PART X

1) Classification of elementary particles.
leptons, hadrons, intermediate bosons.

2) Interactions of leptons.
Electromagnetic and weak interaction.
Reactions

3) Conservation of lepton number.
Neutrino mixing.

4) Light quarks, u, d, s. Barions and mesons.

5) Spin and isospin of quarks.
Isospin vs strangeness diagrams

6) Decays of ρ-mesons, gluons.

7) Quantum numbers of ρ- and π-mesons.

8) Weak interaction of quarks.
Decays of π-mesons.

Elementary particles

1) Leptons
2) hadrons
3) intermediate bosons

1) Leptons: particles that <u>do not</u> interact via strond interaction. They do interact via electromagnetic and weak interaction

3 degeneration of leptons

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

e - electron $\quad m_e = 0.51\, MeV$
μ - muon $\quad m_\mu = 105\, MeV$
τ - τ-lepton $\quad m_\tau = 1777\, MeV$

every particle has an antiparticle

e^- - electron $\leftrightarrow$ e^+ positron
ν_e - electron neutrino $\Leftrightarrow$ $\bar{\nu}_e$ - electron antineu
μ^- - muon $\leftrightarrow$ μ^+ - antimuon

. . .

2) hadrons: particles that interact via strong interaction. They also interact via electromagnetic and weak interaction.

p - proton
n - neutron
Λ - Λ-giperon
Δ - Δ-isobar
Ω - Ω-giperon
. . .

} **Barions.** $\Longleftrightarrow$ have nonzero barion number

$\pi^0, \pi^\pm$ - π-mesons
$\rho^0, \rho^\pm$ - ρ-mesons
ω - ω-meson
. . . .

} **Mesons** $\Longleftrightarrow$ have **zero** barion number

hadron consist of quarks

3 generation of quarks

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

3) Intermediate bosons

γ - photon: mediator of electromagnetic interaction

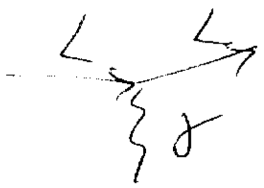
Z - boson
$W^{\pm}$ boson } mediators of weak interaction

g - gluon. there are 8 gluons. mediators of strong interaction

$$\begin{cases} m_\gamma = 0 \\ m_Z = 91.2 \text{ GeV} \\ m_W = 80.4 \text{ GeV} \\ m_g = 0 \end{cases}$$

Interactions of leptons

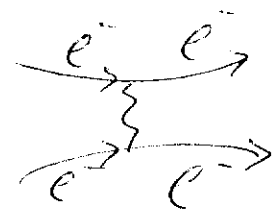
Electromagnetic



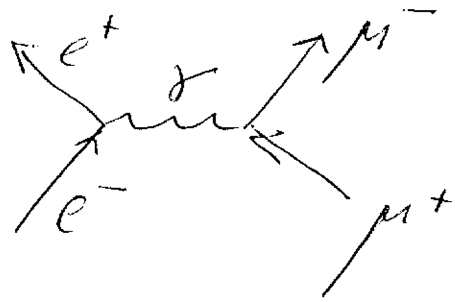
– γ-vertex, $L = e, \mu, \tau$

examples:

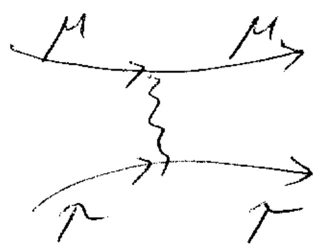
a) ee scattering



b) $e^+e^- \to \mu^+\mu^-$

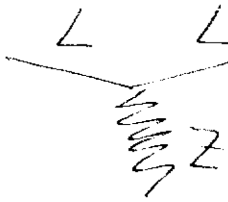


c) $\mu\tau$ scattering



neutrinos (ν) have no electric charge, hence they do not interact electromagnetically.

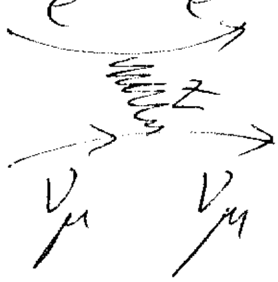
Weak interaction of leptons



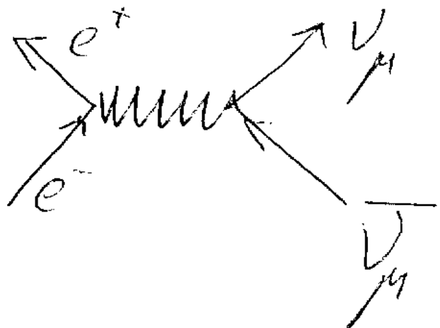
Z - boson vertex, $L = e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$

examples

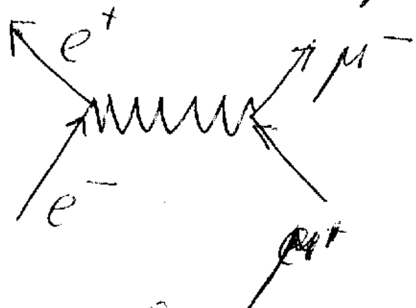
a) $e \nu_\mu$ - scattering



b) $e^+ e^- \to \nu_\mu \bar{\nu}_\mu$

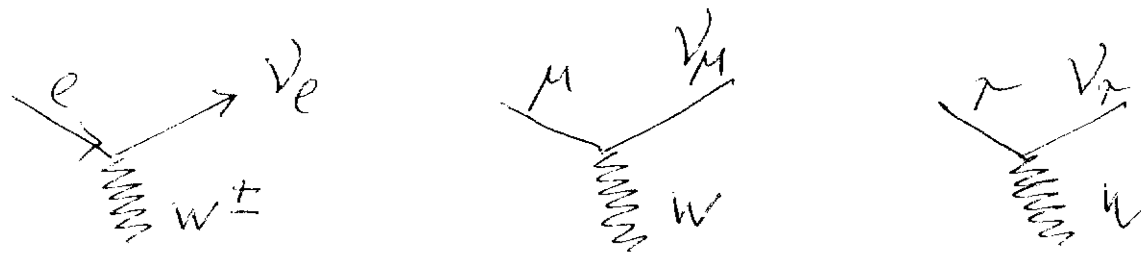


c) $e^+ e^- \to \mu^+ \mu^-$



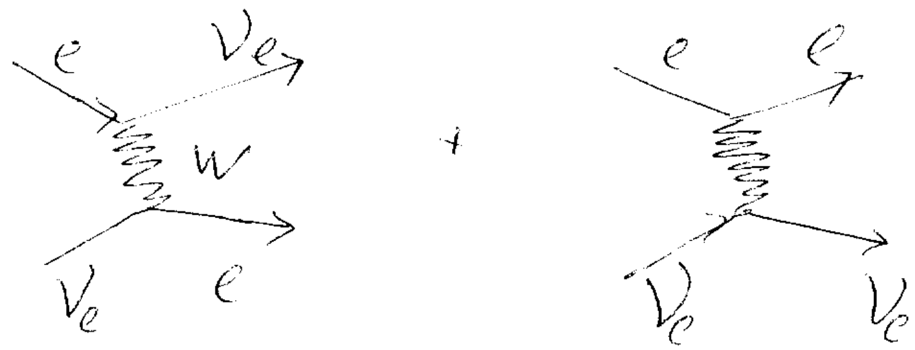
there is also an electromagnetic diagram for this reaction, see page 150.

W-boson vertex

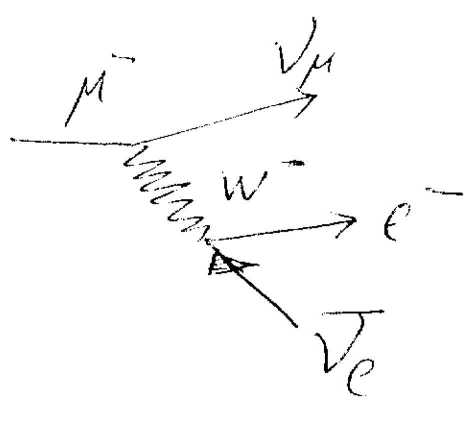


examples

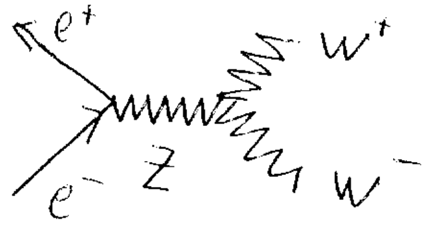
a) $e\nu_e$-scattering

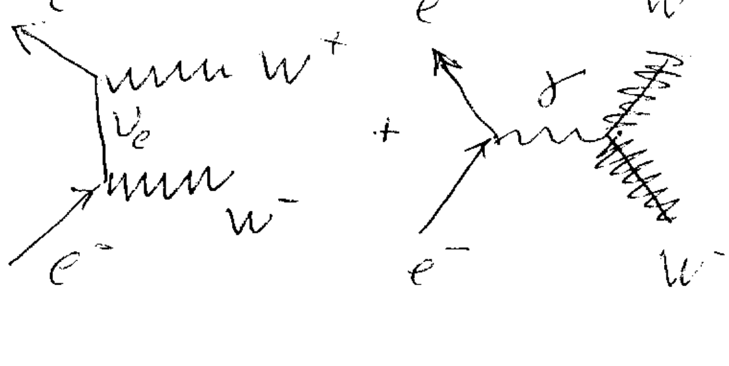


b) μ-decay: $\mu^- \to e^- \bar{\nu}_e \nu_\mu$



c) $e^+e^- \to W^+W^-$:





conservation of the lepton number

$e^-, \nu_e : L_e = +1, \quad e^+ \bar{\nu}_e : L_e = -1$

$\mu^-, \nu_\mu : L_\mu = +1, \quad \mu^+ \bar{\nu}_\mu : L_\mu = -1$

$\tau^-, \nu_\tau : L_\tau = +1, \quad \tau^+, \nu_\tau : L_\tau = -1$

L_e, L_μ, L_τ are conserved

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neutrino mixing.

$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$

$\xrightarrow{\nu_e} \circ \xrightarrow{\nu_\mu}$ observed?

$\xrightarrow{\nu_\mu} \bullet \xrightarrow{\nu_\tau}$ observed?

If neutrino mixing takes place than only $L_e + L_\mu + L_\tau$ is conserved

quarks

Quarks have been suggested by Gell-Mann and Zweig in 1964. The hadron "zoo" can be explained if we assume that hadrons consist of quarks.

Light quarks

u - "up"

d - "down"

s - strange

Quantum numbers

		u	d	s	$\bar{u}$	$\bar{d}$	$\bar{s}$
electric charge	q	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
strangeness	S	0	0	-1	0	0	1
barion number	B	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$

strangeness just separate strange quark from "up" and "down".

Barion number is conserved in all known reactions.

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proton: $p = (uud)$, $\begin{cases} q = \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1 \\ S = 0 \quad \text{- strangeness} \\ B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1 \end{cases}$

neutron: $n = (udd)$, $\begin{cases} q = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0 \\ S = 0 \quad \text{- strangeness} \\ B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1 \end{cases}$

particles with $B \neq 0$ are called barions.

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hadrons with $B = 0$ are called mesons.

π - mesons: $m_{\pi^+} = m_{\pi^-} = 139.6\ MeV$, $m_{\pi^0} = 135\ MeV$.

$$\begin{cases} \pi^+ = (u\bar{d}), \quad q = \frac{2}{3} + \frac{1}{3} = 1, \quad B = \frac{1}{3} - \frac{1}{3} = 0 \\ \pi^- = (\bar{u}d), \quad q = -\frac{2}{3} - \frac{1}{3} = -1, \quad B = -\frac{1}{3} + \frac{1}{3} = 0 \\ \pi^0 = \frac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d), \quad q = 0, \quad B = 0 \end{cases}$$

ρ-mesons:

$$m_{\rho^+} = m_{\rho^-} \approx m_{\rho^0} = 771\,MeV$$

$$\begin{cases} \rho^+ = (u\bar{d}) \\ \rho^- = (\bar{u}d) \\ \rho^0 = \frac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d) \end{cases}$$

π- and ρ-mesons have the same quark structure. What is difference between π and ρ?

The difference is spin.

Spin of π-mesons is 0: pseudoscalar meson.

Spin of ρ-mesons is 1: vector mesons.

From here we conclude that spin of quark $\boxed{s = 1/2}$

Isospin of quarks.

π- and ρ-mesons are isovector ($T=1$) particles (each has 3 isotopic components). Hence isospin of "up" and "down" quarks is $T = 1/2$.

$\begin{pmatrix} u \\ d \end{pmatrix}$ – isotopic doublet

u: $T_z = 1/2$

d: $T_z = -\frac{1}{2}$

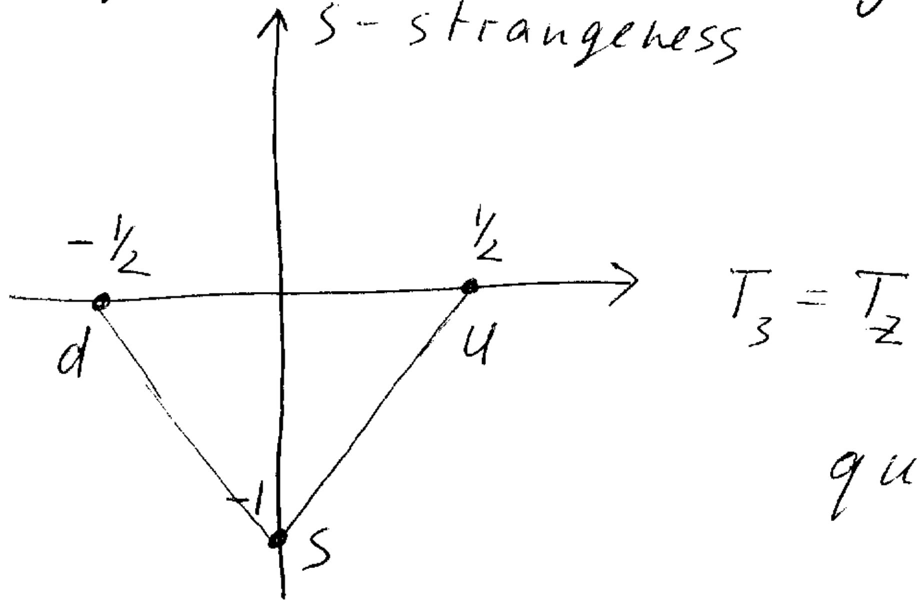
antiquarks:

$\begin{pmatrix} \bar{d} \\ -\bar{u} \end{pmatrix}$ – $T_z = +1/2$, $T_z = -1/2$

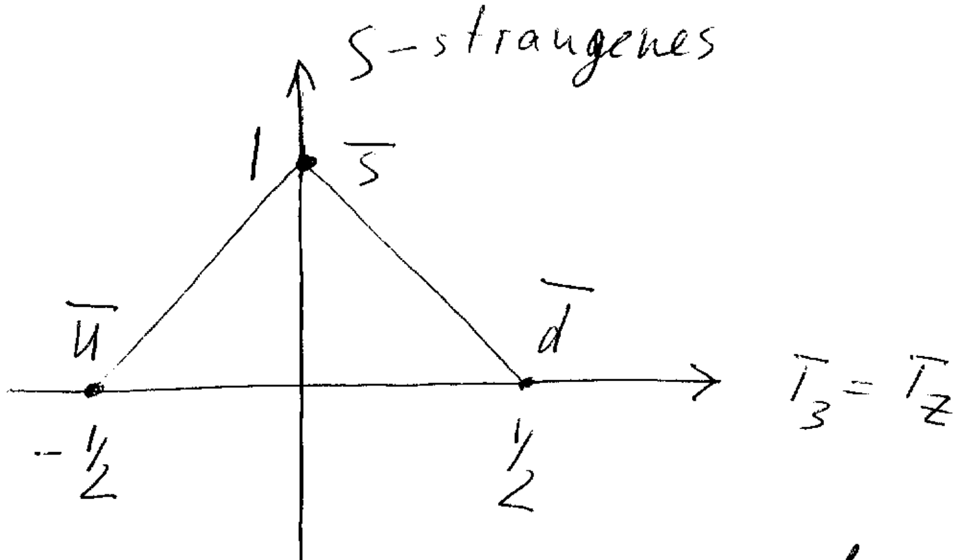
Strange quark has zero isospin

s: $T = 0$

Isospin vs strangeness diagrams.



quarks



antiquarks

Isoscalar vector meson $\Leftrightarrow$ ω-meson

$\omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$, $m_\omega = 782$ MeV.

spin $S = 1$

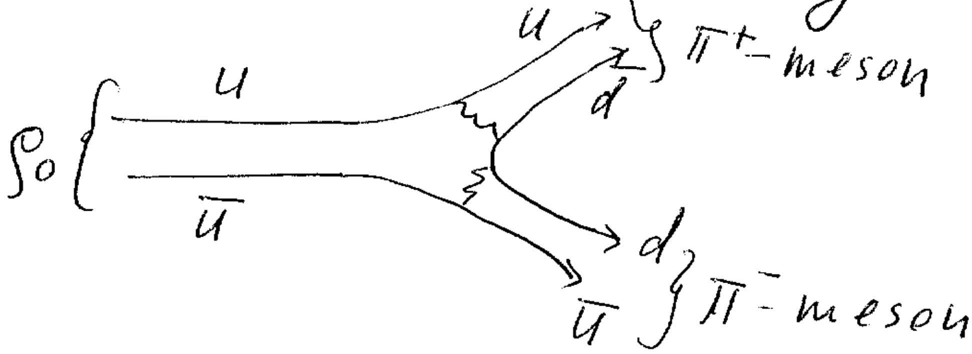
isospin $T = 0$

Vector mesons are unstable with respect to decay via strong interaction mechanism.

$m_\rho > 2 m_\pi \approx 280$ MeV

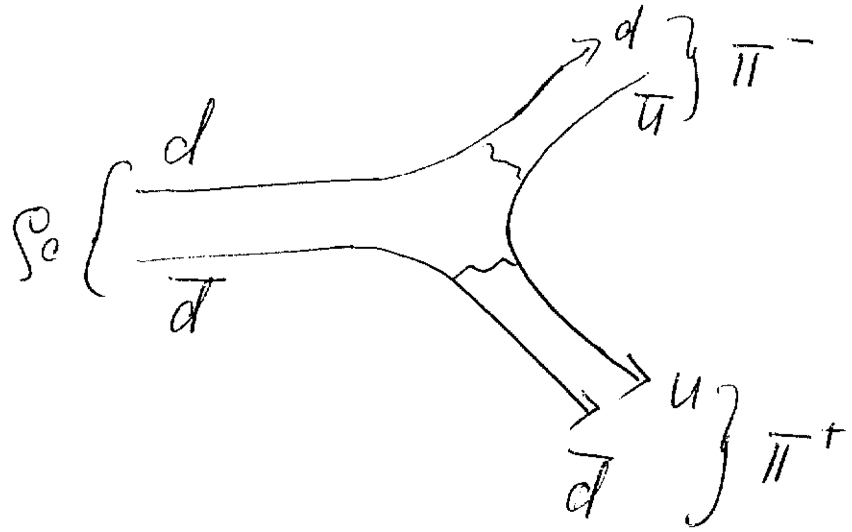
Example: $\rho_0 \rightarrow \pi^+ \pi^-$

Diagrams for the decay



$\sim\!\sim$ = gluon = mediator of strong interactio

Another mechanism for $\rho_0 \to \pi^+\pi^-$ decay



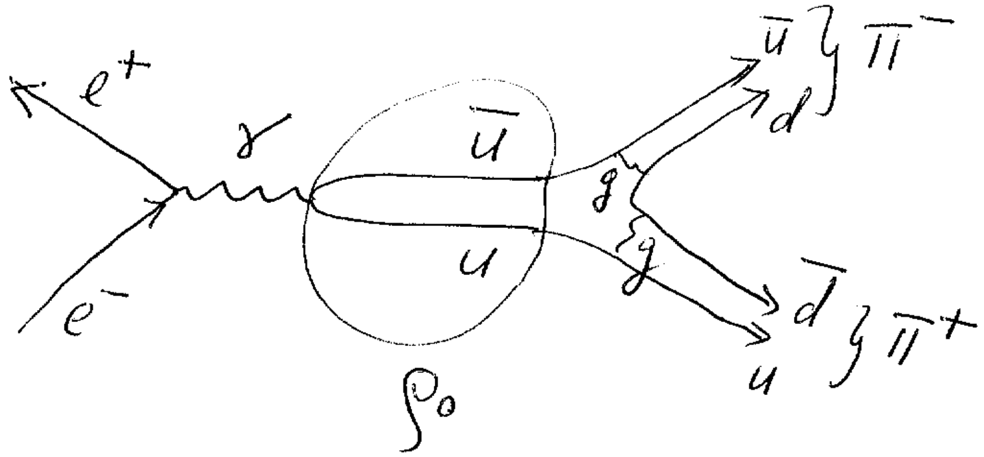
lifetime of ρ_0-meson

$$\tau = 4.3\ 10^{-24}\ \text{sec.}$$

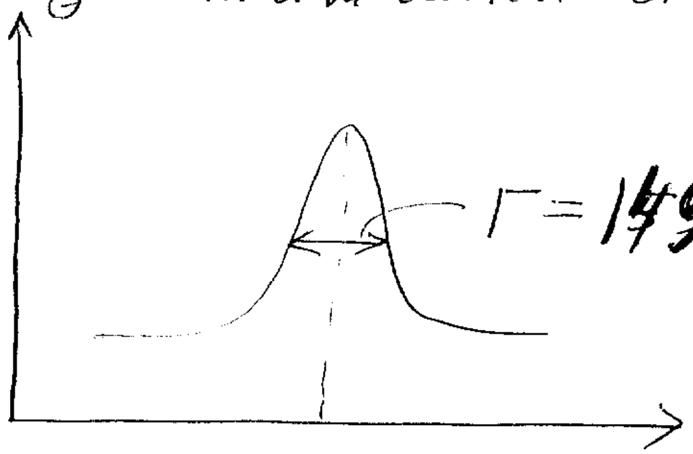
width of ρ_0-meson

$$\Gamma = \frac{\hbar}{\tau} = 149\ \text{MeV}.$$

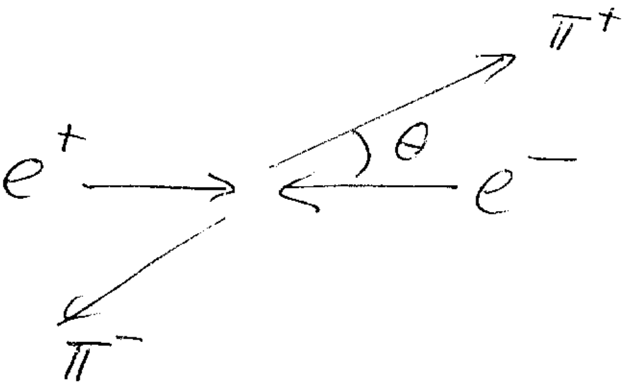
ρ_0-meson can be observed as a resonance in e^+e^--annihilation



σ - annihilation cross section, $e^+e^- \to \pi^+\pi^-$



$m_\rho = 771\,MeV$ — energy $\mathcal{E} = \mathcal{E}_{e^+} + \mathcal{E}_{e^-}$



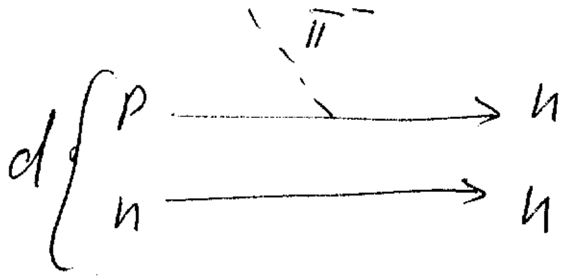
— colliding e^+e^- beams

angular distribution of π-mesons has been measured: $W(\theta) \sim \cos^2\theta$. Hence $\psi \sim \cos\theta \sim Y_{10}(\theta)$ $\Longleftrightarrow$ angular momentum $l = 1$, therefore spin of ρ-meson is 1 and the parity is negative

quantum numbers of ρ-meson $\boxed{J^P = 1^-}$ — vector.

Parity of π-mesons

has been determined from the reaction $\pi^- + d \to n + n$ with very slow pions.



initial π is very slow $\Rightarrow$ reaction goes in s-wave, $l_\pi = 0$

parity of initial state $\boxed{P_i = (-1)^{l_\pi} P_\pi P_d = P_\pi}$

where P_π is internal parity of pion

$P_d = +1$ - parity of deutron ($P_d = 1$ because it is an s-wave boundstate

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angular distribution of final neutrons has been measured: $W(\theta) \sim \cos^2\theta \Rightarrow$
$\Rightarrow \psi \sim \cos\theta \sim Y_{10} \Leftrightarrow l_n = 1$ - relative angular momentum of neutrons.

Hence parity of final state

$\boxed{P_f = (-1)^{l_n} = -1}$

The reaction goes via strong interaction, hence parity is conserved $\boxed{P_i = P_f}$.

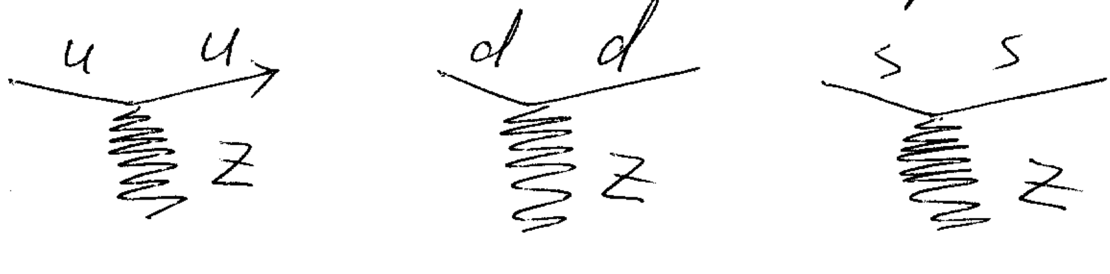
So we conclude that the internal parity of pion is $\boxed{P_\pi = -1}$.

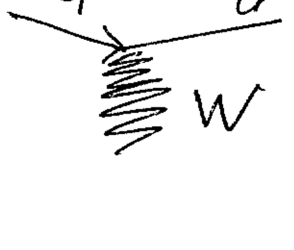
Spin of pion, $s=0$, has been determined in another reaction.

Alltogether this gives that pions are pseudoscalars

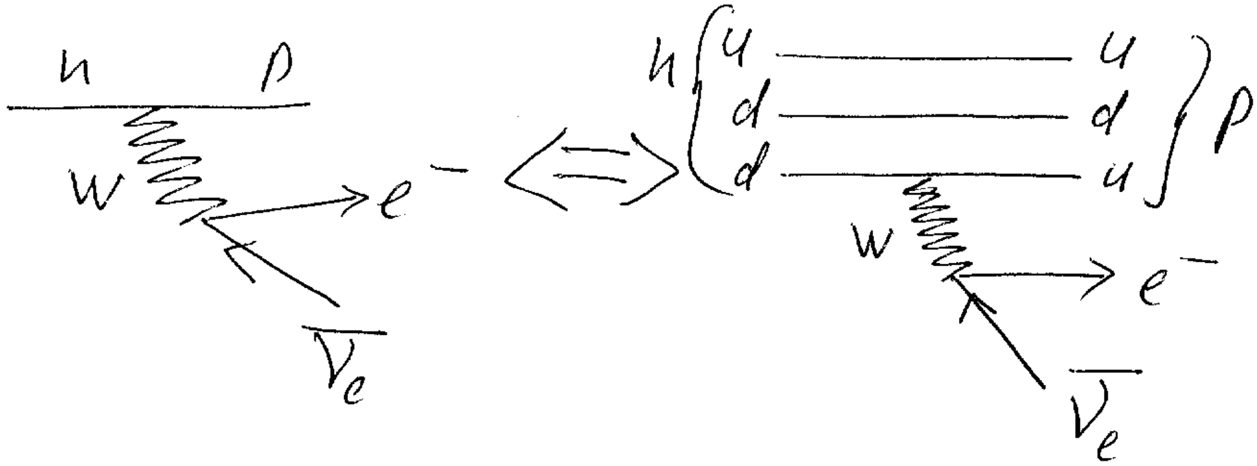
$$\boxed{J^P = 0^-}$$

Weak interaction of quarks





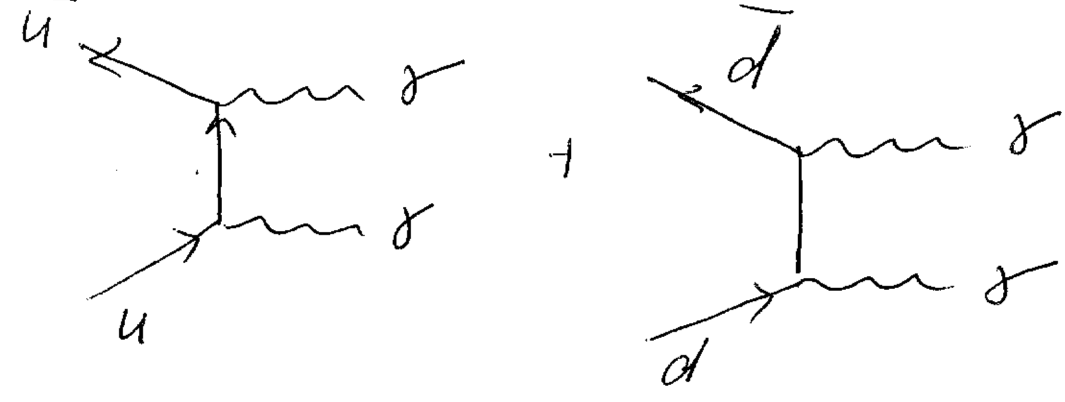
Example: β-decay



π-mesons decays

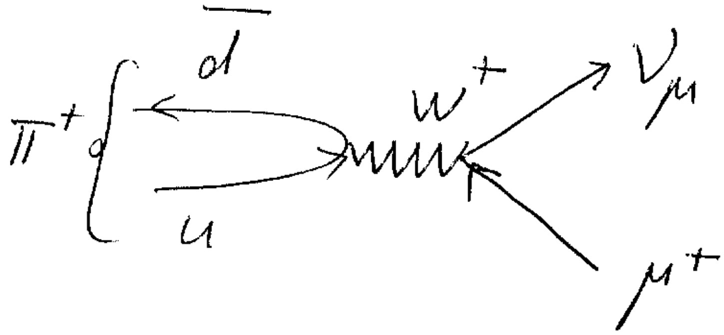
Pions are the lightest hadrons, therefore they cannot decay viaastrong interaction mechanism. However, they decay due to electromagnetic and weak interaction.

$\pi^0 \to 2\gamma$, lifetime $\tau = 8.4\,10^{-17}$ sec.



$\pi^+ \to \mu^+ \nu_\mu$ lifetime $\tau_{\pi^\pm} = 2.6\,10^{-8}$ sec

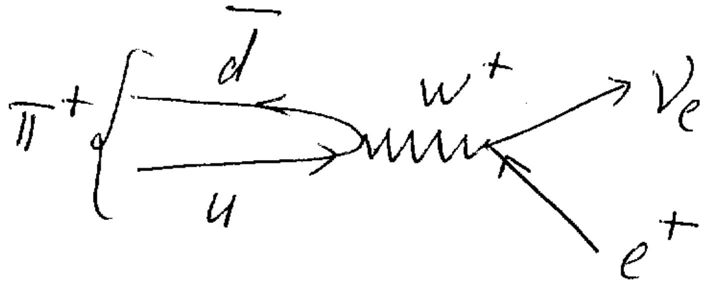
$\pi^+ \to e^+ \nu_e$



lepton number is conserved!

initial: $L_i = 0$

final: $L_f = +1 - 1 = 0$



$\pi^- \to \mu^- \bar{\nu}_\mu$

$\pi^- \to e^- \bar{\nu}_e$