RETURN TO CLASSIFICATIONS

WE CLASSIFY PARTICLES IN A NUMBER OF WAYS

LET'S GO BACK TO THE INTRODUCTORY LECTURE AND LOOK IN MORE DETAIL AT THE PROPERTIES OF SOME OF THE DENIZENS OF THE SUBATOMIC ZOO

TWO EXTREMLY IMPORTANT CLASSIFICATION ATTRIBUTES ARE:

- SPIN / STATISTICS
- FORCE(S) SEEN BY PARTICLE

PARTICLE	SPIN/STAT.	WEAK	EM	STRONG
γ	GAUGE BOSONS	X	✓	X
$W^{\pm}$ Z^{0}		✓	✓	X
GLUON		X	X	✓
LEPTONS				
NEUTRINO ν	FERMION	✓	X	X
ELECTRON e	FERMION	✓	✓	X
MUON μ	FERMION	✓	✓	X
TAU τ	FERMION	✓	✓	X
HADRONS				
MESONS	BOSONS	✓	✓	✓
BARYONS	FERMIONS	✓	✓	✓
QUARKS	FERMIONS	✓	✓	✓

FORCES ACT WHEN PARTICLES COLLIDE, BUT ALSO WHEN THEY DECAY

Is the Universe Made of These?

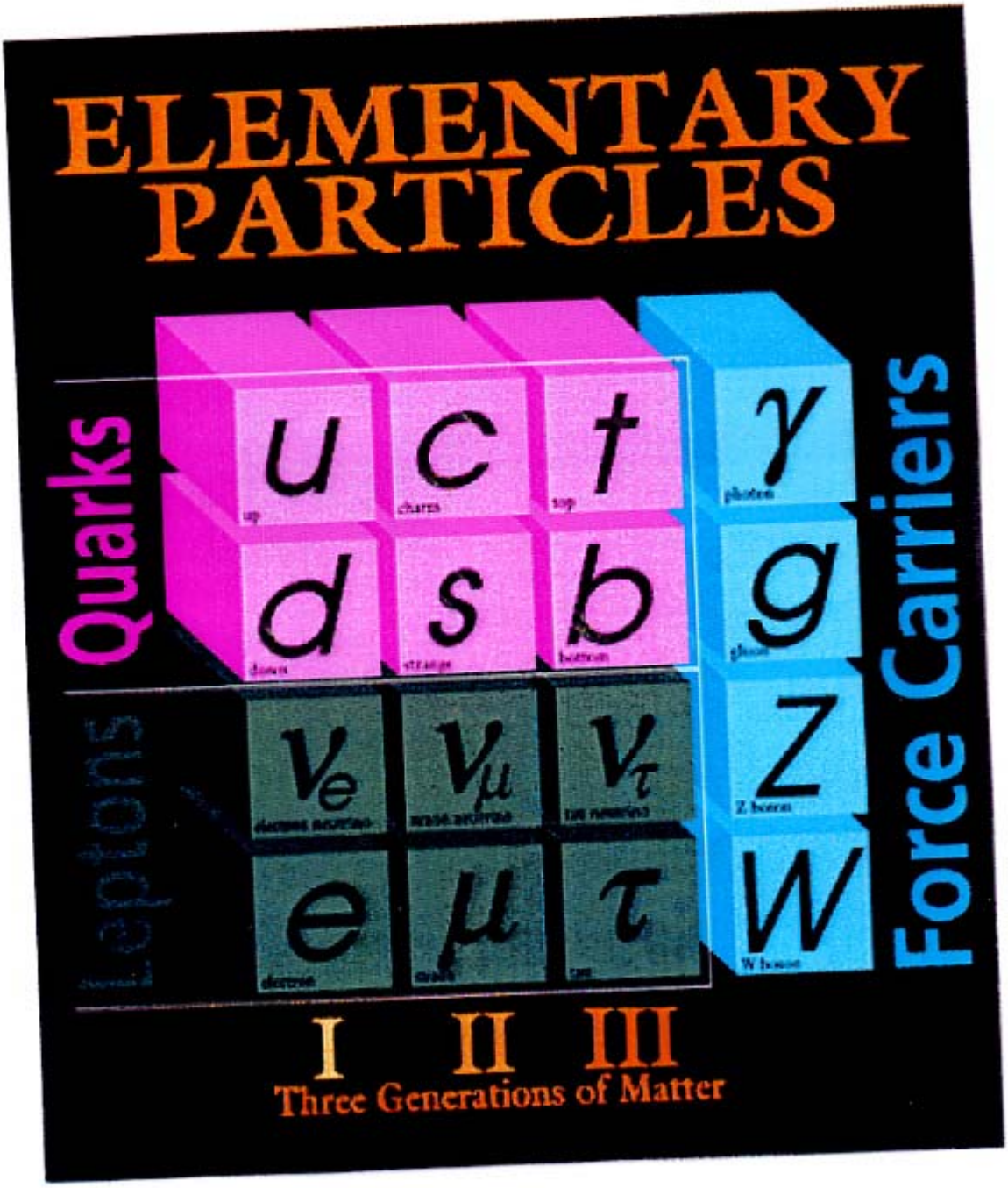


Table 2.2. *Fundamental interactions ($Mc^2 = 1$ GeV)*

	Gravitational	Electromagnetic	Weak	Strong
field boson	graviton	photon	$W^{\pm}, Z$	gluon
spin-parity	2^+	1^-	$1^-, 1^+$	1^-
mass, GeV	0	0	$M_W = 80.2$ $M_Z = 91.2$	0
range, m	∞	∞	10^{-18}	$\leq 10^{-15}$
source	mass	electric charge	'weak charge'	'colour charge'
coupling constant	$\frac{G_N M^2}{4\pi\hbar c}$ $= 5 \times 10^{-40}$	$\alpha = \frac{e^2}{4\pi\hbar c}$ $= \frac{1}{137}$	$\frac{G(Mc^2)^2}{(\hbar c)^3}$ $= 1.17 \times 10^{-5}$	$\alpha_s \leq 1$
typical cross-section, m^2		10^{-33}	10^{-39}	10^{-30}
typical lifetime, s		10^{-20}	10^{-10}	10^{-23}

STRENGTH

Table 1.3. *The boson mediators*

	Interaction	Mediator	Spin/parity
1	strong	gluon, G	1^-
10^{-2}	electromagnetic	photon, γ	1^-
10^{-7}	weak	$W^\pm$, Z^0	1^-, 1^+
10^{-39}	gravity	graviton, g	2^+

$\hbar$

GAUGE GROUP

THE INTERACTIONS

STRONG

SU(3) BINDS QUARKS INTO PROTONS/NEUTRONS

"REMNANT" BINDS NUCLEONS IN NUCLEUS

ELECTROMAGNETIC

U(1) ATOMIC PHYSICS

MOLECULAR "

CHEMISTRY

WEAK

SU(2) RADIOACTIVE β-DECAY

NEUTRINO PHYSICS

GRAVITATION

? BULK MATTER IS ELECTRICALY NEUTRAL

$\Rightarrow$ DOMINATES UNIVERSE

+ "WHAT ELSE" ?

PROPERTIES OF CONSTITUENTS

- FERMIONS – MATTER – 6 QUARKS
  6 LEPTONS

LEPTONS				$Q/\lvert e \rvert$	
	e	μ	τ	-1	spin $\frac{1}{2}\left(\frac{\hbar}{2}\right)$
	ν_e	ν_μ	ν_τ	0	

$\longrightarrow$ MASS

- UNSTABLE τ 2.9×10^{-13} s
  μ 2.2×10^{-6} s

- STABLE e ← EXPERIMENTAL LIMIT
  $\tau(e \to \gamma\nu)$
  $> 4 \times 10^{23}$ y

- FLAVOUR e, μ, τ

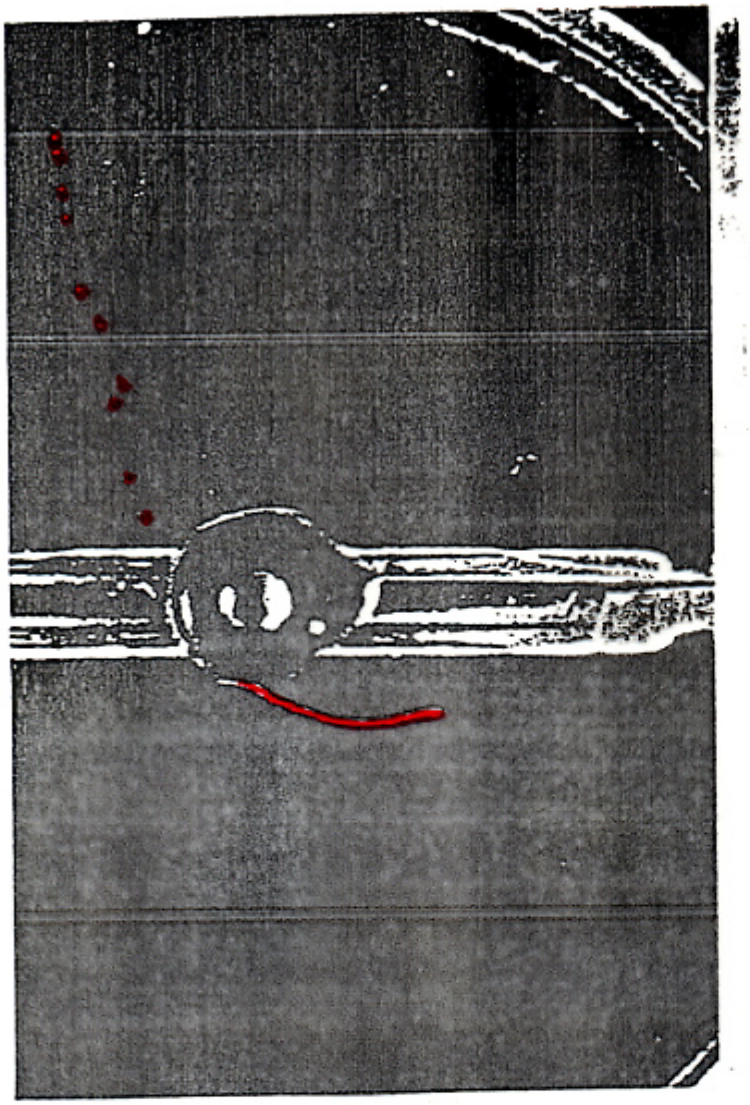


Fig. 5.6 *A photograph by Anderson and Neddermeyer of a positive muon coming to rest before it decays in a cloud chamber that was activated by a Geiger counter inside the chamber. (The counter lies horizontally across the centre of the picture; the circular structure is part of the counter.) The incoming muon leaves a faint track at the upper left of the picture. The track curls round and becomes thicker after the muon loses energy in traversing the glass walls and copper cylinder of the Geiger counter. The chamber was not sensitive enough to record the track of the positron produced in the muon's decay. The muon travels 2.9 cm after emerging from the counter.*

THE MUON

- MISTAKEN FOR YUKAWA PION
- FIRST SIGN OF GENERATION STRUCTURE

I.I. RABII
"WHO ORDERED THAT !?"

$Q_\mu = Q_e$

$m_\mu = 105.65839 \pm 0.00006$ MeV/c^2

$= 207 \times m_e$

$L_\mu = 1$

POINT PARTICLE

$g_\mu = g^\mu_{DIRAC}$

$\approx g_e$

LEPTON FLAVOUR

- e, μ, τ INTERACT VIA • EM • WEAK
- $\nu_e \; \nu_\mu \; \nu_\tau$ " " • WEAK
- $L_e \; L_\mu \; L_\tau = +1$ FLAVOUR
- ANTILEPTONS HAVE CHARGE AND FLAVOUR OF OPPOSITE SIGN
- LEPTON FLAVOUR CONSERVED

NOT A LEPTON

PION $\longrightarrow$ $\pi^+ \rightarrow \mu^+ \; \nu_\mu$

L_μ 0 $\quad \underbrace{-1 \quad +1}_{0}$

$$\nu_e \, n \rightarrow p \, e^-$$

L_e +1 0 0 +1

$$\nu_e \, n \not\rightarrow p \, \mu^-$$

L_e +1 0 0 0

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

L_μ +1 0 0 +1

THIS IS HOW WE KNOW $\nu_e \neq \nu_\mu$

CAVEAT : $\rightarrow$ MASSIVE ν CAN CAUSE SLIGHT VIOLATION OF LEPTON FLAVOUR CONSERVTN.

Table 1.5. *Constituent quark masses*

Flavour	Quantum number FLAVOR	Rest mass, GeV/c^2
up or down	—	$m_u \simeq m_d \simeq 0.31$
strange	$S = -1$	$m_s \simeq 0.50$
charm	$C = +1$	$m_c \simeq 1.6$
bottom	$B = -1$	$m_b \simeq 4.6$
top	$T = +1$	$m_t \simeq 180$

A BIT SUBTLE

			Q/|e|
u	c	t	+2/3
d	s	b	−1/3

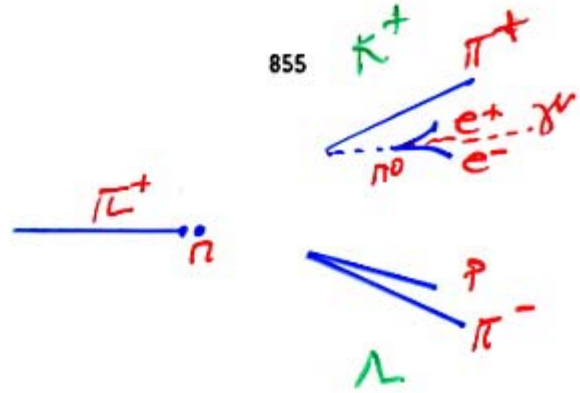
- QUARKS INTERACT VIA COLOUR (STRONG)
  EM
  WEAK

- QUARK FLAVOUR
  - CONSERVED BY STRONG INTERACTION
  - NOT CONSERVED BY WEAK INTERACTION

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER
AND
Dr. C. C. BUTLER
Physical Laboratories, University, Manchester

AMONG some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character.



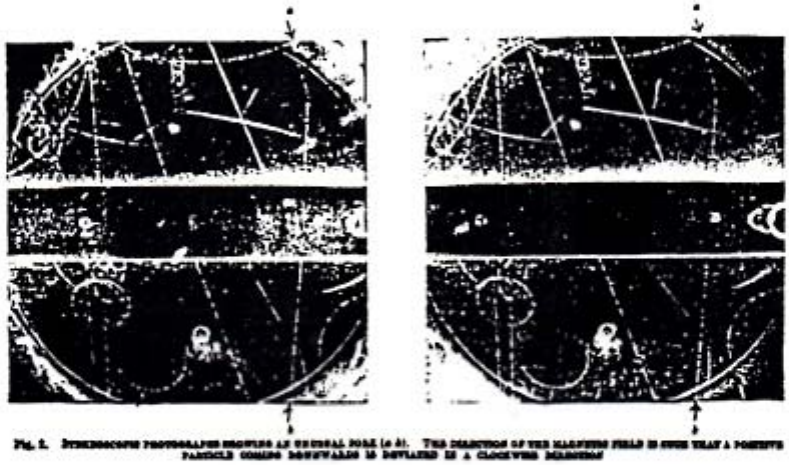


Fig. 2. Stereoscopic photographs showing an external fork (a b). The direction of the magnetic field is such that a positive particle coming downwards is deflected in a clockwise direction

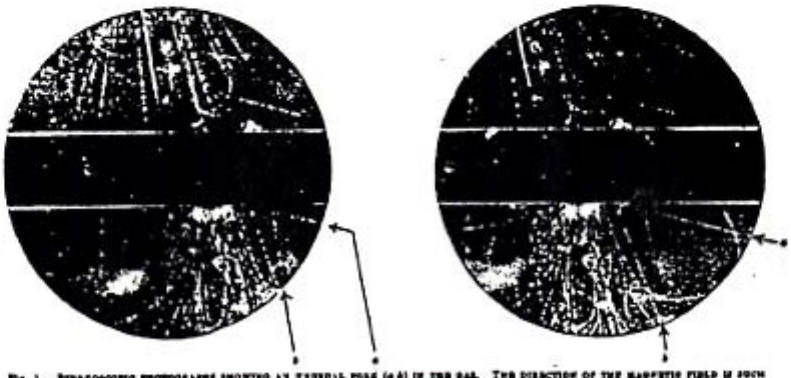


Fig. 1. Stereoscopic photographs showing an internal fork (a b) in the gas. The direction of the magnetic field is such that a positive particle coming downwards is deflected in an anticlockwise direction

Fig. 12.

FIRST EVIDENCE FOR FLAVOUR

$$\pi^+ n \rightarrow K^+ \Lambda$$

$K^+ \rightarrow \pi^+ \pi^0$

$\Lambda \rightarrow p \pi^-$

VERY SLOWLY

- PRODUCED VIA STRONG INTERACTION
- DECAY SLOWLY VIA WEAK INTERACTION
  - BECAUSE STRONG CONSERVES "S" CAN NOT DECAY QUICKLY
  - WEAK DOES NOT CONSERVE "S"
- PRODUCED IN PAIRS OF OPPOSITE "S"
  - SINCE STRONG CONSERVES "S"

STRONG

$$\pi^+ n \rightarrow K^+ \Lambda$$

S: 0 → +1, −1

$K^+ \rightarrow \pi^+ \pi^0$ (S: 0)

WEAK

$\Lambda \rightarrow p \pi^-$ (S: 0)

S

COLOUR

- IN ADDITION TO ELECTRIC CHARGE

  QUARKS CARRY COLOUR CHARGE

  SOURCE OF STRONG INTERACTION

- γ^μ COUPLE TO ELECTRIC CHARGE
- g COUPLE TO COLOUR CHARGE.
- ONE ELECTRIC CHARGE $+e$ $U(1)$
- THREE COLOUR CHARGES RED GREEN BLUE $SU(3)$

- SINGLE FREE QUARKS NEVER OBSERVED

  ONLY COLOUR NEUTRAL BOUND STATES

  PROTONS $u\,d\,u$ + PERMUTATIONS

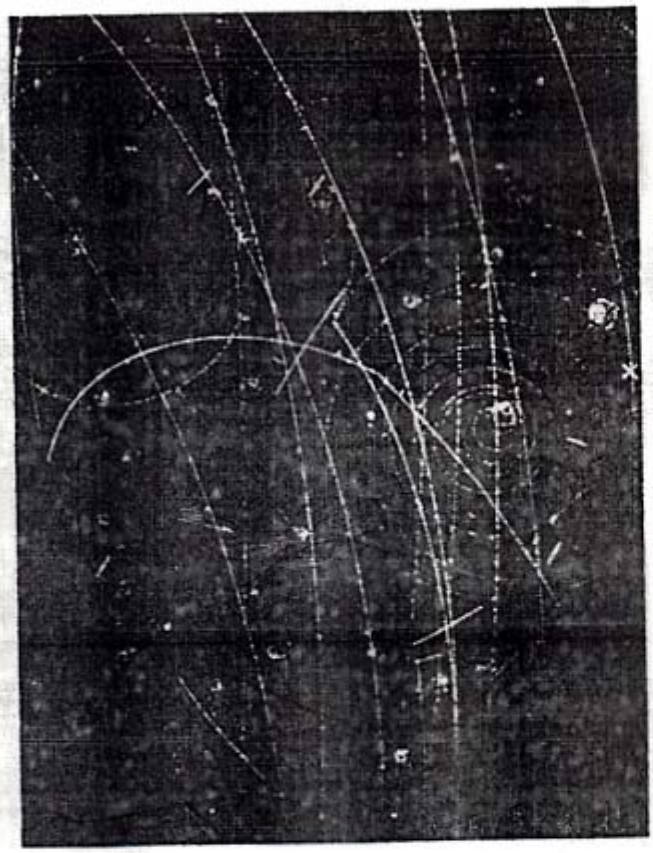
  PION π^+ $u\,\bar{d}$

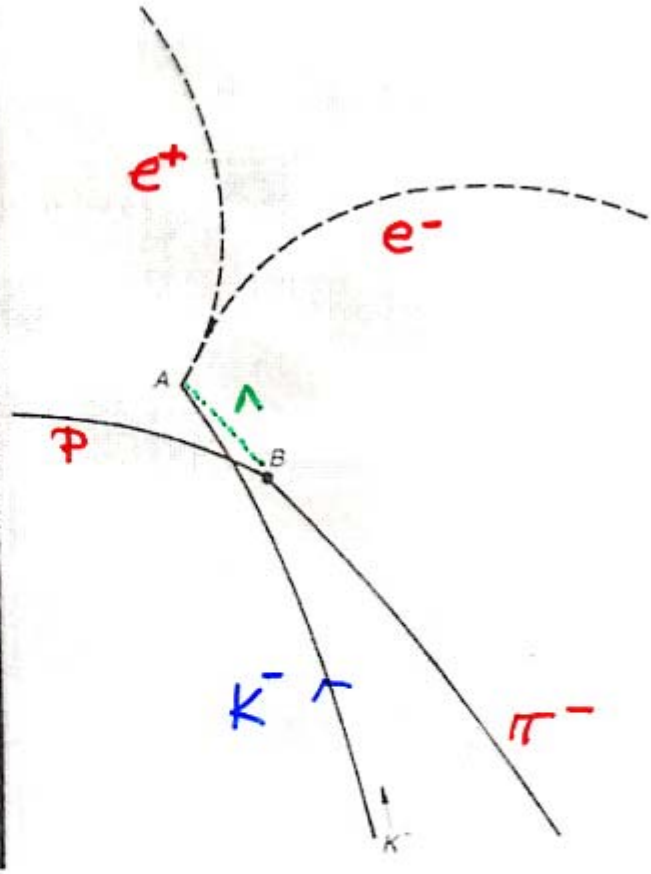
  $\bar{d}$ → ANTIRED

Table 1.6. *Quark composition of some meson and baryon states (masses in MeV/c^2 in parentheses), together with values of strangeness, S*

Meson	Composition	S	Baryon	Composition	S
$\pi^+(140)$	$u\bar{d}$	0	$p(931)$	uud	0
$K^0(498)$	$d\bar{s}$	+1	$\Lambda(1116)$	uds	−1
$K^-(494)$	$\bar{u}s$	−1	$\Xi^0(1315)$	uss	−2
$\rho^-(770)$	$\bar{u}d$	0	$\Sigma^+(1189)$	uus	−1
$\omega^0(783)$	$u\bar{u}$	0	$\Omega^-(1672)$	sss	−3

ANOTHER EXAMPLE OF STRANGENESS CONSERVATION





$$\begin{array}{ccccccc} S & -1 & 0 & & -1 & 0 & \\ & K^- + p & \rightarrow & & \Lambda & + \pi^0 & \\ & & & & & \hookrightarrow \gamma\, e^+ e^- & 0 \end{array} \quad S$$

10^{-16} s

EM

$S = 0$ $\rightarrow$ $p\,\pi^-$

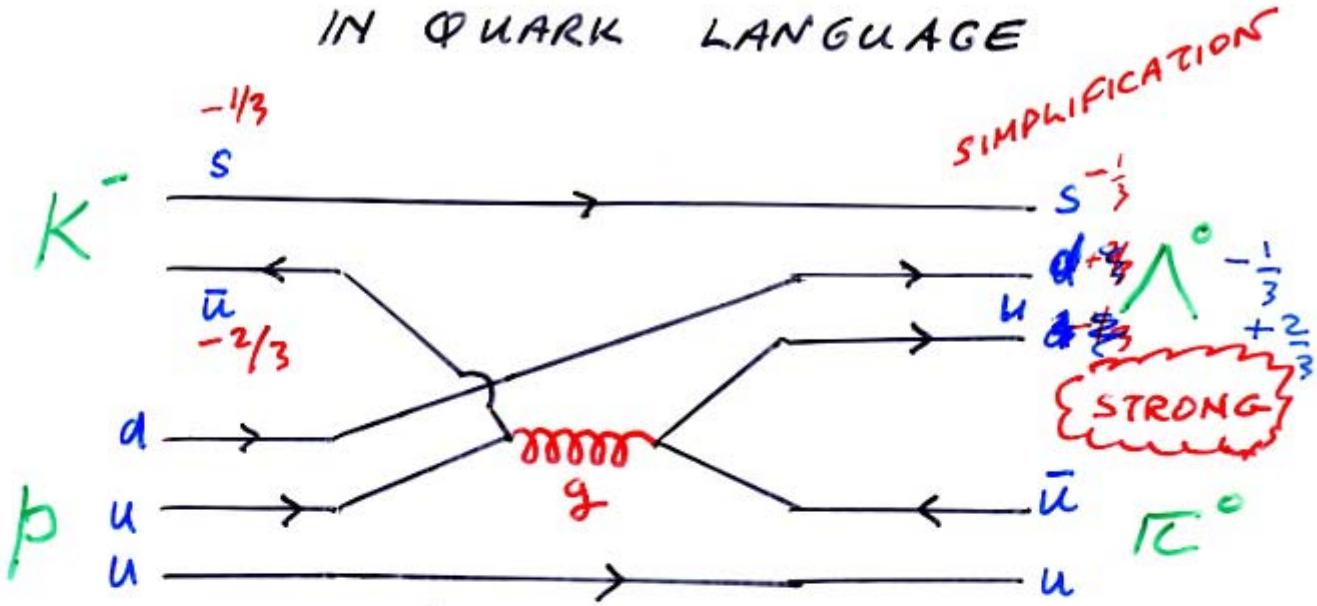
10^{-10} s

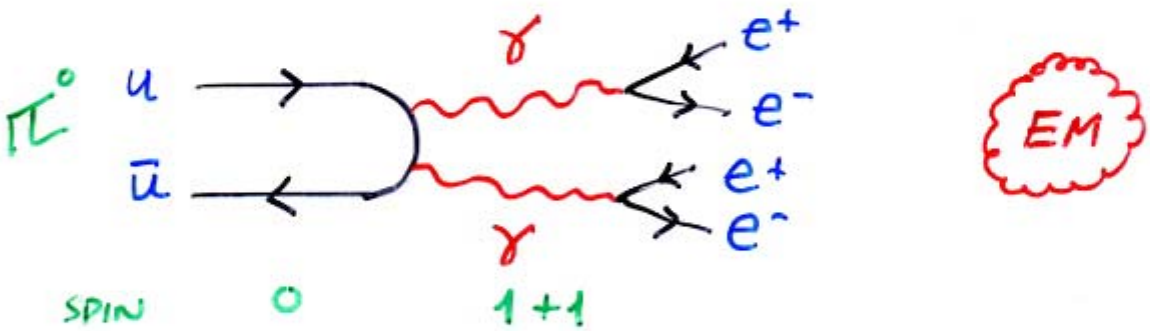
WEAK

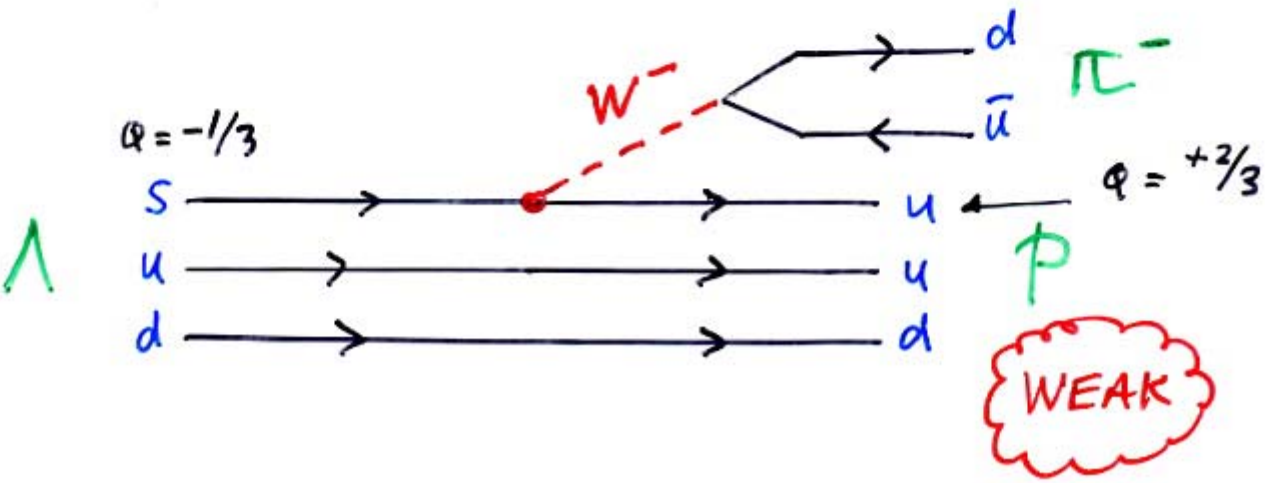
NB. INTERACTION AT REST !

$K^- p \to \Lambda \pi^0$

IN QUARK LANGUAGE







MASS HIERARCHY — WHY?

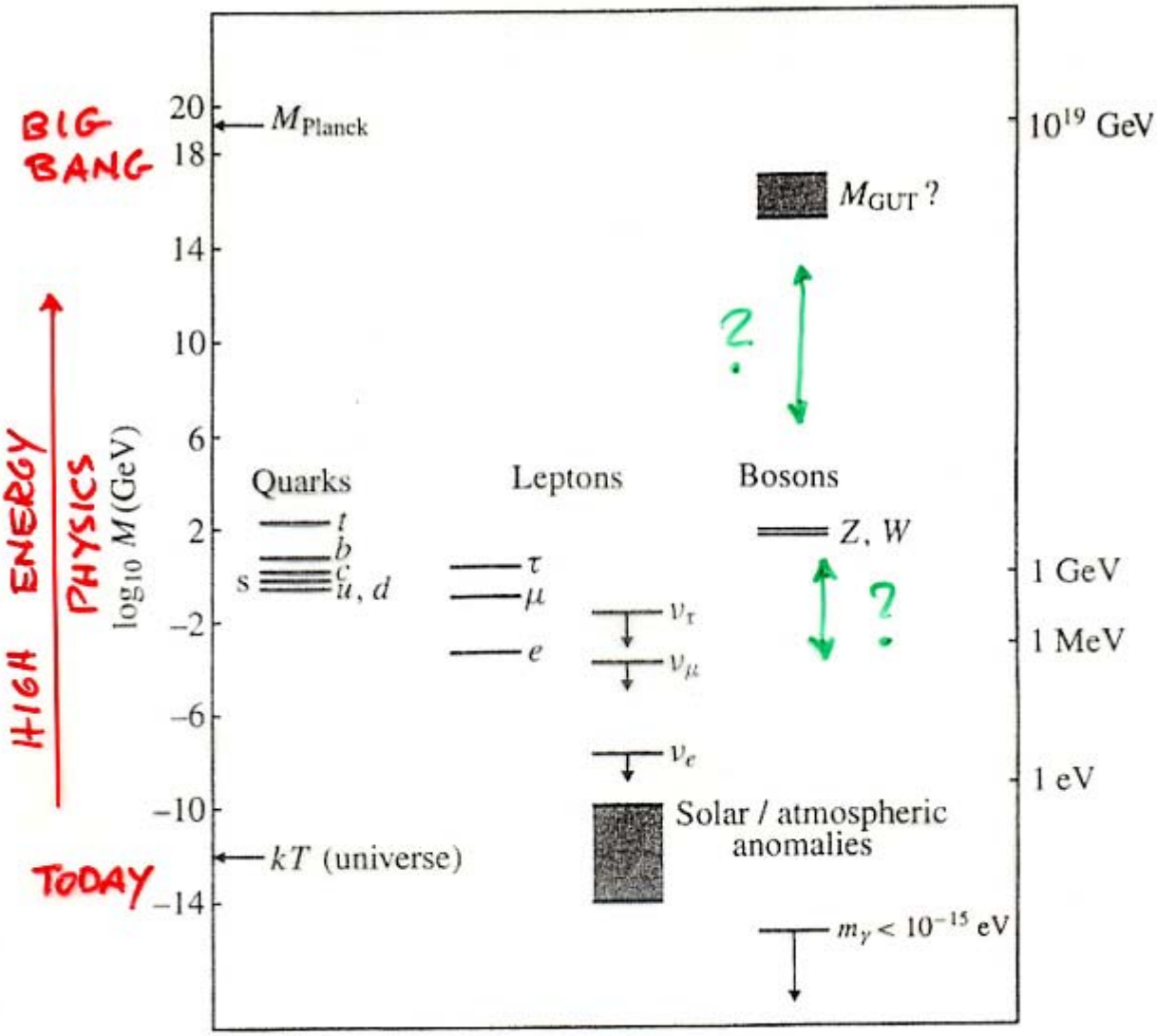


Fig. 1.7. The mass spectrum of leptons and quarks. The values shown for neutrinos are upper limits from direct measurements, and the solar and atmospheric neutrino anomalies (see Chapter 9) suggest even smaller masses. Other important mass scales are also shown: the Fermi or electroweak scale at 100 GeV, typified by the $W^{\pm}$ and Z^0 boson masses; the Planck mass scale, of order 10^{19} GeV, at which gravitational interactions are expected to become strong (see Chapter 2): and the value, $kT \simeq 1$ meV, of the cosmic microwave radiation ($T = 2.7$ K) in the universe today.

$$M_P = \left(\frac{\hbar c}{G_N}\right)^{1/2} = 1.22 \times 10^{19}\ \text{GeV}$$