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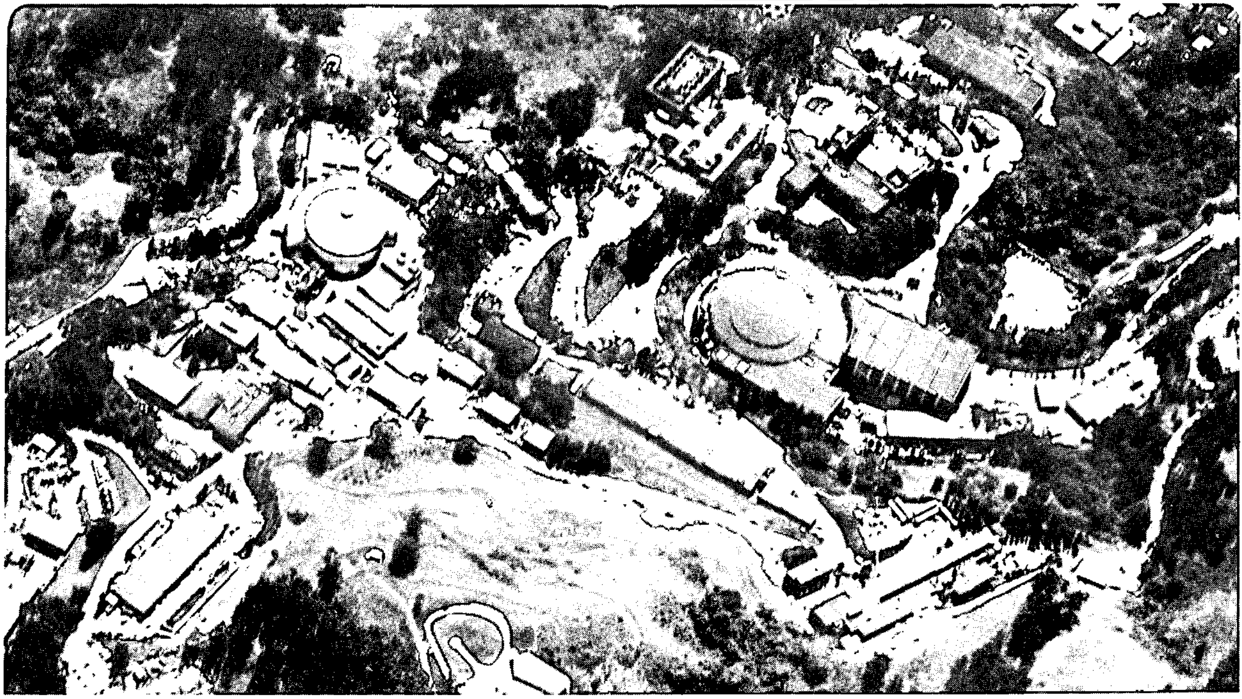
G. Goldhaber

March 1990



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A STUDY OF Z^0 DECAY RESULTS FROM THE MARK II DETECTOR AT THE SLAC LINEAR COLLIDER (SLC)

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We have now been studying the properties of the Z^o at e^+e^- colliders for very nearly one year. The first such event was observed in the Mark II detector at the SLC on April 11, 1989. The primary lessons we have learned are that the people who introduced the electro-weak theory, or what is now called the Standard Model, are to be congratulated. We have tried as hard as we could to find deviation from this model - so far, there are none. To mention a few names: Glashow, Salam 't Hooft Weinberg,[1] as well as many others, were responsible for this magnificent theoretical development.

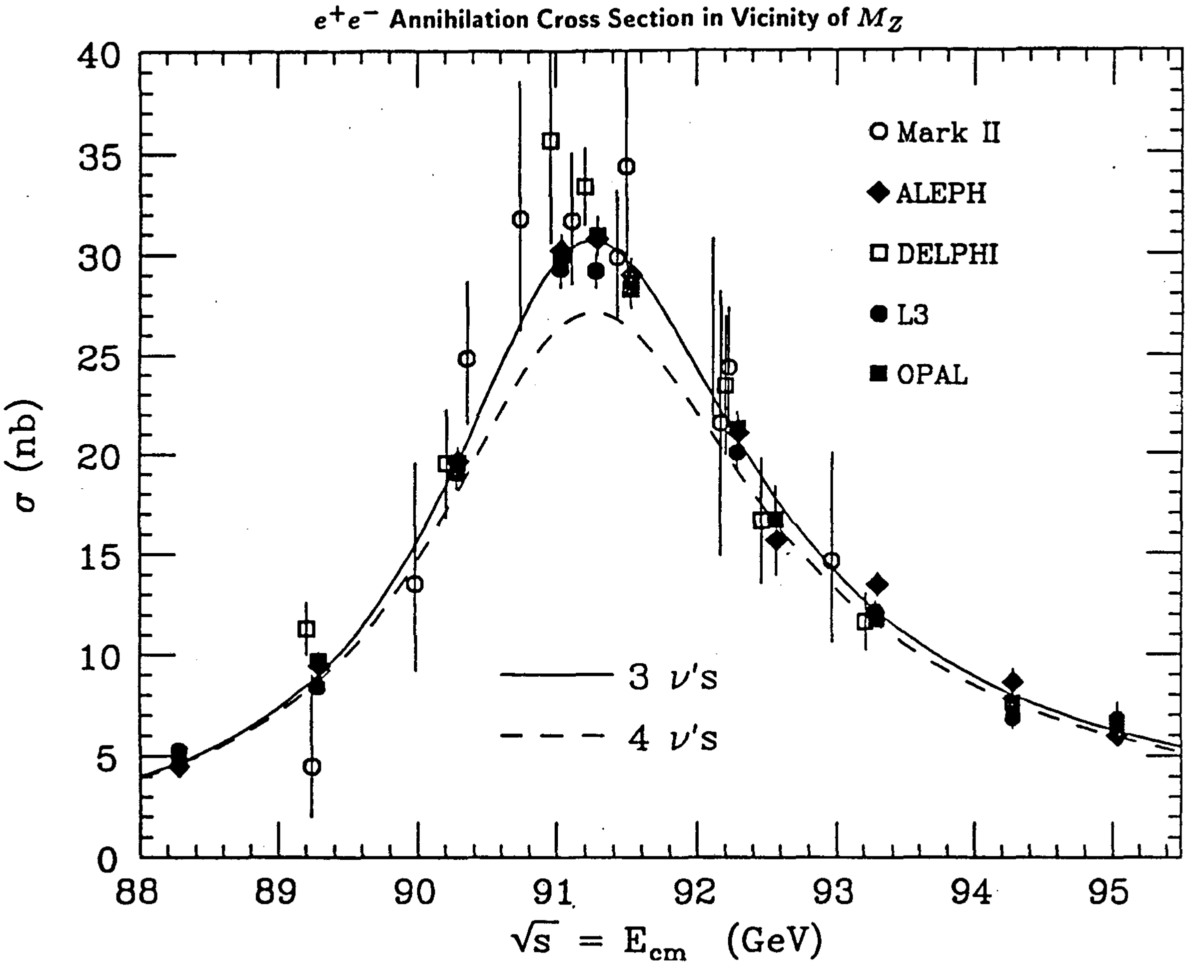
The first important result to emerge from these studies is the fact that there appear to be only three species of light neutrinos. Of course, our colleagues in Astrophysics and Cosmology have respected this[2] for a long time! They are also to be congratulated!

Figure 1 shows a compilation by the particle data group of our data, together with the results from the four LEP experiments - the ones with the smaller error bars! As we noted,[3] the number of neutrino species which is related to the total width Γ_Z of the Z° resonance (where each $\mathbf{v}$ species contributes 177 Mev to Γ_Z) is most accurately determined from the peak cross-section. As can be seen from Figure 1.

1. THE MARK II DETECTOR.

Figure 2 gives an overview of the Mark II detector, and details of the detector can be found elsewhere.[4] A cylindrical drift chamber is a 4.75 kG axial magnetic field measures charged particle momenta with a resolution of $\sigma(p)/\rho^2 = 0.0046\ (\mathrm{GeV}/c)^{-1}$. Photons are detected in liquid argon electromagnetic calorimeters covering the angular region $|\cos\theta| < 0.76$, and end-cap lead-proportional-tube calorimeters with energy resolutions of

$\sigma(E)/E = 0.14/\sqrt{E}$ and $\sigma(E)/E = 0.22/\sqrt{E}$ (E in GeV), respectively. The detector is triggered by two or more charged tracks within $|\cos\theta| < 0.76$, or by neutral-energy requirements of a single shower depositing at least 3.3 GeV in the barrel calorimeter, or 2.2 GeV in an end-cap calorimeter. This combination results in an estimated trigger efficiency of greater than 99% for hadronic Z decays.



Data from the Mark II, ALEPH, DELPHI, L3, and OPAL Collaborations (Refs. 1–5) for the cross section in e^+e^- annihilation into hadronic final states as a function of c.m. energy near the Z. The curves show the predictions of the Standard Model with three species (solid curve) and four species (dashed curve) of light neutrinos. The mass of the Z was fixed by the data to be 91.157 GeV, and there were no other free parameters. The resulting widths are respectively 2.488 GeV and 2.653 GeV, which include QCD corrections for the hadronic channels and assume no t-quark contribution. The asymmetry of the curves is produced by initial-state radiation.

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2. ALEPH—D. Decamp *et al.*, to be published in Phys. Lett. B (1990).
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5. OPAL—M.Z. Akrawy *et al.*, to be published in Phys. Lett. B (1990).

Figure 1

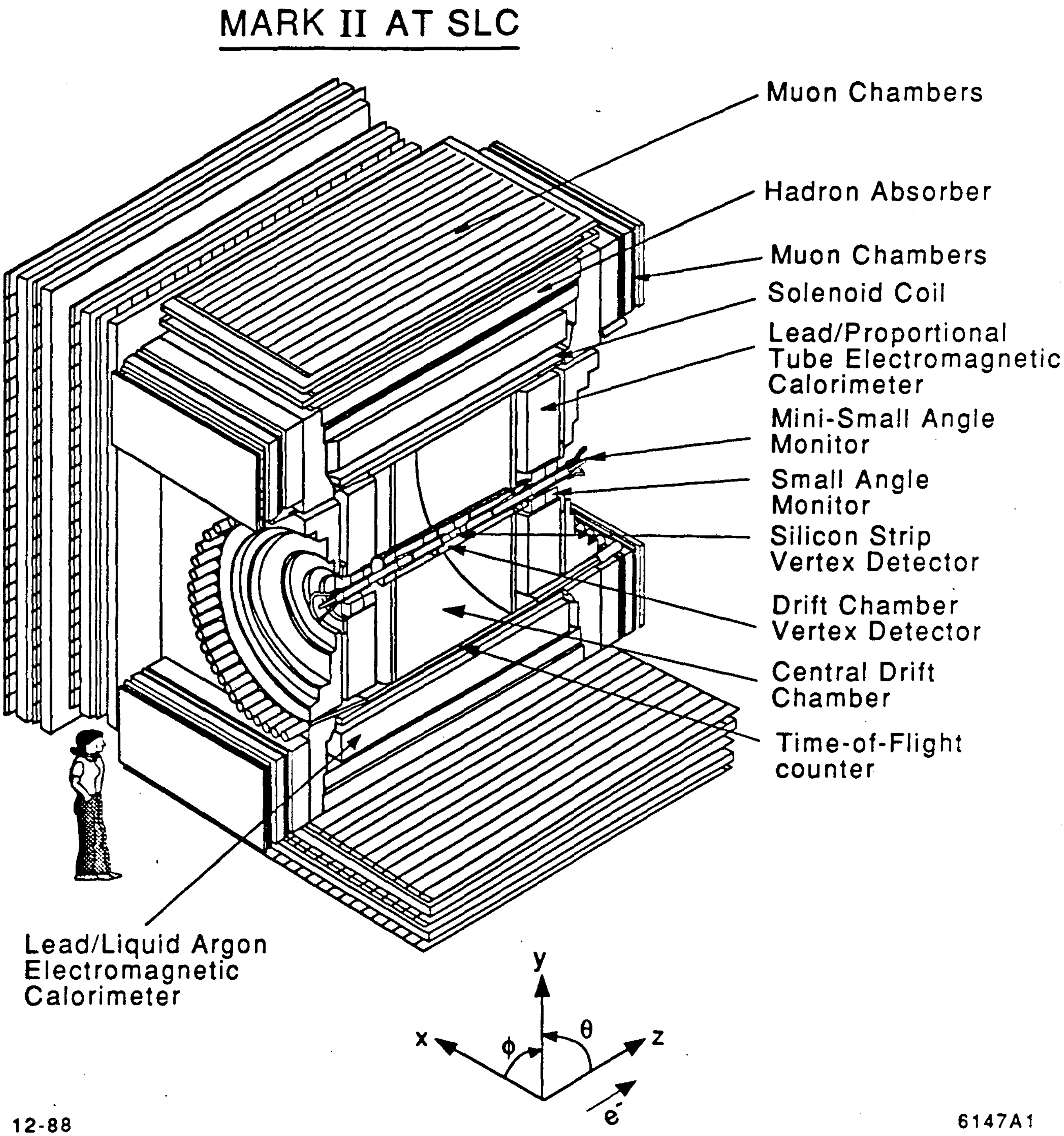
MARK II AT SLC
Muon Chambers
Hadron Absorber
Muon Chambers
Solenoid Coil
Lead/Proportional Tube Electromagnetic Calorimeter
Mini-Small Angle Monitor
Small Angle Monitor
Silicon Strip Vertex Detector
Drift Chamber Vertex Detector
Central Drift Chamber
Time-of-Flight counter
Lead/Liquid Argon Electromagnetic Calorimeter
y
x
φ
θ
z
e⁻
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Figure 2

2. COMMENTS ON PRECISION Z MASS MEASUREMENTS.

Since the Z mass is one of the three fundamental constants of the electroweak theory, viz, G_F, α, M_Z and one wants to measure it as precisely as possible. With high statistics, the final limitation of such a measurement is the systematic error. At the SLC, the absolute energy in the center of mass is obtained by a precise momentum measurement for both the electron and positron beams for <u>each</u> pulse.

Figure 3 is a sketch of one the the spectrometers which act on the beam after the collision and before the beam reaches the beam dump.

The momentum measurement is carried out with a vertical bend. The direction of the beam before and after this bend is determined in a novel fashion by two small horizontal bends. These give rise to synchrotron radiation which is then observed on a fluorescent screen. The measurement consists of measuring the displacement of the vertically deflected beam on the screen with television cameras. The systematic error for each beam measurement is 20 MeV. Combining these quadratically, and including an allowance for beam offsets with finite dispersion, we get an overall systematic error on M_Z of ± 35 MeV.

Figure 4 shows the predicted error on M_Z of a function of the integrated luminosity or, equivalently, the observed number of Z° events. With our current data, based on five hundred events, the predicted error is in agreement with our measured error of 120 MeV.

The four LEP experiments have smaller statistical errors, but finally came up against the common systematic error of ± 30 MeV, based on sending a proton beam through the LEP accelerator.

When the statistical errors became negligible, the residual systematic errors for the SLC and LEP experiments, which at present are comparable, will determine the accuracy to which M_Z is known. At that time, it will be important to have two totally independent sources of systematic errors.

Energy Spectrometer

Precise measurements are made of the energy of both e- and e+ bunches every crossing. The bend angle of the beam through a precision magnet is determined using synchrotron radiation.

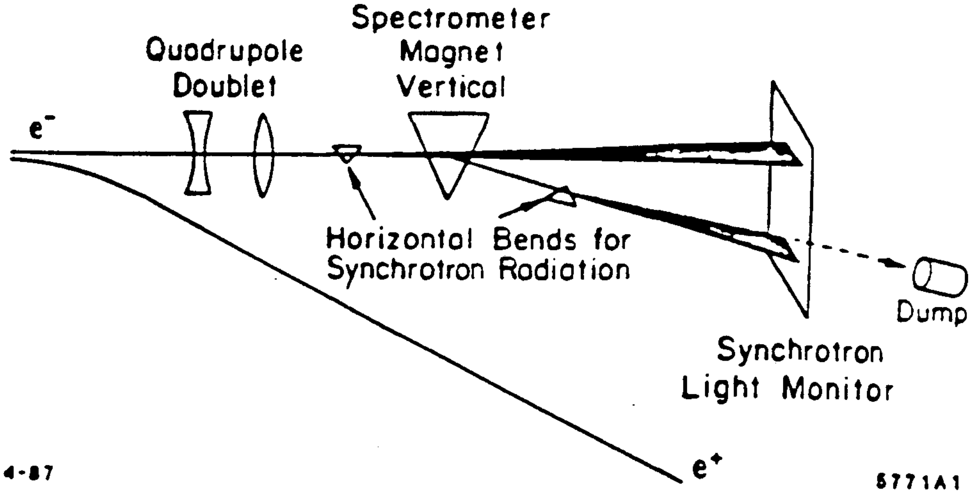

Figure 3

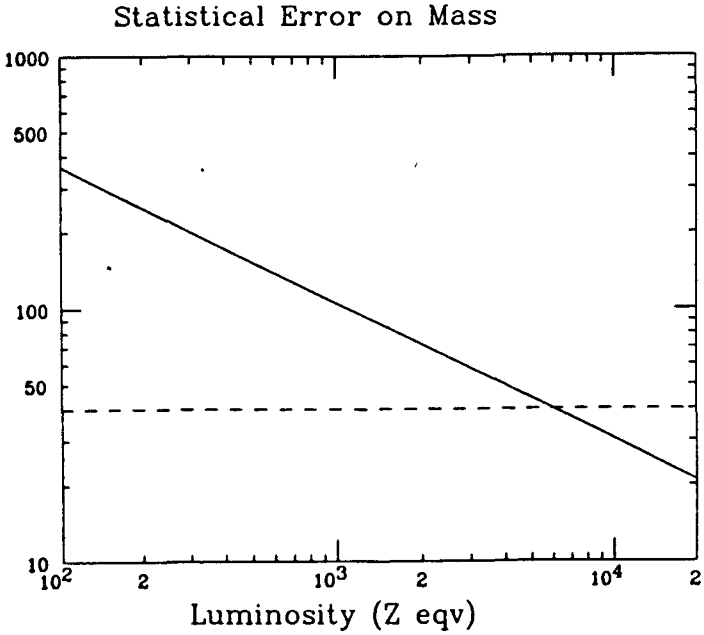

Figure 4. The error in M_Z as a function of number of observed Z's. The dashed line represents the systematic error limit.

3. THE SEARCH FOR NEW PARTICLES.

In Z° decay, any particle that couples to the neutral weak current, and with the mass $<M_Z/2$ can be produced. We have looked hard for many such possible decay modes, and have placed ninety- to ninety-five percent CL limits on the masses, and other properties of such particles.

In this talk, I will single out as an illustrative example our search for a possible neutral lepton, L°. Details on this and other searches, as well as other studies of Z° properties, have been published already.[5]

For L° decay, we assume here that the charged lepton of this possible fourth family is heavier than the neutral one. Thus, for L° to decay, we have to assume some degree of mixing with one or more of the known leptons e, μ, and τ. This mixing is expressed in terms of a unitary matrix in analogy to the Cabibbo-Kohayashi-Mashawa matrix for quarks.

For the moment we restrict our L° search to a sequential fourth generation Dirac neutral lepton, and assume that the weak eigenstates ν_ℓ and mass eigenstates L_i^o of the four generations of neutrinos are mixed:

$$\nu_\ell = \sum_{i=1}^{4} U_{\ell i} L_i^o \tag{1}$$

The possible decay modes of the L° are then $L^\circ \rightarrow \ell + W^*$, ($\ell = e, \mu, \tau$).

We show the limits on the L° lepton mass on a plot of $|(U_{\ell i})|^2$ versus $M_L{}^\circ$. The limits differ somewhat, depending on the particular lepton e, μ, or τ which couples to the L°.

There are four distinct regions of the $|(U_{\ell i})|^2$ versus $M_L{}^\circ$ plane which involve rather different searches. These are:

i. The search for isolated tracks.

The three jet events corresponding to qqg decay of the Z° tend to lie planar with only small momentum components out of the place. The decay $Z^\circ \rightarrow X^\circ$ where X° is a heavy particle such as b', t or L° leads to four jets and frequently to isolated particles.

To search for L° candidates, we use the following event selection criteria: Charged tracks are required to project into a cylindrical volume of radius 1 cm and half-length of 3 cm around the nominal collision point parallel to the beam axis, to be within the angular region $|\cos\theta| < 0.82$, and to have transverse momentum with respect to the beam axis of at least 150 MeV/c. An electromagnetic shower is required to have shower energy greater than 1 GeV and $|\cos\theta| < 0.68$ for the central calorimeter and $0.68 < |\cos\theta| < 0.95$ for the endcap calorimeter. All events are required to contain at least six charged tracks and the sum of charged particle energy and shower energy (E_{vis}) must be greater than $0.1\ E_{cm}$. To ensure that the events are well contained within the detector, the polar angle of the thrust axis (θ_{thr}) of each event must satisfy the condition $|\cos\theta_{thr}| < 0.8$.

The expected number of produced exotic events before cuts is normalized to the total number of hadronic events (N_h) that fulfill the hadronic event selection criteria. The expected number of produced exotic events N_x, x = t, b' or L°, is given by

$$Nx = \frac{N_h\Gamma_x}{\varepsilon_q\Gamma_q + \varepsilon_x\Gamma_x}, \qquad (2)$$

where Γ_q is the partial width of the Z to u, d, s, c, and b (*udscb*) quarks, $\varepsilon_q = 0.953$ is the efficiency for *udscb* quarks to pass the hadronic event criteria, Γ_x is the partial width of the Z to the exotic particle in question, and ε_x is the efficiency for the exotic particle events to pass the hadronic event criteria. First order QCD corrections are used when calculating Γ_q and Γ_x. The data sample consists of $N_h \approx 500$ events, corresponding to an integrated luminosity of $19.7 \pm 0.8\ nb^{-1}$.

Here, an isolated track is one with isolation parameter $\rho > 1.8$ where ρ is defined as follows: The Lund jet-finding algorithm is applied to the charged and neutral tracks excluding the candidate track *i*. We then define

$$\rho \equiv \min_j[(2E_i(1 - \cos \theta_{ij}))^{1/2}], \tag{3}$$

where E_i is the track energy in GeV and θ_{ij} is the angle between the track and each jet axis$_j$. The distribution of the maximum value of ρ for all charged tracks in an event is shown in Figure 5 for our data sample, and for a five-flavor QCD Monte Carlo, and for a 35 GeV/c^2 top which is similar to the L° distribution. Figure 6 shows the excluded regions from this study.

ii. **The search for events with separated vertices.**

From our track selection criteria, we do not pick up tracks from vertices separated by more than 1 cm from the e^+e^- interaction point. This limits the above method to matrix elements with $|U_{\ell i}|^2 \lesssim 10^{-7}$ to 10^{-9} in the M_{L° mass region of 20 to 43 GeV. For lower values of the matrix elements, one begins to get separated vertices due to long L° lifetimes.

To extract the signal events with separated vertices, it is necessary to eliminate the dominant background of beam-gas and beam-beampipe interaction events from the data sample without losing efficiency for the signal events. Since the beam-gas and beam-beampipe interaction events usually have low multiplicity, low energy, and are forward-scattered, we apply the following selection criteria to eliminate them. We require an event to have at least eight charged tracks satisfying the track selection criteria and to have total energy greater than 35% of E_{cm}. In addition, the minimum of the forward and backward charged energy must be greater than 7% of E_{cm}.

The following method is used to extract the $\nu_4\bar{\nu}_4$ signal events from the final data set. The impact parameter *b* in plane perpendicular to the beam axis is defined as the distance of closest approach of a charged track to the average beam position. The significance of a charged track's impact parameter is defined as the impact parameter divided by its error σ_b. An event search

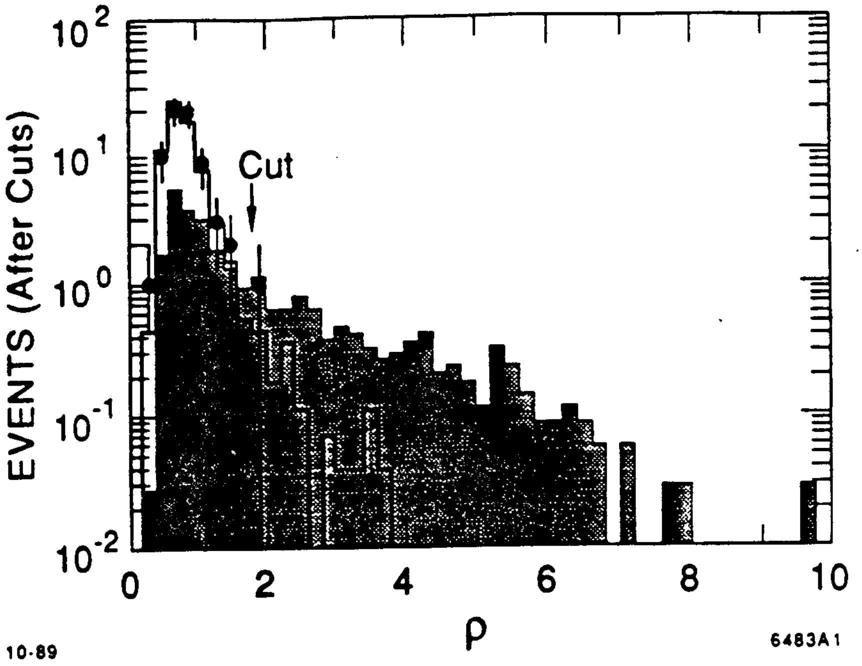

Figure 5. Maximum isolation parameter ρ of all the tracks in an event for data (circles, with statistical errors), *udscb* QCD Monte Carlo (solid line), and a 35 GeV/c^2 top quark (hatched area, normalized to data). The Monte Carlo simulation includes detector and beam background effects.

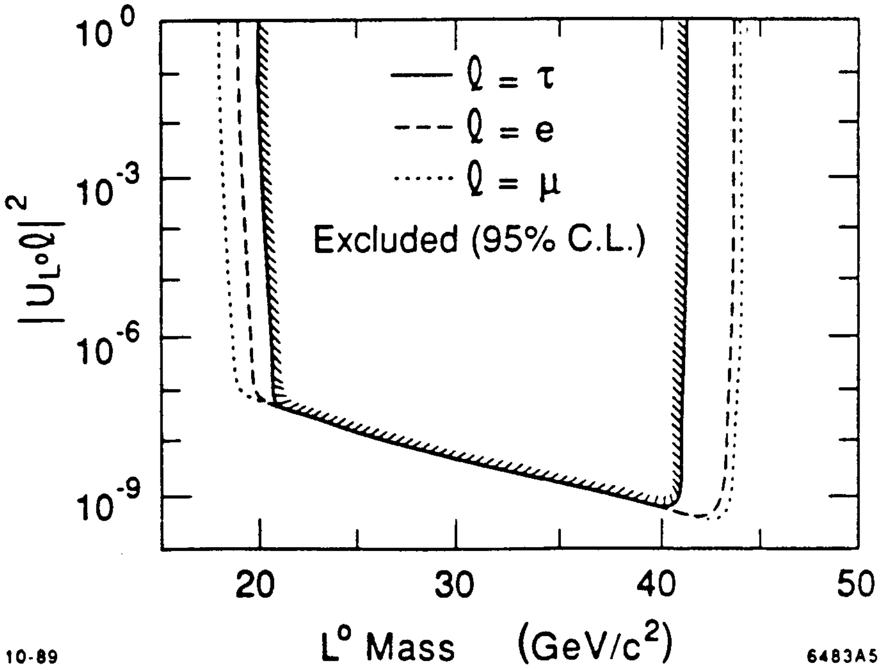

Figure 6. 95% C.L. mass limits for an unstable neutral heavy lepton L^o as a function of mass and mixing matrix element at $|U_{L^o\ell}|^2$ for B.R. ($L^o \rightarrow \tau W^*$) = 100%, B.R. ($L^o \rightarrow eW^*$) = 100%, and B.R. ($L^o \rightarrow \mu W^*$) = 100%, as indicated.

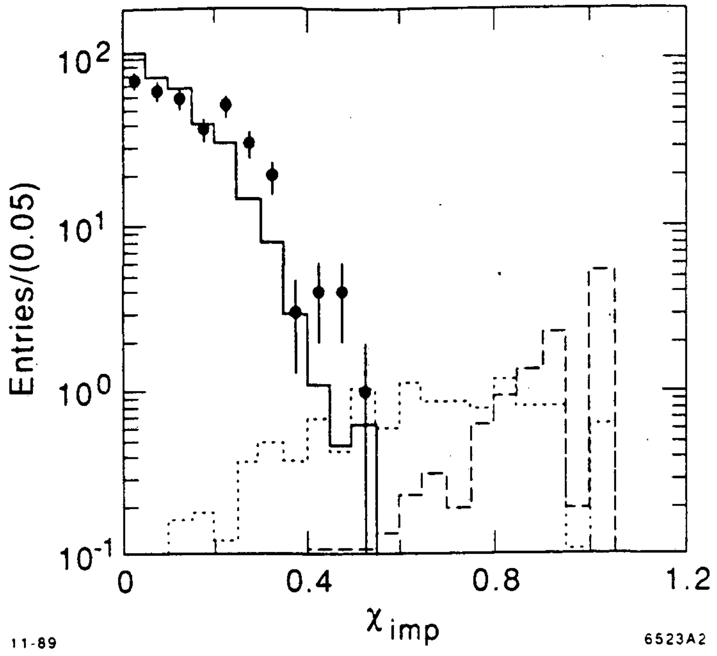

Figure 7. Distribution of ν_4 search parameter χ_{imp} for data (solid dots with error bars), *udscb* Monte Carlo (solid line), a 35 GeV/c^2 ν_4 with a lifetime of 100 ps (dotted line, normalized to data), and a 35 GeV/c^2 ν_4 with a lifetime of 1000 ps (dashed line, normalized to data).

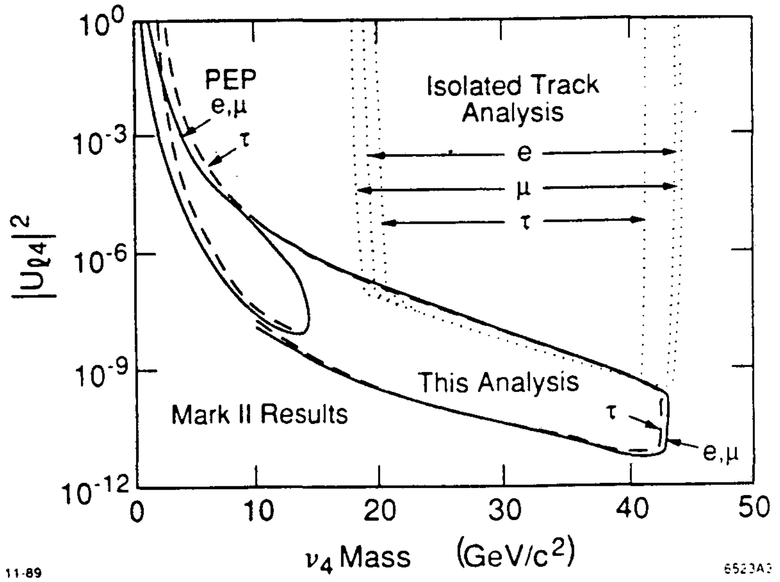

Figure 8. 95% C.L. excluded regions for a hypothesized fourth generation long-lived massive Dirac neutrino ν_4 as a function of mass and mixing matrix element $|U_{\ell 4}|^2$, $\ell = \varepsilon, \mu$, or τ. Also shown are the equivalent excluded regions for the Mark II isolated track search, and a Mark II search for detached vertices at PEP.

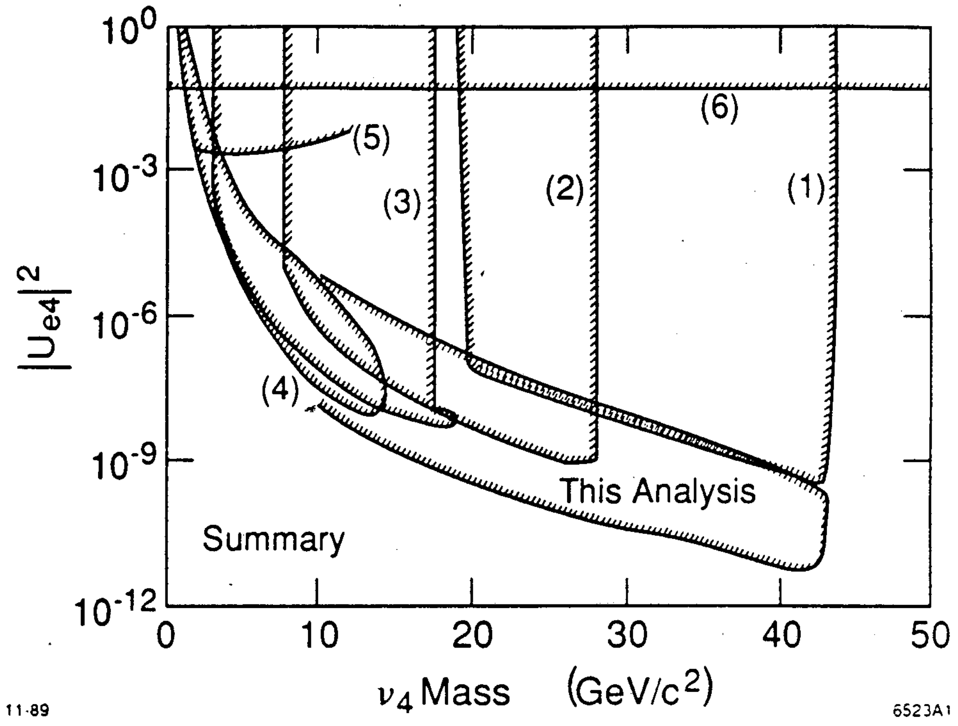

Figure 9. 95% C.L. excluded regions for a hypothesized fourth generation long-lived massive Dirac neutrino ν_4 as a function of mass and mixing matrix element $|U_{\ell 4}|^2$, for the present analysis (lifetime analysis) compared to those obtained by (1) Mark II - from isolated tracks, (2) AMY, (3) CELLO, (4) Mark II secondary vertex search at PEP, (5) monojet searches at PEP, and (6) e - μ universality.

parameter χ_{imp} is defined as the fraction of charged tracks with significance b/σ_b greater than 5.0. This parameter allows us to distinguish the long-lived $L^\circ\bar{L}^\circ$ signal events from the *udscb* hadronic background events. The hadronic background events containing charm, bottom or strange quark decays rarely yield χ_{imp} greater than 0.5 as seen in Figure 7, since there are many other tracks in the events which project to the primary vertex.

Many $L^\circ\bar{L}^\circ$ events with a reasonable lifetime would, however, yield χ_{imp} greater than 0.5, as can also be seen in Figure 7. We therefore demand χ_{imp} of an event greater than 0.6 for it to be tagged as a long-lived $L^\circ\bar{L}^\circ$ signal event. There is no event in the final data set which satisfies these criteria. By comparison with MC calculations we deduce the limits shown in Figure 8. The region outlined as "This Analysis" in Figure 8 corresponds to decay distances for 1 cm to 100 cm.

Figure 9 gives a summary of the data discussed here as well as the data obtained earlier. The horizontal line at $|U_{\ell i}|^2 \simeq 0.07$cuts out the region excluded by e μ universality. The other excluded region corresponds to our earlier searches at PEP as well as searches by CELLO and AMY.

iii. Search for two prong decays of the L^0.

For "low" masses, 2.5 - 22 GeV of the L° we expect a large proportion of L° decays to 2 charged prongs.

The strategy is to search for events in which the Z decays to two particles, one of which decays to a final state containing exactly two charged particles (and any number of visible or invisible neutral particles). This strategy is motivated by the following three points.

1. For $m_4 \lesssim 22$ GeV, the event can be divided into hemispheres by a simple thrust analysis to quite accurately separate the decay products of the L° and the $\bar{L}^\circ$.

2. The expected branching fraction of an unstable L° to two charged particles is large, generally greater than one-third for the mass range considered in this analysis.

3. The theoretical branching fraction of the Z to a new Dirac neutrino is large so that, given the size of our data sample, the number of produced events with a L° decaying to two charged particles is expected to be ≥ 15 for the mass range considered. Conversely, the probability that a hadronic decay of the Z produces a jet of only two charged particles is small.

The limits from this search are included in Figure 10.

iv. Data from the Z^0 resonance parameters.

The same measurements which yield a measure of the number of light neutrinos also provide limits on a heavy neutrino. Figure 10 shows the limits we observed.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC0003-76SF00098.

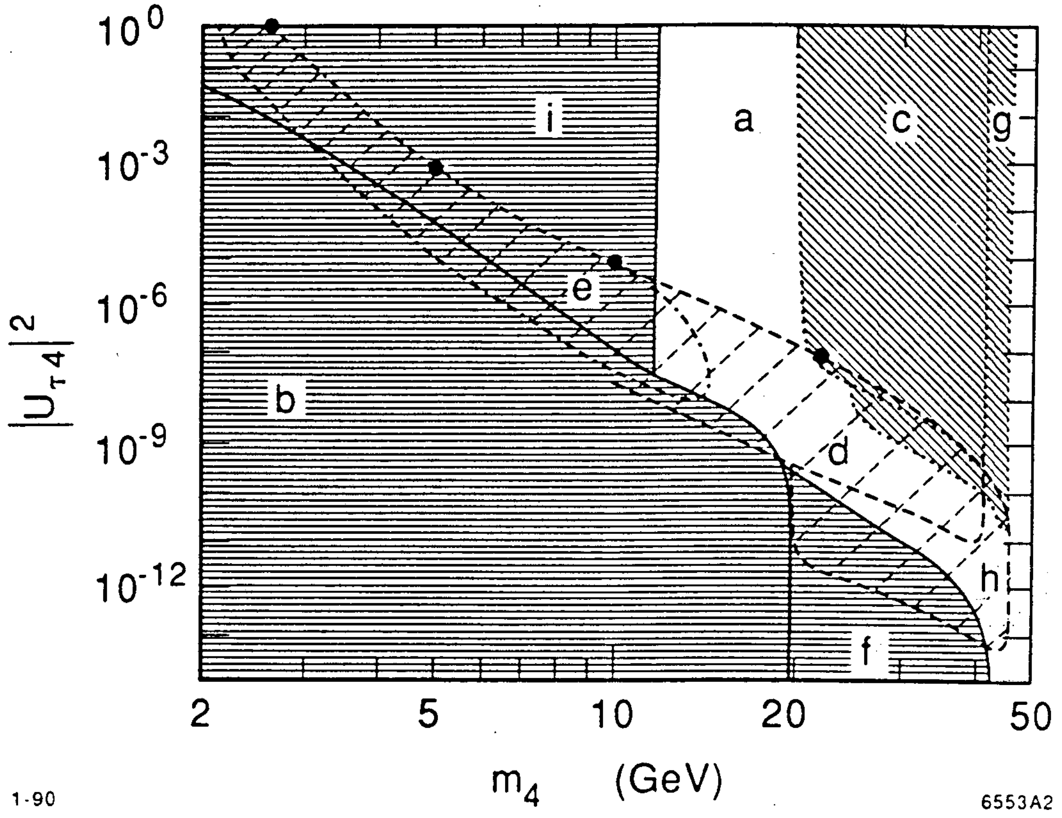

Figure 10. Regions in the plane of m_4 vs $|U_{\tau 4}|^2$ which are excluded at a confidence level of at least 95% for a fourth-generation Dirac neutrino by this analysis (regions a and i above the solid dots), by the measurement of the decay width of the Z to invisible final states at SLC (Ref. 3) (region b), by a search for high-energy, isolated tracks at SLC (region c), by a search for events with a large number of high-impact-parameter tracks at SLC (region d), and by a search for events with track vertices detached from the interaction point at PEP (region e). The additional regions excluded by the ALEPH Collaboration at LEP, but not previously excluded by Mark II, are shown as regions f, g, h, and i as of the time of this conference. The shading has the following meaning: horizontal lines indicate regions excluded by measurements of the Z resonance parameters; dashed diagonal lines indicate regions excluded by direct searches for tracks not originating from the collision point; and solid diagonal lines indicate regions excluded by direct searches for events with isolated tracks. The solid dots indicate the cases simulated to this study.

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