mu\mu$, if the mass of the lightest neutrino is less than 10 meV [5]. In this Letter, we present the first comparison of data with this model and the first search for $H^{\pm\pm} \to \tau^\pm\tau^\pm$ decays at a hadron collider.

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In Left-Right symmetric models, right-handed states ($H_R^{\pm\pm}$) appear in addition to left-handed states ($H_L^{\pm\pm}$). They are characterized through their coupling to right-handed and left-handed fermions, respectively. The cross section for production of right-handed $H_R^{++}H_R^{--}$ pairs is about a factor of two smaller than for $H_L^{++}H_L^{--}$ because of the different coupling to the Z boson. The mass limits for $H_R^{\pm\pm}$ bosons therefore tend to be weaker than for $H_L^{\pm\pm}$ bosons.

Searches for pair production of $H^{\pm\pm}$ bosons have been performed previously at the CERN e^+e^- Collider (LEP) [6] and at the DESY ep Collider (HERA) [7]. Limits on the mass of the $H^{\pm\pm}$ boson were obtained in the range of 95 GeV to 100 GeV, depending on the flavor of the final state leptons. The OPAL and H1 Collaborations searched for single $H^{\pm\pm}$ production in the processes $e^+e^- \to e^\mp e^\mp H^{\pm\pm}$ [8] and $e^\pm p \to \ell^\mp H^{\pm\pm} p$ [7], and through the study of Bhabha scattering $e^+e^- \to e^+e^-$ [8], constraining the $H^{\pm\pm}$ boson's Yukawa couplings $h_{e\ell}$ to electrons. At the Fermilab Tevatron Collider, the D0 Collaboration has searched for the four muon final state and set a mass limit of $M(H_L^{\pm\pm}) > 150$ GeV [9, 10]. The CDF Collaboration published limits for ee final states of $M(H_L^{\pm\pm}) > 133$ GeV, for $\mu\mu$ of $M(H_L^{\pm\pm}) > 136$ GeV, and for $e\mu$ of $M(H_L^{\pm\pm}) > 115$ GeV [11]. CDF also obtained limits for $H_L^{\pm\pm}$ decays into $e\tau$ and $\mu\tau$ of $M(H_L^{\pm\pm}) > 114$ GeV and $M(H_L^{\pm\pm}) > 112$ GeV, respectively [12]. All these mass limits assume 100% decays into the specified final state.

The results in this Letter are based on data collected with the D0 detector at the Fermilab Tevatron Collider and correspond to an integrated luminosity of 7.0 fb^{-1}. The D0 detector [13] comprises tracking detectors and calorimeters. Silicon microstrip detectors and a scintillating fiber tracker are used to reconstruct charged particle tracks within a 2 T solenoid. The uranium/liquid-argon calorimeters used to measure particle energies consist of electromagnetic (EM) and hadronic sections. Muons are identified by combining tracks in the central tracker with patterns of hits in the muon spectrometer. Events are required to pass triggers that select at least one muon candidate.

All background processes are simulated using Monte Carlo (MC) event generators, except the multijet background, which is determined from data. The W+jet, $Z/\gamma^* \to \ell^+\ell^-$, and $t\bar{t}$ processes are generated using ALPGEN [14] with showering and hadronization provided by PYTHIA [15]. Diboson production (WW, WZ, and ZZ) and signal events are simulated using PYTHIA. The signal samples for the model with equal branching ratios for the decays $H^{\pm\pm} \to \tau^\pm\tau^\pm$, $\mu^\pm\mu^\pm$, and $\mu^\pm\tau^\pm$ are generated using Yukawa couplings $h_{\mu\tau} = h_{\tau\mu} = \sqrt{2}h_{\tau\tau} = \sqrt{2}h_{\mu\mu}$. The tau lepton decays are simulated with TAUOLA [16]. All MC samples are processed through a GEANT [17] simulation of the detector. Data from random beam crossings are overlaid on MC events to account for detector noise and additional $p\overline{p}$ interactions. The simulated events are corrected for the dependence of the trigger efficiency in data on the instantaneous luminosity and for differences between data and simulation in the reconstruction efficiencies and in the distribution of the longitudinal coordinate of the interaction point along the beam direction. Next-to-leading order (NLO) quantum chromodynamics calculations of cross sections are used to normalize the $t\bar{t}$ and diboson samples, and next-to-NLO calculations are used for all other processes.

Two types of tau lepton decays into hadrons (τ_h) are identified by their signatures: type-1 tau candidates consist of a calorimeter cluster, with one associated track and no sub-cluster in the EM section of the calorimeter. This signature corresponds mainly to $\tau^\pm \to \pi^\pm\nu$ decays. For type-2 tau candidates, an energy deposit in the EM calorimeter is required in addition to the type-1 signature, as expected for $\tau^\pm \to \pi^\pm\pi^0\nu$ decays. The outputs of neural networks, one for each tau-type, designed to discriminate τ_h from jets, have to be $NN_\tau > 0.75$ [18]. Their input variables are based on isolation variables for objects and on the spatial distribution of showers. The tau lepton energy is measured with the calorimeter.

We select events with at least one muon and at least two τ_h candidates. The muons must be isolated, both in the tracking detectors and in the calorimeters. Each event must have a reconstructed $p\overline{p}$ interaction vertex with a longitudinal component located within 60 cm of the nominal center of the detector. The longitudinal coordinate $z_{\rm dca}$ of the distance of closest approach for each track is measured with respect to the nominal center of the detector. The differences between $z_{\rm dca}$ of the highest-p_T muon and the two highest-p_T τ_h (labeled τ_1 and τ_2), must be less than 2 cm. The pseudorapidity [19] of the selected muons, τ_1, and τ_2 must be $|\eta^\mu| < 1.6$ and $|\eta^{\tau_{1,2}}| < 1.5$, respectively, and for additional τ_h candidates we require $|\eta^\tau| < 2$. The transverse momenta must be $p_T^\mu > 15$ GeV and $p_T^{\tau_{1,2}} > 12.5$ GeV. All selected τ_h candidates and muons are required to be separated by $\Delta\mathcal{R}_{\mu\tau} > 0.5$, where $\Delta\mathcal{R} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and ϕ is the azimuthal angle, and the two leading τ_h must be separated by $\Delta\mathcal{R}_{\tau_1\tau_2} > 0.7$. The sum of the charges of the highest-p_T muon, τ_1, and τ_2 is required to be $Q = \sum_{i=\mu,\tau_1,\tau_2} q_i = \pm 1$ as expected for signal. After all selections, the main background is from diboson production and $Z \to \tau^+\tau^-$, where an additional jet mimics a lepton.

We estimate the multijet background using three independent data samples and identical selections, except with the NN_τ requirements reversed, by requiring that either one or both τ_h candidates have $NN_\tau < 0.75$. The simulated background is subtracted before the samples are used to determine the differential distributions and normalization of the multijet background in the signal region. A second method used to estimate the multijet background is based on the fact that events with $Q = \pm 1$

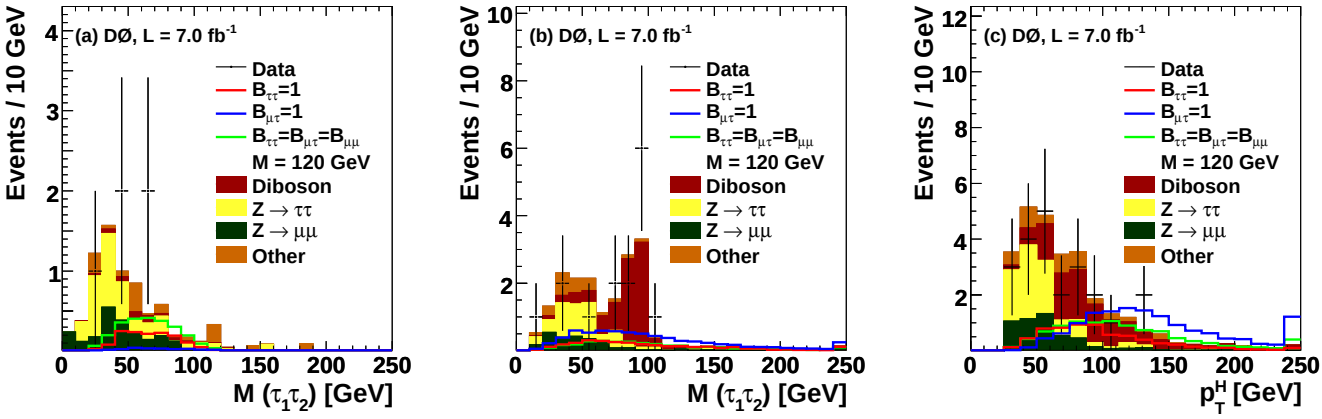

FIG. 1: (color online). $M(\tau_1, \tau_2)$ distribution for the (a) $q_{\tau_1} = q_{\tau_2}$ and (b) $q_{\tau_2} = -q_{\tau_2}$ samples, and (c) transverse momentum of the doubly-charged dilepton system, p_T^H, for all four samples combined, after all selections. The data are compared to the sum of the expected background and to simulations of a $H_L^{\pm\pm}H_L^{\pm\pm}$ signal for $M(H^{\pm\pm}) = 120$ GeV and $\mathcal{B}(H_L^{\pm\pm} \to \tau^\pm\tau^\pm) = 1$, $\mathcal{B}(H_L^{\pm\pm} \to \mu^\pm\tau^\pm) = 1$, and $\mathcal{B}(H_L^{\pm\pm} \to \tau^\pm\tau^\pm) = \mathcal{B}(H_L^{\pm\pm} \to \mu^\pm\mu^\pm) = \mathcal{B}(H_L^{\pm\pm} \to \mu^\pm\tau^\pm) = 1/3$, normalized using the NLO calculation of the cross section. "Other" background comprises W+jet, $Z/\gamma^* \to e^+e^-$, and $t\bar{t}$ processes. All entries exceeding the range of the histogram are added to the last bin.

TABLE I: Numbers of events in data, predicted background, and expected signal for $M(H_L^{\pm\pm}) = 120$ GeV, assuming the NLO calculation of the signal cross section for $\mathcal{B}(H_L^{\pm\pm} \to \tau^\pm\tau^\pm) = 1$, $\mathcal{B}(H_L^{\pm\pm} \to \mu^\pm\tau^\pm) = 1$, and $\mathcal{B}(H_L^{\pm\pm} \to \tau^\pm\tau^\pm) = \mathcal{B}(H_L^{\pm\pm} \to \mu^\pm\mu^\pm) = \mathcal{B}(H_L^{\pm\pm} \to \mu^\pm\tau^\pm) = 1/3$. The numbers are shown for the four samples separately, together with their total uncertainties.

	All	$N_\mu = 1$		$N_\mu = 1$	$N_\mu = 2$
		$N_\tau = 2$		$N_\tau = 3$	$N_\tau = 2$
		$q_{\tau_1} = q_{\tau_2}$	$q_{\tau_1} = -q_{\tau_2}$		
Signal					
$\tau^\pm\tau^\pm$	6.6 ± 0.9	1.4 ± 0.2	3.1 ± 0.4	1.6 ± 0.2	0.4 ± 0.1
$\mu^\pm\tau^\pm$	13.9 ± 1.9	0.3 ± 0.1	6.8 ± 0.9	0.4 ± 0.1	6.3 ± 0.9
Equal $\mathcal{B}$	9.5 ± 1.3	2.5 ± 0.3	3.1 ± 1.0	1.2 ± 0.2	2.6 ± 0.4
Background					
$Z \to \tau^+\tau^-$	8.2 ± 1.1	3.4 ± 0.5	4.8 ± 0.7	< 0.1	< 0.1
$Z \to \mu^+\mu^-$	5.1 ± 0.7	2.2 ± 0.3	2.5 ± 0.4	0.1 ± 0.1	0.2 ± 0.1
$Z \to e^+e^-$	0.3 ± 0.1	< 0.1	0.3 ± 0.1	< 0.1	< 0.1
W + jets	2.9 ± 0.4	1.1 ± 0.2	1.8 ± 0.3	< 0.1	< 0.1
$t\bar{t}$	0.6 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	< 0.1
Diboson	10.5 ± 1.7	0.5 ± 0.1	8.5 ± 1.4	0.4 ± 0.1	1.1 ± 0.2
Multijet	< 0.8	< 0.2	< 0.5	< 0.1	< 0.1
Background Sum	27.6 ± 4.9	7.5 ± 1.2	18.2 ± 3.3	0.6 ± 0.1	1.3 ± 0.2
Data	22	5	15	0	2

are signal-like, whereas events with $Q = \pm 3$ correspond largely to multijet background. To reduce the W+jets contribution in the sample with $Q = \pm 3$, the visible W boson mass $M_W = \sqrt{2p^\mu \not{p}_T(1 - \cos\phi)}$ is required to be < 50 GeV, where p^μ is the muon momentum, $\not{p}_T$ the imbalance in transverse momentum measured in the calorimeter, and ϕ is the azimuthal angle between the muon and the direction of the $\not{p}_T$. The total rate of expected multijet background events following all selections is negligible ($< 3\%$ of the total background).

To improve the discrimination of signal from background, the selected data are subdivided into four non-overlapping samples, depending on the charges of the muon (q_μ) and the τ_h candidates (q_τ), and the number of muons (N_μ) and τ_h candidates (N_τ) in the event. First, we define two samples for events with $N_\mu = 1$ and $N_\tau = 2$. Because the two like-charge leptons are assumed to originate from a single $H^{\pm\pm}$ decay, we consider separately events where both tau leptons have the same charge, $q_{\tau_1} = q_{\tau_2}$, and events with τ_1 and τ_2 of opposite charge, i.e., $q_{\tau_1} = -q_{\tau_2}$, which implies that one of the τ leptons and the muon have the same charge. The third sample is defined by $N_\tau = 3$ and the fourth sample by $N_\mu = 2$, without any additional requirements on the charges.

The distributions of the invariant mass of the two leading tau candidates, $M(\tau_1, \tau_2)$, for the like and opposite-charge samples are shown in Figs. 1(a) and (b). The separation in different samples increases the sensitivity to signal, as the composition of the background is different, with the like-charge sample being dominated by background from Z/γ^* decays and the opposite-charge sample by background from diboson production. The diboson background is mainly due to $WZ \to \mu\nu e^+e^-$ events where the electrons where misidentified as tau leptons. In Fig. 1(c) we show the transverse momentum of the doubly-charged dilepton system, p_T^H, which corresponds to the reconstructed $H^{\pm\pm}$ boson, assuming the two leptons of same charge originate from $H^{\pm\pm}$ boson decay. The expected number of background and signal events for the four samples and the observed numbers of events in data are shown in Table I. The $M(\tau_1, \tau_2)$ distribution is used to discriminate signal from background in

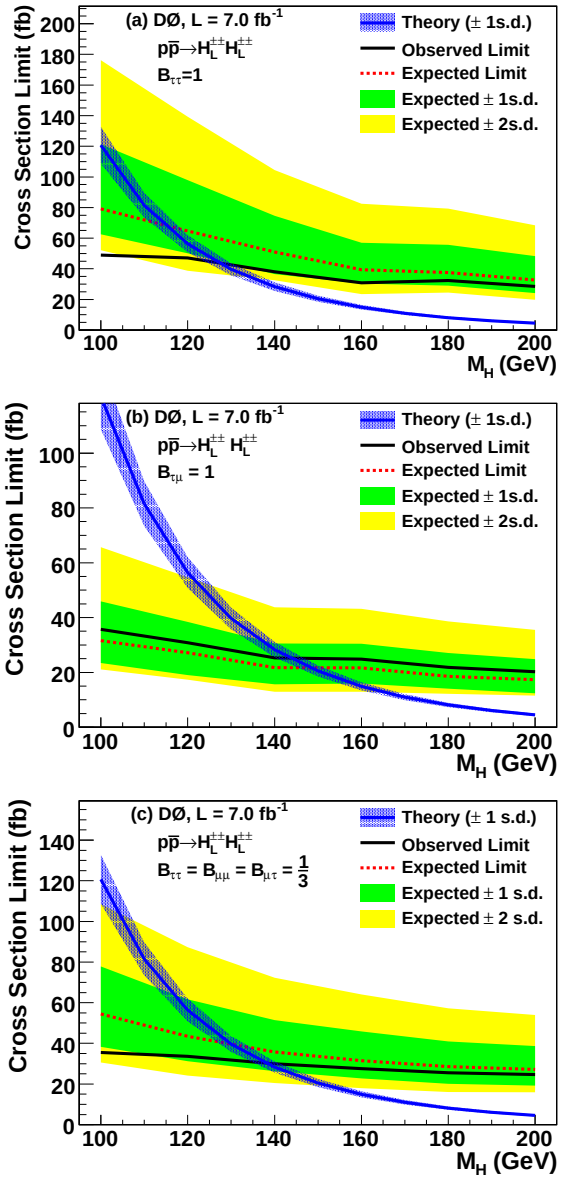

FIG. 2: (color online). Upper limit on the $H_L^{\pm\pm}H_L^{\pm\pm}$ pair production cross section for (a) $\mathcal{B}(H_L^{\pm\pm} \to \tau^\pm\tau^\pm) = 1$, (b) $\mathcal{B}(H_L^{\pm\pm} \to \mu^\pm\tau^\pm) = 1$, and (c) $\mathcal{B}(H_L^{\pm\pm} \to \tau^\pm\tau^\pm) = \mathcal{B}(H_L^{\pm\pm} \to \mu^\pm\mu^\pm) = \mathcal{B}(H_L^{\pm\pm} \to \mu^\pm\tau^\pm) = 1/3$. The bands around the median expected limits correspond to regions of ±1 and ±2 standard deviation (s.d.), and the band around the predicted NLO cross section for signal corresponds to a theoretical uncertainty of $\pm10\%$.

the like and opposite-charge samples and the number of events for the $N_\mu = 1, N_\tau = 3$ and $N_\mu = N_\tau = 2$ samples.

Since the data are well described by the background expectation, we determine limits on the $H^{++}H^{--}$ production cross section using a modified frequentist approach [20]. A log-likelihood ratio (LLR) test statistic is formed using the Poisson probabilities for estimated background yields, the signal acceptance, and the observed number of events for different $H^{\pm\pm}$ mass hypotheses. The confidence levels are derived by integrating the LLR distribution in pseudo-experiments using both the signal-plus-background (CL_{s+b}) and the background-only hypotheses (CL_b). The excluded production cross section is taken to be the cross section for which the confidence level for signal, $CL_s = CL_{s+b}/CL_b$, equals 0.05.

TABLE II: Expected and observed limits on $M(H^{\pm\pm})$ (in GeV) for left and right-handed $H^{\pm\pm}$ bosons. Only left-handed states are considered for the model that assumes equality of branching fractions into $\tau\tau$, $\mu\tau$, and $\mu\mu$ final states. We only derive limits if the expected limit on $M(H^{\pm\pm})$ is ≥ 90 GeV.

Decay	$H_L^{\pm\pm}$		$H_R^{\pm\pm}$	
	expected	observed	expected	observed
$\mathcal{B}(H^{\pm\pm} \to \tau^\pm\tau^\pm) = 1$	116	128		
$\mathcal{B}(H^{\pm\pm} \to \mu^\pm\tau^\pm) = 1$	149	144	119	113
Equal $\mathcal{B}$ into $\tau^\pm\tau^\pm, \mu^\pm\mu^\pm, \tau^\pm\mu^\pm$	130	138		
$\mathcal{B}(H^{\pm\pm} \to \mu^\pm\mu^\pm) = 1$	180	168	154	145

Systematic uncertainties on both background and signal, including their correlations, are taken into account. The theoretical uncertainty on background cross sections for $Z/\gamma^* \to \ell^+\ell^-$, W+jets, $t\bar{t}$, and diboson production vary between $6\% - 10\%$. The uncertainty on the measured integrated luminosity is 6.1% [21]. The systematic uncertainty on muon identification is 2.9% per muon and the uncertainty on the identification of τ_h, including the uncertainty from applying a neural network to discriminate τ_h from jets, is 4% for each type-1 and 7% for each type-2 τ_h candidate. The trigger efficiency has a systematic uncertainty of 5%. The uncertainty on the signal acceptance from parton distribution functions is 4%.

In Fig. 2, the upper limits on the cross sections are compared to the NLO signal cross sections for $H_L^{\pm\pm}H_L^{\pm\pm}$ pair production [22] for some of the branching ratios considered. The corresponding expected and observed limits are shown in Table II.

The $H^{\pm\pm}$ boson mass limits assuming $\mathcal{B}(H^{\pm\pm} \to \tau^\pm\tau^\pm) + \mathcal{B}(H^{\pm\pm} \to \mu^\pm\mu^\pm) = 1$ are determined by combining signal samples generated with pure 4τ, $(2\tau/2\mu)$, and 4μ final states with fractions $\mathcal{B}^2$, $2\mathcal{B}(1-\mathcal{B})$, and $(1-\mathcal{B})^2$, respectively, where $\mathcal{B} \equiv \mathcal{B}(H^{\pm\pm} \to \tau^\pm\tau^\pm)$. Here, we include in the limit setting the distribution of the invariant mass of the two highest p_T muons, including the systematic uncertainties and their correlations, from a search for $H^{++}H^{--} \to 4\mu$ decays performed by the D0 Collaboration in 1.1 fb^{-1} of integrated luminosity [9]. The results are shown in Fig. 3 for varying $\mathcal{B} = 0\% - 100\%$ in steps of 10%. A consistent treatment of the limit setting slightly increases the mass limits for the 4μ final state compared to Ref. [9], shown in Table II.

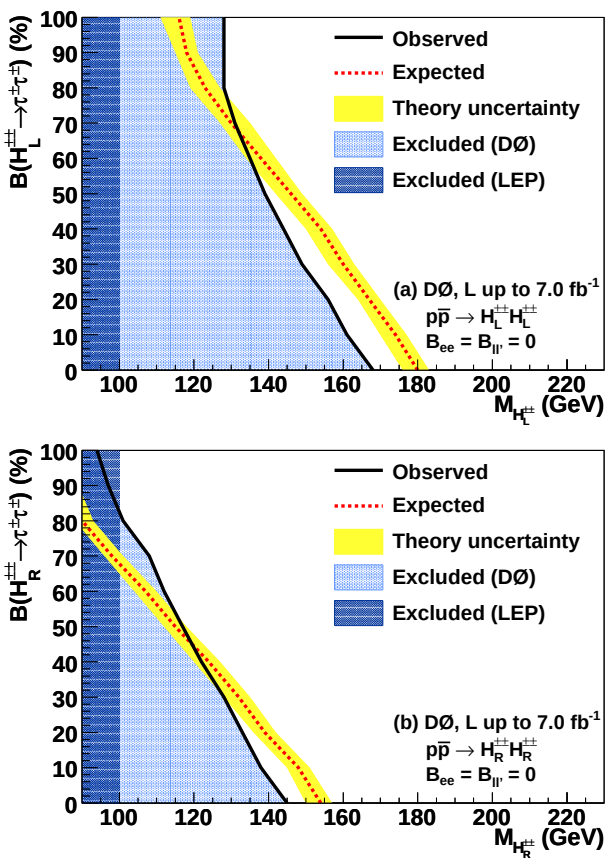

FIG. 3: (color online). Expected and observed exclusion region at the 95% C.L. in the plane of $\mathcal{B}(H^{\pm\pm} \to \tau^\pm\tau^\pm)$ versus $M(H^{\pm\pm})$, assuming $\mathcal{B}(H^{\pm\pm} \to \tau^\pm\tau^\pm) + \mathcal{B}(H^{\pm\pm} \to \mu^\pm\mu^\pm) = 1$, for (a) left-handed and (b) right handed $H^{\pm\pm}$ bosons. The band around the expected limit represents the uncertainty in the NLO calculation of the cross section for signal.

In summary, we have performed the first search at a hadron collider for pair production of doubly-charged Higgs bosons decaying exclusively into tau leptons. We set an observed (expected) lower limit of $M(H_L^{\pm\pm}) > 128$ (116) GeV for a 100% branching fraction of $H^{\pm\pm} \to \tau^\pm\tau^\pm$, $M(H_L^{\pm\pm}) > 144$ (149) GeV for a 100% branching fraction into $\mu\tau$, and $M(H_L^{\pm\pm}) > 130$ (138) GeV for a model with equal branching ratios into $\tau\tau$, $\mu\tau$, and $\mu\mu$. These are the most stringent limits on $H^{\pm\pm}$ boson masses in these decay channels.

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