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TUTORIAL GUIDE TO THE TAU LEPTON AND CLOSE–MASS LEPTON PAIRS*

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ABSTRACT

This is a tutorial guide to present knowledge of the tau lepton, to the tau decay mode puzzle, and to present searches for close-mass lepton pairs. The text is minimal; the emphasis is on figures, tables and literature references. It is based on a lecture given at the 1988 International School of Subnuclear Physics: The Super World III.

1. HISTORY OF CHARGED LEPTON DISCOVERIES

Each of the known charged leptons, e, μ, and τ, was discovered through a different technique. The electron was discovered in the 1890's by Thomson[1] using a cathode ray tube. The muon was discovered in the 1930's by Neddermeyer and Anderson.[2]

The modern history of the search for heavier leptons using the signature

$$\begin{aligned} &e^+ + e^- \to L^+ + L^- , \\ &L^+ \to e^+ + \nu_e + \bar{\nu}_L , \\ &L^- \to \mu^- + \bar{\nu}_\mu + \nu_L , \end{aligned} \tag{1}$$

began at the Adone e^+e^- storage ring with the work of Bernardini *et al.*[3], Fig. 1, and of S. Orito *et al.*[4]

The tau was discovered in 1974–1975 at the SPEAR e^+e^- storage ring by Perl *et al.*[5] using the $e\ \mu$ signature, Fig. 2. In the period 1975–1978 the basic properties of the τ were established by numerous experiments at the SPEAR and DORIS rings. Since then the detailed properties of the τ have been measured by many experiments at the DORIS, PEP, PETRA, SPEAR, and TRISTAN rings.

No other charged leptons have been found,[6] Secs. 8, 9.

2. BASIC PROPERTIES OF THE τ

Almost all data on the τ comes from

$$e^+ + e^- \to \tau^+ + \tau^- , \tag{2}$$

through both γ and Z^0 s–channel exchange, Fig. 3. Up to the highest energy at which the τ has been detected, 56 GeV at TRISTAN, γ–exchange is the main amplitude.

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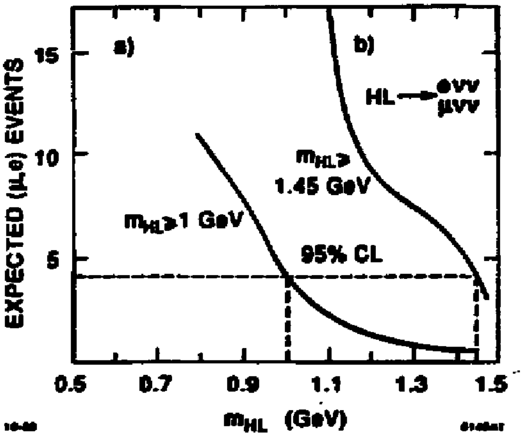

Fig. 1. Results of the search for a heavy lepton, called HL, by M. Bernardini *et al.*[3]

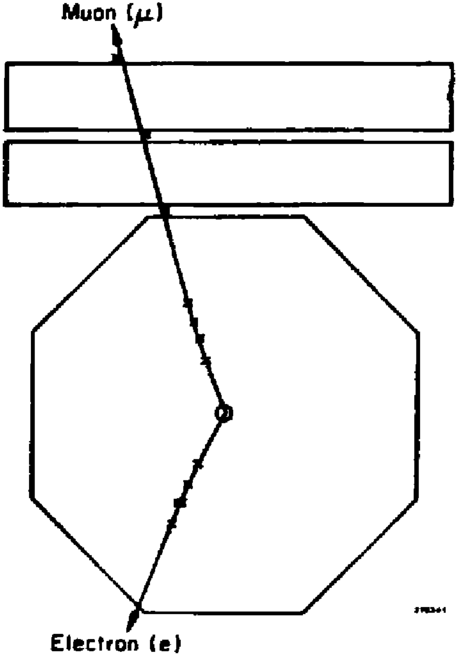

Fig. 2. An $e\ \mu$ of the type found by Perl *et al.*[6] using the Mark I detector at SPEAR.

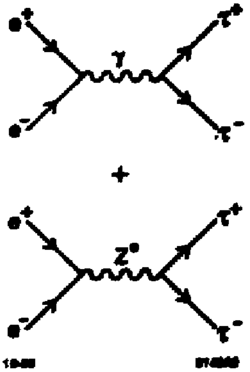

Fig. 3. Feynman diagrams for $e^+e^- \to \tau^+\tau^-$.

All existing data agrees with the τ being a spin 1/2 point particle of unit charge with the V–A weak interaction, and with no strong interaction. The mass based mostly on an old measurement[7] is

$$m_\tau = 1784 \pm 3\ \mathrm{MeV}/c^2\ . \tag{3}$$

The lifetime,[8] Sec. 6.2, is

$$\tau_\tau = (3.03 \pm 0.09) \times 10^{-13}\ s\ . \tag{4}$$

All known decay modes of the τ are consistent with τ lepton number conservation

$$\tau^- \to \nu_\tau + \text{ other particles} \tag{5}$$

No violations have been found, Table 1.

Table 1. Upper Limits on Branching Ratios for τ Decay Modes that would Violate τ Lepton Number Conservation. Limits at 90% Confidence Level. ℓ^- Means e^- or μ^-.

Decay Mode	Upper Limit	Experimental Group	Reference
$\tau^- \to e^-e^+e^-$	3.8×10^{-5}	ARGUS	H. Albrecht *et al.*, Phys. Lett. 185B, 228 (1987)
$e^-\mu^+\mu^-$	3.3×10^{-5}		
$\mu^-e^+e^-$	3.3×10^{-5}		
$\mu^-\mu^+\mu^-$	2.9×10^{-5}		
$\ell^-\ell^\mp\ell^\pm$	3.6×10^{-5}		
$e^-\pi^+\pi^-$	4.2×10^{-5}		
$\mu^-\pi^+\pi^-$	4.0×10^{-5}		
$e^-\rho^0$	3.9×10^{-5}		
$\mu^-\rho^0$	3.8×10^{-5}		
$\ell^\mp\pi^\pm\pi^-$	6.3×10^{-5}		
$e^-\pi^+K^-$	4.2×10^{-5}		
$\mu^-\pi^+K^-$	1.2×10^{-4}		
e^-K^{*0}	5.4×10^{-5}		
μ^-K^{*0}	5.9×10^{-5}		
$\ell^\mp\pi^\pm K^-$	1.2×10^{-4}		
$e^-\gamma$	2.0×10^{-4}	CRYSTAL BALL	S. Keh *et al.*, (1988) DESY 88-065 SLAC-PUB 4634 HEN-25
$e^-\pi^0$	1.4×10^{-4}		
$e^-\eta$	2.4×10^{-4}		
e^-K^0	1.3×10^{-3}	MARK II	K. G. Hayes *et al.*, Phys. Rev. D25, 2869 (1982)
μ^-K^0	1.0×10^{-3}		
$\mu^-\gamma$	5.5×10^{-4}		
$\mu^-\pi^0$	8.2×10^{-4}		
$e^-\pi^0$	2.1×10^{-4}		

The tau neutrino, ν_τ has never been directly detected. All its properties are deduced from τ decays, Eq. 5. The deductions are consistent with the ν_τ being a spin 1/2 point particle with the V–A weak interaction, and with no strong interaction. The 95% C.L. upper limit[9] on the mass is

$$m_{\nu_\tau} < 35 \text{ MeV}/c^2 \ . \tag{6}$$

3. τ DECAYS: THEORETICAL CONCEPTS AND BRANCHING FRACTION MEASUREMENTS

The decay of the τ takes place through W–exchange, Fig. 4. If the three fermion pairs, $(e^-, \bar{\nu}_e), (u^-, \bar{\nu}_\mu), (d, \bar{u})$ are treated equally the following branching fractions are predicted:

$$\begin{aligned} B_e &= B(\tau^- \to \nu_\tau e^- \bar{\nu}_e) = 20\% \ , \\ B_\mu &= B(\tau^- \to \nu_\tau u^- \bar{\nu}_\mu) = 20\% \ , \\ B_{had} &= B(\tau^- \to \nu_\tau \text{ hadrons}) = 60\% \end{aligned} \tag{7}$$

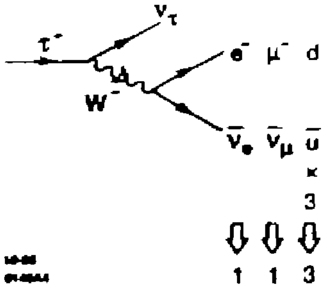

Fig. 4. Feynman diagram for τ decay.

Measurement gives:[8]

$$B_e = (17.6 \pm 0.4)\% \,, \qquad B_\mu = (17.7 \pm 0.4)\% \tag{8}$$

and by subtraction from 100%,

$$B_{had} = (64.7 \pm 0.6)\% \,.$$

The difference between the B's in Eqs. 7 and 8 is mostly caused by final state strong interactions in

$$\tau^- \rightarrow \nu_\tau + \text{ hadrons} \,. \tag{9}$$

The branching fraction B_i for mode i is given by

$$B_i = \Gamma_i/\Gamma \,, \tag{10}$$

where Γ_i and Γ are the decay widths for mode i and for the sum of all modes. The Γ_i's for the e and μ modes are exactly calculated[10] from weak interaction theory. The theory predicts

$$B_e/B_\mu = 0.973 \,, \tag{11}$$

and measurement, Eq. 8, agrees.

Some Γ's for modes containing hadrons can be calculated[11-18] from non-τ data. These modes include

$$\begin{aligned} &\tau^- \rightarrow \nu_\tau + \pi^- \,, \\ &\tau^- \rightarrow \nu_\tau + K^- \,, \\ &\tau^- \rightarrow \nu_\tau + \rho^- \,, \\ &\tau^- \rightarrow \nu_\tau + (4\pi)^- \,. \end{aligned} \tag{12}$$

At present there is no way to calculate the Γ_i for some hadron-containing modes such as

$$\tau^- \rightarrow \nu_\tau + (3\pi)^- \,. \tag{13}$$

The calculation of the total width for all hadron-containing modes, Γ_{had}, is difficult[14] and uncertain by 5 to 10%. Therefore at present calculations of all branching fractions

$$B_i = \frac{\Gamma_i}{\Gamma_e + \Gamma_\mu + \Gamma_{had}} \tag{14}$$

are uncertain by 5 to 10%.

4. τ DECAYS: WELL-MEASURED BRANCHING FRACTIONS

4.1 *Topological Branching Fractions*

The average measured values of the inclusive or topological, branching fractions into 1, 3, 5, or 7-charged particles are[8,15,16]

$$B_1 = (86.6 \pm 0.3)\% , \qquad B_5 = (0.10 \pm 0.03)\% ,$$
$$B_3 = (13.3 \pm 0.3)\% , \qquad B_7 \leq 0.019\% \quad , \qquad 90\% \text{ CL} . \qquad (15)$$

Thus, most decays have 1-charged particle, almost all the rest have 3-charged particles.

4.2 *Well-Measured One-Charged Particle Branching Fractions*

The well-measured 1-charged particle branching fractions are given in Table 2. The sum of these branching fractions is $(77.9 \pm 1.5)\%$. Comparing this sum to B_1 in Eq. 15, there must exist another 8 or 9% in poorly measured or unmeasured 1-charged particle modes, such as

$$\tau^- \rightarrow \nu_\tau + \pi^- + n\pi^0 \quad , \qquad n > 2 ,$$
$$\tau^- \rightarrow \nu_\tau + \pi^- + n\eta \quad , \qquad n > 0 . \qquad (16)$$

Table 2. Well-Measured One-Charged Particle Branching Fractions.

Symbol	Decay Mode	Branching Fraction (%)	Ref.
B_e	$\nu_\tau + e^- + \bar{\nu}_e$	17.6 ± 0.4	8
B_μ	$\nu_\tau + \mu^- + \bar{\nu}_\mu$	17.7 ± 0.4	8
B_π	$\nu_\tau + \pi^-$	10.8 ± 0.6	8
B_ρ	$\nu_\tau + \rho^-$	22.5 ± 0.9	8
$B_{\pi 2\pi^0}$	$\nu_\tau + \pi^- + 2\pi^0$	7.6 ± 0.8	17–19
B_{K1}	$\nu_\tau + mK + n\pi^0$ $\longrightarrow$ 1-charged particle $m \geq 1,\ n \geq 0,\ K = K^0$ or K^-	1.7 ± 0.3	20
	Sum of above	77.9 ± 1.5	

4.3 *Three-Charged Particle Branching Fractions*

The value $B_3 = (13.3 \pm 0.3)\%$ is better understood,[8] Table 3.

Table 3. Three-Charged Particle Branching Fractions.

Symbol	Decay Mode	Branching Fraction (%)
$B_{2\pi^-\pi^+}$	$\nu_\tau + \pi^- + \pi^+ + \pi^-$	6.7 ± 0.4
$B_{2\pi^-\pi^+n\pi^0}$	$\nu_\tau + \pi^- + \pi^+ + \pi^- + n\pi^0$, $n > 0$	5.0 ± 0.5
B_{K3}	$\nu_\tau + mK + n\pi^0$ $\longrightarrow$ 3-charged particles $m \geq 1,\ n \geq 0,\ K = K^0$ or K^-	0.9 ± 0.4
	Sum of above	12.6 ± 0.7

5. THE ONE–CHARGED PARTICLE DECAY MODE PROBLEM

5.1 *Use of Only Direct Branching Fraction Measurements*

Table 4 gives the sum of direct measurements compared with B_1. There is no problem with this restricted information.

Table 4. Summary of Direct Measurements of Branching Fractions of One–Charged Particle Modes Using Only One–Charged Particle Decays.

Type of Information	Row	Decay Mode	Branching Fraction (%)
Sum of well measured modes in Table 3	A		77.9 ± 1.5
Upper limit deduced	B	$\nu_\tau \pi^- 3\pi^0$	< 2.5
or estimated	C	$\nu_\tau \pi^- 4\pi^0 + \nu_\tau \pi^- 5\pi^0$	$\lesssim 4.$
in 1–charged	D	$\nu_\tau \eta$	< 0.3
particle decays	E	$\nu_\tau \eta n \pi^0$	< 2.1
	F	$\nu_\tau 2\eta$	< 1.4
Sum of rows B–F	G		$\lesssim 10.3$
Sum of A + G			$\lesssim 88.2 \pm 1.5$
1–charged particle topological B_1			86.6 ± 0.3

5.2 *Use of Theory and Other Data*

The 1–charged particle decay mode problem appears when theory[11–13] and other data are used to evaluate or set upper limits on the branching fractions in Rows B–F of Table 4. I paraphrase Sec. III of Ref. 21 to explain the use of theory. There are four methods

In method (a), a directly measured 3–particle or 5–charged particle branching fraction is used to set an upper limit on a 1–charged particle branching fraction by invoking strong isospin conservation. For example, direct measurement gives

$$B(3\pi^- 2\pi^+ \nu_\tau) = (0.051 \pm 0.020)\% ,$$

and strong isospin conservation requires

$$B(\pi^- 4\pi^0 \nu_\tau) \leq \frac{3}{4}\, B(3\pi^- 2\pi^+ \nu_\tau) ;$$

hence,

$$B(\pi^- 4\pi^0 \nu_\tau) \leq 0.06\% \quad , \qquad 95\%\text{C.L.} .$$

In method (b) the η decay mode

$$\eta \to \pi^+ + \pi^- + \pi^0 ,$$

is used in the direct measurement of an η containing mode.

In method (c) we calculate a 1–charged particle branching fraction using the conserved vector current rule and a corresponding e^+e^- cross section.

In method (d) the rule against a second class current forbids the decay mode

$$\tau^- \to \pi^- + \eta + \nu_\tau .$$

The results of these considerations are given in Table 5. The 10.3% upper limit in Row G of Table 4 is replaced by 2.7%.

Table 5. Values and Upper Limits of Branching Fractions for One–Charged Particle Modes Deduced from Theory and Other Measurements. The Sum Does Not Include Modes with $\nu_\tau \pi \eta n \pi^0$, $n > 2$.

Mode	Method	Value (%)	Upper Limit (%) 95% C.L.
$\nu_\tau \pi^- 3\pi^0$	c	1.0 ± 0.15	1.25
$\nu_\tau \pi^- 4\pi^0$	a		0.06
$\nu_\tau \pi^- 5\pi^0$	a		0.11
$\nu_\tau \pi^- \eta$	d		0.00
$\nu_\tau \pi^- \eta \pi^0$	c		0.24
$\nu_\tau \pi^- \eta 2\pi^0$	a		0.40
$\nu_\tau \pi^- \eta \eta n \pi^0$, $n \geq 0$	b		0.60
Sum			2.7

5.3 *The τ Decay Mode Problem*

The τ 1–charged particle decay mode problem appears when the upper limits from Table 5 are added to the well-measured branching fractions of Table 2. As shown in Table 6 about 6% of the 86.6% in B_1 is not explained.

Table 6. Branching Fractions for One–Charged Particle Decays.

Source of Information	Branching Fraction (%)
Sum of well-measured modes from Table 2	77.9 ± 1.5
Sum of 95% C.L. upper limits from Table 5	≤ 2.7
Sum of above	$\leq 80.6 \pm 1.5$
Topological branching fraction B_1	86.6 ± 0.3

6. DISCUSSION OF τ DECAY MODE PROBLEM

6.1 *Error Analysis*

The significance of the τ decay problem depends upon the validity of the error analysis. The validity has been examined in two recent paper: Hayes and Perl[8] and Hayes, Perl, and Efron.[22] The former paper uses Gaussian error analyses, the latter uses the much more general bootstrap analysis method, applied to the branching fractions:

$$\begin{aligned} &B_1 \text{ based on 11 measurements} ,\\ &B_e \text{ based on 10 measurements} ,\\ &B_\mu \text{ based on 16 measurements} ,\\ &B_\pi \text{ based on 7 measurements} ,\\ &B_\rho \text{ based on 6 measurements} . \end{aligned} \tag{17}$$

The Gaussian error analysis shows:

(*a*) The errors associated with an individual measurement by the experimenters who made the measurement are either about right or too large. Therefore the decay problem cannot be explained away by arbitrarily enlarging these errors.

(*b*) There is evidence for bias in the B_ρ measurements and hints of bias in other measurements in the sense that the individual measurements cluster more about their central value than their individual errors would predict. We cannot tell if this bias has shifted the central value from the true value.

(*c*) The Gaussian error analysis does not resolve the decay mode problem.

The bootstrap analysis method finds:

(1) The mean values of the branching fractions in Eq. 17 are similar to, but not identical to, the means found by the Gaussian analysis.

(2) The bootstrap method still shows the decay mode problem, but with smaller statistical significance compared to the Gaussian error analysis.

6.2 Comparison of B_e and B_μ with τ Lifetime

The τ lifeline, τ_τ, calculated[8] from B_e and B_μ, is

$$\tau_\tau \text{ (predicted)} = (2.87 \pm 0.04) \times 10^{-13} \text{ s} ,$$

compared to

$$\tau_\tau \text{ (measured)} = (3.03 \pm 0.09) \times 10^{-13} \text{ s} .$$

The difference

$$\tau_\tau\text{(measured)} - \tau_\tau \text{ (predicted)} = (0.15 \pm 0.10) \times 10^{-13} \text{ s} ,$$

is 1.5 standard deviations. This does not have enough significance to require B_e and B_μ to be larger than the values in Table 2.

6.3 Search for an Unconventional Explanation of the Decay Mode Problem

I don't know if unconventional physics in tau decay is the explanation of the decay problem, no satisfactory unconventional explanation has been found. Experiments have ruled out[22] the possibility that the missing 6% could come from η–containing modes. A recent idea of mine has failed,[23] the hypothesized existence of a second tau neutrino with mass close to m_τ.

7. FUTURE RESEARCH ON THE τ

There is much experimental research to be carried out on the τ:

(*a*) resolution of the 1–charged particle decay mode problem;

(*b*) modern measurements of m_τ and tests of V-A;

(*c*) more sensitive study of m_{ν_τ};

(*d*) detection and properties of ν_τ;

(*e*) devise a method to measure $g_\tau - 2$;

(*f*) precise studies of the known decay modes with respect to branching fractions and decay dynamics;

(*g*) study of strong interaction physics in the 1 GeV region.

Some of these goals have been discussed by Burchat,[24] Stroynowski[25] and Perl.[26]

8. CLOSE–MASS LEPTON PAIRS: CONCEPT

About two years ago I pointed out[27] that the standard e^+e^- search methods for heavy charged leptons using

$$\begin{aligned} e^+ + e^- &\to L^+ + L^- , \\ L^+ &\to \bar{L}^0 + \text{other particles} , \\ L^- &\to L^0 + \text{other particles} , \end{aligned} \tag{18}$$

assume that the L^0 mass, m_0, is much less than the L^- mass, m_-. Indeed most searches set

$$m_0 = 0 \ .$$

If m_0 is close to m_-, still with

$$m_0 < m_- \ ,$$

the detected energy, usually called visible energy, will be relatively small in the events described by Eq. 18. Defining the mass difference

$$\delta = m_- - m_0 \ , \tag{19}$$

the standard search methods fail[27] when $\delta \lesssim 4$ GeV/c^2. Stoker and I[28,29] have devised methods to search the $m_- - m_0$ region with δ values as small as 0.3 GeV/c^2.

Riles[30] has developed a different small–δ search method using the radiative process

$$e^+ + e^- \to L^+ + L^- + \gamma \ . \tag{20}$$

This suppresses the backgrounds from the two-virtual-photon processes.

$$e^+ + e^- \to e^+ + e^- + e^+ + e^-, \ e^+ + e^- + \mu^+ + \mu^- \ . \tag{21}$$

The small–δ problem also limits[27] the significance of searches for heavy charged leptons at $\bar{p}p$ colliders. These searches[31] use

$$\begin{aligned} &\bar{p} + p \to W^- + \text{other particles} \ , \\ &W^- \to L^- + \bar{L}^0 \ , \\ &L^- \to L^0 + \text{other particles} \ , \end{aligned} \tag{22}$$

and depend on a relatively large missing transverse momentum[32] in these events.

9. CLOSE–MASS LEPTON PAIRS AND LIMITS ON THE EXISTENCE OF NEW HEAVY CHARGED LEPTONS

Table 7. Publications on limits on new heavy lepton masses, m_- and m_0, when $m_0 \geq 0$.

Method	Lower limit on m_- (GeV/c^2) when $m_0 = 0$	Experiment	Figure	Reference
$e^+e^- \to L^+ + L^-$ at 29 GeV		Mark II	5	28, 29
$e^+e^- \to L^+ + L^-$ at 29 GeV		TPC	6	33
$e^+e^- \to L^+ + L^-$ at 56 GeV	27.6 , 95% C.L.	AMY	7	34
$e^+e^- \to L^+ + L^-$ at 56 GeV	27.6 , 95% C.L.	VENUS	8	35
$\bar{p}p \to W^- + \ldots$ $W^- \to L^- + \bar{L}^0$	41. , 90% C.L.	UA1	9	31, 32

Table 7 lists the published experiments on the existence of new heavy charged leptons where $m_0 > 0$ has specifically been considered in the publication. In the case of the experiments at TRISTAN, AMY[34] and VENUS,[35] and the UA1 result,[31] I also note the lower limit on m_- when $m_0 = 0$. The experiments at TRISTAN will explore smaller values of δ as luminosity is accumulated.

These limits are shown in Figs. 5–8 and the combined limits in Fig. 9.

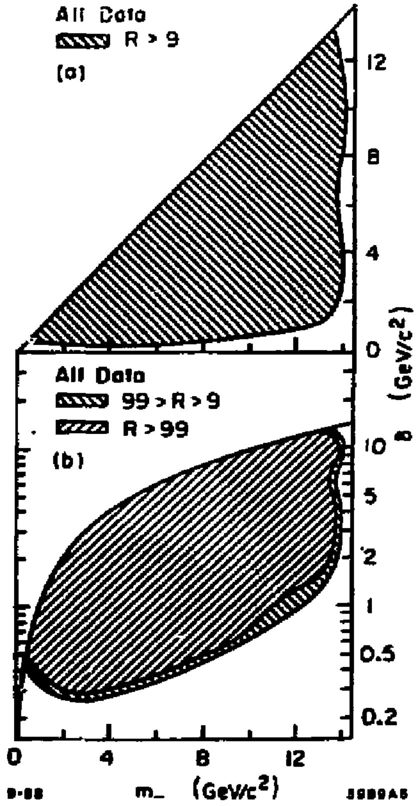

Fig. 5. L^-L^0 pairs are excluded from the hatched $m_-\delta$ region using 29 GeV e^+e^- data from the Mark II experiment at PEP, Ref. 29; $\delta = m_- - m_0$. The same results are shows (a) with a linear δ scale and (b) with a logarithmic δ scale. $R > 9$ means about 90% C.L.

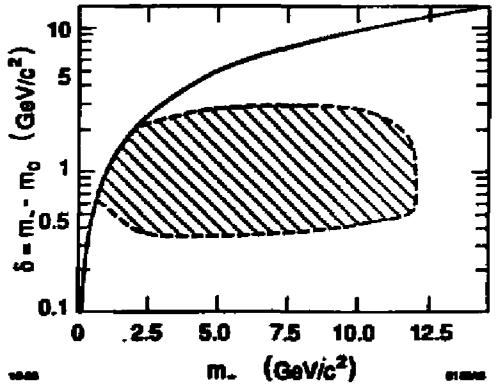

Fig. 6. $L^- - L^0$ pairs are excluded from the hatched $m_- - \delta$ region using 29 GeV e^+e^- data from the TPC experiment at PEP, Ref. 33. $\delta = m_- - m_0$. The boundary gives the 99% C.L.

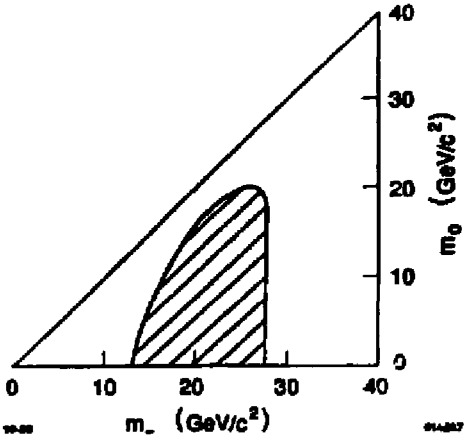

Fig. 7. $L^- - L^0$ pairs are excluded from the hatched $m_- - m_0$ region using 56 GeV e^+e^- data from the AMY experiment at TRISTAN, Ref. 34. The boundary gives the 95% C.L.

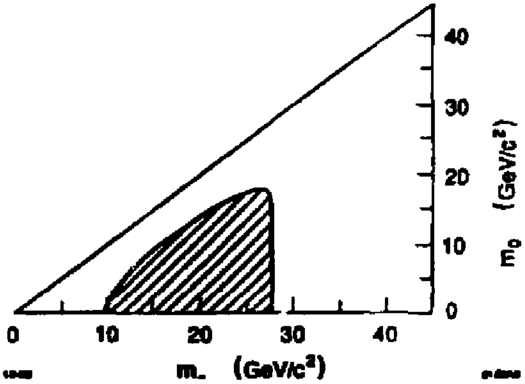

Fig. 8. L^-L^0 pairs are excluded from the hatched m_-m_0 region using 56 GeV e^+e^- data from the VENUS experiment at TRISTAN; Ref. 35. The boundary gives the 95% C.L.

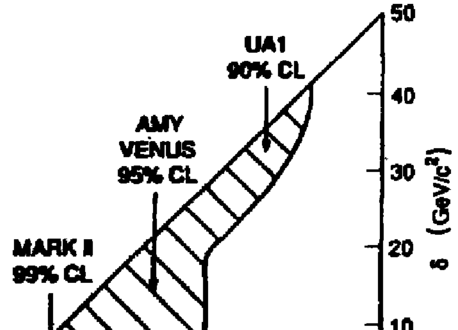

Fig. 9. Composite of $\bar{L}-L^0$ pairs excluded from the hatched $m_- - \delta$ region for: Mark II, Ref. 29; AMY, Ref. 34; VENUS, Ref. 35; UA1, Refs. 31 and 32.

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