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


Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain

Radboud University Nijmegen, Nijmegen, the Netherlands and Nikhef, Science Park, Amsterdam, the Netherlands

Simon Fraser University, Vancouver, British Columbia, and York University, Toronto, Ontario, Canada

IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France


Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic

University of Science and Technology of China, Hefei, People’s Republic of China

Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil

University of Science and Technology of China, Hefei, People’s Republic of China

University of the Andes, Bogotá, Colombia

Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic

11 Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

10 Czech Technical University in Prague, Prague, Czech Republic

19 IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France

20 IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France

13 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France

14 LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France

15 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

16 LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France

17 LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France

18 CEA, Ifremer, Saclay, France

19 IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France

48 Y.-T. Tsai,  S. Uzunyan,  S. Zelitch,  S. Snyder,  L.S. Vertogradov,  V. Simak,

Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany

25 Tata Institute of Fundamental Research, Mumbai, India

32 CINVESTAV, Mexico City, Mexico

33 Nikhef, Science Park, Amsterdam, the Netherlands

34 Radboud University Nijmegen, Nijmegen, the Netherlands and Nikhef, Science Park, Amsterdam, the Netherlands

35 Joint Institute for Nuclear Research, Dubna, Russia

36 Institute for Theoretical and Experimental Physics, Moscow, Russia

37 Moscow State University, Moscow, Russia

38 Institute for High Energy Physics, Protvino, Russia

39 Petersburg Nuclear Physics Institute, St. Petersburg, Russia

40 Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d’Altes Energies (IFAE), Barcelona, Spain

41 Stockholm University, Stockholm and Uppsala University, Uppsala, Sweden

42 Lancaster University, Lancaster LA1 4YB, United Kingdom

43 Imperial College London, London SW7 2AZ, United Kingdom

44 The University of Manchester, Manchester M13 9PL, United Kingdom

45 University of Arizona, Tucson, Arizona 85721, USA

46 University of California Riverside, Riverside, California 92521, USA

47 Florida State University, Tallahassee, Florida 32306, USA

1 Universidad de Buenos Aires, Buenos Aires, Argentina

2 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

3 Universidade de Estado do Rio de Janeiro, Rio de Janeiro, Brazil

4 Universidade Federal do ABC, Santo André, Brazil

5 Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil

6 Simon Fraser University, Vancouver, British Columbia, and York University, Toronto, Ontario, Canada

7 University of Science and Technology of China, Hefei, People’s Republic of China

8 Universidad de los Andes, Bogotá, Colombia

9 Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic

10 Czech Technical University in Prague, Prague, Czech Republic

11 Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

12 Universidad San Francisco de Quito, Quito, Ecuador

13 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France

14 LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France

15 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

16 LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France

17 LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France

18 CEA, Ifremer, Saclay, France

19 IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France

20 IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France

21 III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany

22 Physikalisches Institut, Universität Freiburg, Freiburg, Germany

23 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany

24 Institut für Physik, Universität Mainz, Mainz, Germany

25 Ludwig-Maximilians-Universität München, München, Germany

26 Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany

27 Panjab University, Chandigarh, India

28 Delhi University, Delhi, India

29 Tata Institute of Fundamental Research, Mumbai, India

30 University College Dublin, Dublin, Ireland

31 Korea Detector Laboratory, Korea University, Seoul, Korea

32 CINVESTAV, Mexico City, Mexico

33 Nikhef, Science Park, Amsterdam, the Netherlands

34 Radboud University Nijmegen, Nijmegen, the Netherlands and Nikhef, Science Park, Amsterdam, the Netherlands

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41 Stockholm University, Stockholm and Uppsala University, Uppsala, Sweden

42 Lancaster University, Lancaster LA1 4YB, United Kingdom

43 Imperial College London, London SW7 2AZ, United Kingdom

44 The University of Manchester, Manchester M13 9PL, United Kingdom

45 University of Arizona, Tucson, Arizona 85721, USA

46 University of California Riverside, Riverside, California 92521, USA

47 Florida State University, Tallahassee, Florida 32306, USA
We present a search for pair production of doubly-charged Higgs bosons in the processes $q\bar{q} \rightarrow H^{++}H^{--}$ decaying through $H^{±±} \rightarrow \tau^+\tau^-, \mu^+\mu^-, \mu^±\mu^±$. The search is performed in $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV using an integrated luminosity of up to 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 $H^{±±}$ branching fractions. Models predicting different $H^{±±}$ decays are investigated. Assuming $B(H^{±±} \rightarrow \tau^+\tau^-) = 1$ yields an observed (expected) lower limit on the mass of a left-handed $H^{±±}$ boson of 128 (116) GeV and assuming $B(H^{±±} \rightarrow \mu^+\mu^-) = 1$ the corresponding limits are 144 (149) GeV. In a model with $B(H^{±±} \rightarrow \tau^+\tau^-) = B(H^{±±} \rightarrow \mu^+\mu^-) = B(H^{±±} \rightarrow \mu^±\mu^±) = 1/3$, we obtain $M(H^{±±}) > 130$ (138) GeV.

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

The $H^{±±}$ bosons could be pair-produced and observed at a hadron collider through the process $q\bar{q} \rightarrow Z/\gamma^* \rightarrow H^{++}H^{--} \rightarrow \ell^+\ell^+\ell^−\ell^−$ ($\ell, \ell' = e, \mu, \tau$). Single production of $H^{±±}$ bosons through $W$ exchange, leading to $H^{±±}H^±$ final states, is not considered in this Letter to reduce the model dependency of the results \cite{4}. Some models favor a mass of the $H^{±±}$ boson at the electroweak scale \cite{3}. The decay into like-charge lepton pairs violates lepton flavor number conservation. The decays $H^{±±} \rightarrow \tau^±\tau^±$ are predicted to dominate in some scenarios, such as the 3-3-1 model of Ref. \cite{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 $H^{±±}$ boson...
decays to $\tau\tau$, $\mu\tau$, and $\mu\mu$, if the mass of the lightest neutrino is less than 10 meV [3]. In this Letter, we present the first comparison of data with this model and the first search for $H^{\pm\pm} \rightarrow \tau^\pm\tau^\pm$ decays at a hadron collider.

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 $H_R^{\pm\pm}H_R^{\mp\mp}$ pairs is about a factor of 2 smaller than for $H_L^{\pm\pm}H_L^{\mp\mp}$ because of the different coupling to the $Z$ boson [2]. The mass limits for $H_L^{\pm\pm}$ bosons therefore tend to be weaker than for $H_L^{\pm\pm}$ bosons.

Searches for production of $H^{\pm\pm}$ bosons have been performed previously at the CERN $e^+e^-$ Collider (LEP) [9] and at the DESY ep Collider (HERA) [10]. Limits on the mass of the $H^{\pm\pm}$ boson were obtained in the range of 95–100 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 $e^+e^- \rightarrow e^+e^+H^{\pm\pm}$ [11] and $e^-p \rightarrow \ell^-H^{\mp\mp}p$ [10], and through the study of Bhabha scattering $e^+e^- \rightarrow e^+e^-$ [11], constraining the $H^{\pm\pm}$ boson’s Yukawa couplings $h_{\ell\ell}$ to electrons. Bounds on decays such as $\tau \rightarrow 3\mu$ or $\mu \rightarrow e\gamma$ and the measured $(g-2)_\mu$ also constrain different $h_{\ell\ell}$. At the Fermilab Tevatron Collider, the D0 and CDF Collaborations published limits for $\mu\mu$, $ee$, $\tau\tau$, and $\mu\tau$ final states in the range $M(H_L^{\pm\pm}) > 112$–150 GeV, assuming 100% decays into the specified final state [13, 16].

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 up to 7.0 fb$^{-1}$. The D0 detector [17] 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 and 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, $Z/\gamma^* \rightarrow \ell^+\ell^-$, and $t\bar{t}$ processes are generated using ALPGEN [18] with showering and hadronization provided by PYTHIA [19]. 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 $H^{\pm\pm} \rightarrow \tau^\pm\tau^\pm$, $\mu^\pm\mu^\pm$, and $\mu^\pm\tau^\pm$ are generated using Yukawa couplings $h_{\tau\mu} = h_{\tau\tau} = \sqrt{2}h_{\mu\mu} = \sqrt{2}h_{\mu\tau}$. The tau lepton decays are simulated with TAUOLA [20], which includes a full treatment of the tau polarization. All MC samples are processed through a GEANT [21] simulation of the detector. Data from random beam cross-
the range of the histogram are added to the last bin.

\[
\begin{align*}
\mu_\tau &= 0.50 \\
M(B^0) &= 120 \text{ GeV}
\end{align*}
\]

and expected signal for \(M(H^{\pm \pm}) = 120\) GeV, assuming the NLO calculation of the signal cross section for \(B(H^{\pm \pm} \rightarrow \tau^+ \tau^-) = 1\), \(B(H^{\pm \pm} \rightarrow \mu^+ \tau^-) = 1\), and \(B(H^{\pm \pm} \rightarrow \tau^+ \mu^-) = B(H^{\pm \pm} \rightarrow \mu^+ \mu^-) = B(H^{\pm \pm} \rightarrow \mu^+ \tau^-) = 1/3\). The numbers are shown for the four samples separately, together with their total uncertainties.

<table>
<thead>
<tr>
<th>Region</th>
<th>All</th>
<th>(N_\mu = 1)</th>
<th>(N_\mu = 1)</th>
<th>(N_\mu = 2)</th>
<th>(N_\tau = 2)</th>
<th>(N_\tau = 3)</th>
<th>(N_\tau = 2)</th>
<th>(q_{\tau_1} = q_{\tau_2})</th>
<th>(q_{\tau_1} = -q_{\tau_2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau^\pm \tau^\mp)</td>
<td>6.6 ± 0.9</td>
<td>14.0 ± 0.2</td>
<td>31.0 ± 0.4</td>
<td>16.0 ± 0.2</td>
<td>0.4 ± 0.1</td>
<td>14.0 ± 0.2</td>
<td>31.0 ± 0.4</td>
<td>16.0 ± 0.2</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>(\mu^+ \mu^-)</td>
<td>13.9 ± 1.9</td>
<td>0.3 ± 0.1</td>
<td>6.8 ± 0.9</td>
<td>0.4 ± 0.1</td>
<td>6.3 ± 0.9</td>
<td>0.3 ± 0.1</td>
<td>6.8 ± 0.9</td>
<td>0.4 ± 0.1</td>
<td>6.3 ± 0.9</td>
</tr>
<tr>
<td>Equal (B)</td>
<td>9.5 ± 1.3</td>
<td>2.5 ± 0.3</td>
<td>3.1 ± 1.0</td>
<td>1.2 ± 0.2</td>
<td>2.6 ± 0.4</td>
<td>2.5 ± 0.3</td>
<td>3.1 ± 1.0</td>
<td>1.2 ± 0.2</td>
<td>2.6 ± 0.4</td>
</tr>
<tr>
<td>Background</td>
<td>(Z \rightarrow \tau^+ \tau^-)</td>
<td>8.2 ± 1.1</td>
<td>3.4 ± 0.5</td>
<td>4.8 ± 0.7</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>3.4 ± 0.5</td>
<td>4.8 ± 0.7</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>(Z \rightarrow \mu^+ \mu^-)</td>
<td>5.1 ± 0.7</td>
<td>2.2 ± 0.3</td>
<td>2.5 ± 0.4</td>
<td>0.1 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>2.2 ± 0.3</td>
<td>2.5 ± 0.4</td>
<td>0.1 ± 0.1</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>(Z \rightarrow e^+ e^-)</td>
<td>0.3 ± 0.1</td>
<td>&lt; 0.1</td>
<td>0.3 ± 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>0.3 ± 0.1</td>
<td>&lt; 0.1</td>
<td>0.3 ± 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>(W + \text{jets})</td>
<td>2.9 ± 0.4</td>
<td>1.1 ± 0.2</td>
<td>1.8 ± 0.3</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>1.1 ± 0.2</td>
<td>1.8 ± 0.3</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>0.6 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>(\text{Diboson})</td>
<td>10.5 ± 1.7</td>
<td>0.5 ± 0.1</td>
<td>8.5 ± 1.4</td>
<td>0.4 ± 0.1</td>
<td>1.1 ± 0.2</td>
<td>0.5 ± 0.1</td>
<td>8.5 ± 1.4</td>
<td>0.4 ± 0.1</td>
<td>1.1 ± 0.2</td>
</tr>
<tr>
<td>(\text{Multijet} )</td>
<td>&lt; 0.8</td>
<td>&lt; 0.2</td>
<td>&lt; 0.5</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.2</td>
<td>&lt; 0.5</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Background</td>
<td>(\text{Sum})</td>
<td>27.6 ± 4.9</td>
<td>7.5 ± 1.2</td>
<td>18.2 ± 3.3</td>
<td>0.6 ± 0.1</td>
<td>1.3 ± 0.2</td>
<td>7.5 ± 1.2</td>
<td>18.2 ± 3.3</td>
<td>0.6 ± 0.1</td>
</tr>
</tbody>
</table>

region. A second method used to estimate the multijet background is based on the fact that events with \(Q = \pm 1\) are signal-like, whereas events with \(Q = \pm 3\) correspond largely to multijet background. To reduce the \(W + \text{jets}\) contribution in the sample with \(Q = \pm 3\), the visible \(W\) boson mass \(M_W = \sqrt{2p_Tp_T(1 - \cos \phi)}\) is required to be < 50 GeV, where \(p_T\) is the muon momentum, \(p_T\) the imbalance in transverse momentum measured in the calorimeter, and \(\phi\) is the azimuthal angle between the muon and the direction of the \(\vec{p}_T\). The total rate of expected multijet background events following all selections is negligible (< 3% of the total background). We also use the sample where both \(\tau_1\) and \(\tau_2\) candidates have \(N_\tau < 0.75\) to study the rate of jets that are falsely reconstructed as \(\tau_1\) and \(\tau_2\), and find this rate to be well modeled by the simulation.

To improve the discrimination of signal from background, the data are subdivided into four nonoverlapping samples, depending on the charges of the muon \(q_\mu\) and the \(\tau_h\) candidates \(q_\tau\) and the number of muons \(N_\mu\) and \(N_\tau\) 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 \(q_{\tau_1} = -q_{\tau_2}\), which implies one of the \(\tau\) 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. (a) and (b). The separation into samples with different fractions of signal and background events increases the sensitivity to signal, as the composition of the background is different, with the like-charge sample being dominated by background from \(Z + \text{jets}\) decays and the opposite-charge sample by background from diboson production. The diboson background is mainly due to \(WZ \rightarrow \mu e^+ e^-\) events where the electrons are misidentified as tau leptons. In Fig. (c) we show the transverse momentum of the doubly-charged dilepton system, \(p_T^{\pm \pm}\), which corresponds to the reconstructed \(H^{\pm \pm} \rightarrow e^+ e^-\) decay, where \(\ell^\pm p_T^{\pm \pm} = (\mu^\pm p_T^\pm, \tau_1^\pm p_T^\pm, \tau_2^\pm p_T^\pm)\) is the pairing of the two...
highest-\( p_T \) \( \tau_h \) and the highest-\( p_T \) muon that have the same charges. Since \( |Q| = 1 \), only one such pairing exists per event. The expected number of background and signal events for the four samples and the observed numbers of events in data are shown in Table II with the statistical uncertainties of the MC samples and systematic uncertainties added in quadrature.

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 \[24\]. 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 pseudoeperiments 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. The \( M(\tau_1, \tau_2) \) distribution is used to discriminate signal from background.

Systematic uncertainties on both background and signal, including their correlations, are taken into account. The theoretical uncertainty on background cross sections for \( Z/\gamma^* \rightarrow \ell^+\ell^- \), \( W \) jets, \( t\bar{t} \), and diboson production vary between 6% – 10%. The uncertainty on the measured integrated luminosity is 6.1% \[23\]. The systematic uncertainty on muon identification is 2.9% per muon and the uncertainty on the identification of \( \tau_h \) including the uncertainty from applying a neural network to discriminate \( \tau_h \) from jets, is 4% for each type-1 and 7% for each type-2 \( \tau_h \) 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 \( H^{\pm\pm}H^{\pm\pm} \) pair production \[8\] 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 \( B(H^{\pm\pm} \rightarrow \tau^+\tau^-) + B(H^{\pm\pm} \rightarrow \mu^+\mu^-) = 1 \) are determined by combining signal samples generated with pure \( 4\tau \), \( \{2\tau/2\mu\} \), and \( 4\mu \) final states with fractions \( B^2, 2B(1-B), \) and \( (1-B)^2 \), respectively, where \( B \equiv B(H^{\pm\pm} \rightarrow \tau^+\tau^-) \). 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 \( H^{++}H^{--} \rightarrow 4\mu \) decays performed by
FIG. 3: (color online). Expected and observed exclusion region at the 95% C.L. in the plane of $B(H^{\pm\pm} \to \tau^+\tau^-)$ versus $M(H^{\pm\pm})$, assuming $B(H^{\pm\pm} \to \tau^+\tau^-) + B(H^{\pm\pm} \to \mu^+\mu^-) = 1$, for (a) left-handed and (b) right-handed $H^{\pm\pm}$ bosons. The band around the expected limit represents the uncertainty on 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 $M(H^{\pm\pm}) > 128$ (116) GeV for a 100% branching fraction of $H^{\pm\pm} \to \tau^+\tau^-$, $M(H^{\pm\pm}) > 144$ (149) GeV for a 100% branching fraction into $\mu\tau$, and $M(H^{\pm\pm}) > 130$ (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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Writeup W5013, 1993.


[23] The pseudorapidity is defined as \( \eta = -\ln[\tan(\theta/2)] \), where \( \theta \) is the polar angle with respect to the proton beam direction.
