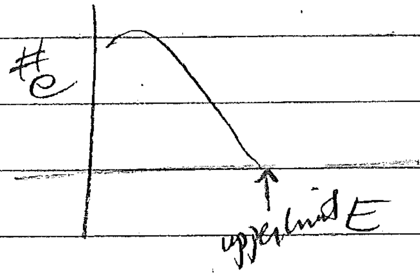
It turns out that $E_e \neq$ constant

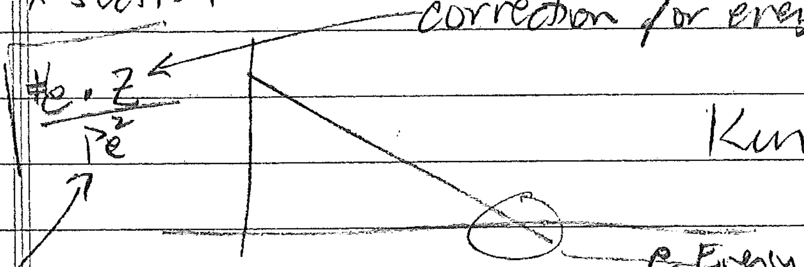


so there must be at least one more (invisible) particle in the final state.... the antineutrino

To measure the mass of the (anti-neutrino)

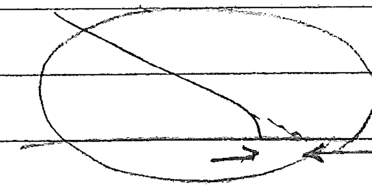
predict QM x-section correctly,

correction for energy loss by e in H Coulomb field



phase space factor

look closely



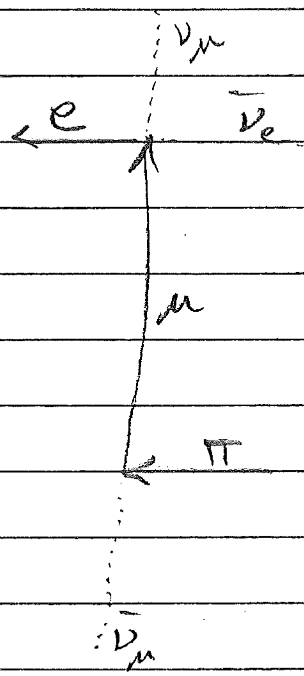
if $m_\nu \neq 0$, curve turns over

indicates m_ν

Precision not yet achieved.

It turns out that ν does not interact strongly, so add it to the lepton family.

Direct evidence for the neutrino (again emulsion)



It turns out that there is > 1 type of ν.
One neutrino is associated with each lepton type

$e - \nu_e$

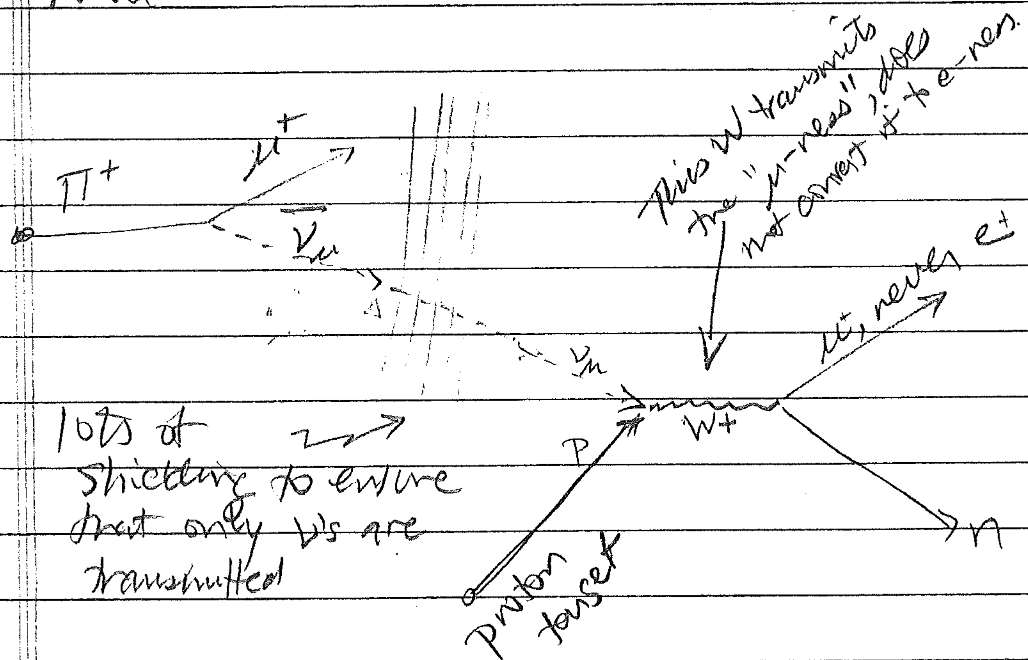
$\mu - \nu_\mu$

$\tau - \nu_\tau$

There are ~~ac~~ 3 kinds of neutrinos
(one matches each of the massive leptons

electron - ν_e
muon - ν_μ
tau - ν_τ

The fact that they are different is an experimental result



Since some interactions keep track of leptons + none allow lepton flavor change, define an accounting system lepton #, L

particles $e^-, \nu_e, \mu^-, \nu_\mu, \tau^-, \nu_\tau$ +1

anti-particles $\underbrace{e^+, \bar{\nu}_e}, \underbrace{\mu^+, \bar{\nu}_\mu}, \underbrace{\tau^+, \bar{\nu}_\tau}$ -1

subdivide into electron # L_e, muon # L_μ, τ-# "L_τ"

For interactions that respect it, ← EM, strong

lepton # in = lepton # out, including subcategories

e.g. $\pi^+ \rightarrow \mu^+ \bar{\nu}_\mu$

$\quad 0 \qquad -1 \quad +1$

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

$-1_\mu \qquad -1_e \quad +1_e \quad -1_\mu$

It's an experimental result: more fundamental reason for no $\underline{\mu \rightarrow e\gamma}$ (for example) not known.
c.f. "mu-to-e conversion experiments"

Why look for lepton flavor violation? We notice families ("generations")

quarks	u	c	t
	d	s	b
leptons	e	μ^-	τ^-
	ν_e	ν_μ	ν_τ
	1st	2nd	3rd

Basis for generational repetition is not known. Perhaps evidence for direct transitions between families ($\mu \to e\gamma$) may point to it.

There is a "baryon number B" analogous to lepton #. It keeps track of the balance of proton-like particles and is also experimentally unviolated.

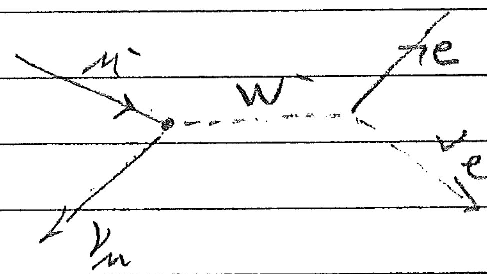
There is no "meson number".

• Characteristic timescales of the interactions

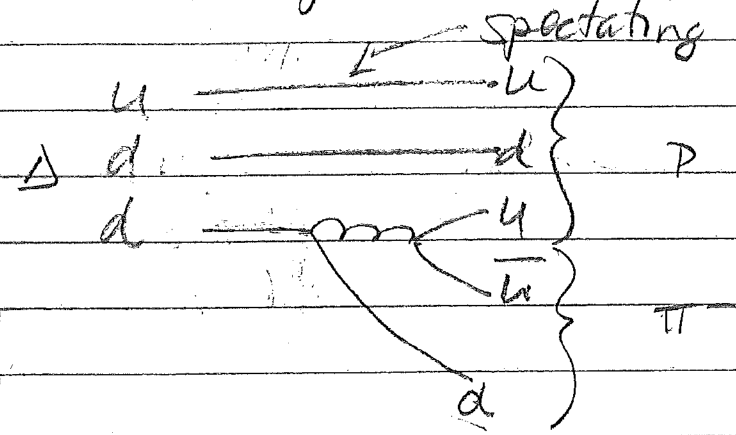
Most elementary particles have finite lifetimes (except p, e, γ, ν ...)

When particle decays, it does not leave nothing — it converts its energy into other particles. The conversion is mediated by one of the fundamental forces.

Ex muon decay



Ex Δ decay



mediated by a gluon (strong force)

The lifetime (mean time until decay) of particle is correlated with the force that mediates it.

Force	typical lifetimes
Strong force	$\sim 10^{-23}$ s
EM	10^{-16} s
Weak	10^{-8} s

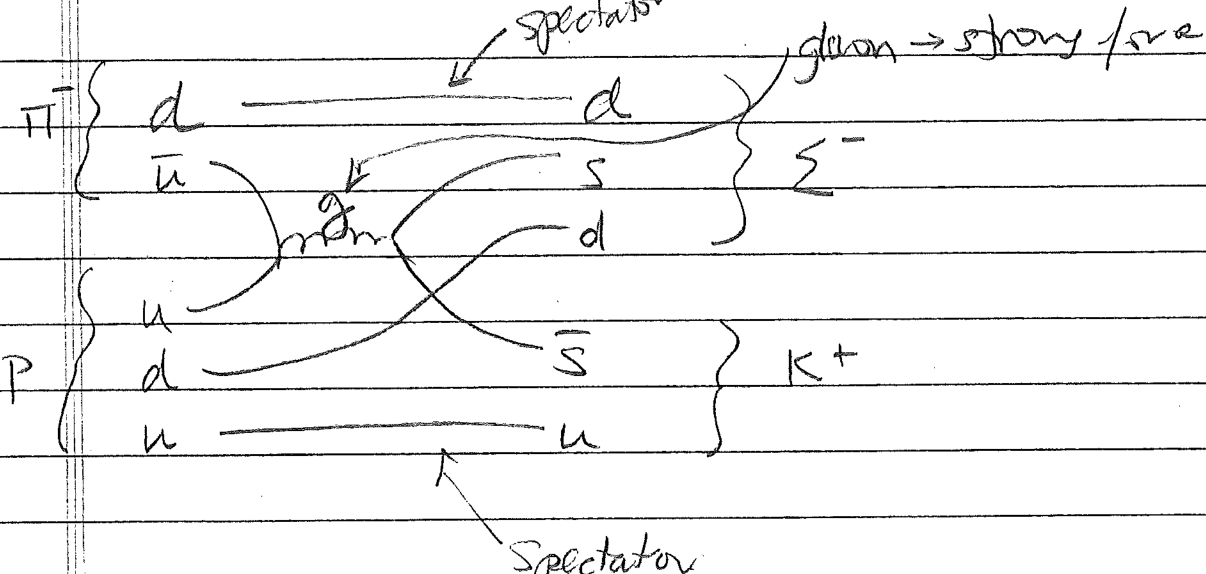
Particles can be produced by one interaction and decayed by another

This topic arises in the discovery of "strangeness": incorporation of the strange quark. Strange particles are produced quickly (strong force); decay slowly (weak force)

i.e., live long

production

$\pi^- p^+ \longrightarrow K^+ \Sigma^-$ — "associated production" of the s-$\bar{s}$ pair

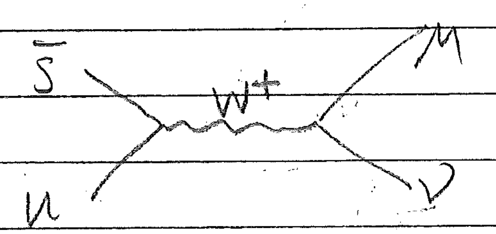


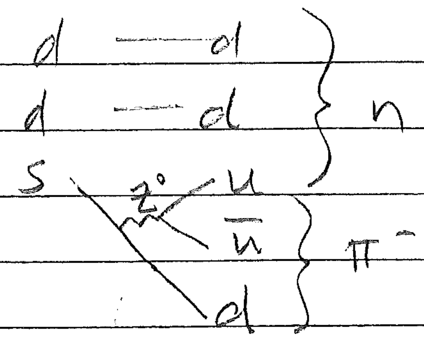
10^{-22} s

Now Σ^- and K^+ must each decay without the help of the other. For energy conservation, they Must decay to lighter bound states — energy tied up in the heavy s must go into lighter species.
Only the weak force can mediate quark flavor change.

$K^+ \to \mu^+ \nu$ $\qquad\qquad$ $\Sigma^- \to n \pi^-$ $\quad (10^{-10}$ s$)$

(63%)

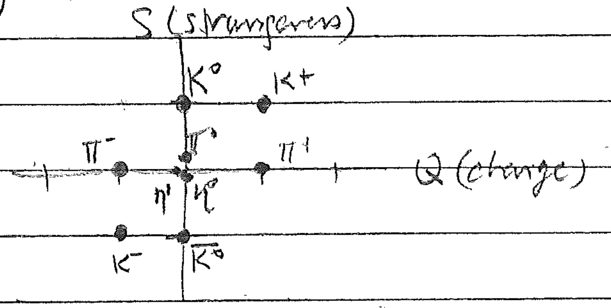




See "particle physics and representation theory"

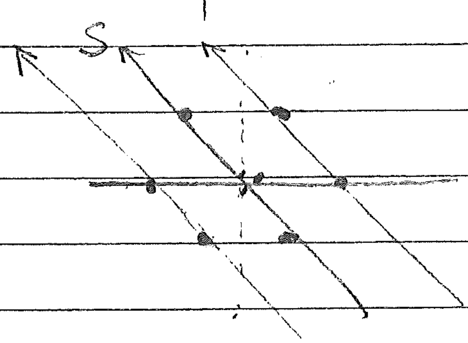
- the quark model

Gell-Mann noticed that when particles are located on graphs with special axes, patterns emerge:



Graph only mesons whose wavefunctions have $J^P = 0^-$

We usually see this with the S axis tipped



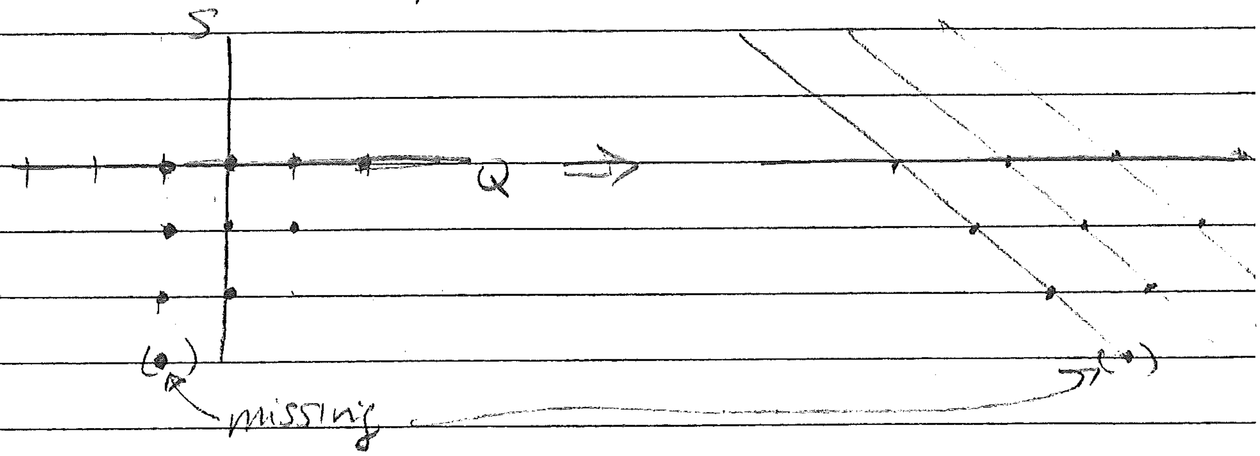
S → inferred from associated production.

Patterns: like Periodic Table, indicate substructure of common constituents

Issues that arise:
1) What about the 3 states @ $(Q=0, S=0)$?
2) Do all bound states fit into patterns like these
3) How this leads to the prediction of color
4) Can the pattern extend out of the plane?

Answers:

(2) In 1963 the baryons formed this pattern:



On the basis of a desire for symmetric completeness, Gell-Mann predicted the $Q=-1$, $S=-3$ state. Its observation (1964, Ω^- particle) strengthened the quark model.

$$\Omega^- : \begin{pmatrix} s^{-1/3} \\ s^{-1/3} \\ s^{-1/3} \end{pmatrix}$$

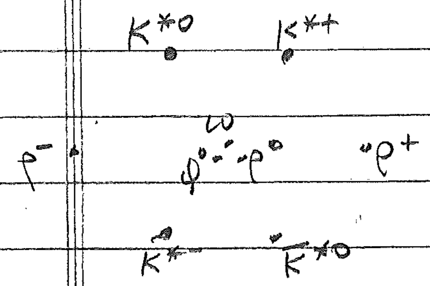
(1) What about the 3 states @ $Q=0$, $S=0$? These are the π^0, η^0, η'. How they differ? First note that a 2-quark bound state does not have to have a form like "$q_1\bar{q}_2$". It can be linear combination of products.

$$\left.\begin{aligned} \pi^0 &= \frac{u\bar{u} - d\bar{d}}{\sqrt{2}} \\ \text{547 MeV} \quad \eta &= \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}} \quad \{\eta \to \pi\pi\pi\} \end{aligned}\right\} \text{in octet}$$

$$\text{958 MeV} \quad \eta' = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3} \quad \{\eta' \to \pi^+\pi^-\eta^0\} \quad \text{singlet}$$

Meson

There is another representation for the $J^P = 1^-$ mesons:



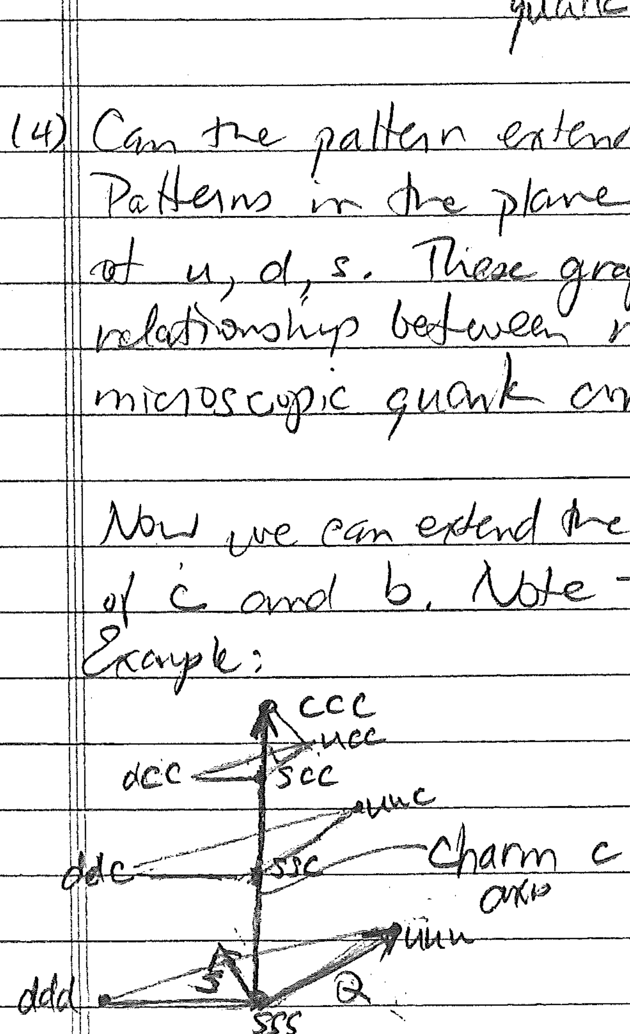
$\phi = s\bar{s}$

$\omega^0 = \dfrac{u\bar{u} + d\bar{d}}{\sqrt{2}}$

$\rho^0 = \dfrac{u\bar{u} - d\bar{d}}{\sqrt{2}}$ $\quad \rho^0 \to \pi^+\pi^-$ Notice ρ^0 and π^0 have same quark content, think of ρ^0 as excited π^0.

(14) Can the pattern extend out of the plane?
Patterns in the plane involve only bound states of u, d, s. These graphs were invented before the relationship between macroscopic Q and S and microscopic quark content was understood.

Now we can extend the graphs to include bound states of c and b. Note t does not form bound states
Example:



See Griffiths p. 45

(3) From these graphs to QCD color:
Recall the spin-statistics theorem of QFT, founded on Lorentz invariance. We expect spin 1/2 particles to have anti-symmetric wavefunctions.
If $\psi_{total} = \psi_{spatial} \cdot \psi_{spin}$ then a state of triple-strangeness:
$(sss) = \Omega^-$, is symmetric in $\psi_{spatial}$ and not fully antisymmetric in ψ_{spin} (can have e.g., $\uparrow\uparrow\uparrow$ or $\uparrow\downarrow\uparrow$).
Propose (Greenberg, 1964) that every quark has a "color charge" (analog to EM charge). There are 3 possible color charges (and 3 anti-charges) such that if a 3-quark state includes 1 of each, it has an antisymmetric "ψ_{color}". Then if $\psi_{tot} = \psi_{spatial} \cdot \psi_{spin} \cdot \psi_{color}$, the Ω^- is still assured to be antisymmetric. Direct evidence for color: measurement of $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$

Checkout www.slac.stanford.edu/spires
and arXiv

- Overview of the Standard Model

3 generations of quarks:

			electric charge
u	c	t	$+2/3$
d	s	b	$-1/3$

3 generations of leptons:

			electric charge
e	μ	τ	-1
ν_e	ν_μ	ν_τ	0

3 types of force mediators

γ - 1
g - 8
$W^+/W^-/Z$ - 3

What to notice about this:

(1) Could there be more generations? How would we know?
No evidence for more generations with masses up to the limits producable at current accelerators.
How we know (2 ways):

(1) Z^0 lifetime. Conserve E, p

Recall (1) Uncertainty Princ., (2) Fermi's Golden Rule:

$\Delta E \Delta t \geq \hbar$ and $\Gamma \sim \int |M|^2 \cdot \frac{d^4p}{(2\pi)^4} \cdot \delta(p_f - p_i)$

decay rate (like σ)

QM matrix elt (probability amplitude)^2

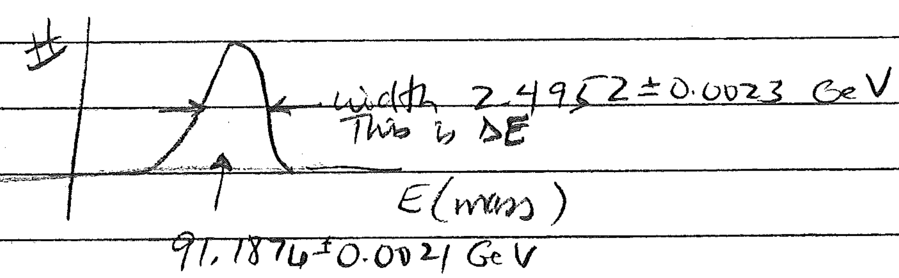
phase space

The $\int d^4p$ means that the more energy/momentum available to the final state, or the more ways this E/p can be manifested, the higher the rate.

High decay rate → fast decay → short lifetime

Short lifetime $\xrightarrow{\text{smaller } \Delta t}$ wide energy uncertainty ΔE

Consider measurements of the mass of the Z^0:



mass	
t	174 GeV
b	4 GeV

Consider ways the Z^0 can decay:

Since it is charge = 0, it can decay to any final state with total charge = 0 and mass $\leq M_{Z^0}$

Z^0 → (1) any $q\bar{q}$ including all 3 color options of each

$u_R\bar{u}_R$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, $b\bar{b}$

$u_G\bar{u}_G$

$u_B\bar{u}_B$

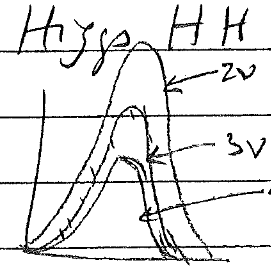
$3 \times 5 = 15$ $q\bar{q}$ final states

$Z^0 \rightarrow$ (2) any $l\bar{l}$ pair
$e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \nu\bar{\nu} * 3$: 6 final states

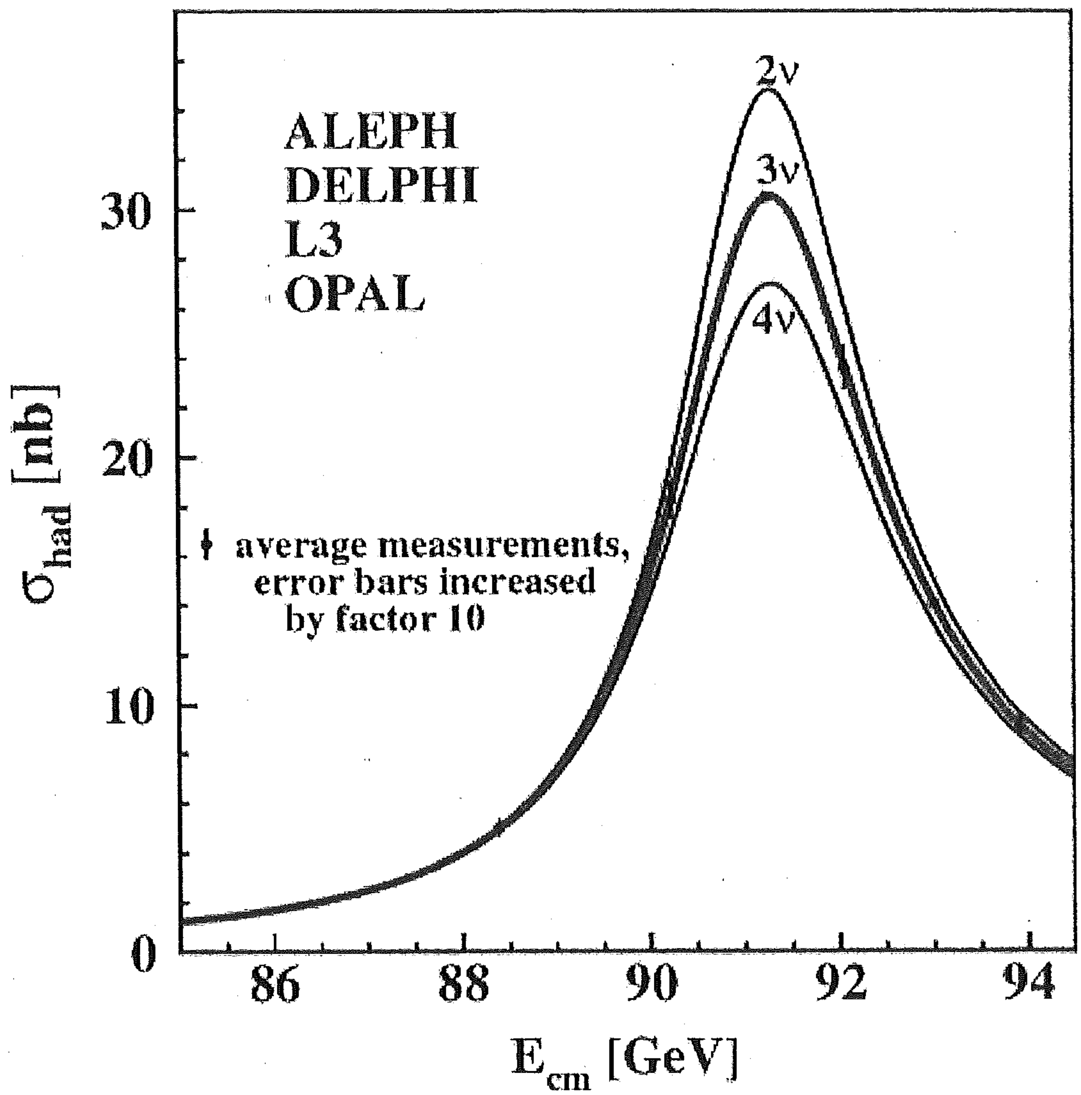
There are a few other decay modes such as
$Z \rightarrow \underbrace{c\bar{c}}_{\psi} \; \underbrace{u\bar{u}}_{\pi}$. Producing all these masses
leaves little phase space so the probabilities for these sorts of channels are small.

Each mode is a path to decay
" " shortens τ, widens Γ

If there were other quarks q' or leptons l' such that $Z^0 \rightarrow q'\bar{q}'$ etc were possible, they would contribute to the width.
The present comparison of data to theory indicates that Γ can be ascribed entirely to existing particles
Additionally there is no room in Γ for Higgs $H\bar{H}$ of mass $< Z/2$, or other new physics.
Ex $N_\nu = 2.984 \pm 0.008$



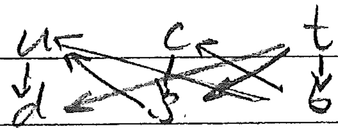
(2) Measured weak transition rates
Recall the weak force can convert quark flavors.
A shorthand for which transitions have been observed is called the Cabibbo-Kobayashi-Maskawa (CKM) matrix.
To construct the matrix note:



ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements, error bars increased by factor 10
σ_{had} [nb]
30
20
10
0
86
88
90
92
94
E_{cm} [GeV]

(i) There is not evidence for 1st order weak neutral decays of the form $c \to u$

(ii) Experimentally these occur:



"Horizontal" transitions not seen to first order

How probable is each type of transition?

Construct a matrix with 1 row, 1 column for each famil

Label rows by the upper member of each family (u, c,

" columns " " lower " " " " (d, s, b

$$\begin{array}{c c} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \left[\begin{array}{ccc} \quad & \quad & \quad \\ & & \\ & & \end{array}\right] \end{array}$$

$\sqrt{\text{Prob}}$

Each matrix element is the experimentally observed amplitude for transition between those quark types. By convention the amplitudes are called "V"

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Measure rates for all possible transitions. The result:

$$\begin{bmatrix} 0.9738 & 0.2272 & 0.0040 \\ 0.2271 & 0.9730 & 0.0422 \\ 0.0081 & 0.0416 & 0.9991 \end{bmatrix}$$

1%
Typical uncertainties: 10%
except $\sigma(V_{ub}) \sim 25\%$
[large diagonal amplitudes support placement of those q's in same multiplet]

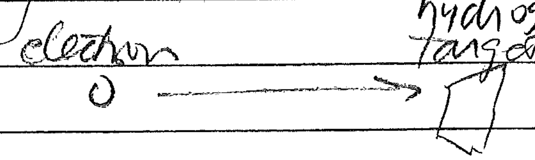
Now find $\sum_j |V_{ij}|^2$ for each row, each column:

$$\begin{bmatrix} & & \\ & & \\ & & \end{bmatrix} \begin{matrix} \rightarrow 0.99992 \\ \rightarrow 1.00008 \\ \rightarrow 0.99999 \end{matrix}$$

$$\begin{matrix} \downarrow & \downarrow & \downarrow \\ 0.99992 & 1.00008 & 0.99999 \end{matrix}$$

Conclude: within experimental uncertainty, the 3-generation matrix is unitary.

(2) What evidence exists for quarks?
Deep inelastic scattering (1969, Nobel 1990 Taylor, Friedman, Kendall,



$E = h\nu = \frac{hc}{\lambda}$ very high, λ short $\rightarrow$ high resolution on short distance structures

$\rightarrow$ collision typically produces new species
(collision is inelastic onto the p but elastic onto its constituent)
Study outgoing e, not p fragment

What was found: "scaling"

The cross section might be expected to have form

$$\frac{d^2\sigma}{dq^2\,d\nu} = \frac{4\pi\alpha^2\hbar^2 E'}{q^4 m c^2 E}\cdot\left\{W_2 + (2W_1 - W_2)\sin^2\frac{\theta}{2}\right\}$$

inelasticity: $\nu = E - E'$

(momentum transfer)^2

incident e energy

scattered e energy

"structure functions" reflect finite extent of proton

[magnetic interaction of spin ½]

scattering angle

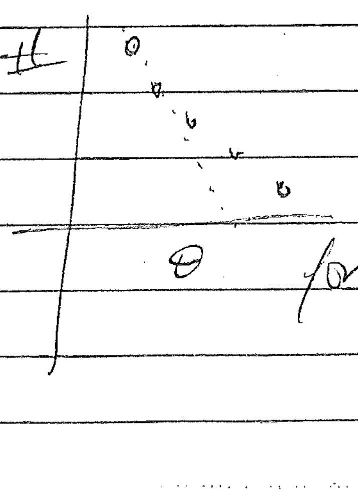
Compare Rutherford: $\frac{d\sigma}{d\Omega} = \frac{4m^2(Z_1 Z e^2)^2}{q^2}$

As $q^2 \to \infty$, $\nu \to \infty$ (but $\frac{q^2}{\nu}$ finite)

One might expect $d^2\sigma$ to depend on both q^2 and ν, however one finds $W_1, W_2 \sim$ a dimensionless parameter $\sim \frac{q^2}{\nu} = x$

which is the fraction of the proton's momentum carried by the struck quark

This looks like



like Rutherford

θ for energies 7-17 GeV

Any analogous evidence for quark substructure:
No, up to energies $\underline{2\,TeV}$

Corresponding distances probed:

$$E = h\nu = \frac{hc}{\lambda} = \frac{hc}{d}$$

$$\text{So } d \sim \frac{hc}{E} \longleftarrow \quad hc = 1238 \text{ MeV-fm}$$

So $d_{\text{probed by } 10\,GeV} = 0.12$ fm characterizes dimension of the structure of nucleon

$d_{\text{probed by } 2\,TeV} = 0.00006$ fm characterizes extent of precision of non-observation of structure in quarks

– End of Ch 1 contextual overview — Now Ch 2:
Now discuss the 3 Standard Model Forces
First qualitatively, then (Ch 7...) quantitatively