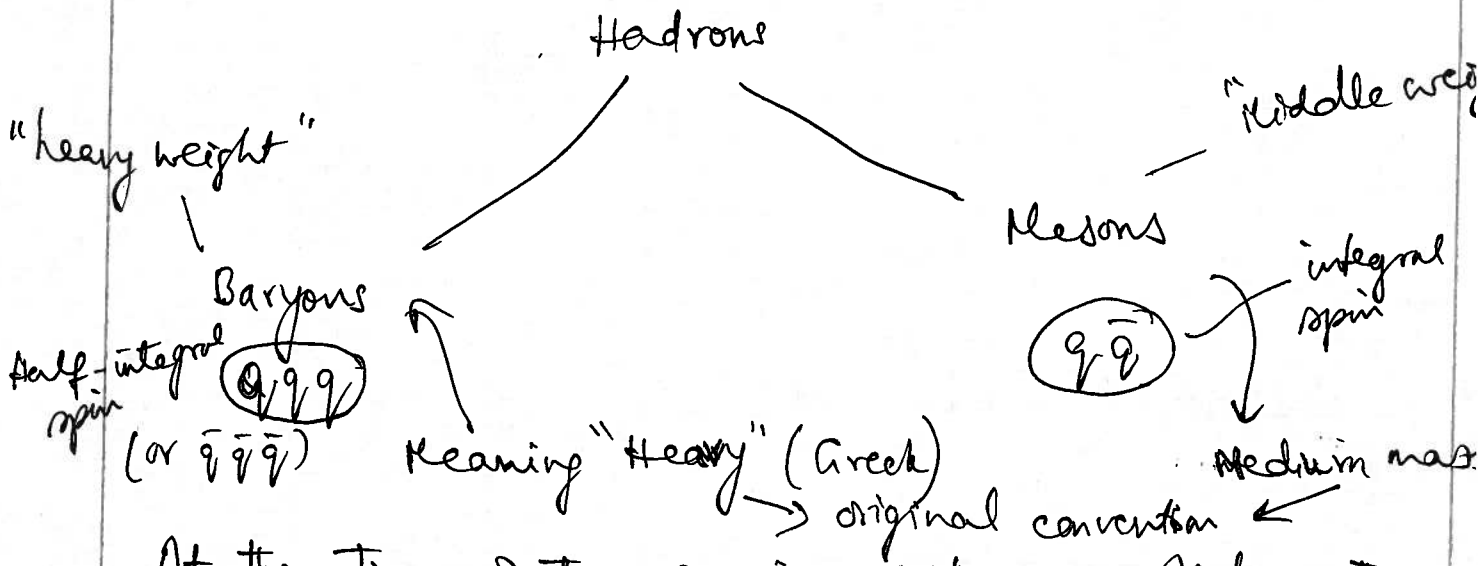
Quarks and Hadrons

- Hadrons are bound states of quarks.
- Quarks and hadrons are "strongly" interacting.

  $\Rightarrow$ "Strong Interaction Physics"
- They also interact by weak and electromagnetic interactions.



At the time of the naming of these particles, the known baryons were proton, neutron. The mesons were thought of as having mass between the electron and proton. At the time, heavier mesons had not been found, quarks were not known and the Standard Model of particle physics had not been formed (It was decades down the road).

Quarks

			Charge
$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$	$+2/3$
			$-1/3$
1st Gen	2nd	3rd	

All of them are known. t (Top quark discover in 1995 by CDF and DØ at Fermilab)

				Charge
Anti-quarks	$\begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix}$	$\begin{pmatrix} \bar{c} \\ \bar{s} \end{pmatrix}$	$\begin{pmatrix} \bar{t} \\ \bar{b} \end{pmatrix}$	$-2/3$
				$+1/3$

Baryon Number (B)

$$B = \frac{n_q - n_{\bar{q}}}{3}$$

n_q = no of quarks

$n_{\bar{q}}$ = no of anti-quarks

$B = 1/3$ for all quarks ; $-1/3$ for all antiquarks

Other Quantum Numbers

Strangeness	$S = -1$ for s, $+1$ for $\bar{s}$; 0 for all others
Charm	$C = +1$ for c, -1 for $\bar{c}$; 0 for all others
Bottomness	$\tilde{B} = -1$ for b, $+1$ for $\bar{b}$; 0 "
Topness	$T = +1$ for t, -1 for $\bar{t}$; — " —

Note: The sign of these "flavor" quantum numbers is same as that of charge for that quark.

Table 14.1: Additive quantum numbers of the quarks.

Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	−1	0	0	0
C – charm	0	0	0	+1	0	0
$\tilde{B}$ – bottomness	0	0	0	0	−1	0
T – topness	0	0	0	0	0	+1

- $Q = I_z + \dfrac{B + S + C + \tilde{B} + T}{2}$

electric charge

$m_t \cong 174\ \mathrm{GeV}/c^2$

- Masses: $m_u \approx m_d = 0.003\ \mathrm{GeV}/c^2$, $m_s \approx 0.5$, $m_c \approx 1.5$, $m_b \approx 4.5$,
- The masses of u, d, c, s, b quarks are inferred indirectly from the observed masses of their hadron bound states. They form various mesons and baryons
- Top quark is too short lived. So, does not form bound states of hadrons that are observable. So, top mass is directly measured from its decay products.
- We can't measure any free quark mass directly, since they are always confined in hadrons.
- Limits for free quarks from experiments
  - $< 10^{-24}$ quarks / nucleon in sea water
  - < 1 per 10^{10} primary cosmic rays, etc.

Hadrons

B for quarks is $\frac{1}{3}$

Baryons (q q q)

Particle	Quark composition	Mass (MeV/c^2)	B (Baryon Number)	Q	S	C	$\tilde{B}$	T
p	uud	938	1	1	0	0	0	0
n	udd	940	1	0	0	0	0	0
Λ	uds	1116	1	0	−1	0	0	0
Λ_c	udc	2285	1	1	0	1	0	0
Λ_b	udb	5624	1	0	0	0	−1	0

Mesons

Note: Baryon Number B = 0

Particle	Quark Composition	Mass (MeV/c^2)	Q	S	C	$\tilde{B}$
π^+	$u\bar{d}$	140	1	0	0	0
K^-	$s\bar{u}$	494	−1	−1	0	0
D^-	$d\bar{c}$	1869	−1	0	−1	0
D_s^+	$c\bar{s}$	1969	1	1	1	0
B^-	$b\bar{u}$	5279	−1	0	0	−1
Υ	$b\bar{b}$	9460	0	0	0	0

Proton is the lightest Baryon $m_p = 938$ MeV/c

Pion is the lightest meson, $m_{\pi^\pm} \simeq 140$ MeV/c^2

$m_{\pi^0} = 135$ MeV/c^2

Some Quantum Numbers

Baryon Number $B = \frac{1}{3}\left[N(q) - N(\bar{q})\right]$

Strangeness $S = -N_s \equiv -\left[N(s) - N(\bar{s})\right]$

Charm $C = N_c \equiv +\left[N(c) - N(\bar{c})\right]$, etc.

Bottomness $\tilde{B} = -N_b \equiv -\left[N(b) - N(\bar{b})\right]$

Topness $T = N_t \equiv \left[N(t) - N(\bar{t})\right]$

N_u and N_d can be inferred from B and other numbers

- The quark numbers of each flavor N_u, N_d, etc are conserved in Strong and EM interactions. So quarks and antiquarks are produced and destroyed in pairs.

Flavor Conservation

E.g., $p + p \longrightarrow p + n + \pi^+$

Strong process

$$(uud) + (uud) \longrightarrow (uud) + (udd) + (u\bar{d})$$

$\Rightarrow$ Same N_u and N_d on both sides + $(d\bar{d})$

$\Rightarrow$ N_u and N_d are separately conserved.

- Weak interactions do not conserve flavor.

β-decay $n \longrightarrow p + e^- + \bar{\nu}_e$

$(udd) \quad (uud) + e^- + \bar{\nu}_e$

Baryon number and charge, however, are conserved

$\Rightarrow$ A 'd' quark has turned into a 'u' quark

- Hadrons have typical size ~ 1 fm.
  So $\tau \sim 1\,\text{fm}/c \sim 10^{-23}$ s.
  Vast majority of hadrons decay via strong interactions to lighter hadrons with lifetimes of this order.
- However, since quark flavors have to be conserved in strong interactions, when there are no lighter hadrons with proper values of these quantum numbers $(B, Q, c, s, \tilde{B}, T)$, they cannot decay by strong interactions.

  $\Rightarrow$ long-lived particles

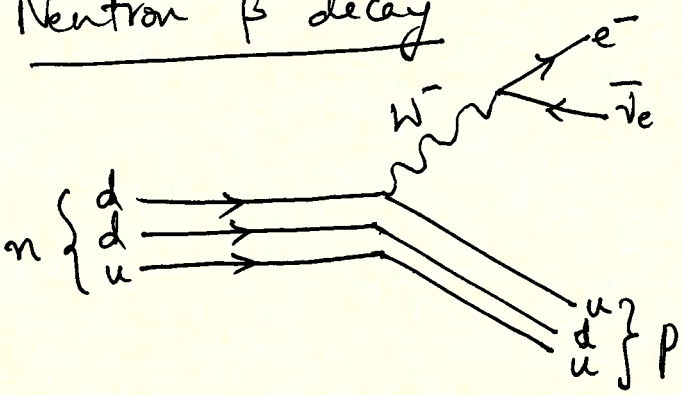
  $\Rightarrow$ Decay by weak or electromagnetic interactions, much slowly.

<u>Characteristic lifetimes of Interactions</u>

Strong	$10^{-23} - 10^{-24}$ s
EM	$10^{-16} - 10^{-21}$
Weak*	$10^{-7} - 10^{-13}$

* Neutron is an exception with $\tau \sim 10^{3}$ s (which we will discuss next)

Neutron "β" decay



$$n \longrightarrow p + e^- + \bar{\nu}_e$$

$$(udd) \longrightarrow (uud) + e^- + \bar{\nu}_e$$

through a W^- emission

Kinetic Energy Released in the decay: "Q value"

$$Q = m_n - m_p - m_e - m_{\bar{\nu}_e} = 0.79 \text{ MeV}$$

(for a particle at rest).

Since the Q value is very small (neutron-proton mass difference is very small) compared to other weak decays which have $Q \sim 100$ MeV – 1 GeV. Because of the small Q value, neutron is very long-lived, with a life-time $\sim 10^3$ sec

Free Proton is stable $\tau > 10^{35}$ yrs. ←

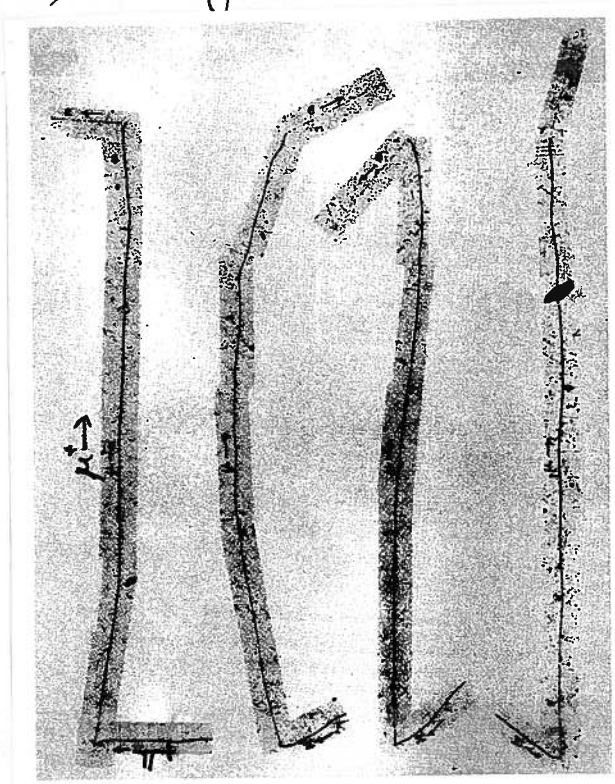
for all practical purposes

⟸ Baryon number conservation

It has nowhere to go.

Pions

- Lightest known meson or hadron
  $\pi^{\pm}$ (~ 140 MeV/c^2) ; π^0 (~ 135 MeV/c^2)
- Predicted by Yukawa in 1935 (we discussed this earlier), as force carrier for strong nuclear interactions
- Mistaken with the muon (and hence muon was initially called mu meson) when it was found in 1936 in cosmic rays.
- Pions ($\pi^{\pm}$) discovered in 1947 by a Bristol Univ. group (led by Powell) using photographic emulsions.



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

* Pions are produced copiously in many hadronic interactions.

Pion Decays

$\pi^+ \to \mu^+ + \nu_\mu$, $\pi^- \to \mu^- + \bar{\nu}_\mu$ (BF = 99.987% Branching Fraction)

These are Weak decays.

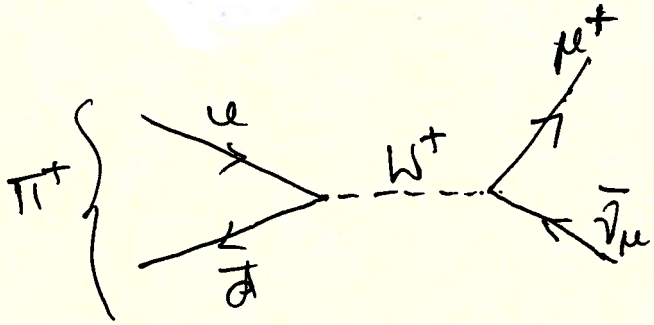
$\tau \simeq 2.6 \times 10^{-8}\,s$ $\qquad c\tau \simeq 7.8\,m$

$\pi^+ \to e^+ + \nu_e$, $\pi^- \to e^- + \bar{\nu}_e$ $\qquad BF = 1.23 \times 10^{-4}$

$$R(\pi \to e\nu_e : \pi \to \mu\nu_\mu) = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi - m_e}{m_\pi - m_\mu}\right)^2$$

$\pi^0 \to \gamma + \gamma$ $\qquad \tau \sim 0.8 \times 10^{-16}\,s$

This is an electromagnetic decay.



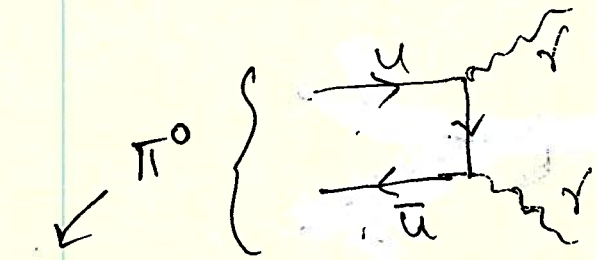
W decays

$W \to e\nu$

$W \to \mu\nu$

Also $W \to \tau\nu$

And $W \to q\bar{q}'$



$\pi^0 \to 2\gamma$

$\pi^0 \to \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$

(Recollect $e^+e^- \to 2\gamma$)

Strange, charm and Beauty (Bottom)

- Strange particles first observed in 1947 (Manchester group – Rochester & Butler) in cloud chamber photography of cosmic ray data.
- Why "Strange"?
  - They had long lifetimes $\sim 10^{-8}$ s characteristic of weak interactions!

    (They were produced via strong interactions. Since there are lighter hadrons, they were expected to decay by strong interactions, with $\tau \sim 10^{-23}$ s)

$$K^+ \rightarrow \mu^+ + \nu_\mu \qquad BF = 0.63 \qquad m(K^+) = 494\ \text{MeV}$$

of 63%

$$K^+ \rightarrow \pi^+ + \pi^0 \qquad BF = 0.21$$

These new particles must have a quark that is different from u and d quarks.

Hence the name "Strange" quark.

$$K^+ = u\bar{s}, \quad K^- = \bar{u}s; \quad K^0 = d\bar{s}, \quad \bar{K}^0 = s\bar{d}$$

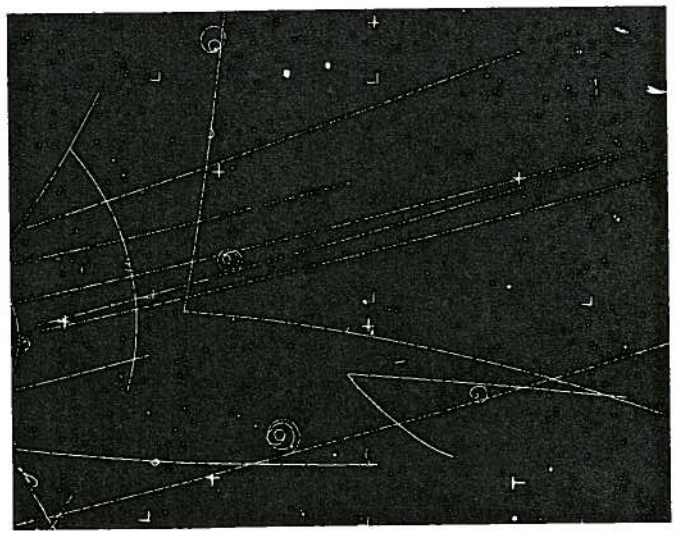
$$m(K^0) = 498\ \text{MeV}/c$$

Similar Strange decays of strong particles

$$\Lambda \rightarrow \pi^- + p \quad BF = 0.64; \quad \Lambda \rightarrow \pi^0 + n \quad BF = 0.36$$

A strange Baryon

$$\tau \sim 2.6 \times 10^{-10}\ s \qquad \Lambda \equiv uds$$



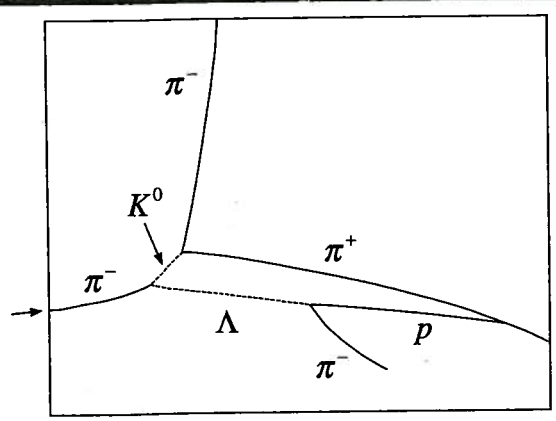


Figure 3.6 A bubble chamber picture of the associated production reaction $\pi^- + p \rightarrow K^0 + \Lambda$. The incoming pion is indicated by the arrow, and the unseen neutrals are detected by their decays $K^0 \rightarrow \pi^+ + \pi^-$ and $\Lambda \rightarrow p + \pi^-$. This picture was taken in the 10 in (25 cm) bubble chamber at the Lawrence Berkeley National Laboratory. (Lawrence Berkeley National Laboratory photo, with permission.)

Strange particles are produced in association with each other so that "strangeness" is conserved.

← Associated Production

Example Above:

$$\pi^- + p \longrightarrow K^0 + \Lambda$$

$$S = 0 \qquad 1 \qquad -1$$

Charm

- For three long decades after pions and kaons were discovered, all observed particles were made of u, d, s quarks.
- A fourth quark was expected (initially proposed by Glashow and Bjorken and named "Charm" ← there were 4 known leptons at the time. So, a 4th quark restored symmetry).

Glashow, Iliopoulos and Maini predicted it in 1969 from theoretical arguments.

- 1974 November Revolution
  - Discovery of the charm quark via J/ψ
  - a $c\bar{c}$ state, Charmonium
  - Found in $p + Be \to e^+ + e^- + X$ (BNL)

$e^+ + e^- \to e^+ + e^-$, $\mu^+\mu^-$, etc. (SLAC) SPEAR

hadrons

$$p + p \to J/\psi + X \to e^+ e^- + X$$

$$e^+ + e^- \to J/\psi + X \to e^+ e^- \text{ etc.}$$

Charmonium

$J/\psi(3097) = c\bar{c}$

$\therefore C = 0$

⟸ "Hidden charm"

In Earlier years (early '70's)

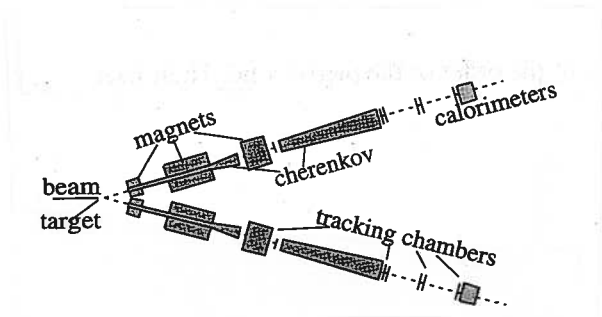
* Leon Lederman & Co Laboratory actually had seen a shoulder in $pp \to \mu^+\mu^- + X$ (p+N) but was ignored ⟸ "Lederman Shoulder"

Charm at BNL

At Brookhaven AGS, in 1974

$p + Be \rightarrow J/\psi \rightarrow e^+e^-$

Proton Energy = 33 GeV



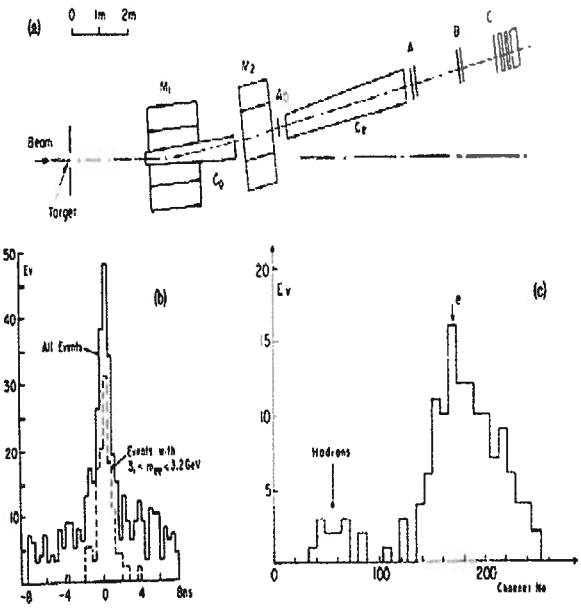


FIG. 1. (a) Simplified side view of one of the spectrometer arms. (b) Time-of-flight spectrum of e^+e^- pairs and of those events with $3.0 < m < 3.2$ GeV. (c) Pulse-height spectrum of e^- (same for e^+) of the e^+e^- pair.

Sam Ting, et al

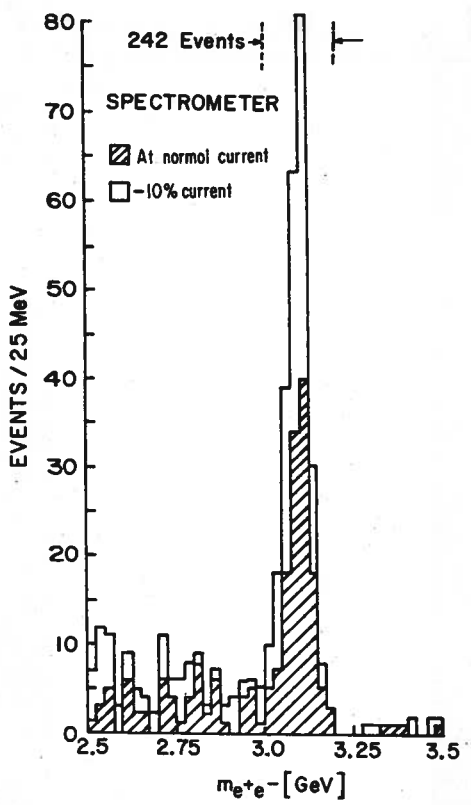
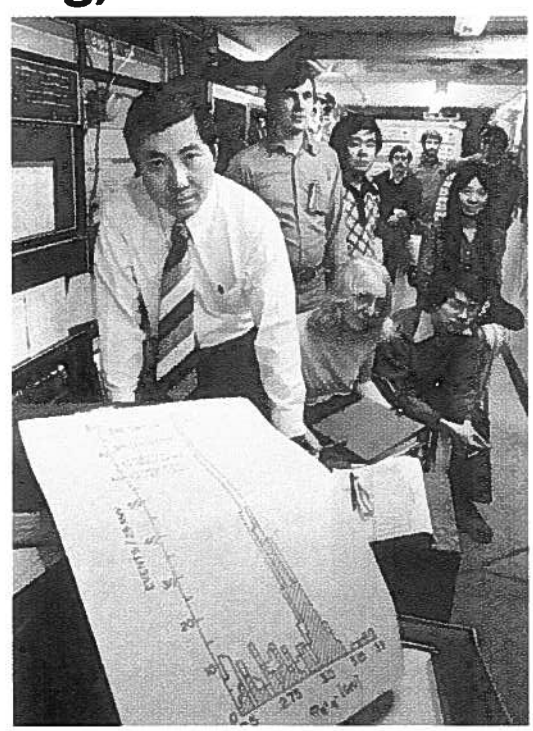


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.



$$m(e^+e^-) = \sqrt{2m_e^2 + 2E_1E_2 - 2p_1p_2\cos(\theta_1+\theta_2)}$$

Charm at SLAC

SPEAR at SLAC

Stanford Positron - Electron Annihilation Ring

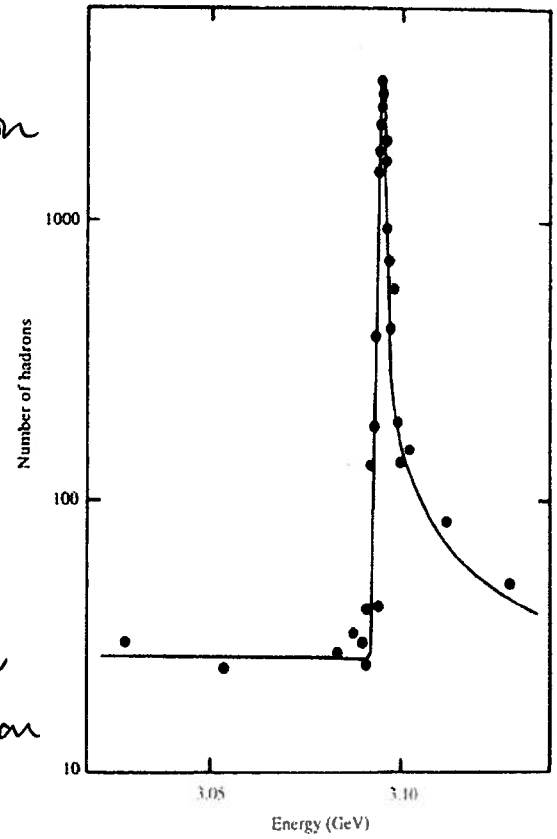
$e^+e^- \to$ hadrons,

e^+e^-, $\mu^+\mu^-$ studied

at $\sqrt{s}$ around 3 GeV

$\sigma(e^+e^- \to \text{hadrons}) > 2300$ nb,

about 100 times the cross-section outside the resonance.



First a rough scan with 200 MeV steps in collider energy showed some jump in cross section around 3.2 GeV.

Then scans with finer steps (2 MeV steps) were made and the narrow resonance of J/ψ found.

Measured $m(J/\psi) = 3.105 \pm .003$ GeV

FWHM $= 1.3$ MeV.

Burton Richter

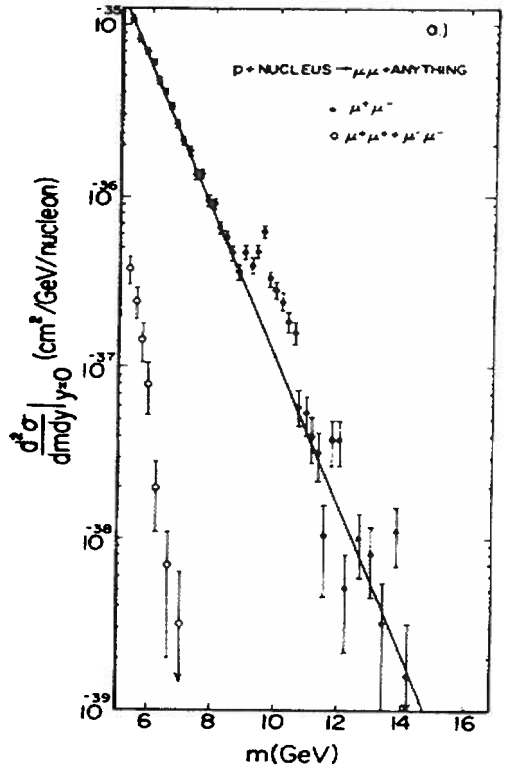
Beauty/Bottom Quark

Discovery 1977 Lederman et al

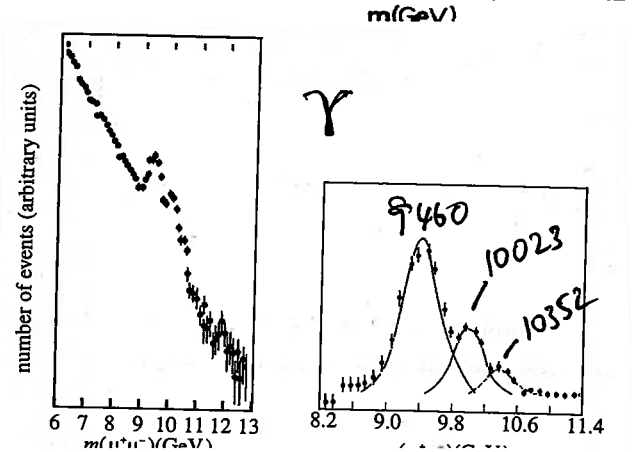
$p + N \rightarrow \mu^+ \mu^- X$

$\Upsilon(9460) = b\bar{b}$ Upsilon particle

Since Lederman missed the charm, he rushed and published in 1976. That is jokingly called "Oops-Leon" particle!



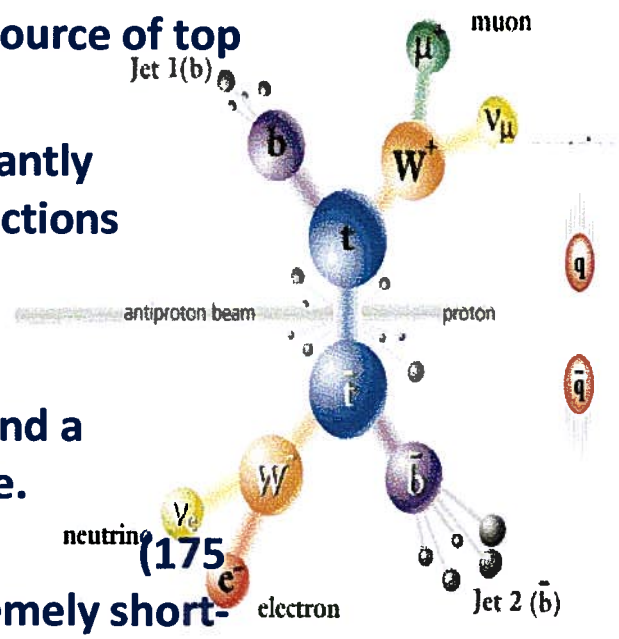
Leon Lederman
Former Director of Fermilab

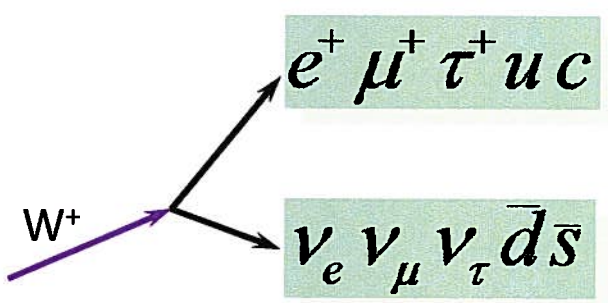


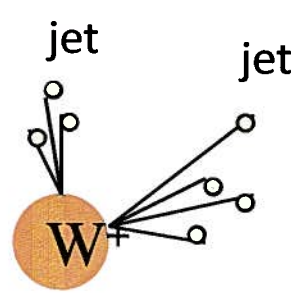
Widths → 53, 43 and 26 keV respectively

The Top Quark

- Top quark discovered at Fermilab in 1995.
- Many of us were actively involved in the discovery!
- Presently, Tevatron is the only source of top quarks!
- At the Tevatron, it is pre-dominantly pair-produced via strong interactions
  - qqbar →ttbar (90%)
  - gg→ttbar (10%)
- Each top decays to a W boson and a b-quark nearly 100% of the time.
- Top quark is extremely heavy (175 times the proton) and it is extremely short-lived! Lifetime ~ 10^{-25} sec!!!!



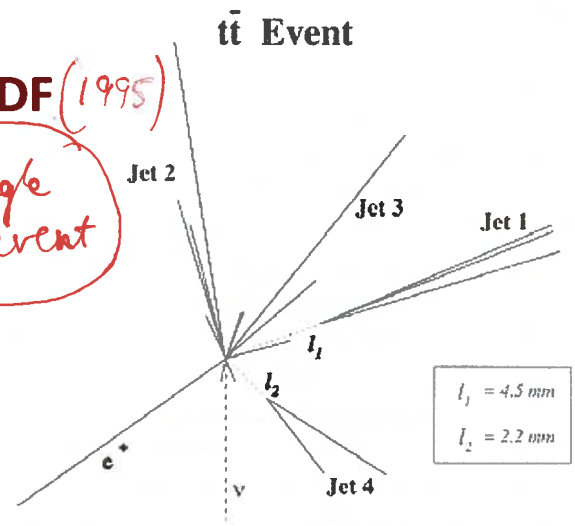


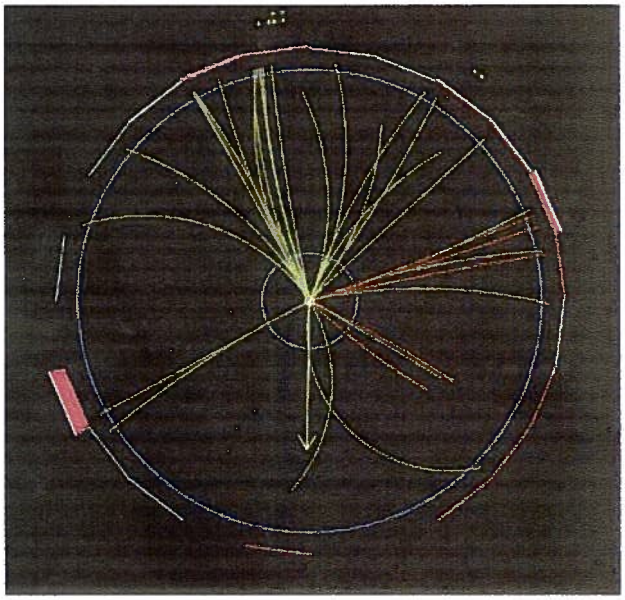


Top Quark Mass

CDF (1995)

Single $t\bar{t}$ event



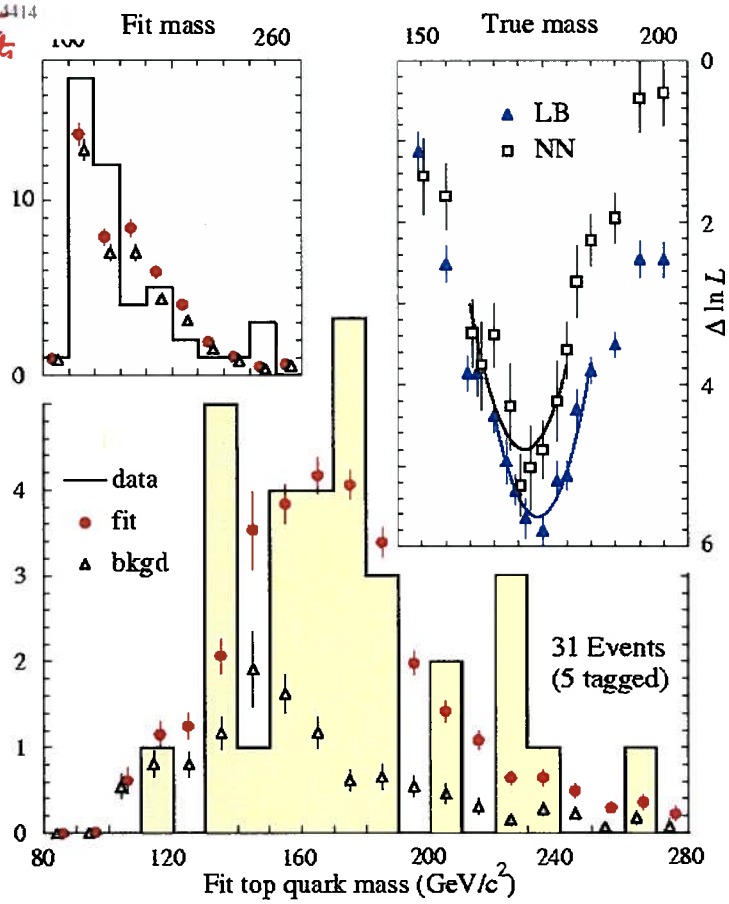


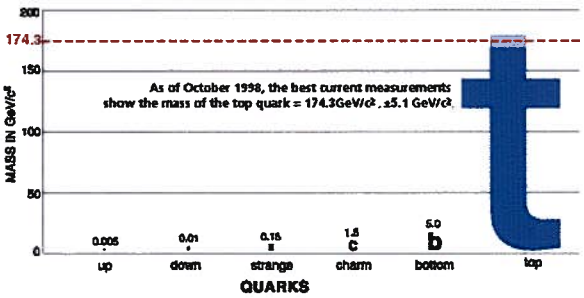
$M_{top}^{Fit} = 170 \pm 10$ GeV/c^2

CDF
24 September, 1992
run #40758, event #44414

There were 37 lepton+jets channel candidate events
Mass → 176±8±10 GeV/c²

DØ 1996





$m_t = 173.3 \pm 5.6(\text{stat.}) \pm 6.2\ (\text{syst.})$ GeV/c^2

There are many more states of "hidden" charm and beauty as well as many other mesons and baryons with "open" (or naked) charm and beauty that have been discovered since J/ψ and Υ.

All the known hadrons are tabulated with their properties in the Particle Data Group's tables.

CDF and DØ have found some new mesons and baryons with heavy flavors (c, b), the most recent being Ω_b (ssb) ← doubly strange + b

We will talk about Spectroscopy of Charmonium and Bottomonium in a later lecture.

σ and R in e^+e^- Collisions

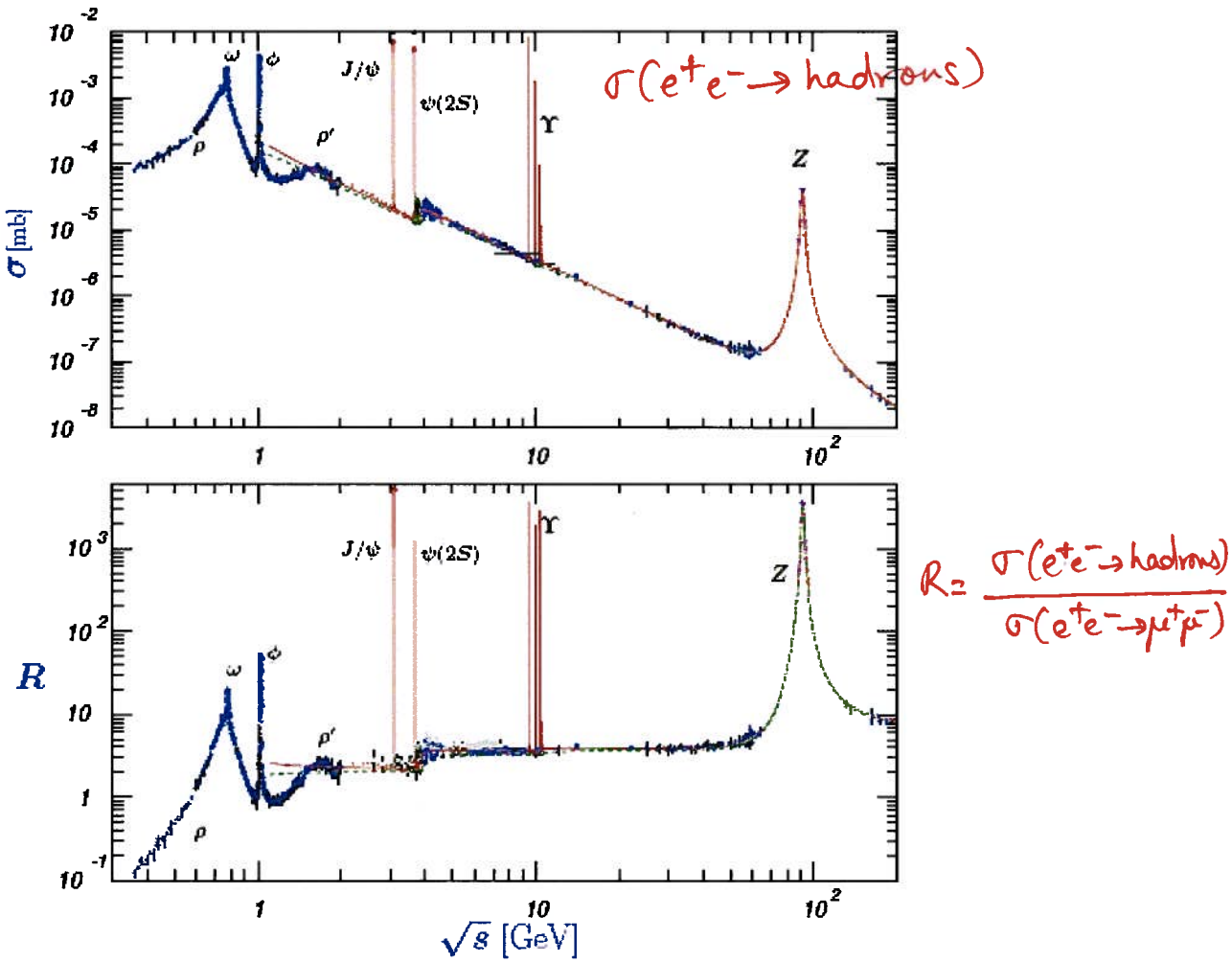
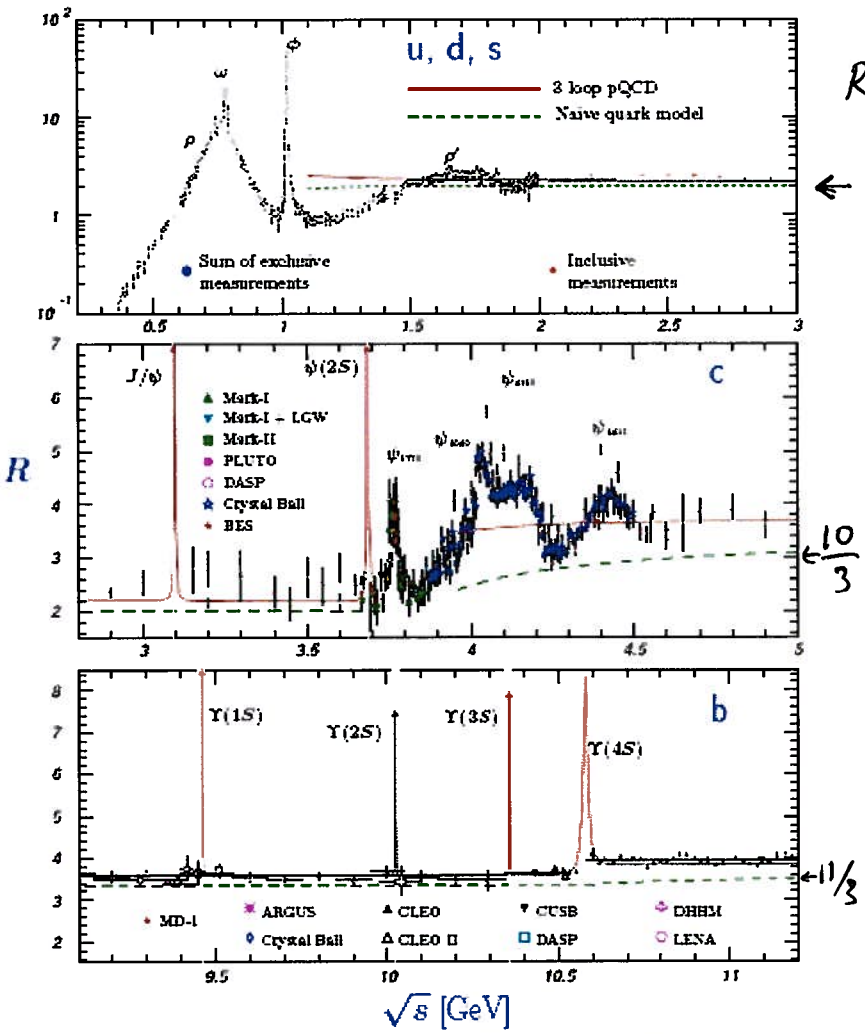


Figure 40.8: World data on the total cross section of $e^+e^- \to$ hadrons and the ratio $R(s) = \sigma[e^+e^- \to hadrons, s]/\sigma[e^+e^- \to \mu^+\mu^-, s]$. $\sigma[e^+e^- \to hadrons, s]$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops. $\sigma[e^+e^- \to \mu^+\mu^-, s] = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model prediction, and the solid one (red) is 3-loop pQCD prediction (see "Quantum Chromodynamics" section of this *Review*, Eq. (9.12) or, for more details, K. G. Chetyrkin et al. Nucl. Phys. B586, 56 (2000) [Erratum ibid. B634, 413 (2002)]. Breit-Wigner parameterizations of J/ψ, $\psi(2S)$, and $\Upsilon(nS)$, $n = 1, 2, 3, 4$ are also shown. The full list of references to the original data and the details of the R ratio extraction from them can be found in [arXiv:hep-ph/0312114]. Corresponding computer-readable data files are available at http://pdg.lbl.gov/current/xsect/. [Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2007. Corrections by P. Janot (CERN) and M. Schmitt (Northwestern U.)]

R in Light-Flavor, Charm, and Beauty Threshold Regions



$R = 3 \sum_{\text{flavor}} q_i^2$

$\leftarrow \frac{6}{3}$

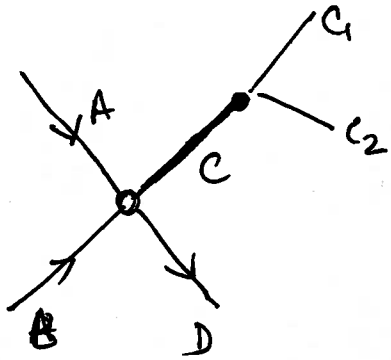
$\leftarrow \frac{10}{3}$

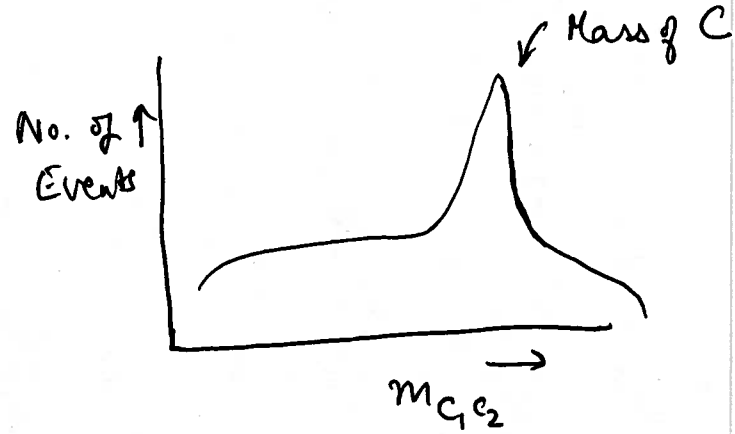
$\leftarrow 11/3$

Figure 40.7: R in the light-flavor, charm, and beauty threshold regions. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are the same as in Fig. 40.6. Note: CLEO data above $\Upsilon(4S)$ were not fully corrected for radiative effects, and we retain them on the plot only for illustrative purposes with a normalization factor of 0.5. The full list of references to the original data and the details of the R ratio extraction from them can be found in [arXiv:hep-ph/0312114]. The computer-readable data are available at http://pdg.lbl.gov/current/xsect/. [Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2007]

Short-lived Hadrons

Hadrons that decay by strong interactions are very short-lived ($\tau \sim 10^{-23}$ s) and are "Resonances"





C is a resonance that is too short-lived. It is identified by its decay products or daughters. Invariant mass distribution of the products shows a peak corresponding to the mass of the decaying particle.

Example: $K^- + p \rightarrow K^{*-} + p \rightarrow \bar{K}^0 + \pi^- + p$

$$m(K^{*-}) = m(\bar{K}^0 \pi^-)$$

The background in the invariant mass spectrum comes from combinations of particles from "non-resonant" processes.

Decay Width

The width of the resonant peak

$$\Delta W = \Delta E \simeq \Gamma = \frac{1}{\tau}$$

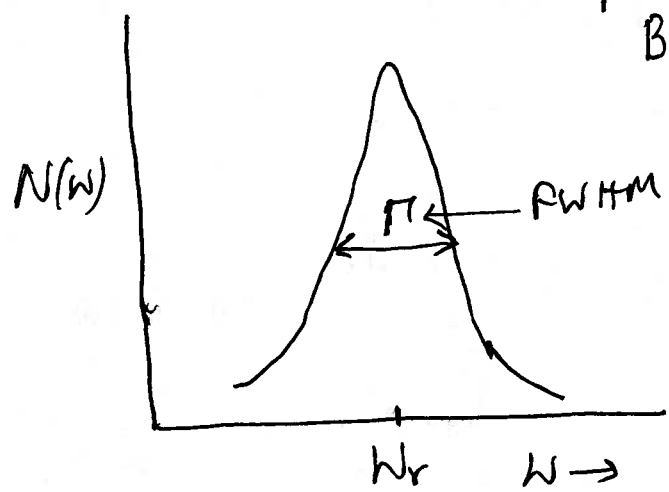
Γ = Natural line width

τ = life time.

$\therefore \tau \sim 10^{-23}$ sec , $\Gamma \sim 67$ MeV

$\sim O(100$ MeV$)$

Shape of an isolated resonant peak has the Breit-Wigner shape



$$N(W) = \frac{K}{(W - W_r)^2 + \Gamma^2/4}$$

For a single particle $W_r = M$ (rest mass of the particle

So the masses and widths of resonances can be found by fitting the invariant mass peak to this formula.

Leptons

(The Light ones)

- Also spin-$\frac{1}{2}$ fermions like the quarks but NO strong interactions
- Three generations

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

τ^- ← charged $Q = -1e$

ν_τ ← neutral

electron discovered by Thomson 1897

- Six different leptonic flavors
- Each generation has an associated Lepton number

$L_e = 1$ for e^- and ν_e, $L_e = -1$ for e^+, $\bar{\nu}_e$, etc.

- Lepton numbers have to be conserved.

So, in electromagnetic processes, since neutrinos are not involved, L_e conservation $\Rightarrow$ electrons and positrons have to be pair produced or annihilated.
Similarly for muons and taus.

- Neutrino hypothesis was put forth by Pauli in 1930, to explain energy, momentum conservation in beta decays.

Leptons (cont'd.)

- $\bar{\nu}_e$ discovered (Reines and Cowan, 1959) in an ingenious experiment using $\bar{\nu}_e$'s from a nuclear reactor.

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Inverse β-decay

$$\sigma \sim 10^{-47} \left(E_\nu / \mathrm{MeV} \right)^2 \mathrm{m}^2$$

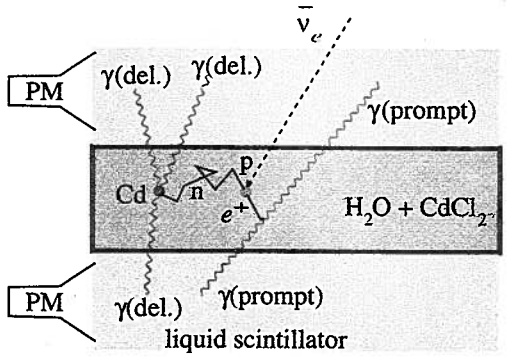
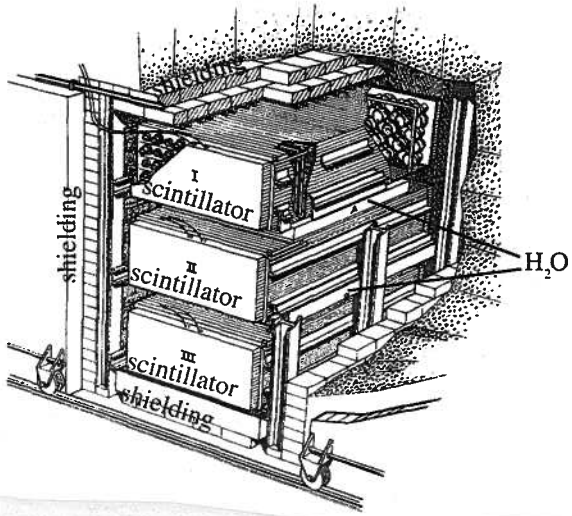


Fig. 2.6. A sketch of the detection scheme of the Savannah River experiment.



First Coinc. Signal

prompt photons from e^+ annihilating with an atomic electron

Delayed Coinc. Signal

Neutron capture by Cd nucleus (radiative)

Photon signals detected in the scintillators

567 such events over 200 hours, with an estimated background of 20% from accidentals.

Second Generation Leptons

- Muon ← Discovered by Anderson & Neddermeyer in 1936
- That the ν_μ is different from ν_e was shown (leading to discovery of ν_μ) by Lederman and others at Brookhaven. (1962)
- Lederman, Steinberger and Schwartz given Nobel Prize for this discovery in 1988.

- Experiment:

Pions produced by targetting intense proton beam on Beryllium. Pions decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad ; \quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

← Note: only muon neutrinos.

All particles ~~at~~ except ν_μ stopped through a long ~~Iron~~ filter.

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

interaction events were detected using spark chambers. Photographs revealed long penetrating tracks of muons, confirming the flavor of the neutrino to be muonic.

Third Generation Leptons

- τ lepton was discovered by Martin Perl and collaborators in e^+e^- (at SPEAR in 1975)

$$e^+ + e^- \longrightarrow \tau^+ + \tau^- \qquad (\text{above } 2m_\tau \text{ threshold})$$

$$\tau^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\tau \; ; \; \tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$$

or $\tau^+ \rightarrow \mu^+ + \nu_\mu + \bar{\nu}_\tau \; ; \; \tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$

Therefore, look for $e^-\mu^+$ or $e^+\mu^-$ pairs that are 'acoplanar' (because of the neutrinos involved).

- ν_τ was discovered at Fermilab in 2000.

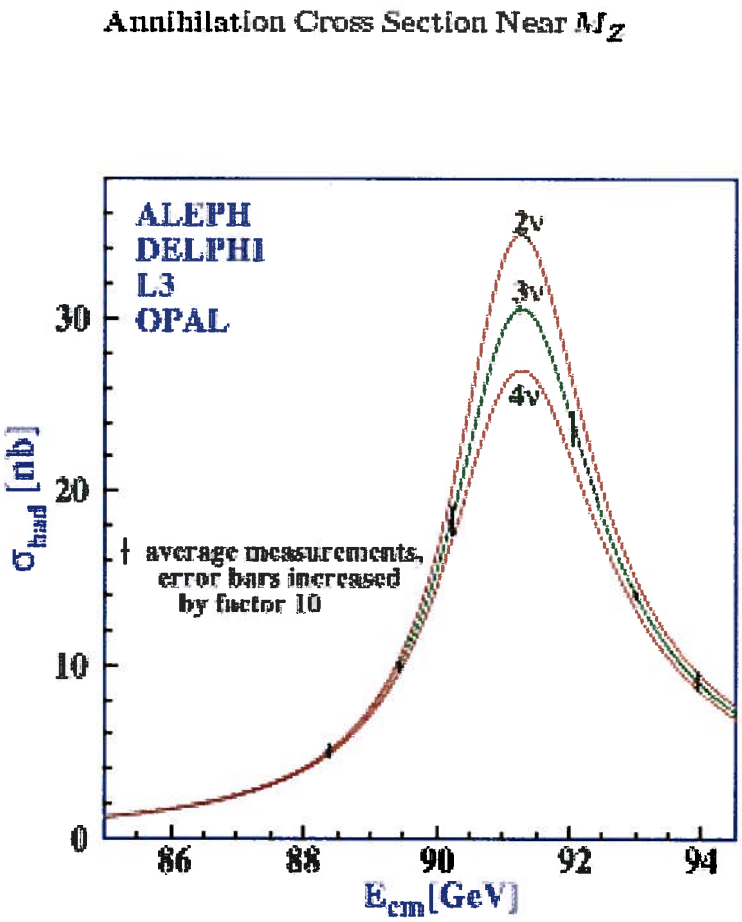
  τ lepton events from ν_τ interactions were detected in emulsions.

  (only 4 events out of a several million recorded)

- $m_\tau = 1777 \text{ MeV}/c^2$

  Lifetime $= 2.9 \times 10^{-13}$ s (while for μ, it is $2.2\,\mu$s)

Are there more generations?



Combined data from e+e- collider experiments at LEP. Cross section Of e+e- annihilation into hadrons as a function of CM energy around the Z mass. Curves show predictions for 2, 3 and 4 species of light neutrinos (m<45 GeV). The asymmetry is due to initial state radiation. The data is in excellent agreement with 3 light neutrinos!

From LEP EW Group combination.