# Modern Experimental Particle Physics

*Oxana Smirnova*
*2011, Spring Semester*

*Division of Experimental High Energy Physics*
*Lund University*
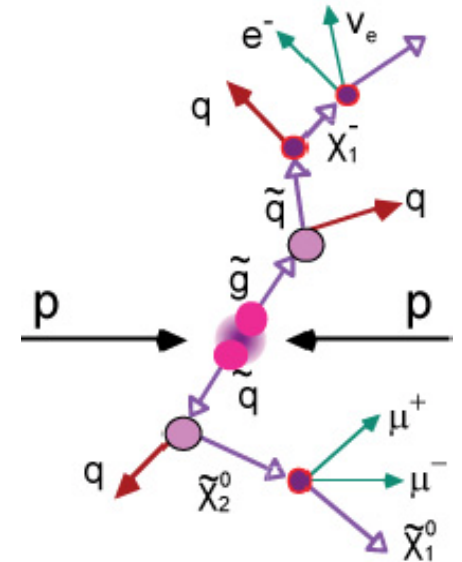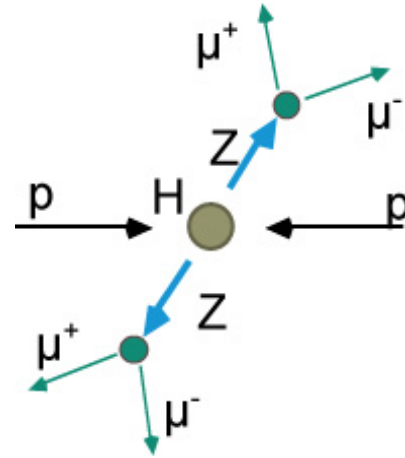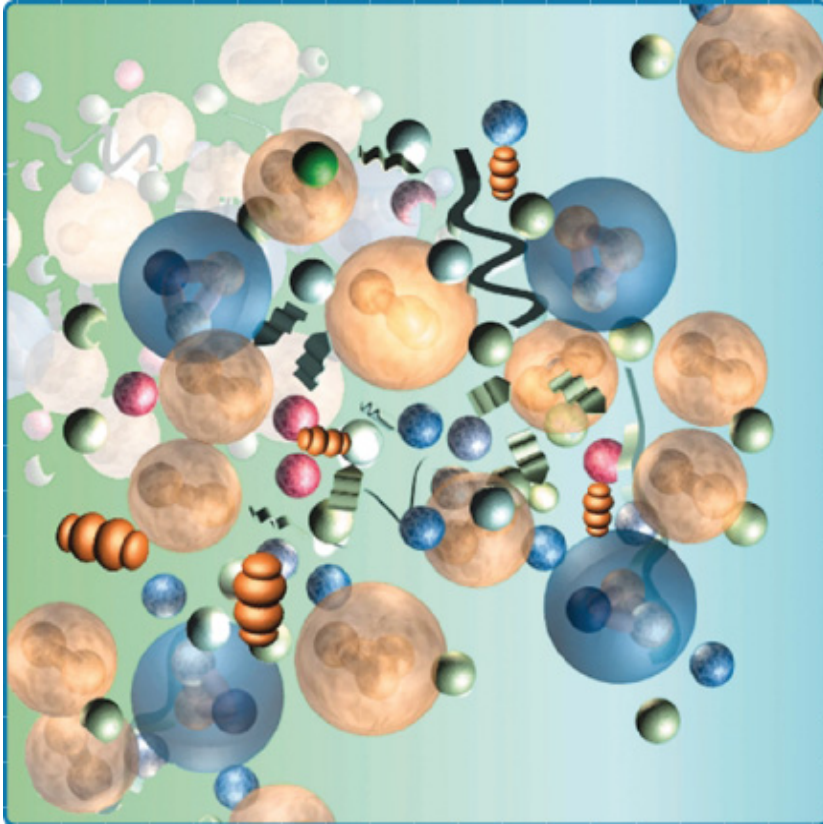
# I. Basic concepts, leptons, quarks and hadrons

❖ 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*:

$$1 \text{ eV} \approx 1.602 \times 10^{-19} \text{ J} \tag{1}$$

⌘ 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*:

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

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

and the "*conversion constant*" is:

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

❖ For simplicity, *natural units* are used:

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

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*:

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

- ⌘ and *covariant*:

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

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

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

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

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

4-vector product of coordinate and momentum represents particle wavefunction

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

4-momentum squared gives particle's invariant mass

For relativistic particles, we can see that

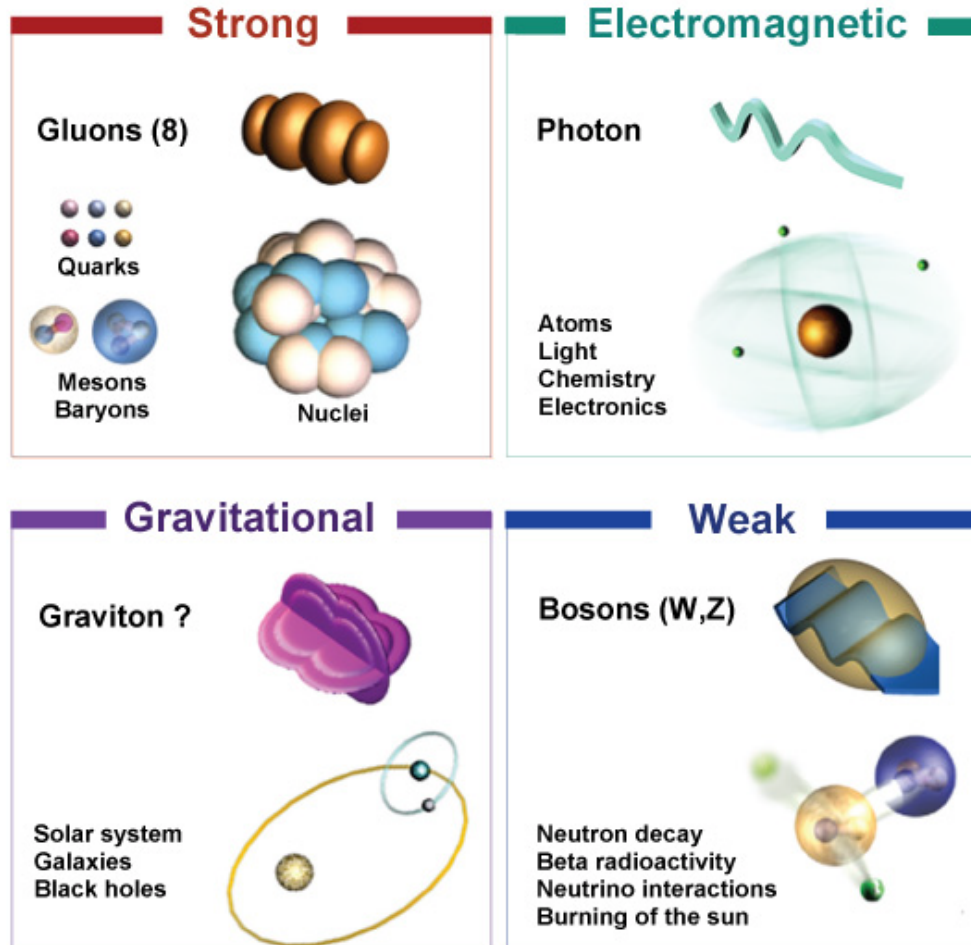$$E^2 = p^2 + m^2 \quad (c=1) \tag{11}$$

# *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<br>*Mass/E-p tensor* | graviton G<br>*(has not yet been observed)* | long<br>$F \propto 1/r^2$ | $\sim 10^{-39}$ | Solar system | Object falling |
| **Weak force** | fermions<br>*hypercharge* | bosons $W^+, W^-$<br>and Z | $< 10^{-17}$ m | $10^{-5}$ | None | $\beta$-decay |
| **Electro-magnetism** | charged particles<br>*electric charge* | photon $\gamma$ | long<br>$F \propto 1/r^2$ | $1/137$ | Atoms, molecules | Chemical reactions |
| **Strong force** | quarks and gluons<br>*colour charge* | gluons g<br>(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*
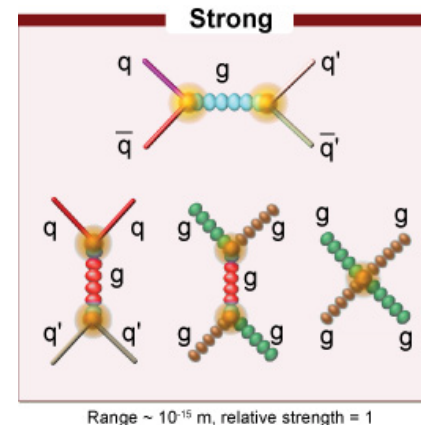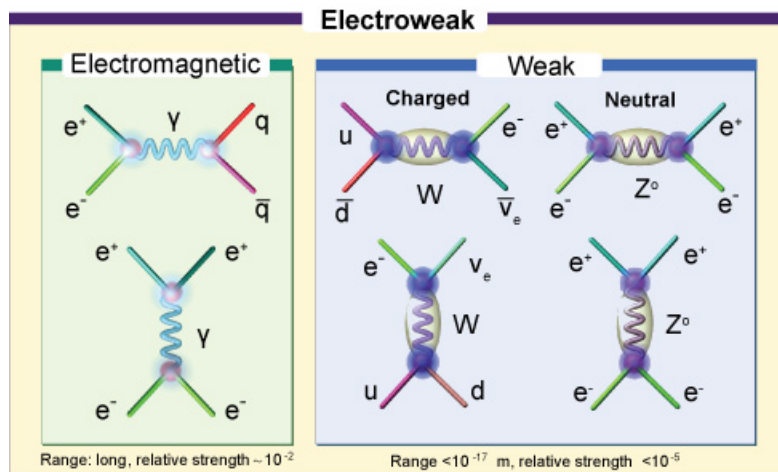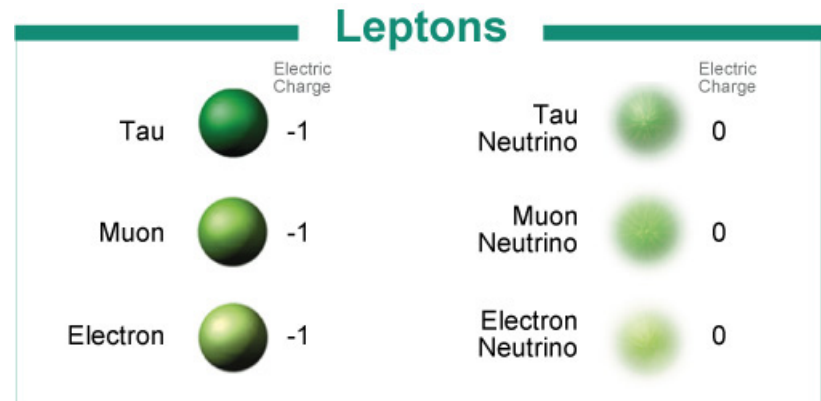
Figure 2:   Standard Model: quarks, leptons and bosons

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

# Antiparticles

❖ Particles are described by wavefunctions:

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

$\vec{x}$ 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, $E^2=p^2+m^2$ (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 $\alpha_i$ and $\beta$ are 4×4 matrices, and $\Psi$ 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 $\alpha_i$ and $\beta$:

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

Here $I$ is a 2×2 unit matrix, 0 is a 2×2 matrix of zeros, and $\sigma_i$ 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*:

$$\alpha_i = \begin{pmatrix} -\sigma_i & 0 \\ 0 & \sigma_i \end{pmatrix} \qquad \beta = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$
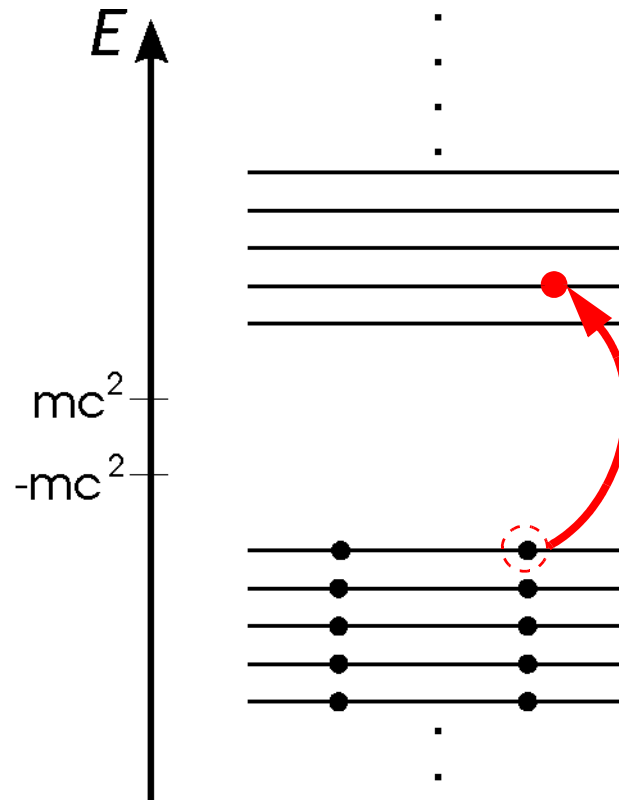
# Dirac's picture of vacuum



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.
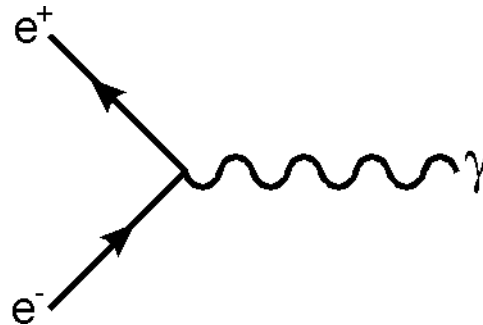


Figure 4:   A Feynman diagram example: e+e- -> $\gamma$

## 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)

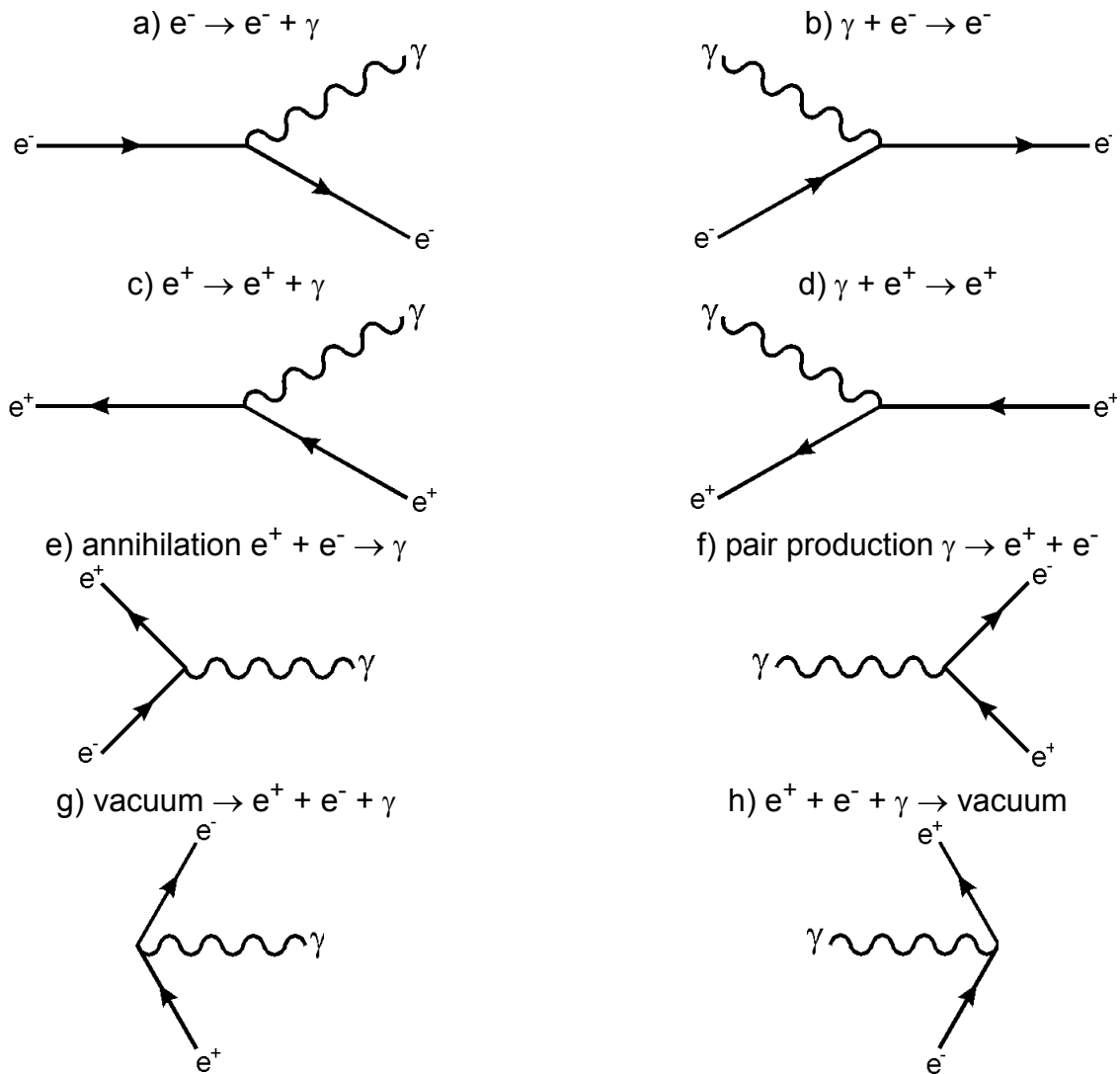⌘ Particles are shown by solid lines, gauge bosons - by helices or dashed lines

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

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

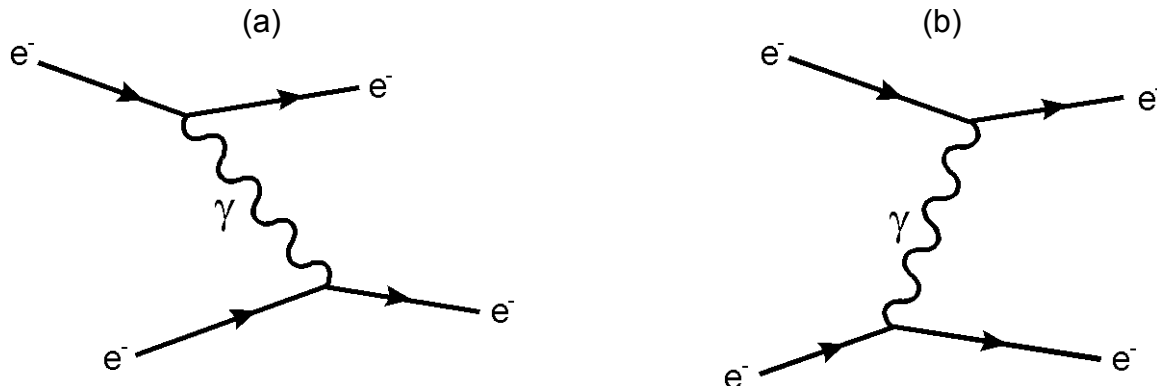❖ A real process demands energy conservation, is a combination of virtual processes:



Figure 6:   Electron-electron scattering, single photon exchange

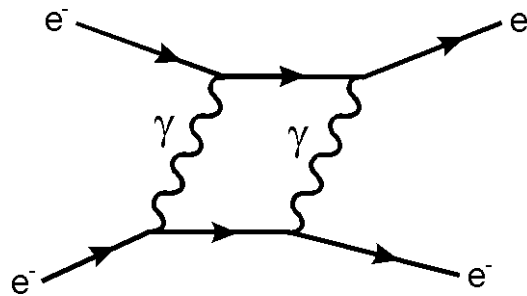❖ Any real process receives contributions from *all the possible* virtual processes:



Figure 7:   Two-photon exchange contribution

❖ Probability $P(e^-e^- \rightarrow e^-e^-) = |M(1\,\gamma$ exchange) $+ M(2\,\gamma$ exchange) $+ M(3\,\gamma$ exchange) $+... |^2$ *(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 "$\alpha$". In discussed processes this constant is

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

⌘ 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 $\alpha^n$.

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

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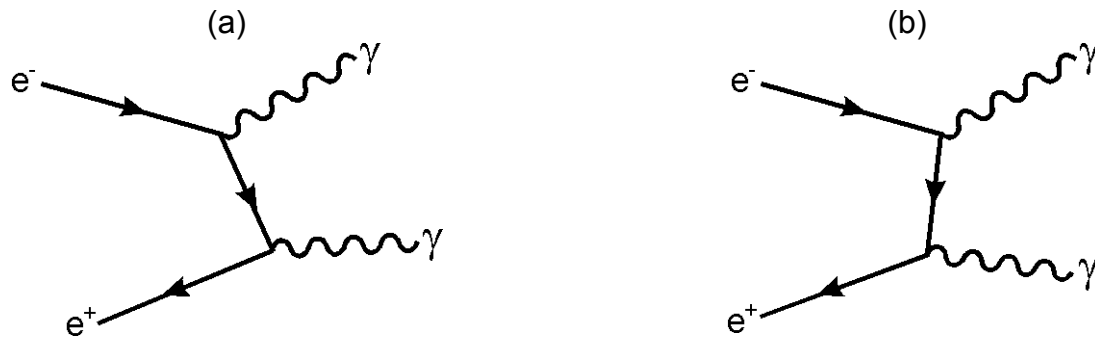
Figure 8:  Lowest order contributions to $e^+e^- \rightarrow \gamma\gamma$. $M = \sqrt{\alpha} \cdot \sqrt{\alpha}$ , $P = |M|^2 = \alpha^2$

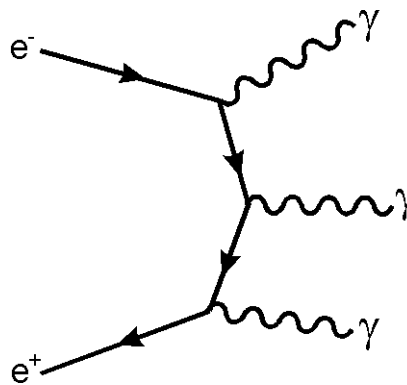⌘ Diagrams which differ only by time-ordering are usually implied by drawing only one of them



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:

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

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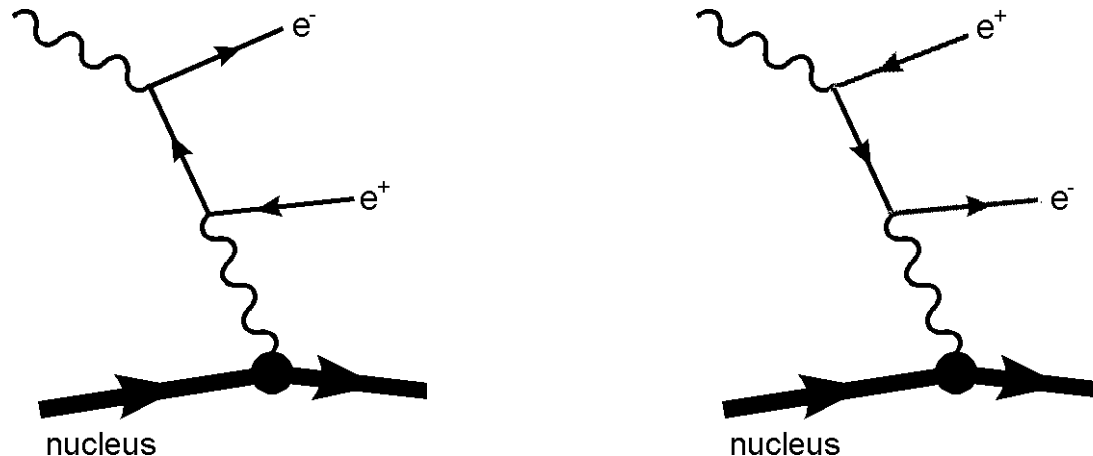


Figure 10:   Diagrams that are **not** related by time ordering

⌘ 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*
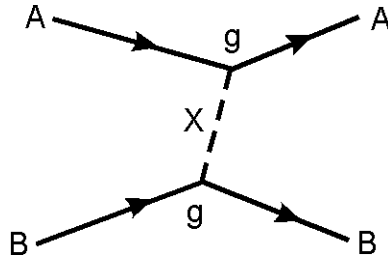


Figure 11: Exchange of a massive particle X

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*:
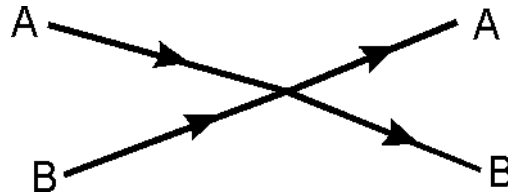


Figure 12:   Point interaction as a result of $M_x \to \infty$

E.g., for a W boson: $R_W = \hbar/M_W = \hbar/(80.4\ \text{GeV}/c^2) \approx 2 \times 10^{-18}$ 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 $\mu^-$ and tau-lepton $\tau^-$ have corresponding neutrinos $\nu_e$, $\nu_\mu$ and $\nu_\tau$

⌘ 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 $\mu^+$, positive tau-lepton $\tau^+$, and antineutrinos:

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

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

❖ *Lepton numbers are <u>conserved</u> in <u>all</u> 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 $\beta$-decays of nuclei, N:

$$N(Z,A) \rightarrow N(Z+1,A) + e^- + \overline{\nu}_e$$
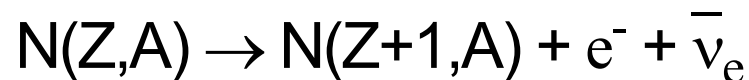
β-decay is simply one of the neutrons decaying:

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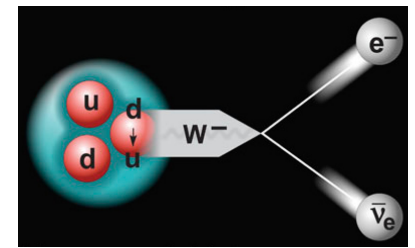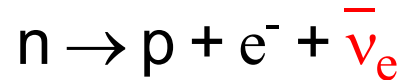


⌘ Experimentally, only proton and electron can be observed, and a fraction of energy and angular momentum is "missing".

❖ 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:

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

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

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

$$\nu_e + n \rightarrow e^- + p \tag{18}$$

or

$$\overline{\nu}_e + p \rightarrow e^+ + n \tag{19}$$

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

Figure 13:   Schematic representation of cosmic rays
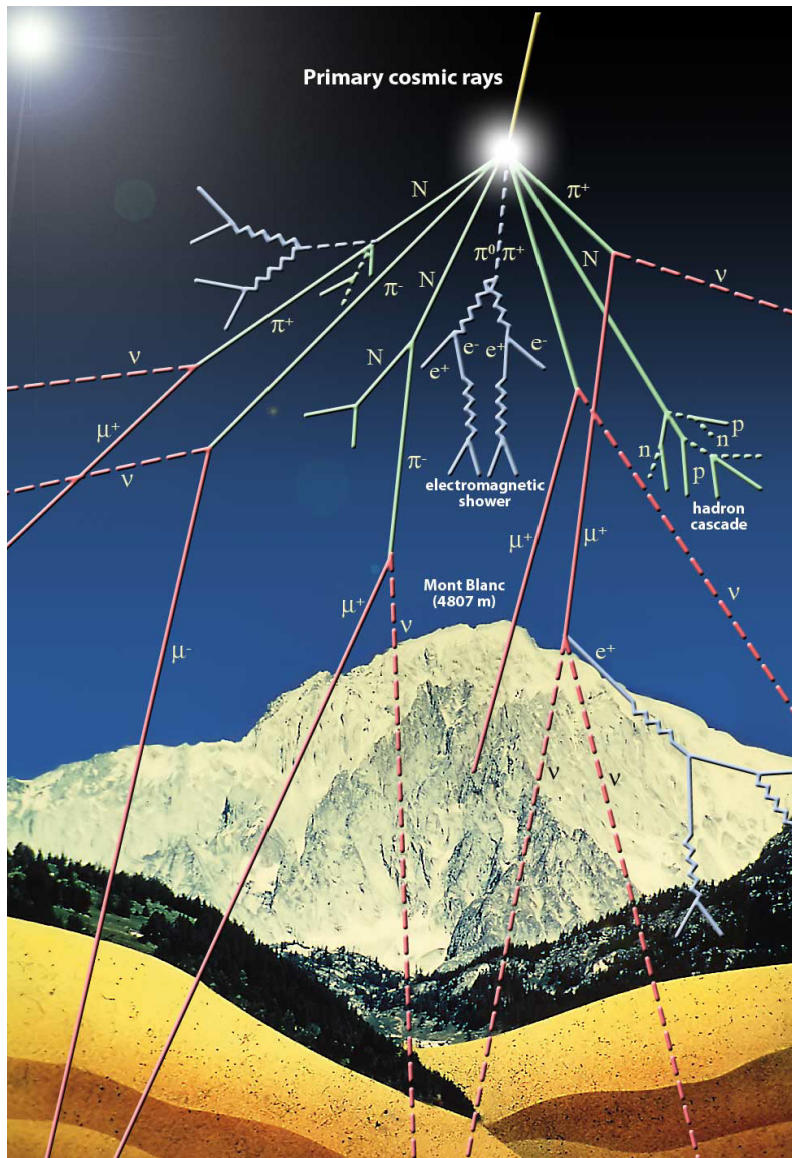
❖ Muons are readily observed in *cosmic rays*

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

⌘ 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
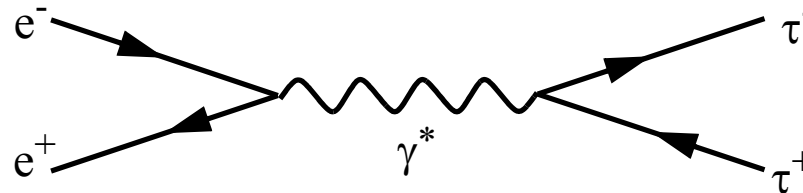


Figure 14:  $\tau$ pair production in $e^+e^-$ annihilation

❖ Electron is a stable particle, while $\mu$ and $\tau$ 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:

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

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

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

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

❖ Note: lepton numbers are conserved in **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 $\tau$ 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 $\Gamma$ of a muon is given by the expression:

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

where $G_F$ is the *Fermi constant* and $m_\mu$ is muon mass.

Substituting $m_\mu$ with $m_\tau$ 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:

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

Here $l$ indicates any other lepton, stands for either $\mu$ or $\tau$ .

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:

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

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 <u>all</u> interactions. Quarks have fractional electric charges.

<span style="color:crimson">Quarks and their bound states are the only particles which interact strongly (via strong force).</span>

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 <u>flavour</u> 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 |
| $\Lambda$ | 1.116 | uds | 0 | -1 | 0 | 0 |
| $\Lambda_c$ | 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 | $\tilde{B}$ |
|---|---|---|---|---|---|---|
| $\pi^+$ | 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 $\pi$ ("pi-mesons"). There are charged pions $\pi^+$, $\pi^-$ with mass of 0.140 GeV/c$^2$, and neutral ones $\pi^0$, 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

<p style="text-align:center;">Some reactions induced by cosmic rays primaries:</p>

$$p + p \rightarrow p + n + \pi^+$$
$$\rightarrow p + p + \pi^0$$
$$\rightarrow p + p + \pi^+ + \pi^-$$
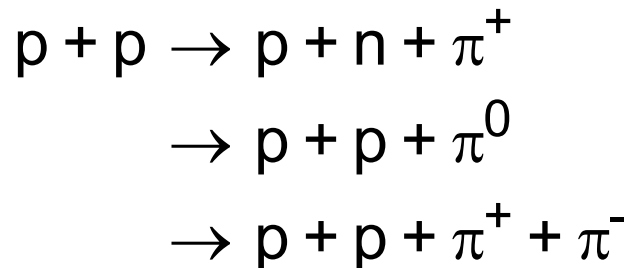
Same reactions can be reproduced in accelerators, with higher rates, although cosmic rays may provide higher energies.

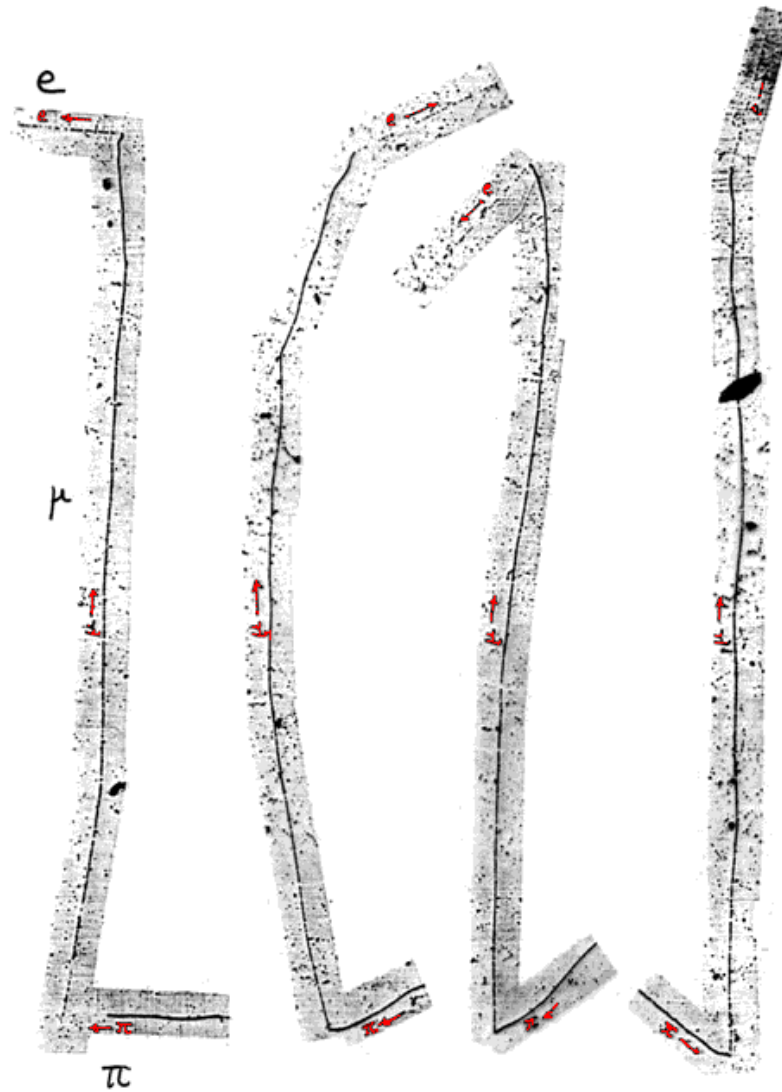Figure 15: First observed pions: a $\pi^+$ stops in the emulsion and decays to a $\mu^+$ and $\nu_\mu$, followed by the decay of $\mu^+$. In emulsions, pions were identified by much more dense ionization along the track, as compared to electron tracks.

Figure 15: examples of the reaction

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

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 $2.6 \times 10^{-8}$ s. In quark terms:

$$(u\bar{d}) \rightarrow \mu^+ + \nu_\mu$$
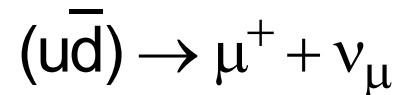
⌘ The decay occurs through weak interaction, hence quark quantum numbers are not conserved. *B* and *L* are conserved

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

$$\pi^0 \rightarrow \gamma + \gamma$$
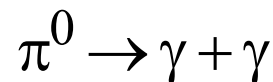
# Strange mesons and baryons

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 $1.2 \times 10^{-8}$ s

⌘ baryon $\Lambda$ , lifetime of $2.6 \times 10^{-10}$ s

Principal decay modes of strange hadrons:

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

The first decay is clearly a weak one. Decays of $\Lambda$ have too long lifetime to be strong: if $\Lambda$ were (udd), the decay *(udd)* $\rightarrow$ *(d$\overline{u}$)* + *(uud)* should have had a lifetime of order $10^{-23}$ s. $\Lambda$ 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
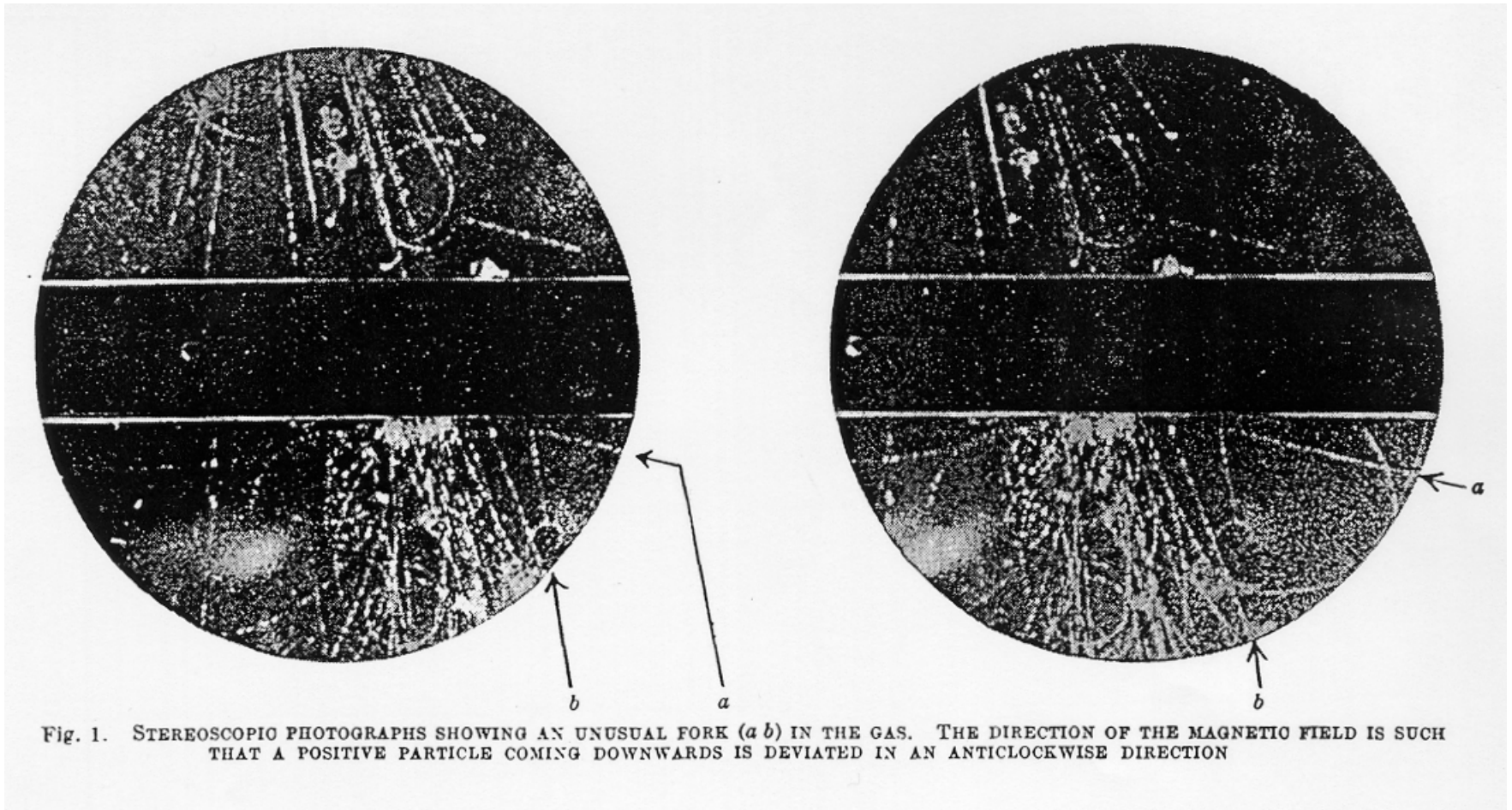
Figure 16:  "Strange" particle discovery (neutral kaon) by Rochester and Butler, 1947

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

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

$$\pi^- + p \rightarrow K^0 + \Lambda \tag{26}$$

In 1952, *bubble chambers* were invented as particle detectors, and also worked as *targets*, providing, in particular, the proton target for reaction (30).
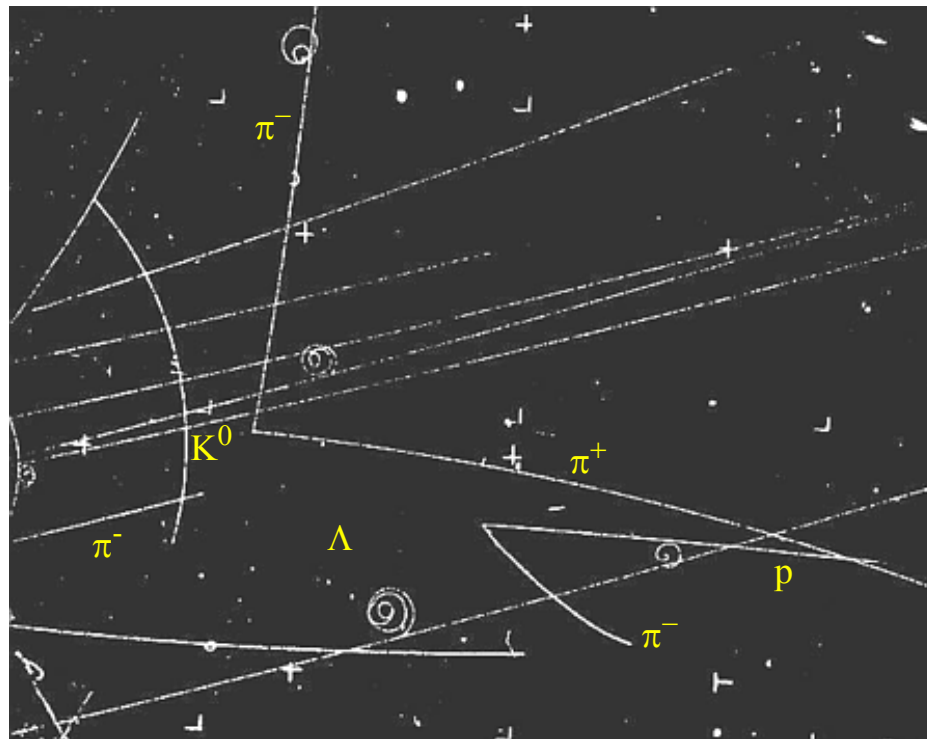
Figure 17:   A bubble chamber picture of the reaction (26)

– 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/$\psi$ (3097), a $c\bar{c}$ meson

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

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

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

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

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

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

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:

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

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

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