An introduction to Particle Physics

Wolfgang Pauli
(1900-1958)

The **Standard Model** describes the fundamental constituents of all matter, and how these distinct entities interact. Essentially, all matter consists of **Fermions** and **Bosons**. Fermions have a quantum mechanical property called **spin**, and **Fermions have half-integer-spin**. The ***Pauli Exclusion principle*** means that **two or more Fermions *cannot* occupy the same quantum state.** Fermions comprise **Leptons** (**electrons**, **muons**, **tau** particles + respective **neutrinos**) and **Hadrons** (e.g. **protons**, **neutrons**). Whereas Leptons are thought to be fundamental particles, Hadrons are combinations of **quarks**. There are six quarks (**up, down, charmed, strange, top, bottom**).

All charged particles have ***anti-particles*** too, which are identical apart from a change in sign of charge (and hence *energy*).

In the Standard Model, Hadrons come in *two* variants. **Mesons** are pairs of quarks and anti-quarks (or linear combinations of these pairs) whereas **Baryons** are a triplet of quarks. Other more exotic groupings (such as a 'penta-quark' have been theorized).

Peter Higgs
(1929-)

Fermions interact via the exchange of integer-spin particles called **Bosons**. These are associated with a particular type of **fundamental force**. **Electromagnetic forces** are associated with the exchange of **photons** γ, i.e. 'energy quanta.' **Quantum Electrodynamics (QED)** is the body of theory which describes the action of this force. **Weak nuclear forces** (which drive radioactive decay) mediate via the exchange of $\mathbf{W^+, W^-}$ and $\mathbf{Z^0}$ bosons. Unlike the photon, *these particles have mass*. This places a significant constraint on the range of these forces (i.e. constrains them to nuclear dimensions of the order of 10^{-15}m). Inside the nucleus, the **Strong** force dominates. This is mediated by eight types of **gluon**, which can be described as a combination of **red**, **green** and **blue** 'colours' (plus *anti-colours*). These can be thought of as a type of 'colour charge', *distinct from electric charge* which is the source of the electromagnetic force. **Quantum Chromodynamics (QCD)** is the body of theory which describes the action of the strong nuclear force. Gravity is the 'odd one out'. Incorporation of gravitation (and its modern description as **General Relativity**) into a **Quantum Mechanical** framework is still an active area of research. If it does behave at a fundamental level via particle exchange, the '**graviton**' is the particle. There is also the **Higg's Boson** (discovered at CERN 2011-2013) which is associated with the attribution of **mass** to particles.

Fermions (half-integer spin) → **Leptons** (e, μ, τ + neutrinos)

Fermions (half-integer spin) → **Quarks** (u,d,c,s,t,b) → **Hadrons**

Hadrons → **Baryons** (*quark triplet* e.g proton which is uud, neutron, which is udd)

Hadrons → **Mesons** (*quark and anti-quark pair* e.g. **pion** or a **kaon**).

Bosons (integer spin) e.g. **photon, W+,W- and Z^0, gluon**, **Higgs**, **graviton** (?)

QCD ← Murray Gell-Mann
(1929-)

The four fundamental interactions of nature https://en.wikipedia.org/wiki/Standard_Model

Property/Interaction	Gravitation	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass - Energy	Flavor	Electric charge	Color charge	Atomic nuclei
Particles experiencing:	All	Quarks, leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Not yet observed (Graviton hypothesised)	W^+, W^- and Z^0	γ (photon)	Gluons	π, ρ and ω mesons
Strength at the scale of quarks:	10^{-41}	10^{-4}	1	60	Not applicable to quarks
Strength at the scale of protons/neutrons:	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Note Particle Physics is really ***"High Energy Physics"***. This is when the **kinetic energy** of the particles is equivalent to the **rest mass energy** of the particles.

Chemical processes have energies of a **few eV.**

Nuclear process have energies of a few **MeV.**

High Energy processes have energies of **GeV** or more.

$$\frac{1}{\sqrt{2}}\left(r\bar{b}+b\bar{r}\right) \quad \frac{1}{\sqrt{2}}\left(r\bar{g}+g\bar{r}\right) \quad \frac{1}{\sqrt{2}}\left(b\bar{g}+g\bar{b}\right) \quad \frac{1}{\sqrt{2}}\left(r\bar{r}-b\bar{b}\right)$$

$$-\frac{i}{\sqrt{2}}\left(r\bar{b}-b\bar{r}\right) \quad -\frac{i}{\sqrt{2}}\left(r\bar{g}-g\bar{r}\right) \quad -\frac{i}{\sqrt{2}}\left(b\bar{g}-g\bar{b}\right) \quad \frac{1}{\sqrt{6}}\left(r\bar{r}+b\bar{b}-2g\bar{g}\right)$$

Eight possible **gluon** quantum states, involving r,g,b (and anti-colour) *colour charges.* These are set up to be independent, and also *cannot be combined* to make a singlet state, which is not allowed.

Not allowed! $\boxed{\frac{1}{\sqrt{3}}\left(r\bar{r}+b\bar{b}+g\bar{g}\right)}$

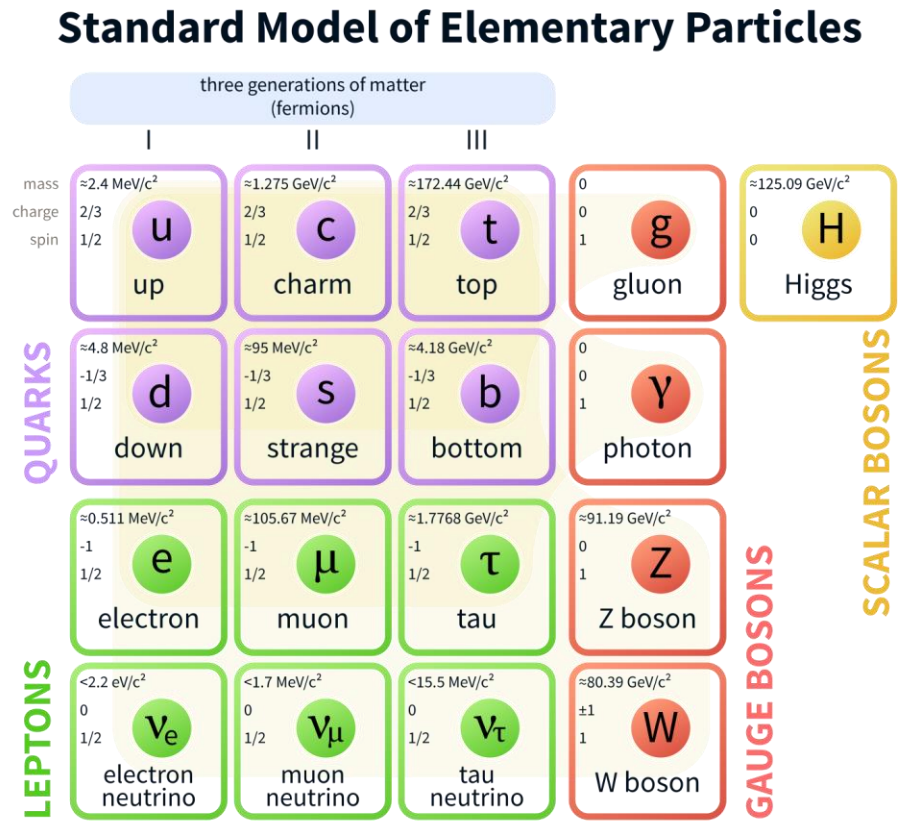
University of California Particle data group (PDG)
http://pdg.lbl.gov/index.html

How many hadrons in the Standard model?

Leptons: Three particles & antiparticles, plus three associated neutrinos & anti-neutrinos.
LEPTON TOTAL = **12**

Mesons: Six quarks + six anti-quarks. Therefore 6 x 6 = 36 possible quark + anti-quark pairs.
Note various linear combinations are possible, so this could easily double, more if triple pairs are allowed.
MESON TOTAL = **64** (?)

Baryons: From six quarks and their anti-quarks, there are ${}^{12}C_3$ = 220 possible triplets. The top quark's mass probably makes combinations unpractical, so this would reduce the number to ${}^{10}C_3$ = 120.
Interestingly http://www.thingsmadethinkable.com/item/baryons.php yields **150**, so this presumably includes some allowed linear combinations.



https://en.wikipedia.org/wiki/Particle_physics#/media/File:Standard_Model_of_Elementary_Particles.svg

Particle	Symbol	Type	Quark composition	Mass / MeV/c²	Max angular momentum	Charge /e	Lifetime /s
electron	e	lepton	-	0.51	1/2	-1	stable
muon	μ	lepton	-	105.7	1/2	1	2.2×10^{-6}
tau	τ	lepton	-	1776.8	1/2	1	2.9×10^{-6}
proton	p	hadron: baryon	uud	938.3	1/2	1	stable
neutron	n	hadron: baryon	udd	939.6	1/2	0	8.8×10^{2}
xi	Ξ^0	hadron: baryon	uss	1314.9	1/2	0	2.9×10^{-10}
lambda	Λ^0	hadron: baryon	uds	1115.7	1/2	0	2.6×10^{-10}
sigma	Σ^-	hadron: baryon	dds	1197.4	1/2	-1	1.5×10^{-10}
omega	Ω^-	hadron: baryon	sss	1672.5	3/2	-1	8.2×10^{-11}
pion	π^+	hadron: meson	$u\bar{d}$	139.6	0	1	2.6×10^{-8}
kaon	K^+	hadron: meson	$u\bar{s}$	493.7	0	1	1.2×10^{-8}

A selection of **leptons**, **baryons** and **mesons** with their quark compositions, masses, charge etc.

Note **angular momentum** is in units of $\hbar$

Most of the other particles have such short lifetimes that they can only be observed in the detectors associated with particle accelerators such as the **Large Hadron Collider** in CERN.

$$c = 299,792,458\,\mathrm{ms}^{-1}$$
$$e = 1.60217662 \times 10^{-19}\,\mathrm{C}$$
$$\hbar = 1.0545718 \times 10^{-34}\,\mathrm{m^2kgs^{-1}}$$

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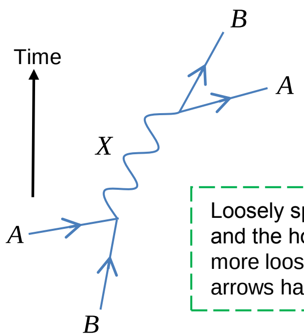
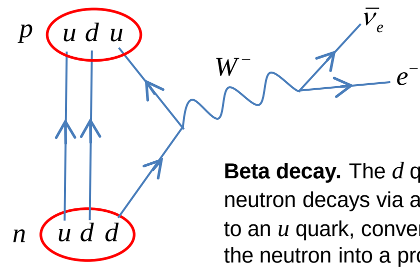
Feynman diagrams are a pictorial way of representing particle physics interactions, such as beta decay. Although a single diagram may be characteristic of a process, it must be noted that a (possibly infinite) series of branching diagrams is the 'complete' representation. Each Feynman diagram represents one term in a series which leads to the **probability** (and total **energy** change) of an interaction.



Interactions always occur **bottom** to **top*** – this is 'the arrow of time'. In the example on the left, particles A and B interact via exchange of boson X.

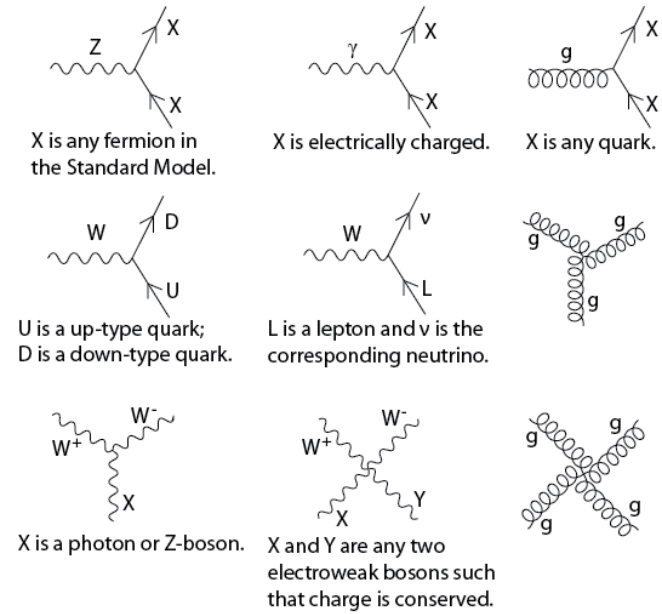
Loosely speaking, the vertical axis* represents 'time', and the horizontal 'space', although the latter has a more loose meaning, as the angles and lengths of the arrows have no particular significance.



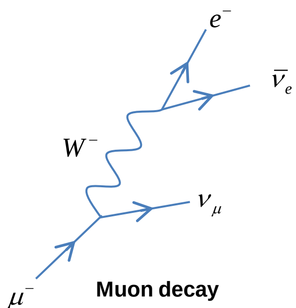
Beta decay. The d quark of a neutron decays via a W- boson to an u quark, converting the neutron into a proton. The W- boson decays into an electron and electron anti-neutrino.

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

Standard Model Interactions (Forces Mediated by Gauge Bosons)

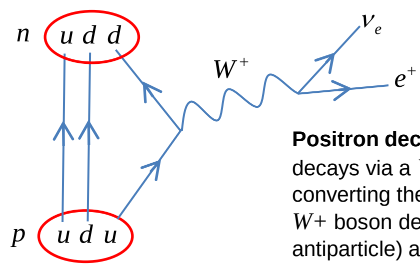


https://en.wikipedia.org/wiki/Standard_Model#/media/File:Standard_Model_Feynman_Diagram_Vertices.png



Muon decay

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



Positron decay. The u quark of the proton decays via a W+ boson to a d quark, converting the proton into a neutron. The W+ boson decays to a positron (electron antiparticle) and electron neutrino.

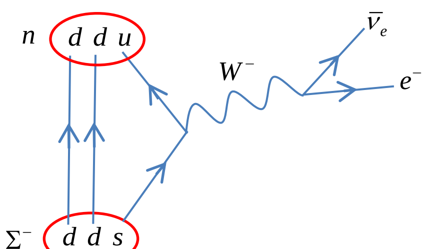
$\boxed{p \rightarrow n + e^+ + \nu_e}$

Baryon (i.e. number of quarks) and Lepton number is also conserved. A *negative* number for antiparticles.

NOTE CHARGE CONSERVATION AT EACH VERTEX OF THE FEYNMAN DIAGRAM

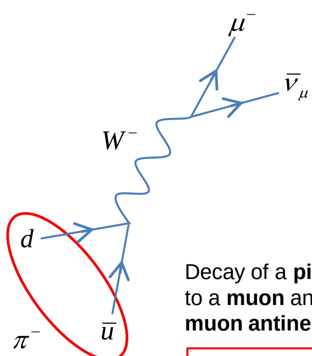
quark	u	d	c	s	t	b
charge /e	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$

Reverse charge sign for anti-quarks



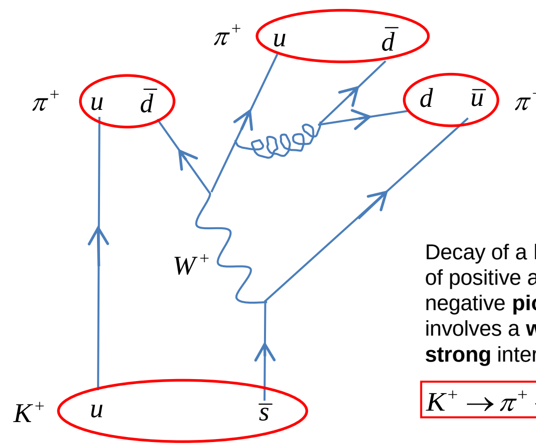
'Beta decay' of a **sigma particle**

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



Decay of a **pion** to a **muon** and **muon antineutrino**

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



Decay of a **kaon** to a pair of positive and one negative **pions**. Note this involves a **weak** *and* a **strong** interaction

$\boxed{K^+ \rightarrow \pi^+ + \pi^+ + \pi^-}$

Richard Feynman (1918-1988)

*In other texts, time corresponds to the *horizontal* axis

What particle physics interactions are allowed?
The **Feynman diagram** (or equivalent) gives a mechanism for working out the **probability** of a given interaction. There are a number of rules which appear to govern which interactions are allowed, although sometimes these rules are broken! At present there is *no agreed theory* which explains the masses of all particles in the Standard Model from much simpler components, so one should conclude that it is still an active research area!

CPT violations
In particle physics, interactions are often described in terms of **violation of C,P,T** (or all three).
C means **Charge Conjugation**. i.e. replace a particle with its **antiparticle**, change the charge sign and *everything else remains the same.*
P means **Parity**. Swap any negative signs in the description of the quantum state and *everything remains the same otherwise.*
T means **Time reversal**. Run the interaction right to left, and *everything remains the same.*

Charge, **spin** and **colour charge** ought to be **conserved** quantities, but since particle physics is *high energy* **momentum**, **mass** and **energy** are related via the relativistic invariant:

$$\boxed{E^2 - |\mathbf{p}|^2 c^2 = m^2 c^4}$$

So particle **mass** can be converted into **energy** and vice versa.

Baryon (i.e. number of quarks) and **Lepton** number is also conserved

Conservation of c, s *or* b quarks appears to be a rule of sorts, or indeed a restriction to +/- changes of these numbers

Particle Physics interactions also obey **Quantum rules**, i.e. *energy,time* and *momentum, position* are related by the **Uncertainty Principle.** This allows us to make approximate calculations regarding the lifetime and distance travelled by a massive boson such as a W^+.

$$\Delta E \Delta t \geq \hbar$$
$$\Delta p \Delta x \geq \hbar$$

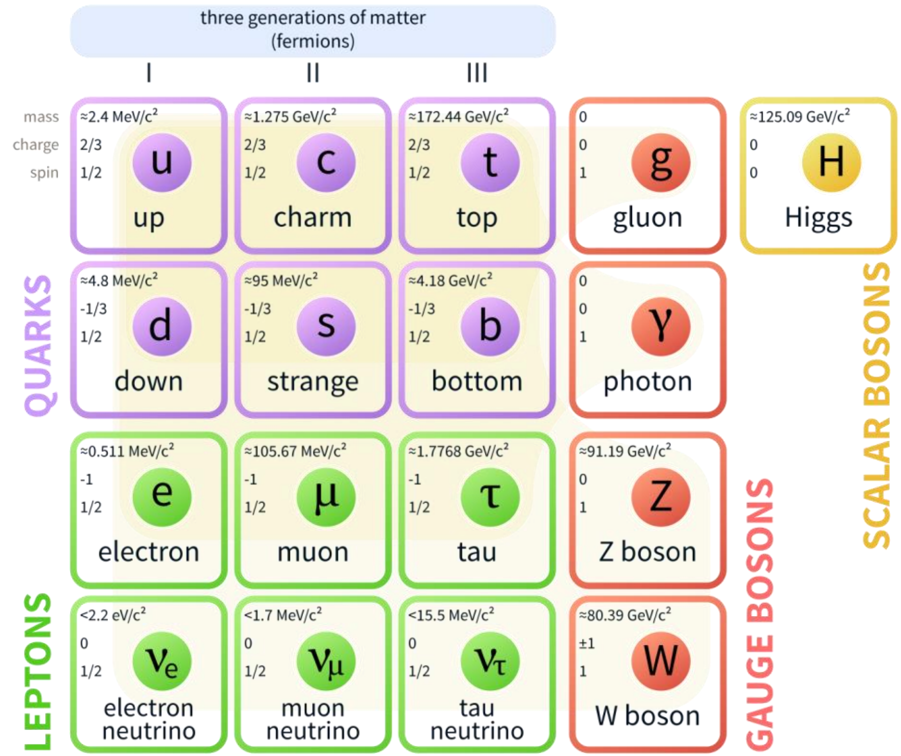
$$\Delta E \approx m_X c^2 \quad \therefore \Delta t \approx \frac{\hbar}{m_X c^2}$$
$$\Delta p \approx m_X c \quad \therefore \Delta x \approx \frac{\hbar}{m_X c}$$

$$m_{W^\pm} = \frac{80.39 \times 10^9 \times 1.602 \times 10^{-19}}{(2.998 \times 10^8)^2} = 1.433 \times 10^{-25}\,\text{kg}$$

$$\therefore \Delta t \approx \frac{\hbar}{m_X c^2} = 8.19 \times 10^{-27}\,\text{s}$$ i.e. a very small time!

$$\therefore \Delta x \approx \frac{\hbar}{m_X c} = 2.45 \times 10^{-18}\,\text{m}$$ i.e. sub-atomic distances

Standard Model of Elementary Particles



$$c = 299{,}792{,}458\,\text{ms}^{-1} \quad e = 1.60217662 \times 10^{-19}\,\text{C} \quad \hbar = 1.0545718 \times 10^{-34}\,\text{m}^2\text{kgs}^{-1}$$

Yukawa potential
The Schödinger Equation (for *spinless* particles) can be extended in a relativistic sense using the energy-momentum invariant, rather than the classical total energy = kinetic energy + potential energy. This yields the **Klein-Gordon equation** for wavefunction ψ

$$\boxed{-\hbar^2 \frac{\partial^2 \psi}{\partial t^2} = -\hbar^2 c^2 \nabla^2 \psi + m_X^2 c^4 \psi}$$

The *time invariant* version can accept potentials of the **Yukawa** form:

$$\boxed{V(r) = -\frac{g^2}{4\pi}\frac{e^{-r/R}}{r}} \quad R \propto \frac{\hbar}{m_X c}$$

g is the 'strength' of the interaction, which can be related to the electromagnetic force via the dimensionless ratio:

$$\alpha_X = \frac{g^2}{4\pi\hbar c}$$
$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \approx \frac{1}{137}$$

Fine structure constant

The Yukawa potential helps to explain why **strong** or **weak** interactions via **massive bosons** are *very short range* (i.e. nuclear dimensions) whereas **electromagnetic** or **gravitational** interactions have *essentially infinite range* since their associated bosons (photons, gravitons) are massless.

Hideki Yukawa (1907-1981)

The mysterious Koide formula

$$\frac{m_e + m_\mu + m_\tau}{\left(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau}\right)^2} \approx \tfrac{2}{3}$$

$$\frac{m_c + m_b + m_t}{\left(\sqrt{m_c} + \sqrt{m_b} + \sqrt{m_t}\right)^2} \approx \tfrac{2}{3}$$

$$\frac{0 + m_s + m_c}{\left(0 + \sqrt{m_s} + \sqrt{m_c}\right)^2} \approx \tfrac{2}{3}$$

This means strange and charmed quarks

Serendipity? Or a hint of something deeper?

Combining the lepton, or quark, masses yields an interesting result.

Note lots of uncertainty from me here too! This is at best a summary of key ideas. A good reference is: **Martin, Nuclear & Particle Physics. An Introduction**