ANOMALOUS LEPTON PRODUCTION IN e^+-e^- ANNIHILATION*

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This is an outline of a paper presented at the International Meeting on Storage Ring Physics at Flaine, France on February 22-28, 1976. For a fuller discussion of the data and interpretation presented here see Ref. 1 and for background matieral see Refs. 2-5. The major conclusion of the paper was that the only simple explanation of the events

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

is that they are the decay products of a pair of U particles produced in the reaction

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

and that the U particle is a sequential heavy lepton[1,5,6] of mass

$$1.6 \leq M_U \leq 2.0 \text{ GeV}/c^2 \qquad (3)$$

These events were found by the SLAC-LBL Magnetic Detector Collaboration[2] using the SPEAR electron-positron colliding beams facility at SLAC.

A sequential heavy lepton ℓ would have the decay modes[1,6-8]

a) leptonic

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

b) semi-leptonic

$$\ell^- \rightarrow \nu_\ell + \pi^- \qquad (5a)$$

$$\ell^- \rightarrow \nu_\ell + K^- \qquad (5b)$$

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$$\ell^- \to \nu_\ell + \rho^- \qquad (5c)$$

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

$$\begin{matrix} \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \end{matrix}$$

The relative decay rates depend upon the lepton mass.[7,8]

The experimental signature[9] for ℓ pair production in e^+e^- annihilation is Eq. (1) through the processes

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

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. Purely leptonic decays would have the form

$$\left.\begin{matrix} M^- \to e^- + \bar{\nu}_e \\ M^- \to \mu^- + \bar{\nu}_\mu \end{matrix}\right\} \text{2-body} \qquad (7)$$

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

$$\left.\begin{matrix} M^- \to e^- + \bar{\nu}_e + K^0_L \\ M^- \to \mu^- + \bar{\nu}_\mu + K^0_L \end{matrix}\right\} \text{3-body decays} \qquad (8)$$

or

$$\left.\begin{matrix} M^- \to e^- + \bar{\nu}_e + \pi^0 \\ M^- \to \mu^- + \bar{\nu}_\mu + \pi^0 \end{matrix}\right\} \text{3-body decays} \, . \qquad (9)$$

The observed production cross section for Eq. (1) is given in Fig. 1. The heavy lepton production cross section is

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

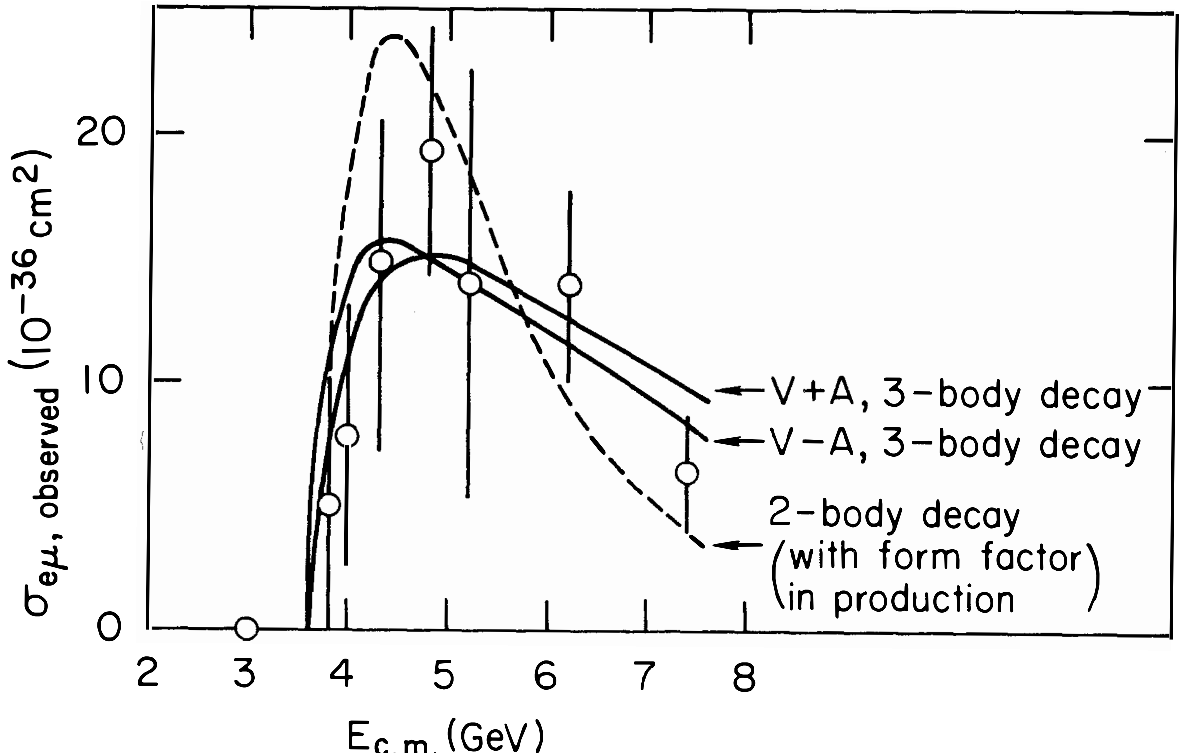

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Fig. 1 Comparison of the observed eμ production cross section, $\sigma_{e\mu,observed}$, with the production cross section for a heavy lepton of mass 1.8 GeV/c^2 (Eq. 10) decaying into 3-bodies (Eq. 4) via V-A or V+A; or with the production cross section 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. 2 and 4.

For meson production I used the formula

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

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:

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

Good evidence that the $e\mu$ events are the decay products of U pair production, Eq. (2), is provided by the collinearity angle, θ_{coll}, distribution where

$$\cos\theta_{coll} = -\underset{\sim}{p}_e \cdot \underset{\sim}{p}_\mu/(|\underset{\sim}{p}_e||\underset{\sim}{p}_\mu|) \tag{12}$$

When the e and μ are moving in exactly opposite directions $\theta_{coll} = 0$. Figure 2 shows the cos θ_{coll} distribution for 86 events already published[4] and Fig. 3 is for an <u>increased</u> statistical sample of 26 events in the threshold region $3.8 \leq E_{cm} < 4.8$ GeV. These 26 events include the 16 in the topmost graph in Fig. 2. The heavy lepton hypothesis provides good fits to the data. The 2-body decay of the meson is not as good in the 4.8 GeV and $4.8 < E_{cm} \leq 7.8$ GeV regions.

The strongest evidence against the 2-body decay of the U is provided by the momentum distributions of the e and μ. To combine the data from different E_{cm} runs we use the parameter (with $M_U = 1.8$ GeV/c^2)

$$\rho = \frac{p - 0.65}{p_{max} - 0.65} \quad , \quad p \text{ in GeV/c} \quad ; \tag{13}$$

This was done for the original 86 events in Ref. 4, reproduced in Figs. 4 and 5. Figures 4 and 5 are corrected for background. 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. 6 we show the ρ distribution of the 26 events in the threshold region, corrected for background. The best fit is again provided by the 3-body decay mode. Hence we conclude that the U must decay predominantly into 3-bodies; and we next need to distinguish between Eq. (4) and Eqs. (8) or (9).

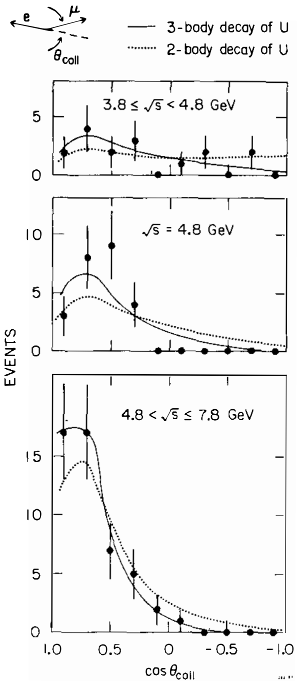

Fig. 2 The cos θ_{coll} distribution for the original 86 events in three $\sqrt{s} = E_{cm}$ intervals. The solid curves are for the 3-body decay of the U taken as a heavy lepton, Eq. (4), with M_U = 1.8 GeV/c^2, M_{ν_U} = 0.0, and V-A. The dotted curves are for the 2-body decay of the U taken as a meson, Eq. (7), with M_U = 1.9 GeV/c^2. The data is not corrected for background.

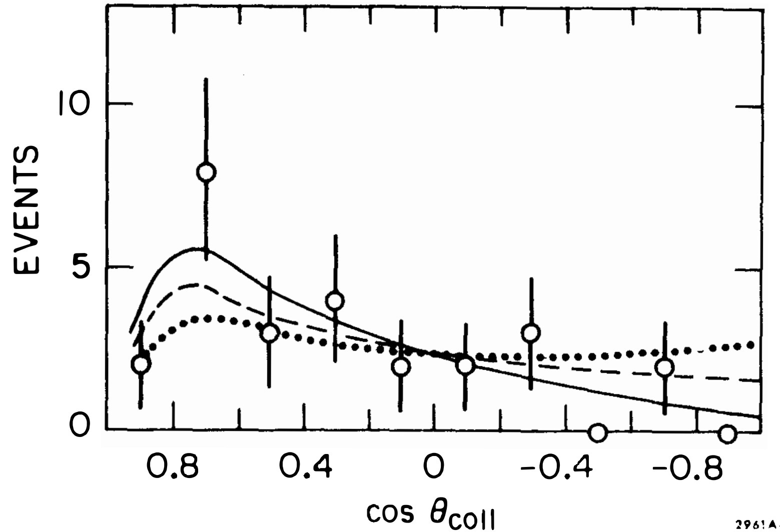

Fig. 3 The cos θ_{coll} distributions for the 26 events in the threshold region 3.8 $\leq E_{cm} <$ 4.8 GeV. The solid curve is for the 3-body decay of the U taken as a heavy lepton, Eq. (4), with M_U = 1.8 GeV/c^2, M_{ν_U} = 0.0, and V-A. The dotted and dashed curves are for the 2-body decay of the 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.

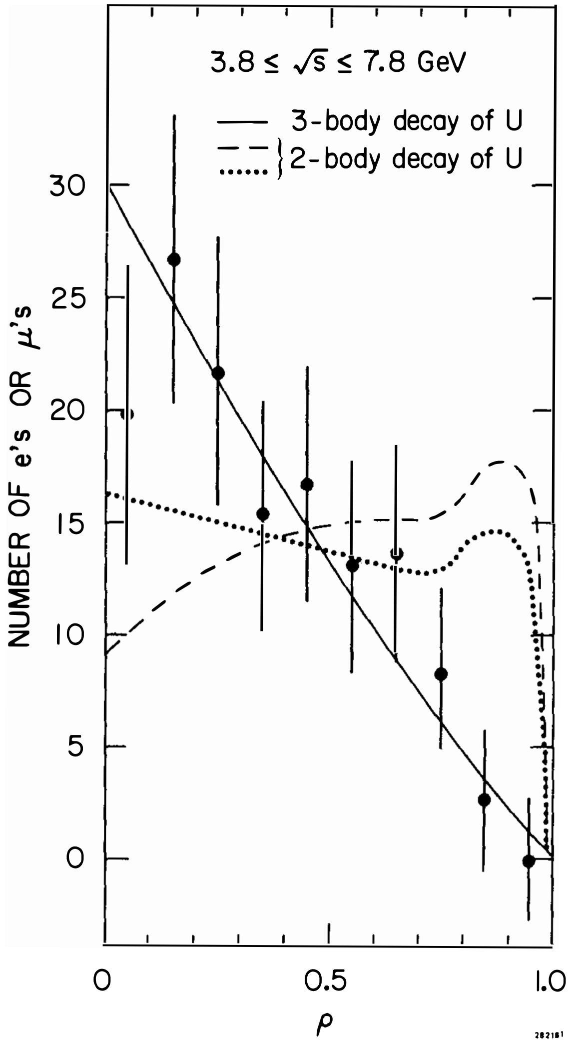

Fig. 4 The distribution in $\rho = (p - 0.65)/(p_{max} - 0.65)$, p in GeV/c. for the original 86 events for all $\sqrt{s} = E_{cm}$. The solid curve is for the 3-body decay of the U taken as a heavy lepton, Eq. (4), with $M_U = 1.8$ GeV/c^2, $M_{\nu_U} = 0.0$ and V-A. The dotted curve is for the 2-body 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. 2.

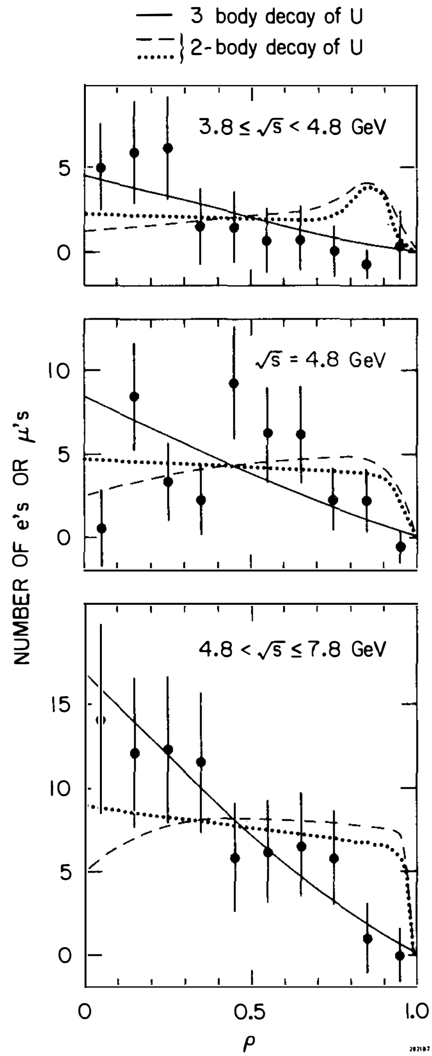

Fig. 5 The ρ distribution for the original 86 events in three different $\sqrt{s} = E_{cm}$ intervals. For the meaning of the curves see the caption of Fig. 4.

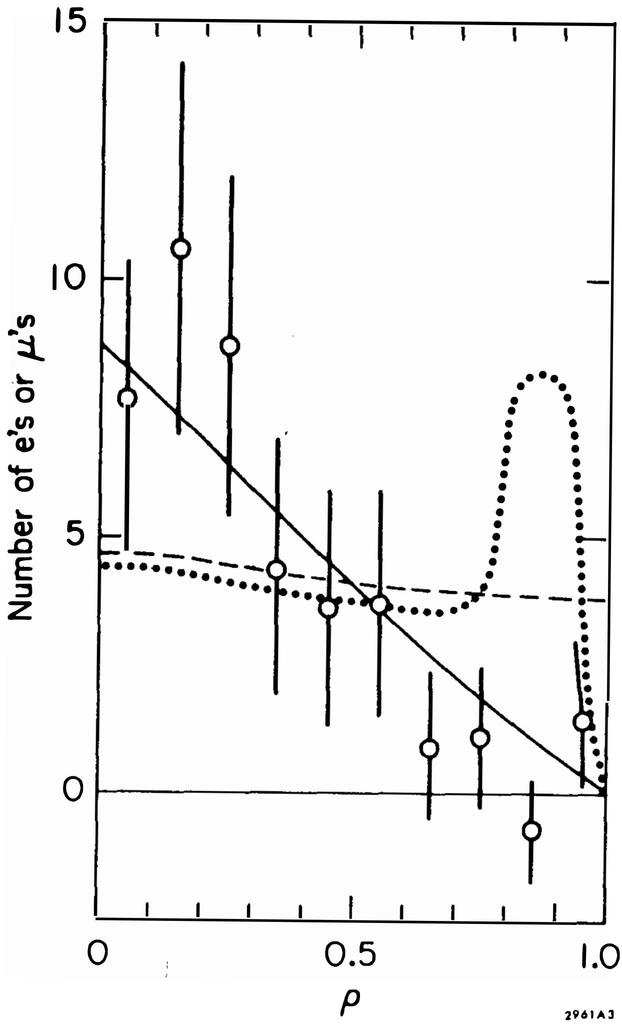

Fig. 6 The ρ distribution for the 26 events in the threshold region $3.8 \leq E_{cm} < 4.8$ GeV corrected for background. The solid curve is for the 3-body decay of the U taken as a heavy lepton, Eq. (4) with $M_U = 1.8$ GeV/c^2, $M_{\nu_U} = 0.0$ and V-A. The dotted and dashed curves are for the 2-body decay of the U taken as a meson, Eq. (7), with $M_U = 1.9$ and 1.8 GeV/c^2 resepctively.

A study has been made by G. Feldman of the possibility of the occurence of the decays in Eqs. (8) or (9). He looked for events of the form

$$e^+ + e^- \rightarrow e^{\pm} + \mu^{\mp} + K^o_S + \text{missing energy} \qquad (14)$$

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

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

were found, he found no events of the form of Eq. (14). He also found no $e^+e^-K^o_S$ or $\mu^+\mu^-K^o_S$ events. This leads to the following limit with 90% confidence:

fraction of observed eμ events meeting the criteria a thru f of Ref. 9 and containing a K^o } < 0.05 (15)

We already knew that decays of the form of Eq. (9) were unlikely because of criteria e. in Ref. 9 -- no photons detected. Feldman's study makes this quantitative; with 90% confidence.

fraction of observed eμ events meeting the criteria a thru f of Ref. 9 and containing one or more π^o's } < 0.09 (16)

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

An additional argument against the observed eμ event being related to charmed mesons is provided by comparing $\sigma_{e\mu,\text{observed}}$, Figs. 7 and 8 with σ_{had} in the threshold region, Fig. 9. 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 8 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 no clustering of eμ events in the 4.05 to 4.15 GeV region or at the 4.4 GeV resonance.

Following Harari's[11] ideas, I define the "new hadronic physics" in e^+e^- annihilation as causing R to rise above 2.5; quantitatively.

$$\sigma_{\text{new hadron physics}}(s) = (R(s) - 2.5)\sigma_{ee \rightarrow \mu\mu}(s) \qquad (17)$$

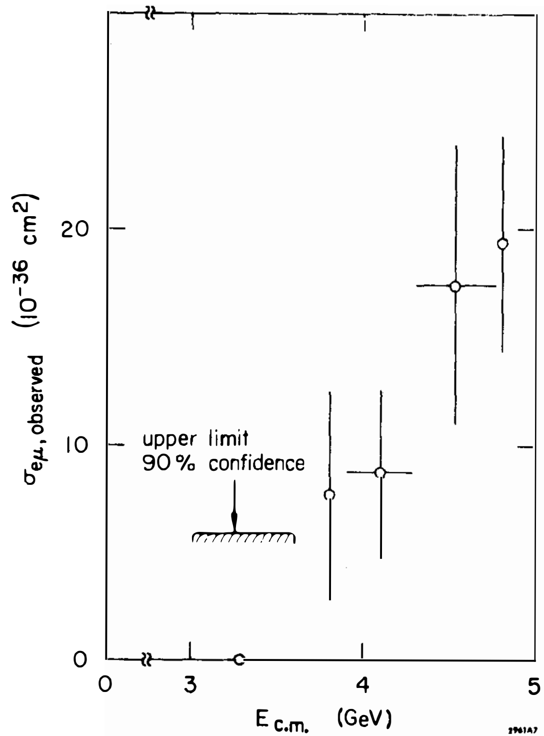

Fig. 7 $\sigma_{e\mu,\text{observed}}$ in the threshold region using 26 events below 4.8 GeV and the old 4.8 GeV point. Background has been subtracted. There are no events in the 3.0 - 3.6 GeV region before background subtraction. The horizontal arms on two of the points mean that the data is added together over the indicated energy range.

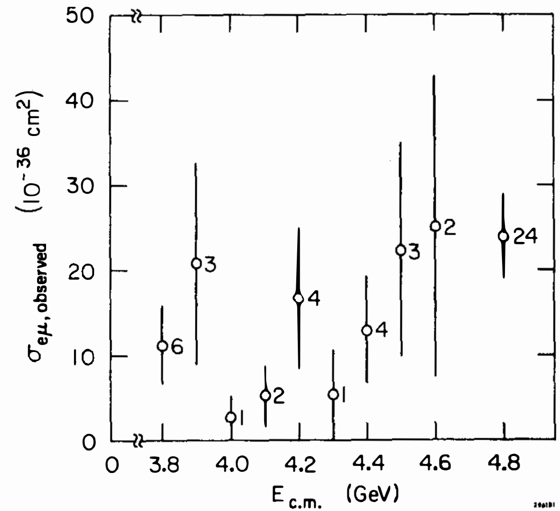

Fig. 8 $\sigma_{e\mu,\text{observed}}$ in the threshold region in 100 MeV bins. The number of events in each bin are given next to the data point and the error bars are set by the square root of that number. There is no background subtraction here, the bins are too small to permit it. However, the background 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. 7, and the sixth thru ninth data point were combined into the 4.5 GeV data point of Fig. 7.

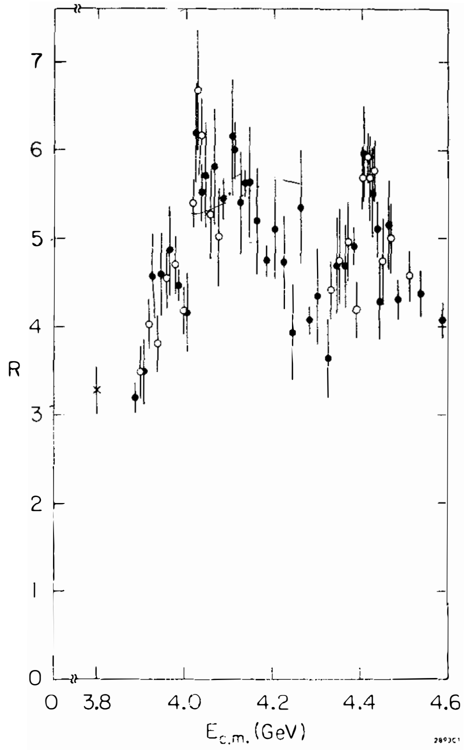

Fig. 9 $R = \sigma_{had}/\sigma_{ee\to\mu\mu}$ for the threshold region. Ref. 10

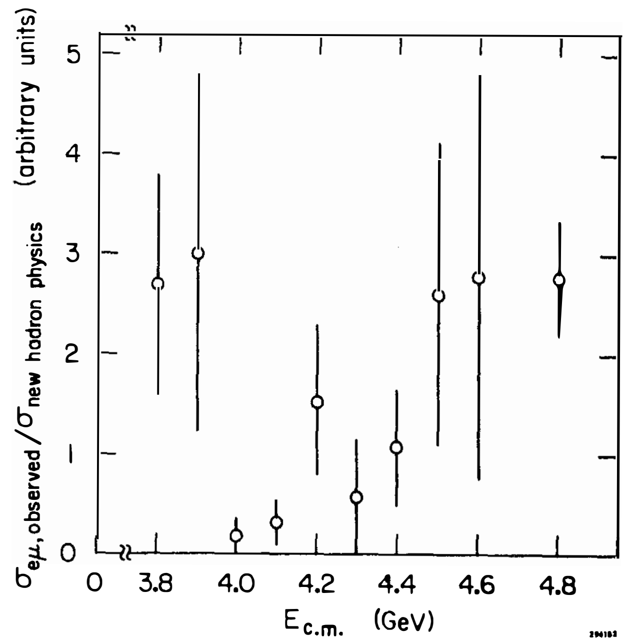

Fig. 10 $\sigma_{e\mu,observed}/\sigma_{new\ hadron\ physics}$ as defined in text.

Figure 10 shows the ratio

$$r = \frac{\sigma_{e\mu,\text{observed}}}{\sigma_{\text{new hadron physics}}} \tag{18}$$

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[1] of the experiment.

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

$$\frac{\text{likelihood that e}\mu\text{ events are from V-A heavy lepton}}{\text{likelihood that e}\mu\text{ events are from "new hadron physics"}} = 130. \tag{19}$$

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

χ^2 probablity 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.

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 ...

$$e^+ + e^- \rightarrow U_1^+ + I_1^-$$

$$e^+ + e^- \rightarrow U_2^+ + U_2^-$$

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

$$e^+ + e^- \rightarrow U^+ + U^-$$

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

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

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. 12.

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9. The experiment criteria for event selection are (see Refs. 2 and 4)
   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°.
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