Recap

constituents of matter $\begin{cases} \text{particle-like} \\ \text{wave-like} \end{cases}$

standard models

quantum field theory

QED, QCD

Feynman diagrams for QED, QCD

Today Feynman diagrams for

weak interaction, quantum flavor dynamics

(QFD)

Two things in one?

What do you see?

a) An old woman smiling
b) A young lady with her head turned

?

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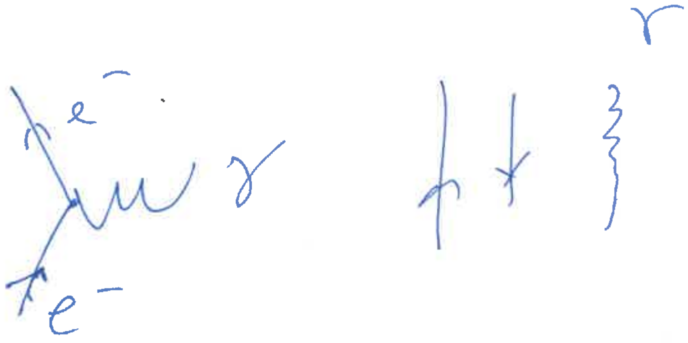
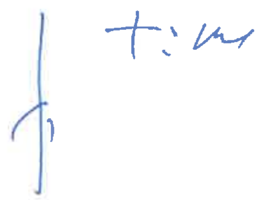
QED → QCD → QFD

em strong flavor (weak)

Basic QED

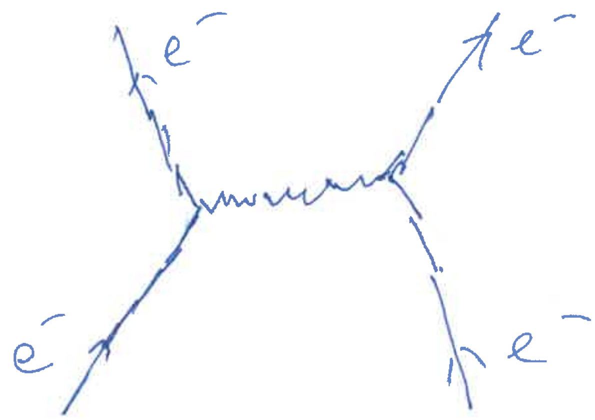


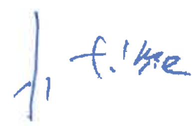


Given a physical process, how to draw a Feynman diagram to represent that physical process?

Ex. 1 $e^- + e^- \to e^- + e^-$

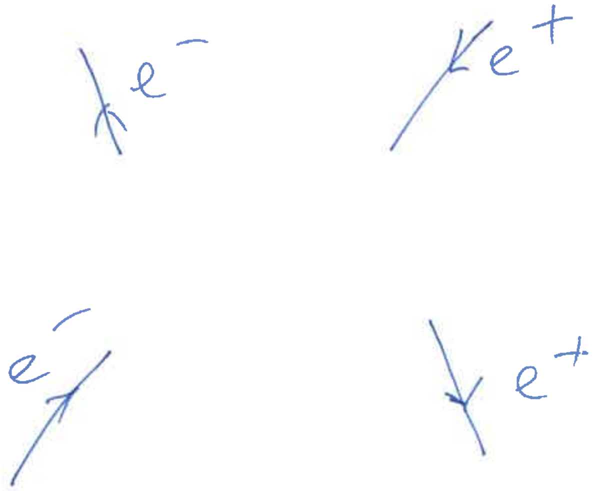
Møller scattering

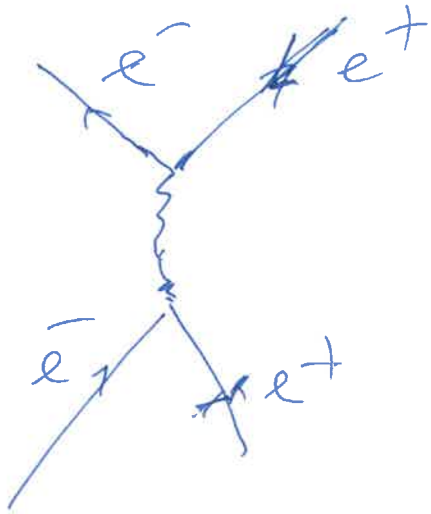




Ex. 2 $e^- + e^+ \to e^- + e^+$

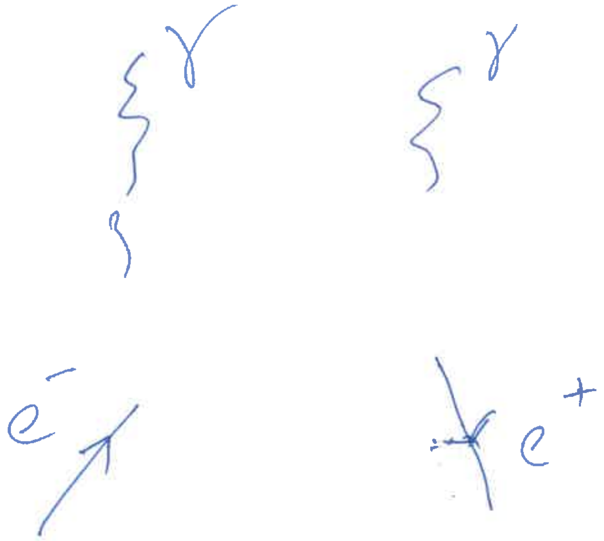
Bhabha scattering

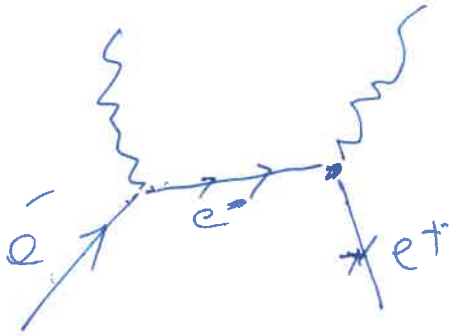




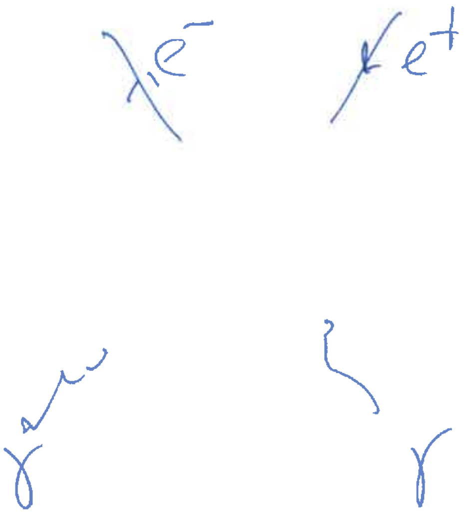
Ex 3. pair annihilation

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



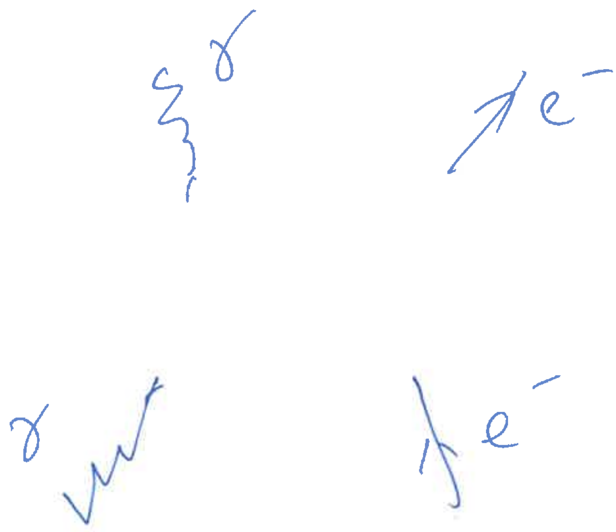


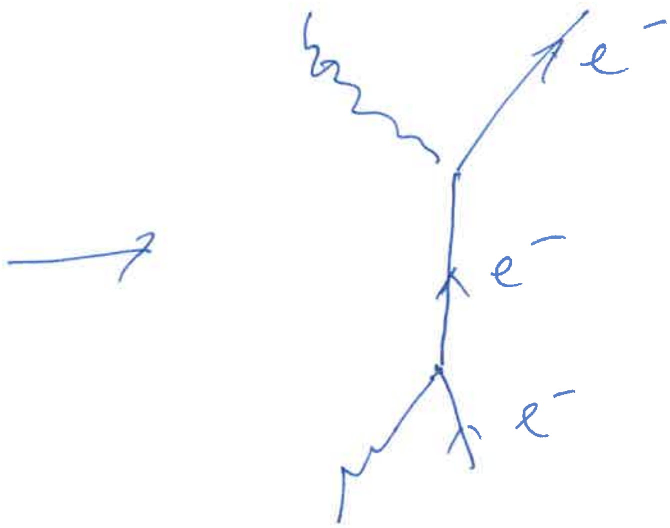
Ex. 4. Pair creation $\gamma + \gamma \to e^- + e^+$



EX5 Compton scattering

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





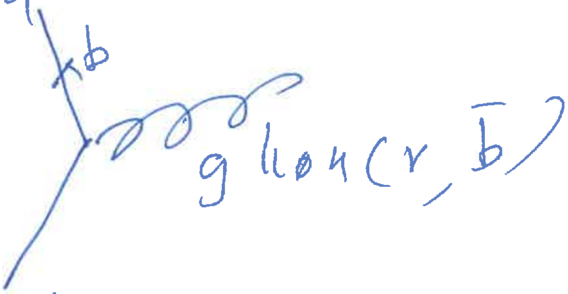
QED Feynman diagrams done

QCD diagram.

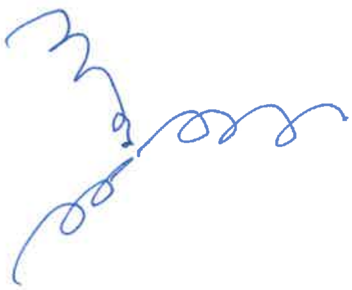
QCD

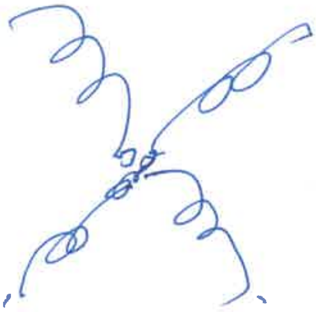
External lines, vertices.

quark antiquark gluon



Gluon vertices





Ex: $p + p \to p + p$

$p = uud$

electric charge

$u \quad \frac{2}{3}$

$d \to -\frac{1}{3}$


d
u
u
u
u
u
d

Have completed QED, QCD diagrams 8

$\downarrow$ em $\quad$ $\downarrow$ strong

weak interaction complicated

basic vertices,

There are many vertices for weak interaction e.g.

neutral weak vertex

charged weak vertex

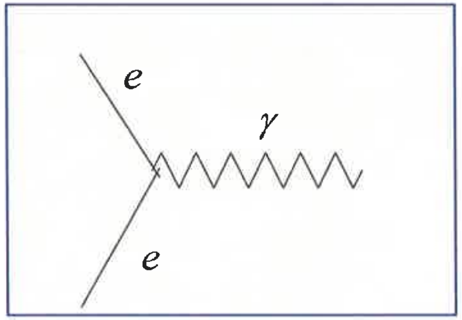
lepton weak vertices

quark weak vertices

W^+, W^-, Z vertices.

All ***em*** processes can be described by patching together two or more of the primitive vertices.

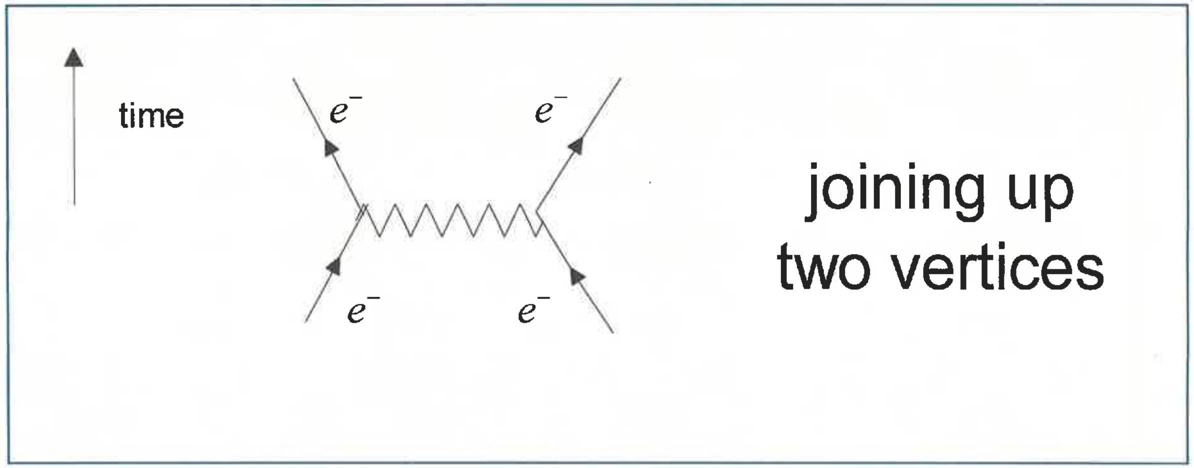
Note: The primitive QED vertex



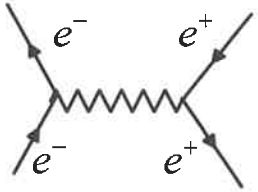
by itself does not represent a possible physical process as it violates the conservation of energy.

Some examples of electromagnetic interaction

1. Møller Scattering $e^- e^- \to e^- e^-$



2. Bhabha Scattering $e^- e^+ \to e^- e^+$

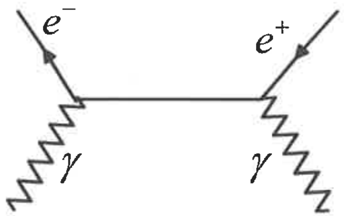


e^- gives up a virtual photon which is absorbed by the position e^+

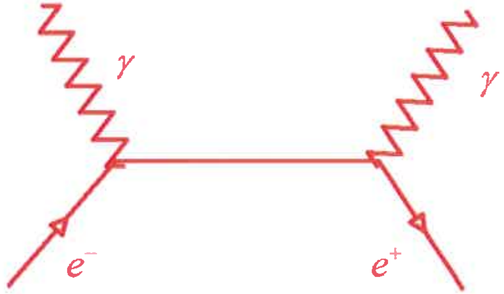
Particle line running backward in time (as indicated by the arrow) is interpreted as the corresponding antiparticle running forward.

$e^+ e^-$ annihilate to produce a virtual photon γ which then pair – produces $e^+ e^-$

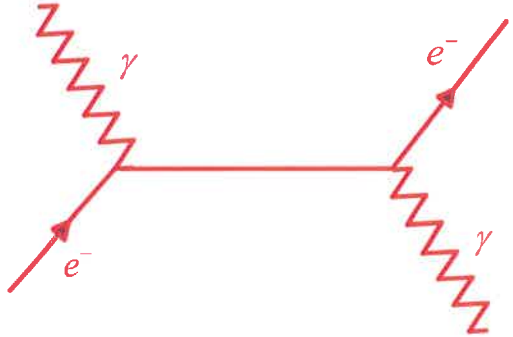
3. Pair Production $\gamma\gamma \to e^+ e^-$



4. Pair Annihilation $e^{+}e^{-} \rightarrow \gamma\gamma$

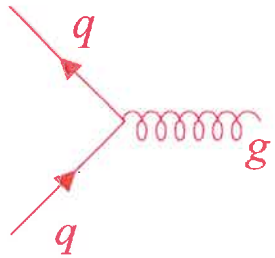


5. Compton Scattering $e^{-}\gamma \rightarrow e^{-}\gamma$

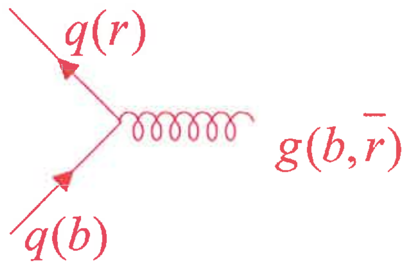


(b) QCD

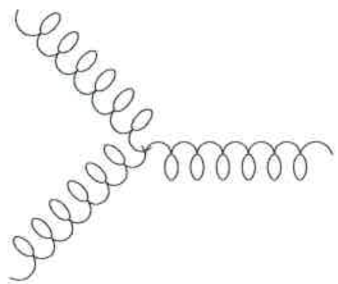
Only quarks and gluons involve basic vertices: Quark-gluon vertex $q \to q + g$

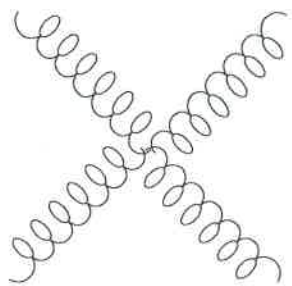


More exactly



Gluon vertices

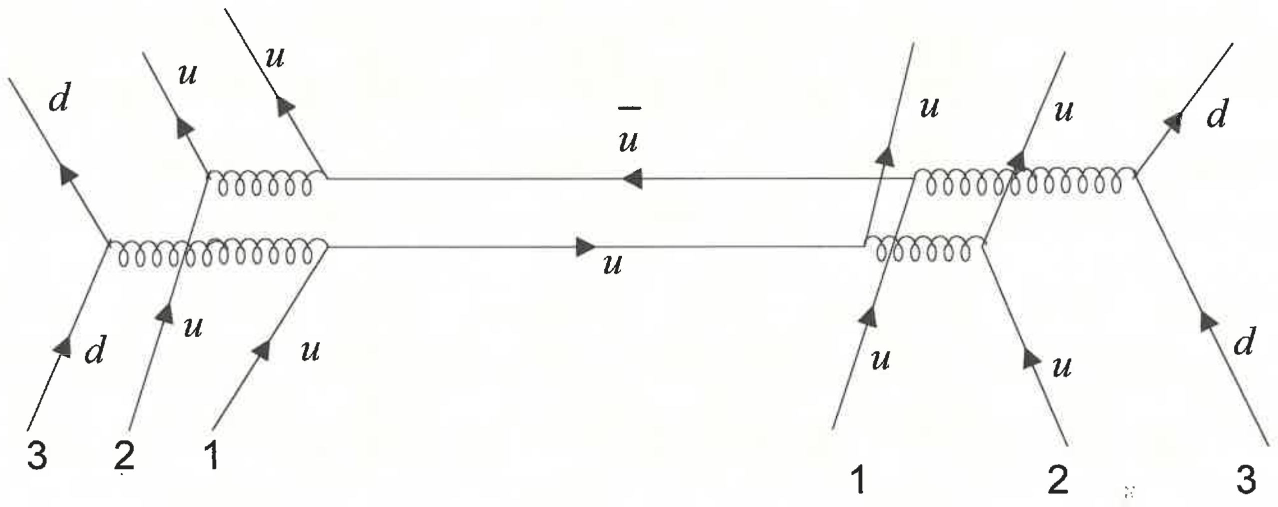




Interaction between two proton

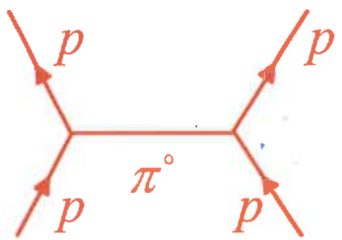
Nucleons (proton or neutron) interact by exchange of π mesons.

e.g.



First *u* quark of LH p interacts with *d* and then propagates to the RH p to become the *u* of the RH p and also interacts with the second *u* of the RH p.

Similarly the first *u* of RH p interacts with the *d* and goes to become a *u* of the LH p and also interacts with the second *u* of the LH p.



$$\pi^\circ = (u\bar{u} - d\bar{d})/\sqrt{2}$$

The coupling constant α_s decreases as interaction energy increases (short-range)

$$\alpha_{s\,eff} = \frac{\alpha_s}{\varepsilon} \qquad \varepsilon = \text{dielectric constant}$$

$\alpha_s(m_Z) = 0.112$ $\qquad m_Z = 91\ GeV/c^2$

known as asymptotic freedom. $\alpha_s(m_\psi) = 0.2$ $\qquad m_\psi = 3.1\ GeV/c^2$

$\alpha_s(200\ MeV) \simeq 1$

For QCD α_s increases as interaction energy decreases (long range)

known as infrared slavery.

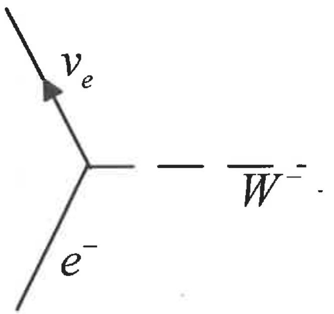
(c) **Weak Interaction**

Two kinds, charged and neutral vertices

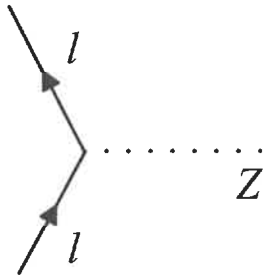
Leptons: primitive vertices connect members of the <u>same</u> generation

Lepton number is separately conserved for each Lepton generation, that is, L_e, L_μ, L_τ separately conserved.

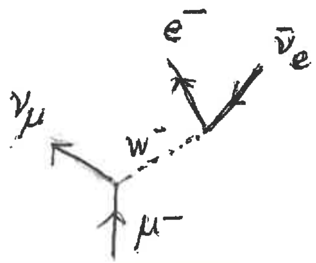
Charged vertex

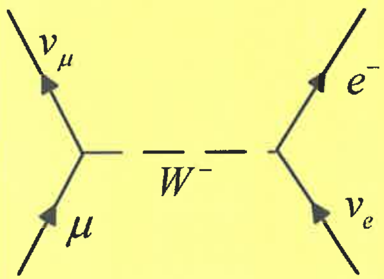


Neutral vertex



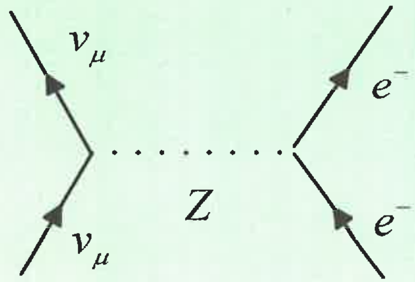
e.g.





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

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

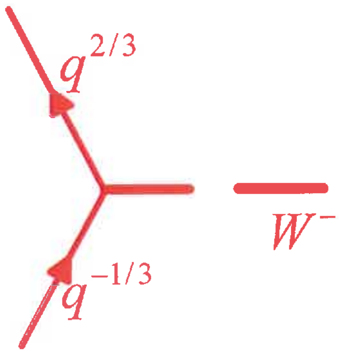


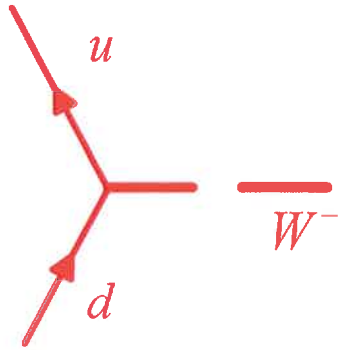
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

Quarks

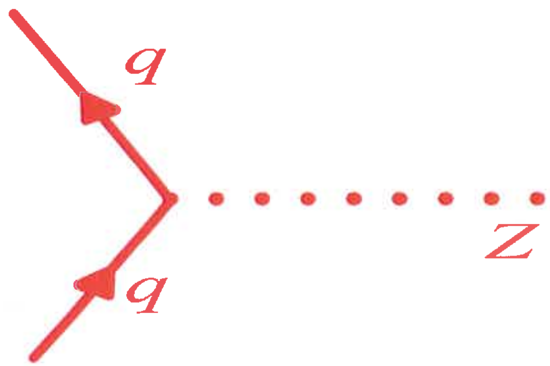
Flavour not conserved in weak interaction .

Charged Vertex.





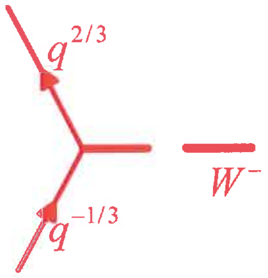
Neutral vertex

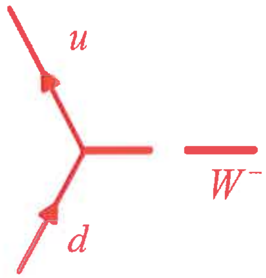


Quarks

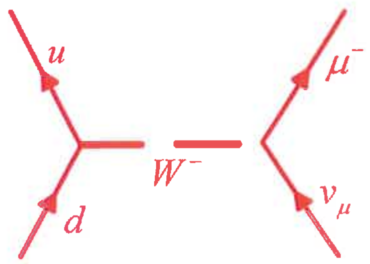
Flavour not conserved in weak interaction

Charged Vertex.





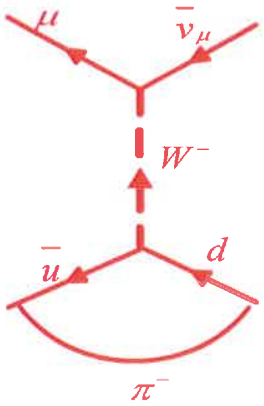
Semileptonic process $d + \nu_\mu \rightarrow u + \mu^-$



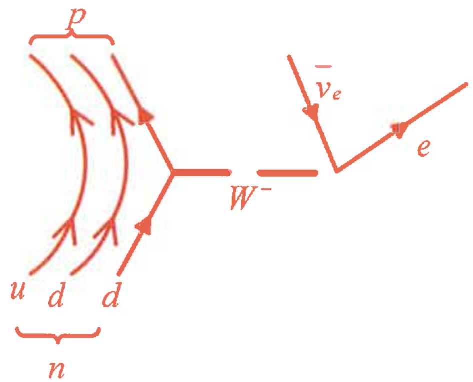
Not observable due to quark confinement

But can be observed in

Decay of $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

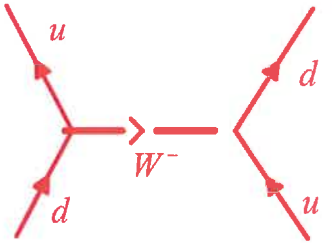


and neutron decay $n \rightarrow p + e^- + \bar{\nu}_e$



Two quarks *u*, *d* in neutron *n* not participating are called spectator quarks.

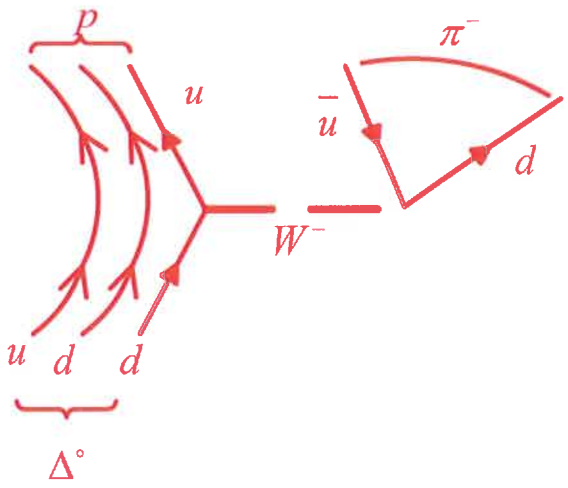
Hadronic decays



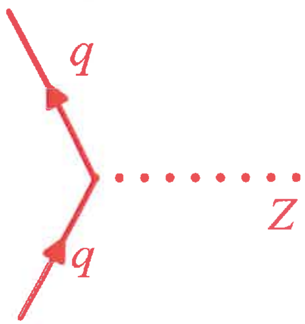
observed in

$\Delta^\circ(udd)$

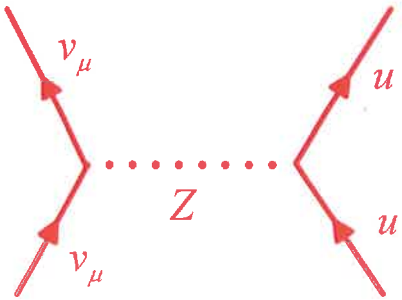
$\Delta^\circ \rightarrow p + \pi^-$



Neutral vertex



e.g.

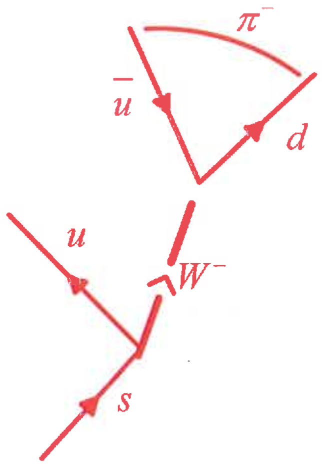


observed in

$\nu_\mu + p \rightarrow \nu_\mu + p$

Decays of quark by weak interaction can involve members of different generations

e.g. a strange quark can decay into an u-quark



The weak force not just couples members of the same generation

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

but **couples also members of different generations**

$$\begin{pmatrix} u \\ d' \end{pmatrix} or \begin{pmatrix} c \\ s' \end{pmatrix} or \begin{pmatrix} t \\ b' \end{pmatrix}$$ where $$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo

Kobayashi –Maskawa matrix

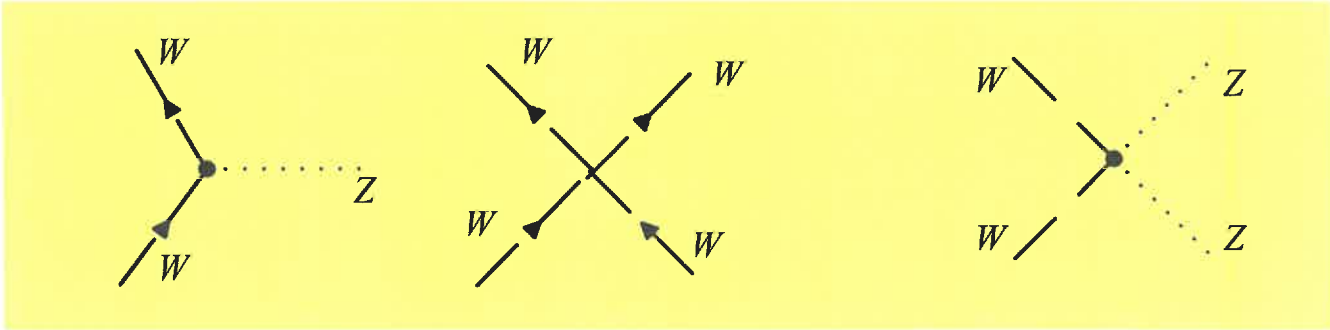
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9747-0.9759, & 0.218-0.224, & 0.001-0.007 \\ 0.218-0.224, & 0.9734-0.9752, & 0.030-0.058 \\ 0.003-0.019, & 0.029-0.058, & 0.9983-0.9996 \end{pmatrix}$$

V_{ud} = coupling of *u* to *d*

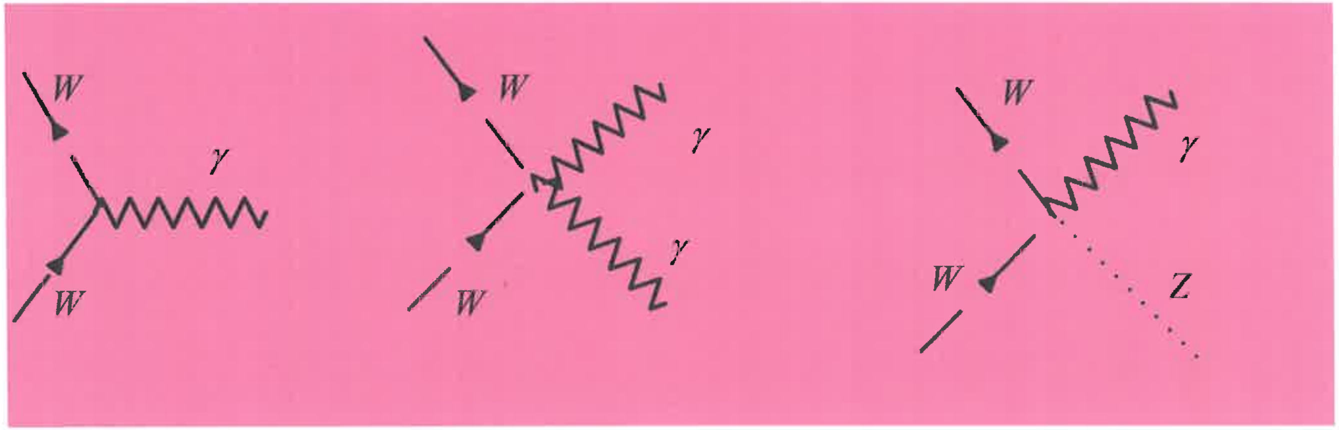
V_{us} = coupling of *u* to *s*

(d) ***wk*** and ***em*** couplings of $W^{\pm}$ and Z

Weak couplings



Couplings involve photon γ



Summary