Lecture 3

- Antiparticles
- Leptons
- Quarks and hadrons
- The strong force

Implications of introducing special relativity

Consider a particle of charge q, mass m with momentum p moving along the x-axis

What is its energy ?

Special relativity gives us a choice: $E = \pm\sqrt{p^2c^2 + m^2c^4}$

$E_+ = \sqrt{p^2c^2 + m^2c^4}$ $E_- = -\sqrt{p^2c^2 + m^2c^4}$

Surely the negative energy solution is unphysical and daft.

Can't we just ignore it ?

No - from quantum mechanics, every observable must have a complete set of eigenstates. The negative energy states are needed to form that complete set.

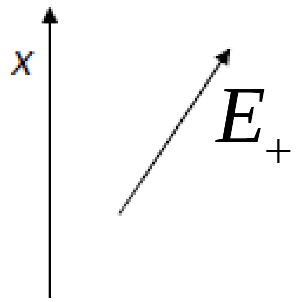
They must mean something....

Negative energy states

Consider an electron moving in space along x-direction

Positive energy solution: $\psi(x,t) = Ne^{-i\left(\frac{px - E_+ t}{\hbar}\right)}$

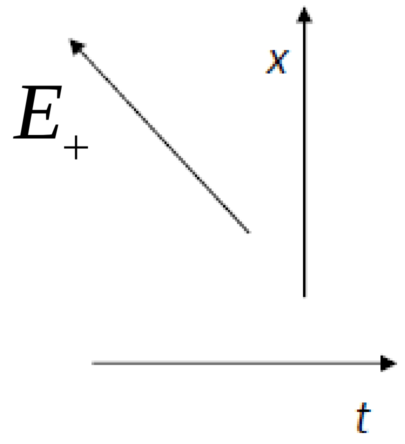
Moves to the right



Negative energy solution:

$$\psi(x,t) = Ne^{-i\left(\frac{px - E_- t}{\hbar}\right)} = Ne^{-i\left(\frac{px + E_+ t}{\hbar}\right)} = Ne^{-i\left(\frac{px - E_+ (-t)}{\hbar}\right)}$$

Moves to the left



$\Rightarrow$ Negative energy state moving forwards in time is equivalent to a positive energy state moving backwards in time.

What does a particle moving backwards in time look like ?

What are the implications of a particle (i.e. an observable state with positive energy) moving backwards in time ?

Lorentz force on an electron in a $\vec{B}$-field travelling forwards in time at a certain point in space and time $\vec{r}$ and t

$$\vec{F}(\vec{r},t) = m\frac{d^2\vec{r}}{dt^2} = q\vec{v}\times\vec{B} = -e\frac{d\vec{r}}{dt}\times\vec{B} \quad \Rightarrow \frac{d^2\vec{r}}{dt^2} = \frac{-e}{m}\frac{d\vec{r}}{dt}\times\vec{B}$$

Consider electron moving backwards in time $(dt \rightarrow -dt)$.

$$\frac{d^2\vec{r}}{d(-t)^2} = \frac{-e}{m}\frac{d\vec{r}}{d(-t)}\times\vec{B} \Rightarrow \frac{d^2\vec{r}}{dt^2} = \frac{+e}{m}\frac{d\vec{r}}{dt}\times\vec{B}$$

An electron moving backwards in time looks like a positively charged electron moving forwards in time!

Antiparticles

Special relativity permits negative energy solutions and quantum mechanics demands we find a use for them.

(1) The wave function of a particle with negative energy moving forwards in time is the same as the wave function of a particle with positive energy moving backwards in time.

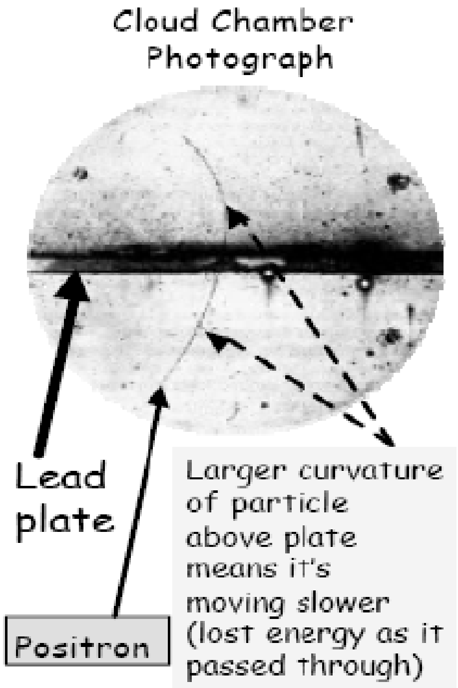
(2) A positive energy particle with charge -q moving backwards in time looks like a positive energy particle with charge $+q$ moving forwards in time.

We expect, for a given particle, to see the "same particle" but with opposite charge: *antiparticles.*

Antiparticles can be considered to be particles moving backwards in time - Feynman and Stueckelberg.

Hole theory (not covered) provides an alternative, though more old fashioned way of thinking about antiparticles.

Electron and the positron



$B = 1.5T \ (out \ of \ page)$

$\vec{F} = q(\vec{v} \times \vec{B})$ (to left)

$r = \frac{p}{eB}$

1897 e^- discovered by J.J. Thompson

1932
Anderson measured the track of a cosmic ray particle in a magnetic field.

Same mass as an electron but positive charge

The positron (e^+) - anti-particle of the electron

Nobel prize 1936

Every particle has an antiparticle.
Some particles, eg photon, are their own antiparticles.
Special rules particles and antiparticles symbols and names.

Feynman diagrams

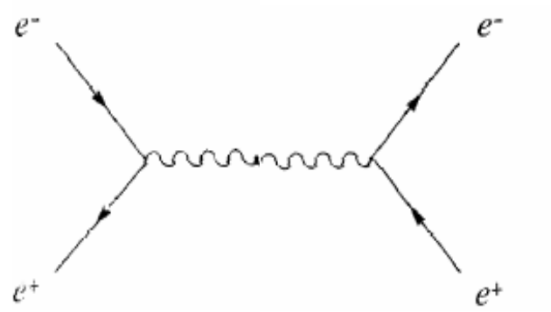
Important mathematical tool for calculating rates of processes - Feynman rules.

Qualitative treatment here

Represent any process by contributing diagrams.

One possible diagram for

$$e^+ + e^- \to e^+ + e^-$$



Strategy:

(1) Build Feynman diagrams for electromagnetic processes

(2) Consider how they can be used for simple rate estimates.

(3) Show Feynman diagram formalism for other fundamental forces.

Electromagnetic processes

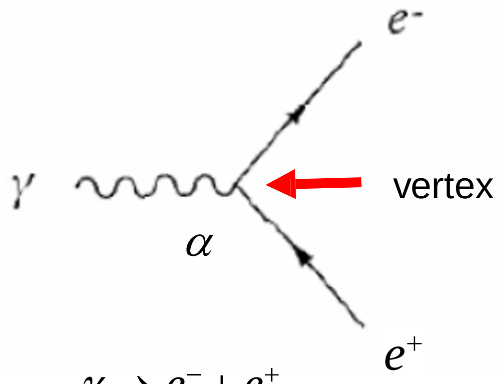
Convention - time flows to the right

The lines do not represent trajectories
of a particle.

Arrow for antiparticle goes "backward in time".

Lines should not be taken as "trajectories" of particles

Interactions occur at a vertex.

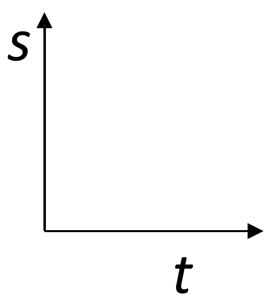


$\gamma \rightarrow e^- + e^+$

A basic process.

Rule of thumb: a vertex carries a factor α associated with the probability of that interaction taking place.

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \approx \frac{1}{137}$$ Fine structure constant

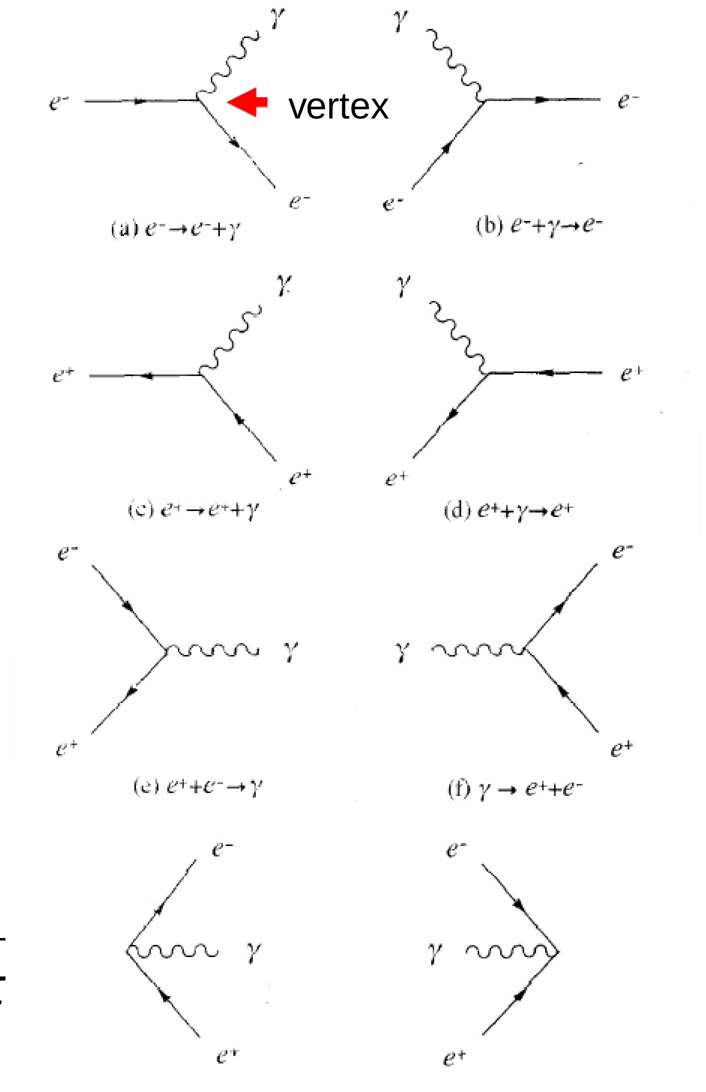


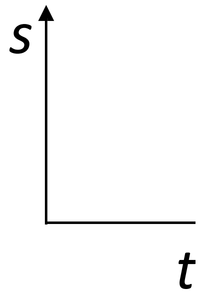
Basic electromagnetic diagrams

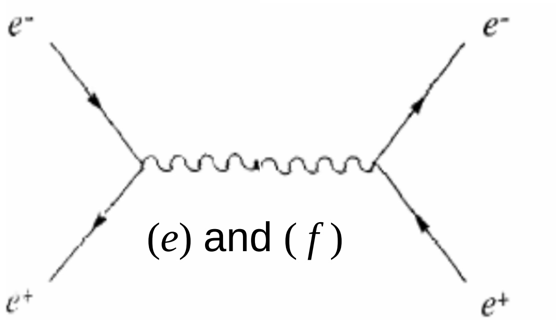
Consider all electromagnetic processes
built up from basic processes: (a) to (h)

The basic processes are never seen since
they violate energy conservation (next slide)

They can be combined to make observable processes:
$e^+ + e^- \to e^+ + e^-$



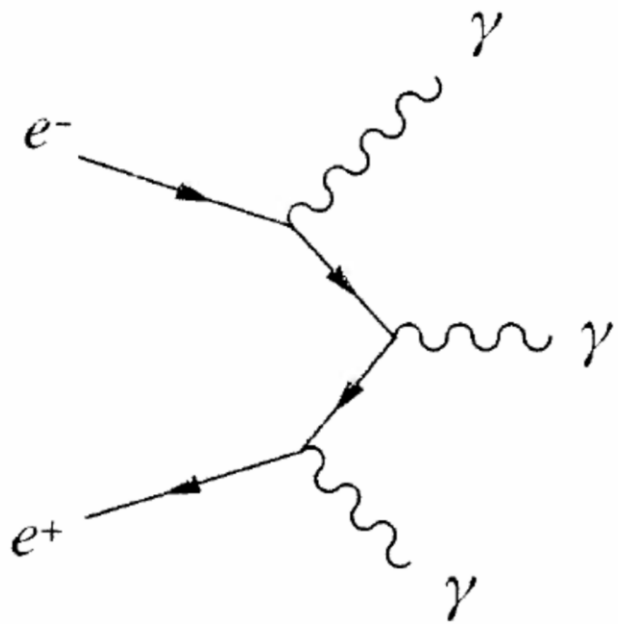




Using Feynman diagrams

$e^+ + e^- \rightarrow \gamma + \gamma + \gamma$

Three vertices $\Rightarrow$ probability $\propto \alpha^3$



+ other contributions

$$R = \frac{Rate\left(e^+ + e^- \rightarrow \gamma + \gamma + \gamma\right)}{Rate\left(e^+ + e^- \rightarrow \gamma + \gamma\right)} \approx \frac{\alpha^3}{\alpha^2}$$

$$= \alpha = 0.7 \times 10^{-2}$$

Observed $R \approx 10^{-3}$

$\Rightarrow$ Qualitative Feynman diagram picture giv

suppression with (very) rough accuracy.

$\Rightarrow$ Full QED calculation gives correct rates.

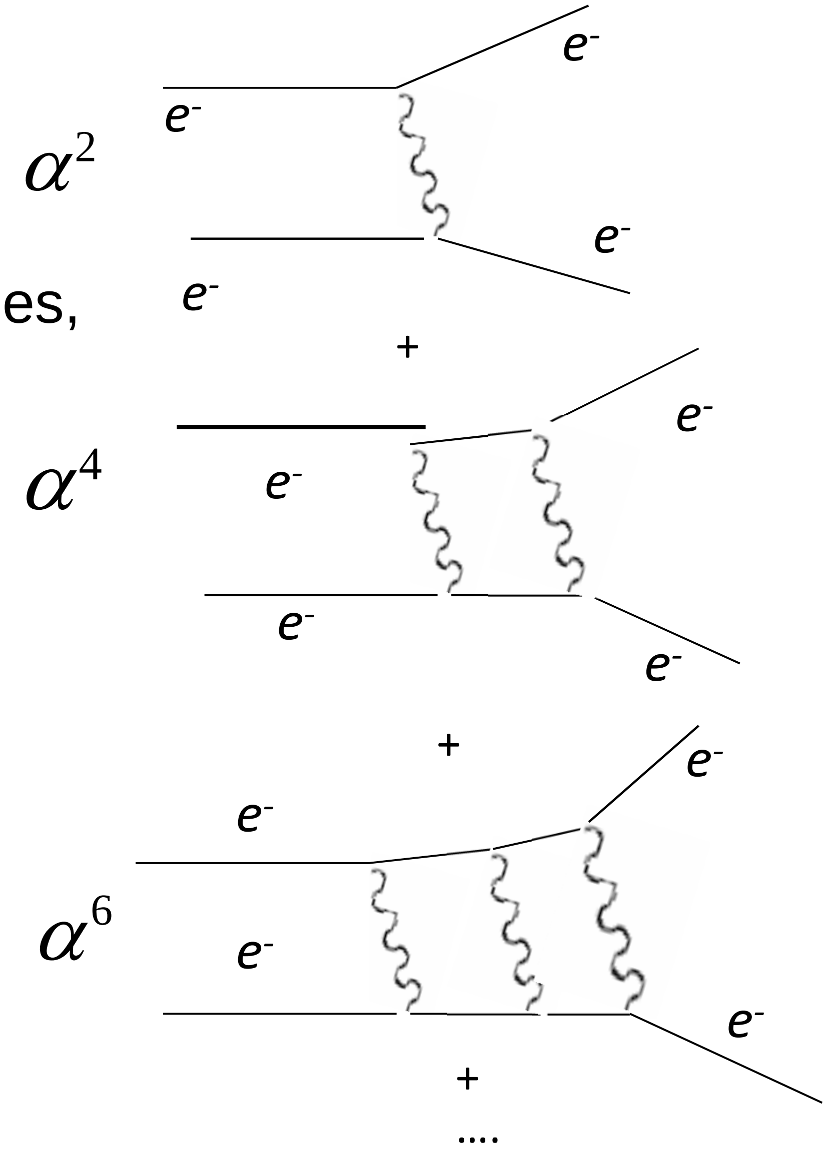
Using Feynman diagrams

Two electrons are observed to repell each other: $e^- + e^- \rightarrow e^- + e^-$

Many different indistinguishable processes, eg one-photon, two-photon exchange, can contribute to the scattering

Coupling is weak $\alpha \approx \frac{1}{137} << 1$

$\Rightarrow$ higher order processes contribute less and less to the calculation and can be safely be neglected in any approximate solution.



The charged leptons

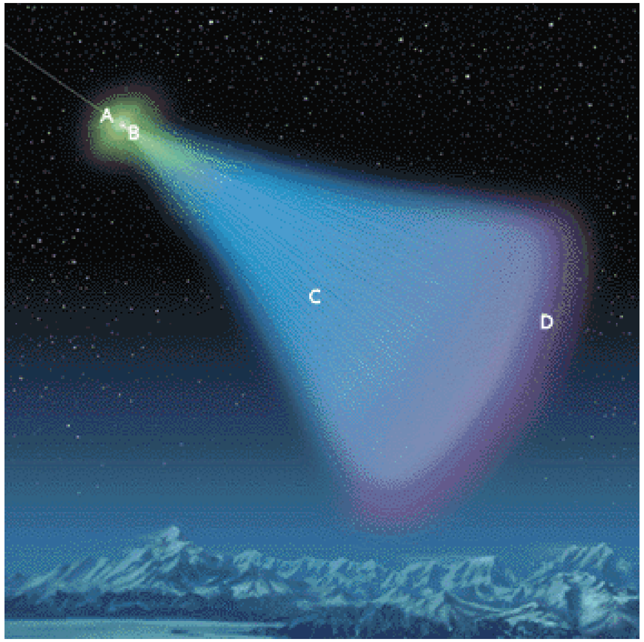
- Three types of charged lepton
- Electron,muon,tau
- e^-, e^+, μ^-, μ^+, τ^-, τ^+
- Charged leptons interact via the weak and electromagnetic forces

Lepton	Charge (e)	Mass (GeV/c^2)
e^-	-1	0.0005
μ^-	-1	0.105
τ^-	-1	1.8

+ antiparticles

Heavier leptons

- Muon μ^- (Stevenson and Street, 1936)
- Measurements of energy loss of cosmic-ray particles.
- New particle with mass between e^- and p (106 MeV/c^2)
- Interacts like a heavy electron



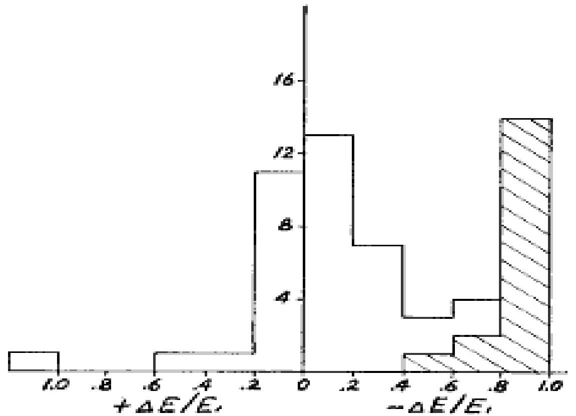
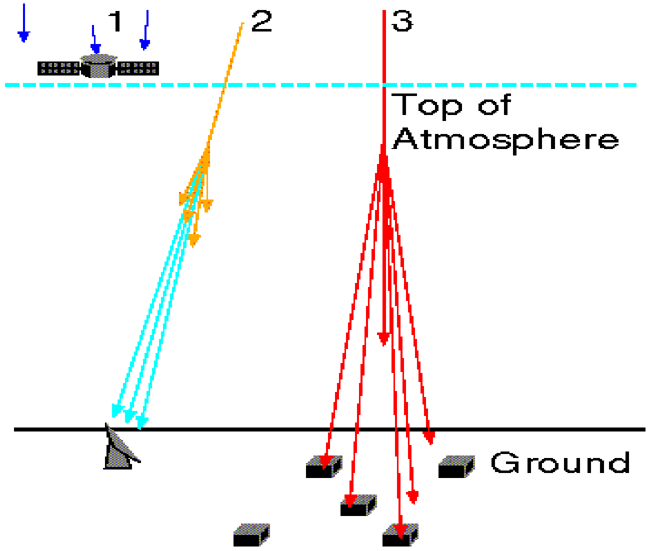
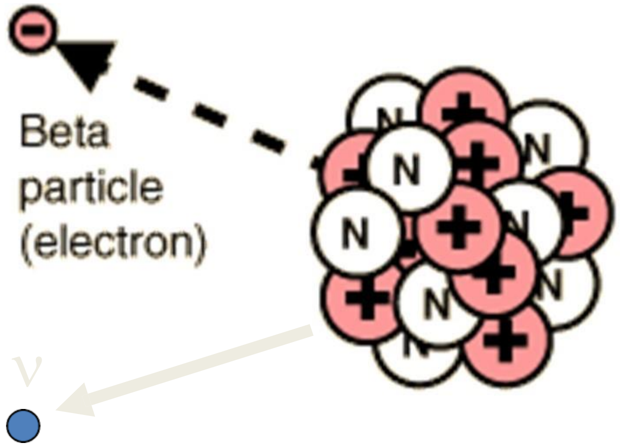
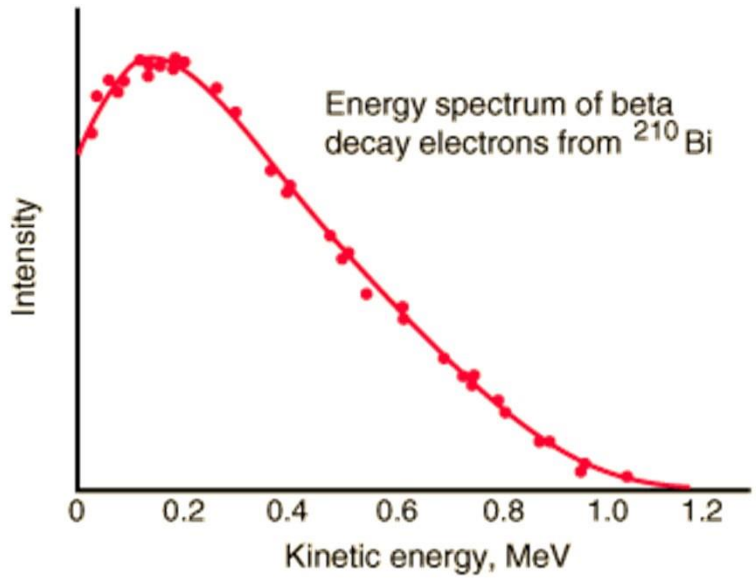


FIG. 2. Distribution of fractional losses in 1 cm of platinum.



Evidence for neutrinos





$$n \rightarrow p + e^{-} + \overline{\nu}$$

- Electrons produced by beta decay do not all have the same energy.
  - Pauli proposed the existence of an unseen neutral particle to explain the observed electron spectrum.

The lepton family

Spin 1/2

Lepton (antilepton)	Charge (e)	Mass (GeV/c^2)
e^- (e^+)	-1 (+1)	0.0005
ν_e, ($\bar{\nu}_e$)	0	≈0
μ^- (μ^+)	-1 (+1)	0.105
ν_μ ($\bar{\nu}_\mu$)	0	≈0
τ^- (τ^+)	-1 (+1)	1.8
ν_τ ($\bar{\nu}_\tau$)	0	≈0

Charged leptons interact via the electromagnetic and weak forces.
Neutrinos interact only via the weak force.

Particles and antiparticles

Convention:

Charged leptons

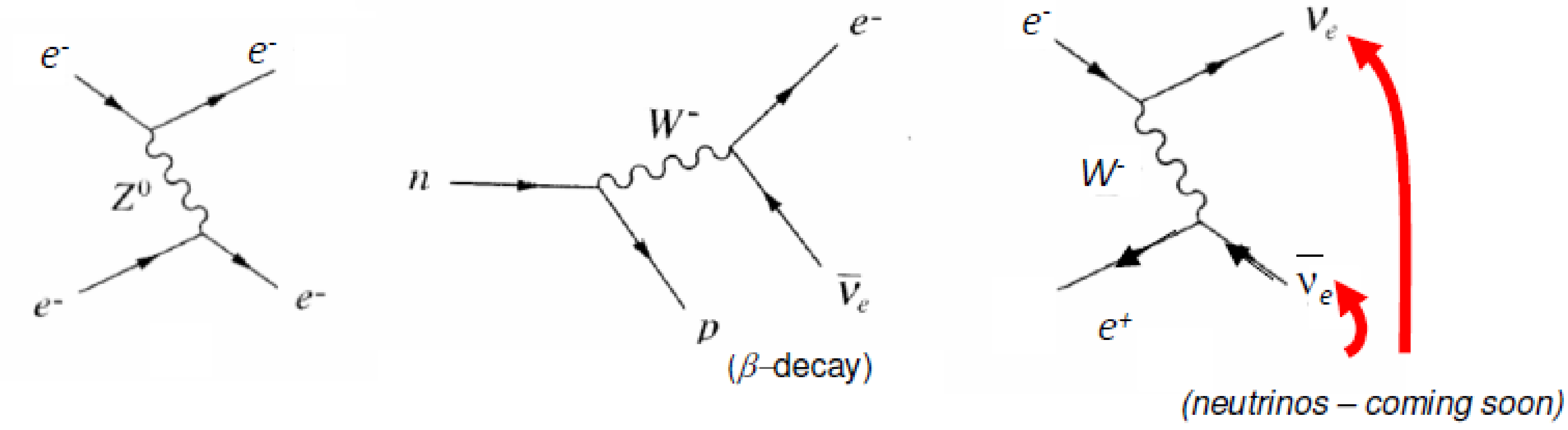
Tend to denote particles/antiparticles with charge:

$\left[\text{electron } \left(e^-\right) \text{ , anti-electron i.e. positron } \left(e^+\right)\right]$

Neutral leptons use bars for antiparticles :

$\left[\text{electron neutrino } \left(\nu_e\right) \text{ , anti-electron neutrino } \left(\bar{\nu}_e\right)\right]$

The weak force



Use same formalism as for electromagnetic force

Very brief overview:

Exchange of 3 spin-1 particles: Z^0 (mass=91.2 GeV/c^2) ,W^+, W^-(mass=80.4 GeV/c^2)

$\Rightarrow$ range $R_{W,Z} \approx \dfrac{\hbar}{M_W c} \approx 2\times 10^{-18}$m (tiny - proton "radius" $\approx 10^{-15}$m)

Define coupling constant analagous to fine structure constant

$$\alpha_W = \frac{g_W^2}{4\pi\hbar c} \quad (1.39) \qquad \alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \quad (1.24)$$

g_W analagous to electric charge (~ "weak charge")

$$\alpha_W = \frac{g_W^2}{4\pi\hbar c} \approx \frac{1}{240} \quad (1.41) \quad \left(\alpha \approx \frac{1}{137}, \text{ the weak force is only weak due to } W, Z \text{ masses}\right).$$

Lepton number conservation

Leptons carry a conserved quantum number.

Flavour specific lepton numbers:

electron lepton number L_e, muon lepton number L_μ, tau lepton number L_μ

(Obviously) for all other particles $L_e = L_\mu = L_\tau = 0$

Lepton	L_e	L_μ	L_τ
e^-	1	0	0
ν_ε	1	0	0
μ^-	0	1	0
ν_μ	0	1	0
τ^-	0	0	1
ν_τ	0	0	1

Antileptons carry the opposite lepton number.

Eg $\bar{\nu}_e, e^+,\ L_e = -1,\ \ L_\mu = L_\tau = 0$

Except for neutrino oscillations (to come) lepton number has never been seen to be violated.

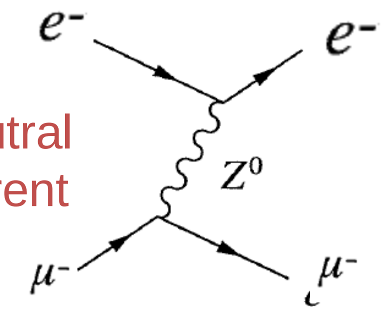
Limits on lepton number violation in charged lepton decays

Decay	Violates	Limit on branching ratio
$\mu^- \to e^- + e^+ + e^-$	$L_\mu,\ L_e$	$< 1.0\times10^{-12}$
$\mu^- \to e^- + \gamma$	$L_\mu,\ L_e$	$< 1.2\times10^{-11}$
$\tau^- \to e^- + \gamma$	$L_\tau,\ L_e$	$< 1.1\times10^{-7}$
$\tau^- \to \mu^- + \gamma$	$L_\tau,\ L_\mu$	$< 6.8\times10^{-8}$
$\tau^- \to e^- + \mu^- + \mu^+$	$L_\tau,\ L_\mu$	$< 2\times10^{-7}$

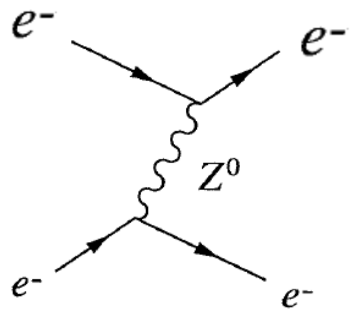
Interactions of leptons

Leading order

Neutral current

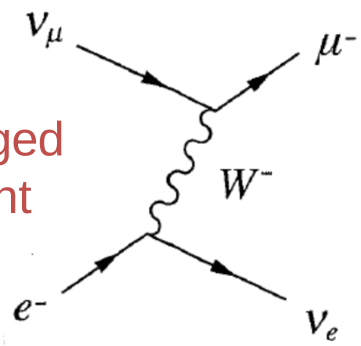


$e^- + \mu^- \rightarrow e^- + \mu^-$

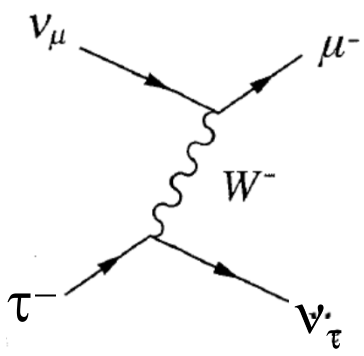


$e^- + e^- \rightarrow e^- + e^-$

Charged current

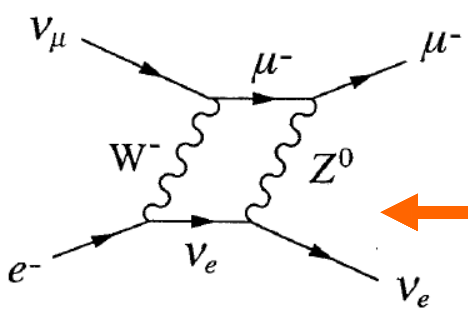


$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$



$\tau^- + \nu_\nu \rightarrow \mu^- + \nu_\tau$

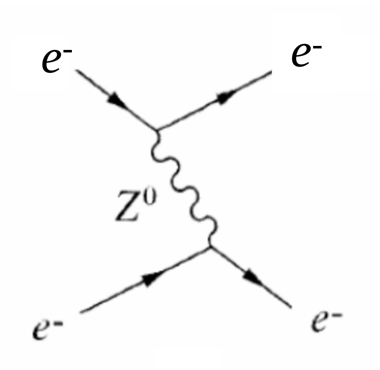
Higher order



$\nu_\mu + e \rightarrow \nu_e + \mu$

suppressed.

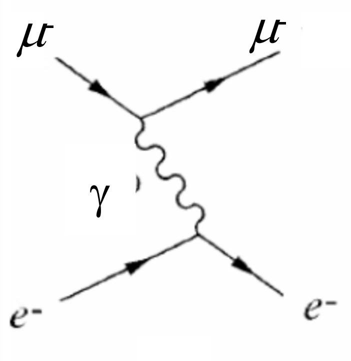
Lepton interactions



Weak; Neutral current

In: $L_e = 2; L_\mu = 0; L_\tau = 0$

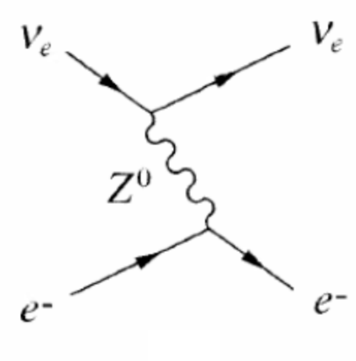
Out: $L_e = 2; L_\mu = 0; L_\tau = 0$



Electromagnetic

In: $L_e = 1; L_\mu = 1; L_\tau = 0$

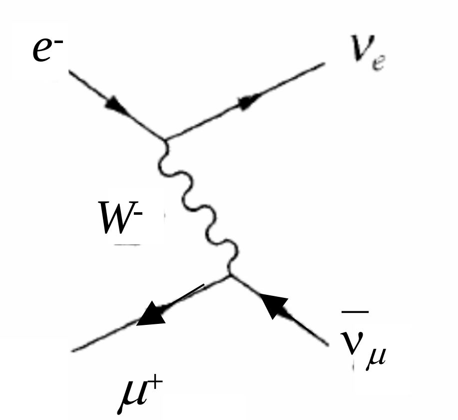
Out: $L_e = 1; L_\mu = 1; L_\tau = 0$



Weak: neutral current

In: $L_e = 2; L_\mu = 0; L_\tau = 0$

Out: $L_e = 2; L_\mu = 0; L_\tau = 0$



Weak: charged current

In: $L_e = 1; L_\mu = -1; L_\tau = 0$

Out: $L_e = 1; L_\mu = -1; L_\tau = 0$

Charged leptons interact via the *em* and weak forces.
Neutrinos only interact via the weak force.

Lepton number is always conserved at a vertex and in the whole process.

As for all forces:

Charge conservation and energy-momentum conservation for incoming and outgoing particles.

Charge is conserved at a vertex though energy can appear to be violated when dealing with "internal lines" (lecture 1).

Question

Draw a Feynman diagram for a muon decay process.

Question

Using Feynman diagrams explain why the reactions $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ and $\nu_\tau + e^- \rightarrow \nu_\tau + e^-$ are suppressed with respect to $\nu_e + e^- \rightarrow \nu_e + e^-$.

The quarks

Quark	Q (e)	Mass (GeVc^2)
u- up	2/3	0.003
d- down	-1/3	0.005
s- strange	-1/3	0.15
c- charm	2/3	1.2
b- bottom	-1/3	4.2
t-top	2/3	171

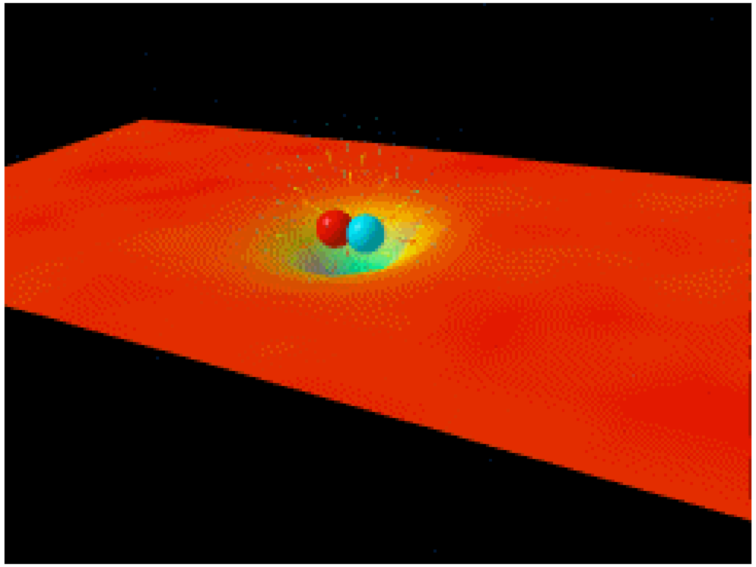
Spin ½ particles

Multiplets:

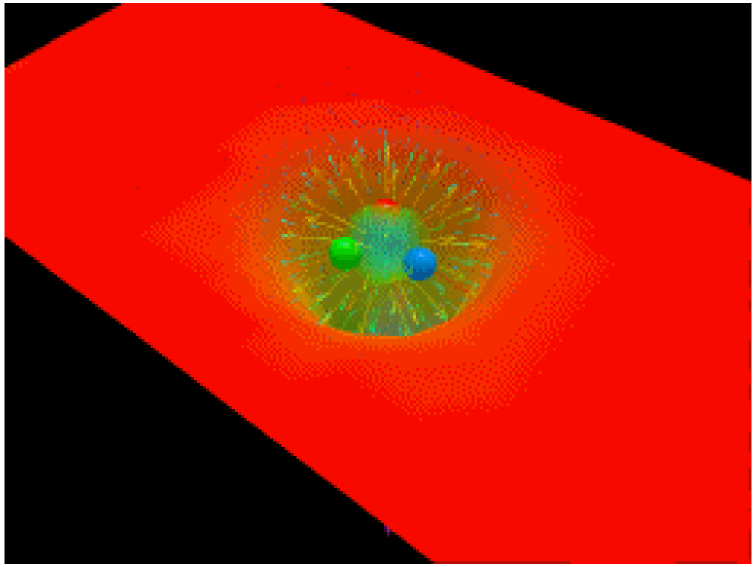
$$\begin{pmatrix} u \\ d \end{pmatrix}\begin{pmatrix} c \\ s \end{pmatrix}\begin{pmatrix} t \\ b \end{pmatrix}$$

+ antiquarks: $\bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}, \bar{t}$ opposite charge: $Q \to -Q$

Mesons and baryons



Meson
(quark-antiquark)



Baryons
(quark-quark-quark)

Strong force is a short range (~1fm) force which acts to confine quarks and antiquarks in hadrons. ”Bare” quarks are not seen.

Hadrons

Two types: mesons (quark+antiquark) and

baryons (quark+quark+quark)

PSEUDOSCALAR MESONS (Spin 0)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
$\pi^\pm$	$u\bar{d}$, $d\bar{u}$	+1, −1	139.569	2.60×10^{-8}	$\mu\nu_\mu$
π^0	$(u\bar{u}-d\bar{d})/\sqrt{2}$	0	134.964	8.7×10^{-17}	$\gamma\gamma$
$K^\pm$	$u\bar{s}$, $s\bar{u}$	+1, −1	493.67	1.24×10^{-8}	$\mu\nu_\mu$, $\pi^\pm\pi^0$, $\pi^\pm\pi^\pm\pi^\mp$
K^0, $\bar{K}^0$	$d\bar{s}$, $s\bar{d}$	0, 0	497.72	K^0_S 0.892×10^{-10} K^0_L 5.18×10^{-8}	$\pi^+\pi^-$, $\pi^0\pi^0$ $\pi e\nu_e$, $\pi\mu\nu_\mu$, $\pi\pi\pi$
η	$(u\bar{u}+d\bar{d}-2s\bar{s})/\sqrt{6}$	0	548.8	7×10^{-19}	$\gamma\gamma$, $\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$
η'	$(u\bar{u}+d\bar{d}+s\bar{s})/\sqrt{3}$	0	957.6	3×10^{-21}	$\eta\pi\pi$, $\rho^0\gamma$
$D^\pm$	$c\bar{d}$, $d\bar{c}$	+1, −1	1869	9×10^{-13}	$K\pi\pi$
D^0, $\bar{D}^0$	$c\bar{u}$, $u\bar{c}$	0, 0	1865	4×10^{-13}	$K\pi\pi$
$F^\pm$ (now $D_s^\pm$)	$c\bar{s}$, $s\bar{c}$	+1, −1	1971	3×10^{-13}	not established
$B^\pm$	$u\bar{b}$, $b\bar{u}$	+1, −1	5271	14×10^{-13} (for $B^\pm$ and B^0)	$D+?$
B^0, $\bar{B}^0$	$d\bar{b}$, $b\bar{d}$	0, 0	5275		
η_c	$c\bar{c}$	0	2981	6×10^{-23}	$KK\pi$, $\eta\pi\pi$, $\eta'\pi\pi$

VECTOR MESONS (Spin 1)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
ρ	$u\bar{d}$, $d\bar{u}$, $(u\bar{u}-d\bar{d})/\sqrt{2}$	+1, −1, 0	770	0.4×10^{-23}	$\pi\pi$
K^*	$u\bar{s}$, $s\bar{u}$, $d\bar{s}$, $s\bar{d}$	+1, −1, 0, 0	892	1×10^{-23}	$K\pi$
ω	$(u\bar{u}+d\bar{d})/\sqrt{2}$	0	783	7×10^{-23}	$\pi^+\pi^-\pi^0$, $\pi^0\gamma$
ϕ	$s\bar{s}$	0	1020	20×10^{-23}	K^+K^-, $K^0\bar{K}^0$
J/ψ	$c\bar{c}$	0	3097	1×10^{-20}	e^+e^-, $\mu^+\mu^-$, 5π, 7π
D^*	$c\bar{d}$, $d\bar{c}$, $c\bar{u}$, $u\bar{c}$	+1, −1, 0, 0	2010	$>1\times10^{-22}$	$D\pi$, $D\gamma$
Υ	$b\bar{b}$	0	9460	2×10^{-20}	$\tau^+\tau^-$, $\mu^+\mu^-$, e^+e^-

BARYONS (Spin $\frac{1}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
N p	uud	+1	938.280	∞	—
N n	udd	0	939.573	900	$pe\bar{\nu}_e$
Λ	uds	0	1115.6	2.63×10^{-10}	$p\pi^-$, $n\pi^0$
Σ^+	uus	+1	1189.4	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
Σ^0	uds	0	1192.5	6×10^{-20}	$\Lambda\gamma$
Σ^-	dds	−1	1197.3	1.48×10^{-10}	$n\pi^-$
Ξ^0	uss	0	1314.9	2.90×10^{-10}	$\Lambda\pi^0$
Ξ^-	dss	−1	1321.3	1.64×10^{-10}	$\Lambda\pi^-$
Λ_c^+	udc	+1	2281	2×10^{-13}	not established

BARYONS (Spin $\frac{3}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
Δ	uuu, uud, udd, ddd	+2, +1, 0, −1	1232	0.6×10^{-23}	$N\pi$
Σ^*	uus, uds, dds	+1, 0, −1	1385	2×10^{-23}	$\Lambda\pi$, $\Sigma\pi$
Ξ^*	uss, dss	0, −1	1533	7×10^{-23}	$\Xi\pi$
Ω^-	sss	−1	1672	0.82×10^{-10}	ΛK^-, $\Xi^0\pi^-$, $\Xi^-\pi^0$

Full particle listings from the
Review of Particle Physics:
http://pdg.lbl.gov/2008/listings/contents_listings.html

Hadron quantum numbers

Mesons (bosons)

Particle	Mass (MeV)	B	Q	S	C	$\overline{B}$
π^+ ($u\bar{d}$)	140	0	1	0	0	0
K^- ($s\bar{u}$)	494	0	-1	-1	0	0
D^- ($\bar{c}d$)	1869	0	-1	0	-1	0
D_s^+ ($c\bar{s}$)	1971	0	1	0	1	0
Υ ($b\bar{b}$)	9460	0	0	0	0	0

Baryons (fermions)

Particle	Mass (MeV)	B	Q	S	C	$\overline{B}$
p (uud)	938	1	1	0	0	0
n (udu)	940	1	0	0	0	0
Λ (uds)	1116	1	0	-1	0	0
Λ_c (udc)	2285	1	1	0	1	0
Λ_b (udb)	5624	1	0	0	0	-1

Particles and antiparticles

Hadrons:

Baryons use a bar $\left[\text{proton } p(uud), \text{ antiprotons } \overline{p}\left(\overline{u}\overline{u}\overline{d}\right)\right]$

Mesons are quark-antiquark i.e. matter-antimatter.

$\Rightarrow$ There are no "anti-mesons"

Can, hwever, swap quark $\rightarrow$ antiquark , antiquark $\rightarrow$ quark

Eg $K^0(d\overline{s}) \rightarrow \overline{K}^0\left(\overline{d}s\right)$ (use bar for neutral mesons)

$K^+(u\overline{s}) \rightarrow K^-(\overline{u}s)$ (use charge)

Some neutral particles are their own antiparticle:

Eg γ, π^0

The quarks

Spin ½ particles **+ antiparticles**

Quark	Q (e)	Mass (GeV/c^2)	B	S	C	$\bar{B}$	T
u- up	2/3	0.003	1/3	0	0	0	0
d- down	-1/3	0.005	1/3	0	0	0	0
s- strange	-1/3	0.15	1/3	-1	0	0	0
c- charm	2/3	1.2	1/3	0	1	0	0
b- bottom	-1/3	4.2	1/3	0	0	-1	0
t-top	2/3	171	1/3	0	0	0	1

For antiquarks: internal quantum numbers change sign.

Charge: $Q \rightarrow -Q$, Baryon number: $B \rightarrow -B$

Flavour: (strangeness) $S \rightarrow -S$, ("charmness") $C \rightarrow -C$,("bottomness") $\bar{B} \rightarrow -\bar{B}, T \rightarrow -T$

Charge is always conserved.

Flavour quantum numbers are conserved in strong and electromagnetic decays but need not be conserved in weak decays.

Hadron flavour quantum numbers

General rule for all hadrons.

Total strangeness $S = \sum$ strangeness

$= N_{\bar{s}} - N_s$ = (no. $\bar{s}$ quarks - no. $\bar{s}$ quarks)

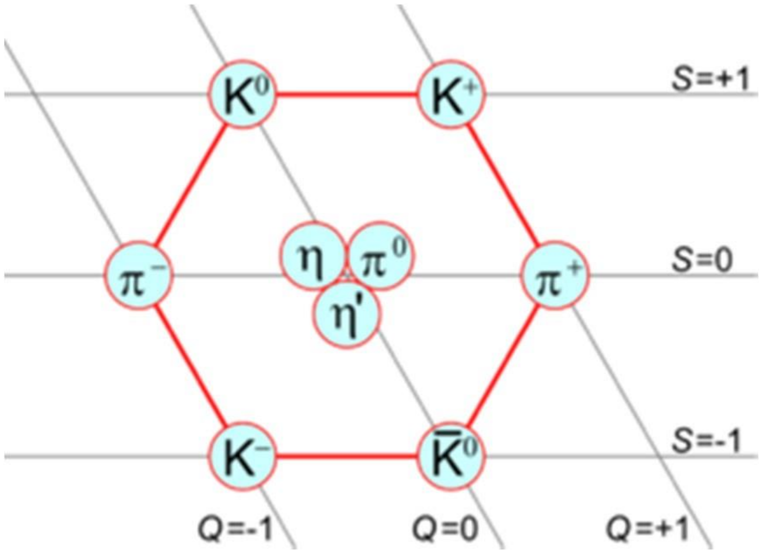
Similarly $C = N_c - N_{\bar{c}}$; $\bar{B} = N_{\bar{b}} - N_b$ (obs! No "top" hadrons)

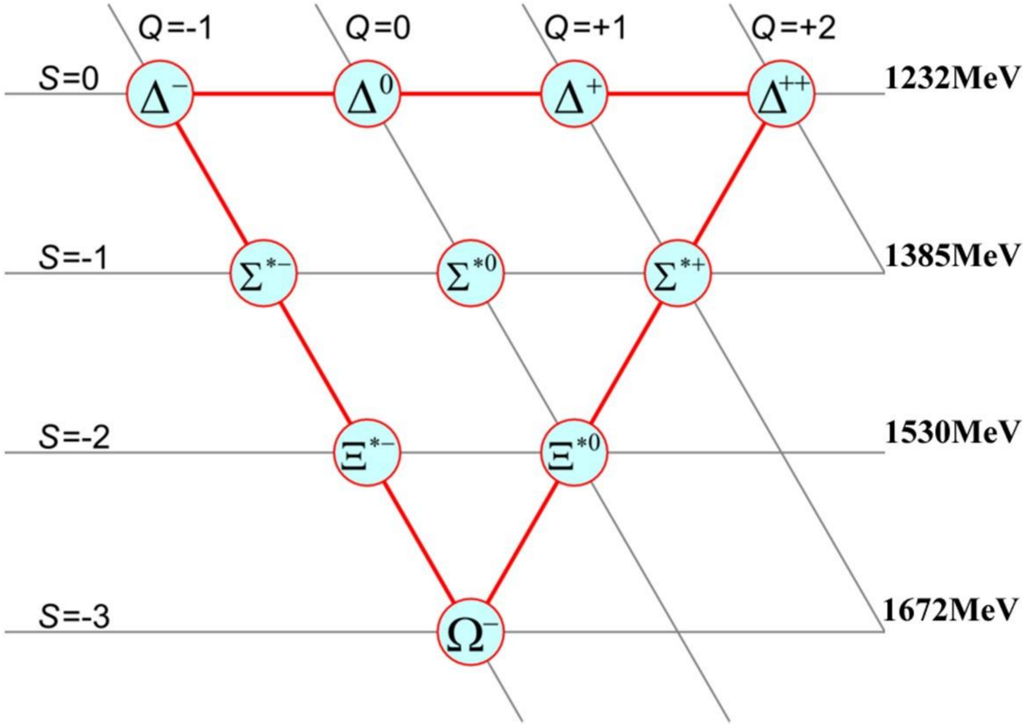
Baryon number: $B = \sum$ quark-baryon-number

Eg proton (uud) : $S = C = \bar{B} = 0$, $B = 3 \times \frac{1}{3} = 1$

$K^+ (u\bar{s})$: $S = 1,\ C = \bar{B} = 0$, $B = \frac{1}{3} - \frac{1}{3} = 0$

Evidence for quarks





Periodic structure of hadrons ($SU(3)$ multiplets).

Evidence for a new quantum number: colour

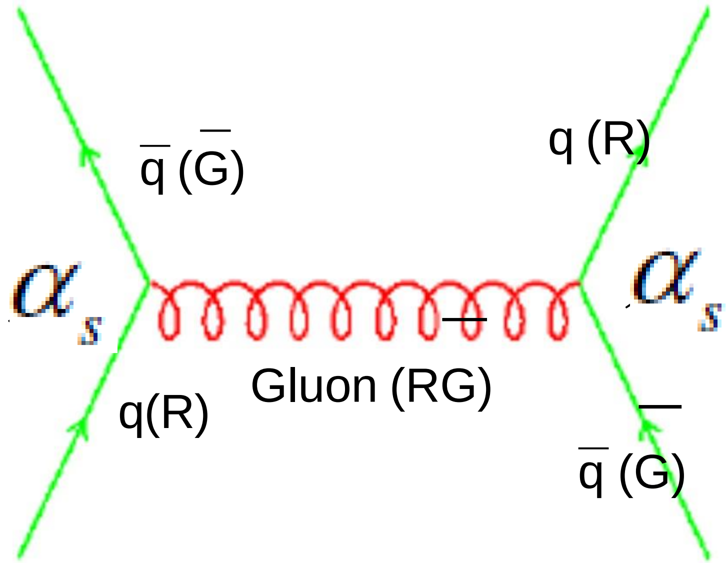
Ω^- : 3 strange quarks, spin 3/2 $\uparrow\uparrow\uparrow$

$$\psi = \psi_{space}\,\psi_{spin}\,\psi_{flavour}\,\psi_{colour} \qquad (4.03)$$

Need an extra quantum number (colour) to distinguish quarks to ensure anti-symmetric wave-function and Pauli's exclusion principle.

Hadrons and the strong force

The strong force occurs between particles carrying "colour" charge.



Range of the strong force ≈ 10^{-15}m.

Coupling at a vertex: α_s

A quark can carry 3 colours: Red (R), Green (G), Blue (B)

There are eight gluons:

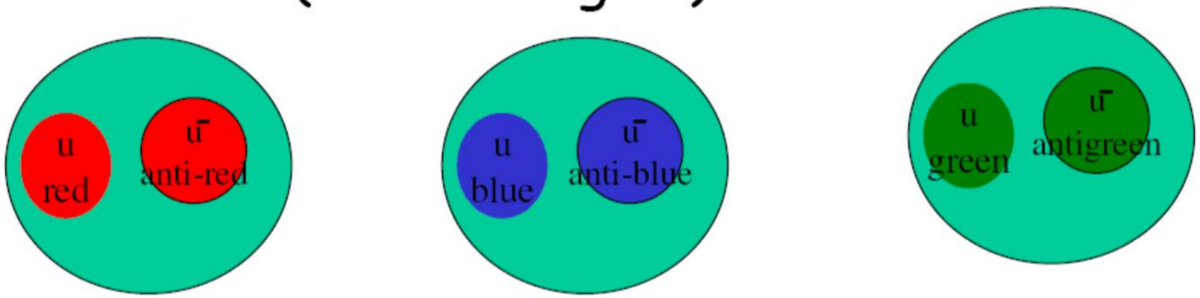
Gluons themselves carry colour and self-interact:

$$|R\bar{G}>, |R\bar{B}>, |G\bar{R}>, |G\bar{B}>, |B\bar{R}>, |B\bar{G}>, \frac{1}{\sqrt{2}}(R\bar{R} - G\bar{G}), \frac{1}{\sqrt{6}}(R\bar{R} + G\bar{G} - 2B\bar{B})$$

The theory of the strong force is quantum chromodynamics (QCD).

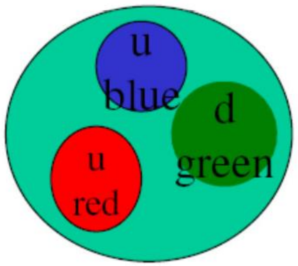
Colour combinations

A meson has a colour-anticolour pair=white (colour singlet)



π^0 π^0 π^0

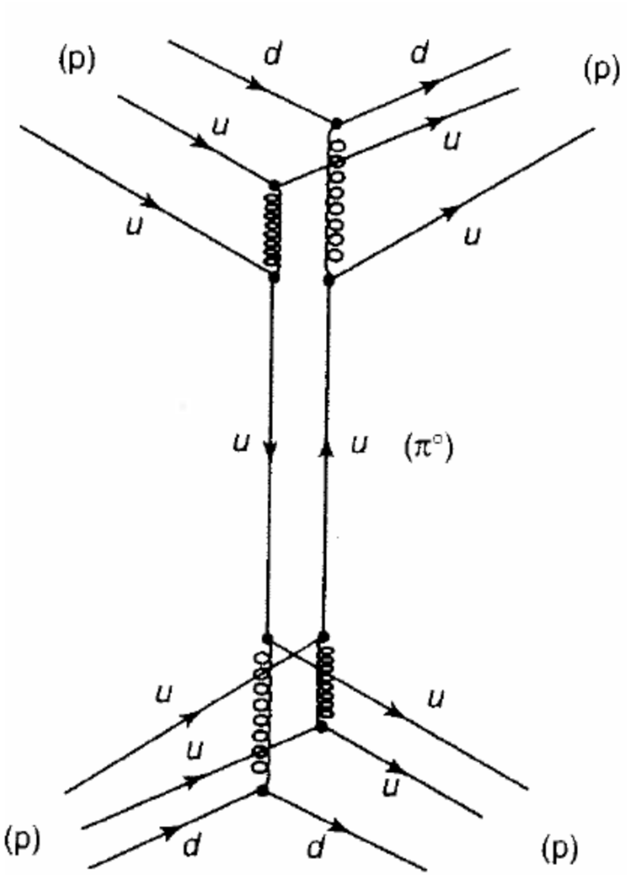
A baryon has red, blue, green triplet=white (colour singlet)



p

We have never seen a quark or gluon!
Nature abhors naked colour.
Every particle in nature is colourless/colour singlet

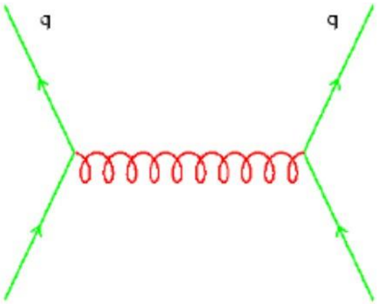
QCD Description of the Strong Nuclear Force



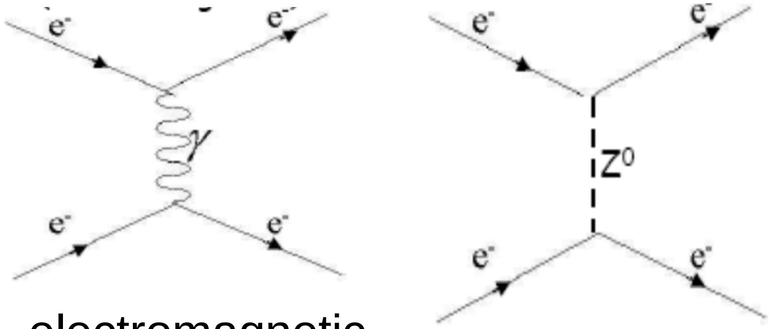
Yukawa model proposed pion exchange
Interaction results from internal gluon lines and quark exchange

The fundamental forces

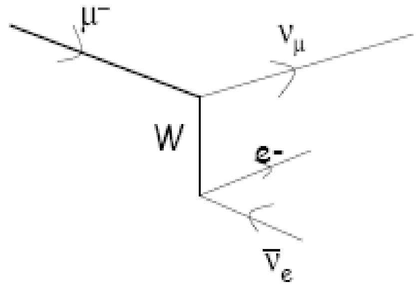
Different exchange particles mediate the forces:



strong



electromagnetic



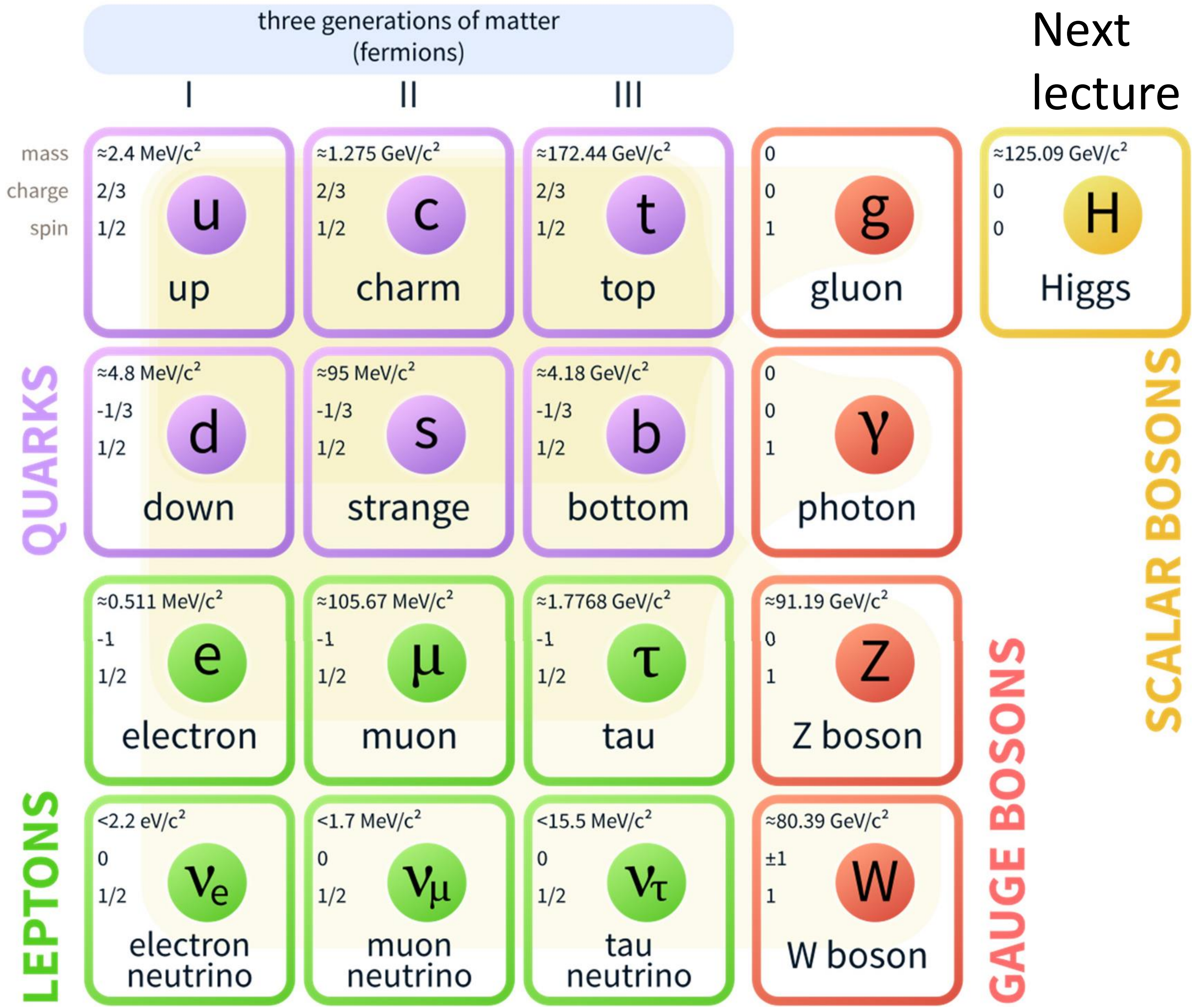
weak

Interaction	Relative strength	Range	Exchange	Mass (GeV)	Charge	Spin
Strong	*1*	Short (º fm)	Gluon	*0*	*0*	*1*
Electromagnetic	*1/137*	Long *($1/r^2$)*	Photon	*0*	*0*	*1*
Weak	*10^{-9}*	Short (º 10^{-3} fm)	*$W^+ W^-$,Z*	*80.4,80.4, 91.2*	*+e,-e,0*	*1*
Gravitational	*10^{-38}*	Long *($1/r^2$)*	Graviton ?	*0*	*0*	*2*

No quantum field theory yet for gravity

Standard Model of Elementary Particles

Next lecture



Particles in nature

PARTICLE DATA

(Mass in MeV/c^2; Lifetime in Seconds; Charge in Units of Proton Charge.)

QUARKS (Spin $\frac{1}{2}$)

	Flavor	Charge	Mass (speculative)		
			Bare	Effective	
				In baryons	In mesons
First generation	d	$-\frac{1}{3}$	7.5	363	310
	u	$+\frac{2}{3}$	4.2		
Second generation	s	$-\frac{1}{3}$	150	538	483
	c	$+\frac{2}{3}$	1100	1500	
Third generation	b	$-\frac{1}{3}$	4200	4700	
	t	$+\frac{2}{3}$	175000		

LEPTONS (Spin $\frac{1}{2}$)

	Lepton	Charge	Mass	Lifetime	Principal decays
First generation	e	-1	0.511003	∞	—
	ν_e	0	small	∞	—
Second generation	μ	-1	105.659	2.197×10^{-6}	$e\nu_\mu\bar{\nu}_e$
	ν_μ	0	small	∞	—
Third generation	τ	-1	1784	3.3×10^{-13}	$\mu\nu_\tau\bar{\nu}_\mu$, $e\nu_\tau\bar{\nu}_e$, $\rho\nu_\tau$
	ν_τ	0	small	∞	—

MEDIATORS (Spin 1)

Mediator	Charge	Mass	Lifetime	Force	
gluon	0	0	∞	strong	
photon (γ)	0	0	∞	electromagnetic	electroweak
$W^\pm$	±1	81,800	unknown	(charged) weak	
Z^0	0	92,600	unknown	(neutral) weak	

BARYONS (Spin $\frac{1}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
N p	uud	+1	938.280	∞	—
N n	udd	0	939.573	900	$pe\bar{\nu}_e$
Λ	uds	0	1115.6	2.63×10^{-10}	$p\pi^-$, $n\pi^0$
Σ^+	uus	+1	1189.4	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
Σ^0	uds	0	1192.5	6×10^{-20}	$\Lambda\gamma$
Σ^-	dds	-1	1197.3	1.48×10^{-10}	$n\pi^-$
Ξ^0	uss	0	1314.9	2.90×10^{-10}	$\Lambda\pi^0$
Ξ^-	dss	-1	1321.3	1.64×10^{-10}	$\Lambda\pi^-$
Λ_c^+	udc	+1	2281	2×10^{-13}	not established

BARYONS (Spin $\frac{3}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
Δ	uuu, uud, udd, ddd	+2, +1, 0, -1	1232	0.6×10^{-23}	$N\pi$
Σ^*	uus, uds, dds	+1, 0, -1	1385	2×10^{-23}	$\Lambda\pi$, $\Sigma\pi$
Ξ^*	uss, dss	0, -1	1533	7×10^{-23}	$\Xi\pi$
Ω^-	sss	-1	1672	0.82×10^{-10}	ΛK^-, $\Xi^0\pi^-$, $\Xi^-\pi^0$

PSEUDOSCALAR MESONS (Spin 0)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
$\pi^\pm$	$u\bar{d}$, $d\bar{u}$	+1, -1	139.569	2.60×10^{-8}	$\mu\nu_\mu$
π^0	$(u\bar{u}-d\bar{d})/\sqrt{2}$	0	134.964	8.7×10^{-17}	$\gamma\gamma$
$K^\pm$	$u\bar{s}$, $s\bar{u}$	+1, -1	493.67	1.24×10^{-8}	$\mu\nu_\mu$, $\pi^\pm\pi^0$, $\pi^\pm\pi^\pm\pi^\mp$
K^0, $\bar{K}^0$	$d\bar{s}$, $s\bar{d}$	0, 0	497.72	K_S^0 0.892×10^{-10}; K_L^0 5.18×10^{-8}	$\pi^+\pi^-$, $\pi^0\pi^0$; $\pi e\nu_e$, $\pi\mu\nu_\mu$, $\pi\pi\pi$
η	$(u\bar{u}+d\bar{d}-2s\bar{s})/\sqrt{6}$	0	548.8	7×10^{-19}	$\gamma\gamma$, $\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$
η'	$(u\bar{u}+d\bar{d}+s\bar{s})/\sqrt{3}$	0	957.6	3×10^{-21}	$\eta\pi\pi$, $\rho^0\gamma$
$D^\pm$	$c\bar{d}$, $d\bar{c}$	+1, -1	1869	9×10^{-13}	$K\pi\pi$
D^0, $\bar{D}^0$	$c\bar{u}$, $u\bar{c}$	0, 0	1865	4×10^{-13}	$K\pi\pi$
$F^\pm$ (now $D_s^\pm$)	$c\bar{s}$, $s\bar{c}$	+1, -1	1971	3×10^{-13}	not established
$B^\pm$	$u\bar{b}$, $b\bar{u}$	+1, -1	5271	14×10^{-13}	$D+?$
B^0, $\bar{B}^0$	$d\bar{b}$, $b\bar{d}$	0, 0	5275		
η_c	$c\bar{c}$	0	2981	6×10^{-23}	$KK\pi$, $\eta\pi\pi$, $\eta'\pi\pi$

VECTOR MESONS (Spin 1)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
ρ	$u\bar{d}$, $d\bar{u}$, $(u\bar{u}-d\bar{d})/\sqrt{2}$	+1, -1, 0	770	0.4×10^{-23}	$\pi\pi$
K^*	$u\bar{s}$, $s\bar{u}$, $d\bar{s}$, $s\bar{d}$	+1, -1, 0, 0	892	1×10^{-23}	$K\pi$
ω	$(u\bar{u}+d\bar{d})/\sqrt{2}$	0	783	7×10^{-23}	$\pi^+\pi^-\pi^0$, $\pi^0\gamma$
ϕ	$s\bar{s}$	0	1020	20×10^{-23}	K^+K^-, $K^0\bar{K}^0$
J/ψ	$c\bar{c}$	0	3097	1×10^{-20}	e^+e^-, $\mu^+\mu^-$, 5π, 7π
D^*	$c\bar{d}$, $d\bar{c}$, $c\bar{u}$, $u\bar{c}$	+1, -1, 0, 0	2010	$>1\times10^{-22}$	$D\pi$, $D\gamma$
Υ	$b\bar{b}$	0	9460	2×10^{-20}	$\tau^+\tau^-$, $\mu^+\mu^-$, e^+e^-

More information available from the Review of Particle Physics: http://www-pdg.lbl.gov/

Summary

Anti-particles for every particle - required by QM+special relativity.

Feynman diagrams - powerful tool for particle interactions.

Three families of leptons and quarks.

Hadrons formed from quarks.

Three forces in the Standard Model of particle physics.