Lecture 11

Weak interactions

1962-66: Formulation of a Unified Electroweak Theory
(Glashow, Salam, Weinberg)

4 intermediate spin 1 interaction carriers ("bosons"):

- the photon (γ)
  responsible for all electromagnetic processes

- three weak, heavy bosons W^+ W^- Z
  $W^\pm$ responsible for processes with electric charge transfer $= \pm 1$
  (Charged Current processes)

  Examples:

  $n \rightarrow p\ e^- \bar{\nu}$: $n \rightarrow p + W^-$ followed by $W^- \rightarrow e\ \bar{\nu}$

  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$: $\mu^+ \rightarrow \bar{\nu}_\mu + W^+$ followed by $W^+ \rightarrow e^+ \nu_e$

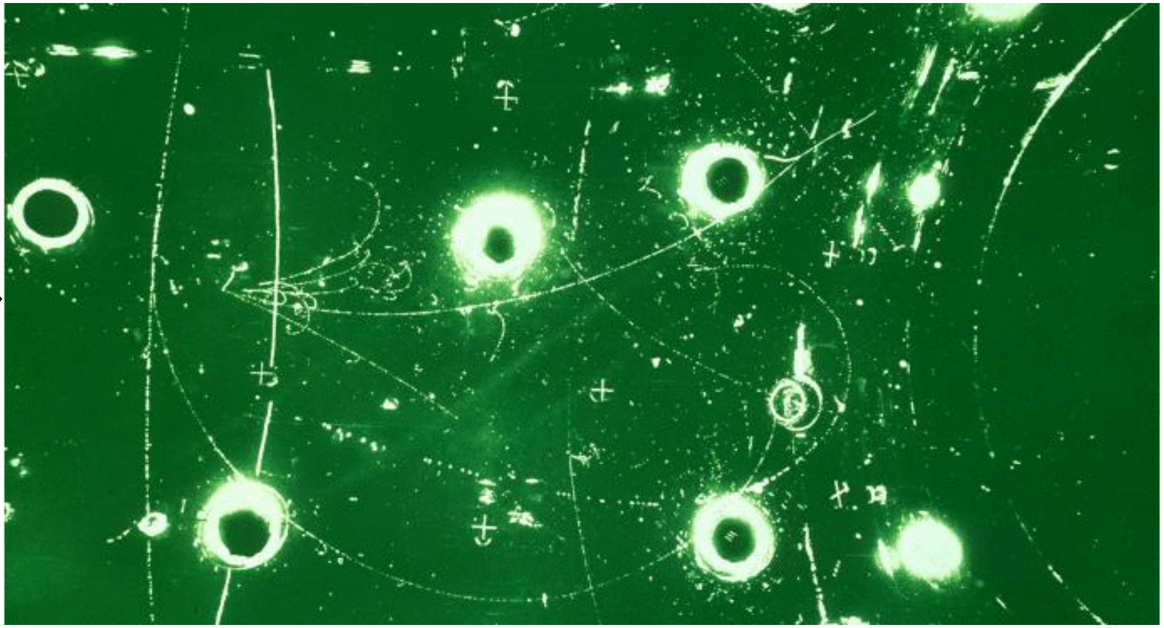
  Z responsible for weak processes with no electric charge transfer
  (Neutral Current processes)
  PROCESSES NEVER OBSERVED BEFORE
  Require neutrino beams to search for these processes, to remove the much larger electromagnetic effects expected with charged particle beams

First observation of Neutral Current processes in the heavy liquid bubble chamber Gargamelle at the CERN PS (1973)

Example of
$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$
(elastic scattering)
Recoil electron energy = 400 MeV

($\bar{\nu}_\mu$ beam from π^- decay in flight)

Example of
$\nu_\mu + p\ (n) \rightarrow \nu_\mu +$ hadrons
(inelastic interaction)
(ν_μ beam from π^+ decay in flight)

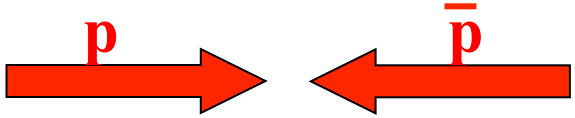


Measured rates of Neutral Current events ➔ estimate of the W and Z masses (not very accurately, because of the small number of events):

$$M_W \approx 70 - 90 \text{ GeV}/c^2 \quad ; \quad M_Z \approx 80 - 100 \text{ GeV}/c^2$$

too high to be produced at any accelerator in operation in the 1970's

1975: Proposal to transform the new 450 GeV CERN proton synchrotron (SPS) into a proton – antiproton collider (C. Rubbia)



Beam energy = 315 GeV ➔ total energy in the centre-of-mass = 630 GeV

Beam energy necessary to achieve the same collision energy on a proton at rest :

$$(E + m_p c^2)^2 - p^2 c^2 = (630\,\text{GeV})^2 \Longrightarrow E = 210 \text{ TeV}$$

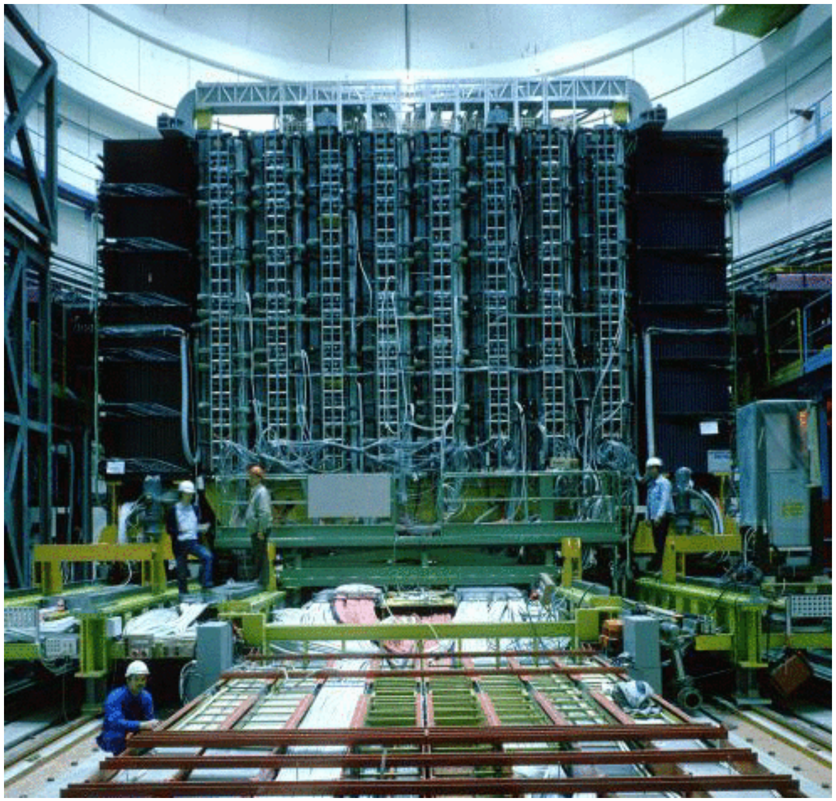
Production of W and Z by quark – antiquark annihilation:

$$u + \bar{d} \rightarrow W^+ \qquad \bar{u} + d \rightarrow W^-$$

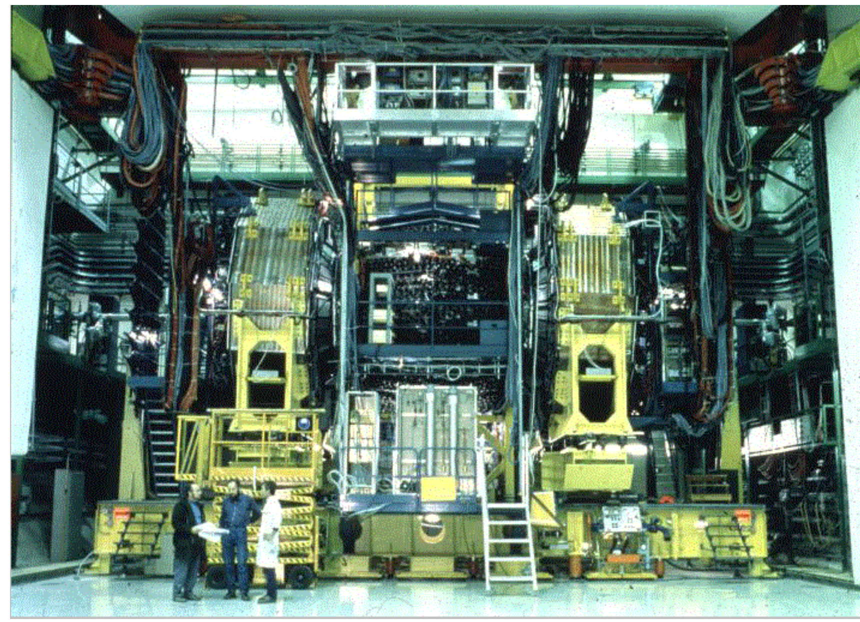
$$u + \bar{u} \rightarrow Z \qquad d + \bar{d} \rightarrow Z$$

UA1 and UA2 experiments (1981 – 1990)

Search for $W^{\pm} \rightarrow e^{\pm} + \nu$ (UA1, UA2) ; $W^{\pm} \rightarrow \mu^{\pm} + \nu$ (UA1)
$Z \rightarrow e^{+}e^{-}$ (UA1, UA2) ; $Z \rightarrow \mu^{+}\mu^{-}$ (UA1)

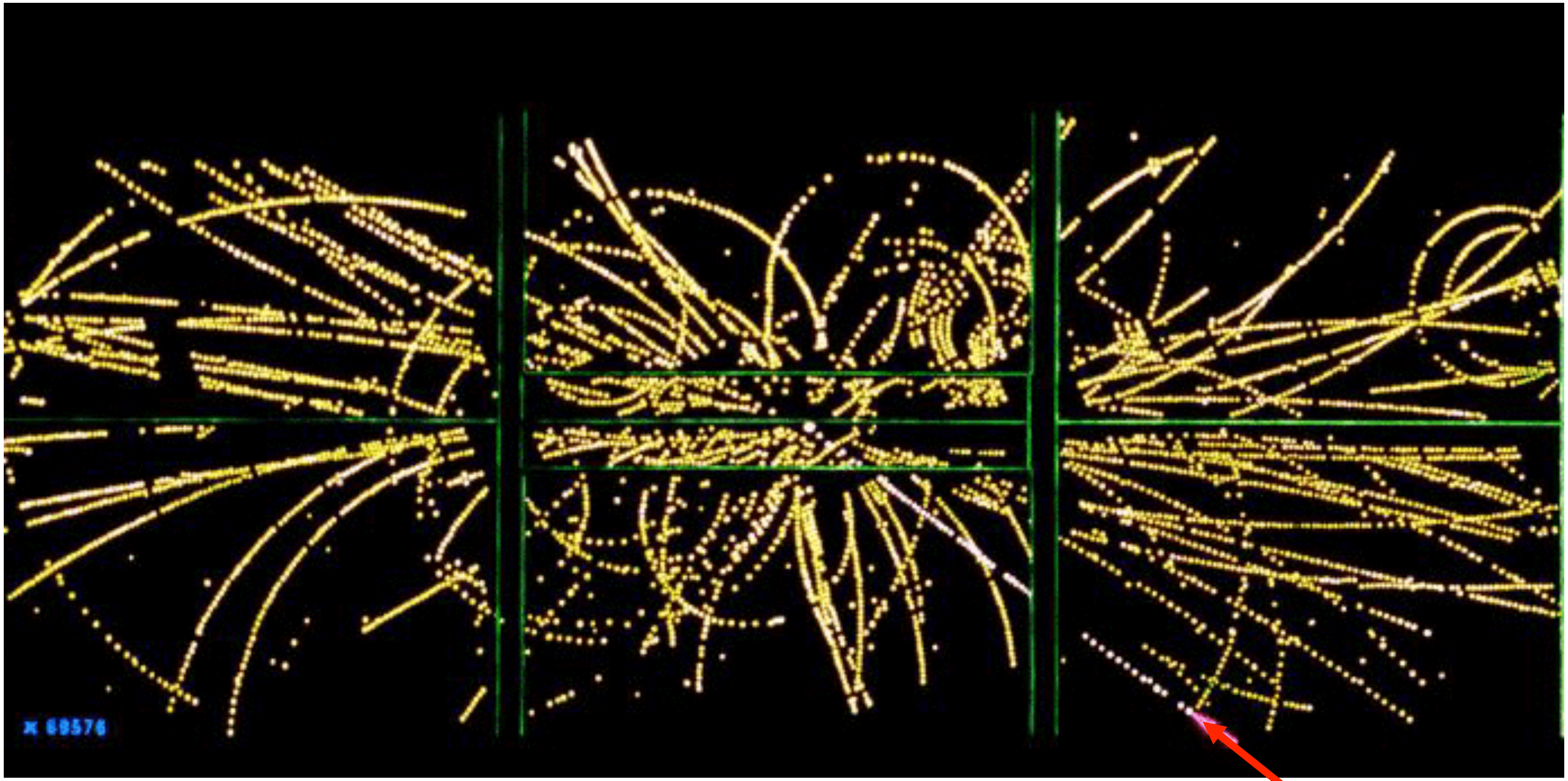


UA1: magnetic volume with trackers, surrounded by "hermetic" calorimeter and muon detectors



UA2: non-magnetic, calorimetric detector with inner tracker

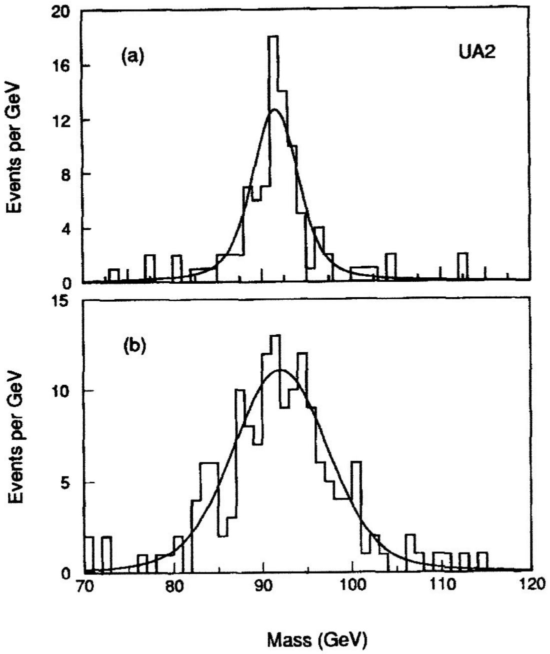
One of the first W → $e + \nu$ events in UA1



48 GeV electron identified by surrounding calorimeters

UA2 final results

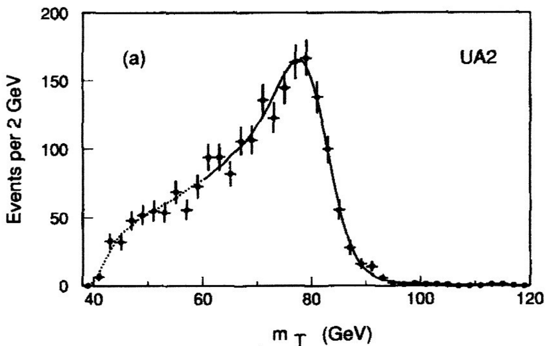
Events containing two high-energy electrons: Distributions of the "invariant mass" M_{ee}



$$(M_{ee}c^2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2$$

(for Z → e^+e^- $M_{ee} = M_Z$)

Events containing a single electron with large transverse momentum (momentum component perpendicular to the beam axis) and large missing transverse momentum (apparent violation of momentum conservation due to the escaping neutrino from W → e ν decay)



m_T ("transverse mass"): invariant mass of the electron – neutrino pair calculated from the transverse components only

M_W is determined from a fit to the m_T distribution: $M_W = 80.35 \pm 0.37$ GeV/c^2

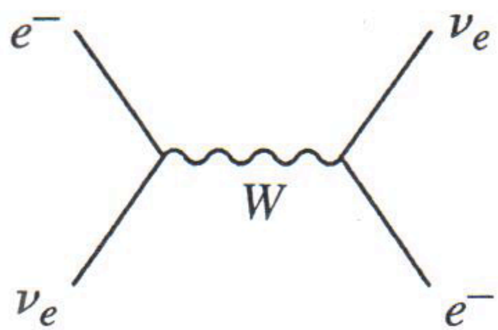
All observed W mediated processes indicate left-handed spin polarization of $W^{\pm}$. So far there is no evidence for right-handed W current. That leads to the uncomfortable list of quarks and leptons from the perspective of their spins: left-handed doublets, right-handed singlets and no info whether right-handed neutrino exist.

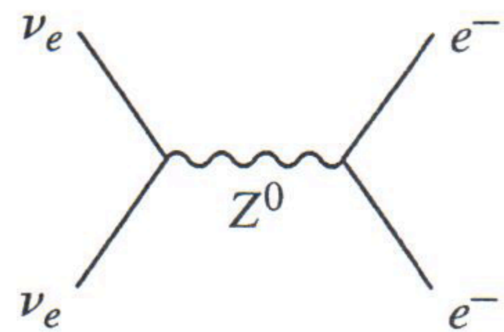
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

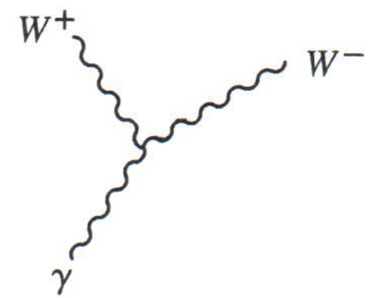
$$u_R \quad c_R \quad t_R$$

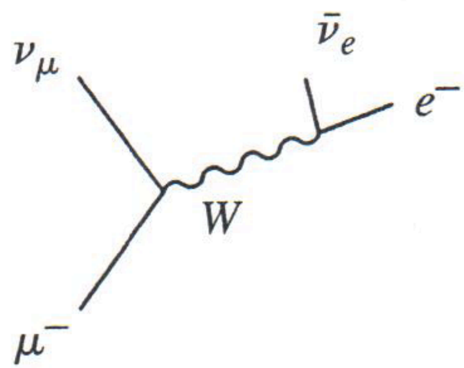
$$d_R \quad s_R \quad b_R \qquad e_R \quad \mu_R \quad \tau_R$$

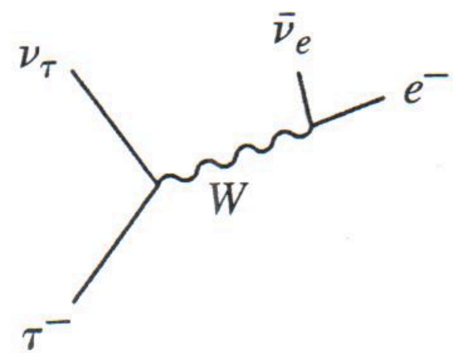
Weak interactions: 3 carriers of the weak force: W^+, W^-, Z^0
Heavy - mass(W) =80.4 GeV, mass(Z) = 91.2 GeV

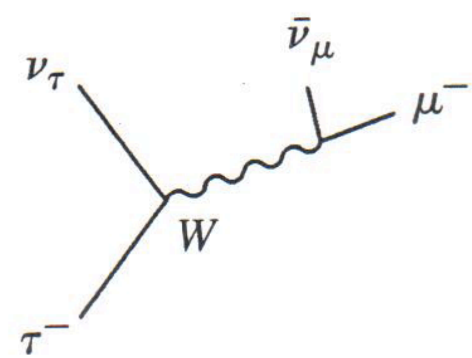




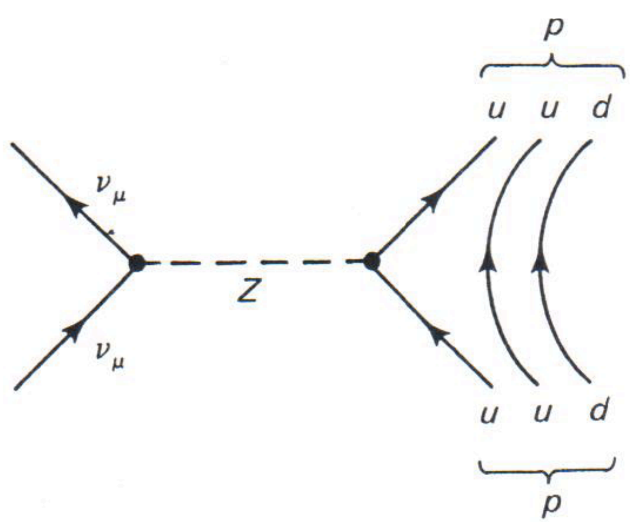


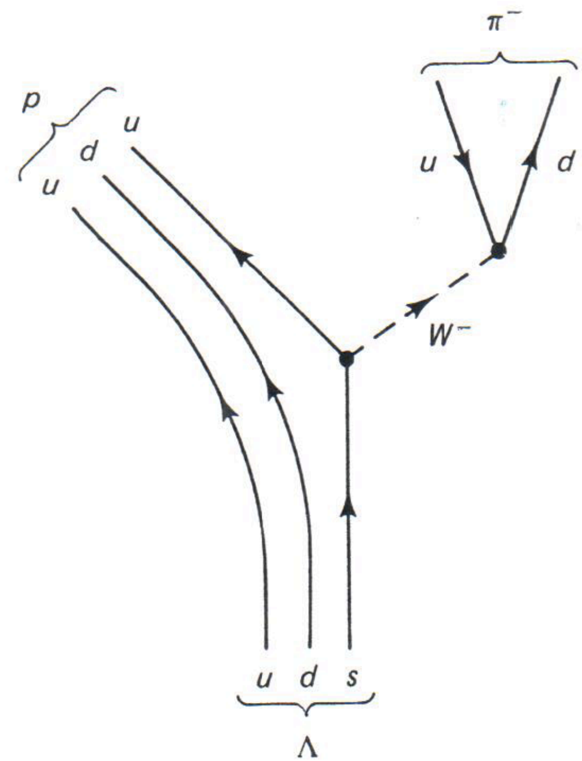






The problem with the quarks: strange particles, e.g., kaons, decay into non-strange particles. The strange quark disappears. That would mean that weak interactions are not universal. The charged carriers of the force, W±, change the "flavor" of the quark while the flavor is conserved in neutral Z interactions .





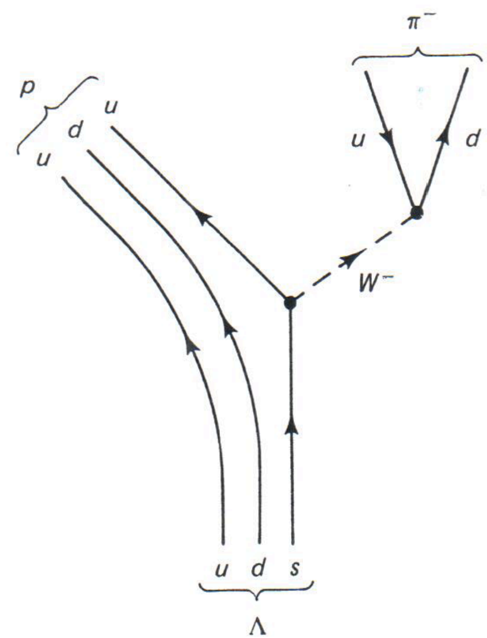
•*The problem with the quarks: strange particles, e.g., kaons, decay into non-strange particles. The strange quark disappears. That would mean that weak interactions are not universal. W can change the "flavor" of the quark. Z does not.*

•*Cabbibo (1963) proposed that the charge -1/3 quark in elementary particles is a* ***superposition*** *of down type quarks*

$$d' = V_{ud}\, d + V_{us}\, s = \cos\theta\, d + \sin\theta\, s$$

V_{ud} *and* V_{us} *are probabilities of down-type quark decaying into the up quark.*

•*The extension of that approach to all six quarks is a Cabbibo-Kobayashi-Maskawa (CKM) matrix*



CKM Matrix – Cabibbo-Kobayashi-Maskawa

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Introducing unitarity – requirement that the total probability of decay is equal to 1 one can rewrite it in terms of sins and cosines and add an arbitrary phase.

$$\begin{bmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{bmatrix}$$

The phase δ is responsible for the asymmetry in the decays of particles versus antiparticles i.e., CP violation.

Rate not sufficient to explain matter-antimatter asymmetry.

Symmetries

Conservation laws for strong and electromagnetic interactions (typically production and fast decays in high energy collisions)

Energy
Momentum
Angular momentum
Parity
Charge
Time reversal
Isospin
Baryon number

New quantum numbers:
flavor
color

Quantities characterizing a particle(or system of particles)

Energy
Momentum
Angular momentum
Parity
Charge
Time reversal
Isospin
Baryon number
Flavor (including lepton flavors)
Color

Strong interactions conserve everything
Weak interaction allow for violations

All allowed interactions act at the same time