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A Search for Doubly Charged Higgs Scalars in Z Decay*

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ABSTRACT

We describe a search for the decay of the Z boson into pairs of doubly charged Higgs bosons (Majorons) with the Mark II detector operating at the SLAC Linear Collider. Each Higgs boson is assumed to decay into a same-sign lepton pair, producing a four-lepton final state. No event candidates are found in a sample of 528 Z decays. For a doubly charged Higgs boson that is a member of a left-handed weak isotriplet, this result excludes the region of mass (M_H) and leptonic coupling $(g_{\ell\ell})$, 6.5 $\mathrm{GeV/c^2} < M_H <$ 36.5 $\mathrm{GeV/c^2}$ and $g_{\ell\ell} > 3 \times 10^{-7}$, with 95% confidence. If the Higgs boson is a singlet of left-handed weak isospin, the excluded region is 7.3 $\mathrm{GeV/c^2} < M_H <$ 34.3 $\mathrm{GeV/c^2}$ and $g_{\ell\ell} > 3 \times 10^{-7}$, with 95% confidence. These limits are independent of the flavors of the final state leptons.

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This Letter presents the result of a search for the decay of the Z boson into a pair of doubly charged Higgs bosons. Doubly charged Higgs bosons (also called Majorons) are a feature of many theories that extend the Standard Model to include left-handed Majorana mass terms for the neutrino sector. If the Majorana mass terms are generated by the vacuum expectation value of a neutral Higgs field, the theory must also include singly and doubly charged Higgs states that couple only to lepton pairs.

The simplest theory of this type, the Gelmini-Roncadelli Model[1] (also called the Majoron Model), contains a single doubly-charged state that couples only to left-handed charged lepton pairs. The third component of (left-handed) weak isospin for this state has unit value (I_3^L = 1). A slightly more complicated example is the Left-Right Symmetric Model[2] which contains a doubly charged Higgs state that couples to left-handed charged lepton pairs (with I_3^L = 1) and a doubly charged state that couples to right-handed charged lepton pairs (with I_3^L = 0).

Most of the existing limits on doubly charged Higgs bosons[3–5] are functions of the coupling strength of the Higgs boson to lepton pairs ($g_{\ell\ell}$) and of the Higgs boson mass (M_H). The only limit that extends to small values of $g_{\ell\ell}$ is rather weak,[5] M_H > 14 GeV/c^2 with 90% confidence. We therefore seek to improve the small-coupling limit by searching for the process $e^+e^- \rightarrow Z \rightarrow H^{++}H^{--} \rightarrow \ell^+\ell^+ l^- l^-$ where ℓ and l may or may not be the same species of charged lepton.[6]

The production cross section for doubly charged Higgs scalars at the Z pole is moderately large. The partial width for the decay $Z \rightarrow H^{++}H^{--}$ (Γ_{HH}) is given by the following, tree-level expression,[7-8]

$$\Gamma_{HH} = \frac{G_F M_Z^3}{6\pi\sqrt{2}}(I_3^L - 2\sin^2\theta_w)^2\beta^3 \tag{1}$$

where: G_F is the Fermi coupling constant; M_Z is the mass of the Z boson;[9] $\sin^2\theta_w$ is the electroweak mixing parameter;' and β is the Higgs boson velocity in the e^+e^- center-of-mass frame. In the limit $\beta \rightarrow 1$, the rate of left-handed Higgs boson ($I_3^L = 1$) production is approximately 14% larger than that for a charged lepton species and the rate of right-handed Higgs boson ($I_3^L = 0$) production is about 14% smaller than the charged lepton rate.

For Higgs boson masses that are less than those of the W and Z bosons, the doubly charged Higgs boson is expected to decay dominantly into same-sign lepton pairs. The Higgs boson lifetime (τ_H) is given by the following expression,[7,5]

$$\tau_H^{-1} = \sum_{\ell} \frac{g_{\ell\ell}^2}{8\pi} M_H \left[1 - \frac{2m_\ell^2}{M_H^2}\right] \left[1 - \frac{4m_\ell^2}{M_H^2}\right]^{1/2} \tag{2}$$

where m_ℓ is the lepton mass. The Higgs bosons are therefore short-lived ($\lesssim 10^{-12}$ sec) unless the coupling constants $g_{\ell\ell}$ are very small.

The search that is described here makes use of a data sample that was collected with the Mark II detector at the SLAC Linear Collider (SLC). The sample corresponds to a total integrated luminosity of 19.7 nb^{-1} taken at nine different center-of-mass energies near the Z pole. The sample includes 455 events that are identified as hadronic final states.[10] Incorporating equation (1) into a complete calculation of the Higgs pair production rate (including the effects of initial state radiation), we predict that the Mark II data would include approximately 22 left-handed (or 16 right-handed) Higgs pairs if the Higgs boson mass is 15 $\mathrm{GeV/c^2}$ (near the current limit on M_H).

A detailed description of the Mark II detector can be found in another publication." Most of the information used in this analysis is provided by the 72-layer drift chamber. The chamber is immersed in a 4.75-kG magnetic field. Isolated charged particle tracks are reconstructed with high efficiency (-99%) in the region of polar angle $|\cos\theta| < 0.80$. In the forward regions, $0.80 < |\cos\theta| < 0.92$, the reconstruction efficiency decreases from 99% to approximately 80%. The detector is also instrumented with an electromagnetic calorimeter that consists of three segments. The barrel section detects electrons and photons in the region $|\cos\theta| < 0.72$. The two endcap calorimeters extend the region of angular coverage to $|\cos\theta| < 0.96$. The detector is triggered by two or more charged tracks in the region of polar angle $|\cos\theta| < 0.76$, or by the localized deposition of at least 3.3 GeV of energy in the barrel calorimeter or 2.2 GeV in one of the endcap calorimeters.

Of the six possible four-lepton final states, the most difficult to detect is the one consisting of four τ leptons. The strategy of this analysis is to define a set of topological selection criteria that can identify the four-r final state with high efficiency. It is clear that such criteria select four-lepton final states that contain two or more stable leptons with comparable or larger efficiency.

Since 90% of all four-r events decay into six or fewer charged particles, we consider only those event candidates that contain six or fewer charged tracks that project into a cylindrical volume of 2 cm radius and 6 cm length that is centered on the interaction point of the SLC. In order to suppress two-photon events and badly accepted hadronic final states, we require that the scalar sum of the track momenta be at least 10 GeV/c.

The 4-vectors of the charged tracks are then subjected to a mass-based clustering algorithm. Each track is initially designated as a cluster. The pair of clusters with the smallest invariant mass is merged if their mass is less than 2.0 GeV/c^2. The procedure is repeated until all pairs have an invariant mass larger than 2.0 GeV/c^2.

We expect most four-lepton events to appear as four-cluster events. There is a reasonable probability, however, that a cluster occurs in one of the forward regions, $|\cos\theta| > 0.80$, and is not detected (approximately 30% of all events fall into this category). We therefore require each event candidate to contain either three or four clusters of energy larger than 1.0 GeV. The net charge of each cluster must be unity. The event must not contain any clusters with charges larger than unity. The net event charge must be zero for four-cluster candidates or unity for three-cluster candidates.

There are no event candidates in the Mark II data sample that satisfy the selection criteria. The number of background events that are expected to satisfy the selection criteria is estimated from several Monte Carlo simulations. We estimate the contributions from two-photon processes: radiative lepton pair production,[13] and low multiplicity hadronic Z decays[14] to be 0.01, 0.11, and 0.52 events, respectively.

In order to interpret this result, we have performed a Monte Carlo simulation of doubly charged Higgs boson production and decay for the Mark II detector. The effect of initial state bremsstrahlung is simulated using the structure function approach of Nicrosini and Trentadue.[15] Each Higgs boson is allowed to decay isotropically into a same-sign lepton pair or into $\ell\ell\gamma$ according to an approximate distribution.[16] The Monte Carlo simulates the displacement of the decay vertices due to finite Higgs boson lifetimes. The τ simulation includes final state spin effects for the dominant single prong decay modes ($\ell\nu\bar{\nu}$, $\rho\nu$, and $\pi\nu$ final states). In order to simulate the effect of machine related backgrounds upon the event reconstruction, the simulated raw data from the Monte Carlo are mixed with real raw data from random triggers of the apparatus. The mixed data are then subjected to trigger emulation and to the complete Mark II event reconstruction program.

Using the Monte Carlo simulation, we find that the efficiency of the detector and selection criteria (ε_H) for τ final states is insensitive to the τ chirality.[17] The overall efficiency is therefore independent of I_3^L. We also find that the acceptance for muon final states is smaller than that for electron final states by a few percent. This difference is due entirely to the presence of the neutral energy trigger which detects electrons but not muons. To simplify the analysis, we choose to ignore this difference and to use the (more conservative) muon acceptance for both species of stable lepton.

-The efficiency function ε_H therefore depends upon the r-pair branching ratio of the Higgs boson (B_τ), the Higgs boson mass, and the Higgs boson lifetime. The efficiency increases steeply with increasing M_H at low masses and becomes independent of mass in the region M_H > 30 GeV/c^2. The function ε_H does not vary with the Higgs boson lifetime in the region τ_H < 30 ps and decreases slowly with increasing τ_H. In the high mass, short-lifetime region, ε_H increases from 63% at B_τ = 1.0 to 81% at B_τ = 0.0.

We extract limits on M_H and the couplings $g_{\ell\ell}$ from the ratio of the observed number of events to the number of detected hadronic Z decays, R_H. Hadronic Z decays are defined by selection criteria that are given in a previous publication.[10] The measured ratio is $R_H = 0/455$. Using binomial statistics,[18] the 90% and 95% confidence limits on R_H are $R_H^{90} = 5.07 \times 10^{-3}$ and $R_H^{95} = 6.61 \times 10^{-3}$, respectively.

The actual limits are determined by finding the values of M_H and τ_H for which the expected value of R_H is equal to the experimentally derived limit. The expected value of R_H is given by the following expression,

$$R_H = \frac{\varepsilon_H(M_H, B_\tau, \tau_H) N_H(M_H, I_3^L)}{\varepsilon_{qq} N_{qq} + \varepsilon'_H(M_H, B_\tau, \tau_H) N_H(M_H, I_3^L)}, \tag{3}$$

where: N_H is the expected number of produced Higgs pairs of mass M_H and isospin I_3^L (correctly summed over all of the Mark II energy-luminosity points); ε_{qq} = 0.953 is the efficiency to detect a hadronic event;[10] N_{qq} is the expected number of produced hadronic events (summed over all energy-luminosity points); and ε'_H is the probability that a produced doubly charged Higgs event fails the selection criteria and satisfies the hadronic event selection criteria. Although this technique is insensitive to the absolute luminosity scale of the experiment, it is reassuring to note that the product $\varepsilon_{qq} N_{qq}$ is calculated to be 451 events, in excellent agreement with the observed number of events (455).

We account for systematic uncertainties on the τ branching ratios (0.4%) and on the tracking efficiency (1.5%) and for the statistical uncertainty of the Monte Carlo calculation (1.4%) by reducing ε_H by the linear sum of the effects. Since the simulation of the trigger is known to underestimate its efficiency, no additional correction is made for trigger efficiency. The systematic uncertainty on the hadronic event detection efficiency is included by increasing ε_{qq} by one sigma (0.6%).

The ratio N_H/N_{qq} is sensitive to our choice of $\sin^2\theta_w$.[9] We account for this effect by taking N_H/N_{qq} to be equal to its minimum value in the interval $\sin^2\theta_w$ = 0.233 $\pm$ 0.007. Note that the minima of the I_3^L = 0 and I_3^L = 1 cases occur at opposite ends of the interval. The result of this procedure is to reduce the expected value of R_H by 6.9% in the I_3^L = 0 case and by 4.2% in the I_3^L = 1 case.

In the short lifetime region, the intervals of M_H that are excluded with 90% confidence and with 95% confidence are listed in Table I for several values of B_τ and

I_3^L. The upper limits on M_H are due to the β^3 suppression of the cross section. The lower limits are due to the loss of efficiency as M_H becomes small. The efficiency function for stable leptons falls sharply at the cluster mass of 2.0 GeV/c^2. The 90% and 95% confidence limits occur quite close to this point. For $B_\tau = 0.5$, the number of events with four stable leptons is sufficient to exclude values of M_H down to the T-pair threshold. The short lifetime constraint requires that there be at least one coupling constant in the region $g_{\ell\ell} \gtrsim 7.4 \times 10^{-7}/\sqrt{M_H}$ (M_H in GeV/c^2). This implies that the dominant coupling(s) be larger than $\sim 5 \times 10^{-7}$ in the small mass region and $\sim 1 \times 10^{-7}$ in the high mass region.

The excluded regions overlap and significantly extend the existing small-coupling limits on M_H (which are independent of I_3^L).[5] The 90% confidence limit for $B_\tau = 0$ is extended from approximately 21.5 GeV/c^2 to 39.7 GeV/c^2 (38.5 GeV/c^2) for left-handed (right-handed) Higgs bosons. For $B_\tau = 1$, the 90% limit is extended from 14 GeV/c^2 to 38.2 GeV/c^2 (36.4 GeV/c^2) for left-handed (right-handed) Higgs bosons.

In order illustrate the dependence of the limits upon the mass and coupling constants, the least restrictive 90% limit ($B_\tau = 1$, $I_3^L = 0$) is plotted in $g_{\ell\ell} - M_H$ space in Figure 1 (the solid curve). Note that it extends to $g_{\ell\ell} = 7.2 \times 10^{-8}$. The limit is compared with two rather specific limits from Reference 5.

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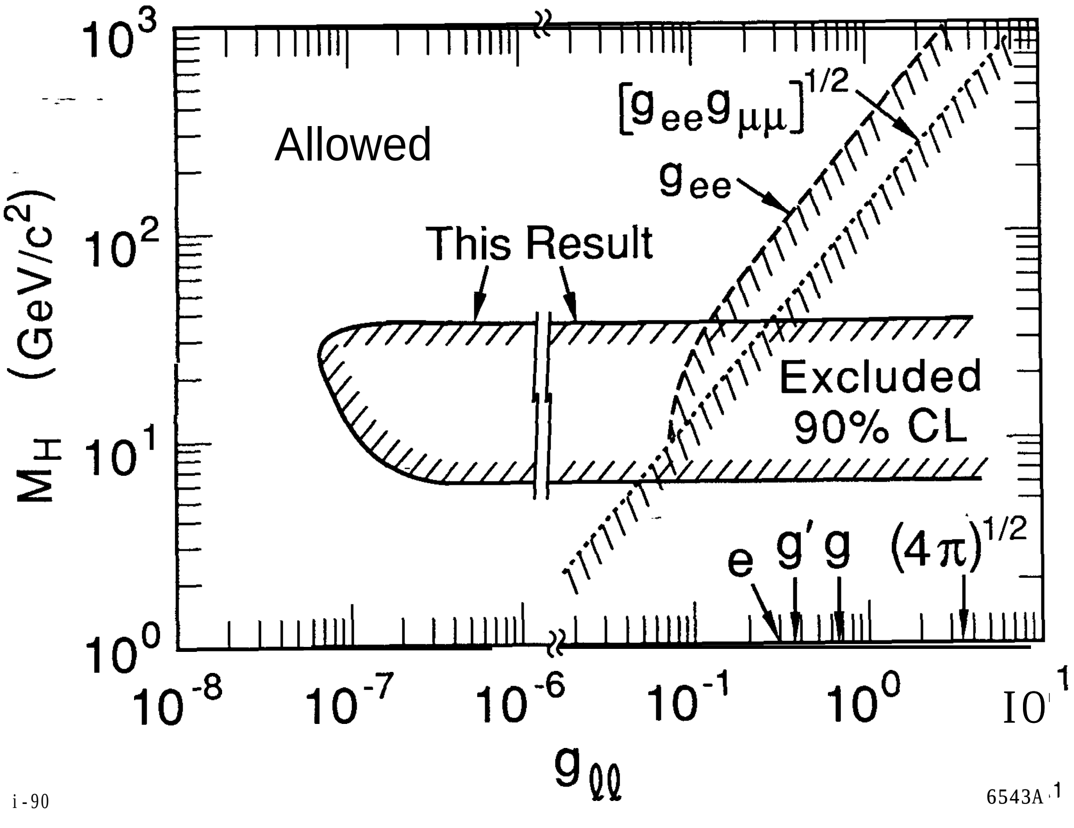
Table I

The intervals of M_H that are excluded at 90% confidence and at 95% confidence for left-handed (I_3^L = 1) and right-handed $(I_3^L$ = 0) doubly charged Higgs bosons. The excluded intervals are tabulated as a function of the τ branching ratio B_τ. They are valid in the region of coupling constant $g_{\ell\ell} \gtrsim 5 \times 10^{-7}$.

I_3^L	B_τ	90% Limit (GeV/c^2)	95% Limit (GeV/c^2)
0	1.0	$6.5 < M_H < 36.4$	$7.3 < M_H < 34.3$
0	0.5	$3.6 < M_H < 37.7$	$3.6 < M_H < 36.0$
0	0.0	$2.0 < M_H < 38.5$	$2.0 < M_H < 36.7$
1	1.0	$5.9 < M_H < 38.2$	$6.5 < M_H < 36.6$
1	0.5	$3.6 < M_H < 39.2$	$3.6 < M_H < 37.9$
1	0.0	$2.0 < M_H < 39.7$	$2.0 < M_H < 38.4$

FIGURE CAPTIONS

1) The 90% confidence contours of M_H versus the leptonic coupling strength $g_{\ell\ell}$ that are obtained from several processes. The excluded regions are indicated by the shaded side of each contour. The result of this search is shown as the solid contour (the limit is independent of lepton flavor). The limit[5] that is obtained from the limit on muonium to antimuonium conversion is shown as a dotted line ($\sqrt{g_{ee}g_{\mu\mu}}$ is plotted along the horizontal axis). The limit [5] that is obtained from the Bhabha scattering data of several PEP and PETRA experiments is shown as a dashed curve (g_{ee} is plotted along the horizontal axis). For reference, the sizes of the coupling constants g, g', and e are indicated. The strong coupling limit occurs at the value $\sqrt{4\pi}$.



Allowed
[g_ee g_μμ]^1/2
g_ee
This Result
Excluded
90% CL
e g' g (4π)^1/2
M_H (GeV/c^2)
10^3
10^2
10^1
10^0
10^-8 10^-7 10^-6 10^-1 10^0 10^1
g_ℓℓ
i-90
6543A.1

Fig. 1