MEASUREMENT OF NUMBER OF LIGHT NEUTRINO FAMILIES AT LEP

$\boxed{1}$

	I	II	III
quarks	u	c	t
	d	s	b

increasing mass →

leptons	e	μ	τ	λ?
	ν_e	ν_μ	ν_τ	ν_λ?

....

why three families? | why stop at three?

could there be a fourth?

(fifth?)

NEVER FOUND FOURTH CHARGED LEPTON

$m_e \simeq 0.5$ MeV

$\times 200$

$m_\mu \simeq 106$ MeV

$\times 20$

$m_\tau \simeq 1.8$ GeV

$m_\lambda = ?$

maybe ~~charged~~ too heavy?

outside of experimental reach of accelerators

<u>BUT</u> $m(\nu_e) = m(\nu_\mu) = m(\nu_\tau) = 0$

So if the families replicate the same scheme, even if fourth lepton is out of reach, there should be a <u>fourth neutrino</u>

TIME : 1983

τ lepton had already been discovered
(BUT NOT ν_τ $\rightarrow$ discovered in 2000)
"allowed" existed

LEP : Large Electron Positron (collider) @ CERN

$\xrightarrow{e^+} \xleftarrow{e^-}$ symmetrical collider

$$\sqrt{s} = E_+ + E_-$$

$$89 \leq \sqrt{s} \leq 94 \text{ GeV}$$

to study Z ($m_Z = 91.19$ GeV)

~~by producing it~~ $e^+e^- \rightarrow Z \rightarrow$ stuff
f
final state

In SM Z couples to all (3) lepton families equally ("Lepton Universality")
So if there's a fourth neutrino, Z should know about it

~~in general for~~ $\cancel{e^+e^- \to Z \to f}$

$$\cancel{\sigma_{e^+e^- \to f}(s) = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_f}{\Gamma^2} \frac{s\Gamma^2}{(s-m_Z^2)^2 + \frac{s^2\Gamma^2}{m_Z^2}}}$$

~~(BREIT WIGNER)~~

~~where~~ $\cancel{\Gamma_x}$ ~~is amplitude of~~ $\cancel{Z \to X}$

Z width:

$$\Gamma_Z = \Gamma_{tot} = \sum_i \Gamma_i$$

in the SM Z couples to quarks
charged leptons
neutrinos

$$\Rightarrow \Gamma = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{hadrons} + \Gamma_{\nu}$$

and $\Gamma_\nu = \Gamma_{\nu e} + \Gamma_{\nu\mu} + \Gamma_{\nu\tau}$

for lepton universality $\Gamma_{ee} = \Gamma_{\mu\mu} = \Gamma_{\tau\tau} = \Gamma_{\ell\ell}$

$\Gamma_{\nu e} = \Gamma_{\nu\mu} = \Gamma_{\nu\tau} = \Gamma_{\nu\nu}$

$$\Rightarrow \Gamma_{SM} = 3\Gamma_{\ell\ell} + \Gamma_{hadrons} + 3\Gamma_{\nu\nu}$$

Let's add a fourth lepton family so that the charged lepton λ has $m_\lambda > \frac{m_Z}{2}$

$$\Rightarrow Z \not\to \lambda\bar{\lambda}$$

but $(\nu_\lambda < m_Z/2)$ $\nu_\lambda \cong 0$ $\Rightarrow$ $Z \to \nu_\lambda \bar{\nu}_\lambda$

$$\Rightarrow \Gamma \to \Gamma' = 3\Gamma_{ee} + \Gamma_{hadrons} + \underline{4}\,\Gamma_{\nu\nu}$$

in general, from Γ one can measure the number of (light) neutrino families

$\uparrow$ $m < \frac{m_Z}{2}$

$$\Gamma = 3\Gamma_{ee} + \Gamma_{hadrons} + N_\nu \Gamma_{\nu\nu}$$

~~Suppose we choose f = hadrons. From the formula~~

~~$\sigma_{hadrons}$~~

In general, for

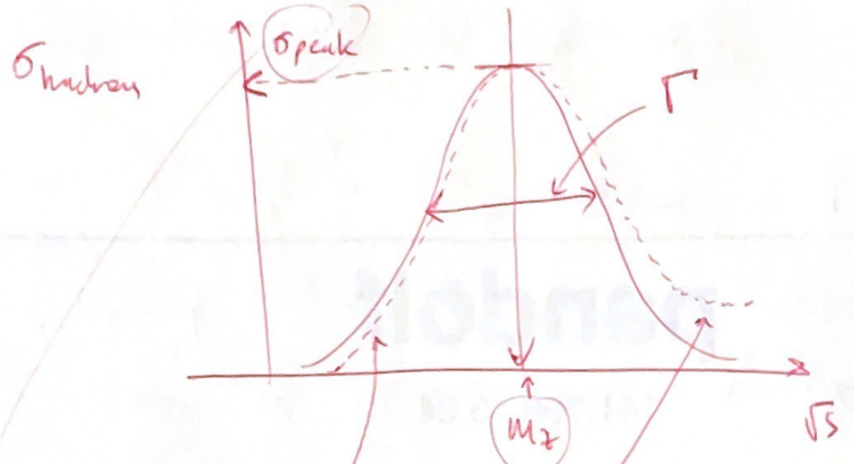
$$e^+e^- \to Z \to f$$

we have:

$$\sigma_{e^+e^- \to f}(s) = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_f}{\Gamma^2} \frac{s\Gamma^2}{(s-m_Z^2)^2 - s^2\Gamma^2/m_Z^2}$$

BREIT-WIGNER

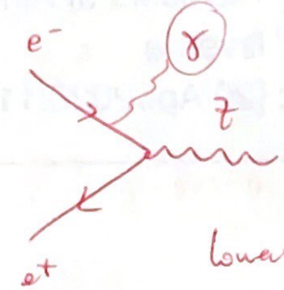
so let's choose $f =$ hadrons:



In reality

higher tail on right side

ISR



electrons emit a lot!

lowers effective $\sqrt{s}$ of initial state

But this can be calculated and corrected for

R "RADIATION FUNCTION"

$$\sigma_{obs}(s) = R(s) \cdot \sigma_0(s)$$

σ_0 └ theoretical lineshape (BW)

FROM FORMULA: $$\sigma_{peak} = \frac{12}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma^2} = \frac{12}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{had}}{(3\Gamma_{ee} + \Gamma_{had} + N_\nu \Gamma_{\nu\nu})}$$

$$\Leftrightarrow \sigma_{peak} = \sigma_{peak}(N_\nu)$$

OK so we need to measure $\sigma_{hadrons}$ vs $\sqrt{s}$

easy: LEP ran at different $\sqrt{s}$

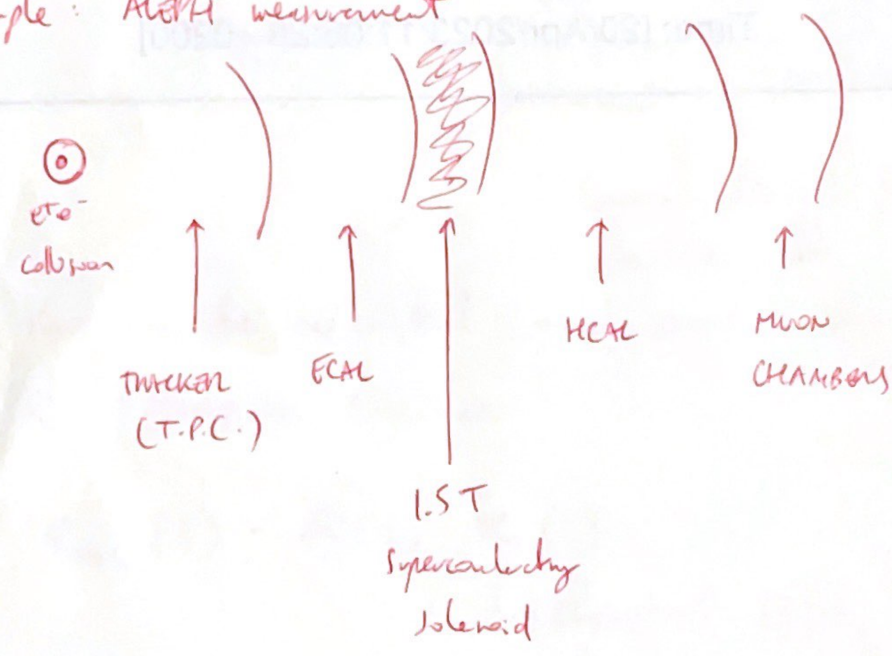
how?

in general $\sigma_x = \dfrac{N_x}{\int \mathcal{L}}$

N_x ← # events ①

$\int \mathcal{L}$ ← integrated lumi ② (total lumi delivered by LEP)

① example: ALEPH measurement



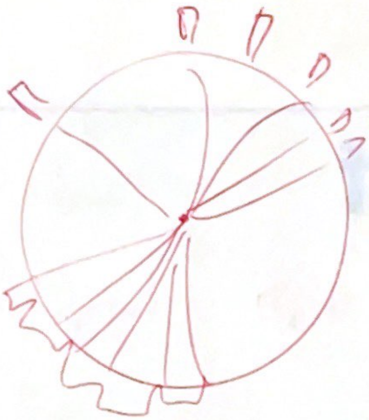
PARTICLE I.D. :

	TRK	ECAL	HCAL	MUON
$e^\pm$	✓	✓	×	×
γ	×	✓	×	×
μ	✓	×	×	✓
hadrons	(✓)	(✓)	✓	×
ν	×	×	×	×

looking for $e^+e^- \to Z \to$ hadrons

$(\searrow q\bar{q} \to$ jets$)$

lots of stuff



~~TWO METHODS~~

COUNT EVENTS WHICH PASS
SIMPLE EVENT SELECTION

require $N(\text{tracks}) \geq 5$

and $\sum_{\text{tracks}} E_{\text{tracks}} > 0.1 \cdot \sqrt{s}$

(not all hadrons reconstructed)

reduce contamination of

$e^+e^- \to Z \to e^+e^-$ (two tracks)

$e^+e^- \to Z \to \mu^+\mu^-$ (two tracks)

$e^+e^- \to Z \to \tau^+\tau^-$ (usually $N \leq 4$)

② $\int \mathcal{L}\, dt$ integrated LEP lumi

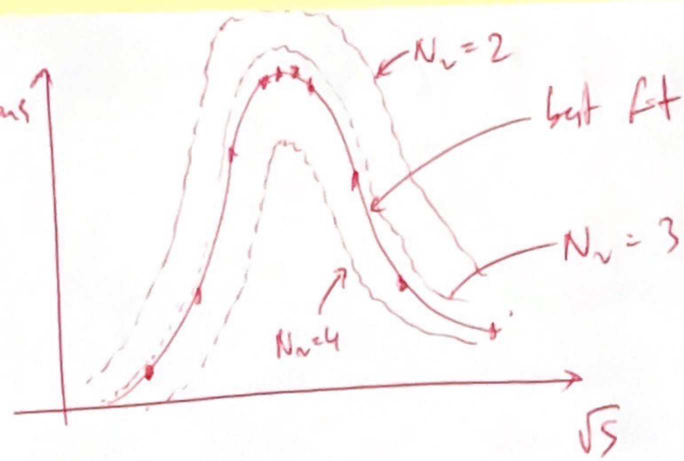
in general $\int \mathcal{L}\, dt = \dfrac{N_x}{\sigma_x}$

TO HAVE GOOD PRECISION
need to find suitable process x that has

Ⓐ high rate $\dot{N}_x$

Ⓑ very well known σ_x

RESULT



ALEPH (1989) best fit : $N_\nu = 3.27 \pm 0.30$

LEP COMBINATION (1999) : $N_\nu = 2.984 \pm 0.008$

(ALEPH, DELPHI, L3, OPAL)

Late 1950s

Wu $\rightarrow$ P violated in weak int.

θ/τ puzzle $\rightarrow$ "θ" $\equiv K^+ \rightarrow 2\pi$

"τ" $\equiv K^+ \rightarrow 3\pi$

K mesons $\rightarrow$ they are "strange"

i.e. produced strongly $\rightarrow$ decay weakly

$\rightarrow$ new quantum number "strangeness"

conserved by strong int.

violated by weak int.

K^+ : $S = +1$

K^- : $S = -1$

But what about the neutral Kaons

	K^0	$\bar{K}^0$
Q	0	0
B	0	0
S	+1	-1

FIRST NEUTRAL MESON WITH CHARGE

FIRST NEUTRAL BOSON FOR WHICH ANTIPARTICLE $\neq$ PARTICLE

eg. γ, π^0

What is the nature of $K^0/\bar{K}^0$?

they differ only by S, a quantity not conserved by weak interactions.

By now Parity has fallen, but it was thought that CP was a good symmetry of the Universe

↑

real symmetry between matter / antimatter

EG.:

$\nu_L + n \to e^- + p$ ✓ weak

P

C $\quad \nu_R + n \to e^- + p$ × P violated by weak int. $\nu_R \nexists$

CP $\quad \bar{\nu}_L + \bar{n} \to e^+ + \bar{p}$ × $\bar{\nu}_L \nexists$

$\bar{\nu}_R + \bar{n} \to e^+ + \bar{p}$ ✓

After the fall of P, CP was last bastion standing

So let's look at $K^0/\bar{K}^0$

$K^0/\bar{K}^0$ are produced strongly, so they are eigenstates of the strong force

But they are not eigenstates of CP:

$$CP|K^0\rangle = |\bar{K}^0\rangle$$

IN GENERAL $P|K^0\rangle = e^{i\varphi}|K^0\rangle$ but we can choose $\varphi = 0$

IF CP IS CONSERVED, the physical states are the eigenstates of CP

these are

$$|K_1^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \qquad CP = +1$$

$$|K_2^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \qquad CP = -1$$

We know ~~that~~ that both K^0 and $\bar{K}^0$ can decay to

$$K^0 \to \pi^+\pi^-$$
$$\bar{K}^0 \to \pi^+\pi^-$$

the $(\pi^+\pi^-)$ state with $L=0$ has $CP = +1$ in fact: both C and P interchange the 2 pions. If $L=0$ (pions in s-wave) then

$$P = (-1)^L = +1$$
$$C = (-1)^L = +1$$

+ intrinsic parity of pions $= -1$

$$\Rightarrow \underset{\pi^+}{(-1)} \cdot \underset{\pi^-}{(-1)} = +1$$

$$\Rightarrow CP = +1$$

So if CP is conserved only $|K_1^0\rangle$ can decay to 2π

$$K_1^0 \to 2\pi$$
$$K_2^0 \not\to 2\pi$$

Using similar arguments

$$CP(\pi\pi\pi) = -1$$

$$\Rightarrow \quad K_1^0 \not\to 3\pi$$

$$K_2^0 \to 3\pi$$

$m_\pi \sim 130$ MeV $\qquad m_K \sim 500$ MeV

$$\Rightarrow \quad 3 m_\pi \sim 400 \text{ MeV}$$

phase space available to the 2π decay <u>much</u> larger

$$\Rightarrow \text{ expect } \quad \tau(K_1^0) \ll \tau(K_2^0)$$

this is why we call them

$K_1^0 \equiv K^0_S$ "short" $\quad \tau_S \sim 0.9 \cdot 10^{-10}$ s

$K_2^0 \equiv K^0_L$ "long" $\quad \tau_L \sim 0.5 \cdot 10^{-7}$ s

10^3

<u>RECAP</u>

two representations:

$\boxed{\text{STRONG FORCE EIGENSTATES}}$ <u>PRODUCTION</u>	$\boxed{\text{CP EIGENSTATES}}$ TIME EVOLUTION
$\vert K^0\rangle \quad \vert\bar{K}^0\rangle$	$\vert K_1^0\rangle \quad \vert K_2^0\rangle$

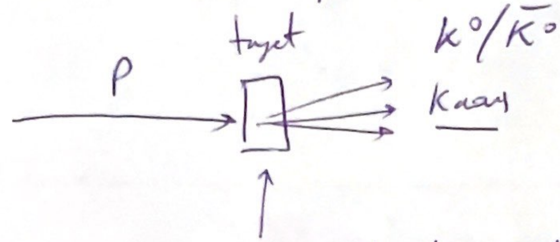
$$|K^0_{1,2}\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle \pm |\bar{K}^0\rangle\right)$$

$$|K^0\rangle = \frac{1}{\sqrt{2}}\left(|K_1^0\rangle + |K_2^0\rangle\right)$$

$$|\bar{K}^0\rangle = \frac{1}{\sqrt{2}}\left(|K_1^0\rangle - |K_2^0\rangle\right)$$

IF CP CONSERVED
these are Hamiltonian
eigenstates too

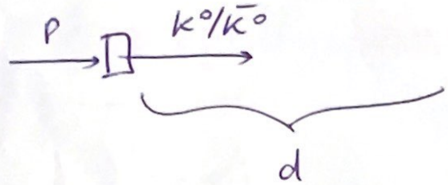
So if we have experiment



Kaons produced in strong interaction

$\Rightarrow$ at $t=0$ $|K^0\rangle$ and $|\bar{K}^0\rangle$

If the $K^0/\bar{K}^0$ then start travelling



time evolution depends on H eigenstates

$$|K_1^0(t)\rangle = e^{-im_1t - \Gamma_1 t/2} \frac{1}{\sqrt{2}}\left[|K^0(0)\rangle + |\bar{K}^0(0)\rangle\right]$$

$$|K_2^0(t)\rangle = e^{-im_2t + \Gamma_2 t/2} \frac{1}{\sqrt{2}}\left[|K^0(0)\rangle - |\bar{K}^0(0)\rangle\right]$$

FIRST CONSEQUENCE: • $K^0-\bar{K}^0$ OSCILLATIONS

If a state ψ is produced at $t=0$ as purely K^0 when it propagates it will oscillate $K^0 \to \bar{K}^0 \to K^0$ with amplitudes:

$$\langle K^0|\psi(t)\rangle = \frac{1}{2}\left(e^{-im_1t - \Gamma_1 t/2} + e^{-im_2t - \Gamma_2 t/2}\right)$$

$$\langle \bar{K}^0|\psi(t)\rangle = \frac{1}{2}\left(e^{-im_1t - \Gamma_1 t/2} + e^{-im_2t + \Gamma_2 t/2}\right)$$