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Direct Search for Pair Production of Heavy Stable Charged Particles in Z Decays

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A search for pair production of stable charged particles from Z decay has been performed with the Mark II detector at the SLAC Linear Collider. Particle masses are determined from momentum, ionization energy loss, and time-of-flight measurements. A limit excluding pair production of stable fourth-generation charged leptons and stable mirror fermions with masses between the muon mass and 36.3 GeV/c^2 is set at the 95% confidence level. Pair production of stable supersymmetric scalar leptons with masses between the muon mass and 32.6 GeV/c^2 is also excluded.

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The e^+e^- collisions at the SLAC Linear Collider (SLC) provide an opportunity to search for new stable charged particles which couple to the Z boson. There are no firm theoretical predictions for the existence of such particles. The most likely candidate which is compatible with the standard model is a fourth-generation charged lepton whose mass is less than that of its neutrino. Several extensions of the standard model provide for the existence of new heavy stable charged particles with masses that could be small enough to allow them to be produced in Z decays. For example, in supersymmetric theories,[1] the scalar lepton could be stable if it is lighter than the photino. Another possibility is the production of mirror fermions.[2] They arise naturally in several unification schemes and the lightest of these right-handed charged leptons could be long lived. The production of stable charged particles beyond the standard model has been excluded[3] up to a mass of 27.6 GeV/c^2 in direct searches at other e^+e^- colliders. So far, the best limit from the CERN e^+e^- collider LEP[4] on stable charged leptons is 26.5 GeV/c^2, obtained from an indirect search based on the difference between the measured Z width and the standard-model prediction. Their production cross section has also been limited[5] for masses between 50 and 200 GeV/c^2 in proton-antiproton collisions.

The expected signal for new-heavy-stable-particle pair production consists of two charged particles in the final state with large and equal mass. In this Letter, the mass determination is made from momentum, ionization energy loss (dE/dx), and time-of-flight (TOF) measurements. The expected values of these measurements with corresponding $\pm 1\sigma$ variations are shown as a function of mass in Fig. 1. These measurements are independent and complementary, with the combination of the three providing the mass assignment.

The Mark II detector is described in detail in Ref. 6. The main components used by this analysis are described below. Charged-particle tracking is provided by the central drift chamber with twelve concentric layers of six sense-wire jet chamber cells extending in radius from 19.2 to 151.9 cm. Tracks can be reconstructed within the angular range $|\cos\theta| < 0.92$, and the chamber is enclosed in a 4.75-kG solenoidal magnetic field. A resolution of $\sigma(p)/p^2 = 0.0031$ $(\mathrm{GeV}/c)^{-1}$ has been achieved for isolated tracks constrained to the beam interaction point during a test run at the PEP storage ring at SLAC.[6] This resolution is confirmed at the SLC using $\mu^+\mu^-$ pair events. A dE/dx measurement is made based on the charge collected on the sense wires. The resolution achieved for minimum ionizing tracks at the SLC is 8.5% of the measured value. The TOF measurement is made with scintillating counters placed at the outer radius of the drift chamber. The Mark II data-acquisition system is triggered by two or more charged tracks with $|\cos\theta| < 0.75$, or by an electromagnetic shower with localized energy deposition greater than 3.3 GeV in the barrel, or greater than 2.2 GeV in the endcap electromagnetic calorimeters.

The understanding of the measurement errors of the above detector systems is critical to this analysis because they contribute to the error in the mass assignment. These errors were found[6] to be well described by Gaussian distributions for the inverse of the momentum $1/p$, the dE/dx, and the TOF measurements in the test run at PEP. This is also found to be true for the momentum and dE/dx measurements at the SLC. However, the TOF measurement errors at the SLC are non-Gaussian, as significant accelerator backgrounds contribute to early measured times. This analysis uses a parametrization of the TOF measurement-error distribution with the function

$$f(t) \propto \begin{cases} \exp\left[-\dfrac{1}{2}\left(\dfrac{\mu-t}{\sigma}\right)^2\right], & t \geq t', \\ \exp\left(-\dfrac{b^2}{2}\right)\left(\dfrac{a}{b}\right)^a \left(\dfrac{\sigma}{\mu-t+\sigma(a/b-b)}\right)^a, & t < t', \end{cases} \tag{1}$$

where $t = \mathrm{TOF}_{\mathrm{measured}} - \mathrm{TOF}_{\mathrm{expected}}$, $t' = \mu - b\sigma$, and the parameters $\mu = -11$ ps, $\sigma = 426$ ps, $a = 17.3$, and $b = 0.83$ are determined from the data. This function, constructed so as to be smooth and continuous, is a Gaussian distribution with an extended tail at early times. A fit of this function that includes both high-momentum tracks ($\beta \simeq 1$) and minimum ionizing pions identified by the momentum and dE/dx measurements is shown in Fig. 2.

The candidate stable charged pair events are required to have two charged tracks emanating from a cylindrical volume of radius 1 cm and half-length 3 cm around the beam line, centered at the interaction point. The tracks should be back to back with $\cos\theta_{\mathrm{acol}} > 0.99$, where θ_{acol} is the acollinearity angle between the tracks. The background from $\tau^+\tau^-$ pairs with both τ's decay to one prong is reduced by requiring that each track has a momentum greater than 5 GeV/c and equal to the other within 3σ. Since the mass determination is based in part on TOF measurements, at least one track must hit the active region of the TOF system and must have a time not more than 1.25 ns earlier than that expected for a $\beta = 1$ particle. This cut on early times assures that the TOF measurement is not used if it has been corrupted by SLC machine backgrounds. The TOF requirement also implies that at least one track must have $|\cos\theta| < 0.70$ due to the solid angle coverage of the TOF system. Finally, stable particles with masses greater than the muon mass are not expected to produce electromagnetic showers; therefore, we require for each track an energy deposition of less than 20 GeV in the calorimeters. This eliminates the background from e^+e^- pairs and reduces it for $\tau^+\tau^-$ pairs with subsequent $\tau \to e\nu\bar{\nu}$ decays. 13

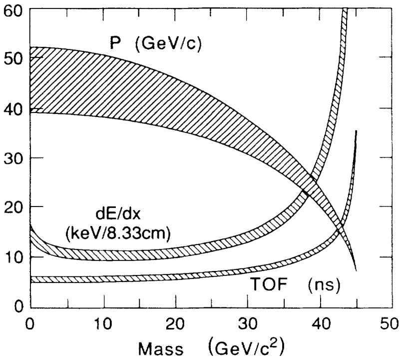

FIG. 1. The expected values of the momentum, dE/dx, and TOF measurements as a function of mass for stable particles produced in pairs from Z-boson decay. The shaded bands show the $\pm 1\sigma$ variation in the measured quantities with $\sigma_p/p = [(0.0031p)^2 + (0.014)^2]^{1/2}$, $\sigma_{dE/dx} = (0.085)dE/dx$, and $\sigma_{\mathrm{TOF}} = 425$ ps.

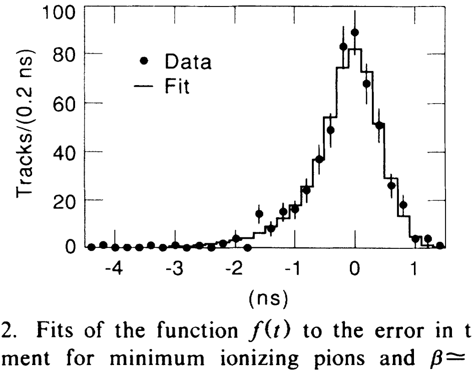

FIG. 2. Fits of the function $f(t)$ to the error in the TOF measurement for minimum ionizing pions and $\beta \simeq 1$ tracks from the SLC data.

events from the data pass the above selection, in good agreement with the expectation of 14.5 events from Monte Carlo simulations of e^+e^-,[7] $\mu^+\mu^-$, and $\tau^+\tau^-$ pairs.[8] The efficiency for $\mu^+\mu^-$ pairs to pass the selection criteria is 0.57 ± 0.01.

A mass assignment for the selected events is obtained from the likelihood function

$$\mathcal{L}(M) \equiv \prod_{\substack{i=1\\ \text{tracks}}}^{2} f(t_i)\, g\left(\frac{dE}{dx_i}\right) g\left(\frac{1}{p_i}\right), \tag{2}$$

with

$$g(x) = \frac{1}{\sqrt{2\pi}\sigma_x(M)} \exp[-\tfrac{1}{2} A(x)] \tag{3}$$

and

$$A(x) = \left(\frac{x_{\text{measured}} - x_{\text{expected}}(M)}{\sigma_x(M)}\right)^2, \tag{4}$$

where $f(t)$ is defined in Eq. (1) with $t = \text{TOF}_{\text{measured}} - \text{TOF}_{\text{expected}}(M)$. The mass $M \geq 0$ which maximizes $\mathcal{L}(M)$ provides the most probable mass assignment under the assumption that both tracks have equal mass constrained by $(p^2+M^2)^{1/2} = M_Z/2$, where M_Z is the mass of the Z boson. A test of this stable pair-production assumption is made by requiring that at the most probable mass M, the χ^2,

$$\chi^2(M) = \sum_{\substack{i=1\\ \text{tracks}}}^{2} \left[A(\text{TOF}_i) + A\left(\frac{dE}{dx_i}\right) + A\left(\frac{1}{p_i}\right)\right], \tag{5}$$

for five degrees of freedom is less than 50. The cut is set at 40 if only one of the two tracks has a good TOF measurement as defined by the event-selection cuts. This requirement reduces background from $\tau^+\tau^-$ pair production with both τ's decaying to one prong. The inefficiency due to stable pairs not passing the cut is negligible. One of the 13 selected events from the data fails the χ^2 test with a value of 895, making the stable-pair hypothesis highly improbable. The remaining 12 events all have most probable mass assignments which are less than 2 GeV/c^2 making them consistent with being $\mu^+\mu^-$ pairs. We find the expected background to heavy-stable-lepton pair production from Monte Carlo e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$ pairs to be negligible above 2 GeV/c^2. Thus, in the absence of observed events, an upper limit[9] Of 3.0 events is obtained at the 95% confidence level.

To set a limit on stable-charged-lepton production we need to estimate the number expected for different masses within the assumptions of the standard model. The expected number of charged-lepton pairs produced with a mass M can be normalized to the number of hadronic decays of the Z as

$$N = \frac{N_h \Gamma_{ee}}{\epsilon_h \Gamma_h} \frac{\beta[\frac{1}{2}(3-\beta^2)v_l^2 + \beta^2 a_l^2]}{v_l^2 + a_l^2}, \tag{6}$$

where N_h is the number of observed hadronic events, ϵ_h is the efficiency for detecting the hadronic events, Γ_h is the partial width of the Z decay into hadrons, Γ_{ee} is the leptonic width for electrons, a_l and v_l denote the axial-vector and vector coupling constants for charged leptons, and $\beta = (1 - 4M^2/E_{\text{c.m.}}^2)^{1/2}$, where $E_{\text{c.m.}}$ is the center-of-mass energy. From a data sample corresponding to an integrated luminosity of 19.7 nb^{-1} and covering a range in $E_{\text{c.m.}}$ between 89.2 and 93.0 GeV, we find that 455 events pass a set of hadronic selection requirements described in Ref. 10. The efficiency of this selection was found[10] from Monte Carlo simulations to be $\epsilon_h = 0.953 \pm 0.006$. Differences in QCD models account for the largest component of this uncertainty. The efficiency for simulated stable-heavy-lepton pairs to pass the hadronic event selection is negligible. The partial hadronic and leptonic widths of the Z and the coupling constants are obtained from the standard model with[10,11] $M_Z = 91.14$ GeV/c^2, $M_{\text{top}} = 100$ GeV/c^2, $M_{\text{Higgs}} = 100$ GeV/c^2, and $\alpha_s = 0.123$. The calculations include radiative effects.[12] The dependence of the expected number of events on these parameters is small. For example, a 0.8% reduction in N is obtained if the values $M_{\text{top}} = 200$ GeV/c^2, $M_{\text{Higgs}} = 1$ TeV/c^2, and $\alpha_s = 0.140$ are used, with the largest contribution coming from the change in the effect of QCD radiative corrections. The systematic error on N due to the uncertainty in $E_{\text{c.m.}}$ is negligible for stable-lepton masses below 40 GeV/c^2. The largest source of uncertainty in N comes from the 4.6% statistical error on N_h.

The expected number of stable-heavy-lepton pairs identified at a given mass is determined using Monte Carlo simulation.[8] In order to distinguish simulated stable-lepton pairs from $\mu^+\mu^-$ pairs we require, in addition to the same cuts applied to the data, that the most probable mass assigned to them be greater than 2 GeV/c^2. The efficiency for the simulated pairs to pass all the cuts is found to rise from 0.06 at 1 GeV/c^2 to 0.56 at 5 GeV/c^2 where the effect of the 2-GeV/c^2 minimum requirement on the most probable mass becomes small. The systematic error is found by shifting the values and resolutions of the TOF, dE/dx, and momentum measurements by 1 standard deviation so as to reduce the efficiency. This error is of order 1% for masses above 20 GeV/c^2. An additional 2% systematic error is taken to account for uncertainties in the lepton-production Monte Carlo model. A slow increase in efficiency is observed above 10 GeV/c^2. This is due to the dominant terms in the differential cross section for e^+e^- annihilation to two spin-$\frac{1}{2}$ fermions near the Z pole[9] which have an angular distribution proportional to $1+\cos^2\theta + (1-\beta^2)\sin^2\theta$. This distribution becomes isotropic at higher masses where $\beta \rightarrow 0$. Multiplying the number of produced pairs, Eq. (6), by the efficiency of the simulated pairs to pass all the cuts, we find the expected number of stable-charged-lepton pairs as a function of mass, shown in Fig. 3(a). The dotted curve is the number of events assuming that all statistical and systematic errors conspire to reduce the expectation. These

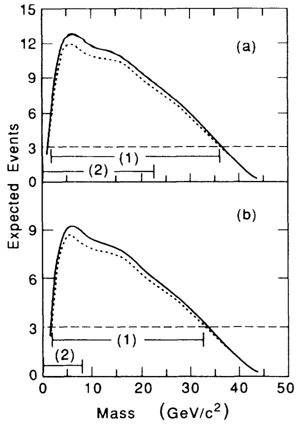

FIG. 3. The expected number of (a) stable-heavy-lepton and (b) stable-scalar-lepton events which pass the selection and identification requirements described in the text. Dotted lines mark the lower bounds obtained by the inclusion of statistical and systematic errors. Dashed lines show the 95%-confidence-level upper limits of 3.0 events detected at the SLC. Also indicated are the mass regions for which production is excluded by (1) the direct and (2) the event-rate-based search analyses described in the text.

errors include the systematic and statistical errors on N and the systematic errors on the efficiency for stable pairs to pass all the cuts as discussed above. The net reduction is about 10% in the 2-GeV/c^2 mass range and falls to about 5% above 15 GeV/c^2. The upper and lower limits on stable-heavy-lepton production can be read from the intersection of the dotted line describing the expectations with the upper limit of 3 observed events. This direct search excludes pair production of stable leptons with masses between 2.0 and 36.3 GeV/c^2 as indicated in Fig. 3(a). The analysis and limits presented also apply to stable mirror fermions,[2] as the only difference in their production rate from Z decay is that the left- and right-handed couplings are interchanged with respect to the standard-model couplings.

The above analysis may be extended to search for supersymmetric scalar leptons. The production rate from Z decays, assuming that the left- and right-handed scalar leptons $\tilde{l}_L$ and $\tilde{l}_R$ are degenerate in mass, is given[1] by

$$\Gamma(Z \to \tilde{l}_L^+ \tilde{l}_L^- + \tilde{l}_R^+ \tilde{l}_R^-)/\Gamma(Z \to e^+ e^-) = \tfrac{1}{2}\beta^3 , \qquad (7)$$

with the decay angular distribution proportional to $\sin^2\theta$. Using this rate in the above analysis, we exclude the production of stable scalar leptons with masses between 2.0 and 32.6 GeV/c^2 as shown in Fig. 3(b).

Finally, we can exclude new-stable-charged-particle pair production for masses below 2 GeV/c^2 down to m_μ, the mass of the muon, using a less direct search method based on event rate only. In this approach, the 13 data events selected above are treated as a combination of both signal from new stable pair production and expected background from known leptons. Then, using the method described in Ref. 9, we find the upper limit at 95% confidence level to be 8.1 signal events for 13 observed and 14.5 expected background events. Taking this upper limit together with the production rate, Eq. (6), and the efficiency for stable pairs to pass the same selection criteria, we exclude the production of new-stable-lepton pairs from m_μ to 22.7 GeV/c^2. For supersymmetric scalar leptons, where the production rate is given by Eq. (7), the excluded region extends from m_μ to 8.0 GeV/c^2. These mass regions are shown in Fig. 3.

In conclusion, we have searched for pair production of stable charged particles from Z decay. A limit excluding pair production of stable fourth-generation charged leptons and stable mirror fermions with masses between m_μ and 36.3 GeV/c^2 has been set at the 95% confidence level. Pair production of stable supersymmetric scalar leptons with masses between m_μ and 32.6 GeV/c^2 has also been excluded at the 95% confidence level under the assumption that the left- and right-handed scalar leptons are degenerate in mass.

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