

**A SEARCH FOR PAIR PRODUCTION OF HEAVY  
STABLE CHARGED PARTICLES IN Z DECAYS\***

E. Soderstrom,<sup>5</sup> J. A. McKenna,<sup>5</sup> G. S. Abrams,<sup>1</sup> C. E. Adolphsen,<sup>2</sup>  
D. Averill,<sup>3</sup> J. Ballam,<sup>4</sup> B. C. Barish,<sup>5</sup> T. Barklow,<sup>4</sup> B. A. Barnett,<sup>6</sup>  
J. Bartelt,<sup>4</sup> S. Bethke,<sup>1</sup> D. Blockus,<sup>3</sup> G. Bonvicini,<sup>7</sup> A. Boyarski,<sup>4</sup> B. Brabson,<sup>3</sup>  
--A. Breakstone,<sup>8</sup> F. Bulos,<sup>4</sup> P. R. Burchat,<sup>2</sup> D. L. Burke,<sup>4</sup> R. J. Cence,<sup>8</sup>  
J. Chapman,<sup>7</sup> M. Chmeissani,<sup>7</sup> D. Cords,<sup>4</sup> D. P. Coupal,<sup>4</sup> P. Dauncey,<sup>6</sup>  
H. C. DeStaebler,<sup>4</sup> D. E. Dorfan,<sup>2</sup> J. M. Dorfan,<sup>4</sup> D. C. Drewer,<sup>6</sup> R. Elia,<sup>4</sup>  
G. J. Feldman,<sup>4</sup> D. Fernandes,<sup>4</sup> R. C. Field,<sup>4</sup> W. T. Ford,<sup>9</sup> C. Fordham,<sup>4</sup>  
R. Frey,<sup>7</sup> D. Fujino,<sup>4</sup> K. K. Gan,<sup>4</sup> E. Gero,<sup>7</sup> G. Gidal,<sup>1</sup> T. Glanzman,<sup>4</sup>  
G. Goldhaber,<sup>1</sup> J. J. Gomez Cadenas,<sup>2</sup> G. Gratta,<sup>2</sup> G. Grindhammer,<sup>4</sup>  
P. Grosse-Wiesmann,<sup>4</sup> G. Hanson,<sup>3</sup> R. Harr,<sup>1</sup> B. Harral,<sup>6</sup> F. A. Harris,<sup>7</sup>  
C. M. Hawkes,<sup>5</sup> K. Hayes,<sup>4</sup> C. Hearty,<sup>1</sup> C. A. Heusch,<sup>2</sup> M. D. Hildreth,<sup>4</sup>  
T. Himel,<sup>4</sup> D. A. Hinshaw,<sup>9</sup> S. J. Hong,<sup>7</sup> D. Hutchinson,<sup>4</sup> J. Hysten,<sup>6</sup>  
W. R. Innes,<sup>4</sup> R. G. Jacobsen,<sup>4</sup> J. A. Jaros,<sup>4</sup> C. K. Jung,<sup>4</sup> J. A. Kadyk,<sup>1</sup>  
J. Kent,<sup>2</sup> M. King,<sup>2</sup> D. S. Koetke,<sup>4</sup> S. Komamiya,<sup>4</sup> W. Koska,<sup>7</sup>  
L. A. Kowalski,<sup>4</sup> W. Kozanecki,<sup>4</sup> J. F. Křal,<sup>1</sup> M. Kuhlen,<sup>5</sup> L. Labarga,<sup>2</sup>  
A. J. Lankford,<sup>4</sup> R. R. Larsen,<sup>4</sup> F. Le Diberder,<sup>4</sup> M. E. Levi,<sup>7</sup> A. M. Litke,<sup>2</sup>  
X. C. Lou,<sup>3</sup> V. Lüth,<sup>4</sup> J. A. J. Matthews,<sup>7</sup> T. Mattison,<sup>4</sup> B. D. Milliken,<sup>5</sup>  
K. C. Moffeit,<sup>4</sup> C. T. Munger,<sup>4</sup> W. N. Murray,<sup>3</sup> J. Nash,<sup>4</sup> H. Ogren,<sup>3</sup>  
K. F. O'Shaughnessy,<sup>4</sup> S. I. Parker,<sup>8</sup> C. Peck,<sup>5</sup> M. L. Perl,<sup>4</sup> M. Petradza,<sup>4</sup>  
R. Pitthan,<sup>4</sup> F. C. Porter,<sup>7</sup> P. Rankin,<sup>9</sup> K. Riles,<sup>4</sup> F. R. Rouse,<sup>4</sup> D. R. Rust,<sup>3</sup>  
H. F. W. Sadrozinski,<sup>2</sup> M. W. Schaad,<sup>1</sup> B. A. Schumm,<sup>1</sup> A. Seiden,<sup>2</sup>  
J. G. Smith,<sup>9</sup> A. Snyder,<sup>3</sup> D. P. Stoker,<sup>7</sup> R. Stroynowski,<sup>5</sup> M. Swartz,<sup>4</sup>  
R. Thun,<sup>7</sup> G. H. Trilling,<sup>1</sup> R. Van Kooten,<sup>4</sup> P. Voruganti,<sup>4</sup> S. R. Wagner,<sup>4</sup>  
S. Watson,<sup>2</sup> P. Weber,<sup>9</sup> A. J. Weinstein,<sup>5</sup> A. J. Weir,<sup>5</sup> E. Wicklund,<sup>5</sup>  
M. Woods,<sup>4</sup> D. Y. Wu,<sup>5</sup> M. Yurko,<sup>3</sup> C. Zaccardelli,<sup>2</sup> and C. von Zanthier<sup>2</sup>

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- <sup>1</sup>Lawrence Berkeley Laboratory and Department of Physics,  
University of California, Berkeley, California 94720**
- <sup>2</sup>University of California, Santa Cruz, California 95064**
- <sup>3</sup>Indiana University, Bloomington, Indiana 47405**
- <sup>4</sup>Stanford Linear Accelerator Center, Stanford University,  
Stanford, California 94309**
- <sup>5</sup>California Institute of Technology, Pasadena, California 91125**
- <sup>6</sup>Johns Hopkins University, Baltimore, Maryland 21218**
- <sup>7</sup>University of Michigan, Ann Arbor, Michigan 48109**
- <sup>8</sup>University of Hawaii, Honolulu, Hawaii 96822**
- <sup>9</sup>University of Colorado, Boulder, Colorado 80309**

## ABSTRACT

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  $36.3 \text{ GeV}/c^2$  is set at the 95% confidence-level. Pair production of stable supersymmetric scalar leptons with masses between the muon mass and  $32.6 \text{ GeV}/c^2$  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: the scalar-lepton could be stable if it is lighter than the photino. Another possibility is the production of mirror fermions.<sup>2</sup> 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<sup>3</sup> up to a mass of  $27.6 \text{ GeV}/c^2$  in searches at  $e^+e^-$  colliders running below the  $Z$  boson peak. Their production cross-section has also been limited<sup>4</sup> for masses between 50 and  $200 \text{ GeV}/c^2$  in proton-antiproton collisions.

The expected signal for new heavy stable 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. 5. The main components used by this analysis are described below. Charged particle tracking is provided by the central drift chamber with 12 concentric layers of 6 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  $\sigma(p)/p^2 = 0.0031 \text{ (GeV}/c)^{-1}$  has been achieved for isolated tracks constrained to the beam interaction point during a test run at the PEP storage ring at SLAC.<sup>5</sup> 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<sup>5</sup> 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.<sup>7</sup> 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 parameterization of the TOF measurement error distribution with the function

$$f(t) \propto \begin{cases} \exp\left(-\frac{1}{2}\left(\frac{\mu-t}{\sigma}\right)^2\right) & t \geq t' \quad ; \\ \exp\left(-\frac{\beta^2}{2}\right)\left(\frac{\alpha}{\beta}\right)^\alpha \left(\frac{\sigma}{\mu-t+\sigma(\frac{\alpha}{\beta}-\beta)}\right)^\alpha & t < t' \quad , \end{cases} \quad (1)$$

where  $t = TOF_{\text{measured}} - TOF_{\text{expected}}$ ,  $t' = \mu - \beta\sigma$  and the parameters  $\mu = -11$  ps,  $\sigma = 426$  ps,  $\alpha = 17.3$  and  $\beta = 0.83$  are determined from the data. 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  $\cos \theta_{\text{acol}} > 0.99$ , where  $\theta_{\text{acol}}$  is the acollinearity angle between the tracks. The background from  $\tau^+\tau^-$  pairs with both T's decaying to one prong is reduced by requiring that each track has a momentum greater than 5 GeV/c and equal to the other within 30. 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  $\tau \rightarrow e\nu\bar{\nu}$  decays. Thirteen events from the data pass the above selection, in good agreement with the expectation of 14.5 events from Monte Carlo simulations of  $e^+e^-$ ,<sup>6</sup>  $\mu^+\mu^-$  and  $\tau^+\tau^-$  pairs.<sup>7</sup> The efficiency for  $\mu^+\mu^-$  pairs to pass the selection criteria is  $0.57 \pm 0.01$ .

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

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

with

$$g(x) = \frac{1}{\sqrt{2\pi}\sigma_x(M)} \exp\left(-\frac{1}{2}A(x)\right) \quad (3)$$

and

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

where  $j(t)$  is defined in Eq. (1) with  $t = TOF_{\text{measured}} - TOF_{\text{expected}}(M)$ . The mass  $\mathbf{M} \geq \mathbf{0}$  which maximizes  $\mathbf{L}(\mathbf{M})$  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  $\mathbf{M}$ , the chi-square

$$\chi^2(M) = \sum_{\substack{i=1 \\ \text{tracks}}}^2 \left( A(TOF_i) + A\left(\frac{dE}{dx_i}\right) + A\left(\frac{1}{p_i}\right) \right), \quad (5)$$

for 5 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  $\tau$ '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 chi-square 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  $2 \text{ GeV}/c^2$  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 be negligible above  $2 \text{ GeV}/c^2$ . Thus, in the absence of observed events, an upper limit<sup>8</sup> 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:

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

where  $N_h$  is the number of observed hadronic events,  $\epsilon_h$  is the efficiency for detecting the hadronic events,  $\Gamma_h$  is the partial width of the  $Z$  decay into hadrons,  $\Gamma_{ee}$  is the leptonic width for electrons,  $a_l$  and  $v_l$  denote the axial-vector and vector coupling constants for charged leptons, and  $\beta = [1 - 4M^2/E_{\text{cm}}^2]^{1/2}$ , where  $E_{\text{cm}}$  is the center-of-mass energy. From a data sample corresponding to an integrated luminosity of  $19.7 \text{ nb}^{-1}$  and covering a range in  $E_{\text{cm}}$  between 89.2 and 93.0 GeV, we find that 455 events pass a set of hadronic selection requirements described in Ref. 9. The efficiency of this selection was found from Monte Carlo simulations to be 0.953  $\pm$  0.006. 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. The calculations include radiative effects." The contributions to the error on  $N$  from uncertainties in the top quark, Higgs and  $Z$  boson masses and from the measurement error on  $E_{\text{cm}}$  are small compared to the statistical error on  $N_h$ .

The expected number of stable heavy lepton pairs identified at a given mass is determined using Monte Carlo simulation.<sup>7</sup> 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  $2 \text{ GeV}/c^2$ . The efficiency for the simulated pairs to pass all the cuts is found to rise from 0.06 at  $1 \text{ GeV}/c^2$  to 0.56 at  $5 \text{ GeV}/c^2$  where the effect of the  $2 \text{ GeV}/c^2$  minimum requirement on the most probable mass becomes small. A slow increase in efficiency is observed

above  $10 \text{ GeV}/c^2$ . This is due to the dominant terms in the differential cross-section for  $e^+e^-$  annihilation to two spin  $1/2$  fermions near the  $Z$  pole<sup>8</sup> 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 our statistical and systematic errors conspire to reduce the expectation. These errors are found from the  $1\sigma$  errors on the quantities in Eq. (6) and by varying the absolute scales and resolutions of the momentum,  $dE/dx$  and TOF measurements together by 1a. The upper and lower limits on stable heavy lepton production can be read from the intersection of the dotted curve 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  $36.3 \text{ GeV}/c^2$  as indicated in Fig. 3(a). The analysis and limits presented also apply to stable mirror fermions,<sup>2</sup> 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 by

$$\Gamma \left( Z \rightarrow \tilde{l}_L^+ \tilde{l}_L^- + \tilde{l}_R^+ \tilde{l}_R^- \right) / \Gamma \left( Z \rightarrow e^+ e^- \right) = \frac{1}{2} \beta^3 \quad , \quad (7)$$

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  $32.6 \text{ GeV}/c^2$  as shown in Fig. 3(b).



Finally, we can exclude new stable charged pair production for masses below  $2 \text{ GeV}/c^2$  down to  $m_\mu$ , the mass of the muon, using an indirect 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. 8, 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  $m_\mu$  to  $22.7 \text{ GeV}/c^2$ . For supersymmetric scalar leptons, where the production rate is given by Eq. (7), the excluded region extends from  $m_\mu$  to  $8.0 \text{ GeV}/c^2$ . These mass regions are shown in Fig. 3.

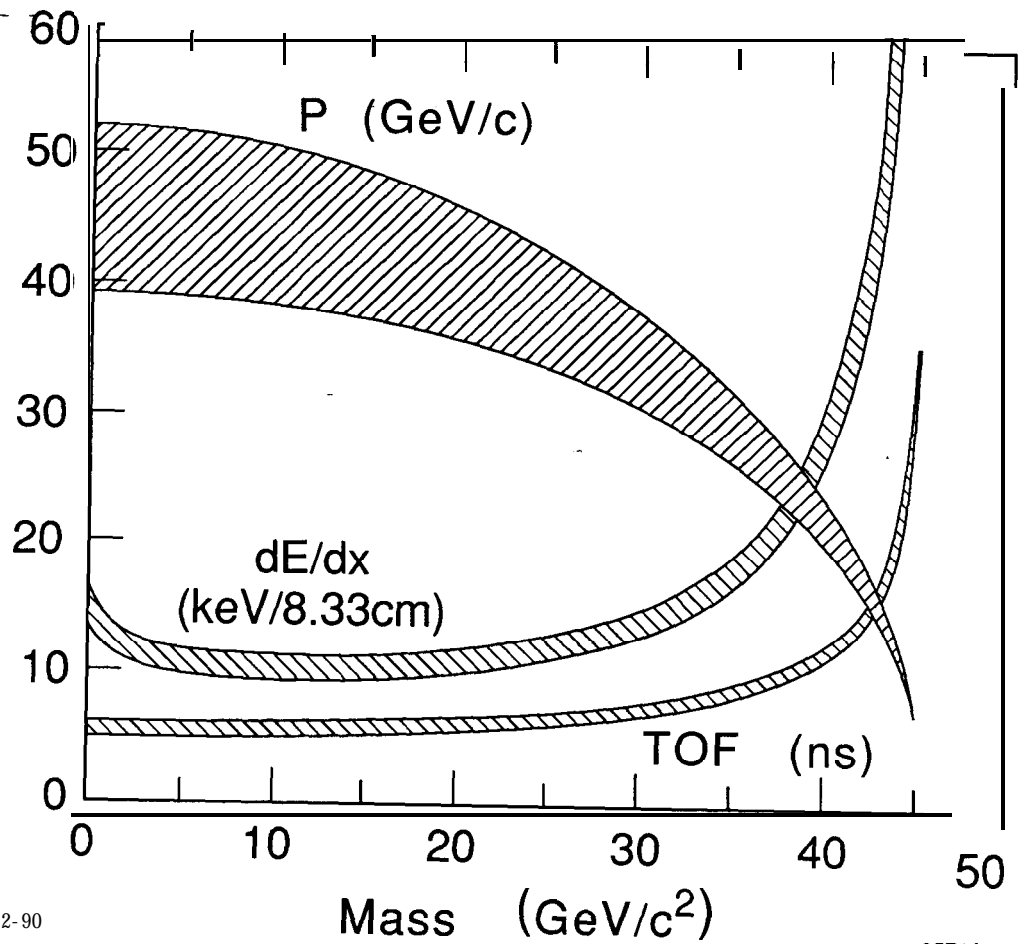
In conclusion, we have searched for pair production of stable charged particles from  $Z$  decay. A limit excluding pair production of stable fourth generation charged leptons and stable mirror fermions with masses between  $m_\mu$  and  $36.3 \text{ GeV}/c^2$  has been set at the 95% confidence-level. Pair production of stable supersymmetric scalar leptons with masses between  $m_\mu$  and  $32.6 \text{ GeV}/c^2$  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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## FIGURE CAPTIONS

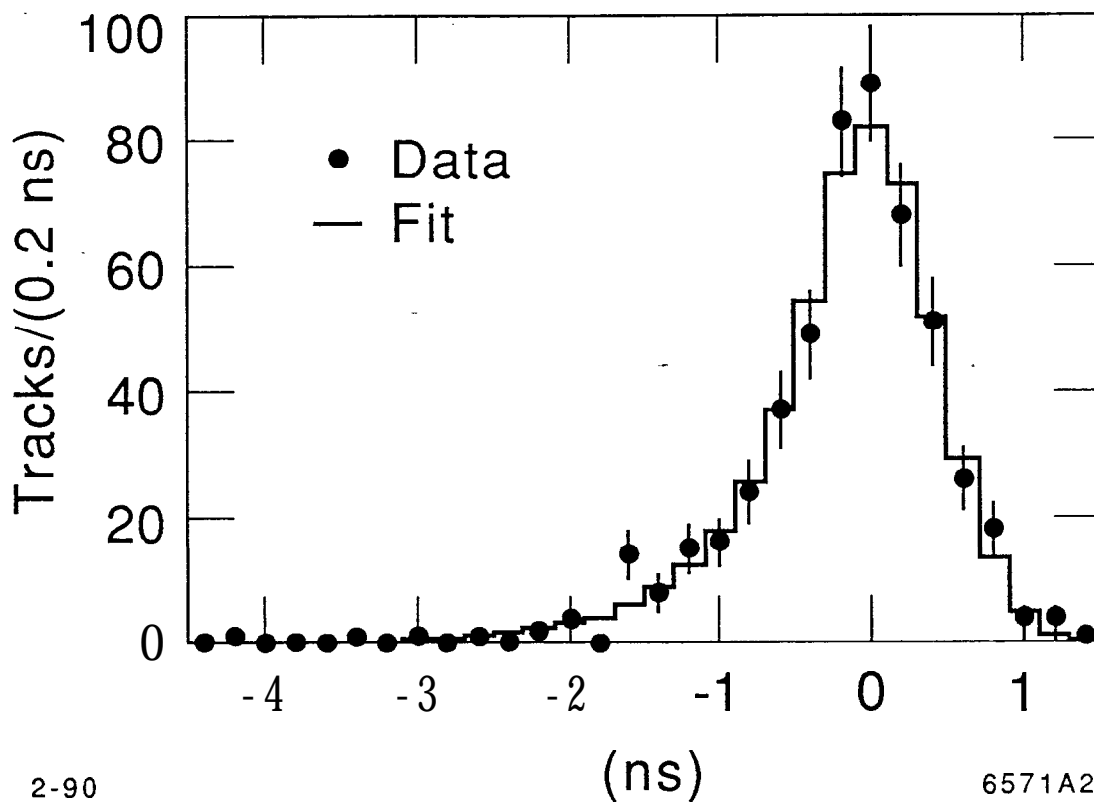
- 1) The expected values of the momentum,  $dE/dx$  and TOF measurements as a function of mass for stable particles produced in pairs from  $Z$  boson decay. The shaded bands show the  $\pm 1\sigma$  variation in the measured quantities with  $\sigma_p/p = [(0.0031p)^2 + (0.014)^2]^{1/2}$ ,  $\sigma_{dE/dx} = (0.085)dE/dx$  and  $\sigma_{TOF} = 425$  ps.
- 2) Fits of the function  $j(t)$  to the error in the TOF measurement for minimum ionizing pions and  $\beta \simeq 1$  tracks from the SLC data.
- 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 indirect search analyses described in the text.



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Fig. 1



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Fig. 2

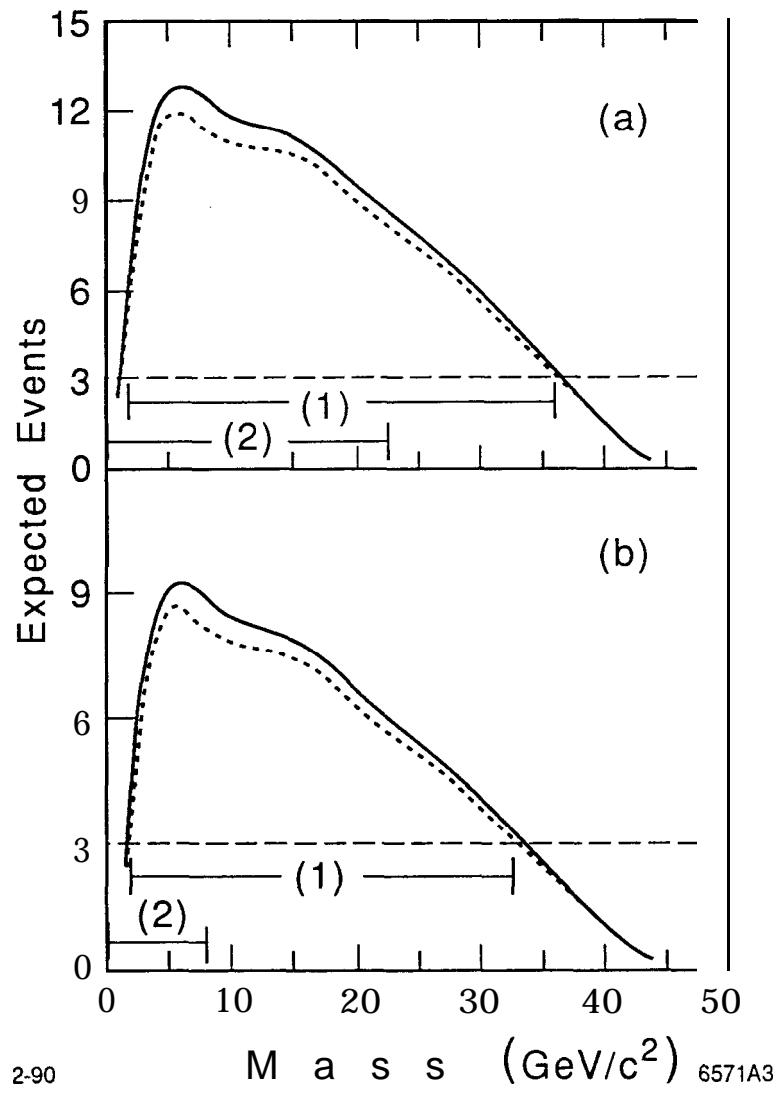


Fig. 3