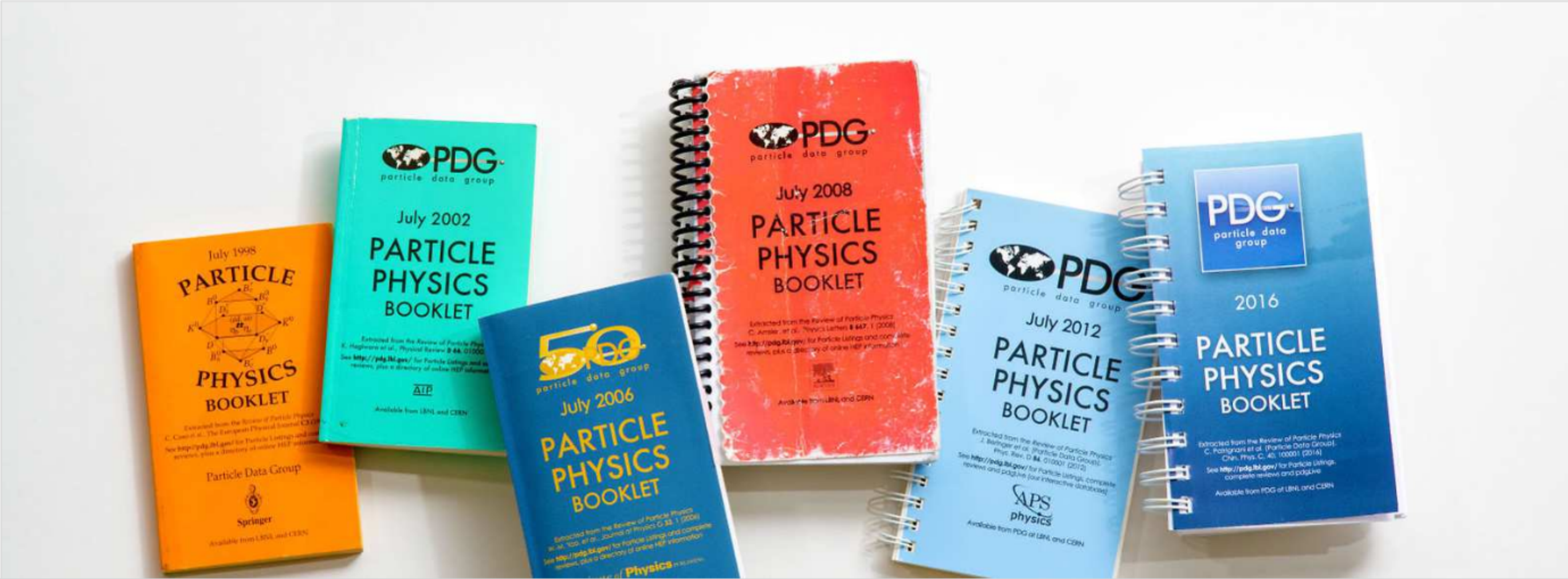

ELEMENTARY PARTICLE PHYSICS

FORCES OF NATURE – FUNDAMENTAL INTERACTIONS (PART IV) - WEAK

MAY 2020 I HANS STRÖHER (FZ JÜLICH, UNIVERSITY OF COLOGNE)

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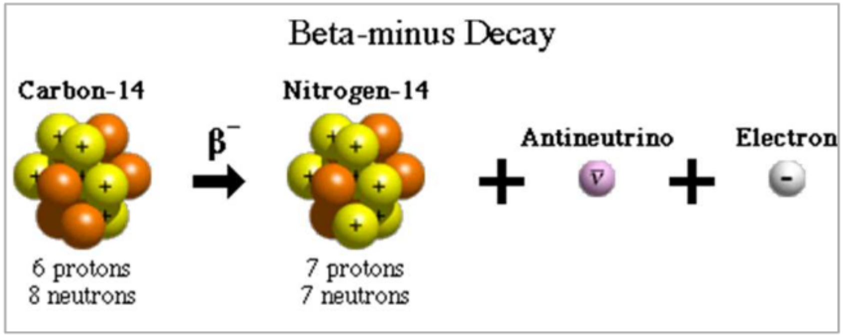
- Outline:
  - A brief **introduction** (history …)
  - The **tools** (accelerators, targets, detectors … kinematics, …)
  - The **particles** (hadrons, baryons, mesons …)
  - The ***fundamental*** **particles** (quarks, leptons)
  - The **forces** (gravitation, nuclear, weak forces)
  - The ***fundamental*** **interactions** (strong and electro-weak IA)
  - The **Standard Model** of EPP
  - Physics **Beyond the Standard Model** (BSM)
  - Spin-offs – **Applications** of EPP

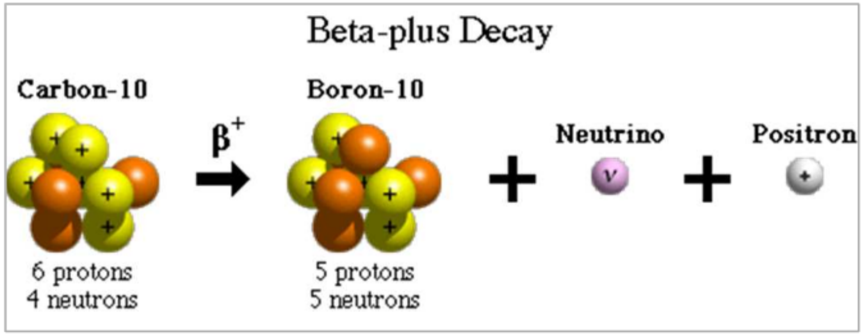
FUNDAMENTAL INTERACTIONS – WEAK

Prelude

History – The early days of β-decay (I)

"**Beta decay**" **(β-decay)** is a type of radioactive decay in which a beta particle (fast energetic **electron or positron**) is emitted from an **atomic nucleus**:





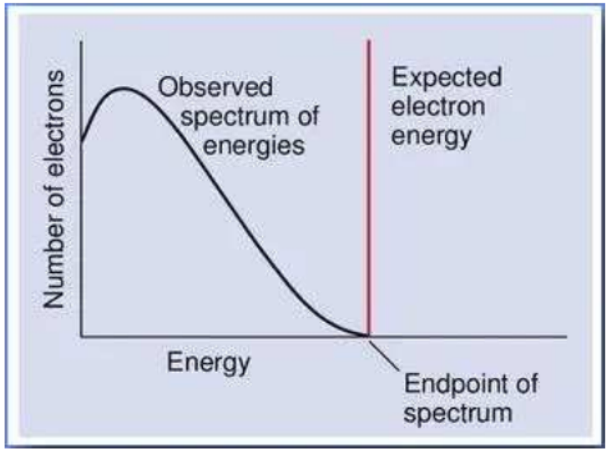
Neither the beta particle nor its associated (anti-)neutrino exist within the nucleus prior to beta decay, but are created in the decay process

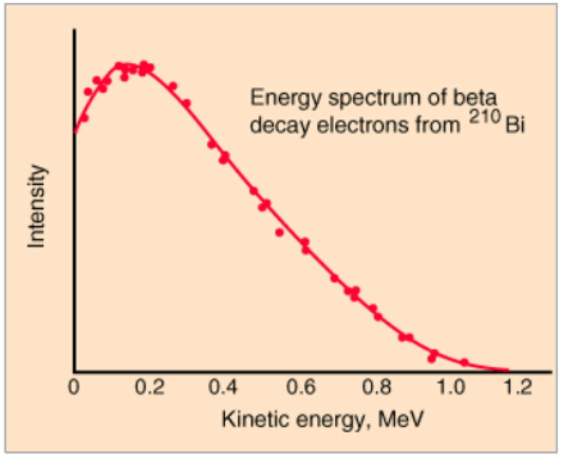
FUNDAMENTAL INTERACTIONS – WEAK

Prelude

History – The early days of β-decay (II)

β-decay produces a **continuous electron (positron) spectrum** up to the maximum possible energy:





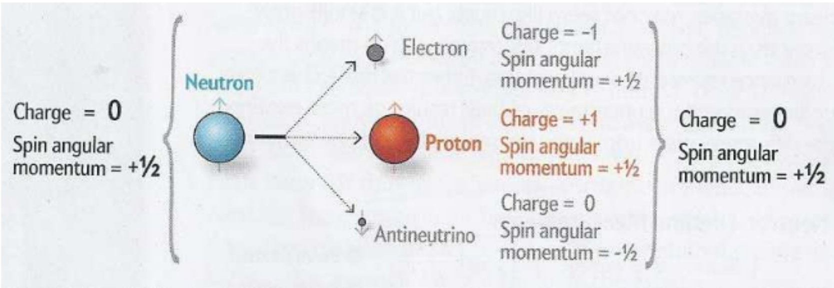
Which implies that it is a **3-body decay** (with electron/positron and anti-/neutrino sharing the energy)

FUNDAMENTAL INTERACTIONS – WEAK

Prelude

History – The early days of β-decay (III)

The simplest β-decay is that of a **free neutron**: n → p + e- + $\bar{\nu}_e$

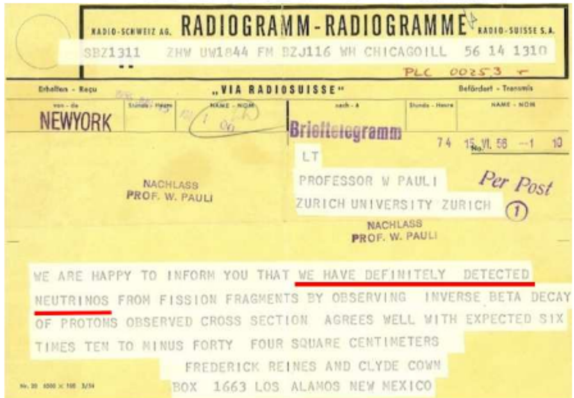


Savannah River

5×10^{13} neutrinos/cm²s

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

the **inverse reaction** was used to demonstrate the **existence** of the **neutrino** (Clyde Cowan and Fred Reines, 1956):


RADIOGRAMM-RADIOGRAMME

NEWYORK

Brieftelegramm

PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

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FUNDAMENTAL INTERACTIONS – WEAK

Prelude

History – The early days of β-decay (IV)

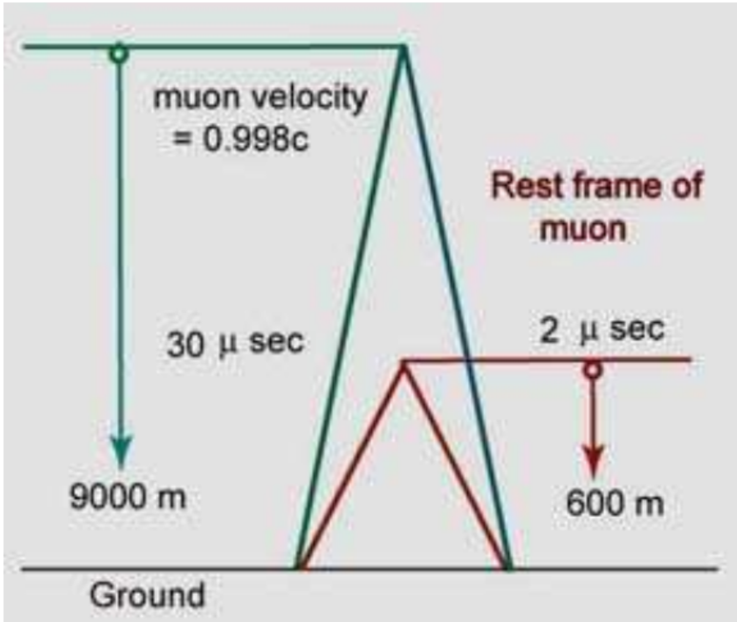
Subsequently, other decays of particles, which were **not due to electro-magnetic** or **strong interactions**, were observed:

Example: muon β-decay

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

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

(Note: **cosmic-ray muons** reach the surface of the earth from the upper atmosphere …)



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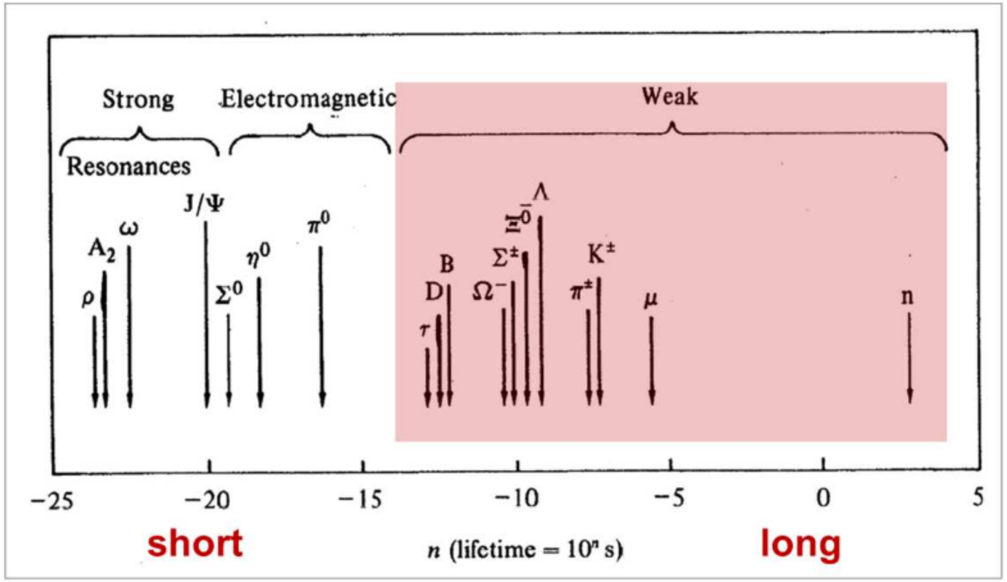
FUNDAMENTAL INTERACTIONS – WEAK

Prelude

History – What makes the weak interaction?

Historically the weak interaction is characterized by "long" decay lifetimes

Examples:



This was thought to be due to the **weakness of the interaction**

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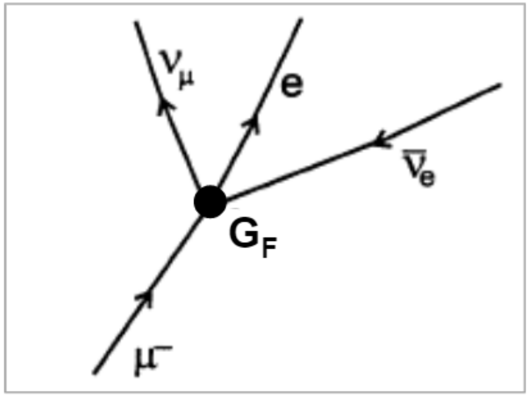
FUNDAMENTAL INTERACTIONS – WEAK

Basics

Facts – theory of the weak interactions – Fermi theory

The precursor to the theory of weak interactions was the "**Fermi-theory**" (1933): a contact force – no range; it described nuclear β-decay and also muon decay (with the same **coupling strength G_F**):



but it failed, e.g., for scattering at high energy (E > 300 GeV)

FUNDAMENTAL INTERACTIONS – WEAK

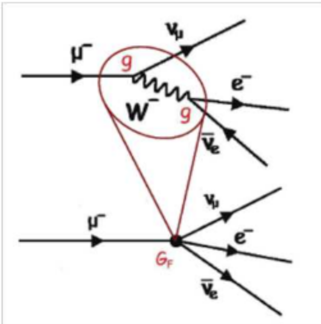
Basics

Facts – theory of the weak interactions – coupling constant (I)

The strength of the interaction is given by the "**Fermi coupling constant**" (G_F). The experimental determination of G_F comes from the muon lifetime (inversely proportional to the square of G_F):

$$\frac{G_\mathrm{F}}{(\hbar c)^3} = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2}\ .$$

<u>Note</u>: this effectively point-like interaction at low momentum transfer (with an apparent coupling strength **G_F**) is due to **virtual W-exchange** with **coupling constant g**; they are related by:



$$\frac{G_\mathrm{F}}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_\mathrm{W}^2}\ ;$$

m_W mass of the exchange boson

FUNDAMENTAL INTERACTIONS – WEAK

Basics

Facts – theory of the weak interactions – coupling constant (II)

Using the W mass $\mathbf{m_w = 80.4}$ **GeV**, one can determine g: **g = 0.65**; this leads to $\boldsymbol{\alpha_w} = g^2/4\pi =$ **1/29** (compared to $\alpha_{em} = 1/137$)

This indicates that the **weak interaction** is **inherently stronger than** the **electromagnetic interaction**! It is only the suppression factor E^2/m_w^2 that makes the weak interaction seem so "weak"

The weak interaction has a coupling constant (an indicator of interaction strength) of between 10^{-7} and 10^{-6}, compared to the strong interaction's coupling constant of 1 and the electromagnetic coupling constant of about 10^{-2} – consequently the weak interaction is 'weak' in terms of strength.

The weak interaction has a very short effective range (around 10^{-17} to 10^{-16} m. At distances around 10^{-18} m, the weak interaction has a strength of a similar magnitude to the electromagnetic force, but this starts to decrease exponentially with increasing distance; at distances of around 3×10^{-17} m, the weak interaction becomes 10,000 times weaker.

FUNDAMENTAL INTERACTIONS – WEAK

Basics

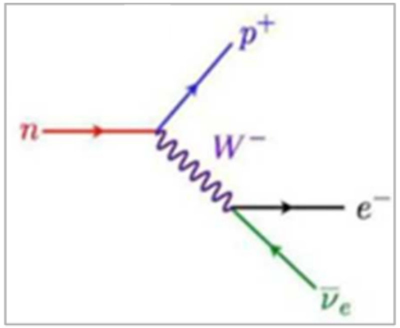
Facts – theory of the weak interactions – V-A theory

In the original theory, Fermi assumed that the form of interaction is a contact coupling of two "**vector currents**" **(V)**

After the discovery of **parity violation**, G. Sudarshan, R. Marshak, and R. Feynman, M. Gell-Mann, determined the correct structure of the four-fermion interaction as **"vector (V) minus axial vector (A)**" **(V-A)**

This meant that the weak interaction could be seen as the **exchange of a spin-1 particle** (similar to the electromagnetic interaction)

Example: neutron-decay



FUNDAMENTAL INTERACTIONS – WEAK

Basics

Facts – theory of the weak interactions – charge

Like the electric interaction (→ electric charges) and the strong interaction (→ color charges) the **weak interactions** are also **due to a "weak charge"** (more complex …); here it is sufficient to note that all particles (quarks and leptons) have it:

	Quarks		Leptons	
Generation 1	u Up	d Down	e Electron	ν_e Electron-neutrino
Colour charge	*X*	*X*		
Electric charge	*X*	*X*	*X*	
Weak charge	*X*	*X*	*X*	*X*

FUNDAMENTAL INTERACTIONS – WEAK

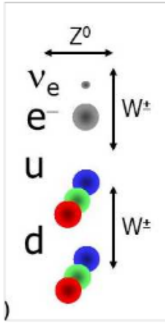
Basics

Facts – theory of the weak interactions – Quantum Flavor Dynamics

The **theory of the weak interaction** is sometimes called "**quantum flavor-dynamics**" (QFD), in analogy with the terms QCD and QED; QFD is based on the field quanta W^+, W^- and Z^0:

$W^\pm$ cause: $u \leftrightarrow d$, $c \leftrightarrow s$ and $t \leftrightarrow b$ transitions
$e \leftrightarrow \nu_e$, $\mu \leftrightarrow \nu_\mu$ and $\tau \leftrightarrow \nu_\tau$ transitions

Z^0 causes: $u \leftrightarrow u$, $d \leftrightarrow d$, $c \leftrightarrow c$, etc. transitions
$e \leftrightarrow e$, $\nu_e \leftrightarrow \nu_e$, $\mu \leftrightarrow \mu$, etc. transitions



In practice the term QFD is rarely used because the weak force is best understood in terms of the so called "**electro-weak theory**" (EWT) (to be discussed later)

FUNDAMENTAL INTERACTIONS – WEAK

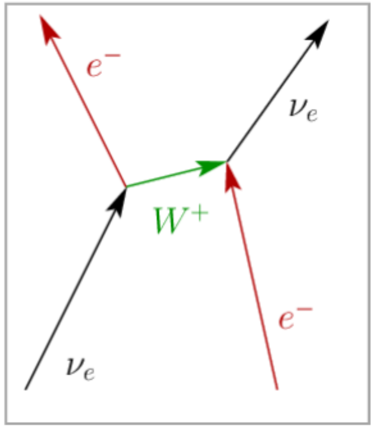
Details

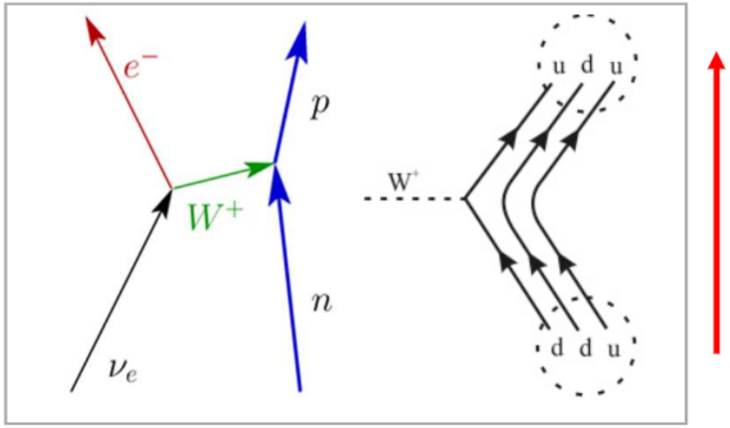
Charged-current interactions – the exchange of W-bosons

The **charged weak interaction bosons** (W^+, W^-) carry away charge to make transitions **within** one of the following doublets:

$$W \updownarrow \quad \begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \begin{pmatrix} d' \\ u \end{pmatrix} \begin{pmatrix} s' \\ c \end{pmatrix} \begin{pmatrix} b' \\ t \end{pmatrix}$$

Examples:



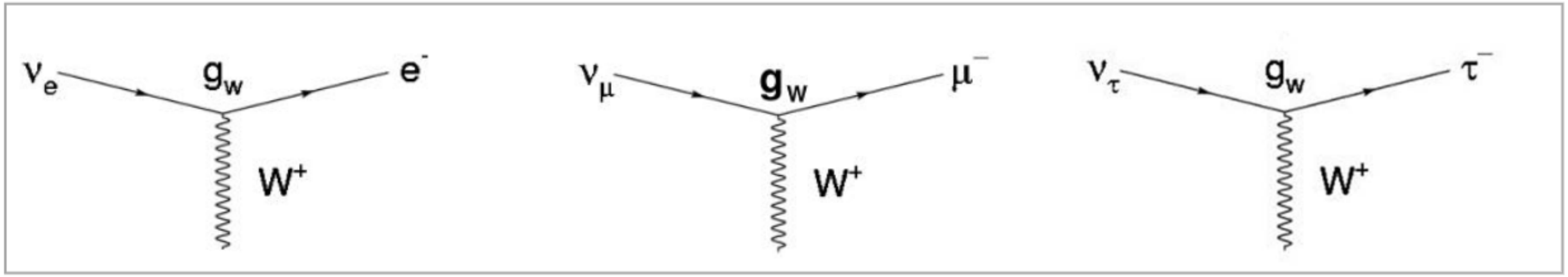


FUNDAMENTAL INTERACTIONS – WEAK

Details

Charged-current interactions – the W-exchange for leptons (I)

The **leptonic** weak charged-current vertex **couples** a **neutrino** and its **corresponding charged lepton**:



i.e. **no coupling** between (**W e** $\mathbf{v_\propto}$) etc. seen

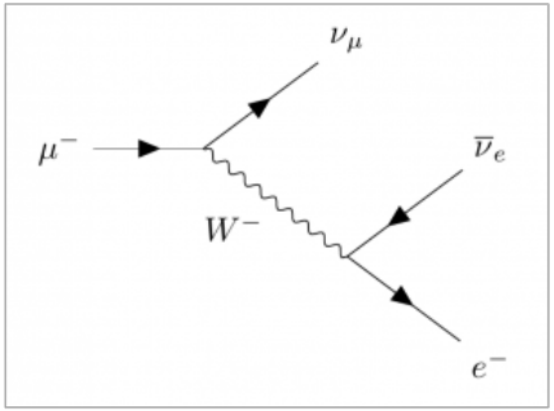
The **coupling strength** $\mathbf{g_W}$ is the same for all three lepton families; this is called "**lepton universality**" – it means that all leptons carry the same weak charge

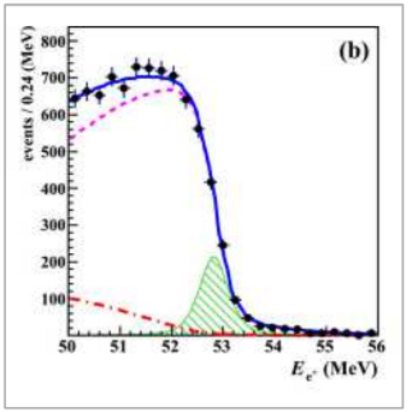
FUNDAMENTAL INTERACTIONS – WEAK

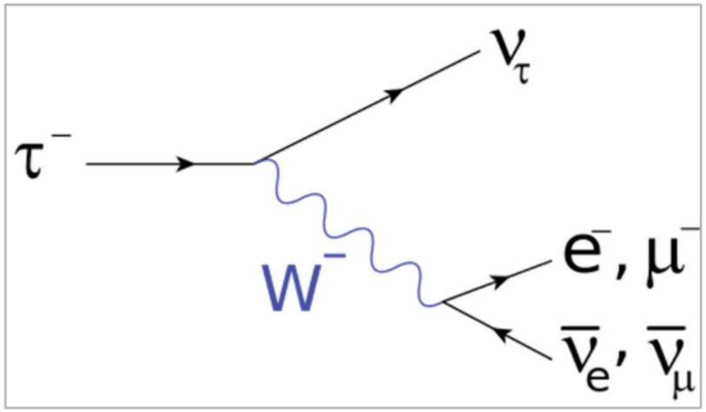
Details

Charged-current interactions – the W-exchange of leptons (II)

The **muon decay** (with muons, e.g. from pion decay: $\pi \rightarrow \propto \nu_{\propto}$) produces **2 distinct neutrinos**; neglecting the tiny neutrino mass, the **maximum electron energy** is half the muon mass (½ x 105.6 MeV, i.e. **52.8 MeV**):







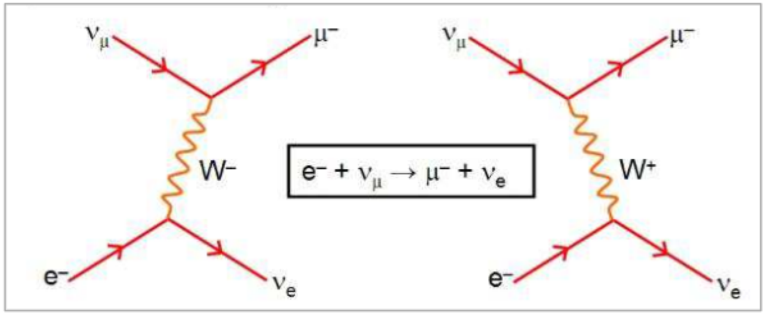
→ Muons (also tauons) therefore decay into neutrino plus the lightest lepton doublet (e, ν_e) with the **electron being stable**

FUNDAMENTAL INTERACTIONS – WEAK

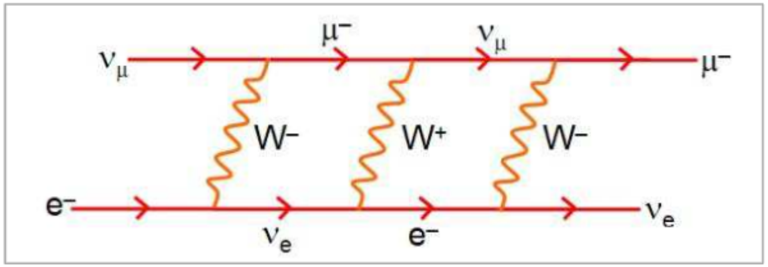
Details

Charged-current interactions – the W-exchange of leptons (III)

The **inverse muon decay**:



is difficult to investigate experimentally (neutrino beam onto electrons bound in nuclei), but straightforward to calculate; higher-order corrections (due to multiple W-boson exchanges) are small:



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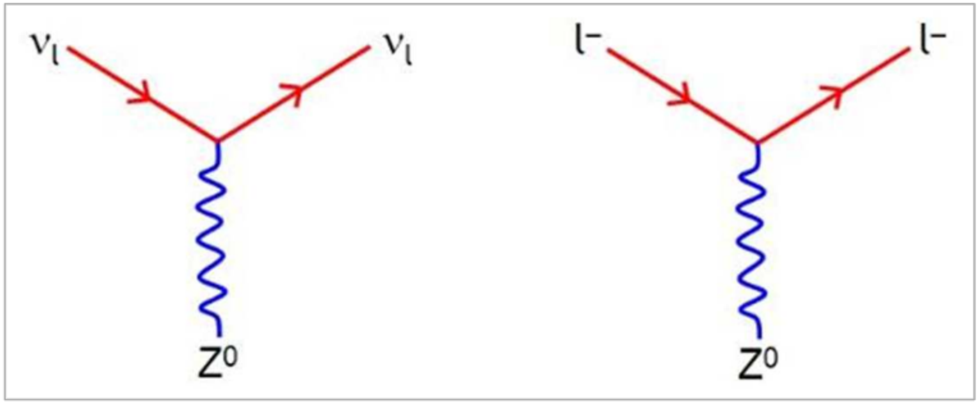
FUNDAMENTAL INTERACTIONS – WEAK

Details

Neutral-current interactions – the Z-exchange of leptons (I)

While the leptonic weak charged current (W) carries away electric charge and transforms a charged lepton into a neutral lepton, the **leptonic weak neutral current** (Z^0) changes neither electric charge nor mass:



Z^0 interactions are extremely difficult to investigate experimentally, since the electromagnetic interaction competes if charges are involved

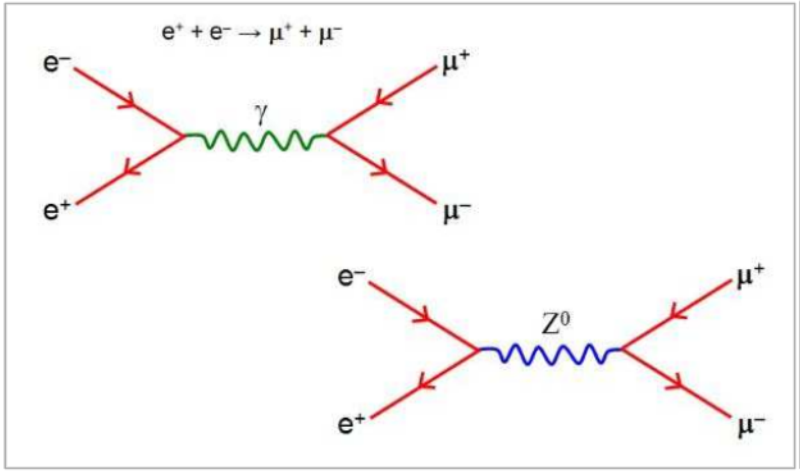
FUNDAMENTAL INTERACTIONS – WEAK

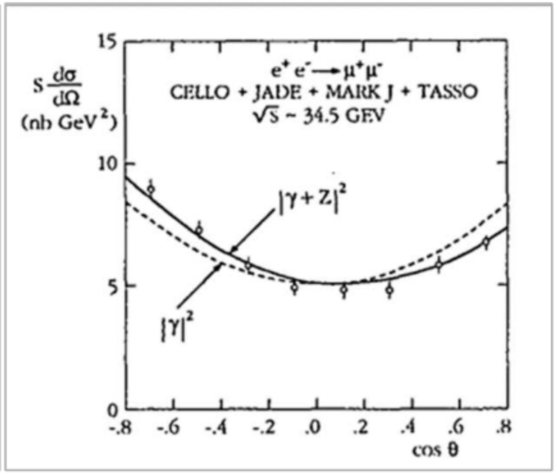
Details

Neutral-current interactions – the Z-exchange of leptons (II)

On the other hand, **all electromagnetic processes** also have a (tiny) **weak neutral-current component**:

Example:





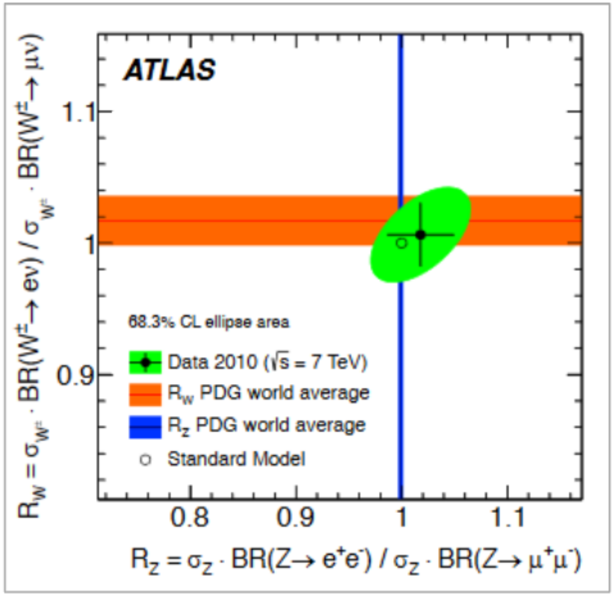
(Note: the electromagnetic IA conserves, the **weak IA violates parity**; see later)

FUNDAMENTAL INTERACTIONS – WEAK

Details

Neutral-current interactions – the Z-exchange of leptons (III)

The **coupling g_Z** of the neutral weak gauge boson is also independent of the lepton flavor (lepton universality, LU):



Not a fundamental symmetry → searches for LU-violations are ongoing

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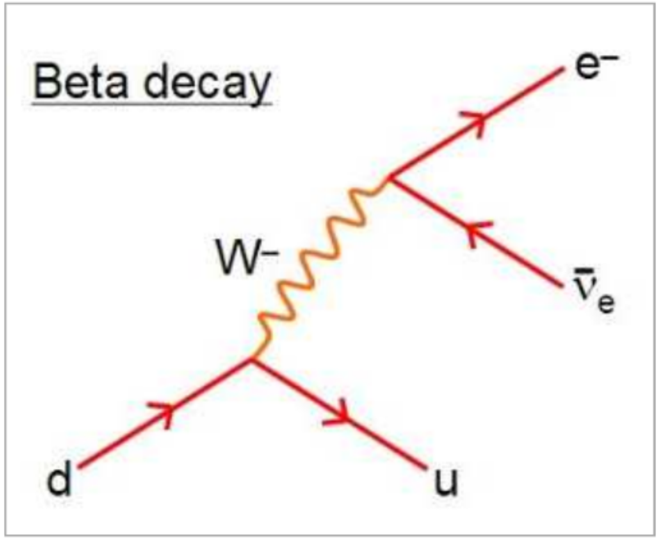
FUNDAMENTAL INTERACTIONS – WEAK

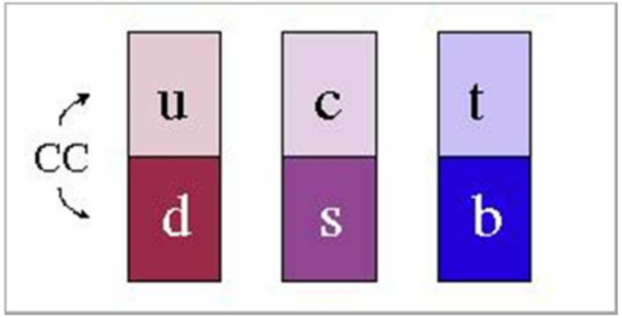
Details

Charged-current interactions – the W-exchange for quarks (I)

The **charged current vertices** change quark flavor; they connect **quarks (antiquarks)** of the **same family**:

Example:





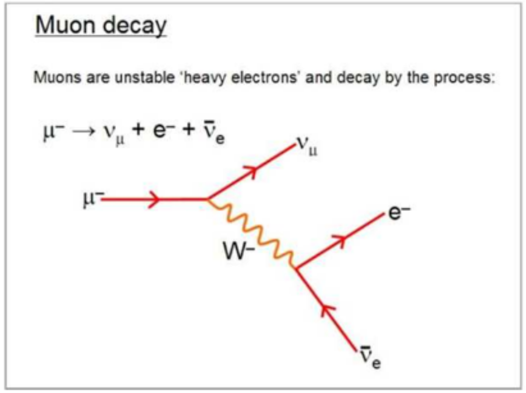
This is like for leptons (see above)!

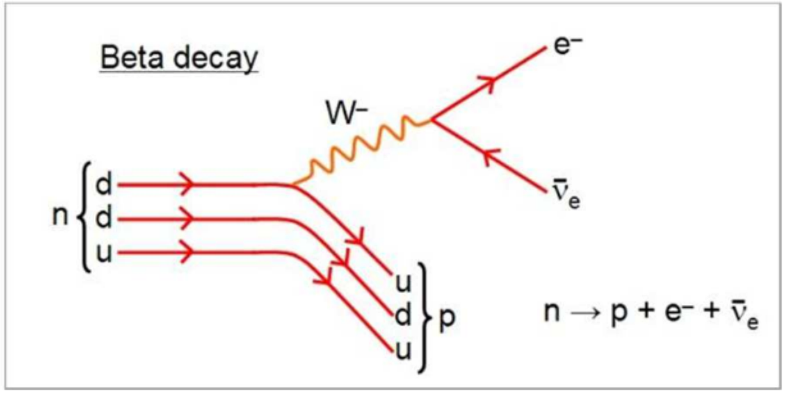
FUNDAMENTAL INTERACTIONS – WEAK

Details

Charged-current interactions – the W-exchange for quarks (II)

The **coupling constant** (Fermi G_F ←→ weak g_w) in muon decay and in nuclear β-decay – are they **the same**?





Experimentally, one finds: $G_F(\beta)/G_F(\propto) = 0.974(3)$, i.e. **charged weak currents** are **almost** (but not quite!) **equal** for **leptons** and **up/down quarks**!

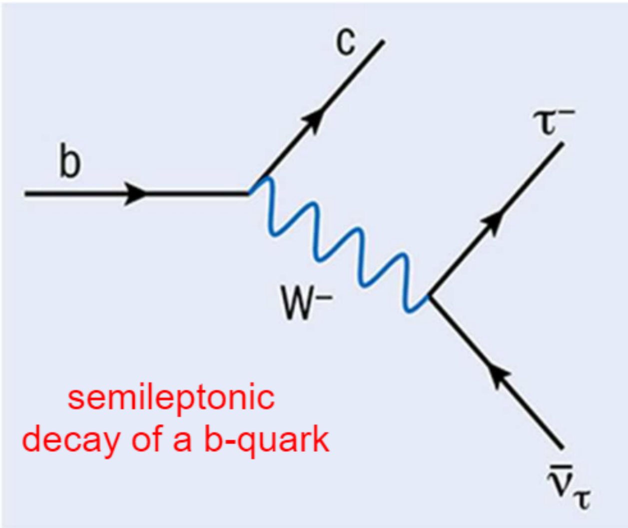
FUNDAMENTAL INTERACTIONS – WEAK

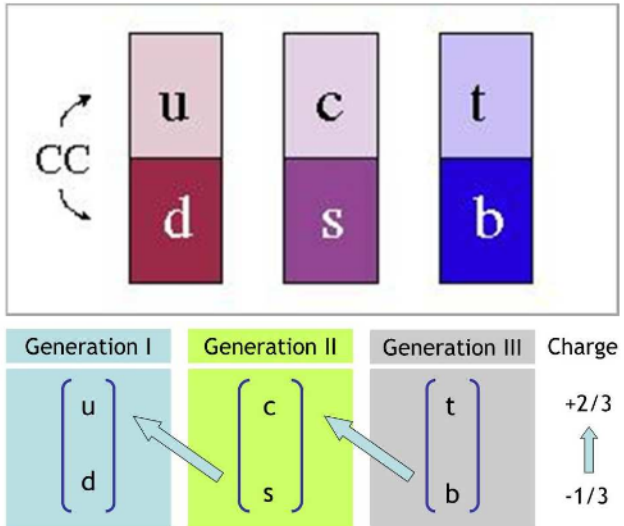
Details

Charged-current interactions – the W-exchange for quarks (III)

The **charged current vertices** also connect **quarks (antiquarks)** of **two different families**:

Example:





This is **not seen for leptons**!

FUNDAMENTAL INTERACTIONS – WEAK

Details

Charged-current interactions – the W-exchange for quarks (IV)

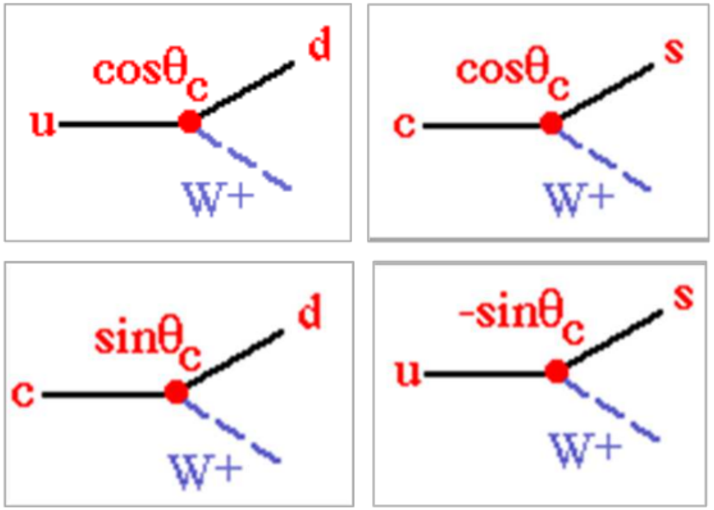
The **coupling constants** at quark-W vertices are **not always the same**; coupling **within a generation**/family is different from coupling of quarks of **two separate generations** (note: when this was first discovered, only 2 generations (u,d,s) were known): parametrized by an **angle** θ_c

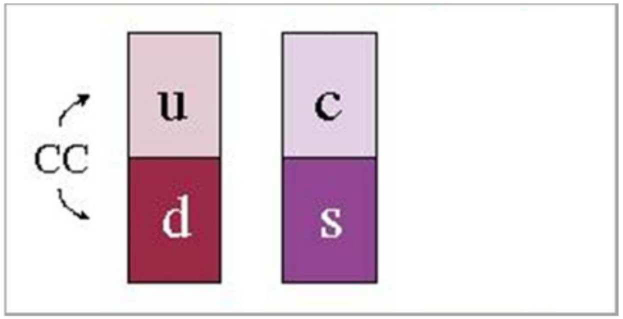
u-d

c-s

c-d

u-s





FUNDAMENTAL INTERACTIONS – WEAK

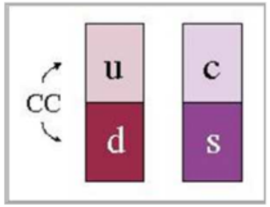
Details

Charged-current interactions – the W-exchange for quarks (V)

Nicola Cabibbo introduced the so called "**Cabibbo angle**" (θ_c) in 1963 to preserve the universality of the weak interaction; the object that couples to the up quark via charged-current weak interaction is a superposition of **down-type quarks** (denoted by d′):

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

or (with θ_c): $$d' = \cos\theta_c\, d + \sin\theta_c\, s$$



When the **charm quark** was discovered in 1974, it was noticed that the down and strange quark could decay into either the up or charm quark, leading to: $$s' = V_{cd}\, d + V_{cs}\, s$$

$$s' = -\sin\theta_c\, d + \cos\theta_c\, s$$

FUNDAMENTAL INTERACTIONS – WEAK

Details

Charged-current interactions – the W-exchange for quarks (VI)

In matrix notation, this is written as (“Cabibbo matrix”):

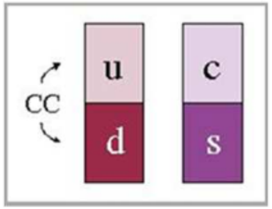
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$M = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix}$$

What it means, is: there is a **difference** is how the electromagnetic and the strong interactions “see” quarks (the so called “**mass eigenstates**”) and how the weak interactions does (“**weak eigenstates**”); for the latter the weak eigenstates are a mixture of the mass eigenstates;

Convention:

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = M \begin{pmatrix} d \\ s \end{pmatrix}$$



$$\begin{pmatrix} u' \\ c' \end{pmatrix} = M \begin{pmatrix} u \\ c \end{pmatrix}$$

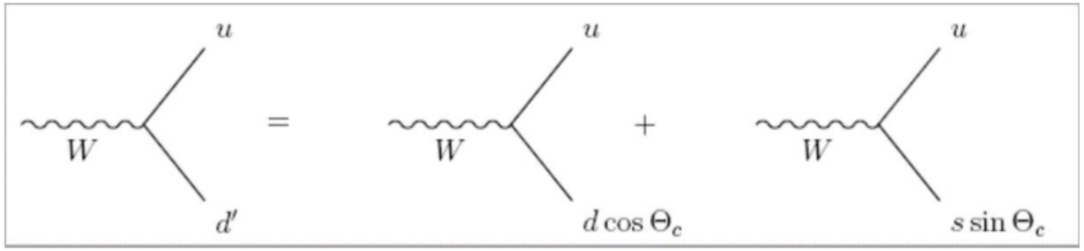
FUNDAMENTAL INTERACTIONS – WEAK

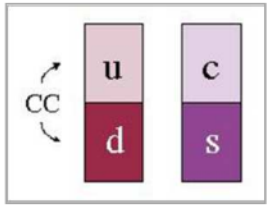
Details

Charged-current interactions – the W-exchange for quarks (VII)

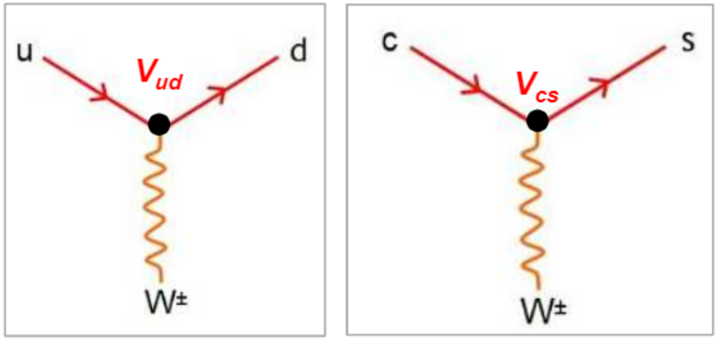
Bottomline: one may look at **weak vertices** in two different (equivalent) ways:

(i) mixing:





(ii) coupling:



Note: the Cabibbo-angle is experimentally found to be **$\theta_c \sim 13°$**

THE FORCES

Stop here for today

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