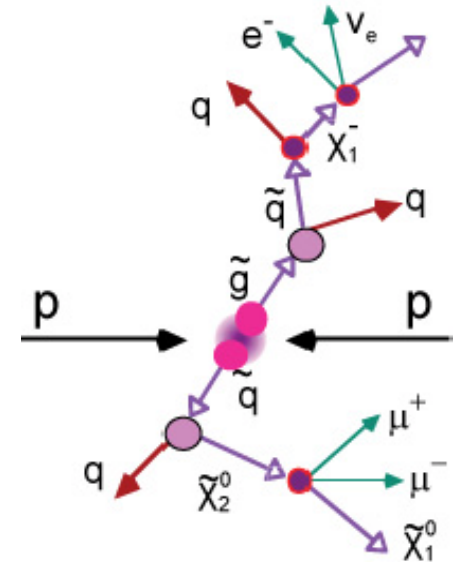
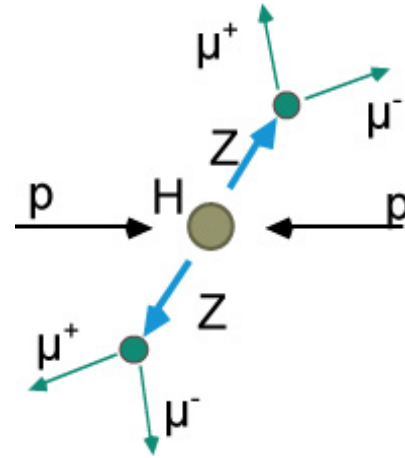
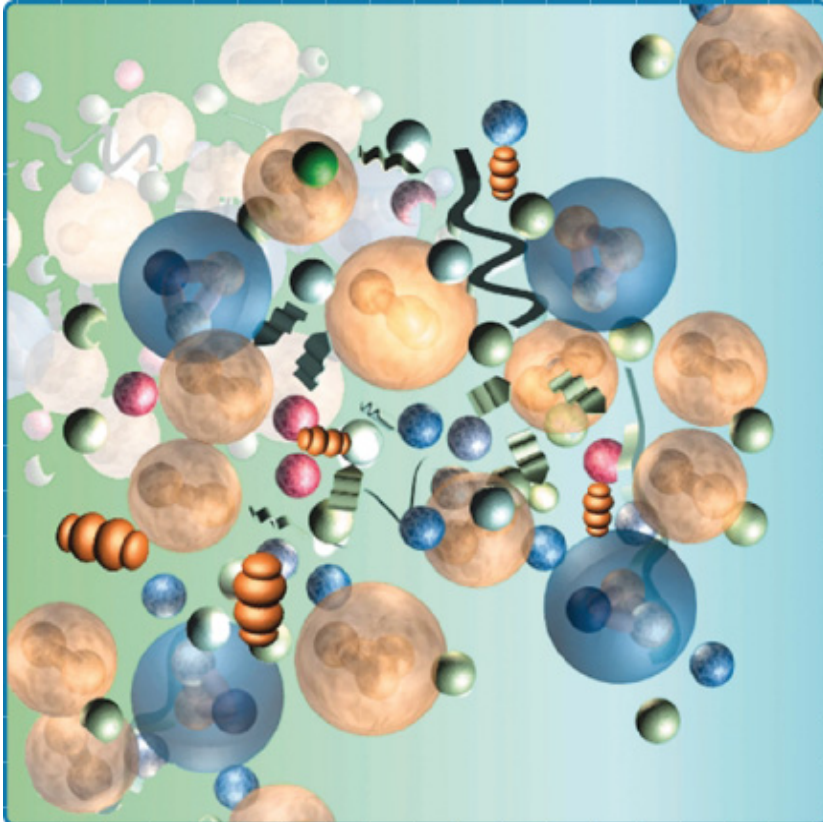


Modern Experimental Particle Physics



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*:

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

⌘ 1 eV is energy of an electron upon passing a voltage of 1 Volt.

⌘ $1 \text{ keV} = 10^3 \text{ eV}$; $1 \text{ MeV} = 10^6 \text{ eV}$; $1 \text{ GeV} = 10^9 \text{ eV}$

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

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

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

and the “*conversion constant*” is:

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

❖ For simplicity, *natural units* are used:

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

thus the unit of mass is eV/c^2 , 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*:

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

⌘ and *covariant*:

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

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

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

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

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

4-vector product of coordinate and momentum represents particle
wavefunction

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

4-momentum squared gives particle's invariant mass

For relativistic particles, we can see that

$$E^2 = p^2 + m^2 \quad (c=1) \quad (11)$$

Forces of nature

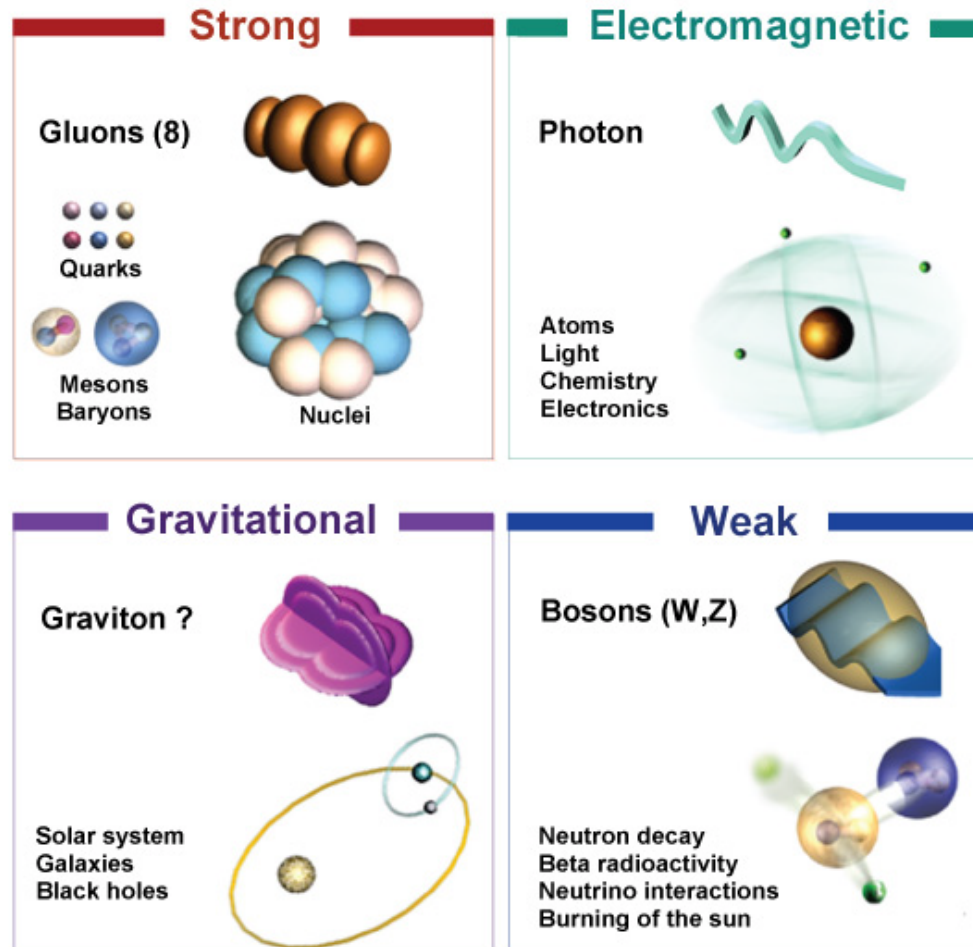


Figure 1: Forces and their carriers

Summary table of forces:

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

The Standard Model

- ❖ Electromagnetic and weak forces can be described by a single theory
⇒ 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*

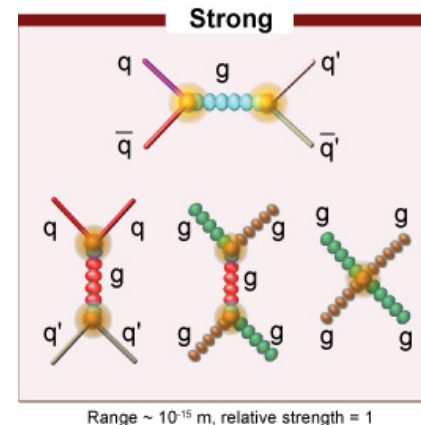
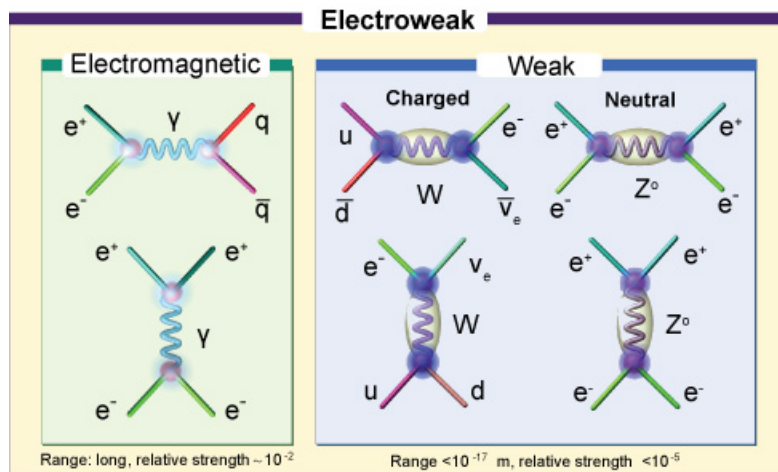
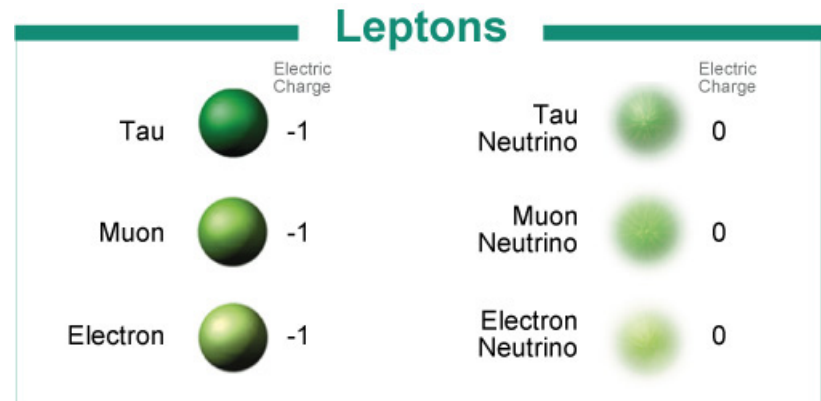


Figure 2: Standard Model: quarks, leptons and bosons

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

Antiparticles

❖ Particles are described by wavefunctions:

$$\Psi(\vec{x}, t) = N e^{i(\vec{p}\vec{x} - Et)} \quad (12)$$

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

Particles obey the classical Schrödinger equation:

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

$$\text{here } \vec{p} = \frac{\hbar}{2\pi i} \nabla \equiv \frac{\nabla}{i} \quad (14)$$

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

⇓

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

❖ 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:

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

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 :

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

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

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

Also possible is *Weyl representation*:

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

Dirac's picture of vacuum

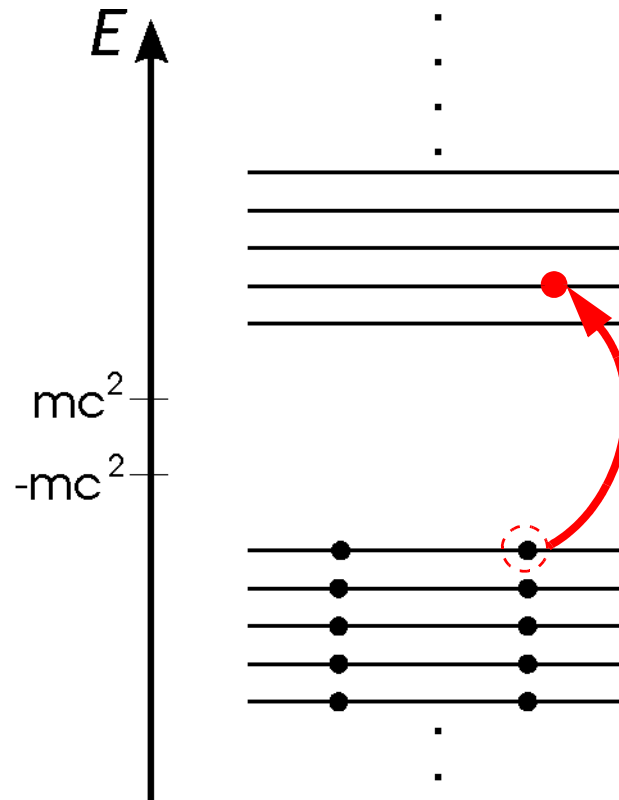


Figure 3: Fermions in Dirac's representation

- ◎ 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.

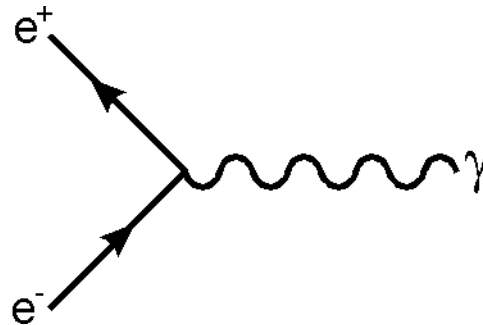


Figure 4: A Feynman diagram example: $e^+e^- \rightarrow \gamma$

Main assumptions and requirements:

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

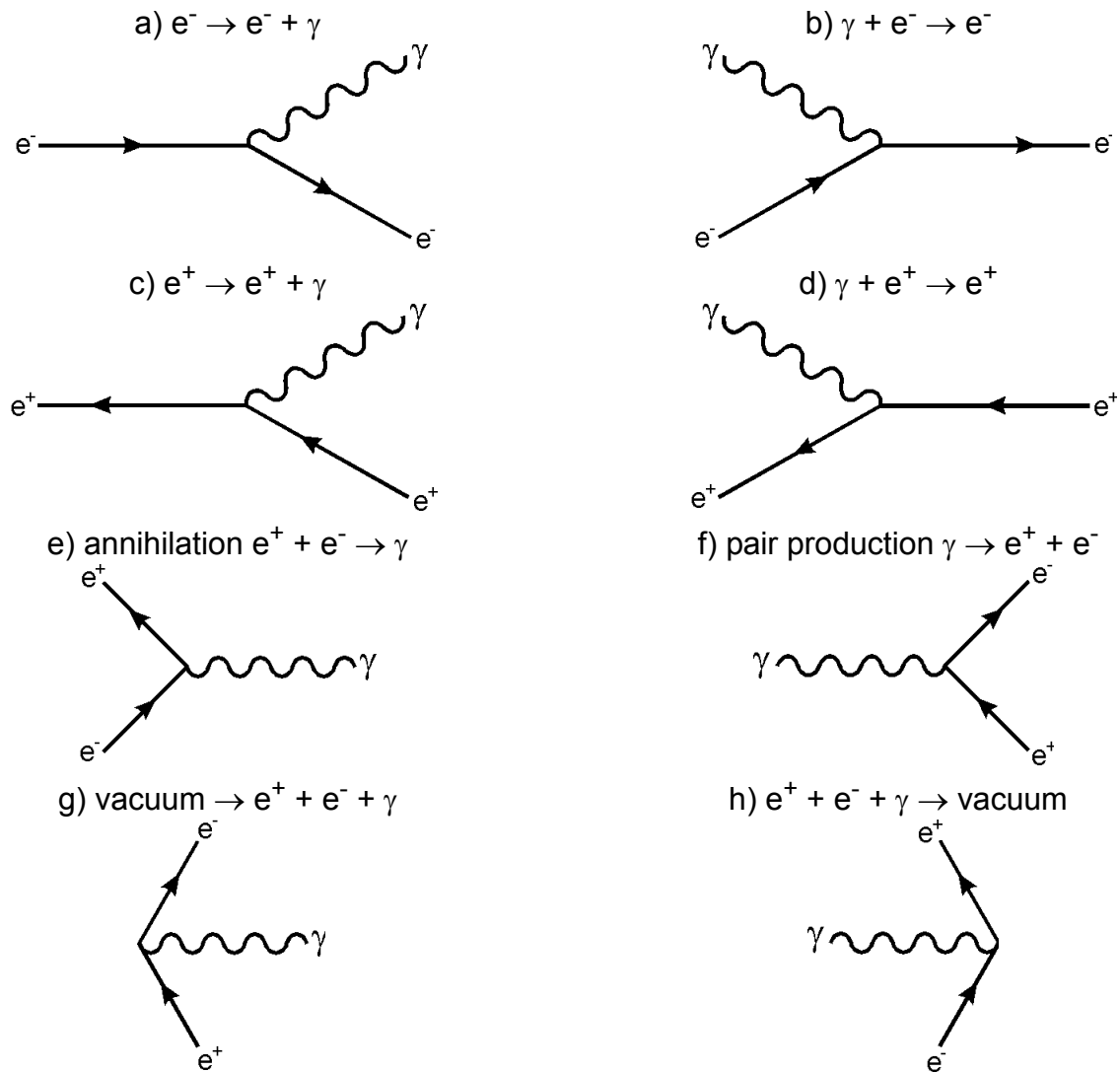


Figure 5: Feynman diagrams for **VIRTUAL** processes involving e^+ , e^- and γ

⌘ A virtual process does not require energy conservation

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

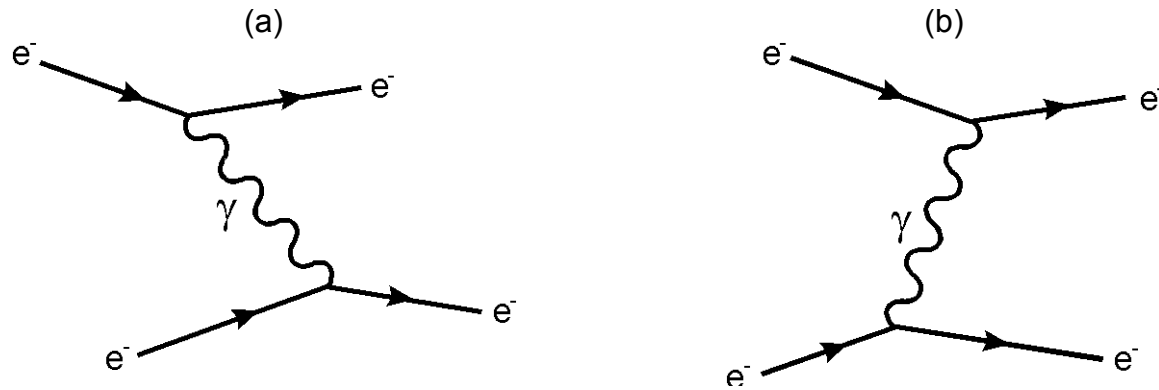


Figure 6: Electron-electron scattering, single photon exchange

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

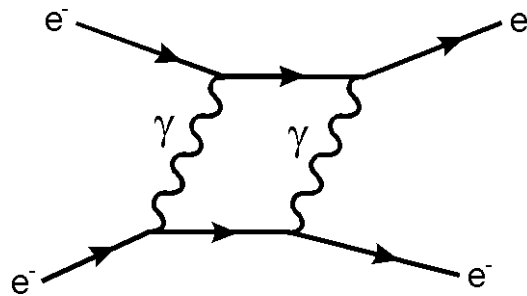


Figure 7: Two-photon exchange contribution

❖ Probability $P(e^-e^- \rightarrow e^-e^-) = |M(1 \gamma \text{ exchange}) + M(2 \gamma \text{ exchange}) + M(3 \gamma \text{ exchange}) + \dots|^2$ (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

$$\alpha_{em} = \frac{e^2}{4\pi\epsilon_0} \approx \frac{1}{137} \ll 1 \quad (17)$$

⌘ 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: $P(\text{real}) = |M(\alpha)+M(\alpha^2)+M(\alpha^3)\dots|^2$

Often lowest order calculation is precise enough.

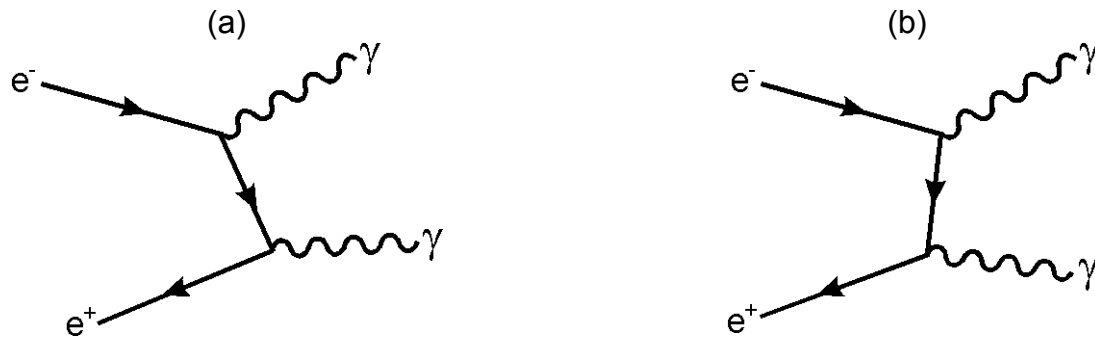


Figure 8: Lowest order contributions to $e^+e^- \rightarrow \gamma\gamma$. $M = \sqrt{\alpha} \cdot \sqrt{\alpha}$, $P=|M|^2=\alpha^2$

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

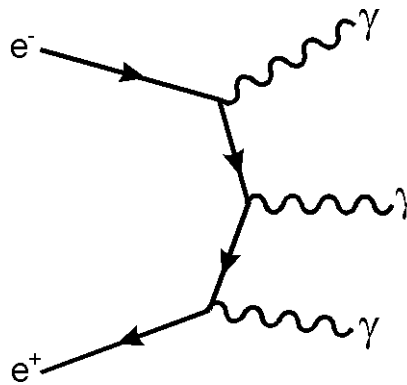


Figure 9: Lowest order of the process $e^+e^- \rightarrow \gamma\gamma\gamma$. $M = \sqrt{\alpha} \cdot \sqrt{\alpha} \cdot \sqrt{\alpha}$, $P=|M|^2=\alpha^3$

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:

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

This ratio can be measured experimentally; it appears to be $R = 0.9 \times 10^{-3}$, which is smaller than α_{em} , being only a first order prediction.

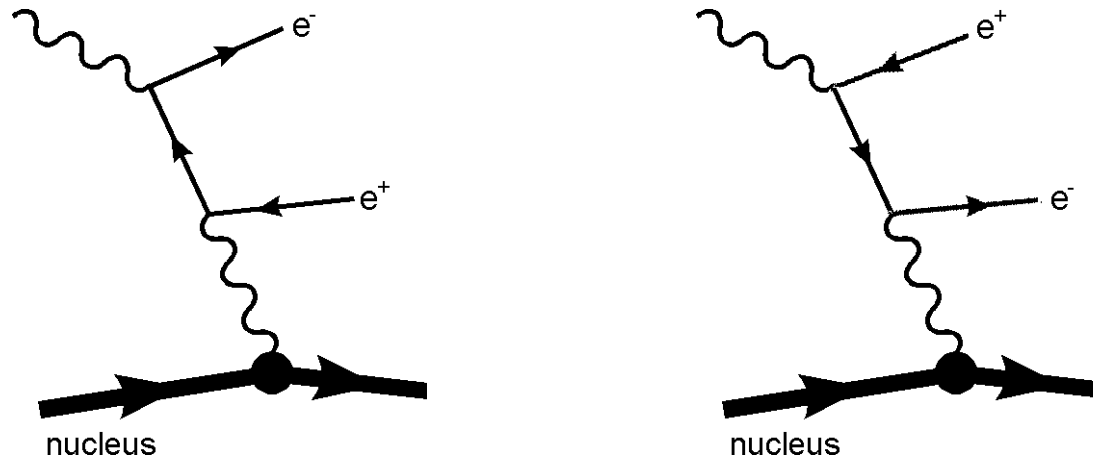


Figure 10: Diagrams that are **not** related by time ordering

⌘ 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

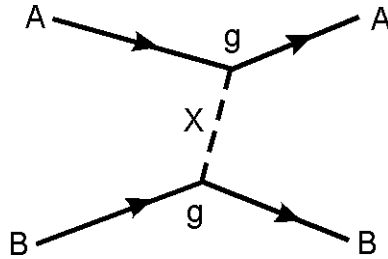


Figure 11: Exchange of a massive particle X

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*:

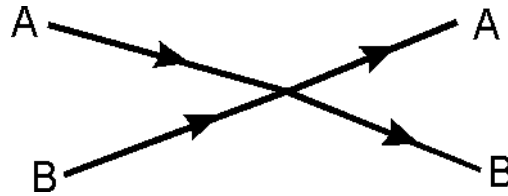


Figure 12: Point interaction as a result of $M_x \rightarrow \infty$

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

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:

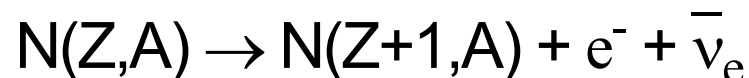
$$\begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix}, \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}, \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$$

- ❖ Neutrinos and antineutrinos differ by the *lepton number*. Leptons possess lepton numbers $L_\alpha = 1$ (α stands for e, μ or τ), and antileptons have $L_\alpha = -1$

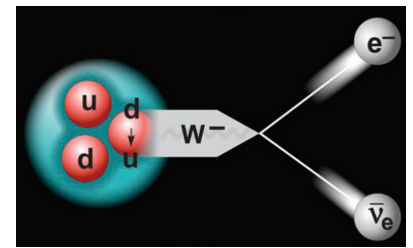
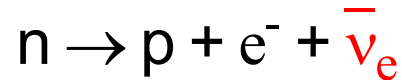
- ❖ *Lepton numbers are conserved in all interactions!*

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:



β -decay is simply one of the neutrons decaying:



⌘ 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 antineutrino!

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:



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

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



or

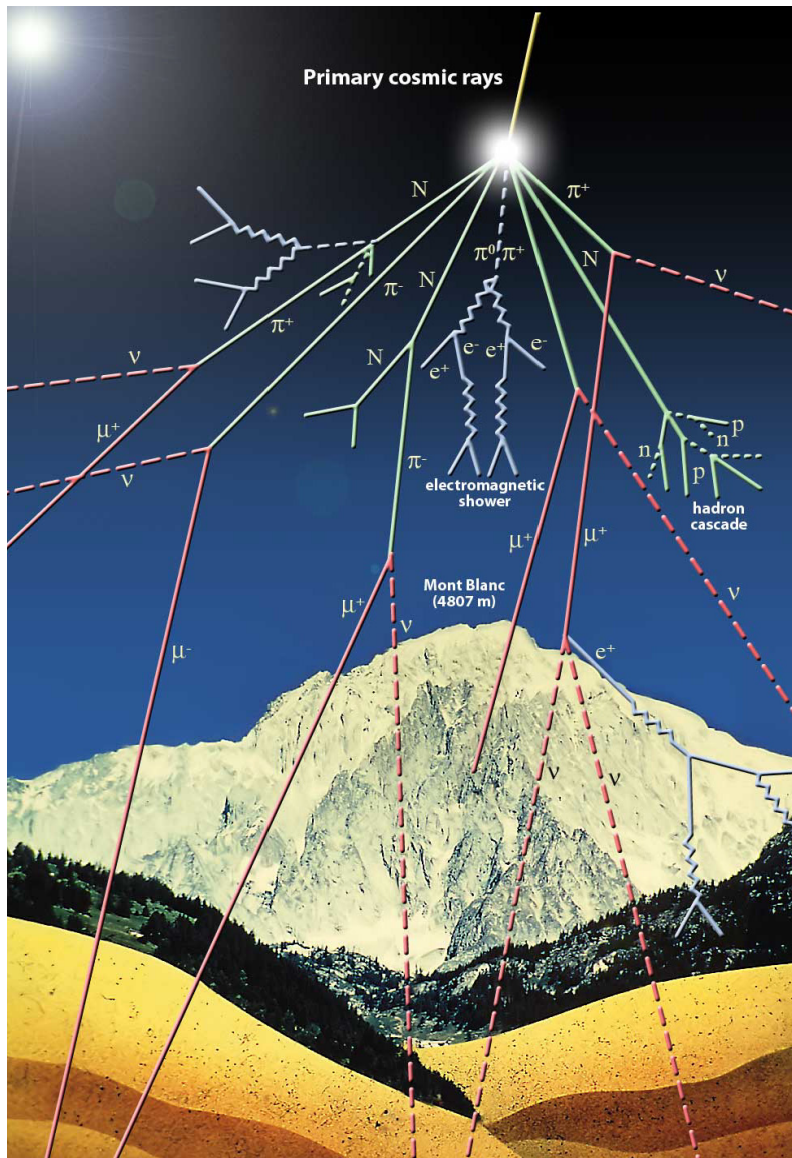


Probabilities of these processes is very low, therefore to register any, one needs a very intense flux of neutrinos. Nevertheless, this was the process used for neutrino discovery (1956)

❖ **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

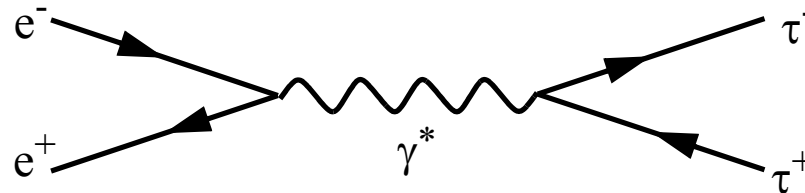


Figure 14: τ pair production in e^+e^- annihilation

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

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

Muon decays in a purely leptonic mode:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{20}$$

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

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

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

- ❖ **Note: lepton numbers are conserved in all reactions ever observed**
- ❖ Fraction of a given decay mode with respect to all possible decays is called *branching ratio*, denoted by B
- ❖ *Decay rate*: $\Gamma = B/\tau$, 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 final state lepton masses for many basic calculations

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

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

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 only decaying particle mass enters (23), decay rates are equal 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:

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

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

Since muons have basically only one decay mode, $\mathbf{B=1}$ in their case. Using experimental values of B and formula (23), one obtains the ratio of muon and tau lifetimes:

$$\frac{\tau_{\tau}}{\tau_{\mu}} \approx 0.178 \cdot \left(\frac{m_{\mu}}{m_{\tau}} \right)^5 \approx 1.3 \times 10^{-7}$$

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 all 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” led 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:

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

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
Y	9.460	$b\bar{b}$	0	0	0	0

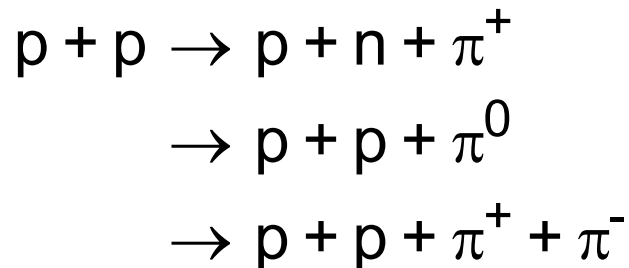
- ⌘ Majority of hadrons are unstable and tend to decay by the strong interaction to the state with the lowest possible mass (lifetime about 10^{-23} s)
- ⌘ Hadrons with the lowest possible mass for each quark number (S, C, etc.) may live significantly longer before decaying weakly (lifetimes 10^{-7} - 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 $0.140 \text{ GeV}/c^2$, and neutral ones π^0 , mass $0.135 \text{ GeV}/c^2$
- ❖ 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:



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

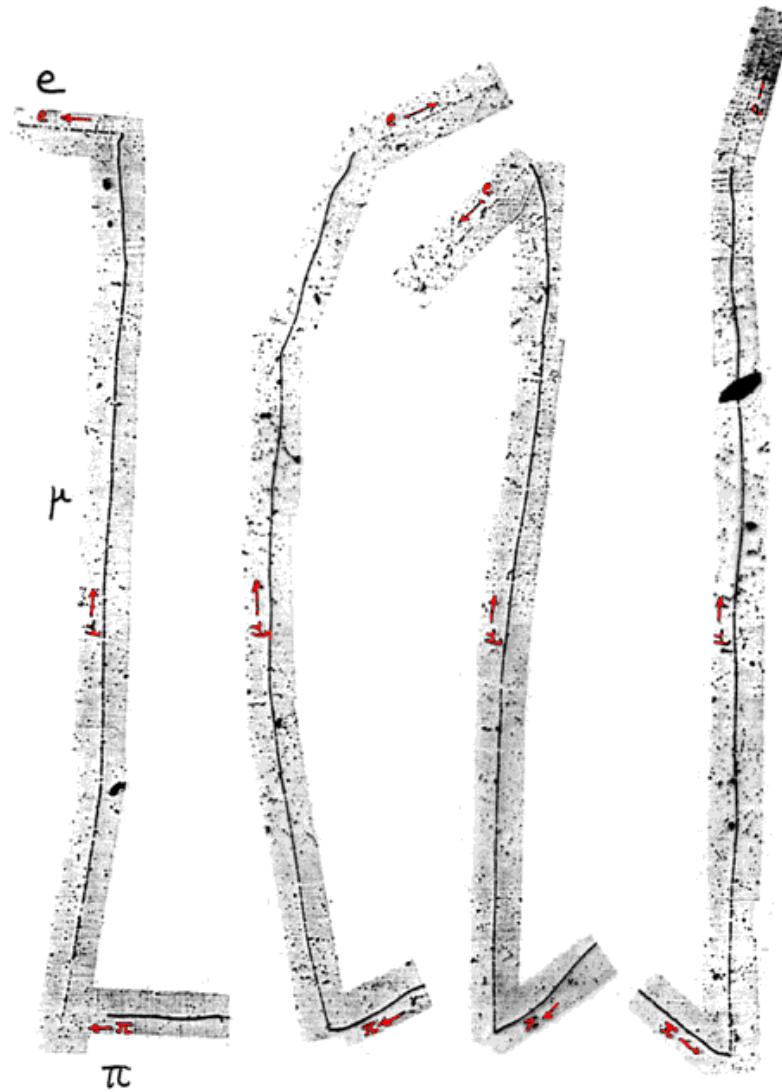


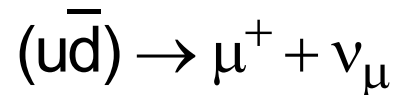
Figure 15: First observed pions: a π^+ stops in the emulsion and decays to a μ^+ and ν_μ , followed by the decay of μ^+ . In emulsions, pions were identified by much more dense ionization along the track, as compared to electron tracks.

Figure 15: examples of the reaction



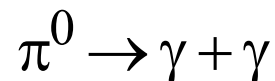
where the pion comes to rest, producing muons which in turn decay by the reaction $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

❖ 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:



⌘ 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:



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 , \bar{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:

$$K^+ \rightarrow \mu^+ + \nu_\mu \quad (B=0.64)$$

$$K^+ \rightarrow \pi^+ + \pi^0 \quad (B=0.21)$$

$$\Lambda \rightarrow \pi^- + p \quad (B=0.64)$$

$$\Lambda \rightarrow \pi^0 + n \quad (B=0.36)$$

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.

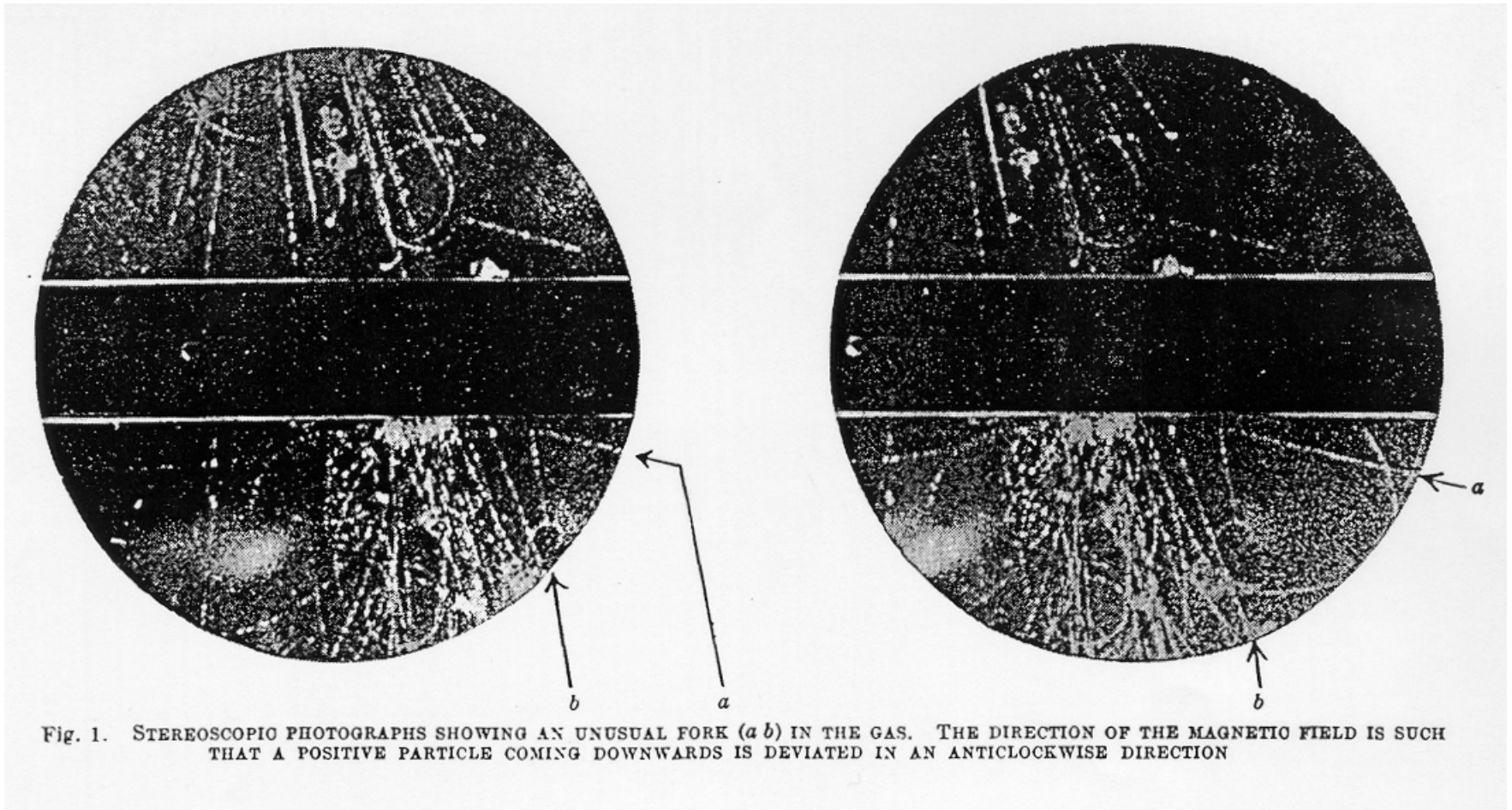


Fig. 1. STEREOCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

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

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

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



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

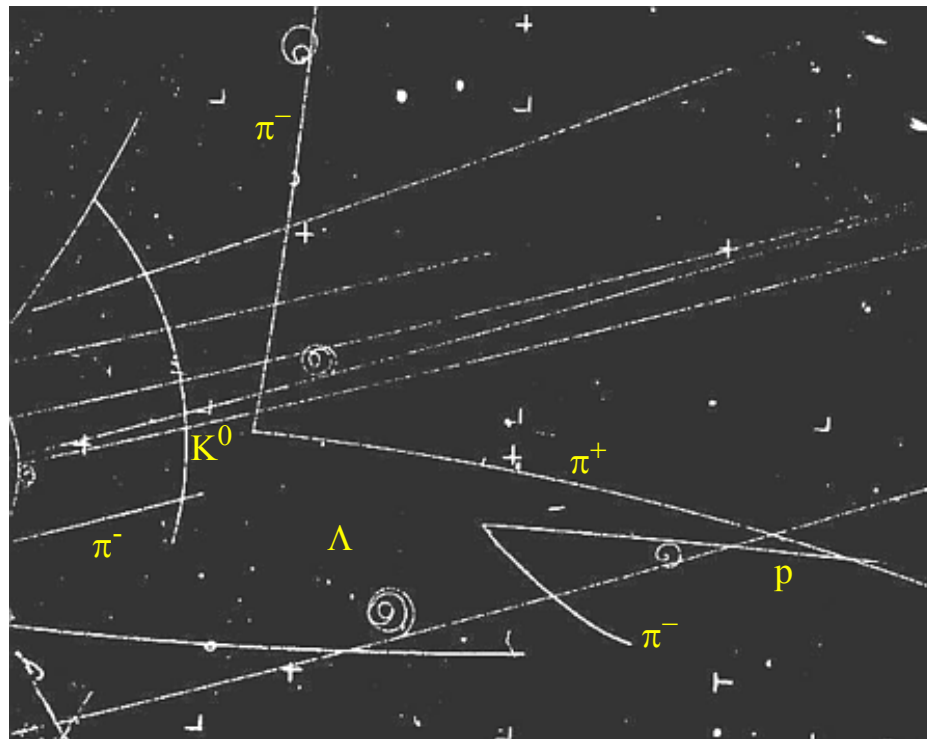


Figure 17: A bubble chamber picture of the reaction (26)

- 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 \Rightarrow pressure drops \Rightarrow 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:

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

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:

$$\begin{aligned} Y(9460) &= b\bar{b} \\ B^+(5279) &= u\bar{b}, B^0(5279) = d\bar{b} \\ B^-(5279) &= b\bar{u}, \bar{B}^0(5279) = b\bar{d} \end{aligned}$$

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

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