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Threshold and Other Properties of U Particle Production in e^+e^- Annihilation[†*]

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1. INTRODUCTION

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

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

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

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

In this paper I will present (a) new data on the U particles in the energy region just above their production threshold and (b) results of a study of the nature of the particles carrying off the missing energy in Eq. (1). While presenting these new results I will briefly review the present status of our knowledge of the anomalous $e\mu$ events and their U particle explanation. 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. MOTIVATION

The motivation for the work that led to the discovery of the $e\mu$ events was a search for heavy leptons[5,6] with unique leptonic quantum numbers. We

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visualize the sequence

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

The ℓ, called a <u>sequential</u> 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

$$\left.\begin{array}{l} \ell^- \to \nu_\ell + e^- + \bar{\nu}_e \\ \ell^- \to \nu_\ell + \mu^- + \bar{\nu}_\mu \end{array}\right\} \text{3-body decays} \qquad \begin{array}{r} (4a) \\ (4b) \end{array}$$

b) semi-leptonic

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

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

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

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

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

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

$$\begin{array}{lll} e^+ + e^- \rightarrow \ell^+ & + & \ell^- \\ \qquad\qquad \llcorner\!\!\rightarrow \bar{\nu}_\ell \mu^+ \nu_\mu & & \llcorner\!\!\rightarrow \nu_\ell e^- \bar{\nu}_e \end{array} \tag{6}$$

However, the identification of the sequential heavy lepton is complicated by the possibility that Eq. (1) may result from the pair production and decay of a new type of meson M; the charm theory providing the most popular examples.[8,9] Purely leptonic decays would have the form

$$\left.\begin{array}{l} M^- \rightarrow e^- + \bar{\nu}_e \\ M^- \rightarrow \mu^- + \bar{\nu}_\mu \end{array}\right\} \text{2-body decays} \tag{7}$$

Semileptonic decays in which no charged particles other than the e or μ occur would have the form

$$\left.\begin{array}{l} M^- \rightarrow e^- + \bar{\nu}_e + K^0_L \\ M^- \rightarrow \mu^- + \bar{\nu}_\mu + K^0_L \end{array}\right\} \text{3-body decays} \tag{8}$$

(K^0_S mesons would decay in the detector) or

$$\left.\begin{array}{l} M^- \rightarrow e^- + \bar{\nu}_e + \pi^0 \\ M^- \rightarrow \mu^- + \bar{\nu}_\mu + \pi^0 \end{array}\right\} \text{3-body decays} \tag{9}$$

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). Unfortunately, I do not have the time in this talk to discuss the interesting theories of Patti and Salam[10] or of Feinberg and Lee.[11]

3. REVIEW OF EVENT SELECTION, BACKGROUNDS AND OBSERVED PRODUCTION CROSS SECTION

The selection of the eμ events, the background subtraction and the observed production cross section has been fully discussed in Refs. 1,3,12.

Events from the SLAC-LBL magnetic detector[4] 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 is greater than 20°.

In Refs. 1 and 3, 86 $e\mu$ events were used. In these 86 events we calculated a background of 22 ± 5 events or 30 ± 6 events depending upon the method of background calculation. Since then we have continued to acquire $e\mu$ events and now have over 100. The new events in the threshold region $3.8 \leq E_{cm} < 4.8$ GeV will be discussed in the next, and later, sections of this talk.

The observed production cross section based on the 86 events is shown in Fig. 1. The curves are theoretical U pair production cross sections corrected for geometric acceptance, momentum and angular cuts, triggering and tracking efficiency, so as to yield the observed production cross sections. The solid curves are for the U a heavy lepton of mass $M_U = 1.8$ GeV/c^2; this mass is a good fit to the data. The mass of the associated neutrino is $M_{\nu_U} = 0.0$. The coupling between the U and its neutrino is V-A or V+A. The lepton production cross section is

$$\sigma_{ee \to UU} = \frac{43.4\beta(3 - \beta^2)}{s} \text{ nb} \quad , \quad U \equiv \text{heavy lepton } \ell \qquad (10)$$

Here $s = E_{cm}^2$ and $\beta = v_U/c$; v_U being velocity of the U. The dashed curve in Fig. 1 is for the U a meson of mass 1.9 GeV/c^2 with the 2-body decay modes of Eq. (7). The production cross section is not known a priori, I used the formula

$$\sigma_{ee \to UU} = \frac{\eta\beta^3}{s} |F_U(s)|^2 \; ; \quad U \equiv \text{meson M} \tag{11a}$$

Here η is a constant, $\beta = v_U/c$, β^3 is a guess at a threshold factor, and $F_U(s)$ is a production form factor:

$$F_U(s) = 4M_U^2/s \tag{11b}$$

The meson mass of 1.9 GeV/c^2 was used to make the meson production threshold above the ψ' (the ψ' mass is 3.68 GeV/c^2).

All the curves are acceptable fits to the data given the large errors. And regardless of which of these hypothesis one chooses the mass of the U is in the range

$$1.6 \leq M_U \leq 2.0 \text{ GeV}/c^2 \tag{12}$$

4. THRESHOLD BEHAVIOR OF $\sigma_{e\mu,\text{observed}}$

In Fig. 1 the three data points below 4.8 GeV were based on a total of 16 events. 10 new events have now been acquired in the $E_{cm} < 4.8$ GeV region giving a total of 26 events. The observed eμ production cross section, $\sigma_{e\mu,\text{ observed}}$, is shown in Fig. 2 for the 26 events as well as the old point at 4.8 GeV. No eμ events, before background subtraction, were found in the region $3.0 \leq E_{cm} \leq 3.6$ GeV. The cross hatched edge shows the 90% confidence upper limit, 6.0 nb, for that region. Figure 2 reinforces the conclusion about the U mass in Eq. (12). Indeed it makes a mass as low as 1.6 GeV improbable, and pushes the lower limit on the mass closer to 1.8 GeV. (The possibility of the mass being as low as 1.6 GeV is now being tested using the new events reported here and other new events.) Figure 2 also emphasizes that the production cross section rises smoothly above the threshold.

We can also use these 26 threshold events to see if their production is related to the structure[13] in the total hadronic production cross section $\sigma_{had}(s)$ in the region $3.9 \leq E_{cm} \leq 4.8$ GeV. This structure is shown in Fig. 3 using the R parameter[4]

$$R(s) = \frac{\sigma_{had}(s)}{\sigma_{ee \to \mu\mu}(s)} \tag{13}$$

Here

$$\sigma_{ee \to \mu\mu} = \frac{4\pi\alpha^2}{3s} = \frac{86.8}{s} \text{ nb} \tag{14}$$

where $s = E_{cm}^2$ is in GeV^2. We note the peak in the 4.05 to 4.15 GeV region and the resonance at 4.4 GeV. If these peaks are related to charm particle production and if the eμ events are charm particle decay products, we should see some clustering of the eμ events in the two peak regions. Figure 4 shows $\sigma_{e\mu,\ \text{observed}}$ spread over 10 bins in $3.75 \leq E_{cm} < 4.8$ GeV, as well as the old 4.8 GeV point. The statistics are poor; however, there is <u>no</u> clustering of eμ events in the 4.05 to 4.15 GeV region or at the 4.4 GeV resonance.

Figure 5 portrays this observation in another way. Following Harari's[14] ideas, I define the "new hadronic physics" in e^+e^- annihilation as causing R to rise above 2.5; quantitatively.

$$\sigma_{\text{new hadron physics}}(s) = (R(s) - 2.5)\sigma_{ee \to \mu\mu} \tag{15}$$

Figure 5 shows the ratio

$$r = \frac{\sigma_{e\mu,\ \text{observed}}}{\sigma_{\text{new hadron physics}}} \tag{16}$$

in arbitrary units. If the production of eμ events follows the "new hadron physics" production cross section, r should be a constant. It is not a constant, but is smaller in the 4.0 to 4.4 GeV region. This effect is not caused by the acceptance of the experiment. This acceptance, Fig. 6, takes account of the angular acceptance of the apparatus, the angular cut, and the momentum cut. As discussed in the next section the eμ events are best fit by taking the leptonic decay mode of the U to be into 3-bodies. Hence the lower set of curves in Fig. 6 apply.

To quantify my conclusion that eμ event production in the threshold region does not follow the "new hadron physics" I compare the hypothesis that eμ production follows the "new hadron physics" with the hypothesis that eμ production follows a smoothly rising production cross section. To be precise I use the hypothesis that the U is a V-A heavy lepton to represent a smoothly rising production cross section, although the use of V+A or 3-body phase space for the U makes little difference.

We obtain the following statistical conclusions for the eμ events in the region $3.75 \leq E_{cm} \leq 4.8$ GeV

$$\frac{\text{likelihood that e}\mu\text{ events are from V-A heavy lepton}}{\text{likelihood that e}\mu\text{ events are from "new hadron physics"}} = 130. \qquad (17)$$

χ^2 probability that eμ events are from V-A heavy lepton = 10%

χ^2 probability that eμ events are from "new hadron physics" = 1%

Admittedly, the statistics are poor; however, we have here one more argument against the eμ events being related directly or indirectly to charm particle production.

5. THRESHOLD BEHAVIOR OF ANGULAR DISTRIBUTION

We define the collinearity angle by

$$\cos\theta_{coll} = -\underset{\sim}{p}_e \cdot \underset{\sim}{p}_\mu / (|\underset{\sim}{p}_e||\underset{\sim}{p}_\mu|) \qquad (18)$$

When the e and μ are moving in exactly opposite directions $\theta_{coll} = 0$. $\underset{\sim}{p}_e$ and $\underset{\sim}{p}_\mu$ are the vector three-momenta of the e and the μ respectively. In Ref. 3 the $\cos\theta_{coll}$ distribution for the 86 events was thoroughly discussed.

The major point, Fig. 7, was that the small number of events with $\theta_{coll} > 90^\circ$ in the 4.8 GeV and $4.8 < E_{cm} \leq 7.8$ GeV regions argues against the 2-body decay mode of the U. As emphasized in Table VI of Ref. 3, only a U mass as low as 1.6 GeV/c^2 allows the 2-body decay to fit. But as discussed in the last section this low a U mass is becoming improbable.

A new study of the threshold region's cos θ_{coll} distribution, using the 26 events, is shown in Fig. 8. The 2-body decay of the U, Eq. (7), for a mass of 1.9 GeV/c^2 is in poor agreement with the data Lowering the U mass to 1.8 GeV/c^2 improves the fit, however this mass would prevent the interpretation of the U as a charmed particle of the conventional theory.[8,9] Table I presents a comparison of the data with various models for events with $\theta_{coll} > 90^\circ$.

TABLE I

Comparison of the number of $\theta_{coll} > 90^\circ$ eμ events (penultimate row) with various U masses and U decay hypotheses for $3.75 \leq E_{cm} < 4.8$ GeV, (Note that the last row gives the total number of eμ events for use in statistical tests.)

Decay Mode	Mass GeV/c^2	Number events with $\theta_{coll} > 90^\circ$
3-body, V-A, Eq. 4	1.8	6.6
2-body, Eq. 7	1.8	9.6
2-body, Eq. 7	1.9	12.2
Data: eμ events with $\theta_{coll} > 90^\circ$		7
Data: total number of eμ events		26

Finally, we note that the threshold region $\cos\theta_{coll}$ distribution does not provide by itself a strong argument against the 2-body decay of the U. Putting the data in Fig. 8 into 5 bins, to increase the events per bin and make a χ^2 test feasible, we find the following χ^2 values for 4 degrees of freedom.

DECAY MODE	χ^2
3-body, V-A, $M_U = 1.8$ GeV/c^2, $M_{\nu_U} = 0.06$, Eq. (4)	0.2
2-body, $M_U = 1.8$ GeV/c^2, Eq. (7)	2.0
2-body, $M_U = 1.9$ GeV/c^2, Eq. (7)	6.3

However, in the next section we shall see that the momentum distributions in the threshold region do provide a strong argument against the 2-body decay mode of the U.

6. THRESHOLD BEHAVIOR OF MOMENTUM DISTRIBUTION

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 heavy object into <u>two</u> very light objects produces a flat momentum spectrum, Fig. 9a. However, a decay into three very light objects produces the spectrum of Fig. 9b, 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 was done for the original 86 events in Ref. 3, reproduced in Figs. 10 and 11. To combine the data from different E_{cm} runs we use the parameter

$$\rho = \frac{p - 0.65}{p_{max} - 0.65} \quad , \quad p \text{ in GeV/c} \quad ; \tag{19}$$

where p_{max} is calculated for $M_U = 1.8$ GeV (the use of $M_U = 1.9$ makes very little difference) and p is $|p_e|$ or $|p_U|$. Each event thus appears twice. Figures 10 and 11 are corrected for background.

The solid and dotted curves in Figs. 10 and 11 are the predicted distributions for the 3-body and 2-body decay modes of the U respectively (Eqs. (4) and (7)). All spin-spin correlations are ignored in these calculations. The bump at the high ρ end of the dotted curves occurs because of the events at $E_{cm} = 3.8$ GeV -- the threshold for $M_U = 1.9$ particles. Incidently, if we distort the predicted 2-body decay mode θ_{coll} distribution to fit the θ_{coll} distribution data, we obtain the dashed curves in Figs. 10 and 11. Thus we see that the 2-body mode usually predicts too many large ρ, that is large p, points. Only at 4.8 GeV are the 2-body and 3-body hypotheses equally applicable.

In Fig. 12 we show the ρ distribution of the 26 events in the threshold region, corrected for background. The best fit is provided by the sloping spectrum for the 3-body decay mode represented by V-A, $M_U = 1.8$ GeV/c^2, $M_{\nu_U} = 0.0$ GeV/c^2, and Eq. (4). Two 2-body decay modes, Eq. (7) are shown for $M_U = 1.8$ GeV/c^2 and for $M_U = 1.9$ GeV/c^2. In both the 2-body modes, the U is assumed to decay isotropically in its center of mass as was the case for the dotted curves in Figs. 10 and 11. To make a χ^2 test we put the data into 5 bins. We find for 4 degrees of freedom

DECAY MODE	χ^2
3-body, V-A, $M_U = 1.8$ GeV/c^2, $M_{\nu_U} = 0.0$, Eq. (4)	2.2
2-body, $M_U = 1.8$ GeV/c^2, Eq. (7)	28.3
2-body, $M_U = 1.9$ GeV/c^2, Eq. (7)	38.1

Hence, we now have the new information that even in the threshold region the ρ distribution favors the 3-body mode. We can only resurrect the 2-body decay mode in the threshold region by reducing the U mass to 1.6 GeV/c^2. But that does not help in the high energy regions of Fig. 11, and I am now beginning to believe that 1.6 GeV/c^2 is too low a mass on other grounds. As I noted before a qualitative study of the M_U = 1.6 GeV/c^2 possibility is now being made.

7. THE MISSING ENERGY IN eμ EVENTS

The cos θ_{coll} and ρ distributions favor the 3-body decay of the U. The question then arises: are the missing particles all neutrinos according to the heavy lepton hypothesis,

$$U^- \rightarrow \nu_U + e^- + \bar{\nu}_e$$

$$U^+ \rightarrow \bar{\nu}_U + \mu^+ + \nu_\mu \qquad (20)$$

(Here we use the example of the U^- going to an e^- and the U^+ to a μ^+, the charge conjugate case of course also occurs.) Or is some of the energy carried off in undetected hadrons? The only two possibilities in the latter case are that K_L^o's are being produced

$$U^- \rightarrow e^- + \bar{\nu}_e + K_L^o$$

$$U^+ \rightarrow \mu^+ + \nu_\mu + K_L^o \ ; \qquad (21)$$

or that there are undetected π^o's

$$U^- \rightarrow e^- + \bar{\nu}_e + \pi^o$$

$$U^+ \rightarrow \mu^+ + \nu_\mu + \pi^o \qquad (22)$$

A study has been made by G. Feldman[15] of the possibility of the occurence of the decays in Eqs. (21) or (22).

To look for the decays in Eq. (21), Feldman looked for events of the form

$$e^+ + e^- \to e^\pm + \mu^\mp + K^0_S + \text{missing energy} \qquad (23)$$

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

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

were found, he found no events of the form of Eq. (23). He also found no $e^+e^-K^0_S$ or $\mu^+\mu^-K^0_S$ events. Now unless the U particle is exceedingly strange, decay modes containing K^0_S particles must be equal in rate to those containing K^0_L particles. This leads to the following limit with 90% confidence:

$$\left.\begin{array}{l}\text{fraction of observed e}\mu\text{ events meeting}\\ \text{the criteria a thru f of Sec. 3 and}\\ \text{containing a }K^0\end{array}\right\} < 0.05 \qquad (24)$$

We already knew that decays of the form of Eq. (22) were unlikely because of criteria e. in Sec. 3 -- no photons detected. Feldman's[15] study makes this quantitative; with 90% confidence.

$$\left.\begin{array}{l}\text{fraction of observed e}\mu\text{ events meeting}\\ \text{the criteria a thru f of Sec. 3 and}\\ \text{containing one or more }\pi^0\text{'s}\end{array}\right\} < 0.09 \qquad (25)$$

Therefore, in most of the eμ events which are observed the missing energy is carried off by neutrinos.

8. DISCUSSION AND CONCLUSIONS

Before listing the conclusions, I will make a few remarks on the eμ events. If the U particle has decays of the form of Eq. (4), or indeed if it has any of the decay in Eqs. (7) thru (9), we should see anomalous events of the form

$$e^+ + e^- \to e^+ + e^- + \text{missing energy} \qquad (26a)$$

$$e^+ + e^- \to \mu^+ + \mu^- + \text{missing energy} \quad . \qquad (26b)$$

Furthermore, if the e and μ decay rates of the U are equal, we should find

$$\frac{\sigma_{ee,\text{observed}}}{\sigma_{e\mu,\text{observed}}} = \frac{\sigma_{\mu\mu,\text{observed}}}{\sigma_{e\mu,\text{observed}}} = 0.5 \qquad (27)$$

As reported by F.B. Heile[16] we have found anomalous ee and μμ events as in Eq. (26) after correcting for background from processes such as

$$\begin{aligned} e^+ + e^- &\rightarrow e^+ + e^- + \mu^+ + \mu^- \\ e^+ + e^- &\rightarrow e^+ + e^- + \gamma + \gamma \qquad (28) \\ e^+ + e^- &\rightarrow \mu^+ + \mu^- + \gamma + \gamma \end{aligned}$$

The numbers of anomalous ee and μμ events are compatible with Eq. (27). Quantitative studies are in progress to see what ratios very different from 0.5 can be excluded.

Another remark related to the eμ events concerns the existence of events of the form

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \text{charged hadrons in detector} \qquad (29a)$$

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \gamma\text{'s from } \pi^0\text{'s in detector} \qquad (29b)$$

or combinations of Eqs. (29a) and (29b). Our studies do not exclude such events. In our studies these events are treated as background to yield a convservative calculation of the background in our eμ events. Indeed a several hundred picobarn real signal

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \text{detected hadrons} \qquad (30)$$

could exist. Therefore, the statement in the previous section that our observed eμ events do not contain hadrons, does not exclude the reaction in Eq. (30); it simply means that our observed eμ events are not related to Eq. (30).

Finally, we note that anomalous events of the form:

$$e^+ + e^- \rightarrow \mu^\pm + \text{one charged particle} + \text{missing energy} \qquad (31)$$

have been seen at SPEAR by the Maryland, Pavia, Princeton Group.[17,18,19] According to Refs. 18 and 19 these events are compatible with the heavy lepton interpretation of our eμ events.

Our conclusions are as follows.

a. The anomalous eμ events described by Eq. (1) exist; we have not found any conventional explanation for all such events; and only 20 to 35% of them can be explained by various background mechanisms.

b. The data are consistent with the hypothesis of the production of pairs of new particles of one or more types U_1, U_2 ...

$$\begin{aligned} e^+ + e^- &\rightarrow U_1^+ + U_1^- \\ e^+ + e^- &\rightarrow U_2^+ + U_2^- \end{aligned} \tag{32}$$

provided at least one of these types has 3-body decay modes.

c. The data is not consistent with all the events coming from 2-body leptonic decays of the U's.

d. We know of nothing which is inconsistent with the hypothesis that all the events come from the 3-body decay of a U particle.

e. Very little or none of the missing energy in the eμ events is carried off by hadrons.

f. The observed eμ production cross section is not correlated with the "new hadron physics" cross section structure in the 3.9 - 4.6 GeV region.

g. Combining conclusions c, d, e, and f I believe it is unlikely that the U particle is a charmed particle or is primarily produced by the decay of a charmed particle.

If we assume that all the eμ events are produced by a single mechanism, that is, that there is just one reaction

$$e^{+} + e^{-} \rightarrow U^{+} + U^{-} \qquad (33)$$

and one type of U particle, then we can draw further conclusions:

h. The simplest explaination of the data is the existence of a sequential heavy lepton of mass

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

i. We cannot yet distinguish V-A from V+A or other coupling combinations for the heavy lepton. Nor can we determine the mass of the associated neutrino ν_U beyond noting that M_{ν_U} is certainly less than 1 GeV/c^2. Such a large mass would distort the ρ spectrum severely.

j. To fully establish that the U is a sequential heavy lepton we have to find the semi-leptonic decay modes of Eq. (5). Some evidence for such modes appears to have been found in Ref. 17.

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FIGURE CAPTIONS

Figure 1 Comparison of the observed eμ production cross section, $\sigma_{e\mu,\ observed}$, with the production cross section for a heavy lepton of mass 1.8 GeV/c^2 (Eq. 10) decaying into 3-bodies (Eq. 4) via V-A or V+A; or with the production cross section for a meson of mass 1.9 GeV/c^2 (Eq. 11) decaying into 2-bodies (Eq. 7). $\sigma_{e\mu,observed}$ is corrected for background as discussed in Refs. 1 and 3.

Figure 2 $\sigma_{e\mu,observed}$ in the threshold region using 26 events below 4.8 GeV and the old 4.8 GeV point. Background has been subtracted. There are <u>no</u> events in the 3.0 - 3.6 GeV region before background subtraction. The horizontal arms on two of the points mean that the data is added together over the indicated energy range.

Figure 3 $R = \sigma_{had}/\sigma_{ee \rightarrow \mu\mu}$ for the threshold region.

Figure 4 $\sigma_{e\mu,observed}$ in the threshold region in 100 MeV bins. The number of events in each bin are given next to the data point and the error bars are set by the square root of that number. There is no background subtraction here, the bins are too small to permit it. However, the background seems uniform at about 25% in this region. Incidently, the second thru fifth data point here were combined into the 4.1 GeV data point of Fig. 2, and the sixth thru ninth data point were combined into the 4.5 GeV data point of Fig. 2

Figure 5 $\sigma_{e\mu,observed}/\sigma_{new\ hadron\ physics}$ as defined in text.

Figure 6 The acceptance of the experiment including the geometric acceptance of the detector, momentum cuts and angular cuts. The U mass is 1.8 GeV/c^2, the 2-body decay mode is defined in Eq. (7) for a meson; and the 3-body decay mode is defined in Eq. (4) for a heavy lepton.

Figure 7 The cos θ_{coll} distribution for the original 86 events in three $\sqrt{s}$ = 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 dotted cruves are for the 2-body decay of the U taken as a meson, Eq. (7), with $M_U = 1.9$ GeV/c^2. The data is not correct-for background.

Figure 8 The cos θ_{coll} distribution for the 26 events in the threshold region $3.8 \leq E_{cm} < 4.8$ GeV. 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, $M_{\nu_U} = 0.0$, and V-A. The dotted and dashed curves are for the 2-body decay of the U taken as a meson, Eq. (7), with $M_U = 1.9$ and 1.8 GeV/c^2 respectively The data is not corrected for background.

Figure 9 The momentum spectrum from (a) a 2-body decay and (b) a 3-body decay.

Figure 10 The distribution in $\rho = (p - 0.65)/(p_{max} - 0.65)$; p in GeV/c for the original 86 events for all $\sqrt{s} = E_{cm}$. 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, $M_{\nu_U} = 0.0$ and V-A. The dotted curve is for the 2-body decay of the U taken as a meson, Eq. (7), with $M_U = 1.9$ GeV/c^2, assuming isotropic decay of the U in its rest frame. The dashed curve is the same as the dotted curve except that the θ_{coll} distribution has been distorted to fit the data in Fig. 7.

Figure 11 The ρ distribution for the original 86 events in three different $\sqrt{s}$ = E_{cm} intervals. For the meaning of the curves see the caption of Fig. 10

Figure 12 The ρ distribution for the 26 events in the threshold region 3.8 E_{cm} 4.8 GeV corrected for background. The solid curves is for the 3-body decay of the U taken as a heavy lepton, Eq. (4) with $M_U = 1.8$ GeV/c^2, $M_{\nu_U} =$ 0.0 and V-A. The dotted and dashed curves are for the 2-body decay of the U taken as a meson, Eq. (7) with $M_U = 1.9$ and 1.8 GeV/c^2 respectively.

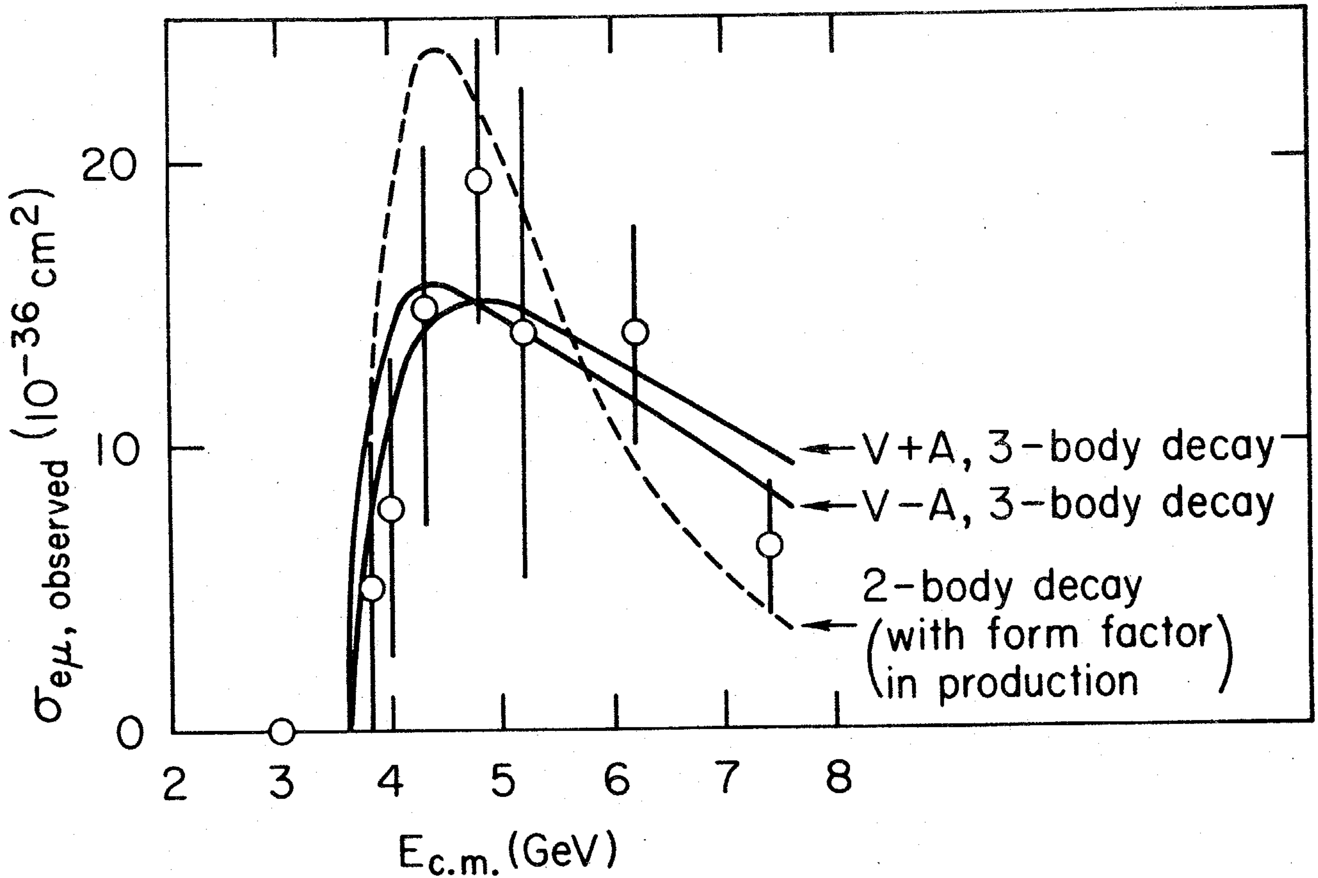

$\sigma_{e\mu}$, observed $(10^{-36}\,cm^2)$
0
10
20
2
3
4
5
6
7
8
$E_{c.m.}$ (GeV)
V+A, 3-body decay
V−A, 3-body decay
2-body decay
(with form factor in production)

Fig. 1

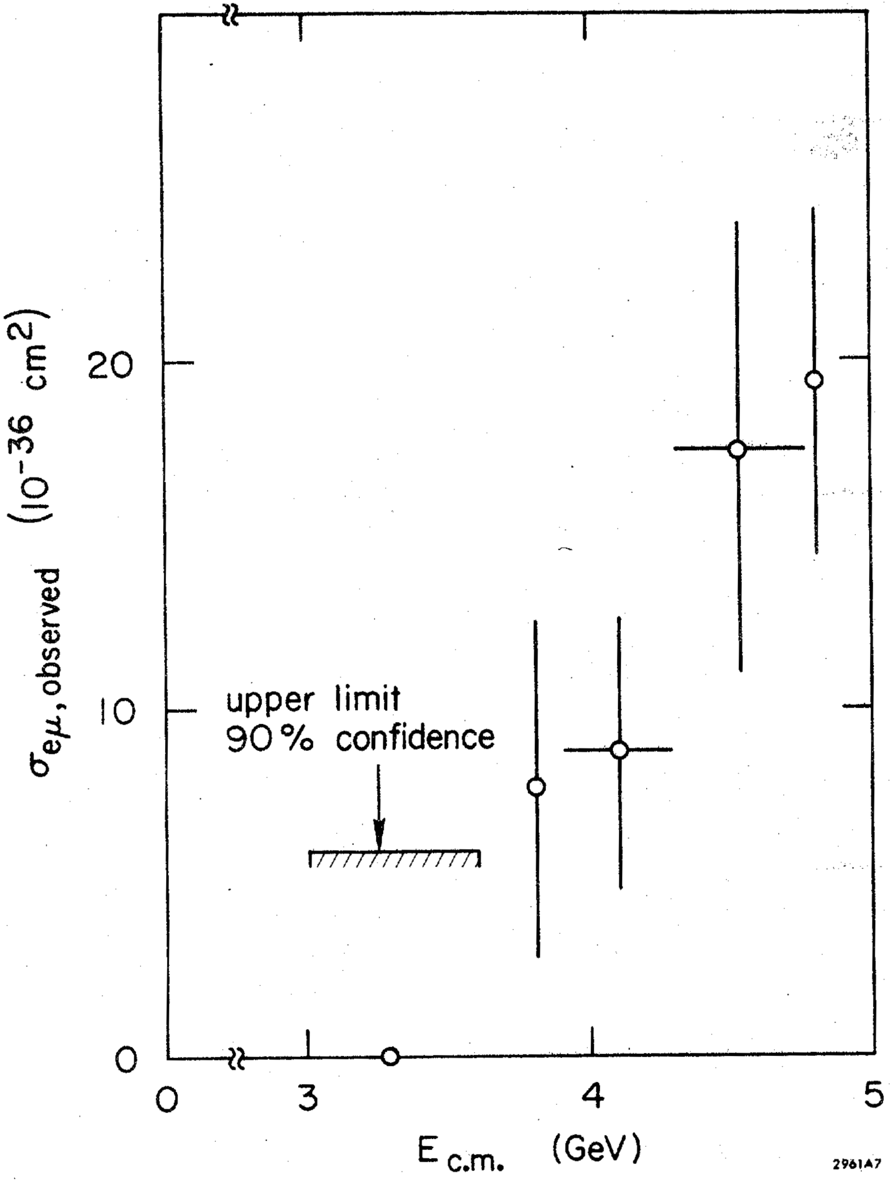

$\sigma_{e\mu,\text{observed}}$ $(10^{-36}\ \text{cm}^2)$
20
10
0
upper limit
90% confidence
0
3
4
5
$E_{\text{c.m.}}$ (GeV)
2961A7

Fig. 2

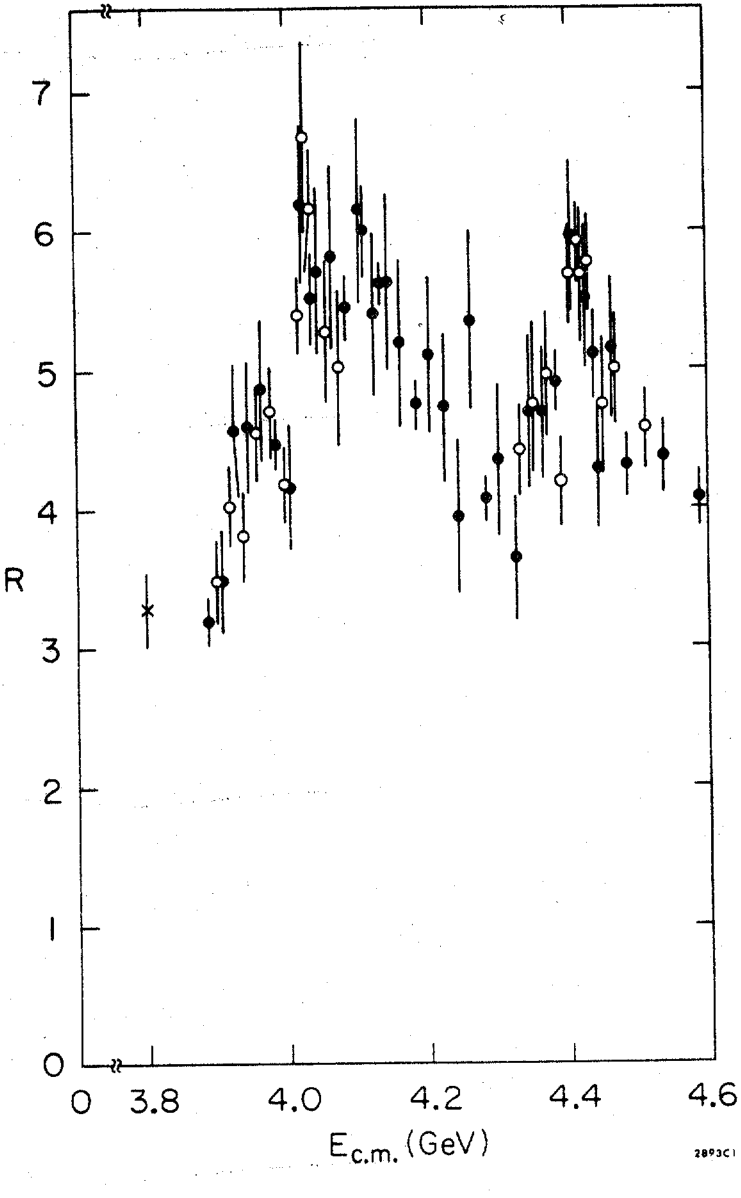


Fig. 3

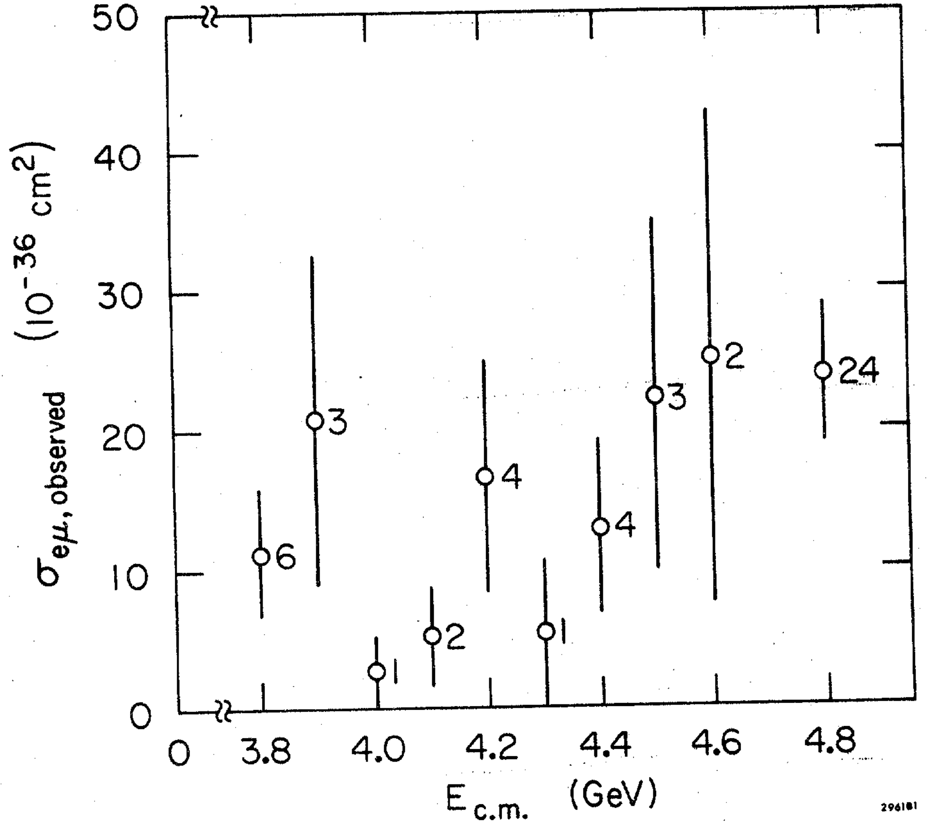
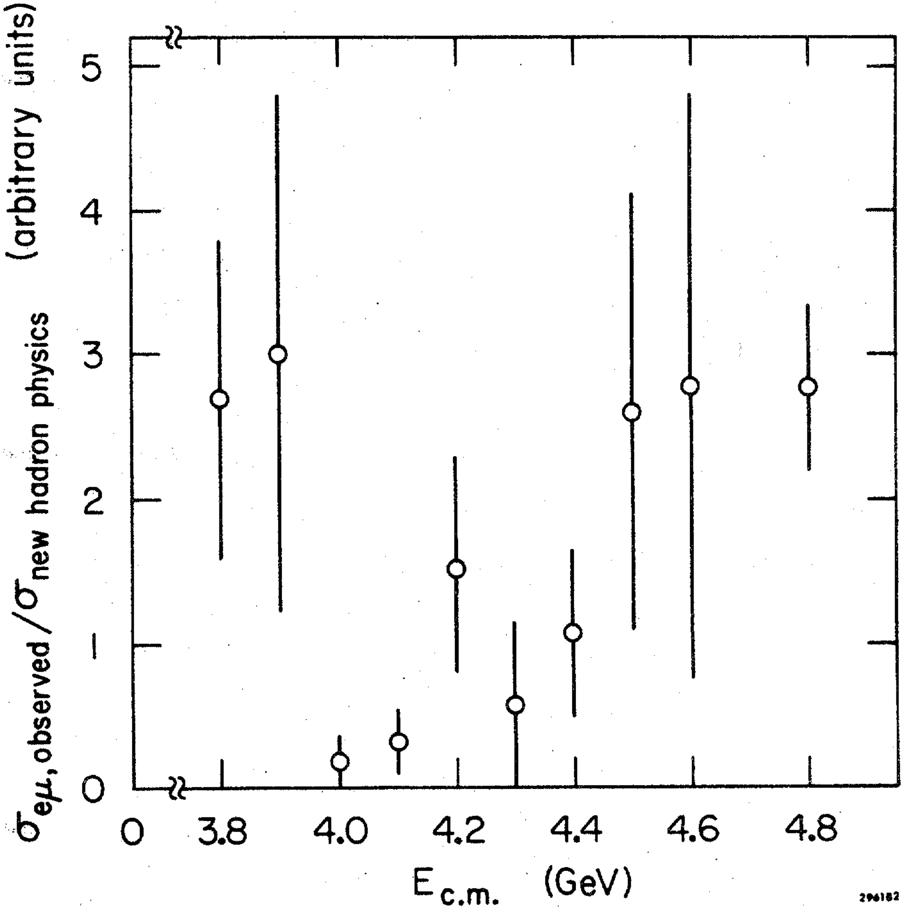

$\sigma_{e\mu,\text{observed}}$ $(10^{-36}\ \text{cm}^2)$
50
40
30
20
10
0
0
3.8
4.0
4.2
4.4
4.6
4.8
$E_{c.m.}$ (GeV)
6
3
1
2
4
1
4
3
2
24
296181

Fig. 4



$\sigma_{e\mu,\text{observed}}/\sigma_{\text{new hadron physics}}$ (arbitrary units)
0
1
2
3
4
5
0
3.8
4.0
4.2
4.4
4.6
4.8
$E_{c.m.}$ (GeV)
296182

Fig. 5

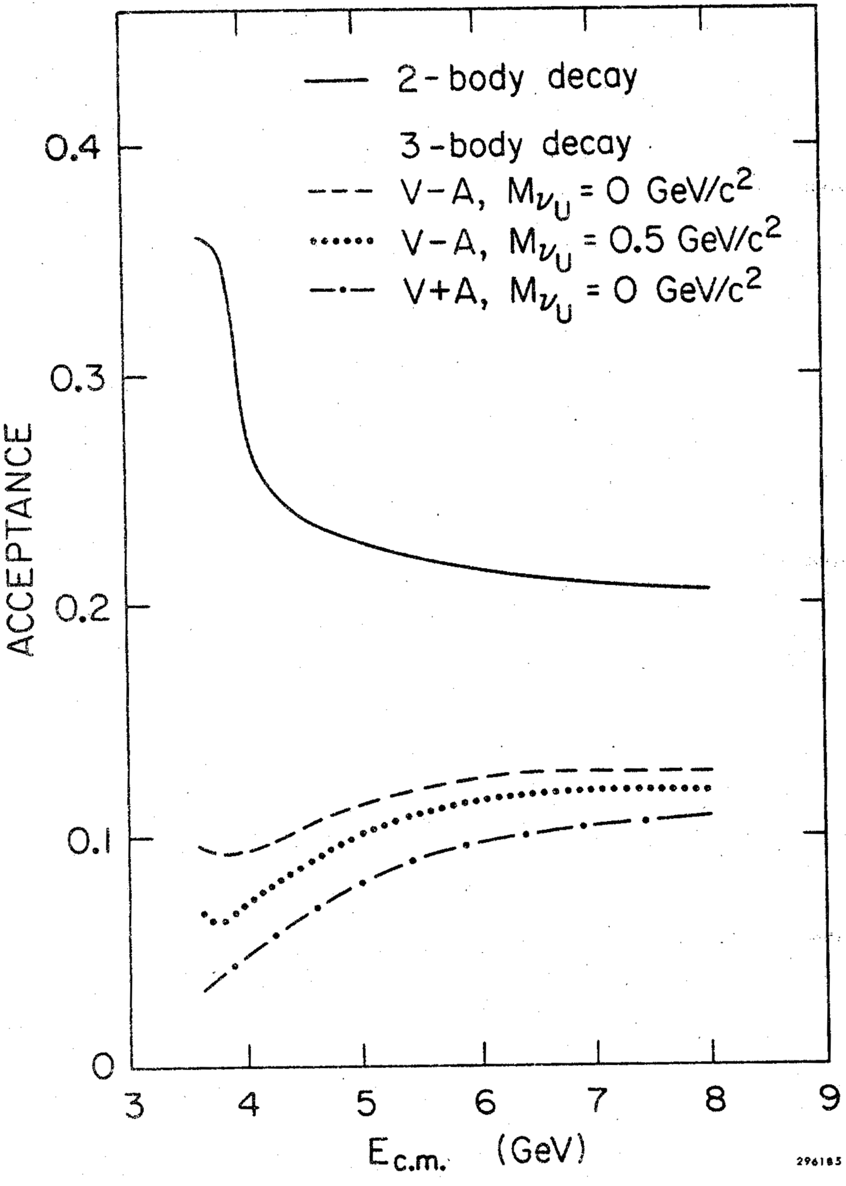

2-body decay
3-body decay
V−A, M_{ν_U} = 0 GeV/c^2
V−A, M_{ν_U} = 0.5 GeV/c^2
V+A, M_{ν_U} = 0 GeV/c^2
ACCEPTANCE
0
0.1
0.2
0.3
0.4
3
4
5
6
7
8
9
$E_{c.m.}$ (GeV)
296183

Fig. 6

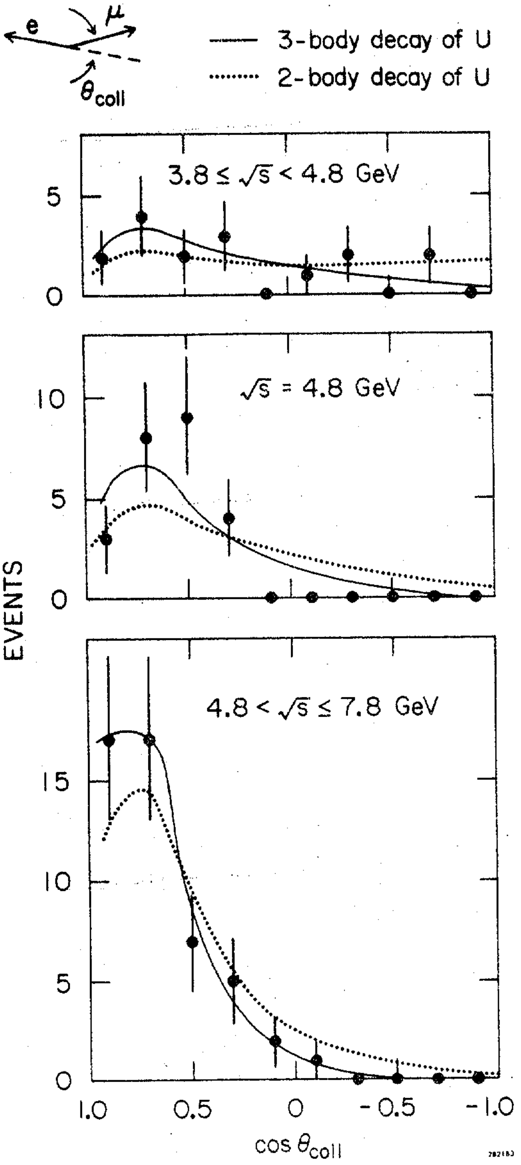

e
μ
θ_coll
3-body decay of U
2-body decay of U
3.8 ≤ √s < 4.8 GeV
√s = 4.8 GeV
4.8 < √s ≤ 7.8 GeV
EVENTS
0
5
10
15
1.0
0.5
0
-0.5
-1.0
cos θ_coll
782183

Fig. 7

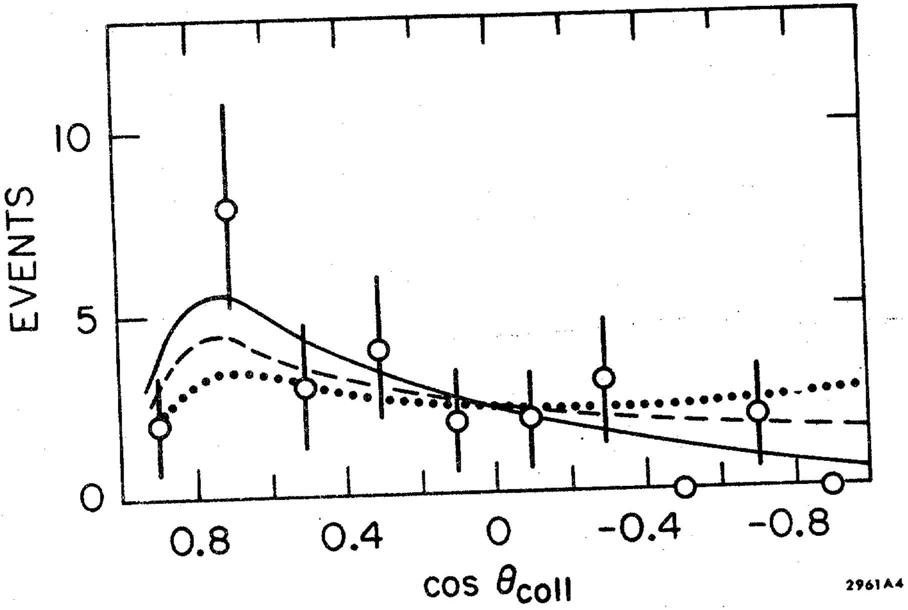


Fig. 8

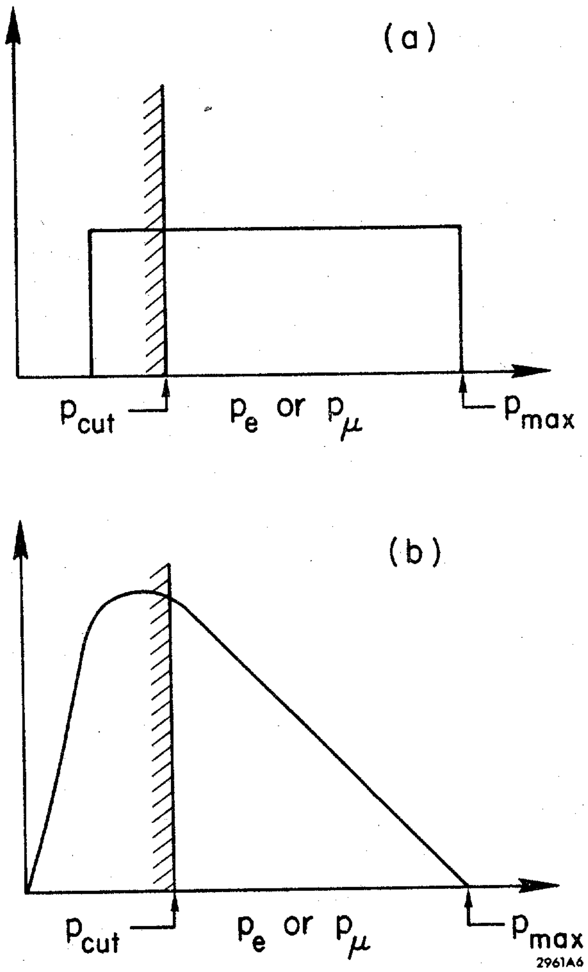


Fig. 9

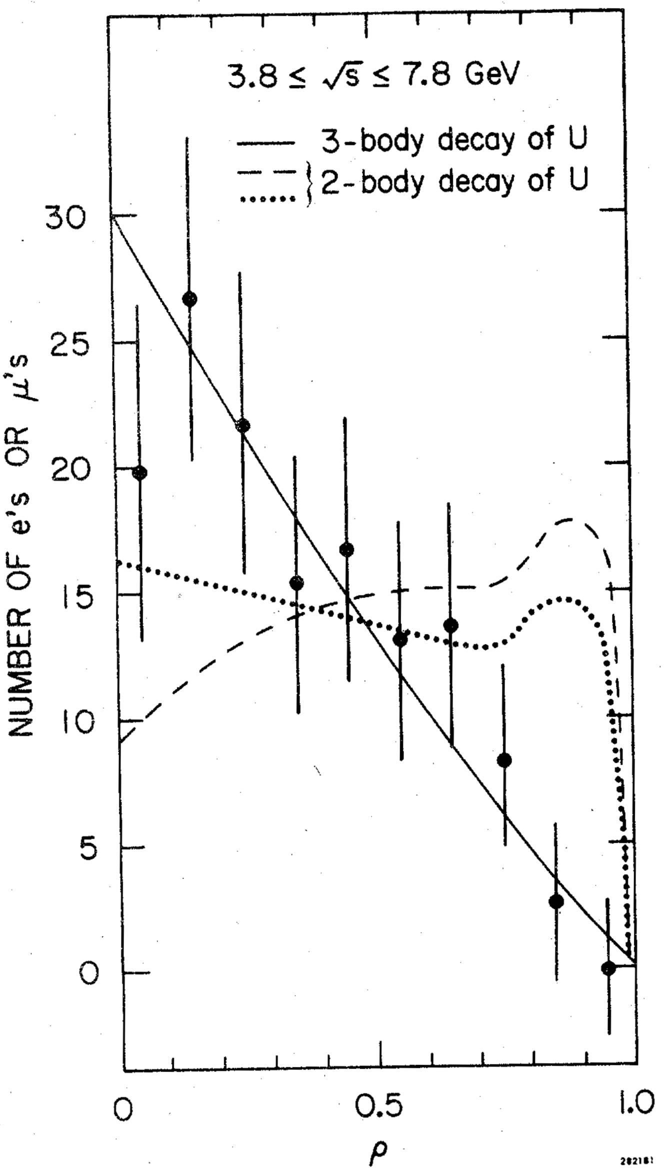

3.8 ≤ √s ≤ 7.8 GeV
3-body decay of U
2-body decay of U
NUMBER OF e's OR μ's
30
25
20
15
10
5
0
0
0.5
1.0
ρ
282181

Fig. 10

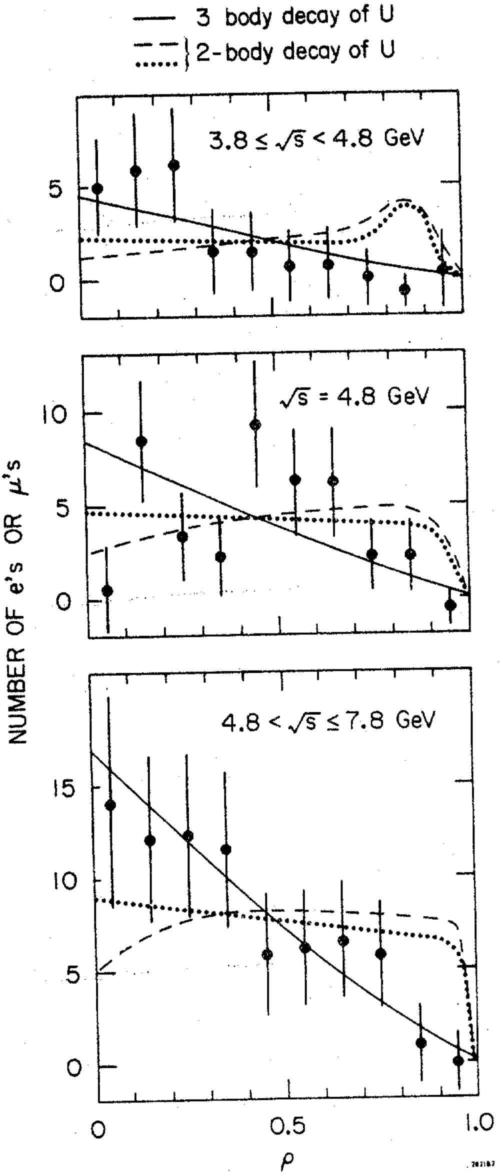

3 body decay of U
2-body decay of U
3.8 ≤ √s < 4.8 GeV
√s = 4.8 GeV
4.8 < √s ≤ 7.8 GeV
NUMBER OF e's OR μ's
0
5
10
15
0
0.5
1.0
ρ

Fig. 11

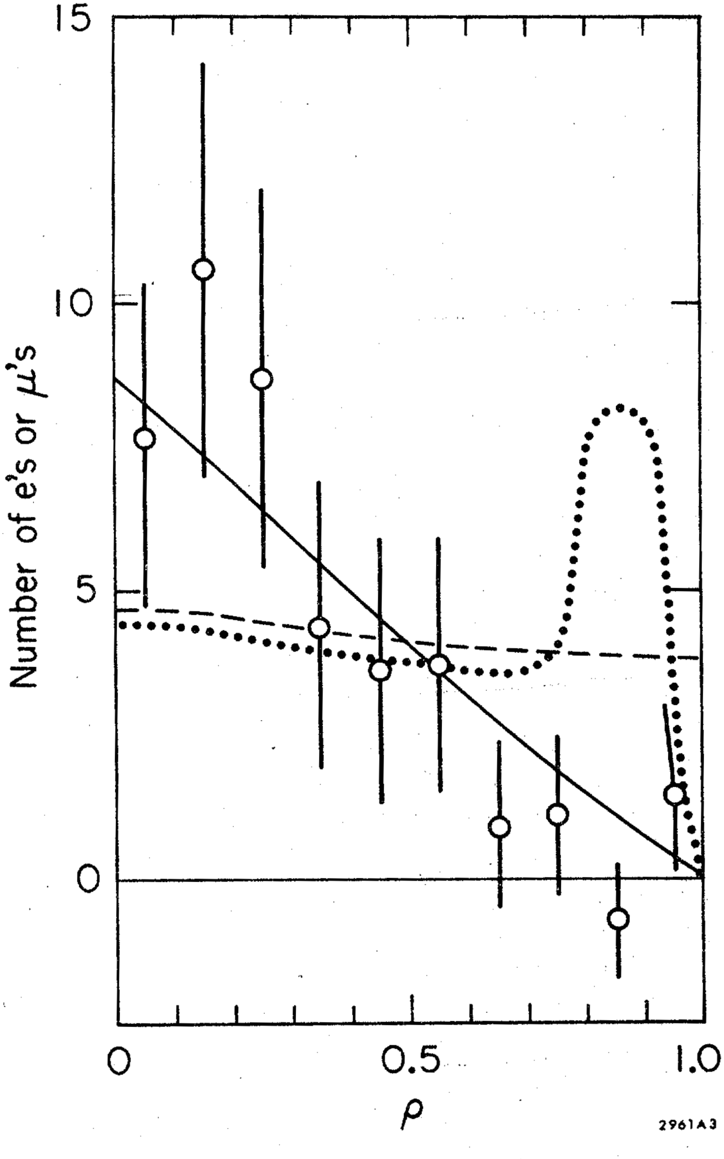


Fig. 12