

## Neutrino vs antineutrino

Neutrino is a neutral particle—a legitimate question: are neutrino and anti-neutrino the same particle?

Compare: photon is its own antiparticle,  
 $\pi^0$  is its own antiparticle,  
 neutron and antineutron are different particles.

**Dirac neutrino:** If the answer is *different*, neutrino is to be called *Dirac neutrino*

**Majorana neutrino:** If the answer is *the same*, neutrino is to be called *Majorana neutrino*

1959 **Davis and Harmer** conducted an experiment to see whether there is a reaction  $\bar{\nu} + n \rightarrow p + e^-$  could occur. The reaction and technique they used,  $\bar{\nu} + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$ , was proposed by B. Pontecorvo in 1946. The result was negative<sup>1</sup>...

## Lepton number

However, this was not unexpected:

1953 **Konopinski and Mahmoud** introduced a notion of lepton number L that must be conserved in reactions:

- electron, muon, neutrino have  $L = +1$
- anti-electron, anti-muon, anti-neutrino have  $L = -1$

**This new ad hoc law would explain many facts:**

- decay of neutron with anti-neutrino is OK:  $n \rightarrow p e^- \bar{\nu}$   $L=0 \rightarrow L = 1 + (-1) = 0$
- pion decays with single neutrino or anti-neutrino is OK  $\pi \rightarrow \mu^- \bar{\nu}$   $L=0 \rightarrow L = 1 + (-1) = 0$
- but no pion decays into a muon and photon  $\pi \rightarrow \mu^- \gamma$ , which would require:  $L=0 \rightarrow L = 1 + 0 = 1$
- no decays of muon with one neutrino  $\mu^- \rightarrow e^- \nu$ , which would require:  $L=1 \rightarrow L = 1 \pm 1 = 0$  or  $2$
- no processes searched for by Davis and Harmer, which would require:  $L = (-1)+0 \rightarrow L = 0 + 1 = 1$

**But why there are no decays  $\mu \rightarrow e \gamma$ ?<sup>2</sup>**

## Splitting lepton numbers

1959 **Bruno Pontecorvo** suggests that the lepton numbers for electrons and muons should be treated separately:

- electron, and electron-neutrino have  $L_e=+1$ ; their anti-particles have  $L_e=-1$ ;
- muon, and muon-neutrino have  $L_\mu=+1$ ; their anti-particles have  $L_\mu=-1$ ;
- THUS, there should be two types of neutrinos: electron-kind and muon-kind

Re-write all decays:

- $n \rightarrow p e^- \bar{\nu}_e$
- $\pi^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_e$
- $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

If one thinks in terms of Feynman's diagrams, it is a rather natural proposition: when muons or electrons participate in a weak interaction by exchanging with  $W^\pm$  and change into neutrinos, these neutrinos might be of two different kinds, too.

<sup>1</sup> However, the question on "neutrino vs anti-neutrino" turned out to be much more complicated than one would think...

The difficulty came from the fact that *parity* (quantity related to mirror reflection symmetry) was discovered not to conserve in the weak interactions. We will discuss this non-conservation later. It was discovered in 1956 and caught everybody by surprise. One of the consequences was that only left-handed neutrinos and only right-handed anti-neutrinos could participate in the weak interactions—the only force affecting neutrinos (besides gravity). Therefore, the observation that the two particles interact differently might not result from their intrinsic differences, but simply because of them being born with different handedness (or helicity)...

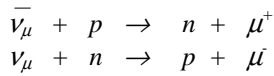
However, if neutrinos do have a mass (as the recent observations of neutrino flavor oscillations tend to indicate), then, their handedness is not uniquely defined, or Lorentz invariant and one can set up special very delicate experiments to tackle this question... We will discuss these issues later.

For now we will assume that neutrinos are of Dirac kind, i.e. described by the Dirac equation, very much the same way as electrons, the only difference being that neutrinos do not have any electric charge and their mass is very close to zero.

<sup>2</sup> Feynman's rule of thumb: "whatever is not explicitly forbidden is MANDATORY!"

## Discovery of Muon Neutrino

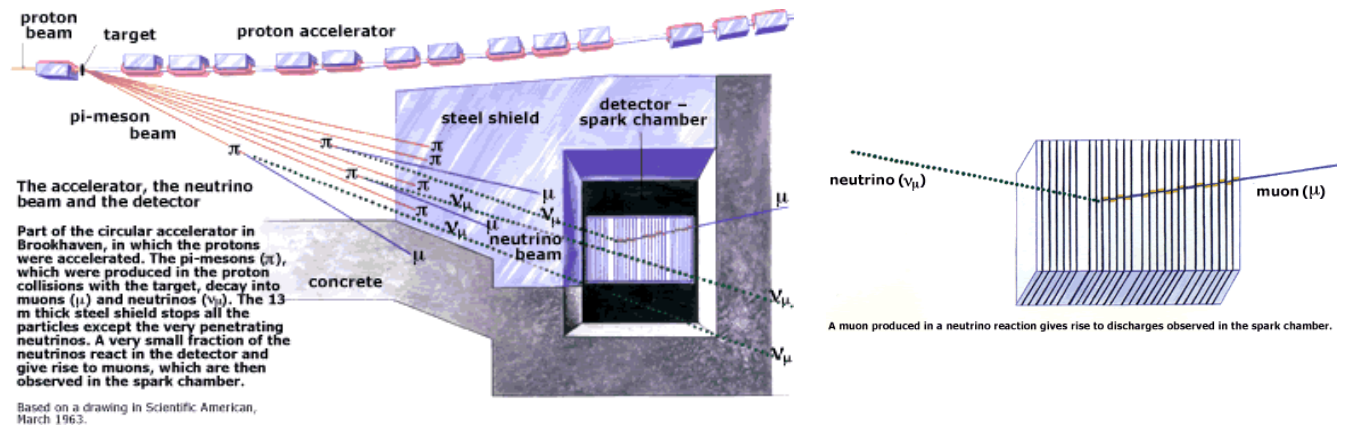
1962 **Lederman, Schwarts, Steinberger** (Brookhaven) make an experiment to check whether muon and electron neutrino indeed different. One has to start from muon neutrinos and see whether all they can make are muons:



Pions is an excellent source of muon neutrinos...  
The idea of neutrino beams actually belongs to Pontecorvo...

- 15 GeV protons  $\rightarrow$  Be target  
 $\rightarrow$  lots of pions:  $\pi^+$ ,  $\pi^-$ ,  $\pi^0$
  - 20 m decay distance: not too short (good fraction of pions decay), not too long (muons do not decay)  
 $\pi^+ \rightarrow \mu^+ \nu_\mu$  ( $10^{-8}$  s),  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$  ( $10^{-6}$  s)  
 $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$  ( $10^{-8}$  s),  $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$  ( $10^{-6}$  s),  
 $\rightarrow$  lots of photons, pions, muons, and high energy muon neutrinos and antineutrinos
  - 13 m of steel to absorb all particles but neutrinos;
  - spark chamber with Al sheets
  - cover detectors with scintillator to veto cosmic rays
- $\rightarrow 10^{14}$  muon neutrinos and antineutrinos

muons should produce nice tracks running throughout the entire detector (29 events)  
electrons should produce showers as they cross Al sheets (none)



Mass limit from direct mass measurements <200 keV

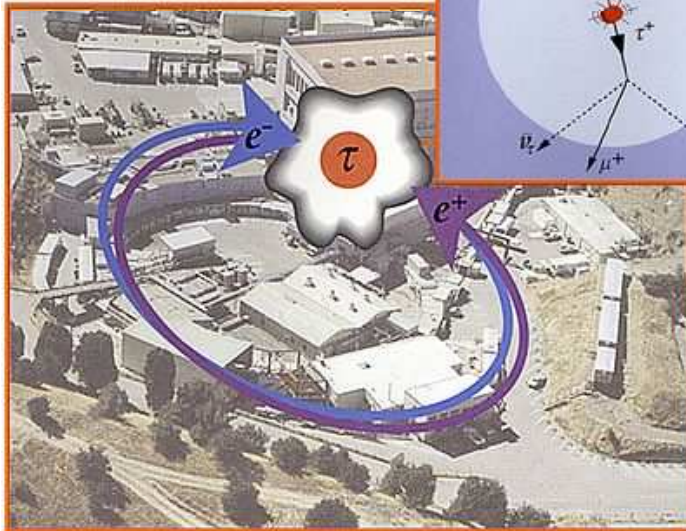
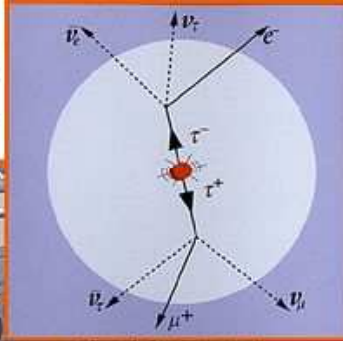
1988 **Lederman, Schwarts, Steinberger** receive the Nobel Prize "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

## Discovery of $\tau$ -lepton

1975 Mark I experiment at SPEAR (Stanford Linear Accelerator Center) claims discovering new lepton. Most of the work on this analysis was credited to Martin Perl.



The tau leptons can be created when temperature and density are high enough, such as was the case in Big Bang. The figure shows the decay of a pair of taus into a muon  $\mu$ , an electron  $e$  and "invisible" neutrinos  $\nu$ .



In the SPEAR collider electrons  $e^-$  and positrons  $e^+$  crash head-on in a little "Big Bang", whereupon, among many possible reactions, taus are created in pairs.

*No one could come up with any plausible background source for these mixed pairs*

"Distribution of 513, 4.8 GeV, 2-prong, events that meet the criteria:  $p_e > 0.65 \text{ GeV}/c$ ,  $p_\mu > 0.65 \text{ GeV}/c$ ,  $|\phi_{\text{cop}}| > 20^\circ$ ".

Number photons =	Total Charge = 0			Total Charge = $\pm 2$		
	0	1	>1	0	1	>1
ee	40	111	55	0	0	0
e $\mu$	24	8	8	0	0	3
$\mu\mu$	16	15	6	0	0	0
eh	18	23	32	2	3	3
$\mu h$	15	16	31	4	0	5
hh	13	11	30	10	4	6
Sum	126	184	162	16	8	17

Table 3. From Perl (1975a). The caption read:

"Misidentification probabilities for 4.8 GeV sample"

Momentum range (GeV/c)	$P_{h \rightarrow e}$	$P_{h \rightarrow \mu}$	$P_{h \rightarrow h}$
0.6- 0.9	.130 $\pm$ .005	.161 $\pm$ .006	.709 $\pm$ .012
0.9-1.2	.160 $\pm$ .009	.213 $\pm$ .011	.627 $\pm$ .020
1.2- 1.6	.206 $\pm$ .016	.216 $\pm$ .017	.578 $\pm$ .029
1.6- 2.4	.269 $\pm$ .031	.211 $\pm$ .027	.520 $\pm$ .043
Weighted average using hh, $\mu h$ , and $e\mu$ events	.183 $\pm$ .007	.198 $\pm$ .007	.619 $\pm$ .012

$\tau$ -lepton has a mass of 1.777 GeV and lifetime of  $2.9 \times 10^{-13}$  s.

It has lots of modes of decays:

- ~18%  $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$
- ~17%  $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$
- ~64%  $\tau^- \rightarrow \text{hadrons} + \nu_\tau$

(Now, WHO the hell ordered THAT?)

1995 Perl receives the Nobel Prize "for the discovery of the  $\tau$ -lepton"

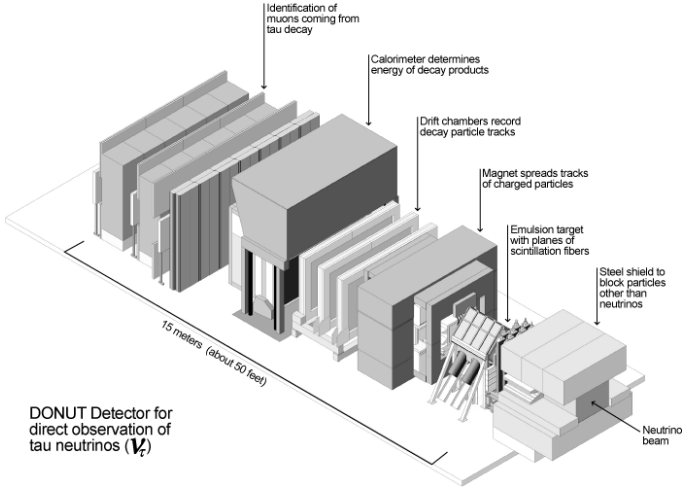
## Discovery of $\tau$ -neutrino

2000 **DONUT experiment** at Fermilab claims discovering  $\tau$ -neutrino (spokesmen Lundberg, and Paolone)

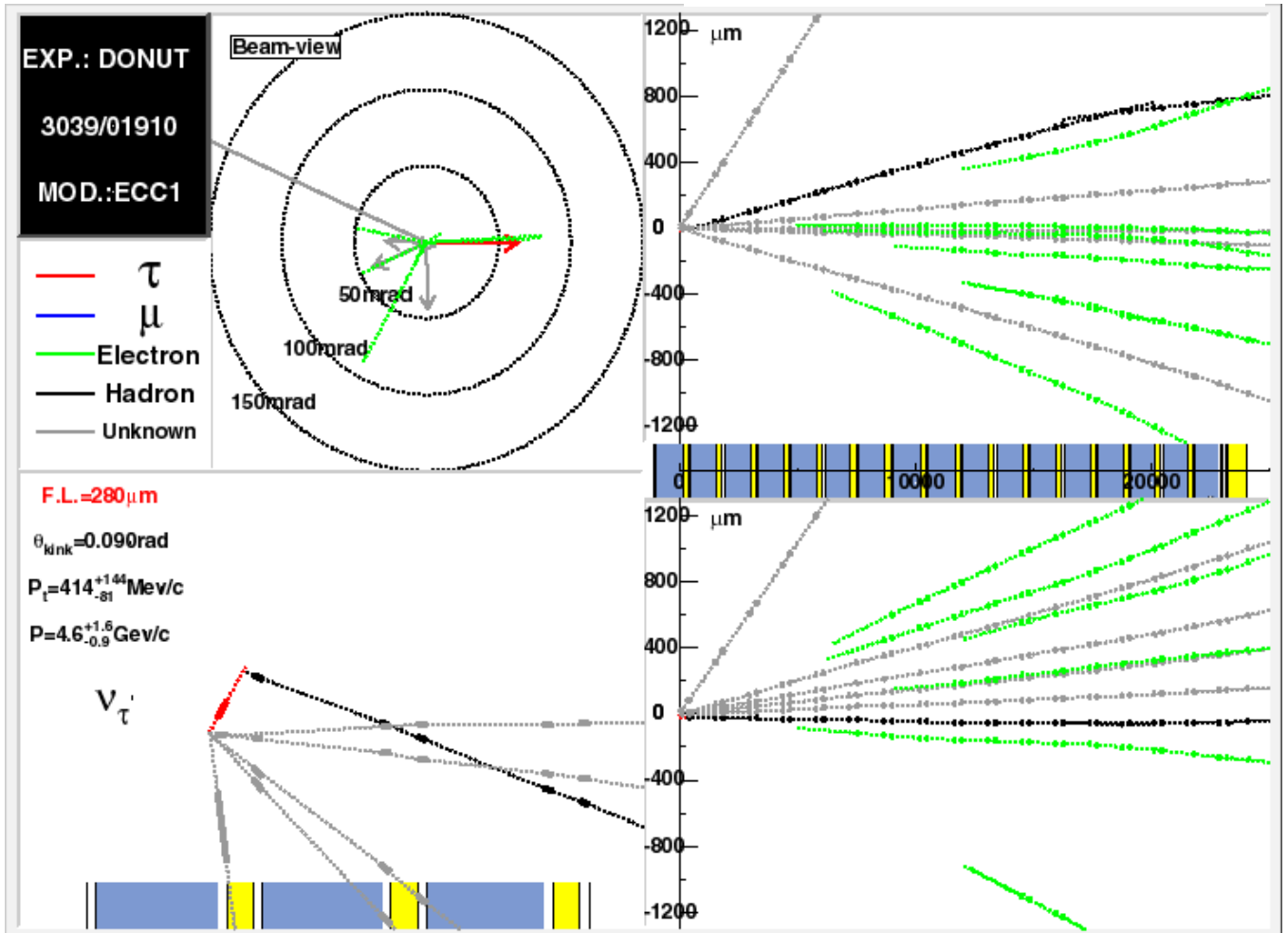
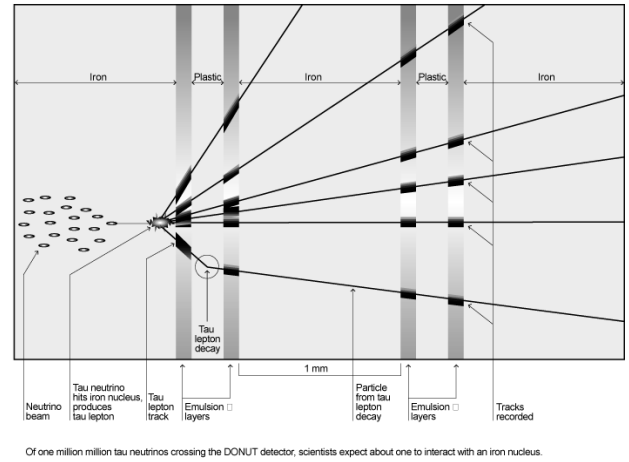
6,000,000 candidates on the “tape”

4 clean  $\tau$ -decay events... truly “one in a million”

### DONUT Detector



### Detecting a Tau Neutrino



Mass limit from direct mass measurements in  $\tau$ -lepton decays  $<24\text{ MeV}$  (different experiments)

## Lepton Universality

### Muon and tau-lepton lifetimes:

$$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau \quad \Gamma_{\tau \rightarrow e \bar{\nu} \nu} = 2\pi |M|^2 \rho \quad \text{GeV} = \frac{1}{\text{GeV}^4} (\text{GeV}^5)$$

$\rho$  must have dimensions of  $(\text{GeV}^5)$ ,

while the only energy variable available is tau mass  $m_\tau$  ( $m_e$  and  $m_\mu$  can be neglected)

$$\Gamma_{\tau \rightarrow e \bar{\nu} \nu} = 2\pi G^2 m_\tau^5$$

$$\Gamma_{\tau \rightarrow e \bar{\nu} \nu} = 0.1784 \cdot \Gamma_{total}$$

$$\tau_\tau(\text{lifetime}) = \frac{1}{\Gamma_{total}} = \frac{0.1784}{2\pi G^2 m_\tau^5}$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\Gamma_{\mu \rightarrow e \bar{\nu} \nu} = 2\pi G^2 m_\mu^5$$

$$\tau_\mu(\text{lifetime}) = \frac{1}{\Gamma_{total}} = \frac{1}{2\pi G^2 m_\mu^5}$$

$$\text{Prediction: } \frac{\tau_\tau}{\tau_\mu} = 0.1784 \frac{m_\mu^5}{m_\tau^5} = 1.33 \times 10^{-7}$$

$$\text{Experiment: } \frac{\tau_\tau}{\tau_\mu} = \frac{2.9 \times 10^{-13}}{2.2 \times 10^{-6}} = 1.32 \times 10^{-7}$$

### Branching ratios of tau-lepton decaying into a muon or electron:

$$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau \quad \Gamma_{\tau \rightarrow \mu \bar{\nu} \nu} = 2\pi |M|^2 \rho_\mu = 2\pi G^2 m_\tau^5$$

$$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau \quad \Gamma_{\tau \rightarrow e \bar{\nu} \nu} = 2\pi |M|^2 \rho_e = 2\pi G^2 m_\tau^5$$

$$\Gamma_{\tau \rightarrow \mu \bar{\nu} \nu} = Br(\tau \rightarrow \mu \bar{\nu} \nu) \cdot \Gamma_{total}$$

$$\Gamma_{\tau \rightarrow e \bar{\nu} \nu} = Br(\tau \rightarrow e \bar{\nu} \nu) \cdot \Gamma_{total}$$

$$\text{Prediction: } \frac{Br(\tau \rightarrow e \bar{\nu} \nu)}{Br(\tau \rightarrow \mu \bar{\nu} \nu)} = \frac{\Gamma_{\tau \rightarrow e \bar{\nu} \nu}}{\Gamma_{\tau \rightarrow \mu \bar{\nu} \nu}} = 1$$

$$\text{Experiment: } \frac{Br(\tau \rightarrow e \bar{\nu} \nu)}{Br(\tau \rightarrow \mu \bar{\nu} \nu)} = \frac{0.1884}{0.1737} = 1.03$$

### Note: this does not work for pion decays into muon or electron:

$$\pi \rightarrow \mu \nu \quad (99.99\%)$$

$$\pi \rightarrow e \nu \quad (0.01\%)$$

There are special reasons for that to be discussed later...