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A NEW LEPTON?

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CONTENTS

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I. Introduction

In this third lecture we will review the data and arguments which are leading us to the conclusion that a new charged lepton exists in the mass range 1.6 to 2.0 GeV/c^2. We will first discuss the evidence for the existence of anomalous $e\mu$ events. Next we will consider the properties of these events and conclude that the only simple hypothesis compatible with all the data is that these events come from the decay of pairs of new leptons. Accepting this as a working hypothesis we will then investigate six predictions of this hypothesis.

The nature of the material in this lecture will force us to concentrate on experimental details to a much greater extent than in the first two lectures. For this reason it is worthwhile to review the properties of the SLAC-LBL magnetic detector at SPEAR.[1,2] Figure 1 shows a side view of the detector. The trigger for an event is two or more charged particles each of which fires a trigger and shower counter. These counters subtend about 65% of the solid angle. Charge particles are detected and momentum analyzed by the cylindrical spark chambers over about 70% of the solid angle.

Electrons are identified solely by the presence of a large pulse height in the shower counters. The criterion that was applied for most of the analysis was that the pulse height be greater than that of a 500 MeV electron. As we will see, hadrons will be misidentified as electrons roughly 20% of the time.

The shower counters are also useful for the detection of photons. The detection efficiency for photons is 50% at 100 MeV and rises to over 90% at 250 MeV.

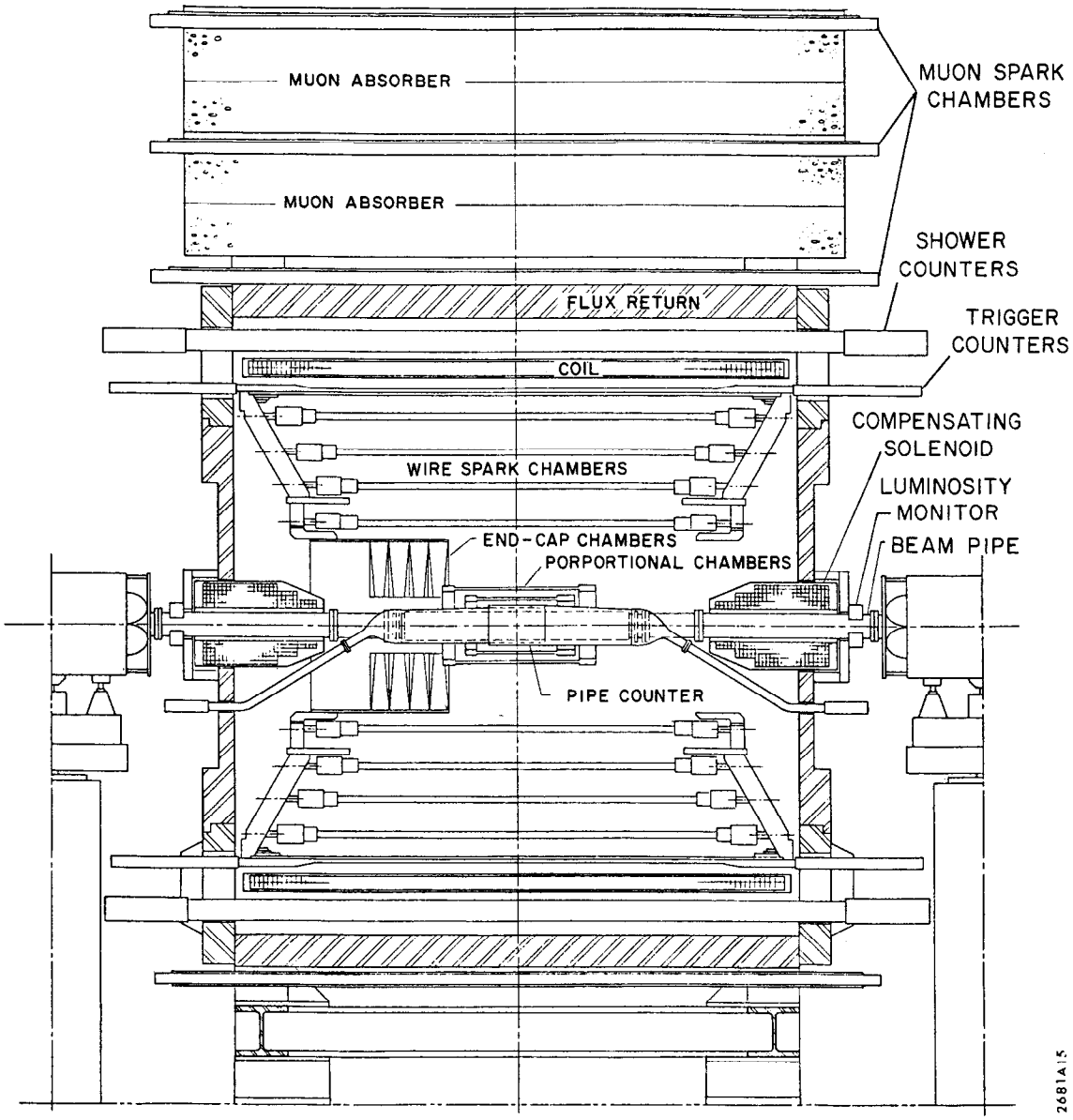

FIG. 1. Side view cross section of the SLAC-LBL magnetic detector at SPEAR

Muons are identified by penetrating the coil, shower counters, and the 20 cm iron flux return and by being detected in a muon spark chamber. Since this material only corresponds to about 1.7 hadronic interaction lengths, there is roughly a 20% probability that a hadron will be misidentified as a muon. Starting in January 1975, additional muon detectors were added above the main detector. These detectors, called the muon tower, consist of two 222 gm/cm^2 thick barite-loaded concrete slabs each followed by spark chambers. The muon tower subtends only 9% of the total solid angle, but provides much smaller hadron misidentification.

II. Existence of anomalous $e\mu$ events

II.A. Original data

The anomalous signal is an electron, a muon and no other charged or neutral particles detected in the detector. We have now observed about 180 of these events with an estimated background of about 45 events.

To illustrate how these events are found and the nature of the backgrounds, it is pedagogically easiest to consider the original data in which the signal was discovered.[3] One reason for this is that the muon spark chambers covered the full azimuthal angle for these data (Fig. 2, SPEAR I), while for later data the side chambers were moved to the muon tower (Fig. 2, SPEAR II). These modifications do not change the basic analysis, but make it slightly more complicated.

The motivation for searching for this signal was in fact to look for a new sequential lepton,

$$e^+e^- \to L^+L^- \qquad \begin{cases} \hookrightarrow e^-\bar{\nu}_e\nu_L \\ \hookrightarrow \mu^+\nu_\mu\bar{\nu}_L \end{cases} \quad . \tag{1}$$

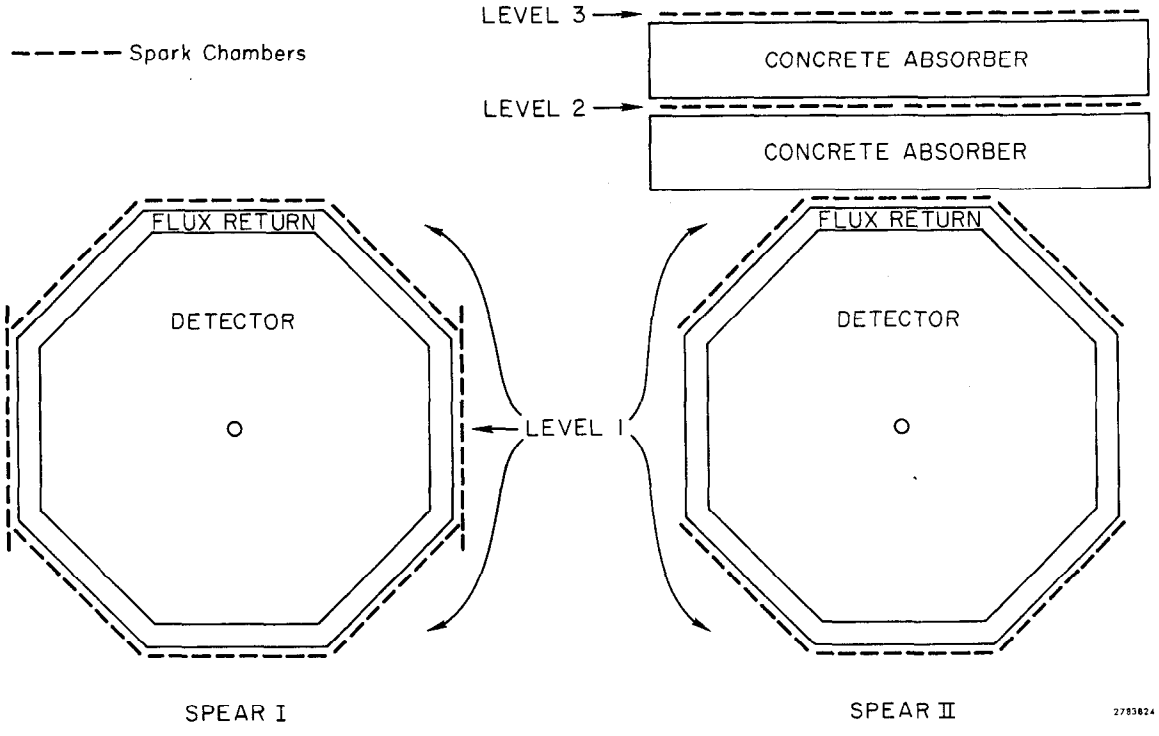

FIG. 2. Configuration of the magnetic detector muon identification system for SPEAR I and SPEAR II.

To find such events the following criteria were used:

1) two and only two charged tracks,
2) the two prongs acoplanar with the incident beams by at least 20° (to help eliminate backgrounds from radiative lepton pairs),
3) both momenta over 650 MeV/c (to reduce misidentification of hadrons as leptons),
4) no extra shower counters firing (since there should be no photons in the event), and
5) the two prongs should be oppositely charged.

Table I contains the events satisfying criteria 1 through 3 for a sample of events taken at E_{cm} = 4.8 GeV. The events are categorized by the identification of the prongs, whether they have the same or opposite charge, and by the number of detected photons. The 24 $e\mu$ events with no associated photons are the events that we wish to investigate to see if they could come from well known sources. One possible source is the two-virtual-photon process $e^{+} + e^{-} \rightarrow e^{+} + e^{-} + \mu^{+} + \mu^{-}$. Calculations indicate that this source is negligible, and the absence of $e\mu$ events with charge 2 confirms this point since the number of charge 2 $e\mu$ events should equal the number of charge 0 $e\mu$ events from this source.

We determine the background from hadron misidentification or decay by using three-or-more-prong events and assuming that every particle called an e or a μ by the detector either was a misidentified hadron or came from the decay of a hadron. We use $P_{h \rightarrow l}$ to designate the sum of the probabilities for misidentification or decay causing a hadron h to be called a lepton l. Since the P's are momentum dependent we use all the

TABLE I. Distribution of 513 two-prong events, obtained in the SPEAR I configuration at $E_{c.m.} = 4.8$ GeV, which meet the criteria listed in the text. Events are classified according to the number N_γ of photons detected, the total charge, and the nature of the particles. All particles not identified as e or μ are called h for hadron.

N_γ	0	1	>1	0	1	>1
Particles	Total charge = 0			Total charge = ±2		
ee	40	111	55	0	1	0
eμ	24	8	8	0	0	3
μμ	16	15	6	0	0	0
eh	20	21	32	2	3	3
μh	17	14	31	4	0	5
hh	14	10	30	10	4	6

eh, μh, and hh events in column 1 of Table 1 to determine a "hadron" momentum spectrum, and weight the P's accordingly. We obtain the momentum-averaged probabilities $P_{h \to e} = 0.183 \pm 0.007$ and $P_{h \to \mu} = 0.198 \pm 0.007$. Collinear ee and μμ events are used to determine $P_{e \to h} = 0.056 \pm 0.02$, $P_{e \to \mu} = 0.011 \pm 0.01$, $P_{\mu \to h} = 0.08 \pm 0.02$, $P_{\mu \to e} < 0.01$.

Using these probabilities and assuming that all eh and μh events in Table I result from particle misidentifications or particle decays, we calculate the corrected number of events for column 1 of Table I in Table II. The total eμ background is then 4.6 ± 1.2 events. The statistical probability of such a number yielding the 24 signature eμ events is very small. The same analysis applied to columns 2 and 3 of Table I yields 5.6 ± 1.5 eμ background events for column 2 and 8.6 ± 2.0 eμ background events for column 3, both consistent with the observed number of eμ events.

II.B. Muon tower data

We now have sufficient data analyzed by the above methods (about 180 events with about 45 background) that a statistical fluctuation is completely out of the question. The only valid question is whether the background has been calculated correctly.

For this reason it is worthwhile to look at a subset of the data in which the backgrounds due to misidentifications will be smaller. This is possible using data from the muon tower. We will refer to muons being identified at three levels (see Fig. 2). Level 1 corresponds to particles which penetrate the shower counters, the coil, and the flux return. The original data were analyzed exclusively at this level. Level

TABLE II. Corrections to data from column 1 of Table I.

Particles	events	from ee	from μμ	from hh	corrected events
ee	40		0	1.5 ± 0.3	44.3 ± 6.9
eμ	24	1.0 ± 1.0	< 0.3	3.3 ± 0.6	19.7 ± 5.3
μμ	16	0		1.8 ± 0.3	17.0 ± 4.5
eh	18	4.7 ± 1.7	0	10.2 ± 1.8	3.1 ± 5.7
μh	15	0	2.8 ± 0.7	11.0 ± 10	1.2 ± 5.4
hh	13	0.1 ± 0.1	0		40.7 ± 6.4

2 or 3 correspnds to particles which penetrate level 1 and one or two of the concrete slabs.

We take all SPEAR II data with $E_{c.m.}$ ranging from 3.9 to 7.8 GeV and require that

a) two and only two oppositely charged tracks be visible in the detector, and no photons be visible in the shower counters.

b) both momenta be over 650 MeV/c,

c) one particle be a muon candidate at level 2 or 3 and the other particle be a muon candidate at level 1,

d) the two particles be acoplanar by at least 20°,

e) the square of the missing mass recoiling against the two particles be greater than 1.5 $(GeV/c^2)^2$.

A muon candidate is defined as a particle which has sufficient momentum and is heading in the right direction to be seen in a muon spark chamber if it were a muon. The last two requirements are included to reduce the number of radiative e^+e^- and $\mu^+\mu^-$ pairs.

A total of 109 events satisfied these criteria. Fifteen were identified as e^+e^-, 18 events were identified as $\mu^+\mu^-$, and the other 76 events were identified as other combinations of e's, μ's, and hadrons, including 13 events which appear to be an $e\mu$ pair with the μ identified at level 2 or 3.

We now want to calculate the number of $e\mu$ events which would be expected to occur from misidentifications of known processes. We determine the probability that an electron is identified as a muon or vice versa by studying collinear lepton pairs. The probability that an electron gives a small pulse height in a shower counter and also gives a signal at levels 1 and 2 in the muon tower is less than 2×10^{-3}. And the probability

that a muon both gives a large pulse height in the shower counter and fails to fire a muon chamber is less than 3×10^{-3}. The probability for a hadron to be identified as an electron is the same as in Sec. II.A, about 0.18. The probability for a hadron to be misidentified as a muon in the tower was calculated with the aid of the Oak Ridge High Energy Nucleon-meson Transport Code HETC.[4] For the momenta involved in this case it averages 0.033.

We take the number of ee and μμ events detected as the number of true ee and μμ events and make the conservative assumption that the other 76 events come from multihadronic events in which all but two charged hadrons were undetected. The arithmetic is summarized in Table III. The expected number of background events in the 13 eμ events is 0.53. The statistical probability of backgrounds accounting for all 13 events is completely negligible.

Figure 3 shows a computer reconstruction of an eμ event in the muon tower. The event occurred in $E_{c.m.} = 6.6$ GeV. The positively charged particle heading into the muon tower is clearly identified as a muon. It has a momentum of 1.6 GeV/c. The other particle has a negative charge and a momentum of 1.0 GeV/c and is identified as an electron by the large pulse height (113 units) in the shower counter. On the average, a 1.0 GeV electron typically gives a pulse height of 100 in a shower counter.

II.C. Other experiments

The DASP collaboration has announced "one extremely clean" eμ event with no additional detected charged or neutral particles.[5] At the Topical Conference, Hinrich Meyer will report on 6 eμ events from the Pluto experiment.[6]

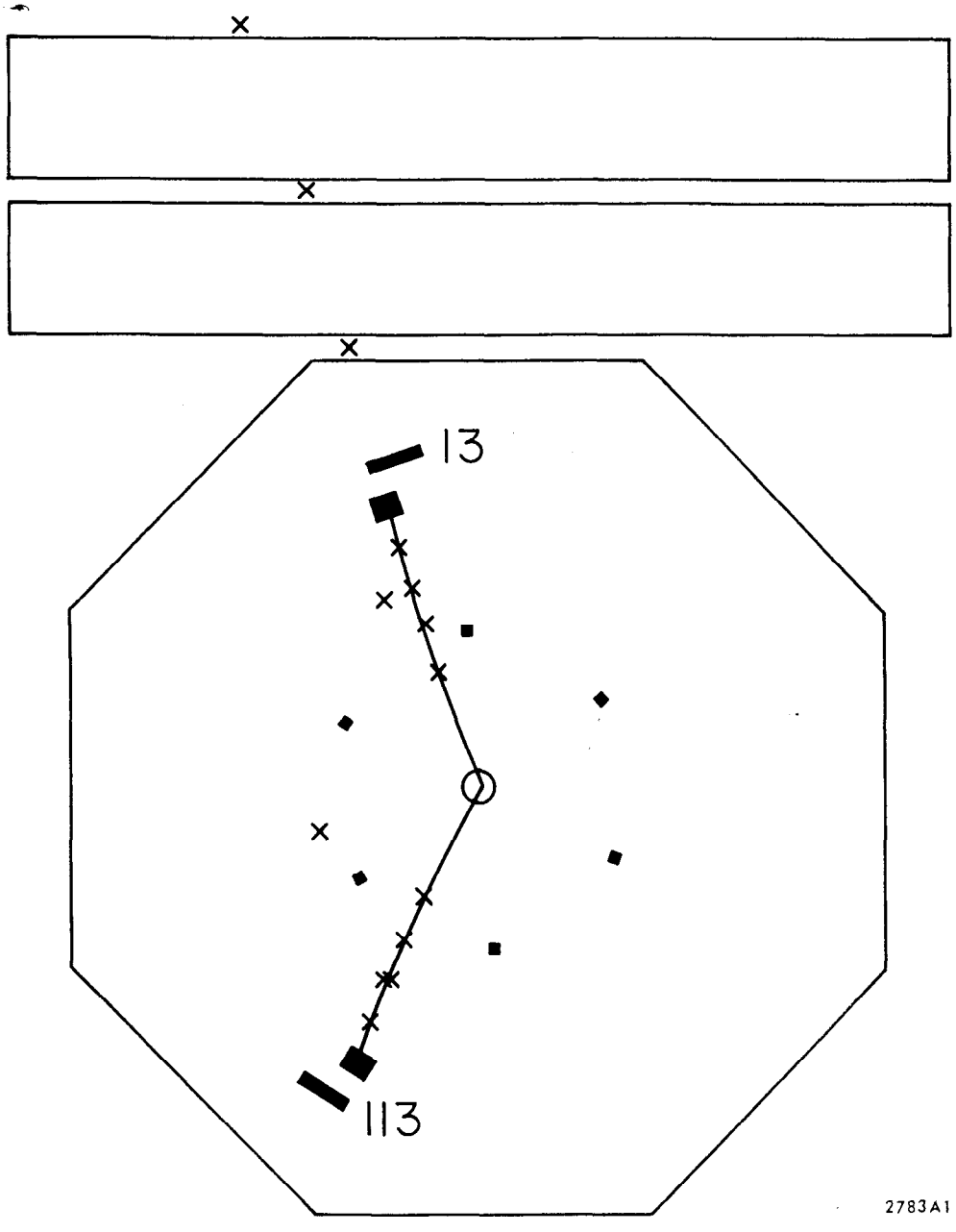

FIG. 3. Computer reconstruction of an eμ event. The numbers indicate shower counter pulse heights.

TABLE III

Calculation of expected backgrounds from misidentifications to the 13 $e\mu$ events observed in the muon tower.

mode	events	misidentification probability	expected background
ee	15	0.002	0.03
$\mu\mu$	18	0.003	0.05
hh	76	0.18×0.033	0.45
total	109		0.53

Given all these data, we take the existence of the anomalous $e\mu$ signal to be established. We now address ourselves to the question What is it?

III. Hypotheses for the origin of the anomalous $e\mu$ events

We can imagine several hypothetical new processes which could account for these events. One possibility is the process which motivated the search in the first place, the leptonic decays of a new sequential lepton

$$e^+e^- \to L^+L^- \quad \begin{cases} \to e^-\bar{\nu}_e\nu_L \\ \to \mu^+\nu_\mu\bar{\nu}_L \end{cases} \qquad (1)$$

A second possibility is that these events result from the two-body leptonic decay of a charged (and presumably vector) meson,

$$e^+e^- \to V^+V^- \quad \begin{cases} \to e^-\bar{\nu}_e \\ \to \mu^+\nu_\mu \end{cases} \qquad (2)$$

And a third possibility is that these events arise from semileptonic decays of new mesons, for example

$$e^+e^- \to M^+M^- \quad \begin{cases} \hookrightarrow e^-\bar{\nu}_e K^o \\ \hookrightarrow \mu^+\nu_\mu \bar{K}^o \end{cases} \tag{3a}$$

or

$$e^+e^- \to M^o\bar{M}^o \quad \begin{cases} \hookrightarrow e^-\bar{\nu}_e K^o \\ \hookrightarrow \mu^+\nu_\mu K^- \end{cases} \tag{3b}$$

To decide between these hypotheses, we will want to determine

1) whether the decay is two-body or three-body, and

2) whether there are undetected hadrons in the decay.

IV. Properties of the anomalous $e\mu$ events[7]

IV.A. Colinearity angle distribution

Evidence that the origin of these events is the decay of a pair of new particles is obtained from the distribution of the angles between the two prongs. Figure 4 shows the distribution of the cosine of the colinearity angle for three E_{cm} regions. At low energy the angles are much more uncorrelated than at high energy. This is characteristic of the decay of a pair of fixed mass particles; as the energy increases, the Lorentz transformation forces the decay products back to back. The data in Fig. 4 have been corrected for background events, which do not exhibit this behavior (Fig. 5).

IV.B. Momentum spectrum

From the inclusive momentum spectrum we can obtain information on the number of particles in the decay. To combine data from different

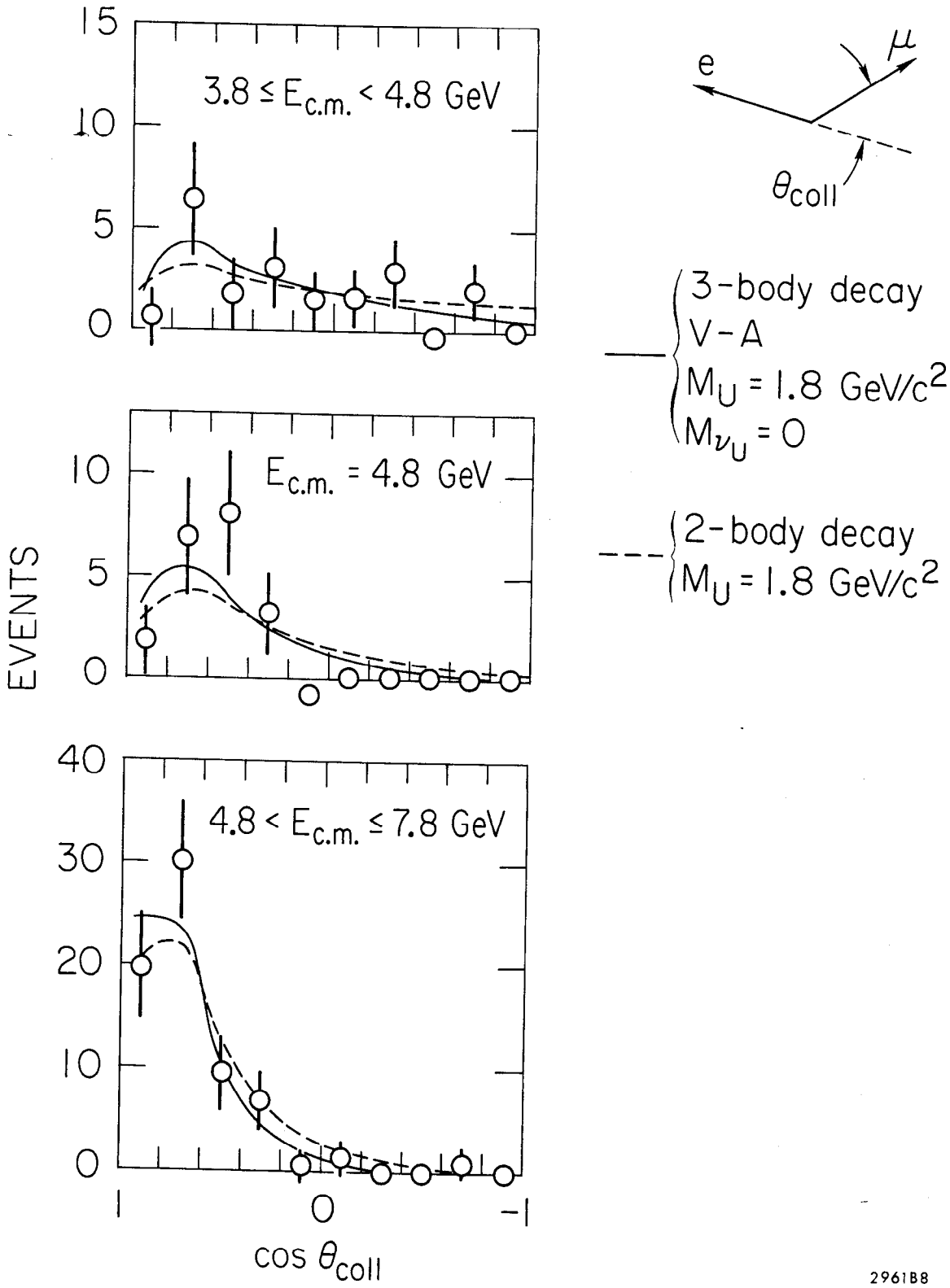

FIG. 4. Cosine of the colinearity angle.

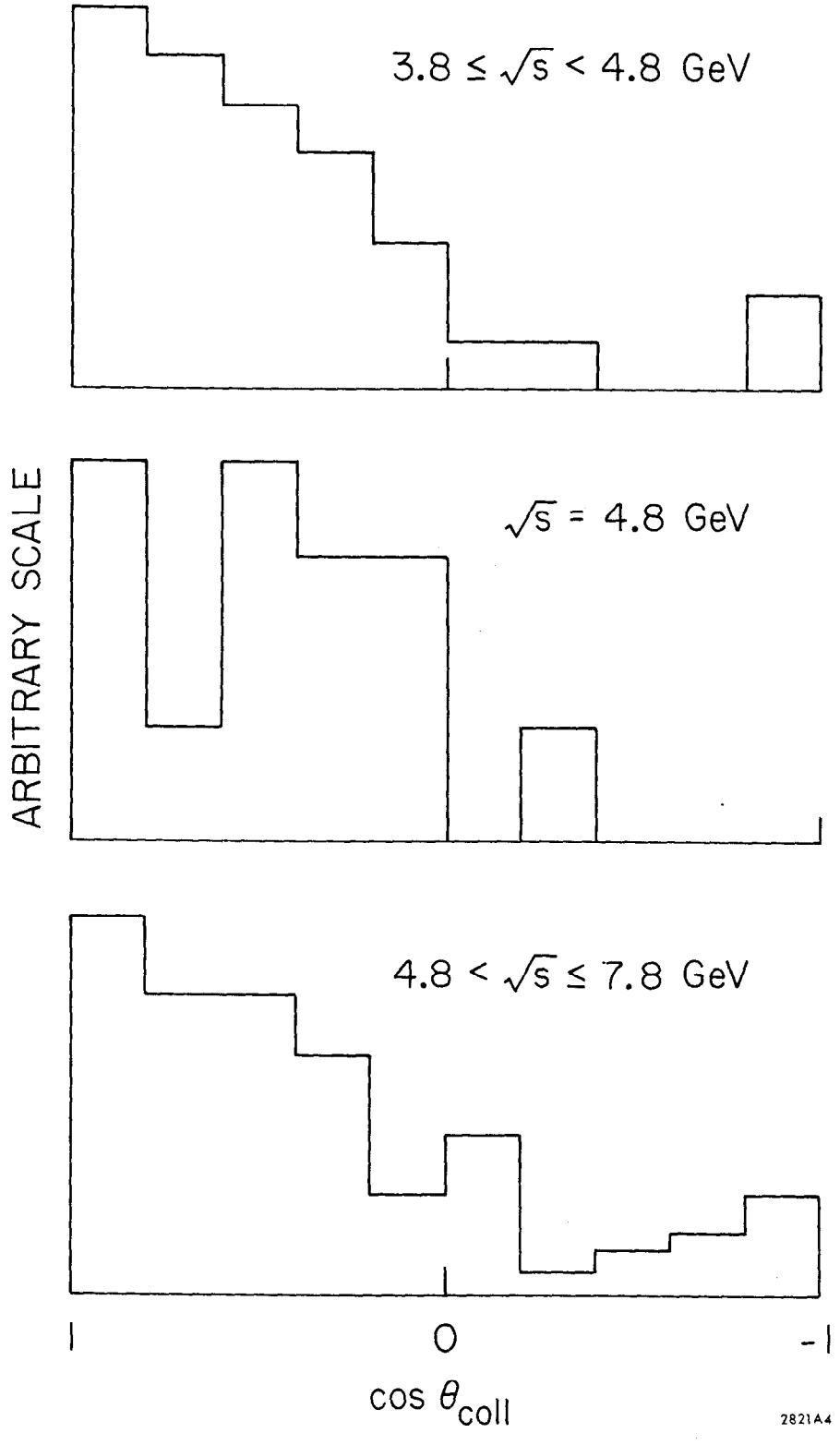

FIG. 5. Cosine of the colinearity angle for background events.

energies we construct the reduced momentum, ρ,

$$\rho = \frac{p - 0.65}{p_{max} - 0.65} \quad , \tag{4}$$

where p is the momentum of each detected particle in GeV/c and p_{max} is the maximum momentum allowed for the decay of 1.8 GeV/c^2 particle into massless particles. (The use of any mass in the range 1.6 to 2.0 GeV/c^2 would not alter these conclusions.) The ρ distribution is given in Fig. 6 for all the data and in Fig. 7 for three energy ranges. Background contamination has been subtracted. The background ρ distribution, shown in Fig.6, is similar to the signal ρ distribution; thus, the background subtraction does not appreciably alter this distribution.

In Figs. 6 and 7, the solid curve is for a heavy lepton with mass 1.8 GeV/c^2 and a V-A coupling. The dashed curve is for a mass 1.8 GeV/c^2 boson with a 2-body decay mode ignoring spin correlations or polarization effects. The dot-dashed curve represents an extreme case of polarization of a 1.8 GeV/c^2 vector meson with a 2-body decay mode, the meson being only in the helicity = 0 state. Values of χ^2 for these hypotheses are shown in Table IV for the three energy ranges. Taking all of the data together, two body decay modes are excluded.

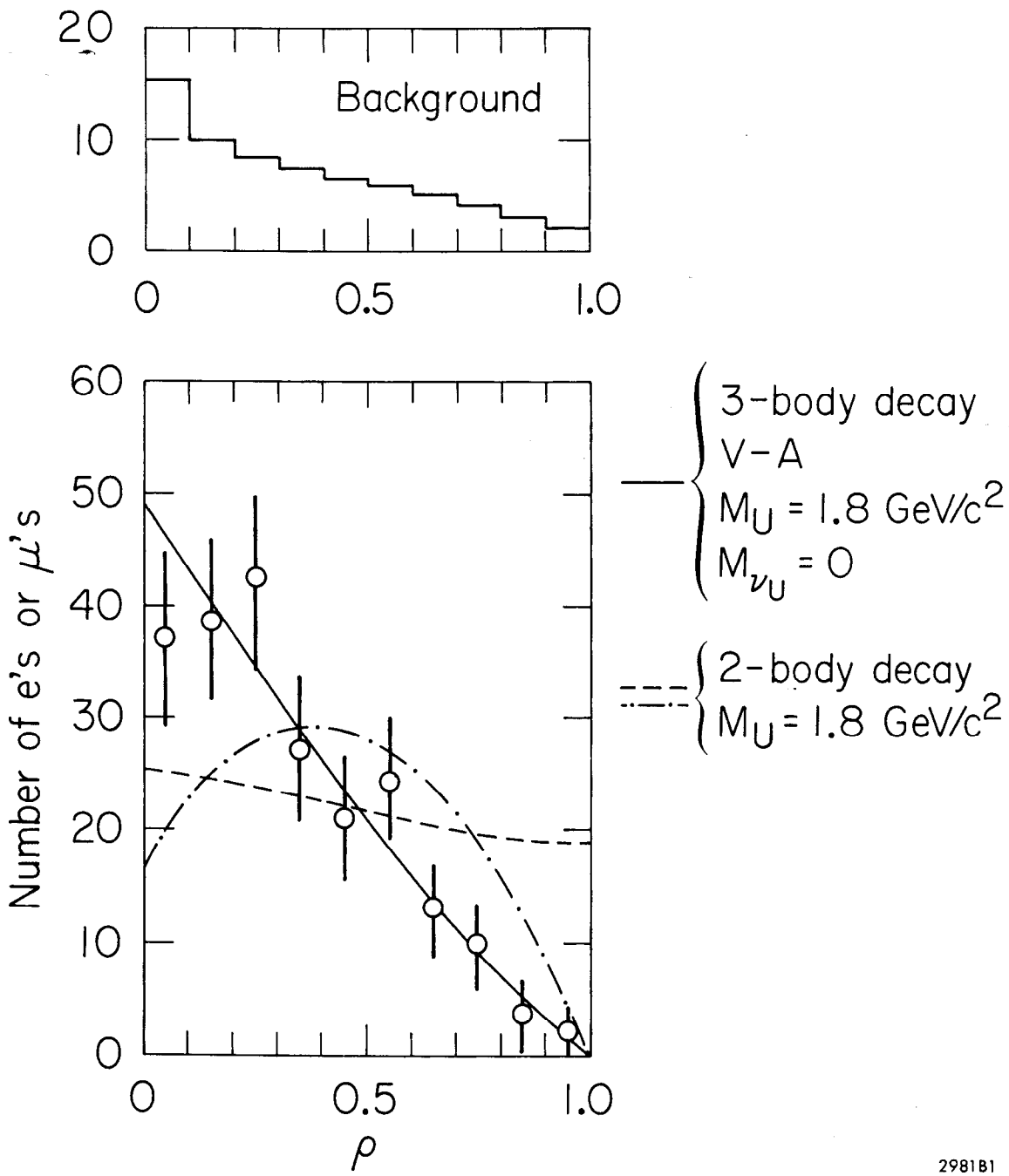

FIG. 6. Reduced momentum (Eq. 4) spectrum.

TABLE IV

χ^2 tests of ρ distributions. E_{cm} in GeV

	$3.8 < E_{cm} < 4.8$	$E_{cm} = 4.8$	$4.8 < E_{cm} < 7.8$	$3.8 < E_{cm} < 7.8$
Degrees of freedom	4	4	9	9
χ^2 for heavy lepton, $M_U = 1.8$ GeV/c^2, $M_{\nu_U} =$ 0.0 V-A coupling	2.2	9.5	8.6	4.3
χ^2 for boson with 2-body decay $M_U =$ 1.8 GeV/c^2 no spin correlation or polarization	28.3	10.5	98.0	107.4
χ^2 for vector meson with 2-body decay $M_U =$ 1.8 GeV/c^2 each meson only in helicity = 0 state	20.6	3.3	38.1	35.4

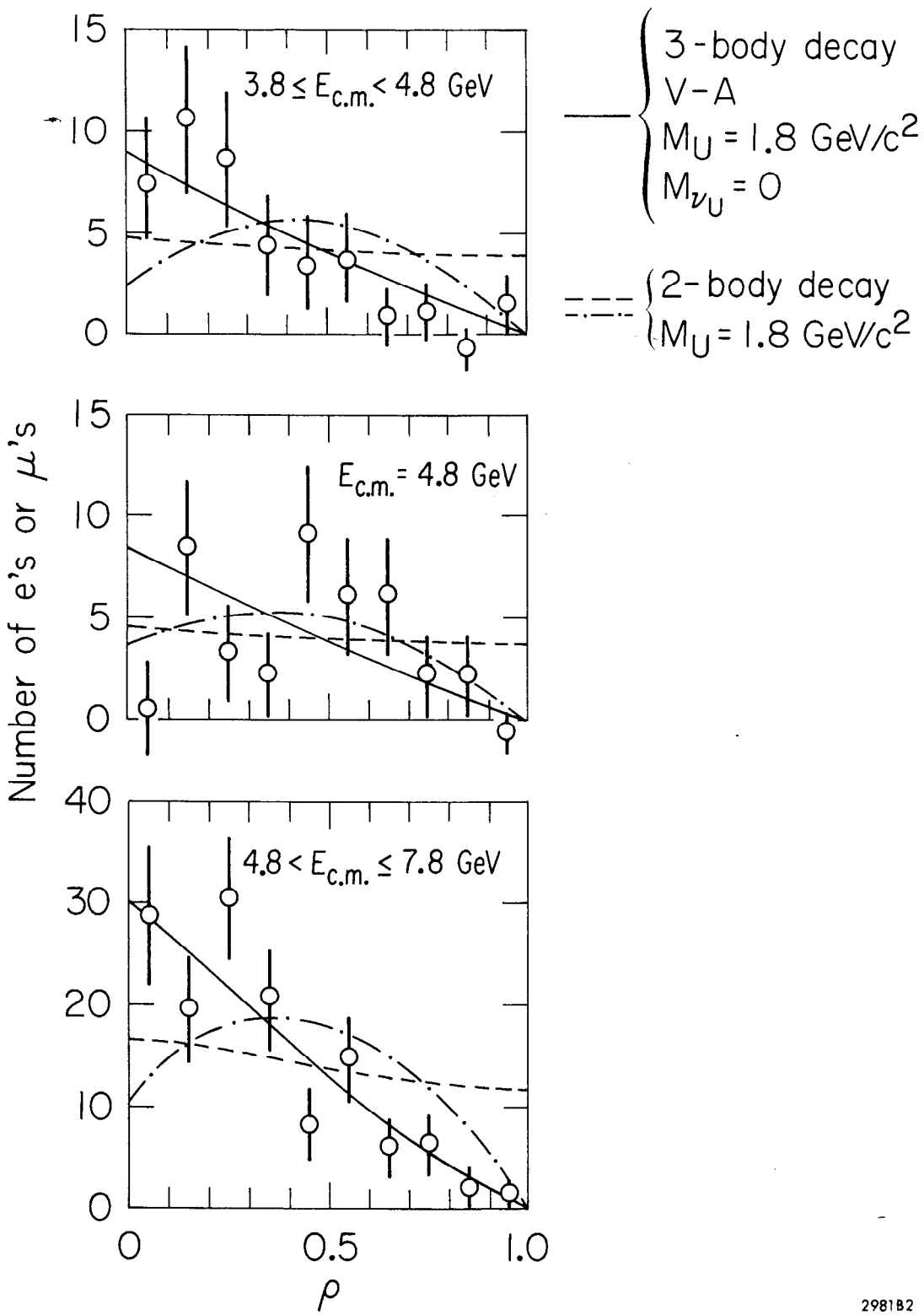

FIG. 7. Reduced momentum spectra for three energy ranges.

II.C. Are there missing hadrons?

We have so far seen evidence that we are observing the decays of a pair of fixed mass particles and that each decays into at least three particles. Are all the missing particles neutrinos or are there some hadrons which escape detection? We will show that most of the time the missing particles can only be neutrinos by systematically eliminating all other possibilities.

The neutron is eliminated as a candidate for one of the undetected particles by the ρ distributions which set an upper limit of 0.7 GeV/c^2 (95% confidence level) on the mass which can be possessed by any of the undetected particles in the three body decay. Figure 8 shows these distributions with curves representing the distributions expected for a 1.8 GeV/c^2 heavy lepton decaying to two massless particles and a heavy neutrino via a V-A coupling. The use of other couplings or of phase space has no effect on this conclusion since a high mass undetected particle limits the maximum value of ρ independent of the coupling.

To determine whether a K_L^o could be one of the undetected particles, we searched for events of the form

$$e^+e^- \rightarrow e^{\pm}\mu^{\mp}K_s^o + \text{missing mass} \qquad (5)$$

where the K_S^o is detected by its decay $K_S^o \rightarrow \pi^+\pi^-$. In a data sample which contained 82 eμ events with no other detected particles,[8] only one example of reaction (5) was observed. Assuming that the decay rate of the new particle into K_L^o is equal to the decay rate into K_S^o, the fraction of decays in reaction (1) containing a K^o is less than 0.09 at the 90% confidence level.

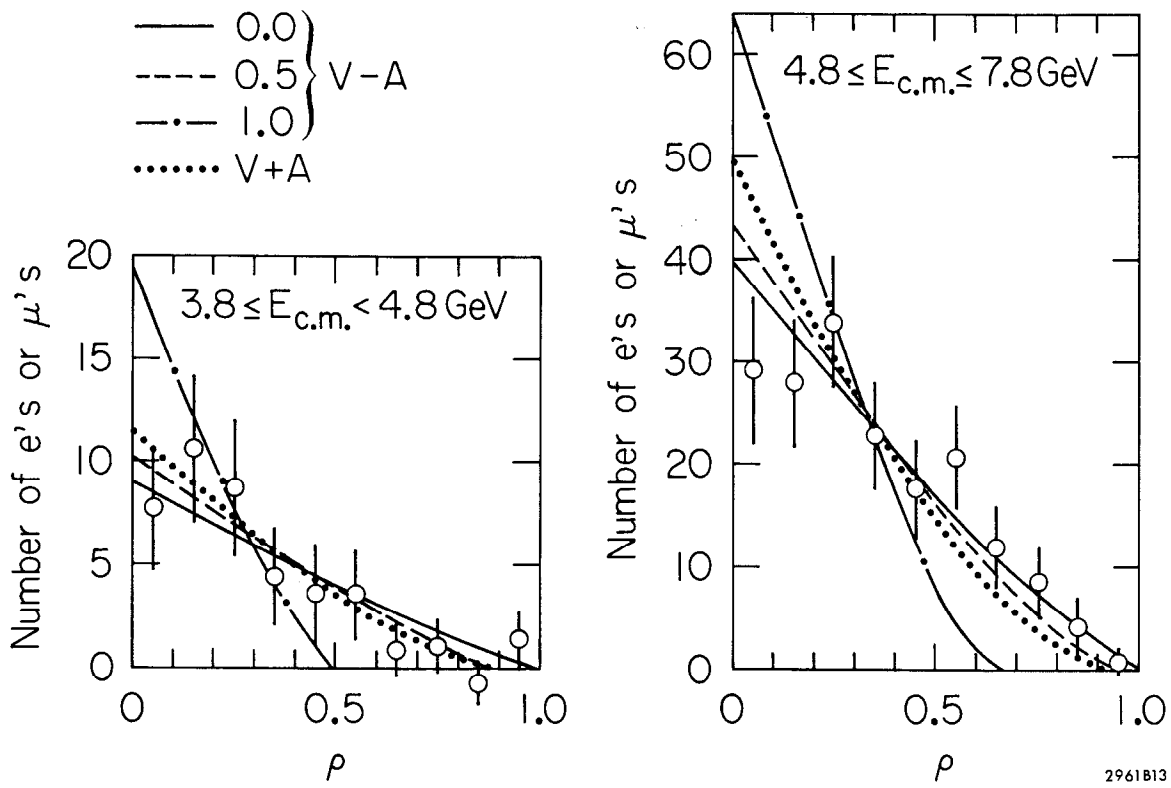

FIG. 8. Reduced momentum spectra with curves showing the effect of a heavy neutrino.

To determine whether the undetected particles could be photons, π^o's, or charged particles which escape detection by passing through uninstrumented sections of the detector, we construct a table, Table V, of all events which contain an oppositely charged electron and muon. Events are categorized by charged multiplicity and whether photons were detected in the shower counters. The data sample is the same as was used for the K_S^o search. The e and μ selection is similar to that used in Sec. II.A except that no coplanarity requirement was imposed in events with three or more charged prongs.

Two estimates of the number of events we expect from misidentifications of hadronic events are included in Table V. The first is an estimate obtained from misidentification probabilities as a function of momentum measured in ψ decays, assuming no anomalous sources of lepton production in these decays. The second is an estimate obtained from three or more prong events in the data set from which the table is constructed. The true number of events caused by hadron misidentifications is probably somewhere between the two limits given in Table V because misidentification probabilities can increase with c.m. energy, particularly for hadrons being misidentified as electrons.

At the present stage of analysis, Table V argues neither for nor against anomalous di-lepton production in topologies other than the two prong, no photon, topology. The sole function of the table is to show that there are an insufficient number of events in the other topologies to explain the anomalous $e\mu$ events as events in which additional charged particles or photons are produced, but escape detection.

For example, assume that the anomalous $e\mu$ were to be explained as events in which each new particle decayed into a lepton, a π^o, and a

TABLE V

The number of events with an identified oppositely charged electron and muon categorized by total observed charged multiplicity and by whether photons are detected. The numbers in parentheses represent minimal and maximal background estimates and are explained in the text.

charged multiplicity	no photons	> one photon
2	110 (14-28)	109 (51-104)
3	67 (28-58)	198 (94-193)
4	79 (37-76)	338 (180-356)
> 5	101 (56-109)	884 (506-971)

neutrino, but that neither π^o was detected by the shower counters. Since the typical efficiency for detecting at least one photon from a π^o decay is 0.65, there is only a 0.12 probability of $2\pi^o$'s escaping detection. Thus, to explain the 82 anomalous two prong events without photons, we would have to observe 600 two prong events with photons. From Table V, there are only 109 events of this type, and only 58 events after the subtraction of the minimal background.

Similar arguments can be made for any combination of undetected charged and neutral particles. Table VI gives upper limits on the fraction of decays in the anomalous eμ events which could have undetected photons or charged particles of various types, using the minimal background estimates from Table V. Overall, using very conservative estimates of backgrounds, at the 90% confidence level only 39% of the anomalous decays can contain undetected photons or charged particles.

IV.D. Conclusion

We have seen that there is evidence

1) that the anomalous eμ events come from decays of a pair of fixed mass particles,

2) that, most of the time, the missing particles are neutrinos.

Thus, the decays that lead to the anomalous eμ events seem to have the form,

$$U^- \rightarrow \ell^- \nu\nu, \qquad (6)$$

the usual signature of a heavy lepton.[9] This is the only simple hypothesis which fits all of the data.

Assuming that the U is a new lepton with V-A coupling, its mass is

TABLE VI

90% confidence level upper limits on the fraction of decays in the anomalous $e\mu$ events which can contain an undetected particle or combination of particles. The smaller backgrounds given in Table V have been used. The total is less than the sum of the limits due to the quadratic addition of errors and elimination of double counting between modes.

Undetected particles	90% confidence level
K^o	0.09
π^o or γ	0.18
Charged particle	0.09
Charged particle + π^o or γ	0.11
TOTAL	0.39

in the range 1.6 to 2.0 GeV/c^2 and its leptonic branching ratio is

$$\frac{\Gamma(U^- \to \nu_U e^- \bar{\nu}_e)}{\Gamma(U^- \to \text{all})} = \frac{\Gamma(U^- \to \nu_U \mu^- \bar{\nu}_\mu)}{\Gamma(U^- \to \text{all})} = 0.17 \begin{matrix} +0.06 \\ -0.03 \end{matrix} \quad . \tag{7}$$

V. Consistency checks to the hypotheses of a new lepton

We now have a new lepton as a working hypothesis. The nice thing about this hypothesis is that there are almost no free parameters. We can make a large number of predictions. The verification of any one of them, or even all of them, does not prove the hypothesis, but the hypothesis is destroyed if even one of them is disproved.

For some of the predictions, it will be necessary to know how a heavy lepton decays. These decays are calculable from experimental measurements and rather mild theoretical assumptions. Table VII gives a calculation of the branching fractions along with the inputs to the calculation. The basic formulae are all given by Tsai.[10] Gilman recalculated some of the values.[11] The most uncertain calculation is the decay to the "hadron continuum". This depends on the measurement of R ($\sigma_{tot}/\sigma_{\mu\mu}$) in the region below 1.8 GeV. Unfortunately it is measured poorly in this region, as can be seen from Fig. 9. In calculating the values for Table VII, I set R = 0 for $E_{cm} < 1.2$ GeV and R = 2 for $1.2 < E_{cm} < 1.8$ GeV.

One interesting result of the calculation in Table VII is that 87% of all heavy lepton decays will contain only one charged particle (assuming that 40% of the hadron continuum decays contain one charged particle). Thus most of the heavy lepton pair production events will be two-prong events.

TABLE VII

Calculation of the decays of a 1.8 GeV/c^2 lepton.

	fraction (%)	input
$e\nu\bar{\nu}$	20	measurement of μ decay
$\mu^-\nu\bar{\nu}$	20	measurement of μ decay
$\pi^-\nu$	12	measurement of π decay
$K^-\nu$	1	measurement of K decay
$\rho^-\nu$	23	measurement of $e^+e^- \to \rho^o$ and conserved vector current
$K^{*-}\nu$	1	above plus sum rules on the vector and axial vector currents
$A_1^-\nu$	8	
hadron continuum	15	measurements of $e^+e^- \to$ all, $E_{cm} < 1.8$ GeV[a], conserved vector current, and equal contributions from the vector and axial-vector currents.

a. $R = 0$, $E_{cm} < 1.2$ GeV and $R = 2$, $1.2 < E_{cm} < 1.8$ GeV assumed.

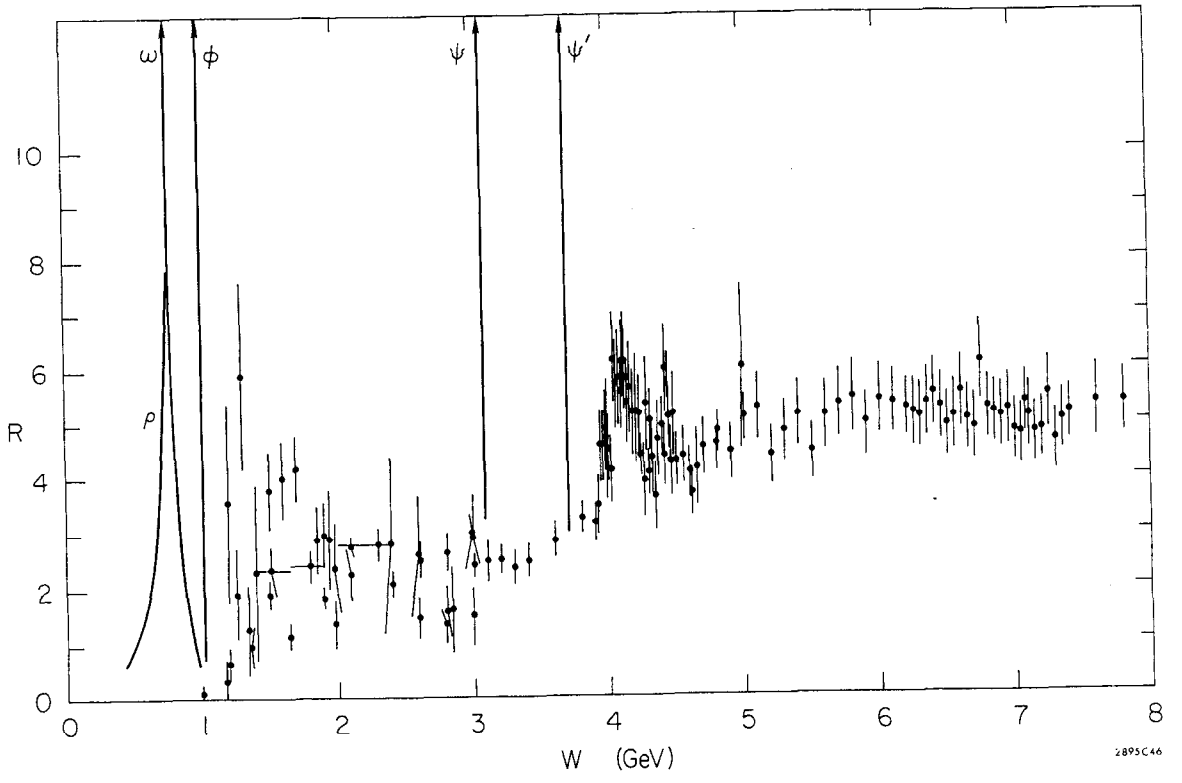

FIG. 9. R as a function of center-of-mass energy.

V.A. Point-like energy dependence

The first consistency check is that we must have a point-like production cross section as a function of E_{cm}. This is implicit in what we mean by a lepton. The observed cross sections are shown in Fig. 10 along with the predicted values for a 1.8 GeV/c^2 lepton. Although the statistical errors are large, the data are consistent with being point-like.

V.B. Total e^+e^- annihilation cross section

R, the ratio between the total e^+e^- annihilation cross section and the μ pair production cross section, measures the sum of squares of charges of the fundamental fermions in the conventional models. Thus if we have a new lepton, we must have room for it in the total cross section. This point was discussed in detail in Sec. II.C of lecture 1. We not only have room for it, but measurements of R seem to require a new fermion.

V.C. Leptonic branching fraction

Based on very general theoretical considerations, Table VII requires about a 20% branching fraction to each leptonic mode. The measured value is 17^{+6}_{-3}%.

V.D. Anomalous ee and $\mu\mu$ events.

Since we interpret the anomalous $e\mu$ events to be the result of independent decays, one containing an e and one containing a μ, we expect half as many anomalous ee and $\mu\mu$ events. These events are harder to measure because there are backgrounds from leptonic processes which are comparable to the anomalous signal. We have subtracted backgrounds from

$$e^+e^- \rightarrow \ell^+\ell^-\gamma,^{12} \tag{8}$$

$$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma,^{13} \tag{9}$$

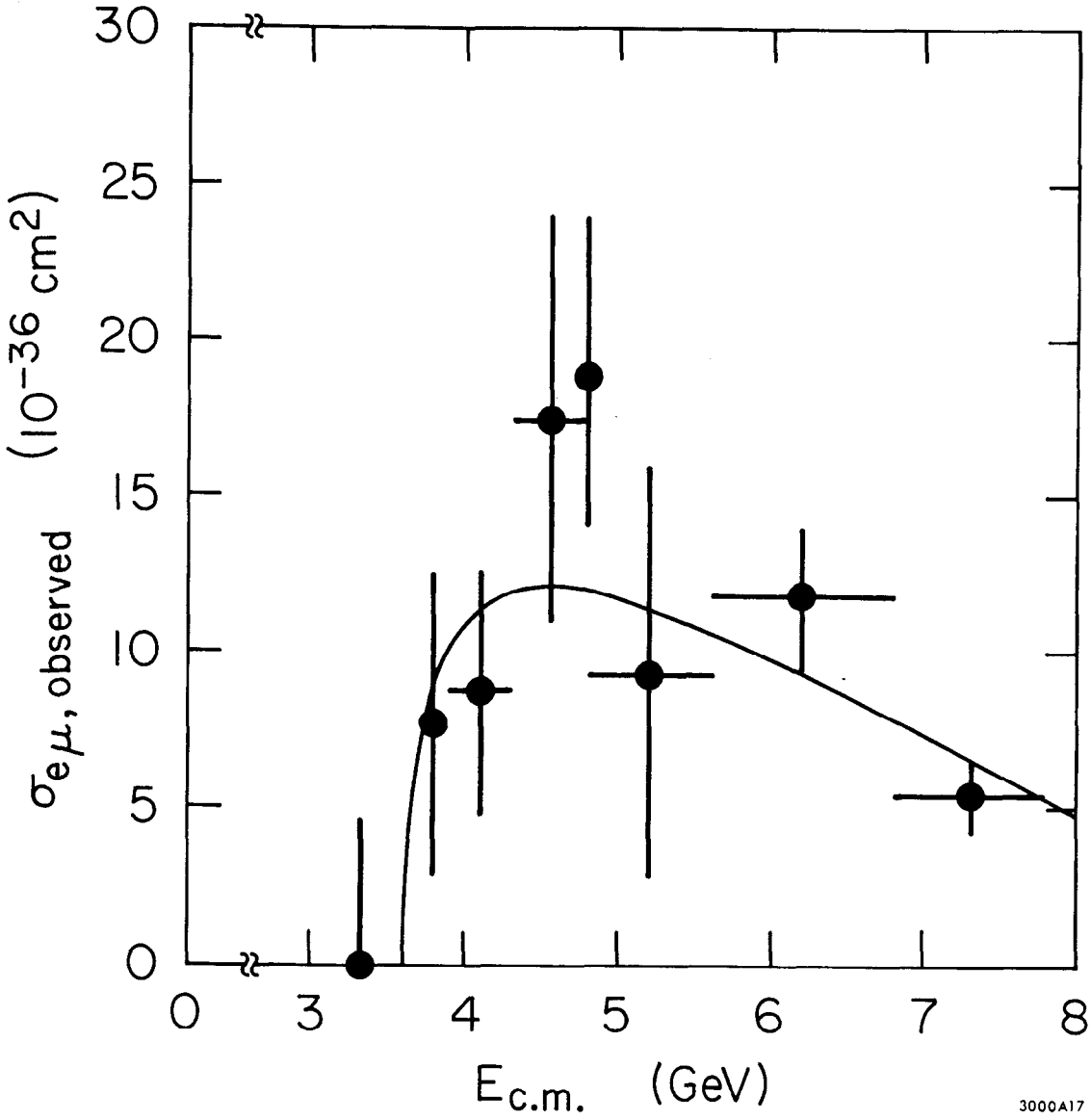

FIG. 10. Observed eμ cross section as a function of center-of-mass energy. The curve represents the expected observed cross section for a 1.8 GeV/c^2 lepton decaying to $\mu\nu\bar{\nu}$ and $e\nu\bar{\nu}$ each with a branching fraction of 0.17 via a V-A interaction.

and

$$e^+e^- \to e^+e^-\ell^+\ell^-,^{14} \tag{10}$$

where ℓ stands for either e or μ. The preliminary results are[15]

$$\frac{\sigma_{ee}}{\sigma_{e\mu}} = 0.39 \pm 0.21 \tag{11}$$

and

$$\frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = 0.66 \pm 0.16 \quad . \tag{12}$$

Within large errors, these results agree with the expected value of 0.5.

V.E. Anomalous μ-hadron events.

From Table VII, we expect to observe two-prong events with one of the particles a μ and the other a hadron. To search for these events we will repeat the analysis given in Sec. II.B, where we looked for $e\mu$ events with the μ in the muon tower. To search for μ-hadron events we make two changes in the criteria listed in Sec. II.B:

1) We require the particle not heading toward the muon tower to be identified as a hadron, and
2) we allow photons in the events.

There are 109 events satisfying these criteria. In 16 events the particle going toward the tower is identified as a muon. To conservatively estimate backgrounds we take all 109 events to be hadron-hadron events. Then misidentification of the hadron as a muon will give 3.6 events background. The only other important source of background are $\mu\mu$ events in which a μ^- is identified as a hadron. There are 24 $\mu\mu$ events which give a background of 1.1 events. Thus the total background is 4.7 events out of 16 events observed. The probability that this could be due to a statistical fluctuation is less than one part in 10^{-4}.

V.F. Inclusive anomalous two-prong μ events[16]

In the previous sections we have seen evidence for anomalous μe, $\mu\mu$, and μ-hadron events. It is thus obvious that there will be anomalous μ-anything events. Nevertheless, it is useful to study these events as a final consistency check since we will have sufficient statistics to calculate a meaningful cross section.

We take as the initial sample of events all two-prong events, with or without photons, in which one prong is a muon candidate at level two or three of the muon tower. (As in Sec. II.B, a muon candidate is defined as a particle which has sufficient momentum and is heading in the right direction to fire a muon spark chamber if it were a muon.) To simplify the background calculations, events in which both prongs are identified as electrons are eliminated. We then require the two prongs to be acoplanar with the incident beams by at least 20° and for the square of the missing mass recoiling against the two observed prongs to be greater than 1.5 $(\mathrm{GeV}/c^2)^2$. Backgrounds from hadron penetration and decay and leptonic backgrounds as discussed in Sec. V.D are then subtracted to obtain the number of anomalous two-prong μ events.

The results for three energy ranges are summarized in Table VIII. (There were negligible data taken in the missing energy range from 4.8 to 5.8 GeV.) The anomalous muon cross section in all three energy ranges is compatible with that expected from the decays of pairs of heavy leptons. The later cross sections listed in Table VIII are for a mass range 1.6 to 2.0 GeV/c^2, a branching fraction into $\mu\nu\bar{\nu}$ of 0.17, and other branching fractions as given in Table VII.

TABLE VIII

Inclusive anomalous muon production in two prong events.

E_{cm} range (GeV)	3.9 to 4.3	4.3 to 4.8	5.8 ± 7.8
Average E_{cm} (GeV)	4.05	4.4	6.9
Integrated luminosity (pb^{-1})	2.44	2.35	16.2
Candidates	181	224	902
Muons	24	29	177
Radiative μ pairs	2.3	2.2	17
eeμμ events	1.4	1.8	29
Hadron penetration or decay	5.0	6.4	28
Anomalous muons	15.3 ± 5.1	18.6 ± 5.7	103 ± 18
Anomalous cross section (pb)	194 ± 71	253 ± 86	212 ± 49
Expected heavy lepton contribution (pb)	252 ± 57	290 ± 197	195 to 218

Two other experiments have made measurements of inclusive anomalous muon production in two-prong events. The Maryland-Princeton-Pavia group reported 13 events with 4 background at 4.8 GeV, corresponding to a cross section of $285 \begin{smallmatrix} +151 \\ -113 \end{smallmatrix}$ pb.[16] I calculate that one would expect about 275 pb from heavy lepton decays in that experiment. Unfortunately there was a factor of two error in calculating the background from radiative μ pair production.[17] This will reduce the anomalous cross section to the vicinity of 190 pb, but the errors are sufficiently large that the result is still compatible with that expected from heavy lepton decays.

The PLUTO experiment has searched for anomalous muons in the energy range 4.0 to 4.2 GeV. Preliminary results will be presented by Hinrich Meyer in the Topical Conference.[6] At present this experiment gives only an upper limit, but one that is not incompatible with a heavy lepton in the mass range 1.6 to 2.0 GeV/c^2.

VI. Summary

There is strong evidence for anomalous $e\mu$ events. The properties of these events indicate that they come from decays of a pair of particles, each of which decays to a charged lepton and two neutrinos. Taking the existence of a new lepton as a working hypothesis, we examined six consistency checks, the point-like energy dependence, the value of the total e^+e^- annihilation cross section, the leptonic branching fraction, anomalous ee and $\mu\mu$ events, anomalous μ-hadron events, and anomalous μ-anything events. In all cases, the present data are compatible with the hypothesis. Thus, the answer to the question which forms the title of this lecture is: We either have a new lepton or a very good imitation.

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