PH102, 2012W, Lecture Notes: March 12, Mon, Class 23

Elementary particles and fundamental forces

In the modern view of physics, a fundamental force between particles is defined as an exchange of a mediating particle that is specific to that force. Some examples are:

- Gravitational force mediated by graviton (?)
- Electrostatic force mediated by photons
- Weak force mediated by W^+, W^-, and Z^0
- Strong force mediated by Gluon

The mediating particle is called a field quantum, and the study of field quanta in relation to their corresponding fundamental force is called "Quantum field theory."

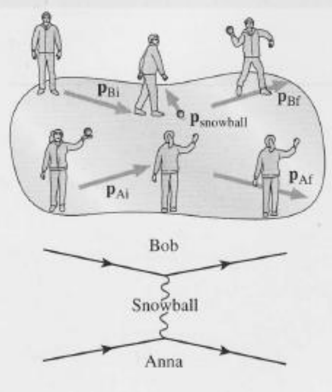
An analogy for exerting force by exchanging a particle: Snowball exchange

Figure 12.1 illustrates how exchanging a snowball between Bob and Anna can result in a force exerted on both Bob and Anna without direct contact. Anna and Bob are sliding with initial momenta of $\vec{p}_{Bob}$ and $\vec{p}_{Anna}$ on a frictionless frozen pond. Anna has a snowball and throws it to Bob while sliding. This changes Anna's momentum as well as Bob's momentum as follows:

$$\vec{p}_{Anna(after\ snowball\ throwing)} = \vec{p}_{Anna} - \vec{p}_{snowball}$$

$$\vec{p}_{Bob\ (after\ snowball\ receiving)} = \vec{p}_{Bob} + \vec{p}_{snowball}$$

Figure 12.1 A force between students conveyed by exchange of a snowball.



The force exerted on both Bob and Anna is repulsive as both of them move away from each other. A Feynman diagram is shown this exchange.

This snowball analogy has limitations if it is to apply to fundamental forces:

- It does not show attractive force.
- For fundamental forces, mediating particles only exist during their exchange.
- Mediating particles do not obey the usual momentum and energy rules in the way that real particles do, thus called "virtual particles."

The range of force for mediating particles

- From the uncertainty principle $\Delta t \Delta E \approx \hbar$
- A particle of energy ΔE can exist without violating energy conservation as long as it exists less than $\Delta t \approx \frac{\hbar}{\Delta E}$.
- Consider ΔE is the energy of the mediating particle created and exchanged when the force is exerted, then $\Delta E = mc^2$

$$\Delta t \approx \frac{\hbar}{\Delta E} \approx \frac{\hbar}{mc^2}$$

- Range (Δx) becomes

$$\Delta x \approx c\Delta t \approx \frac{\hbar}{c}\frac{1}{m}$$

From this result, we can see that if a mediating particle has a mass, the range of force is limited. If a mediating particle has no mass, the corresponding force is long ranged. Consider photons in the electromagnetic force.

Antiparticles

- For each kind of particle, there is an antiparticle that shares all the properties of the particle except it is of opposite charge, e.g. electron and positron, proton and antiproton, neutron and antineutron.
- A common notation for an antiparticle is a bar over the notation of particle, e.g. $p\ and\ \bar{p}, n\ and\ \bar{n}$. Sometimes, + and – are used: $e^{-} and\ e^{+}, \mu^{+} and\ \mu^{-}$.
- Particles and their antiparticles can be created together by pair production and can disappear by pair annihilation after producing photon energy equal to their mass energy.
- Antiparticles are detected experimentally.
- Relativistic quantum mechanics provides a theoretical basis for the existence of antiparticles.

Use the following relationship from relativity

$$E = mc^2$$

$$E^2 = m^2c^4 = \frac{{m_0}^2c^4}{1-\frac{v^2}{c^2}} = {m_0}^2c^4\left(\frac{1}{1-\frac{v^2}{c^2}}\right) = {m_0}^2c^4\left(\frac{1}{1-\frac{v^2}{c^2}} - 1 + 1\right)$$

$$= {m_0}^2c^4 + {m_0}^2c^4\left(\frac{\frac{v^2}{c^2}}{1-\frac{v^2}{c^2}}\right) = {m_0}^2c^4 + c^2v^2\frac{{m_0}^2}{1-\frac{v^2}{c^2}} = {m_0}^2c^4 + c^2v^2m^2 = {m_0}^2c^4 + p^2c^2$$

Therefore,

$$E^2 = {m_0}^2c^4 + p^2c^2$$

Using operator notations

$p = -i\hbar\nabla$ and $E = i\hbar\frac{\partial}{\partial t}$

$$E^2\psi = {m_0}^2c^4\psi + p^2c^2\psi$$

$$-c^2\hbar^2\nabla^2\psi + {m_0}^2c^4\psi = -\hbar^2\frac{\partial^2}{\partial t^2}\psi$$

This equation is called the Klein-Gordon equation which can predict the behavior of spinless massive particles at all speeds. For particles with spin, use Dirac Equation where spin is incorporated into the Dirac Equation.

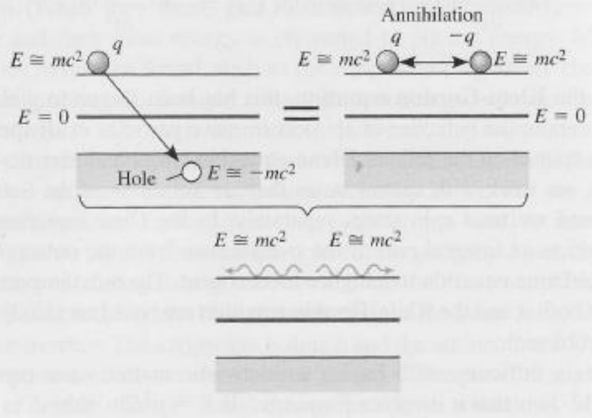
Compare Schrodinger Equation and Klein-Gordon Equation for free particles

	Schrodinger Equation	Klein-Gordon Equation
Energy relation	$E = T$	$E^2 = {m_0}^2c^4 + p^2c^2$
Equation	$-\frac{\hbar^2}{2m}\nabla^2 \psi = i\hbar\frac{\partial\psi}{\partial t}$	$-c^2\hbar^2\nabla^2\psi + {m_0}^2c^4\psi = -\hbar^2\frac{\partial^2}{\partial t^2}\psi$
Energy	Since $E = \frac{p^2}{2m}$, E is positive	Both positive and negative E values can satisfy the equation.
$\psi^*\psi$	Does not change with time	Changes with time.
Interpretation of $\psi^*\psi$	Probability density of finding a particle in space.	If $\psi^*\psi$ is set in such a way that it does not change with time, then it should be interpreted as Charge density since $\psi^*\psi$ over time remains constant but may be of either charge. The positive energy solution is for a particle while the negative energy solution is for its antiparticle.

It can be considered that the antiparticle state is similar to a hole in a sea of allowed but usually filled negative-energy states of the particle. Figure 12.2 shows that

- the sea of filled antiparticle states will not be detectable.
- A particle can be annihilated when a hole (an antiparticle state) is available (i.e. its antiparticle exists), emitting photon energy of twice the energy of the particle.

Figure 12.2 Whether a positive-energy particle drops into an empty negative-energy state, or two positive-energy particles annihilate, the result is the same.



Fundamental forces

The unified theory is intended to describe all interactions as different aspects of a single fundamental interaction. Why we believe this might be the case:

- Fundamental particles experiencing a force are fermions and mediating particles for the force are bosons.
- For a fermion to engage in a force, the fermion has a property associated with the force:
  - Mass/energy for gravitational force
  - Charge or weak charge for electroweak force
  - Color charge for strong force

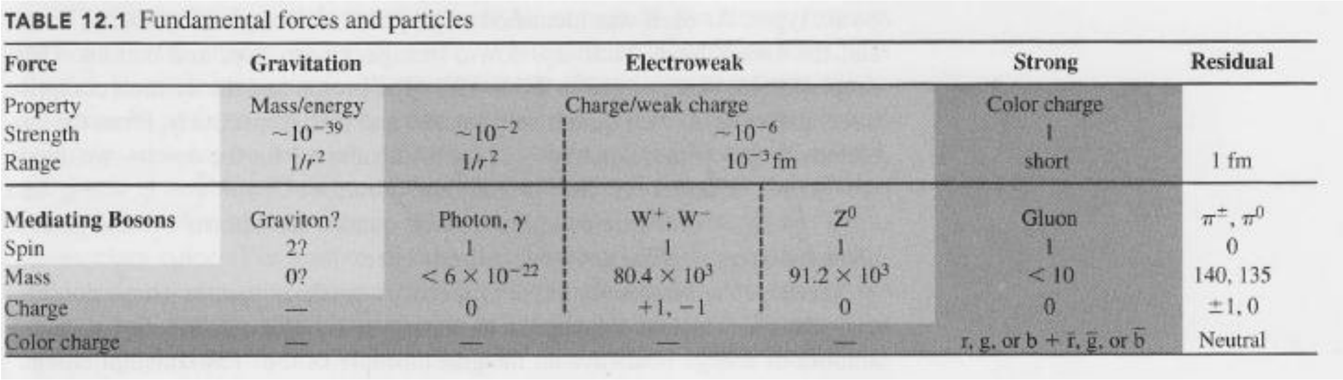
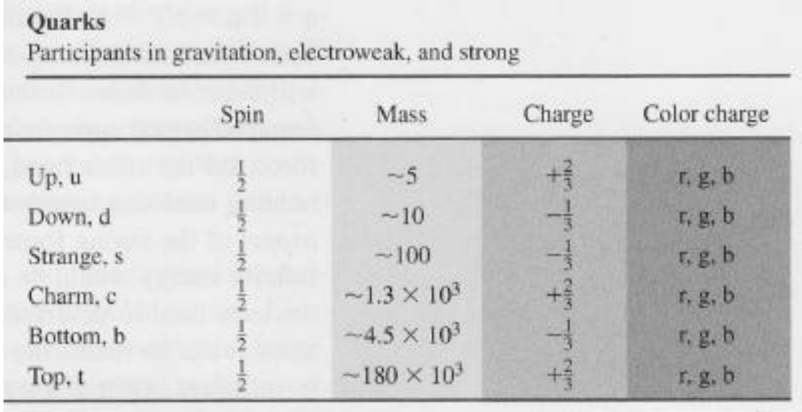


TABLE 12.1 Fundamental forces and particles

Force	**Gravitation**	**Electroweak**			**Strong**	**Residual**
Property	Mass/energy	Charge/weak charge			Color charge	
Strength	$\sim 10^{-39}$	$\sim 10^{-2}$	$\sim 10^{-6}$		1	
Range	$1/r^2$	$1/r^2$	10^{-3} fm		short	1 fm
Mediating Bosons	Graviton?	Photon, γ	W^+, W^-	Z^0	Gluon	$\pi^{\pm}, \pi^0$
Spin	2?	1	1	1	1	0
Mass	0?	$< 6 \times 10^{-22}$	80.4×10^3	91.2×10^3	< 10	140, 135
Charge	—	0	$+1, -1$	0	0	$\pm 1, 0$
Color charge	—	—	—	—	r, g, or b + $\bar{\text{r}}$, $\bar{\text{g}}$, or $\bar{\text{b}}$	Neutral

Strong Force

- Protons and neutrons that make up a nucleus are not fundamental particles. They are made up of quarks that are bound by the strong force.



Quarks
Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	r, g, b
Down, d	$\frac{1}{2}$	~10	$-\frac{1}{3}$	r, g, b
Strange, s	$\frac{1}{2}$	~100	$-\frac{1}{3}$	r, g, b
Charm, c	$\frac{1}{2}$	$\sim 1.3 \times 10^3$	$+\frac{2}{3}$	r, g, b
Bottom, b	$\frac{1}{2}$	$\sim 4.5 \times 10^3$	$-\frac{1}{3}$	r, g, b
Top, t	$\frac{1}{2}$	$\sim 180 \times 10^3$	$+\frac{2}{3}$	r, g, b

- Six types of quarks exist: up, down, strange, charm, bottom and top. See the Table on the right.
- Quarks have a spin of ½, have mass, have either +2/3 or -1/3 charge.
- Hadrons are particles made up of quarks. For example,
  - Proton (uud)=spin ½ and charge +1 $\left(=\frac{2}{3}+\frac{2}{3}-\frac{1}{3}\right)$
  - Neutron (udd)=spin ½ and charge 0 $(=\frac{2}{3}-\frac{1}{3}-\frac{1}{3})$
- Quarks are not separable, making a fundamental charge of $e = 1.6 \text{ x } 10^{-19}$C safe.
- The internal structure of a nucleon (thus quark existence) is shown by deep inelastic scattering experiments where high energy electrons (greater than 20 GeV and a scattering length of 0.1 fm, smaller than the size of a nucleus).
- Gluons are the mediating boson of the strong force and have spin-1 and massless.
- The property quarks need to have to carry the strong force is color (charge).
  - Three color charge types: red, blue, and green.
  - Each color has anti-color charge: antired, antiblue, and antigreen
  - Only quarks possess charge color so only quarks carry the strong force.
  - Gluons carry a color-anticolor pair of color charge (e.g. blue-antigreen) and thus interact with one another. This makes the strong force different from electroweak force where photons do not carry charge and do not interact with one another.
  - Hadrons are color charge neutral, but there are attractions in a color charge neutral system, similarly to that atoms are charge neutral but there is attraction in a charge neutral system.
  - Hadrons are color charge neutral
    - Three quarks that carry one of each color (blue+red+green=neutral)
    - Quark (color)-antiquark (anticolor) pair (red +antired=neutral)

- Gluons are not separable and thus colors are not separable
- The study of strong interactions is called quantum chromodynamics (QCD).
- Though a nucleon consists of three quarks, the nucleon mass cannot be just consisting of three quark masses. The nucleon mass should also account for the sizable cloud of energetic gluons and virtual quark-antiquark pairs constantly undergoing creation and annihilation. This cloud consists of the majority of the nucleon mass.

Hadrons consist of quarks. There are six quarks and corresponding six antiquarks. Commonly produced hadrons are shown in Table 12.2.

- Baryons consist of three quarks: examples-proton and neutron
    - Most baryons are heavier than proton and neutron and short lived. For very short-lived Baryons energy width is used instead of time. An energy width of 50 MeV corresponds with a lifetime of 10^{-23} second.
- Mesons consist of two quarks: example: π mesons
    - $\pi^+ = u\bar{d}$, charge 2/3+1/3=+1; color should be red-antired or blue-antiblue or green-antigreen
    - $\pi^0 = u\bar{u} + d\bar{d}$, charge = 0 since a mixture of 2/3 and -2/3 as well as 1/3 and -1/3
    - $\pi^- = d\bar{u}$, this is antiparticle of π^+, thus opposite charge -

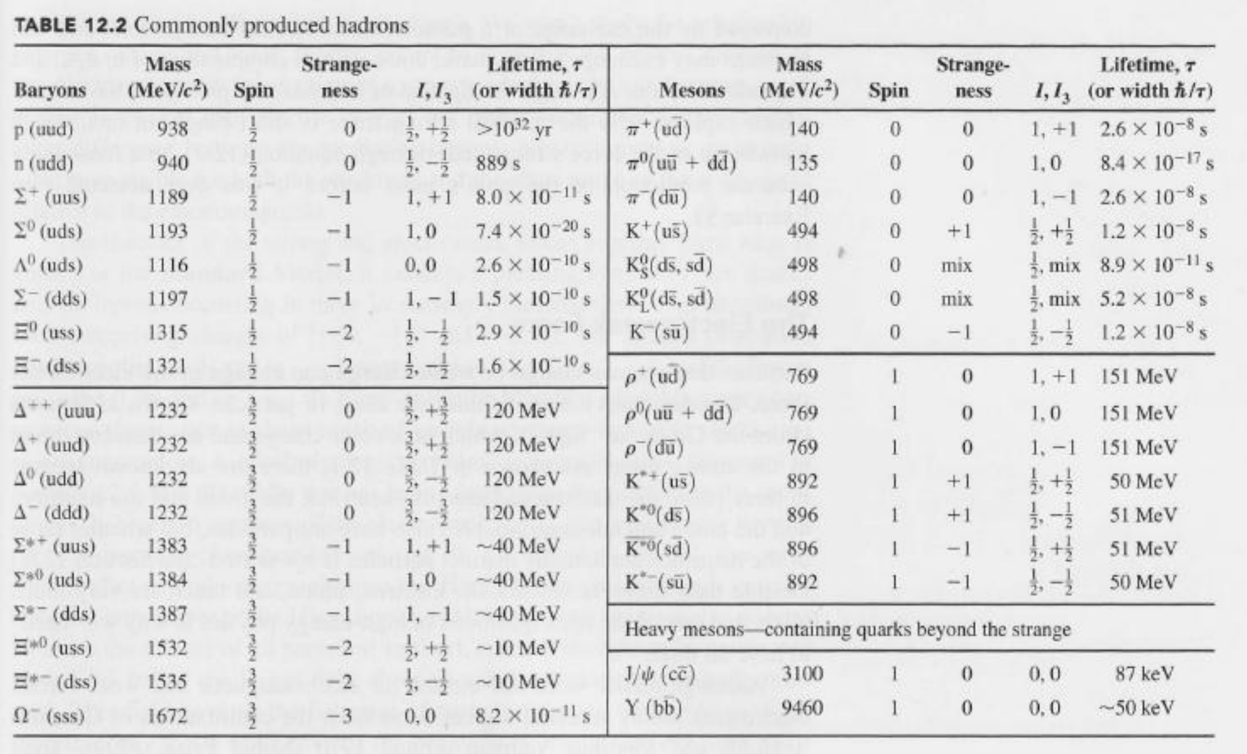


TABLE 12.2 Commonly produced hadrons

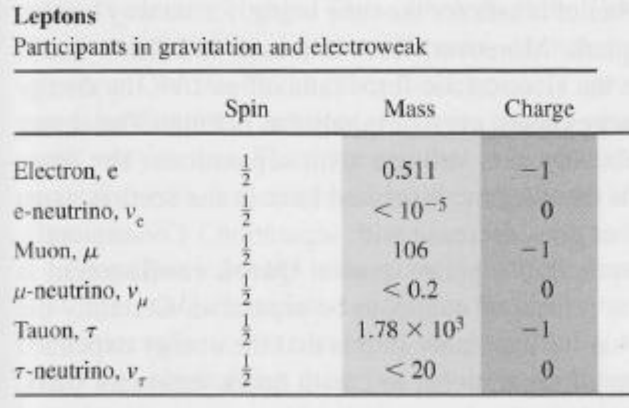
Baryons	Mass (MeV/c^2)	Spin	Strange-ness	I, I_3	Lifetime, τ (or width $\hbar/\tau$)	Mesons	Mass (MeV/c^2)	Spin	Strange-ness	I, I_3	Lifetime, τ (or width $\hbar/\tau$)
p (uud)	938	$\frac{1}{2}$	0	$\frac{1}{2}, +\frac{1}{2}$	$>10^{32}$ yr	$\pi^+(u\bar{d})$	140	0	0	1, +1	2.6×10^{-8} s
n (udd)	940	$\frac{1}{2}$	0	$\frac{1}{2}, -\frac{1}{2}$	889 s	$\pi^0(u\bar{u} + d\bar{d})$	135	0	0	1, 0	8.4×10^{-17} s
Σ^+ (uus)	1189	$\frac{1}{2}$	−1	1, +1	8.0×10^{-11} s	$\pi^-(d\bar{u})$	140	0	0	1, −1	2.6×10^{-8} s
Σ^0 (uds)	1193	$\frac{1}{2}$	−1	1, 0	7.4×10^{-20} s	$K^+(u\bar{s})$	494	0	+1	$\frac{1}{2}, +\frac{1}{2}$	1.2×10^{-8} s
Λ^0 (uds)	1116	$\frac{1}{2}$	−1	0, 0	2.6×10^{-10} s	$K^0_S(d\bar{s}, s\bar{d})$	498	0	mix	$\frac{1}{2}$, mix	8.9×10^{-11} s
Σ^- (dds)	1197	$\frac{1}{2}$	−1	1, − 1	1.5×10^{-10} s	$K^0_L(d\bar{s}, s\bar{d})$	498	0	mix	$\frac{1}{2}$, mix	5.2×10^{-8} s
Ξ^0 (uss)	1315	$\frac{1}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	2.9×10^{-10} s	$K^-(s\bar{u})$	494	0	−1	$\frac{1}{2}, -\frac{1}{2}$	1.2×10^{-8} s
Ξ^- (dss)	1321	$\frac{1}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	1.6×10^{-10} s	$\rho^+(u\bar{d})$	769	1	0	1, +1	151 MeV
Δ^{++} (uuu)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, +\frac{3}{2}$	120 MeV	$\rho^0(u\bar{u} + d\bar{d})$	769	1	0	1, 0	151 MeV
Δ^+ (uud)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, +\frac{1}{2}$	120 MeV	$\rho^-(d\bar{u})$	769	1	0	1, −1	151 MeV
Δ^0 (udd)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, -\frac{1}{2}$	120 MeV	$K^{*+}(u\bar{s})$	892	1	+1	$\frac{1}{2}, +\frac{1}{2}$	50 MeV
Δ^- (ddd)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, -\frac{3}{2}$	120 MeV	$K^{*0}(d\bar{s})$	896	1	+1	$\frac{1}{2}, -\frac{1}{2}$	51 MeV
Σ^{*+} (uus)	1383	$\frac{3}{2}$	−1	1, +1	~40 MeV	$\overline{K^{*0}}(s\bar{d})$	896	1	−1	$\frac{1}{2}, +\frac{1}{2}$	51 MeV
Σ^{*0} (uds)	1384	$\frac{3}{2}$	−1	1, 0	~40 MeV	$K^{*-}(s\bar{u})$	892	1	−1	$\frac{1}{2}, -\frac{1}{2}$	50 MeV
Σ^{*-} (dds)	1387	$\frac{3}{2}$	−1	1, −1	~40 MeV	Heavy mesons—containing quarks beyond the strange					
Ξ^{*0} (uss)	1532	$\frac{3}{2}$	−2	$\frac{1}{2}, +\frac{1}{2}$	~10 MeV						
Ξ^{*-} (dss)	1535	$\frac{3}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	~10 MeV	J/ψ $(c\bar{c})$	3100	1	0	0, 0	87 keV
Ω^- (sss)	1672	$\frac{3}{2}$	−3	0, 0	8.2×10^{-11} s	Υ $(b\bar{b})$	9460	1	0	0, 0	~50 keV

- Hadrons' Intrinsic Properties
    - Spin:
        - Since Baryons consist of three quarks, their spins can be either 3/2 or ½.
        - Since Mesons consist of two quarks, their spins can be either 1 or 0.

    - Isospin, (I, I_z): this is not an angular momentum, but treated similarly in terms of mathematical treatment.
        - Up and down quarks have I=1/2 and strange quark has I=0.
        - Isospin can differentiate $\Sigma^0$and Λ^0 where both has the same quark makeup uds and the same spin of ½. But the isospin of ud quarks are aligned for Σ^0 and antialigned for Λ^0, giving I=1 for the former and I=0 for the latter.
    - Strangeness arises with the strange quark. One strange quark gives -1; two -2, no strange quark 0, one anti strange quark +1, etc.
- Residual strong force
    - This force holds two nucleons together in the nucleus.
    - This force can be conveyed between uud protons and udd neutrons by the exchange of a particle called pion which can consist of two of u, d, $\bar{u}$, and $\bar{d}$.

Electroweak Force

- Particles that possess charge or weak charge can engage in the electroweak force.
- Quarks and leptons can be engaged in the electroweak force.
- Leptons do not have color charges and there are six leptons shown in the Table on the right.
- All six leptons have antiparticles, but whether antiparticles of the neutrinos are distinct is not determined.
- Electron, muon, and tauon are very much alike except their masses.
- The electroweak force is conveyed by the exchange of the four mediating bosons:
    - Massless photon for the electromagnetic part of the force
    - Heavy bosons, W^+, W^-, Z^0, for the weak part of the force



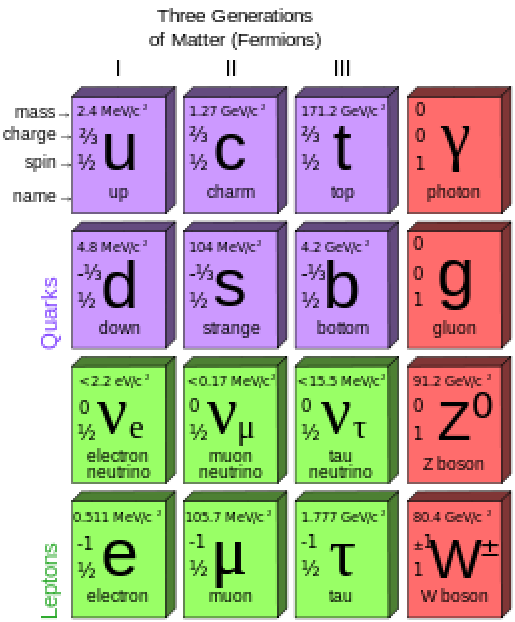
Leptons

Participants in gravitation and electroweak

	Spin	Mass	Charge
Electron, e	$\frac{1}{2}$	0.511	−1
e-neutrino, ν_e	$\frac{1}{2}$	$< 10^{-5}$	0
Muon, μ	$\frac{1}{2}$	106	−1
μ-neutrino, ν_μ	$\frac{1}{2}$	< 0.2	0
Tauon, τ	$\frac{1}{2}$	1.78×10^3	−1
τ-neutrino, ν_τ	$\frac{1}{2}$	< 20	0

- Why we have four different types of field quanta for the same field?
    - Spontaneously broken symmetry occurs at low particle energies.
    - At very high energies, the intrinsic mass of a particle becomes irrelevant and the behaviors of the mediating particles converge.
    - Neutrinos are not charged and thus do not engage in electromagnetic interactions. But all leptons have weak charge and engage in weak interactions. The reason why the electromagnetic force is larger than the weak force is due to whether the mediating particles have mass or not. Since photons do not have mass, the electromagnetic force is stronger than the weak force which is short-ranged.

The Standard Model combines the electroweak force and the strong force to show the symmetry among six leptons, six quarks, and 4 mediating bosons. See the Figure below. The particles are organized by mass from light to heavy (left to right) and by charge (2/3. -1/3, 0, -1)e. The electroweak force's spontaneously broken symmetry provides a problem to the Standard Model. A solution might be related to Higgs Boson, its discovery is one of the most important goals of the current elementary particle physics.



Three Generations of Matter (Fermions)

	I	II	III	
mass charge spin name	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon
Quarks	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon
	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson
Leptons	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson

Gravitational Force

- Gravitational force applies to all particles with mass or any other form of energy.
- The force is attractive.
- No quantum aspects of the force have been observed possibly due to its weakness.
- In theory, the mediating boson should have a spin of 2 and massless (because it is long range).