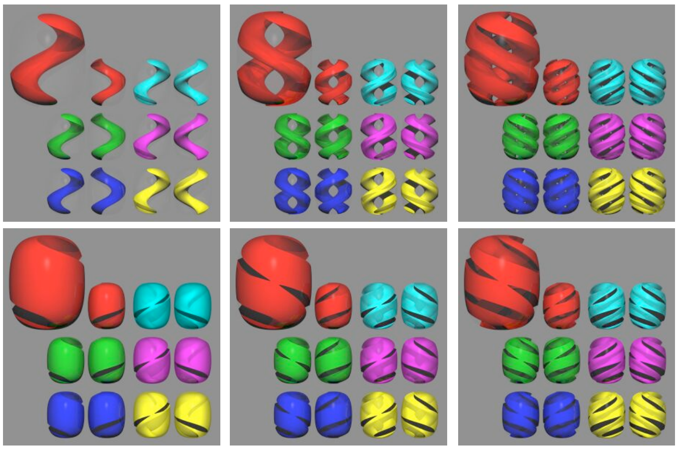
Nuclear and Particle Physics Junior Honours:

Particle Physics

Lecture 5: Quarks and Leptons

February 22nd 2007



- **Leptons**
  - Quantum Numbers
- **Quarks**
  - Isospin
  - Strangeness
  - Quark Model
  - J/ψ
  - Heavy Quarks: bottom and top

Leptons

- Six leptons: e^- μ^- τ^- ν_e ν_μ ν_τ
- Six anti-leptons: e^+ μ^+ τ^+ $\overline{\nu}_e$ $\overline{\nu}_\mu$ $\overline{\nu}_\tau$

- Three quantum numbers used to characterise leptons:
  - Electron number, L_e, muon number, L_μ, tau number L_τ
  - Total Lepton number: $L = L_e + L_\mu + L_\tau$
  - L_e, L_μ, L_τ & L are conserved in all interactions

Lepton		L_e	L_μ	L_τ	$Q(e)$
electron	e^-	+1	0	0	−1
muon	μ^-	0	+1	0	−1
tau	τ^-	0	0	+1	−1
electron neutrino	ν_e	+1	0	0	0
muon neutrino	ν_μ	0	+1	0	0
tau neutrino	ν_τ	0	0	+1	0
anti-electron	e^+	−1	0	0	+1
anti-muon	μ^+	0	−1	0	+1
anti-tau	τ^+	0	0	−1	+1
electron anti-neutrino	$\bar{\nu}_e$	−1	0	0	0
muon anti-neutrino	$\bar{\nu}_\mu$	0	−1	0	0
tau anti-neutrino	$\bar{\nu}_\tau$	0	0	−1	0

Think of L_e, L_μ and L_τ like electric charge:

- They have to be conserved at every vertex.
- They are conserved in every decay and scattering process

Parity: intrinsic quantum number.
π=+1 for lepton
π=−1 for anti-leptons

Introduction to Quarks

- Six quarks: d u s c t b
- Six anti-quarks: $\bar{d}$ $\bar{u}$ $\bar{s}$ $\bar{c}$ $\bar{t}$ $\bar{b}$

Parity: intrinsic quantum number.
π=+1 for quarks
π=−1 for anti-quarks

- Lots of quantum numbers used to describe quarks:
  - Baryon Number, $\mathcal{B}$ - total number of quarks
    - $\mathcal{B}$=+1/3 for quarks, $\mathcal{B}$=−1/3 for anti-quarks
  - Strangeness: S, Charm: C, Bottomness: B, Topness: T - number of s, c, b, t
    - S=N($\bar{s}$)−N(s) C=N(c)−N($\bar{c}$) B=N($\bar{b}$)−N(b) T=N(t)−N($\bar{t}$)
  - Isospin: I, I_Z - describe the up and down quarks

Quark		I	I_Z	S	C	B	T	$Q(e)$
down	d	1/2	−1/2	0	0	0	0	−1/3
up	u	1/2	1/2	0	0	0	0	+2/3
strange	s	0	0	−1	0	0	0	−1/3
charm	c	0	0	0	+1	0	0	+2/3
bottom	b	0	0	0	0	−1	0	−1/3
top	t	0	0	0	0	0	+1	+2/3

- $\mathcal{B}$ conserved in **all** interactions
- S, C, B, T conserved in **strong** and **electromagnetic**
- I, I_Z conserved in **strong** interactions only

Conservation Laws

Noether's Theorem: Every symmetry of nature has a conservation law associated with it, and vice-versa.

- **Energy & Momentum; Angular Momentum**
  conserved in all interactions
  Symmetry: translations in space and time; rotations in space
- **Charge conservation**
  conserved in all interactions
  Symmetry: gauge transformation - underlying symmetry in QM description of electromagnetism
- **Lepton Number and Baryon Number symmetry**
  L_e, L_μ, L_τ baryon number, $\mathcal{B}$
  symmetry: mystery!
- **Quark Flavour, Isospin, Parity**
  conserved in strong and electromagnetic interactions
  violated in weak interactions
  Symmetry: unknown

Isospin

- Protons uud and neutrons udd have almost equal mass:
  - m_p = 938.3 MeV/c^2 m_n = 939.6 MeV/c^2
- $\pi^{\pm}$ ($u\bar{d}$, $\bar{u}d$) and π^0 ($u\bar{u}$, $d\bar{d}$) have almost the same mass
- To describe this symmetry between sets of hadrons we define a new quantum number: **isospin, *I***
  - In baryons, we combine isospin in the same way as spin
  - **total isospin *I*** and **third component of isospin, I_Z:** $I \le I_Z \le -I$
- p and n form an 'isospin doublet' with I=½
  - proton has I_Z=+½ neutron has I_Z=−½

$$I_Z = \frac{1}{2}\left[N(\mathrm{u}) - N(\mathrm{d}) + N(\bar{\mathrm{d}}) - N(\bar{\mathrm{u}})\right]$$

- π^+, π^0 and π^- form an 'isospin triplet' with I=1
  - π^+ has I_Z=+1, π^0 has I_Z=0, π^- has I_Z=−1

Isospin sets for the lightest baryons

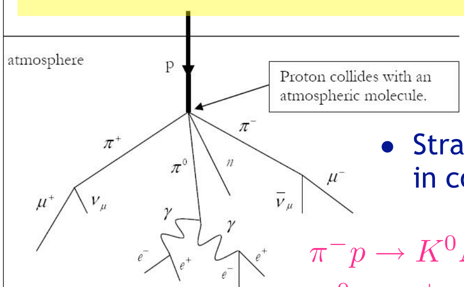
$\eta = |0,0\rangle$

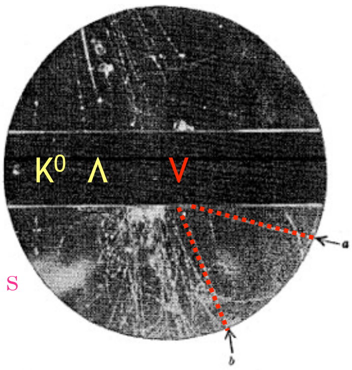
$p = |\tfrac{1}{2},\tfrac{1}{2}\rangle$ $n = |\tfrac{1}{2},\tfrac{1}{2}\rangle$

$\pi^+ = |1,1\rangle$ $\pi^0 = |0,0\rangle$ $\pi^+ = |1,-1\rangle$

$\Delta^{++} = |\tfrac{3}{2},\tfrac{3}{2}\rangle$ $\Delta^{+} = |\tfrac{3}{2},\tfrac{1}{2}\rangle$ $\Delta^{0} = |\tfrac{3}{2},-\tfrac{1}{2}\rangle$ $\Delta^{-} = |\tfrac{3}{2},-\tfrac{3}{2}\rangle$

Strangeness

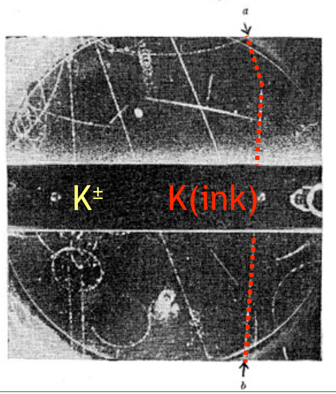




- Strange particles found 1947 in cosmic rays: "V" and "K"

$$\pi^- p \to K^0 \Lambda \qquad \tau(K^0) = \mathcal{O}(10^{-23}\ \mathrm{s})$$
$$K^0 \to \pi^+ \pi^- \qquad \tau(K^0) = 0.9 \times 10^{-10}\ \mathrm{s}$$
$$\Lambda \to \pi^- p \qquad \tau(\lambda) = 2.6 \times 10^{-10}\ \mathrm{s}$$

- Entirely unexpected!
- Particles are produced in pairs via strong interaction. Decay via weak interaction.
- Introduce a new quantum number to describe these particles: **Strangeness**.
  - conserved in strong interactions and electromagnetic interactions.
  - violated in weak interactions.



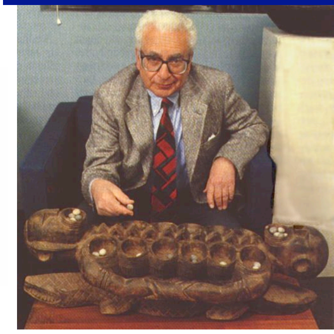
Quark Model

- By the mid-1960's so many particles were being found no one knew what was going on...
  - These could not all be fundamental particles...

Mesons	⟨Mass⟩	J^{PC}	I	S
π^-, π^0, π^+	138.0	0^{-+}	1	0
K^0, K^+	495.7	0^-	1/2	+1
$K^-, \bar{K}^0$				−1
η	547.3	0^{-+}	0	0
ρ^-, ρ^0, ρ^+	770.0	1^{--}	1	0
ω	781.9	1^{--}	0	0
K^{*0}, K^{*+}	893.7	1^-	1/2	+1
$K^{*-}, \bar{K}^{*0}$				−1
η'	957.8	0^{-+}	0	0
ϕ	1019.5	1^{--}	0	0

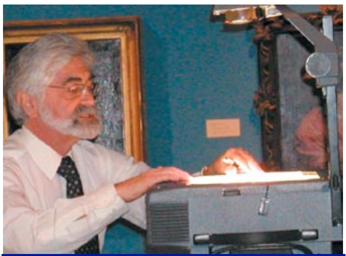
Baryons	⟨Mass⟩	J^P	I	S
p, n	938.9	$1/2^+$	1/2	0
Λ	1116	$1/2^+$	0	−1
$\Sigma^-, \Sigma^0, \Sigma^+$	1193	$1/2^+$	1	−1
$\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$	1232	$3/2^+$	3/2	0
Ξ^-, Ξ^0	1318	$1/2^+$	1/2	−2
$\Sigma^{*-}, \Sigma^{*0}, \Sigma^{*+}$	1385	$3/2^+$	1	−1
Ξ^{*-}, Ξ^{*0}	1533	$3/2^+$	1/2	−2

Murray Gell-Man, 1969 Nobel Prize in Physics



- In 1964 Gell-Mann and Zweig proposed the idea of ***quarks*** to explain isospin symmetry and strangeness.
- Three quarks: up, down and strange.

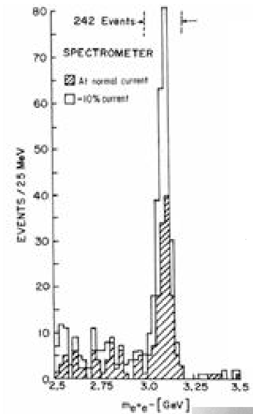
Quark	Charge, e	Isospin |I, Iz>	Strange-ness, S
Up	+2/3	|½, +½>	0
Down	−1/3	|½, −½>	0
Strange	−1/3	|0, 0>	−1

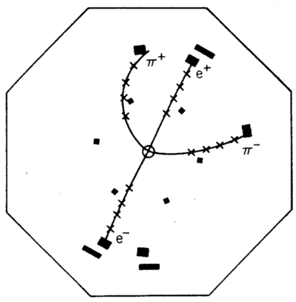


George Zweig

Discovery of the J/ψ

- In 1974 a new resonance state found in strong interactions: p+Be→J/ψ+X
- Decay: J/ψ→e+e−, J/ψ→μ+μ−
- Lifetime τ(J/ψ) = 7.6×10^{-21} s - decays by electroweak force.
- Mass M(J/ψ) = 3.1 GeV/c^2.
- The discovery caused a revolution in particle physics. Lead to acceptation of Gell-Mann and Zweig's idea that hadrons were composed of quarks.
- J/ψ is composed of c and c̄.





Richter and Ting independently discovered the J/ψ. 1976 Noble prize in physics

Bottom Quark

- Bottom quark was discovered in 1977. New resonance state ϒ.
- M(ϒ) = 9640 MeV/c^2
- Decays: $\Upsilon \to e^+e^-$, $\Upsilon \to \mu^+\mu^-$
- Lifetime $\tau(\Upsilon)=1.3\times10^{-20}$ s
- $\Upsilon = b\bar{b}$

DO NOT MAKE PUBLIC

Memo: From the people who brought you the ϒ, a bigger (but not necessarily better) resonance — JKY 11/17(76)

Two recent e^+e^- event at 9.51 and 9.67 GeV stirred some memory of clustering of 6 μμ events near 9.6 GeV from 1100 amp Cu data. Here is an attempt to assess the significance of the "9.6" clustering in the dilepton mass spectrum.

At right is a plot of the acceptance for various ee/μμ mode normalized to 1.0 at 9 GeV — thus sensitivity at 9±1 to 2 GeV is almost flat — it is not rising between 8-10 GeV. Thus, a plot of events would reflect dσ/dm dy. plots a, b, c reflects respectively ee I, ee II and $\sum_{I,II}$ ee; note the 4 events between 9.45 and 9.7. d is the μμ I data ([redacted]) as published with tight cuts (μA). μB, μC μD are progressively relaxed μμ cuts in order to gain more μμ events. Poisson statistics on combined ee+μμ (A, A+B, A+B+C and A+B+C+D) showed that signal/back. is not improved.

figure		Signal (9.45-9.75)	normalized Back (±.6 GeV)	P(S,B)×100*	normalized Back (±1.2 GeV)	P(S,B)×100*
h	ee+μA	10	1.75	1 in 776	2.125	1 in 160
i	ee+μ(A,B)	12	2.5	1 in 980	3.25	1 in 90
j	ee+μ (A+B+C)	13	3.5	1 in 174	4.125	1 in 38
k	ee+μ (A+B+C+D)	14	3.75	1 in 341	4.375	1 in 74

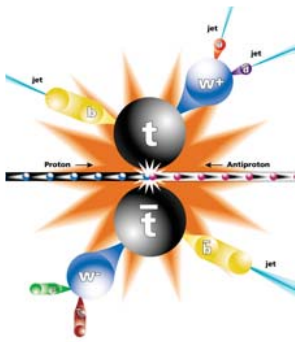
* factor of 100 to take care of ~50 "locations" where 6 adjacent bins can be placed

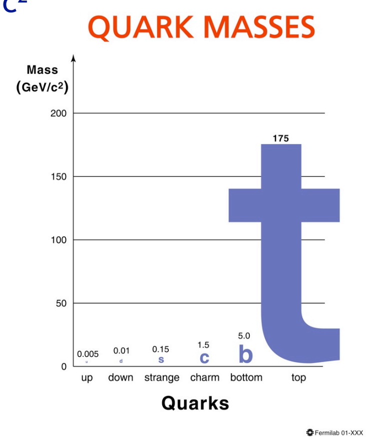
Note that background as determined by ±.6 GeV outside signal bins is smaller than that of ±1.2 GeV – mostly because of events near 8.5.

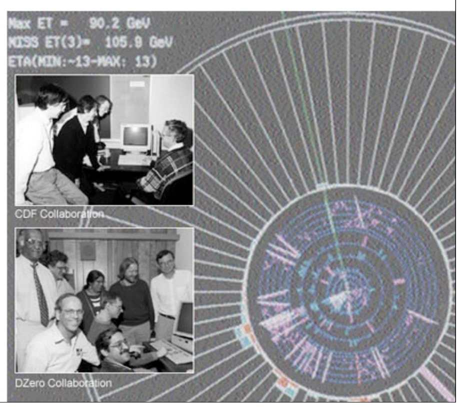
The significance of this signal is very much reminiscent of the ϒ.

Top Quark

- The top quark was discovered in 1995 at CDF and DØ at the Tevatron.
- Production: $p\bar{p} \to t\bar{t}$
- The top is so heavy it decays via **weak** force before it forms hadrons.
- Decay $t \to Wb$
- M(t)≈170 GeV/c^2







Summary

Leptons are described by three quantum numbers: L_e, L_μ, L_τ

- conserved in all interactions.

Quarks, mesons, baryons are described by six quantum numbers:

- Baryon Number, $\mathcal{B}$ - total number of quarks
  - $\mathcal{B}$=+1/3 for quarks, $\mathcal{B}$=−1/3 for anti-quarks
  - Conserved in all interactions.
- Strangeness: *S*, Charm: *C*, Bottomness: *B*, Topness: *T* - number of s, c, b, t
  - $S=N(\bar{s})-N(s)$ $C=N(c)-N(\bar{c})$ $B=N(\bar{b})-N(b)$ $T=N(t)-N(\bar{t})$
  - Conserved in strong and electromagnetic interactions.
- Isospin, *I*, I_Z $I_Z = \frac{1}{2}\left[N(\mathrm{u}) - N(\mathrm{d}) + N(\bar{\mathrm{d}}) - N(\bar{\mathrm{u}})\right]$
  - Describes the symmetry between the up and down quarks
  - Conserved in strong interactions.

Strange, charm, bottom and top quarks discovered in strong interactions production of a $q\bar{q}$ pair.

- Decay by electromagnetic or weak decay indicated that something new had been created!