SLAC-PUB-2699
February 1981
(T/E)

REVIEW OF NEW EXPERIMENTAL UPPER LIMITS ON FORBIDDEN DECAY MODES OF THE TAU LEPTON†*

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ABSTRACT

This paper presents a review of experimental upper limits on the branching fractions for various forbidden decay modes of the tau lepton. These are modes which cannot occur in the conventional model in which the tau and its associated neutrino have a unique, conserved lepton number. The limits are based on data acquired by the Mark II Detector Collaboration at SPEAR.

†To be published in the Proceedings of the Workshop on Weak Interactions as Probes of Unification, Virginia Polytechnic Institute and State University, Blacksburg, December, 1980.
*Work supported by the Department of Energy under contract DE-AC03-76SF00515.

I. INTRODUCTION

When we presented this paper at the Workshop on Weak Interactions as Probes of Unification, we reviewed some of the current and much of the proposed research on the tau lepton and its associated neutrino. However most of that material has been published elsewhere.[1-4] Therefore we will restrict this written version to a review of new experimental upper limits[5] on the branching fractions of various tau decay modes which are forbidden by the sequential lepton model[1] of the tau. In that model the tau and its associated neutrino have a unique, conserved lepton number. Hence, in that model, a decay mode of a τ^- or a τ^+ must contain a ν_τ or a $\bar{\nu}_\tau$ respectively. The new results reviewed here are from data collected by the Mark II Detector Collaboration at the SPEAR electron-positron facility.

II. GENERAL SEARCH METHOD

If the τ^- and ν_τ have a unique, conserved lepton number, there are many forbidden decay modes. Some of the simpler forbidden decay modes which do not contain hadrons are:

$$\begin{aligned}
&\tau^- \to e^- + \gamma \\
&\tau^- \to \mu^- + \gamma \\
&\tau^- \to e^- + e^+ + e^- \\
&\tau^- \to e^- + e^+ + \mu^- \\
&\tau^- \to e^- + \mu^+ + \mu^- \\
&\tau^- \to \mu^- + \mu^+ + \mu^- \;;
\end{aligned} \qquad (1)$$

and some simple, forbidden, hadron-containing, decay modes are:

$$\begin{aligned} &\tau^- \to e^- + \pi^o \\ &\tau^- \to \mu^- + \pi^o \\ &\tau^- \to e^- + K^o \\ &\tau^- \to \mu^- + K^o \\ &\tau^- \to e^- + \rho^o \\ &\tau^- \to \mu^- + \rho^o \end{aligned} \tag{2}$$

Reference 5 contains a discussion of the possible theoretical implications of the existence of some of these decay modes.

We searched for the decay modes listed in Eqs. (1) and (2) using data acquired by the Mark II Detector Collaboration at SPEAR. This data was in the center of mass energy range of 3.9 GeV to 6.7 GeV; and contained 48,108 produced $\tau^+\tau^-$ pair. A produced $\tau^+\tau^-$ pair is a pair that would have been detected if the apparatus had 100% detection efficiency for all decay modes of the τ.

We selected events from this data sample which had the following properties:

(a) 2, 3, or 4 charged tracks;

(b) total charge = 0 for 2 or 4 track events;

(c) total charge = ± 1 for 3 track events;

(d) any number of photons; and

(e) the 2 charged track events have an acoplanarity angle[6] greater than 5^o.

Such a sample includes the basic signature

$$
\begin{array}{llll}
e^+ + e^- \rightarrow & \tau^+ & + & \tau^- \\
& \downarrow & & \downarrow \\
& \text{1 charged track} & & \text{1 or 3 charged track} \\
& \text{allowed decay modes} & & \text{forbidden decay modes} \\
& \text{such as} & & \text{such as} \\
& e^+ + \nu_e + \bar{\nu}_\tau & & e^- + \gamma \\
& \text{or} & & \text{or} \\
& \mu^+ + \nu_\mu + \bar{\nu}_\tau & & \mu^- + \gamma \\
& \text{or} & & \text{or} \\
& \pi^+ + \bar{\nu}_\tau & & e^- + e^+ + e^- \\
& & & \text{or} \\
& & & e^- + \rho^0 \\
& & & \quad \hookrightarrow \pi^+ + \pi^-
\end{array}
\tag{3}
$$

The charge reversed reactions were also used of course. The sample containing a total of three charged tracks allowed us to use events in which the three charged particles in a forbidden decay such as $e^-+e^++e^-$ were detected, but the track from the allowed decay was not detected.

III. EXAMPLE: SEARCH FOR $\tau^- \rightarrow \mu^- + \gamma$

The search method for a specific forbidden decay mode depended on the mode. We shall use as an example the search method for the mode

$$\tau^- \rightarrow \mu^- + \gamma \tag{4}$$

From the sample defined by requirements a.-e., we selected events of the type

$$e^+ + e^- \rightarrow x^\mp + \mu^\pm + 1 \text{ or more photons} \tag{5}$$

Here x is an e, μ, or charged hadron. We suppose that a μ-γ combination comes from the reaction and decay sequence

$$\begin{aligned} &e^+ + e^- \rightarrow \ell^+ + \ell^- \\ &\ell^- \rightarrow \mu^- + \gamma \qquad ; \end{aligned} \tag{6}$$

where the $\ell^\pm$ have an unknown mass m_ℓ. If this was true

$$E_\mu + E_\gamma = E_b \tag{7}$$

where E_μ, E_γ, and E_b are the μ energy, γ energy, and beam energy respectively. The mass m_ℓ is given by

$$m_\ell = \left[m_\mu^2 + 2E_\gamma(E_\mu - p_\mu \cos\theta_{\mu\gamma})\right]^{\frac{1}{2}} \tag{8}$$

where p_μ is the muon momentum, m_μ is the muon mass, and $\theta_{\mu\gamma}$ is the angle between the momenta of the μ and γ.

In Eq. (8) the quantity with by far the largest measuring uncertainty is E_γ. Therefore we calculated

$$E_{\gamma,\text{ predicted}} = E_b - E_\mu \tag{9}$$

and

$$D = \left| E_{\gamma,\text{ predicted}} - E_{\gamma,\text{ measured}} \right| / E_{\gamma,\text{ predicted}} \tag{10}$$

The quantity D is normally distributed with a sigma of $0.13/\sqrt{E_{\gamma,\text{ predicted}}\ (\text{GeV})}$. Therefore we defined

$$Z = D\sqrt{E_{\gamma,\text{ predicted}}} \qquad ; \tag{11}$$

and selected for further study all events of the form of

Eq. (5) with

$$Z < 0.20 \tag{12}$$

We also required

$$E_{\gamma,\ \text{predicted}} > 0.23E_b \tag{13}$$

to avoid problems associated with poorly measured or poorly identified low energy photons. The criteria of Eqs. (12) and (13) reduced the event sample to the m_ℓ mass spectrum[8] of Fig. 1. Many of the events come from the electromagnetic reactions

$$e^+ + e^- \rightarrow \mu^+ + \mu^- + \gamma \tag{14a}$$

$$e^+ + e^- \rightarrow \mu^+ + \mu^- + \gamma + \gamma \tag{14b}$$

We eliminated many of these events by a set of electromagnetic background cuts[5]. For example, the μ^+, μ^-, γ in Eq. (14a) are coplanar, hence we required some noncoplanarity in the event. These cuts reduced the mass spectrum to that shown in Fig. 2.

The fundamental question is, of course, how many of these events have a mass m_ℓ compatible with the τ mass of 1782 MeV/c^2? Fig. 3, an expanded scale section of Fig. 2, answers this question. The smooth curve shows the calculated τ mass resolution function. There is no accumulation of events at the τ mass and only one event falls within the resolution function.

It is now easy to calculate an upper limit on the decay mode $\tau^- \rightarrow \mu^- + \gamma$. The detector acceptance for this mode, including the signature of Eq. (3) and the selection criteria, is 7.3%. Since one event was found inside the mass resolution function, the 90% confidence upper limit on the branching ratio is given by

$$B(\tau^- \to \mu^- + \gamma) \leq \frac{3.9}{96{,}216 \times .073} = 5.5 \times 10^{-4}$$

Here 96,216 is the number of produced τ's.

IV. RESULTS

Using methods analogous to the example described in the last section we searched for the decay modes listed in Eqs. (1) and (2). We did not find a statistically significant accumulation of events at the τ mass for any of the decay modes. Table I lists the 90% confidence upper limits on the branching fractions. We have also given the detection efficiency for each decay mode including the event selection criteria. Note that the larger upper limits are mostly due to smaller acceptances.

Hence we have not found any decay modes of the τ which violate the concept that the τ and its associated neutrino have a unique, conserved lepton number. This agrees, as do all other published results, with the τ being a sequential lepton.

The upper limits in Table 1 are factors of 10 or more smaller than previously measured upper limits[7]. This improvement comes chiefly from the large data sample. Since it is difficult to increase the detector acceptances by more than a factor of 2 or 3, any substantial reduction in these upper limits will require the acquisition of a yet larger data sample.

A detailed paper on how these limits were obtained is in preparation, authored by the Mark II Detector Collaboration members. This work was supported by the U. S. Department of Energy under Contract Nos. DE-AC03-76SF00515 and W-7405-ENG-48.

Table 1. For the decay modes of the τ lepton listed in column 1, this table gives the upper limits on the branching fractions with 90% confidence, column 2. The detector acceptance for each mode is given in column 3; and the number of events found within the τ mass resolution is given in column 4.

Decay Mode $\tau^- \to$	Upper Limit on Branching Fraction	Efficiency(%)	Number Events Found at τ Mass
$\mu^-+\gamma$	5.5×10^{-4}	7.3	1
$e^-+\gamma$	6.4×10^{-4}	6.3	1
$\mu^-+\mu^++\mu^-$	4.9×10^{-4}	4.9	0
$e^-+\mu^++\mu^-$	3.3×10^{-4}	7.3	0
$\mu^-+e^++e^-$	4.4×10^{-4}	9.3	1
$e^-+e^++e^-$	4.0×10^{-4}	10.1	1
$\mu^-+\pi^o$	8.2×10^{-4}	2.9	0
$e^-+\pi^o$	$21. \times 10^{-4}$	3.5	3
μ^-+K^o	$10. \times 10^{-4}$	2.4	0
e^-+K^o	$13. \times 10^{-4}$	3.1	1
$\mu^-+\rho^o$	4.4×10^{-4}	5.5	0
$e^-+\rho^o$	3.7×10^{-4}	6.5	0

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5. K. G. Hayes, Ph.D.Thesis, Stanford Univ. (1981), unpublished.
6. The acoplanarity angle is defined by $\arccos\left[(\underset{\sim}{u}_1 \times \underset{\sim}{u}_b) \cdot (\underset{\sim}{u}_2 \times \underset{\sim}{u}_b)\right] \Big/ \left[|\underset{\sim}{u}_1 \times \underset{\sim}{u}_b| \; |\underset{\sim}{u}_2 \times \underset{\sim}{u}_b|\right]$ where $\underset{\sim}{u}_1$, $\underset{\sim}{u}_2$, $\underset{\sim}{u}_b$, are unit vectors in the direction of each of the final particles and of the beam respectively. This eliminates a very large background from $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$.
7. M. L. Perl, Proc. of 1977 Int. Symp. on Lepton and Photon Interactions at High Energies (DESY, Hamburg, 1977) p. 145.
8. The quantity m_ℓ is calculated using $E_{\gamma,\ \mathrm{predicted}}$ in Eq. (8).

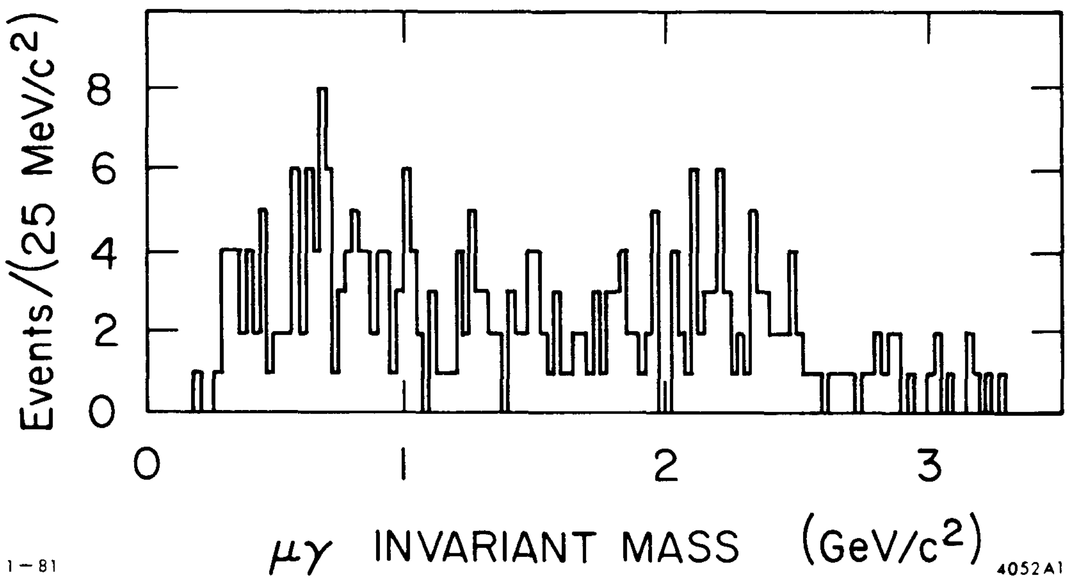

Fig. 1. The $\mu\gamma$ invariant mass spectrum with the 5° acoplanarity angle cut and the photon energy cuts of Eqs. (12) and (13).

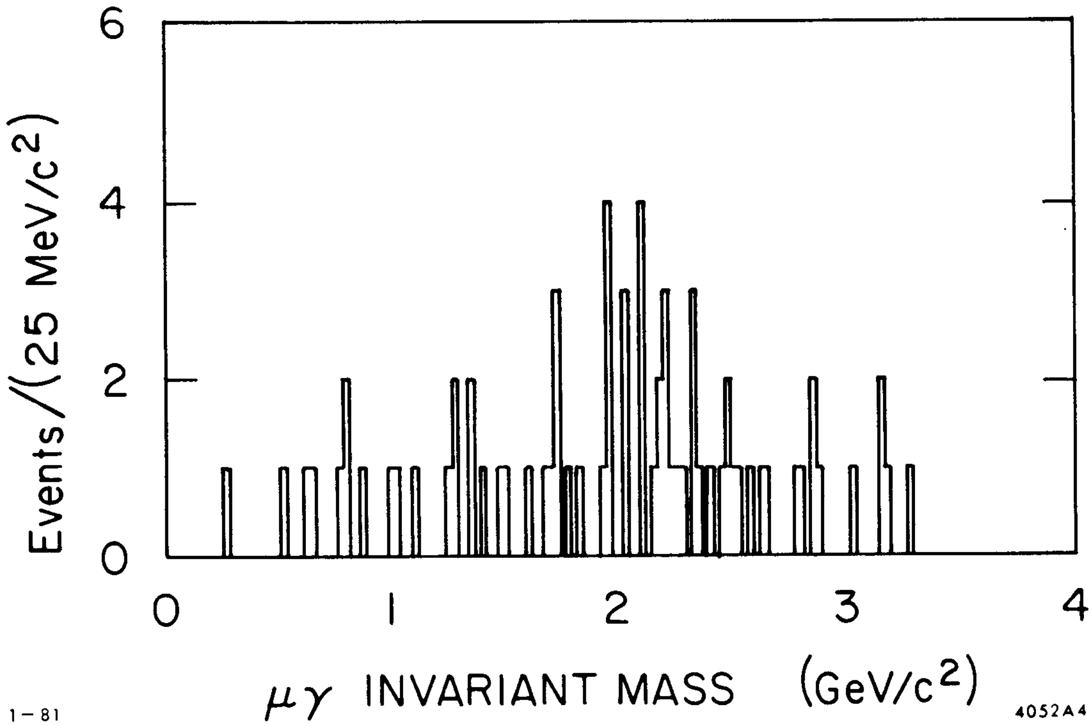

Fig. 2. The $\mu\gamma$ invariant mass spectrum with all cuts.

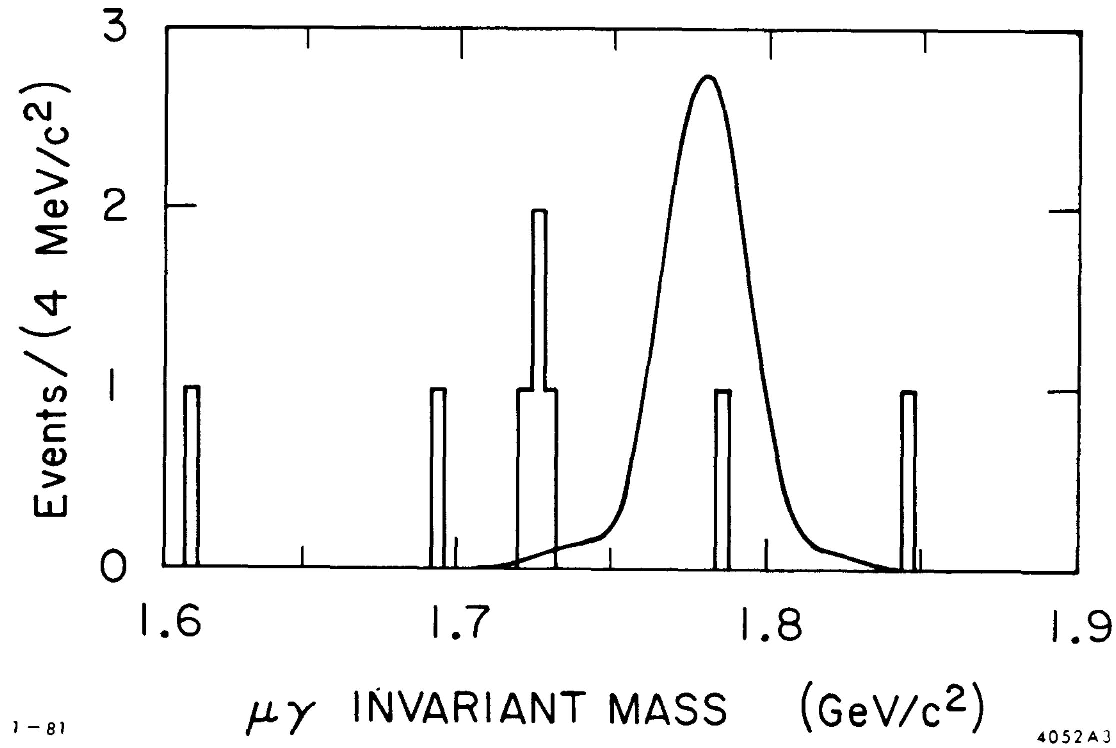

Fig. 3. The $\mu\gamma$ invariant mass spectrum in the neighborhood of the τ mass with all cuts. The smooth curve shows the expected τ mass resolution.