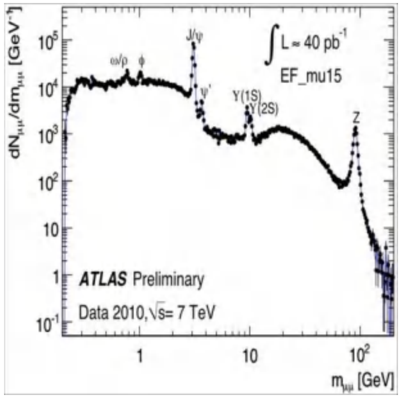
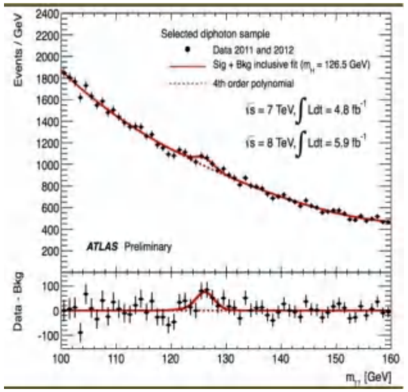




An Introduction to Particle Physics

The Universe started with a Big Bang

What do you think?

What is all the matter in the Universe made of?

and

What holds it together?

1. All matter is comprised of Leptons and Quarks.
2. Force carrier particles hold all matter together.
   – (There are 4 fundamental forces – Strong, Weak, Electromagnetic, Gravity).

The Universe started with a Big Bang

What is our Universe 'made of'?

- Particle physics aims to understand
  - Elementary (fundamental) particles
  - Elementary (fundamental) forces

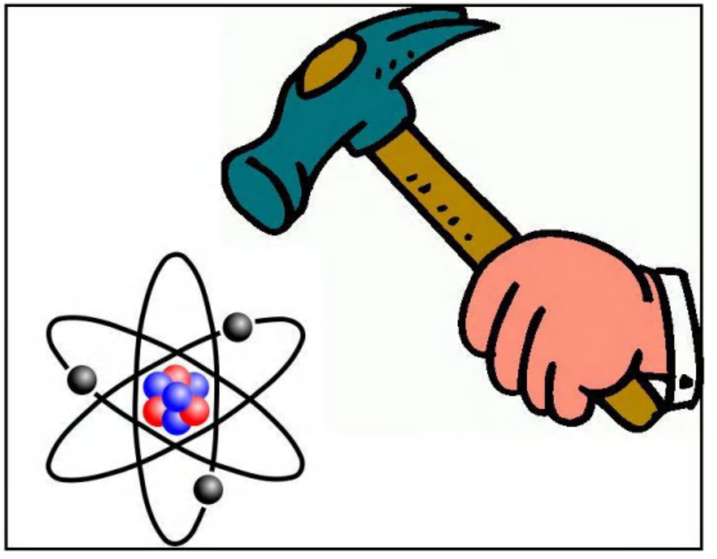
What do we mean when we say a particle or force is 'elementary' or 'fundamental'?

Fundamental Particles

In particle physics, an elementary particle or fundamental particle is a particle **not <u>known to have substructure</u>**

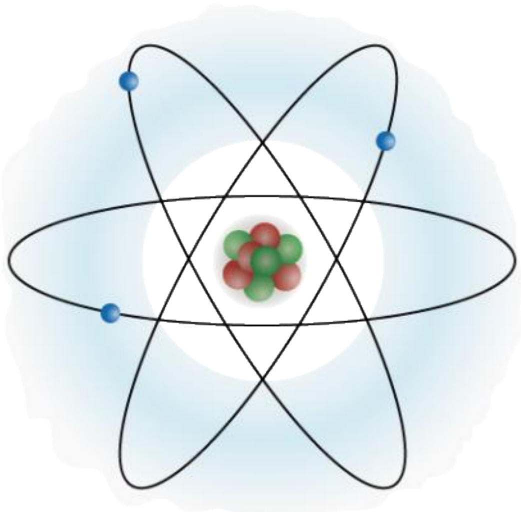
If an elementary particle truly has no substructure, then it is one of the **basic building blocks of the universe** from which all other particles are made.

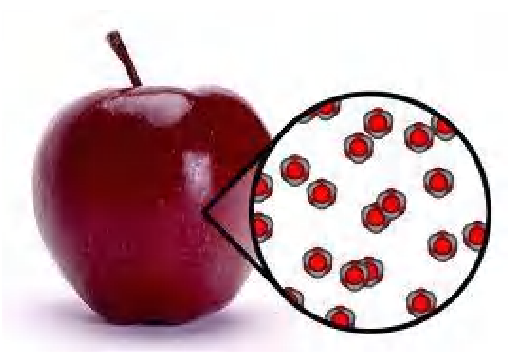
What are the fundamental particles of nature?



Inside the Atom

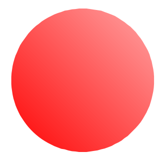
Atom



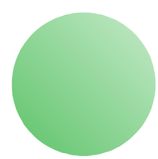


Electron

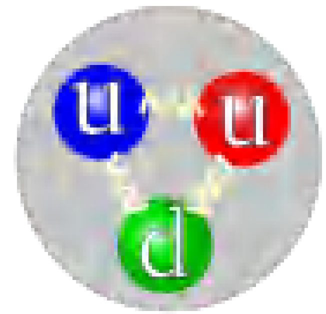
Proton



Neutron

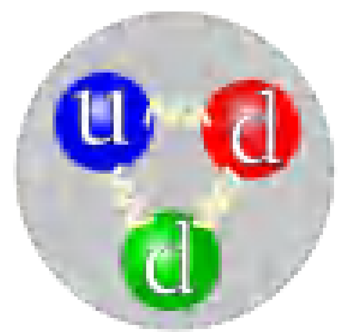


Proton



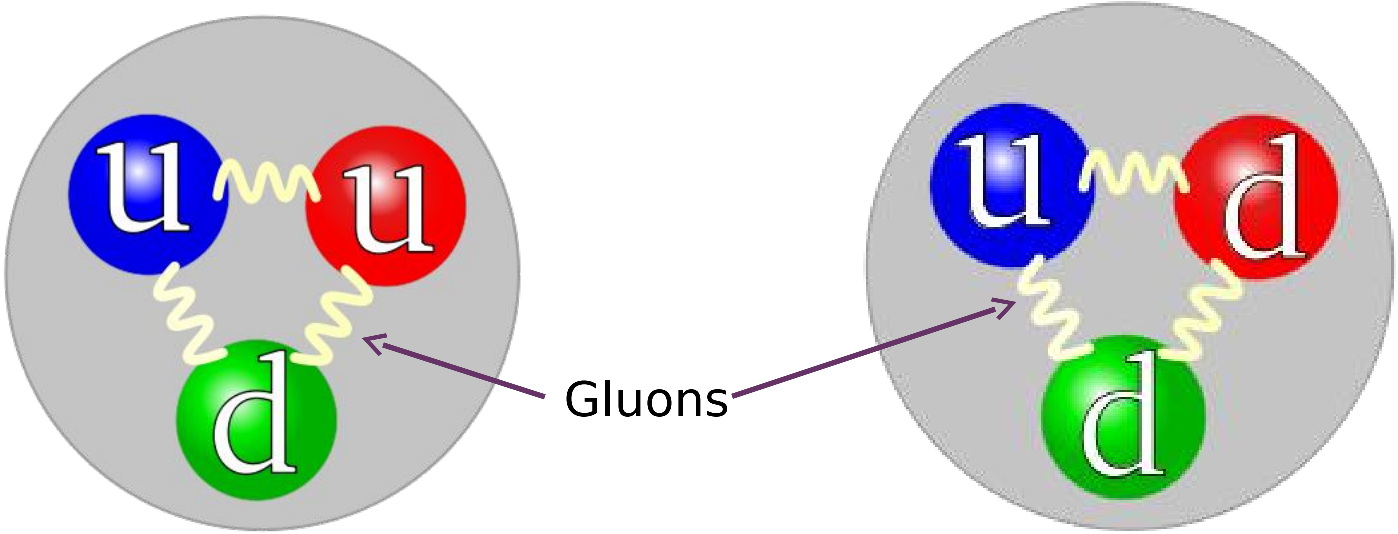
Quarks &
Gluons

Neutron



Particles made of
quarks and gluons
are called **hadrons**

Inside the Atom



Proton

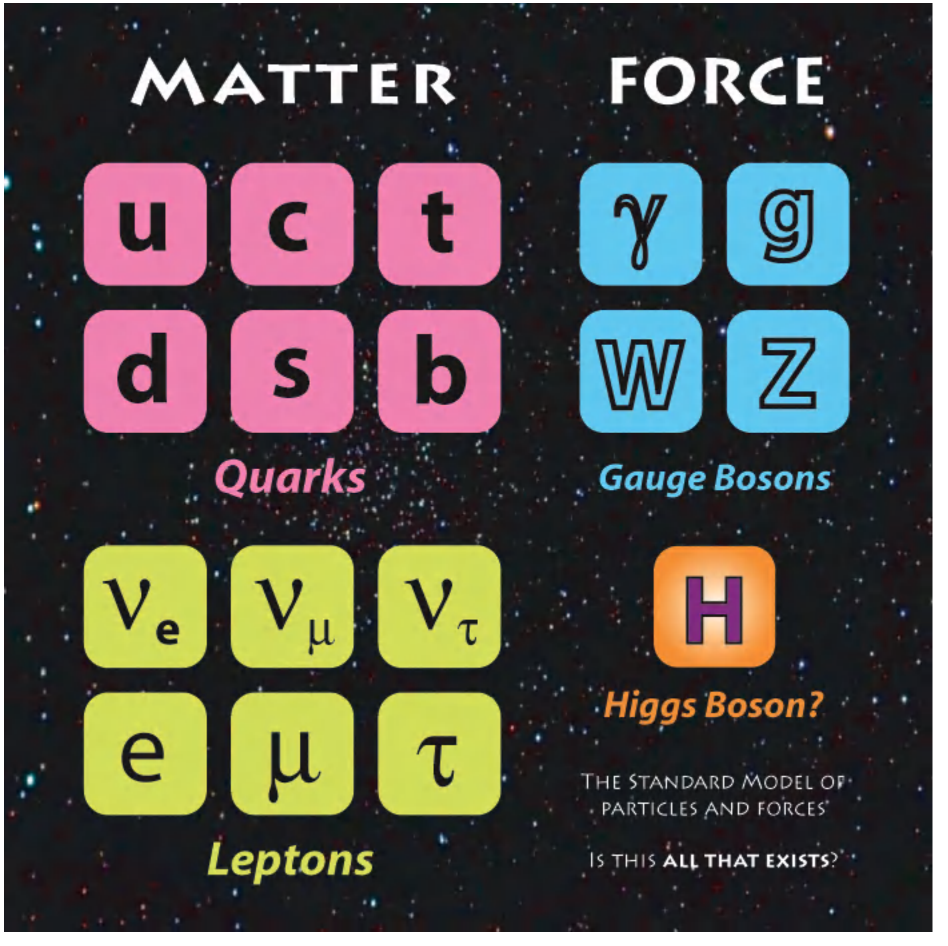
Quarks:
Up (charge 2/3)
Up (charge 2/3)
Down (charge -1/3)

Neutron

Quarks:
Up (charge 2/3)
Down (charge -1/3)
Down (charge -1/3)

What is the electric charge of the Proton and the neutron?

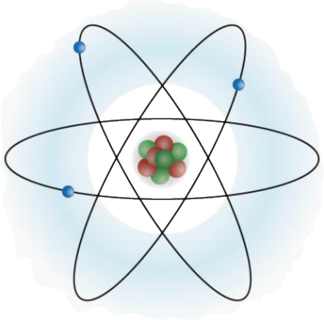
The Standard Model of Particle Physics



The Standard Model of Particle Physics

Fundamental Particles:

- ☑Electron (e)
- ☑Up Quark (u)
- ☑Down Quark (d)
- ☑Gluon (g)



The Standard Model of Particle Physics

Quarks and Leptons

Matter particles:

Fermions - spin ½ particles

Force carriers

Mediate the forces

Bosons – spin integer particles (0, 1,…)

Higgs **responsible for mass**

What are Leptons and Quarks?

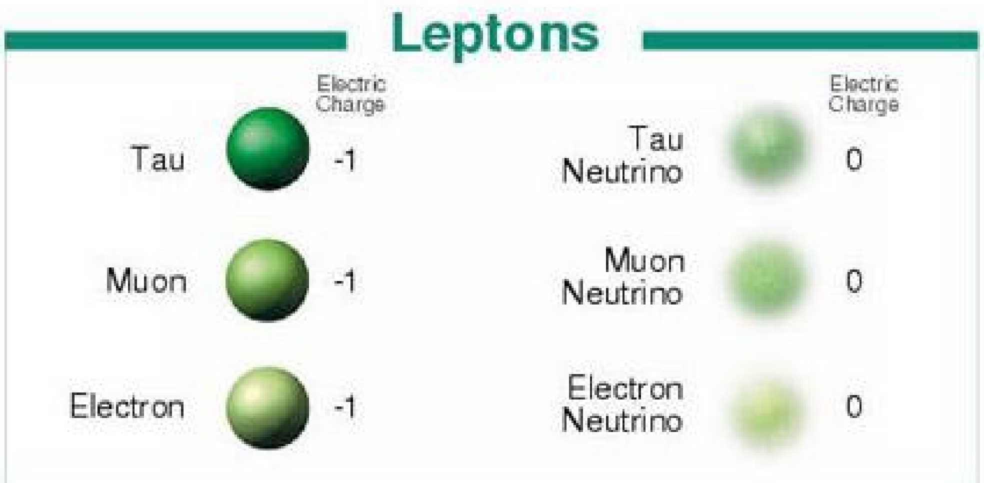
- They are sub-atomic particles.
- They are fundamental particles incapable of being subdivided into smaller particles.
  a. There are 6 Leptons and 6 Quarks.
  b. The nucleus is a conglomeration of quarks which manifest themselves as protons and neutrons.
  c. Each elementary particle has a corresponding antiparticle.

Neutrinos

- Neutrinos are three of the six leptons
- They have no electrical or strong charge
- Neutrinos are very stable and are all around
- Most neutrinos never interact with any matter on Earth

The Standard Model of Particle Physics

Leptons



Electrically Charged **Electrically Neutral**

Only electrons are **stable**!
Muon(μ) lifetime = 2 x 10-6 s
Tau (τ) lifetime = 3 x 10-13 s

Neutrinos have almost no mass and are electrically neutral

Muons can be detected from cosmic rays hitting the Earth’s atmosphere

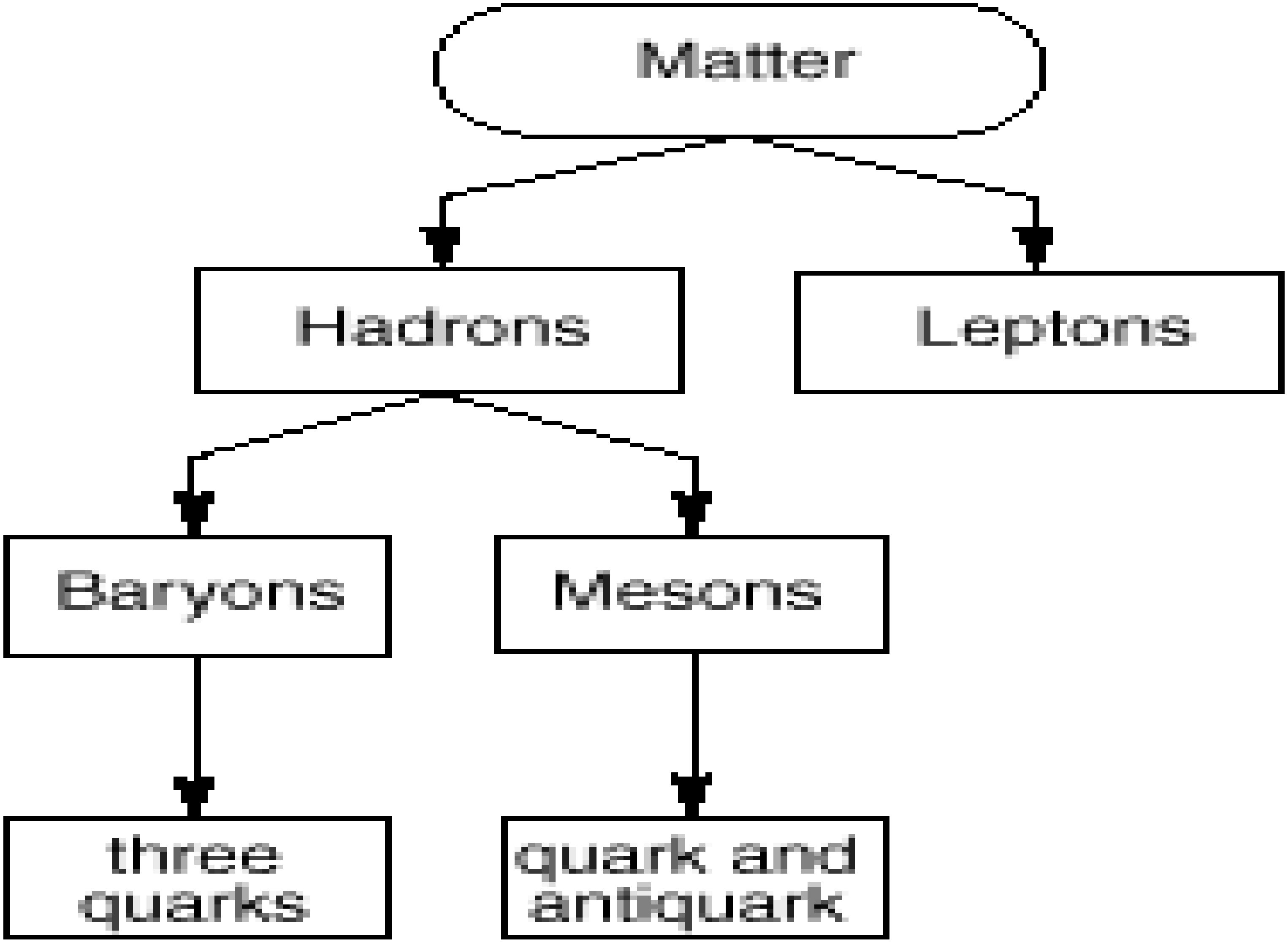
Leptons

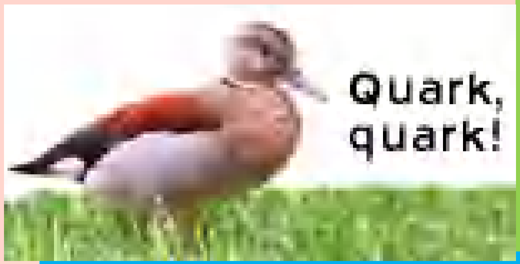
- They are elementary particles
- Have no measurable size or structure
- Known leptons:
  - Electron &electron neutrino
  - Muon &muon neutrino
  - Tau &tau neutrino
- The neutrinos do not have electric charge
- And each of the six has an anti-particle

Electron, Muon, Tau

- All three have a charge of -1
- The electron is found in everyday matter
- The muon and the tau have a lot more mass than the electron
- The muon and the tau are not part of everyday matter because they have very short lifetimes

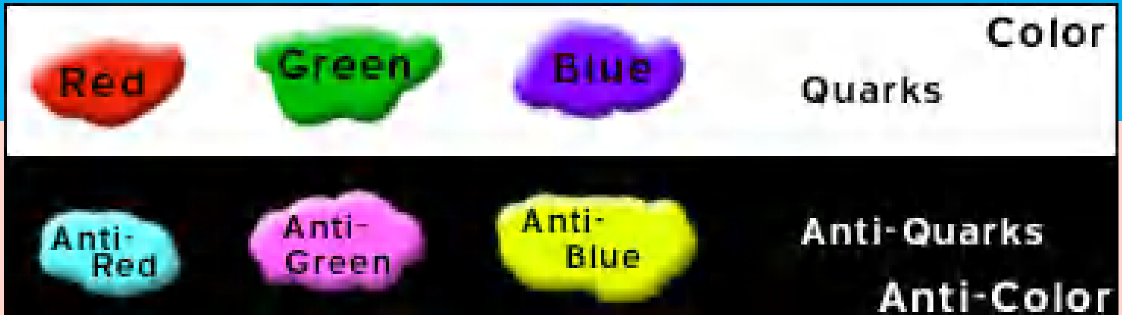
Classification of Matter





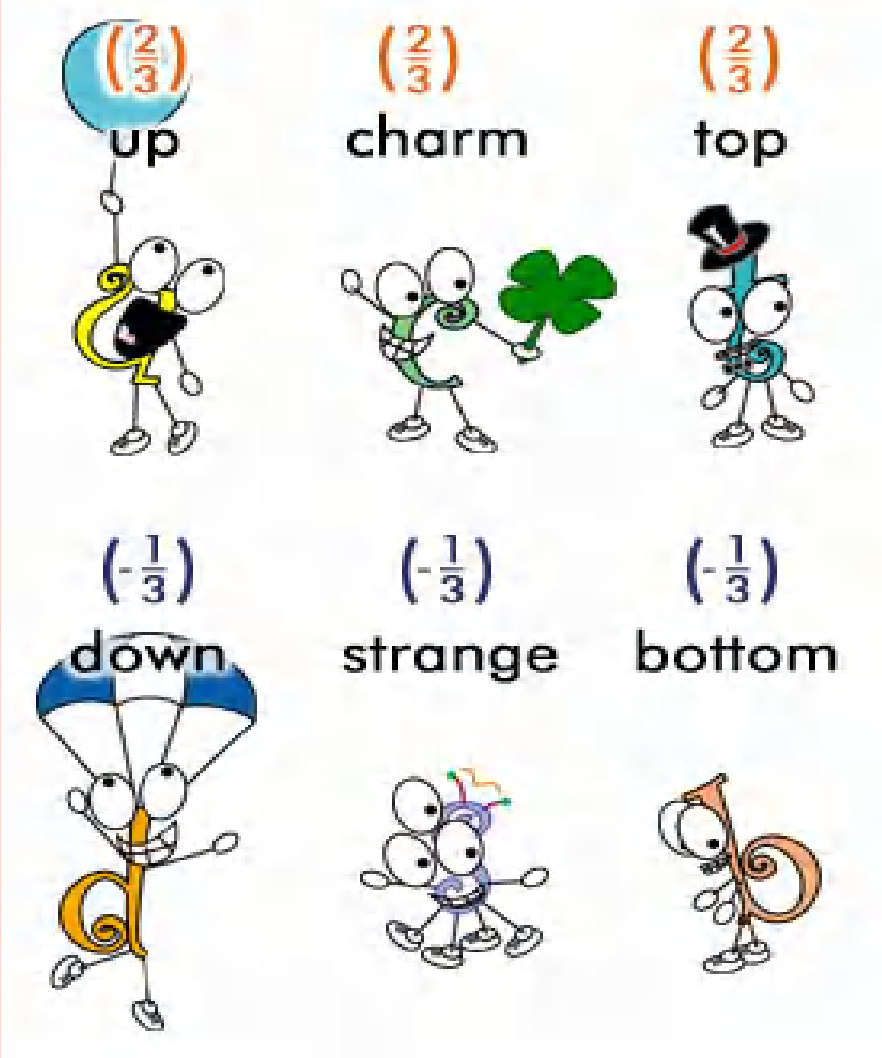
Quarks

- Each quark has an anti-particle
- Quarks have a physical property called color, it could be blue, green or red
- Each color also has an anti-color
- They are not really different colors, it is a property, like charge
- Quarks cannot exist individually because the color force increases as they are pulled apart.



Quarks

- Elementary particles
- Used to create other particles
- Six quarks:
  - Up
  - Down
  - Strange
  - Charm
  - Bottom
  - Top



The Standard Model of Particle Physics

Quarks

Electrically Charged

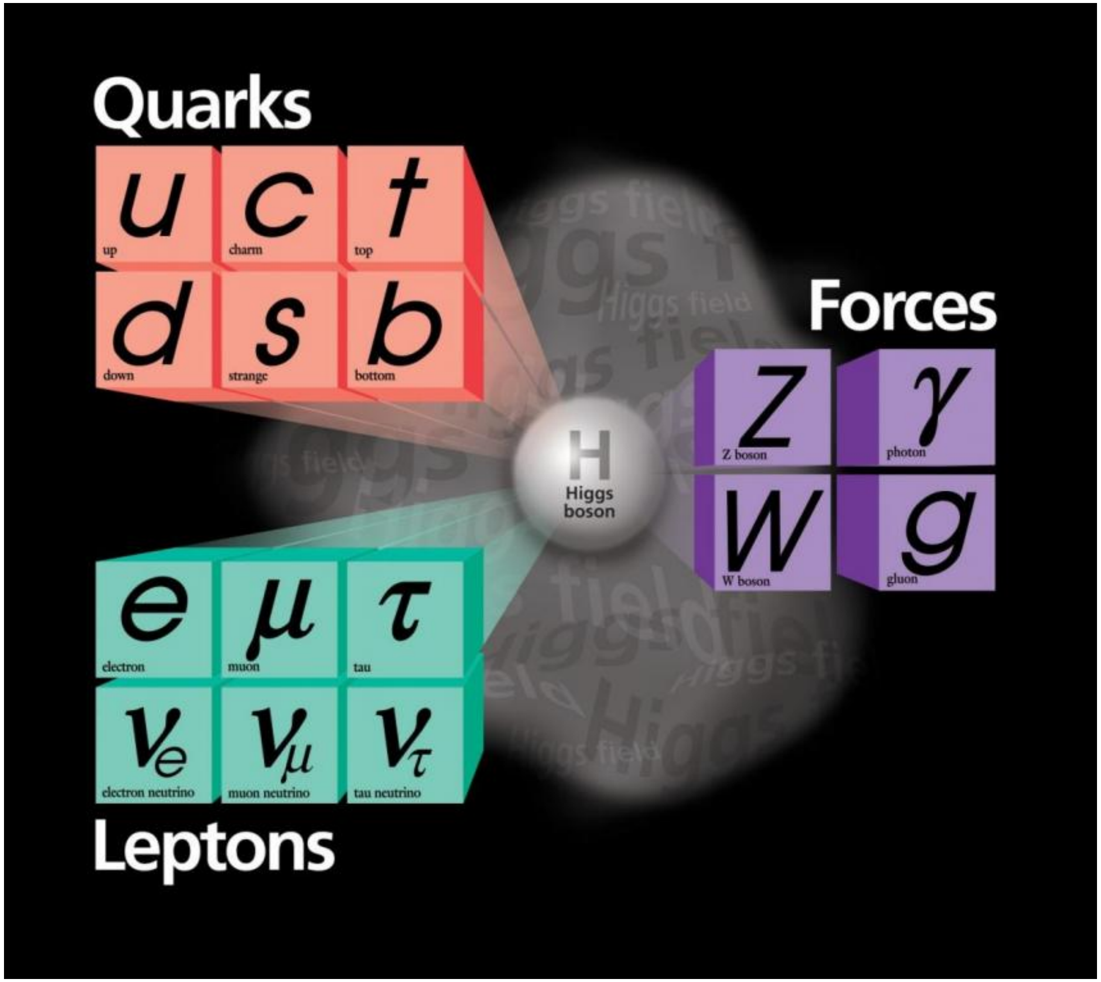
Quarks **must** exist as Hadrons in groups of TWO (Mesons) of THREE (Baryons)*

Proton

Neutron

The Standard Model of Particle Physics

Higgs Boson



July 2012 the experiments at the LHC finally found our missing part of the Standard Model

The Higgs Boson

This particle gives mass to all other fundamental particles

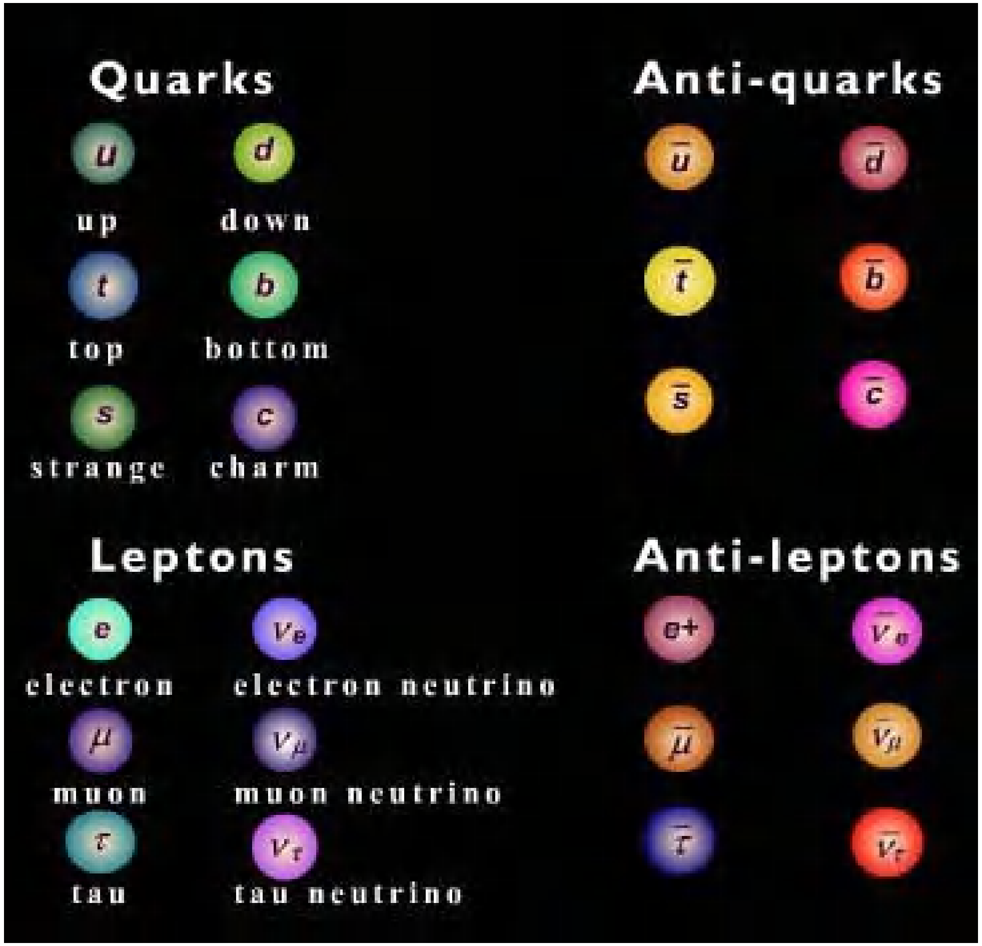
The Standard Model of Particle Physics

Higgs Boson

On the 8th October 2013 the Nobel Prize for Physics was awarded to Francois Englert and Peter Higgs for their contribution to the development of the theory that predicted the Higgs boson

Matter and Antimatter

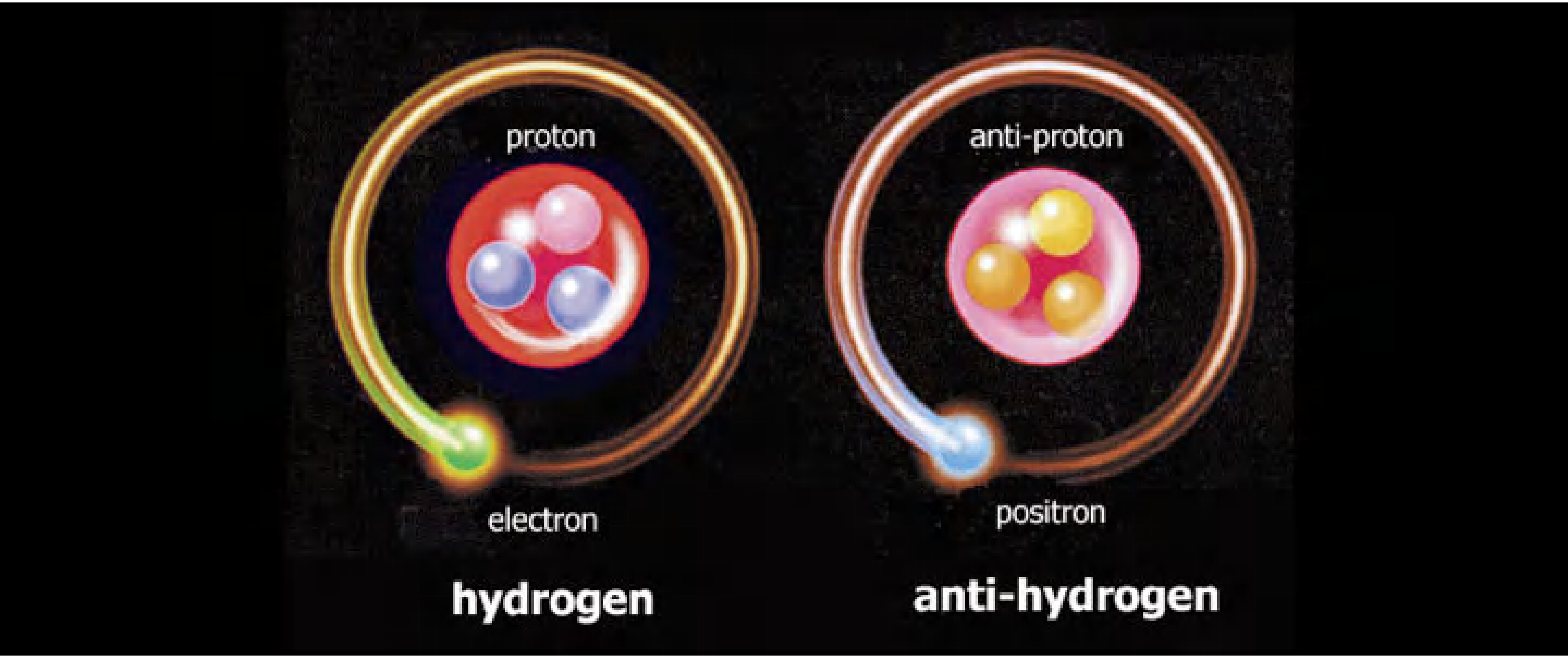
Antiparticles



Each particle has a partner with the same mass (and other properties) but **OPPOSITE** charges

Matter and Antimatter

Anti Matter



Matter and Antimatter

Anti Matter

Matter and Antimatter

Antiparticles

Annihilation of a particle and its antiparticle into a force mediator, a photon, gluon or W or Z

Pair Production into two new particles with opposite charge

Matter vs. Anti-Matter

- For every particle, there is an anti-particle.
  - Anti-particles have the same mass as the particle.
  - Anti-particles have the same but opposite charge.
  - Anti-particles have the opposite spin.

	Particle	Anti-particle
Name	up quark	Anti-up quark
Symbol	u	$\bar{u}$
mass	7.11×10^{-30} kg	7.11×10^{-30} kg
Charge	$+\frac{2}{3}$	$-\frac{2}{3}$

Generations of Matter

Particles of the Standard Model

Quarks

Name	up	charm	top
Symbol	u	c	t
Charge	$+\frac{2}{3}$ e	$+\frac{2}{3}$ e	$+\frac{2}{3}$ e
	down	strange	bottom
	d	s	b
	$-\frac{1}{3}$ e	$-\frac{1}{3}$ e	$-\frac{1}{3}$ e

Leptons

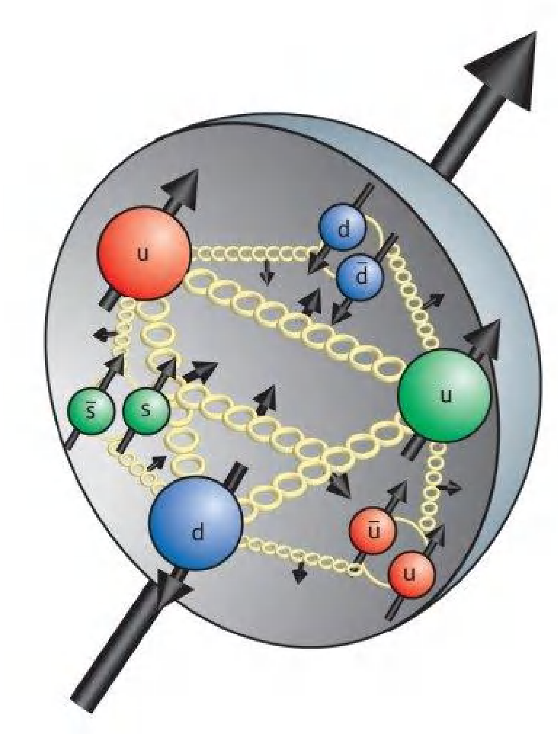
electron	muon	tau
e	μ	τ
-1e	-1e	-1e
electron neutrino	muon neutrino	tau neutrino
ν_e	ν_μ	ν_τ
0	0	0

Note: For each particle there is a corresponding antiparticle with a charge opposite that of its associated particle.

The Standard Model of Particle Physics

Strong Force

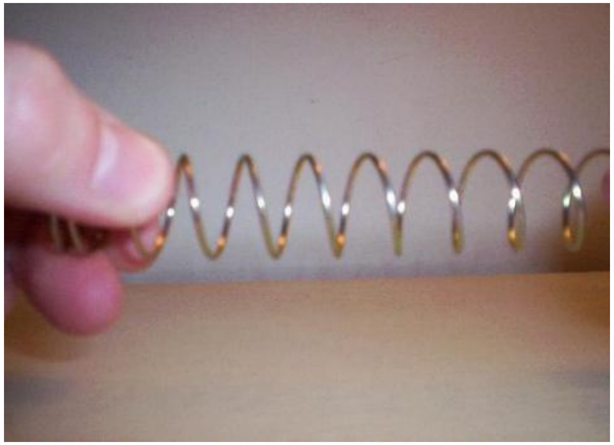
Strong force is found inside hadrons (protons and neutrons)



- The gluon ‘glues’ the hadrons together

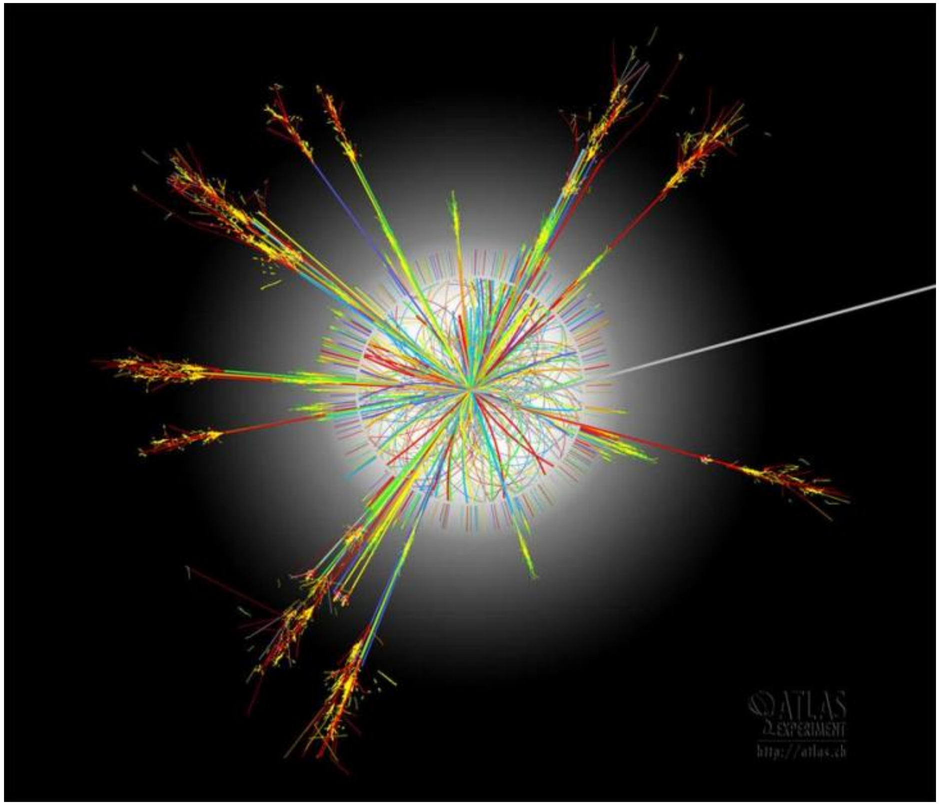
- The strong force is different because as particles get further away from one another…

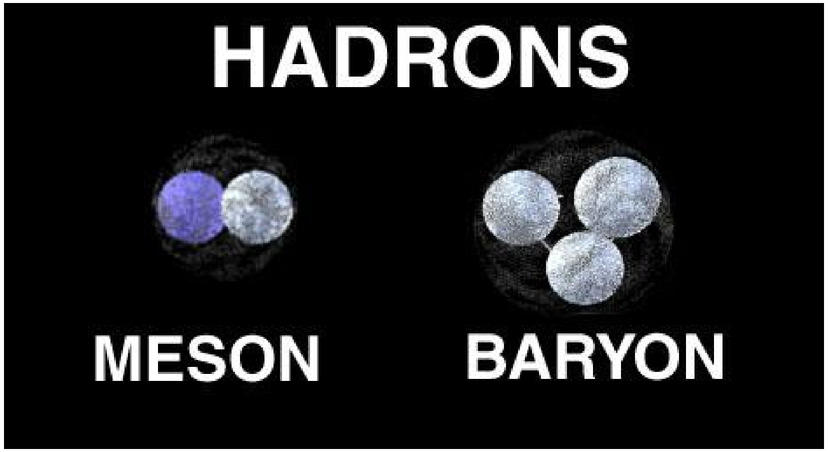
The force gets stronger!



The Standard Model of Particle Physics

Strong Force





So what happens when we collide particles at high energies?

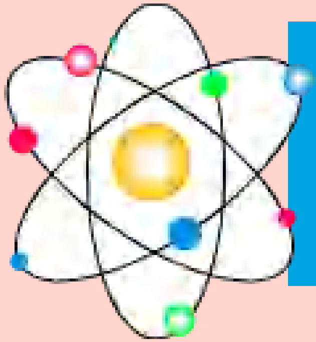
Don’t we pull the quarks inside the hadrons apart?

Hadrons

- Consist of particles that interact through the strong force.
- Hadrons are set apart from leptons because they are composed of other, smaller particles
- Separated into two categories
  - Baryons & Mesons
- These are distinguished by their internal structure
- Most of the mass we observe in a hadron comes from its kinetic and potential energy.

Baryons

- Baryons are composed of three quarks
- All but two baryons are very unstable, they are:
  - The proton and neutron!!
- Most baryons are excited states of protons and neutrons
- Other Baryons



Protons & Neutrons

- Protons are made of three quarks, two up quarks and a down quark
  - This is written as **uud**
- Neutrons are also made up of three quarks, one up quark and two down quarks
  - This is written as **udd**

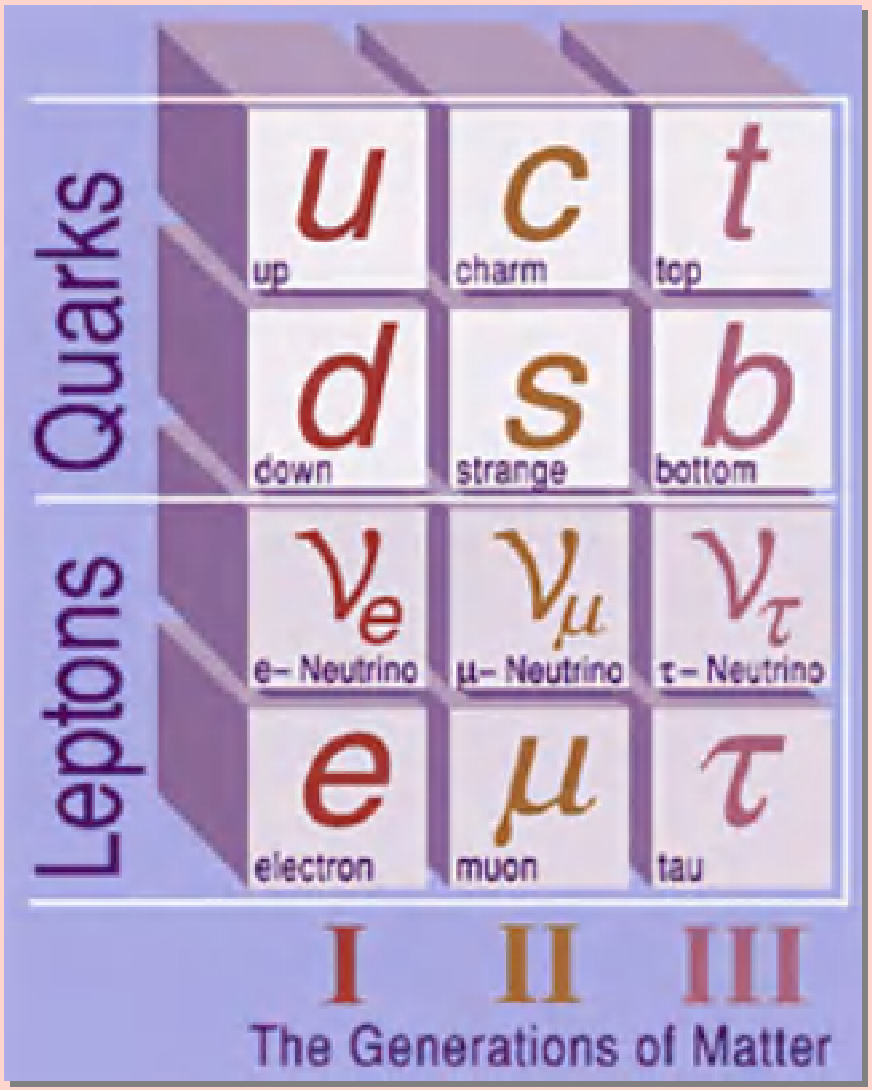
Mesons

- Composed of a quark and anti-quark
- All are very unstable
- They are not part of everyday matter
- Have a mass between that of the electron and the proton
- All decay into electrons, positrons, neutrinos and photons.

Baryons, Mesons, & Leptons

- These three types of particles were originally categorized by their masses
  - Baryons from the Greek for heavy
  - Mesons from the Greek for intermediate
  - Leptons from the Greek for light
- Now they are classified by internal structure
  - Leptons are elementary particles
  - Mesons are made of a quark and anti-quark
  - Baryons consist of three quarks

Generations of Matter



- Mass increases from 1 generation to the next
- Going down in each generation, the charges are:

  +2/3, -1/3, 0, -1
- These are all in multiples of the elementary charge

Fermions

- Fermions are particles that obey the Pauli Exclusion Principle
- A fermion is any particle that has a half-integer spin.
  - Ex. 1/2, 3/2, 5/2
- Quarks and leptons, as well as most composite particles, like protons and neutrons, are fermions.

Bosons

- Bosons are particles that do not obey the Pauli Exclusion Principle
- All the force carrier particles are bosons, as well as those composite particles with an even number of fermion particles (like mesons).
- They have integer spins
  - Ex. 0, 1, 2

Summary

Fermions			Bosons
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = 1*	Force Carrier Particles
Baryons (qqq)	Spin = $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$...	Spin = 0, 1, 2...	Mesons ($q\bar{q}$)

Contents

The Standard Model of Particle Physics

Fundamental Forces

Strong force:

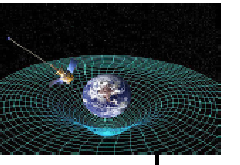
- occurs between all objects that carry colours (**only quarks**)
- very short range force ~ 1 fm
- responsible:
  - holding quarks together inside hadrons
  - the stability of the nuclei (glues protons together)

Weak Force:

- occurs between quark and between leptons including neutrinos
- very short range force ~ 0.001 fm
- responsible:
  - for radioactive decay (manufacturing new elements)
  - hydrogen fusion inside stars

The Standard Model of Particle Physics

Fundamental Forces



Gravity:

- the first known force, occurs between all objects that carry energy
- long range force related to space and time
- responsible for the movements of the planets, stars and galaxies
- well described by general relativity (GR)

Electromagnetic:

- occurs between all objects that carry electric charge (quarks and charged leptons)
- responsible for almost all phenomena countered in the daily life: chemistry biology, friction, etc.
- long range force and well described by Maxwell's equations

The Four Fundamental Forces

Strong	Weak
Electromagnetic	Gravity

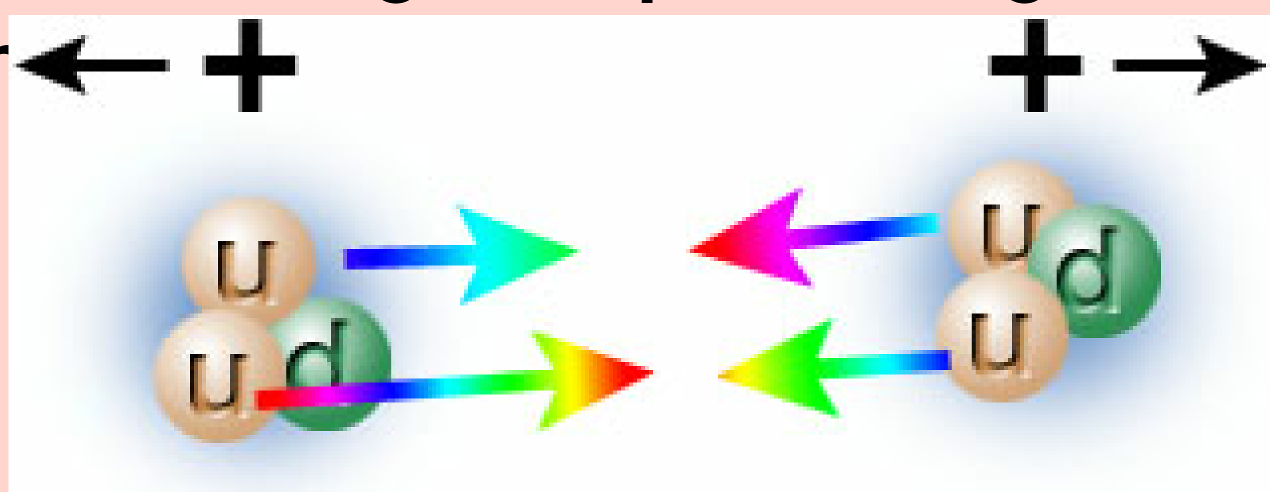
These forces include interactions that are attractive or repulsive, decay and annihilation.

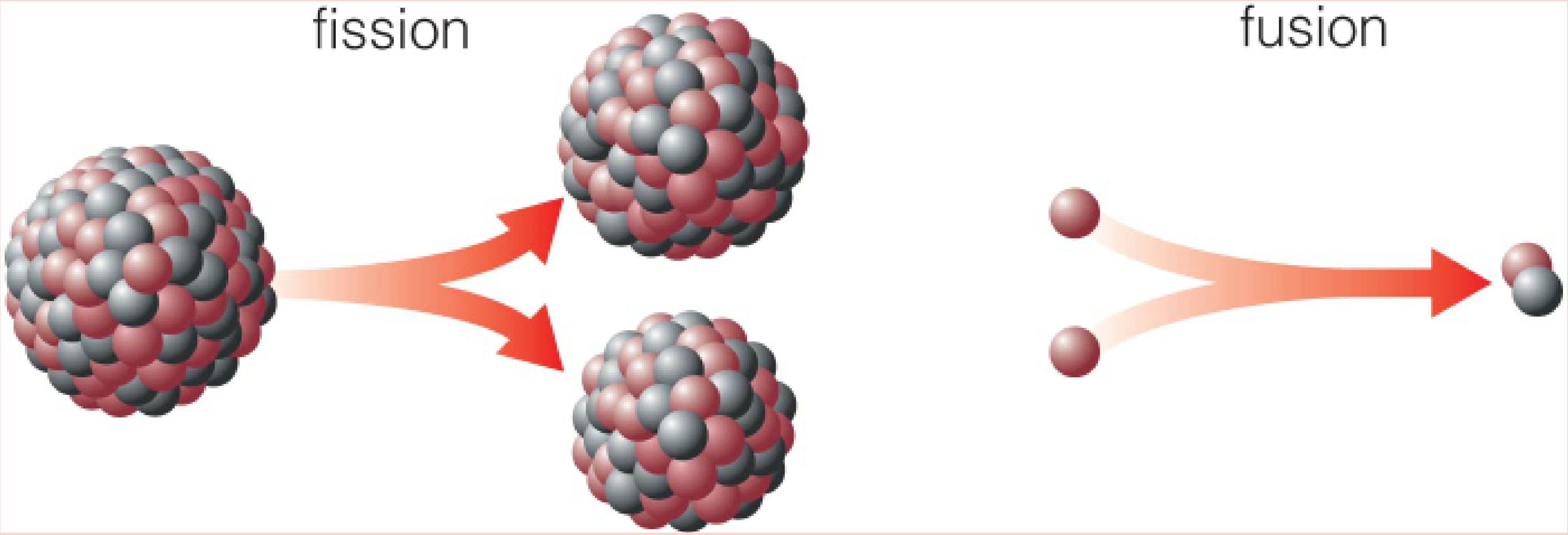
The Strong Force

- The strongest of the 4 forces
- Is only effective at distances less than 10^{-15} meters (about the size of the nucleus)
- Holds quarks together
- This force is carried by gluons

Residual Strong Force

- We know that protons and neutrons are bound together in the nucleus of an atom
- This is due to the residual strong force that is binding the quarks together in each





Fission

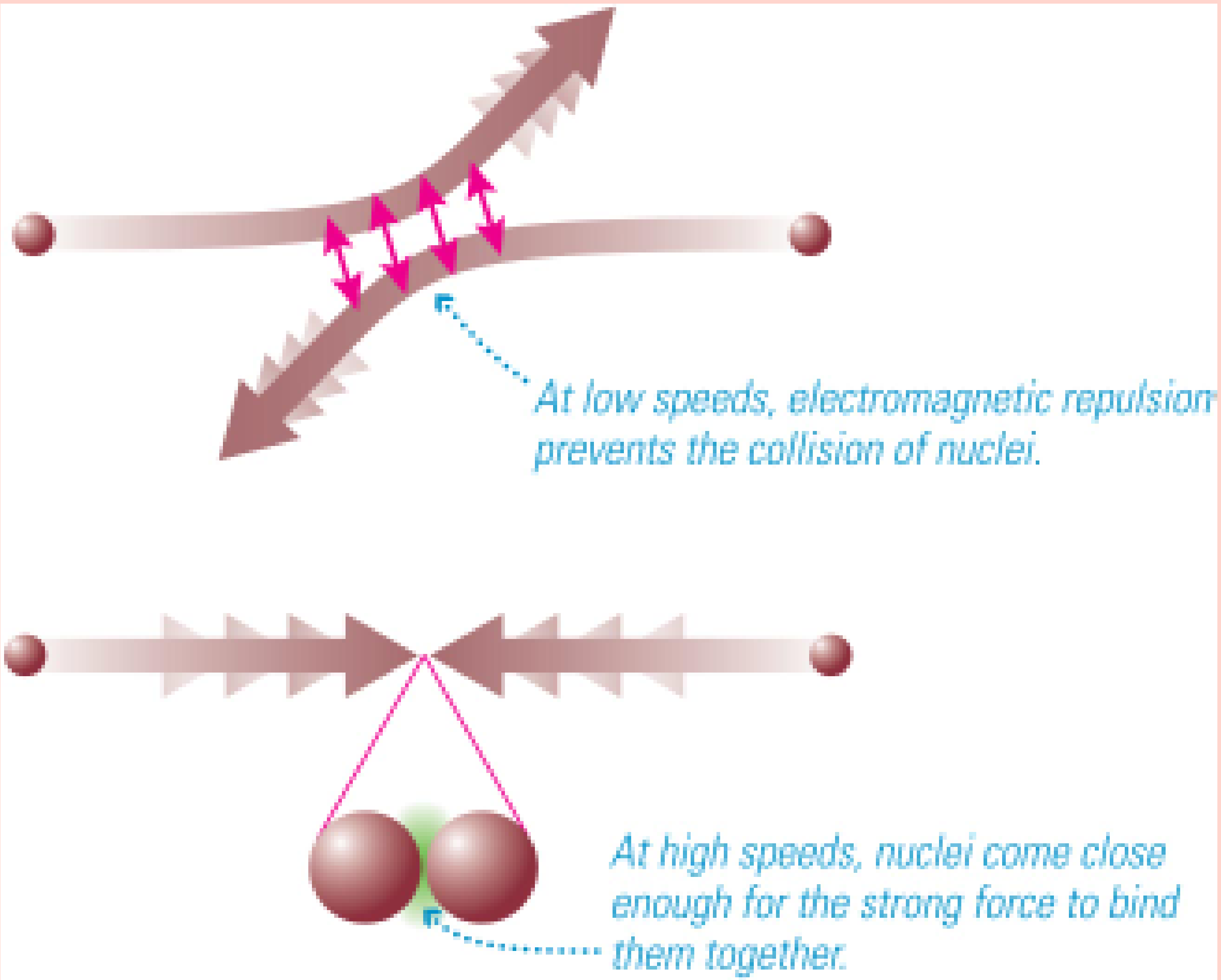
Big nucleus splits into smaller pieces

(Nuclear power plants and atomic bombs)

Fusion

Small nuclei stick together to make a bigger one

(Sun, stars)



High temperature and pressure enables nuclear fusion to happen in the core of the Sun.

Gravitational contraction ensures that the density is high enough such that collisions will occur at a high enough rate (~10^{38}) per second.

Example (Using Atomic Mass Units)

- Alternatively, we could solve the problem using the atomic mass unit instead of the mass in kilograms.
  - $m_p + m_n = 2(1.00728\ u) + 2(1.00867\ u) = 4.03190\ u$
  - $m_{He} = (6.6447 \times 10^{-27}\ kg)/(1.6605 \times 10^{-27}\ kg/u) = 4.0016\ u$
  - $\Delta m = (m_p + m_n) - m_{He}$
  - $\Delta m = 4.0319\ u - 4.0016\ u = 0.0303\ u$
  - Since 1 u = 931.5 MeV
  - $E = (0.0303\ u)(931.5\ MeV/u) = 28.2\ MeV$

The Weak Force

- A very short-ranged nuclear interaction that is involved in beta decay
- This is ten thousand billion times weaker than the strong force (10^{-13})
- Effective only at distances 1000 times smaller than the strong force
- This force is carried by the W^+, W^-, and the Z^o boson particles.

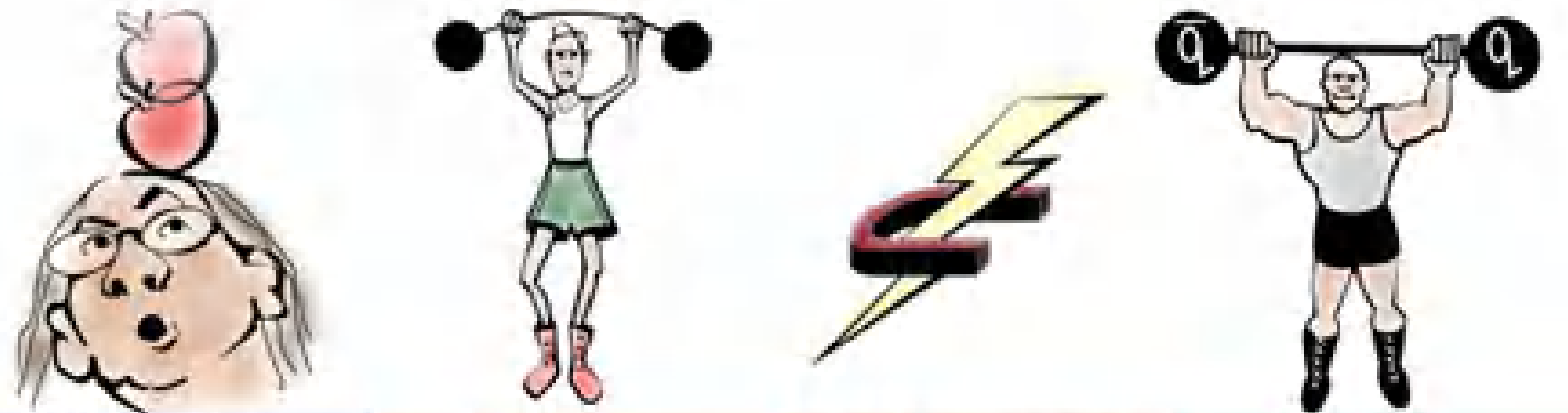
The Electromagnetic Force

- Causes opposite charges to attract and like charges to repel
- Carried by a particle called a photon
- It’s effects decrease with the inverse square of the separation (as we learned earlier)

Gravity

- Has a negligible effect on elementary particles
- A long-range force (as we learned earlier)
- Carried by the graviton
- This is by far the weakest of the 4 fundamental forces

Fundamental Forces Summary



	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Summary

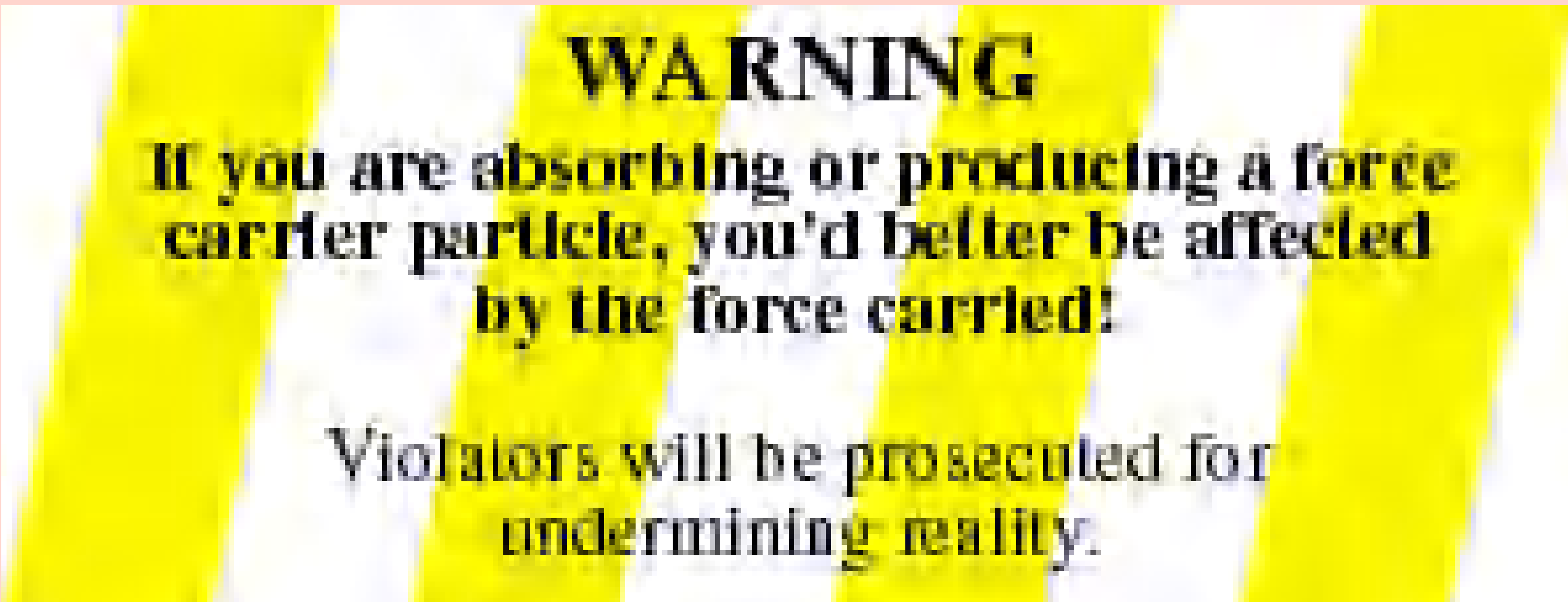
The fundamental interactions of nature

Interaction (force)	Relative strength	Range of force	Mediating field particle
strong	1	≈ 1 fm	gluon
electromagnetic	10^{-2}	proportional to $1/r^2$	photon
weak	10^{-13}	$< 10^{-3}$ fm	$W^{\pm}$ and Z bosons
gravitational	10^{-38}	proportional to $1/r^2$	graviton

Which Fundamental Interaction/ Force is responsible for:

- Friction?
  - Electromagnetic.
- Nuclear Bonding?
  - Residual Strong Nuclear.
- Orbiting Planets?
  - Gravity.
- Which force carriers have not been observed?
  - Gravitons (Gluons have been observed indirectly)

Force Carrying Particles



Gluons

- Gluons are exchanged between all particles that have color
- Gluons are a mixture of color and anti-color
- Gluons themselves can be a source of other gluons
- But, as their name implies, they are bound together and cannot travel forever
- Interesting Fact

W^+, W^-, and Z Bosons

- These particles carry the weak force
- The W's have a charge of +1 and -1, each is the antiparticle of the other
- W's decay to form a quark and a differently charged anti-quark or a lepton and a neutrino
- Z's have no distinguishing characteristics so it is it's own anti-particle
- Z's decay to form quark & anti-quark pairs

Photons

- Carry the electromagnetic force
- They have no mass
- Photons do not carry charge
- Photons do carry energy

Gravitons

- Have not yet been observed
- Although, there is indirect evidence that gravitons do exist
- Gravitons should have no mass or charge
- If gravitational energy is radiated, it would be in discrete quanta

Other Baryons

- The Sigma Particle
  - Positive
  - Negative
  - Neutral
- The Lambda Particle
  - Single particle with no charge
- The Cascade
  - Two particles that have negative and no charge

More About Quarks

Flavor		Mass (GeV/c^2)	Electric Charge (e)
u	up G	0.004	+2/3
d	down G	0.008	-1/3
c	charm G	1.5	+2/3
s	strange G	0.15	-1/3
t	top G	176	+2/3
b	bottom G	4.7	-1/3

More About Leptons

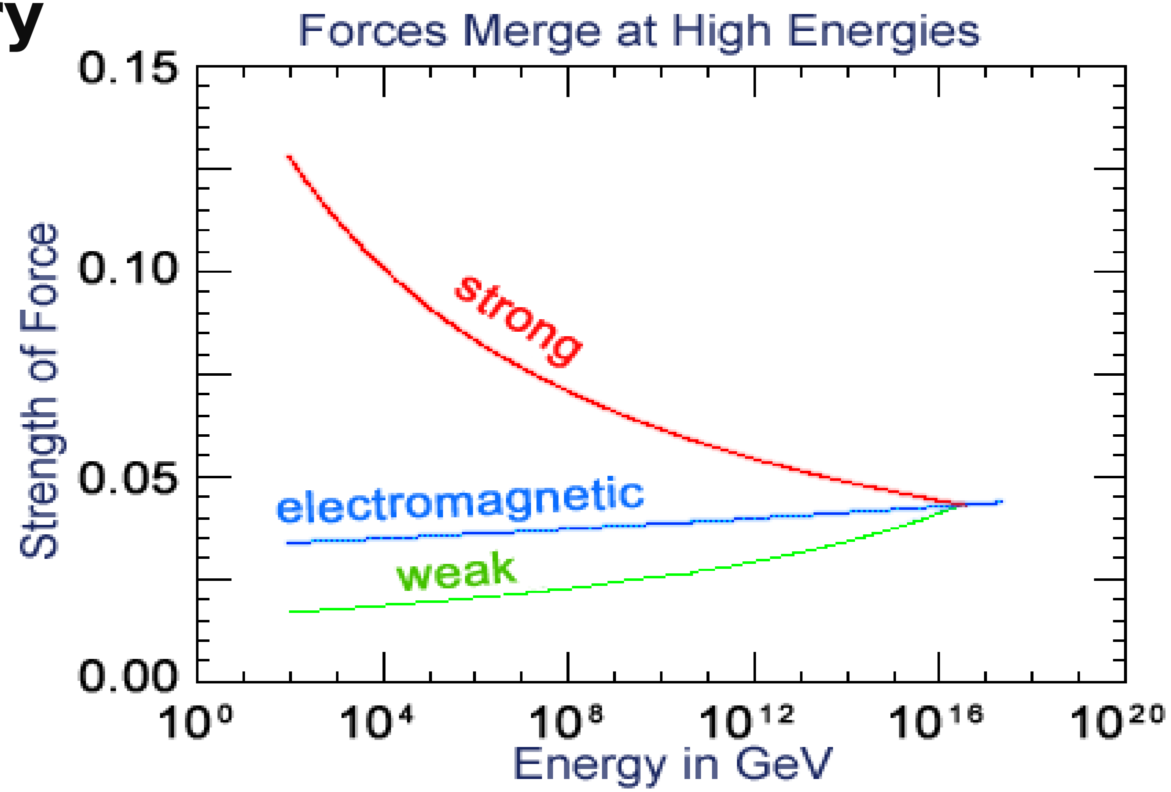
Flavor		Mass (GeV/c^2)	Electric Charge (e)
ν_e	electron neutrino	<7 x 10-9	0
e^-	electron	0.000511	-1
ν_μ	muon neutrino	<0.0003	0
μ^-	muon (mu-minus)	0.106	-1
ν_τ	tau neutrino	<0.03	0
τ^-	tau (tau-minus)	1.7771	-1

The Muon and Tau

- These two heavier leptons decay into lighter leptons or quarks
- When they decay, three particles are produced
- One of the particles produced is always it's corresponding neutrino
- The other particles could be a quark and it's anti-quark or another lepton and it's anti-neutrino
- Muon decay experiment on Mt. Washington in NH was explained through Einstein's theory of relativity.

Beyond the Standard Model

Grand Unified Theory



Finally we must incorporate Gravity (described by General Relativity) to form what physicists call **The Theory of Everything!**

Beyond the Standard Model

Beyond the Standard Model

Matter Antimatter Asymmetry

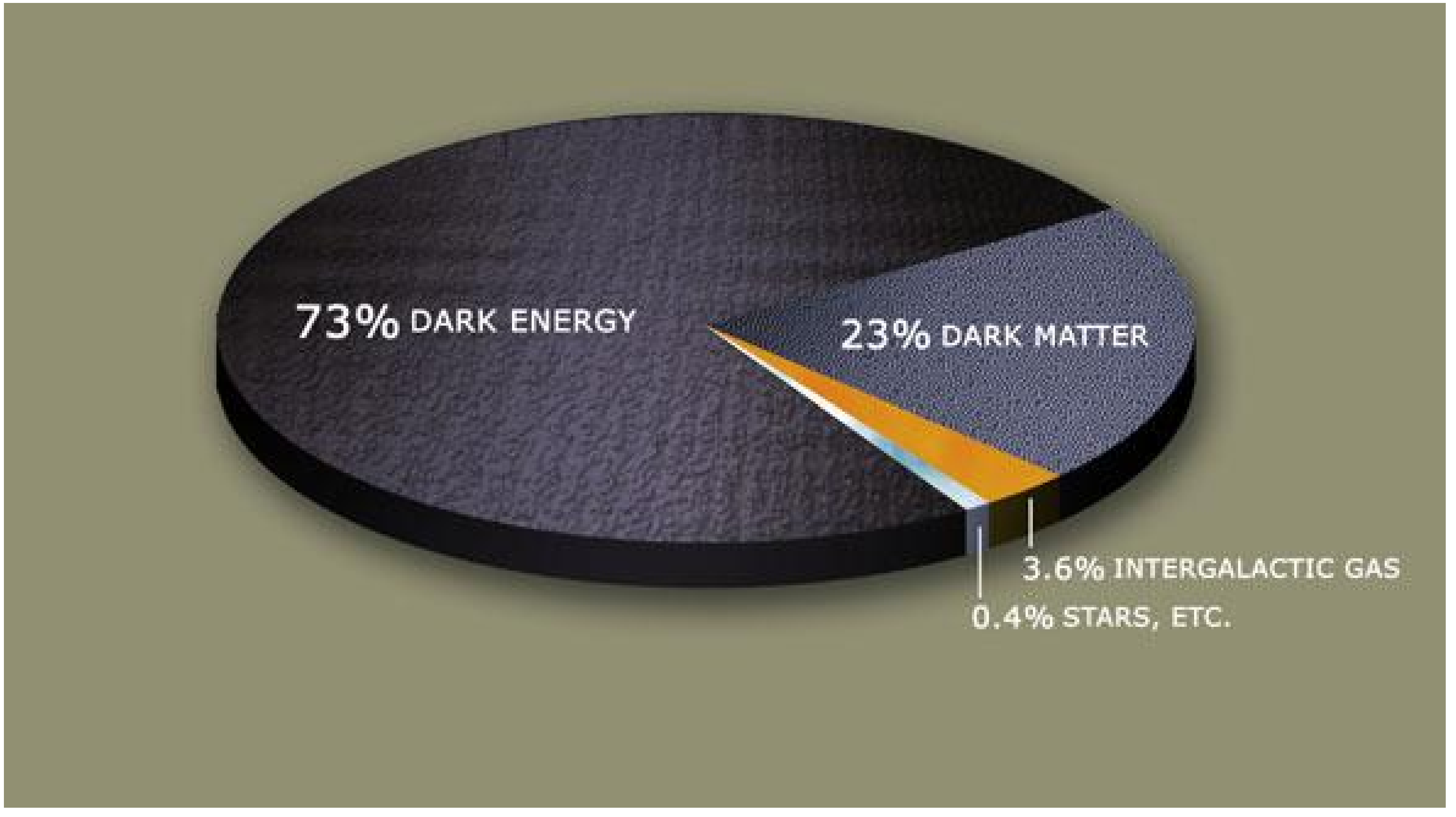
The Universe we see seems to be dominantly made from matter (not antimatter)

However the Standard Model predicts that they should have been created in equal amounts….
which would have annihilated each other as the Universe cooled

Beyond the Standard Model

Dark Energy and Dark Matter

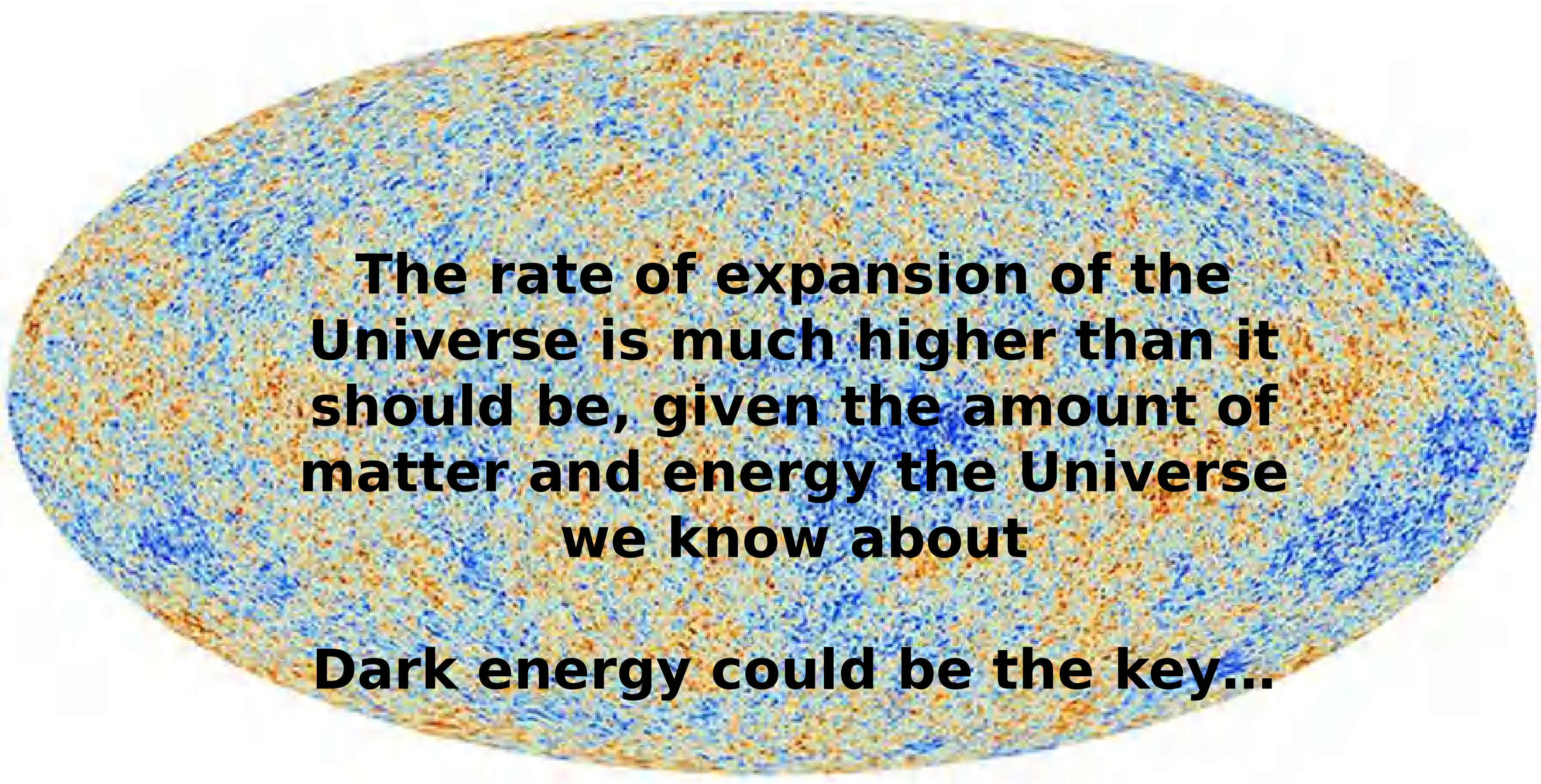
Cosmological observations have shown that the Standard Model explains only ~4% of the energy of our Universe!



Beyond the Standard Model

Dark Energy

Planck Telescope map of the universe



The rate of expansion of the Universe is much higher than it should be, given the amount of matter and energy the Universe we know about

Dark energy could be the key…

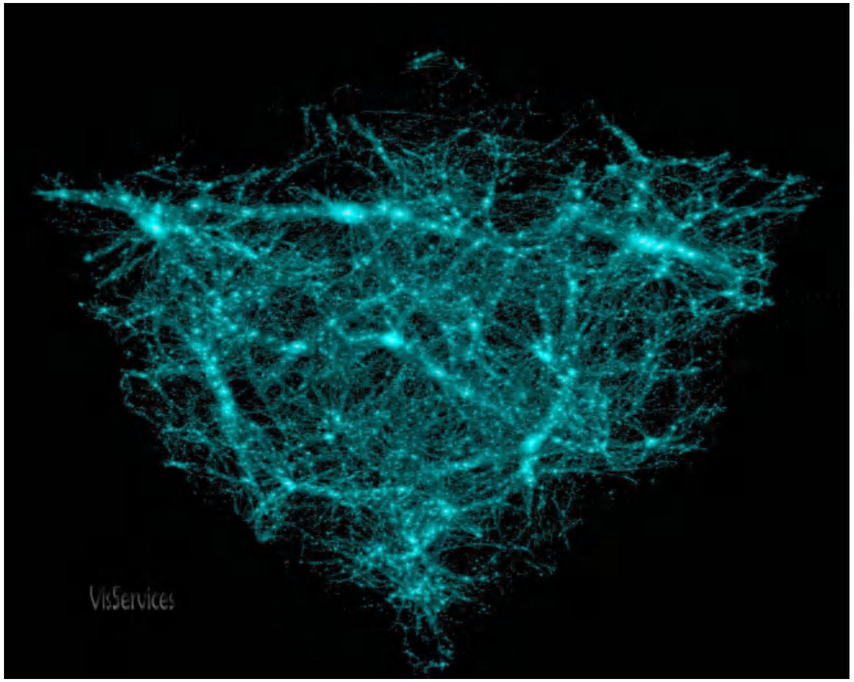
Beyond the Standard Model

Dark Matter

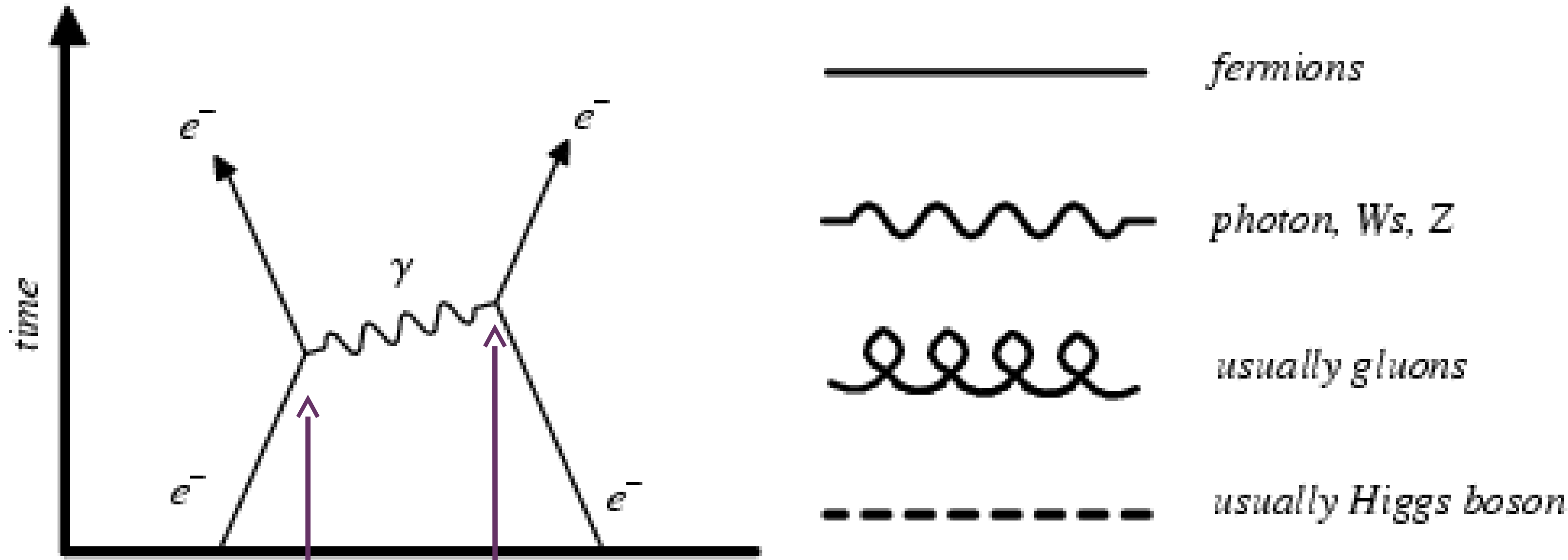
By studying Galaxy motion Cosmologists have estimated there should be *~23% of matter in the Universe that we cannot see*

…meaning that it does not interact electromagnetically (give off light)

Thus it feels the gravitation force and weak force only (weakly interacting)



Feynman Diagrams



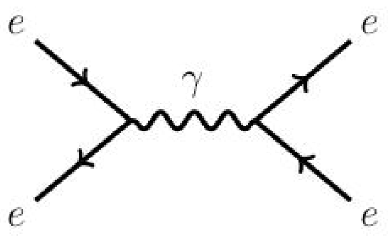
Pair production

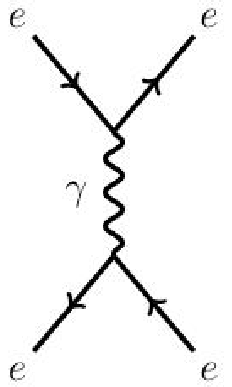
Particle-antiparticle
annihilation

Feynman Diagrams

Electromagnetic force

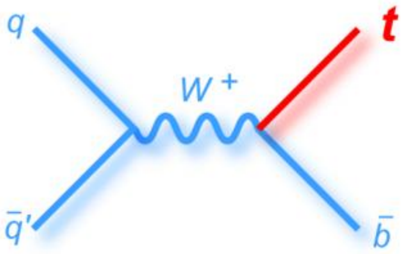
Exchange of a photon g between electrically charged particles

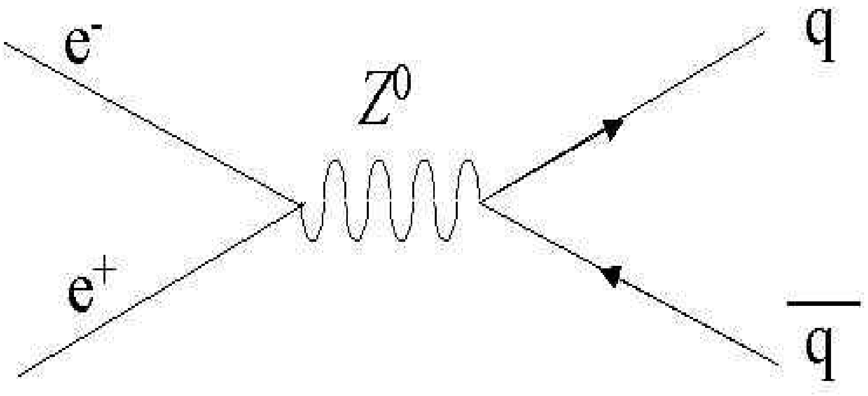




Weak force

Exchange of a W^+ W^- or Z^0 between particles

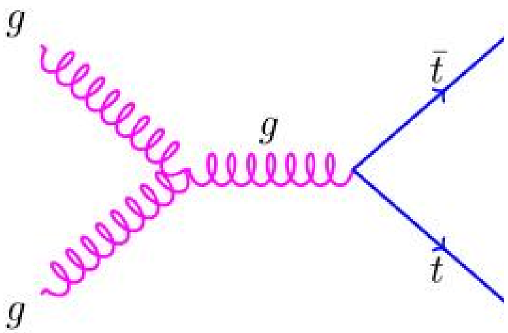


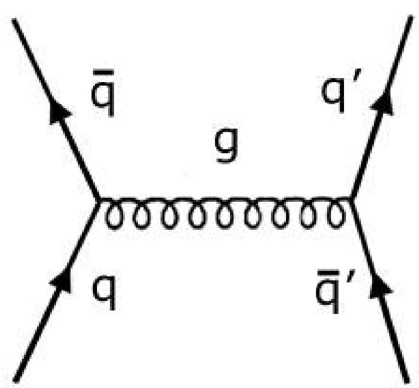


Feynman Diagrams

Strong Force

Exchange of a photon g between quarks or other gluons
This is the strongest force
And acts a little differently to the others…





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Finding New Particles