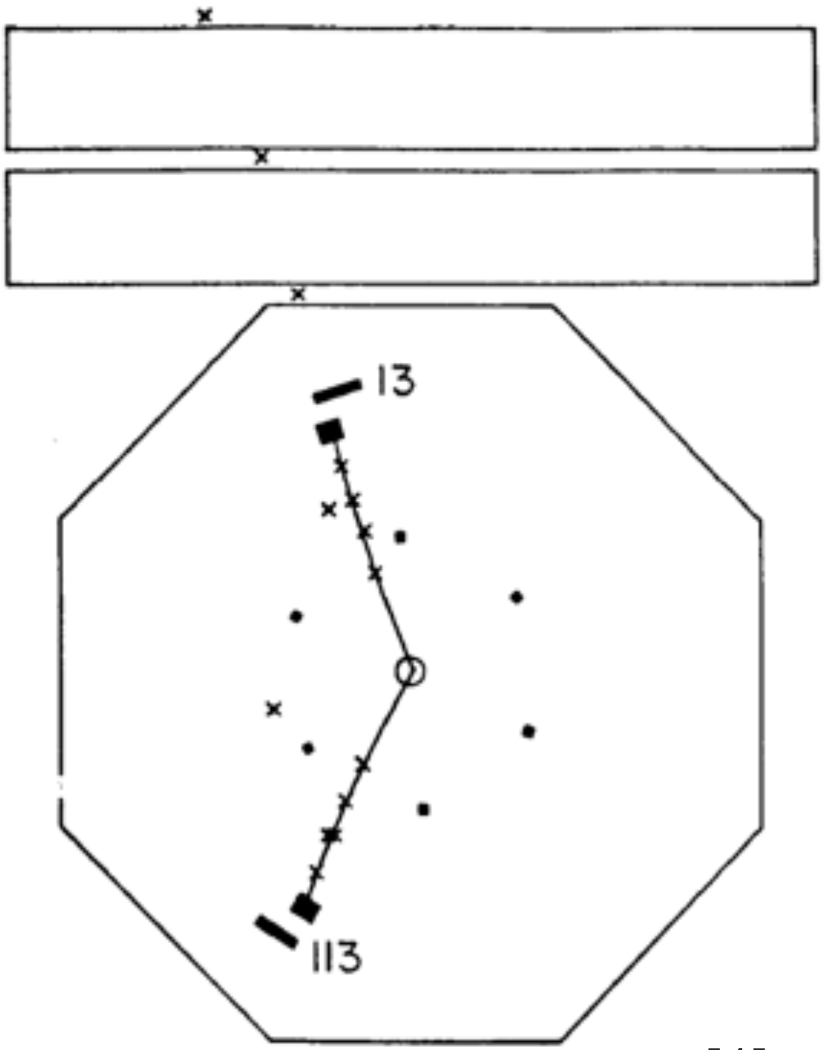
Discovery and Establishment of the τ Neutrino



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15th Recontres du Vietnam
5 August 2019

Introduction

- I have been asked to give an historical talk on the discovery and the establishment of the nature of the τ neutrino.
- For the most part, this talk will cover the period between 1975 and 1986.
- I am indebted to Alain Blondel for his talk “The Third Family of Neutrinos” at the 2018 History of the Neutrino Conference in Paris [2].

The Proposal (1)

- The discovery of the τ neutrino starts with the discovery of the τ lepton, and that starts with the 1971 proposal for the Mark I detector at SPEAR [3].

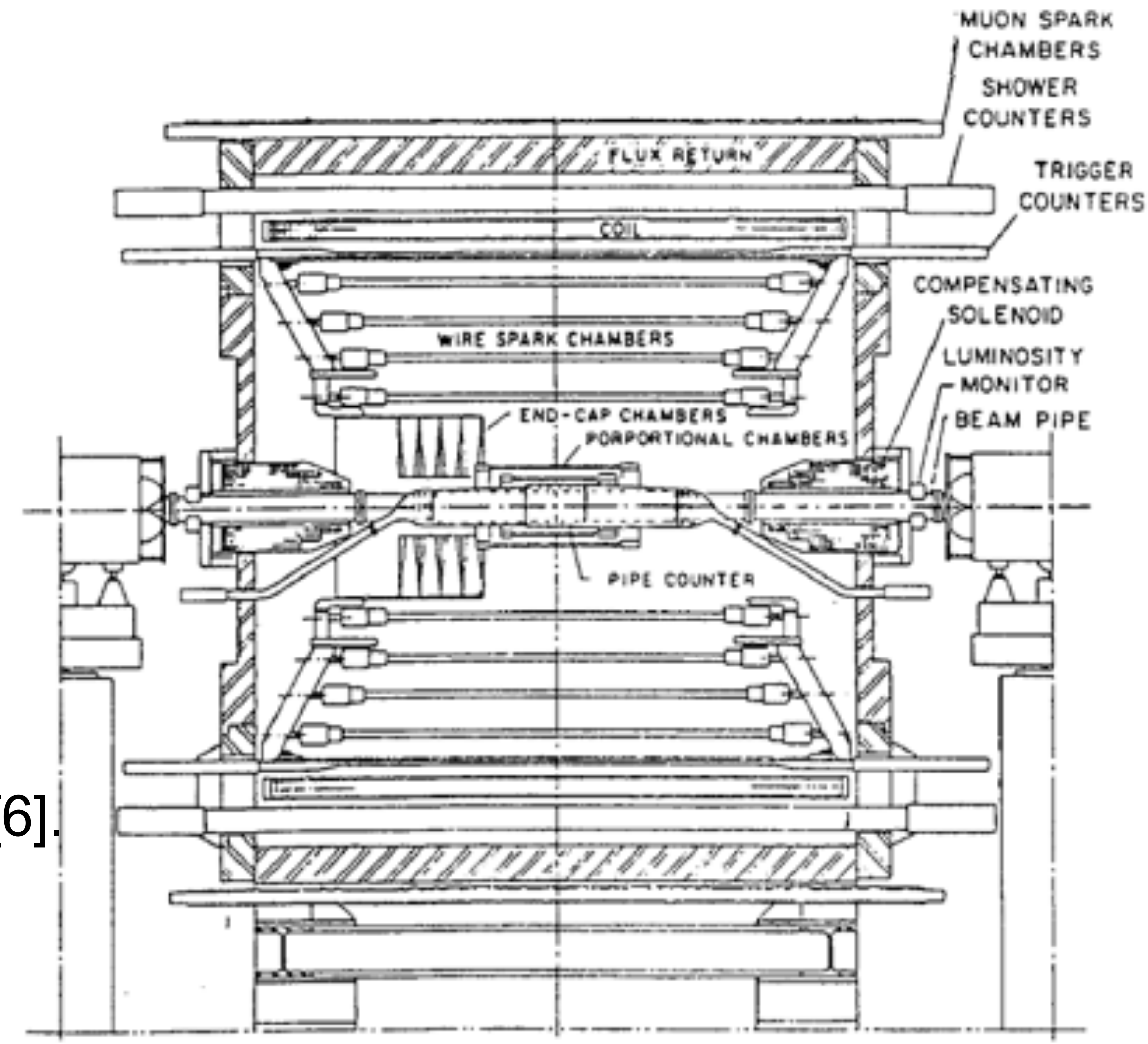
- The first 3 items were considered the real physics. The fourth item was considered Martin Perl's crazy idea.

The Proposal (2)

- In 1971, SLAC theorist Paul Tsai had made what turned out to be an amazingly accurate pre-QCD calculation of the decays of a sequential heavy lepton [4, 5].
  - A hypothetical 1.8 GeV heavy lepton would have about a 20% branching ratio into $e\nu\nu$ and $\mu\nu\nu$ and about a 9% branching ratio into $\pi\nu$.
- Thus, the proposal called for searching e^+e^- annihilation events for non-coplanar events with one muon and one electron, and no other activity, since there was no known process that could give a significant signal with this signature.

The Mark I Detector (pre-summer 1974)

- By today's standards, the detector was quite crude.
- Muons were identified by passing through the 20-cm iron flux return.
- The lead-scintillator shower counters had been scratched during construction and had a factor of 50 attenuation from one end to the other [6]. An electron was identified by a signal 4 times minimum ionizing.



- The probability that a hadron would be identified as a lepton was 18% for electrons and 20% for muons [7].

First Data 1974

- Martin Perl began looking at 2-prong data at 4.8 GeV C.M. energy in 1974. He made a table of all 2-prong events with each prong having p > 650 MeV and were noncoplanar by greater than 20°.

Particles \ N_γ	0	1	>1	0	1	>1
	Total charge = 0			Total charge = ±2		
$e-e$	40	111	55	0	1	0
$e-\mu$	24	8	8	0	0	3
$\mu-\mu$	16	15	6	0	0	0
$e-h$	20	21	32	2	3	3
$\mu-h$	17	14	31	4	0	5
$h-h$	14	10	30	10	4	6

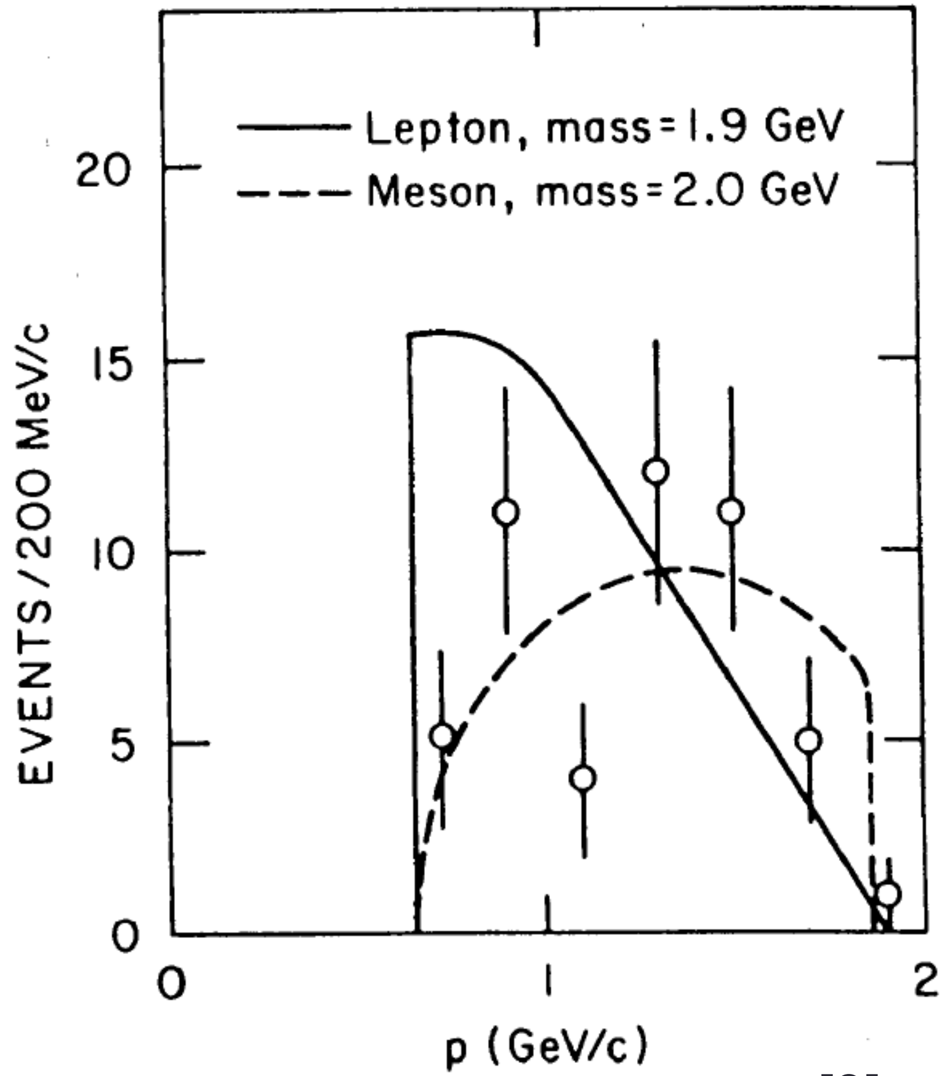
- The searched-for anomaly is in the red box.

First Data 1974-5

- A conservative estimate of the background from misidentifications and undetected particles was 4.7 events.
  - Even increasing the background to 7 events, the probability of it fluctuating to 24 events is less than 1 in 1,000,000.
- Perl challenged the Mark I collaboration to find any objection to his analysis for several months and no one could.
- We went public with talks at a series of conferences in the summer of 1975 [1, 8-12] and published the first paper in August 1975 [13].

First Data 1975

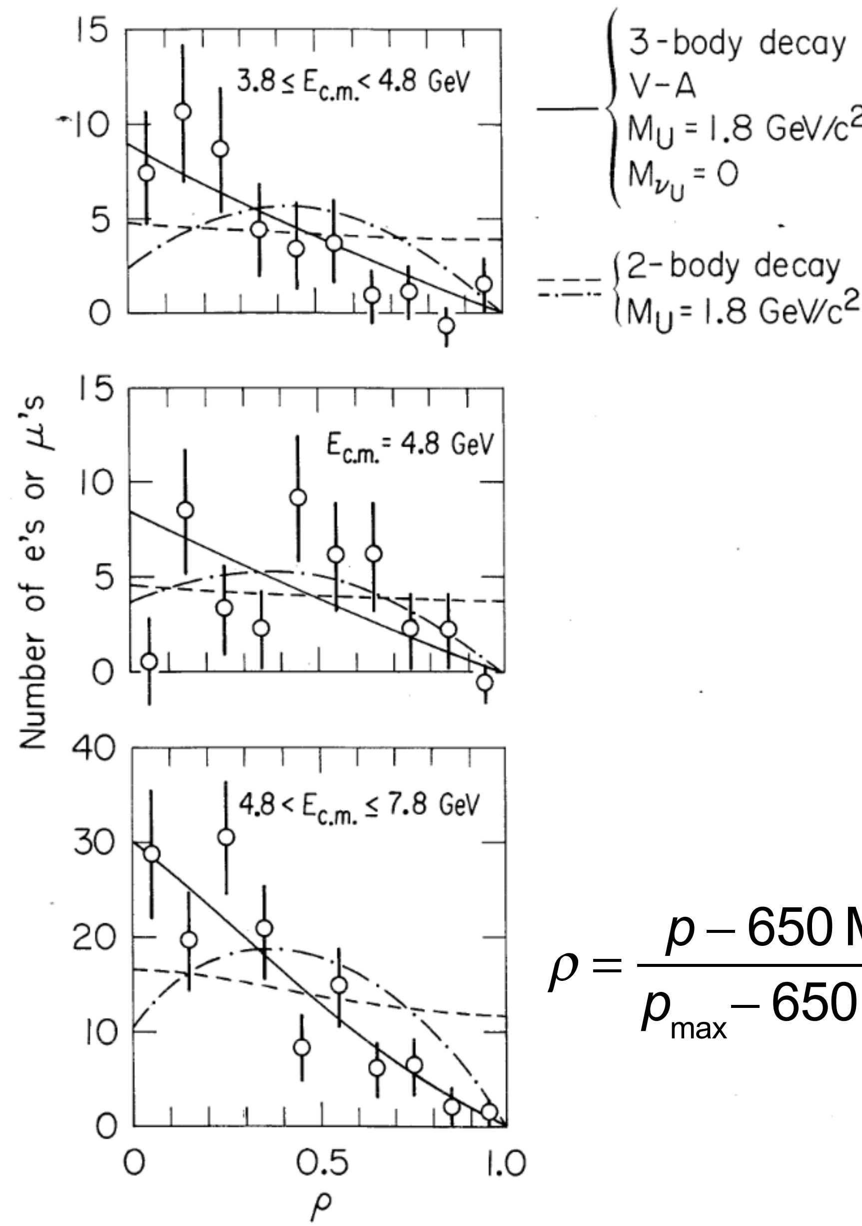
- The 24 $e^{\pm}\mu^{\mp}$ events were not consistent with any conventional process.
- However, there were 2 possible process, (1) that they were from a new heavy boson *B*,
  $e^{+}e^{-} \to B^{\pm}B^{\mp}, B^{\pm} \to e^{\pm}\nu, B^{\mp} \to \mu^{\mp}\nu,$
  or (2) a new heavy lepton *L*,
  $e^{+}e^{-} \to L^{\pm}L^{\mp}, L^{\pm} \to e^{\pm}\nu\bar{\nu}, L^{\mp} \to \mu^{\mp}\nu\bar{\nu}.$
- With only 24 events, these both of these process were possible, but both require 1 or 2 neutral, spin ½, light, effectively non-interacting particles, i.e., neutrinos.



[9]

1976

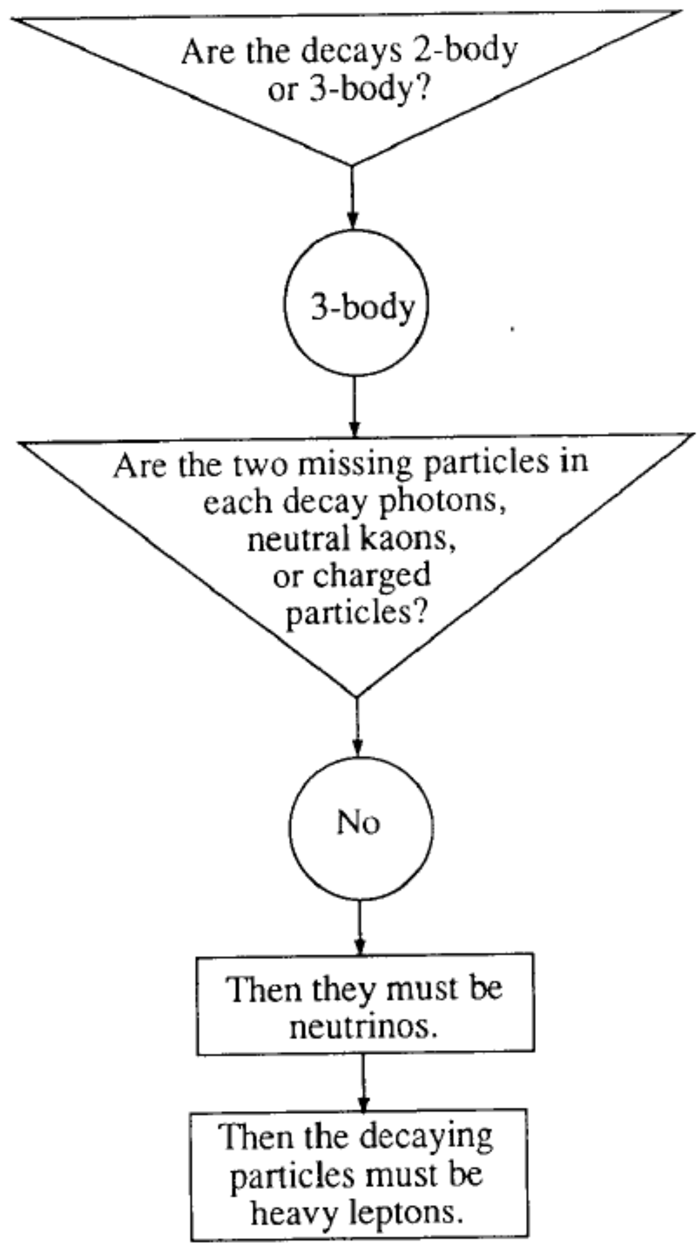
- By the summer of 1976, we had 105 $e^{\pm}\mu^{\mp}$ events. [14]
  - 4.8 GeV data remained ambiguous, but including higher and lower energy data ruled out 2-body decays.



$$\rho = \frac{p - 650\text{ MeV}}{p_{max} - 650\text{ MeV}}$$

1976-7

- The 1976 Mark I paper had a tight argument that the anomalous events were from heavy lepton pair production [14].
- In spite of this, there was skepticism at the summer 1976 conferences because neither of the DORIS storage ring experiments in Hamburg [15] could confirm the heavy lepton discovery. However, confirmation came from both the PLUTO and DASP experiments the following year [16, 17].



Spin of the τ and Its Associated Neutrino

- In 1978-9, the $\tau \to \pi\nu$ decay mode was measured by the PLUTO experiment at DORIS [18] and the DELCO experiment at SPEAR [19]. Since the pion has spin 0, the τ and its associated neutrino have to have the same spin.
- This raises the question "What is the spin of the τ?" In 1978-9, the DASP and DELCO experiments eliminated all possibilities except spin ½ by studying the threshold behavior of $\tau^+\tau^-$ pair production [20-22].
  - Particles with integer spins rise too slowly near threshold.
  - Particles with half-integer spins greater than spin ½ have too high a production cross section at higher energies.

Character of the τ Decay

- A 1977 Mark I paper showed a strong preference for a V - A rather than a V + A coupling. [23]
- In 1979, the DELCO experiment at SPEAR made a more precise measurement of the coupling of the τ to its neutrino by measuring the Michel ρ parameter [24, 25]. This parameter is 0.75 for V – A, 0 for V + A, and 0.375 for either pure V or A. DELCO measured $\rho = 0.72 \pm 0.15$, in good agreement with the left-handed coupling expected for a sequential neutrino.

- The most restrictive upper limit on the mass of the neutrino associated with the τ in 1978 was given by the DECLO experiment at 250 MeV/c^2 at the 90% confidence level [21, 22].

Does the ν_τ Exist? (1)

- At this point, there are only two possibilities for the neutrino associated with the τ:
  1. It is the ν_e or ν_μ or a combination of them, or
  2. It is a new neutrino, which we can define as the ν_τ.
- We need two pieces of information to decide between these alternatives:
  - The strength of the $\tau - \nu_\tau$ current.
  - The strength with which τ's are produced by ν_e's and ν_μ's.
- The strength of the $\tau - \nu_\tau$ current can be determined by measuring the τ lifetime. If the τ has the same weak coupling as the muon, then its lifetime will be

$$2.91 \times \tau_\tau = \left(\frac{m_\mu}{m_\tau} \right)^5 \tau_\mu B_\mu = 10^{-3}\,\text{s},$$

where B_μ is the τ branching fraction into $\mu\nu\nu$.

Does the ν_τ Exist? (2)

- In 1981, the TASSO experiment at PETRA set an upper limit on the τ lifetime of 5.7 x 10^{-13} s at the 95% confidence level [26].
- In the same year, the Mark II experiment at PEP measured the τ lifetime, obtaining $\tau_\tau = (4.6 \pm 1.9) \times 10^{-13}$ s, about one standard deviation higher than the expected (and current) value [27, 28, 29].
- If we assume that the ν_τ does not exist, then the τ must couple via the weak current to the combination $(\varepsilon_e \nu_e + \varepsilon_\mu \nu_\mu)$, where the ε's are normalized so that either $\varepsilon = 1$ gives the normal full strength weak coupling.
- These τ lifetime measurements gave the condition that

$$\varepsilon_\mu^2 + \varepsilon_e^2 > 0.40 \text{ at } 90\% \text{ C.L.}$$

Does the ν_τ Exist? (3)

- On the second needed piece of information, there were two experiments with useful results:
  - In an experiment using the Fermilab neutrino beam incident on the Fermilab 15-foot bubble chamber saw no evidence of excess electron production, which would be expected from τ decays, and set an upper limit of $\varepsilon_\mu^2 < 0.025$ at the 90% confidence level [30].
  - An experiment at CERN had the 400-GeV SPS proton beam incident on a beam dump, with the neutrinos produced in the beam dump entering two bubble chambers [31, 32]. A study of the neutral current-charged current ratio indicated no evidence of τ production, leading to a determination that $\varepsilon_e^2 < 0.35$ at the 90% confidence level [33].
- In a talk in 1981 [27], I put this together and said that assuming the ν_τ does not exist implies

$$\varepsilon_\mu^2 + \varepsilon_e^2 > 0.40 \text{ and } \varepsilon_\mu^2 + \varepsilon_e^2 < 0.38 \text{ both at 90\% C.L.}$$

- Admittedly, the statistical level is quite modest, but this convinced the PDG to accept the ν_τ as established by "indirect" evidence [34].

Additional Evidence on the Existence of the ν_τ (1)

- More significant results were not long in coming.
  - In the following year, 1982, the Mark II detector at PEP added a vertex detector that could increase the resolution of the previous Mark II measurement by a factor of 5 [35].
  - The new measurement was presented at the 1982 ICHEP conference with the result [36]

$$\tau_\tau = (3.31 \pm 0.57(stat.) \pm 0.60(syst.) \times 10^{-13} s.$$

  - This result was published in 1983 with twice as much data [37]

$$\tau_\tau = (3.20 \pm 0.41(stat.) \pm 0.35(syst.) \times 10^{-13} s.$$

    corresponding to $\varepsilon_\mu^2 + \varepsilon_e^2 > 0.69$ at 90% C.L.
  - The existence of the ν_τ was sufficiently evident that the paper just assumed it without further comment.
- Results with similar values and errors were reported by the TASSO detector at PETRA in 1984 [38] and the MAC experiment at PEP in 1985 [39].

Additional Evidence on the Existence of the ν_τ (2)

- In 1986, the UA1 experiment at the CERN proton-antiproton collider measured the ratio of W decays into $\tau\nu$ and $e\nu$ [40].
  - The τ's were detected as low-multiplicity hadrons opposite to missing energy.
  - The result agreed well with e-μ-τ universal weak interactions,

$$\frac{B(W \to \tau\nu)}{B(W \to e\nu)} = 1.02 \pm 0.20(stat.) \pm 0.10(syst.).$$

  - Note that, assuming only weak interactions, this measurement is equivalent to measurements of the τ lifetime, corresponding to

$$\varepsilon_\mu^2 + \varepsilon_e^2 > 0.67 \text{ and at } 90\% \text{ C.L.}$$

  - However, the τ lifetime could be shortened by anomalous (non-weak) decays, but no significant anomalies were found in measurements of τ decays [41].

Additional Evidence on the Existence of the ν_τ (3)

- The key experiment on the $\varepsilon_\mu^2 + \varepsilon_e^2 < x$ side of the argument came in 1986 from Fermilab E531.
  - E531 was designed to measure charmed particle lifetimes. It used the Fermilab 350 GeV neutrino beam incident on a hybrid emulsion detector [42].
  - The experiment found 1870 events with a μ^- and an estimated 53 events with an e^-, but no τ^- candidates [43].
  - This corresponded to $\varepsilon_\mu^2 + \varepsilon_e^2 < 0.09$ at the 90% C. L.
- Putting everything together, in 1986 if we assume the ν_τ does not exist, we have

$$\varepsilon_\mu^2 + \varepsilon_e^2 > 0.69 \text{ and } \varepsilon_\mu^2 + \varepsilon_e^2 < 0.09 \text{ both at 90\% C.L.}$$

- Thus, I can endorse Alain Blondel's statement that **"In 1986, the existence of the τ neutrino was solidly established."** [2]

Comments on the DONuT Experiment (1)

- The DONuT (Direct Observation of Nu-Tau) experiment used the 800 GeV Tevatron proton beam into a tungsten beam dump to produce D_s mesons, which would decay into τ's and ν_τ's. The ν_τ's were then identified by their production of τ's, whose decays would leave a kink in an emulsion detector.
- DONuT starting running in 1997 and published its first results in 2000 with 4 observed τ decays with an estimated background of 0.34 events [44]. Eventually, 9 decays were detected with an estimated background of 1.5 events [45].

Comments on the DONuT Experiment (2)

- I get annoyed by hearing that "The τ neutrino was discovered by the DONuT experiment in 2000," usually as a "throw-away" line in a colloquium on some neutrino topic.
- Blondel has defined a discovery as " the act of finding something that was not known before."
- The DONuT experiment did not discover the ν_τ, because, as we have discussed, its existence had been known at least 14 years earlier.
  - The DONuT experiment never claimed that it discovered the ν_τ. Its first paper stated that the reason it could say that the ν_τ interaction was being observed was because the existence of the ν_τ had been established by earlier experiments [44].

Comments on the DONuT Experiment (3)

- However, Fermilab public relations hyped it as [46]:
  - "DONUT… finally found the missing puzzle piece." ("puzzle" refers to the standard model.)
  - "It's simply been accepted that this guy exists" (quote from a senior scientist).
  - "[DONuT] announced the first **direct** evidence for the τ neutrino."
- It is true that DONuT observed the first charged current interaction of the τ neutrino with matter.
- Bondel has a lengthy discussion on the use of the words "indirect" and "direct" with respect to scientific evidence and whether one should be considered more reliable than the other [2].
- If time, a Bjorken anecdote.

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