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INTERPRETATION OF ANOMALOUS $e\mu$ EVENTS PRODUCED IN e^+e^- ANNIHILATION†*

Martin L. Perl

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

1. INTRODUCTION

We have explained the anomalous $e\mu$ events in e^+e^- annihilation,[1,2]

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \text{missing energy}, \qquad (1)$$

as the decay products of a pair of U particles[3] produced in the reaction

$$e^+ + e^- \rightarrow U^+ + U^- \qquad (2)$$

This talk has two purposes. (1) The properties of a total sample of 139 anomalous $e\mu$ events, Eq. 1, are presented. Previous publications[1-3] were based on a sample of 86 events. (2) These properties are used to test five different general hypotheses as to the nature of the U particle, Eq. 2. We show that among these hypotheses, the only one compatible with all our data is that the U particle is a heavy lepton.

The work presented here is based on the data obtained by the SLAC-LBL Magnetic Detector Collaboration using the SPEAR electron-positron colliding beam facility at the Stanford Linear Accelerator Center.

2. HYPOTHESES

Hypotheses as to the nature of the U particle must meet the experimental requirement (Sec. 3) that the decay mode of the U we observe can contain only one charged particle, an e or μ. And the only known neutral particles in the decay mode can be neutrinos, K_L^o mesons or neutrons. Other neutral particles would be detected by their decay modes, π^o mesons through their decay photons, K_S^o mesons

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through their decay photons or charged pions. There are five general hypotheses which fit these criteria and require the existence of only one new particle.

A. Sequential Heavy Lepton: We visualize the sequence[5,6]

$$
\begin{array}{ll}
\text{charged lepton} & \text{associated neutrinos} \\
e^{\pm} & \nu_e, \bar{\nu}_e \\
\mu^{\pm} & \nu_\mu, \bar{\nu}_\mu \\
\ell^{\pm} & \nu_\ell, \bar{\nu}_\ell \\
\cdot & \cdot \\
\cdot & \cdot \\
\cdot & \cdot
\end{array}
\tag{3}
$$

The ℓ, called a sequential heavy lepton, would not have substantial radiative decays. The dominant decays would be: (We use the ℓ^- as the example; for the ℓ^+ decay, change each particle to its antiparticle.)

a) leptonic

$$\ell^- \rightarrow \nu_\ell + e^- + \bar{\nu}_e \tag{4a}$$

$$\ell^- \rightarrow \nu_\ell + \mu^- + \bar{\nu}_\mu \tag{4b}$$

b) semi-leptonic

$$\ell^- \rightarrow \nu_\ell + \pi^- \tag{5a}$$

$$\ell^- \rightarrow \nu_\ell + K^- \tag{5b}$$

$$\ell^- \rightarrow \nu_\ell + \rho^- \tag{5c}$$

$$\ell^- \rightarrow \nu_\ell + \pi^+ + \pi^- + \pi^-$$

$$\begin{array}{cc} \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \end{array}$$

The relative decay rates depend upon the lepton mass.[6,7]

The experimental signature for ℓ pair production in e^+e^- annihilation is Eq. 1 through the processes

$$e^+ + e^- \to \underset{\llcorner\!\to \bar{\nu}_\ell \mu^+ \nu_\mu}{\ell^+} + \underset{\llcorner\!\to \nu_\ell e^- \bar{\nu}_e}{\ell^-} \qquad (6)$$

The heavy lepton production cross section is

$$\sigma_{ee \to UU} = \frac{43.4\beta(3 - \beta^2)}{s}\ \text{nb} \quad , \quad U \equiv \text{heavy lepton } \ell \qquad (7)$$

Here $s = E_{cm}^2$ and $\beta = v_U/c$; v_U being velocity of the U

B. Electron-related Heavy Lepton:[8] The ℓ could have the lepton number of the oppositely charged e, inhibiting radiative decay, and giving the leptonic decay modes.

$$\ell^- \to \bar{\nu}_e + e^- + \bar{\nu}_e \qquad (8a)$$

$$\ell^- \to \bar{\nu}_e + \mu^- + \bar{\nu}_\mu \qquad (8b)$$

The muon-related heavy lepton is ruled out by neutrino experiments[9] at masses accessable to this experiment.

C. Purely Leptonic Decay of Heavy Boson: Eq. 1 may result from the pair production and 2-body leptonic decay of a boson or meson M; the charm theory providing the most popular examples[10,11] for hadronic mesons. Purely leptonic decays would have the form

$$\begin{aligned} M^- &\to e^- + \bar{\nu}_e \\ M^- &\to \mu^- + \bar{\nu}_\mu \end{aligned} \qquad (9)$$

The M production cross section is not known a priori, I use the formula

$$\sigma_{ee \to UU} = \frac{\eta\beta^3}{s}\,|F_U(s)|^2 \quad ; \quad U \equiv \text{boson M} \qquad (10a)$$

Here η is a constant, $\beta = v_U/c$, β^3 is a guess at a thereshold factor for a spin 1 particle, and $F_U(s)$ is a production form factor. I use

$$F_U(s) = 1 \quad ; \quad M \equiv \text{point boson} \tag{10b}$$

$$F_U(s) = 4M_U^2/s \quad , \quad M = \text{hadronic meson} \tag{10c}$$

D. Semi-leptonic Decay of Heavy Meson: The only 3-body semi-leptonic decay of the M which meets the requirements given at the beginning of this section is

$$\begin{aligned} M^- &\to e^- + \bar{\nu}_e + K_L^o \\ M^- &\to \mu^- + \bar{\nu}_\mu + K_L^o \end{aligned} \tag{11}$$

E. New Baryon: The U might be a new type of baryon with the decay mode

$$\begin{aligned} B^- &\to e^- + \bar{\nu}_e + n \\ B^- &\to \mu^- + \bar{\nu}_\mu + n \end{aligned} \tag{12}$$

where n is a neutron. Such baryons are predicted by charm theories and by an old speculation of M. Goldhaber[12] on the doubling of fermions.

In this paper we shall use U to represent ℓ or M or other particles whose pair production and decay would lead to Eq. 1. I do not have the time in this talk to discuss the interesting theories of Pati and Salam[13] or of Feinberg and Lee;[14] these theories predict particles with decay modes which experimentally would fall into one of the above classifications.

3. REVIEW OF EVENT SELECTION AND BACKGROUNDS

The selection of the eμ events, the background subtraction and the observed production cross section has been fully discussed in Refs. 1,3,15. Events from the SLAC-LBL Magnetic Detector[4], Fig. 1, were selected using the following criteria:

a. two and only two charged prongs in the detector;

b. prongs of opposite electric charge;

c. each prong has a momentum greater than 0.65 GeV/c.

d. one prong is identified as an electron and the other as a muon by the detector;

e. no photons detected;

f. the coplanarity angle, θ_{copl}, is greater than 20^o where

$$\cos\theta_{copl} = -(\underset{\sim}{n}_1 \times \underset{\sim}{n}_{e^+}) \cdot (\underset{\sim}{n}_2 \times \underset{\sim}{n}_{e^+})/(|\underset{\sim}{n}_1 \times \underset{\sim}{n}_{e^+}||\underset{\sim}{n}_2 \times \underset{\sim}{n}_{e^+}|) \qquad (13)$$

Here $\underset{\sim}{n}_1$, $\underset{\sim}{n}_2$, $\underset{\sim}{n}_{e^+}$ are unit vectors along the directions of particle 1, 2 and the e^+ beam.

We have acquired a total of 139 eμ events in the energy range $3.8 \leq E_{cm} \leq 7.8$ GeV. These events were obtained using the entire muon detection system of the magnetic detector, Fig. 1. Using the method of Refs. 1 and 3 we calculate the background in this sample to be 34.1 ± 8 events, a background contamination of 25%.

Using the special muon detection tower, Fig. 2, of the magnetic detector we can obtain a substantial reduction of background contamination at the expense of much lower statistics. (The tower has only 21% of the coverage of the entire muon detection system and requires muons to have about 900 MeV/c or greater momentum.) In previous publications[3,15] we reported 5 eμ events where the μ penetrated the tower. We now have a total of 12 such events with a background[3,5] of only 2.0 events! This provides very strong additional evidence that the magnitude and nature of our anomalous eμ signal is correct.

4. OBSERVED PRODUCTION CROSS SECTION

Our first step in identifying the nature of the U particle is to determine its mass, M_U. We do this using the observed production cross section, Fig. 3, and the angular distributions discussed in the next section.

The observed eμ production cross section, $\sigma_{e\mu,\ observed}$, based on the 139 eve and corrected for background is shown in Fig. 3. The curves are theoretical U pair production cross sections corrected for geometric acceptance, momentum cuts, and angular cuts; and normalized to fit the observed production cross sections.

The object of these curves is to show that the $\sigma_{e\mu,observed}$ threshold is not strongly dependent on the hypothesis as to the nature of the U. The solid and dash-dot curves are for the U a heavy lepton of mass 1.8 and 1.6 GeV/c^2 respective with zero mass, M_{ν_U}, for the associated neutrino ν_U. The coupling between the U and its neutrino is V-A, and the production cross section of Eq. 7 was used. These curves are changed very little if the coupling is V+A of if M_{ν_U} is of the order of 0.5 GeV/c^2. The dashed curve in Fig. 3 is for the U a meson of mass 1.8 GeV/c^2 with the 2-body decay modes of Eq. 9 and the production cross section of Eq. 10a and 10c. Note that a form factor varying as 1/s is used here. Although it is not a part of the main line of argument being presented here; we remark that $\sigma_{e\mu,\text{observed}}$ cannot be fit by a hypothesis which requires a form factor as strong as 1/s. Point particle production or weakly energy dependent form factors are required. This is shown by the dotted curve for a boson of mass 1.8 GeV/c^2, 2-body decay, and point particle pair production, Eqs. 10a and 10b.

Returning to our main argument the upper limit on M_U is set by the following table.

	Number $e\mu$ events	Calculated Background
$E_{cm} < 4.0$ GeV	10	3.8
$E_{cm} < 4.2$ GeV	14	4.6

With respect to a lower limit on M_U we see in Fig. 3 that there are <u>no</u> $e\mu$ events <u>before</u> background subtraction in the $3.0 \leq E_{cm} \leq 3.6$ GeV region. Unfortunately we have low total luminosity in this region and the 90% confidence upper limit on $\sigma_{e\mu,\text{observed}}$ is 6 nb, as indicated by the cross hatched line in Fig. 3. These considerations, and studies of the angular distribution in the next section, lead us to set the U mass in the region

$$1.6 \leq M_U \leq 2.0 \text{ GeV}/c^2 \tag{14}$$

For the remainder of this paper we use $M_U = 1.8$ GeV/c^2. In some previous publications[1-3,16] I used $M_U = 1.9$ GeV/c^2 when discussing the charmed meson hypothesis in an effort to make the U compatable with the theoretical charmed meson requirement: $M_U > M_{\psi'}/2 = 1.84$ GeV/c^2. However an increase in the meson mass makes fits to the angular and momentum distributions worse.

5. ANGULAR DISTRIBUTION

We define the collinearity angle by

$$\cos \theta_{coll} = -\mathbf{p}_e \cdot \mathbf{p}_\mu / (|\mathbf{p}_e| |\mathbf{p}_\mu|) \tag{15}$$

When the e and μ are moving in exactly opposite directions $\theta_{coll} = 0$. $\mathbf{p}_e$ and $\mathbf{p}_\mu$ are the vector three-momenta of the e and the μ respectively. The distribution in $\cos \theta_{coll}$, Fig. 4, shows us four things about the eμ events.

a) The number of events with $\theta_{coll} > 90^\circ$ is a sensitive measure of M_U when $E_{cm} \leq 4.8$ GeV, as shown in Table I. This information was used to determine the limits on M_U, in Eq. 14.

b) The $\cos \theta_{coll}$ distribution corrected for background in Fig. 4 shows that the angular data is compatible with U particle pair production.

c) For <u>fixed</u> M_U, a 3-body decay such as Eqs. 4 or 11 is favored compared to the 2-body decay of Eq. 9. This is shown in Fig. 4 using the heavy lepton to illustrate the 3-body decay; however the 3-body semi-leptonic decay of Eq. 11 will look very similar to the heavy lepton decay. As shown in Table I, the 2-body decay requires a lower M_U.

d) We can fit the data in all the E_{cm} ranges using a single hypotheses, that is, with a single mechanism.

6. MOMENTUM DISTRIBUTION

We have so far fixed limits on the mass of the U; and we have shown that $\sigma_{e\mu,observed}$ and the $\cos \theta_{coll}$ distribution can be fit by the hypotheses of Sec. 2. (We have some restrictions on this hypothesis; for example, strongly energy dependent form factors are forbidden.) Our next step is to eliminate the 2-body hypothesis of Eq. 9 using the momentum distributions of the e and μ.

The momentum distributions of the e and μ provide the strongest evidence that the U decays into 3-bodies, if the eμ events are produced by a single mechanism. This is because the decay of a fast moving heavy object into <u>two</u>

lighter objects produces a flat momentum, Fig. 5a. However, a decay into three objects produces the spectrum of Fig. 5b, whether it be V-A, V+A, or phase space. Furthermore, our 0.65 GeV/c lower limit on the e and μ momentum cuts off the lower momentum part of the spectra. Hence, we only need to compare a flat spectrum with a sloping spectrum. This is done for the 139 events in Figs. 6 and 7. To combine the data from different E_{cm} runs we use the parameter.

$$\rho = \frac{p - 0.65}{p_{max} - 0.65} \quad , \quad p \text{ in GeV/c} \quad ; \qquad (16)$$

where p_{max} is calculated for $M_U = 1.8$ GeV. Each event thus appears twice. Figure 6 and 7 are corrected for background.

The solid and dashed curves in Fig. 6 and 7 are the predicted distribution for the 3-body and 2-body decay modes of the U respectively (Eqs. 4 and 9). All spin-spin correlations are ignored in these calculations, since they have minor effects on the ρ distributions. We see that the 2-body mode predicts too many large ρ, that is large p, points in the low E_{cm} and high E_{cm} regions. Only at 4.8 GeV are the 2-body and 3-body hypotheses equally applicable. The χ^2 values are:

E_{cm} range (GeV)	Degrees of Freedom	3-body, Eq. 4 $M_U = 1.8$ GeV/c^2 $M_{\nu_U} = 0.0$ V-A	2-body, Eq. 9 $M_U = 1.8$ GeV/c^2
$3.8 \le E_{cm} < 4.8$	4	2.2	28.3
4.8	4	9.5	10.5
$4.8 < E_{cm} \le 7.8$	9	8.6	98.0

Therefore, we have eliminated hypothesis 2C, the 2-body purely leptonic decay of a heavy meson, and we are left with the 3-body decay hypotheses.

The ρ distributions cannot discriminate between the 3-body decay hypothesis, for example between Eq. 4 and Eq. 11, because relative to our statistics, changes of the coupling to V+A or to phase space have little effect on the basic sloping ρ distribution. This is shown in Fig. 8. However, we can eliminate the hypothesi that the 3-body decay includes a neutral particle with a mass as large as 1 GeV/c^2. As shown in Fig. 8, such a neutral particle drastically reduces the upper limit on

Hence we eliminate hypothese 2E - the new baryon; and we are left with hypothesis 2A or 2B - some variety of heavy lepton - or 2D - a semi-leptonic decay of a heavy meson with a K_L^o as one of the neutral particles.

7. MISSING ENERGY IN eμ EVENTS

We now come to the question of what undetected particles carry off the missing energy in the eμ events. We first consider whether the undetected particles can be K_L^o mesons. We then consider the very general case of whether these are undetected π^o mesons or undetected charged mesons.

Hypotheses 2D assumes the U to have the decay modes.

$$U^- \to e^- + \bar{\nu}_e + K_L^o \tag{17a}$$
$$U^- \to \mu^- + \bar{\nu}_\mu + K_L^o$$

Then the U must also have the decay modes

$$U^- \to e^- + \bar{\nu}_e + K_S^o \tag{17b}$$
$$U^- \to \mu^- + \bar{\nu}_\mu + K_S^o$$

unless the U is a very queer object. A study has been made by G. Feldman[17] of the possibility of the occurence of the decays in Eq. 17a by looking for

$$e^+ + e^- \to e^\pm + \mu^\mp + \underbrace{K_S^o}_{\hookrightarrow \pi^+ + \pi^-} + \text{missing energy} \tag{17c}$$

In a data sample in which 49 of the standard eμ events

$$e^+ + e^- \to e^\pm + \mu^\mp + \text{missing energy}$$

we found, Feldman found no events of the form of Eq. 17c. He also found no $e^+e^-K_S^o$ or $\mu^+\mu^-K_S^o$ events. This leads to the following limit with 90% confidence:

$$\left.\begin{array}{l}\text{fraction of observed e}\mu\text{ events meeting}\\ \text{the criteria a thru f of Sec. 3 and}\\ \text{containing a }K^o\end{array}\right\} < 0.09 \tag{18}$$

Hence hypothesis 2D is eliminated and our data is only compatible with hypotheses

2A or 2B, that is, with the hypothesis that the U is some sort of heavy lepton.

Before considering further the heavy lepton hypothesis we examine again the possibility that the missing energy is carried off by π^o mesons or undetected charged mesons. The $e\mu$ event selection criteria in Sec. 3 are designed to eliminate these possibilities; but perhaps these are a very large number of $e\mu$ events associated with π^o's or charged hadrons; and our $e\mu$ events are just the "tip of the iceberg". By looking directly at the raw data, Table II, we can show that this is not true.

Table II shows the total number of events, before background subtraction which contain:

a) at least one e and one μ of opposite electron charge,

b) $p_e \geqslant 0.65$ GeV/c and $p_\mu \geqslant 0.65$ GeV/c,

c) $\theta_{copl} > 20^o$ for the 2-prong events,

d) there is no θ_{copl} condition on the multiprong events.

These events are classified according to total prong multiplicity and whether there are zero or greater than zero associated photons. The 110 2-prong, no photon events correspond to the 139 used in the body of this paper; this table has a smaller sample because data from the first year's running is not used in the table.

Two estimates of the number of events we expect from misidentifications of hadronic events are included in Table II. The first is a minimal 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 a maximal estimate obtained from three or more prong events in the data set from which the table is constructed. (This is the method used to give the 34 ± 8 background calculation for the total sample of 139 2-prong, no-photon events used in this paper; Sec. 3.) Misidentification probabilities can increase with c.m. energy. For example, if a photon and charged particle enter the same shower counter there is an increased probability that the charged particle will be labeled an electron. As the c.m. energy increases, the average number of photons per event increases, and as a result, the electron misidentification increases somewhat. Thus, the true numbers of events caused by hadron misidentifications is probably somewhere between the two limits given in Table II.

At the present stage of analysis, Table II neither argues for or against anomalous di-lepton production in topologies other than 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 excess of events from reaction (1) as events in which additional charged particles or photons are produced, but escape detection.

For example suppose that the U particle is neutral

$$e^+ + e^- \to U^o + \bar{U}^o \; ; \tag{19a}$$

with the decay modes

$$\begin{aligned} U^o &\to e^- + \bar{\nu}_e + \text{hadron}^+ \; ; \\ U^o &\to \mu^- + \bar{\nu}_\mu + \text{hadron}^+ \; ; \end{aligned} \tag{19b}$$

and that the observed $e\mu$ events are due to the loss of both charged hadrons thru the ends of the detector. The detector covers 0.70 of 4π solid angle, hence the probability of not detecting a charged hadron which is randomly distributed in production angle is 0.3. The charged hadrons produced in reaction (19) will have no strongly preferred direction, hence the probability of missing both of them is $(0.3)^2 = 0.09$. Then the roughly 80 2-prong, no-photon $e\mu$ events in Table II must come from a total sample of about 800 multiprong, no-photon $e\mu$ events. But even <u>before</u> background subtraction there are only about 250 multiprong, no-photon $e\mu$ events in Table II. Therefore reaction 19 cannot be a major source of our observed 2-prong, no-photon events.

Similar arguments can be made for any combination of undetected charged and neutral hadrons such as

$$U^- \to e^- + \bar{\nu}_e + 2 \text{ charged hadrons} \tag{20a}$$

$$U^- \to \mu^- + \bar{\nu}_\mu + 2 \text{ charged hadrons} \tag{20b}$$

In particular we can eliminate the π^o decay mode

$$U^- \to e^- + \bar{\nu}_e + \pi^o \tag{21a}$$

$$U^- \to e^- + \bar{\nu}_\mu + \pi^o \tag{21b}$$

With 90% confidence

$$\left.\begin{array}{l}\text{fraction of observed } e\mu \text{ events meeting} \\ \text{the criteria a thru f of Sec. 3 and} \\ \text{containing one or more } \pi^o\text{'s}\end{array}\right\} < 0.18 \tag{22}$$

using the minimum background estimate in Table II. (The limit is 0.09 for the maximum background estimate.) Summarizing this section we conclude that in most of our observed $e\mu$ events the missing energy is carried off exclusively by neutrinos -- a result which combined with our previous arguments leads us to the heavy lepton hypothesis.

Before considering further the heavy lepton hypothesis we make a remark related to the $e\mu$ events concerning the existence of events such as

$$e^+ + e^- \rightarrow e^{\pm} + \mu^{\mp} + \text{undetected hadrons} \tag{23}$$

Our studies do not exclude such events. In our studies these events are treated as background to yield a conservative calculation of the background in our $e\mu$ events, Table II. Indeed a several hundred picobarn real signal could exist. Therefore, the statement in the previous section that our observed $e\mu$ events do not contain hadrons, does not exclude the reactions such as Eq. 23, it simply means that our observed $e\mu$ events are not related to Eq. 23.

8. COMPATIBILITY OF HEAVY LEPTON HYPOTHESIS WITH DATA

Next we test the heavy lepton hypothesis against all the data we have on the $e\mu$ events and related processes.

A. General compatability: First, a heavy lepton of mass 1.6 to 2.0 GeV/c^2 clearly fits all the properties presented in Figs. 3, 4, 6, 7 and 8. Next the normalization of Eq. 7 to the data in Fig. 3 yields the following leptonic branching ratios, assuming equal decay rates to the e and μ modes, V-A coupling and M_U = 1.8 GeV/c^2:

$$\frac{(U^- \rightarrow \nu_U e^- \bar{\nu}_e}{(U^- \rightarrow \text{all})} = \frac{(U^- \rightarrow \nu_U \mu^- \bar{\nu}_\mu}{(U^- \rightarrow \text{all})} = 0.17 \begin{array}{l} + 0.06 \\ - 0.03 \end{array} \tag{24}$$

the uncertainty includes both statistical and systematic errors. Such a value for the leptonic decay mode branching ratio of a heavy lepton is theoretically reasonable.[5-7] A similar result has been deduced by Snow[23,24] from the data of Cavalli-Sforza et al.[23]

B. Anomalous e^+e^- and $\mu^+\mu^-$ Events: If the U is a heavy lepton we should see anomalous events of the form

$$e^+ + e^- \rightarrow e^+ + e^- + \text{missing energy}$$

$$e^+ + e^- \rightarrow \mu^+ + \mu^- + \text{missing energy}$$

analogous to those in reaction (1). Such events have been found.[19] Determining the precise number of such events is much more difficult than for the standard $e\mu$ events because of the quantum electrodynamic background processes.

$$e^+ + e^- \rightarrow e^+ + e^- + \gamma \quad , \quad e^+ + e^- \rightarrow \mu^+ + \mu^- + \gamma \tag{25a}$$

$$e^+ + e^- \rightarrow e^+ + e^- + \gamma + \gamma \quad , \quad e^+ + e^- \rightarrow \mu^+ + \mu^- + \gamma + \gamma \tag{25b}$$

$$e^+ + e^- \rightarrow e^+ + e^- + \mu^+ + \mu^- \tag{25c}$$

These cross sections are relatively large and lead to backgrounds when the photons or the additional leptons escape the detector. The one-photon processes are removed using missing mass cuts; the two-photon processes and the four lepton process[20] are removed by calculating their theoretical contribution and subtracting them from the data. This leads to large statistical errors. We have obtained the ratios[19]

$$\frac{\sigma_{ee}}{\sigma_{e\mu}} = .39 \pm .21 \ , \ \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = .66 \pm .16 \ , \ \frac{\sigma_{ee}}{\sigma_{\mu\mu}} = .59 \pm .33 \tag{26}$$

These ratios are compatible with what we expect for a sequential heavy lepton, namely 0.5, 0.5, and 1.0 respectively. We further note that the third ratio eliminates the possibility that the U could be an electron-related heavy lepton with V-A coupling.[21] Such a heavy lepton would have the ratio[21] $\sigma_{ee}/\sigma_{\mu\mu} = 4.0$ if there is complete momentum and angle acceptance. For our momentum cuts this ratio should be[22] 2.8.

9. CONCLUSION

We conclude that of the hypotheses considered in this paper, the only one compatible with all our data is that U particle is a heavy lepton;[25] either of the sequential type, or if it is electron-related, it does not have V-A coupling. The mass lies in the range 1.6 to 2.0 GeV/c^2.

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25. The term U particle was used as a temporary name for the particles yielding the anomalous eμ events, Ref. 3. If the conclusions of this paper are accepted a more descriptive name is needed. We would like to reserve ℓ for the general class of leptons, even though the conclusions of this paper would strictly speaking destroy the meaning of the term lepton. If the conclusion that the U particle has leptonic nature remains valid we suggest the use of a lower case tau, τ, for the particle designation; following the μ and ν we would like to use lower case Greek letters, and the τ could be the third charged lepton to be found. We feel there will be no confusion with the τ decay mode of the K meson.

TABLE I

Comparison of the number of $\theta_{coll} > 90^{o}$ eμ events (penultimate row) with various U mass and U decay hypotheses for three E_{cm} regions. (Note that the last row gives the total number of eμ events for use in statistical tests.) The data is corrected for background contamination.

Decay Hypothesis	M_U (GeV/c^2)	Expected number of $\theta_{coll} > 90^{o}$ events		
		$3.8 \leq E_{cm} < 4.8$ GeV	$E_{cm} = 4.8$ GeV	$4.8 < E_{cm} \leq 7.8$ GeV
3-body V-A $M_{\nu_U} = 0.0$ Eq. 4	1.6	1.6	0.6	0.2
	1.8	4.5	1.9	1.3
	1.9	6.0	2.9	2.3
	2.0		4.4	3.4
	2.2		7.9	6.9
2-body Eq. 9	1.6	3.3	1.6	1.0
	1.8	7.0	3.7	3.1
	1.9	8.8	5.1	4.9
	2.0		6.9	6.8
	2.2		9.6	14.5
Data: eμ events with $\theta_{coll} > 90^{o}$		6.2	0.0	1.1
Data: total number of eμ events		19.0	18.9	67.0

TABLE II

The upper numbers in each box are the number of events containing at least one e and one μ of opposite electric charge. The numbers in parenthesis are the background calculations as discussed in the text.

Number of Charged Prongs	Number Photons	
	0	> 0
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)

FIGURE CAPTIONS

Fig. 1 The magnetic detector without the muon detection tower.

Fig. 2 Cross section of magnetic detector showing the muon detection tower on the top of the detector.

Fig. 3 The observed eμ production cross section, $\sigma_{e\mu,\mathrm{observed}}$, corrected for background. The curves are theoretical U particle pair production cross sections corrected for geometric acceptance, momentum cuts, and angular cuts; and normalized to fit $\sigma_{e\mu,\mathrm{observed}}$. The solid and dash-dot curves are for a heavy lepton, Eq. 4, of mass 1.8 and 1.6 GeV/c^2 respectively with $M_{\nu_U} = 0.0$; with V-A coupling; and with the point Dirac production cross section of Eq. 7. $\sigma_{e\mu,\mathrm{observed}}$ for a boson or meson of mass 1.8 GeV/c^2 with the 2-body decay of Eq. 9 is given by the dotted curve for point particles, Eq. 10b, and by the dashed curves for a production form factor varying as $1/s$, Eq. 10c. All spin-spin correlations and polarization effects are ignored.

Fig. 4 The $\cos\theta_{\mathrm{coll}}$ distribution in three E_{cm} intervals. The solid curves are for the 3-body decay of the U taken as a heavy lepton, Eq. 4, with M_U = 1.8 GeV/c^2, $M_{\nu_U} = 0.0$, and V-A. The dashed curves are for the 2-body decay of the U taken as a meson, Eq. 9, with M_U = 1.8 GeV/c^2 assuming isotropic decay of the U in its rest frame. The data is corrected for background.

Fig. 5 The momentum spectrum from (a) a 2-body decay and (b) a 3-body decay.

Fig. 6 The distribution in $\rho = (p - 0.65)/(p_{max} - 0.65)$, p in GeV/c for all E_{cm} corrected for background. The solid curve is for the 3-body decay of the U taken as a heavy lepton, Eq. 4, with M_U = 1.8 GeV/c^2, M_{ν_U} = 0.0 and V-A. The dashed curve is for the 2-body decay of the U taken as a boson, Eq. 9, with M_U = 1.8 GeV/c^2, assuming isotropic decay of the U in its rest frame. All spin-spin correlations and polarization effects are ignored.

Fig. 7 The ρ distribution in three different E_{cm} intervals corrected for background. For the meaning of the curves see the caption of Fig. 6.

Fig. 8 Comparison of ρ distributions with: curves marked V-A are heavy lepton with M_U = 1.8 GeV/c^2, and M_{ν_U} as indicated by the numbers attached to the curves in GeV/c^2; dotted curve, V+A heavy lepton, M_U = 1.8 GeV/c^2, and M_{ν_U} = 0.0.

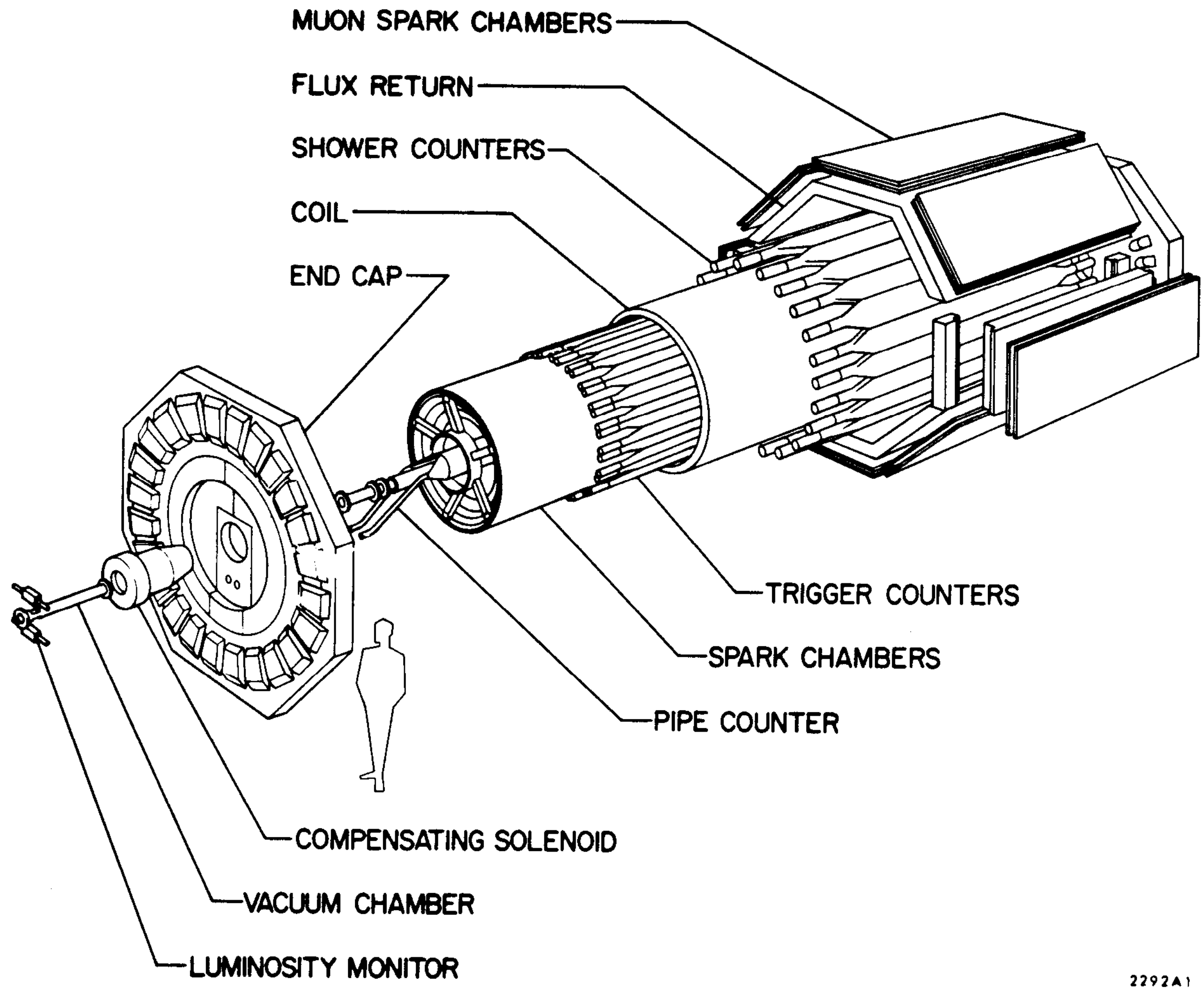
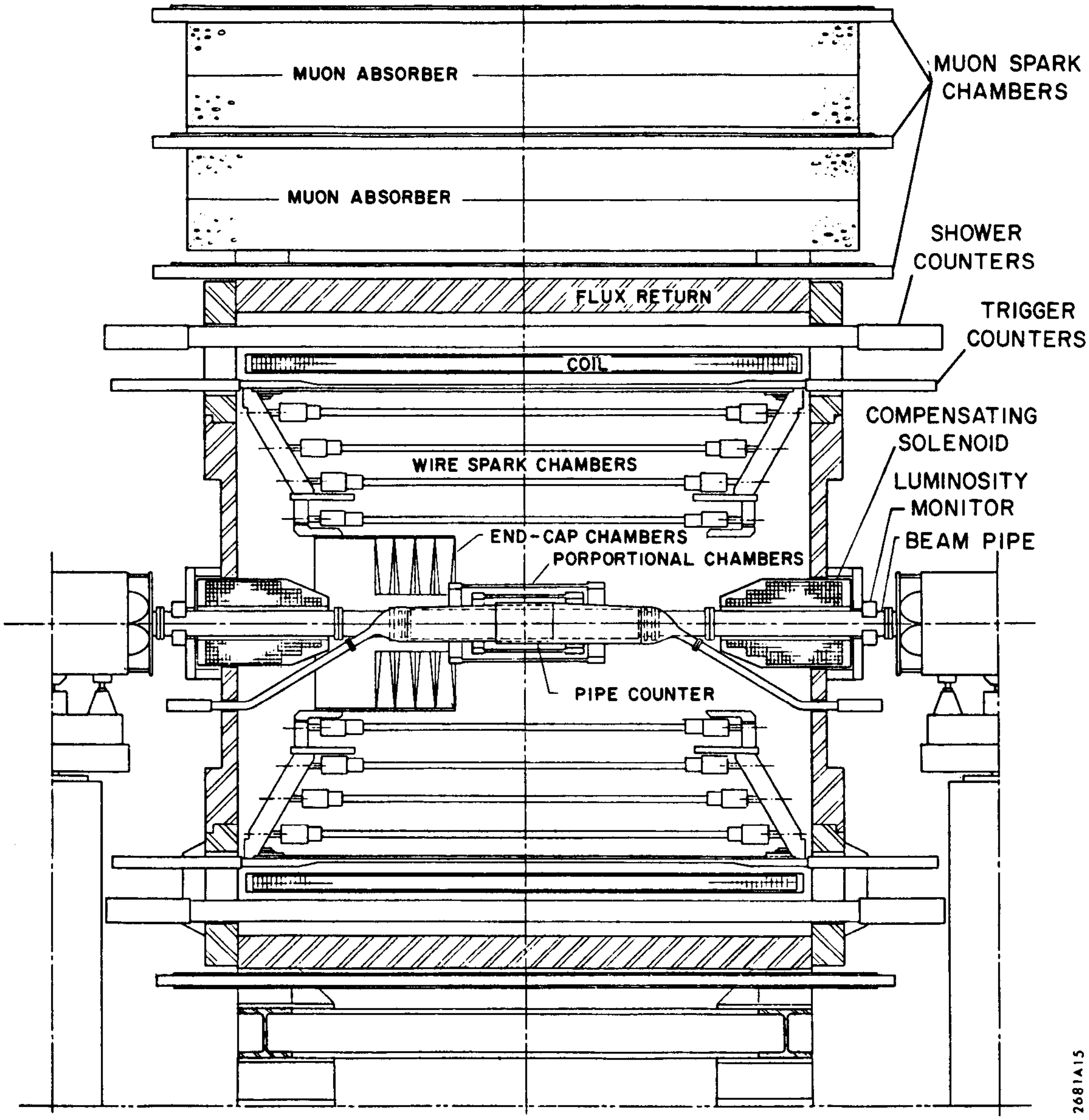
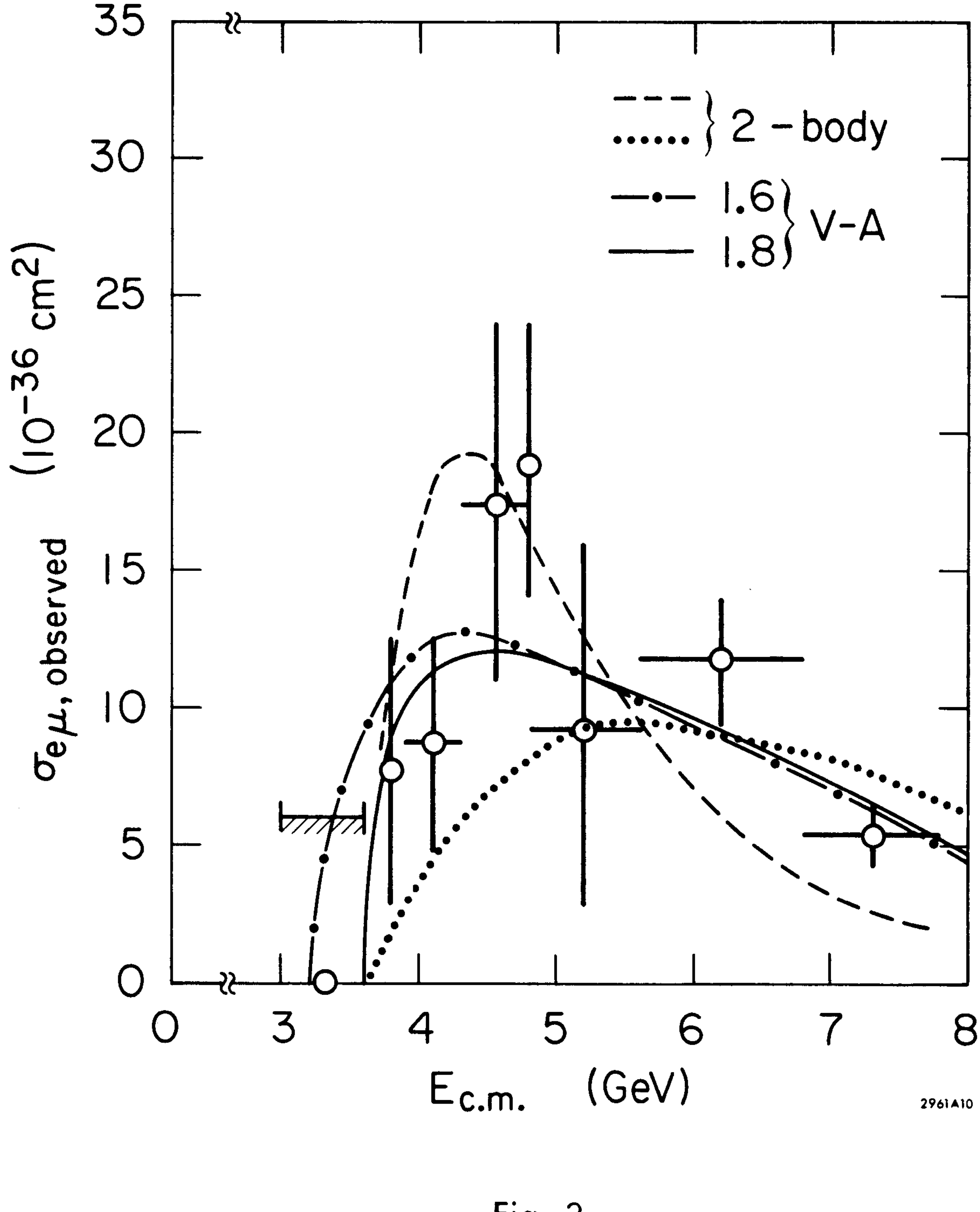

MUON SPARK CHAMBERS
FLUX RETURN
SHOWER COUNTERS
COIL
END CAP
TRIGGER COUNTERS
SPARK CHAMBERS
PIPE COUNTER
COMPENSATING SOLENOID
VACUUM CHAMBER
LUMINOSITY MONITOR
2292A1

Fig. 1



MUON ABSORBER
MUON ABSORBER
MUON SPARK CHAMBERS
SHOWER COUNTERS
FLUX RETURN
TRIGGER COUNTERS
COIL
COMPENSATING SOLENOID
WIRE SPARK CHAMBERS
LUMINOSITY MONITOR
END-CAP CHAMBERS
BEAM PIPE
PORPORTIONAL CHAMBERS
PIPE COUNTER
2681A15

Fig. 2



2 - body
1.6
1.8
V-A
$\sigma_{e\mu}$, observed $(10^{-36}\ cm^2)$
$E_{c.m.}$ (GeV)
0
5
10
15
20
25
30
35
0
3
4
5
6
7
8
2961A10

Fig. 3

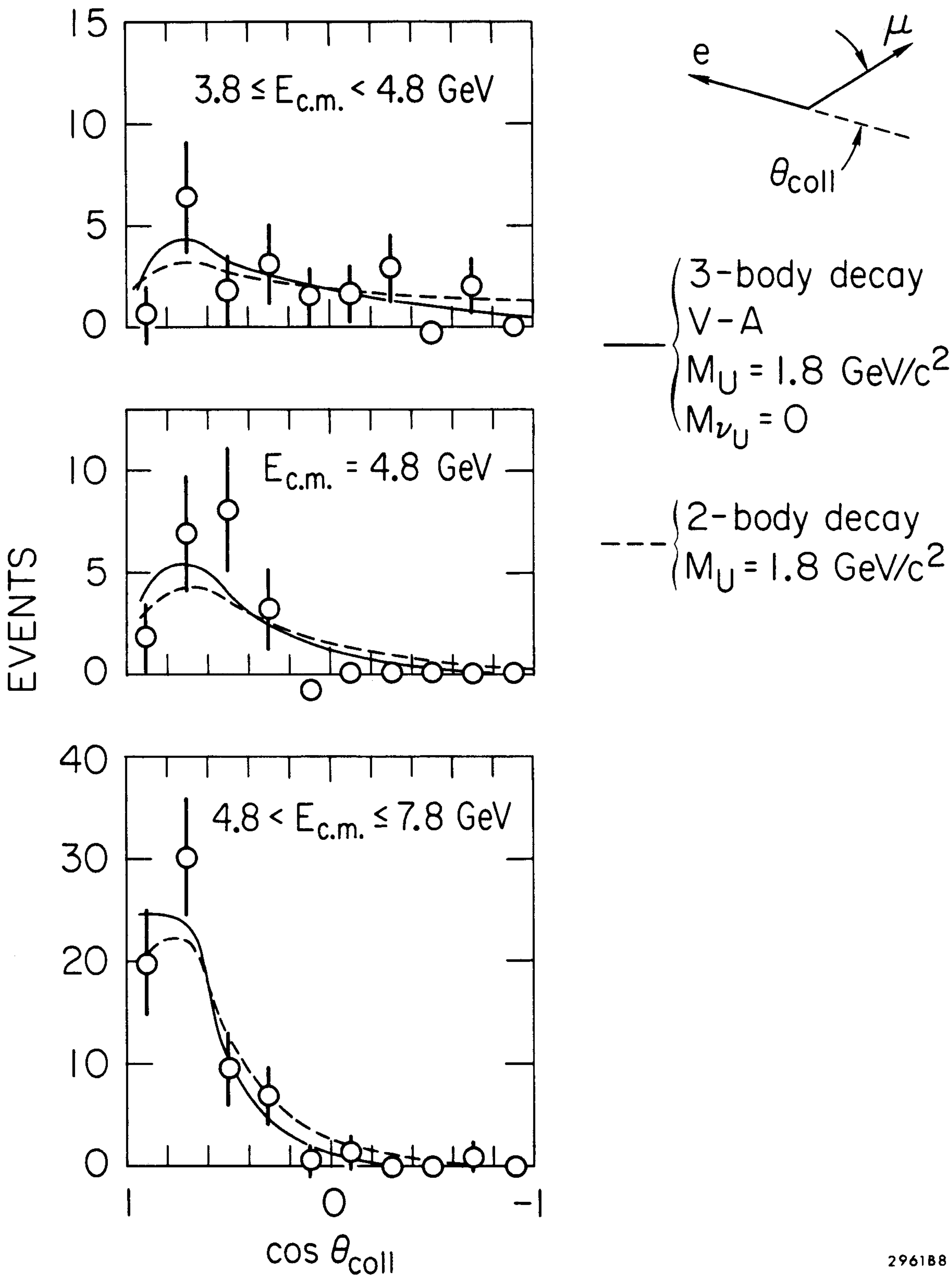

3.8 ≤ E$_{c.m.}$ < 4.8 GeV
E$_{c.m.}$ = 4.8 GeV
4.8 < E$_{c.m.}$ ≤ 7.8 GeV
EVENTS
cos θ_{coll}
e
μ
θ_{coll}
3-body decay
V-A
M_U = 1.8 GeV/c^2
M_{ν_U} = 0
2-body decay
M_U = 1.8 GeV/c^2
296188

Fig. 4

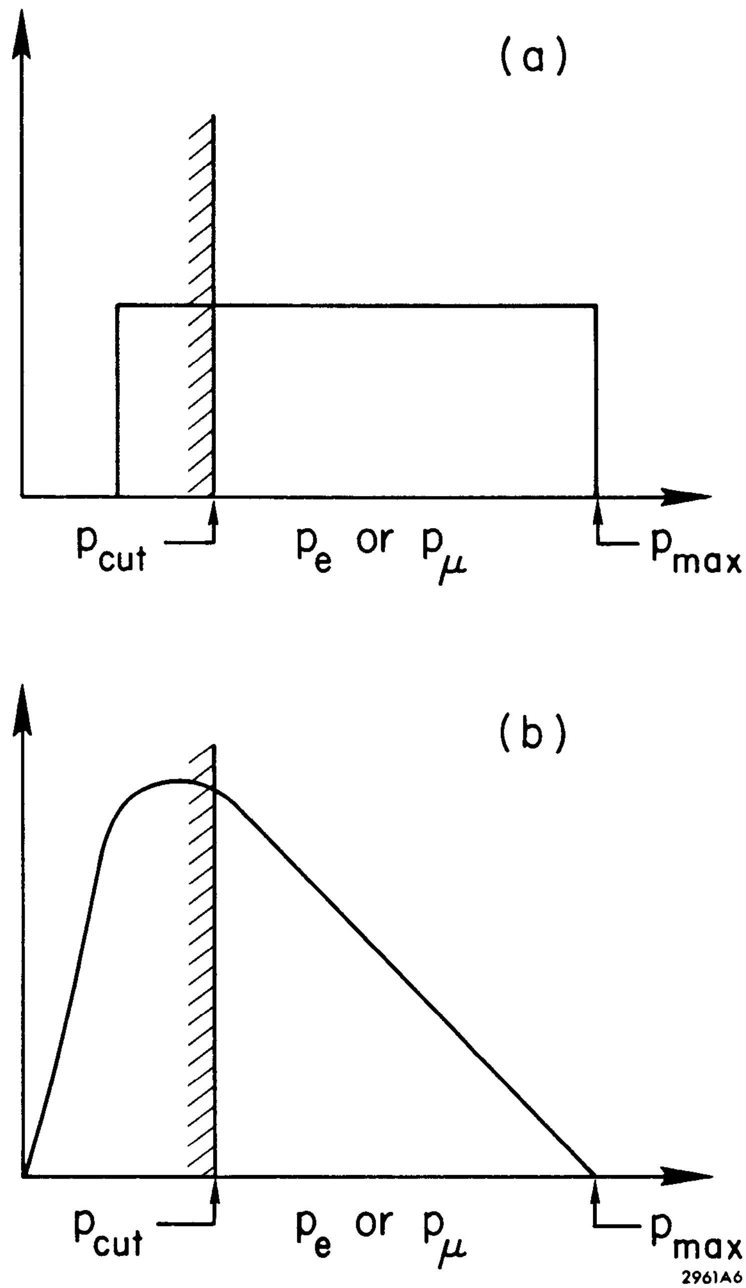


Fig. 5

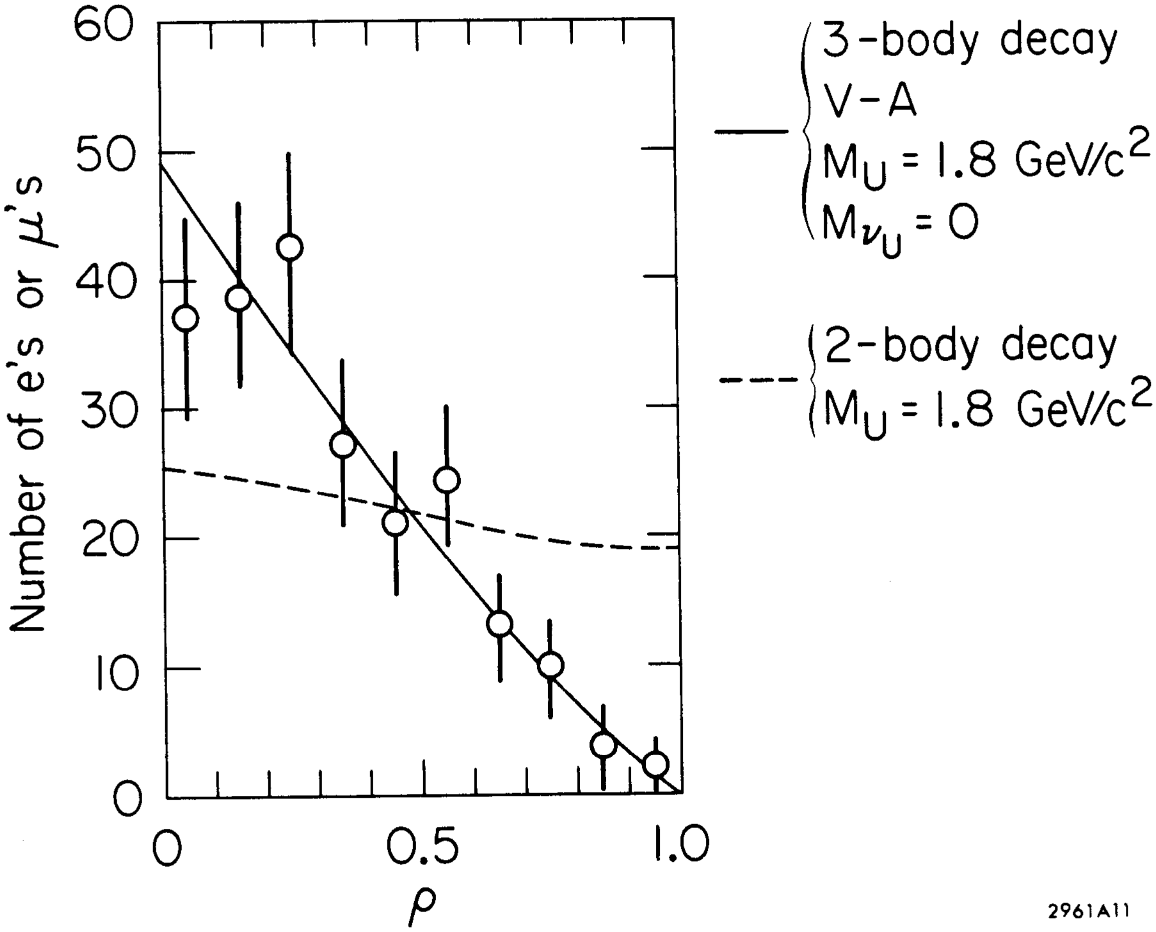
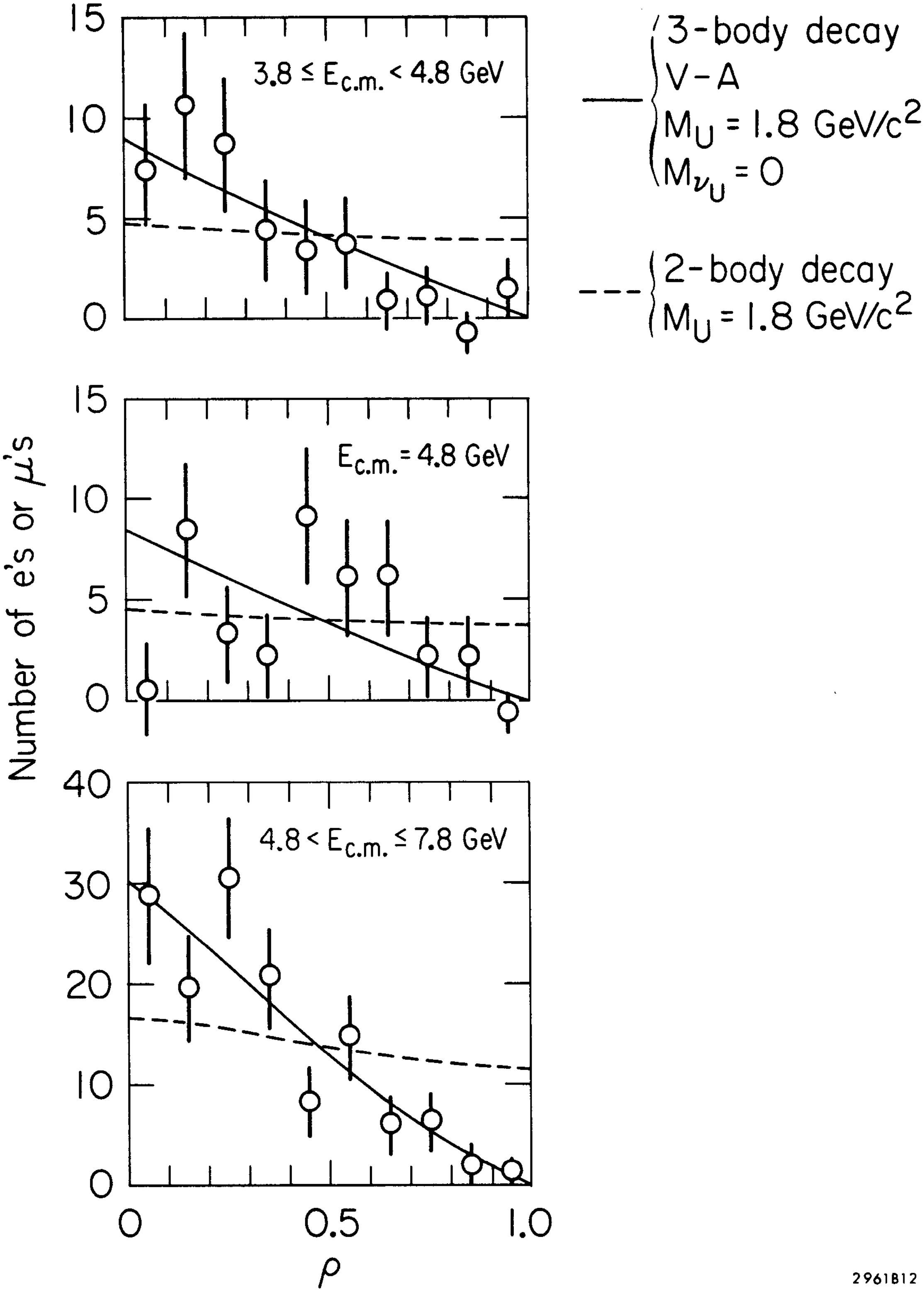
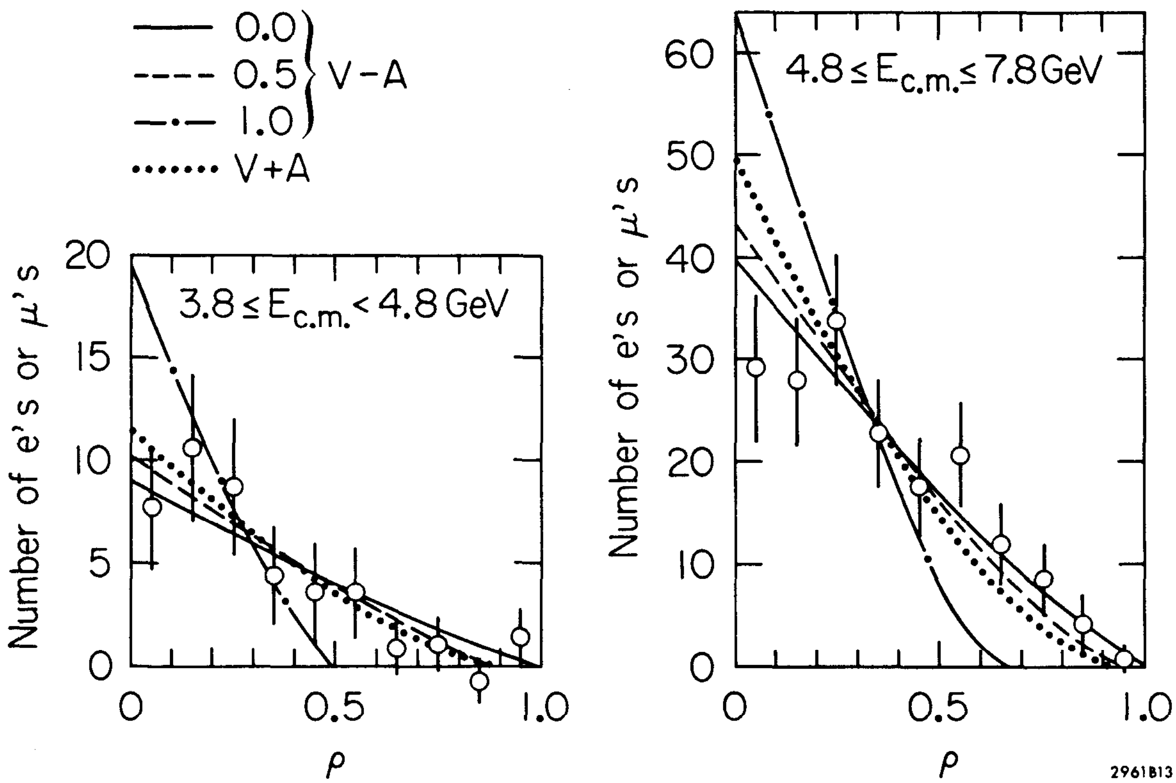

60
50
40
30
20
10
0
Number of e's or μ's
0
0.5
1.0
ρ
3-body decay
V-A
M_U = 1.8 GeV/c^2
M_{ν_U} = 0
2-body decay
M_U = 1.8 GeV/c^2
2961A11

Fig. 6



3-body decay
V−A
M_U = 1.8 GeV/c²
M_νU = 0
2-body decay
M_U = 1.8 GeV/c²
3.8 ≤ E_c.m. < 4.8 GeV
E_c.m. = 4.8 GeV
4.8 < E_c.m. ≤ 7.8 GeV
Number of e's or μ's
ρ
2961B12

Fig. 7



0.0
0.5
1.0
V−A
V+A
Number of e's or μ's
3.8 ≤ E c.m. < 4.8 GeV
4.8 ≤ E c.m. ≤ 7.8 GeV
ρ
2961B13

Fig. 8