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Review of Heavy Leptons in e^+e^- Annihilation

by

Günter Flügge

Abstract

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REVIEW OF HEAVY LEPTONS IN e^+e^- ANNIHILATION

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ABSTRACT

A review is given of the existing evidence for the production of a pair of new heavy leptons in e^+e^- annihilation. The new phenomenon has been detected in four different experiments. Data are in good agreement with the assumption, that a sequential heavy lepton τ of mass $1.9 \pm .1$ GeV/c^2 is produced in e^+e^- collisions.

(Invited talk given at the Vth International Conference on Experimental Meson Spectroscopy, Northeastern University, Boston, Massachusetts, April 29-30, 1977)

CONTENTS

I INTRODUCTION

Since the first results about $e\mu$ final states at SLAC in 1975 there has been increasing evidence for a new heavy lepton in e^+e^- annihilation. In this paper I will briefly summarize the existing data and then discuss the evidence for the new particle and its known properties. Following the suggestion of M.L. Perl[1] I will call this third charged lepton τ.

II HEAVY LEPTON SIGNATURES

1. Sequential Heavy Leptons

In the most popular model for a heavy lepton, a third lefthanded doublet (ν_τ,τ) is added to the existing leptons giving a sequence

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix} \quad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix} \quad \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix} \quad \ldots.$$

In the simplest version such a sequential heavy lepton[2] would have its own lepton number and all lepton numbers were separately conserved.

The production cross section for a pair of these new leptons in e^+e^- annihilation is given by

$$\sigma_{\tau\tau} = \sigma_{\mu\mu} \frac{3\beta - \beta^3}{2}$$

where $\sigma_{\mu\mu}$ is the cross-section* for the production of a pair of massless pointlike spin 1/2 particles and β is the velocity of the τ.

The decay of such a new lepton has been calculated by many authors[3,4,5]. Assuming a conventional V - A coupling of the τ and its massless neutrino to the usual weak current, the branching ratios of Table I have been calculated for a lepton mass of 1.9 GeV/c^2 [1,3]. In the following discussion, the hypothesis of a sequential heavy lepton with the above properties will be referred to as the "standard model".

2. Signatures

As indicated in Table I, the dominant fraction of final states contains only one charged particle (about 80%). In half of these cases, the final state is purely leptonic. Thus the following signatures characterize this new phenomenon:

TABLE I

Predicted branching ratios for a sequential heavy lepton τ^- with mass 1.9 GeV/c^2 and V-A coupling to a massless neutrino. The numbers, based on Ref.3, are taken from Ref. 1.

decay mode	branching ratio	number of charged particles in final state
$\nu_\tau e^- \bar{\nu}_e$	.20	1
$\nu_\tau \mu^- \bar{\nu}_\mu$	.20	1
$\nu_\tau \pi^-$	.11	1
$\nu_\tau K^-$	.01	1
$\nu_\tau \rho^-$	.22	1
$\nu_\tau K^{*-}$	.01	1
$\nu_\tau A_1^-$	.07	1, 3
ν_τ(hadron continuum)$^-$	.18	1, 3, 5

---

* $\sigma_{\mu\mu} = \frac{4\pi\alpha^2}{3s} = \frac{21.71 \text{ nb}}{E^2}$, $\frac{\sqrt{s}}{2}$ = E = beam energy in GeV

		$\sigma/\sigma_{\tau\tau}$
(i)	$e^+e^- \rightarrow$ 2 charged particles + missing energy	$\lesssim .7$
(ii)	$e^+e^- \rightarrow \begin{pmatrix} e \\ \mu \end{pmatrix}$ + 1 charged particle + missing energy	$\lesssim .4$
(iii)	$e^+e^- \rightarrow \begin{pmatrix} e \\ \mu \end{pmatrix} + \begin{pmatrix} e \\ \mu \end{pmatrix}$ + missing energy	$\lesssim .16$

$\begin{pmatrix} e \\ \mu \end{pmatrix}$ indicates either electron or muon

In this sequence the selectiveness of the signatures is increasing whereas the relative cross-section $\sigma/\sigma_{\tau\tau}$ decreases.

Experiments have been carried out by the following groups:

		using signatures
SPEAR :	SLAC-LBL[6,7,8]	(ii), (iii)
	MPP(S)[9]	(ii)
DORIS :	DASP[10]	(ii)
	PLUTO[11,12,13]	(i), (ii), (iii)

I do not include preliminary data from the ironball at SPEAR[14].

3. Competitive Reactions

From quantum electrodynamics (QED) a number of reactions is known to contribute to these signatures. Besides the collinear ee and $\mu\mu$ final states, radiative processes $e^+e^- \rightarrow e^+ \bar{e}\gamma$, $\mu^+\mu^-\gamma$, $e^+e^-\gamma\gamma$, and $\mu^+\mu^-\gamma\gamma$ have to be eliminated. In addition two-photon processes of the type $e^+e^- \rightarrow e^+e^- + X$ have to be taken into account. For instance the reaction $e^+e^- \rightarrow \mu\mu ee$ may fake signature (iii) if a μe pair escapes detection.

The other main competitive source for leptonic final states are charmed mesons which are known to be produced above about 4 GeV and decay with sizable ($\sim$ 20%) leptonic branching ratios[15]. Contrary to the heavy lepton, the main decay channels are expected to be semi-leptonic, with several charged hadrons in the final state and a relatively soft momentum spectrum of the lepton[10] (Fig. 1). Consequently, the differences in multiplicity and lepton momentum will be used to discriminate heavy leptons against charm.

III DATA AVAILABLE

1. Total Cross Section and Twoprong Cross Section

The data available from the two solenoidal detectors PLUTO[11] and SLAC-LBL[16] show the following gross features:

(i) $R = \sigma_{tot}/\sigma_{\mu\mu}$ levels off at values of 4.5 to 5.3 in the energy range $4.5 < \sqrt{s} < 5.5$ GeV[11,16]

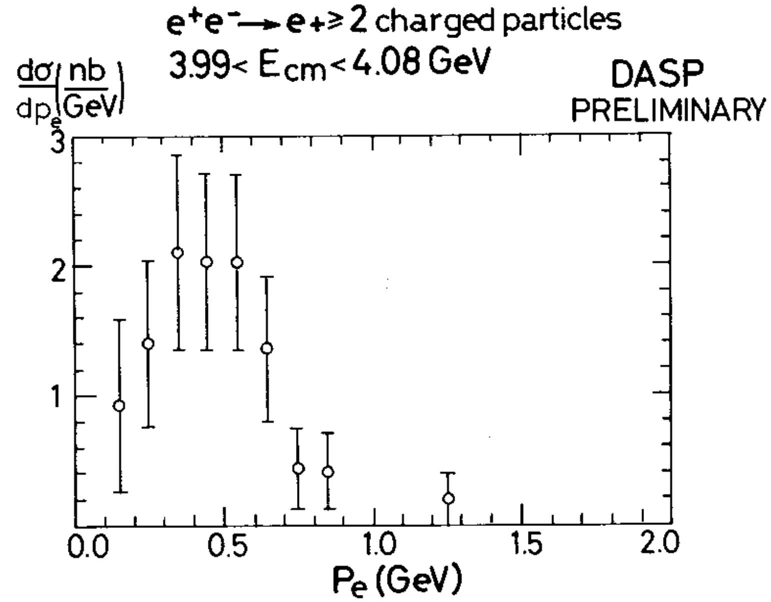

Fig. 1 DASP[17], inclusive electron spectrum of multiprong events (attributed to charm) at $3.99 \leq \sqrt{s} \leq 4.08$ GeV[29].

(ii) The ratio of the twoprong cross-section and the total cross-section is roughly constant between $3.5 < \sqrt{s} < 5.5$ GeV[11]

(iii) $R_{2prong} = \sigma_{2prong}/\sigma_{\mu\mu}$ is of the order of 1.5 to 2 for $4.5 < \sqrt{s} < 5.5$ GeV[11].

Although this is in no way conclusive with regard to the heavy lepton, data indicate that there is room for a new particle with strong coupling to the twoprong channel.

2. Inclusive Lepton Data

a. Electrons

The DASP group at DORIS has measured inclusive electron production using Č, shower, dE/dx, and TOF techniques to identify electrons in both spectrometers[10]. The momentum cutoff is as low as 100 MeV/c. Discrimination against QED and charm is accomplished by asking for one and only one additional charged hadron or muon in the detector:

$$e^+e^- \to e^\pm + 1 \text{ charged hadron or muon} + \text{no photons}$$

$$p_e \geq 100 \text{ MeV/c}$$

The cross-section displayed in Fig. 2a shows the characteristic energy dependence expected in the standard model (full curve).

b. Muons

The other three experiments - MPP(S)[9], SLAC-LBL[8], and PLUTO[12] have measured inclusive muon production with momentum cutoff between .9 and 1.05 GeV given by the range in their hadron absorbers. Most of the QED background is removed by acoplanarity and missing mass requirements, the remaining contributions can be calculated. Contributions from inclusive J/Ψ production have been measured at PLUTO and found to be small[17]. Data are corrected for hadron punchthrough and decay. Since the momentum of the muon is high, both reactions

(1) twoprongs

$$e^+e^- \to \mu^\pm + 1 \text{ charged particle} + \text{missing energy}$$
$$p_\mu \gtrsim 1 \text{ GeV/c}$$

(2) multiprongs

$$e^+e^- \to \mu^\pm + \geq 2 \text{ charged particles}$$
$$p_\mu \gtrsim 1 \text{ GeV/c}$$

are expected to have only small charm content, at least at low CM energies.

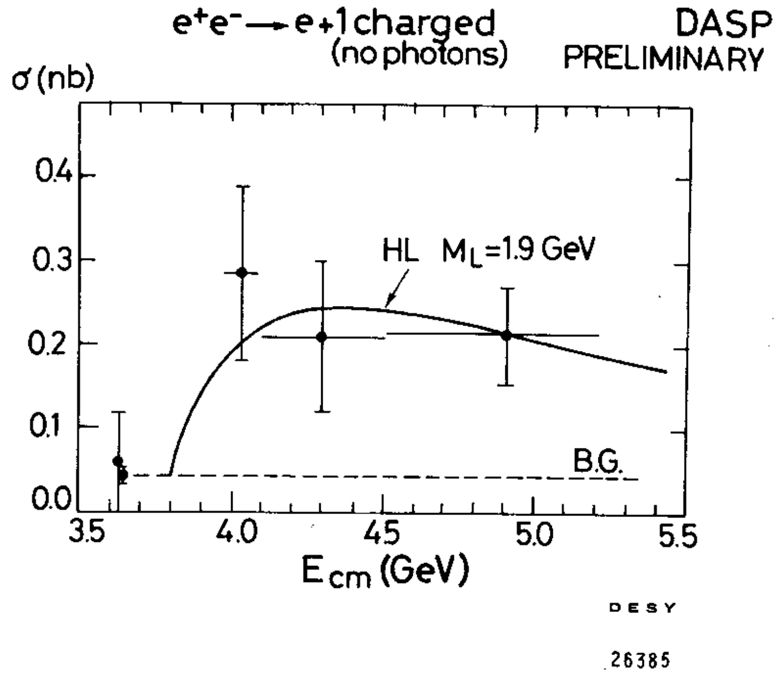

Fig. 2a DASP[10], inclusive electron production in twoprong events without photons as a function of CM energy. The dotted line is the calculated background[29].

In fact DASP has measured the momentum distribution of electrons in multiprong events[10]. This distribution which is mainly attributed to charm decay dies off for momenta beyond 1 GeV/c (Fig. 1). Possible charm content for momenta p > 1 GeV/c has been estimated from these data and found to be only a few percent of the total electron distribution for CM energies between 4 and 5 GeV[18]. These estimates are model dependent and sizable contributions from charm decay especially in the multiprong data cannot be excluded on these grounds. As will be shown later (section V,1) there are however other indications that charm contributions are in fact low.

Fig. 2b shows all existing data on reaction (1) and (2). Data are corrected for acceptance and scaled to the same momentum cut of $p_\mu \geq 1$ GeV/c (see figure captions for more details). All data are in good agreement. The curves are fits to the PLUTO data assuming production and decay of a pair of heavy leptons of mass 1.9 GeV/c^2 with massless neutrinos and V-A coupling (standard model). In the twoprong case the fit extrapolates very nicely into the high energy point at 7 GeV. For multiprongs, the 7 GeV data are higher than expected, probably due to charm contributions at these energies[8,18].

It should be noted that already from these data the mass of the heavy lepton can be determined as 1.9 ± .1 GeV/c^2. I will come back to this point later.

3. Dilepton Events

A very clean - and historically the first[6] - signature for heavy leptons are events of the type

(3) $e^+e^- \to \mu^\pm e^\mp$ + missing energy.

There are only small contributions from QED, e.g.due to the channel $e^+e^- \to \mu\mu ee$ with one μe pair lost in the detector. The background from simultaneous hadron punchthrough and electron misidentification can be kept relatively small even with moderate lepton identification. There are two sets of data available from PLUTO[13] and SLAC-LBL[1,6,7] which are complementary in the sense that the SLAC-LBL data have considerably higher statistics whereas the PLUTO data are very clean:

SLAC-LBL	190 μe - events	(46 background)	3.6 GeV $\leq \sqrt{s} \leq$ 7.8 GeV
PLUTO	23 μe - events	($\leq$2 background)	3.6 GeV $\leq \sqrt{s} \leq$ 5.0 GeV

An example of a PLUTO μe event is given in Fig. 3. Fig. 4a shows the SLAC-LBL cross-section for reaction (3) as a function of energy. As in the μ inclusive case, the data are well represented by the full curves based on a heavy lepton with mass between 1.8 and 2.0 GeV/c^2. The PLUTO results, shown in Fig. 4b, are in good agreement with the standard model (full curve).

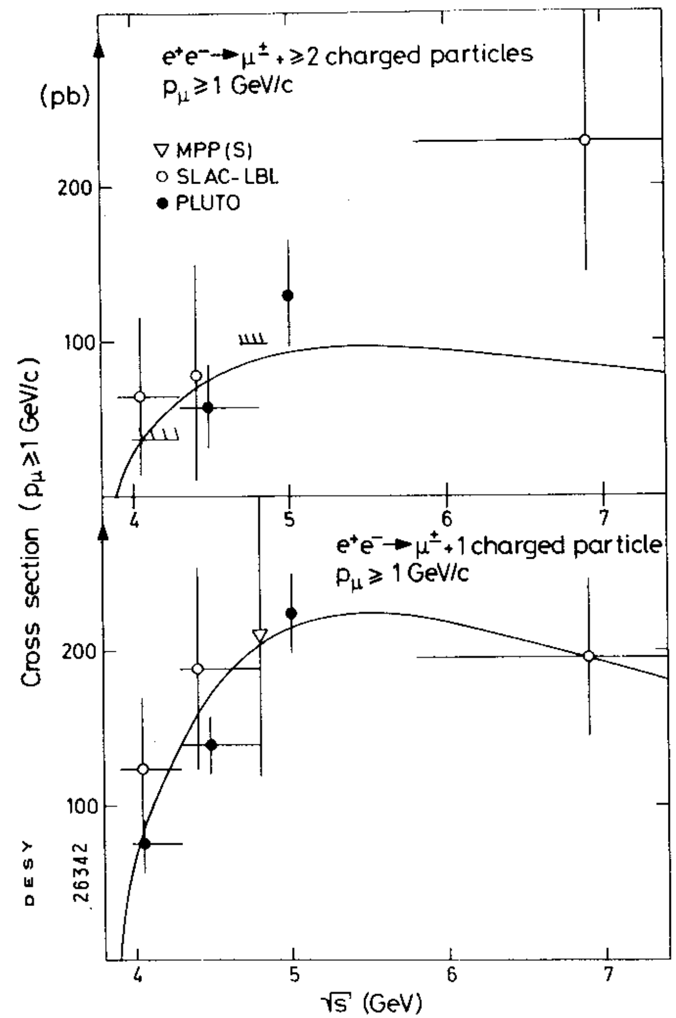

Fig. 2b MPP(S), SLAC-LBL, and PLUTO[8,9,12,13], inclusive muon production in the 4 to 7 GeV CM energy range. The SLAC-LBL data are scaled to the 1 GeV/c momentum cut using factors of .637, .744, .925 for $\sqrt{s}$ = 4.05, 4.4, 6.9. This assumes V-A and approximate cancellation of the difference between PLUTO and SLAC-LBL in acoplanarity and missing mass cuts. The MPP(S) data are for $p_\mu \geq 1.05$ GeV/c, extrapolated to the full solid angle assuming an isotropic distribution of muons. The full curve is a fit to the PLUTO data using the standard model[29].

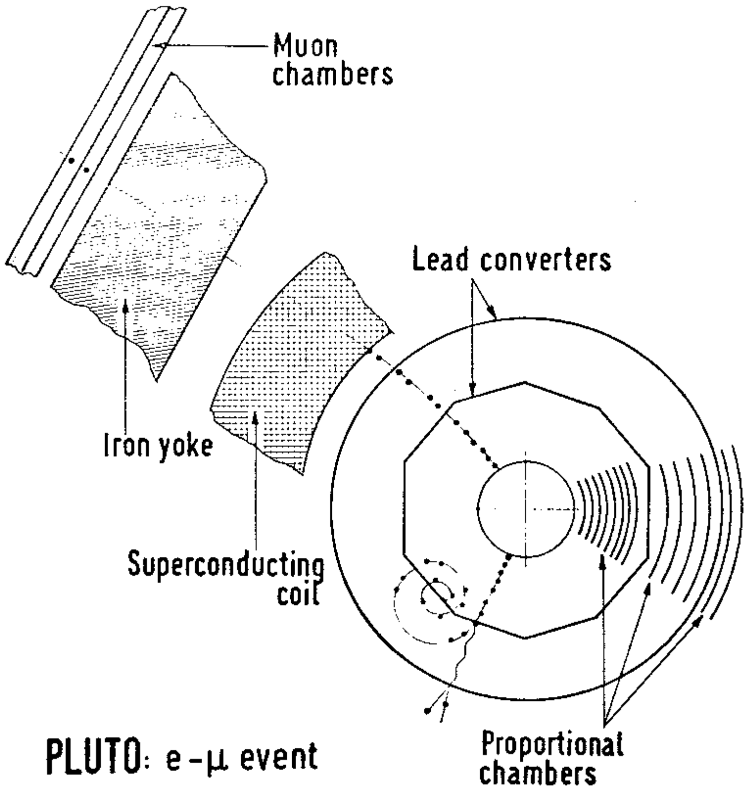

Fig. 3 PLUTO, example of a μe event.

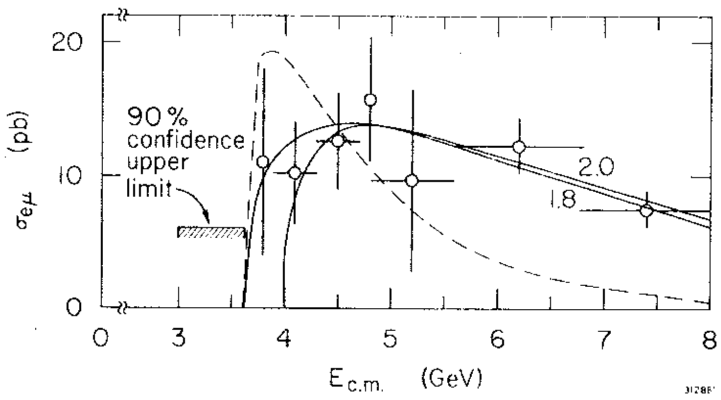

Fig. 4a SLAC-LBL[1], observed μe cross section as a function of CM energy. The full curves are fits for heavy leptons of mass 1.8 and 2.0 GeV(otherwise standard). The dashed line includes a form factor[29].

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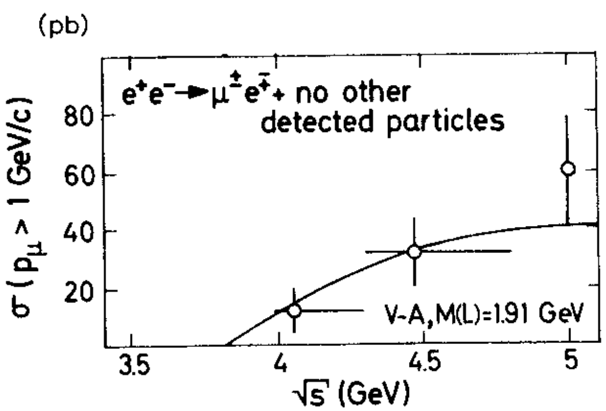

Fig. 4b PLUTO[13], μe cross section for $3.6 \leq \sqrt{s} \leq 5.0$ GeV[29]. Cross sections are given for muon momenta > 1 GeV/c and have been corrected for acceptance and efficiency.

IV EVIDENCE FOR AND PROPERTIES OF A NEW HEAVY LEPTON

Looking at all data presented in section III let me try and answer the following questions:

- Is there a common source for all data?
- If so, is it really some kind of heavy lepton and what are its properties?

1. Threshold Behaviour

As shown in section III, the energy dependence of the cross-sections for

μ inclusive twoprongs

e inclusive twoprongs

μe events

is similar and each well compatible with the expected threshold behaviour for a heavy lepton. This is also true for μ inclusive multiprongs near threshold.

2. Momentum Distribution

If the observed leptons originate from the decay of heavy leptons, their decay characteristics should be completely independent of the special type of event.

$$e^+e^- \to \tau^+\tau^-, \quad \tau^+ \to \mu^+\nu\bar{\nu}, \quad \tau^- \to \text{something}$$

In particular, the lepton momentum distributions in reactions (1), (2), and (3) should be the same. Moreover, the shape of the distributions can be calculated (e.g. Ref.5).

Figs.5 to 9 show momentum distributions for both electrons and muons for all event classes. In all figures, the full lines represent fits to the data with the standard assumptions for heavy leptons.

The comparison is convincing: all data show in fact the same characteristics

- the spectra are relatively hard (compared to charm Fig. 1)
- they are independent of the specific final state
- they are all well described by 3-body decay of the standard heavy lepton model
- 2-body decay is ruled out.

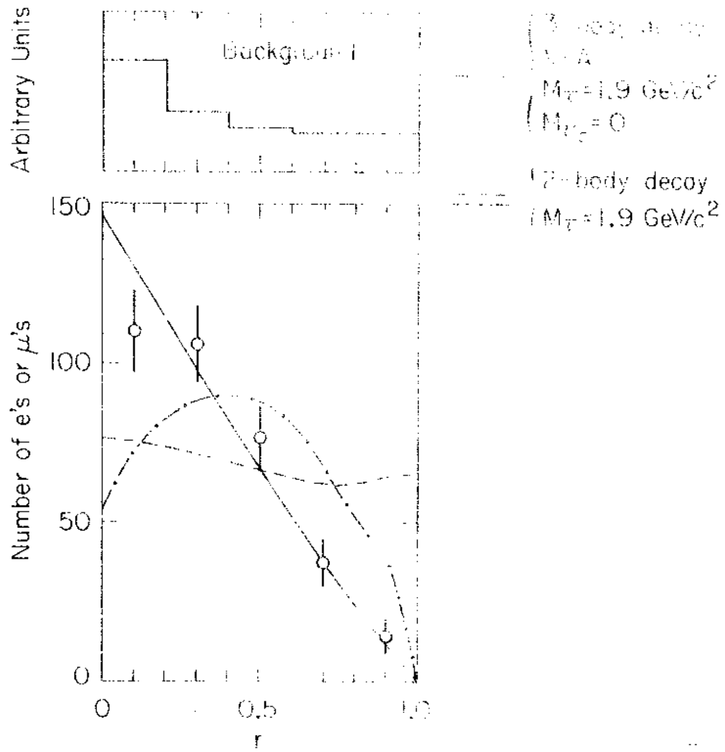

Fig. 5 SLAC-LBL[1], distribution of the scaled momentum

$$r = \frac{p - .65}{p_{max} - .65}, \ p \ (GeV/c)$$

for $3.8 \leq \sqrt{s} \leq 7.8$ GeV. The dash and dash-dot curves are for 2-body decays of bosons without and with spin correlations (see Ref.1 for details)[29].

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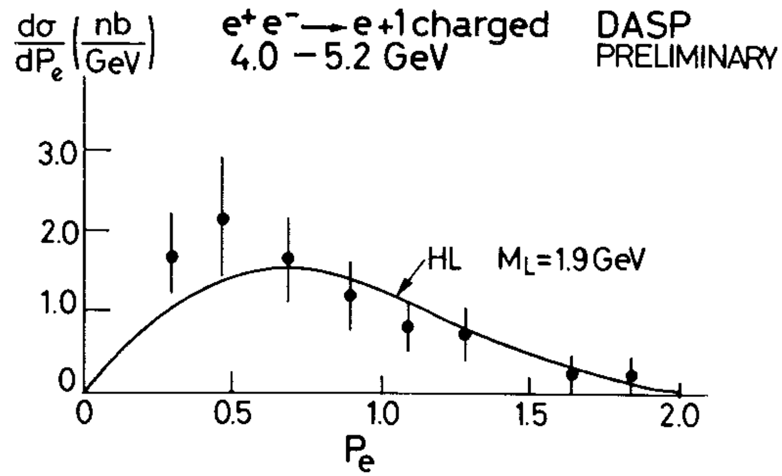

Fig. 6 DASP[10], momentum distribution of the electron in inclusive twoprong events[29].

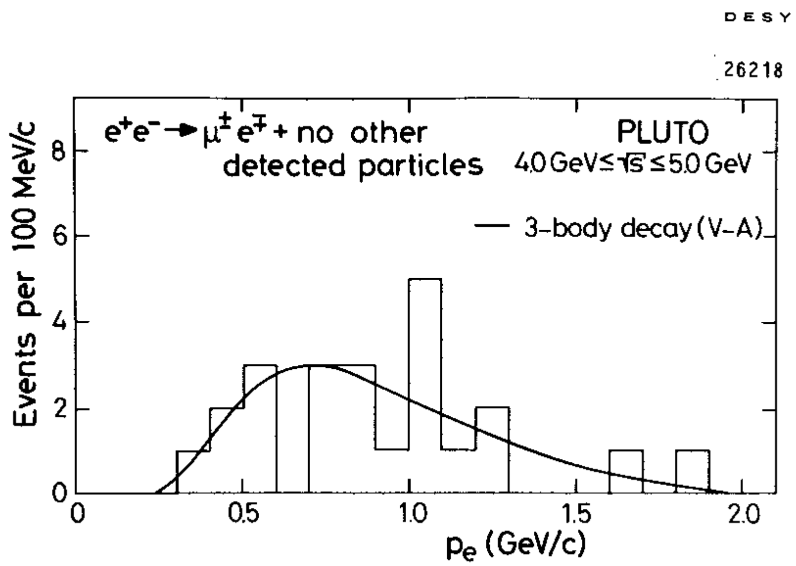

Fig. 7 PLUTO[13], momentum distribution of the electron in μe events[29].

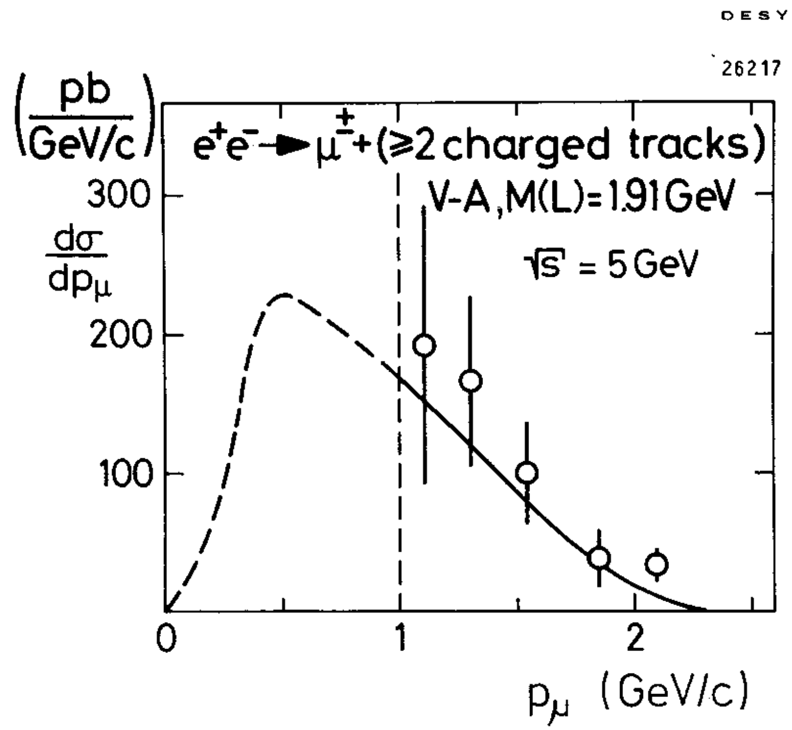

Fig. 8 PLUTO[12], momentum distribution of the muon in inclusive multiprong events at $\sqrt{s}$ = 5 GeV[29].

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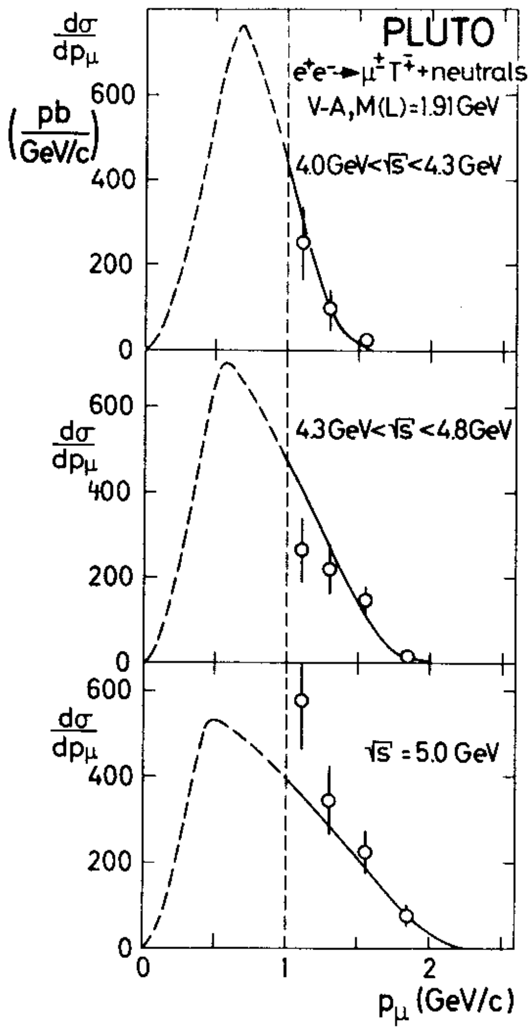

Fig. 9 PLUTO[12], momentum distribution of the muon in inclusive twoprong events for three different energy bins[29].

3. Pair Production of Heavy Particles

So far pair production of two heavy particles was assumed. This is in fact supported by the threshold behaviour of the cross-sections shown in section III.

There are two other quantities, which yield even stronger arguments, the momentum of the lepton and the collinearity angle between the two leptons in μe events. All three quantities or combinations of them have also been used to determine the mass of the pair produced particle.

a. Momentum Boost

Let us turn again to Fig. 9 showing the momentum distribution of the inclusive muons for different energy intervals. The momentum boost expected from elastic production and decay of a pair of fixed mass particles is clearly displayed in the data. Quantitatively, the expected shift of the endpoint is very well reproduced.

b. Shrinking Collinearity

Another manifestation of the Lorentz boost would be, that the decay products of the two heavy leptons are forced back to back with increasing energy[6,7]. This is nicely demonstrated in Fig. 10 for the μe events from SLAC-LBL[1]. The collinearity distribution of the two leptons is in fact shrinking with increasing energy, again in good agreement with the quantitative predictions of the standard model.

c. Heavy Lepton Mass

The mass of the new heavy lepton has been estimated in different ways using the energy dependence of the cross-section, the momentum spectrum, and the collinearity distribution of the leptons in $e\mu$ events or combinations of these quantities[1,12]. A conservative average with minimal assumptions yields

$$M_\tau = 1.9 \pm 0.1 \text{ GeV/c}^2$$

for pointlike spin 1/2 particles, V ± A and a neutrino mass less than 1 GeV/c^2. For more restrictive assumptions of V-A and massless neutrino (which seem to be justified as we will see), the best value is[12]

$$M_\tau = 1.91 \pm 0.03 \text{ GeV/c}^2.$$

The error does not include systematic uncertainties.

4. Undetected Particles

The high missing mass of twoprong events (typically MM^2 > 3 (GeV/c^2)^2) and the large missing energy (typically > $\sqrt{s}/2$) already suggest the presence of at least two undetected particles (or one with high mass). Furthermore, from the momentum spectra we concluded

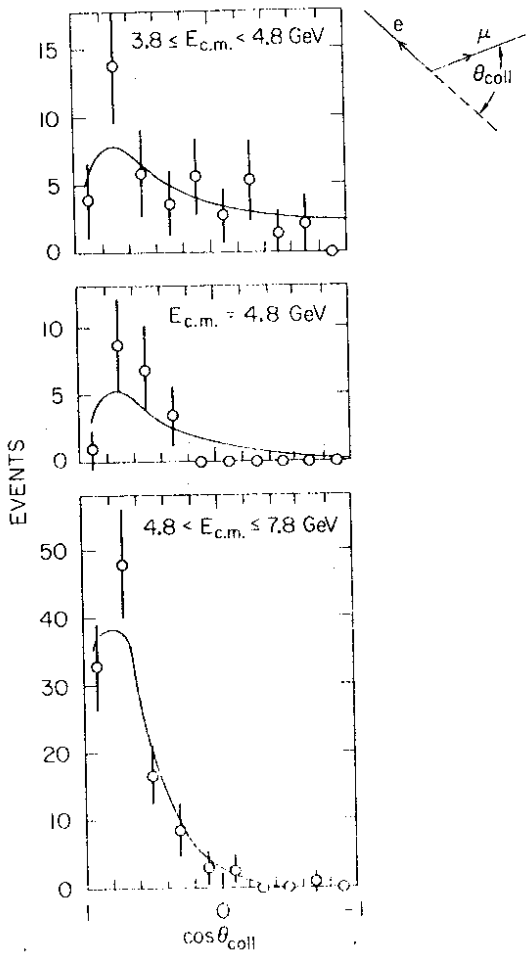

Fig. 10 SLAC-LBL[1], collinearity distribution of the two leptons in eμ events at different energies[29].

that the leptons are accompanied by two other particles.

To determine the nature of those undetected particles experimentally, let us consider reactions of the type

$$(4) \quad e^+e^- \to \mu e + X$$

where X are ≥ 2 charged particles, $\geq 2\pi^0$'s, or $\geq 2\gamma$'s. Of course, these events should be absent, if the standard heavy lepton hypothesis was right. In fact, from upper limits on these processes the probability can be estimated[7] that the μe events are faked by events of type (4) with X escaping the detector. PLUTO gives an upper limit of 9% (90% C.L.) including the most dangerous case, where two K^0's are produced[13] (charmed D meson decay).

Consequently, in most of the events the additional particles have to be neutrinos or neutrons. From the shape of the momentum distribution, upper limits can be set on the mass of the neutral particles involved. The numbers are (95% C.L.)

$m_\nu < 600$ MeV SLAC-LBL[1]

$m_\nu < 500$ MeV PLUTO[12]

for the standard hypothesis. The result is valid for any combination of V and A coupling. Note that this excludes the neutron as a possible third particle.

5. Branching Ratios

a. Leptonic Decays

From the cross-sections of reactions (1) to (3) all branching ratios (BR) involved can be determined. The muon data from PLUTO yield the following set of values[13]:

$BR(\tau \to e\nu\nu) = .14 \pm .04$ (V-A)
$.13 \pm .04$ (V+A)

$BR(\tau \to \mu\nu\nu) = .15 \pm .03$ (V-A)
$.19 \pm .04$ (V+A)

$BR(\tau \to 1\text{prong}) = .70 \pm .10$

$BR(\tau \to \geq 2\text{prong}) = .30 \pm .10$

To determine these numbers, the standard hypothesis was used. Note that the mass dependence is small and only BR (μ) depends strongly on V ± A. The SLAC-LBL muon data yield leptonic branching ratios of[1]

$$BR(\tau \to e\nu\nu) \sim BR(\tau \to \mu\nu\nu) \sim .18 \pm .05$$

From preliminary electron data, the electron branching ratio seems to be somewhat higher[19].

The DASP group quotes a preliminary value of .17 for the electron branching ratio[10]. Both DASP and SLAC-LBL assume the standard model with a oneprong branching ratio of .85.

In summary, the leptonic branching ratio seems to be equal for electrons and muons and of the order of .15 to .20. The measured multiprong contribution of about .3 is higher than theoretically expected. It is however possible that charm multiprongs are artificially increasing this number (compare section V,1).

b. Hadronic Decays

As indicated in Table I a sizable fraction of the τ decay should be hadronic with one charged particle in the final state. From the difference of BR ($\tau \to$ 1prong) and the leptonic BR we can estimate

$$BR\ (\tau \to 1\ \text{hadron}) \sim 30\% - 40\%$$

as expected theoretically. Furthermore, the ratio σ (μ + 1 charged hadron (+ photons))/σ (μe) has been determined experimentally. Preliminary ratios of 1.6 ± .7 from PLUTO[20] and 1.4 ± .7 from SLAC-LBL[19] are in fairly good agreement with the expected value of about 2.

If the (τ-ν) couples to the usual Cabibbo weak current, decays into π, ρ, A_1, and K should occur with predictable relative rates (Table 1). In particular, the kaon decay should be suppressed by $\sin^2\Theta_c \sim .05$. DASP has determined

$$\frac{\sigma\ (eK^\pm)}{\sigma\ (e\pi^\pm)} = \begin{cases} .06 \pm .06 & (3.99 < \sqrt{s} < 4.52\ \text{GeV}) \\ .14 \pm .14 & (4.52 < \sqrt{s} < 5.2\ \text{GeV}) \end{cases}$$

from twoprong events[10] in accordance with the prediction.

To look for a possible decay into the A_1, PLUTO has searched for events of the type

(5) $e^+e^- \to \mu$ + 3 charged particles + no photons

From 7 candidate events fulfilling the kinematical requirements of the chain

$$e^+e^- \to \mu + A_1 + \text{missing energy}$$
$$A_1 \to \pi\rho^0, \quad \rho^0 \to \pi\pi$$

the preliminary upper limit is[20]

$$BR\ (\tau \to A_1\nu) < .06 \quad (95\%\ \text{C.L.})$$

to be compared with an expectation of about .07.

c. Rare Decays

PLUTO has found only one candidate in the sample of reaction (5) with the invariant mass of the 3 charged particles close to 1.9 GeV/c^2 and their energy close to the beam energy, which yields a preliminary upper limit of[20]

$$BR\ (\tau \to 3\ \text{charged particles}) \leq .01 \quad (95\%\ \text{C.L.})$$

This result includes the extremely important case

BR ($\tau \to$ 3 charged leptons)	$\leq$ .01	PLUTO[20] 95% C.L.
	$\leq$ .006	SLAC-LBL[1] 90% C.L.

which bears on the conservation of lepton numbers and will be discussed later. In the same context, upper limits on the semileptonic branching ratio are important which have been determined from the absence of μe + 'something' events in the PLUTO detector[13]

$$BR\ (\tau \to e + \text{charged part.}) + BR\ (\tau \to \mu + \text{charged part.}) < .04$$
$$BR\ (\tau \to e + \text{photons}) + BR\ (\tau \to \mu + \text{photons}) < .12$$
$$(90\%\ \text{C.L.})$$

Possible electromagnetic decay modes of the τ have been investigated. SLAC-LBL quotes an upper limit (90% C.L.) for[1]

$$BR\ (\tau \to e + \gamma) + BR\ (\tau \to \mu + \gamma) < .06.$$

Similar results are obtained in the PLUTO group[21].

6. Leptonic Nature and Weak Decay Structure

It has been pointed out by many authors how the leptonic nature of the new particle - pointlike spin 1/2 - could be tested experimentally[22,23]. The cross-section for the production of a pair of pointlike spin 0 particles (e.g.Higgs bosons) is given by

$$\sigma_{HH} = 1/4\ \sigma_{\mu\mu} \cdot \beta^3 \qquad \text{(spin 0)}$$

in contrast to

$$\sigma_{\tau\tau} = \sigma_{\mu\mu} \cdot \frac{3\beta - \beta^3}{2} \qquad \text{(spin 1/2)}$$

and

$$\sigma_{11} = 3/4\ \sigma_{\mu\mu} \cdot \beta^3 \qquad \text{(spin 1)}$$

The inclusive muon data from PLUTO are incompatible with the first assumption, since they lead to inconsistencies in the branching ratios (BR ($\tau \to \mu\nu\nu$) $\sim$ 100%!)[12]. Spin 1 cannot easily be excluded. Spin 1/2 is in perfect agreement with the data.

One way to reveal the structure of the weak decay of the τ is to determine the hadronic decays into ρ, A_1, and π as predicted for instance from a V-A interaction[3,4,5]. The experimental knowledge in this area is still very poor (section IV,5). Data are compatible with the standard model but certainly not conclusive.

On the other hand, attempts have been made to determine the structure of the $\tau - \nu_\tau$ coupling from the momentum distribution in leptonic decays, which is fairly well known (section IV,2). Fig. 11 indicates fits to the data of SLAC-LBL[1], assuming V-A with different neutrino masses (full curves)and V + A coupling (dashed curve). Obviously, the χ^2 for V + A is bad - less than 5% probability even if the low energy data point is neglected. For the PLUTO data again V-A gives a better fit - 30% χ^2 probability compared to 7% for V + A.

In conclusion, V-A is clearly favoured by the data, though one might be reluctant to exclude V + A in view of systematic uncertainties which may still be present.

V EXPLANATIONS OTHER THAN HEAVY LEPTONS

So far everything seems to be in good agreement with the heavy lepton hypothesis. But to what extent are other explanations really excluded?

1. Charm

The μe events could be due to leptonic decays of charmed mesons c

$$c \to \begin{pmatrix} e \\ \mu \end{pmatrix} \nu$$

This is excluded by the decay spectra, which are incompatible with 2 body decay.

They could also originate from semileptonic decay of a charmed meson pair

$$e^+e^- \to c\bar{c}\ (X) \quad \begin{cases} \to \mu\nu + \text{hadrons} \\ \to e\nu + \text{hadrons} \end{cases}$$

where the hadrons and X escape the detector. As shown in section IV no more than 9% of the data could be due to this source.

This upper limit also holds for the inclusive lepton data if one assumes comparable branching ratios ($\sim$ 20%) for $\tau \to e\nu\nu$ and

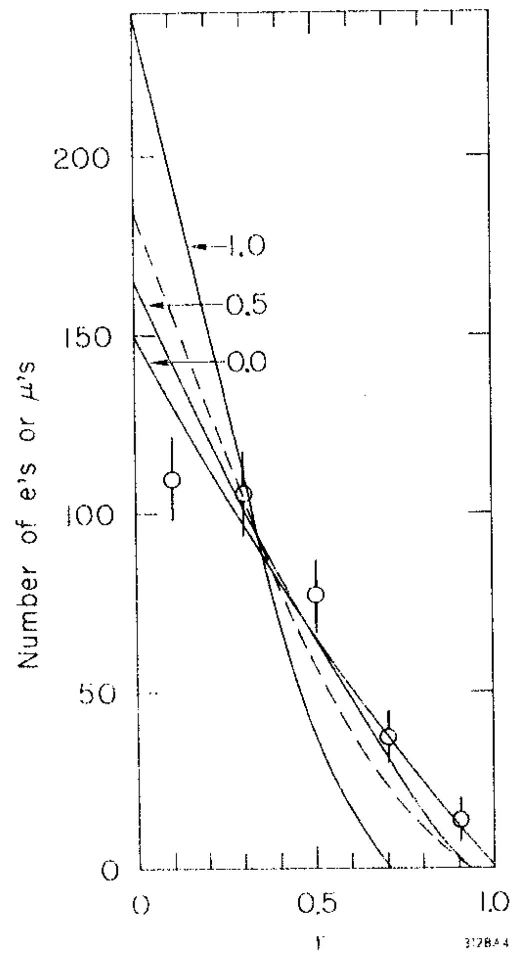

Fig. 11 SLAC-LBL[1], distribution of the scaled momentum r compared to different hypothesis. The solid curves are for the standard model, V-A coupling, with the neutrino mass indicated in the figure. The dashed curve is for V+A coupling and massless neutrino[29].

$c \to e\nu$ + hadrons. A comparison of the fraction of lepton momenta above 1 GeV/c from "charm" (Fig. 1) and "heavy leptons" (Figs. 6 to 9) yields a similar result.

Since charm events would be concentrated in the multiprong channel, the above limits would allow for nearly half of all multiprong data to be due to charm production. From the muon spectrum (Fig. 8) however this is hardly conceivable, unless one assumes that most of these charm events are due to elastic production of charmed mesons decaying into three light particles

$$c \to e\ \nu\ K^o.$$

This would imply an improbably high branching ratio for this charm decay mode. Also the K^o signal expected under these assumptions is not present in the data.

In conclusion charm can be ruled out as a major contribution to the μe and μ inclusive twoprong events. It is unlikely that a large fraction of the multiprong signal (p_μ > 1 GeV/c) between 4 and 5 GeV originates from charm.

2. Higgs Bosons

Higgs bosons proposed as a possible explanation of the data[23] are excluded by spin considerations (section IV,6).

3. Quarks

Attempts to explain the data by lepto-quarks[24] or integer charge quarks[25] cannot be ruled out by present limits on neutral current and semileptonic decays (see section VI). However the form of the decay spectra argues against the cascade decays involved in these schemes.

VI WHAT KIND OF HEAVY LEPTON

So far we have only considered the standard sequential heavy lepton. Many other ideas have been formulated. It is far beyond the scope of this paper to discuss all these models. Let me instead quickly go through some rough classification:

1. Minimal Theories

Recently, the question has been discussed whether minimal assumptions with just one additional charged lepton $L^\pm$ (no neutral partner) could explain the heavy lepton data[26]. Due to lepton number mixing, this model leads to neutral current contributions with branching ratios:

$$BR\ (L \to \binom{e}{\mu} + \text{hadrons}) \quad \sim .30$$

$$BR\ (L \to 3 \text{ charged leptons}) \quad \sim .05$$

which is excluded by the data (section IV.5)

2. Ortholeptons and Paraleptons

Llewellyn Smith has proposed a classification for models of new leptons with old lepton numbers[27]. Ortholeptons are particles with the quantum number of an old lepton of the same charge, whereas paraleptons are those with the quantum number of the oppositely charged electron or muon.

In the ortholepton case, a neutral current coupling can occur and, like in the minimal theories - produce semileptonic and three charged lepton decays[28]. The strength of this coupling depends on the model, which does not allow a general conclusion.

For paraleptons the case is much clearer[4]. There are no neutral current contributions and everything is exactly like in the standard model. The only difference is a factor of 2 in the statistical weight of muon and electron decay. Consequently for the electron type lepton $E^\pm$

$$BR\ (E^- \to \bar\nu_e\ e^-\ \bar\nu_e)/BR\ (E^- \to \bar\nu_e\ \mu^-\bar\nu_\mu) = 2$$

whereas for the muon type lepton this ratio is 0.5.

Experimentally, electronic and muonic branching ratios are similar, certainly not different by a factor 2 (section IV.5). In addition, SLAC-LBL has measured relative ee, $\mu\mu$, and μe cross-sections[1] and finds

$$\frac{\sigma\ (ee)}{\sigma\ (e\mu)} \sim \frac{\sigma\ (\mu\mu)}{\sigma\ (\mu e)} \sim .5 \pm .3$$

in agreement with the sequential lepton prediction.

In summary, paraleptons are disfavoured by the data. Ortholeptons are neither supported nor definitely excluded.

3. Sequential Leptons

We are back to our starting point, the standard model of sequential heavy leptons. As we have seen throughout the discussion, data are in good agreement with all predictions.

VII CONCLUSION

There is overwhelming evidence for the existence of a new particle which has all properties of a new heavy lepton. Charm is ruled out as a major source of the data.

The "standard model" of a new sequential heavy lepton of mass 1.9 GeV/c^2 is in good agreement with all existing data.

More data are required from future experiments to further clarify the properties of the particles and interactions involved:

(i) Is the new particle really pointlike, is its spin really 1/2?

(ii) What is the structure of the weak current, what are the exact π, ρ, A_1, K branching ratios, what is the lepton number and mass of the associated neutrino?

(iii) What is the lifetime of the new particle?

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