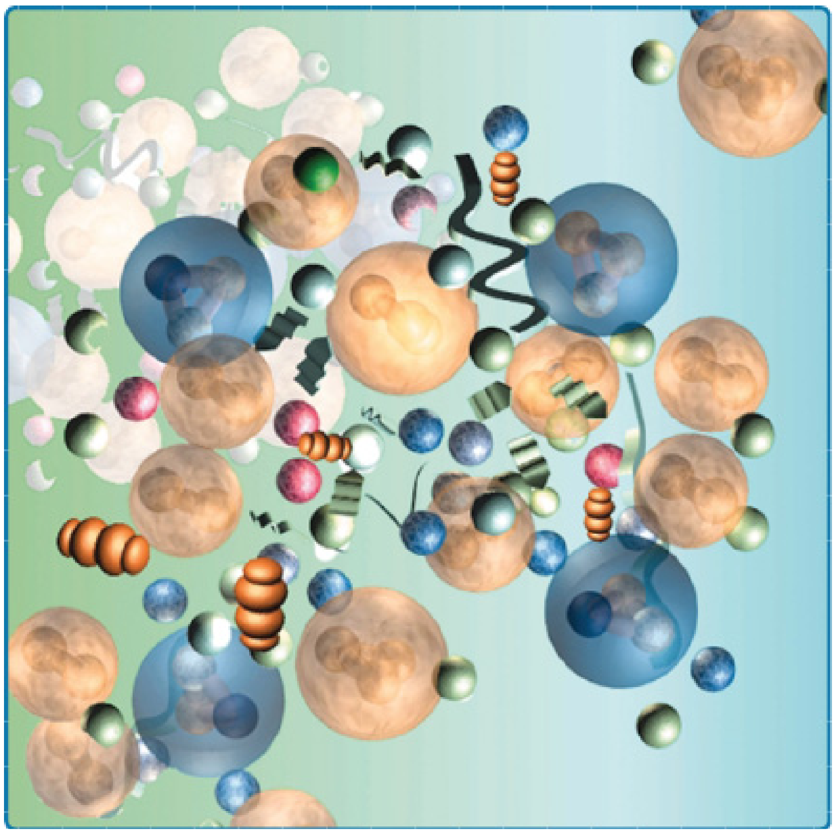
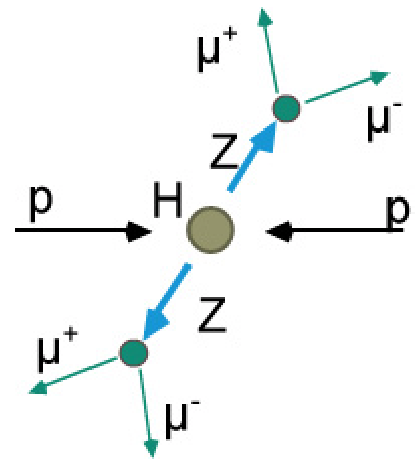
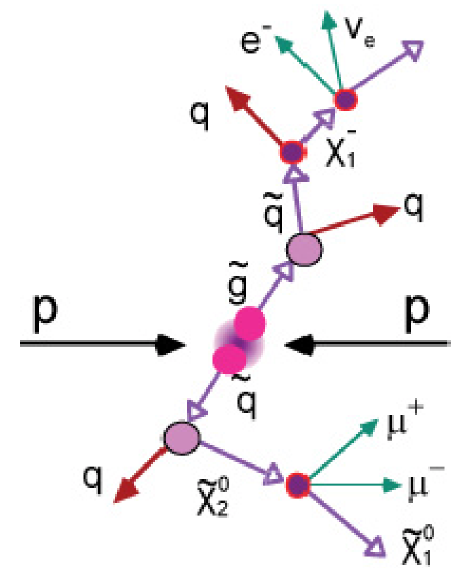
Modern Experimental Particle Physics







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I. Basic concepts, leptons, quarks and hadrons

- Particle physics studies elementary “building blocks” of *matter* and *interactions* between them.
- Matter consists of *particles*.
  - Matter is built of particles called “fermions”: those that have half-integer spin, e.g. 1/2; obey *Fermi-Dirac statistics*.
- Particles interact via *forces*.
  - Interaction is an exchange of a force-carrying particle.
- Force-carrying particles are called *gauge bosons* (spin-1).

Units and dimensions

- Particle energy is measured in *electron-volts*:

$$1\ \text{eV} \approx 1.602 \times 10^{-19}\ \text{J} \qquad (1)$$

  - 1 eV is energy of an electron upon passing a voltage of 1 Volt.
  - 1 keV = 10^3 eV; 1 MeV = 10^6 eV; 1 GeV = 10^9 eV

- The reduced *Planck constant* and the *speed of light*:

$$\hbar \equiv h/2\pi = 6.582 \times 10^{-22}\ \text{MeV s} \qquad (2)$$

$$c = 2.9979 \times 10^{8}\ \text{m/s} \qquad (3)$$

and the "*conversion constant*" is:

$$\hbar c = 197.327 \times 10^{-15}\ \text{MeV m} \qquad (4)$$

- For simplicity, *natural units* are used:

$$\hbar = 1 \qquad \text{and} \qquad c = 1 \qquad (5)$$

thus the unit of mass is *eV/c²*, and the unit of momentum is *eV/c*

Four-vector formalism

Relativistic kinematics is formulated with four-vectors:

- space-time four-vector: $x=(t,\bar{x})=(t,x,y,z)$, where t is time and $\bar{x}$ is a coordinate vector (c=1 notation is used)
- momentum four-vector: $p=(E,\bar{p})=(E,p_x,p_y,p_z)$, where E is particle energy and $\bar{p}$ is particle momentum vector

Calculus rules with four-vectors:

- 4-vectors are defined as
  - *contravariant*:

$$A^{\mu} = (A^{0}, \vec{A}), B^{\mu} = (B^{0}, \vec{B}), \tag{6}$$

  - and *covariant*:

$$A_{\mu} = (A^{0}, \overrightarrow{-A}), B_{\mu} = (B^{0}, \overrightarrow{-B}). \tag{7}$$

⌘ *Scalar product* of two four-vectors is defined as:

$$A \cdot B = A^0 B^0 - (\vec{A} \cdot \vec{B}) = A_\mu B^\mu = A^\mu B_\mu . \qquad (8)$$

⌘ Scalar products of momentum and space-time four-vectors are thus:

$$x \cdot p = x^0 p^0 - (\vec{x} \cdot \vec{p}) = Et - (\vec{x} \cdot \vec{p}) \qquad (9)$$

4-vector product of coordinate and momentum represents particle wavefunction

$$p \cdot p = p^2 = p^0 p^0 - (\vec{p} \cdot \vec{p}) = E^2 - \vec{p}^2 \equiv m^2 \qquad (10)$$

4-momentum squared gives particle's invariant mass

For relativistic particles, we can see that

$$\boldsymbol{E^2 = p^2 + m^2} \quad (c=1) \qquad (11)$$

Forces of nature

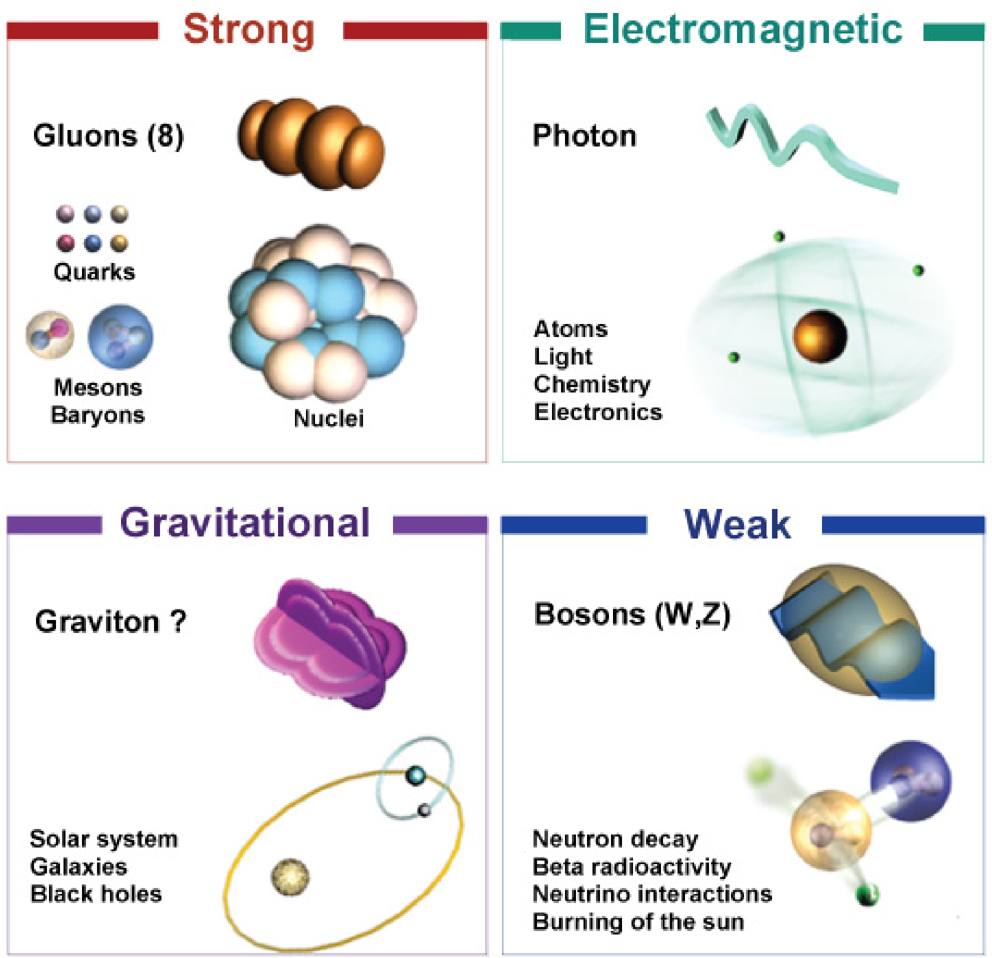


Figure 1: Forces and their carriers

Summary table of forces:

Force	**Acts on/ *couples to:***	**Carrier**	**Range**	**Strength**	**Stable systems**	**Induced reaction**
Gravity	all particles *Mass/E-p tensor*	graviton G *(has not yet been observed)*	long $F \propto 1/r^2$	$\sim \mathbf{10^{-39}}$	Solar system	Object falling
Weak force	fermions *hypercharge*	bosons W^+,W^- and Z	$< 10^{-17}$ m	$\mathbf{10^{-5}}$	None	β-decay
Electro-magnetism	charged particles *electric charge*	photon γ	long $F \propto 1/r^2$	$\mathbf{1/137}$	Atoms, molecules	Chemical reactions
Strong force	quarks and gluons *colour charge*	gluons g (8 different)	10^{-15} m	$\mathbf{1}$	Hadrons, nuclei	Nuclear reactions

The Standard Model

- Electromagnetic and weak forces can be described by a single theory $\Rightarrow$ the *"Electroweak Theory"* was developed in 1960s (Glashow, Weinberg, Salam).

- Theory of strong interactions appeared in 1970s: *"Quantum Chromodynamics"* (QCD).

- The *"Standard Model"* (SM) combines all the current knowledge.
  - Gravitation is VERY weak at particle scale, and it is not included in the SM. Moreover, quantum theory for gravitation does not exist yet.

Main postulates of SM:

1) Basic constituents of matter are *quarks* and *leptons* (spin 1/2)

2) They interact by exchanging *gauge bosons* (spin 1)

3) Quarks and leptons are subdivided into 3 *generations*

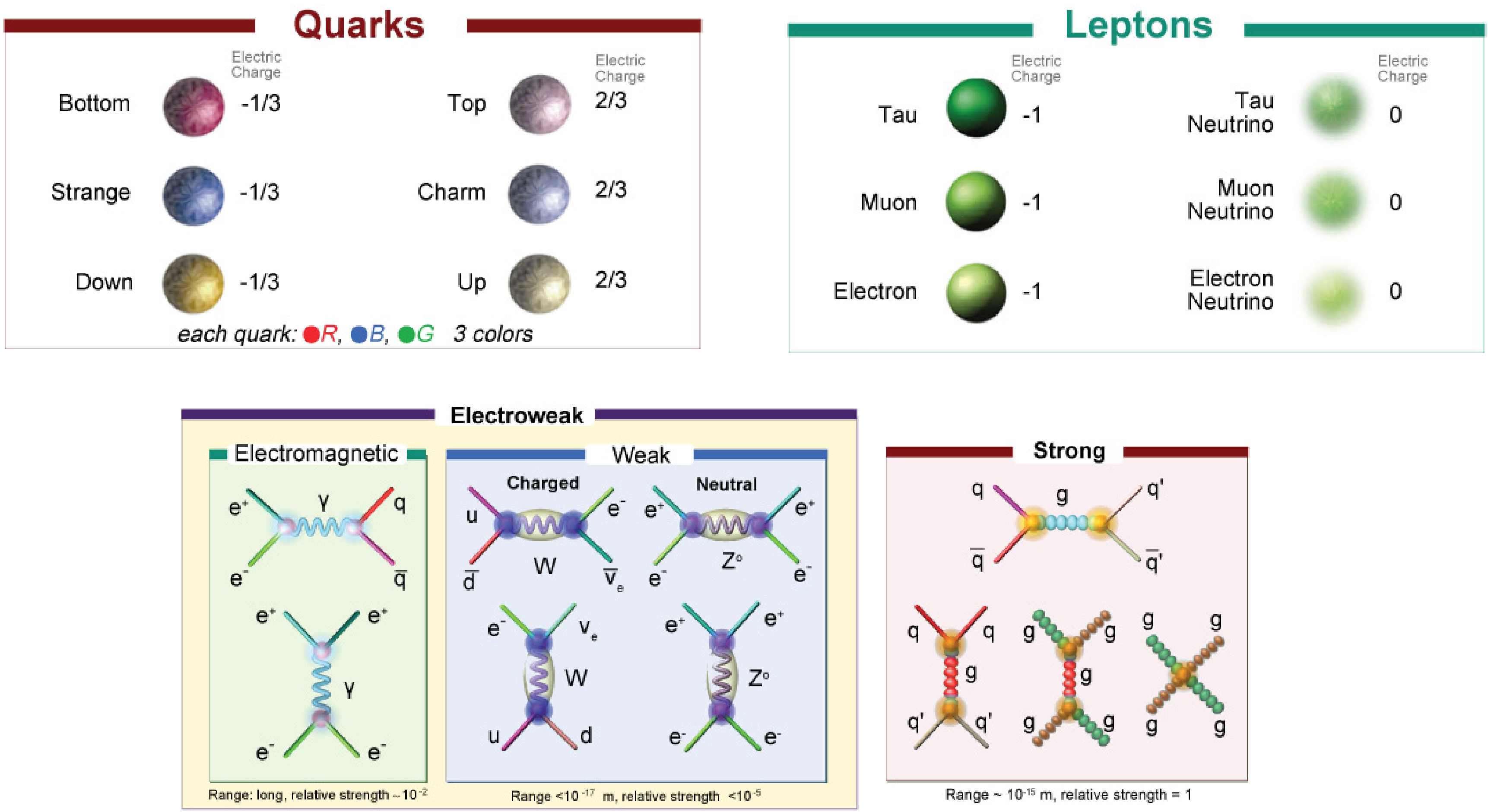


Figure 2: Standard Model: quarks, leptons and bosons

⌘ SM does not explain neither appearance of the mass nor the reason for existence of the 3 generations.

Antiparticles

- Particles are described by wavefunctions:

$$\Psi(\vec{x}, t) = Ne^{i(\vec{p}\vec{x} - Et)} \tag{12}$$

$\vec{x}$ is the coordinate vector, $\vec{p}$ - momentum vector, E and t are energy and time.

Particles obey the classical Schrödinger equation:

$$i\frac{\partial}{\partial t}\Psi(\vec{x}, t) = H\Psi(\vec{x}, t) = \frac{\vec{p}^2}{2m}\Psi(\vec{x}, t) = -\frac{1}{2m}\nabla^2\Psi(\vec{x}, t) \tag{13}$$

$$\text{here } \vec{p} = \frac{h}{2\pi i}\nabla \equiv \frac{\nabla}{i} \tag{14}$$

For relativistic particles, $\boldsymbol{E^2=p^2+m^2}$ (11), and (13) is replaced by the Klein-Gordon equation (15):

$$\Downarrow$$

$$-\frac{\partial^2}{\partial t^2}(\Psi) = H^2\Psi(\vec{x}, t) = -\nabla^2\Psi(\vec{x}, t) + m^2\Psi(\vec{x}, t) \qquad (15)$$

- There exist *negative* energy solutions with $E_+ < 0$!

$$\Psi^*(\vec{x}, t) = N^* \cdot e^{i(-\vec{p}\vec{x} + E_+ t)}$$

- There is a problem with the Klein-Gordon equation: it is second order in derivatives. In 1928, Dirac found the first-order form having the same solutions:

$$i\frac{\partial\Psi}{\partial t} = -i\sum_i \alpha_i \frac{\partial\Psi}{\partial x_i} + \beta m\Psi \qquad (16)$$

Here α_i and β are 4×4 matrices, and Ψ are four-component wavefunctions: *spinors* (for particles with spin 1/2).

$$\Psi(\vec{x}, t) = \begin{bmatrix} \Psi_1(\vec{x}, t) \\ \Psi_2(\vec{x}, t) \\ \Psi_3(\vec{x}, t) \\ \Psi_4(\vec{x}, t) \end{bmatrix}$$

Dirac-Pauli representation of matrices α_i and β:

$$\alpha_i = \begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix} \qquad \beta = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$$

Here I is a 2×2 unit matrix, 0 is a 2×2 matrix of zeros, and σ_i are 2×2 *Pauli matrices*:

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Also possible is *Weyl representation*:

$$\alpha_i = \begin{pmatrix} -\sigma_i & 0 \\ 0 & \sigma_i \end{pmatrix} \qquad \beta = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

Dirac's picture of vacuum

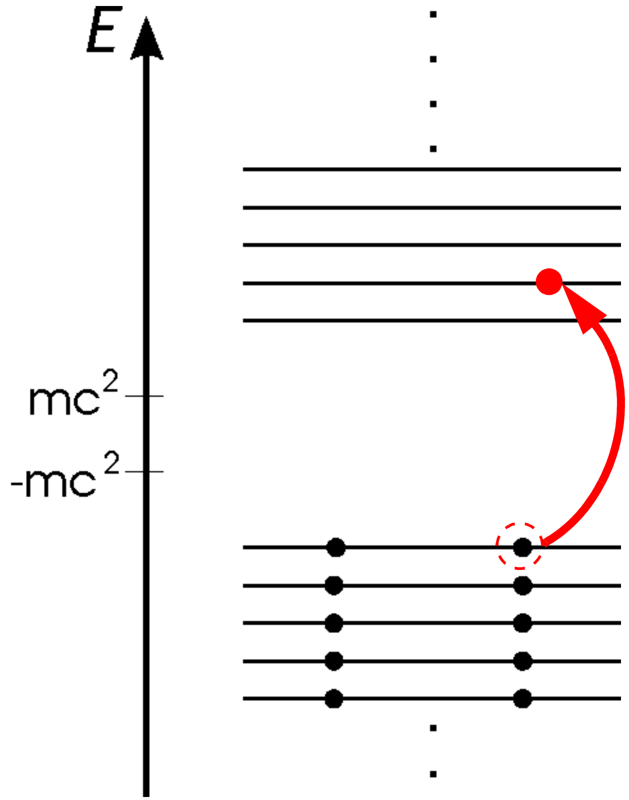


Figure 3: Fermions in Dirac's representation

- The "hole" created by appearance of an electron with "normal" energy is interpreted as the presence of electron's *antiparticle* with the opposite charge.
- Every charged particle must have an antiparticle of the same mass and opposite charge, to solve the mystery of "negative" energy.

Feynman diagrams

In 1940s, Richard Feynman developed a diagram technique for representing processes in particle physics.

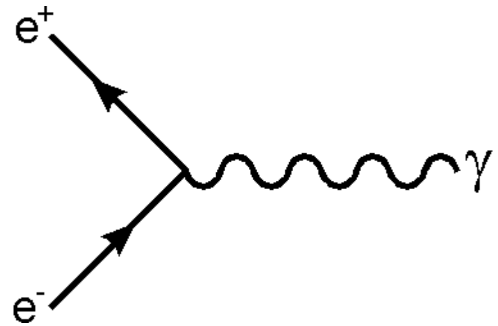


Figure 4: A Feynman diagram example: e+e- -> γ

Main assumptions and requirements:

- Time runs from <u>left to right</u>
- Arrow directed towards the <u>right</u> indicates a particle, and otherwise - antiparticle
- At every vertex, <u>momentum</u>, <u>angular momentum</u> and <u>charge</u> are conserved (but not necessarily energy)
- Particles are shown by solid lines, gauge bosons - by helices or dashed lines

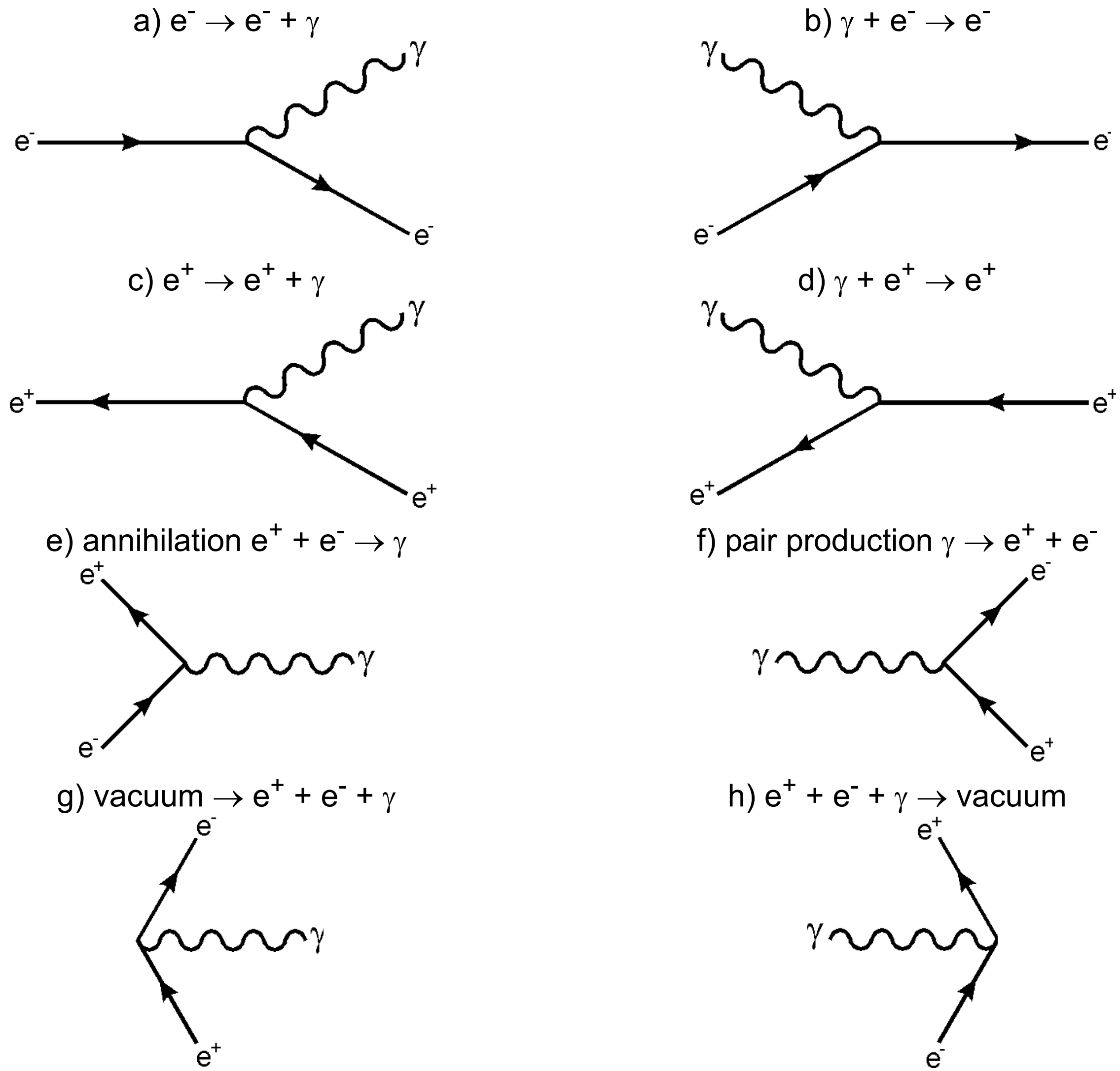


Figure 5: Feynman diagrams for **VIRTUAL** processes involving e^+, e^- and γ

⌘ A virtual process <u>does not</u> require energy conservation

- A real process demands energy conservation, is a combination of virtual processes:

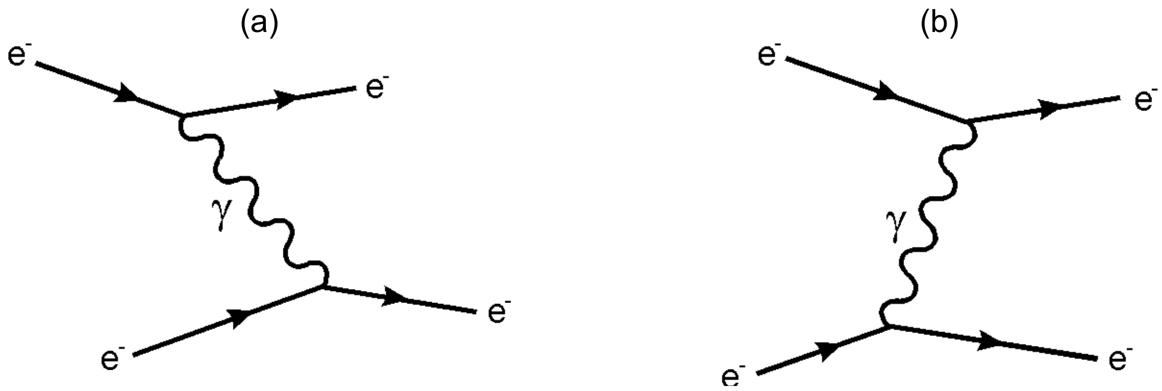


Figure 6: Electron-electron scattering, single photon exchange

- Any real process receives contributions from *all the possible* virtual processes:

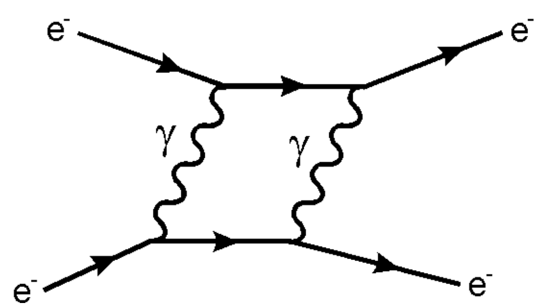


Figure 7: Two-photon exchange contribution

- Probability $P(e^-e^- \to e^-e^-) = |M(1\ \gamma \text{ exchange}) + M(2\ \gamma \text{ exchange}) + M(3\ \gamma \text{ exchange}) + \ldots|^2$ *(M stands for contribution, "Matrix element")*
  - Number of vertices in a diagram is called its *order*.
  - Each vertex has an associated probability proportional to a *coupling constant*, usually denoted as "α". In discussed processes this constant is

$$\alpha_{em} = \frac{e^2}{4\pi\varepsilon_0} \approx \frac{1}{137} \ll 1 \qquad (17)$$

  - Matrix element for a two-vertex process is proportional to $M = \sqrt{\alpha} \cdot \sqrt{\alpha}$, where each vertex has a factor $\sqrt{\alpha}$. Probability for a process is $P=|M|^2=\alpha^2$
  - For the real processes, a diagram of order n gives a contribution to probability of order α^n.

Provided sufficiently small α, high order contributions are smaller and smaller and the result is convergent: $P(\text{real}) = |M(\alpha)+M(\alpha^2)+M(\alpha^3)\ldots|^2$

Often lowest order calculation is precise enough.

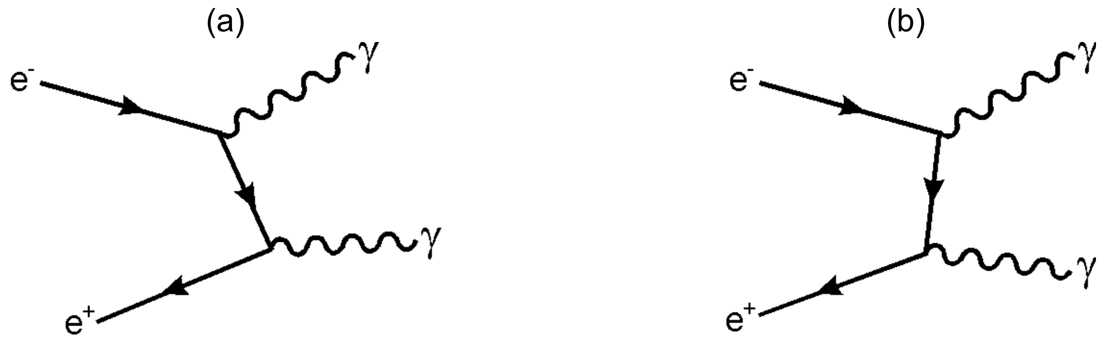


Figure 8: Lowest order contributions to $e^+e^- \to \gamma\gamma$. $M = \sqrt{\alpha} \cdot \sqrt{\alpha}$, $P=|M|^2=\alpha^2$

⌘ Diagrams which differ only by time-ordering are usually implied by drawing only one of them

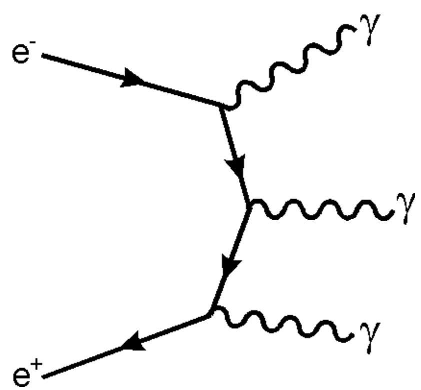


Figure 9: Lowest order of the process $e^+e^- \to \gamma\gamma\gamma$. $M = \sqrt{\alpha} \cdot \sqrt{\alpha} \cdot \sqrt{\alpha}$, $P=|M|^2=\alpha^3$

This kind of process implies 3!=6 different time orderings

❖ Knowing order of diagrams is sufficient to estimate the ratio of appearance rates of processes:

$$R \equiv \frac{Rate(e^+e^- \to \gamma\gamma\gamma)}{Rate(e^+e^- \to \gamma\gamma)} = \frac{O(\alpha^3)}{O(\alpha^2)} = O(\alpha)$$

This ratio can be measured experimentally; it appears to be $R = 0.9\times10^{-3}$, which is smaller than α_{em}, being only a first order prediction.

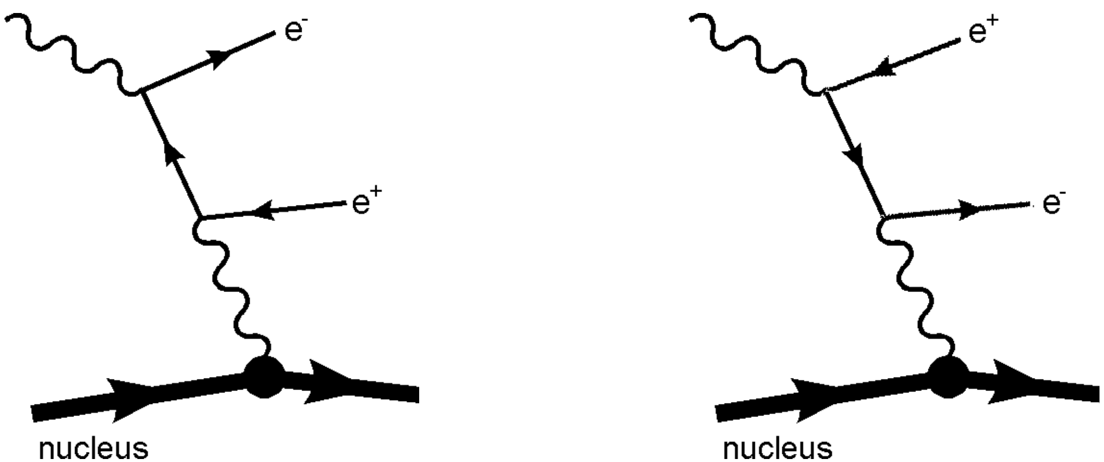


Figure 10: Diagrams that are ***not*** related by time ordering

⌘ For nuclei, the coupling is proportional to $Z^2\alpha$, hence the rate of this process is of order $Z^2\alpha^3$

Exchange of a massive boson

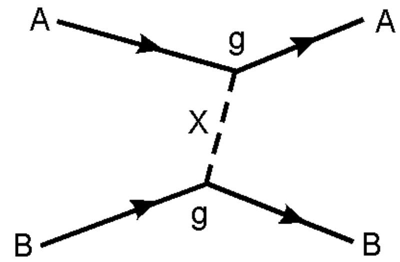


Figure 11: Exchange of a massive particle X

In the rest frame of particle A: $A(E_0, \vec{p}_0) \rightarrow A(E_A, \vec{p}) + X(E_x, -\vec{p})$

where $E_0 = M_A, \vec{p}_0 = (0, 0, 0)$, $E_A = \sqrt{p^2 + M_A^2}$, $E_X = \sqrt{p^2 + M_X^2}$

From this one can estimate the maximum distance over which X can propagate before being absorbed: $\Delta E = E_X + E_A - M_A \geq M_X$, and this energy violation can exist only for a period of time $\Delta t \approx \hbar / \Delta E$ (Heisenberg's uncertainty relation), hence the *range of the interaction* is

$r \approx R = \Delta t\, c = (\hbar / M_X)c$

- For a massless exchanged particle, the interaction has an infinite range (e.g., electromagnetic)
- In case of a very heavy exchanged particle (e.g., a W boson in weak interaction), the interaction can be approximated by a *zero-range*, or *point interaction*:

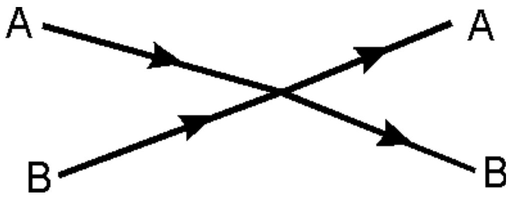


Figure 12: Point interaction as a result of $M_x \rightarrow \infty$

E.g., for a W boson: $R_W = \hbar/M_W = \hbar/(80.4\ \mathrm{GeV}/c^2) \approx 2 \times 10^{-18}$ m

Leptons

- *Leptons* are spin-1/2 fermions, not subject to strong interaction

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

$$M_e < M_\mu < M_\tau$$

- Electron e^-, muon μ^- and tau-lepton τ^- have corresponding neutrinos ν_e, ν_μ and ν_τ
- Electron, muon and tau have electric charge of $-e$; neutrinos are neutral
- Neutrinos have *very small* masses (were thought to be massless)
- For neutrinos, only weak interactions have been observed so far
- In addition to “usual” quantum numbers (spin, parity, electric charge etc), leptons carry *lepton numbers*

- Antileptons are: positron e^+, positive muon μ^+, positive tau-lepton τ^+, and antineutrinos:

$$\begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix}, \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}, \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$$

- Neutrinos and antineutrinos differ by the *lepton number*. Leptons posses lepton numbers L_α=1 (α stands for e, μ or τ), and antileptons have L_α= -1

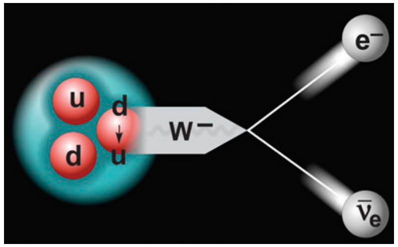
- *Lepton numbers are conserved in all interactions!*

Neutrinos can not be directly registered by any detector, there are only indirect measurements of their properties

- First indication of neutrino existence came from β-decays of nuclei, N:

$$N(Z,A) \rightarrow N(Z+1,A) + e^- + \bar{\nu}_e$$

β-decay is simply one of the neutrons decaying:



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

⌘ Experimentally, only proton and electron can be observed, and a fraction of energy and angular momentum is "missing".

❖ Note that for the sake of the lepton number conservation, electron must be accompanied by an electron-type <u>anti</u>neutrino!

The $\bar{\nu}_e$ mass can be estimated from the electron energy in the β-decay:

$$m_e \leq E_e \leq \Delta M_N - m_{\bar{\nu}e}$$

Current results from the tritium decay indicate a very small upper limit:

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e \qquad m_{\bar{\nu}e} \leq 3 \text{ eV}/c^2$$

❖ Recently observed neutrino mixing suggests *non-zero* mass

An inverse β-decay (neutrino "capture") also takes place:

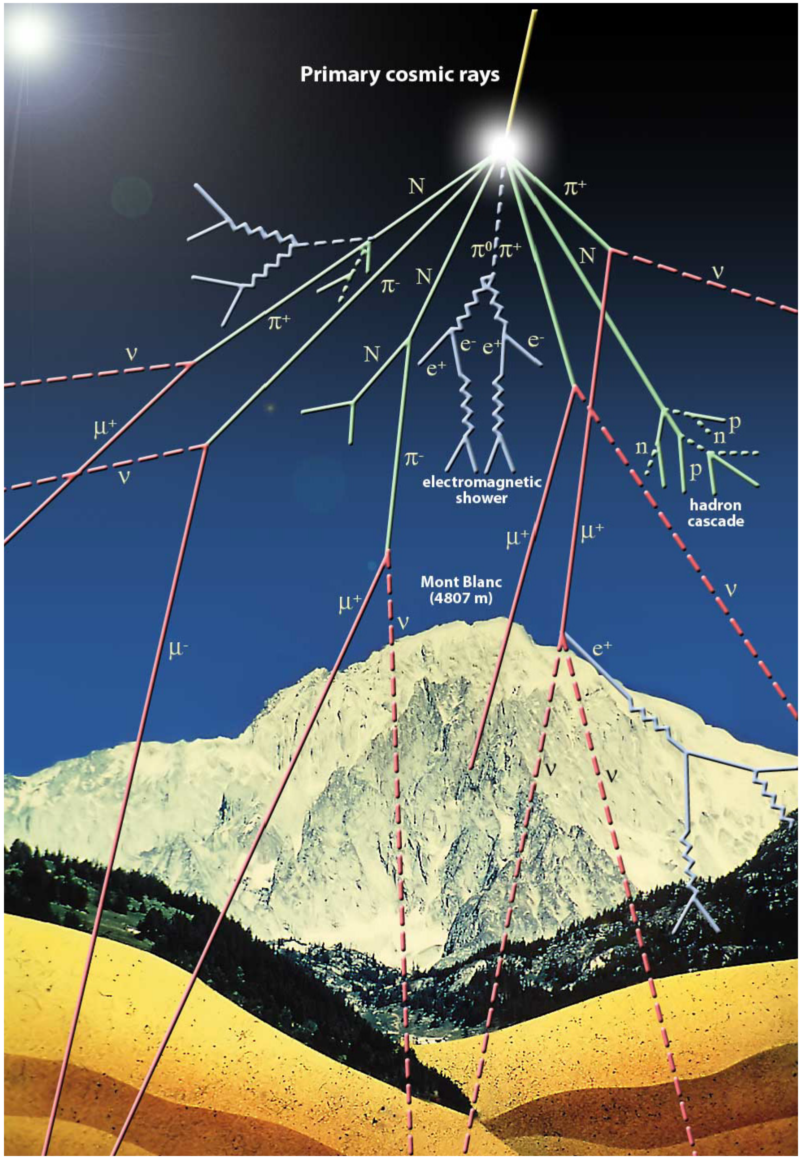
$$\nu_e + n \rightarrow e^- + p \qquad (18)$$

or

$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad (19)$$

Probabilities of these processes is very low, therefore to register any, one needs a very intense flux of neutrinos. Nevertheless, this was the process used for neutrino discovery (1956)

- Antiparticles naturally accompany particle production in order to satisfy respective conservation laws
  - positrons are produced even in thunderstorms...
  - ... but annihilate with much more abundant matter particles



- Muons are readily observed in *cosmic rays*

Cosmic rays have two components:

1) *primaries*, which are high-energy particles coming from the outer space, mostly hydrogen nuclei
2) *secondaries*, the particles which are produced in collisions of primaries with nuclei in the Earth atmosphere; muons belong to this component

Figure 13: Schematic representation of cosmic rays

- Muons are 200 times heavier than electrons and are very penetrating particles.
- Electromagnetic properties of muon are identical to those of electron (except the mass difference)

- Tau is the heaviest lepton, discovered in e^+e^- annihilation experiments in 1975

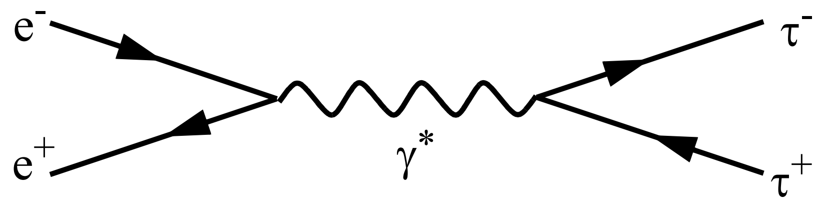


Figure 14: τ pair production in e^+e^- annihilation

- Electron is a stable particle, while μ and τ have finite lifetimes:

$$\tau_\mu = 2.2 \times 10^{-6}\ \mathrm{s} \quad \text{and} \quad \tau_\tau = 2.9 \times 10^{-13}\ \mathrm{s}$$

Muon decays in a purely leptonic mode:

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \qquad (20)$$

Tau has a mass sufficient to decay into hadrons, but it has leptonic decay modes as well:

$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau \qquad (21)$$

$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \qquad (22)$$

- Note: lepton numbers are conserved in **<u>all</u>** reactions ever observed
- Fraction of a given decay mode with respect to all possible decays is called *branching ratio*, denoted by B
- *Decay rate*: Γ=B/τ, where τ is decaying particle's lifetime

Branching ratio B of the process (21) is 17.84%, and of (22) – 17.37%.

Important assumptions:

- Weak interactions of leptons are identical, just like electromagnetic ones (*"universality of weak interactions"*)
- One can neglect <u>final</u> state lepton masses for many basic calculations

Decay rate Γ of a muon is given by the expression:

$$\Gamma(\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu) = \frac{G_F^2 m_\mu^5}{195\pi^3} \tag{23}$$

where G_F is the *Fermi constant* and m_μ is muon mass.

Substituting m_μ with m_τ in (23), one obtains decay rates of leptonic tau decays.

- ⌘ Since <u>only decaying particle mass</u> enters (23), decay rates are <u>equal</u> for processes (21) and (22).
- ⌘ It explains why branching ratios of these processes have such close values.

Lifetime of a lepton can be calculated using measured decay rate:

$$\tau_l = \frac{B(l^- \rightarrow e^- \bar{\nu}_e \nu_l)}{\Gamma(l^- \rightarrow e^- \bar{\nu}_e \nu_l)} \tag{24}$$

Here l indicates any other lepton, stands for either μ or τ .

Since muons have basically only one decay mode, **B=1** in their case. Using experimental values of B and formula (27), one obtains the ratio of muon and tau lifetimes:

$$\frac{\tau_\tau}{\tau_\mu} \approx 0.178 \cdot \left(\frac{m_\mu}{m_\tau}\right)^5 \approx 1.3\times10^{-7}$$

This again is in a very good agreement with independent experimental measurements

- Universality of lepton interactions is proved to a great extent. That means that there is basically no difference between lepton generations, apart of the mass and the lepton numbers.

Quarks and hadrons

- *Quarks* are spin-1/2 fermions, subject to <u>all</u> interactions. Quarks have fractional electric charges.

Quarks and their bound states are the only particles which interact strongly (via strong force).

Some historical background:

- Proton and neutron ("nucleons") were known to interact strongly
- In 1947, in cosmic rays, new heavy particles were detected ("hadrons")
- By 1960s, in accelerator experiments, many dozens of hadrons were discovered
- An urge to find a kind of "periodic system" lead to the "Eightfold Way" classification, invented by Gell-Mann and Ne'eman in 1961, based on the SU(3) symmetry group and describing hadrons in terms of "building blocks"
- In 1964, Gell-Mann invented quarks as the building blocks (and Zweig invented "aces")

- The quark model: *baryons* (*antibaryons)* are bound states of three quarks (antiquarks); *mesons* are quark-antiquark bound states

- *Hadrons* is a common name for baryons and mesons

Like leptons, quarks and antiquarks occur in three generations:

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

Name ("Flavour")	Symbol	Charge (units of e)	Mass
Down	d	-1/3	4-8 MeV/c^2
Up	u	+2/3	1.5-4.0 MeV/c^2
Strange	s	-1/3	80-130 MeV/c^2
Charmed	c	+2/3	1.15-1.35 GeV/c^2
Bottom	b	-1/3	4.1-4.9 GeV/c^2
Top	t	+2/3	≈178 GeV/c^2

- Despite numerous attempts, free quarks could never be observed
- More quantum numbers:
  - Each quark flavour is associated with an own quantum number, which is conserved in strong and electromagnetic interactions, but **not in weak ones**.

Quark *flavour quantum numbers* are defined as:

- *strangeness* S= -1 for s-quark
- *charm* C=1 for c-quark
- *beauty* $\tilde{B}$ = -1 for b-quark
- top-quark has lifetime too short to form hadrons before decaying, thus *truth* T=0 for all hadrons
- Up and down quarks have nameless flavour quantum numbers

- Baryons "inherit" quantum numbers of their constituents: there are "strange", "charmed" and "beautiful" baryons

Some examples of baryons:

Particle	Mass (GeV/c^2)	Quark composition	Q (units of e)	S	C	$\tilde{B}$
p	0.938	uud	1	0	0	0
n	0.940	udd	0	0	0	0
Λ	1.116	uds	0	-1	0	0
Λ_c	2.285	udc	1	0	1	0

Baryons are assigned own *baryon quantum number*

$$B=(N(q)-N(\bar{q}))/3$$

- $B = 1$ for baryons
- $B = -1$ for antibaryons
- $B = 0$ for mesons

- B is conserved in all interactions, thus the lightest baryon, proton, is stable

Some examples of mesons:

Particle	Mass (Gev/c^2)	Quark composition	Q (units of e)	S	C	$\tilde{B}$
π^+	0.140	$u\bar{d}$	1	0	0	0
K^-	0.494	$s\bar{u}$	-1	-1	0	0
D^-	1.869	$d\bar{c}$	-1	0	-1	0
D_s^+	1.969	$c\bar{s}$	1	1	1	0
B^-	5.279	$b\bar{u}$	-1	0	0	-1
Υ	9.460	$b\bar{b}$	0	0	0	0

- Majority of hadrons are unstable and tend to decay by the strong interaction to the state with the lowest possible mass (lifetime about 10^{-23} s)
- Hadrons with the lowest possible mass for each quark number (*S*, *C*, etc.) may live significantly longer before decaying weakly (lifetimes 10^{-7}-10^{-13} s) or electromagnetically (mesons, lifetimes 10^{-16} - 10^{-21} s). Such hadrons are called *long-lived particles* (sometimes even “stable”)
- The only truly stable hadron is proton – *that is, if baryon number conservation is not violated*

Brief history of hadron discoveries

- First known hadrons were proton and neutron
- The lightest are pions π ("pi-mesons"). There are charged pions π^+, π^- with mass of 0.140 GeV/c^2, and neutral ones π^0, mass 0.135 GeV/c^2

- Pions and nucleons are the lightest particles containing u- and d-quarks only

Pions were discovered in 1947 in cosmic rays, using photoemulsions to detect particles

Some reactions induced by cosmic rays primaries:

$$
\begin{aligned}
p + p &\to p + n + \pi^+ \\
&\to p + p + \pi^0 \\
&\to p + p + \pi^+ + \pi^-
\end{aligned}
$$

Same reactions can be reproduced in accelerators, with higher rates, although cosmic rays may provide higher energies.

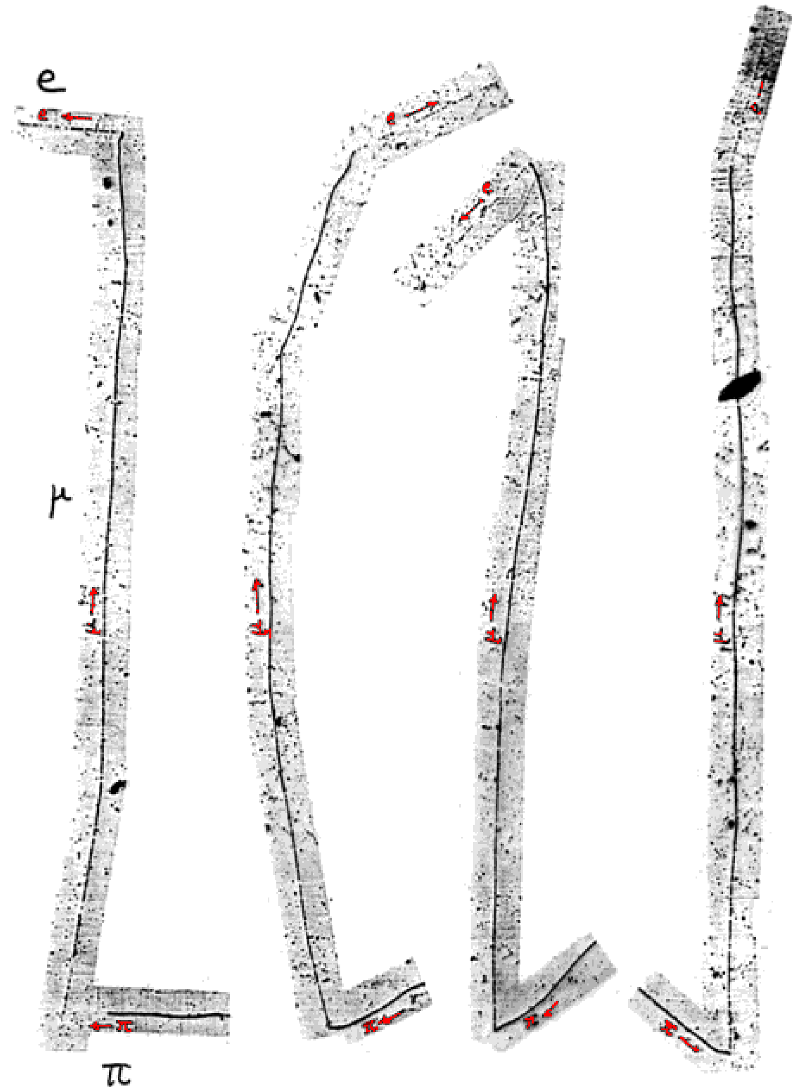


Figure 15: First observed pions: a π^+ stops in the emulsion and decays to a μ^+ and ν_μ, followed by the decay of μ^+.In emulsions, pions were identified by much more dense ionization along the track, as compared to electron tracks.

Figure 15: examples of the reaction

$$\pi^+ \to \mu^+ + \nu_\mu \tag{25}$$

where the pion comes to rest, producing muons which in turn decay by the reaction $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

- Charged pions decay mainly to the muon-neutrino pair (branching ratio about 99.99%), having lifetimes of 2.6×10^{-8} s. In quark terms:

$$(u\bar{d}) \to \mu^+ + \nu_\mu$$

  - The decay occurs through weak interaction, hence quark quantum numbers are not conserved. *B* and *L* are conserved

- Neutral pions decay mostly by the electromagnetic interaction, having shorter lifetime of 0.8×10^{-16} s:

$$\pi^0 \to \gamma + \gamma$$

Strange mesons and baryons

were called so, because they were produced in strong interactions, and yet had quite long lifetimes, and decayed weakly.

The lightest particles containing s-quarks are:

- mesons K^+, K^- and K^0, $\overline{K}^0$:*"kaons"*, lifetime of K^+ is 1.2×10^{-8} s
- baryon Λ, lifetime of 2.6×10^{-10} s

Principal decay modes of strange hadrons:

$$K^+ \rightarrow \mu^+ + \nu_\mu \qquad \text{(B=0.64)}$$
$$K^+ \rightarrow \pi^+ + \pi^0 \qquad \text{(B=0.21)}$$
$$\Lambda \rightarrow \pi^- + p \qquad \text{(B=0.64)}$$
$$\Lambda \rightarrow \pi^0 + n \qquad \text{(B=0.36)}$$

The first decay is clearly a weak one. Decays of Λ have too long lifetime to be strong: if Λ were (udd), the decay *(udd)* $\rightarrow$ *($d\bar{u}$)* + *(uud)* should have had a lifetime of order 10^{-23} s. Λ cannot be (udd) like the neutron.

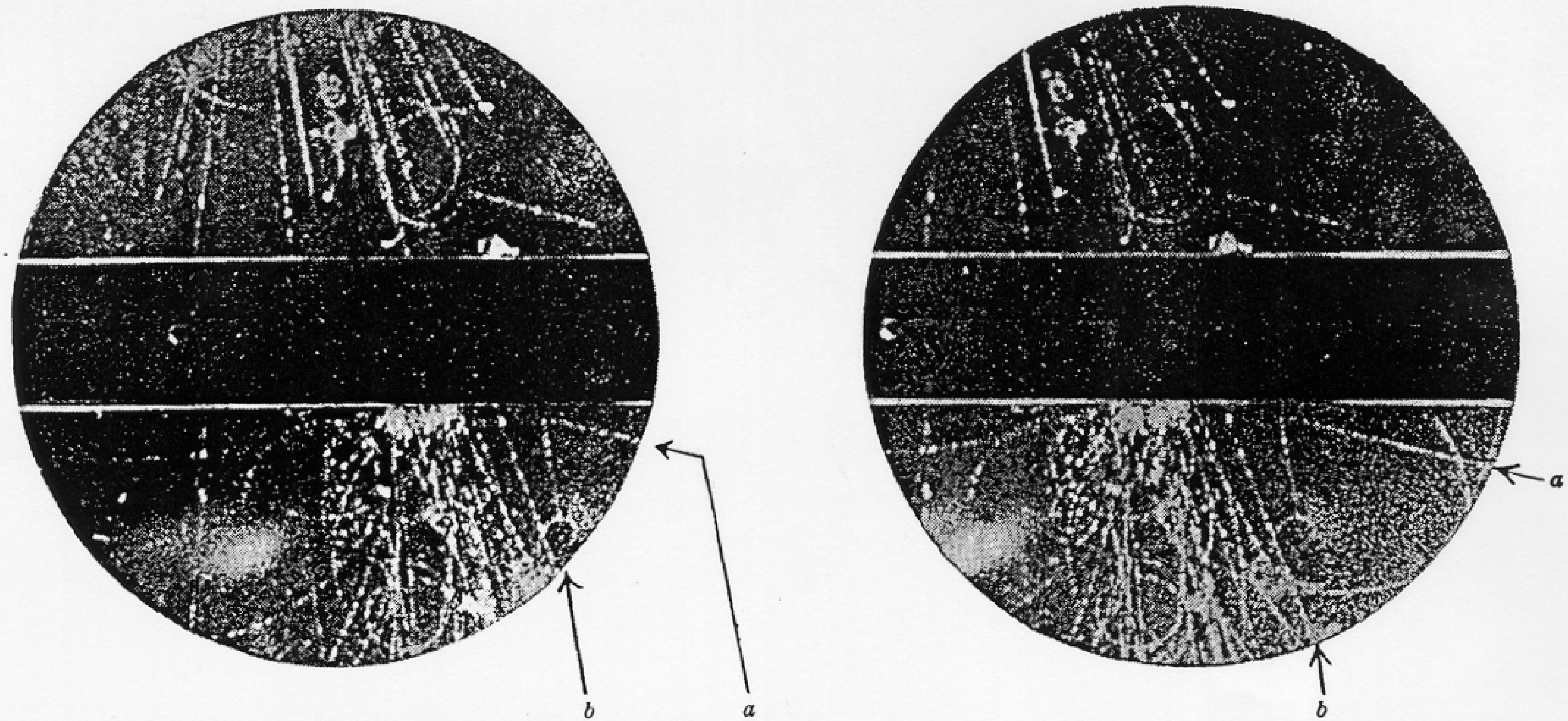


Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

Figure 16: “Strange” particle discovery (neutral kaon) by Rochester and Butler, 1947

Solution: to invent a new *"strange"* quark, bearing a new quark number, *"strangeness"*, which does not have to be conserved in weak interactions

$S = 1$	$S = -1$
$\overline{\Lambda}$ (1116) = $\overline{uds}$	Λ (1116) = uds
K^+(494) = $u\bar{s}$	K^-(494) = $s\bar{u}$
K^0 (498) = $d\bar{s}$	$\overline{K}^0$(498) = $s\bar{d}$

- In strong interactions, strange particles have to be produced in pairs in order to conserve total strangeness (*"associated production"*):

$$\pi^- + p \rightarrow K^0 + \Lambda \qquad (26)$$

In 1952, *bubble chambers* were invented as particle detectors, and also worked as *targets*, providing, in particular, the proton target for reaction (26).

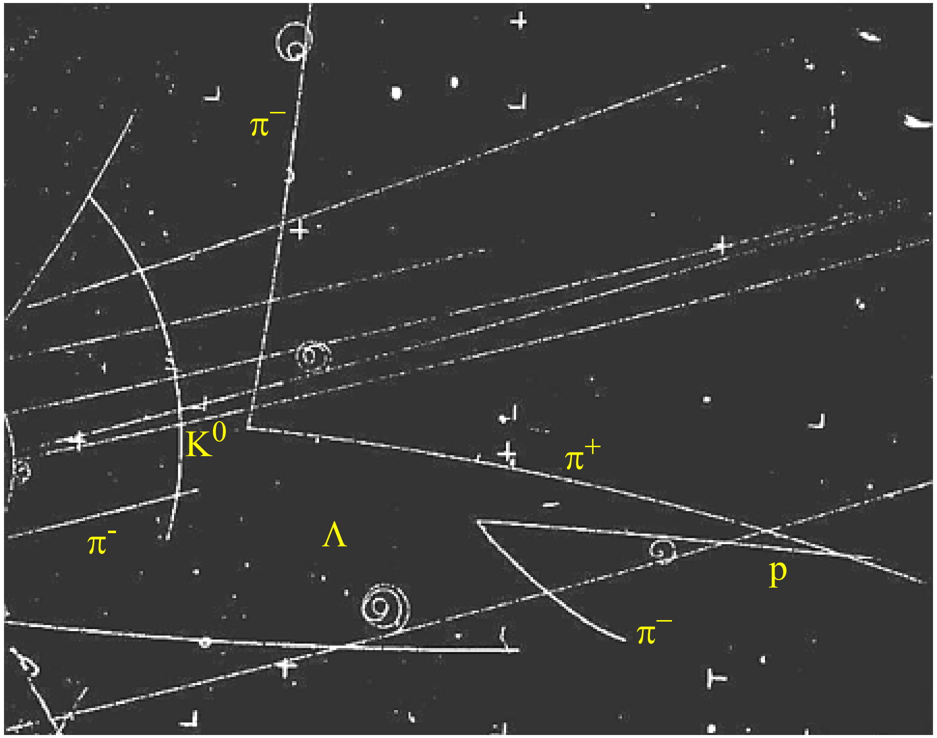


Figure 17: A bubble chamber picture of the reaction (26)

- A bubble chamber is filled with a liquid (hydrogen, propane, freons) under pressure, heated above its boiling point.
- Particles ionize the liquid along their passage.
- Volume expands ⇒ pressure drops ⇒ liquid starts boiling along the ionization trails.
- Visible bubbles are stereo-photographed.

- Bubble chambers were great tools in particle discoveries, providing physicists with numerous hadrons, all of them fitting u-d-s quark scheme until 1974.
  - In 1974, a new particle was discovered, which demanded a new flavour to be introduced. Since it was detected simultaneously by two groups in Brookhaven (BNL) and Stanford (SLAC), it received a double name: J/ψ (3097), a $c\bar{c}$ meson

The new quark was called *"charmed"*, and the corresponding quark number is *charm,* *C*. Since J/ψ itself has C=0, it is said to contain "hidden charm".

Shortly after that particles with "open charm" were discovered as well:

$$D^+(1869) = c\bar{d},\ D^0(1865) = c\bar{u}$$

$$D^-(1869) = d\bar{c},\ \bar{D}^0(1865) = u\bar{c}$$

$$\Lambda_c^+(2285) = udc$$

Even heavier charmed mesons were found – those which contained strange quark as well:

$$D_s^+(1969) = \mathrm{c\bar{s}},\ D_s^-(1969) = \mathrm{s\bar{c}}$$

Lifetimes of the lightest charmed particles are of order 10^{-13} s, well in the expected range of weak decays.

- Discovery of "charmed" particles was a triumph for the electroweak theory, which demanded number of quarks and leptons to be equal.

In 1977, *"beautiful"* mesons were discovered:

$$\Upsilon(9460) = \mathrm{b\bar{b}}$$
$$B^+(5279) = \mathrm{u\bar{b}},\ B^0(5279) = \mathrm{d\bar{b}}$$
$$B^-(5279) = \mathrm{b\bar{u}},\ \bar{B}^0(5279) = \mathrm{b\bar{d}}$$

and the lightest b-baryon: $\Lambda_b^0(5461) = \mathrm{udb}$

And this is the limit: top-quark is too unstable to form observable hadrons